# PERFORMANCE OF THE LEP200 SUPERCONDUCTING RF SYSTEM

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## *Abstract*

The LEP Superconducting (SC) RF system has reached its maximum configuration of 288 four-cell cavities powered by 36 klystrons. This has allowed the beam energy to be raised from 45.6 GeV where physics of the Z-particle was studied to well above 80.5 GeV, the threshold of W pair production. The search for Higgs bosons and other new particles requires even higher beam energies. Currently the maximum operational energy achieved is 101 GeV with the RF system supplying a circumferential voltage of 3500 MV. This requires not only operating the cavities well beyond their design gradient but also demands a very high operational reliability from the entire system. The major developments necessary to achieve this performance are described.

## 1 INTRODUCTION

LEP, CERN's largest accelerator is an electron-positron collider [1] with 26.5 km circumference. Initially operated for physics around the energy of the Z particle production peak at 45.6 GeV it has been upgraded to study the W particles at beam energies above 80.5 GeV. The energy for W production was first reached in October 1996 and subsequently further increased. The search for new particles such as the Higgs and super-symmetrical particles has become a major focus of research. This has created a very strong interest in running LEP at the highest attainable energy.

The counter-rotating electron and positron beams, each consisting of four short bunches, collide in the four symmetrically located experiments. The RF system is located in straight sections of about 200 m length on each side of the experiments. The cavities are supplied with RF power from klystron amplifiers situated in a separate service tunnel running parallel to the straight sections. The klystron high voltage interface and all the control electronics are also located in this tunnel which is accessible during machine operation.

Currently the maximum operational energy achieved is 101 GeV where the energy loss in the form of synchrotron radiation is 3.0 GeV/turn. With a beam current of 6 mA the power transferred to the beam is 18.2 MW.

In this paper the major developments required to reach this energy and performance of the whole system are described.

## 2 EVOLUTION OF THE RF SYSTEM

The conceptual design of LEP planned a staged upgrading from LEP Phase 1 to higher energies using either copper (Cu) or superconducting cavities (SC) [1].

### *2.1 LEP Phase 1*

LEP Phase 1 started operation in 1989 with a beam energy of around 46 GeV. The RF system used only copper (Cu) cavities and because RF power consumption was a major concern a scheme of coupled accelerating-storage cavities was developed which gave 40% higher voltage for the same RF power [2]. The major specifications of this Cu system are shown in Table 1.

Table 1: Specification of the LEP Cu RF System

| | |
|---|---:|
| Design beam energy (0-luminosity) | ~ 60 GeV |
| Maximum circumferential voltage | 401 MV |
| RF frequency | 352.2 MHz |
| Five-cell cavities | 128 |
| Shunt impedance | 40 MΩ/m |
| Klystrons (1 MW) | 16 |

The maximum energy upgrade potential of this system with Cu cavities was 75 GeV. This envisaged occupying all available space with a total of 384 cavities and 48 klystrons providing a maximum accelerating voltage of 1200 MV.

### *2.2 Upgrading with Superconducting Cavities*

Early in the LEP project a superconducting alternative for increasing the energy was studied and a program of SC development was launched at CERN. Since the design aimed for maximum compatibility with the Cu system the SC frequency was also fixed at 352 MHz. The first SC cavities were installed in September 1992 for testing with beam. From 1992-1999 the number continually increased by adding to the existing system and later by replacing some Cu cavities.

In October 1995 the energy was raised above 80 GeV for the first time. The evolution of cavities and beam energy are shown in Fig. 1.

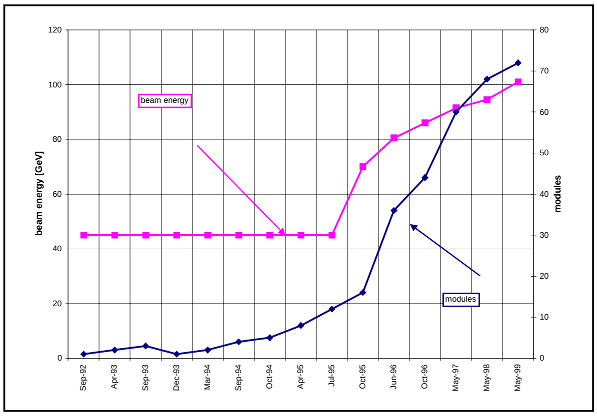

Fig 1: Evolution of LEP energy and number of SC modules. One module consists of four four-cell cavities.

The parameters of the present system are given in Table 2.

Table 2: Present configuration of the LEP RF system

| | |
|---|---|
| Cu cavities | 48 |
| Klystrons for Cu system | 8 |
| SC cavities | 288 |
| Klystrons for SC system | 36 |
| Maximum circumferential voltage | 3560 MV |

Four cryogenic plants provide the liquid He at a temperature of 4.5 K to cool the cavities. Initially the power available from each plant for dynamic losses was 6.7 kW. However, because of operation at higher accelerating gradients than initially foreseen and increased beam induced losses the available power was insufficient. Consequently for operation in 1999 the plants were upgraded. The design cooling power of the individual plants is now between 12.3 and 13.6 kW for dynamic load. Including the static loads and the liquefaction requirements each plant now has a total capacity of about 16 kW equivalent at 4.5 K.

## *2.3 The SC RF System*

Table 3 lists some important parameters of the LEP Superconducting RF System [3]. The technology of a thin film of niobium (Nb) sputtered onto Cu cavities was developed at CERN and most cavities (272) were manufactured using this technique. The 16 prototypes made of solid Nb sheet metal are also installed but operated at a lower gradient.

Table 3: Major parameters of the LEP superconducting RF system

| | |
|---|---|
| Operating temperature | 4.5 K |
| Cells/cavity | 4 |
| Cavities/cryostat-module | 4 |
| R/Q (linac Ohms) | 464 Ω |
| Accelerating gradient | 6 MV/m design up to 9 MV/m in some cavities<br>4-5 MV/m for solid Nb |
| Qo (for Nb/Cu cavities) specified | $> 6.4 * 10^9$ at low field<br>$> 3.2 * 10^9$ at 6 MV/m |
| Superconducting surface | 1728 $m^2$ |
| Total active length | 490 m |
| RF power at window: | 80 kW |

The frequency tuning of the cavities is done by longitudinal deformation using a combination of a fast magnetostrictive tuner with a slower thermal tuner having ranges of 1.8 kHz and 50 kHz respectively.

The power coupler design uses fixed coaxial lines with cylindrical ceramic windows [4]. The Higher Order Mode (HOM) couplers with an integrated fundamental mode filter are also of coaxial design [5].

## 3 DIFFICULTIES ENCOUNTERED EN ROUTE

Between the installation of the first SC prototypes in LEP and the achievement of stable operation required for physics many problems had to be solved, the most important of which are described below.

## *3.1 HOM Couplers*

Quenching of the solid Nb superconducting HOM couplers was observed mainly during conditioning. This was attributed to field emitted electrons from the cavities hitting the HOM couplers and was cured by reducing the couplers penetration into the beam tube. Although this reduced the coupling strength it was still sufficient for effective damping of the most important HOM's excited by the beam.

The HOM power extracted from the cavities by these couplers was transported to RF absorbers outside the cryostats through coaxial cables. The power rating of these cables was 150 W which with two cables/coupler and two couplers/cavity gave a maximum HOM power extraction capacity of 600 W/cavity. This was insufficient when operating LEP with more than four bunches per beam using the Pretzel Scheme [6] or bunch trains [7] and with beam currents ($i_b$) exceeding the 6 mA originally specified. All these cables have been replaced by rigid coaxial lines tested up to 850 W at the most important modes around 640 MHz. In the solid Nb cavities the rigid lines could not be fitted; consequently different coaxial cables with a higher power rating were installed.

## *3.2 Power Couplers*

The SC coaxial power coupler was developed with the same ceramic RF window used for the Cu cavity power coupler. The coaxial line links the cryogenic cavities at 4.5 K to the RF window at room temperature. The temperature profile along this line varies according to power and matching conditions and electron multipacting in this line was a major problem. The most important improvement — among many others — was the application of a bias voltage of +2500 V to the central conductor of the coaxial line. Couplers in this configuration have been tested on a cold cavity with 500 kW power throughput for many days and up to 600 kW for several hours [4].

## *3.3 Ponderomotive oscillations*

When the cavities were operated near their design gradient with a total beam current above 4 mA, large amplitude oscillations of the cavity fields at frequencies around 100 Hz were observed. This was due to a deformation of the cavity walls under the Lorentz force leading to a ponderomotive instability [8] when the cavities were detuned from their resonant frequency. The oscillation occurs at a mechanical resonance of the cavity structure and the instability threshold is inversely proportional to the tuning angle and the square of the cavity field. Cavity detuning increases with beam current due to action of the tuning system.

Presently two cures for this problem are available:

a) keeping the cavities at resonance by compensating the beam induced detuning with a phase offset into the tuning system. The required offset is set as a function of $i_b$ and cavity voltage by the control system.

Unfortunately an identical offset is not ideal for all cavities but needs optimizing for each cavity. This method however is satisfactory for $i_b$ of up to 6.5 mA.

b) An active damping system is being implemented which operates in parallel to the existing tuning system. A block diagram is shown in Fig.2.

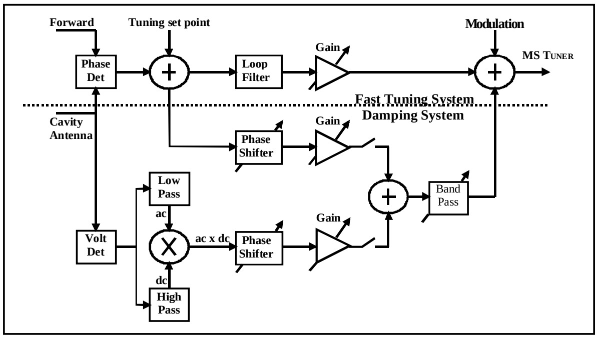

Fig. 2: Block diagram of the active damping system

### 3.4 *Beam induced cryogenic load*

With many SC cavities installed a clear influence of the beam on the cryogenic heat load was observed [9]. It has a strong dependence on bunch length (Fig. 3).

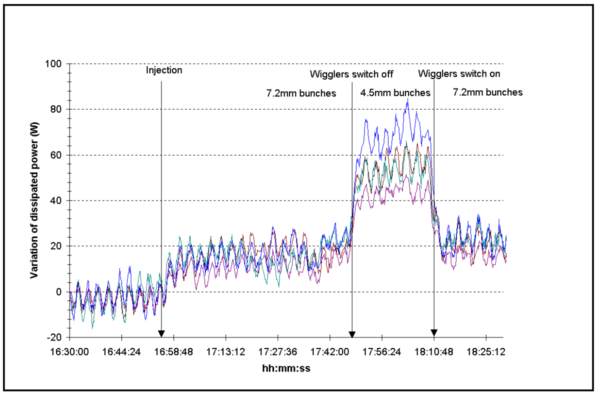

Fig. 3: Influence of r.m.s. bunch length on cryogenic load

The dependence of the cryogenic load $P_{bcr}$ per four-cavity module on beam current can be characterized by an impedance Z given by

$$P_{bcr} = Z*n_b*i_b^2$$

where $n_b$ is the total number of bunches in both beams.

For a bunch length of 8 to 10 mm Z was measured to be (before cable change, see below) 16 MΩ.

The origin of this heat load was twofold:

a) Beam induced fields deposit power on the normal-conducting bellows located between the cavities of a module. This power is eventually conducted to the cold cavities.

b) Cables connected to the field probes heat up due to beam-induced signals. This is described below.

### 3.5 *Antenna Cables*

Each cavity is equipped with two antenna type field probes located in the cut-off tubes. Thin coaxial cables transport these antenna signals out of the cryostat where the are used for cavity tuning and voltage measurement.

These cables traverse the super insulation and insulating vacuum and operation with short bunch lengths led to them overheating and eventually breaking. By the end of 1998 operation a total of 31 cables were broken and on eight cavities both antenna signals had been lost. The power spectrum measured on these cables is significantly different from the HOM coupler spectrum since it has no components at 640 MHz but contains other modes extending to much higher frequencies.

The antennas are not mounted directly onto the cavities but are located in a small cavity type structure. It is the beam induced modes of this structure which overheat the cables.

Consequently for start up in 1999 all cables were replaced with new cables having a higher power rating. Fortunately the cryostats could be opened for access without displacing the modules. In total 512 cables were replaced in two months.

The beam current dependent heat load for the cryogenic system reduced by 50% after this operation to Z ~ 8 MΩ on average, which corresponds to 36 W per four-cavity module at a total beam current of 6 mA.

## 4 DESCRIPTION OF THE RF SYSTEM AND DEVELOPMENTS

RF power is distributed from each klystron to eight cavities through a symmetrical system of waveguides, using magic-T power splitters. A schematic diagram is shown in Fig. 4.

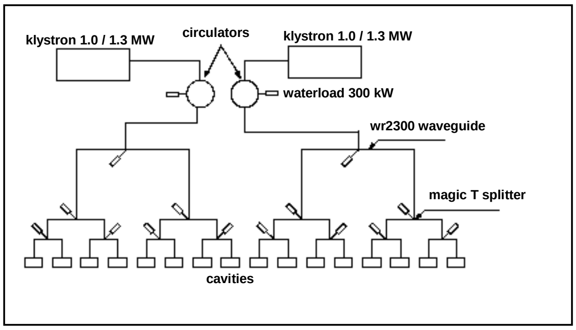

Fig. 4: Schematic layout of RF distribution system

At four RF Units the waveguide power distribution system is asymmetric, one module being located 100 m further away from the klystron than the other. The long length of waveguide introduces RF phase variations due to RF losses causing heating and thermal expansion of the waveguide. The calculated phase change between the two modules is 22 degrees with an RF power flow of 500 kW/module. This phase variation is automatically compensated by a feedback system driving the magnetic field of a high power ferrite phase shifter which has a phase range of 40 degrees.

The RF reference signal is generated by a synthesizer locked to the Global Positioning System. This master generator is located in the main control room and the signal is distributed to the RF stations in LEP through optical fibres [10]. The long term phase variation over these links which are up to 9.5 km long is up to 600 degrees. This is reduced to ±2 degrees by a feedback system [10].

### *4.1 Field Equalization*

For individual cavities the external Q value which characterizes the coupling strength varies by up to about ± 30 % due to fabrication tolerances  The parallel RF distribution to eight cavities and the absence of individually adjustable power couplers leads to a spread in cavity fields. The effective coupling strength can be changed by introducing λ/4 plates into the waveguides at the appropriate electrical distance from the couplers. This solution was applied to 41 cavities and result is shown in Fig. 5.

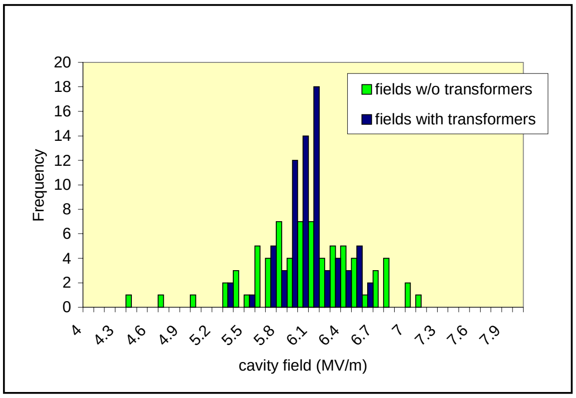

Fig. 5:  Result of λ/4 plates

### *4.2 Adjustment of electrical length*

A large divergence of cavity fields was observed during filling of LEP with beam. This is shown in Fig. 6a. The fields of eight cavities fed from one klystron together with the beam current are shown as a function of time. During the first 35 min while beam is accumulated at injection the field in some cavities becomes too small for the tuning system to properly control the cavity. A large campaign of adjustments of electrical length of the waveguides from the klystrons to each individual cavity, as well as readjustments of the directivity of waveguide directional couplers, gave a much improved situation, shown in Fig. 6b.

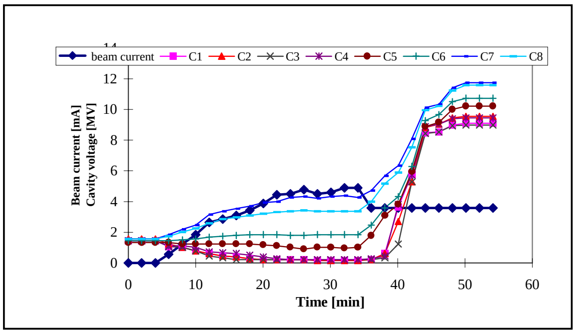

Fig 6a:  Cavity fields before electric length adjustments

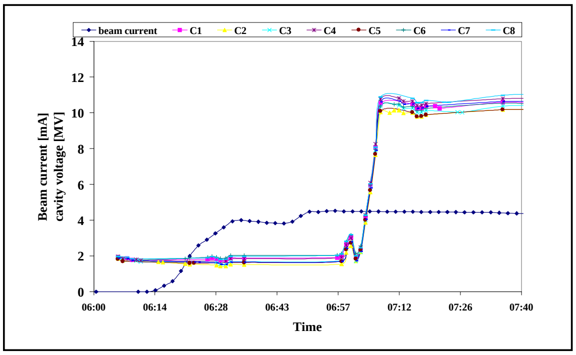

Fig 6b:  Cavity fields after electric length adjustment

## 5  CAVITY PERFORMANCE

The operational gradients of the LEP SC cavities has been continually increased. The evolution of cavity performance during 1999 is shown in fig 7. Here the gradients of all Cu/Nb cavities are shown at the start and the end this year's operation. The cavities are permanently operated near their limits. This and several conditioning campaigns in cw and pulse mode have allowed the gradients to be raised.

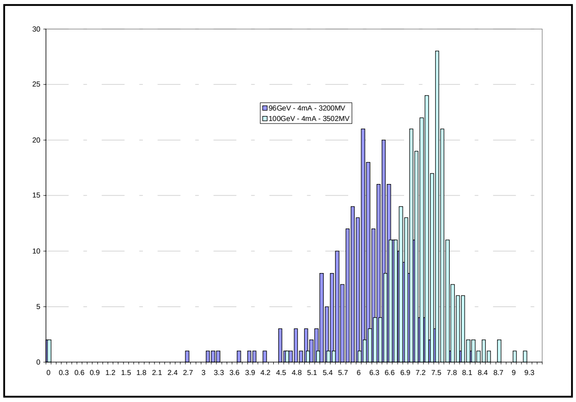

Fig. 7:  Accelerating gradients at the beginning and at the end of 1999 operation

Four cavities degraded during the year, three of which could be recovered through conditioning, the fourth recovered only partially. An unsuccessful attempt at *in-situ* helium processing using a klystron was tried on a module which had been limited to low fields since its installation.

## 6  OPERATION

### *6.1  System performance*

Presently the RF system of LEP has more than 10'000 interlocks. These either trip the RF signal of one klystron or a high-voltage power converter, leading to losses of about 95 MV or 190 MV respectively.

In order to reach the highest beam energy possible the voltage reserve is at the very minimum. This is demonstrated on the example of running at 100 GeV, calculated for a quantum lifetime of 24 h:

| | |
|---|---|
| Synchrotron radiation loss: | 2923 MV |
| Required for 24 h quantum lifetime: | 3200 MV |
| With reserve for one HV trip | 3390 MV |
| Typically available: | 3420 MV |

This small margin imposes very stringent demands on the reliability of the system. The turn-around time between the end of a physics coast and the next one is typically one hour; the optimum time to keep beams in physics is about three hours. In order to minimize beam losses due to RF trips, an automatic frequency shift has been implemented which often allowed the beam to be kept in case of simultaneous trips. A shift of 100 Hz corresponds to about 40 MV in additional reserve. A measure for the system reliability is the number of physics coasts lost due to RF faults. Of all physics fills at 100 GeV:

57% were dumped intentionally,
37% were lost due to the RF system,
6% were lost due to failures of other systems.

The average time between RF trips is about 30 min.

### *6.2 Control of circumferential voltage*

The RF voltage provided by each RF unit consisting of eight cavities driven by one klystron is controlled locally in each unit. The scalar sum of the eight cavity voltages is fed back to the klystron, where the output power is adjusted by the modulating anode. The bandwidth of this system is about 10 Hz.

A fast system has been developed, using the vector sum of the cavity fields as a reference. This system acts on the drive signal into the klystrons both in amplitude and phase, with a bandwidth of 3 kHz. This system is used presently only on three klystrons.

The total circumferential voltage is controlled via a Global Voltage Control system (GVC). This system reads the voltage of the 44 RF units every 100 ms and updates the settings of each unit according to its present state. Tripped units are compensated by increasing the others. The system adjusts the required voltage at injection, acceleration and top energy.

## 7 FUTURE POSSIBILITIES

The complete LEP RF system will become available when LEP ceases operation and is dismantled in autumn 2000. Some of the projects currently under study which envisage using all or part of the LEP RF system are listed below:

a) Free electron laser [11]
b) Proton accelerator of about 2 GeV [12]
c) ELFE — 25 GeV racetrack recirculator for nuclear physics [13,14]

## 8 CONCLUSION

Since first installation the LEP RF system has constantly evolved. Its transformation to a superconducting system has been successfully brought into operation, enabling LEP to provide beams for physics at ever higher energies. Many new developments were necessary and many problems required solving before reaching the present performance. Considering the size and complexity of the system the reliability is extremely high, allowing the voltage reserve to be kept to the very minimum. The SC accelerating gradients have greatly exceeded the original specification and the performance of the whole system has allowed LEP to explore a new range of energies at very high luminosity.

## 9 ACKNOWLEDGEMENTS

This work has been accomplished through a collaboration of many people, both at CERN and in industry. Without the dedication of all collaborators, the success of this vast enterprise would not have been possible.

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