Progress in the Design of LINAC4, the SPL Normal- Conducting Front-End (< 180 MeV)


Abstract

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INTRODUCTION

Linac4 is designed for two different applications: 1) as a new (low duty cycle) injector for the PS booster, replacing the ageing Linac2, and 2) as front-end for the SPL [1], a high power (high duty cycle) H− linac replacing the PS booster and injecting directly into the CERN PS or into a new accumulator ring. For this purpose Linac4 will be relocated into a new tunnel and extended to 180 MeV. From this energy onwards the superconducting cavities of the SPL will continue to accelerate the beam up to its final energy of 3.5 GeV. While the initial average beam power of Linac4 is relatively modest (5 kW) the machine is designed to deliver an average beam power of 205 kW as part of the SPL. The main parameters for both applications are given in Table 1.

The CERN management is expected to take a decision on the construction of Linac4 by the end of 2006. The case of the SPL will be considered in 2010-2011, as one of the possible options for the upgrade of the CERN proton accelerator complex.

DESIGN PHILOSOPHY

The basic design consists of RFQ, a Medium Energy Beam Transport line (MEBT) with a beam chopper at 3 MeV, an Alvarez type Drift Tube Linac (DTL) up to an energy of 40 MeV, a Coupled Cavity DTL (CCDTL) up to 90 MeV, followed by a Cell Coupled Linac (SCL) accelerating the beam to its final energy of 160 or 180 MeV, respectively (Fig. 1). At 90 MeV after the transition from CCDTL to SCL, the frequency changes from 352.2 MHz to 704.4 MHz in order to profit from higher accelerating gradients, higher efficiency and a more compact accelerating structure. The choice of structures and basic beam dynamics have already been analysed in some detail (see e.g. [2], [3], [4], [5]). The front-end test stand preceding the construction of the full Linac4 already in preparation [6].

The current planning foresees Linac4 to be installed in the PS south hall at CERN where only limited space is available. Since the RF equipment for the 352.2 MHz part of the linac is already available (recuperated from LEP), this new design concentrates on raising the electric gradients and optimizing the lattice for the shortest length possible.

In order to achieve a low loss design, Linac4 follows the standard design rules for high-intensity hadron linacs: a) zero current tune per period below 90 deg (Fig. 2), b) smooth variation of the focusing forces across all transitions between accelerating structures (Fig. 3), and c) avoiding emittance exchange between the longitudinal and transverse planes by keeping the ratio of the depressed longitudinal over transverse tunes in the stable areas of Hofmann’s stability charts [7] (Fig. 4). The resulting beam envelopes are plotted in Fig. 5.

Table 1: Main linac parameters

<table>
<thead>
<tr>
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<th>Phase I (Linac4)</th>
<th>Phase II (SPL)</th>
</tr>
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<tbody>
<tr>
<td>ion species</td>
<td>H−</td>
<td>H−</td>
</tr>
<tr>
<td>length</td>
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</tr>
<tr>
<td>beam energy</td>
<td>160</td>
<td>180</td>
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<tr>
<td>beam power</td>
<td>5.1</td>
<td>205</td>
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<tr>
<td>source current</td>
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<td>80</td>
</tr>
<tr>
<td>peak current</td>
<td>64*</td>
<td>64*</td>
</tr>
<tr>
<td>chopper beam-on</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>chopping scheme</td>
<td>133/355</td>
<td>3/8</td>
</tr>
<tr>
<td>av. pulse current</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>av. current</td>
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<td>1.14</td>
</tr>
<tr>
<td>beam pulse length</td>
<td>0.4</td>
<td>0.57</td>
</tr>
<tr>
<td>beam duty cycle</td>
<td>0.08</td>
<td>2.85</td>
</tr>
<tr>
<td>particles p. pulse</td>
<td>1.0</td>
<td>1.42</td>
</tr>
<tr>
<td>particles p. bunch</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>ε₁r, rms</td>
<td>0.29</td>
<td>0.35</td>
</tr>
<tr>
<td>ε₁L, rms</td>
<td>0.45</td>
<td>0.50</td>
</tr>
</tbody>
</table>

These parameters ensure a smooth transition between the different sections and avoid emittance exchange via space charge resonances.
DESIGN PROGRESS

The base line design of the DTL and CCDTL sections of Linac4 [8] was recently re-assessed resulting in major changes for the DTL. At the same time the overall design of Linac4 and the SPL evolved, yielding new values for peak current, synchronous phases and electric field gradients.

peak current

The most recent change in the design of Linac4 concerns peak current, pulse length, and chopping ratio. Linac4 now uses the same chopping ratio (38 % instead of 25 %) as the SPL, leading to equal requirements for peak current (64 mA in the linac), average current (40 mA), and numbers of particles per linac bunch ($1.14 \cdot 10^9$). This choice also yields less injection turns into the booster and provides a larger safety margin for low-loss H$^-$ injection [9]. It also implies equal space charge forces for the beam transport and equal RF peak power.

DTL PMQs

A major change in the hardware design is the use of permanent magnetic quadrupoles (PMQs) in the DTL. Due to the low starting energy of 3 MeV it is very challenging to construct electromagnetic quadrupoles which are small enough to fit inside the first drift tubes of DTL tank 1. Even though the electro-formed JPARC electromagnetic quadrupoles might be adapted for the use in Linac4, PMQs offer a number of additional advantages: a) they are cheaper to construct, require less cooling, and need only little maintenance, b) the smaller drift tube diameter...
raises the shunt impedance and therefore allows to raise
the field gradient while maintaining the same number of
klystrons for the same output energy, c) the higher mag-
netic gradients may allow to use FD focusing instead of
FFDD from the first tank onwards, depending on the PMQ
technology used. This choice would yield a stronger fo-
cusing and a smaller beam size. The clear disadvantage is
that PMQs do not allow to change the focusing settings in
the DTL. Nevertheless, in the case of Linac4, this choice is
considered viable since the whole DTL is only 13 m long
and profits from a dedicated matching section at the transi-
tion from the MEBT into the DTL. Adapting the elements
of the matching section for different currents, multi particle
simulations (TRACE\textsuperscript{\textregistered}WIN [10]) confirmed that beam cur-
cents between 20 and 60 mA can be matched into a DTL
with PMQs without any degradation in beam quality.

synchronous phase & field ramp

The previous DTL [8] design employed a phase and field
ramp in the first tank from $-42 \text{ deg}$ to $-25 \text{ deg}$ and from
1.5 to 3 MeV, respectively. In the new design the first
drift tubes are slightly longer in order to reduce the trans-
mit time factor. Additionally the starting phase was raised
from $-42 \text{ deg}$ to $-30 \text{ deg}$. Both measures lower the lon-
gitudinal focusing and thus the field ramp can be elimi-
nated without major changes in the evolution of the lon-
gitudinal focusing. Furthermore the field level was raised
from 3 MV/m to 3.5 MV/m, taking advantage of the higher
shunt impedance due to the smaller drift tubes. Another
optimization was done with respect to the maximum syn-
chronous phase in the DTL and throughout Linac4. The
new design features a maximum synchronous phase of
$-20 \text{ deg}$ instead of $-25 \text{ deg}$, which slightly raises the ac-
celeration per metre and thus shortens the structure. This
rise, however, might yield two problems: a) more filamen-
tation and possibly emittance blow-up in longitudinal phase
space, and b) a rise in phase and energy jitter due to statisti-
cal errors in the RF system. The effect on the emittance
was analysed by simulating the two linac versions: a) $-42$
to $-25 \text{ deg}$ and b) $-30$ to $-20 \text{ deg}$ with a range of lon-
gitudinal emittances (0.07 $\pi$ deg MeV to 0.35 $\pi$ deg MeV
instead of the nominal value of 0.18).

Figure 6 shows the output versus input longitudinal emi-
tance for the two cases. Both versions are close to the theo-
retical 45 deg line, meaning that the different phase settings
have little influence on the longitudinal dynamics. An ad-
titional outcome of this study was that larger longitudinal
input emittances increase the transverse emittance growth.

To test the influence of different synchronous phase set-
tings on the development of phase and energy jitter a simple
drift-kick code was written to evaluate large sets of statisti-
cal errors [11]. Figure 7 shows the energy jitter evolution
along the present linac design for an rms error of 0.5 % and
0.5 deg.

Due to the frequency jump at 90 MeV at around 40 m the
energy and phase variations double. Using a Gaussian error

distribution and 100 different error sets the two settings for
the synchronous phase were simulated. Table 2 shows the
results of these simulations and confirms that the difference
between the “old” synchronous phase settings and the new
one is marginal.

<table>
<thead>
<tr>
<th></th>
<th>“old” Linac4</th>
<th>“new” Linac4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_0$</td>
<td>$-42$ to $-25 \text{ deg}$</td>
<td>$-30$ to $-20 \text{ deg}$</td>
</tr>
<tr>
<td>$\Delta E_\sigma$</td>
<td>612 keV</td>
<td>678 keV</td>
</tr>
<tr>
<td>$\Delta \phi_\sigma$</td>
<td>8.9 deg</td>
<td>7.3 deg</td>
</tr>
</tbody>
</table>
SUMMARY

In the latest iteration of the Linac4 design several changes were implemented: the use of PMQs in the DTL, the field ramp in the first DTL tank was eliminated, raising the maximum synchronous phase from -25 to -20\(^\circ\) without degrading longitudinal phase space, raising the electric gradient in DTL and CCDTL. All these measures resulted in a length reduction of 3 m (out of 16.4 m) for the DTL, and a reduction of \(\approx 7\) (out of 58 m) for CCDTL and SCL. At the same time the influence of smaller/larger longitudinal input emittances was tested as well as the effects of RF errors on the development of phase and energy jitter.

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REFERENCES

[1] K. Hanke et.al., ‘Superconducting proton linac development at CERN’, this workshop


