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STATUS OF SUPERCONDUCTING CAVITIES IN LEP

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The upgrade of the Large Electron Positron collider (LEP) with superconducting cavities is nearing a successful completion. There are presently 240 superconducting cavities installed which, together with the original copper RF system, provide up to 2.6 GV per turn. The majority of the superconducting cavities are of niobium sputtered on copper and run at an operating gradient of 6 MV/m. In 1997, LEP has operated routinely at an energy of 91.5 GeV per beam and with a total current of over 5 mA. The operation of the RF system has been very satisfactory, with only a few cavities limited in field. This paper will concentrate on describing the operation of this system during 1997, including new features, operational procedures and present limitations. Future plans, notably the work towards improving performance and the installation of the remaining cavities, will also be covered.

Keywords: Superconductivity; Radiofrequency; Cavities; LEP

1. INTRODUCTION

LEP is an electron positron storage ring with a circumference of 26.7 km. Collisions of the counter-rotating bunches take place at four equi-spaced interaction points housing the physics experiments. The RF is installed in eight straight sections on either side of these points. Z_0 physics started in 1989 with the 352 MHz LEP1 copper RF system.[1] The LEP2 project consisted of increasing the energy to above W pair production by the addition of superconducting RF, also operating at 352 MHz.[2] In 1996, LEP operated in physics at 80.5 GeV per beam

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and, after a summer shutdown to install additional cavities, 86 GeV. For 1997 operation, a further 64 superconducting cavities were installed.

The year's performance of the machine has been very satisfactory. The majority of physics coasts were at 91.5 GeV, and 5 mA total beam current in four equi-spaced bunches per beam was commonplace. In the last week of operation, after a change to 102°/90° phase advance optics, a record single beam energy of 93.5 GeV was achieved and physics was carried out at 92 GeV. The total integrated luminosity at high energy was 63.8 pb^{-1}. In addition 9.5 pb^{-1} was accumulated during physics runs at 45, 65 and 68 GeV. At the latter energy, physics was performed with a maximum current of 7.2 mA in four equi-spaced trains of two bunchlets in each beam, with a bunchlet separation of 335 ns.

2. OVERVIEW OF THE LEP2 RF SYSTEM

Sixteen of the superconducting cavities installed in LEP are solid niobium prototypes specified at 5 MV/m. For series production, copper sputtered with niobium was chosen because of better thermal stability, higher quality factor, lower sensitivity to external magnetic fields and lower cost. The cavities are housed in groups of four inside a common cryostat, termed a module. A one-cavity section is shown in Figure 1. The cavity is surrounded by a stainless steel helium bath and its three nickel tuner bars. Tuning is achieved by elastic deformation of the cavity via both the thermal expansion and the more rapid magnetostriction of the bars. Production is now complete and all cavities have been accepted by CERN. They were manufactured by three European companies guaranteeing an unloaded Q of 3.4×10^9 at 6 MV/m on the bare cavities and 3.2×10^9 at 6 MV/m on the completed modules.

Cavity conditioning is first performed at low power without the RF couplers and is often accompanied by helium processing. High power conditioning with a klystron is performed in a test string on the surface and in LEP after installation and after any cavity warm-up. Pulse processing with peak fields up to 8 MV/m is often employed. Only after conditioning is the main coupler 2.5 kV bias switched on.[3] This

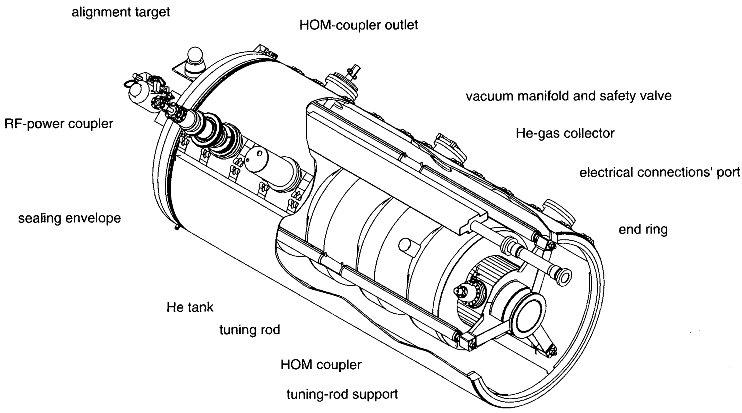

FIGURE 1 LEP superconducting cavity.

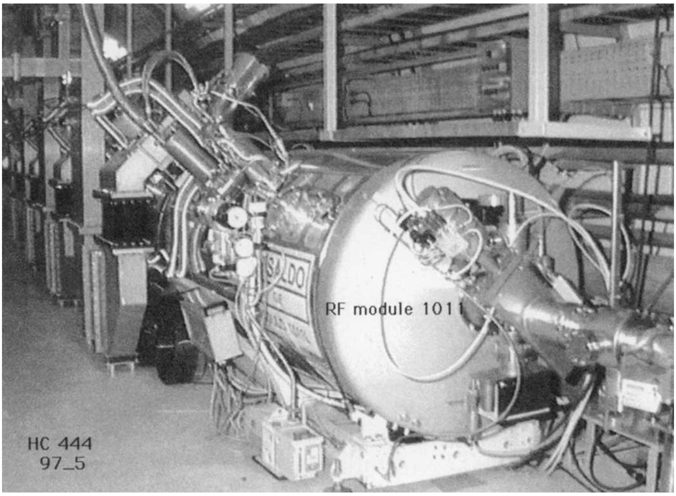

FIGURE 2 Superconducting module installed in LEP.

eliminates multipacting during operation. This year, helium processing has been tried successfully on several cavities installed in LEP and equipped with couplers.[4]

A photograph of a module installed in LEP is given in Figure 2. Two such modules, fed by one 1.3 MW klystron, form an RF unit. The units are grouped in pairs sharing a common high voltage supply

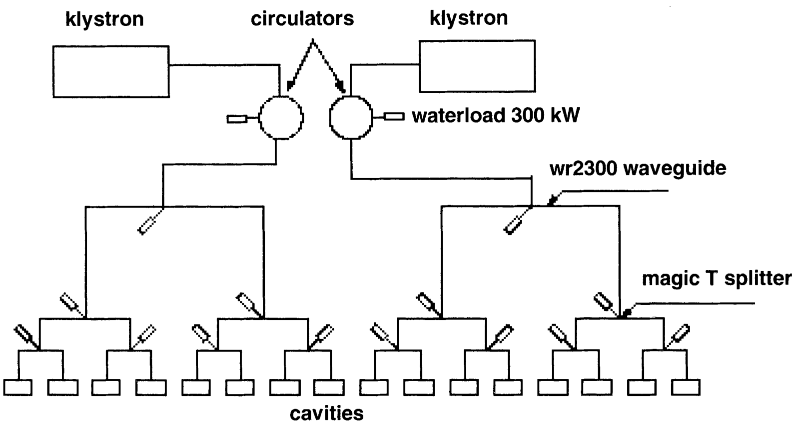

FIGURE 3 Layout of twin RF units sharing common klystron supply.

(Figure 3). In order to make some of the space available for the 16 additional modules installed during the 1996/1997 shutdown, 36 copper cavities were removed. The numbers of cavities in LEP for 1997 running were 84 copper, 16 niobium and 224 niobium/copper, giving a maximum available accelerating voltage of 2645 MV.

3. RF SYSTEM OPERATION DURING 1997

3.1. New for 1997

As well as the addition of the superconducting cavities and the removal of the copper, several other modifications were made to the RF system for 1997. The 200 W loads for the higher order mode (HOM) couplers were replaced by lossy cables. This was because several loads were destroyed in the previous year with peak power. There were also problems in 1996 with the coaxial components between the klystrons' circulators and the 300 kW coaxial water loads. They were provoked by the large transients in reflected power during abrupt switch-off of RF power and the first manifestation of the problem was arcing in a coaxial bend. In two cases the consequence was circulator damage. These bends have now been replaced by waveguide bends and the coaxial transformers between waveguide and load have been removed.

Vector sum feedback,[5] already available in 11 RF units in 1996, was installed throughout. This RF feedback loop provides fast stabilisation of the sum of the cavity fields in the unit. The cavity fields are sampled individually with antennae and then summed vectorially. This sum signal is subtracted from a reference value and the error signal drives the klystron. The reference signal can either be controlled locally or set by a programme that controls the entire circumferential voltage.[6] Slow control of the cavity field amplitude sum via the klystron modulator is still available and an RF unit can be changed from one system to the other with a short intervention. The main advantages of the vector sum loop are:

- Reduction of total cavity impedance at the fundamental frequency and improved beam stability.
- Concealing cavity oscillations from the beam.
- Fast correction of transients. An over-voltage transient occurs when there is beam loss. An under-voltage transient can occur if another RF unit trips, due to the rapid change in stable phase angle.

Because of its fast reaction time, the system is very sensitive to transients. Experience has shown that the RF trip rate is higher in units equipped with vector sum feedback. This year, a maximum of 10 units were running with vector sum feedback.

In addition to the above modifications, numerous smaller hardware and software changes were made with the aim of improving operational performance and reliability.

3.2. Operational Procedure

From an RF standpoint, it is preferable to inject and accumulate beam with all RF units on and with a high synchrotron tune. This is for two reasons. Firstly, this avoids problems of switching on units at higher energies and saves time (the thermal tuning of a cavity can be slow). Secondly, setting the unit minimum accelerating voltages as high as possible can avoid problems due to the malfunctioning of voltage or tuning loops (in a badly phased cavity the field may drop to zero). During this year's operation, injection has typically been with a circumferential voltage of around 380 MV. A pause in the energy ramp is made at 87 GeV where the quantum lifetime is still high and there is sufficient reserve in accelerating field that beam loss due to RF unit tripping is very unlikely. It is necessary because the cavities have a strong tendency to oscillate ponderomotively at high fields and with large detuning angles. The oscillations are removed by adding tuning offsets to the cavities (see Section 3.4.3). The RF voltage is then ramped to its final value, the oscillation levels are again checked and any further adjustments made. Only when the RF system is stable is the energy (bending field) ramped to its final value, normally 91.5 GeV. The criterion for choosing this energy was that, in the typical situation of 95% of the total nominal field being available, the quantum lifetime should be sufficiently high for the beam to survive a simultaneous trip of two klystrons (maximum 164 MV lost). Only 15 physics fills were limited at 91 GeV because an RF unit was unavailable. The beams are then brought into collision and physics coasts proceed from 5 to 8 h. The turn-around time injection, accumulation, RF adjustments, collisions reduced throughout the course of the year and was $1\frac{3}{4}$ h on average.

3.3. Statistics

Some statistics for the operational performance of the LEP RF system for the last two years are given in Table I. Notwithstanding the additional 64 superconducting cavities, the reliability has improved in 1997. The proportions of both machine down time due to RF faults and lost physics fills due to RF unit trips have decreased. The improvement is due both to experience obtained in running this large system as well as to numerous hardware and software modifications.

TABLE I RF system performance during 1996 and 1997 physics runs

	1996	1997
Fills not leading to physics due to an RF trip	16%	11%
Down time due to RF	22%	10%
Successful physics fills	111	198
Physics fills lost during coast	39	46
Physics fills lost during coast due to an RF trip	24	19

3.4. Limitations

3.4.1. Cavities Running below Nominal Field

One of the Nb/Cu modules was exposed to nitrogen in a vacuum accident during the 1996/1997 shutdown and could not be fully recovered after conditioning and helium processing. It has been limited to 4 MV/m throughout this year. For most of the year, three Nb/Cu cavities were completely detuned, two due to helium pressure rises and one due to an intermittent tuning problem. The four Nb modules are run at 3.6 MV/m due to helium pressure rises. The copper system is missing about 30 MV. This is mainly due to one unit where a power coupler had to be replaced and requires further conditioning. Other miscellaneous problems have occurred and been resolved throughout the course of the year. Globally, about 95% of the total specified field has been available for acceleration at any one time.

3.4.2. Electron Emission

Radiation detectors are mounted at the ends of each of the modules installed in LEP. The level, rising sharply with field, is typically around 5–10 krad/h at 6 MV/m. However, in some cavities it can be as high as 50 krad/h and is accompanied by abnormally high thermal losses. Pulse and helium processing have both been effective in reducing the radiation level in such cases.

3.4.3. Ponderomotive Oscillations

Many of the cavities are prone to oscillate at around 100 Hz and with field amplitude variations up to 100%. The mechanism for the instability is as follows. A change in field level results, via the Lorentz force, in a cavity deformation. This shifts the cavity's resonant frequency, which in turn leads to a field level variation. The instability threshold is inversely proportional to the square of the cavity field and to the tangent of the detuning angle. The latter, for a conventional cavity tuning loop, is proportional to the beam current. In operation, the cavity fields are observed at 87 GeV and a phase offset is added to the tuning loop of any unstable cavity reducing the detuning angle until the oscillation is eliminated. This procedure is performed on a cavity by cavity basis and must be repeated after any significant increase in beam current. A computer programme has been developed this year that performs these adjustments automatically.

An alternative is to avoid these oscillations by running the cavities on tune, irrespective of beam current. With this aim, a novel tuning system is being developed which employs synchronous detection of a 40 Hz modulation applied through the cavity's tuner bars. First tests with beam are positive and operational implementation has now to be studied.

3.4.4. Cavity HOM Power

Each superconducting cavity is equipped with two HOM couplers.[3] These have been tested to 850 W and are not expected to limit the operation of LEP. However, ten modules were installed with flexible cables between coupler and cryostat wall and their connectors limit permissible HOM power to 300 W per coupler. Measurements have been made of HOM power in LEP in order to determine whether or not these cables should be replaced.[7] The measurements, with four bunches in each beam, indicate that the limitation is not reached before 8 mA total current. If these same results were extrapolated to LEP operation with bunch trains (four trains of two bunchlets per beam) then, in the most pessimistic case of coherent addition of fields, the total current could be limited to 5.6 mA. Consequently, these cables will start to be replaced during the next shutdown. This is a considerable task since it requires removing the modules from the LEP tunnel.

3.4.5. Cryogenic Losses

Higher than expected cryogenic losses have been observed in the LEP cavities during operation and a series of measurements was undertaken to ascertain their origin.[8] They were found to be proportional to the square of the bunch current and to increase sharply with reducing bunch length. HOMs in the cold, but not superconducting, inter-cavity bellows have been identified as one cause.

At present 92 W/cavity is available for cooling the dynamic load in the worst case. Without beam, the cavity dissipates 70 W at a field of 6 MV/m and there is sufficient reserve for a total beam current of 6.7 mA in four bunches per beam. When the final modules are installed, this limitation would drop to 5.2 mA. In order to remove these constraints to both beam current and operating gradient, the cryogenic system will be upgraded and an extra 6 kW cooling will be provided at each interaction point.

3.4.6. Spread in Cavity Fields

Large spreads in the fields of cavities fed by the same klystron have been observed. For a unit average of 6 MV/m, some cavities run at 7.5 MV/m. It is not just at high fields that the spread in fields is problematic. During accumulation, some cavity fields can drop to near zero impairing the proper functioning of the tuning loop. There are a number of reasons for these variations. There is a spread in the loaded Q values of the cavities and the power distribution via the magic tees may not be uniform. Beam dependent field variations arise from differences in waveguide electrical lengths, reflections in the waveguide system and the finite directivity of the directional couplers used for obtaining the tuning reference signal. A major source is believed to be the waveguide electrical length variations and a campaign is under way to quantify them accurately and to correct for them by adding capacitive posts in the waveguides. For reasons of precision, the preferred method for this measurement is to use the beam as a reference. The maximum phase difference found to date is 16° between two modules.

The field in one cavity having a too high loaded Q and running at 7.5 MV/m has been reduced by placing a $\lambda/4$ transformer plate in the waveguide.

3.4.7. Miscellaneous

The RF system presently contains 324 cavities and 44 klystrons. The electronics associated with them is contained in 500 19″ racks. There are over 9000 interlocks which can trip an RF unit or its high voltage power supply. It is therefore not surprising that a variety of problems occur due to equipment failure and software bugs. From the start of operation, there has been a continual programme of identifying and eliminating weak points. This has contributed significantly to the improved reliability of the overall system.

4. FUTURE PLANS AND CONCLUSIONS

This year has witnessed the coming of age of the LEP2 RF system. The vast majority of cavities is now installed and is running at nominal gradient. The system has performed reliably in physics fills at 91.5 GeV throughout the year. With this success comes the question of whether or not the operating gradient of the Nb/Cu cavities can be increased above 6 MV/m. Clearly, several of the limitations mentioned above put severe constraints on any increase and this question presently remains unanswered. However, a principal motivation for the efforts being made to tackle these limitations is the hope of making a modest increase in gradient.

In the forthcoming shutdown, 36 copper cavities will be removed to make room for the installation of eight additional superconducting modules. The modification of the modules with flexible HOM cables will commence. There will be time to remove four modules from the tunnel, modify them and reinstall.

The LEP2 upgrade will culminate during the 1998/1999 shutdown with the installation of the final four modules. This will bring the total circumferential voltage to 3030 MV. At the same time, the cryogenic upgrade will be completed.

Acknowledgements

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