TEST OF THE FIRST FULL-SIZE LEP SUPERCONDUCTING CAVITY MODULE

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Abstract

The results of a first laboratory test of a full-size superconducting cavity module are reported. It is composed of four 352 MHz four-cell cavities (total length 12 m), two fabricated by industry and two by CERN. RF power is supplied by one 1 MW klystron and is distributed to the four cavities by a waveguide system very similar to the existing one of the LEP copper RF cavities. The total accelerating voltage achieved in the module was 32 MV. Liquid Helium is fed from a 450 W refrigerator via a 50 m long horizontal transfer line. Results are given on RF performance, mechanical oscillations of cavities and cross talk between cavities, controls and interlocks, X-radiation and cryogenic losses.

Introduction

With the electron positron collider LEP successfully commissioned in summer 1989 [1], the energy upgrade program has been started right away. In a first phase 32 Superconducting (SC) 4-cell cavities will be installed. As a first step 4 SC cavities were installed during the first winter shutdown of LEP. These four cavities were fabricated from niobium sheet material of high purity (RRR >= 100, cavity grade). Two of these cavity cryostat units (called cryounit) were fabricated by industry, the other two by CERN. The test results of the cryounits from industry and CERN were essentially the same [2], proving that the transfer of know how from CERN to industry was successful and that industry was able to meet the specifications without major problems. Consequently, the order of a larger number (20) of sheet metal cavities was placed in industry, the first prototypes of which are due for summer 1990.

In what follows, the laboratory test of the four cryounits assembled together (called a cryomodule) is described, whereas a companion paper [3] deals with the first experience in LEP.

The aim of this test was to gain maximum information on the cryomodule without interfering with the LEP operation. We made use of the existing test area ("string") for the LEP copper RF system very similar to that of the tunnel.

The cryounit and the cryomodule

The design criteria of the cavity and cryostat are essentially the same as already described elsewhere [4]. Modifications are the following:

(a) The beam image current generates heat in the stainless steel transition cone between the cavity and the LEP beam pipe. To reduce these losses it is coated by a 3 μm thick aluminium layer by evaporation. To increase absorption of infrared radiation from the outside this layer itself is covered by aluminium oxide of 5–7 μm thickness.

(b) To retain more liquid He from the gas returning to the refrigerator, the gas collector on the top of the cryostat was widened and the gas-liquid interface increased.

(c) To reduce radiation heat transfer from the radiation shield at 80 K to the liquid helium vessel superinsulation layers (40) were installed in between.

(d) To reduce piping cost the He gas distribution system was modified: the two outlet pipes cooling each half of each of the tuner bars are replaced by one with a single valve.

(e) To reduce conduction heat transfer to the higher order mode (HOM) couplers the RF cables' outer conductor was thermally anchored to the radiation shield.

The individual cryounits being tested successfully [2] including all ancillary equipment as tuners, RF power and HOM couplers [5] were then assembled together in a clean area (class 10000) to the cryomodule by mounting bellows between adjacent cavities (stainless steel), the transition cones and the gate valves at the two ends of the cryomodule.

The HOM couplers are identical to those described in [2].

An arbitrary number of cryounits can be mounted together, the maximum length of the cryomodule (12 m) being given by the dimension of the access shaft to the LEP tunnel. The design is such that by removing the stainless steel vacuum skin access is possible to vital components as, for example, HOM couplers, tuners, antenna probes, He distribution piping, etc.

The RF system

The layout of the high and low power RF installation is an exact replica of the installation foreseen for LEP. Since the SC cavities will be integrated into the existing LEP acceleration system, presently equipped with copper cavities, maximum use is being made of equipment already developed for this system.

For high power generation a standard LEP klystron driven by a 200 W solid state amplifier, is used [6, 7]. It is specified for 1 MW cw output power. The klystron output is protected against reflections by a circulator with > 20 dB isolation. The RF power is distributed to the cavities via WR 2300 waveguides, the power splitting is done with magic TEE's. The power coupler of the SC cavity is integrated into a waveguide/coax transformer of the doorknob type.

The cavity tuning works on the phase between the forward traveling wave feeding the cavity, obtained from a directional coupler in the waveguide immediately in front of the power coupler, and the cavity field itself. The phase discrimination is done at an IF frequency of 20 kHz.

The cryogenic system

The old 1.8 K BOC refrigerator plant of CERN, producing as 4.5 K refrigerator 450 W and being recently equipped with an industrial ASEA control system, delivers liquid He via a 50 m long rigid transfer line to the string. This transfer line manifold includes the cold gas return line, cold control valves on the flexible transfer line connections with the cryostats, and a gas-cooled radiation screen. The liquid He distribution system to the cryostat is designed for maximum flexibility: it allows various schemes for cooling 1 to 4 cavities in a common cryomodule, either with individual control of the liquid He level or as integrated liquid He bath system with one liquid He supply and one He gas return line.

The cryogenic losses of the two 4.5 K pipes in the transfer line were measured as 0.2 W/m, not including losses in valves and flexible extensions. The cryopower available for cooling the RF losses in the cavities was measured to be 250 ± 20 W. With the tuner and radiation shield circuits of a cryomodule requiring a mass flow of 4 × 0.2 g/s, corresponding to 80 W, and the static load of the cryomodule being 80 W, we estimate the losses in the transfer system to be (450–250–80–80) W = 40 W. In the string the slope at the interaction points 2 and 6 of LEP of 0.14% was simulated.

Controls and interlocks

The digital control of the RF installation is based on the existing RF control [8], with some modifications to accomodate the additional requirements of the SC system. Each major piece of equipment is interfaced to an "Equipment Controller (EC)". Each cavity, as well as the common cryostat for 4 cavities has it's own EC. The klystron, the power supply, the HV interface, the low level electronics, the RF distribution also have their dedicated ECs. They monitor and control the status of their associated equipment and provide the interface to the "RF data manager (DM)" which allows manual operation of the unit via a touch screen, or in LEP also remote operation from the main control room via the LEP controls network.

There are two levels of security, one is to protect the equipment by acting on the cause of the problem without perturbing the circulation of the beam directly when the cryomodule will be installed in LEP. The other level consists of the interlocks, which cut the RF voltage and, in a further stage, the klystron high voltage. The different component checks and interlocks are summarized in table 1.

Table 1

Component checks and interlocks

Equipment	Measured parameter	Action
Tuner (magnetostrictive)	T too high	Cut current
Tuner (thermal)	T too high	Cut current
Heater gas	T too high	Cut current
Heater gas	T too low	Adjust valve
Power coupler	T too high	fast RF cut (PIN diode)
RF window	dto.	dto.
Cavity	Vacuum cryostat	dto.
Cavity	Vacuum beam	dto.& klystron HV cut
Cavity	He level	fast r.f. cut (PIN diode)
Cavity	He pressure	dto.& klystron HV cut
T-gauges (Pt100)	Current	fast RF cut (PIN diode)
Waveguide air blower	Pressure	dto.
Cavity (quench)	Fast decay of E_a	dto.

Legend: T = temperature, E_a = accelerating gradient, HV = high voltage.

Experimental results

Although the RF layout in the string has the virtue to test all four cavities simultaneously, the cavities were tested and conditioned individually by detuning the remaining ones, if necessary. This allowed to detect problems and limitations of individual cavities. The total maximum accelerating voltage obtained with all four cavities operated simultaneously was 32 MV, corresponding to an average field of 4.7 MV/m. The results concerning maximum accelerating fields are summarized in table 2.

The accelerating field is determined as follows: With the cavity and tuner bars cold and in thermal equilibrium, the coaxial-waveguide doorknob transition is fed with low power RF from a 50 Ohm tracking generator spectrum analyzer system. The external Q-value of the input line is determined from the 3 dB bandwidth df: Qextin = f/df. The external Q-values of the different output ports is determined from the ratio of incident power Pi and transmitted power Pt: Qextout = 4 Qextin* Pi/Pt. The external Q-value of the two output antennas is always cross checked with the measurement at room temperature, which is virtually the same. The accelerating field is then determined by two independent methods. For (R/Q) = 464 Ohm and the active length of the cavity L = 1.7 m, Ea = 2 $((R/Q)*Qextin*Pi)^{.5}/L$ or Ea = $((R/Q)*Qextout*Pt)^{.5}/L$, the latter being more reliable.

After assembly of the individual cavities into a cryomodule an extended period of RF conditioning (55 h) was necessary to obtain accelerating gradients of 5 MV/m, the design gradient. One cavity, however, showed a thermal breakdown at Ea = 3.5 MV/m (table 2, No. 4), induced by electron field emission,

confirmed by Fowler-Nordheim characteristics of its strong X-radiation (430 rad/h). It could not be overcome by RF conditioning, instead conditioning at a He partial pressure of 10^{-5} mbar (He conditioning) had to be applied. After this the maximum gradient could be raised beyond 5 MV/m, as in the other cavities.

Table 2

Maximum accelerating fields [MV/m] of individual cavities

No.	Test (RF source)	Cavity			
	Name of cavity Position in string	LEP3 12	LEP4 9	LEP5 10	LEP6 11
1	Individual cryounit without HOM & power couplers (200 W)	5.4	8.6	–	–
2	Individual cryounit with HOM & power coupler (50 kW tetrode)	5.4	3.0	9.0	5.5
3	Retreatment[a] (50 kW tetrode)	–	7.1	–	–
4	Assembling to 4 cavity cryomodule (1 MW klystron), 55 h RF processing	5.0	3.5	4.7	5.0
5	6 h He Processing	5.4	5.1	5.4	5.3
6	warm up, leaks[b] repaired	5.1	5.0	5.0	5.3
7	Installation into LEP	see [3]			

(a) Chemical polishing (20 μm) and water rinsing.
(b) Leaks were present at O-ring of vacuum tank and at multipin vacuum feedthrough.

Another observation is electron multipacting, which required some hours of RF conditioning after the first cooldown and a shorter time after each warm up, with breakdowns (quenches) above 4.5 MV/m.

Concentrating the conditioning action on one particular cavity by detuning the others resulted for two particular cavities in a heating up and runaway of the temperature at the upper part of the RF power coupler. By measuring the time derivative of this temperature as a function of the detuning angle (thus changing the standing wave pattern in the coaxial line in a well defined way) revealed that the heat source was the upper flange of the power input coupler line. This temperature rise was not observed for the cavities on tune.

The maximum RF voltage, when all cavities were operated simultaneously, was 32 MV, which corresponds to an average gradient of 4.7 MV/m, somewhat less than the average gradient in the individual tests. The reason is the scatter in the external Q-values of the input line; for the same forward power in all waveguides the cavity with the highest external Q-value has the largest accelerating gradient. Unfortunately, the external Q-value is largest ($2.4*10^6$) in a cavity which was limited to 5.3 MV/m by a thermal breakdown (LEP6) thus limiting the forward RF power for all other cavities, which could not be pushed to their ultimate field limit. Once a variable input power coupler is available, the tolerable forward power to that cavity could be increased, and hence the total accelerating voltage. We observed a slight decrease of the external Q-value (14%) with increasing temperature measured at the inner conductor tip (110 K to 280 K) attributed to a change of its length.

The Q-value could not be precisely measured by RF methods, as the power dissipated in the cavity is so small (50 W) compared to the forward and reflected power (20 kW, Q_0/Qextin = 1000). It could, however, be estimated with an error of ± 20% from the difference of the He bath heater power with and without RF. This heater controls the He pressure in the He tank and hence the cryogenic load of evaporation to a constant value (1250 mbar), provided the refrigerator is operated in a stable regime. The Q-value averaged over all four cavities is shown in fig. 1. The Q-value of the individual cavities was also measured, in spite of the larger error it could be concluded that the losses in cavity LEP 3 were about twice of each of those in the other 3 cavities.

The Q–values are lower than the design (3*10^9), as expected [9], because of the strong ambient magnetic field inhomogeneity in the test area (930 ± 700 mG), the high permeability shielding not yet installed.

Occasionally, in particular for two cavities (LEP 5, 6) the phase between input and output RF signal oscillated by up to 10 degrees, caused by an oscillation at 6 Hz in the tuner gas circuits. In addition, the AC thyristor based He bath heater had to be replaced by a DC heater, as it excited mechanical vibrations in the cavities at 100 Hz close to mechanical resonances. The mechanical cross talk between adjacent cavities is negligible except at mechanical resonances of the cavities, the lowest one being at 35 Hz. The phase jitter of the other cavties (LEP3, 4) was lower by a factor 5, which is considered to be a consequence of their stiffer He tank.

Table 3

External Q–values(a) for fundamental mode

	LEP3	LEP4	LEP5	LEP6
Qextin [10^6]	2.2	1.8	2.1	2.4
Qextout (RF probe) [10^11]	.97	.82	1.7	1.2
Qextout HOM(b) coupler [10^10]	.80	39	1.1	5.5

(a) Defined at the cryostat RF dome.
(b) Total Q_{ext} (i.e.composed from total power leaving the cavity).

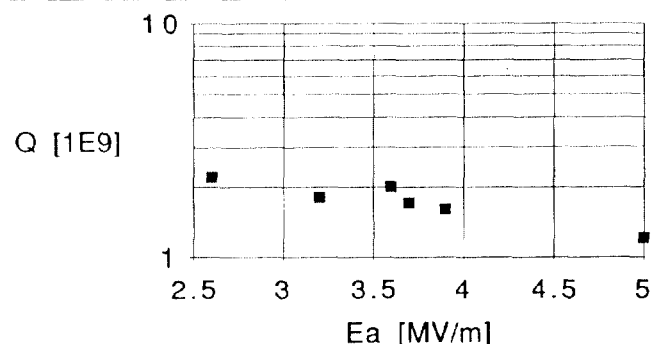Fig. 1: Average Q–value vs. average accelerating gradient for cryomodule in string. The Q–value is measured cryogenically and has a relative error of ± 20%.

The external Q–values of the most prominent higher order modes were measured (table 4). It turned out that one mode at 689.5 MHz was only weakly damped (Qext = 3.9*10^6). The HOM frequencies for different cavities scatter by an amount largely superior to the frequency distance of the beam current spectral lines (44 kHz), up to some MHz. The suppression of the fundamental mode was sufficient (Qext >= .8*10^10, table 3).

Table 4

Q_{ext} of most prominent higher order modes

Frequency [MHz]	464 479	507 515	640 683	689 691	1010
Q_{ext} [10^3]	11 11	41 114	12 244	390075	17
Mode	TE111	TM110	TM011		TM012

If the vacuum before cooldown is too high (10^-6 mbar), we know from experience that RF conditioning can be very cumbersome and time consuming. The vacuum before cool down in this test was ≤ 1.7*10^-7 mbar (measured at the cryostat end opposite the pump). When the cryopumping started the valve between the cavities and the 400 l/s ion pump installed at one end was closed, to avoid any risk of contamination of the cold surface.

During conditioning the X-radiation measured by an ionization chamber 1 m off the cavity in axial position was 600 rad/h (6 Sv/h) about a factor 6 larger than the sum of the radiation from the individual cavities. Thermoluminescent dosimeters distributed around the cryomodule revealed a total maximum dose of about 6000 rad (60 Gray) at the cryostat end plates, about a factor 5 lower near the cryostat cylindrical parts. With about 60 h total operation time at maximum accelerating gradient this corresponds to about 100 rad/h (1 Sv/h).

Cool down and fill up with liquid He was achieved within 3 days, evaporation of the liquid and warm up also within 3 days, which fits perfectly with the time needed to warm up a cold mass of 2 tons with 600 W heater power. Cool down by He gas of only one cavity in direct flow and the three others coupled to the collector by convection is fully satisfactory. Liquid He cooling with one supply to top or bottom cavity and one return from the collector at the opposite end is working well. For inclined groups, liquid flow from top cavity to bottom cavity seems to be preferable because of the lower level in the collector (Roman fountains). Grouping of warm gas lines with orifices for equal distribution is possible, reducing the number of independent flow controls from 24 to 7 per group of 4 cavities. The evaporation losses of the cryomodule of about 65 W is not including the heat entering above the liquid He level, this is why the total static losses are estimated 80 W. The remaining cryogenic power available for cooling the RF losses of the four cavities (250 W) was sufficient to operate the cryomodule up to 4 MV/m CW.

Typical frequency increase by evacuating the cryostat from atmospheric pressure at room temperature is 37 ± 7 kHz, by cooling down to 4.5 K (tuners at 4.5 K) the frequency goes up by 463 ± 5 kHz. A readjustment of the cavity frequency at room temperature (by putting spacers to increase the total length) was necessary once and could be accomplished within half a working day.

Conclusion

The total accelerating voltage of the 4 cavities assembled together into one single cryostat (cryomodule) was 32 MV . The average accelerating gradient (4.7 MV/m) was somewhat lower than the average of the individual cavities.The maximum accelerating gradient (quench) in one particular cavity being attained, the scatter in the input coupling was such that in the other cavities the accelerating gradient was lower. RF and He processing had to be applied to eliminate electron loading. All cavities were operated individually beyond 5 MV/m. The radiation level under operation conditions amounts to several hundred rad/h. The preferred cryogenic operation mode was supply of the liquid at the upper end of the cryomodule and return of the gas at the lower end (the slope of the LEP tunnel was simulated).

References

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