Conceptual Design of the Low-Power and High-Power SPL
A Superconducting H⁻ Linac at CERN

Editor: F. Gerigk
Knowledge transfer is an integral part of CERN’s mission.
CERN publishes this report Open Access under the Creative Commons Attribution 4.0 license (http://creativecommons.org/licenses/by/4.0/) in order to permit its wide dissemination and use. The submission of a contribution to a CERN Yellow Report shall be deemed to constitute the contributor’s agreement to this copyright and license statement. Contributors are requested to obtain any clearances that may be necessary for this purpose.

This report is indexed in: CERN Document Server (CDS), INSPIRE.

This report should be cited as:
Abstract

The potential for a superconducting proton linac (SPL) at CERN started to be seriously considered at the end of the 1990s. In the first conceptual design report (CDR), published in 2000 [1], most of the 352 MHz RF equipment from LEP was re-used in an 800 m long linac, and the proton beam energy was limited to 2.2 GeV. During the following years, the design was revisited and optimized to better match the needs of a high-power proton driver for neutrino physics. The result was a more compact (470 m long) accelerator capable of delivering 5 MW of beam power at 3.5 GeV, using state-of-the-art superconducting RF cavities at 704 MHz. It was described in a second CDR, published in 2006 [2]. Soon afterwards, when preparation for increasing the luminosity of the LHC by an order of magnitude beyond nominal became an important concern, a low-power SPL (LP-SPL) was studied as a key component in the renovation of the LHC injector complex. The combination of a 4 GeV LP-SPL injecting into a new 50 GeV synchrotron (PS2) was proposed to replace the ageing Linac2, PSB, and PS. In a later stage, if necessary for future physics programmes (neutrino production or generation of radioactive ion beams), the linac could be brought up to multimegawatt beam power by upgrading the cooling, the electrical infrastructure, and the power supplies.

The construction of the low-energy front end of the LP-SPL started in 2008 as the Linac4 project [3], aimed at the replacement of Linac2, with the potential for being adapted later to the needs of a low-power or high-power SPL (HP-SPL). In parallel, the R&D on the superconducting linac continued, initially to refine the design of the LP-SPL and afterwards that of the HP-SPL.

This report presents the design of the LP-SPL and the work accomplished in preparing a proposal for new LHC injectors with the support of the European Commission under the Framework Programmes 6 and 7 and in collaboration with multiple laboratories and institutions worldwide. The status of the R&D towards an HP-SPL is summarized.
Contributors


---

1 European Spallation Source
2 GSI Helmholtzzentrum für Schwerionenforschung GmbH
3 Imperial College London
4 Karlsruhe Institute of Technology
# Contents

## List of tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## 1 Introduction and Executive Summary

## 2 Applications and Choice of Parameters

2.1 Basic parameter and layout choices

2.2 Comparison of different LHC injector options

2.3 Location of the SPL at CERN

2.4 Neutrino facility

2.4.1 Neutrino factory

2.4.2 Super-beam for a medium-baseline neutrino beam

2.5 Compatibility with PS2, ISOLDE, and EURISOL

## 3 Front End and Normal-conducting Linac (Linac4)

3.1 Introduction

3.2 \( \text{H}^- \) source

3.2.1 LP-SPL

3.2.2 HP-SPL, low-current

3.2.3 HP-SPL, high-current

3.2.4 Conclusion

3.3 Radio frequency quadrupole

3.3.1 Introduction

3.3.2 Beam dynamics design

3.3.3 RF design

3.3.4 Mechanical design and assembly

3.3.5 Radio frequency quadrupole commissioning

3.4 Beam chopping

3.4.1 Chopper structure

3.4.2 Chopper amplifier: design considerations

3.4.3 Basic module

3.4.4 Power and control pulse isolator

3.4.5 2 Hz pulser ensemble prototype

3.4.6 Measured performance

3.5 Normal-conducting linac (Linac4)

3.5.1 Drift tube linac

3.5.2 Cell-coupled drift tube linac

3.5.3 Pi-mode structure

3.6 Beam dynamics in Linac4

3.6.1 Nominal beam dynamics
3.6.2 Chopping ......................................................... 42
3.6.3 Energy ramping ............................................... 43
3.6.4 Error studies .................................................. 43

4 Superconducting Linac ................................................. 49
4.1 Basic design choices ............................................. 49
4.1.1 Pros and cons of alternative SPL architectures .............. 49
4.1.2 Choice of cryotemperature .................................... 50
4.1.3 Choice of accelerating gradient ................................ 51
4.1.4 Segmented or continuous cryomodule layout ................. 51
4.1.5 Surface or underground location of RF gallery ................ 52
4.2 Accelerator design ............................................... 53
4.2.1 Choice of geometric betas at 704.4 MHz ....................... 53
4.2.2 Beam dynamics in superconducting section ................. 54
4.2.3 H⁻ stripping ..................................................... 60
4.2.4 Higher-order-mode effects ..................................... 67
4.3 Beam extraction and transfer lines .............................. 72
4.3.1 Transfer line between Linac4 and SPL ......................... 72
4.3.2 Extraction to ISOLDE .......................................... 74
4.3.3 Extraction to a radioactive ion beam facility ................ 75
4.3.4 Transfer line to PS2 ............................................ 76
4.3.5 PS2 injection issues ............................................ 79
4.4 Superconducting cavities ......................................... 80
4.4.1 Introduction ....................................................... 80
4.4.2 Design of the β = 1 cavity ..................................... 80
4.4.3 Superconducting material ...................................... 83
4.4.4 Manufacturing considerations for β = 1 cavities .......... 84
4.4.5 Frequency and field adjustment ............................... 88
4.4.6 Specificities of the β = 0.65 cavity ............................ 93
4.4.7 Preparation of superconducting cavities ....................... 93
4.4.8 Performance tests of cavities .................................. 97
4.4.9 Clean assembly .................................................. 107
4.5 Ancillaries ......................................................... 109
4.5.1 Helium tank ....................................................... 109
4.5.2 Fundamental power coupler .................................... 110
4.5.3 Damping of higher-order modes ............................... 113
4.6 Radio frequency system .......................................... 116
4.6.1 Cavity operation ............................................... 116
4.6.2 General description and functionality of the LLRF system .... 120
4.6.3 Tests with a prototype LLRF system with a low-β 704 MHz cavity and tuner ............................. 122
4.6.4 RF system architecture ........................................ 125
4.6.5 LLRF power overheads ........................................ 129
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6.6</td>
<td>RF power sources</td>
<td>130</td>
</tr>
<tr>
<td>4.6.7</td>
<td>Klystron modulators</td>
<td>132</td>
</tr>
<tr>
<td>4.6.8</td>
<td>IOT powering</td>
<td>134</td>
</tr>
<tr>
<td>4.7</td>
<td>Cryogenics</td>
<td>135</td>
</tr>
<tr>
<td>4.7.1</td>
<td>Cryomodules and machine architecture</td>
<td>135</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Description of the SPL short cryomodule</td>
<td>136</td>
</tr>
<tr>
<td>4.7.3</td>
<td>Cryogenic layout and infrastructure for the SPL</td>
<td>144</td>
</tr>
<tr>
<td>4.7.4</td>
<td>Cryogenic system</td>
<td>145</td>
</tr>
<tr>
<td>4.8</td>
<td>Power consumption and scope for savings</td>
<td>146</td>
</tr>
<tr>
<td>4.8.1</td>
<td>Power consumption with present assumptions</td>
<td>146</td>
</tr>
<tr>
<td>4.8.2</td>
<td>RF power generation</td>
<td>146</td>
</tr>
<tr>
<td>4.8.3</td>
<td>Dissipated power in cavities</td>
<td>147</td>
</tr>
<tr>
<td>4.9</td>
<td>Safety considerations for beam dumps for the SPL</td>
<td>149</td>
</tr>
<tr>
<td>4.9.1</td>
<td>Introduction</td>
<td>149</td>
</tr>
<tr>
<td>4.9.2</td>
<td>Parameters of dumped negative hydrogen ion beams</td>
<td>150</td>
</tr>
<tr>
<td>4.9.3</td>
<td>Generic design of an SPL beam dump</td>
<td>150</td>
</tr>
<tr>
<td>4.9.4</td>
<td>Impact on radiation safety of the SPL and PS2 dumps</td>
<td>151</td>
</tr>
<tr>
<td>4.9.5</td>
<td>Summary and conclusions</td>
<td>155</td>
</tr>
<tr>
<td>5</td>
<td>Layout and Infrastructure</td>
<td>157</td>
</tr>
<tr>
<td>5.1</td>
<td>Depth and slope of the SPL tunnel</td>
<td>157</td>
</tr>
<tr>
<td>5.2</td>
<td>SPL layout and dimensions</td>
<td>159</td>
</tr>
<tr>
<td>5.3</td>
<td>Infrastructure for RF powering</td>
<td>160</td>
</tr>
<tr>
<td>5.4</td>
<td>Access to the SPL underground areas</td>
<td>164</td>
</tr>
</tbody>
</table>

Acknowledgements 165

References 166
### Tables

1.1 Beam characteristics for Low-Power and High-Power SPL ........................................... 2
1.2 Main layout parameters for all linac sections for low- and high-current operation ................. 4
1.2 Nominal beam parameters ................................................................. 5
1.3 Requirements for a proton driver for a neutrino factory .................................................. 7
1.4 Main parameters of the accumulator and compressor rings ............................................... 7
1.5 Possible LP-SPL beam parameters for LHC, PS2, fixed target, and radioactive ion beams ......... 8

2.1 Ion source parameters for Linac4 and for the high- and low-current options for the LP-
SPL and HP-SPL ................................................................. 13
2.2 H⁺ ion source parameters for caesium-surface (Cs-surf.), Penning (P-dis.), and magnetron (M-dis.) discharge ion sources operated at accelerator facilities ................................. 13
2.3 Summary of the main beam dynamics parameters for the Linac4 RFQ ............................... 17
2.4 RFQ electrical parameters ................................................................. 17
2.5 Elements in the chopper line ............................................................................. 21
2.6 Main parameters of beam chopper ............................................................................. 22
2.7 Main pulse amplifier parameters ............................................................................. 28
2.8 Main DTL parameters ......................................................................................... 30
2.9 Main CCDTL parameters ..................................................................................... 33
2.10 Main PIMS parameters ......................................................................................... 36
2.11 Transverse errors ............................................................................................... 45
2.12 Effects of klystron errors in the DTL ..................................................................... 47
2.13 Effects of klystron errors in the CCDTL ............................................................. 47
2.14 Effects of klystron errors in the PIMS .................................................................... 48

3.1 Comparison of layouts ......................................................................................... 55
3.2 Distances between quadrupoles, cavities, etc. in medium- and high-β SPL cryomodules (Fig. 4.6) .................................................................................................................. 57
3.3 Comparison of r.m.s. normalized emittance for different layouts ................................. 60
3.4 Maximum quadrupole gradient at 5 GeV for Gaussian and double exponential distributions 64
3.5 Minimum quadrupole magnetic length at 5 GeV for Gaussian and double exponential distributions ......................................................................................................................... 66
3.6 Machine parameters for HOM simulation .................................................................. 68
3.7 TM010 modes and the expected damping by the fundamental power coupler .............. 72
3.8 Extraction parameters for ISOLDE and EURISOL ................................................... 74
3.9 Parameters for the SPL-to-PS2 transfer line ......................................................... 77
3.10 Parameters of the five-cell β = 1 cavity .................................................................. 82
3.11 Technical specifications of niobium for superconducting cavities ........................... 83
3.12 Parameters of the five-cell β = 0.65 cavity ............................................................ 95
3.13 Main parameters of the SPL fundamental power coupler ..................................... 113
3.14 Choices of LLRF frequencies .............................................................................. 121
**Acronyms and abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Antiproton Decelerator</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue–Digital Converter</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BIMP</td>
<td>Budker Institute of Nuclear Physics, Russia</td>
</tr>
<tr>
<td>BNL</td>
<td>Brookhaven National Laboratory, USA</td>
</tr>
<tr>
<td>BPM</td>
<td>Beam Position Monitor</td>
</tr>
<tr>
<td>CCDTL</td>
<td>Cell-Coupled Drift Tube Linac</td>
</tr>
<tr>
<td>CEA</td>
<td>Commissariat pour l’Energie Atomique, France</td>
</tr>
<tr>
<td>CEBAF</td>
<td>Continuous Electron Beam Accelerator Facility, USA</td>
</tr>
<tr>
<td>CNSG</td>
<td>CERN Neutrinos to Gran Sasso</td>
</tr>
<tr>
<td>CNRS-IPN</td>
<td>Centre National de la Recherche Scientifique–Institut de Physique Nucléaire d’Orsay</td>
</tr>
<tr>
<td>CP</td>
<td>Chemical Polishing</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology AG, Germany</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave (operation)</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital–Analogue Converter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DESY</td>
<td>Deutsches Elektronen SYnchrotron, Germany</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>DTL</td>
<td>Drift Tube Linac</td>
</tr>
<tr>
<td>DWT</td>
<td>double-walled tube</td>
</tr>
<tr>
<td>EB</td>
<td>Electron-Beam (welding)</td>
</tr>
<tr>
<td>ECL</td>
<td>Emitter-Coupled Logic</td>
</tr>
<tr>
<td>EMQ</td>
<td>Electromagnetic Quadrupole</td>
</tr>
<tr>
<td>EP</td>
<td>Electropolishing</td>
</tr>
<tr>
<td>ESS</td>
<td>European Spallation Source</td>
</tr>
<tr>
<td>EURISOL</td>
<td>EURopean Isotope Separation On-Line (study)</td>
</tr>
<tr>
<td>EUROnu</td>
<td>European Commission FP7 Design Study, ‘A High Intensity Neutrino Oscillation Facility in Europe’</td>
</tr>
<tr>
<td>FLUKA</td>
<td>FLUKtuierende KAskade, Monte Carlo simulation package</td>
</tr>
<tr>
<td>FNAL</td>
<td>Fermi National Accelerator Laboratory, USA</td>
</tr>
<tr>
<td>FP7</td>
<td>European Framework Programme 7</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>GSI</td>
<td>GSI Helmholtzzentrum für Schwerionenforschung GmbH</td>
</tr>
<tr>
<td>HFSS</td>
<td>High Frequency Structural Simulator, Ansys Inc., USA</td>
</tr>
<tr>
<td>HOM</td>
<td>Higher-Order Mode</td>
</tr>
<tr>
<td>HP-SPL</td>
<td>High-Power SPL</td>
</tr>
<tr>
<td>HPR</td>
<td>High-Pressure Water Rinsing</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage; Vickers pyramid number</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>ILC</td>
<td>International Linear Collider</td>
</tr>
<tr>
<td>INFN</td>
<td>Istituto Nazionale di Fisica Nucleare, Italy</td>
</tr>
<tr>
<td>IOT</td>
<td>Inductive Output Tube</td>
</tr>
<tr>
<td>ISIS</td>
<td>ISIS Pulsed Neutron Source, UK</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>ISOLDE</td>
<td>Isotope Separator On Line DEvice, experiment at CERN</td>
</tr>
</tbody>
</table>
ISR  Intersecting Storage Rings
ISTC  International Science and Technology Center, Russia
JLAB  Jefferson Laboratory, USA
LANL  Los Alamos National Laboratory, USA
LEBT  Low-Energy Beam Transport
LEIR  Low-Energy Ion Ring
LEP  Large Electron–Positron Collider at CERN
LHC  Large Hadron Collider at CERN
Linac  Linear Accelerator
Linac4  160 MeV proton linac at CERN
LLRF  Low-Level RF
LO  Local Oscillator
LP-SPL  Low-Power SPL
MEBT  Medium-Energy Beam Transport
MLI  Multilayer Insulation
MOSFET  Metal–Oxide–Semiconductor Field Effect Transistor
MTBM  Mean Time Between Maintenance
NC  Normal-Conducting
NCBJ  National Centre for Nuclear Physics, Poland
nTOF  Neutron Time-Of-Flight Experiment at CERN
OFE  Oxygen-Free Electronic (copper)
OST  Oscillating Superleak Transducer
PIMS  PI-Mode Structure
PMQ  Permanent Magnetic Quadrupole
ppp  protons per pulse
PS  Proton Synchrotron at CERN
PS2  Proton Synchrotron 2 at CERN (study)
PSB  PS Booster at CERN
RCS  Rapid Cycling Synchrotron
RF  Radio Frequency
RFQ  Radio Frequency Quadrupole
r.m.s.  root mean square
RRR  Residual Resistivity Ratio (resistivity at 300 K/residual resistivity at operating temperature)
SC  Superconducting
SCL  Side-Coupled Linac
sLHCpp  super Large Hadron Collider preparatory phase
SMD  Simulation of Higher-Order Mode Dynamics
SNS  Spallation Neutron Source, USA
SPC  Scientific Policy Committee, CERN
SPL  Superconducting Proton Linac at CERN (study)
SPS  Super Proton Synchrotron at CERN
SRF  Superconducting Radio Frequency
TEM  Transverse Electric Magnetic
TESLA  TeV Energy Superconducting Linear Accelerator project. Lead laboratory, DESY, Germany (study)
UHV  Ultrahigh Vacuum
VME  Versa Module Europa (bus standard)
VNA  Vector Network Analyser
VNIITF  All-Russian Scientific Research Institute of Technical Physics, Russia
XFEL  X-ray Free Electron Laser, Europe
Chapter 1

Introduction and Executive Summary

The ‘low-power’ version of the superconducting proton linac (LP-SPL) has been studied in recent years as a component of a new LHC injector complex to increase the collider luminosity by an order of magnitude beyond nominal (this was initially called the Super LHC (sLHC) programme, but is now known as the High Luminosity LHC (HL-LHC)). In that context, the replacement of all of the accelerators in front of the SPS was considered, and the SPS itself was planned to be extensively upgraded [4]. Two accelerators (the LP-SPL and a new 50 GeV synchrotron, PS2) would replace the three existing ones (Linac2, the PSB, and the PS), bringing the injection energy in the SPS to 50 GeV, much further than today from the transition energy (Fig. 1.1). The layout at the CERN site was therefore reconsidered with respect to the previous SPL proposal [2] to minimize construction cost and tunnel length. This resulted in a new location for the SPL, with a 160 MeV Linac4 front end close to the PSB, as shown in Fig. 1.2 and described in Chapter 5. As an intermediate stage, Linac4 could be built and replace Linac2 as the injector of the PSB, doubling its beam brightness.

The renovated injector complex was aimed at beam characteristics that would reliably exceed twice the ultimate values for the LHC ($3.4 \times 10^{11}$ protons/bunch within 3.75 mm mrad and with 25 ns bunch spacing), without beam gymnastics and with the injection flat porch in the SPS reduced to 2.4 s (to be compared with the 10.8 s nominal value). An ejection system at 1.4 GeV was included in the SPL for supplying beam to ISOLDE. A new neutrino physics facility requiring multimegawatt beam power at 4–5 GeV and/or a future radioactive isotope beam facility requiring 5 MW at 2.5 GeV could be implemented later by upgrading the linac infrastructure [5]. All of these possible applications are described in Chapter 2, and the corresponding beam characteristics, including high-power options, are summarized in Table 1.1.
Fig. 1.2: Layout of Linac4, SPL, and PS2 at the CERN site

Table 1.1: Beam characteristics for Low-Power and High-Power SPL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>LP-SPL</th>
<th>HP-SPL, low-current</th>
<th>HP-SPL, high-current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum kinetic energy</td>
<td>GeV</td>
<td>4</td>
<td>5(^a)</td>
<td>5(^a)</td>
</tr>
<tr>
<td>Average beam current during pulse</td>
<td>mA</td>
<td>20</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Pulsing rate</td>
<td>Hz</td>
<td>2</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>ms</td>
<td>0.9</td>
<td>0.8</td>
<td>0.4(^b)</td>
</tr>
<tr>
<td>Beam power</td>
<td>MW</td>
<td>0.14</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^a\) 5 GeV is required for a neutrino factory; for other applications, a lower final energy may be sufficient.
\(^b\) For multiple users requiring >4 MW beam power simultaneously, this value has to be increased.

The design of the Linac4 front end has evolved slightly with respect to its previous version [2], the main modification being the use of 352 MHz pi-mode structures (PIMS) for acceleration above 100 MeV, instead of a side-coupled linac (SCL) at 704 MHz [6]. The Linac4 project was officially approved in 2007 and construction started in 2008. More details are given in Chapter 3. The design of the superconducting part of the SPL has been refined, and sections have been included for ejection at 1.4 and 2.5 GeV. A lower-cost version with only 20 mA of beam current during the pulse and half the number of klystrons is also envisaged (the first HP-SPL option in Table 1.1). Imperfections and high-intensity effects have been investigated in more detail. The construction of a four-cavity cryomodule has been started, together with the infrastructure upgrades necessary for assembly and for characterizing cavities at high RF power (cryogenic cooling, high-power RF at 704 MHz, clean room, etc.). Progress on these subjects is reported in Chapter 4. Following the decision taken in 2010 to base the high-luminosity upgrade of the LHC on an upgrade of the existing PSB and PS instead of on constructing the LP-SPL and PS2, the R&D for the SPL has been focused on superconducting cavities, cryomodules, and RF in view of the potential high-power applications.
Chapter 2

Applications and Choice of Parameters

The present parameter set of the SPL is driven by two potential uses of the machine: (i) a low-power injector (LP-SPL) \[7\] into PS2 \[8\], a machine that would replace the present PS, and thus SPL+PS2 would replace the present CERN proton injector chain up to injection into the SPS; and (ii) a high-power proton driver (HP-SPL) \[9\] that could be used in the same way as the LP-SPL, but which could also produce high-power beams for neutrino facilities and/or a radioactive ion beam facility such as EURISOL \[10\].

2.1 Basic parameter and layout choices

Linac4, which is presently under construction, was conceived as the normal-conducting front end of the SPL. Its output energy of 160 MeV was chosen to reduce the space charge forces at injection into the PS Booster (PSB) by 50% compared with Linac2, and should thus allow the brightness of the beam out of the PSB to be increased by a factor of 2. Since Linac4 was designed as a stand-alone machine, it does not contain any superconducting cavities, which would have neither shortened the linac nor significantly reduced the operating cost of Linac4, owing to its very low duty cycle. Nevertheless, Linac4 was designed to operate at the SPL duty cycle and can be upgraded for this purpose with modest means (see Section 4.3.1).

From 160 MeV onwards, two families of superconducting cavities, with geometrical betas of 0.65 and 1.0, respectively, accelerate the beam up to its final energy (see Fig. 2.1). For use as a high-power proton driver (HP-SPL) for neutrino applications, an energy of 5 GeV was chosen (see Section 2.4), while for use as a low-power injector (LP-SPL) into PS2 a final energy of 4 GeV is sufficient (see Section 2.2). Since the RF system is a major cost driver for the facility \[11\], a ‘low-current’ version of the HP-SPL was conceived, using 20 mA of beam current with twice the pulse length instead of 40 mA. The assumption is that in the low-current version two cavities can be powered by one megawatt-class klystron, while the HP-SPL design assumes one klystron per cavity. Thus, the low-current SPL would need only half the number of klystrons.

![Fig. 2.1: Layout of superconducting linac with intermediate extraction](image_url)

Since the SPL design is very flexible in terms of energy, pulse length, repetition rate, and beam power, it can be adapted to the needs of many high-power proton beam applications. Pulse length changes...
have the least influence on cost and layout. Higher currents are limited for the following reasons: (i) increased peak power is needed from the klystrons, (ii) there are limitations on peak power in the power couplers, and (iii) the current out of the H− source is limited. Energy upgrades are limited only by the available tunnel space, and the repetition rate should not go beyond some tens of hertz. In this report, we focus on applications to neutrino facilities (the high-power version) and the LHC injector chain (LP-SPL) as detailed in Tables 2.1 and 2.2. Further discussion of the parameter set chosen for the superconducting linac can be found in Section 4.1.

2.2 Comparison of different LHC injector options

In 2007, the SPL was compared with a rapid cycling synchrotron (RCS) [12] as an option for injecting into PS2. This study was done following a recommendation of the CERN SPC Review Panel [13], with the goal of comparing the two machines considering only the needs of the LHC and not the full physics potential of a 4 MW linac-based proton driver. Thus the LP-SPL was conceived as a linac delivering a 4 GeV beam, cycling at 2 Hz and with half the average pulse current (20 mA instead of 40 mA) of the original SPL [14]. These choices reduce the initial investment in infrastructure (electrical distribution, water-cooling plant, and cryoplant) and in the accelerator itself (almost 30 fewer klystrons and 1 GeV

<table>
<thead>
<tr>
<th>Section</th>
<th>Output energy (MeV)</th>
<th>Cavities</th>
<th>Gaps/ cavity</th>
<th>Cavities/ cryo-module</th>
<th>Klystrons</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source, LEBT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.045</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>RFQ&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3</td>
<td>1</td>
<td>–</td>
<td>1</td>
<td>SS</td>
<td>3.1</td>
</tr>
<tr>
<td>Chopper line</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>–</td>
<td>39, 42, 30</td>
<td>3.7</td>
</tr>
<tr>
<td>DTL&lt;sup&gt;c&lt;/sup&gt; (FFDD)</td>
<td>50.3</td>
<td>3</td>
<td>39, 42, 30</td>
<td>–</td>
<td>3</td>
<td>19.1</td>
</tr>
<tr>
<td>CCDTL&lt;sup&gt;d&lt;/sup&gt; (F0D0)</td>
<td>102.9</td>
<td>7 × 3</td>
<td>3 × 3</td>
<td>–</td>
<td>4</td>
<td>26.2</td>
</tr>
<tr>
<td>PIMS&lt;sup&gt;e&lt;/sup&gt; (F0D0)</td>
<td>160</td>
<td>12</td>
<td>7</td>
<td>–</td>
<td>6</td>
<td>21.5</td>
</tr>
<tr>
<td>Transfer line</td>
<td>160</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5</td>
</tr>
<tr>
<td><strong>Normal-conducting linac (Linac4), 352.2 MHz</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β = 0.65 (FD0)</td>
<td>753</td>
<td>60</td>
<td>5</td>
<td>30/60</td>
<td>129.6</td>
<td></td>
</tr>
<tr>
<td>β = 1.0 (FD0)</td>
<td>1464</td>
<td>40</td>
<td>8</td>
<td>20/40</td>
<td>75.3</td>
<td></td>
</tr>
<tr>
<td>Extraction 1</td>
<td>1464</td>
<td>15.1</td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β = 1.0 (FD0)</td>
<td>2605</td>
<td>48</td>
<td>8</td>
<td>24/48</td>
<td>90.4</td>
<td></td>
</tr>
<tr>
<td>Extraction 2</td>
<td>2605</td>
<td>14</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β = 1.0 (F0D0)</td>
<td>[4005], 5005</td>
<td>[56], 96</td>
<td>5</td>
<td>8</td>
<td>[28], 48/96</td>
<td>[98.8], 169.3</td>
</tr>
<tr>
<td><strong>Total NC&lt;sup&gt;f&lt;/sup&gt;</strong></td>
<td>40</td>
<td>14</td>
<td>14</td>
<td>81.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total SC&lt;sup&gt;g&lt;/sup&gt;</strong></td>
<td>[204], 244</td>
<td>[102], 122/244</td>
<td>[430.3], 500.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>[244], 284</td>
<td>[116], 136/258</td>
<td>[511.9], 582.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Low-Energy Beam Transport.
<sup>b</sup> Radio Frequency Quadrupole.
<sup>c</sup> Drift Tube Linac.
<sup>d</sup> Cell-Coupled Drift Tube Linac.
<sup>e</sup> Pi-Mode Structure.
<sup>f</sup> Normal-Conducting.
<sup>g</sup> Superconducting.
Table 2.2: Nominal beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>HP-SPL</th>
<th>LP-SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low-current</td>
<td>High-current</td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Beam power</td>
<td>MW</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>mA</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Peak pulse current</td>
<td>mA</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>Source current</td>
<td>mA</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Chopping ratio</td>
<td>%</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>ms</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Protons per pulse</td>
<td>$10^{14}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

less of accelerating structures), but they preserve the possibility of an upgrade whenever necessary.

If this new injector is the RCS, the only economically competitive solution is to make it fill PS2 with more pulses than the ratio of sizes PS2/RCS. This is only possible if the RCS delivers one bunch per cycle, resulting in 14 cycles (13 bunches plus one empty bucket) at 10 Hz being needed to fill PS2. This scheme, however, results in the need for multiple bunch splittings in PS2, as in the PS today. Using a 400 MeV injector linac, the incoherent tune spread $\Delta Q$ in the RCS can be limited to around $-0.3$.

Therefore, even though both injectors should make PS2 able to deliver a beam with the same characteristics for the LHC, their complexity and operational margins are very different. With the SPL (or LP-SPL), PS2 is filled in 0.6 ms, while it takes 1.3 s with the RCS. Therefore the beam from the SPL can be accelerated quickly and suffers from high space charge for only a very limited amount of time. Moreover, the SPL can directly deliver a beam with the time structure required by the LHC, which avoids using beam gymnastics in PS2. This is not the case with the RCS beam, which has to be submitted to three successive splittings to obtain an adequate time structure.

There is also a significant difference between the proton fluxes that can be delivered by the low-energy accelerators (up to 50 GeV) to other users once the needs of the high-energy machine are satisfied. In most cases, there are approximately 2.5 times more protons available at 50 and 4 GeV when the LP-SPL is used. In the extreme case where the SPS is operating at its maximum rate for a fixed target (CNGS-like operation), the RCS injector will not allow PS2 to cycle for any other user, while the LP-SPL would still make this possible.

For heavy ions, the RCS-based option is a satisfactory solution that eases operation of PS2 and could re-use all the sophisticated beam gymnastics foreseen today for the PS. In the case of the SPL option, the heavy-ion beam from LEIR would have to be injected directly into PS2 at a lower field (with a magnetic rigidity of 0.4 times the value at proton injection) and additional or different RF equipment would be needed. However, no effort has yet been invested in an optimum scheme for that case.

A preliminary cost comparison, considering only the items that differ between the two options, gave a 28% difference in favour of the RCS solution [12], which is remarkably similar to the outcome of an analysis at FNAL in 2005 [15].

2.3 Location of the SPL at CERN

Before the start of construction of Linac4, several different locations for the SPL and PS2 were studied [16], taking into account the requirements of future facilities such as EURISOL or a neutrino factory, as well as the existing physics programmes (heavy ions for the LHC, a neutrino super-beam from the SPS, fixed-target experiments, the neutron Time-Of-Flight (nTOF) facility, ISOLDE, and AD).
A tunnel trajectory had to be found that maintained sufficient distance from public areas (e.g., basements of surface buildings and service tunnels) in order to comply conservatively with radiological protection safety rules. Furthermore, the drilling of the tunnel had to be possible without impacting on beam operation in any of the surrounding beam tunnels, which also meant that during the civil engineering work, personnel must not be subjected to unacceptable dose rates from neighbouring tunnels.

The chosen site for Linac4 is to the south-west of the PS under a small artificial hill made from excavation materials from the construction of the PS. This location allows the possibility of a short, simple connection to the present transfer line from Linac2 to the PSB and of an extension to a long underground tunnel housing the LP-SPL followed by a straight transfer line to the PS2 machine, nearly tangential to the SPS. The precise position of Linac4 is dictated by the need to have a stable foundation for the equipment building on the surface (the site has a substantial slope towards the PS area) and to keep sufficient distance between this building and the Swiss–French border, where construction is forbidden by international laws. Other sites considered for Linac4 were (i) the existing PS South Hall, which would be economic but impossible to extend to the SPL and where connection to the PSB through the PS would be difficult [3]; (ii) the present Linac2 location, which would be impossible to extend to the SPL and would force a long interruption for switching between the two machines [3]; and, finally, (iii) the SPS West Hall, which would offer a limited option for extension but would require a long, expensive transfer line to the PSB.

Apart from the easy connection to the PSB and LP-SPL, the selected location was one of the few areas on the Meyrin site which was free from construction (see Fig. 1.2). The Linac4 tunnel was built using the cut-and-cover technique, which is less expensive than tunnelling, at nearly the same level as the PSB and PS machines. The remaining layer of earth between the accelerator tunnel and the surface provides effective radiation shielding that allows the minimum thickness of accelerator walls, when compared with solutions above ground or within existing halls. The LP-SPL is located in an underground extension of the Linac4 tunnel with a slope of \( \approx 1.7\% \). The klystrons and power supplies of the medium-\( \beta \) section will be housed in a gallery parallel to the accelerator tunnel at 9 m horizontal spacing. For the high-\( \beta \) section, the klystrons and power supplies will be housed on the surface and connected via vertical waveguide ducts to the accelerator tunnel.

PS2 will be built close to the SPS and at the same level, for better shielding and to ease beam transfer. The line between the LP-SPL and PS2 will therefore have a slope of \( \approx 8\% \). The radius of curvature in all of the bending magnets of the transfer line has to be higher than 400 m, to minimize beam loss due to \( \text{H}^- \) stripping. Services and access pits will be located in surface buildings located on land plots already allocated for CERN use.

The depth and shielding of Linac4 and the LP-SPL are the result of radiation protection requirements [17], taking into account the fact that these machines could later be upgraded to the high beam power required by potential future physics facilities. An essential constraint is to keep the estimated dose in public access areas (surface buildings and infrastructure, service tunnels, etc.) conservatively below the limits defined by radiation protection safety rules. The result is that the Linac4 beam axis must be 2.5 m below the present PSB–PS level. Figure 2.2 shows a side view of the accelerator complex, and Ref. [17] reports on the interferences between the SPL, the transfer line tunnels, and the closest existing infrastructure. Moreover, to preserve the possibility of hands-on maintenance, activation in the accelerator tunnel must be minimized and tightly controlled. The new accelerator complex will therefore be designed for and have to be operated with a maximum of 1 W/m of uncontrolled beam loss [18].

2.4 Neutrino facility

2.4.1 Neutrino factory

An important motivation for the study of the SPL at CERN has consistently been its interest as a proton driver for a neutrino factory [1, 5]. The performance goals for that purpose (Table 2.3) were specified
more precisely in 2009, as a result of the International Scoping Study [19].

Table 2.3: Requirements for a proton driver for a neutrino factory [19]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average beam power</td>
<td>4 MW</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Beam kinetic energy</td>
<td>10 ± 5 GeV</td>
</tr>
<tr>
<td>Bunch length (r.m.s.)</td>
<td>2 ± 1 ns</td>
</tr>
<tr>
<td>Number of proton bunches</td>
<td>3 or 5</td>
</tr>
<tr>
<td>Sequential extraction delay</td>
<td>≥ 17 µs</td>
</tr>
<tr>
<td>Pulse duration (liquid Hg target)</td>
<td>≤ 40 µs</td>
</tr>
<tr>
<td>Pulse duration (solid target)</td>
<td>≥ 20 µs</td>
</tr>
</tbody>
</table>

To meet these demanding requirements, a linac-based scheme was then developed using the 5 GeV HP-SPL and two fixed-energy rings of approximately 300 m circumference [20,21]. Two possible sets of HP-SPL beam characteristics are feasible, as shown in Table 2.2. The low-current option (20 mA during a beam pulse) needs half the peak RF power of the nominal-current option (40 mA) and is therefore significantly less expensive. It is sufficient for a neutrino factory but not for simultaneously supplying a high-power beam to another facility.

In the first ring (the accumulator), the chopped linac beam is accumulated in a few long bunches, using charge-exchange injection. The accumulator is isochronous to preserve the time structure of the linac beam, and it has no RF system, to minimize the impedance. Once accumulation is finished, bunches are transferred one by one to the second ring (the compressor), where they are rotated in the longitudinal phase plane and ejected to the target when their length is at a minimum. Bunch rotation takes place, with energy being stored in the cavities of the low-frequency RF system. The principle of operation is sketched in Fig. 2.3 in the case of six bunches, for which it was initially conceived.

The lattices of the accumulator and compressor rings have been designed, and particle-tracking simulations have shown that bunches of 2 ns r.m.s. length can indeed be generated (see Fig. 2.4) [20,21]. A study of collective effects in the accumulator has shown that the impedances required for stability are within reach [22].

A more ambitious scenario has been developed for better matching of the required beam characteristics by generating three bunches. The main parameters of the rings in both cases are shown in Table 2.4. A tentative layout of a neutrino factory complex at the CERN site is sketched in Fig. 2.5.

Table 2.4: Main parameters of the accumulator and compressor rings

<table>
<thead>
<tr>
<th>Ring</th>
<th>Parameter</th>
<th>Units</th>
<th>6 bunches</th>
<th>3 bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulator</td>
<td>Circumference</td>
<td>m</td>
<td>318.5</td>
<td>185.8</td>
</tr>
<tr>
<td></td>
<td>Accumulation turns</td>
<td></td>
<td>690</td>
<td>1180</td>
</tr>
<tr>
<td></td>
<td>Type of magnets</td>
<td>NC</td>
<td>SC</td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>Circumference</td>
<td>m</td>
<td>314.2</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Compression turns</td>
<td></td>
<td>36</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>RF voltage at $h = 3$</td>
<td>MV</td>
<td>4</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Transition gamma</td>
<td></td>
<td>2.3</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>Type of magnets</td>
<td>SC</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interval between bunches</td>
<td>µs</td>
<td>12</td>
<td>30</td>
</tr>
</tbody>
</table>
2.4.2 Super-beam for a medium-baseline neutrino beam

For the needs of a medium-baseline neutrino super-beam, which could be the first stage of a neutrino factory, the HP-SPL combined with a single fixed-energy accumulator ring is sufficient. Once the linac beam pulse has been accumulated, the beam is rapidly ejected from the accumulator onto the target. Pions are then focused by one or multiple horns as in conventional facilities, and their decay produces a muon neutrino beam. A beam delivery system has been studied in the context of the EUROnu design study [23], where successive pulses from the accumulator are distributed to different targets and horns, each of them operating at 12.5 Hz with 1 MW of beam power [24].

A tentative layout of such a super-beam facility at the CERN site is sketched in Fig. 2.6, where the neutrino beam is directed towards a remote detector located in the Fréjus tunnel, as proposed in EUROnu. Any other direction would obviously be possible.

2.5 Compatibility with PS2, ISOLDE, and EURISOL

The high proton flux and fast cycling rate of the SPL would basically decouple the operation of PS2 and ISOLDE. PS2 would not compete with ISOLDE for particles from the injectors, in contrast to the present situation with the PSB and PS. Using the SPL as the injector, PS2 would not be linked to the present repetition rate of the linac and the PSB (i.e., multiples of 1.2 s), and magnetic cycles of ‘any length’ can be envisaged in principle. In the present SPL layout, extraction at 1.5 GeV (see Section 4.3.2) is foreseen to provide beam to ISOLDE. Using the LP-SPL together with PS2 in order to replace the present chain of the PSB and PS enables the operational scenario listed in Table 2.5.

Table 2.5: Possible LP-SPL beam parameters for LHC, PS2, fixed target, and radioactive ion beams (either for ISOLDE II or for the first stage of a EURISOL-type facility) using a pulse length of 1.2 ms instead of the nominal 0.9 ms.

<table>
<thead>
<tr>
<th>User</th>
<th>Units</th>
<th>PS2 (LHC)</th>
<th>PS2 (fixed target)</th>
<th>ISOLDE II</th>
<th>EURISOL (first stage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>4</td>
<td>4</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Average beam power</td>
<td>kW</td>
<td>20</td>
<td>40</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Max. repetition rate</td>
<td>Hz</td>
<td>0.42</td>
<td>0.42</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Pulse length</td>
<td>ms</td>
<td>0.6</td>
<td>0.96</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>mA</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Protons per pulse</td>
<td>$10^{13}$</td>
<td>7.5</td>
<td>12</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

It its conceptual design, EURISOL [10] was conceived using a low-energy (1 GeV) Continuous-Wave (CW) beam in order to minimize beam-induced stresses in the targets. Pulsed beams generally reduce the target lifetime, but this effect can be mitigated using a high repetition rate (50 Hz or higher) and long enough beam pulses (in the millisecond range) [25]. For a EURISOL-type facility, the SPL could provide a multimegawatt beam at 2.5 GeV. Using, for instance, a 40 mA beam with a 0.8 ms pulse length at a 50 Hz repetition rate provides 4 MW of proton beam power, a value that can be increased further by lengthening the beam pulse. A draft layout of a possible EURISOL facility at CERN is sketched in Fig. 2.7.
APPLICATIONS AND CHOICE OF PARAMETERS

Fig. 2.2: Side view of Linac4, SPL, and PS2 at the CERN site.
Fig. 2.3: Bunch generation in a linac-based proton driver for a neutrino factory

(a) Bunch rotation
(b) Density at ejection

Fig. 2.4: Longitudinal beam parameters in bunch compressor
APPLICATIONS AND CHOICE OF PARAMETERS

Fig. 2.5: Draft layout of a neutrino factory at CERN

Fig. 2.6: Draft layout of a medium-baseline super-beam facility
Fig. 2.7: Draft layout of a possible EURISOL facility at CERN (blocks above Building 193)
Chapter 3

Front End and Normal-conducting Linac (Linac4)

3.1 Introduction

Linac4, the normal-conducting SPL front end, is presently under construction and is expected to be ready for beam by the end of 2016 [26]. Linac4 will start low-duty-cycle operation as a 160 MeV replacement for Linac2 (50 MeV) but is designed for the more demanding HP-SPL duty cycle. Connection to the PS Booster is planned to take place during the second long LHC shutdown (LS2) in 2018. In the following, the design features of Linac4 are described and the differences between low- and high-duty-cycle operation are highlighted.

3.2 $\text{H}^-$ source

The goal of this section is to identify operational ion source types which have the potential to meet the needs of the SPL. The R&D required to adapt those ion sources which have proven operational performance closest to the requirements of each of the three SPL operation schemes will be listed.

The parameters of the 45 kV $\text{H}^-$ ion sources needed for Linac4, the LP-SPL, and the high- and low-current HP-SPL are given in Table 3.1. The ion sources successfully operating at BNL, ISIS, and the SNS were considered. They each have 10 or more years of operation and their main parameters are listed in Table 3.2.

Table 3.1: Ion source parameters for Linac4 and for the high- and low-current options for the LP-SPL and HP-SPL (see Table 2.2).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Linac4</th>
<th>LP-SPL</th>
<th>HP-SPL, low-current</th>
<th>HP-SPL, high-current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>2</td>
<td>2</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Source current</td>
<td>mA</td>
<td>40/80</td>
<td>40</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>ms</td>
<td>0.4</td>
<td>0.9</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Plasma pulse length</td>
<td>ms</td>
<td>0.7</td>
<td>1.2</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Emittance norm r.m.s.</td>
<td>mm mrad</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 3.2: $\text{H}^-$ ion source parameters representative of caesiumated-surface (Cs-surf.), Penning (P-dis.), and magnetron (M-dis.) discharge ion sources operated at accelerator facilities [27–29].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>ISIS</th>
<th>SNS</th>
<th>BNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>keV</td>
<td>17–35</td>
<td>65</td>
<td>35, 40</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>ms</td>
<td>0.5</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>50</td>
<td>60</td>
<td>6.6</td>
</tr>
<tr>
<td>$\text{H}^-$ current</td>
<td>mA</td>
<td>35</td>
<td>60</td>
<td>65, 100</td>
</tr>
<tr>
<td>$\text{H}^-$ production mode</td>
<td>Cs arc</td>
<td>Cs-surf.</td>
<td>Cs-surf.</td>
<td></td>
</tr>
<tr>
<td>Plasma heating</td>
<td>P-dis.</td>
<td>RF</td>
<td>M-dis.</td>
<td></td>
</tr>
<tr>
<td>Emittance norm r.m.s.</td>
<td>mm mrad</td>
<td>0.2</td>
<td>0.25</td>
<td>0.4, 0.56</td>
</tr>
<tr>
<td>Cs consumption</td>
<td>mg/day</td>
<td>100</td>
<td>&lt;1</td>
<td>12</td>
</tr>
<tr>
<td>Operational MTBM</td>
<td>weeks</td>
<td>5</td>
<td>6</td>
<td>36</td>
</tr>
</tbody>
</table>
In the BNL magnetron and ISIS Penning ion sources, pulsed hydrogen gas and a constant flow of caesium vapour are injected between hot electrodes, where an electrical discharge ignites and sustains a plasma. A mixture of plasma and surface processes (i.e., ionization on a low-work-function caesiated surface and charge exchange in the plasma) leads to the production of H\(^-\).

In the SNS source, a constant flow of hydrogen gas is injected into the plasma chamber and 300 W power of 13.56 MHz RF sustains a low-density CW plasma. A 60 kW, 2 MHz RF pulse is then superimposed to begin H\(^-\) production, with the H\(^-\) being produced via the interaction of protons and neutral hydrogen with a caesiated molybdenum surface located around the extraction hole. The caesiation of this surface occurs once at start-up after 4 h of plasma conditioning of the molybdenum surface, kept at elevated temperature; the effect of the caesium monolayer lasts for up to six weeks, after which the source is exchanged and regenerated offline.

When H\(^-\) ions are produced with these caesiated sources, the current of electrons co-extracted with the H\(^-\) beam is relatively low, so for H\(^-\) currents larger than 30 mA caesiation seems unavoidable if one is to avoid the complications of extracting and dumping a high-power electron beam. Caesium is a reactive alkali metal; its injection into the ion source may possibly need a specific recuperation system such as the refrigerated caesium condenser operated at the exit of the ISIS Penning ion source. The prototype 40 mA Linac4 ion source that is currently being produced is inspired by the SNS ion source, which is today’s record holder for the smallest caesium consumption per H\(^-\) produced.

### 3.2.1 LP-SPL

The H\(^-\) source for the LP-SPL differs from the 40 mA Linac4 H\(^-\) source in pulse duration only. Assuming successful operation of the Linac4 source at a 2 Hz repetition rate, the pulsed high-voltage system developed for the Linac4 ion source now operating with a flat top of 0.6 ms would have to be doubled, which fits within the existing equipment design. The 2 MHz RF plasma generator heating has already achieved 1.2 ms pulse duration, although the stabilization of the H\(^-\) current requires demonstration, but the SNS source on which the Linac4 source is based already operates at a pulse length of 1 ms.

### 3.2.2 HP-SPL, low-current

The SNS H\(^-\) surface ion source type is suitable for the HP-SPL low-current option. The 2 MHz RF amplifier developed in the framework of the sLHC European Union project already meets the requirements of an SNS-type source at 50 Hz. On the other hand, the constant gas injection requires a new pumping design, a 13.6 MHz sustained low-power-density CW plasma, an insulated RF solenoid immersed in the plasma, and a 50 Hz pulsed high voltage. Cooling of the 5–6 kW average-power plasma heating and extraction of a high-average-power beam will require intense, extended simulation and learning. Operation of this source at 45 instead of 65 kV may increase the beam emittance. The lifetime of the internal solenoid RF antenna is critically dependent on its production quality assurance. An external-antenna version of the SNS surface source has been operated at the SNS for 1 month; this is being considered as an option and is closer to the design of the 2 Hz Linac4 ion source that is being built. After a review of the state of the art and production of a technical design report, a coarse estimate of 2–3 years of detailed design and production followed by 2–5 years of commissioning has been deemed necessary to reach the stability achieved at the SNS after 10 years of operation. In view of today’s 5 weeks operational lifetime of this complex system followed by a start-up phase of a few days with the risks of failure inherent in the installation of a newly refurbished ultra-high vacuum (UHV) high-voltage system, regular machine stops of at least 4 days for ion source exchange are mandatory.

Transforming the LEBT into a merging switchyard, or doubling the system and adding a second RFQ with a merging station afterwards, and alternating operation could be considered in order to minimize downtime. Access to both ion sources during operation of these twin sources would then become a necessity.
To summarize, experience has shown that simply copying SNS source hardware and its 10 cm electrostatic LEBT is not an option. The source, LEBT, pre-chopper, high voltage, pumping, plasma chamber cooling, beam optics, and uninterrupted operation all require a major effort. As a figure of merit, the operation of the SNS ion source requires 5.5 FTE/y, and the team consists of three physicists and three technicians.

3.2.3 HP-SPL, high-current

All of the ion sources listed above need more development in order to reach the HP-SPL parameters. The SNS and Penning sources will require considerable R&D to scale them for increased current. The feasibility of a high H\textsuperscript{−} current has been demonstrated with the BNL magnetron source, but with a larger emittance. Demonstration of the operation of a magnetron source at 50 Hz requires careful analysis of the thermal load, and a dedicated cooling design is necessary. The lifetime of the system when scaled with the repetition rate also implies typically a few weeks of uninterrupted operation. The required flow of caesium deserves special attention, including book-keeping, design of the caesium condensation system, and cleaning during maintenance. In summary, a positive outcome of a dedicated preliminary study aimed at demonstrating 50 Hz operation of the magnetron is a prerequisite. Therefore, reviewing the latest progress in operational sources (where the SNS and ISIS are still strongly active in R&D on their high-current H\textsuperscript{−} sources) and successfully achieving the HP-SPL low-current option as an intermediate milestone seems to be a prerequisite for the design of an HP-SPL high-current option.

3.2.4 Conclusion

H\textsuperscript{−} ion sources for the LP-SPL are within reach, provided successful operation is achieved in the Linac4 ion source prototype that is currently being produced. The SNS surface ion source type has potential for the low-current option of the high-power SPL, while the identification of a candidate for the high-current option requires further dedicated R&D. The feasibility of H\textsuperscript{−} sources that meet the HP-SPL specification within today’s availability figure (98% over 9 months duration) in the existing building remains to be demonstrated. A study of a dedicated injector involving all specialist support teams is mandatory for providing a suitable answer.

3.3 Radio frequency quadrupole

3.3.1 Introduction

The low-energy front end of Linac4 and the SPL is based on a 352 MHz, 3 m long radio frequency quadrupole accelerator [30]. The RFQ accelerates a 70 mA, 45 keV H\textsuperscript{−} beam from the RF source to an energy of 3 MeV.

The RFQ was designed to operate initially in Linac4 to fill the PS Booster, delivering 70 mA beam pulses of 0.4 ms duration at 1.1 Hz, and, at a later stage, to work with longer RF pulses of 1.2 ms duration and a higher repetition rate of 2 Hz to accelerate a 40 mA beam. The option is left open to operate with 70 mA, 1.2 ms, 50 Hz pulses if a high-intensity-beam programme is approved.

The fabrication of the RFQ started at CERN in 2009 and was completed at the beginning of 2013. After initial commissioning on the 3 MeV Test Stand, which was completed in May 2013, the RFQ was moved to the Linac4 tunnel and commissioned with the low-intensity beam available from the H\textsuperscript{−} source. Figure 3.1 shows the RFQ installed in the Linac4 tunnel.

3.3.2 Beam dynamics design

Owing to the very different operational modes envisaged for the RFQ in Linac4 and the SPL, beam dynamics design was done with the purpose of maintaining good beam transmission over a wide range of accelerated beam current while preserving the longitudinal emittance. The result of the design was
a compact RFQ 3 m long, made of three 1 m modules directly coupled together, with an intra-vane voltage of 78 kV and a peak surface field of 34 MV/m (1.84 times the Kilpatrick limit). The main design parameters are shown in Fig. 3.2.

The compactness of the accelerator was made possible by setting the injection energy from the ion source to 45 keV, by designing a profile with a high focusing factor, and by limiting the beam current to 80 mA. The value of the peak surface field appears acceptable, as it is reached over only a short section and the RFQ is meant to work at a maximum duty cycle of 7.5%. The minimum value of the aperture $a$ is 0.18 cm and the maximum modulation factor $m$ is 2.38. The main beam parameters, evaluated for a nominal 70 mA beam current, are summarized in Table 3.3.

### 3.3.3 RF design

The RF design was performed in two steps, with a preliminary design being done at CERN and a more detailed design being done by CEA within a formal collaboration agreement with CERN in the context
Table 3.3: Summary of the main beam dynamics parameters for the Linac4 RFQ

<table>
<thead>
<tr>
<th>RFQ beam parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam input energy</td>
<td>0.045 MeV</td>
</tr>
<tr>
<td>Beam output energy</td>
<td>3.0 MeV</td>
</tr>
<tr>
<td>Nominal beam current</td>
<td>70 mA</td>
</tr>
<tr>
<td>Average aperture $r_0$</td>
<td>0.33 cm</td>
</tr>
<tr>
<td>Ratio $r/r_0$</td>
<td>0.85</td>
</tr>
<tr>
<td>Focusing parameter</td>
<td>5.77</td>
</tr>
<tr>
<td>Input emittance (r.m.s., norm)</td>
<td>$0.25\pi$ mm mrad</td>
</tr>
<tr>
<td>Acceptance at zero current</td>
<td>$1.7\pi$ mm mrad</td>
</tr>
<tr>
<td>Longitudinal emittance (out, r.m.s.)</td>
<td>$0.13\pi$ deg MeV</td>
</tr>
<tr>
<td>Transmission</td>
<td>95%</td>
</tr>
<tr>
<td>Transverse emittance growth</td>
<td>0%</td>
</tr>
</tbody>
</table>

of the exceptional French contribution to the LHC [31]. The 2D section of the RFQ cavity was kept constant over the full RFQ length, in order to simplify mechanical fabrication. Table 3.4 summarizes the main electrical parameters of the RFQ.

Table 3.4: RFQ electrical parameters (2D simulation)

<table>
<thead>
<tr>
<th>RFQ electrical parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vane voltage</td>
<td>78.27 kV</td>
</tr>
<tr>
<td>Quality factor (unloaded)</td>
<td>10269</td>
</tr>
<tr>
<td>Stored energy</td>
<td>0.372 J/m</td>
</tr>
<tr>
<td>Dissipated power</td>
<td>78.738 kW/m</td>
</tr>
<tr>
<td>Magnetic field (max.)</td>
<td>5444 A/m</td>
</tr>
</tbody>
</table>

The design of a relatively short RFQ helped to minimize the RF power requirements from the klystron, and one klystron is sufficient to drive the RFQ under all conditions. This also allows the use of a single input RF coupling port, namely an iris-coupled ridged waveguide connecting a WR2300 reduced-height RF window to the RFQ cavity. The impact of vane modulation on the cut-off frequency of the transmission line modes was studied by means of 3D simulations, which showed a frequency reduction of 0.208 MHz for the quadrupole mode and of 3.871 MHz for the fundamental dipole mode when the modulation was taken into account.

The frequency separation between the accelerating quadrupole mode and the adjacent dipole modes was found to exceed 1 MHz after final tuning, which should guarantee sufficient stability during operation under all conditions. A study of the tuning of the end cells showed that dipole rods are not required to displace the dipole modes, which are closer to the accelerating mode owing to the favourable length of this design. Proper tuning of the end cells was able to guarantee a voltage error in the RFQ of within $\pm1\%$.

Thermomechanical simulations showed that eight cooling channels were sufficient to allow temperature stabilization of the RFQ cavity, because of the limited dissipated power in pulsed mode. The dynamic tuning strategy is based on two cooling circuits, one using four channels drilled inside the vane pole tips and the other using four channels in the RFQ body. Dynamic tuning of the RFQ cavity is obtained by regulating the difference in water temperature between the two circuits.

Thirty-two fixed tuners (80 mm diameter) plus the RF and dummy RF ports allowed a flat electrical field to be achieved for the quadrupole accelerating mode. The nominal tuner position was close to the nominal value of 15 mm penetration inside the cavity, which allows a linear frequency variation as a
3.3.4 Mechanical design and assembly

In the Linac4 and SPL RFQ, the 2D section was constant over the full length in order to simplify machining. The vane modulations were machined using a wheel-shaped cutting tool. The assembly technique used a two-step brazing process, with a horizontal brazing operation for the assembly of the four vanes and a final vertical brazing operation to assemble the stainless steel end flanges, tuners, and vacuum ports [32].

The vacuum ports were brazed onto the module in order to avoid machining the grids directly into the major vanes and also because this allows excellent compensation of the field distortion introduced by the vacuum port itself. As shown in Fig. 3.3, 4 mm of port penetration into the RFQ cavity was sufficient to obtain the required compensation in module T1, for example.

![Fig. 3.3: Detuning (y-axis, in MHz) as a function of different penetration depths (mm) produced by different vacuum port geometries.](image)

A constant check of the mechanical precision achieved during machining and assembly was performed by metrology and RF bead-pull measurements. Based on a lossless loaded four-wire transmission line model, these RF bead-pull measurements associated mechanical imperfections and tuning errors with relative errors in the ideal vane-to-vane capacitance distribution [33].

The last voltage error profile was measured on the Linac4 RFQ just after its installation in the Linac4 tunnel in September 2013 and is shown in Fig. 3.4; the voltage errors slightly above what was specified suggest that a retuning of the RFQ field profile could be necessary before running with a high-intensity beam.

3.3.5 Radio frequency quadrupole commissioning

The RFQ was commissioned with a low-current beam on the 3 MeV Test Stand and subsequently in the Linac4 tunnel at the duty cycle foreseen for filling the PSB. The main beam parameters were confirmed during commissioning; in particular, by tracing the beam transmission as a function of the RF cavity voltage, it was shown that the design transmission, which is dependent on the beam quality delivered by the ion source, could be achieved with the specified inter-vane voltage. In the graph given in Fig. 3.5, the
beam transmission is plotted as a function of the RF power for different values of the LEBT gas pressure, thus applying different neutralization times to the incoming $H^-$ beam.

![Fig. 3.5: Beam transmission through the RFQ as a function of the applied RF power (measurements versus simulation).](image)

### 3.4 Beam chopping

The beam chopper has to establish the required micropulse structure by deflecting part of the RFQ output beam into a dedicated beam dump. The beam chopper structure is located between the RFQ and the DTL, both operating at 352.2 MHz, and the transfer energy of 3 MeV was chosen as a compromise between the demands of beam dynamics and the chopper voltage attainable with a feasible amplifier. While lower beam energies reduce the voltage requirements for the chopper amplifier, they increase the space charge forces and generally yield more emittance growth. The bunches are spaced by 2.84 ns and come in 0.57 ms pulses repeated at 50 Hz, which means that in order to avoid partially chopped bunches the
chopper rise time has to be of the order of 2 ns (assuming a maximum bunch phase length of \(\pm 45^\circ\) at 352.2 MHz). The deflector itself consists of two 50 \(\Omega\) transmission lines facing each other, which are driven by two pulse amplifiers with opposite-polarity signals (of 700 V).

The most challenging mode of operation will occur when the SPL is injecting 4 MW of beam power into an accumulator ring. The chopper will help to minimize longitudinal capture losses in the accumulator by providing a gap in the injected beam. In all modes of operation, the chopper can also be used to remove the first 20–30 \(\mu\)s of the pulse, which is generally not very stable during the start-up of the source because space charge compensation has not yet been established in the LEBT.

A 3D technical drawing of the chopper line is shown in Fig. 3.6. The elements of the complete line are (from left to right, downstream) a matching section (four quadrupoles plus a buncher cavity), the beam chopper (two quadrupoles with chopper plates inside), a buncher cavity plus a quadrupole plus a dump (for the chopped beam), and another matching section (four quadrupoles plus a buncher cavity). The completed chopper line and part of the RFQ, installed in the Linac4 tunnel, are shown in Fig. 3.7.

![3D image of the chopper line with support structure](image)

**Fig. 3.6:** 3D image of the chopper line with support structure

The beam dynamics of the entire chopper line was designed to minimize the plate voltage by increasing the deflection via beam optics. On the other hand, there was an effort to keep the actual chopper structure as short as possible in order to minimize emittance blow-up during long drifts.

The chopper line was tested in spring 2013 on the 3 MeV Test Stand at CERN [34], comprising the source, LEBT, RFQ, medium-energy beam transport (MEBT), and a diagnostics line to qualify the beam
outside the chopper line. The chopping principle was confirmed, and all hardware components of the chopper were validated at the Linac4 duty cycle (<0.01%). A list of the elements is given in Table 3.5, and the performance requirements are listed in Table 3.6.

**Table 3.5: Elements in the chopper line**

<table>
<thead>
<tr>
<th>Element</th>
<th>Number</th>
<th>Length (mm)</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long quadrupole I</td>
<td>2</td>
<td>255</td>
<td>$G = 0.6\text{–}2.4 \text{T/m}$</td>
<td>With chopper plates inside</td>
</tr>
<tr>
<td>Long quadrupole II</td>
<td>1</td>
<td>155</td>
<td>$G = 4.3 \text{T/m}$</td>
<td></td>
</tr>
<tr>
<td>Short quadrupole I</td>
<td>6</td>
<td>56</td>
<td>$G = 12\text{–}30 \text{T/m}$</td>
<td></td>
</tr>
<tr>
<td>Short quadrupole II</td>
<td>2</td>
<td>82</td>
<td>$G = 8\text{–}11 \text{T/m}$</td>
<td></td>
</tr>
<tr>
<td>Chopper plates</td>
<td>2</td>
<td>400</td>
<td>Distance 20 mm</td>
<td></td>
</tr>
<tr>
<td>Dump</td>
<td>1</td>
<td>200</td>
<td>Conical hypervapotron</td>
<td></td>
</tr>
<tr>
<td>Buncher cavities</td>
<td>3</td>
<td>200</td>
<td>$V = 100/165 \text{kV}$</td>
<td>$P = 12\text{–}23 \text{kw}$</td>
</tr>
</tbody>
</table>

### 3.4.1 Chopper structure

Rise and fall times in the nanosecond range have been obtained using travelling-wave stripline structures, where the striplines are meander-folded in order to match the speed of the travelling wave to the beam velocity (Fig. 3.8a).

In the present design, a section 1.2 m long accommodates two chopper units 0.5 m long, each housing two deflecting plates of length 0.4 m. To minimize the total length of the chopper line, the chopper units are fitted inside the bore of existing quadrupoles (Fig. 3.8b). The deflecting plates are driven simultaneously with opposite polarity, and water cooling is employed to remove heat arising from beam losses and from the deflecting signal. Since the striplines do not completely cover the deflector plates, an ‘effective surface coverage factor’ has to be applied to the electric field seen by the beam. In
Table 3.6: Main parameters of beam chopper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Overall MEBT length</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Number of chopper structures (inside quadrupoles)</td>
<td>2</td>
</tr>
<tr>
<td>Number of quadrupoles</td>
<td>11</td>
</tr>
<tr>
<td>Length of chopper plates</td>
<td>400 + 400 mm</td>
</tr>
<tr>
<td>Distance between chopper plates</td>
<td>20 mm</td>
</tr>
<tr>
<td>Separation between chopped and unchopped beam</td>
<td>15 mm</td>
</tr>
<tr>
<td>Chopper structure rise-and-fall time (10–90%)</td>
<td>&lt;2 ns</td>
</tr>
<tr>
<td>Chopper voltage pulse (per plate)</td>
<td>700 V</td>
</tr>
<tr>
<td>Effective chopper voltage pulse</td>
<td>≈560 V</td>
</tr>
<tr>
<td>Remaining voltage for unchopped beam</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Maximum chopper frequency</td>
<td>44 MHz</td>
</tr>
<tr>
<td>Minimum pulse length</td>
<td>8 ns</td>
</tr>
<tr>
<td>Maximum chopping factor (duty cycle)</td>
<td>40%</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1–50 Hz</td>
</tr>
<tr>
<td>Chopper deflection angle</td>
<td>6.3 mrad</td>
</tr>
</tbody>
</table>

In our case this factor amounts to ≈ 80%, which means that for a deflection voltage of ±700 V (i.e., 1.4 kV in total, or 1120 V effective voltage) at a beam energy of 3 MeV one can achieve a total deflection angle of 6.3 mrad for both units.

![Alumina ceramic plate with a printed meander structure and mounting holes](image1)

![Chopper structure installed in a quadrupole](image2)

**Fig. 3.8:** The MEBT chopper

As shown in Fig. 3.8a, the travelling-wave structure consists of a double-meander stripline matched to a beam velocity of $\beta = 0.08$. The structure is printed on an alumina substrate 3 mm thick. The SPL chopper structure is made of notched microstriplines with separating ridges in between. An alumina substrate is used, which has the advantage of being resistant to ionizing radiation and having a low vacuum outgassing rate, as well as a high heat transfer coefficient.

The first two plates which were constructed [35] used a MoMn base layer (fired at 1500°C in an H$_2$/N$_2$ atmosphere) with several layers of other metals added. Their final shape was determined by a
chemical etching process. The results of extensive numerical simulations and measurements of the rise and fall times and the deflecting efficiency are summarized in Ref. [36].

As an alternative to the MoMn process with chemical etching (done at CERN), a different technique was then proposed by Kyocera. In this technique, the base layer is a silk-screen-printed silver alloy, normally used for brazing ceramic–metal interfaces. This layer (a few microns thick) is fired at high temperature under vacuum and has an adhesion strength greater than 100 N/mm$^2$, which is nearly as good as that of MoMn. Subsequently, the thickness of the conductor (copper) is increased to 30 µm by electrochemical deposition, followed by a flash of gold to avoid surface degradation due to contact with air.

A 3D view of the complete chopper with vacuum tank, water-cooling system, and feedthroughs is shown in Fig. 3.9, and a summary of the main parameters is given in Table 3.6.

### 3.4.2 Chopper amplifier: design considerations

#### 3.4.2.1 Available devices

The most suitable devices for this application are MOSFETs. These components can handle high voltages and high currents and are also very fast, but none of those presently on the market satisfy our entire set of requirements. As the switching time is the only characteristic that cannot be achieved other than by the device itself, a parallel/series combination of lower-voltage and lower-current devices must be used.

#### 3.4.2.2 Stacking configuration

Paralleling MOSFETs is a common practice for increasing the available current and power and does not present particular difficulties. However, connecting them in series to handle voltages higher than that rated for a single device requires special attention. If the MOSFET series stack has to be supplied from a single voltage source, precautions must be taken to guarantee equal voltage sharing and that the
maximum rating is not exceeded. This is a difficult task because even minor problems, such as a slight drive synchronization error, can result in severe device overvoltage and the loss of an entire MOSFET stack.

An intrinsically safe, multistage configuration that allows high output voltages to be built up from lower-voltage units is possible provided each unit is floating and can be individually supplied. The basic circuit is shown in Fig. 3.10. The energy being transferred to the load \( (R) \) is stored in the capacitors \( (C) \). All capacitors are charged to the same voltage and are floating. When the MOSFETs \( (Q) \) turn on, the capacitors become series connected and discharge into the load, which will see the sum of the voltages on the individual capacitors. Each stage has to supply the full load current and thus sees an equivalent load \( R/N \).

If the modules are not switched in perfect synchronism or if some MOSFETs do not turn on at all, a current path always exists through the diodes \( (D) \) so that the output voltage will simply be reduced by the contribution of the missing stages. If for any reason the voltage across a diode \( D \) rises above the capacitor voltage, the MOSFET reverse diode will turn on and automatically prevent overvoltage across the MOSFETs.

As the circuit is completely floating, either point \( \text{OUT}^+ \) or point \( \text{OUT}^- \) may be grounded to invert the output signal polarity. Of course, in reality each stage will have some leakage capacitance, whose effects at high frequency must be controlled to achieve the required switching speed.

![Stacking configuration](image)

**Fig. 3.10:** Stacking configuration

### 3.4.2.3 Supplying the power

In pulsed operation, supplying the required energy to the capacitors while maintaining them floating is achieved as shown in Fig. 3.11. With the switch \( SW \) in the charging position, \( V_{\text{supply}} \) charges all the capacitors in parallel through the diodes \( D_A \) and \( D_B \). Opening \( SW \) will reverse-bias \( D_A \) and \( D_B \), thus isolating each stage from the others. Low-reverse-capacitance diodes must be used. Note that \( V_{\text{switch}} \) must be higher than the maximum output voltage to ensure reverse bias conditions for the diodes in all the stages.

### 3.4.2.4 Gate drivers and MOSFET selection

The choices of the power device and the gate driver are strictly linked because the ensemble must satisfy the rise/fall time and voltage specifications, and also the requirements in terms of jitter and thermal
stability. There is no need for the pulse amplifier to be linear.

### 3.4.2.5 Isolating the driving signals

While building up the output pulse, each stage will rise to a voltage level corresponding to its position in the stack. Therefore the common input control pulse has to be applied independently to each stage through individual level shifters/isolators.

### 3.4.3 Basic module

The basic module (Figs. 3.12 and 3.13) was built around Freescale RF MOSFETs, type MRF6V2010N. These are high-speed devices that can typically withstand 110 V and have a saturation current above 1.5 A, very limited internal capacitances ($C_i \approx 17$ pF, $C_o \approx 8$ pF, and $C_r \approx 0.13$ pF), and a low threshold voltage ($\approx 2$ V). The standard logic family best suited as a gate driver in this application is the AC/ACT family. Its internal output stage configuration, based on symmetric MOSFETs, allows parallel connection of the outputs and guarantees high peak switching current, high-frequency operation, and fast transitions. With these two components, switching times of about 1 ns can be achieved.

Six MRF6V2010N MOSFETs are connected in parallel on a 10 Ω characteristic-impedance stripline. Ferrite cores are used to limit the effect of leakage capacitance on the load at high frequency. Two such modules are connected facing each other, so that at the centre the characteristic impedance is halved to 5 Ω. The voltage achievable from this module is $\approx 80$ V.

### 3.4.4 Power and control pulse isolator

Generation of the floating driving pulses from the common input signal is done by the circuit shown in Fig. 3.14. A common amplifier drives 10 pulse transformers in parallel (one for each of the stages required). The transformer provides galvanic isolation, has two counter-phase outputs, and is arranged...
so as to minimize the capacitance between the input and the floating outputs. Each output signal is derived using a high-pass filter to obtain short pulses corresponding to the rising and falling fronts of the input signal. A flip-flop is then set and reset by these pulses to reconstruct the original driving signal. Individual adjustment of the delays of the rising and falling fronts allows exact synchronization.

To achieve the speed and time stability requirements, emitter-coupled logic (ECL) is used to reconstruct the driving pulse. The circuit also provides the floating supply required by the gate drivers. It uses commercial 2 W isolated DC–DC converters with only 2 pF capacitance between input and output.

3.4.5 2 Hz pulser ensemble prototype

A prototype pulse amplifier operating at a 2 Hz burst repetition frequency has been built and tested. Increasing the burst repetition frequency to 50 Hz brings the power dissipation per device to ≈2 W. This can easily be handled with adequate forced air cooling. Upgrading of the DC supply current is also needed, and therefore more powerful units are required. The amplifier is housed in a 19 inch, 6 units high, 730 mm long rack mount chassis. Ten 5 Ω modules are mounted in a box that also contains the level shifters, power supplies, and protection interlocks (Fig. 3.15).

The 10 Ω characteristic-impedance striplines are made from a thin, flexible printed-circuit material. They are mechanically and electrically stacked at their centre, where the signals are summed. Each level shifter card drives the two 10 Ω subcircuits used in a 5 Ω module in parallel. High-frequency common-mode isolation is implemented using ferrite cores. These surround each stripline, the connec-

![Fig. 3.13: 10 Ω subcircuit card](image)

![Fig. 3.14: Power and control pulse isolation](image)
Ancillary circuitry takes care of turn-on sequencing, timing control, and protection of the power supplies, as well as remote ON/OFF control and status acquisition. Although each individual 10 Ω subcircuit can be operated safely on an open or short circuit, a load status interlock enables the pulse amplifier only when the load resistance is in the range 25–100 Ω.

The input control pulses are transferred to the output during a time window (2 ms max) started by a dedicated trigger pulse.

### 3.4.6 Measured performance

The pulse amplifier has been fully characterized using a 50 Ω attenuator. Measurements were done for both output polarities, and almost identical results were obtained. Polarity switching is extremely easy, as one needs only to invert the output cable connection. The pulse output voltage during a burst varies from a minimum of 650 V to 700 V. This value could be increased by 50 V simply by acting on the DC power supply. The measurements were done at a 2 Hz burst repetition frequency. The pulse length distortion and the input–output delay are limited to 300 ps, but they are not constant. The first is proportional to the pulse length, while the latter increases during the burst and with frequency. Table 3.7 summarizes the performance achieved, and the plots in Figs. 3.16–3.19 show measured signals.
Table 3.7: Main pulse amplifier parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage ((V_{max}))</td>
<td>(\geq 650) V</td>
</tr>
<tr>
<td>Load impedance</td>
<td>50 (\Omega)</td>
</tr>
<tr>
<td>Pulse frequency</td>
<td>(\geq 45) MHz</td>
</tr>
<tr>
<td>Burst length</td>
<td>1 ms</td>
</tr>
<tr>
<td>Burst repetition frequency</td>
<td>50 Hz(^a)</td>
</tr>
<tr>
<td>10–90% rise and fall time</td>
<td>1.5 ns typically</td>
</tr>
<tr>
<td>3–90% rise and fall time</td>
<td>(\leq 2.5) ns</td>
</tr>
<tr>
<td>Minimum pulse length</td>
<td>(\leq 8.0) ns</td>
</tr>
<tr>
<td>Minimum off time of pulse</td>
<td>(\leq 10.0) ns</td>
</tr>
<tr>
<td>Maximum pulse length</td>
<td>100 (\mu s)^a</td>
</tr>
<tr>
<td>Residual voltage between pulses</td>
<td>(\leq 3% ) of (V_{max})</td>
</tr>
<tr>
<td>Pulse length distortion variation</td>
<td>(\leq 300) ps</td>
</tr>
<tr>
<td>Input–output delay variation</td>
<td>(\leq 300) ps</td>
</tr>
</tbody>
</table>

\(^a\) See text.

Fig. 3.16: 1 MHz, 300 ns pulse; rise and fall times are from 3\% to 90\% (200 ns/div, 200 V/div)

Fig. 3.17: 45 MHz, 8.6 ns pulse; rise and fall times are from 3\% to 90\% (10 ns/div, 200 V/div)
(a) 45 MHz, 8.6 ns positive pulse, 200 µs/div, 200 V/div

(b) 100 µs pulse; rise and fall times are from 3% to 90% (20 µs/div, 200 V/div)

Fig. 3.18

(a) View of single pulse, 400 ns/div, 200 V/div

(b) View of pulse transition, 10 ns/div, 200 V/div

Fig. 3.19: Two 1450 ns pulses separated by 10 ns; rise and fall times are from 3% to 90%
3.5 Normal-conducting linac (Linac4)

3.5.1 Drift tube linac

Three DTL cavities operating at 352.2 MHz accelerate H\(^-\) ion beams from 3 to 50 MeV. Tank 1 is powered by an LEP klystron, while tanks 2 and 3 take advantage of the higher output power (2.8 MW) of the new Linac4 klystrons. Permanent magnetic quadrupoles (PMQs) were chosen for transverse focusing. Their small diameter leads to a cavity design with high shunt impedance, thus increasing the efficiency of beam acceleration in the DTL. Beam dynamics simulations with different beam currents showed that the chopper line provides sufficient flexibility for matching different beam currents into a DTL with fixed magnetic gradients. The absence of electrical connections allows a simpler drift tube design and makes it possible to place the PMQs in vacuum.

A constant accelerating gradient of 3.1 MV/m in tank 1 and 3.3 MV/m in tanks 2 and 3 was established as the best compromise between RF optimization and beam dynamics requirements. Keeping the gradient constant in tank 1 leads to a compact design [37] and makes tuning of the cavity easier. The peak fields are reduced by design in the first 10 cells of tank 1 in order to limit the risk of breakdown in the presence of magnetic fields [38, 39]. In order to provide a margin for longitudinal matching from the chopper line, the synchronous phase starts at \(-35^\circ\) in tank 1 and ramps linearly to \(-24^\circ\) over the tank. A focusing scheme of FFDD over all three tanks proved to be the least sensitive to alignment and gradient errors in the transverse plane [40]. The missing longitudinal focusing between the tanks is compensated by lowering the synchronous phase in the first and last accelerating gaps of each tank. The diagnostics and steering in the inter-tank areas fit within \(3\beta\lambda\) between tanks 1 and 2 and within \(2\beta\lambda\) between tanks 2 and 3. The final design parameters are shown in Table 3.8.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cavity 1/2/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Output energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Frequency</td>
<td>352.2 MHz</td>
</tr>
<tr>
<td>Accelerating gradient (E_0)</td>
<td>3.1/3.3/3.3 MeV/m</td>
</tr>
<tr>
<td>Peak surface electric field</td>
<td>1.49/1.40/1.44 Kilpatrick</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>40 mA</td>
</tr>
<tr>
<td>Design RF duty cycle</td>
<td>10%</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>(-35^\circ) to (-24^\circ)</td>
</tr>
<tr>
<td>Lattice</td>
<td>FFDD</td>
</tr>
<tr>
<td>Quadrupole length</td>
<td>45/80/80 mm</td>
</tr>
<tr>
<td>Beam aperture (cavity)</td>
<td>20 mm</td>
</tr>
<tr>
<td>Tank diameter</td>
<td>0.52 m</td>
</tr>
<tr>
<td>No. of cells per cavity</td>
<td>39/42/30</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>3</td>
</tr>
<tr>
<td>Number of segments</td>
<td>2/4/4</td>
</tr>
<tr>
<td>Length per cavity</td>
<td>3.90 / 7.34 / 7.25 m</td>
</tr>
<tr>
<td>RF peak power (DTL total)</td>
<td>5.02 MW</td>
</tr>
<tr>
<td>RF beam power (DTL total)</td>
<td>1.89 MW</td>
</tr>
<tr>
<td>Vacuum</td>
<td>(10^{-7}) mbar</td>
</tr>
</tbody>
</table>

Following the design of the DTL at the SNS [41], a self-supporting structure using copper-plated ring-forged stainless steel cylinders 50 mm thick serves as the resonating cavity. Based on an idea previously employed in Linac2, copper drift tubes are mounted on girders positioned on the steel tanks. The three DTL tanks were assembled and bolted together from segments up to 2 m long (Fig. 3.20). These
dimensions were found to be acceptable for tank splitting, raw material purchase, precision machining, assembly, and copper plating. The function of the tanks is to provide the vacuum and RF envelopes. Aluminium girders with stainless steel bushings are placed flat on top of the tanks. Cooling is achieved by 12 mm diameter cooling channels along the tanks [38].

In order to reduce the complexity further, these bushings were precision machined. Differently from other DTLs, the drift tubes were mounted to their final tolerances without any adjustment mechanism. Neither bellows nor flexible rubber seals are required. Instead, industrial-grade Helicoflex® metal seals between the drift tubes and tanks provide vacuum tightness and RF continuity at the same time, making the design basically maintenance-free. The principal functions of sealing and positioning are assigned to two separate workpieces that can be manufactured in parallel at individual work sites.

The drift tubes are held in place by a patented mounting mechanism (Fig. 3.21). Spring washers are slid onto a sleeved bushing that is inserted into the base plate, the sleeve preventing the washers from misaligning and obstructing the common opening. The assembly is tightened with a pre-stress socket on a press and fixed with a pre-stress screw on either side. A stainless steel mounting screw is installed without force through the sleeve, directly into the drift tube. A stop on the screw abutting the drift tube prevents excessively tight mounting, and leaves the required exact clearance for the metal seal. When the pre-stress screws are released, the compression force of the spring washers of about 20 kN is transferred uniformly onto the drift tube through the mounting screw [42].
the cavities during operation. For SPL duty cycles, the tuners and post couplers are water-cooled, and the cooling water needs to be thermally stabilized. All drift tubes need to be cooled in parallel, and each drift tube is equipped with a thermal probe to detect overheating due to insufficient cooling-water supply and to protect the permanent magnet quadrupoles. These probes are installed in channels passing through the tank and protruding into the copper stem of the drift tube (Fig. 3.21). The flow switches foreseen in low-duty-cycle operation would not be reliable and fast enough to detect a critical reduction in water flow.

The principal design features have been tested in a full-scale prototype with 12 drift tubes, corresponding to about half a tank segment (Fig. 3.22). The prototype has been assembled, and the drift tube positions were verified by a laser tracker to be within tolerance. The prototype was designed for a nominal average accelerating-field level of 3.3 MV/m. The unloaded $Q$-value was measured as 33,700, which corresponds to 80% of the $Q$-value found with Superfish. At the nominal field, a power of 220 kW is required. The structure was conditioned in 15 days to a 7.5% duty cycle with a 1.5 ms pulse width and 50 Hz repetition rate, the highest rate expected for operation in a superconducting proton linac [43]. The cooling was tested for CW operation at a power level equivalent to the 10% maximum design duty cycle at the nominal power.

![Fig. 3.22: DTL prototype in the assembly stage](image)

Finally, a complete drift tube equipped with a PMQ and a cooling circuit was built and tested at high RF power. The drift tube was installed in the cavity using the new mounting mechanism. Reconditioning to a 3% duty cycle after insertion of the drift tube was achieved in four days using an automated procedure. High-power RF tests of the DTL prototype, with a half drift tube in the end wall equipped with a second PMQ, demonstrated that the voltage was held in the first gaps in the presence of magnetic fields. The mechanical design features that were tested on the DTL prototype have been improved for series production. The prototype was financed by INFN, machined at CINEL, and assembled at CERN.

The construction of the DTL relies on the CERN workshops for the assembly and finishing technologies. The manufacturing of the drift tubes has recently been completed in collaboration with ESS-Bilbao. The tank segments are being manufactured by CADINOX, and the girder segments are being produced by various companies and finally machined in part at CERN.

### 3.5.2 Cell-coupled drift tube linac

The cost and mechanical complexity of a DTL are driven by the required alignment precision of the quadrupoles, which are housed inside the drift tubes. At low beam energies, the high space charge forces within the beam require very short focusing periods, meaning that there are hardly any alternative structures to the DTL. At higher energies, the focusing periods can be lengthened and one can use structures which have several accelerating cells between quadrupoles. In the Linac4 CCDTL, short
DTL-type tanks each containing two drift tubes are connected to off-axis coupling cells, which transfer RF power from one tank to the next. Three accelerating cavities and two coupling cells form one Linac4 CCDTL module (see Fig. 3.23), operating in the $\pi/2$ mode.

![Fig. 3.23: Scheme of a CCDTL module, with electric field lines](image)

The accelerating tanks operate in the usual DTL 0 mode and RF power is supplied via iris coupling to the central cavity. Once the cavities have established their steady-state standing-wave pattern, the coupling cells are basically field-free and therefore do not contribute to RF surface losses during operation. The coupling cells provide a distance of $(3/2)\beta\lambda$ between the centres of the last and first gaps of neighbouring tanks, which—from an energy of 40 MeV onwards—provides enough space to fit quadrupoles between adjacent tanks. The main parameters of the Linac4 CCDTL are summarized in Table 3.9.

<table>
<thead>
<tr>
<th>Table 3.9: Main CCDTL parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy</td>
</tr>
<tr>
<td>Output energy</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Accelerating gradient $E_0$</td>
</tr>
<tr>
<td>Peak electric surface field</td>
</tr>
<tr>
<td>Peak RF power per module</td>
</tr>
<tr>
<td>Average pulse current</td>
</tr>
<tr>
<td>Design RF duty cycle</td>
</tr>
<tr>
<td>Synchronous phase</td>
</tr>
<tr>
<td>Lattice</td>
</tr>
<tr>
<td>No. of PMQs</td>
</tr>
<tr>
<td>No. of EMQs</td>
</tr>
<tr>
<td>Beam aperture (cavity)</td>
</tr>
<tr>
<td>Cell diameter</td>
</tr>
<tr>
<td>No. of cells per cavity</td>
</tr>
<tr>
<td>No. of cavities per module</td>
</tr>
<tr>
<td>No. of modules</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>RF peak power (CCDTL total)</td>
</tr>
<tr>
<td>RF beam power (CCDTL total)</td>
</tr>
<tr>
<td>Vacuum</td>
</tr>
</tbody>
</table>

The first CCDTL was originally developed at LANL for CW operation [44]. One of its advantages is the separation of the quadrupoles from the drift tubes, which leads to (i) less demanding tolerances for the alignment of the drift tubes and (ii) easier alignment of the quadrupoles, which can be referenced and adjusted with respect to alignment targets outside the RF structure. In the case of Linac4, PMQs are
used between the cavities of each module. Between modules, electromagnetic quadrupoles (EMQs) are employed to provide intermediate beam matching.

Each cavity consists of two half-cells, which were machined out of pre-shaped 3D-forged stainless steel. The half-cells were then copper plated (see Fig. 3.24) and connected with Helicoflex® gaskets, which close the vacuum and provide RF continuity. The flange areas for the gaskets are copper plated in order to maintain a high quality factor in the cavities. The fixation mechanism for the stems is similar to that used for the DTL.

![Copper-plated CCDTL half-tank with coupling slot and installed drift tube](image)

The development of this particular CCDTL structure started at CERN in 1997. A first hot prototype, consisting of two half-cavities and one coupling cell, was constructed at CERN and high-power tested in SM18 [45]. A second hot prototype was constructed in Russia in the framework of an ISTC project at VNIITF Snezhinsk and BINP Novosibirsk. This second prototype consisted of two full cavities and one coupling cell and was also successfully high-power tested at CERN [46]. Series construction started in 2010 within the framework of two ISTC projects at these Russian institutes. CERN delivered the first electromagnetic design, largely based on Superfish® calculations and 3D simulations of the coupling irises (between cells and between cavities and waveguides). BINP verified the design with 3D simulations. The mechanical design of the modules was then developed at VNIITF, which fabricated all cavities. The design of the drift tubes and their construction were the responsibility of BINP, which also assembled and will tune the CCDTL. At the time of writing, all seven modules have been delivered and assembled at CERN. High-power conditioning started in autumn 2012 and will conclude in early 2014. Figure 3.25 shows the first module, mounted on a test support at BINP. Linac4 will be the first accelerator where a CCDTL will be used in routine operation.

### 3.5.3 Pi-mode structure

Since the effective shunt impedance per unit length, $Z T^2$, of 0-mode structures such as DTLs and CCDTLs decreases continuously from an energy of 20 MeV onwards, other accelerating structures have been studied. Above approximately 100 MeV, $\pi / 2$- and $\pi$-mode structures (the angles $\pi / 2$ and $\pi$ refer to the phase advance from one cell to the next) can accelerate the beam more efficiently than 0-mode structures, as illustrated in Fig. 3.26.
For acceleration above 100 MeV, it was originally foreseen [3] that a side-coupled structure (an SCL) would be employed, operating in the $\pi/2$ mode at 704 MHz. The challenges of the frequency jump, two different RF systems, the large number of coupled cells (about 500)—which would require precise machining and tuning—and the high peak power per coupled structure (about 5 MW) triggered the study of a $\pi$-mode structure, similar to the normal-conducting LEP accelerating structure [47]. Because of its compact, robust construction, the $\pi$-mode structure was adapted and modified for operation in Linac4, which will be the first machine to employ this structure type for low-$\beta$ protons.

The PIMS section accelerates the beam from 102 MeV to 160 MeV and consists of 12 cavities, each powered by 1 MW at a frequency of 352 MHz. (Further modules can be added to increase the output energy to 180 MeV and above.) The cavities are made from seven cells of equal length. Each cavity is adapted to the particle velocity of its energy range, so that the RF designs differ in cell length (distance between gaps) and gap length. The gap length between the nose cones is used as a parameter to adjust the resonance frequency, while the inside radius of all cells is kept constant (in contrast to the LEP design). This saves material and facilitates machining. Table 3.10 lists the main parameters of the PIMS section.
The major change with respect to the LEP design is in the coupling slots that connect adjacent cells and distribute the electromagnetic field along the cavity. As the group velocity in $\pi$-mode structures is zero, strong coupling between cells is necessary to maintain the required electromagnetic field distribution, in particular when movable tuners and beam-loading transients interfere dynamically. Tilts of $\pm 5\%$ can be tolerated by the beam [48]. The RF design of the PIMS is described in detail in Ref. [49]. The average cell-to-cell coupling will be 5.4% for the first cavity and 4.7% for the 12th cavity. The design was validated by a ‘cold’ model, confirming the simulation results and the tuning principle [49]. The electric field in a cavity is shown in Fig. 3.27.

![Electric field in one quarter of a seven-cell PIMS cavity](image)

The mechanical design was developed for a duty cycle of 10%. The average dissipated power of about 80 kW (11.4 kW per intermediate wall) requires a good thermal conductivity and a high yield strength, especially in the material of the discs. The PIMS components will be machined from 3D-forged OFE copper. In order to save material, cells will be formed from discs and rings (Fig. 3.28), joined together by electron beam welding. Brazing is avoided to preserve material quality; only the central rings need to be brazed, owing to the wide waveguide connection. ‘V’-shaped cooling channels

---

**Table 3.10: Main PIMS parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy</td>
<td>102 MeV</td>
</tr>
<tr>
<td>Output energy</td>
<td>160 MeV</td>
</tr>
<tr>
<td>Frequency</td>
<td>352.2 MHz</td>
</tr>
<tr>
<td>Accelerating gradient $E_0$</td>
<td>3.9–4 MV/m</td>
</tr>
<tr>
<td>Peak surface electric field</td>
<td>1.8 Kilpatrick</td>
</tr>
<tr>
<td>Peak RF power per cavity</td>
<td>1 MW</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>40 mA</td>
</tr>
<tr>
<td>Design RF duty cycle</td>
<td>10%</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>$-20^\circ$</td>
</tr>
<tr>
<td>Lattice</td>
<td>F0D0</td>
</tr>
<tr>
<td>No. of quadrupoles</td>
<td>12</td>
</tr>
<tr>
<td>Beam aperture</td>
<td>40 mm</td>
</tr>
<tr>
<td>Cell diameter</td>
<td>0.52 m</td>
</tr>
<tr>
<td>No. of cells per cavity</td>
<td>7</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>12</td>
</tr>
<tr>
<td>Length</td>
<td>21.5 m</td>
</tr>
<tr>
<td>RF peak power (PIMS total)</td>
<td>11.9 MW</td>
</tr>
<tr>
<td>RF beam power (PIMS total)</td>
<td>2.3 MW</td>
</tr>
<tr>
<td>Vacuum</td>
<td>$10^{-7}$ mbar</td>
</tr>
</tbody>
</table>
are drilled into the discs and connected by flexible hoses from the outside. In this way, there are no brazed or welded joints between vacuum and water—a concept that was adopted from the LEP cavities.

![Discs and rings before welding](image)

**Fig. 3.28:** Discs and rings before welding

The PIMS cavities will be tuned (Fig. 3.29) in two steps. Before the welding of the discs and cylinders, the elements will be clamped to measure the single-cell frequencies and field flatness. With these results, the tuning rings (also called tuning islands) located on each disc will be re-machined to individually chosen heights to adjust the resonance frequency and the field distribution of the accelerating mode. After welding of the entire cavity, the piston tuners will be cut. This second tuning operation is necessary because the welding shortens the cells by 0.3–0.6 mm and changes the $Q$-values of individual cells by a not entirely predictable amount. Furthermore, when a change is made from low- to high-duty-cycle operation, the temperature of the cavity might change, and the corresponding frequency shift (e.g., 200 kHz) can be compensated by exchanging the piston tuners.

A prototype cavity has been built [50] and high-power tested [51] at CERN (Fig. 3.30). The cavity was conditioned very quickly, even without a prior bake-out: after 30 h, the cavity could be fed by pulses of 800 µs length and 700 kW peak power (the nominal peak power for the first module) at a repetition rate of 2 Hz (similar to Linac4 conditions). Thereafter, the cavity was conditioned within 24 h to 1100 kW, the maximum power available from the klystron, and tested for 72 h. The stored energy in the cavity was proportional to the energy delivered from the klystron for all power levels—no missing energy was observed. Moreover, no instabilities were seen, even when one half of the cavity was cooled while the water flow in the other half was closed off for one hour. In a second test, the cavity was fed with a continuous power of 85 kW, corresponding to the average dissipated power of SPL pulses with a 12% duty cycle. The cavity performed thermally as predicted by simulations. The temperature on the outside rose by 20 K compared with the cooling-water temperature; the corresponding temperature increase in the nose cone tips (the hottest points) was 45 K. No instabilities were observed. Two challenges noticed in relation to high-duty-cycle operation were that (i) a rapid change in resonance frequency is caused by strong cooling of the cavity when an interlock stops the klystron, and (ii) there is a need to balance the water flow in the discs in order to maintain the desired field distribution in the cavity under high heat load.

After the successful tests of the prototype, it was decided to use this cavity as the first PIMS cavity for Linac4/SPL. Construction of a further 12 cavities is presently taking place in Poland at the National Centre for Nuclear Physics (NCBJ), Swierk.
Fig. 3.29: Bead-pull measurements during the tuning of the PIMS prototype

Fig. 3.30: PIMS prototype during a high-(average)-power test
3.6 Beam dynamics in Linac4

3.6.1 Nominal beam dynamics

The beam dynamics in each of the four accelerating structures of Linac4 (RFQ, DTL, CCDTL, and PIMS) was carefully optimized to guarantee minimum emittance growth together with maximum transmission. Efforts were made to control the transverse and longitudinal phase advance in order to avoid resonances and sharp transitions at any time [52]. Efforts were also made to accept a wide range of beam currents in the focusing lattice, two thirds of which are permanent magnet quadrupoles. In general, the best beam quality is obtained when the focusing is as extended as possible and when drift spaces without active elements are minimized, basically when the time during which space charge forces are left unbalanced is reduced to a minimum. This approach, especially at the low-energy end, leads to limited space for passive elements such as diagnostics, which are nevertheless necessary for good functioning of the machine. The integration of the accelerating structures into a real beam line therefore causes a general degradation of the emittance, accompanied by formation of a halo. There are two sections in Linac4 in which most of the emittance increase is localized: the 45 keV LEBT and the 3 MeV MEBT housing the chopper line. In the LEBT (1.9 m long), the beam is assumed to be 90% neutralized, and therefore the emittance increase is due not to space charge but mostly to the very high divergence (about 200 mrad) with which the beam comes out of the source. In fact, such a divergence is almost comparable to the transverse momentum given by the entrance fringe field of the first solenoid, making it impossible to completely cancel out the azimuthal component at the solenoid exit fringe field. This effect accounts for a 15% emittance increase, but most importantly leads to a distortion of the transverse phase space (see Fig. 3.31) that pushes a few per cent of the particles outside the RFQ transverse acceptance.

In order to minimize irradiation at high energy and, in general, to better tailor the 352 MHz time structure of the linac pulse to the 1 MHz CERN PS Booster bucket, a device capable of removing a defined number of microbunches from the linac pulse is housed in the space between the RFQ and the DTL. This device (a chopper) [35,53] provides an electric field perpendicular to the direction of propagation of the beam, applied between two parallel plates. The strict requirements on the rise time (less than 2 ns) limit the maximum applicable voltage to the kilovolt range, therefore forcing us to use plates with an active length of the order of one metre to achieve the separation needed to remove the
unwanted beam. Such a bulky object cannot be spread over several focusing periods (which would nullify its effect), and therefore the only solution is to increase (in our case by a factor of 10) the length of the focusing period in the transition between the RFQ and the DTL. This is, however, detrimental to the continuity of the phase advance and to conservation of transverse and longitudinal beam emittance, especially in the presence of space charge forces. The transverse-emittance increase in the MEBT is of the order of 20%, to be compared with an overall emittance increase over the whole of Linac4 of about 40%. After 12 MeV, there is virtually no emittance increase within statistical fluctuations.

Figure 3.32 shows the r.m.s. transverse emittances along Linac4; the transitions between structures are indicated by triangular markers. The emittance decrease at \( z = 8 \) m, corresponding to the 3 MeV offline beam dump, is due to a controlled beam clean-up that is intended to remove the halo particles coming from the source, LEBT, and RFQ. The amount of particles removed (between 3 and 12%) depends on the optics, and operational experience with the nominal beam will lead to the final setting.

Linac4 will start operating as an injector to the PS Booster at a moderate duty cycle \((10^{-3})\), but it has been designed with the potential to become the front end of the HP-SPL, operating at a beam duty cycle of up to 6%; therefore control of the losses and of the activation of the machine was a design criterion built into the basic layout. It has been decided to have a ratio between the r.m.s. beam size and the size of the beam vacuum chamber of at least 6 everywhere after the beam reaches an energy of 3 MeV, which is considered the threshold for neutron production in copper. Figure 3.33 shows the ratio between the bore aperture and the r.m.s. beam size in Linac4: the bottlenecks are at low energy, in the LEBT and in the MEBT, whereas from 3 MeV the ratio is always above 6 and from 100 MeV is above 8. In simulations, no losses were observed in the LEBT, whereas in the MEBT there were losses located on the chopper plates and in the dump. Activation is not an issue at these energies. The nominal transmission from the source to the end of the PIMS is 85%, not including H\(^-\) stripping losses. The

---

**Fig. 3.32:** Normalized transverse emittances along Linac4. The triangles indicate the transitions between the different structures.
loss pattern is shown in Fig. 3.34. In the following, two special features of Linac4, chopping and energy ramping, are described in detail. Both of these actions, which are costly in terms of pure linac beam dynamics, are aimed at better matching of the linac beam longitudinally into a ring.

Fig. 3.33: Ratio between the bore aperture and the r.m.s. beam size in Linac4

Fig. 3.34: Nominal losses in Linac4, predicted by two different beam dynamics codes
### 3.6.2 Chopping

The 3 MeV line between the RFQ and the DTL houses a fast-switching electrostatic device able to remove 150 out of 352 microbunches (and ultimately 3 out of 8 microbunches) and a conical-shaped dump to dispose of the chopped microbunches [54]. The device is embedded in a quadrupole to limit beam quality deterioration. An effective applied voltage of 560 V per plate translates into a kick of 6.3 mrad, which guarantees almost complete separation of the wanted and unwanted microbunches: according to simulations, a mere 0.03% of the chopped beam is not intercepted at the dump and is lost in the DTL. The transverse phase space in the plane of chopping at the end of the chopper and at the end of the dump is shown in Fig. 3.35.

![Graphs showing phase space at the end of the chopper and at the location of the dump](image)

(a) At the end of the chopper  
(b) At the location of the dump

**Fig. 3.35:** Chopped and unchopped beam

The chopped beam will be intercepted by a conical-shaped dump [54] 120 mm in length with a minimum radius of 6 mm. The power deposition on the dump is as uniform as possible, in order to minimize the power per unit surface area. This is an issue for high-duty-cycle operation only, as the dump can withstand up to 2 MW/m². The footprint of the chopped beam on the dump can be seen in Fig. 3.36.

![Graph showing footprint of the beam on the conical surface of the dump](image)

**Fig. 3.36:** Footprint of the beam on the conical surface of the dump. The rings indicate the size of the dump cross-section and the dots represent the beam. The beam travels from right to left.
3.6.3 Energy ramping

In order to obtain a more uniform longitudinal distribution inside the PS Booster bucket, it is planned that the average energy of the linac will be varied over 20 injection turns by 1 MeV (up and down) [55, 56]. In this way, the longitudinal bucket of the PS Booster will be ‘painted’ as shown in the sketch in Fig. 3.37. From the point of view of the linac dynamics and hardware, this operation implies that the field in the last two tanks of the PIMS is varied linearly (up and down) by 10% over 10 + 10 µs (20 turns). In order to ease this task, the last two tanks of the PIMS will be run at a lower field than the maximum attainable (2.9 instead of 3.8 MV/m). The field distribution in the PIMS tanks is shown in Fig. 3.38, and Fig. 3.39 shows the effect on the longitudinal phase space of the beam: the beam distribution is unmodified and the average energy is changed by ±1 MeV.

![Sketch of energy ‘painting’ in the PS Booster (courtesy of C. Carli)](image)

**Fig. 3.37:** Sketch of energy ‘painting’ in the PS Booster (courtesy of C. Carli)

![Accelerating field in the PIMS: the last two tanks are varied for energy ramping](image)

**Fig. 3.38:** Accelerating field in the PIMS: the last two tanks are varied for energy ramping

3.6.4 Error studies

The behaviour of the machine under the influence of beam alignment errors, quadrupole alignment errors, quadrupole gradient errors, beam energy jitter, and RF phase and amplitude errors was evaluated in a dedicated series of statistical runs. For simplicity, the errors have been divided into two main categories: transverse and longitudinal. The transverse errors include alignment errors (beam and quadrupoles) and quadrupole gradient errors. The longitudinal errors include beam energy jitter and RF phase and amplitude errors. Typically, transverse errors affect the transmission, the transverse emittance, and the orbit of the beam, whereas longitudinal errors have an effect on the ‘effective’ transmission, i.e., the
percentage of accelerated particles, as well as on the longitudinal emittance and energy jitter. It has been verified that the effects of transverse and longitudinal errors add up and that, to a first approximation, there is not any strong cross-correlation. In the following paragraphs, the results of the studies of the transverse and longitudinal errors are described in detail.

3.6.4.1 Transverse-error studies—procedure

The purpose of the transverse-error studies was threefold. First of all, we aimed to probe the stability of the machine under the influence of errors; secondly, we aimed to define an alignment tolerance for the focusing elements; and, finally, we aimed to define the number, positions, and strengths of the dipole correctors (steerers) and monitors needed to control the remaining trajectory errors in the machine. The procedure that was followed was to perform a series of about 2000 runs with PATH or TraceWin (which give equivalent results) with different error settings and to log for each run the beam losses, the emittance growth, and the beam trajectory. In the first phase, we could observe the sensitivity of the machine, identify the weak spots and the sensitive parameters, and possibly make modifications to the optics to reduce the sensitivity. Once this first phase was over, a correction system was applied to the worst cases and a steering procedure identical to that which would be used in the operation of a real accelerator was put in place. An optimizing routine cycled over the steerers in order to find the minimum orbit excursion at the positions of the monitors, together with the maximum transmission. Often the maximum transmission was not achieved with the minimum orbit excursion, owing to possible misalignment of the focusing elements. The numbers of steerers and monitors were increased until the maximum average losses were below 1 W/m at 6% beam duty cycle and the additional transverse-emittance growth at 2 sigma was limited to 15–20% with respect to the nominal case. These two conditions were dictated by the shielding and by the emittance budget of the PS Booster.
The results of these studies [57] show that errors as detailed in Table 3.11 can be compensated by a system composed of 15 independent horizontal and vertical steerers with an integrated field of $3.5 \times 10^{-3}$ T m and 15 beam position monitors with an accuracy of at least 0.5 mm. An example of beam trajectories in the DTL before and after steering can be seen in Fig. 3.40, and the corresponding transmission in Fig. 3.41.

### Table 3.11: Transverse errors

<table>
<thead>
<tr>
<th>Error</th>
<th>Amplitude</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole transverse position</td>
<td>±0.1 mm at 1 sigma</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Quadrupole angles</td>
<td>±1 mrad at 1 sigma</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Quadrupole gradient</td>
<td>±0.5% total</td>
<td>Uniform</td>
</tr>
<tr>
<td>Beam transverse position</td>
<td>±0.3 mm at 1 sigma</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Beam angles</td>
<td>±0.3 mrad at 1 sigma</td>
<td>Gaussian</td>
</tr>
</tbody>
</table>
**Fig. 3.41:** Transmission under the influence of one possible set of transverse errors, before and after steering in the DTL.

**Fig. 3.42:** Loss map of Linac4, starting from the DTL input (3 MeV)

we do not know whether the phase and amplitude vary from bunch to bunch or on a longer time-scale. The klystron errors affect mostly the output beam energy and phase jitter. They are correlated over many gaps (all the gaps powered by the same klystron, up to 40 in Linac4) and cannot be cured.

The gap amplitude errors are due to tuning and/or manufacturing imperfections; they are static and affect mostly the longitudinal emittance. They are uncorrelated between one gap and the next, or,
if they are correlated, their average is zero over several gaps. Their effect can generally be mitigated by increasing the RF power above nominal.

For the klystron errors, we considered values between \( \pm 0.5\% \) and \( \pm 2\% \) for the amplitude and values between \( 0.5^\circ \) and \( 2^\circ \) for the phase. We also introduced a uniform input energy jitter coming from the previous stage of acceleration, which we estimated as 6 keV at the input of the DTL, 90 keV at the input of the CCDTL, and 250 keV at the input of the PIMS. Those values turned out to be coherent with the results of the error studies.

In Table 3.12, we report in detail the results for the effect of klystron errors on the phase and energy jitter of the beam and the r.m.s. emittance at the end of the DTL. From these results, we can deduce that the amplitude errors have more effect than the phase errors and that a variation of \( \pm 2\% \) in amplitude causes an emittance growth and an energy jitter above what is acceptable. Control of the amplitude and phase to within \( \pm 0.5\% \) and \( \pm 0.5^\circ \) would be ideal, but control to within \( \pm 1\% \) and \( \pm 1^\circ \) is also acceptable.

Table 3.12: Effects of klystron errors in the DTL

<table>
<thead>
<tr>
<th>Klystron amplitude and phase errors</th>
<th>Phase jitter (deg @ 1( \sigma ))</th>
<th>Energy jitter (keV @ 1( \sigma ))</th>
<th>R.m.s. emittance (deg MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.167</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5% and 0.5(^\circ)</td>
<td>0.8</td>
<td>13</td>
<td>0.169 ( \pm 0.003 )</td>
</tr>
<tr>
<td>0.5% and 1(^\circ)</td>
<td>0.9</td>
<td>18</td>
<td>0.171 ( \pm 0.004 )</td>
</tr>
<tr>
<td>0.5% and 2(^\circ)</td>
<td>1.1</td>
<td>31</td>
<td>0.175 ( \pm 0.009 )</td>
</tr>
<tr>
<td>1% and 0.5(^\circ)</td>
<td>1.6</td>
<td>23</td>
<td>0.171 ( \pm 0.005 )</td>
</tr>
<tr>
<td>1% and 1(^\circ)</td>
<td>1.6</td>
<td>28</td>
<td>0.172 ( \pm 0.006 )</td>
</tr>
<tr>
<td>1% and 2(^\circ)</td>
<td>1.8</td>
<td>36</td>
<td>0.177 ( \pm 0.011 )</td>
</tr>
<tr>
<td>2% and 0.5(^\circ)</td>
<td>5.1</td>
<td>43</td>
<td>0.179 ( \pm 0.014 )</td>
</tr>
<tr>
<td>2% and 1(^\circ)</td>
<td>5.7</td>
<td>46</td>
<td>0.180 ( \pm 0.017 )</td>
</tr>
<tr>
<td>2% and 2(^\circ)</td>
<td>8.6</td>
<td>49</td>
<td>0.187 ( \pm 0.024 )</td>
</tr>
</tbody>
</table>

Equivalent runs were done for the CCDTL and the PIMS (Tables 3.13 and 3.14), and the results confirmed that the klystron phase and amplitude should ideally be controlled to within \( 0.5\% \) and \( 0.5^\circ \) to control energy and phase jitter at the CCDTL and PIMS outputs, but that values of \( 1\% \) and \( 1^\circ \) would still be acceptable. For the PIMS, the values of \( 1\% \) and \( 1^\circ \) are hard limits, as the maximum energy jitter acceptable for successful energy painting is 125 keV (1 sigma value).

Table 3.13: Effects of klystron errors in the CCDTL

<table>
<thead>
<tr>
<th>Klystron amplitude and phase errors</th>
<th>Phase jitter (deg @ 1( \sigma ))</th>
<th>Energy jitter (keV @ 1( \sigma ))</th>
<th>R.m.s. emittance (deg MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.196</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5% and 0.5(^\circ)</td>
<td>0.5</td>
<td>39</td>
<td>0.196 ( \pm 0.003 )</td>
</tr>
<tr>
<td>1% and 1(^\circ)</td>
<td>1</td>
<td>63</td>
<td>0.196 ( \pm 0.005 )</td>
</tr>
<tr>
<td>2% and 2(^\circ)</td>
<td>2</td>
<td>115</td>
<td>0.198 ( \pm 0.009 )</td>
</tr>
<tr>
<td>5% and 2(^\circ)</td>
<td>4</td>
<td>237</td>
<td>0.200 ( \pm 0.015 )</td>
</tr>
</tbody>
</table>

The effects of the ‘static’ errors were evaluated independently of the effects of the ‘dynamic’ errors. In the three DTL tanks, gap amplitude errors were assigned randomly and independently to the 111 gaps with a uniform distribution over a range of \( \pm 1\% \) to \( \pm 10\% \) of the nominal voltage of each gap. In the CCDTL, a tilt was applied inside each tank, correlated over the module, with an amplitude varying from \( \pm 1\% \) to \( \pm 5\% \). In the PIMS, two types of error distribution were applied: a tilt in each tank and an elliptical distribution with a variation from \( \pm 1\% \) to \( \pm 10\% \). In all cases the average of the
Table 3.14: Effects of klystron errors in the PIMS

<table>
<thead>
<tr>
<th>Klystron amplitude and phase errors</th>
<th>Phase jitter (deg @ 1σ)</th>
<th>Energy jitter (keV @ 1σ)</th>
<th>R.m.s. emittance (deg MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3% and 0.3°</td>
<td>0.3</td>
<td>65</td>
<td>0.181 ± 0.00088</td>
</tr>
<tr>
<td>0.5% and 0.5°</td>
<td>0.4</td>
<td>78</td>
<td>0.181 ± 0.00094</td>
</tr>
<tr>
<td>1% and 1°</td>
<td>0.66</td>
<td>126</td>
<td>0.181 ± 0.0012</td>
</tr>
<tr>
<td>2% and 1°</td>
<td>0.85</td>
<td>220</td>
<td>0.181 ± 0.0013</td>
</tr>
</tbody>
</table>

Individual errors was readjusted to be equal to the nominal value, which in practical terms was equivalent to adjusting the RF power in each tank to achieve the nominal average field. In all cases we found that the structures of Linac4 were quite insensitive to static errors, and that an amplitude of 2% in the DTL and CCDTL and a tilt of up to 5% in the PIMS can be tolerated if the average field is adjusted to the nominal value.

An example of the field error distribution applied in the cases of linear and elliptical tilts in the PIMS is shown in Fig. 3.43. All of the results of the simulation are reported in Ref. [58].

Beam losses were never observed in any of the cases analysed.

![Voltage distribution vs gap number, 5% linear tilt](image1)

![Voltage distribution vs gap number, 5% elliptical tilt](image2)

**Fig. 3.43:** Static voltage error distribution in the PIMS for a 5% field tilt. The black lines indicate the 5% limit and the average corresponds to the nominal value.
Chapter 4

Superconducting Linac

4.1 Basic design choices

When the construction of Linac4 started in 2008, detailed studies for the SPL and PS2 were started in order to prepare for the submission of project proposals by mid 2012. In this context, the basic parameters of the SPL were reassessed \[59\] in the first half of 2008, to optimize cost and performance and to make the best use of the extensive experience accumulated around the world, especially at 800 MHz with the SNS and at 1.3 GHz with the ILC. During a dedicated review meeting in April 2008 \[60\], all options were presented and this then led to the frequency, accelerating-gradient, and operating-temperature choices used in this report. The main findings are reported in the following.

4.1.1 Pros and cons of alternative SPL architectures

The nominal layout which was used for the comparison of different SPL architectures was very similar to the one presented in this report. Here, two families of 704.4 MHz five-cell superconducting cavities \((\beta = 0.65)\) and \((\beta = 0.92)\) accelerate the beam to its final energy. A value of the cavity gradient of 25 MV/m was assumed for a cavity with a geometric \(\beta = 1.0\) and then scaled to lower beta values using the approximation \[61\]
\[
\frac{E_p}{E_{acc}} \approx \frac{1.84}{\beta_{geom}} + 1.17\beta_{geom} - 1.02. \tag{4.1}
\]

The first alternative makes use of three families of seven- to nine-cell superconducting cavities \((\beta = 0.6, \beta = 0.76, \text{and } \beta = 0.94)\) at 1408.8 MHz. An increase in the number of cells per cavity is necessary to keep the filling factor (active cavity length over real-estate length) approximately constant when compared with the nominal version. The maximum accelerating gradient was adjusted in the same way as for the nominal architecture. Owing to the high number of cells per cavity, the phase slippage increases and three families of cavities become necessary for efficient acceleration. For the same reason, the lower-energy range uses a seven-cell instead of a nine-cell cavity. The \(4 \times \) frequency jump requires careful longitudinal matching, which together with the slightly shorter active cavity lengths results in a linac approximately 15% longer than that in the nominal 704.4 MHz layout.

The second alternative design which was compared was a ‘mixed’ option, using two families of 352.2 MHz spoke cavities up to an energy of 760 MeV and then again nine-cell 1408.8 MHz elliptical cavities up to the final energy. The gradients of the spoke cavities were assumed to be 8.5 MV/m for the \(\beta = 0.67\) triple-spoke cavities and 9.5 MV/m for the \(\beta = 0.8\) quadruple-spoke cavities. From the beam dynamics point of view, this version appears very interesting because the \(4 \times \) frequency jump is shifted to a higher energy, where the beam is less sensitive to longitudinal disturbances.

4.1.1.1 Beam dynamics comparison and implications for layout and construction effort

Beam dynamics simulations were done with and without (i) statistical longitudinal errors and (ii) a longitudinal mismatch at injection from Linac4 into the SPL. The second alternative showed the least longitudinal-emittance growth, followed by the ‘nominal’ layout and then the first alternative, which showed the worst performance. Another consequence of the \(4 \times \) frequency jump is that a certain length before and after the jump is needed for longitudinal beam matching, which adds to the total length of the accelerator. As a result, the first alternative results in a 500 m long machine, the second alternative results in a length of 485 m, and the nominal design has the shortest footprint, with a length of 439 m.
In terms of construction effort, the second alternative requires engineering experience with spoke-plus-elliptical cavities and the design of three different superconducting structures and cryomodules. For the first alternative, three different superconducting elliptical cavities are needed, and the nominal design requires only the design of two different elliptical cavities plus cryomodules.

4.1.1.2 Power consumption (704.4 MHz versus 1408.8 MHz)
Owing to their larger volume and higher $Q$-value, 704.4 MHz cavities store more energy than 1408.8 MHz cavities. This leads to larger filling and decay times in pulsed operation and therefore to more power being lost during these periods. In the case of operation with a 0.4 ms pulse length and 40 mA pulse current, the nominal 704.4 MHz SPL needs around 30% more RF power than the 1408.8 MHz alternative (taking into account the different numbers of cavities and the different filling times in the two scenarios). This difference becomes smaller for operational scenarios with longer pulses (at the same current), since then the ratio of filling time to pulse length diminishes.

4.1.1.3 Impact of frequency choice on RF hardware
Increasing the RF frequency decreases the size of the cavities but also the size of the klystrons, klystron collectors, circulators, waveguide dumps, etc. While multibeam 1300 MHz klystrons with 10 MW peak power have been developed for the XFEL, one needs to recognize that they work at a much lower duty cycle. Increasing the duty cycle means an increased power density in the above-mentioned components, and in many cases the volume of the components will have to be increased in order to cope with the average power values needed. For this reason, we do not expect any savings (neither in cost nor in size) on the RF power hardware when moving from 704.4 to 1408.8 MHz. On the contrary, we expect the design of these components to become much more complex, taking existing lower-frequency RF hardware (e.g., 5 MW, 805 MHz SNS klystrons) as a reference.

4.1.1.4 Higher-order modes for 704.4 MHz and 1408.8 MHz cavities
Reference [59] contains a worst-case study comparing higher-order-mode (HOM) excitation in 704.4 and 1408.8 MHz cavities. It was found that the threshold current for beam break-up caused by HOMs is up to two orders of magnitude lower when nine-cell 1408.8 MHz cavities are used instead of five-cell 704.4 MHz cavities. In Ref. [62], a comparison was made between a 704.4 MHz and a 1300 MHz linac and it was found that the HOM voltages excited in the higher-frequency case were approximately eight times higher. The 704.4 MHz case was then studied further by statistical bunch simulations in Refs [63] and [64] and is reported in detail in Section 4.2.4.

4.1.2 Choice of cryotemperature
There is little experimental data on the use of 4.5 K for high-field cavities (with surface fields in the range of 50 MV/m) at frequencies in the 700–1400 MHz range, so the decision about whether to run in the superfluid regime (below 2.2 K at saturated vapour pressure) or in the boiling regime (e.g., at 4.5 K) has to be taken on the basis of (i) operational issues and (ii) cost (initial investment and operating cost).

4.1.2.1 Operational issues
Operation at 2 K generally offers the advantage of lower microphonics owing to the superfluid state of the helium coolant, which is especially important when operating in pulsed mode. On the other hand, operation at 4.5 K in saturated pool boiling offers the advantage of a pressure above atmospheric pressure (1.3 bar), limiting the risk of helium contamination due to air leaks, which has a direct impact on the cost of the helium distribution system. However, when operating in the boiling regime it is essential to ensure the venting of helium vapour bubbles from the upper points of all helium enclosures, which requires specific design of the helium vessels.
4.1.2.2 Cost
When 4.5 K is used instead of 2 K, the quality factor $Q$ decreases and the equivalent heat load (at 4.5 K) increases. For the LP-SPL, an increase of around 60% is observed, while for the HP-SPL the total heat load is multiplied by more than a factor of 4 to values close to 100 kW, which is well beyond the range of state-of-the-art cryoplants. Furthermore, the power consumption of the cryocompressors would come into the same range as the power consumption of the RF system. For low- and high-power operation and for both of the frequencies under consideration (704.4 and 1408.8 MHz), the minimum total electrical power consumption is found at a temperature of 2 K or slightly below.

4.1.3 Choice of accelerating gradient
The nominal accelerating gradient (25 MV/m for a $\beta = 1$ cavity) has been kept constant since the 2006 SPL design report [2], where it was described as challenging but achievable. This assessment was repeated in 2009 after a survey of accelerating gradients achieved in various laboratories [59], which showed that, with state-of-the-art processing, accelerating gradients of 16–23 MV/m (with $\beta = 1$ cavities) were possible with a production yield of 90%. Higher gradients of up to 30 MV/m were also within reach, but at the cost of a lower production yield (50%), which is equivalent to a higher reprocessing rate. With the start of industrial cavity production for the XFEL, these numbers have improved [65] to an average usable gradient of $25 \pm 7.7$ MV/m, which was achieved after the first treatment cycle. When a second treatment cycle was applied to 14 out of a total of 64 cavities, the average usable gradient was improved to $29 \pm 3.9$ MV/m. These values give a good indication that the value of 25 MV/m which was chosen as the SPL nominal gradient is indeed achievable.

4.1.4 Segmented or continuous cryomodule layout
The question of whether to use a continuous cryomodule layout or a segmented design was extensively discussed during a dedicated workshop in November 2009 [66]. The two main arguments for a segmented design are (i) the possibility of using fast (warm) vacuum valves to separate individual cryomodules in the case of a vacuum leak, which could otherwise contaminate a complete string of cavities, and (ii) the option of fast exchange of individual cryomodules, which would take weeks with the continuous approach. In the following, we list some of the points which were discussed.

4.1.4.1 Advantages of a continuous approach
- **Lower static heat load.** In the case of the LP-SPL, the lower static heat load may be relevant. However, for high-power operation (HP-SPL), the cryogenic heat load is largely dominated by the dynamic load, and the difference between segmented and continuous cryomodules will be insignificant.
- **Lower initial investment.** This is likely to be offset by a much reduced risk during operation and the possibility of quickly exchanging modules when a segmented layout is used.
- **Shorter linac.** The cold–warm transitions will inevitably lengthen the linac. However, since a module exchange is very time-consuming, one needs to have a certain number of spare cavities already in the nominal linac layout to compensate for potentially lower-performing cavities or even failing cavities. With this in mind, any length difference is negligible.

4.1.4.2 Advantages of a segmented approach
- **Fast vacuum valves.** The warm sections between cryomodules can house fast (warm) vacuum valves, which can quickly isolate vacuum leaks in single modules. However, experiments at DESY have shown an air propagation speed of only 4 s per module, which means that specifically developed cold gate valves could be fast enough to protect neighbouring modules in the case of a leak.
– Fast module exchange. This will decrease significantly any machine downtime when repairs are necessary.
– Warm quadrupoles. The use of warm quadrupoles between the modules has the potential to (i) ease the alignment of the quadrupoles, (ii) ease the cryomodule design, and (iii) enable faster changes of the transverse focusing, but (iv) it will increase power consumption.
– Faster cycling. Warm-up and cool-down times can be faster, since the cryomodules are mechanically disconnected.

One of the conclusions of the study was that for very long machines (>1 km), continuous cryomodules become almost mandatory simply for cost reasons, while for shorter machines the engineering and prototyping effort required to produce ‘non-failing’ cryomodules becomes too large. For superconducting proton linacs with a length of a few hundred metres, one cannot expect to get the extensive prototyping statistics which are available for the ILC/XFEL cryomodules. For this reason, it is prudent to have easily exchangeable modules in shorter linacs.

The decision was taken to use segmented cryomodules in the SPL [9, 66].

4.1.5 Surface or underground location of RF gallery

Originally, the SPL study always assumed a two-tunnel layout: one tunnel for the accelerator, and another tunnel to house the klystrons and modulators, with sufficient distance from the accelerator tunnel to allow maintenance on these components during operation with beam. Preliminary integration studies showed that the RF system for the LP-SPL already needs a tunnel diameter of 6–7 m (see Fig. 4.1), basically making it prohibitive to house an HP-SPL RF gallery in a drilled tunnel.

Fig. 4.1: Integration study of tunnel cross-sections for the LP-SPL. The central area in the klystron gallery and the left area in the SPL tunnel are reserved for transport.

For this reason, it was decided to explore an alternative scenario with the RF gallery for the high-ß section above ground. Here, the cavities are connected via vertical waveguide shafts to the klystrons, which entails waveguide lengths of up to 80 m. For this maximum length, additional RF power losses of approximately 7% in the waveguides have to be covered by the RF system. A preliminary study [67] of the low-level RF (LLRF) system concluded that the additional group delay will be acceptable as long as waveguides with a low intrinsic group delay (e.g., WR1150) are used.

To confirm this choice, some further work is needed on the optimum waveguide geometry, which should have (i) low losses, (ii) a small group delay, and (iii) small external dimensions to minimize the size of the waveguide shafts, and (iv) it should be easy to cool, since for high-power operation the lost heat will have to be extracted from the shafts.
4.2 Accelerator design

4.2.1 Choice of geometric betas at 704.4 MHz

The partitioning of the SPL into different sections using different types of superconducting cavities was done with the aim of minimizing (i) the number of cavities, (ii) the number of different cavity types, (iii) the linac length, and (iv) the power consumption. The process of optimizing the layout was based on the following definitions:

- An SPL $\beta = 0.65$ cavity has a geometric cell length of $0.65\lambda/2$, where $\lambda$ is the RF wavelength. This is different from the definition used in GenLin [68], which is one of the programs widely used to optimize the partitioning of a linac. There, a $\beta = 0.65$ cavity is one that has its highest transit time factor at $\beta = 0.65$.
- All cavities have the same maximum peak surface field of 50 MV/m.
- The accelerating field for a given peak surface field is estimated as [59, 69]

$$\frac{E_p}{E_{acc}} \approx -1.02 + \frac{1.84}{\beta_{geom}} + 1.17\beta_{geom}. \quad (4.2)$$

- The $(R/Q)$ value of the cavity scales approximately as

$$\left(\frac{R}{Q}\right) \approx n_{cells}(160\beta - 47). \quad (4.3)$$

- The cut-off fields are estimated with the model implemented in GenLin.

The choice of five-cell cavities at 704.4 MHz was triggered by the assumed power coupler limit of $\approx 1$ MW and the maximum accelerating gradient ($\approx 25$ MV/m) according to the above criteria. In the high-$\beta$ region, a five-cell cavity will thus need around 1 MW from a single power coupler to provide an accelerating field of 25 MV/m. Another advantage of the five-cell approach is that the entire range between 160 MeV, the output energy of Linac4, and 5 GeV can be covered with only two cavity types.

The geometric beta of $\beta = 0.65$ for the medium-$\beta$ section was chosen by searching for the highest geometric beta which still allows reasonable acceleration from 160 MeV onwards. In the high-$\beta$ section, there are two possibilities ($\beta = 0.92$ and $\beta = 1$), which were compared in Ref. [70] using two scenarios: (A) with equal accelerating fields in all cavities of each cavity type, and (B) with a gradient limitation in the first cavities of each section, which limits the longitudinal phase advance per period to $75^\circ$. This was done in order to allow the ratio of the transverse to the longitudinal zero-current phase advance to be larger than 1. In both scenarios, we used a synchronous phase of $-15^\circ$. A comparison of real-estate gradients is shown in Fig. 4.2.

From Fig. 4.2, one can see that limiting the longitudinal phase advance after the transition reduces the advantage of the $\beta = 0.92$ cavity regarding its higher real-estate gradient at lower energies. For an SPL with a lower output energy (3 or 3.5 GeV), there would be an advantage in having $\beta = 0.92$ cavities instead of $\beta = 1.0$ cavities in the high-energy section of the SPL. For a final energy of 5 GeV, the two versions are more or less equivalent, but when upgrades to even higher energies are considered, $\beta = 1.0$ cavities would be more efficient. The resulting numbers of cavities and modules are exactly the same for both layouts and the only difference is a slightly reduced linac length (17 m), which comes from the shorter cavities, in the $\beta = 0.92$ case.

Comparing the power consumption for the two different high-$\beta$ sections, one has to take into account the following points:

- different $(R/Q)$ and $Q$ values;
- a lower accelerating voltage and cavity length for $\beta = 0.92$;
4.2.2 Beam dynamics in superconducting section

4.2.2.1 Focusing lattice and general layout

Altogether, three different layouts were considered for the superconducting section: one based on doublet focusing, one based on F0D0 focusing, and a ‘mixed layout’ as explained in the following. The difference is negligible from the strict beam dynamics point of view (beam quality, sensitivity to errors) [71], but the implications for the magnet design are very different. A F0D0-type layout is incompatible, at least for the medium-$\beta$ section, with a fully segmented cryomodule and would rule out the use of warm quadrupoles. On the other hand, a doublet focusing system, which requires higher magnetic fields for the same average beam size, limits the minimum length of the quadrupole to about 450 mm at high energy, where magnetic stripping is an issue (see Fig. 4.3). In order to use only one family of warm quadrupoles, a mixed layout was adopted [72], consisting of a doublet focusing lattice up to 2.5 GeV and long F0D0 cells from 2.5 GeV to the final energy. This layout has the two advantages that it is highly segmented and uses warm quadrupoles, which are much easier to align, and lower fields in the quadrupoles, which reduces the probability of Lorentz stripping. As an additional minor advantage, the mixed layout uses 12 quadrupoles fewer than a doublet layout. The general features of the three different

(a) Equal accelerating gradients in all cavities in each beta family

(b) Restricted accelerating gradients, which limit the longitudinal phase advance per period to $75^\circ$

Fig. 4.2: Comparison of scaled real-estate gradients

- changes in filling times;
- equal values of beam loss per metre.

This results in a total dynamic heat load per module of 82.4 W for eight $\beta = 0.92$ cavities in one module, and 83.9 W for a module with $\beta = 1$ cavities. For these numbers, we have assumed a beam pulse length of 0.4 ms and a repetition rate of 50 Hz. We can thus conclude that, regarding the heat load, there is a slight advantage with the $\beta = 0.92$ cavities, but it is not significant enough for us to make a choice.

Using the assumption that cavities with a smaller geometric beta are intrinsically less stiff, the choice was made to use $\beta = 1$ cavities for the high-energy section of the SPL. The final choice, however, should only be made once the final energy for the construction project has been fixed.

During the HOM analysis of the SPL presented in Section 4.2.4, it was found that the $(4/5)\pi$ mode can be excited to significant levels when multicell cavities are used over a large velocity range. In the case of the present SPL partitioning, it was found that in the first and last cavities of the $\beta = 0.65$ section, the $(R/Q)$ value of the $(4/5)\pi$ mode slightly exceeded that of the accelerating mode. The analysis of the actual excitation of this mode presented in Section 4.2.4.6, however, resulted in negligible beam disturbance, so that we assume that the present SPL layout is feasible.
layouts are summarized in Table 4.1 and the energy evolution along the layouts is shown Fig. 4.4.

**Table 4.1:** Comparison of layouts. The values for the medium-$\beta$ and the high-$\beta$ regions are separated by a ‘/’.

<table>
<thead>
<tr>
<th>Lattice</th>
<th>Length (m)</th>
<th>$E$ (MeV)</th>
<th>Focal periods</th>
<th>Cavities/period</th>
<th>Cryo-modules</th>
<th>Total quads (PS)$^a$</th>
<th>Total cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doublets</td>
<td>501</td>
<td>786/4989</td>
<td>20/23</td>
<td>3/8</td>
<td>20/23</td>
<td>86 + 4 warm (54)</td>
<td>244</td>
</tr>
<tr>
<td>F0D0$^b$</td>
<td>510</td>
<td>710/5020</td>
<td>24/24</td>
<td>2/8</td>
<td>12/24</td>
<td>96 + 4 warm (59)</td>
<td>240</td>
</tr>
<tr>
<td>Mixed$^c$</td>
<td>505</td>
<td>753/5005</td>
<td>20/23</td>
<td>3/8/16</td>
<td>20/23</td>
<td>78 warm</td>
<td>244</td>
</tr>
</tbody>
</table>

$^a$ PS, number of power supplies.  
$^b$ Unsegmented layout.  
$^c$ With longer drift in 2.5 GeV extraction region.

**Fig. 4.3:** Left: relative gradients of the quadrupoles along the line in all three layouts. The medium-$\beta$ region extends to 120 m, and the jump in gradient happens after the transition. Right: maximum gradient which gives less than 0.1 W/m of loss for Gaussian and double Gaussian (Dex) distributions with two r.m.s. sizes.

**Fig. 4.4:** Energy of beam along the linac in all three layouts

In the following, the beam dynamics of the mixed layout is reported and—where interesting—is
compared with the full doublet or full F0D0 layout.

The magnetic length of the quadrupoles, 350 mm, is such that for a chosen transverse focusing the maximum gradient is below the threshold to keep $\text{H}^-$ stripping losses below 0.1 W/m. In this architecture, the distances between two adjacent cavities, between quadrupoles and cavities, and from a cavity to the end wall of the cryomodule are based on a highly segmented SPL design, i.e., with warm quadrupoles; the values are quoted in Table 4.2. All quadrupoles are equipped with a steerer, and nested coils are assumed. In this compact design, the resulting sextupole component has to be controlled to a few units to avoid exciting an envelope oscillation.

In the medium-energy region, there are three cavities per period housed in a “short” cryomodule, followed by a pair of normal-conducting quadrupoles. The optimum number of cavities per period is given by the necessity to avoid space charge resonances. In our case, and without compromising on the gradient, three cavities per period turns out to be the optimum number to limit the longitudinal phase advance to below 75° per period, while the transverse phase advance must be lower than 90°, as explained in Section 4.2.2.2. Falling on a resonance carries a risk of causing emittance exchange between the longitudinal and transverse planes, resulting in an unacceptable emittance increase in the transverse plane.

In the high-energy region, starting from 750 MeV and going up to 2.5 GeV, a normal-conducting pair of quadrupoles is followed by eight cavities housed in one “long” cryomodule, while after the 2.5 GeV branching each individual quadrupole will be followed by one cryomodule, making a long F0D0 focusing optical system, for example F–Cryo–D–Cryo–. The length of the low-energy cryomodules is 4.68 m and the period length is 6.48 m, while the length of the high-energy cryomodules is 13.26 m, with a period length of 15.06 m before the branching and 28.22 m after the branching.

In summary, the focusing periods along the SPL are composed of the following (Fig. 4.5):

- 3 cavities (medium-$\beta$ cryomodule) with a normal-conducting doublet per period in the low-energy part;
- 8 cavities (high-$\beta$ cryomodule) and a normal-conducting doublet in the high-energy region before the 2.5 GeV point;
- 2 × one high-$\beta$ cryomodule and one single normal-conducting quadrupole after 2.5 GeV. This makes a F0D0 lattice twice the length of the FD lattice previously discussed.

![Fig. 4.5: Building blocks of the SPL mixed solution](image)

In the SPL layout, there is provision to deliver a beam to the existing ISOLDE (Isotope Separator On Line DEvice) and to a potential EURISOL (EURopean Isotope Separation On-Line) facility at energies of 1.5 and 2.5 GeV, respectively. Magnetic stripping of the extra loosely bound electron in $\text{H}^-$ ions limits the maximum magnetic field in the bending magnets, resulting in long dipoles in the extraction regions. To ensure low-loss extraction to ISOLDE, a length of 15.1 m (equal to one SPL high-$\beta$ period)
Table 4.2: Distances between quadrupoles, cavities, etc. in medium- and high-β SPL cryomodules (Fig. 4.6).

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Length (mm)</th>
<th>Element sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole</td>
<td>Cryowall</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Cavity</td>
<td>Cavity</td>
<td>430(^a)</td>
<td>2</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>Quadrupole</td>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td>Cryowall</td>
<td>Cavity</td>
<td>800</td>
<td>4</td>
</tr>
<tr>
<td>Cavity</td>
<td>Cryowall</td>
<td>650 (medium-β)/670 (high-β)(^a)</td>
<td>5</td>
</tr>
<tr>
<td>Cryowall</td>
<td>Quadrupole</td>
<td>400(^c)</td>
<td>6</td>
</tr>
<tr>
<td>Cavity length, medium-β</td>
<td></td>
<td>690(^b)</td>
<td></td>
</tr>
<tr>
<td>Cavity length, high-β</td>
<td></td>
<td>1060(^b)</td>
<td></td>
</tr>
<tr>
<td>Quadrupole length</td>
<td></td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Total length of cryomodule, medium-β</td>
<td></td>
<td>4680</td>
<td></td>
</tr>
<tr>
<td>Total length of cryomodule, high-β</td>
<td></td>
<td>13260</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Distance from end of last cell iris to the first cell iris.
\(^b\) Distance from first cell iris to last cell iris.
\(^c\) In the doublets upstream of 2.5 GeV branching; afterwards there is just one quadrupole.

![Element sequence for Table 4.2](image)

has been added between cryomodules 5 and 6, leaving an extraction region of 12.8 m. Low-loss extraction to EURISOL at 2.5 GeV requires that a longer drift length of 22.5 m is added between the high-β cryomodules 11 and 12, leaving an extraction region of 21.05 m.

4.2.2.2 Beam dynamics

The layout respects three general beam dynamics criteria:

1. The phase advance per period for zero current does not exceed 90°.
2. The phase advance per metre changes smoothly.
3. The longitudinal-to-transverse phase advance ratio should not fall at peaks in the Hofmann plots [73], to avoid resonances which cause emittance exchange (see Fig. 4.7).

The beam dynamics simulations were performed for a 60 mA beam from Linac4. In the absence of any manufacturing and assembly errors and any RF amplitude and phase errors, the SPL transports and accelerates the H\(^-\) beam from Linac4 while preserving the beam quality, i.e., with full transmission and minimum emittance growth.

Beam dynamics design, simulation, and calculations were done using the multiparticle code Trace-Win [68], which includes routines for 2D and 3D space charge calculations, using 50 000 macroparticles. The phase advances in each section were chosen so that there were equal phase advances per metre, meaning the same average focusing force. At the interconnection of two regions, this means that the quadrupoles next to the transition region have a negligible difference from their nominal value. The difference is somewhat larger at the transition from the medium-β region to the high-β region, where the two structures are connected seamlessly.
Fig. 4.7: The red circles show the working points of the mixed layout on a Hofmann plot for a peak current of 60 mA.

Fig. 4.8: Emittance evolution in the SPL

Matching must be done very carefully at the transition from low to high energy and also across the extraction branches, since long extraction drift spaces can have a significant impact on beam halo development, as is visible in the graphs in Figs. 4.8 and 4.9. The longitudinal halo increases at 1.4 GeV, 200 m from the beginning of the SPL, where the acceleration is interrupted for several $\beta\lambda$s. The transverse halo is increased mainly where there is a change in the focusing scheme from doublet to $F_0D_0$, namely at 310 m. The major emittance increase in the transverse plane happens in the 2.5 GeV extraction region, where the long drift is followed by a change of focusing scheme. At the same place, the maximum beam size occurs, with an r.m.s. value of 4 mm in the horizontal plane, resulting in a minimum ratio of aperture to r.m.s. beam size of 17, while in the rest of the machine this value stays below 3 mm (see Fig. 4.10).

The outermost particles stay confined within 10 mm, almost all the way along the linac (see Fig. 4.11). In the longitudinal plane, the beam is well within the acceptance, although the bucket size has not been kept constant across the frequency jump, in order to shorten the overall length of the linac. For
a completely smooth longitudinal transition, one would need a bigger margin in the synchronous phase and the accelerating voltage in the superconducting cavities would have to be decreased, which would result in a longer linac.

The performance of the mixed architecture is comparable to that of the doublet and the F0D0 interlacing architectures from the beam dynamics point of view. It is worth mentioning that the mixed architecture has a longer drift space, to allow lossless extraction at 2.5 GeV. The extra few per cent emittance increase is mostly due to this increased free space (see Table 4.3).

The work on the effects of errors and the correction system is summarized in Ref. [72].
Transverse beam density along the linac

Longitudinal acceptance at 165 MeV; the phase on the abscissa is in degrees at 352.2 MHz and the ordinate is the energy spread in MeV

Fig. 4.11: SPL beam density

Table 4.3: Comparison of r.m.s. normalized emittance for different layouts

<table>
<thead>
<tr>
<th>Layout</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial (π mm mrad)</td>
<td>Both</td>
<td>0.328</td>
<td>0.334</td>
</tr>
<tr>
<td></td>
<td>Mixed</td>
<td>0.387</td>
<td>0.384</td>
</tr>
<tr>
<td>Final (π mm mrad)</td>
<td>Doublet</td>
<td>0.369</td>
<td>0.365</td>
</tr>
<tr>
<td></td>
<td>F0D0</td>
<td>0.359</td>
<td>0.356</td>
</tr>
<tr>
<td>Δε/ε_in (%)</td>
<td>Mixed</td>
<td>18.0</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Doublet</td>
<td>12.5</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>F0D0</td>
<td>9.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

4.2.3 H\(^-\) stripping

In the following, we review the relevant H\(^-\) stripping mechanisms and evaluate them for the case of the SPL.

4.2.3.1 Magnetic stripping

When an H\(^-\) ion moves in a magnetic field \(B\), it experiences a Lorentz force that bends its trajectory and also tends to strip its electrons. For a particle travelling at a reduced velocity \(\beta\), a transverse magnetic field in the laboratory frame produces a transverse electric field in the rest frame of the particle, the magnitude of which is, according to the Lorentz transformation,

\[
|E_t| = \beta \gamma c |B_t|.
\] (4.4)

This electric field, if strong enough, can remove the extra electron of an H\(^-\) ion. The resulting H\(^-\) lifetime, in its rest frame, has been expressed by Scherk [75] as

\[
\tau(z) = \frac{A_1}{E_t} e^{A_2/E_t},
\] (4.5)
where $A_1 = 2.47 \times 10^{-6}$ V/s/m and $A_2 = 4.49 \times 10^9$ V/m. The fraction $f$ of stripped ions per unit path length can be expressed as [76]

$$\frac{df}{dx} = -\frac{f}{\beta\gamma c} = \frac{f B_1}{A_1} e^{-A_2/\beta\gamma c B_1},$$

(4.6)

which leads to a stripping probability

$$f(\beta, g, d) = e^{-\frac{grd}{A_1}} e^{-A_2/\beta\gamma cgr},$$

(4.7)

where $g$ is the quadrupole gradient, $d$ is the quadrupole length, and $r$ is the radius for which the calculation is performed. For 1 GeV H$^-$ ions, a magnetic field of a few tenths of a tesla is sufficient to strip the first electron, owing to its low binding energy (0.755 eV).

To estimate the probability of stripping in a quadrupole, we have to take account of the fact that the magnetic field $B$ increases linearly with radius. For a given distribution, the probability is very low for particles travelling around the magnetic centre of the quadrupole, and it increases with the distance from the axis. In general, the problem of magnetic stripping concerns only the halo particles. However, if the beam is off-centre, the high-density part becomes closer to the higher-$B$-field region and the total number of stripped particles will increase. The stripping probability as a function of energy for the two SPL linac layouts is shown in Fig. 4.12 and reaches its maximum at 5 GeV. The probability as a function of the quadrupole length at this energy is plotted in Fig. 4.13.

![Graph](image)

**Fig. 4.12:** Stripping probability for the nominal SPL quadrupole (50 mm bore radius, 450 mm long) as a function of beam energy.

Assuming a magnet with a bore of 50 mm and a length of 450 mm, the probability of stripping is extremely low for both the FD and the F0D0 layouts if the beam is contained within a radius of 12.5 mm. However, to quantify the amount of stripped particles, we have to combine the stripping probability with
the probability of a particle being at a certain distance from the centre. For these reasons, we express $B$ as a function of $r$ ($|B(r)| = gr$) and derive the amount of losses in the quadrupole by integrating over the particle distribution $f(r, r_0, \sigma)$ and the length $d$, obtaining

$$P(\beta, \sigma, r_0, g, d) = \int_0^{r_{\text{max}}} \int_0^{2\pi} f(r, r_0, \sigma) e^{-\frac{gd}{\beta\gamma c}} e^{-\frac{A_2}{\beta\gamma c} r} r \, dr \, d\theta.$$  

(4.8)

The result depends on the type of the distribution (Gaussian, double exponential, etc.), on the width $\sigma$ of the distribution itself, and on the displacement $r_0$ from the centre.

Since the distribution at the ion source output is not yet experimentally known, two types of distribution were used to test the effect of the magnetic-stripping probability on a beam with various radial extents, the Gaussian distribution

$$\text{Gauss}(r, r_0) = \frac{1}{2\pi\sigma^2} e^{-\frac{(r-r_0)^2}{2\sigma^2}}$$  

(4.9)

and the double exponential distribution (Dex)

$$\text{Dex}(r) = \frac{3}{2\pi\sigma^2} e^{-\sqrt{3}(r-r_0)/\sigma}.$$  

(4.10)

Both of these distributions are normalized to 1 and have the same standard deviation $\sigma$. The kurtosis parameter $k$ (given by $k = \int x^4 f(x) \, dx/\sigma^4$) is 3 for the Gaussian distribution and 6 for the double exponential distribution and can be directly converted into the geometrical halo parameter $h = k - 2$ [77].

The two distributions were cut off at $5\sigma$ and the results in terms of losses were renormalized.
We have analysed two $\sigma$-value scenarios (see Fig. 4.14):

(i) $\sigma = 1.7$ mm, corresponding to the nominal case with input beam jitter $\pm 0.2$ mm/$\pm 0.2$ mrad, quadrupole gradient error $\pm 0.5\%$, and quadrupole misalignment $\pm 0.2$ mm with full steerer correction ($r_0 < 1$ mm).

(ii) $\sigma = 2.5$ mm, corresponding to the nominal case without correction ($r_0 < 10$ mm).

The plots in Fig. 4.15 show the radial extent of the beam distribution in the worst case compared with the stripping probability at 5 GeV for both layouts and for the nominal SPL quadrupole. The probability of stripping is sufficiently low in the F0D0 layout in all of the cases considered, whereas for the doublet (FD) layout at high energy, problems could arise if the beam centre position error is not fully compensated by the steerers.

The maximum beam losses acceptable in the SPL are 1 W/m, which represents about one particle in $10^7$ at the highest energy. The losses per unit length were calculated assuming that all the particles are lost inside the magnet, i.e., the power of the beam losses obtained via the stripping probability is divided by the length of the magnet.
Table 4.4: Maximum quadrupole gradient at 5 GeV for Gaussian and double exponential distributions

<table>
<thead>
<tr>
<th>Limit</th>
<th>$\sigma = 1.7$ mm</th>
<th>$\sigma = 2.5$ mm</th>
<th>$\sigma = 1.7$ mm</th>
<th>$\sigma = 2.5$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 W/m</td>
<td>14.0 T/m</td>
<td>5.5 T/m</td>
<td>10.8 T/m</td>
<td>4.9 T/m</td>
</tr>
<tr>
<td>1 W/m</td>
<td>15.6 T/m</td>
<td>6.1 T/m</td>
<td>12.0 T/m</td>
<td>5.4 T/m</td>
</tr>
</tbody>
</table>

The dependence of the losses on the beam displacement is shown in Fig. 4.16: for the same integrated gradient, it is possible to reduce the quadrupole length until the loss limit is reached. With a quadrupole length of 450 mm, there is no risk of going beyond the limit even for the FD layout without beam steering correction.

Fig. 4.16: Total beam losses in an SPL quadrupole at 5 GeV for different quadrupole lengths with respect to the radiation protection limit of 1 W/m. The F0D0 scenario is not shown, as the limit of less than 10 mm on displacements is reached for none of the distributions.

For low losses, such as the values required by the radiation protection limit, the stripping probability is proportional to the length of the magnet. This means that the maximum gradient as a function of beam energy that can be accepted is independent of the length of the magnet itself and is uniquely determined.

This value was calculated using distributions with maximum displacements of 1 mm for $\sigma = 1.7$ mm and 10 mm for $\sigma = 2.5$ mm, and is reported in Fig. 4.17 for the 1 W/m limit and a more conservative 0.1 W/m limit. Since the slope of these curves is always greater than that derived from Fig. 4.3 for the nominal 450 mm quadrupole, the bottleneck is represented by the values at 5 GeV, which are reported in Table 4.4.

Given the maximum quadrupole gradient as a function of the beam energy (see Fig. 4.17) and the integrated gradient along the machine for the FD and F0D0 scenarios, it is possible to calculate the minimum magnetic length required as a function of energy (Figs. 4.18 and 4.19). Again the bottleneck is found for the values obtained at 5 GeV (see Table 4.5).

Considerations of H\textsuperscript{−} stripping are an important input to the decision about the focusing lattice.
Fig. 4.17: Maximum quadrupole gradient as a function of beam energy and distribution

Fig. 4.18: Minimum quadrupole magnetic length for the F0D0 layout

of the SPL. If an FD lattice with constant quadrupole length is adopted for the SPL, then the minimum magnetic length should be 450 mm (5 GeV limit). This implies that the quadrupoles at low energy are largely overspecified. When a mixed lattice (FD at medium energy, F0D0 above 2.5 GeV) is used, the choice of keeping one family of quadrupoles for the whole linac becomes more natural.
4.2.3.2 Intra-beam stripping

Another phenomenon which causes unwanted $\text{H}^-$ stripping is so-called intra-beam stripping. This phenomenon occurs when two $\text{H}^-$ particles with very different velocities come very close to each other. The relative velocity ($\beta$) has to be more than $2 \times 10^{-4}$. If a Gaussian distribution is assumed for both the spatial and the velocity distribution and the three planes are decoupled, the resulting fractional loss can be written as

$$
- \frac{dN}{ds} \simeq \frac{N \sigma_{\text{stripping}}}{8\pi^2 \sigma_{vx}\sigma_{vy}\sigma_{vz}\gamma^2 \beta c} \sqrt{\sigma_{vx}^2 + \sigma_{vy}^2 + \sigma_{vz}^2} \cdot F(\theta_x, \theta_y, \theta_z),
$$

(4.11)

where $\sigma_{\text{stripping}} \approx 3.0 \times 10^{-13}$ mm$^2$, $\sigma$ is the r.m.s. spatial width of the bunch, $\sigma_v$ is the r.m.s. velocity width, and $F(\theta_x, \theta_y, \theta_z)$ is a form factor with a maximum value of $2/\sqrt{3}$ in the case where all three velocity spreads are equal. The first evidence of this phenomenon was reported in Ref. [78] and its cross-section was reviewed in Ref. [79]. It is important to underline that the fractional loss is proportional to the peak current: if the product of the peak current and the pulse length is kept constant (i.e., the beam power is maintained), the power loss is proportional to the peak current itself.

In Fig. 4.20, we show the fractional loss calculated by means of a program supplied by FNAL [80] for all of the SPL beam dynamics previously described: since the transverse and longitudinal phase advances are almost the same for the three cases, so are the beam sizes and the velocity distributions.
This means that the three cases are indistinguishable. The resulting power loss exceeds the 0.1 W/m limit in many areas and, in particular, in the achronatic-bend transfer line from Linac4, where a tight waist in both the transverse and the longitudinal plane is achieved. The only way to reduce these losses is to reduce the peak current: if the low-current scenario is chosen instead of the high-current one, the power loss is reduced by a factor of 2, preserving the above limit.

![Fractional loss and power loss calculated as functions of position along the linac for the high-current scenario. The data were generated by a program supplied by FNAL [80].](image)

**Fig. 4.20:** Fractional loss and power loss calculated as functions of position along the linac for the high-current scenario. The data were generated by a program supplied by FNAL [80].

### 4.2.4 Higher-order-mode effects

The effect of HOMs on beam quality has been analysed in detail for the SPL in order to define damping requirements as a function of the operation parameters. For this purpose, a dedicated beam dynamics simulation code, Simulation of higher order Mode Dynamics (SMD), focusing on beam–HOM interactions, was developed. SMD allows one to analyse beam behaviour under the influence of HOMs, taking into account many important effects, such as the HOM frequency spread, beam input jitter, different chopping patterns, and klystron and alignment errors. SMD performs bunch-tracking simulations of point-like bunches taking into account the effects on the time of flight and energy gain induced by HOMs and initial energy errors. Space charge effects are neglected in all simulations.

In the SPL case, HOMs are only a concern in the longitudinal plane, the deflection forces of non-monopole modes being too weak to cause transverse beam break-up [64, 81].
Table 4.6: Machine parameters for HOM simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity</td>
<td>40–400 mA</td>
</tr>
<tr>
<td>Intensity bunch-to-bunch jitter</td>
<td>3%</td>
</tr>
<tr>
<td>Injection energy</td>
<td>$160 \pm 0.078$ MeV</td>
</tr>
<tr>
<td>Synchronous phase at 704 MHz</td>
<td>$-15 \pm 0.4^\circ$</td>
</tr>
<tr>
<td>RF phase and amplitude jitter</td>
<td>$0.5^\circ, 0.5%$ (uniformly distributed)</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>352.2 MHz</td>
</tr>
<tr>
<td>Pulse length</td>
<td>1 ms</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

4.2.4.1 Simulation input parameters

The simulation input parameters can be separated into machine-specific and cavity-specific parameters. All machine parameters used in the simulations are listed in Table 4.6 and are based on Linac4 simulations [82] and experience at the SNS [83]. A Gaussian distribution was assumed, unless otherwise stated.

The cavity-specific simulation parameters are the mode frequencies and their $\left(\frac{R}{Q}\right)(\beta)$ values. The first three monopole bands of the SPL baseline cavities and their maximum $\left(\frac{R}{Q}\right)$ values are shown in Fig. 4.21. Figure 4.22 shows the $\left(\frac{R}{Q}\right)(\beta)$ dependence of some modes, which can vary over several orders of magnitude. A Gaussian HOM frequency spread of 1 MHz was assumed for all non-TM$_{010}$ modes, based on experience at DESY [84] and JLAB [85]. The properties of the modes above the beam pipe cut-off frequency depend on the geometry of the inter-cavity sections and are under investigation [86].

![Fig. 4.21:](image)

*Fig. 4.21:* The first three monopole bands of the SPL baseline cavities and their maximum $\left(\frac{R}{Q}\right)$ value in the energy range used. The beam pipe cut-off frequency is indicated by the dashed line.
4.2.4.2 Reference simulation

In all simulations, one or more pulses consisting of 350,000 point-like bunches (∼1 ms) were tracked through the nominal SPL and then the phase space area created by the last pulse was recorded. The effective phase space of the pulse in the longitudinal plane was calculated from

\[ \varepsilon = \sqrt{\langle dE^2 \rangle \langle d\phi^2 \rangle - \langle dE \rangle \langle d\phi \rangle^2}. \]  

(4.12)

Tracking one pulse with a Gaussian-distributed injection energy and phase error and no RF errors through the linac resulted in the phase space distribution shown in Fig. 4.23.

Fig. 4.23: 2D phase space histogram of one pulse at the end of the linac which was not disturbed by HOMs. This distribution was used as a reference for the HOM simulations described in the following paragraphs.

4.2.4.3 Effects of RF errors

Amplitude and phase errors in the RF system lead to an increase in the average energy and phase error of the bunches along the linac, which can also be represented as a phase space increase. The result of 1000 end-to-end simulations with the nominal RF errors (see Table 4.6) for one pulse is shown in the
histogram in Fig. 4.24.

![2D phase space histogram at the exit of 1000 linacs with RF errors, but where no HOMs are present, and the phase space distribution of single pulses.](image)

**Fig. 4.24:** 2D phase space histogram at the exit of 1000 linacs with RF errors, but where no HOMs are present, and the phase space distribution of single pulses. The phase space area is increased significantly compared with Fig. 4.23. On average, $\varepsilon$ is $\approx 3.8$ times higher.

The phase space increase due to RF errors can be used as an upper limit for the tolerable impact of HOMs.

### 4.2.4.4 Effects of higher-order monopole modes

For the following simulations, the modes with the highest $(R/Q)(\beta)$ values were chosen, while the beam current $I_b$ and the damping were varied. Figure 4.25 shows the resulting phase space increase. For each value of $Q_{ex}$, 100 linacs were simulated while the HOM frequency patterns were changed. One can see that for all values of the current and damping, the impact of HOMs can be neglected compared with the influence of RF errors. The beam noise is not strong enough to drive HOMs.

### 4.2.4.5 Resonances

Resonances created by the pulse substructure (due to chopping) as well as the principal machine lines (created by the bunch spacing) can drive significant HOM instabilities, as shown in Fig. 4.26. Three different pulse substructures are shown, and the mean HOM frequency was set to the resonance frequencies between the third and fourth fundamental machine lines. The notation $n/m$ means that $n$ out of $m$ bunches remain in the pulse, while $(m - n)$ bunches in between are chopped. In order to keep the total charge per pulse constant, the charge per bunch was increased accordingly. The principal machine lines are the most critical, but chopping at the highest repetition rate can also cause a significant HOM impact. Hence, no mode with a high $(R/Q)(\beta)$ value should be close to such a resonance line. The fundamental machine lines can be considered during cavity design. Nevertheless, in order to keep full flexibility in the chopping pattern, the case in which a HOM falls on a high-frequency chopping-induced machine line cannot be a priori excluded. Therefore, to guarantee a stable beam for any chopping pattern, a damping on the order of $Q_{ex} = 10^5$ is required for modes with high $(R/Q)$ values (>10 $\Omega$; compare Fig. 4.21).

### 4.2.4.6 TM$_{010}$ passband modes

The modes other than the accelerating $\pi$ mode in the TM$_{010}$ band have a small frequency spread and can have an artificially high $(R/Q)$ value for velocities different from the geometric beta ($\beta \neq \beta_g$). HOM
Fig. 4.25: Average longitudinal phase space increase and deviation for 100 linacs plotted against the damping $Q_{\text{ex}}$ for different $I_b$. The increase is approximately quadratic with $I_b$. The plateau around $Q_{\text{ex}} \approx 4 \times 10^7$ is due to the pulse period structure.

Fig. 4.26: Longitudinal phase space increase versus HOM frequency assuming a HOM falls on a chopping-induced machine line at nominal current and $Q_{\text{ex}} = 10^7$, for different chopping patterns. The RF-induced growth (black dashed line) is indicated together with the identified monopole modes (violet dashed lines) in the frequency range investigated (see Fig. 4.21).

dampers are generally insensitive to these modes, owing to the rejection filter for the accelerating mode. Hence, only the fundamental power coupler can provide damping for these modes. The modes and the damping calculated with different electromagnetic simulation tools are listed in Table 4.7. The most critical mode is the $(4/5)\pi$ mode. For a beam current of 400 mA, a certain longitudinal-emittance increase is visible, but it remains below the growth caused by RF errors at the expected damping.

The chopping pattern can cause a further longitudinal-emittance increase, especially if a chopping-induced machine line exactly matches a TM$_{010}$ mode, as illustrated in Ref. [87].
4.2.4.7 HOM power dissipation

The additional load on the cryogenic system was estimated for the SPL in Ref. [88]. At moderate damping ($Q_{ex} = 10^7$), the dissipated HOM power at a chopping resonance line can easily exceed 10 W/Ω. This is an enormous load on the cryogenic system if the power is dissipated at 2 K. A $Q_{ex}$ of $10^7$ is expected when a slightly lossy material between cavities is used as the only HOM damping mechanism. Instead, a dedicated HOM coupler can reduce the $Q_{ex}$ further and decrease the dissipated HOM power on resonance. On the other hand, it also increases the width of the resonances and the power dissipation close to a resonance. Nevertheless, this situation is preferable, because it enables operation with HOMs at chopping-induced machine lines and does not limit operation to low-frequency chopping patterns.

4.2.4.8 Damping requirements

Based on the scenarios discussed here, a moderate damping on the order of $Q_{ex} = 10^7$ is sufficient as long as no high-frequency chopping pattern is introduced. If any chopping pattern is allowed, a damping of $Q_{ex} = 10^5$ or even stronger is required to reduce the heat load caused by resonant excitation to a tolerable level and avoid beam degradation.

4.3 Beam extraction and transfer lines

4.3.1 Transfer line between Linac4 and SPL

The transfer line between Linac4 and the SPL accommodates a collimation system, vertical bending, and beam instrumentation.

Several options were studied, and the one retained was the simplest possible line that allowed enough free space for the collimation system and for the vertical bending without degradation of the beam dynamics even in the presence of errors. This contains two vertical bendings, six quadrupoles, and an RF cavity at 352 MHz within an overall length of 9 m. A schematic layout is shown in Fig. 4.27.

The quadrupoles are standard Linac4 transfer line quadrupoles, and the buncher cavity is a copy of the last PIMS module. The two vertical bendings, of length 300 mm and radius of curvature 41 m, were chosen such that the $B$ field necessary to bend the beam does not strip the H⁻ beam.

The achromatic vertical bend between Linac4 and the SPL was designed to accommodate beam collimators in between the two vertical bendings, with an effective free space of about 1.5 m on each side.
The phase advance between the two collimators was set to about 80°. The beam envelopes from the beginning of the PIMS to the input of the SPL are shown in Fig. 4.28.

To assess the sensitivity of the HEBT, a set of statistical runs were performed, including the PIMS. A correction system of integrated steerers inside quadrupoles plus BPMs corrected the beam centre position error due to static displacements of magnetic elements. The errors assumed were:

- 0.3 mm, 0.3 mrad uniform error as input beam jitter;
- 0.1 mm Gaussian misalignment error in quadrupoles;
- 0.5% gradient error in quadrupoles;
- 0.5% error in dipole field for the study of dispersion.

No losses were detected in any cases, and the emittance increase at the input of the DTL was about 1% at 3 sigma. The dispersion jitter was below 1 mm. The beam dynamics in the HEBT was therefore validated.
Fig. 4.28: Top to bottom: radius in $x$ direction (horizontal), radius in $y$ direction (vertical), phase spread at 352 MHz, and vertical dispersion.

4.3.2 Extraction to ISOLDE

The beam parameters assumed for the design of the extraction to ISOLDE [89] and to the possible EURISOL [10] radioactive ion beam facility are listed in Table 4.8.

<table>
<thead>
<tr>
<th>ISOLDE</th>
<th>EURISOL</th>
<th>LP-SPL</th>
<th>HP-SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy (GeV)</td>
<td>1.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Beam power (kW)</td>
<td>45</td>
<td>56</td>
<td>4000</td>
</tr>
<tr>
<td>Beam rigidity (T m)</td>
<td>7.14</td>
<td>11.03</td>
<td>11.03</td>
</tr>
<tr>
<td>Max. dipole field (T)</td>
<td>0.29</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>Min. radius (m)</td>
<td>29.5</td>
<td>64.1</td>
<td>74.0</td>
</tr>
</tbody>
</table>

To keep the losses by magnetic stripping below 0.1 W/m.

Extraction to ISOLDE requires a pulsed dipole magnet operating at 1.25 Hz to deflect the H$^-$ beam from the SPL. One empty lattice period is assumed, with an extraction geometry as shown in Fig. 4.29. The outer radius of the cryomodule is assumed to be 0.65 m. The warm–cold transition is assumed to have the same radius, and to be 2 m long. The free drift between the cryomodules is 13 m, including the warm–cold transitions. The minimum spacing between the elements is assumed to be 0.5 m.
and the dipole full gap height is assumed to be 0.15 m.

The losses in the dipole from Lorentz stripping are at the 0.02 W/m level. The stripping foil, which will be located somewhere downstream of the extraction, will produce losses of about 2 W, as shown in Fig. 4.30, for a foil thickness of about 1200 µg/cm².

**Fig. 4.29:** Extraction of 1.5 GeV beam to ISOLDE within one standard SPL period

**Fig. 4.30:** Losses from foil processes at stripping point after ISOLDE extraction

### 4.3.3 Extraction to a radioactive ion beam facility

Extraction to a radioactive ion beam facility such as EURISOL requires a slowly pulsed or quasi-DC dipole magnet to deflect the H⁻ beam from the SPL linac, and a septum is required to avoid the need
for dipoles with \( \approx 1.0 \) m wide apertures. Again, one empty lattice period is required, with an extraction geometry as shown in Fig. 4.31. The outer radius of the cryomodule is again assumed to be 0.65 m. However, owing to the constraints on the maximum dipole field, in this layout the radius of the warm–cold transition must be reduced to 0.5 m, and its length to 1.0 m. This is not expected to pose significant technical challenges, but without this change to the warm–cold transition geometry the beam cannot be extracted within one period. The free drift between the warm–cold transitions is then 11 m, and the extraction can be accomplished with two dipoles 2.75 m long and with a strength of 0.15 T, and a single septum 1.25 m long running at the same field. The horizontal gap required for these dipoles is 0.5 m, and that for the septum 0.3 m. One other important requirement for accommodating the extraction within a single lattice period is that the inter-element spacing is 0.3 m, which appears feasible. The dipole and septum full gap heights are assumed to be 0.15 m, and the septum thickness about 20 mm. Losses from Lorentz stripping in the dipoles and the septum will be at the 0.1 W/m level.

An extraction in this short drift seems just feasible, but the lack of space means that there are difficulties in accommodating all the elements, that two types of magnet are needed (septum and dipoles), and also that a non-standard warm–cold transition is needed. Increasing the available free drift length to around 21 m is the solution that was adopted in a new version of the SPL optics (see Section 4.2.2.1), which would then enable the extraction to be accomplished with a single dipole about 4.5 m long, operating at 0.14 T, as shown in Fig. 4.32.

4.3.4 Transfer line to PS2

Full details of the transfer line linking the SPL and PS2 are given in Ref. [90]. The TTL1 beam line will link the SPL to PS2 (Fig. 4.33), where the low-power H\(^-\) beam will be injected into PS2 by charge-exchange injection over a few hundred turns. In addition to the classical use of a foil to strip electrons off the H\(^-\) ions, a laser stripping scheme was also considered. The first part of TTL1 will potentially be used for the transport of HP-SPL beams up to the point where a beam line to a future neutrino facility can branch off, and it must therefore be compatible with both the LP-SPL and the HP-SPL. However, the second part needs to be compatible only with the LP-SPL. The general beam parameters for the design of the transfer line are listed in Table 4.9.
Fig. 4.32: Extraction of 2.5 GeV beam for EURISOL in a special long SPL lattice period

Table 4.9: Parameters for the SPL-to-PS2 transfer line

<table>
<thead>
<tr>
<th></th>
<th>LP-SPL</th>
<th>HP-SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy (GeV)</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam power (MW)</td>
<td>0.192</td>
<td>4.0</td>
</tr>
<tr>
<td>Max. $B$ field (T)</td>
<td>0.115</td>
<td>0.086</td>
</tr>
<tr>
<td>Min. radius (m)</td>
<td>141</td>
<td>228</td>
</tr>
<tr>
<td>Normalized emittance H/V (µm)</td>
<td>0.35/0.35</td>
<td>0.35/0.35</td>
</tr>
<tr>
<td>Beam rigidity (T m)</td>
<td>16.16</td>
<td>19.55</td>
</tr>
</tbody>
</table>

The start and end points of the TTL1 transfer line are the SPL end point and the location of the stripping foil in PS2, respectively. Between these points, TTL1 has to cross existing tunnels, for example the TI2 transfer line (at point C in Fig. 4.34). Over a total distance of only 410 m, the beam line has to overcome an altitude difference of 21 m. However, owing to constraints from existing tunnels and limitations on the bending field, the maximum slope of the main part of the tunnel reaches the large value of $-8.1\%$.

Based on these constraints, the beam line layout shown in Fig. 4.34 has been proposed for TTL1. This consists of a regular F0D0 lattice with 90° phase advance per cell and a cell length of 25 m, which is matched to the SPL and PS2 using four and nine quadrupole magnets, respectively. The bending is performed with combined horizontal and vertical achromats at the start and end of the line, and horizontal achromats in between. In the achromats, the dipoles are arranged in pairs with a 180° phase advance to cancel the effects of dispersion. The optics functions are shown in Fig. 4.35.

In the present design, these achromats consist of 5.75 m long dipole magnets, which could possibly be made from former LEP dipole magnet yokes equipped with new coils. These magnets would be ideally suited for the TTL1 transfer line owing to their low magnetic field. With this magnet type, the beam loss
requirements are fulfilled for HP-SPL beams in the first two achromats and for 4 GeV LP-SPL beams in all four achromats. Therefore, the first half of the beam line could indeed be used as a transfer line to a future neutrino facility, which could branch off TTL1 at the empty cell in the middle of the second achromat. With this configuration, it must be noted that the transfer of 5 GeV LP-SPL beams is not possible towards PS2. If this feature is needed, 7.2 m long dipole magnets will be needed.

Aperture envelopes have been calculated, showing that a 30 mm half-aperture would be sufficient over the whole beam line. In addition, preliminary space charge investigations have been done (Fig. 4.36), which show rather small emittance increases in the transverse plane. The beam energy spread increases from $\pm 1.5$ MeV to $\pm 7$ MeV. In the case of laser stripping, buncher cavities might therefore be required to reduce the energy spread and hence the laser power.
Fig. 4.35: Optics functions for TTL1. Note the suppression of dispersion using achromatic bends, and the matching to the PS2 lattice parameters at the end of the line.

Fig. 4.36: Space charge effects in TTL1 (TraceWin) for 62 mA beam current. The emittance growth (H/V) is 23%/2%, and the energy spread increases from ±1.5 MeV to ±7 MeV.

4.3.5 PS2 injection issues

The H⁻ injection into PS2 is affected by the SPL parameters. In particular, the proposed laser stripping [91] is sensitive to variations in the beam energy (see Fig. 4.37). With such an injection system, it would not be possible to run the SPL in a degraded-energy mode at 3.5 GeV, for example, since this would detune the resonance to such an extent that the 1064 nm laser could no longer excite the neutral H₀ to the \( n = 3 \) state as a prelude to the final field-stripping step, which would result in use of the \( n = 2 \) state and a huge emittance growth. The SPL energy would also need to be constant at 4.0 GeV, since any energy
change would require a new geometrical set-up of the laser-stripping insertion.

A divergence in the laser beam is needed to cover the spread of exciting resonance frequencies due to Doppler broadening, and the laser frequency range is then determined by the effective momentum spread. To have no large effect on the laser power required, the energy jitter should be kept one order of magnitude below the initial momentum spread, implying a jitter of $\Delta E_{\text{kin}} \leq 10^{-4}$ GeV.

![Fig. 4.37: Laser stripping: resonance conditions for different SPL energies as a function of intersection angle. For 3.5 GeV, the $n = 3$ state is not accessible. It is also clear that 4.5 GeV would be a much better choice than 4.0 GeV as concerns laser stripping, since the highest-lying states are energetically accessible.]

### 4.4 Superconducting cavities

#### 4.4.1 Introduction

The SPL superconducting accelerating cavities are five-cell standing-wave structures whose fundamental TM mode has a frequency of 704.4 MHz [59]. Two versions will be used. The $\beta = 1$ version has a length of about 1 m, and the $\beta = 0.65$ version is correspondingly shorter. Both designs are based on a development from CEA Saclay, France [92, 93]. The cavities are made from solid niobium, and are bath-cooled by superfluid helium at 2 K. Each cavity is equipped with a helium tank; a tuning system, designed by CEA Saclay [94]; a coaxial RF power coupler [95]; a pickup probe; and HOM couplers, one on each side, following a design from the University of Rostock, Germany [96]. Depending on the beam characteristics, the HOM couplers may be omitted under certain conditions. The superconducting resonators are fabricated from bulk niobium sheets by electron-beam (EB) welding of spun half-cells. The tubes for the beam pipes and the coupler ports are made by back extrusion and are joined to the cavity by EB welds. A schematic view of the $\beta = 1$ cavity inside its helium tank, equipped with the required ancillary equipment, is shown in Fig. 4.38. The principal cavity parameters are listed in Table 4.10.

#### 4.4.2 Design of the $\beta = 1$ cavity

The RF design of the $\beta = 1$ cavity was developed at CEA Saclay [92]. Figure 4.39 shows its dimensions.

Since this cavity needs to reach a challenging gradient of 25 MV/m in operation, the RF design was carefully optimized. The precise location of the high-power coupler was determined to achieve the optimal external coupling at full beam current. The shape of each outer cell was adjusted separately to optimize the RF parameters while fitting onto beam tubes with different diameters. Although smaller diameters could help to increase the shunt impedance, a 140 mm diameter tube is fixed onto one side.
Fig. 4.38: Schematic sectional view of a five-cell cavity inside its helium tank, with the power coupler and HOM coupler (right) and the pickup probe port, transition bellows, and tuner (left).

Fig. 4.39: Dimensional plot of the $\beta = 1$ five-cell cavity, as designed by CEA Saclay

owing to the geometry of the fundamental power coupler and the $Q_{\text{ext}}$ specification. Since the frequency piezo tuner has to fit onto the beam tube at the opposite side, the diameter is fixed at the maximum value (130 mm). The cavity ends with 80 mm diameter flanges, which means tapered tubes on both sides of the cavity. The nominal length of the cavity at the 2 K operating temperature is 1393 mm. The accelerating mode ($\pi$ mode) in the optimized SPL cavity is shown in Fig. 4.40.

The mechanical design [92, 97, 98] of the cavities ensures their safe use under maximum loading
Table 4.10: Parameters of the five-cell $\beta = 1$ cavity (note that $R = V^2/(2P)$, where $P$ is the dissipated power and $V$ is the peak voltage in the equivalent LCR circuit)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of accelerating structure</td>
<td>$\beta = 1$ five-cell standing wave</td>
</tr>
<tr>
<td>Accelerating mode</td>
<td>TM$_{010}$, $\pi$ mode</td>
</tr>
<tr>
<td>Fundamental frequency $f_{RF}$</td>
<td>704.4 MHz</td>
</tr>
<tr>
<td>Nominal gradient $E_{acc}$</td>
<td>25 MV/m</td>
</tr>
<tr>
<td>Required field flatness $\Delta V/V$</td>
<td>$&lt; \pm 2.5%$</td>
</tr>
<tr>
<td>Quality factor $Q_0$ at nominal gradient</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Active length $L$</td>
<td>1.065 m</td>
</tr>
<tr>
<td>Cell-to-cell coupling $k_{cc}$</td>
<td>1.92%</td>
</tr>
<tr>
<td>Iris diameter (inner cells)</td>
<td>129.2 mm</td>
</tr>
<tr>
<td>Iris diameter (outer cells adjacent to power coupler/tuner)</td>
<td>130/140 mm</td>
</tr>
<tr>
<td>$(R/Q)$</td>
<td>566 $\Omega$</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_{\text{acc}}$</td>
<td>2.0</td>
</tr>
<tr>
<td>$B_{\text{peak}}/E_{\text{acc}}$</td>
<td>4.2 mT/MV/m</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>270 $\Omega$</td>
</tr>
<tr>
<td>Required tuning range</td>
<td>$\pm$ 300 kHz</td>
</tr>
<tr>
<td>$\Delta f/\Delta L$</td>
<td>164 kHz/mm</td>
</tr>
<tr>
<td>Lorentz force detuning constant $K_L$</td>
<td>$-1$ Hz/(MV/m)$^2$</td>
</tr>
<tr>
<td>$Q_{ex}$ of input coupler ($I_B = 40$ mA and $\phi_s = -15^\circ$)</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>Cavity bandwidth $f/Q_{ex}$</td>
<td>590 Hz FWHM</td>
</tr>
<tr>
<td>Filling time constant $\tau$ when matched to 20/40 mA</td>
<td>550/270 $\mu$s</td>
</tr>
<tr>
<td>Number of HOM couplers</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 4.40: Electric field of the TM$_{01}$ fundamental mode in a $\beta = 1$, 704.4 MHz SPL cavity

conditions during their entire life cycle. Since these cavities are intended to work in a pulsed mode, their sensitivity to Lorentz forces is also especially critical. The effects of the detuning due to these forces have been limited by adding stiffening rings between the inner-cavity half-cells. Figure 4.41 shows a qualitative comparison of the mechanical deformation of the cavity with and without stiffening rings, under the influence of the Lorentz forces induced by the electromagnetic field.

Fig. 4.41: Cavity with and without stiffening rings, deformed by Lorentz forces
The cavity was also dimensioned to cope with several mechanical constraints, namely ensuring elastic deformation during maximum pressure and during all transport and handling conditions, minimizing the sensitivity to pressure fluctuations, avoiding buckling due to external pressure, and maximizing the frequency of the first longitudinal natural mode. A final thickness of 3 mm was calculated to be acceptable in order to cope with all the mechanical constraints as well as minimizing the cost of production of the cavities.

### 4.4.3 Superconducting material

All SRF cavities for contemporary accelerators for high-\(\beta\) particles use bulk niobium. There is good reason for this: niobium has the largest critical temperature \(T_c\) and the largest critical magnetic field \((T_c = 9.2 \text{ K and the superheating field is approximately } 240 \text{ mT})\) among all chemical elements, it is relatively ductile, and it is commercially available in large quantities and different shapes and as bulk and sheet material. There exist superconductors with higher critical temperatures and fields, such as some niobium-based alloys, but, in practice, cavities based on these materials have shown much inferior performance compared with niobium cavities (except for small accelerating gradients). The bulk niobium option was adopted for the material of the SPL cavities.

A high thermal conductivity in the cavity wall is needed (at least 10 W/(m K) at 2 K) to transfer the dissipated RF power to the liquid helium coolant; this is of particular importance in the presence of tiny normal-conducting defects, which are difficult to entirely avoid. For bulk niobium cavities, this requires niobium of exceptional purity. The requirements for such high-purity niobium are listed in Table 4.11.

The Residual Resistivity Ratio (RRR) (equal to 300 for the SPL cavities) is a common indicator of the purity level. The main interstitially dissolved impurities that act as scattering centres for unpaired electrons and reduce the RRR and, therefore, the thermal conductivity are oxygen, nitrogen, hydrogen, and carbon. Oxygen is dominant owing to the high affinity of niobium for oxygen. The influence of hydrogen on the RRR is not so significant, but the content of hydrogen should be kept small (less than 3–5 µg/g) to prevent hydride precipitation and degradation of the \(Q\)-value of high-RRR cavities under certain cool-down conditions (hydrogen \(Q\)-disease).

**Table 4.11: Technical specifications of niobium for superconducting cavities**

<table>
<thead>
<tr>
<th>Electrical and mechanical properties of niobium</th>
<th>Maximum limits on main impurity contents (weight per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual resistivity ratio &gt; 300</td>
<td>Ta: 0.05</td>
</tr>
<tr>
<td>Thermal conductivity (\lambda) at 4.2 K (^a) &gt; 75 W/(m K)</td>
<td>H: 0.0002</td>
</tr>
<tr>
<td>ASTM overall/local grain size number &gt; 6/4</td>
<td>W: 0.007</td>
</tr>
<tr>
<td>Yield stress min./max. &gt; 50/100 N/mm(^2)</td>
<td>O: 0.001</td>
</tr>
<tr>
<td>Tensile strength &gt; 140 N/mm(^2)</td>
<td>Mo: 0.005</td>
</tr>
<tr>
<td>Elongation at fracture &gt; 30%</td>
<td>N: 0.001</td>
</tr>
<tr>
<td>Vickers hardness HV 10 60</td>
<td>Ti: 0.005</td>
</tr>
<tr>
<td>Roughness (R_t) of the surface exposed to RF &lt; 15 µm</td>
<td>Other metallic impurities, each: 0.003</td>
</tr>
</tbody>
</table>

\(^a\) \(\lambda\) @ 4.2 K = RRR/4 is a convenient rule of thumb.

Among the metallic impurities, tantalum (Ta) has the highest concentration (0.05 weight per cent). This element accompanies niobium in most ores; modern separation methods are based on solvent extraction. This impurity level is normally harmless for cavities, since tantalum is a substitutional impurity and does not substantially affect the scattering mechanism. Next in abundance among substitutional impurities are metals such as tungsten (W), titanium (Ti), and molybdenum (Mo), usually at a level of less than 0.003 weight per cent.
Several remelting steps in a high-vacuum electron-beam furnace allow purification of niobium ingots. Light elements evaporate during this process. Four to six melting steps are generally necessary to reach the RRR = 300 level with a few times $10^{-4}$ weight per cent of interstitial impurities, which are much more harmful in terms of degrading the thermal conductivity. It is essential that the impurity content achieved by melting should be maintained during fabrication and treatment.

In addition, parallel surfaces and bulk material have to be free from defects such as pores, shrinkage, laminations, cracks, scratches, marks, blisters, segregation, niobium oxide, and other exogenous inclusions due to entrapped particles. All of these imperfections may initiate thermal breakdown.

The niobium sheets must be free from grease, fingerprints, and any other contamination. The surface must be ultrasonically inspected for any defects (continuity faults) and for variations in attenuation which may be indicative of microstructural heterogeneities.

### 4.4.4 Manufacturing considerations for $\beta = 1$ cavities

#### 4.4.4.1 Requirements for shaping of half-cells

The fabrication procedure for the SPL cavities consists of spinning and EB welding of the parts into a cavity assembly. The ‘inner’ surface of the niobium sheet is handled with the greatest care to avoid any contamination or damage by the spinning process. The surfaces of the tooling and the niobium disc must be carefully cleaned prior to each spinning operation, such that no dirt, metal particles, or other matter can become embedded in the niobium surface. The use of silicone is forbidden. The cooling lubricant must be free from silicone, halogens, and sulphur. Any lubricant or spinning foil used is completely removed by the ensuing cleaning operations.

Half-cells are produced from niobium sheets ($520 \text{ mm} \times 520 \text{ mm} \times 3.6 \text{ mm}$, $\text{RRR} > 300$) and cut into discs, which are pressed into shape using a set of dies. The dies are usually fabricated from anodized aluminium alloy. In establishing the form of the spinning tools, the spring-back of the niobium sheet material has to be taken into consideration.

The spinning is sensitive to the mechanical properties of the niobium. In particular, a small, uniform grain size is essential unless monocrystalline sheets can be used. The niobium sheet must be annealed to achieve complete recrystallization and to remove lattice defects without growing large grains. Excessively large grains would result in a roughening effect during the forming process (orange peeling).

If the material is incompletely recrystallized, it will tear during shaping. Achieving good mechanical properties in high-RRR niobium requires the proper choice of annealing temperature and time. The final annealing of the 3.6 mm thick niobium sheets is normally done at $750$–$800^\circ\text{C}$ in a vacuum oven at a pressure of $10^{-5}$–$10^{-6} \text{ mbar}$ for 1–2 h. Niobium also has a low degree of work hardening, which is advantageous for mechanical forming. In almost all cases, when the proper mechanical properties of the sheet are achieved, cavity parts can be spun to final shape without intermediate annealing.

The accuracy of the half-cells is controlled by 3D measurement and by sandwiching the half-cell between two plates and measuring the resonant frequency (Fig. 4.42). This frequency must be the same as that computed with an electromagnetic-field simulation code.

#### 4.4.4.2 Welding requirements

It is preferable that all EB welds are performed with full penetration. Welding from the inside (RF side) is recommended wherever possible.

Welds at the equator and iris of the cells and at the HOM coupler parts are especially critical because they will be exposed to high magnetic or electric fields. Therefore, thorough cleaning by ultrasonic degreasing, chemical etching, rinsing with ultrapure water, and clean-room drying is mandatory; absolutely clean conditions must be ensured during welding. Touching the weld preparation area after the last cleaning must be strictly avoided. Since niobium is a strong getter material for oxygen, it is important to
carry out the EB welds in a sufficiently good vacuum with no residual hydrocarbons present. Tests have shown that RRR 300 niobium suffers less than 10% RRR degradation as a result of welding at a pressure lower than $5 \times 10^{-5}$ mbar. Only after the temperature of the welded parts has dropped below 100°C can the welding chamber be vented. The repair of any defective weld is forbidden.

### 4.4.4.3 Manufacture of dumb-bells and extremities

The half-cells are ultrasonically cleaned and chemically etched. Two inner half-cells are welded together at their irises to form four dumb-bells in total (Fig. 4.43). Defects and imprints of foreign material from previous fabrication steps are removed by grinding. Two outer half-cells, with slightly different dimensions, are joined to two end groups into two extremities. The selection of the two half-cells for one dumb-bell is guided by the evaluation of a resonant-frequency measurement. It is recommended that the iris weld receives a smooth surface on the inside by welding from inside. A stiffening ring is welded to the dumb-bell. It is necessary to ensure a 100% penetration weld in order to avoid cracks on the back surface of the stiffening rings. Otherwise, this would reduce the mechanical strength and the dumb-bell could suffer chemical contamination, since acid cannot be removed from cracks.

Weld shrinkage produced by the sequence of welds must be considered, and it is highly important to ensure parallelism of the equatorial planes of the two half-cells joined. The dumb-bell is finally inspected for correct dimensions and weld characteristics. After completion of the dumb-bells (welding of the iris and stiffening ring), the resonant frequency is measured again in order to achieve simultaneously the correct length and resonant frequency of the finished dumb-bells and extremities. The machining of the equators, determined by the evaluation of the frequency, must not damage the inner surface or expose it to welding splashes.

The two end groups are composed of beam tubes and beam tube flanges. The beam tubes are either purchased as extruded seamless tubes or rolled from sheet and EB welded. The flanges for the beam tubes are of the standard ConFlat® type, made of austenitic stainless steel type X2CrNIMoN 17-13-3 (1.44029, AISI 316LN). The sealing surface must have a very good surface quality and must be free of any scratches.

The stainless steel flanges are brazed onto the niobium tube flanges (niobium RRR > 300 material). The filler metal is high-purity copper (OFE) wire. The pressure in the vacuum chamber is less than $5 \times 10^{-5}$ mbar during brazing. Precautions must be taken in order to compensate for the difference in
dilatation between the stainless steel and the niobium during brazing. The tubes, including their stainless steel flanges, are EB butt welded to the main beam pipe (niobium RRR > 300 material).

The stainless steel bellows support is brazed onto the niobium tube (end group 1) following the same procedure as above. Every brazed joint is leak-tested with a helium mass spectrometer leak detector. The leak-tightness must be better than $1 \times 10^{-10}$ mbar l/s. Every brazed joint is ultrasonically inspected. Voids must not exceed 5% of the brazed area.

Finally, after proper cleaning, four dumbbells and two extremities are assembled in a precise fixture to carry out the five equator welds, which are done from the outside.

4.4.4.4 Sequence of manufacturing operations

A five-cell cavity consists of five inner cells and two end groups, accommodating two beam ports and four ‘tubes’ to fit one RF power coupler, two HOM couplers, and one RF pickup probe. All beam ports and tubes are equipped with stainless steel flanges of the ConFlat® type, which are brazed onto the cavity body made from niobium. Figure 4.44 shows the fully manufactured cavity after all welding steps. Figure 4.45 shows the manufacturing sequence, starting with the extremities and the half-cells and then finishing with the final assembly.

In summary, the cavities are manufactured according to the following sequence, in which the most important steps for one five-cell cavity are listed:
**Fig. 4.45:** Manufacturing sequence of the niobium five-cell $\beta = 1$ cavity
– Provision of the niobium sheets and tubes and the stainless steel flanges and discs.
– Spinning of half-cells (eight middle and two end) (niobium RRR > 300 material).
– Machining of iris and grooves to carry stiffening rings as preparation for welding (taking into account shrinkage after welding).
– Manufacturing of two end groups, including the interface with the helium tank and stainless steel flanges for the beam ports and the various tubes.
– Leak-tightness measurement of end groups.
– Manufacturing of stiffening rings (niobium RRR > 40 material).
– Degreasing of half-cells, end groups, and stiffening rings.
– Shape accuracy control by 3D means for each half-cell.
– RF measurement of half-cell frequencies as an additional check of shape accuracy.
– Ultrasonic cleaning of half-cells, end groups, and stiffening rings; Chemical Polishing (CP) 20 µm on each side and the inner and outer surfaces; rinsing in de-ionized filtered (0.2 µm maximum pore size) hot water; drying in laminar airflow in a class 6 (ISO 14644-1) or better clean room.
– EB welding of the irises (eight half-cells and two end groups) from inside and outside (within 8 h maximum from previous step, otherwise additional 3 µm CP in iris area within 8 h before welding) to form the two extremities and four dumb-bells.
– Leak-tightness measurement of dumb-bells and extremities.
– EB welding of stiffening rings.
– Inspection and dimensional control of dumb-bells and extremities.
– RF measurement of dumb-bells and extremities to calculate the trimming value for the equator welding.
– Trimming of equators as per RF measurement results and machining the welding area, taking into account shrinkage after welding.
– RF measurement of dumb-bells and extremities.
– Ultrasonic cleaning of dumb-bells and extremities; CP (20 µm on each side) on inner and outer surfaces; rinsing in de-ionized filtered (0.2 µm maximum pore size) hot water; drying in laminar airflow in class 6 (ISO 14644-1) or better clean room.
– Grinding if needed, plus 20 µm CP, rinsing, and drying of dumb-bells and extremities.
– 3 µm CP of dumb-bells and extremities.
– EB welding of all equators (four dumb-bells and two extremities) from outside with full penetration. Niobium vapour and splashes from welding must be prevented. This manufacturing step must be executed within 8 h after the previous step, otherwise an additional 3 µm CP is required in the equator area within 8 h before welding.
– Leak-tightness measurement of final cavities.
– Field flatness and RF frequency measurement, and tuning if needed (both frequency and field flatness) of the final cavity.
– Final degreasing.
– Installation of handling and transport frame on the cavities.
– Storage in clean plastic foil under nitrogen atmosphere.

4.4.5 Frequency and field adjustment

Three steps are undertaken to achieve the correct resonant frequency of the cavity during operation in the accelerator.
The first step is performed during the manufacturing process, by trimming the equators of the dumb-bells and end-groups to the target frequency (and length) prior to final assembly of the cavity.

The second step is performed at room temperature on the welded cavity and consists of tuning each cell by plastic deformation to adjust the cavity frequency and the field homogeneity of the cavity.

The third step is to adjust the cavity frequency at the operating temperature (2 K) using a cold tuner by deforming the entire cavity elastically.

This section focuses on the development of the systems for resonant-frequency and field profile measurements of the half-cells, dumb-bells, end groups, and final cavities. In addition, the tuning machine which is used to deform the cavity at room temperature in order to achieve the design frequency and the desired field flatness is described.

### 4.4.5.1 Measurement and trimming of sub-assemblies

Any mechanical imperfection in a resonant volume results in a shift of the resonance. To bring the frequency closer to its nominal value in the final assembly, the subparts of the cavities, i.e., half-cells, dumb-bells, and end groups, are subjected to RF measurements again in order to estimate the required correction. Even though measurements of the half-cells are not essential as far as frequency adjustment is concerned, these measurement results are important for providing feedback on the quality of the manufacturing process. They provide information about the average resonant frequency and its spread among the different half-cells. The average frequency gives information about the shape outline, while its spread shows the reproducibility of the fabrication. Figure 4.46 shows the sensitivity of an SPL centre half-cell to small deformations of the outline, assuming a circularly symmetric configuration. The result was obtained with the Superfish [99] simulation program.

![Fig. 4.46: Effect of deformation of the SPL centre half-cell outline on the monopole resonant frequency calculated with Superfish.](image)

All of the half-cells are fabricated with extra lengths at the iris and the equator. The reason for this, in addition to the welding shrinkage, is to allow frequency compensation for shape errors. The extra lengths affect the frequency in opposite directions; however, only the equator can be trimmed to compensate for shape errors, since trimming the iris would change the coupling strength between the cells in the final assembly. As elongation of the cell at the equator decreases the frequency, cells with resonant frequencies lower than nominal must be over-trimmed. The simulated trimming sensitivity requires validation by measurements.

In the case of the dumb-bells, the trimming of the equator of the half-cell components can be symmetric or asymmetric. The former assumes that the individual frequencies of the half-cells are equal, while the latter supposes that they deviate. The method of calculating the deviation requires an additional measurement in which the half-cells are perturbed and the resulting resonant-frequency change is
determined.

In the case of a tight final length requirement, the dumb-bells and end groups must be adjusted to the right length in addition to the right frequency [100]. For that purpose, the tuning sensitivity of the cells in the final cavity needs to be predetermined. The parts are trimmed to an intermediate frequency such that they will have the right length and frequency in the final assembly after tuning.

The resonant frequency is measured by enclosing the subparts of the cavity between two end plates, creating a closed resonator. The measurement set-up for the half-cells is shown in Figure 4.47. It consists of the following three parts:

- an apparatus that holds the cavity parts and forms a closed RF volume;
- two antennas; and
- a vector network analyser (VNA).

![Fig. 4.47: Measurement system consisting of apparatus, antennas, and VNA. The screen shows the resonant-frequency measurements for the first three circular modes.](image)

The system was developed with the aim of achieving a measurement accuracy on the order of $10^{-4}$ of the resonant frequency. Providing a proper RF contact along the equator is crucial. Several additional error sources can perturb the measurement, namely changes in the ambient temperature, the electromagnetic properties of humid air, the antenna design and length, shell deformation, and the accuracy of the VNA. After careful analysis, we achieved a reproducibility of ± 30 kHz.

4.4.5.2 Measurement and tuning of the complete cavity

After the final equatorial welding, it has to be ensured that the design frequency and the field flatness are within the range of the tuning machine.

The field flatness is the magnitude homogeneity of the electric field located in the cell centres and
is quantified by

\[ FF = 100 \cdot \frac{v_{\pi j_{\text{max}}} - v_{\pi j_{\text{min}}}}{\left( \sum_{j=1}^{5} v_{\pi j} \right)/5} \]  (4.13)

where \( FF \) stands for the field flatness and \( v_{\pi j_{\text{max}}} \) indicates the electric-field magnitude of the \( \pi \) mode located in the centre of cell \( j \) (\( j = 1, \ldots, 5 \)). According to the specification, the SPL cavities must achieve a final field flatness lower than 2.5% after tuning.

An automated bead-pull test stand has been designed and commissioned for the purpose of field distribution mapping (Figure 4.48). The measurement method is based on Slater’s perturbation theorem [101], which asserts a proportionality between the resonant-frequency shift and the change in the stored energy of the cavity. In the bead-pull set-up, a frequency shift is induced in the resonant volume by a perturbing object, a dielectric spherical bead with a diameter of \( \sim 5 \) mm. Under the assumption of the presence of a sufficiently small volume on the cavity axis, where the magnetic field vanishes, the square of the electric field strength is expected to be mapped directly by the resonant-frequency shift.

![Figure 4.48: Automated bead-pull test stand for SPL cavities. Top left: transverse displacement of the wire. Top right: longitudinal displacement of the bead. Bottom left: bead centralization. Bottom right: control box.](image)

The hardware design of the set-up enables longitudinal and transverse guidance of the bead to position it on the cavity axis. The motion system consists of five stepper motors together with their drivers and a controller box. The longitudinal bead movement is generated by a reel attached to the shaft of one motor. To enable transverse positioning, linear slides are attached to the other four motors. The thread which provides support for the bead is moved by a pulley system, which can be installed in an
open- or closed-loop configuration. All the parts are supported by a static system, which is of aluminium profile construction. The resonant frequency is measured by a VNA, with the excitation and pickup antennas adjusted to the proper length, so that they have the least effect on the frequency and the highest transmitted power. The measurement is fully automated, and is controlled by a National Instrument Labview program.

There are several different methods that can be followed to determine the resonant-frequency shift of the cavity from a transmission measurement ($S_{21}$ scattering parameter). If the transmission resonant curve is considered, the resonant frequency can be obtained from the maximum of the amplitude curve (Lorentz, half-power) or from the phase curve by tracking a constant phase. In these cases, the stepping of the bead is synchronized to the RF data acquisition. In the case where the bead shifts the resonant frequency by a relatively small amount and therefore the corresponding phase change stays in its linear region (tangential curve), one can track the phase change at the unperturbed frequency provided that the number of points collected by the vector network analyser ensures sufficient resolution for data processing. This method provides a quick measurement process, and therefore is preferable because the SPL cavities are very sensitive to changes in ambient conditions. Proper care should be taken in the selection of the bead size and material to ensure linearity between the phase and frequency changes.

Two five-cell copper cavities have been tested, which we will call SPL1 and SPL2 in the following. These cavities were constructed (i) to better understand the construction procedures, (ii) to establish whether frequency measurement and frequency tuning of the dumb-bells are necessary, (iii) to establish procedures for field flatness measurements, and (iv) to perform cell-by-cell tuning of the completed cavities. SPL1 had an initial (post-production) field flatness of 9.68 ± 0.6%; meanwhile, SPL2 showed worse initial performance, with 24.77 ± 1.1% field flatness. The bead-pull results for the copper cavities showed the essential importance of quality assurance by RF measurements in an intermediate process in the production chain. In the case of SPL1, frequency adjustment of the dumb-bells was implemented by trimming the overall length symmetrically on both sides. In most cases the correction resulted in a shorter length compared with the design; hence the dumb-bells were over-trimmed. There were no corrections for frequency in the case of SPL2; the dumb-bells were trimmed to the nominal length. For the construction of the niobium cavities, it was decided to perform frequency tuning of the dumb-bells such that in the final assembly after tuning they would have the right length and frequency.

The field inhomogeneity of the cavity assembly is due to mechanical imperfections, resulting in individual cell shape deviations. A flat field profile can be achieved by eliminating the deflections relative to each other. For this purpose, a tuning machine (Figure 4.49) was developed to adjust the frequency of each cell of the cavity by plastically deforming it. Two plates were designed to touch the outside of the cell close to the stiffening-ring parts such that the individual cell could be either squeezed or pulled. In the former configuration, the plates encompass the cell, while in the latter they are in contact with the neighbouring cells. The force required for the deformation is applied by a hydraulic system. The tuning machine can be used simultaneously together with the bead-pull test stand.

A method [102] based on circuit model theory will be used to calculate the required amounts of tuning for the cells, hence reducing the number of iterations in the tuning. The required corrections for each cell can be calculated from the data collected in the bead-pull measurements of all the resonant modes of the cavity in the first band, and finally can be converted to $\pi$-mode frequency shifts.

### 4.4.5.3 Cold tuner

Frequency variation of a cavity while cold may be induced by several factors: the remaining error in the room temperature tuning; the effect of the final chemical treatments; differential shrinkage of the materials of the cavity, helium vessel, and tuner; fluctuations in the helium pressure; and detuning due to Lorentz forces. The differential shrinkage of the materials of the cavity, helium vessel, and tuner can be coped with within the tuning strategy for a series of cavities after a full test of the first prototype. All remaining sources of errors have to be compensated by using a tuner able to adjust the cavity frequency.
while cold within a suitable tuning range. The cavities to be installed in the SPL cryomodule will be equipped with a tuner that will be able to adjust the cavity while cold within a range of approximately 3 mm, representing a total frequency adjustment range of about 500 kHz for our cavities. The tuner was developed at CEA Saclay.

4.4.6 Specificities of the $\beta = 0.65$ cavity

The RF parameters of the $\beta = 0.65$ cavity are slightly different from those of the $\beta = 1$ cavity. Table 4.12 provides preliminary results for the main RF parameters while the design optimization is still ongoing [103]. The design of the $\beta = 0.65$ cavity follows the same guidelines as those documented for the $\beta = 1$ cavity. However, compatibility of designs is not always easy to achieve, and standardization must be envisaged right from the start of the project. Among other things, the compatibility issues concern the niobium sheets (thickness), and the interfaces with the helium tank, the tuner, and the cryomodule. Figures 4.50 and 4.51 depict the $\beta = 0.65$ cavity.

4.4.7 Preparation of superconducting cavities

4.4.7.1 General considerations

The fundamental advantage of superconducting cavities is their extremely low surface resistance, leading to RF losses which are five to six orders of magnitude lower than in copper cavities. The drawback is that even tiny amounts of surface contamination are potentially harmful, as they decrease the quality factor and may even lead to a thermal breakdown or quench of the superconductor due to local overheating. Perfect cleaning of the inner cavity surface is of utmost importance. Cavity treatment and assembly are, therefore, carried out in clean rooms conforming to semiconductor standards.

A niobium layer of 180 µm total thickness is removed in several steps from the inner cavity surface to obtain good RF performance in the superconducting state. At present, the standard method applied for material removal is electropolishing (EP). After rinsing with ultrapure water and drying in a class 100 clean room (class ISO 5, following ISO 14644-1 clean-room standards), the cavities are annealed.
at 600°C in a UHV oven to outgas any possible dissolved hydrogen and to relieve mechanical stresses introduced into the niobium during deep drawing in the fabrication of the cavity.

After the heat treatment, the cavities are mechanically tuned to adjust the resonant frequency to the design value and to obtain equal field amplitudes in all five cells. This is followed by light EP with about 30 µm material removal, a rinse with ultrapure water at high pressure (100 bar), and drying in a class 10 clean room (class ISO 4, following ISO 14644-1 clean-room standards). This surface treatment is followed by the assembly of the HOM antennas, the RF pickup probe, and a provisional input antenna for the low-power acceptance test. Even if this is done under controlled clean-room conditions, the cavities are rinsed with high-pressure ultrapure water several times to remove particles that may be introduced
Table 4.12: Parameters of the five-cell $\beta = 0.65$ cavity (note that $R = V^2/(2P)$, where $P$ is the dissipated power and $V$ is the peak voltage in the equivalent LCR circuit).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of accelerating structure</td>
<td>$\beta = 0.65$ five-cell standing wave</td>
</tr>
<tr>
<td>Accelerating mode</td>
<td>TM$_{010}$, $\pi$ mode</td>
</tr>
<tr>
<td>Fundamental frequency $f_{RF}$</td>
<td>704.4 MHz</td>
</tr>
<tr>
<td>Nominal gradient $E_{acc}$</td>
<td>19.3 MV/m</td>
</tr>
<tr>
<td>Quality factor $Q_0$ at nominal gradient</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>Active length $L$</td>
<td>0.692 m</td>
</tr>
<tr>
<td>Cell-to-cell coupling $k_{cc}$</td>
<td>1.45%</td>
</tr>
<tr>
<td>Iris diameter (inner cells)</td>
<td>96 mm</td>
</tr>
<tr>
<td>Iris diameter (outer cells adjacent to power coupler/tuner)</td>
<td>140/130 mm</td>
</tr>
<tr>
<td>$(R/Q)$</td>
<td>275 $\Omega$</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td>2.63</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$</td>
<td>5.12 mT/(MV/m)</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>197 $\Omega$</td>
</tr>
<tr>
<td>$\Delta f/\Delta L$</td>
<td>164 kHz/mm</td>
</tr>
<tr>
<td>Lorentz force detuning constant $K_L$</td>
<td>$-1.6$ Hz/(MV/m)$^2$</td>
</tr>
<tr>
<td>$Q_{ex}$ of input coupler ($I_B = 40$ mA and $\phi_s = -15^\circ$)</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>Cavity bandwidth $f/Q_{ex}$</td>
<td>590 Hz FWHM</td>
</tr>
<tr>
<td>Filling time (when matched to 20/40 mA)</td>
<td>540/270 $\mu$s</td>
</tr>
</tbody>
</table>

during the assembly process. The final acceptance step is an RF test in a superfluid helium bath cryostat, a vertical dewar.

Based on this standard preparation technique, high acceleration gradients of about 40 MV/m have been achieved (Fig. 4.52 [104]). Thus, this process was chosen as the baseline for the SPL cavities.

Fig. 4.52: Progress of field gradient in single-cell cavities [104]
4.4.7.2 Surface preparation methods

4.4.7.2.1 Degreasing, ultrasonic cleaning, drying

The process starts with degreasing and ultrasonic cleaning with mildly alkaline tensides (Tickopur R33 or equivalent, as used at DESY, Hamburg), followed by rinsing in de-ionized, filtered water (<0.2 µm pore size ideally), and this precedes all etching operations. Rinsing is done until a resistivity of >1 MΩ cm is reached at the water outlet point. Hot water (at a temperature of about 60°C) is preferred for its more intense cleaning action. If possible, drying should be carried out in a laminar airflow in a class 6 clean room (ISO 14644-1) or better. The parts should be stored under a protective gas atmosphere to avoid drying stains on the surfaces exposed to RF.

4.4.7.2.2 Chemical polishing, rinsing, drying

Generally, all etching operations should be carried out with the niobium part immersed in the acid mixture, i.e., over the entire surface. The acid mixture consists of HF (48% concentration), HNO₃ (65%), and H₃PO₄ (85%) in a volume ratio of 1 : 1 : 2. The removal rate is roughly 1 µm/min for fresh acid at 15°C, but depends on agitation, as well as the niobium content and temperature of the acid mixture. After etching, the parts are quickly (within a maximum of 15 s) immersed in a rinsing bath. At no time during etching and transfer to the rinsing bath may the acid temperature be permitted to exceed 20°C.

The acid mixture is replaced when its niobium content reaches 10 g/l, corresponding to an etching rate of about 0.5 µm/min. The etched parts should be rinsed with de-ionized, filtered water until a resistivity of 1 MΩ cm is reached at the water outlet point.

If available, drying should be carried out in a laminar airflow in a clean room of class 6 (ISO 14644-1) or better. The parts should be stored under a protective gas atmosphere to avoid drying stains on the surfaces exposed to RF.

4.4.7.2.3 Electropolishing

Electropolishing, also known as electrochemical polishing or electrolytic polishing (especially in the metallographic field), is an electrochemical process that removes material from a metallic workpiece. It is used to polish, passivate, and deburr metal parts. Being an electrical process, EP preferentially removes surface regions where the current is enhanced, i.e., protrusions are removed faster than recesses. It therefore results in a very smooth, shiny surface.

Here, for electropolishing, an acid mixture of hydrogen fluoride (HF) (48%) and H₂SO₄ (>96%) mixed in a volume ratio of 1 : 9 is used. The acid temperature is adjusted to a maximum of 20°C (if possible, 10°C), and a constant voltage of 12 V is applied between an optimized electrode made from pure copper and the cavity body. Nevertheless, the applied potential is a function mainly of the geometry of the cavity, the cathode, and the bath composition. Closed-loop pumping of the acid through the cavity is used. Figure 4.53 shows a schematic view of the process.
4.4.8 Performance tests of cavities

Measuring the RF characteristics of the cavities is crucial to deciding on the adequacy of the production and processing chain. It is also a powerful check of the success of the quality control measures in place. The performance of the cavities is measured by measuring their quality factor $Q_0$ versus the accelerating electric field $E$ in a vertical cryostat. Pictures of a vertical test stand and a cryostat, as were used in a test of an SPL mono-cell cavity prototype, are shown in Fig. 4.54. An example of the resulting $Q_0$ versus $E$ curve for the same mono-cell prototype is illustrated in Fig. 4.55.

At low field levels, the $Q_0$ of a cavity is usually at its maximum, but then decreases with increased field level within the cavity, owing to intrinsic and extrinsic effects. An example of an intrinsic effect is the dependence of the surface resistance on the magnetic field, while for extrinsic effects, examples include electron multipacting and field emission. (‘Multipacting’ means ‘multiple electrons impacting’;
electrons emitted from the cavity surface are accelerated and hit the surface, yielding secondary electrons. If the secondary electrons are generated in resonance with the RF frequency and if their average number exceeds one, an avalanche is generated. ‘RF processing’ reduces the average number of secondary electrons (the secondary emission coefficient of the surface).

For the low-power acceptance tests done in a vertical-bath cryostat at a temperature of 1.8 K, the standard measurement set includes measurement of the gradient limit, determination of the onset of field emission (if any), and detection of RF losses on the cavity surface due to localized heating and/or quenches, should they be observed. (The term ‘quench’ describes a sudden loss of stored energy...
Fig. 4.55: Quality factor and field emission (with star markers) as a function of the accelerating gradient for a SPL mono-cell cavity prototype from Research Instruments (November 2013). The data in red, cyan, and magenta are for the cavity at 1.8, 2.4, and 4.2 K, respectively. The data in green are for the same cavity but taken in October 2012, prior to the replacement of a cut-off tube. Shown in blue is the field emission as measured outside the vertical cryostat for the data taken at 1.8 K in November 2013. Also shown (in grey) are the contours of constant dissipated cavity power.

(within milliseconds) provoked by tiny defects in the cavity surface, inducing strong dissipation in the surrounding superconducting surface as a consequence of a superconducting-to-normal transition.)

4.4.8.1 Acceptance tests of cavities in vertical cryostat: RF test set-up

The vertical test stand infrastructure comprises a bath cryostat and the ancillary equipment needed to cool the cavity down to 1.8 K using liquid helium (see [105]), and a low-level feedback system based on a phase-locked loop (see Figs. 4.56 and 4.57) so that the cavity can be kept on resonance. A solid state CW 500 W RF amplifier is used to power the cavity, and calibrated directional couplers and RF power meters are used to measure the forward, reflected, and transmitted RF power ($P_{\text{Fwd}}$, $P_{\text{Rfl}}$, and $P_{\text{Txm}}$, respectively). An oscilloscope and a spectrum analyser are used to monitor cavity signals, and the data acquisition and measurement are done via a LabView-based software platform.

The $Q_0$ versus $E$ curve of the cavity is determined in a three-step process:

- **Cable calibration.** Calibration of both the warm and the cold sections of the cabling is performed in order to map the readings on the power meters to power levels at the cavity. This is the relation between the power terms $P'_x$ and $P_x$ (with $x = \text{TXM, Fwd, Rfl}$) in Fig. 4.56.

- **Probe calibration.** At low field, the scaling between the transmitted power $P_{\text{Txm}}$ and the stored energy $U$ is established. This scaling then allows determination of $Q_0$ and $E$ for any $P_{\text{Txm}}$ measurement. As described in Ref. [106], this calibration comprises the following:

  - The time decay constant of the cavity $\tau$ is measured with the spectrum analyser, and the
loaded $Q$-factor $Q_L = \tau \omega_0$ is evaluated.

- From the calibrated readings of the power meters, the coupling factor $\beta$ and the (unloaded) quality factor of the cavity $Q_0 = Q_L (1 + \beta)$ are calculated. Using these calculations, the effect of the input coupler in the measurement of the $Q$-factor is compensated.

- The power dissipated in the cavity ($P_{\text{cav}} = P_{\text{Fwd}} - P_{\text{Rfl}} - P_{\text{Txm}}$) is measured, thereby giving the stored energy $U$ in the cavity ($U = Q_0 \cdot P_{\text{cav}} / \omega_0$). For this low-field calibration point, the scaling $K_1 = U / P_{\text{Txm}}$ can be determined. $K_1$ takes into account the contribution of the pickup probe, is practically independent of the field level, and permits a determination of $U$ for any measured $P_{\text{Txm}}$.

- From simulations of the cavity geometry, the scaling of the stored energy in the cavity with the accelerating gradient $E$ can be derived (and is assumed as an input in the electromagnetic modelling of the cavity). The accelerating field can then be determined from $K_2 = U / E^2$, which is independent of the field level.

- $Q$ versus $E$ measurement. Measurement of the $Q_0$ versus $E$ curve is done by applying stepwise increments to the incident power sent to the cavity and measuring the resulting power level at the probe. From this, the $Q$-factor ($Q_0 = \omega_0 U / P_{\text{cav}}$) and $E$ (using $U$ and $K_2$) are determined.

Electron multipacting can occur at distinct accelerating gradients [107], but in elliptical $\beta = 1$ cavities such multipacting is rather rare and easily dealt with. Acceleration gradient limitations typically arise from thermal breakdown (quenches) caused by defects or inclusions heating up the cavity surface or from X-rays produced from field-emitted electrons (recall Fig. 4.55). Field emission can contribute to the cavity dark current and increase the power dissipated inside the cavity. The consequence is a reduction in the quality factor, and hence an emitted dark current can limit the cavity performance.
Fig. 4.56: Schematic illustration of the test equipment used for RF measurements on a superconducting cavity.
Fig. 4.57: Detail of the control room: instrumentation for the RF measurements.
4.4.8.2 Cavity diagnostics

4.4.8.2.1 Online diagnostics

For a complete evaluation of the bare cavities, the vertical RF test stand employs a full set of complementary diagnosis tools, such as tools for temperature mapping, X-ray mapping and measurement of overall X-ray activity, quench location detection, quench dynamics analysis, residual-resistance measurements, and measurements of cavity material properties (via frequency shift measurements as a function of temperature). These tools are essential for assessing cavity surface preparation and for identifying potential performance limitations with respect to the accelerating gradient of the cavity and its $Q$-value.

- The temperature-mapping equipment allows relatively complete detection of precursor defects before quench events occur, as well as detection of global RF loss and of quench locations, over the entire cavity surface, but it is relatively complex.

- With similar advantages and drawbacks, X-ray mapping is sensitive only to X-rays generated by high-energy electron impact.

- The measurement of the overall X-ray activity is easily feasible and very reliable.

- The location of quenches using oscillating superleak transducers (OSTs) is fairly straightforward and its incorporation into the cavity test stand is relatively easy. But the use of OSTs is restricted to superfluid helium, preferentially below 1.7 K, where the speed of second sound is constant (Fig. 4.58) and the sensitivity of OSTs is large (Fig. 4.59).

\[V_{ss} = \frac{\partial P}{\partial T} = \frac{\text{constant}}{T}\]

\[\text{Second sound velocity vs. } T(K)\]

\[\text{Second sound time of flight}\]

Fig. 4.58: Second sound as measured by an OST sensor when triggered by a heat pulse at $t = 0$

The picking up of the electron (dark) current is a fast diagnostic method but may miss electrons if they do not hit the current probe.

All of these diagnostic methods are well known and have been in use for a long time [108], except for the OST location method [109, 110], and will not be described here in more detail.

The diagnostic equipment planned for the RF tests of the SPL cavities consists of OST devices and temperature-mapping equipment [111, 112]. A dedicated cavity ($\beta = 0.65$) has been equipped with 28 OST sensors with the aim of detecting quench locations (Fig. 4.60). Twelve sensors are placed around the equator and eight around each iris (Fig. 4.61). Tests of the response of the OST sensors, manufactured at Cornell and CERN, were performed in CERN’s Cryolab. A typical second-sound response as detected by an OST sensor is shown in Fig. 4.62.

It should be noted that the design operating temperature is 2 K, which is in a range of smaller sensitivity and relatively large variation of the second-sound speed of the OST sensors. Hence measures
must be taken to cool the SPL cavity, in its vertical test cryostat, further below 2 K, say to 1.8 K or even less.

Fig. 4.60: Superconducting $\beta = 0.5$ niobium cavity (left) being equipped with OST sensors (right) for second-sound detection.

In an initial test with the OSTs, the cavity quenched at an accelerating gradient of about 3.1 MV/m during helium processing. Afterwards, the cavity was electropolished and high-pressure rinsed. In the following test, an accelerating gradient of 25 MV/m was achieved, limited by quench. Second sound created by the quench was first detected by OST2 (red line in Fig. 4.62) and OST1 (green), and then by OST3 (light blue). This indicates a quench location close to the iris in the vicinity of OST2. This surface area will be inspected with a recently commissioned optical inspection system.

4.4.8.2 Offline diagnostics

The ultimate accelerating gradient of a superconducting cavity can be limited by a single submillimetre-sized normal-conducting surface defect. The location of such a weak spot can be detected during a cold performance test in the vertical cryostat either by temperature mapping or by use of OSTs.
Fig. 4.61: Arrangement of OSTs around the $\beta = 0.65$ Saclay cavity. Sensors 1–7 (red numbers) are connected to one connector on the cryostat insert. Data taken with these sensors are displayed in Fig. 4.62. Sensors 1–23 (black numbers) are connected to a separate connector. The data obtained with these sensors are displayed in Fig. 4.63.

![Diagram of OST arrangement](image)

Fig. 4.62: The blue curve (‘RF’) shows the transmitted power decreasing during a quench. The sensor signals plotted were obtained with sensors 1–7 (red) indicated in Fig. 4.61.

In order to find a suitable treatment to eliminate such imperfections and to understand their characteristics and origin to avoid further formation, the defects need to be observed with a high-resolution camera [105]. Currently, the most commonly used device for this purpose is a product from the Kyoto–KEK collaboration, which has been commercialized by Japan Neutron Optics [113] (see also [112]).

Such an optical inspection bench (Fig. 4.64) was adapted for the SPL five-cell cavities. An aluminium profile frame structure makes up the support for the cavity and the alignment system of the optics. The optical system consists of a high-resolution CMOS camera, stripline illuminators, and a rotatable mirror (Fig. 4.65). Each part is housed within a long 7 cm diameter cylindrical shaft fitting the aperture of the cavity. To ensure investigation of a whole cross-section of the cavity volume, the end of the cylinder, where the lighting system and the mirror are located, was designed to be fully rotatable. There is also the possibility of turning the multicell resonator around its axis. Moving the cavity with respect to the shaft enables one to scan the entire inner surface. The alignment system enables transverse positioning of the shaft as well as adjustment of its horizontality (parallelism to the cavity axis). Its
Fig. 4.63: The blue curve (‘Pulse’) shows the transmitted power decreasing during a quench. The sensor signals plotted were obtained with sensors 1–19 (black) indicated in Fig. 4.61.

accurate rotation can be regulated as well. The alignment can be controlled by laser light.

Fig. 4.64: Optical inspection bench for the SPL multicell cavity diagnostics (mock-up of cavity under examination).

All electron-beam welding seams will be diagnosed in the equatorial and iris part of the cells. Inspection will be started immediately on reception of the cavities, after the bulk electropolishing process, and following the cold performance test in the vertical cryostat if the cavity was limited by quenching and the quench site has been located by OSTs or temperature mapping.
4.4.9 Clean assembly

4.4.9.1 Ultrapure water, high-pressure rinsing, and clean-room gases

4.4.9.1.1 Control of ultrapure water used for cavity rinsing

The main ultrapure-water supply and the point-of-use stations (tap connections) are controlled for particles by online measurements of particulate contamination, total organic carbon content, and the resistance of the water. Outlet measurements must be used as a cleanliness indicator.

4.4.9.1.2 High-pressure rinsing

To control the quality and efficiency of the high-pressure rinsing, the resistivity of the drain water coming from the inside of the resonator is measured. In addition, at periodic intervals, the drain water is passed through a filter, which is examined with a scanning light microscope to identify particulates.

4.4.9.1.3 Clean room and process gas (nitrogen)

The air and the process gas (nitrogen) are subject to general monitoring of particle contamination and airflow conditions (flow speed and flow direction). During the assembly procedures, the working area is monitored by additional air particle counters. These data, taken at the point of work, are the basis of the quality control of the assembly procedure.

4.4.9.2 Welding of helium tank

In preparation for the welding of the helium tank, the cavities are individually disassembled from the vertical test inserts, always under vacuum with the valves closed, and transported to the clean room. After slow venting with clean, filtered (dust-free) nitrogen gas, the antennas and valves used for the vertical test are removed, and the cavity is closed, kept under protective gas under overpressure, and stored.

4.4.9.3 String assembly

After a total of four cavities have been deemed to comply with the specified performance, they are combined inside a class 10 clean room (class ISO 4, following ISO 14644-1 clean-room standards) to form a cryomodule string. To this end, the cavities are equipped with pickup probes, couplers, intercavity bellows, and gate valves at the end of the cavity string.

During the assembly procedures, the working area is monitored by air particle counters. After an integral leak check, a mild bake-out (120–130°C) finalizes the string assembly before roll-out of the string for module assembly, ‘cryostating’, and RF tests in the horizontal position. (The mild bake-out
reduces or eliminates the so-called ‘Q-drop’, a sudden decrease of the Q-value at large accelerating gradients.)

4.4.9.3.1 Specific equipment requirements

Specific equipment must be provided for the various cavity preparation steps. This includes items for

- transport and storage (under N₂ at atmospheric pressure);
- clean-water provision and control systems (low- and high-pressure rinsing with ultrapure water);
- mechanical and room temperature RF (equipment for measuring field flatness and for tuning of the whole cavity, and a cavity model manufactured from copper to test, for example, the damping action of the HOM coupler);
- online diagnosis systems for vertical tests (temperature mapping, quench detection);
- offline inspection;
- tools for assembling the string of cavities into a cryomodule;
- clean-room equipment (online particle monitoring and alarm devices, ionized air shower);
- ultrapure-water control (particle counting, water resistivity (inlet and outlet), total organic carbon, bacterial analysis).

4.4.9.3.2 Summary of cavity-processing sequence

After manufacture of the five-cell cavity (checked for leak-tightness, field flatness, and resonant frequency), the following processing steps are applied. In parallel, several preparation steps must be taken in order to guarantee a smooth cavity-processing and assembly procedure (Fig. 4.66).

1st stage:

- ‘Hard’ EP (thickness 140 µm)—to be done at CERN.
- High-Pressure water Rinsing (HPR) to remove residuals left by EP.
- High-vacuum annealing at 600°C (24 h, 10⁻⁵–10⁻⁶ mbar).
- Field flatness measurement + retuning if needed.
- Short EP (20 µm).
- HPR in clean room.
- Closing of cavity, assembly of pickup probes and vacuum valves, and drying by pumping, where all actions are performed in clean room; storage under vacuum.

2nd stage:

- Assembly on vertical cryostat.
- Baking at 120°C.
- Cold RF test in vertical cryostat.

3rd stage:

- Analysis of RF test; if OK, go to 4th stage.
- If not, either (if no quench) go to 1st stage ‘HPR in clean room’ or (if quench) go to optical inspection system for identification of problem, mechanical intervention (guided repair) by grinding the defect, short CP, and continue to 1st stage (HPR).

4th stage:
Fig. 4.66: Workflow diagram, including parallel actions, from the delivery of the five-cell cavity to be mechanically tested up to the horizontal test under RF of the complete cryomodule.

- Transport under vacuum with the valves closed into clean room.
- Slow venting with dust-free (filtered) nitrogen gas and disassembling in clean room of the antennas and vacuum valves for the vertical measurement; cavity closed and kept under protective gas under overpressure.
- Welding of the helium tank to the cavity under protective gas.
- Leak test of helium tank.
- Storage of cavity in clean-room cabinet.

5th stage:

- Assembling of the string of four cavities in clean room with the pickup probes, couplers, and gate valves assembled.
- Pumping, leak test, and baking in clean room.
- Assembling of full cryomodule outside clean room.
- Horizontal cold test in bunker.

4.5 Ancillaries

4.5.1 Helium tank

The helium tank will contain saturated superfluid helium at 2 K, which will cool the cavity and allow extraction of the heat dissipated in the bulk niobium wall by the RF electromagnetic field, as well as the heat injected by all the adjacent components, such as the main power coupler. Superfluid helium is an excellent thermal conductor. However, this is true only for small heat fluxes. Above a critical heat flux, the temperature increases drastically, and eventually the superfluidity is lost. The geometry of the helium tank has been determined to allow the maximum heat extraction while optimizing the quantity of helium.
The design of the helium tank for the $\beta = 1$ cavities that will be tested in a cryomodule at CERN is shown in Fig. 4.67.

![Fig. 4.67: Helium tank for cavities to be tested in a cryomodule at CERN](image)

The helium tank also has a structural role, since it transmits the force applied by the tuner to the cavity, its rigidity thus being very important in the tuning process. The stiffness of the helium tank has a direct impact on the Lorentz detuning, defining the boundary conditions of the cavity. A longitudinal stiffness higher than 100 kN/mm is required.

Two choices of material were studied for the helium tank: stainless steel and titanium. Titanium has the advantage of having the same thermal contraction as niobium (on the order of 1.5 mm/m from ambient temperature to 2 K), while the thermal contraction of stainless steel is approximately twice as much. The use of a stainless steel tank therefore induces larger thermal stresses in the cavity. The advantage of stainless steel is manufacturability and thus reduced cost.

A major concern for the mechanical design was the transitions from the helium tank to all the adjacent components, in particular the main coupler and the flanges for connection to the helium pipes. Stainless steel has been selected for the SPL cryomodule.

### 4.5.2 Fundamental power coupler

The fundamental power coupler [95] will have to meet the following requirements:

- It must provide the correct coupling, or the optimum $Q_{ex}$, as described by $Q_{ex} = \frac{V_{acc}}{(R/Q)I_{DC}} \cos \phi_s$. Here, $V_{acc}$ is the accelerating voltage; $(R/Q) = \frac{V_{acc}^2}{\omega U}$ (linac definition), with $\omega$ being the frequency and $U$ the stored energy; $I_{DC}$ is the DC current per pulse; and $\phi_s$ is the synchronous phase.
- It must withstand the RF power, up to full reflection, at any phase.
- It must cause minimum cryogenic heat load.
- It must fulfill the mandatory cleanliness requirements for a high-gradient SRF cavity during manufacture.
- It must withstand mechanical stresses at all temperatures, warm and cold.
- It must allow ease of installation, both during clean-room mounting and in the accelerator.
- It must show no or only ‘mild’ multipacting.
- It must require minimum conditioning time.
- It must minimize the series production costs.
A coaxial RF power input coupler has been developed, consisting of a double-walled tube which is mounted on the cavity in the clean room and closed by a ceramic window, and a transition from the coaxial line to the waveguide. A one-window solution was chosen in preference to a two-window solution because, for large average power, it provides better cooling. However, the risk of contamination of the cavity, or even the whole cryomodule, is larger than for a two-window solution. Hence extreme care must be taken to prevent window fracture by means of a suitable interlock system.

There are still two possibilities for the window design, a coaxial disc or a coaxial cylindrical design (Fig. 4.68); both design choices are being pursued for the moment.

Fig. 4.68: Two design possibilities for the fundamental power coupler, equipped with air-cooling systems

Another important issue concerns the type of coupler, variable or fixed. A fixed-coupler solution was chosen because there will be only one power source per cavity and the manufacturing tolerances can be such as to guarantee a spread in $Q_{ex}$ of only $\pm 2\%$. Should the match be inadequate, there exist other matching methods that are being explored, such as three-stub waveguide tuners [124] and $\lambda/4$ waveguide transformers. In addition to the matching issue, construction challenges are significantly reduced.

Owing to the high average power, thermal screens are not enough to insulate the coupler between cold and warm. A double-walled tube is needed to minimize heat flow. This has several features:

- It is part of the coupler, i.e., the outer part of the 50 $\Omega$ coaxial line.
- Because of RF considerations, it has an ideal thickness of 4 $\mu$m of copper plated on the inside.
- Cryogenically, it must maintain a thermal interface between 2 K and ambient air temperature.
- The possibility of its use as a support for the cavity has been decided on, as this is independent of the coupler design itself.
- For a mass flow of 35 mg/s, the coupler-related losses at 2 K are reduced to 0.2 W per unit [115].
- RF conditioning of the couplers will be done independently prior to mounting the couplers onto
the cavities. A pair of couplers will be brought into the clean room with a test cavity (Fig. 4.69). Then, the couplers together with their own double-walled tubes will be mounted onto the SPL cavity horizontally (at the same time as the HOM couplers, antenna, and other components) to minimize the risk of cavity contamination.

Since the pre-assembled string of cavities is slid into the cryomodule, the length of the coupler is a constraint on the minimum diameter of the vessel. This is a very important decision for the design of the coupler, because this requires a short distance from the ceramic to the beam axis, and this defines the internal size of the cryomodule. As several coupler designs will be tested, the largest one will set the minimum size of the test cryomodule.

The test box was designed with all flanges directly machined into the top cover. As it has to be robust enough to bear the weight of two couplers, it is made of stainless steel. Owing to the rather large average power, in order to reduce losses, its inner side is copper coated. In order to ease the coating process, it was designed in two parts (Fig. 4.70). A special Helicoflex® gasket has been designed as well.

Two mounting positions, a lower and an upper position, are acceptable but a vertical 90° position is mandatory, to reduce stress on the antenna and to ease mounting. The decision to assemble the power coupler from below was dictated by the need to actively cool the HOM coupler opposite the power coupler with liquid helium. This cooling can only reliably achieved if the HOM coupler is located above the cavity. Hence the power coupler must be located below the cavity.

The lower position of the power coupler offers the possibility of using the double-wall outer conductor tube as a support for the cavity. For long-term operation, it will be extremely useful to have...
High-Voltage (HV) DC biasing between the inner and outer conductors, to suppress multipacting.

The main parameters of the SPL power coupler are summarized in Table 4.13.

**Table 4.13: Main parameters of the SPL fundamental power coupler**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of coupler</td>
<td>Fixed coupling</td>
</tr>
<tr>
<td>Mounting position</td>
<td>Below cavity</td>
</tr>
<tr>
<td>Additional functionalities</td>
<td>Support for cavity</td>
</tr>
<tr>
<td>Other design issues</td>
<td>Single air-cooled window/double-wall outer conductor with cold helium gas cooling/HV DC bias</td>
</tr>
<tr>
<td>Frequency $f_0$</td>
<td>704.4 MHz</td>
</tr>
<tr>
<td>HP-SPL</td>
<td>1000 kW pulsed, 100 kW average</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.4 ms rise time, 1.2 ms flat top, 0.4 ms decay time</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz (20 ms)</td>
</tr>
<tr>
<td>$Q_{ex}$</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>Input line</td>
<td>Coaxial 50 $\Omega$ line (100 mm/43.5 mm)</td>
</tr>
<tr>
<td>Waveguides</td>
<td>WR1150</td>
</tr>
</tbody>
</table>

### 4.5.3 Damping of higher-order modes

The influence of HOMs on the beam stability of the SPL has been extensively simulated [64] with regard to injection beam noise, HOM frequency spread, RF errors, machine lines, and substructured pulses. It turns out that for a fixed chopping pattern with the SPL design parameters, only the spectral lines of the bunch current will contribute to instabilities. These spectral lines are relatively widely spaced and well known. Therefore the HOMs may be individually tuned, keeping the fundamental-mode resonant frequency unchanged, to avoid them. No HOM frequency will meet such a spectral line. However, machine lines created by the pulse substructure depend on the chopping pattern and can occur at any frequency. A strong HOM damping of $Q_{ex} = 10^5$ is recommended to allow any possible pulse substructure. In the absence of any pulse substructure, only moderate damping on the order of $Q_{ex} = 10^7$ is needed. Hence, the objective for the design of the HOM coupler, in view of the uncertainty in the bunch pattern in the SPL, is required to be $Q_{ex} = 10^5$. 

---

Fig. 4.70: Assembly of the ‘test box’ with a Helicoflex® gasket
Various existing HOM coupler designs (LEP, SNS, TESLA, BNL, and ILC) have been compared and optimized taking into account the operating frequency, the smaller coupler port (45 mm diameter), and the different geometry of the extremities (see Fig. 4.44). The currently preferred designs, which feature very different advantages and disadvantages, such as good monopole coupling, dipole coupling, robustness, and tunability, are shown in Fig. 4.71.

![Fig. 4.71: Design approaches for HOM couplers](image)

The first design goal of a HOM filter is to block the transmission of the accelerating mode, while transmitting HOMs, which have significant \((R/Q)\) values. Several 3D codes (CST-Microwave Studio, HFSS, and ACE3P) have been applied to simulate the electromagnetic fields inside a cavity and, in particular, the distribution of HOMs and their damping by a specific HOM coupler design. The simulated transmission from the beam pipe port to the output port of the HOM coupler (not including the tapered beam pipe) is shown in Fig. 4.72. Studies of the sensitivity of the principal notch filter at 704.4 MHz to dimensional errors have been carried out. Owing to the relatively high bandwidth of the notch filter in the probe and hook designs (\(\sim 40\) MHz), high robustness with mechanical tolerances in the range of \(\pm 0.2\) mm is provided by these designs. The modified TESLA design needs to be tuned because of the very small mechanical tolerances of its notch filter (\(\pm 0.02\) mm). This tuning, however, can easily be achieved by pulling and pushing the upper plate of the pickup tube (Fig. 4.73(a)).

A larger coupling port increases the transmission in the low-frequency regime, but has little effect on the parasitic notch near 2.1 GHz. This notch, which is not shown in Fig. 4.72, is the TM\(_{01}\) cut-off frequency of the cut-off tubes and therefore is mainly dependent on their radii. However, this parasitic notch does not constitute a problem even if it is located close to three times the fundamental mode frequency. Modifications of the HOM coupler design shift the parasitic notch sufficiently.

Mechanical restrictions on the TESLA design make it more difficult to optimize the coupler for the SPL cavities. The use of a flange and its relatively long distance from the beam pipe (46 mm), together with a small tube diameter (45 mm), limit the potential for optimizing the transmission properties in the high-\(\beta\) case. Nevertheless, it is foreseen that we will study a similar design with a smaller diameter of the inner conductor, which leads to more flexibility in the RF transmission but complicates the possibility of active cooling by liquid helium flowing through the entire coupler.

The probe and hook designs feature a relatively large bandwidth of the notch filter at 704.4 MHz because of a more complex filter design (Fig. 4.71). Moreover, they provide better coupling to the HOMs at lower frequencies, starting from \(\sim 900\) MHz. The probe design is at the moment the best
option, especially for the high-$\beta$ cavity.

To efficiently damp the two polarizations of the dipole modes, the second HOM coupler port (left side in Fig. 4.44) is rotated by $60^\circ$ out of the vertical plane.

A further design constraint is given by the requirement to efficiently remove the heat dissipated by the fundamental mode in the inner part of the HOM coupler. The required cooling may be possible by conduction, but the possibility of cooling with superfluid liquid helium should not be a priori excluded. All of the designs described above (Fig. 4.72) have a sufficiently large diameter ($\sim 10.5$ mm) for an inner cooling circuit (Fig. 4.73(a)).

The power dissipation is estimated as 16 mW at 25 MV/m for a surface resistance of $R_s = 50$ n$\Omega$. It is evident from these numbers that the HOM coupler must have a superconductive surface. The dissipation and heat generation due to the surface resistance have been simulated with HFSS and ANSYS.
Even under extreme conditions ($R_s = 200 \, \text{n}\Omega$, CW mode), the surface loss ($\sim 10 \, \text{mW}$) and temperature increase ($\sim 2 \, \text{K}$) are very moderate, as shown in Fig. 4.73(b). The simulation considers only the accelerating mode, which is expected to account for $\sim 50\%$ of the total heat loss.

Further studies of the power dissipation, and also of the multipacting sensitivity and the mechanical response of the HOM couplers will be conducted in the future. Moreover, the first prototypes will be fabricated soon, for the first RF measurements.

### 4.6 Radio frequency system

The design of an RF system for a superconducting linac with the high energy and beam intensity of the SPL is challenging. The RF power system is a major cost driver in the overall project. The final design has to be an overall compromise between performance, reliability, and ease of operation and maintenance on one side and equipment, infrastructure, and running costs on the other. Important decisions have to be taken about the types of power sources and modulators, the system configuration, the power margins to be allowed, and the design of the low-level RF and control systems.

In this section, the basic operating parameters of the cavities and their powering requirements are reviewed, and then possible layouts and designs of the RF power system are presented, together with possible choices of power sources and system components. First, the overall power requirements for the cavities and beam are estimated, then margins for non-optimum coupling, stability, and feedback are considered, and finally the power margins and losses in the RF power system itself are added. Issues of construction and operating costs for the different layouts are compared broadly, and some operational issues discussed. Detailed cost estimates for the various options have been provided in a separate publication [11].

#### 4.6.1 Cavity operation

RF power levels were obtained using the standard simple equivalent-circuit model of an RF cavity driven by a power source, transmission line, and power coupler. This and the corresponding vector diagram are shown in Figs. 4.74 and 4.75, respectively. Note that the power coupler is not shown; all currents and impedances are referred to the cavity, with the source current and impedance transformed across the coupler.

![Equivalent-circuit representation of cavity and power source](image)

Fig. 4.74: Equivalent-circuit representation of cavity and power source

In Fig. 4.75, $I_g$ is the generator current referred to the cavity. If $I_1$ and $I_2$ are the forward and reflected waves, respectively, in the transmission line, then $I_g$ is the short-circuit current in the transmission line and is equivalent to $2I_1$. $I_b$ is a function of the DC beam pulse current $I_{DC}$ and the synchronous phase $\phi_s$. (We use the linac convention here, i.e., the synchronous phase is the advance of the beam passage with respect to the RF waveform peak.) We can take $I_b = 2I_{DC}$, which is valid for short bunches.
The total current $I_t$ is the vector sum of $I_g$ and $I_b$. The cavity voltage is given by $V_{\text{acc}} = I_t Z_t$, where $Z_t$ is the total effective cavity impedance. Resistive losses in the superconducting cavity itself are assumed to be negligible. The power loss back through the coupler to the klystron load is represented by a parallel resistance $R_{\text{ex}}$ (in circuit ohms), the transformed impedance of the transmission line, the value of which depends on the degree of coupling to the cavity. $R_{\text{ex}}$ is given by $R_{\text{ex}} = (R_c/Q) Q_{\text{ex}}$, where $(R_c/Q)$ is a function of the cavity design and $Q_{\text{ex}}$ is a function of the penetration of the coupler antenna into the cavity. For a given impedance angle $\phi_z$, the magnitude of the RF voltage is given by $V_{\text{acc}} = I_t R_{\text{ex}} \cos \phi_z$. Note that for non-zero beam current the minimum generator current (and hence the minimum forward power) corresponds not to the cavity being on tune, but to a certain detuning angle $\phi_z$ which makes $I_g$ and $V_{\text{acc}}$ in phase. The magnitude of $I_g$ in this case is given by

$$I_g = \frac{V_{\text{acc}}}{R_{\text{ex}}} + I_b \cos \phi_s \quad \text{(circuit } \Omega\text{)}.$$  \hspace{1cm} (4.14)

The forward power is simply $I_t^2/2R_{\text{ex}}$ (note that $R_{\text{ex}}$ is in circuit ohms!), and hence

$$P_{\text{for}} = 0.125 R_{\text{ex}} \left( \frac{V_{\text{acc}}}{R_{\text{ex}}} + I_b \cos \phi_s \right)^2 \quad \text{(circuit } \Omega\text{)},$$

or, written in linac ohms (with $R = 2R_c$),

$$P_{\text{for}} = 0.25 R_{\text{ex}} \left( \frac{V_{\text{acc}}}{R_{\text{ex}}} + I_{\text{DC}} \cos \phi_s \right)^2 \quad \text{(linac } \Omega\text{)}.$$  \hspace{1cm} (4.15)

This minimum forward power is dependent on the shunt resistance and is at its least when $R_s$ has the matched value

$$R_{\text{ex}} = \frac{V_{\text{acc}}}{I_{\text{DC}} \cos \phi_s},$$

this minimum being

$$P_{\text{for}} = \frac{V_{\text{acc}}^2}{R_{\text{ex}}}, \quad V_{\text{acc}} I_{\text{DC}} \cos \phi_s,$$

i.e., all power is transferred to the beam. The corresponding optimum (matched) $Q$-value $Q_{\text{ex}} m$ is given by

$$Q_{\text{ex}} = \frac{V_{\text{acc}}}{I_{\text{DC}}(R/Q) \cos \phi_s}.$$  \hspace{1cm} (4.19)

The above is valid when the cavity $\beta$ value corresponds exactly to that of the beam, which is clearly not the case for most of the cavities in the SPL, in which the beam $\beta$ varies considerably along the linac and there are just two fixed design values of $\beta$, $\beta_0 = 0.65$ and $\beta_0 = 1.0$, used in the low- and high-energy sections, respectively. For $\beta \neq \beta_0$, the effective voltage (seen by the beam) is reduced
owing to the non-nominal transit time. As a consequence,

\[
\left(\frac{R}{Q}\right) = \frac{(V_0T)^2}{\omega W}
\]  

(4.20)

is also reduced. One can appreciate these dependences by replacing \(V_{\text{acc}}\) with \(V_0T\) and \(R_{\text{ex}}\) with \((R/Q)Q_{\text{ex}}\) in Eq. (4.16). Hence the forward power can be written as

\[
P_{\text{for}} = 0.25 Q_{\text{ex}} \left(\frac{R}{Q}\right) \left(\frac{V_0T}{Q_{\text{ex}}(R/Q)} + I_{DC}\cos\phi_s\right)^2,
\]

(4.21)

where \((R/Q)\) is a function of \(T^2\).

### 4.6.1.1 Basic power requirements of SPL cavities

The cavity-powering requirements depend on the beam current and, for each cavity, the cavity voltage, the synchronous phase, the beam transit time, and the nominal beta, and also on the coupling factor, the optimum value of which is dependent on all the other factors.

Using the beam energy, the synchronous-phase settings, and the transit time factors for all cavities along the linac, we can calculate the peak effective cavity voltages at the nominal beta and the values of the forward power into the cavities, for both 20 mA and 40 mA operation. We have done this first for optimum matching, with each cavity at its own optimum coupler setting, or \(Q_{\text{ex}}\). The results are shown in Fig. 4.76.

![Fig. 4.76: Cavity voltages and basic beam power requirements for the HP-SPL and LP-SPL (with optimum coupling in each cavity).](image)

To obtain the above values, a different coupler setting would be needed for each cavity, requiring an adjustable power coupler, a complication best avoided. Hence all cavities within the same geometric-\(\beta\) family will most likely be set to the same value, incurring various degrees of penalty in the required forward power due to the mismatch. The possibility of arranging cavities in batches of different standard coupling values is looked at in the following section.

### 4.6.1.2 Cavity-powering overheads

A number of overheads must be taken into account when estimating the power that the RF power system needs to make available at the cavity coupler. These include the non-optimum coupling and a number of
other effects to be taken care of by the LLRF system, such as compensation of tuning-system errors and ponderomotive effects, phase errors, and system noise.

4.6.1.3 Non-ideal coupling for low-current (20 mA) operation

The most important factor contributing to the additional forward power for non-optimum coupling is the beam current. For the initial low-current (20 mA) operation of the LP-SPL, the HP-SPL high-current (40 mA) coupling settings will most likely be used, to avoid a major refit of all cavities to change the coupling when we move to the higher current. This power penalty can easily be calculated. If the matched value of the shunt resistance is \( R_{ex\, mh} \), which is optimum for a high beam current of \( I_{bh} \), and we operate with a lower beam current of \( I_{bl} \) (having a matched value of shunt resistance \( R_{ex\, ml} \)), the forward power will be

\[
P_{for} = 0.25 \, R_{ex\, mh} \left( \frac{V_0 T}{R_{ex\, mh}} + \frac{V_0 T}{R_{ex\, ml}} \right)^2.
\]

If we take the case where the SPL is matched for a current higher by a factor \( m \), then \( I_{bh} = m I_{bl} \); hence \( R_{ex\, mh} = R_{ex\, ml}/m \), and

\[
P_{for} = 0.25 (V_0 T)^2 \, R_{ex\, mh} \left( \frac{1}{R_{ex\, mh}} + \frac{1}{R_{ex\, ml}} \right)^2,
\]

and we obtain

\[
P_{for} = P_{for\, ml} \frac{(m + 1)^2}{m}.
\]

Hence, for 40 mA matching but with operation at 20 mA, we have \( m = 2 \) and there will be a 12.5% power overhead with respect to the optimum 20 mA matching for when the particle speed corresponds to the geometric beta of the cavities. This value can increase to up to 50% at the beginning of the medium- and high-\( \beta \) sections owing to the mismatched particle velocity. Figure 4.77 shows the high-current power requirements with optimum coupling of individual cavities and with a fixed value of the coupling for all cavities. Figure 4.78 shows the corresponding power requirements for low-current operation, assuming that the couplers are matched for high current.

![Figure 4.77: Cavity power requirements for high-current HP-SPL with optimum coupling and with a fixed value of \( Q_{ex} \).](image)
Figure 4.78: Cavity power requirements for low-current SPL with optimum coupler matching and for couplers with a fixed $Q_{ex} = 1.2 \times 10^6$, suited for high-current operation.

Figure 4.77 indicates that, for a constant current, there is no point in having adjustable couplers (or batches with different coupler settings) in order to better match the different cavity loads to the RF power sources. However, if the SPL is operated at the low current (20 mA) using couplers matched for the high current (40 mA), there is a difference in total power consumption of $\sim 17\%$, instead of the 12.5% calculated above. This is the result of the combined mismatch resulting from (i) having a mismatch due to a fixed coupler $Q$ for all cavities, and (ii) running at half the current. One approach to minimizing the reflected power in this condition is to use three-stub waveguide tuners to match the waveguide impedance to the cavity external $Q$s, but it needs to be verified that this does not lead to increased voltages in sensitive parts of the power coupler, for example around the ceramic windows.

Unless indicated otherwise, we assume in the following that the couplers are matched to the current in the SPL, meaning to either 20 or 40 mA.

### 4.6.2 General description and functionality of the LLRF system

The functionality of the SPL LLRF system will be very similar to the system for Linac4 currently being built at CERN [3]. In order to keep the cavities on tune, achieve the required field flatness in amplitude and phase in the presence of strong beam loading, and suppress the influence of high-voltage ripple and droop of the klystron modulator on the flatness of the RF pulse, the following loops are foreseen:

- a tuner loop to keep the cavities on tune using mechanical tuners and fast piezo elements;
- RF feedback and feedforward using the measured field in the cavities to regulate the drive signal to the power source in order to keep the field flat during the beam segment, in the presence of beam loading and during cavity filling; and
- an optional klystron polar loop which compensates for slow variations due to ripple and HV droop, taking the klystron forward power as input.

The low-level systems are complemented by limiting and interlock circuits for protection and to avoid driving the klystron into saturation, as well as a system for conditioning suited for superconducting cavities, similar to what has been developed for the LHC 400 MHz superconducting RF system. Distribution of the RF reference frequency can be done using a large coaxial cable with integrated couplers, as for Linac4 [116], or by optical fibre when, owing to the length of the accelerator and the frequency that needs to be distributed, the losses in a copper coaxial distribution system would become prohibitive. The choice will depend on the final length of the machine constructed, with a preference for distribution.
by copper coaxial cable if a reduced-length, lower-energy SPL is built in the initial stage. The reference distribution system can be upgraded to fibre when a full-length SPL is built.

![Figure 4.79: LLRF conceptual overview](image)

Figure 4.79 shows a possible architecture for the LLRF system. For each cavity, three RF signals are digitized, namely the cavity forward and cavity return (reflected) signals, both provided by a coupler, and a calibrated antenna signal for the cavity voltage. The cavity antenna signal is used in a feedback loop. The tune state (the detuning \( \Delta \omega \)) of the cavity can be computed from the amplitude and phase of the calibrated forward and cavity antenna signals, both with and without active driving of the cavity:

\[
\Delta \omega = \frac{d\phi_{\text{ANT}}}{dt} - \omega_{12} \frac{V_{\text{FWD}}}{V_{\text{ANT}}} \cdot \sin (\phi_{\text{FWD}} - \phi_{\text{ANT}}). \tag{4.26}
\]

The bandwidth \( \omega_{12} \) of the cavity is assumed to be known here. The computation of the tune state and the correction signal for the slow mechanical tuner (stepping motor), as well as the computation for pulse generation for the piezo tuner, is conveniently carried out in hardware with a floating-point dedicated digital signal processor (DSP), as has already been done for the PSB, LHC, and Linac4 LLRF systems. The simpler algorithms for the fast feedback loop are programmed on a field-programmable gate array (FPGA) dedicated to these fast loops. An additional input is foreseen for the klystron forward signal, permitting the optional implementation of a polar loop around the klystron. The proposed choices of frequencies, which were also used in the prototype system described in Section 4.6.3, are (for an RF frequency of 704.4 MHz) listed in Table 4.14.

| Reference and RF frequency | \( f_{\text{RF}} \) | = 704.4 MHz |
| Local-oscillator frequency | \( f_{\text{LO}} = (39/40)f_{\text{RF}} \) | = 686.8 MHz |
| Intermediate frequency | \( f_{\text{IF}} = f_{\text{RF}} - f_{\text{LO}} \) | = 17.61 MHz |
| Sampling frequency | \( f_{\text{S}} = f_{\text{RF}}/10 = 4f_{\text{IF}} \) | = 70.44 MHz |

121
Instead of using the analogue I/Q modulator used in the prototype system, the output digital–
analogue converters (DACs) can directly generate an intermediate frequency (IF) signal in I and Q, which can be summed and upconverted using the local oscillator (LO) to eliminate tedious adjustments of DC offsets in the output DACs. The proposed choices of sampling and intermediate frequencies are relatively low. It may be possible to profit from the latest developments in analogue–digital converters (ADCs) (and DACs) with higher sampling rates when the project is actually put into practice [117]. This would permit direct sampling of the RF, eliminating the analogue RF downconversion, as has been done for instance in the HIE-ISOLDE project.

For reasons of development costs and compactness during installation, we are interested in building the system with the minimum number of electronic circuit boards. For construction using a VME-based system similar to the latest generation of LLRF systems at CERN, it can be envisaged that we will have ADCs for a maximum of two cavities and one klystron on a single VME board, requiring eight RF channels for I/Q demodulation, accounted for by the RF reference, the klystron forward signal, and three RF signals per cavity. In this case the system for one RF station can be spread out over three VME boards, namely one analogue board, one digital board with an FPGA, and a DSP board, which may be based on commercially available hardware or derived from LLRF developments at CERN for ongoing projects. In a topology with more than two cavities per klystron, the functionality must be spread out over more boards, increasing the level of complexity of the connectivity. In this case, for each cavity, a mixed analogue board with digitization would be required, plus a digital board, a DSP board, and a separate board for generating the klystron drive signal. One more variant of VME board is therefore required in this case, with the connectivity being implemented with digital serial links between the boards. Such a system would be more complex, but also more modular and easier to adapt to changing requirements and topology (number of cavities per klystron).

### 4.6.3 Tests with a prototype LLRF system with a low-$\beta$ 704 MHz cavity and tuner

A particular difference between the superconducting cavities used in pulsed mode for the SPL and the normal-conducting structures for Linac4, also used in pulsed mode, is the sensitivity to Lorentz force detuning of the superconducting cavities during the RF pulse. The magnetic field of the stored electromagnetic energy in the cavity interacting with the surface currents exerts a force that detunes the cavity frequency by an amount that can be comparable to the bandwidth of the cavity resonance. While feedback systems can maintain the field flat when the cavity is off-tune under these conditions, significantly more power is required.

Therefore, fast piezoelectric tuners are commonly integrated into the mechanical tuning system of cavities, for example as developed for the XFEL project [118], and are planned to be used on a large number of cavities in this project. For the SPL cavities, these piezoelectric tuners offer the possibility to have an actuator for each cavity, enabling each cavity to be tuned independently even when several cavities are driven from a single RF power source. Together with optional, and difficult-to-construct, vector modulators they provide a means to cure control instabilities, as observed in simulations when several cavities are driven from the same power source. Vector modulators [119] at the required power levels in the range of 1 MW are difficult and costly to construct; consequently, R&D has been focused more recently on gaining experience with piezo tuners on a cavity at the SPL frequency of 704 MHz. In the framework of the EU FP7 programme, two medium-$\beta$ 704 MHz elliptical cavities with two different piezo tuners were available for testing at the nominal $Q_{ex}$. Within the same framework an experimental programme with these two cavities and tuners were carried out in a horizontal cryostat at CEA Saclay.

A prototype LLRF system [120] based on hardware from the LHC was modified for the SPL frequencies as described above and configured to acquire cavity forward, cavity reflected, and antenna signals for tests at CEA Saclay [121]. Piezo and tuner control signals and also RF and high-voltage pulses were generated by analogue function generators, triggered together in common with the LLRF acquisition system. The RF pulses were shaped to achieve a flat-topped pulse, for which, in the absence...
of beam loading in the test stand, the forward power had to be reduced to one quarter of the value used for filling the cavity. The RF pulse generation was done in open loop only. Tests with the LLRF system permitted us to compute fields in amplitude and phase—as required for a closed-loop feedback system—and to manually adjust the piezo pulses to achieve a plateau in the voltage that was as flat as possible after cavity filling. Different pulse repetition rates were used, up to the maximum rate of 50 Hz envisaged for the SPL. With 50 Hz pulsing, the mechanical oscillations of the cavity created by the preceding RF pulse were still present when a new pulse started, underlining the importance of adaptive piezo control for keeping the cavity on tune as best as possible and avoiding a build-up of mechanical oscillations from pulse to pulse. Such a build-up was not observed in the tests at CEA Saclay. The mechanical resonance frequencies were not a multiple of the repetition rate used. The test programme for the two cavities and tuners, built by INFN (Milan, Italy) and CEA Saclay, has been documented within the sLHCpp Project as part of EU FP7 [122].

![Figure 4.80: Comparison of a test pulse used with a medium-β cavity in the case of a high-power, high-current SPL pulse with the canonical values for a high-β cavity at the end of the accelerator with 1 MW forward power into the beam.](image)

Figure 4.80 (left) shows the test conditions for the CEA-built cavity in the horizontal cryostat when the gradient was pushed to the design value for this $\beta = 0.5$ cavity. The cavity gradient and forward power needed for the pulse in the test stand were computed and are displayed. This can be compared with the pulse needed for a $\beta = 1$ cavity at the high-energy end of the high-power, high-current option of the SPL, for which a short beam pulse of 0.4 ms, a beam current of 40 mA, and an RF power of 1 MW are used to achieve an accelerating voltage of 26.6 MV. In the ‘no beam’ case in the test stand, the forward power has to be dropped to one quarter of the value used for filling the cavity. An added difficulty in the test stand is that the klystron phase changes with output power. During the tests, the phase and amplitude of the klystron output were programmed (feedforward) to maintain a constant flat-top forward power at the correct phase.

For a 25 Hz pulse repetition frequency, Fig. 4.81 shows the results of measurements with the prototype LLRF system where the cavity voltage and the forward and reflected wave amplitudes were acquired without using piezo compensation of the Lorentz force detuning. The forward power visible after the RF pulse is caused mainly by a mismatch of the circulator output to the cavity, which results in power being reflected when the cavity field decays. The $Q_{ex}$ computed from the field decay in the cavity is $1.84 \times 10^6$.

Figure 4.82 shows the improvement obtained by using the piezo tuner, with pulsed excitation with an optimized trigger time and pulse shape, to maintain a constant field in phase and amplitude during the flat top. Without a closed feedback loop around the cavity during the flat top, the variation in the
amplitude is within 0.5% and the variation in the RF phase is limited to $\pm 10^\circ$. This demonstrates the excellent properties of the piezo tuner, which can hence be used in a feedforward manner to compensate for Lorentz force detuning and consequently minimize the power required when the feedback loop is closed around the cavity.

For 50 Hz pulsing, which was only achieved for short periods of time, mechanical resonances of the cavity persist between pulses, and the variations of the field in amplitude and phase caused by Lorentz force detuning are larger during the flat top. Nonetheless, it was possible to limit amplitude variations to less than 2% and phase variations to less than $\pm 20^\circ$ in this case [121].
4.6.4 RF system architecture

There are potential financial savings to be obtained from using a single large klystron for multiple cavities, associated with the cost of the klystron and the auxiliary equipment needed for it (HV modulator, power converters, controls). Ongoing linac projects with superconducting cavities which use highly relativistic electron beams, such as the XFEL, can profit fully from the advantages of multiple cavities per klystron. The task of controlling the field is more relaxed for this type of machine, firstly because the beam loading is usually smaller and secondly because, for ultrarelativistic beams, a downstream cavity can make up more easily for insufficient acceleration as the times of flight and arrival of the beam are close to independent of energy.

In a proton accelerator, in particular in the low- and medium-\(\beta\) sections, the arrival time of the beam in a cavity changes significantly with changes in the accelerating gradient in the upstream part of the accelerator, so that correct control of the field in each individual cavity becomes much more important. In order to provide fully independent control of the cavity fields in the low- and medium-\(\beta\) sections, it is strongly advised to use a single power source per cavity in this part of the accelerator.

For the high-\(\beta\) section, several different scenarios have been simulated with respect to the LLRF system and its capability to minimize the effects on the beam when the parameters of the cavities, operated from a single power source, are varied [123]. The following configurations were considered:
– one power source for a string of four cavities;
– one power source for two cavities;
– a single power source for each cavity.

Hardware requirements, costs, and operational issues will be compared in broad terms for each of these configurations. Note that in all options we assume the presence of a circulator near to the cavity to protect the RF power source.

A length of 80 m of WR850 waveguide from the surface-installed power sources to each cavity was assumed, with a loss of 4 mDB/m and a consequent 7% power loss, to be added to other waveguide system losses. In addition, we also assumed 3% circulator losses for each scenario. The LLRF system overheads are treated separately in Section 4.6.5.

4.6.4.1 Option 1: one power source per group of four cavities (not retained)

This option is shown in Fig. 4.83.

![Fig. 4.83: RF-powering layout option 1, with one power source for a unit of four cavities](image)

This layout appears attractive, mainly because of the economy of the reduced number of klystrons. A linear waveguide distribution, rather than symmetrical splitting with magic tees, takes up less space and uses ‘planar’ hybrids with individually adjusted coupling. Vector modulators for fast phase and amplitude control are needed for each cavity, however. A circulator is also needed in each cavity line to prevent reflected power feeding into neighbouring cavities, owing to mismatch and other imperfections in the waveguide system. Mechanically adjusted phase shifters are needed to bring the phase of the cavity drive to a value correctly inside the working range of the vector modulators. The disadvantages of this configuration are the complexity of the waveguide system, the complexity of the LLRF system, limited flexibility, and generally poorer overall fault tolerance than for other configurations. A single, very large klystron modulator is also required. Even without having a cost estimate for each of the components, we consider that the saving obtained from the use of a single klystron will be more than offset by the cost of the vector modulators and their waveguide connections.
**Power overheads.** We assume a 10% power loss in the waveguides and circulator and another 5% for the system components, not counting the vector modulators, for which we take an additional 3%, making a total of 18%. In addition, a further 10% increase in installed RF power is needed to provide an operating margin for the vector modulators, leading to 28% (plus LLRF overheads) overall. The increased operating and installed power required for the vector modulators is a serious disadvantage for this option.

### 4.6.4.2 Options 2a and b: one power source for each pair of cavities

This option is shown in Fig. 4.84.

![RF-powering layout option 2a, with one power source for each pair of cavities](image)

This configuration uses hybrids, vector modulators, and mechanical phase shifters. It is similar to option 1, but with two power sources per unit of four cavities. Fault tolerance and operating flexibility are improved, but the disadvantages of using vector modulators remain. The cost and complexity of the waveguide system are reduced compared with option 1, but there is increased cost for the additional klystrons.

**Power overheads.** We assume a 10% power loss in the waveguides and circulators and another 3% for the system components, not counting the vector modulators, for which we again take an additional 3%, making a total of 16%. In addition, a further 10% increase in installed RF power is needed to provide an operating margin for the vector modulators, leading to 26% overall. The increased operating and installed power required for the vector modulators is again a serious disadvantage for this option.

An important saving can be made in this configuration by eliminating the vector modulators, using three-stub waveguide tuners to match the waveguide system to the differences in $Q_{ex}$ between the individual cavities. This layout is shown as option 2b in Fig. 4.85. This is the preferred option for the low-current HP-SPL and the LP-SPL. Note, however, that it will probably require fast piezo tuners in the cavities—see the simulation results presented in the following section. Another very important advantage of this layout is that there is the potential to use the stubs to adapt the power couplers to differ-
ent operating currents. This would eliminate the power overhead associated with operating mismatched couplers (e.g., 17% of the power (compare Section 4.6.1.2) when the high-current (40 mA) optimum coupling is used in a low-current SPL (20 mA)). This option, however, has to be studied in order to make sure that standing waves between the stub tuners and the power coupler do not limit the performance of the couplers.

Fig. 4.85: RF-powering layout option 2b, with one power source for each pair of cavities, but using three-stub waveguide tuners. Preferred option for LP-SPL.

Power overheads. Again we assume a 10% power loss in the waveguides and circulators, with 3% in the rest of the waveguide system, including the three-stub tuners, and no increase in installed power as there are no vector modulators in the waveguide system, leading to 13% (plus LLRF overheads) overall.

4.6.4.3 Option 3: one power source for each cavity
This option is shown in Fig. 4.86.

This configuration requires no hybrids, no vector modulators, and no mechanical phase shifters. It does, of course, require a total of 240 klystrons. Nevertheless, it offers complete flexibility, needs the least power to operate, and needs only a very simple LLRF system. Piezo tuners are not essential, but their absence would require additional power as the RF feedback would have to compensate for the effects of slower and less efficient tuning. The power economy, flexibility, and fault tolerance compared with the two previous options make the option of a single klystron per cavity the preferred one for the high-current (40 mA) HP-SPL. Additionally, upgrading from one klystron for two cavities in the low-current (20 mA) HP-SPL to one klystron for each cavity in the high-current (40 mA) HP-SPL can be done with the minimum of layout changes, by simply doubling up with additional klystrons of the same type. Nevertheless, a certain amount of waveguide material will not be needed any more. A decision on whether to keep the three-stub waveguide tuners if an upgrade from option 2b is done and even about whether to add additional ones could be made depending on experience with low-current operation. The cost is certainly more than that of a two-cavity-per-source solution, but if the construction scenario is to
go from the low-current LP-SPL to the high-current HP-SPL this will be more than covered by the re-use of the klystrons. A summary of the power overheads for all options is given in Table 4.15.

**Power overheads.** We assume 10% for the waveguides and circulators (plus LLRF overheads) and no other installed power overhead.

**Table 4.15:** RF system power overheads for the different powering schemes (excluding LLRF)

<table>
<thead>
<tr>
<th>Units</th>
<th>Option 4</th>
<th>Option 2a</th>
<th>Option 2b</th>
<th>Option 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide losses</td>
<td>%</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Circulator</td>
<td>%</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>System components</td>
<td>%</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Vector modulators</td>
<td>%</td>
<td>3</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>Operating margin</td>
<td>%</td>
<td>10</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>%</td>
<td>29</td>
<td>27</td>
<td>13</td>
</tr>
</tbody>
</table>

* a Chosen for LP-SPL and low-current HP-SPL.
* b Chosen for high-current HP-SPL.

### 4.6.5 LLRF power overheads

The options retained are those of two cavities per klystron for low-current operation of the LP-SPL or HP-SPL and a single cavity per klystron for high-current operation of the HP-SPL. These configurations are suitable for demonstrating some of the fundamental issues related to operation with multiple cavities per klystron, as will be described in the following.

The coupling is adjusted to maintain a constant forward power during cavity filling and during the beam segment. If all parameters are adjusted correctly, good stability of the RF field during the beam
segment is possible even without feedback, as has also been shown in the tests carried out at CEA Saclay (see Section 4.6.3). The role of the RF feedback (and feedforward) techniques is to maintain a field that is as flat as possible in amplitude and phase, with a specification of $\pm 0.5\%$ permitted deviation in amplitude and $\pm 0.5^\circ$ in phase during the beam segment in the presence of perturbations and deviations from the ideal case. The important deviations and perturbations are:

- varying beam current during the pulse;
- non-optimal coupling ($Q_{ex}$), i.e., an unmatched cavity;
- non-optimal resonant frequency and changes in resonant frequency during the beam pulse (Lorentz force detuning).

Feedback can keep the field constant in the presence of these deviations and perturbations, but at the cost of excess power from the source, which must be available even if it is only required for brief moments at the start of the beam pulse, at the closure of loops, or at the end of the beam pulse. Spikes are expected during closure of the feedback loops at the start of ramping of the field.

Table 4.16 shows some of the key simulation parameters. Note that the feedback loop delay of 5 $\mu$s easily permits the accommodation of the expected delay estimated from the delay budget in Table 4.17, assuming a distance of 80 m between the LLRF system and the cavities. The feedback loop bandwidth of 100 kHz has been shown to be sufficient to maintain good field flatness.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lorentz force detuning</td>
<td>$k_L$</td>
</tr>
<tr>
<td>Lorentz force time constant</td>
<td>$\tau$</td>
</tr>
<tr>
<td>Feedback loop delay</td>
<td>5 $\mu$s</td>
</tr>
<tr>
<td>Feedback bandwidth</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

Table 4.17: Tentative group delay budget (ns)

<table>
<thead>
<tr>
<th>Component</th>
<th>Delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron</td>
<td>250</td>
</tr>
<tr>
<td>80 m waveguides (WR1150)</td>
<td>360</td>
</tr>
<tr>
<td>80 m cabling (0.9 velocity factor)</td>
<td>270</td>
</tr>
<tr>
<td>Driver amplifier</td>
<td>40</td>
</tr>
<tr>
<td>Waveguide components (circulator, etc.)</td>
<td>40</td>
</tr>
<tr>
<td>Local cabling (LLRF to klystrons, etc.)</td>
<td>50</td>
</tr>
<tr>
<td>LLRF latency</td>
<td>250</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1260</strong></td>
</tr>
</tbody>
</table>

In order to have some operational margin, we estimate that the saturated power of the klystron should be around 10% higher (15% in the medium-$\beta$ section) than what is required in Table 4.18. Therefore a klystron with 1.42 MW saturated power would be required for the operation of two high-$\beta$ cavities with one klystron. The reactive beam loading can be compensated by statically detuning the cavity. However, this changes the conditions for the ramp-up of the field and must be considered not only from the point of view of power saving but also with respect to added complexity.

### 4.6.6 RF power sources

The choice of power sources includes klystrons, inductive output tubes (IOTs), solid state amplifiers, and magnetrons.
Table 4.18: Estimation of peak power needs for operation of one cavity (1 MW, 40 mA) or two cavities (2 × 500 kW, 20 mA) from a single klystron.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>1 cavity/klystron</th>
<th>2 cavities/klystron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power minimum at cavity input kW</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Mismatched coupler kW</td>
<td></td>
<td>(166)(^a)</td>
<td></td>
</tr>
<tr>
<td>Reactive beam-loading reserve kW</td>
<td>20</td>
<td>2 × 10</td>
<td></td>
</tr>
<tr>
<td>Detuning reserve (Lorentz force + microphonics) kW</td>
<td>20</td>
<td>2 × 10</td>
<td></td>
</tr>
<tr>
<td>Transients for loops kW</td>
<td>50</td>
<td>2 × 25</td>
<td></td>
</tr>
<tr>
<td>Variation in Q(_L) kW</td>
<td>15</td>
<td>2 × 7.5</td>
<td></td>
</tr>
<tr>
<td>Variation in cavity parameters kW</td>
<td>15</td>
<td>2 × 7.5</td>
<td></td>
</tr>
<tr>
<td>Beam current fluctuations kW</td>
<td>40</td>
<td>2 × 20</td>
<td></td>
</tr>
<tr>
<td>RF transport losses (see Table 4.15) kW</td>
<td>100</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Klystron output power kW</td>
<td>1260</td>
<td>1290</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Not counted, since we assume that the couplers are matched to 40 or 20 mA operation, respectively.

4.6.6.1 Comparison of devices

High-power klystrons at the frequency of interest are available from industry and are already in use in test stands at Saclay and CERN. Klystrons, however, have relatively low efficiency, need very high DC voltages, and are subject to voltage-dependent phase shifts due to the transit time of the beam from cathode to collector.

IOTs are presently limited to much lower powers than those needed for the SPL, less than 100 kW, their main application being in the domain of TV transmission. Nevertheless, manufacturers are looking at developing multibeam IOTs in the range of several hundreds of kilowatts at 700 MHz; 600 kW is already considered feasible. The efficiency of IOTs is expected to be higher, reaching 75% compared with the 60–65% maximum attainable from klystrons (in saturation). Multibeam IOTs operate at a lower DC voltage, of the order of 40 kV, which avoids the need for the HV circuit elements to be in oil—avoiding the associated fire and safety hazards and reliability issues. IOTs are shorter in length, and hence give less transit time delay and resulting phase shifts than those that have to be dealt with for klystrons. The lifetime of high-power IOTs is expected to be about the same as for klystrons. IOTs, however, have only about 20 dB of gain, compared with the 35 dB of klystrons, and need significantly more drive power, which increases the complexity and cost of the system. The drive characteristic of an IOT saturates towards the maximum output power and does not become negative as does that of a klystron, considerably simplifying the drive control and LLRF systems.

Solid state amplifiers, built up from many kilowatt or sub-kilowatt modules, offer modularity, ease of configuration, and straightforward low-voltage DC powering. However, combination of the RF outputs of many small modules is a challenge, although several viable solutions are being developed [125]. Efficiency is also a challenge, and water cooling may be required. The power-to-volume ratio overall is probably better than for IOT- or klystron-based amplifiers, making a future retrofit a viable option in the RF system designs should the technology develop to higher power in the foreseeable future.

Magnetrons have also been proposed as power sources for superconducting cavities. Promising results have been achieved at 2.45 GHz with an injection-locked CW magnetron [126]. The potential advantages are high efficiency, small size, and low cost. However, when pulsing on the order of milliseconds is used, as in the SPL, maintaining phase and amplitude control requires a relatively sophisticated LLRF system and special shaping of the power pulse, which may be expensive in view of the high power levels.
4.6.6.2 Availability and cost of devices

Over recent years, close discussions have taken place with manufacturers of RF power sources. Initial tentative information has been gathered on the commercial feasibility of alternative solutions to klystrons and on their cost. Development programmes are being initiated with industry. For this report, however, we have retained the use of klystrons.

4.6.6.3 High-power RF system for the LP-SPL

The preferred RF layout for the LP-SPL is option 2b, which has two cavities per klystron and a three-stub waveguide tuner for each cavity. The assumed RF power overhead required to compensate for waveguide system losses and LLRF overheads is taken from Table 4.18. In order to stay sufficiently below saturation of the klystrons, we have added a margin of 15% for the medium-β section and 10% for the high-β section. These values then give the power ratings for the klystrons shown in Fig. 4.87.

For cavities 1–60 (medium-β section), klystrons with a power rating of 800 kW can be used, and then 1.45 MW klystrons are needed for the remainder. If there are no losses caused by mismatched couplers, the power ratings can be dropped to the values for the HP-SPL as described in the following.

4.6.6.4 High-power RF system for the HP-SPL

The preferred RF layout for the high-current HP-SPL is option 3, a single cavity per klystron. The assumed RF power overheads are again taken from Table 4.18. As with the low-current version of the SPL, for cavities 1-60 klystrons with a power rating of 800 kW can be used, one per cavity, and then 1.45 MW klystrons are needed for each cavity of the remainder. The power values are such that the upgrade from the LP-SPL to the HP-SPL is essentially a doubling-up of the klystrons with additional ones of the same rating (or slightly lower), going from two cavities per klystron to one.

![Fig. 4.87: Overall power requirements and klystron ratings for low-current and high-current SPL with feedback margins and RF power system losses included.](image)

4.6.7 Klystron modulators

A summary of the parameters used for the assessment of the LP-SPL and HP-SPL powering using klystrons is given in Table 4.19. As a reminder, the klystrons are voltage modulated to limit power dissipation when operation is not required.

As can be seen in Table 4.19, the power required for the high-current HP version is greater than 10 times the power required for the low-current LP version. Hence, equipment optimized for HP operation
Table 4.19: Parameters for klystron modulators for low-current, low-power and high-current, high-power operation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>LP-SPL, 20 mA</th>
<th>HP-SPL, 20 mA</th>
<th>HP-SPL, 40 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron $P_{\text{peak, out}}$</td>
<td>kW</td>
<td>800</td>
<td>1450</td>
<td>800</td>
</tr>
<tr>
<td>Klystron efficiency</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Klystron $V_{\text{cath}}$</td>
<td>kV</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Klystron $P_{\text{peak, in}}$</td>
<td>kW</td>
<td>1600</td>
<td>1900</td>
<td>1600</td>
</tr>
<tr>
<td>Cavity $t_{\text{fill, total}}$</td>
<td>µs</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Beam $t_{\text{pulse}}$</td>
<td>µs</td>
<td>900</td>
<td>900</td>
<td>800</td>
</tr>
<tr>
<td>Modulator $t_{\text{rise}}$</td>
<td>µs</td>
<td>160</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td>Modulator $t_{\text{pulse, total}}$</td>
<td>µs</td>
<td>1860</td>
<td>1855</td>
<td>1745</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>2</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Klystron $P_{\text{av, in}}$</td>
<td>kW</td>
<td>5.8</td>
<td>10.3</td>
<td>136</td>
</tr>
<tr>
<td>No. of klystrons</td>
<td></td>
<td>30</td>
<td>72</td>
<td>60</td>
</tr>
</tbody>
</table>

Note: Counting 78.5% of the modulator rise time at full power.

The parameters and technology choices for the modulator powering in such a linac are driven by maintenance and availability criteria. We make the conservative assumption that operation will still be allowed with up to two klystrons missing. Assuming 244 klystrons running 24 h per day, every 7 days a total of $41 \times 10^3$ klystron operating hours are accumulated. Provided the modulators are designed for easy maintenance and access and replacement if required, a reasonable MTBF design criterion of $50 \times 10^3$ h will result on average in $\sim 1$ modulator failure per week. If a modulator takes 24 h to be repaired or replaced, a modulator availability of 99.94% is assured.

Based on the above criteria, several long-pulse modulator topologies either found in the technical literature or proposed by commercial manufacturers should be capable of meeting the requirements. Care would be needed about certain requirements such as ease of maintenance and AC power quality; however, these remain the domain of engineering development and not fundamental R&D. A suitable prototyping and qualification phase before the start of production would permit the selection of the most appropriate technological solution.

The key technical requirements for the modulators are summarized in Table 4.20, assuming conventional pulse parameters (such as those used in Linac4, for example). The rise time, which has to be added to the RF pulse length when the power consumption of the RF system is calculated, is calculated as follows. We assume an exponential curve for the rise of the output power, which has a time constant corresponding to $\sim 2\%$ of the total RF pulse length (filling time plus beam pulse length):

$$P_m(t) = P_m \text{max} \left(1 - e^{t/\tau}\right), \quad \text{where} \quad \tau = 0.02 \cdot t_{\text{RF on}}. \quad (4.27)$$

The rise time values in Table 4.19 were calculated on the assumption that the RF input signal for the klystron is switched on when the modulator has reached 99% of its nominal DC voltage.

Powering of multiple klystrons from each modulator will introduce some cost savings and better...
Table 4.20: Klystron modulator requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>LP-SPL, 20 mA</th>
<th>HP-SPL, 20 mA</th>
<th>HP-SPL, 40 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOT $P_{\text{peak, out}}$</td>
<td>kW</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>IOT efficiency</td>
<td>%</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>IOT V</td>
<td>kV</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>IOT $P_{\text{peak, in}}$</td>
<td>kW</td>
<td>1140</td>
<td>1140</td>
<td>1140</td>
</tr>
<tr>
<td>Cavity $t_{\text{fill, total}}$</td>
<td>µs</td>
<td>800</td>
<td>800</td>
<td>400</td>
</tr>
<tr>
<td>Beam $t_{\text{pulse}}$</td>
<td>µs</td>
<td>900</td>
<td>800</td>
<td>400</td>
</tr>
<tr>
<td>Modulator $t_{\text{rise}}$</td>
<td>µs</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total $t_{\text{pulse}}$</td>
<td>µs</td>
<td>1710</td>
<td>1610</td>
<td>810</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>2</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>IOT $P_{\text{av., in}}$</td>
<td>kW</td>
<td>3.9</td>
<td>91.8</td>
<td>46.2</td>
</tr>
<tr>
<td>No. of IOTs</td>
<td></td>
<td>30</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

The relative complexity of an IOT modulator can be equated to ‘half a klystron modulator’. The simplest approach would be to implement a controlled capacitor charger. This would, however, result in a large stored energy (see Table 4.22) that would require careful management, both for safety reasons...
Table 4.22: IOT powering requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse rise and settling time</td>
<td>10 µs</td>
</tr>
<tr>
<td>Pulse flat-top performance</td>
<td>1%</td>
</tr>
<tr>
<td>Pulse reproducibility</td>
<td>0.1%</td>
</tr>
<tr>
<td>Modulator electrical efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Arc maximum energy</td>
<td>10 J</td>
</tr>
<tr>
<td>Mean time between failures</td>
<td>$50 \times 10^3$ h</td>
</tr>
</tbody>
</table>

and to limit the energy in the case of IOT arcing (using a series- or parallel-connected crowbar). The rise time would be limited mainly by the parasitic inductances between the modulator and the IOT anode.

4.7 Cryogenics

4.7.1 Cryomodules and machine architecture

Machine architecture and integration studies done for the SPL at CERN, featuring 60 $\beta = 0.65$ cavities and 184 $\beta = 1$ cavities in an SRF linac about 500 m long, have led to the choice of housing eight $\beta = 1$ cavities in stand-alone cryomodules, individually connected to a cryogenic distribution line cryostat running parallel to the linac (see Fig. 4.88). As previously mentioned, a comparative analysis of a segmented version and a continuous-cryostat version, as adopted for longer machines such as the XFEL and the ILC, was done and was the subject of a workshop. The advantages of a fully segmented machine were decisive, leading to the choice of stand-alone cryomodule units housing only cavities, while the magnets will be warm and will be placed between the cryomodules in inter-cryomodule spaces. As a consequence, the cryomodules feature two cryostat end closures, equipped with cold-to-warm transitions for the beam tube, as well as a connection to the cryogenic distribution line for the feeding of helium at cryogenic temperatures.

![Fig. 4.88: Layout (top view) of an SPL cryomodule for $\beta = 1$ cavities](image)

Considering that in the initial R&D phase, owing to budget constraints, only four out of the eight $\beta = 1$ cavities would be constructed, and considering the need to test them in a string as they would operate in a machine-type cryomodule, a half-length cryomodule, the so-called ‘short cryomodule’ [127], was designed and is being constructed. This cryomodule, which will serve primarily as a test bench for
RF testing of the cavities, powered by specifically developed RF couplers, will also provide an opportunity to develop an initial prototype of a machine-type unit for the SPL or for a similar high-power proton driver. For this reason, the cryomodule was designed under the constraint of being compatible with a full-size unit housing eight cavities. The cryomodule was designed for the $\beta = 1$ cavities, according to the main parameters listed in Table 4.23.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>$\beta = 0.65$</th>
<th>$\beta = 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gradient</td>
<td>MV/m</td>
<td>19.3</td>
<td>25</td>
</tr>
<tr>
<td>Quality factor $Q_0$ (worst case)$^a$</td>
<td>$10^9$</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>$(R/Q)$ (worst case)</td>
<td>$\Omega$</td>
<td>275</td>
<td>566</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>$K$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cryogenic duty cycle (worst case)$^b$</td>
<td>%</td>
<td>8.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Dynamic heat load</td>
<td>W</td>
<td>18.3</td>
<td>20.7</td>
</tr>
<tr>
<td>Cavity alignment (transverse), r.m.s.</td>
<td>mm</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.3$</td>
</tr>
</tbody>
</table>

$^a$ Assuming 50% of the nominal value.

$^b$ Assuming low-current (20 mA) HP-SPL operation.

4.7.2 Description of the SPL short cryomodule

A detailed view of the short cryomodule [127] is illustrated in Fig. 4.89. The design of the cryomodule was done in collaboration with the French institute CNRS-IPN, Orsay.

The cryomodule contains four bulk niobium 704 MHz cavities, each housed independently in a stainless steel helium tank designed to match the tuning requirements when CEA Saclay lever-arm-type tuners are used.

The fixed RF coaxial coupler, with a single ceramic window, providing 100 kW average power (1 MW peak), is mounted onto the cavity via a ConFlat™ flange assembly equipped with a special vacuum/RF seal, designed at CERN and widely used in cryomodules in other machines (including the LHC). The single window of the RF coupler requires that it is mounted as a whole onto the cavity in the
clean room, constraining by its large radial size the subsequent assembly activities of the cryomodule. For this reason, the vacuum vessel was designed in two parts, to allow vertical assembly of the string inside the vessel.

4.7.2.1 Cavity-supporting system

An innovative cavity-supporting concept [128] has been proposed for the SPL cryomodule, where the double-walled tube of the RF coupler is also used as the main mechanical support for the dressed cavities, as illustrated in Fig. 4.90. With the aim of minimizing the static heat load from room temperature to 2 K by solid thermal conduction, the number of mechanical elements between the two extreme temperatures has been reduced to a strict minimum: the cavities are supported directly via the external conductor of the RF coupler, the double-walled tube (DWT) [129]. The latter is made out of a stainless steel tube with an internal diameter of 100 mm, which is actively cooled by gaseous helium circulating inside a double-walled envelope in order to improve thermal efficiency. An additional supporting point to keep the straightness and alignment stability of the cavities within requirements is obtained by supporting each cavity on an adjacent one via an inter-cavity support, which is composed of a stem sliding inside a spherical bearing. As a result, a pure vertical supporting force is exchanged by adjacent cavities, whereas all other degrees of freedom remain unrestrained, allowing thermal-contraction movements to occur unhindered. Since this inter-cavity support connects bodies at the same temperature, no additional conduction paths are created. Although the double-walled tube alone can withstand the mechanical load of the cavity/helium vessel/tuner assembly, the inter-cavity support keeps the vertical straightness within acceptable limits (on the order of 0.1 mm), as illustrated in Fig. 4.91.

Fig. 4.90: Cross-sectional view of the SPL cryomodule

Fig. 4.91: Vertical sag due to self-weight with inter-cavity supports (sketched on one cavity only). The displacements are amplified by a factor of 200. Maximum value (in blue) 0.09 mm. (Finite element calculations using Ansys™.)
In order to enhance the thermal performance of the supporting system, efficient vapour cooling of the double-walled tube of the RF coupler is employed between 4.5 and 300 K. A flow regulation valve and an electrical heater on the warm side of the double-walled tube are needed for control reasons, depending on the operation of the RF coupler (Fig. 4.92).

![Vacuum-vessel-power-coupler interface](image)

**Fig. 4.92:** Cavity/helium vessel assembly, supported by an actively cooled RF coupler

Table 4.24 illustrates the mass flow and heater power settings when the RF coupler is powered and when it is not, and the residual heat load at 2 K.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow</td>
<td>mg/s</td>
<td>42</td>
</tr>
<tr>
<td>RF power</td>
<td>–</td>
<td>ON OFF</td>
</tr>
<tr>
<td>Temperature of gas out</td>
<td>K</td>
<td>232 180</td>
</tr>
<tr>
<td>Thermal load at 2 K</td>
<td>W</td>
<td>0.1 0.1</td>
</tr>
<tr>
<td>Heater power</td>
<td>W</td>
<td>46 44</td>
</tr>
</tbody>
</table>

### 4.7.2.2 Thermal shielding and multilayer insulation system

The thermal shield is made of rolled aluminium sheets, and is composed of four main parts assembled before the vertical insertion of the string of cavities: two half-shells mounted around the string of cavities and two closure parts at its two extremities. The shield is suspended from the vacuum vessel via adjustable tie rods made of titanium alloy, which can also cope, by angular movements, with thermal contraction of the vessel. The absence of mechanical contact between the shield and the string of cavities eliminates the risk of interference with the alignment of the cavities induced by differential contraction and cooling transients.

The thermal shield is actively cooled to about 50 K via an aluminium cryogenic cooling line of 15 mm internal diameter. The same line ensures intermediate cooling of the two cold-to-warm transitions of the beam tube at the cryostat’s extremities. A 30-layer multilayer insulation system (MLI) prefabricated blanket, of the same technology as that developed for the LHC superconducting-magnet cryostats, protects the thermal shield, and 10-layer blankets are mounted around each helium vessel.

### 4.7.2.3 Magnetic shielding

The cavities are protected by individual magnetic shields made of 2 mm thick Cryoperm™ sheets. The shields are made of two half-shells mounted around the helium tank and fixed to it on the tuner side. Simulations have confirmed the effectiveness of the shielding, which keeps the penetration of the Earth’s magnetic field into the cavity region to within $\sim 1 \, \mu T$. 

138
4.7.2.4 Cryogenic scheme and piping

The cavities are housed in individual stainless steel helium tanks, connected by a 100 mm-diameter two-phase pipe placed above the cavities. This pipe ensures the feeding of liquid to the cavities by gravity, and is also used as a pumping line for gaseous helium. A saturated helium bath at 31 mbar maintains the operating temperature of the cavities at 2 K. Helium vapour is pumped along the two-phase pipe and through a phase separator reservoir of 5 l capacity, which collects the excess liquid helium and houses a superconducting liquid level gauge for the purpose of cryogenic operation and control. Subcooled liquid helium, previously expanded through Joule–Thomson valves, is supplied to the two-phase tube through 10 mm capillaries (one for each cavity) and routed along the two-phase pipe. The cavities are also equipped with one additional 6 mm capillary each (also routed along the two-phase pipe), for effective cooling down and warming up of the cavities. The double-walled tubes of the RF couplers are cooled by a parallel circuit of 6 mm diameter pipes feeding 4.5 K helium vapour. The vapour is warmed up to room temperature before being recovered outside the vacuum vessel, where individual mass flow regulation is made possible by regulation valves.

This cryogenic scheme, illustrated in Fig. 4.93, offers operational flexibility and redundancy for cavity filling and level control, as shown by the individual cavity-filling valves and level sensors, making it an ideal test bench for exploring various operational scenarios, including the simplest machine-type scheme, where it is proposed to fill from one single point at one extremity of the bi-phase tube, and control the He level in the phase separator only. The entire cryomodule can be inclined longitudinally by up to about 2%, which will allow investigation of cryogenic operation for machines in a sloping tunnel, as is foreseen for the SPL at CERN. The cryomodule will have a single thermal shield, cooled by a dedicated circuit at around 50 K.

4.7.2.5 Vacuum vessel

For reasons of compactness and ease of assembly of the string of cavities inside the cryomodule, the vacuum vessel (shown in Fig. 4.94) has been designed in two parts, a main 10 mm-thick bottom part and a 6 mm-thick top cover. The bottom part of the vessel supports the cavities via adjustable flanged interfaces to the double-walled tube of the RF coupler, and the top cover is closed at the very end of the cryomodule assembly process. This allows the possibility of checking the alignment of the cavities with optical devices (laser trackers, for example) while making fine adjustments through the adjustable flanges. The top cover is closed onto the bottom part via a flanged assembly; a 10 mm diameter O-ring seal keeps the leak-tightness to better than $10^{-8}$ mbar/l/s in an insulation vacuum of $10^{-6}$ mbar.

The vacuum vessel has a number of ports mounted on it, which serve for routing instrumentation and for interfacing vacuum and cryogenic equipment (pumps, He level gauges), as well as overpressure safety devices (burst discs for the cryogenic circuit and a safety relief plate for the insulation vacuum). Apart from the main flanges and ports, which are made from AISI 304L stainless steel, the vessel is made from low-carbon steel in order to provide a first level of magnetic shielding of the cavities against external fields.

This design concept was chosen while keeping in mind that it could be extended to a full-size eight-cavity cryomodule, which will be roughly twice the length of the short cryomodule.

4.7.2.6 Cryomodule assembly

The assembly of the cryomodule is composed of two distinct parts, the first part being one in which the string of cavities is put together, which will take place in a class ISO 4 clean room in Building 2173 (SM18). The second part will be the assembly of the string of cavities in the cryostat together with all the related ancillaries (tuners, magnetic and thermal shielding, cryogenic circuitry and instrumentation, etc.). This activity will take place in Building 3173 (SMA18). The assembled cryomodule will then be ready for moving back to Building 2173, where the RF test bunker is located. Figure 4.95 illustrates, in
Fig. 4.93: Cryogenic scheme for the short cryomodule

Fig. 4.94: View of the two-part vacuum vessel
SUPERCONDUCTING LINAC

a bird’s-eye view, the buildings foreseen for these activities at CERN.

Fig. 4.95: Bird’s-eye view of the cryomodule assembly and test facilities at CERN

4.7.2.6.1 Assembly of cavities in clean room

Figure 4.96 illustrates the layout of the CERN clean room in SM18 where the string of cavities is to be assembled, which has recently been refurbished to comply with the required gradients of 25 MV/m. The clean-room enclosure also contains an HPR machine, which is essential for the processing of the cavities and related components.

Fig. 4.96: View of the clean-room facility at CERN (SM18)

The assembly of the string of cavities consists essentially of the assembly of each cavity (previously housed in a helium vessel) with its main RF coupler, mounting of gate valves with cold-to-warm transitions on the end cavities, and finally connecting the cavities to each other via inter-cavity bellows.
Figure 4.97 illustrates the sequence of operations. Once the string of cavities has been leak-checked and sealed, it can exit the clean room and pass on to the cryostat assembly phase.

4.7.2.6.2 Cryostat assembly

The string of cavities is subsequently taken from the exit platform of the clean room by means of a special girder and moved to SMA18. The same girder is also used as the main element of the cryostat assembly tooling, as illustrated in Fig. 4.98.

The individual cavities in the string are aligned with respect to an ideal beam line. The main assembly steps which follow are:

- mounting of the tuners and the inter-cavity supports;
- mounting of MLI blankets on the helium vessels;
- mounting of the cryogenic piping (bi-phase tube, phase separator, cooling lines, etc.);
- mounting of magnetic shields;
- mounting of the thermal shields and MLI blankets;
- mounting of instrumentation.

When the equipped string is ready, the bottom part of the vacuum vessel can be lifted to match the interface flanges of the double-walled tubes, which are then fixed and allow load transfer from the assembly tooling to the vacuum vessel. At this stage of the assembly process, the alignment of the cavities can still be checked thanks to the open top of the vessel, which allows a survey of cavity-mounted reference targets. A final adjustment of the alignment can be done by adjusting the screws of the vacuum vessel interface flanges. Finally, the top lid of the vacuum vessel can be closed and clamped. Vacuum tightness is ensured by an elastomeric O-ring. Final acceptance tests will be carried out at room temperature before the cryomodule is declared ready for transport to the RF test bunker.
4.7.2.7 Cryomodule heat loads

Estimates of the static and dynamic heat loads for a four-cavity short cryomodule are given in Table 4.25. The residual resistance at the surface of the cavities yields the dominant contribution to the 2 K heating, with a value of $\sim 20$ W per cavity. For this estimate, we have taken the maximum expected heat load using (i) a scenario with the maximum pulse length (low-current HP-SPL), resulting in a cryogenic duty cycle of 8.22%, and (ii) assuming half the nominal $Q_0$ of $5 \times 10^9$ instead of $1 \times 10^{10}$. The remaining contributions, mostly static heat loads, account for less than 10% of the total at 2 K. The total heat load of about 95 W at 2 K is equivalent to a mass flow of about 4.5 g/s of helium vapour in the two-phase line. The 50 K-level circuit collects about 50 W from the two cold-to-warm transitions of the beam tubes and heating of the thermal shield by radiation.

Finally, the active cooling of the double-walled tubes of the RF couplers, with the nominal RF power, requires a 4.5 K helium mass flow of 42 mg/s per coupler, i.e., 168 mg/s in total, to which 40 mg/s for a similar actively cooled support of the phase separator has to be added.

Extrapolating to a full-size eight-cavity cryomodule simply by rescaling with respect to length (taking twice the length) and doubling the number of cavities yields the heat loads for a high-beta cryomodule listed in Table 4.26.

For the installed capacity, we applied an overcapacity factor of 1.5 for the static load. The dynamic load has already been calculated assuming the worst-case scenario, which consists of having half the nominal $Q$-value and of using the low-current, long-pulse option for the HP-SPL. This means that if the HP-SPL is operated with a high current (and short pulses) and the nominal $Q$-values of the cavities are achieved, the cryogenic system has four times more capacity than is needed to cover the dynamic load. Before construction, these numbers should be adapted to the actual needs and adjusted according to test experience. Table 4.27 summarizes the heat loads and the installed capacity.
Table 4.25: Static\(^a\) and dynamic heat loads for four-cavity high-\(\beta\) cryomodule

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>2 K (W)</th>
<th>4.5–300 K (mg/s)</th>
<th>50 K (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cold-to-warm transitions</td>
<td>~2</td>
<td>~15</td>
<td>~15</td>
</tr>
<tr>
<td>4 RF coupler DWTs</td>
<td>&lt;1</td>
<td>168</td>
<td>~168</td>
</tr>
<tr>
<td>1 phase separator support</td>
<td>&lt;0.5</td>
<td>40</td>
<td>~40</td>
</tr>
<tr>
<td>Thermal radiation to thermal shield</td>
<td>~1.5</td>
<td>~35</td>
<td>~35</td>
</tr>
<tr>
<td>Total static</td>
<td>~5</td>
<td>208</td>
<td>~50</td>
</tr>
<tr>
<td>4 cavities, RF power</td>
<td>82.4</td>
<td>~85</td>
<td>~85</td>
</tr>
<tr>
<td>8 HOM couplers</td>
<td>&lt;1</td>
<td>~85</td>
<td>~85</td>
</tr>
<tr>
<td>Beam loss (1 W/m)</td>
<td>7.3</td>
<td>~85</td>
<td>~85</td>
</tr>
<tr>
<td>Total dynamic</td>
<td>90.7</td>
<td>~85</td>
<td>~85</td>
</tr>
<tr>
<td>Total</td>
<td>~95.7</td>
<td>208</td>
<td>~50</td>
</tr>
</tbody>
</table>

\(^a\) No contingency, and excluding instrumentation-induced heat loads.

Table 4.26: Static\(^a\) and dynamic heat loads for a three-cavity medium-\(\beta\) cryomodule and an eight-cavity high-\(\beta\) cryomodule of the low-current HP-SPL, in watts per module.

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>2 K (W)</th>
<th>4.5–300 K (mg/s)</th>
<th>50 K (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity (\beta)</td>
<td>0.65 (W)</td>
<td>1.0 (W)</td>
<td>0.65 (W)</td>
</tr>
<tr>
<td>2 cold-to-warm transitions</td>
<td>~2</td>
<td>~2</td>
<td>~166</td>
</tr>
<tr>
<td>3 or 8 RF coupler DWTs</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>126</td>
</tr>
<tr>
<td>1 phase separator support</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>40</td>
</tr>
<tr>
<td>Thermal radiation to thermal shield</td>
<td>~1</td>
<td>~3</td>
<td>~25</td>
</tr>
<tr>
<td>Total static</td>
<td>~4.5</td>
<td>~7.5</td>
<td>166</td>
</tr>
<tr>
<td>3 or 6 cavities, RF power</td>
<td>53.4</td>
<td>164.8</td>
<td>~187.6</td>
</tr>
<tr>
<td>6 or 16 HOM couplers</td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>~187.6</td>
</tr>
<tr>
<td>Beam loss (1 W/m)</td>
<td>4.7</td>
<td>13.3</td>
<td>~187.6</td>
</tr>
<tr>
<td>Total dynamic</td>
<td>59.1</td>
<td>180.1</td>
<td>~187.6</td>
</tr>
<tr>
<td>Total</td>
<td>~63.6</td>
<td>~187.6</td>
<td>166</td>
</tr>
</tbody>
</table>

\(^a\) No contingency, and excluding instrumentation-induced heat loads.

4.7.3 Cryogenic layout and infrastructure for the SPL

The general cryogenic layout already presented in the 2006 report [2] remains a valid option (see Fig. 4.99). This consists of three cryogenic strings, one for the medium-beta cavities (20 cryomodules, with an approximate length of 130 m) and two the for high-beta cavities (23 cryomodules in total, with an approximate length of 370 m). A single cryogenic plant, placed at one extremity of the SPL, distributes helium to the individual cryomodules via a distribution line which runs along the cryomodules. The intermediate thermal screens are cooled in series (lines C–D and E–F in Fig. 4.99). The cooling at 2 K is supplied in parallel. The cavities are immersed in a saturated superfluid helium bath filled through a 2 K two-phase header by gravity. The saturated 2 K helium is produced by expansion of subcooled liquid (line A) through a Joule–Thomson valve. At the interconnections in each cryomodule, the two-phase header is connected to the pumping return line (line B).

Power conversion factors from thermal to electric loads were taken from recent LHC experience [130], and these values are considered to be state of the art. A summary is presented in Table 4.28.
Table 4.27: Total heat loads and installed capacity for the low-current HP-SPL (static heat loads multiplied by 1.5).

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>2 K (W)</th>
<th>4.5–300 K (W)</th>
<th>50 K (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>263</td>
<td>12 g/s</td>
<td>2755</td>
</tr>
<tr>
<td>Expected dynamic, high-current HP-SPL</td>
<td>1647</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Expected dynamic, low-current HP-SPL</td>
<td>2871</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Worst-case dynamic, low-current HP-SPL</td>
<td>5319</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Installed capacity</td>
<td>5712</td>
<td>18 g/s</td>
<td>4132</td>
</tr>
<tr>
<td>Equivalent at 4.5 K</td>
<td>26930</td>
<td>1800 W</td>
<td>304</td>
</tr>
<tr>
<td>Total installed at 4.5 K</td>
<td>29.0 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical plug power, compressors</td>
<td>7.2 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ 1 g/s = 100 W equivalent heat load at 4.5 K.

Table 4.28: Electrical power needed to cool 1 W (thermal) at cryogenic temperature [130]

<table>
<thead>
<tr>
<th>Cryogenic temperature</th>
<th>$P_{el}/P_{th}$</th>
<th>Carnot efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 K</td>
<td>990 W/W</td>
<td>~15%</td>
</tr>
<tr>
<td>4.5 K</td>
<td>210 W/W</td>
<td>~30%</td>
</tr>
<tr>
<td>50 K</td>
<td>16 W/W</td>
<td>~30%</td>
</tr>
</tbody>
</table>

4.7.4 Cryogenic system

The SPL cryogenic system is based on that of the ILC. The same working principles and process layout have been used. However, the description presented here does not include all of the technical parameters.
which need to be addressed for a detailed technical design.

The cold boxes will be placed in a dedicated building close to the centre of the superconducting section. A standard CERN metallic wall construction of approximately 1000 m$^2$ is foreseen (Building SDH). This will contain two cold boxes, electrical and controls cabinets, and some additional space for unloading. A composite cryogenic distribution line is required to link the cold boxes to the cryomodule lines at the higher end of the superconducting linac section. This connection requires a special shaft.

For the compressor, a standard CERN concrete wall construction of about 1650 m$^2$ is foreseen (Building SH). This contains screw compressors with their oil removal systems (oil separator, coalescers, and charcoal adsorber), as well as electrical substations, instrumentation air production, and some free space for unloading, spare parts storage, and working space.

Assuming a maximum cryogenic duty cycle of 8.4% and a power factor of 210 W/W at 4.5 K, the electrical input power is about 6.1 MW, or 7.2 MW when the electrical efficiency of the compressors is taken into account. For the design of the cooling-water capacity required, a value equal to the nominal power consumption is assumed, i.e., 6.1 MW. This covers the needs of the compressors and the cold boxes. The ventilation required for the compressor building will be about 4% of the nominal power consumption, i.e., 244 kW.

### 4.8 Power consumption and scope for savings

#### 4.8.1 Power consumption with present assumptions

The overall power consumption of a 4 MW SPL is estimated to be around 40 MW (see Table 4.29).

**Table 4.29:** Electrical power requirements of the SPL (r.m.s. values, installed capacity/expected consumption)

<table>
<thead>
<tr>
<th>Load</th>
<th>LP-SPL, 20 mA (MW)</th>
<th>HP-SPL, 20 mA (MW)</th>
<th>HP-SPL, 40 mA (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF system</td>
<td>2.04</td>
<td>26.5</td>
<td>26.1</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>1.34</td>
<td>7.2/4.3</td>
<td>7.2/2.9</td>
</tr>
<tr>
<td>Cooling and ventilation</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.38</strong></td>
<td><strong>41.7/38.8</strong></td>
<td><strong>41.3/37</strong></td>
</tr>
</tbody>
</table>

#### 4.8.2 RF power generation

Though very reliable in operation, present-day klystrons have two big disadvantages when used in $\beta < 1$ hadron accelerators. (i) Owing to the precise phase adjustment requirements, the klystrons need to work below their saturation point, so that the LLRF system can make phase and amplitude adjustments. This means, however, that the efficiency of the klystrons drops from the catalogue values of around 60–70%, which are quoted at saturation, to values of around 50%. (ii) The klystron modulators (pulsed HV and pulsed current) themselves have a considerable rise time, which for the SPL is expected to be on the order of 75–150 μs (for high-current or low-current operation) and to have an exponential power profile during that time. Even though this value can certainly be optimized, an IOT-type power supply (lower DC voltage, pulsed current) needs only 10 μs rise/settling time. For the SPL, using IOTs is being considered in the medium-energy part, where the power per cavity is lower than in the high-energy part. For this purpose, CERN is collaborating with the European Spallation Source (ESS) in an R&D project on high-power IOTs [131].
4.8.3 Dissipated power in cavities

Pulsed operation incurs some inevitable losses, which are linked to the repeated filling and emptying of the superconducting cavities [132]. Figure 4.100 shows typical curves for the reflected voltage and ‘wasted’ power during this process.

![Graph showing reflected voltage and power during charging, matched operation, and discharging of a cavity.]

Fig. 4.100: Reflected voltage and power during charging, matched operation, and discharging of a cavity

The RF duty cycle takes into account the filling and steady-state periods of each pulse plus the rise time of the modulator. For the cryogenic duty cycle, one has to consider the filling, steady-state, and decay times. In summary, we obtain the duty cycles listed in Table 4.30.

<table>
<thead>
<tr>
<th>Operation</th>
<th>RF duty cycle (%)</th>
<th>Cryogenic duty cycle</th>
<th>Beam duty cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP-SPL, low-current, $\beta = 0.65$</td>
<td>0.36</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>LP-SPL, low-current, $\beta = 1.0$</td>
<td>0.36</td>
<td>0.35</td>
<td>0.18</td>
</tr>
<tr>
<td>HP-SPL, low-current, $\beta = 0.65$</td>
<td>4.3</td>
<td>4.2</td>
<td>4.0</td>
</tr>
<tr>
<td>HP-SPL, low-current, $\beta = 1.0$</td>
<td>4.2</td>
<td>4.1</td>
<td>4.0</td>
</tr>
<tr>
<td>HP-SPL, high-current, $\beta = 0.65$</td>
<td>8.5</td>
<td>8.4</td>
<td>2.0</td>
</tr>
<tr>
<td>HP-SPL, high-current, $\beta = 1.0$</td>
<td>8.4</td>
<td>8.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

During the time when there is field in the cavities, the dissipated power is given by

$$P_d = \frac{V_{acc}^2}{(R/Q)Q_0}.$$  

(4.28)

The dissipated power represents a thermal heat load at 2 K and, according to Table 4.28, each thermal watt at 2 K will incur $\sim 1$ kW of electrical power. There are two options to reduce the dissipated power: (i) reducing the accelerating voltage $V_{acc}$ or (ii) increasing the quality factor $Q_0$ of the cavities. Both options are discussed in the following.

4.8.3.1 Reducing the accelerating voltage

Reducing the accelerating voltage yields a quadratic reduction of the dissipated power per cavity. However, if one keeps the final energy, beam power, and beam pulse structure constant, then the number of cavities (and RF power sources) has to be increased. Apart from reducing the dissipated power, a smaller accelerating gradient also reduces the filling time of the cavities, which is given by

$$\tau_l = \frac{Q_l}{\omega_0} \approx \frac{V_{acc}}{\omega_0(R/Q)I_{beam} \cos \phi}.$$  

(4.29)
Taking account of both effects together and also taking into account static heat loads, modulator rise time, etc., we obtain the curves in Fig. 4.101 for variation of the maximum accelerating gradient between 12 and 38 MV/m. For example, a 20% reduction in the accelerating gradient from 25 to 20 MV/m would increase the number of cavities from 244 to 305 and lengthen the SPL from 500.5 to 616.5 m. At the same time, the total power consumption of the RF system (including cryogenics) would decrease by \( \sim 10\% \).

**Fig. 4.101:** Linac length and RF and cryogenic power consumption versus maximum accelerating gradient at \( \beta_{\text{geom}} = 1 \).

### 4.8.3.2 Increasing the quality factor

Recent results at FNAL [133] using high-temperature baking with nitrogen gas have raised hopes for increased \( Q_0 \) values. If the test results can be reproduced, there seems to be the potential to increase the \( Q_0 \) of the SPL cavities by a factor of 2–7, even at the nominal gradient of 25 MV/m. Although still to be demonstrated in working accelerators, these numbers would enable high-duty-cycle or even CW superconducting linacs with high gradients. Nevertheless, for pulsed operation, the problem of ‘wasting’ RF power during the filling time will remain and will even become worse if higher accelerating gradients become technically feasible.

### 4.8.3.3 Summary

Table 4.31 summarizes the options for potential power savings. The biggest impact would come from high-efficiency RF sources, and R&D in this field is highly recommended. The second highest impact would come from high-\( Q \) cavities, a technology that already seems within reach. Further improvements can be made by improving on any of the efficiencies which have been used in the present study, which are summarized in Table 4.32.

In view of the prospect of achieving higher \( Q \)-values in the near future, substantial savings in the initial investment could be made by running CW with smaller beam currents. This would bring the power per cavity into the range of tens of kilowatts, meaning that one can consider high-efficiency IOTs or solid state amplifiers. Depending on the \( Q \)-values which can be achieved, one may have to consider lengthening the linac in order to reduce the cryogenic losses due to high accelerating gradients.
Table 4.31: Summary of measures to increase power efficiency

<table>
<thead>
<tr>
<th>Measure</th>
<th>Power-saving potential</th>
<th>Disadvantage</th>
<th>SPL case</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Q research</td>
<td>50–90% of cryogenic electrical power</td>
<td>–</td>
<td>−4.3 MW</td>
</tr>
<tr>
<td>Lower $V_{acc}$</td>
<td>10% power saving for 20% lower gradient</td>
<td>20% longer and costlier linac</td>
<td>−3.3 MW</td>
</tr>
<tr>
<td>IOTs in medium-β section</td>
<td>70% IOT efficiency instead of 50% klystron efficiency and reduced modulator rise time</td>
<td>R&amp;D needed</td>
<td>−1.1 MW</td>
</tr>
<tr>
<td>High-efficiency RF source in high-β section</td>
<td>70% efficiency RF source with short rise time</td>
<td>Heavy R&amp;D</td>
<td>−7.4 MW</td>
</tr>
<tr>
<td>Combining high-Q cavities and high-efficiency RF sources</td>
<td></td>
<td></td>
<td>−12.8 MW</td>
</tr>
</tbody>
</table>

Table 4.32: Efficiencies used in this study

<table>
<thead>
<tr>
<th>Item</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron efficiency (at working point)</td>
<td>0.5</td>
</tr>
<tr>
<td>IOT efficiency</td>
<td>0.7</td>
</tr>
<tr>
<td>Waveguide transmission (surface to tunnel)</td>
<td>0.93</td>
</tr>
<tr>
<td>Splitting network to feed two cavities from one klystron</td>
<td>0.97</td>
</tr>
<tr>
<td>LLRF active overhead</td>
<td>0.86</td>
</tr>
<tr>
<td>Cryocompressor</td>
<td>0.85</td>
</tr>
<tr>
<td>Klystron modulator electric efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Klystron modulator rise time</td>
<td>75–150 μs</td>
</tr>
<tr>
<td>IOT rise time</td>
<td>10 μs</td>
</tr>
<tr>
<td>Klystron static DC power needs</td>
<td>7.05 kW</td>
</tr>
</tbody>
</table>

4.9 Safety considerations for beam dumps for the SPL

4.9.1 Introduction

In a high-energy particle accelerator, a beam dump serves the purpose of absorbing—in a controlled manner—the power of a beam of particles which is of no further use. A beam dump may be located after an interaction point of the beam with a target, or in an auxiliary beam line into which the beam is diverted. The design of the beam dump must ensure the physical integrity of the dump at the beam energies and intensities to be employed, and ensure protection of workers, the public and the environment from the detrimental effects of ionizing radiation emerging from the beam dump. Only the second aspect is treated in detail in this section.

Two beam dumps were studied within the SPL project: a set-up beam dump, which could be used to absorb a low-intensity beam from the SPL for the purposes of commissioning and annual set-up, and an injection beam dump for the charge-exchange injection into the PS2 synchrotron, to absorb the fraction of the beam (5%) which is not captured in the synchrotron orbit. It turns out that identical designs of the beam dump can fulfil the safety requirements for both purposes.

In Section 4.9.2, the particle beams to be absorbed and their physical parameters are described. Section 4.9.3 gives a description of the beam dump, and Section 4.9.4 shows its impact on the safety of workers, the public, and the environment.
4.9.2 Parameters of dumped negative hydrogen ion beams

The SPL will produce high-intensity \( \text{H}^- \) beams with energies between 4 and 5 GeV. The full intensity of these beams, or a fraction thereof, must be safely disposed of under several different circumstances:

- Set-up of the SPL while the facilities downstream of it are not yet ready (this also applies to the period of commissioning).
- Disposal of the neutral and negatively charged portions of the beam upon injection into the PS2 synchrotron.
- Emergency abort of a beam if a problem occurs in one of the facilities downstream of the SPL.

The physical parameters of the beams for the set-up dump [134] and the injection dump [135] are given in Table 4.33. The case of the emergency abort dump is covered by the set-up dump; we observe that the full-power beam would have a higher intensity than the set-up beam, but that in an emergency situation, the source would be turned off and only a very few bunches would have to be absorbed by the dump.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set-up dump</th>
<th>PS2 injection dump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy ( E ) (GeV)</td>
<td>4–5</td>
<td>4</td>
</tr>
<tr>
<td>Particles per pulse</td>
<td>( 1.5 \times 10^{14} )</td>
<td>( 0.05 \times 1.5 \times 10^{14} )</td>
</tr>
<tr>
<td>Repetition frequency ( f ) (Hz)</td>
<td>0.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Instantaneous beam power ( P ) (kW)</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Particles total (commissioning)</td>
<td>( 10^{20} )</td>
<td>–</td>
</tr>
<tr>
<td>Particles per year (set-up)</td>
<td>( 2.5 \times 10^{19} )</td>
<td>( 10^{19} ) (^a)</td>
</tr>
<tr>
<td>Particles per year (routine operation)</td>
<td>–</td>
<td>( 5.4 \times 10^{19} )</td>
</tr>
</tbody>
</table>

\(^a\) Figure includes annual set-up and set-up after foil change.

For the purposes of safety considerations, both (i) the instantaneous energy and intensity of the beam at the dump and (ii) the total energy deposited are of interest. The first parameter determines the instantaneous intensity of secondary radiation emerging from the dump, and the second parameter is required to estimate long-term effects such as activation of material (both in the accelerator and in the environment) and the ambient radiation dose rate from the activated material once the accelerator has stopped operating.

The figures given in Table 4.33 show that the total beam loads on the two types of beam dumps are similar within a factor of 3 for the different modes of operation (commissioning, set-up, and routine operation). At this preliminary stage of the design, the same dump design can be used for all of these modes to explore the implications for safety of such a beam dump.

4.9.3 Generic design of an SPL beam dump

The generic design of the set-up dump and the injection dump is based on a concept from the Fermilab ‘Project X’ [136]. This is a study of a high-intensity \( \text{H}^- \) injector accelerator, working at a beam energy \( E \) of 8 GeV. Behind the injection chicane into the synchrotron, the neutral and negatively ionized fractions of the beam must be absorbed in an injection dump. During operation, the average beam power \( P \) of the particles to be dumped amounts to 6.5 kW. The dump consists of a layered core made from tungsten and graphite layers, surrounded by a water-cooled aluminium sleeve and a tungsten absorber. This core is inserted into a steel block for radiation attenuation. The steel block is covered with a 20 cm thick concrete layer. The purpose of the concrete is to partly protect personnel from the decay radiation from
the activated iron shield. In a secondary particle cascade from accelerated protons, concrete becomes less activated than steel or iron, per unit volume, and its activation products decay more rapidly.

For the beam parameters of the SPL (Table 4.33), it is possible to:

- shorten the length of the dump core (because of the lower beam energy);
- reduce the size of the iron shield (because of the lower beam intensity).

The overall layered design of the dump was preserved, as was much as the 0.2 m thick concrete liner around it. The SPL dump has a footprint of 3.4 m long by 2 m wide at a height of 2 m. Figure 4.102 shows a schematic view of the dump core of the original Project X design, and Figure 4.103 shows the adaptation to the SPL.

As noted above, this study focuses on the radiation safety aspects of the dump. Consequently, the heat deposition in the dump core and the cooling necessary to remove the heat were not modelled.

![Axial Symmetric Model of Beam Absorber](http://example.com/figure.png)

**Fig. 4.102:** Dump core for an 8 GeV, 6.5 kW H⁻ injection dump for Project X at Fermilab [137]

### 4.9.4 Impact on radiation safety of the SPL and PS2 dumps

The SPL and PS2 injection dumps are subject to bombardment by high-energy H⁻ ions, leading to the following radiation effects:

- generation of stray radiation in the form of a secondary radiation cascade;
- activation of the dump material and irradiation of personnel working close to the dump location after the accelerator is shut down;
- activation of earth and groundwater, leading to an impact on the environment.

In this study, the activation of air by the secondary radiation cascade during dump operation was not considered. This is justifiable if the dump shielding is designed to contain most of the energy of the secondary radiation cascade. In this case, the cascade would activate air to a lesser degree than, for example, an uncontrolled beam loss point at an arbitrary, unshielded location in the accelerator.
To assess the various hazards from ionizing radiation, a model of the dump and its surroundings (underground tunnel wall, earth coverage) was created in the FLUKA 2008 Monte Carlo radiation transport code [138, 139]. The FLUKA code allows one to estimate particle fluences of secondary radiation cascades and the associated parameters of interest for radiation protection, such as the ambient dose equivalent $H^*(10)$ and the concentration of radionuclides from activation reactions. In a second step, the intensity of decay radiation from activation products can also be estimated. The code has been benchmarked in many circumstances. The estimation of activation and decay has been benchmarked for radionuclides of comparatively short half-life (less than 1 year) [140]. In all simulations, $\text{H}^-$ ions were replaced by protons, which cause the same radiation effects.

4.9.4.1 Stray radiation

Stray radiation from the dump is of interest for the lifetime of electronics installed in the dump’s vicinity. Figure 4.104 shows a two-dimensional representation of the absorbed dose rate $D$ for standard operation conditions of the SPL dump ($1.5 \times 10^{14}$ ppp at $f = 0.1$ Hz). The absorbed dose rate at a distance of 1 m from the dump in the upstream direction amounts to 1 Gy h$^{-1}$. Highly integrated electronic devices may show more rapid ageing if installed in this location. This coarse estimate shows that the effects of radiation on electronics must be studied in greater detail, also taking into account other estimators of the radiation field such as the neutron fluence equivalent and the fluence of high-energy hadrons.

The SPL dump will be located under a roundabout on the public road from Meyrin in Switzerland to Saint-Genis-Pouilly in France (Fig. 4.105). This place cannot be fenced off, and the dose rate limit for an area accessible to the public must be respected. This limit is fixed at 0.5 µSv h$^{-1}$, which can be relaxed to 2.5 µSv h$^{-1}$ because the zone is not permanently occupied.

To assess the attenuation of stray radiation from the dump, the ambient dose equivalent rate $H^*(10)$ [141] was scored as a function of the depth underground (Fig. 4.106). As expected, the dose rate decreases exponentially in the shielding material, more rapidly in concrete ($\varrho = 2.3 \text{ g cm}^{-3}$) than in earth (in this model, $\varrho = 2.0 \text{ g cm}^{-3}$). The dose rate decreases by a factor of 10 every metre, and for the attenuation to exceed the dose rate criterion above, an earth coverage of at least 7 m is necessary.

4.9.4.2 Activation of the dump

The PS2 injection dump would be placed rather close to the injection chicane and the stripping foils which convert $\text{H}^-$ ions into protons. This equipment requires periodic maintenance during accelerator shutdowns, and workers must not be exposed excessively to radiation coming from the activated beam dump. An estimation of the radiation levels in the vicinity of the dump has been done with the FLUKA
**Fig. 4.104**: Two-dimensional plot of absorbed dose rate $D$ in air for standard operation conditions of the SPL dump ($1.5 \times 10^{13}$ particles s$^{-1}$). To speed up the calculation, the dump and the tunnel were assumed to have cylindrical symmetry around the beam axis, and only one half of the dump and the tunnel is shown in the figure.

2008 Monte Carlo code [142]. Irradiation of the beam dump during 10 years of operation was simulated, assuming $6.4 \times 10^{19}$ protons impinging on the dump for 8 months, followed by a shutdown 4 months long. For a waiting time of 8 days after the last 8 month run, Fig. 4.107 shows a two-dimensional representation of the ambient dose rate $H^*(10)$ from the activation products in the dump.

With the exception of the face at the beam entrance, the ambient dose rate is lower than 10 $\mu$Sv h$^{-1}$. This means that the beam dump will contribute a negligible amount to the dose rate that personnel working on the injection septum will be exposed to.
**Fig. 4.106:** Attenuation of ambient dose equivalent rate $H^*(10)$ in the tunnel wall and earth coverage over the SPL dump.

**Fig. 4.107:** Two-dimensional plot of ambient dose rate $H^*(10)$ in the vicinity of the PS2 injection dump after 10 years of operation and 8 days of waiting time.

### 4.9.4.3 Impact on the environment

The stray radiation emerging from the dump will activate the dump, the ground, and the groundwater surrounding the dump’s location. The estimates presented here follow the approach described in Ref. [143].
Using the same numerical model as in Section 4.9.4.1, the activation of the ground passed through by the secondary radiation has been simulated. The radionuclides of highest interest are \(^{3}\)H (tritium) and \(^{22}\)Na, because they have a significant half-life and they are soluble in groundwater and could be carried into drinking-water reservoirs. Figure 4.108 shows the estimated activation profile, i.e., the concentrations of these two radionuclides as a function of depth in the ground. It was assumed that \(2.5 \times 10^{19}\) protons would hit the dump each year. One can immediately recognize an exponential decrease with increasing distance from the source. One can also observe that the reduction factor of the activity is approximately \(10 \text{ m}^{-1}\). This is not surprising, and reflects only the fact that the activation is produced by interactions with the secondary radiation cascade, the fluence of which decreases according to the same function.

![Saturation activation profiles of the two most important water-soluble radionuclides in the ground](image)

Fig. 4.108: Saturation activation profiles of the two most important water-soluble radionuclides in the ground

The calculation was performed for saturation, when the rates of production and radioactive decay of a specific isotope balance each other. This occurs only after many half-lives of the radionuclide, and the values presented in Fig. 4.108 can be considered as conservative.

From the saturation activity concentrations and the solubility of the two species, one can estimate that the groundwater would contain up to \(2.4 \text{ kBq l}^{-1}\) of \(^{3}\)H and \(100 \text{ Bq l}^{-1}\) of \(^{22}\)Na. In spite of the lower absolute value, the \(^{22}\)Na content of groundwater would make it unfit for human consumption. This is of little concern, as there are no important aquifers close to the CERN site. Rainwater may wash out radionuclides from the ground and then penetrate into the underground tunnels. In this case, the concentration of \(^{22}\)Na in the water ingress would mean that it would have to be treated as radioactive waste. However, the estimated activity concentration is only a factor of 3 higher than the limit. This factor is easily covered by the numerous conservatism contained in the model. Should a large quantity of water ingress into a tunnel, it is recommended to periodically sample and check for residues of activity before releasing it.

4.9.5 Summary and conclusions

In this work, a generic design for a set-up dump for the SPL and for the injection dump into the PS2 synchrotron has been presented. The design is based on a similar dump for Project X at Fermilab. The design does not consider the heat load on the absorber and its removal by active or passive cooling. The following parameters of interest for radiation safety were treated:

- \textit{Stray radiation}. During operation, the absorbed dose rate in the vicinity of the dump may attain values of 1 Gy h\(^{-1}\) or more. Such a radiation level may degrade highly integrated electronic devices. Additional studies, including also the radiation field parameters of neutron equivalent fluence and high-energy hadron fluence, are necessary. The stray radiation from the dump that
penetrates the covering earth and emerges in areas accessible to the public is negligible for an earth cover of 7 m or more.

– *Activation of the dump.* The design of the dump has been optimized to protect personnel working in its vicinity during accelerator shutdowns. An ambient dose rate equivalent of not more than $10 \, \mu\text{Sv} \, \text{h}^{-1}$ at the surface of the dump is obtained after a waiting time of 8 days after stopping the accelerator; only on the beam entrance side may the dose rate attain higher values.

– *Activation of soil and groundwater.* Stray radiation emerging from the dump penetrates into the ground and activates the soil. The two radionuclides $^3\text{H}$ and $^{22}\text{Na}$ are soluble in water and may be transported by groundwater to drinking-water supplies. This is of no concern at CERN, as no drinking water is sourced close to the Meyrin site. Groundwater entering tunnels should be sampled for residual activity before releasing it.

The layout of the beam dump presented here is a starting point for a more detailed design study. The findings and the methods developed can be readily applied to other high-intensity proton accelerators in the energy range between 2 and 5 GeV, for example the linear accelerator at the ESS in Lund, Sweden.
Chapter 5

Layout and Infrastructure

5.1 Depth and slope of the SPL tunnel

The SPL footprint has already been presented in Fig. 1.1. This is the result of a careful study of the underground situation at the CERN Meyrin site. The slope of the SPL tunnel results from three existing civil engineering works that needed to be taken into account: the computer centre (Building 513), the nTOF target area, and the TI2 beam line, which brings protons from the SPS to the LHC. The positions of these elements along the SPL beam line are indicated in Fig. 5.1.

![Fig. 5.1: SPL footprint with elements constraining the slope of the linac](image)

The computer centre is and must remain a non-designated area concerning radiation protection. This requires shielding with about 7 m of earth to absorb radiation resulting from accidental beam loss in the SPL. Figure 5.2 shows an elevation indicating possible vertical positions of the SPL tunnel and klystron gallery relative to the slab of Building 513. As this building is only 80 m away from Linac4, this constraint fixes the altitude of Linac4, which is slightly lower than the PS complex and is the origin of the 3.5 m vertical step in the transfer line from Linac4 to the PS Booster.

The nTOF target area is close to the midpoint of the SPL. This is a highly activated area, and we want to avoid any interference between the nTOF and SPL facilities during the whole of their con-
struction, operation, and maintenance phases. This again requires a certain minimum amount of earth shielding, and the distances indicated in the elevation in Fig. 5.3 ensure that it will be possible to access the klystron gallery when the nTOF target is receiving $7 \times 10^{12}$ protons per pulse at an energy of 20 GeV and a frequency of 0.33 Hz. One can also note on this elevation that there are other underground civil engineering works constraining the position of the SPL tunnel.

Fig. 5.3: Elevation of nTOF target area (384 m from end of Linac4)
At the end of the SPL, the TI2 transfer tunnel that feeds the clockwise-circulating beam of the LHC has to be crossed from above. Here also we want to avoid interference between different facilities, and the corresponding shielding is achieved with 8 m of earth, as indicated in the elevation in Fig. 5.4.

These obstacles along the SPL beam line strongly constrain the position of the SPL tunnel and lead to the 1.7% slope indicated in Fig. 5.5. The transfer line to PS2 has a much steeper slope of 8.4% in order to reach the SPS level.

5.2 SPL layout and dimensions

Several types of cryostat assemblies were considered. Finally, a ‘mixed’ configuration (see Section 4.2.2.2) was considered, with independent modules consisting of:

- warm quadrupoles and three cavities in the medium-β part;
- warm quadrupoles and eight cavities in the high-β part.

This configuration leads to the overall layout dimensions reported in Table 2.1 and Fig. 5.6.
A compact version was also envisaged, where sequences of magnets and cavities would be installed in common cryostats as sketched in Fig. 5.7. In this case, the total length of the 5 GeV High-Power SPL is 42.24 m less than that obtained with separate cryomodules.

Despite the moderately higher cost due to the increased length, the segmented approach with warm quadrupoles appears most efficient for the installation, operation, and maintenance of the SPL. The magnet and cavity layout in the medium-\(\beta\) and high-\(\beta\) sections is described in Fig. 5.8, and the total length of the 5 GeV High-Power SPL becomes 529 m if one includes two cryomodules for debunching.

5.3 Infrastructure for RF powering

Space is required alongside the linac tunnel to host the services, powering, and control systems required to run the SPL components. The cavity-powering system (modulators and klystrons) is the most demanding in terms of space. In the medium-\(\beta\) section, IOTs could provide the RF power (one IOT per cavity), and this results in a quite compact system. However, the high-\(\beta\) section requires much more power, and this can only be achieved with klystrons: the HP-SPL would require one klystron per cavity (or per two cavities; see Section 4.6). Considering the state of the art, a modulator able to produce the power needed for one cavity in the high-\(\beta\) section has a footprint of some 10 m\(^2\). We would need more than 200 of
those and, if they were hosted in an underground gallery, the corresponding civil engineering work would need to have already been completed at the start of the project. This led us to study the installation of the RF powering of the high-$\beta$ section in surface buildings: these could be extended according to the power requirements, and also taking account of the evolution of powering techniques. As the medium-$\beta$ section is located under the computer centre, an underground service gallery appears unavoidable here, with a diameter in the 6–7 m range as indicated in Fig. 5.9.

![Fig. 5.9: Preliminary integration of the control and powering systems in a service gallery alongside the medium-$\beta$ section, with a diameter of 6 m.](image)

In the high-$\beta$ section, shafts 2.8 m in diameter could bring 16 waveguides to the surface, which corresponds to the RF powering of two modules. Figure 5.10 illustrates how the network of waveguides could be arranged in such a configuration. We would need 12 shafts to cover the entire high-$\beta$ section. The positions of these shafts need to take account of the existing infrastructure on the CERN Meyrin site, and the ISR tunnel plays a role as can be seen in the elevation in Fig. 5.11: in this area, the shafts would be located on the right side of the SPL tunnel when looking downstream. The longest waveguide would serve to power the cavity that was furthest away from the deepest shaft:

- Its routing in the surface building hosting the klystron ($\sim$200 m$^2$) would be some 15 m long.
- It would then go down a shaft that would be about 35 m deep at the high-energy end.
- It would pass along a horizontal gallery, which would be about 10 m long.
- It would run alongside a full module, which would be 14 m long in the high-$\beta$ section.
- We should also foresee some length for a proper arrangement of the waveguide network; some 6 m seems realistic, considering that there would be five or six bends.

So, in total, waveguide lengths of about 80 m have to be considered.
Replaced by waveguides coming from the surface

Shaft, $\beta = 2.8$ m for 16 waveguides

$\beta = 1$ section

$\beta = 0.65$ section

Fig. 5.10: Preliminary study of routing of the waveguides to the surface in the high-$\beta$ section
Fig. 5.11: Elevation in the ISR area (410 m from end of Linac4). The red dashed lines indicate the location of the waveguide shafts.
5.4 Access to the SPL underground areas

Access to the underground areas, for personnel and for materials, also needs to be considered. A service lift located at the end of the klystron gallery in the medium-$\beta$ section could accommodate both personnel and materials. A large shaft is required to lower the cryomodules and the machine elements: it could be elliptical, of the same type as the PMI2 shaft used to lower the LHC cryomagnets, which are of similar length to the eight-cavity high-$\beta$ modules. This shaft could also be used for the services (EL power and fluids); it would then be best located close to the middle of the SPL tunnel. Finally, we need to ensure that there are safety exits to escape through in case of accident: corresponding personnel passages and shafts are foreseen at the extremities of the SPL. The complete pattern of underground civil engineering work related to the SPL is shown in Fig. 5.12.
Acknowledgements

This work was supported in part by the Preparatory Phase of the Large Hadron Collider upgrade (sLHC-PP), a project co-funded by the European Commission in its 7th Framework Programme under Grant Agreement No. 212114. The information contained in this document reflects only the authors’ views and the Community is not liable for any use that may be made of the information contained therein.

The input provided by numerous contributors from many collaborating institutes around the world on the occasion of workshops and conferences has been extremely helpful. They are gratefully acknowledged, although they cannot unfortunately be individually quoted. The following list of references is an attempt to give proper credit to these extremely valuable contributions.
References


[21] M. Aiba, A first analysis of 3-bunches and 1-bunch scenario for the SPL based proton driver,


[23] EURONu, A high intensity neutrino oscillation facility in Europe, European Commission FP7 design study [http://www.euronu.org/].


[31] O. Piquet et al., The RF design of the Linac4 RFQ, Proc. IPAC10, Kyoto, Japan, 2010 [https://cds.cern.ch/record/1307876].


[39] J. Stovall, S. Ramberger, and R. Lown, RF breakdown in drift tube linacs, CERN-sLHC-Project-
Note-0007 (2009) [https://cds.cern.ch/record/1216158].

[40] G. Bellodi et al., Beam dynamics optimisation of LINAC4 structures for increased operational flexibility, Proc. LINAC10, Tsukuba, Japan, 2010 [CERN-ATS-2010-202] [https://cds.cern.ch/record/1302723].


[50] F. Gerigk et al., The hot prototype of the PI-mode structure for Linac4, Proc. LINAC10, Tsukuba, Japan, 2010 [CERN-ATS-2010-207] [https://cds.cern.ch/record/1302737].


[58] A.M. Lombardi et al., Alignment and field error tolerance in Linac4, CERN-ATS-Note-2011-021
REFERENCES

(2011) [https://cds.cern.ch/record/1342092].


[62] M. Schuh, HOM issues in 704.4 MHz and 1.3 GHz superconducting cavities, sLHC-Project-Note-0031 (2011) [https://cds.cern.ch/record/1341238].


[66] CERN, Workshop on Cryogenic and Vacuum Sectorisations of the SPL. [https://indico.cern.ch/conferenceDisplay.py?confId=68499]

[67] W. Hofle, SPL LLRF simulations, feasibility and constraints for operation with more than one cavity per klystron, power overhead, 3rd SPL collaboration meeting, CERN, 2009 [https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=63935].


169
abstract/PRSTAB/v5/i12/e124202].


[85] F. Marhauser, personal communication.


[98] O. Capatina, Mechanical design considerations for beta=1 cavities, Presentation at 4th SPL
References


[121] W. Höfle et al., Testing of superconducting low-beta 704 MHz cavities at 50 Hz pulse repetition rate in view of SPL—first results, Proc. LINAC10, Tsukuba, Japan, 2010 [CERN-ATS-2010-213] [https://cds.cern.ch/record/1302752].


[125] J. Jacob, Implementation of high power RF solid state amplifiers and development of innovative concepts at the ESRF, TIARA Workshop on RF Power Generation for Accelerators, Ångström Laboratory, Uppsala University, Sweden, 2013.


[134] F. Gerigk, personal communication, 8 April 2010, CERN.


[137] Z. Tang, I. Rakno, and D. Johnson, Project X injection beam absorber: thermal and stress analysis
REFERENCES


