OPERATIONAL EXPERIENCE WITH THE LEP2 SC CAVITY SYSTEM

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Abstract

The LEP energy upgrade programme (LEP2) consists of increasing the e^+e^- colliding beams' energies far beyond the W pair production threshold, up to 96 GeV. The large increase in accelerating voltage required, from 250 MV for LEP1 at 45 GeV to 2700 MV at 96 GeV, will be provided by 272 superconducting (sc) cavities. Almost all are of the Nb/Cu type, with a nominal accelerating field of 6 MV/m at 352 MHz. A first set of 56 sc cavities was installed during 1995 and made possible a short physics run at energies of 65, 68 and for a short time 70 GeV. The experience gained during this run, as well as that obtained previously on the machine, will be presented. The cavities and their upgraded ancillary equipment worked satisfactorily at their nominal field and with the LEP beam currents (~ 7 mA). Apart from the usual problems of debugging many new pieces of equipment, the difficulties encountered were microphonic oscillations, together with effects due to the much larger impedance at the RF frequency. An RF feedback working on the vector sum of the signals from the eight cavities driven by a common klystron has been implemented to address these problems. The next steps towards the completion of the LEP2 programme will also be presented.

1 INTRODUCTION

LEP, the largest particle accelerator in the world, is an electron-positron collider located close to Geneva (Switzerland). It started operation in 1989 at a collision energy of 45 GeV (the Z_0 energy) with a room-temperature RF system (using the storage cavity technique) [1] capable of delivering up to 340 MV at 352 MHz.

LEP was however conceived from the very beginning as a machine with an energy capability much higher than the Z_0 energy. This requires much more RF voltage, because of the very steep increase in synchrotron radiation losses. The so-called LEP2 programme was aimed at reaching at least the energy of W pair production and to go even beyond. It is essentially based on the superconducting (SC) cavity technology developed at CERN since 1979.

The basic choices for the LEP SC cavities were made early in the project: 352 MHz frequency (for compatibility reasons and to minimize the critical transverse impedance of LEP), four-cell structure with couplers on the beam tubes, 4.5 K operating temperature, modular cryostat with easy access to the cavities and ancillary equipment, thermal and magnetostrictive tuners inside the cryostat. It was also decided that industrial firms would produce the SC cavity modules. The major difference, when compared to other large SC cavity projects (notably CEBAF) is that the cavities would be specified and accepted by CERN according to their RF performance (RF quality factor at the design accelerating field), as measured by CERN.

A pilot project of 20 niobium (Nb) cavities was started in 1989 to evaluate the feasibility of LEP2 SC cavities. Four modules (16 cavities) from this project will finally be installed at Point 2 of LEP. In the meantime the niobium-copper (Nb/Cu) technology developed at CERN became mature enough to justify the decision to base the LEP2 programme on Nb/Cu cavities [2]. Their inherent advantages — much better thermal stability against quenching, savings on Nb material, insensitivity to small magnetic fields, higher quality factor, the possibility of replacing the Nb coating by a better one in the future — were decisive in making this choice.

2 THE LEP2 SC CAVITIES

Table 1. LEP2 cavity parameters

Frequency	352.209	MHz
Operating field	6	MV/m
Operating voltage	10.2	MV
Number of cells	4	
Effective length (four cells)	1.70	m
Modular length (between cryostat flanges)	2.82	m
R/Q ($R = V^2/2P$)	232	Ω
Field flatness tolerance $\delta E/\langle E \rangle$	±5	%
Q_0 at operating field (4.5 K)	$>3.2\times10^9$	
RF losses at 6 MV/m and 4.5 K	<70	W
Cryogenic standby losses per complete module	<90	W
Q_{ext} of RF coupler (nominal)	2×10^6	

As shown in the parameter list of Table 1 [3], the major design objective of the LEP2 SC cavities is their nominal accelerating field of 6 MV/m (10.2 MV per four-cell cavity). At the operating temperature of 4.5 K the quality factor of the cavity is larger than 3.2×10^9. This is obtained with the niobium copper technology where a thin film of Nb material (1.5 µm average thickness) is sputtered on to the inside of a copper cavity using a magnetron discharge [4].

The most critical operations are indeed the preparation of the bare cavity before sputtering and the Nb coating itself. Observed defects are often the lack of coating adherence of the Nb film ("peel-off") or surface irregularities probably linked with the Cu substrate metallurgy and preparation. A defect of a few square millimetres on the 6 m^2 surface of a cavity can completely spoil the performance! It has been observed that most of the cases of "peel-off" of the Nb film are strongly related to staining by chemical products which have not been correctly rinsed off. Very careful control of procedures during chemical polishing is absolutely necessary, as well as thorough maintenance of the chemical installations.

The CERN acceptance specifications for bare cavities ($Q_0 = 3.4\times10^9$ at 6 MV/m and 4.5 K) are fairly close to the best performance ever achieved in Nb/Cu cavities at 352 MHz. Therefore a significant fraction of the cavity production has to be recovered by helium processing (as part of the acceptance procedure), possibly by rinsing and in difficult cases by replacement of the Nb layer.

If helium processing and rinsing are not successful in recovering a cavity which did not meet specifications, the defective Nb layer is chemically removed at CERN and the cavity returned to the manufacturer for a second or even a third coating.

After the intermediate step at CERN, where the quality of the Nb coating is verified, the cavities are returned to industry for assembly into modules (four cavities in a common cryostat). The critical operation is the connection of the large diameter (Ø = 24 cm) beam tube bellows in a class 100 clean room. After assembly of the ancillary equipment (tuner, helium piping etc.) inside the cryostat the modules are sent to CERN for final acceptance, without the HOM and RF couplers.

3 RF COUPLERS

The RF coupler of the LEP2 cavity is located on the enlarged beam tubes at the end of the four-cell structure. The open end of the inner conductor of a 75 Ω coaxial line protrudes slightly inside the tube, close to the end cell. At the other end of the line a cylindrical RF window is part of the waveguide-to-coaxial transition.

While the inner conductor of the line is all along at ambient temperature (air cooled), the outer one is submitted to the full temperature gradient from cavity to outside. It is made of a thin-walled stainless-steel tube, copper-plated by sputtering and cooled by helium gas. To avoid any welds in this critical area the tube and its end flanges are machined out of a single forging.

The major problem found with this type of coupler is multipacting (resonant electron loading) in the coaxial line [5]. Simple calculations and simulations have shown that one-sided multipacting occurring on the outer conductor of the line is by far the most critical.

To completely suppress any multipacting in the coaxial line during operation of the couplers a d.c. bias voltage of +2.5 kV is applied to the inner conductor. In this way no resonant electron discharge can occur.

There must be a blocking capacitor in the doorknob transition to separate RF and d.c. paths. The final version is a coaxial capacitor which can be easily exchanged without dismounting the doorknob.

The RF window has been considerably improved compared to the original design derived from LEP copper cavities. The aim was to reduce RF heating (and subsequent outgassing) of the window, and was achieved by better brazing of the kovar ferrules on the ceramic, by better contact of the (copper-plated) ferrules to the copper body, additional air-cooling and improved titanium coating of the ceramic.

It is well known that RF couplers and windows need conditioning before operation. All LEP2 couplers are conditioned on a warm bench test where two identical couplers are connected to a strongly overcoupled copper cavity. RF power is transmitted through the two couplers in a travelling-wave mode. Processing of the couplers (with the local coupler vacuum used to control the RF power) takes a few days to reach the 200 kW level. Conditioned couplers are later installed on the SC cavities in a clean room.

It has been found that the already processed couplers (on the warm bench) had to be reprocessed (often for much longer) on the cold cavities, a phenomenon called "deconditioning". This is due to the gas molecules adsorbed by the ceramic when exposed to air, which are released by RF heating. They become trapped on the cold surface of the outer conductor of the line and considerably increase the secondary emission coefficient of the surface. The solution to this problem is to bake *in situ* the windows before cooling down the cavity. The outer conductor of the line is cooled last to avoid trapped molecules on its critical surface.

It must be mentioned that, even if d.c. bias completely suppresses multipacting during operation, conditioning (without d.c. bias) is absolutely necessary to avoid catastrophic discharges in case of capacitor failure.

The critical parameter of the RF coupler is the peak electric field which determines the multipacting levels in the coaxial line. Some LEP2 power couplers have been tested, on a cold cavity, up to 450 kW equivalent power (power of a travelling wave which would produce the same peak electric field) much larger than the nominal value of 110 kW.

4 HOM COUPLERS

Each LEP2 cavity is equipped with two higher-order mode (HOM) couplers. They are of the "hook" type [6] where a series notch filter at the RF frequency is established with the inductance of the "hook" and its capacitance to the wall port. This type of HOM coupler is better suited to the Nb/Cu technology of LEP2 cavities. Liquid helium fills the hook tube (niobium material) to keep the notch filter elements superconducting. Adjustment of the notch frequency can be made outside the machine vacuum by elastic deformation of the base of the hook.

The power transmission capability of the HOM assembly is limited, not by the HOM coupler itself but rather by the connecting line, inside the insulation vacuum, between the cold coupler and the warm cryostat enclosure. The solution adopted is to use a rigid 25 Ω coaxial line consisting of two thin-walled stainless-steel tubes, copper-plated. Finger contacts at either end of the tubes allow some mechanical flexibility during the cryostat cooldown. It has been demonstrated experimentally that more than 850 W can be transmitted through the HOM coupler and its line, at 630 MHz (frequency of the dominant longitudinal HOM of the LEP2 cavity). This figure is beyond what is expected in LEP2 operation.

Initial measurements of power deposited by single bunches in the HOM coupler loads have confirmed the expected value of the loss factor of the cavities (0.44 V/pC at $\sigma_s = 16$ mm, excluding the fundamental). With several bunches in the machine, the dominant HOM fields are not completely damped at the next bunch passage; therefore coherent addition of fields from several bunches may occur, leading to an obvious increase of HOM power. Such occurrences have rarely been observed during LEP operation; the associated power increase remained well within the HOM coupler capability.

Above 2.2 GHz (cut-off frequency of the 10 cm diameter beam tube) HOM power may propagate outside the SC cavity module. Using calorimetric measurements on RF ferrite absorbers installed in the LEP vacuum chamber (one close to an SC module, one far away), the first experimental evidence of HOM power radiated outside the SC modules was obtained.

5 ACCELERATING FIELD

It is well known that the maximum accelerating field attainable in SC cavities is limited by thermal quenches or electron emission. In contrast with the two niobium sheet LEP2 cavities (over the 12 tested) which are clearly and reproducibly limited by a thermal quench below 6 MV/m, there are no such obvious limitations on the many more Nb/Cu cavities accepted at CERN. However, two cavities should be mentioned out of the 140 tested in the LEP tunnel, which are, at present limited to 3-4 MV/m by a very strong loss of Q_0, which was not apparent during the test in the surface. For scheduling reasons, these cavities cannot be taken out of the machine for further inspection and analysis, and therefore no explanation for their behaviour is available yet.

In LEP, the most frequent field limitation of the SC cavities is electron loading, diagnosed by the radiation levels measured at the end of a module, 13 cm off axis. Helium processing is often used during the module reception tests (without HOM and RF couplers mounted) where maximum fields of 7 or 8 MV/m are currently reached (limited by the available RF power). After installation of RF and HOM couplers, helium processing is no longer employed.

The complete modules are processed with a 1 MW klystron before and after their installation in the LEP tunnel. As long as the outer conductor of the RF coupler line is not cooled, pulsed power processing is employed to avoid excessive heating of this element (pulse length 10-12 ms, repetition ~ 150 ms). Usually, conditioning of a module, up to peak fields of 6.5-7 MV/m takes a few days. After cooling down of the coupler line, CW RF conditioning is attempted, with coupler vacuum (no d.c. bias on the coupler), radiation level or helium pressure as regulating parameters. Radiation levels up 40-45 krad/h as measured on the detector are accepted during CW conditioning. Pulsed power processing is often needed at this stage to complete the conditioning of a module. Peak fields are limited to 7 MV/m and peak radiation levels to 70 krad/h. It has been observed that radiation levels are proportionally higher when the four cavities of a module are operating together and that the secondary electron spectrum extends up to 40 MeV. At the end of the processing typical radiation levels at 6 MV/m are below 20-30 krad/h.

To recover the performance of the cavities, even when installed in the tunnel, pulsed power processing is very useful. However, this puts some additional strain on several elements of the RF system. When RF power is abruptly switched off at the end of the pulse, the electromagnetic energy stored in the cavities flows back to the circulator load, giving a peak reflected power of about 1 MW. After pulsed power processing, some arcing was observed in the waveguide to coaxial transition and coaxial bends located in the load arm of the 1 MW circulator. A new design, with waveguide bends and a straight 10 Ω waveguide to coaxial load transition has been successfully tested with MW pulses and is being implemented in LEP.

When pulsed power processing is applied, it is suspected that brief discharges occur in the HOM coupler, during which time large bursts of fundamental RF power may flow outside the coupler whose notch filter becomes temporarily detuned. A number of HOM loads (thin film type, not designed to accept overrated power bursts) have been found burnt. The adopted solution is for the HOM couplers to be connected to their loads via long lengths (> 150 m) of lossy RF cable.

In LEP, where eight cavities are driven by a common klystron, the fields in all cavities are not exactly equal, which means that to obtain the average nominal field of 6 MV/m, some cavities must run at a higher field (up to about 7 MV/m). Disregarding probe calibration errors (which cannot be completely excluded at this stage but which will be checked with beam systematically) the spread in cavity fields comes from the spread in Q_{ext} and the imperfect balance of the waveguide distribution system. The latter depends critically on the VSWR of the matched loads in the fourth arm of the magic-Ts. This is being improved by replacing demineralized water loads by salt-water loads.

Typical Q_{ext} dispersion (±10 to ±15%) can be attributed to mechanical tolerances which affect the field distribution in the cavities. The specified tolerance for field flatness (±5%) has been verified with beam on a number of cavities by comparing the amplitudes of the four excited cavity modes.

For the few cases where a larger deviation of Q_{ext} has been measured, a $\lambda/4$ transformer in the long waveguide section is employed. The transformer is a simple metallic slab $\lambda/4$ long bolted inside the waveguide and whose thickness and longitudinal position are determined by the Q_{ext} error to compensate. Such a transformer has already been successfully tested, even with beam.

Cryogenic measurements have been used to evaluate the average RF losses of a module at its operating field. The results are in agreement with the specified Q_0 at 6 MV/cm. Although there is at present excess cryogenic capacity as not all cavities are installed, the safety margin for the final LEP2 (about 20%) is not very large.

6 STABILITY

The total cavity impedance at the RF frequency increases from about 10 GΩ for the original 45 GeV to 135 GΩ for LEP2. This is due to the desired higher impedance of each cavity and to the large number of cavities. The consequence is that beam loading plays an important role in the behaviour of the LEP2 RF system, especially at injection energy where the RF voltage is low and radiation damping weak. In particular it can be shown that the operating conditions of the RF system become dangerously close to the threshold of the second Robinson instability.

Coupling from cavity to cavity via the beam has been observed. When the total RF voltage drops suddenly due to the trip of a klystron, the relatively fast increase of stable phase angle causes a voltage loss in the remaining cavities due to the new combination of current vectors and to the limited speed of the voltage regulation loop. In some cases an avalanche effect occurred leading to a complete beam loss.

Optimum cavity detuning to compensate the reactive part of the beam current is automatically ensured by the tuning system which, normally, keeps the RF drive and cavity voltage in phase. A very important effect of cavity detuning is the onset of electroacoustic instabilities, also called ponderomotive oscillations [7]. Low-frequency (~ 100 Hz) modulations of the cavity voltage have been observed during operation with beam. Some of them could be attributed to mechanical vibrations (microphonics) of the cavity excited by outside sources (notably the cryogenic system); others were intrinsic to the cavity and gave large phase and voltage modulations (up to 50%).

It is known that in high-field cavities the resonance frequency depends slightly upon the RF field (radiation pressure effect). This effect (proportional to V^2) measured on LEP2 cavities in static conditions corresponds to about -35 to -70 Hz at 6 MV/m and can easily be corrected by the tuning system. This is not the case, however, in the vicinity of the first mechanical longitudinal resonances of the cavity (the first two resonances are at ~ 95-105 Hz). Any cavity voltage perturbation in this frequency region is transformed into a tune modulation of the cavity, which in turn modulates the cavity voltage whenever there is a static detuning of the cavity.

Changing the cavity parameters (e.g. position and damping of mechanical resonances) or trying to compensate by active means (feedforward or feedback) looks very difficult. The instability growth rate is proportional to the square of the accelerating voltage (radiation pressure) and to beam current (cavity detuning) and would severely limit the LEP2 cavity performance with beam.

The only practical solution is to run the cavities at a detuning angle which is not optimum, by changing the set point of the tuning loop phase detector. This has been shown to be an effective solution for suppressing instabilities. The RF power needed for a given voltage and beam current increases when deviating from optimum detuning. The excess power remains modest (4.25 kW per cavity at 90 GeV and 10 mA) even if the cavity is run on tune. However the peak field in the main coupler increases; the equivalent coupler power becomes 160 kW at 90 GeV and 10 mA beam current which is still within the capability of the LEP2 couplers.

A fast RF feedback system is being implemented on all modules now installed in LEP. The total RF voltage seen by the beam when crossing the eight cavities driven by a common klystron is reconstructed from the field-probe signals of each cavity. Great care must be applied to the calibration of the probes and cable connections (in amplitude and phase) to ensure that the overall vector sum signal is a faithful representation of the RF voltage experienced by the beam. The “vector sum” signal is maintained equal to the demanded RF voltage by the action of an RF feedback loop.

A klystron phase loop which keeps the phase at the output of the circulator constant with respect to the feedback error signal has been added. With it the vector sum feedback does not have to compensate the klystron phase variations. This loop has been made slow in order to avoid unwanted couplings with the vector sum feedback loop. A second slow loop which varies the klystron current as function of output power has also been added. This loop keeps the klystron collector dissipation below about 700 kW and acts as an energy saver by keeping the klystron current low when the required output power is low.

The open loop gain of the vector sum feedback RF loop has been adjusted to 26 dB for a klystron current of

10 A but it varies linearly with the klystron current. It is actually limited by the precision with which the vector sum can be constructed.

The loop gain is sufficient to reduce the equivalent impedance of the SC cavities so that cavity coupling via the beam becomes negligible and the operating conditions of the RF system remain far from the Robinson threshold. The phase deviations of the cavities (either from residual microphonics or from various phase settings of the servo tuners) are corrected by the fast RF feedback, as well as the cavity overvoltage when the beam is suddenly lost.

Vector sum RF feedback, which is more sensitive to noise and transients in the low-power part can easily be replaced if needed for a few units by the conventional control system in use with the copper RF system of LEP. Here the drive level is kept constant at a level which saturates the klystron to obtain maximum efficiency. In this case the cavity voltage which is controlled via the klystron current by action on the modulation anode, can only be changed slowly.

To avoid conflicts between the klystron phase loop and the vector sum feedback at switch-on the latter will not be turned on before the klystron phase loop has stabilized and the cavities are tuned. During this time the klystron drive level is kept constant with a limiter in front of the driver amplifier. When the vector sum feedback is switched on, transients are avoided by keeping the operational conditions such that the limiter still determines the drive level. The loop gain is then virtually zero. The current in the klystron is then gradually increased and at a certain level normal operating conditions are established.

With high beam current the switch-on procedure is more complicated because the useful range of the tuning system can be considerably reduced. An unstable situation is avoided by changing the unit phase in such a way that the generator voltage is in opposite phase to the beam-induced voltage. If the power from the generator is sufficient there is no ambiguity for the tuning system.

7 THE 68 GEV RUN AND FUTURE

With 14 newly installed SC modules in LEP and about 800 MV of available RF voltage altogether, a high energy physics run was carried out during a period of three weeks in autumn 1995. After a rapid setting-up and some 45 GeV physics, the world's first e^+e^- colliding beam physics at 65 GeV took place on 31st October 1995 with an initial luminosity of about $10^{31}cm^{-2}s^{-1}$. LEP ran at 65 GeV for the first part of the run, and after a short period where 70 GeV was reached, the energy for the rest of the run was set at 68 GeV.

It was decided that the new RF system would be operated very cautiously by limiting the klystron power and thus the beam current (2 mA per beam). Only at the end of the run 5.8 mA total beam current was put into physics at 68 GeV, giving a peak initial luminosity of $3.4 \times 10^{31}cm^{-2}s^{-1}$. The maximum stored beam current was 7 mA, not during a physics run.

The SC cavities operated on average at their nominal field of 6 MV/m. Most of the problems encountered during the physics run were due to a few newly installed RF units (klystron and interlocks) which obviously needed more debugging time. Cavities prone to ponderomotive instabilities were operated with a constant offset in the tuner detector and several units ran with vector sum feedback.

During the long shutdown from December 1995 to June 1996, the impressive number of 21 additional Nb/Cu modules have been installed and successfully conditioned in the LEP tunnel. The operating energy in summer 1996 will be 80.5 GeV, at the threshold of W pair production, as required by physics. Future steps are indicated in Table 2.

Table 2 Number of cavities in LEP and available voltage

	June 96	*Oct. 96*	*May 97*	*May 98*
#Cu cav	120	120	86	52
MV Cu	300	300	215	130
# Nb cav	4	12	16	16
MV Nb	34	102	136	136
#Nb/Cu cav	140	160	224	256
MV Nb/Cu	1434	1638	2294	2621
Σ MV max	1768	2040	2645	2887
ΣMV operat	1600	1873	2478	2720
E GeV	84.1	87.5	93.9	96.1

In conclusion, the success of the 1995 high-energy run augurs well for the future steps of LEP2 and in particular for the first W pair production at LEP which, we all hope, should happen shortly after the closure of this Conference. Finally, it is a pleasure to associate to this presentation all the team who engineered, constructed and put into operation the largest superconducting RF system in the world and whose competence, dedication and long-lasting enthusiasm were essential to its success.

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