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The LEP Superconducting RF System

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Abstract

The basic components and the layout of the LEP RF system for the year 2000 are presented. The superconducting system consisted of 288 four-cell cavities operating at 352 MHz powered by 36 klystrons providing on average of 0.6 MW of RF power. This system was complemented by 56 cavities of the original copper RF system. A total accelerating voltage of 3630 MV could be provided routinely allowing operation up to 104 GeV. The installation schedule of the superconducting cavities is shown and comments are made about the evolution of the system over the years. The performance and the reliability of the final system are described.

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1. DESCRIPTION OF THE SYSTEM

The superconducting rf system [1,2,3,4] of LEP consisted of 288 four-cell standing wave cavities which operated at 352 MHz and had an active length of 1.7m (2 lambda rf). The first 16 cavities were constructed of solid Nb and had a nominal accelerating gradient of 5 MV/m. All the other cavities were made of Cu with a thin film of Nb sputtered on the cavity walls, a technology developed at CERN [5,6]. The nominal gradient for the latter cavities was 6 MV/m. The Cu substrate gives a high mechanical stability and makes the cavities virtually quench-free due to its high thermal conductivity. The cavities were mounted in groups of four in one cryostat, called a module. They were immersed in a liquid He bath at 4.5K. The He was provided by four large cooling plants with a total of 53 kW installed power [7]. Fig. 1 shows a cavity in the cryomodule.

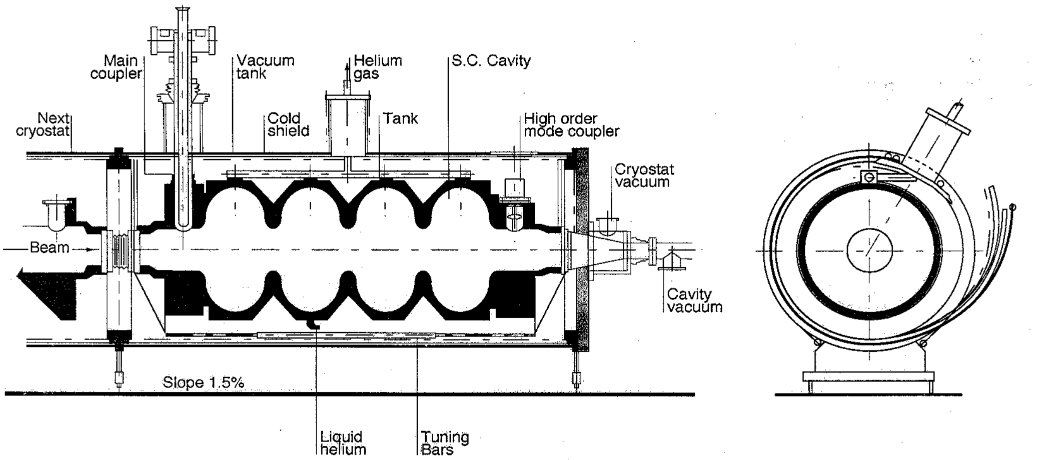

FIG. 1: Superconducting cavity in module.

Eight cavities were fed by one klystron which was rated for 1.1 or 1.3 MW cw operation. Two klystrons shared one common dc power supply. Circulators protected the klystrons against excessive reflected power. Initially, LEP started with only a copper rf system [8] which consisted of 128 five-cell standing wave cavities. Two klystrons powered 16 cavities. In order to make space for the sc rf cavities, a number of Cu cavities has been removed so that finally only 56 cavities remained powered by eight klystrons. They provided a total maximum voltage of 140 MV and typically 130 MV. The rf system was installed in the four even-numbered long straight-sections of LEP, symmetrically arranged around the mid-point where the large LEP detectors were located. Table I gives the layout of the cavities in LEP in the year 2000. The 16 solid Nb cavities were located on one side of straight section 2.

Table I. Layout of the LEP acceleration system.

Straight section	sc cavities	Cu cavities
2	64	28
4	80	
6	64	28
8	80	

II. INSTALLATION SCHEDULE

Fig. 2 shows the installation schedule of the modules. Production of the Nb cavities started in 1991 while the Nb-film cavities were produced from 1992 onwards. Systematic module installation started at the end of 1994 somewhat delayed due to problems with the rf power coupler which were solved in 1994. Installation continued during 1995 and 1996 leading to frequent stops in operation. From the winter shutdown 96/97 onwards the installation only took place during the regular long winter shut downs of the CERN accelerators. The production of the sc cavities ended in the first half of 1998 and the last modules were installed in the winter shutdown 98/99. The last modification of the rf system configuration occurred in the winter shutdown 99/00 with the re-installation of eight additional Cu cavities in order to mobilise all possible reserves to increase the beam energy.

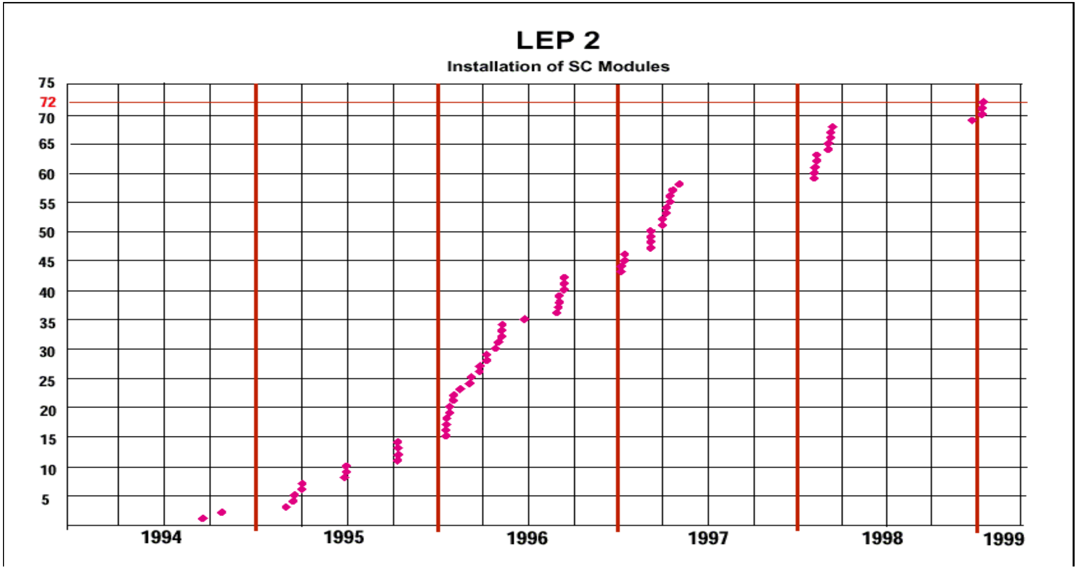

FIG. 2: Installation history of rf modules each containing four sc cavities.

III. SC CAVITY PERFORMANCE

The solid Nb cavities were conditioned up to their nominal gradient of 5 MV/m and operated up to 4.5 MV/m. The Nb-film superconducting rf system reached an average gradient of 6.1 MV/m already in 1996 but was pushed to an average of 7.5 MV/m (6 MV/m nominal) by 2000 mainly by careful, but in the end aggressive, rf conditioning. Field emission was the hard limitation as it led to local heating of the cavity walls and, consequently, to an increase in the pressure of the He bath which triggered a safety interlock. The resulting distribution is shown in Fig. 3.

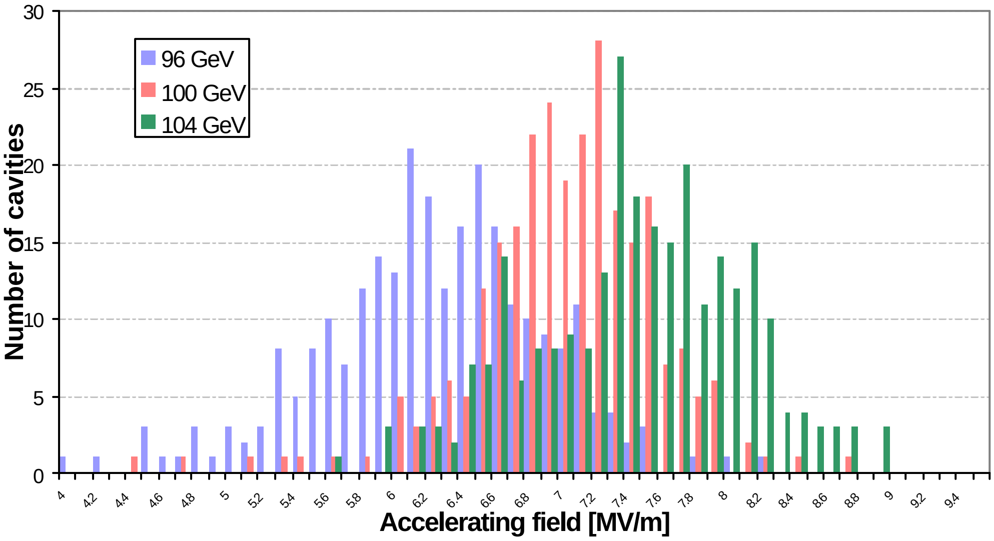

FIG. 3: Number of cavities operating at a given gradient for three different beam energies in 1999 and 2000 [3].

In situ He processing of installed modules had been applied but produced mixed results. It was used in isolated cases but was eventually abandoned due to the inherent risk of damage by the klystron delivering excessive power to the cavity via strongly overcoupled power couplers. A number of ancillary systems were improved and limitations were systematically removed whenever possible. All this required a sizeable and sustained effort often after installation. The following main improvements were made: The voltage control per klystron maintaining the sum of the eight cavity voltages independent of the beam loading was changed to be based on the vector sum instead of the scalar sum for some of the units; The accelerating voltage of the cavities powered by the same klystron was equalized by inserting lambda/4 plates into the waveguide at the appropriate distance before the couplers; this compensated for the spread in the external Q between the cavities; The directivity of the directional couplers upstream of the main coupler was adjusted to better than 30 dB in order to avoid perturbation of the frequency tuning of the individual cavities; The electrical length of the waveguides feeding a group of eight cavities per klystron was adjusted to a precision of about 3 degrees; Electro-acoustic (ponderomotive) oscillations [9] were limited by an active damping system on all cavities making use of the existing tuning system [2]; The cables connecting the HOM couplers to the loads outside the cryostat were replaced by rigid coaxial lines in all Nb-film cavities and by new cables in the Nb cavities in order raise the limit on the beam current imposed by the insufficient power rating of the original cables; All the cables connecting the two antennas in each cavity with the outside control circuits had to be changed because many of them were found to be damaged by HOM in installed cavities; these changes had to be done in situ for 248 Nb-film cavities which was a monumental task; Continuous upgrading of the control system including a GPS timing based diagnostic system for analysis of trips.

The result of this painstaking effort, which extended over many years, is given in Fig. 4 showing the evolution of the installed rf voltage over the years [10]. The installed voltage was constant between 1989 and 1995 when LEP operated at the Z_0 resonance. It can be seen that the available voltage exceeded the nominal voltage after the upgrading of the cryogenics in the shutdown 98/99 because then the accelerating gradient of the Nb-film rf system could be pushed above its nominal value. The concurrent increases in beam energy are also shown in Fig. 4.

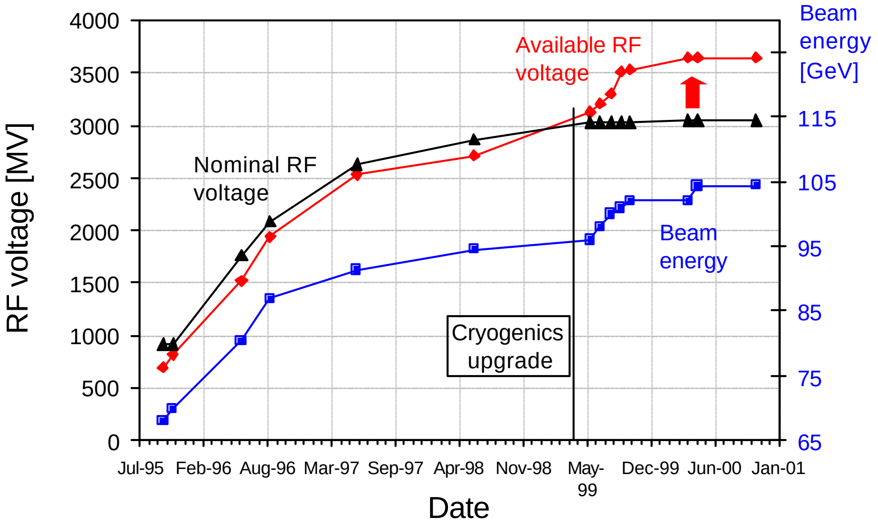

FIG. 4: The evolution of beam energy, available and nominal rf voltage [10].

IV. RELIABILITY

During operation only a few cavities degraded in performance. Six cavities were recovered by rinsing with ultra-pure water and one cavity was recoated with a new Nb-film. The mean time between trips (i.e. one klystron off) (MTBT) was rather independent of the accelerating gradient and the beam current as long as the nominal values (6 MV/m and 6 mA) were not exceeded. Under these conditions the MTBT reached about 2 h. Since the rf system was operated with a voltage margin corresponding to 2 klystrons, trips did rarely result in beam loss. By keeping 2 klystrons in reserve, beam loss by a trip of the common power supply was also avoided. Most of the beams were dumped at the end of the run by the operator. The situation changed drastically in 2000 when the cavities had to operate with 7.5 MV/m on average. The MTBT dropped to 14 min. This operation beyond the safe limits led to equipment damage: arcing in the waveguides led to destruction of several components and damaged three circulators. By the end of the year, 4 cavities were damaged and 3 partially damaged. Hence, they had to be completely, respectively partially detuned.

V. CONCLUSIONS

The excellent performance of this very large superconducting rf system was decisive for the success of LEP at high energy. The capability of the rf system to operate above nominal values lead to an extension of the LEP run into 2000 in order to push the Higgs boson discovery limit to a maximum. Eventually, the beam reached a maximum 104.5 GeV with useful integrated luminosity up to 104 GeV. A wealth of physics results [11] was obtained providing a solid basis for the investigations at the Tevatron and LHC which will take over from LEP. Their results will end the speculation whether full exploitation of LEP by equipping it with the maximum number of cavities which could be supported by the existing infrastructure, would have lead to the discovery the Higgs particle. The rf system together with the rest of LEP has been dismantled in 2001 in order to make space for LHC.

VI. ACKNOWLEDGEMENTS

The successful operation and the excellent performance of the large LEP rf system which was pushed far beyond the nominal performance would not have been possible without the competence, dedication and perseverance of all the members of the RF Group supported by a number of services in the Accelerator and Technical Sector of CERN. I would like to thank P. Brown and G. Geschonke for reading the manuscript and for many useful comments. Thanks are also due to H. Gaillard who provided Fig. 2.

VII. REFERENCES

[1] D. Boussard, Proc. PAC, Vancouver (1997) p.2879.
[2] P. Brown et al., Proc. 9th Workshop on RF Superconductivity, Santa Fe (1999). Report LA-13782-C, p.1.
[3] P. Brown et al., to be published Proc. PAC, Chicago (2001), see report CERN-SL-2001-018 HRF.
[4] P. Brown et al., “The LEP Superconducting RF System”, to be submitted to NIM.
[5] C. Benvenuti, S. Calatroni, and G. Orlandi, Physica B 197 (1994) p.72.
[6] D. Boussard et al., Proc. PAC, New York City (1999) p.946.
[7] Gayet et al., Proc. 8th LEP Performance workshop, Chamonix (1998). Report CERN-SL-98-006-DI.
[8] G. Geschonke and S. Hansen, Part. Accel.28 (1990) p.779.
[9] D. Boussard, P. Brown and J. Tückmantel, Proc. EPAC, Sitges (1996) p.187.
[10] R.A. Assmann, Proc. of the LHC Workshop, Chamonix (2001). Report CERN-SL-2001-003 DI, p.323.
[11] W. Venus, “LEP Summary”, to be published proceedings of EPS HEP Conference, Budapest 2001