UPGRADING OF LEP ENERGIES BY SUPERCONDUCTING CAVITIES

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ABSTRACT

The upgrading of LEP to energies above 90 GeV by superconducting cavities is considered. Development work at CERN has allowed to reach the design values for accelerating fields and quality factors, $E_{acc} = 5$ MV/m and $Q_v = 3 \times 10^8$ respectively in 350 MHz, 4 cell cavities and the fabrication of a few cavities and cryostats by industry is prepared. Two possible scenarios of upgrading are discussed, involving installation of sc cavities in interaction regions 2 and 6 only or in all 4 interaction regions. The corresponding costs and time schedules are presented.

The installation of 128 copper accelerating cavities in LEP will allow to reach particle energies around 55 GeV [1]. Already at a very early stage of the planning for LEP it was considered to upgrade energies to the design value of LEP ($\sim 100$ GeV) by installing superconducting (sc) cavities. Recent progress [2] in the sc cavity development programme at CERN looks sufficiently promising to confirm this hope.

In the following the possibilities of the new technology are shortly discussed and the present status of development work at CERN is reviewed. Possible scenarios for the installation of sc cavities in LEP are presented and the costs and time schedules are explored. This presentation relies largely on ideas which have already been published in a 1985 LEP note [3].

1. BASICS OF RF SUPERCONDUCTIVITY [4]

1.1 rf losses

At high frequencies and for temperatures below the critical temperature $T_C$ the rf resistance of a superconductor decreases exponentially with temperature and its value can be made typically $10^4$ to $10^8$ times smaller than for copper at room temperature. The corresponding decrease of rf losses in sc cavities has attracted accelerator constructors because much higher acceleration efficiencies and higher CW accelerating fields than in Cu cavities can be reached.

Due to the Meissner effect the penetration depth of rf fields in a superconductor is much smaller than the normal skin depth and ranges in the region of 50–200 nm. rf superconductivity is therefore a surface effect. One may characterise rf losses of a superconductor by the surface resistance $R_s$ (in Ohm). For cavities, losses are generally expressed by the so-called quality factor $Q$. For a given cavity geometry and rf mode, quality factor and surface resistance are related by the relation

$$Q = C/R_s$$

Presented by H. Lengeler at the Workshop LEP 200
29 September–1 October 1986, Aachen, Germany
where \( G \) is a constant. For LEP accelerating cavities, one calculates \( G = 278 \text{ Ohm} \). It is possible to reach reliably in large multicell cavities \( Q \)-values well above \( 10^9 \) which may be compared with typical \( Q \) values for Cu accelerating cavities of \( 4 \times 10^6 \).

At present the favourite material for cavity fabrication is pure niobium (Nb). It has mechanical properties which allow easy shaping and welding of cavities with complicated geometrical layouts.

1.2 Field limitations

In normal temperature cavities rf fields are limited either by the warming-up of walls due to the large rf losses or by the electric field component causing field emission, microdischarges or electron resonance phenomena (multipactor). For sc cavities one has to add the critical magnetic rf field \( H_c \) as another limit. For ideal Nb surfaces one would expect to reach acceleration fields of the order of \( 50 \text{ MV/m} \). However, for real surfaces, fields are limited at much lower levels. There exist in cavities well-localised point-like defects with increased rf losses. These defects, which are not related to the sc properties of the cavity walls, heat up their surrounding and eventually drive the superconductor to temperatures above its critical temperature \( T_c \) thereby inducing a thermally unstable process which finally leads to a fast field breakdown. These surface defects are mostly of trivial nature like e.g., cracks and holes in weldings, welding beads, inclusions of other materials, tooling marks, dust particles or residues from chemical treatments or rinsings.

Another cause of field limitations are point-like electron sources - similar to the DC field emission sources observed at large area high voltage electrodes - and located at regions exposed to high electric surface rf fields. The emitted electrons are accelerated in large cavities to energies in the 100 keV or MeV range and hit cavity surfaces causing heating and emitting bremsstrahlung X-rays. Field loading is produced not only by the acceleration of electrons but also by the increased rf losses at regions warmed up by electron impact.

Special diagnostic methods like e.g. temperature mapping of the cavity surfaces had to be developed to localise and to characterise surface defects and electron sources. They opened the way for the repair of such defects by local grinding and local chemical treatments. They also allowed to device more efficient inspection methods and to develop improved surface treatments and weldings. One of the most probable causes of electron emission are dust particles. Therefore clean room techniques for rinsing and assembling large cavities had to be applied. With the development of these methods fields could be gradually increased and 5–7 MV/m can now be reached reliably even in large multicell cavities.

The preparation of clean and defect free surfaces of many m² size remains one of the biggest technological challenge in the field. The progress in the performances of sc cavities with respect to rf losses and achievable fields will be bound to a more detailed understanding of the interaction between rf fields and real sc surfaces and to the transfer of this understanding to large scale cavity systems needed in accelerators and storage rings.

An important step towards higher gradients was the insight in the role of thermal conductivity \( \lambda \) for stabilising localised defects [5]. Computer simulations have shown that breakdown levels scale with \( \sqrt{\lambda} \). By now industry has produced Nb material whose \( \lambda \) has been raised from an initial \( 10 \text{ W/m x K} \) to over \( 30 \text{ W/m x K} \) and cavity results have confirmed the predictions.
A follow-up of this idea is to replace the bulk niobium by copper with a high thermal conductivity (typically > 400 W/m x K) and to deposit a thin Nb layer of a few μm thickness on a Cu cavity [6]. A remarkable feature of Nb/Cu cavities is the absence of fast thermal breakdowns. This behaviour is particularly interesting for large storage rings where a string of cavities is powered by a common rf generator (for LEP e.g. 16 cavities). If a single cavity would deteriorate without producing a fast breakdown the additional cryogenic losses may be tolerable for some time and this may avoid switching off a whole array of sc cavities. For low frequency cavities as the ones foreseen for LEP the use of Cu instead of Nb cavities will also lead to a substantial reduction in cavity costs.

1.3 Advantages of sc cavities

The main advantage of sc cavities is their high acceleration field which can exceed the ones reached in Cu cavities (1.5 MV/m) by more than a factor 3-5. rf power, which can be produced in large CW klystrons with an efficiency of up to 70%, can be converted into acceleration with negligible losses. Even if one takes into account that a small part (~ 10^{-2}) of the rf power is dissipated in the cavity walls at LHe temperatures the overall efficiency is larger than for ac systems (cf. Appendix I).

For LEP the main current limits are given by transverse instabilities linked to the internal modes of individual bunches (short range wake fields). The main contribution [7] to the total transverse impedance causing this type of instability are stemming from the rf cavities and from the vacuum chamber bellows. For a bunch length of 40 mm the contributions are:

- 2880 bellows: $0.4 \times 10^5$ V/pC,
- 128 Cu cavities: $1.1 \times 10^5$ V/pC,
- 256 sc cavities: $0.2 \times 10^5$ V/pC.

The contribution of sc cavities is relatively small because their iris opening 2a can be made much larger (table I) and because the transverse impedances per unit length scale approximately like $a^{-3.8}$ [8].

Resonant built-up of higher order modes (horm) can also be kept sufficiently small in sc cavities because couplers have been developed which attenuate the most dangerous horm to levels even below the ones produced by the (natural) damping of Cu-cavities.

2. STATUS OF SC CAVITIES AT CERN

Up to 1983 the efforts in cavity development at CERN were mainly concentrated on 500 MHz cavities [9], leading to the successful test of a 5-cell, 500 MHz cavity at PETRA [10]. The results confirmed that the achievable accelerating fields do not decrease at lower frequencies as strongly as previously suspected. Therefore it was decided in 1984 to concentrate efforts on 352 MHz cavities [11]. This frequency choice is suggested by the fact that LEP will be equipped at the beginning with 128 Cu cavities at 352 MHz. There is an obvious interest to install at a later stage sc cavities with the same frequency and to use at maximum the existing installation of rf power sources. With the installed rf power of 16 MW, LEP can be upgraded to more than 90 GeV by using sc cavities.
Developments on 352 MHz LEP cavities have been pushed along two lines: Nb cavities and Cu cavities coated by a thin layer of Nb.

### TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>Cu cavity</th>
<th>Sc cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency $f$</td>
<td>352.209 MHz</td>
<td>352.209 MHz</td>
</tr>
<tr>
<td>Wavelength $\lambda$</td>
<td>0.851 m</td>
<td>0.851 m</td>
</tr>
<tr>
<td>Number of cells</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Cavity active length</td>
<td>2.13 m</td>
<td>1.70 m</td>
</tr>
<tr>
<td>Iris hole diameter</td>
<td>100 mm</td>
<td>241 mm</td>
</tr>
<tr>
<td>Shunt impedance/quality factor $r/Q$</td>
<td>650 Ohm/m$^2$</td>
<td>276 Ohm/m$^2$</td>
</tr>
<tr>
<td>$Q$ (Cu, 300 K)</td>
<td>40000</td>
<td>-</td>
</tr>
<tr>
<td>$Q$ (Nb, 4.2 K)</td>
<td>-</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>$2 (f_{m} - f_{o})/(f_{m} + f_{o})$</td>
<td>1.28%</td>
<td>1.76%</td>
</tr>
</tbody>
</table>

(a) Accelerating cavity without storage cavity.

#### 2.1 Nb cavities

With single cell cavities accelerating fields up to 10 MV/m and quality factors above $3 \times 10^9$ at the design field of 5 MV/m have been reached. In some cases maximum fields were reached without rf- and He-processing. Exposures to dust-free, dry air and warm ups to room temperature did not degrade fields and $Q$ values.

Based on the experience gained during the PETRA test the cavity design (fig. 1 and table 1) has been improved with respect to rf properties and manufacturing simplicity [12]. A first 4-cell cavity [2] using the new geometry and fabricated from Nb material of improved thermal conductivity ($\lambda = 28$ W/m x K) has reached $E_{acc} = 7.5$ MV/m and a quality factor above $3 \times 10^9$ at 5 MV/m (fig. 2). These performances remained unchanged after 2200 h of high field operation, after a vacuum failure whereby the vacuum degraded to $\sim 10^{-3}$ mbar and after an exposure to X-ray radiation of many tenths of krad.

#### 2.2 Nb coated copper cavities

Two methods of coating Cu copper cavities with a thin (1-5 μm) layer of Nb have been developed and tested at CERN: diode sputtering [6] and magnetron sputtering [13]. Magnetron sputtering has the advantage of a less complicated sputtering layout and of faster deposition rates. Recently a few excellent results have been obtained with this method. Fields up to $\sim 10$ MV/m with excellent $Q$-values have been reached in single cell 500 MHz cavities. There remain however still problems of $Q$ degradation toward higher fields, and of blistering of the Nb layers [19]. At present efforts are pursued to overcome these problems and to get more information on the long-term behaviour of thin Nb layers. A first attempt for sputtering a 4-cell, 350 MHz cavity by the magnetron method has been performed. Fields up to 5 MV/m were reached but $Q$ values are still limited by defects presumably due to inadequate cleaning of the underlying Cu surface. As expected these defects did not produce fast thermal breakdowns.
Fig. 1. Geometry of 350 MHz, 4-cell cavity for LEP with main coupler MC and higher order mode coupling ports (EH1, EH2).

Fig. 2. Quality factor as function of accelerating field for the first 350 MHz Nb 4-cell cavity for LEP. The design values are $Q_0 = 3 \times 10^8$ and $E_{acc} = 5$ MV/m.
2.3 Cryostats, couplers and tuners

Besides sc cavities the development of cryostats, couplers and frequency tuners has been pushed.

A first prototype LEP cryostat [14] of new and simplified design has been fabricated at CERN and tested successfully with a 4-cell sc cavity. Static cryogenic losses amount to 14 W. The cryostat has been designed as a module allowing the assembly of up to 8 cavities in a common vacuum vessel under clean and dust-free working conditions. Coaxial high power couplers [15] have been already operated successfully under warm and cold conditions and rf power levels foreseen for operation in LEP have been reached. The design of higher order mode couplers [16] has made great progress. Several types of compact hom couplers have been developed and tested. The damping provided to the most dangerous hom should be largely sufficient for LEP operation conditions. Frequency tuners of a new type [17] not involving moving mechanical parts are under development and first tests have already been performed.

It is at present intended to order from industry two sc Nb-cavities with cryostats and tuners of the type developed at CERN.

2.4 Long-term behaviour

Storage ring tests of sc cavities performed during the last years have shown that there are no major problems for operating such cavities in large storage rings [18]. However, some uncertainties concerning the degradation of cavity performances in a storage ring environment with respect to vacuum, dust transport and synchrotron radiation still remain. Therefore it is proposed to install a LEP sc cavity in the SPS accelerator-collider as soon as possible and to operate it with electron and proton beams for longer periods. In this way it will be possible to study the long-term behaviour in a well understood accelerator and well before such studies can be started inside LEP. This test will be backed up by systematic investigations on vacuum failures and air and dust exposures in test cavities.

Besides these tests, preparations are pursued for installing at an early stage of operation inside LEP a few sc cavities with all auxiliary items so that a maximum experience can be gained before upgrading at a larger scale will start.

3. POSSIBLE SCENARIOS FOR THE INSTALLATION OF SC CAVITIES IN LEP

For the first stage of LEP, 128 Cu-cavities with an effective length of 272.4 m and with \( E_{\text{acc}} = 1.47 \text{ MV/m} \) are installed. They supply a circumferential voltage \( U_{\text{rf}} = 402 \text{ MV} \) and a particle energy of \( \sim 55 \text{ GeV} \). Cavities will be installed in interaction regions 2 and 6 and will occupy on each side of the interaction point 4 rf-cells (fig. 3). Each rf cell contains eight 5-cell Cu cavities which are powered by one 1 MW klystron (or more precisely: 16 sc cavities and storage cavities located in adjacent rf cells are powered by a combined system of two 1 MW klystrons at slightly different frequencies. This layout of cavities and klystrons within two rf cells is shown in fig. 4.)
Fig. 3 Layout of one rf station containing 7 rf cells for installation of 8 rf cavities each.

Fig. 4 Layout of cavities and klystrons for 2 rf cells with Cu cavities. For sc cavities one klystron can be removed and the corresponding place can be occupied by the cold box of a refrigerator.

For the installation of sc cavities it is tried to keep changes of the existing layouts in the machine lattice, in the klystron and waveguide layout to a minimum and a number of eight sc cavities per half-cell has been adopted (table 2). With a given length of rf cells one can only locate eight 4-cell cavities in a rf-cell [3]. Even with 4-cell cavities the available space will be very marginal and it may turn out difficult to locate additional items like correction magnets and beam monitors. Therefore it would be highly desirable to increase the length of rf cells. The extra length of cell QS4-QS5 (fig. 3) would give a possibility for this.
The much higher accelerating efficiency of sc cavities allows to power 16 cavities with one 1 MW klystron as long as a beam current of 2 x 3 mA together with an accelerating field of 7 MV/m is not exceeded (table 2 and Appendix 1). Therefore the place foreseen in the Cu cavity layout for each second klystron will be free. It is proposed to install on each side of the interaction points and at one of the free klystron locations the cold box of the refrigerator (fig. 4). The available space allows installation of a cold box with up to 6 kW refrigeration power [20]. This should be sufficient to cool sc cavities in 6 rf cells up to a gradient of ~ 7 MV/m (table 2 and Appendix 1).

**TABLE 2**

A few parameters of rf cells equipped with sc cavities (cf. Appendix 1)

<table>
<thead>
<tr>
<th>Number of cavities</th>
<th>Eight 4-cell cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{eff}$</td>
<td>13.6 m</td>
</tr>
<tr>
<td>$E_{acc}$</td>
<td>5 MV/m</td>
</tr>
<tr>
<td>$U_{rf}$</td>
<td>68 MV</td>
</tr>
<tr>
<td>$P_{cry}$ (cavities + cryostats + transfer lines at 4.2 K)</td>
<td>544 W</td>
</tr>
<tr>
<td>Mains power for cryogenics</td>
<td>0.165 MW</td>
</tr>
<tr>
<td>$P_{rf}$ (2 x 3 mA)</td>
<td>355 kW</td>
</tr>
<tr>
<td></td>
<td>7 MV/m</td>
</tr>
<tr>
<td></td>
<td>95.2 MV</td>
</tr>
<tr>
<td></td>
<td>952 W</td>
</tr>
<tr>
<td></td>
<td>0.288 MW</td>
</tr>
<tr>
<td></td>
<td>496 kW</td>
</tr>
</tbody>
</table>

From the above considerations it turns out that a gradient of ~ 7 MV/m is a natural limit from the point of view of available rf generators and refrigerators. If currents above 2 x 3 mA are considered then either the accelerating fields have to be reduced or the number of klystrons has to be doubled. Similarly for gradients well above 7 MV/m the number of cold boxes has to be increased (unless Q values well above 3 x 10^9 can be attained at those higher gradients). It should be mentioned that a cost optimization (Appendix 2) of the sc acceleration system for LEP including cavities, rf and cryogenic systems as well as operating costs shows a broad minimum for acceleration fields between 7 and ~ 15 MV/m. In order to keep the possibility for such upgradings it would be desirable to equip only six rf cells with sc cavities and to reserve the 7th rf cell for installation of more refrigeration capacity.

The possible installation of a proton ring is taken into account by leaving the space above the cryostats free from He transfer lines and from rf couplers and waveguides.

A crucial question for LEP upgrading will be whether at higher energies the concentration of acceleration in two interaction regions only will be possible [7]. As this question may be not answerable by simulation methods only we present two basic scenarios, one using only interaction regions 2 and 6 for accelerating and one using interaction regions 2, 4, 6 and 8.
In the following all LEP energies are calculated for an improved "90° phase advance" lattice [7]. Horn losses are sufficiently small to apply the simple extrapolation formula

\[ E = 13.25 \sqrt{U_{rf}} \]  
(E in GeV, \( U_{rf} \) in MV)

where \( U_{rf} \) is the (peak) circumferential voltage supplied by the rf system.

All scenarios are based on accelerating fields of 5 or 7 MV/m. Intermediate steps of installation are of course always possible.

Scenario 1: Installation in interaction regions 2 and 6 only

Two stages can be considered and are detailed in table 3.

(a) Installation of 8 rf cells with a total of 64 SC cavities

One has to install four klystron systems and four 6 kW cold boxes (with 2 kW compressors). The energy can be upgraded to 73-77 GeV. The system of Cu cavities remains operational. This stage would be essentially a learning stage for producing and installing cavities at high rate and for operating LEP with two rf stations only at higher energies. A short shutdown will be sufficient for installation.

(b) Removal of all Cu cavities and replacement by SC cavities

This brings up the total number to 24 rf cells with 192 sc cavities. Klystron systems have to be reshuffled. Additional compressors and He transfer lines have to be installed. Energies can be brought up to 84-91 GeV and W\(^4\) production will be possible. A very long shutdown will be needed for the removal of all Cu-cavities, for rearrangement of klystron systems and for installation of sc cavities.

We recall that this scenario is envisageable if LEP can be operated with two rf stations only at high energies. It has the drawback that Cu cavities have to be removed at a rather early stage.

For stage (b) installation of sc cavities in 6 rf cells on each side of the interaction points is assumed. Equipping the 7th cell also with sc cavities would bring up energies from

- 84 to 87.3 GeV for \( E_{acc} = 5 \) MV/m
- 91.5 to 95.1 GeV for \( E_{acc} = 7 \) MV/m.

An upgrading to even higher energies will need acceleration fields above 7 MV/m. This will ask for an increase of the number of klystron systems (if \( i_p \geq 2 \times 3 \) mA has to be conserved) and of refrigerator units. Because of the quantization of systems this will be relatively costly.

Scenario 2: Installation in all 4 interaction regions

We consider 3 stages (cf. table 3):
(a) **Installation** (as in the first scenario) of 8 rf cells with 64 sc cavities in 2 and 6 Cu cavities remain operational.

(b) **Installation of 8 rf cells with 64 sc cavities in regions 4 and 8**

Klystron galleries and their access pits have to be constructed.

One has to install an additional 4 klystron systems and four 6 kW cold boxes with 2 kW compressors. Cu cavity systems can continue to operate. LEP will operate with 4 rf-stations which are only slightly different in acceleration voltage. An energy of 82–88 GeV can be reached. A short shutdown will be sufficient because the klystron systems can be prepared in advance in the klystron tunnels and no Cu cavities have to be removed.

(c) **Installation of another 16 rf cells with 128 sc cavities in regions 2, 4, 6 and 8**

One has to remove at least half of the Cu cavities. Klystron systems have to be reshuffled and the compressor power has to be upgraded everywhere to 4 kW. The 4 rf stations are now symmetric and energies can be upgraded to 90–98 GeV, largely sufficient for W⁻ production.

This scenario is more costly (see sect. 5), because of the additional civil engineering and installations in regions 4 and 8. It has nevertheless a few major advantages:

- LEP is operated with four rf stations.
- Cu cavities are removed at a much later stage (and 8 rf cells could even continue to operate if so wanted).
- Civil engineering, installation of klystron systems and refrigerators in 4 and 8 can be done without major interference with LEP operation. Shutdowns can be made shorter.

An upgrading of LEP to even higher energies could be achieved by increasing the number of sc cavities.

Passing from 32 to 48 rf cells would bring up energies from 90 to 100 GeV for $E_{acc} = 5$ MV/m and from 98 to 108 GeV for $E_{acc} = 7$ MV/m.

4. **PRODUCTION AND INSTALLATION OF SC CAVITIES**

For the upgrading of LEP one can assume that the construction of cavities and cryostats will be on the critical path and that the budget situation is allowing production of a very high rate.

The construction, assembly and testing of many cavity-cryostat units with all auxiliary facilities could be performed at a rate of about 2 cavities/week. This would almost certainly imply at least two production chains and several independent installations for rf and cryogenic tests and for
the final assembly. From similar constructions by industry it is concluded that a period of about 2 years will be needed from the placing of fabrication orders to the moment where production at high rate can be performed.

It is proposed to install cryostats and cavities in independent units of one cryostat containing two cavities assembled and tested before their transport to the LEP tunnel. These units will have a length of \( \sim 6 \) m so that the normal machine pits can be used for installation and so that no magnets have to be removed for the transport of units to their final position. For the installation two independent teams could be envisaged which would allow installation at a rate of \( \sim 8 \) cavities/week.

In fig. 5 we have illustrated a possible time schedule for production and installation. For scenario 1 we assume a minimum duration based on the above assumptions. For scenario 2 an additional decision point has been assumed after step 2(a) for the civil engineering in regions 4 and 8. Some delay has been added, allowing to gain experience for the operation of LEP at higher energies and with 2 rf stations only. It is assumed that the construction of klystron tunnels and access pits will take one year. As can be seen, energies for \( W^2 \) production are reached for both scenarios at about the same moment, i.e. about 4 years after the initial decision for upgrading.

![Graph showing time schedule for production and installation](image)

**Fig. 5** A possible production and installation time schedule and the LEP energies reached at each step (for \( E_{\text{acc}} = 7 \) MV/m).
5. **COST ESTIMATES**

In table 3 and fig. 6 the costs for the sc cavity systems are given. For this estimate we have taken into account all information on costs of sc acceleration systems available to us (Appendix 2). They include:

- Cost of sc cavities and cryostats.
- Cost of complete rf system.
- Cost of complete cryogenic system.

There is some uncertainty in those cost estimates in particular for the costs of cryostats and cavities. We believe that the assumed costs are nevertheless realistic and may be somewhat reduced if mass production can be applied.

We have done a cost optimisation (Appendix 2 and fig. 7) for the accelerating field by taking into account in addition to the costs mentioned above the costs of electricity for 4000 h of operation during 5 years.

Additional costs directly related to the sc acceleration systems have also been estimated and are given in table 3. They include:

- Civil engineering of klystron tunnels and access pits in regions 4 and 8.
- Cooling and ventilation.
- Additional electricity installation.
- Surface buildings for cryogenics.
- Reshuffling of klystron systems.

For completeness we give also a rough estimation of additional costs for LEP upgrading from 65 to 100 GeV not directly related to the sc cavity systems. They include:

- Cooling and ventilation for magnets and synchrotron radiation.
- Additional electricity installations.
- Power converters for magnets.
- Low B systems.
- Additional magnets for injection.

An estimation of costs for energies above the ones of scenarios 1 and 2 are given in fig. 6.

6. **SUMMARY**

For the upgrading of LEP energies it is proposed to use superconducting cavities operated at the same frequency of 352 MHz as the existing Cu-cavities. In this way a maximum use of the already installed rf systems can be made. With the existing sixteen 1-MW klystrons foreseen for the first stage, energies can be upgraded well above 90 GeV.
TABLE 3
Scenarios and costs of LEP upgrading (in MSF)

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 and 6 (a)</td>
<td>2, 4, 6 and 8 (a) + (b) + (c)</td>
</tr>
<tr>
<td>(a)</td>
<td>(a) + (b)</td>
</tr>
<tr>
<td>Number of rf cells/number of sc cavities</td>
<td>8/64</td>
</tr>
<tr>
<td>Costs of cavities and cryostats</td>
<td>22.7</td>
</tr>
<tr>
<td>Number of klystron systems to be bought</td>
<td>4</td>
</tr>
<tr>
<td>Costs of klystron systems to be bought</td>
<td>7.2</td>
</tr>
<tr>
<td>Number of refrigerators</td>
<td>4</td>
</tr>
<tr>
<td>Costs of refrigerators</td>
<td>20</td>
</tr>
<tr>
<td>Costs of cavities, rf, cryogenics</td>
<td>~ 50</td>
</tr>
<tr>
<td>Additional costs related to sc cav. system</td>
<td>5</td>
</tr>
<tr>
<td>Additional costs of upgrading not related to sc cavity system</td>
<td>36</td>
</tr>
<tr>
<td>Total costs of LEP upgrading</td>
<td>91</td>
</tr>
<tr>
<td>LEP energy (GeV)</td>
<td>73–77</td>
</tr>
</tbody>
</table>

**Fig. 6**
Total costs of upgrading for two different scenarios as a function of LEP energy (for \( E_{\text{acc}} = 7 \text{ MV/m} \)). Costs are interpolated graphically between the different scenario steps of table 3. Possible further upgradeings are indicated by a broken line (increase of gradients from 7 to 10 MV/m for scenario 1(b); increase of number of rf-cells equipped with sc cavities from 32 to 48 for scenario 2(c)).
The first LEP 4-cell Nb cavities have been fabricated and tested at CERN and have exceeded the design values

\[ E_{\text{acc}} = 5 \text{ MV/m} \quad \text{and} \quad Q_0 = 3 \times 10^9 \]

Cryostats, main couplers, horn couplers and frequency tuners for operation in LEP have been developed, constructed and tested successfully.

It is intended in near future to have some cavities and cryostats fabricated by industry in order to start the transfer of knowhow from CERN to industry and in order to get more precise information on costs. This should enable the installation of a few sc cavities in LEP at an early stage of operation.

For the upgrading two scenarios have been considered:

- Installation of sc cavities in interaction regions 2 and 6 only. If six rf cells on each side of interaction points will be equipped with sc cavities an energy of 84 GeV and \( \sim 92 \text{ GeV} \) can be reached (for \( E_{\text{acc}} = 5 \) and 7 MV/m respectively). It has, however, to be checked whether LEP can be operated at higher energies with 2 rf stations only.

- Installation of sc cavities in all 4 interaction regions. This will enable an upgrading to 90 GeV and 98 GeV respectively but will need additional civil engineering and facilities in regions 4 and 8. A later additional upgrading up to 100 and 108 GeV respectively would be possible.

Total costs of upgrading including cavities and cryostats, rf systems, refrigerator systems and additional costs for civil engineering, surface buildings and upgrading of other machine components would amount to:

- 152 MSF (scenario 1, \( E_{\text{acc}} \leq 7 \text{ MV/m}, E \leq 92 \text{ GeV} \))
- 234 MSF (scenario 2, \( E_{\text{acc}} \leq 7 \text{ MV/m}, E \leq 98 \text{ GeV} \)).

Construction and installation time will extend over a period of 5-6 years. This includes a preparatory period of 2 years for transfer of knowhow and for preparing fabrication at high rate.

It has to be stressed that up to now no large accelerating system involving many sc cavities has ever been tested in a storage ring. Therefore it will be of utmost importance to install a string of sc cavities in LEP at an early stage of operation. In this way one should gain experience in the operation of cavities with all auxiliaries, study the influence of such systems with all their components on beam stability and higher order mode excitation. One has to study also the long terms effects of an accelerator environment on cavity performances. Therefore it is intended to install a sc cavity in the SPS and to operate it for long periods. This test will be backed up by systematic investigations on vacuum failures, air exposures and dust transport with test cavities.

Acknowledgements

Many aspects of the upgrading programme have been discussed with members of the rf and cryogenics groups of EF Division and with members of the LEP Division. We would like to thank all those who participated in these discussions.
APPENDIX 1

A FEW FORMULAE AND SYSTEM PARAMETERS

Cryogenic losses

We assume in the following 4-cell cavities operated in the \( r \) mode at a frequency of \( 352.21 \text{ MHz} \) (\( \lambda = 0.851 \text{ m} \)). For the cavity geometry shown in fig. 2 this gives the parameters of Table 1. We assume a quality factor

\[ Q_0 = 3 \times 10^9 \text{ at 4.2 K and at design field,} \]

a value which has been repeatedly reached in 350 MHz test cavities [2].

The (cryogenic) rf losses per unit length of the cavity are given by

\[ P_c = \begin{cases} \frac{E_{acc}^2}{(r/Q)Q_0} & \text{for } E_{acc} = 5 \text{ MV/m} \\ \sim 30 \frac{W}{m} & \text{for } E_{acc} = 7 \text{ MV/m} \end{cases} \]  
(A1)

\( E_{acc} \): accelerating field
\( r/Q \): shunt impedance/quality factor

To these losses we have to add the cryostat and He-transfer line losses \( P_s \). Taking into account values obtained during the PETRA test and with other comparable cryostats and transfer systems we estimate for these additional losses 10 W/m. The total cryogenic losses per unit length at 4.2 K then amount to

\[ P_{cry} = \begin{cases} 40 \frac{W}{m} & \text{for } E_{acc} = 5 \text{ MV/m} \\ 70 \frac{W}{m} & \text{for } E_{acc} = 7 \text{ MV/m} \end{cases} \]  
(A2)

These values do not include synchrotron radiation losses and rf losses due to the vacuum tube tapers and vacuum valves located near the cavities which may be partly absorbed at 4.2 K walls. It is assumed that the overall technical efficiency for evacuating these losses at 4.2 K is \( \eta_{cry} = 0.33\% \) [21].

rf power requirements

For a sc cavity the rf losses can be completely neglected against the rf power transferred to the beam. Therefore the rf power per unit length needed is

\[ P_b = 2 \times i_b E_{acc} \times \sin \phi_s \]  
(A3)

\( i_b \): current per beam
\( \phi_s \): synchronous phase angle
For the LEP design current of $2 \times 3$ mA and for $\sin \phi_s = 0.87$ we get

$$P_b = \begin{cases} 
26.1 \text{ kW/m} & \text{for } E_{\text{acc}} = 5 \text{ MV/m} \\
36.5 \text{ kW/m} & \text{for } E_{\text{acc}} = 7 \text{ MV/m}
\end{cases}$$

For one half-cell with $L_{\text{eff}} = 8 \times 1.7 = 13.6$ m this amounts to 355 kW respectively 496 kW. It is thus clear that one 1-MW klystron can feed 2 half-cells. We note, that the bandwidth of the sc cavities may be somewhat increased for ease of operation above the optimum value. This leads to some additional reflection of rf power at the cavity entry.

For the scenario given above we assume always that one 1-MW klystron will feed 2 half-cells although this may ask in some cases for a reduction of klystron power. We also assume that the overall efficiency of rf production (including rf losses in the waveguides) is about $\eta_{\text{rf}} = 60\%$.

**Acceleration efficiency**

The acceleration efficiency $\eta_{\text{acc}}$ is given by

$$\eta_{\text{acc}} = \frac{P_b}{(P_b + P_c)} = \frac{P_b}{P_{\text{mains}}}$$

- $P_b$: power given to the beam.
- $P_c$: rf losses at cavity walls.
- $P_{\text{mains}}$: mains power needed for the production of $P_b$ and $P_c$.
- $\eta_{\text{rf}}$: overall efficiency for rf production, $\eta_{\text{rf}} \approx 60\%$.

For nc cavities one gets from (A1) and (A3)

$$\eta_{\text{acc}} = \frac{2 i_b E_{\text{acc}} \times \sin \phi_s}{\left( \frac{E_{\text{acc}}^2}{2 i_b} + \frac{E_{\text{acc}}^2}{(R/Q) \times Q_0} \right)}$$

For a given cavity with fixed $R/Q$ and $Q_0$, the efficiency depends on the gradient and on the beam current.

For sc cavities, $P_c \ll P_b$ and $P_c$ can be neglected in the rf power balance. However, it cannot be neglected for the electric power production because it is dissipated at low temperatures. In addition the static cryogenic losses of cryostats and He-transfer lines have to be taken into account. One gets for sc cavities with (A1), (A2) and (A3)

$$\eta_{\text{acc}} = \frac{2 i_b E_{\text{acc}} \times \sin \phi_s}{\eta_{\text{rf}} + \left[ \frac{E_{\text{acc}}^2}{(R/Q) \times Q_0} + P_s \right]}$$

For the cavity parameters from table 1 and for LEP conditions one obtains the values given in table A.1.
TABLE A.1

Accelerating efficiencies in LEP (for different beam currents and accelerating fields)

<table>
<thead>
<tr>
<th>nc cavities</th>
<th>sc cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 MV/m</td>
<td>5 MV/m</td>
</tr>
<tr>
<td>2 x 3 mA</td>
<td>7.5%</td>
</tr>
<tr>
<td>2 x 6 mA</td>
<td>13.3%</td>
</tr>
</tbody>
</table>

The large difference in efficiency explains that a total rf power of 16 MW for LEP produces with nc cavities a voltage $U_{rf} = 402$ MV (E = 55 GeV), and with sc cavities a voltage $U_{rf} = 5044$ MV (E = 98 GeV).
A COST OPTIMISATION FOR A SC ACCELERATION SYSTEM FOR LEP

We include in the cost optimisation:

- Cost of sc cavities and cryostats with all auxiliaries (like couplers, tuner, pumps).
- Cost of klystrons with circulators, power supplies, waveguide system, control, regulation and drive systems.
- Cost of refrigerators with He transfer lines and He storage.
- Cost of electricity for a given total number of operating hours.

With the length available to rf-cavities already fixed we exclude from the optimization civil engineering and possible machine component upgradings.

We assume a given particle energy of LEP which is related to the total accelerating voltage $U_{rf}$ by the formula

$$E = 13.23 \sqrt[4]{U_{rf}} \text{ (E in GeV, } U_{rf} \text{ in MV)}$$

and we use the field gradient $E_{acc} = U_{rf} / \tau_{eff}$ as an optimization parameter.

The total costs are then given by

$$C = C_{cav} \times \tau_{eff}$$
$$+ C_{rf} \times 2 \delta_{p} \times U_{rf} \times \sin \phi_{s}$$
$$+ 2.5 \left( E_{acc}^{2} \times \frac{\delta_{eff}}{r_{Q} \times Q_{o}} + P_{s} \times \tau_{eff} \right)^{0.6}$$
$$+ N_{h} \times C_{kWh} \left( \frac{2 \delta_{p} U_{rf} \sin \phi_{s}}{\eta_{rf}} + \left( E_{acc}^{2} \times \frac{\delta_{eff}}{r_{Q} \times Q_{o}} + P_{s} \times \tau_{eff} \right) \frac{1}{\eta_{cry}} \right)$$

- First term: cavity and cryostat costs. $C_{cav}$: cost of cavities and cryostats per unit length; we have assumed as our best guess from presently known production costs

$$C_{cav} = \begin{cases} 0.21 \text{ MSF/m for } 5 \text{ MV/m} \\ 0.25 \text{ MSF/m for } 10 \text{ MV/m} \end{cases}$$

which we interpolate linearly for other gradients.

- Second term: Cost of rf system. We assume that rf power is delivered by 1-MW klystrons. The cost for a complete rf system, $C_{rf}$, is estimated to 1.8 MSF/MW [22]. We assume $I_{b} = 3$ mA and $\sin \phi_{s} = 0.87$.

- Third term: Cost of a complete refrigeration system. We assume that refrigerator costs including compressors and transfer lines are given by the formula [22]
\[ C_{\text{cry}} \text{ (MSF) } = 2.5 \left( P_{\text{cry}} \text{ (kW)} \right)^{0.6}. \]

\( P_{\text{cry}} \) is the sum of cavity losses, cryostat and He transfer line losses.

- Fourth term: Cost of electricity.
  - \( N_h \): total number of operating hours.
  - \( C_{\text{kWh}} = 0.07 \text{ SF/kWh} \): Mean cost of kWh at CERN.
  - \( \eta_{\text{rf}} = 60\% \): total efficiency of rf production.
  - \( \eta_{\text{cry}} = 0.33\% \): total technical efficiency of refrigerator system for cooling at 4.2 K.

The result of an optimization for \( E = 100 \text{ GeV}, \ U = 3264 \text{ MV}, \ N_b = 20000 \text{ h}, \ G_o = 3 \times 10^9 \) and for three different sets of \( C_{\text{cav}} \) is given in fig. 7. There exists a broad minimum which shifts as expected towards higher accelerating fields for high \( C_{\text{cav}} \). It can be seen that a gradient of 7 MV/m corresponds to costs less than 10% above the minimum costs. The cost optimization does not take into account the "quantization" of klystron and cold box numbers in a real storage ring.

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**Fig. 7** Cost optimization for a so acceleration system as a function of accelerating fields and for three different values of \( C_{\text{cav}} \). Costs are normalized to the value for \( E_{\text{acc}} = 7 \text{ MV/m} \) and \( C_{\text{cav}} = 0.21 \text{ MSF/m} \).
REFERENCES