

Three years of Operational Experience with the LEP RF system

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Abstract

The LEP copper RF system is characterised by the use of storage cavities coupled to the accelerating cavities; the number of such assemblies installed in the accelerator and the total RF power available. The physical distance between the various elements that makes up the total RF system is also specific to LEP.

The RF system has now been running for more than three years under operational conditions in LEP. We report here on the global operational experience during this period and on the performance of the various elements making up the LEP RF system.

INTRODUCTION

The beams circulated in LEP in July 1989 less than two months after the installation of the last accelerating cavity, and colliding beams for physics started two months later. A full description of the copper RF system can be found in [1], but as a reminder, there were initially 128 copper cavity assemblies installed powered by 16 1MW CW klystrons at 352 MHz. The 128 cavities are divided into 8 Units of 16 cavities each powered by two klystrons. 22 racks of low power and controls electronics have been installed in each Unit. Each of these Units can be run completely independent of each other. There are 230 protective equipment interlocks per unit, where any activated will switch off that Unit but not affect any of the other Units.

In each Unit there are 1342 control points that can be addressed over the control system either locally or remotely.

The cavities are installed around two diametrically opposite collision points [2 and 6] spaced about 13.5 kilometres apart around the circumference of the LEP tunnel. The central control room (PCR) is situated at a physical distance of about 6 KM from pt 2 and 13 KM from pt 6.

Superconducting cavities for the LEP upgrade to higher energies are integrated into the RF system as they are being installed. At present the installed sc cavities are still in a commissioning stage and are not used routinely for operation although some cavities have been used for physics operation for about 700 hours. The part of the RF system involving these cavities is not included in this review.

OPERATIONAL ASPECTS

For a nominal output power of 1 MW from each klystron, the copper system with 128 cavities can deliver a maximum of about 375 MV circumferential volts taking into account the losses in the waveguide system which amounts to about 6% of the total power. The total available voltage was reduced in 1992 when 8 cavities were removed to make room for electrostatic separators for eight bunch Pretzel operation.

The way LEP is normally run for physics will allow one RF Unit to drop out without losing the circulating beams.

Some rapid adjustments to the remaining units to compensate for the lost circumferential volts are normally required. [2] The drop out of one RF Unit is referred to as an "RF trip".

By constant improvements to the equipment reliability, the number of RF trips have considerably decreased since the initial commissioning. Statistics from the operations group show a decrease in lost coasts caused by RF from nine in 1991 to five in 1992. A coast lost due to RF failure requires more than one RF Unit to drop out simultaneously or some abnormality that affects several units. (RF phase jumps, water failure, etc.)

Until 1992 LEP operated with a 60° phase advance lattice and a constant synchrotron tune during the ramp from injection energy of 20 GeV to the collision energy with a Qs of 0.085. For a collision energy around the Z⁰ peak (45.6 GeV), this required the RF system to deliver a maximum of 250 MV circumferential voltage, corresponding to about 450 KW RF output from each klystron with all units operational.

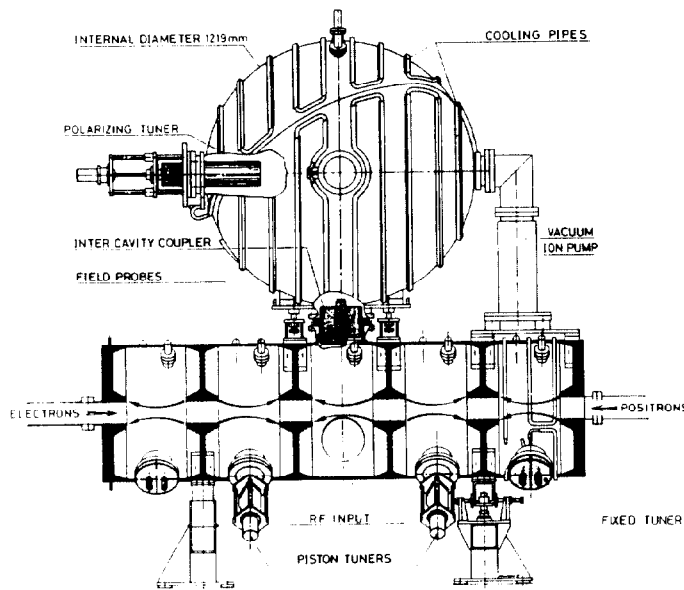
In 1992 LEP was run with a lattice of 90° phase advance with a corresponding change in the momentum compaction factor by two compared to the 60 degree lattice, and therefore doubled the required RF voltage for the same Qs and collision energy. With the presently available RF volts it was no longer possible to keep the Qs constant at 0.085 during the ramp all the way up 45 GeV. So for physics during 1992 LEP run with a lower Qs at the collision energy than in the previous years.

The synchrotron frequencies of the two beams are monitored continuously in the control room. These signals are transmitted from one of the RF Units in the tunnel to the control room via the optical transmission system. The global voltage control system will eventually allow the RF voltage to be adjusted directly as a function of the synchrotron frequency.

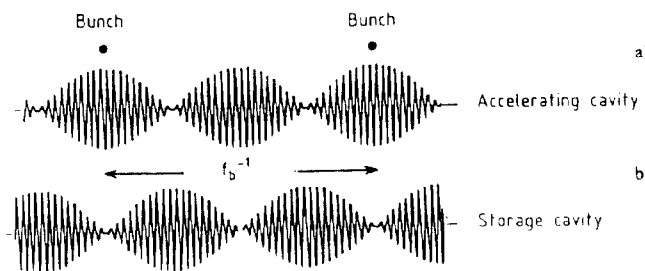
Each of the accelerating cavities is coupled to a low loss spherical storage cavity (fig1). This concept increases the shunt impedance of the accelerating cavities from 26 MΩ/m to 40 MΩ/m and in this way requires less drive power to produce a given accelerating voltage than for a single accelerating cavity. The modulated waveform in the cavities (fig1) set up by the coupled system has been chosen to be two times the bunch frequency for four bunch operation or the bunch frequency for eight bunch operation per beam. For more than eight bunches per beam, one would have to run the RF system with a single frequency and with a correspondingly lower shunt impedance.

The modulated waveform can be shifted in phase with respect to the bunch position at each RF Unit. This possibility was used to run LEP with slightly different synchrotron frequencies for the electrons and the positrons, allowing longitudinal feedback to be applied via the RF cavities to the electrons and positrons independently. In 1992 a dedicated longitudinal feedback system working at 1 GHz was installed and made operational [3].

Energy calibration of the LEP beams by the LEP experiments to a precision of a few MeV imposed a very precise knowledge and stability in time of the RF phase with respect to the beams. Dedicated recording equipment have been installed for this purpose.



One unit of the LEP coupled-cavity accelerating structure



Modulated RF waveforms for a) accelerating cavity, b) storage cavity

Fig. 1

EQUIPMENT BEHAVIOUR

A. The Cavities

Prior to installation in LEP, the assemblies of accelerating/storage cavities have all been baked to 150 °C for 24 hours and RF conditioned up to 140 KW, well above the nominal value of 125 KW. The cavities have not been rebaked after installation.

At present the cavities have about 18 000 operating hours (including conditioning before installation) at various power input levels ranging from a few kilowatts (injection level) to close to one hundred kilowatts (collision level).

Out of the 128 input power couplers, we have changed six which had developed a vacuum leak in the ceramic window. Five of these couplers were all in the same straight section at adjacent cavities and happened after a shut down. We strongly suspects that mechanical stresses set up by distortions to the

waveguide system (someone run into the system with a transport vehicle ?) is the main cause for these leaks.

There are 768 ceramic cups in total installed on the cavities. These cups houses loops used for monitoring and the tuning control system. After some initial problems with vacuum leaks these ceramic cups have behaved reliably.

The 384 active piston tuners together with their drive electronics have performed very satisfactory. So has the rather complex tuning system for the two cavity assembly.[4] Regular maintenance of the drive mechanism for the piston tuners (cleaning and greasing) as well as frequent changes of air filters for cooling fans has reduced trips due to reflections from the cavities and other interlocks related to the cavities.

B. Klystrons and Circulators

The 1 MW CW klystrons working at 352 MHz developed specially for LEP by two European firms [5] have performed extremely well.

Out of the 16 initially installed klystrons, 11 have by the end of 1992 operated for more than 17000 hours in LEP. The five others have been replaced for various reasons during the first 5000 hours of operation, all under guarantee from the manufacturer.

Klystron instabilities that might appear at high output power have not been a problem during these three years of operation. It should be noted however that the required output power from a single klystron rarely exceeds 700 KW for normal LEP operation for physics. Reflected power back into the klystron from the circulator is kept to a minimum and constant by the use of a regulation system that compensates impedance variation in the circulator as a function of the output temperature of the cooling water.

Electrically the 1 MW CW circulators have performed well. However, a weakness in the mechanical design of the water cooling circuit leading to water leaks, provoked some problems early on in LEP operation. This weakness in the design has since been corrected for by the manufacturer.

C. High Voltage Equipment

The maximum operating voltage for the 1 MW klystron is 90 KV. For normal LEP operation, the klystrons are operated either at 77 KV or 88 KV depending on the required output power. The 100 KV high voltage power supply is located on the surface, whilst the high voltage interface equipment sits in the klystron gallery next to the machine tunnel. Neither the power supply nor the several hundred meter long HT cable have ever created any serious problems.

The high voltage interface equipment consist basically of a smoothing capacitor, a modulator connected to the modulation anode of the klystron, series resistors, insulating transformers and a fast acting crowbar device. The various elements are located in separate oil tanks and connected with cables fitted with connectors for easy dismantling.

Initially we considered to use a spark-gap as the crowbar element, based on excellent experience with such a device in the ISR. We did, however, pursue a development in collaboration with EEV to see if a multigap thyatron could be used. Finally we decided to use a five gap thyatron rated for 90 KV. This choice was based on several factors, the main one being its compactness and easy triggering. In the initial design, a rather complex triggering circuit based on semiconductors

was used to insure multi-triggering of the thyatron. This way of triggering the thyatron gave rise to a lot of spurious firing of the crowbar and have since been changed to a straight-forward current transformer. This direct firing of the crowbar has proven to be efficient and reliable, and spurious triggering of the thyatron has by now become very rare.

D. Low power and controls

Two optical fibre links are used for the transmission from the LEP control room (PCR) of RF phase and frequency reference to the RF stations at pt.2 and pt.6 of LEP [6]. These links have a total length of 5.4 km and 7.9 km respectively and uses a total of eight monomode fibres per cable without repeaters. A rather complex transmission system including optical feedback forms part of these links. A maximum phase variation of 800 electrical degrees at 176 MHz has been measured due to length variation of the fibres caused by temperature fluctuations. The feedback system reduces these variation to less than a few degrees.

Spurious phase jumps (glitches) have been responsible from time to time of beam losses. These kind of faults are rather difficult to localise, especially in a huge system like the one in LEP. These phase jumps have in most cases been attributed to the regeneration electronics located in the klystron galleries rather than the optical transmission system. To detect and localise such glitches additional analogue diagnostic equipment have been installed.

Apart from these occasional problems with phase jumps, the low power electronics has turned out to work very reliably. The same approach and design is used for low power high frequency electronics that is being installed for the LEP upgrading with 192 superconducting cavities.

The modular approach [7] for the digital control of the LEP RF system, together with an interactive local control facility has turned out to be vital for the commissioning, testing and operation of the RF system. It also allows for additional units with superconducting cavities to be integrated gradually into the controls system with minimum disturbance to the operation of the accelerator. Over the years a number of improvements have been incorporated into the digital controls

system without modifying the basic concept. Direct Ethernet access to the Data Manager of the individual units together with more powerful processors and corresponding software improvements in the Data Managers have been the most important changes. These changes allow for a permanent logging and storage locally of all important RF parameters and also remotely via the general LEP controls system.

Due to the distances involved, the possibility for direct access to the RF Units from anywhere on the controls network has turned out to be of paramount importance for surveillance and remote fault diagnostics by the equipment specialists.

CONCLUSIONS

To keep a huge high power rf plant like the one in LEP operational around the clock is not an easy task. The importance of reliable equipment is obvious, but a certain built in redundancy is almost as important. This redundancy in the LEP RF system is not only found in the design of the equipment, but also in the modular way the total plant is built up. The fact that the beams in LEP will survive if one RF unit drops out, has made coasts in LEP lasting for 12 hours almost a routine, and more generally beams lost due to RF failure has become less and less frequent.

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