Operation of Superconducting Cavities in LEP

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Abstract

By mid 1991 the first 12 of the planned 192 superconducting 352 MHz cavities for the LEP200 energy upgrade had been installed in the LEP tunnel. They have since been commissioned and integrated into the LEP RF and control systems, where together with the copper cavities they have been used during physics runs. Tests with beam have been done at injection energy, during ramping and at top energy. In particular, the effects of higher order modes induced by the beam, quench detection, cavity tuning and the optimization of switch-on procedure with beam have been studied. This together with experience gained during commissioning and initial operation of the superconducting cavities is described.

1. INTRODUCTION

The superconducting (SC) cavities are all installed in RF unit 233 close to point 2. The schematic layout and numbering is shown in Fig. 1.

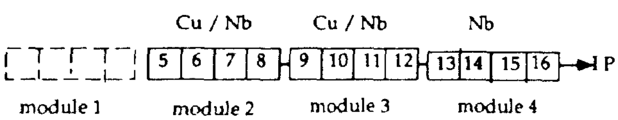

Fig. 1. Layout of the first 12 SC cavities in LEP.

An SC module consists of four four-cell cavities with their individual helium tanks assembled together in a common insulation vessel [1, 2]. In total three such modules were installed, one containing cavities made from solid niobium sheet, the others from copper sheet cavities sputter coated with a thin film of niobium [3].

2. PERFORMANCE

2.1 *Before Installation in LEP tunnel*

The four-cell cavities are all individually tested after production without accessories. Only after they have achieved their design specifications are they equipped with two higher order mode (HOM) couplers, a power-coupler and other accessories. Finally they are assembled into four-cavity modules.

The complete modules are then tested on the surface in a test stand which is an exact copy of the LEP tunnel configuration with respect to RF distribution and controls. Long term testing at high fields was not possible because the installed cryogenic power is only sufficient to test a four-cavity module at the maximum average design field of 5 MV/m for a few minutes. From April 1992 a cooling power of 1.2 KW at 4.2 K will be available and this will allow up to three modules to be tested simultaneously at and above the design field.

A summary of the surface test results obtained for the three modules installed in LEP is shown in table 1.

Table 1.
Results of tests on cavities and modules before installation in LEP.

Module number	*Cavity Number*	*Max Field bare cavity MV/m [4]*	*Max average of module MV/m*
2	*5*	*8.0*	*5.3*
Sputtered	*6*	*7.4*	
Niobium	*7*	*6.5*	
	8	*7.6*	
3	*9*	*6.1*	*5.0*
Sputtered	*10*	*7.1*	
Niobium	*11*	*5.4*	
	12	*6.1*	
4	*13*	*5.4*	*4.7*
Solid	*14*	*5.1*	
Niobium	*15*	*5.1*	
	16	*5.3*	

2.2 *After Installation in LEP.*

After installation the maximum field levels obtained were considerably less than those tabulated above and many hours of conditioning were required to increase them. The design field of 5 MV/m was achieved individually in each of the two sputtered modules and a maximum of 4.4 MV/m in the solid niobium module. These levels however could only be maintained for a few minutes. RF operation was usually ended by an interlock from the electronic quench detector, helium liquid level drop or helium gas overpressure. Also many slow quenches not detectable by the electronic quench detector were recorded. Often after such interlock trips the cavities lost their conditioning and for several hours it was not possible to reach the previously obtained maximum field.

3. Operation

Since September 1991 the SC unit has been regularly used as part of the LEP RF system. During this time a total of 815 hours of operation has been accumulated, out of which 695 hours were during physics.

During physics runs the 12 SC cavities typically contributed 15 MV at injection and up to 56 MV at top energy (102 MV corresponds to the design field of 5 MV/m). During machine experiments the cavities were routinely used up to fields of 74 MV (3.6 MV/m). The maximum field obtained was 89 MV (4.4 MV/m).

By the end of the running period it was considered operationally safe to run the cavities up to a maximum field of 70 MV (3.4 MV/m) .

Throughout the whole running period the SC cavities proved to be as reliable as the copper system. This is particularly important because not only does the SC interlock system act on the SC unit but additionally the second level interlocks from He level-low and He overpressure are directly connected to the LEP beam dump. This interlock was activated three times during the operation period. At low fields trips due to He pressure rises were troublesome. The electronic quench detection system is based on the detection of sudden changes in cavity field. As originally installed the system was found to be too sensitive. Unavoidable fluctuations in individual cavity voltages were sufficient to provoke false trips. At present the system is set to trigger if a decrease in voltage of 24% occurs within 40 milliseconds.

4. Behaviour

4.1 General

Initially the synchrotron tune Q_s was found to vary with accumulated current. This was caused by the beam induced higher-order modes being seen by the detectors of the RF voltage control loop. The problem was solved by the addition of low pass filters in front of these detectors.

The accelerating voltage provided by the SC unit was then checked by measuring the Q_s changes. This confirmed that the calibrations of the RF pick up antennae in the cavities were correct.

Liquid He level instabilities were damped by optimizing operating parameters and procedures of the cooling plant control [5].

4.2 Cavity Tuning

The cavity is tuned by changing the length of three nickel bars which constrict the cavity longitudinally. Narrow range (2 KHz) fast tuning is done by magnetostriction. Thermal expansion is used for wider range (50 KHz) but slower tuning by changing the temperature of the bars [6].

The tuning system operated very reliably and an improved tuning inhibit on idling units prevented beam-induced signals activating the tuning system and thereby detuning the cavities far off resonance.

The open loop transfer function of the tuning control system shows a rapid fall in response and phase rotation due mainly to induced eddy current effects in the nickel bars. The result of this is that for stable operation the cut off frequency of the loop filter must be made less than 0.5 Hz which is much lower than would be necessary to simply avoid exciting the mechanical resonances of the system.

During the early part of 1991 operation was considerably disturbed by frequent trips due to detuning of the cavities caused by bursts of oscillations in the helium pressure. This resulted in variations of up to ±30° in the RF phase. Because of the low cut off frequency of the tuning loop this detuning was only partially corrected by the tuning system. Apart from undesirable phase jitter the resulting variation in individual cavity voltage was interpreted as a cavity quench and the protection system switched off the unit. Although later modifications to the cryostat considerably reduced the amplitude of the oscillations, they have not completely disappeared and currently the worst cavities show RF phase oscillations of about ±5°.

4.3 Beam loading

The effect of beam loading is different in each of the three modules as shown in Table 2. This table compares the sum of the cavity voltages of each module, measured via the cavity antennae, with circulating beam (4.2 mA) and without beam. During accumulation the total voltage of the three modules is kept constant. The individual module voltages change continuously as a function of accumulated beam current. The table shows that after accumulation of a circulating current of 4.2 mA the module voltages vary by a factor of 3.5. This can be explained by phasing errors and different values of coupling strength for the power couplers. (The external Q value of the individual cavities varies by a factor of up to two.)

Table 2.
Module voltage for different beam currents. The sum voltage of all modules is kept constant by the control system.

Module	Ib = 0 mA	Ib =4.2 mA
2	4.5 MV	2.0 MV
3	5.5 MV	5.3 MV
4	4.3 MV	7.0 MV

When the RF is switched on in an SC unit with a high intensity circulating beam, the beam induced signal can cause the cavity to mis-tune if the applied RF power is insufficient. Switching on with high RF power is undesirable because the voltage produced once all cavities have tuned will be large and may bring Q_s across a dangerous region of machine resonances. A modified version of the switch on software procedure is in preparation. In a first step all cavities are tuned close to but not exactly to the LEP frequency. In a second step the applied power is reduced before the cavities are tuned to the correct frequency It is also envisaged to use beam current and energy to determine the amplitude and phase of the induced signal such that minimum switch on power can be used.

4.4 *HOM performance*

The measured power extracted by HOM couplers for both single and multiple circulating bunches agrees well with the calculated power [7] for the modes below the beam tube cut-off frequency. These calculations also show that the total higher order mode power deposited in the cavities is much larger than the part below the cut-off frequency of the cavity beam tube. The power contained in this part of the spectrum can leave the cavities and studies are going on to locate where this is deposited. Preliminary measurements of temperatures on bellows between cavities and at the cold-warm transition hint that at least some of this power is dissipated in the beam tube bellows at the extremities of the modules. Figure 2 shows first measurements on bellows as a function of accumulated current.

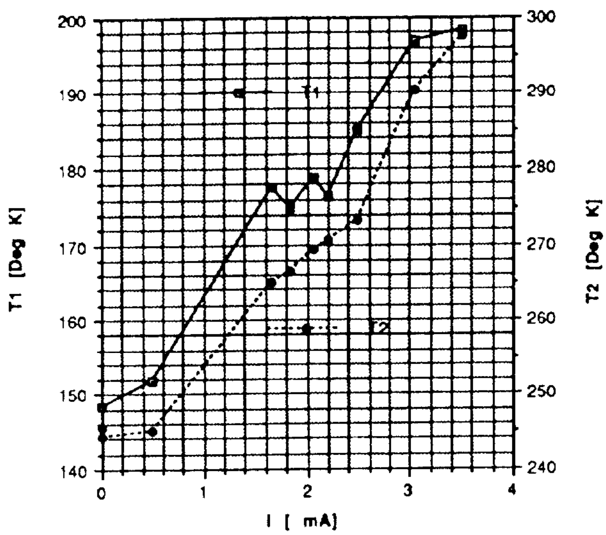

Fig. 2. Temperatures measured on the small diameter beam tube bellows at the cold/warm transition. T2 is at the conical transition, T1 in the middle of the bellows.

The 16 HOM couplers mounted on the sputtered cavities were all the new "Type-5" design [8]. Two of these had fundamental power of up to 100 W leaking through the filter. Initially the fundamental power levels out of these couplers varied erratically but then stabilized at these high levels. Later measurements on all couplers confirmed that three of these couplers had suffered permanent detuning of their fundamental frequency rejection filters.

These HOM couplers are d.c.-coupled so that it was possible to measure electron currents originating from the couplers. Measurements indicated the presence of electrons on 13 of the 16 couplers, and high currents on four of them. In the worst cases as the RF power is raised the electron current shows at first an erratic behaviour with many polarity reversals and then as RF power is further increased the current increases rapidly by several orders of magnitude. These electron current appears at lower accelerating field with circulating beam than without beam.

This electron current might indicate multipactoring in the coupler, which could cause detuning of the coupler's filter. Alternatively it might come from impacting electrons originating elsewhere in the cavity. They could heat the HOM coupler sufficiently to quench or detune the filter.

In order to investigate these effects module 3 was removed from the tunnel for extensive testing in the surface test area. This module will be equipped with more temperature probes and other diagnostics in order to study the phenomena observed in LEP. Additionally it is planned to individually remove and replace the HOM couplers in these cavities testing the cavity performance at each step. It is also foreseen that long-term tests of the complete cavity modules operated above the nominal field will be carried out

5. CONCLUSION

Superconducting cavities are now an integral part of the LEP RF system and have been successfully used during many physics runs and machine experiments. During this time no adverse effects on the beam were recorded. Indeed during energy calibrations using protons the lower noise of the SC unit increased the proton lifetime from 15 s to 4 min. The SC unit proved to be very useful in operation in particular for development of the 90° phase advance optics which required a much higher circumferential voltage than the standard LEP optics. Much experience was gained in the operation of SC cavities in preparation for the LEP upgrading program. Apart from the experience gained with the cavities operation in LEP allowed testing of all the other components of an SC RF station. This included the RF power generation and distribution system, the low-power electronics, control loops, interlocks and digital controls. Many of the necessary application programs could already be developed.

Apart from the problem of the HOM couplers no degradation in the performance of the cavities was recorded

Improved test facilities with increased cryogenic power will provide the possibility to carry out long term tests outside LEP in order to improve the performance and reliability of the SC cavities and their accessories.

6. ACKNOWLEDGEMENTS

The work described above is the result of close collaboration between many groups and services. The authors would particularly like to thank the LEP operations team and the AT division RF and cryogenic groups.

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