Thermal loss analysis of cryostats and accessories for the superconducting cavities of the LEP energy upgrade

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Abstract

The cryogenic aspects of design and operation of the 224 superconducting cavities for the energy upgrade of LEP are presented. Basic choices for the layout of the 4-cavity module, active or passive cooling of accessories and the thermal insulation are explained. Static or RF related dynamic losses are given and compared to experimental results obtained from measurements on prototype cavities or during reception tests on modules manufactured in industry. Special attention is given to the heat dissipation and cooling problems of main power couplers and higher-order mode couplers. Operational aspects of the beam-related effects on the cryogenic system are also discussed.

1. INTRODUCTION

CERN is in the process of producing, equipping and installing 224 superconducting (SC) cavities for the energy upgrade of the LEP collider. The general status of this project, known as LEP2, is presented elsewhere at EPAC94 [1]. The general features of the cavities, of their accessories and of their cryostats have undergone a considerable development from the first prototypes made of niobium (Nb) sheet to the most recent, series-produced versions with Nb-sputtered copper cavities; this history and the results obtained so far have recently been reviewed [2,3]. The operation of such strings of SC cavities near 4.5 K require very powerful cryogenic systems for production and distribution of the cold helium; their status and performance were described in several papers and summarized in [4]. First operational experience from running modules in the LEP tunnel was reported in [5]. The purpose of the present paper is to give a closer look to the cryogenic aspects of design and operation of the cavities themselves and of their accessories inside the cryostats.

2. CRYOSTAT DESIGN AND LOSSES

The LEP2 SC cavities are 4-cell cavities designed for 352 MHz fundamental mode operation; four such cavities are assembled together and installed as one module with common vacuum tank. Each of the 4 cavities in a module is surrounded by a stainless-steel (st.st.) container for bath cooling by boiling liquid helium (LHe). To assure a sufficient thermal insulation, the 4 cavities in the module are each suspended inside the vacuum tank on 2 x 4 st.st. rods for taking the weight and the longitudinal position is defined by a fifth horizontal rod. The vacuum tank is a modular cylinder with wide ports for easy access to accessories, cabling and instrumentation, closed by a st.st. skin with a gasket [3].

In the first prototype an actively cooled copper screen was installed between 40 outer and 20 inner layers of superinsulation, but in the final design, for the sake of simplicity in piping and cost, the screen was eliminated at the expense of more superinsulation (from 60 to 80 layers, applied in pre-fabricated mattresses of 20) and about 3 W more per cavity in static heat load. The composition of the typical static heat load per 4-cavity module is shown in Table 1.

The average value per unit length of 8 W/m may appear as rather high (in particular when compared to typical figures of 1 W/m for SC magnet strings); this is, however the results of the special situation of SC cavities where high radiofrequency (RF) related 'dynamic' losses make it in attractive to strive for low static losses and accept loss of flexibility and access to components.

Table 1
Analysis of the static thermal load on the 4.5 K system of a LEP2 module

Thermal radiation across superins.	4 x < 9 W
Conduction in support rods	4 x 2.5 W
Conduction in cooled beam cones	4 x < 1 W
Conduction in cooled MC's ext.	4 x < 1 W
Conduction in cooled HOM cables	4 x < 1 W
Conduction from heated tuners	4 x <0.1 W
Conduction in various piping	4 x < 2 W
Various smaller loads, incl. sensor cables and passages across insul.	4 x < 5 W
Typical total static load	≈ 80 W
Tolerance limit for reception test	< 90 W

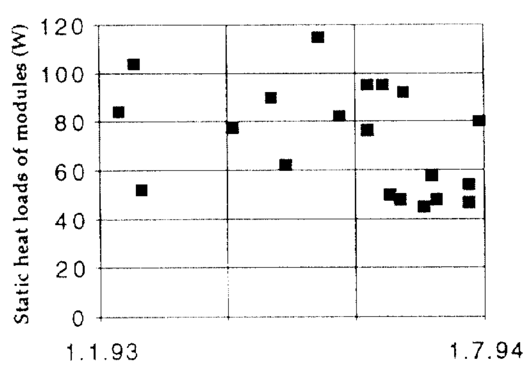

Figure 1
Static heat loads at 4.5 K level, measured on LEP2 modules as received from industry

The results of measurement for the static heat load of the LEP2 modules produced in industry is now part of the current reception procedure at CERN; Figure 1 is giving the results observed during the last 18 months. The considerable spread of the values was either (where they are too high) due to the initial learning process, usually because of bad overlap of superinsulation mattresses, or (where they are rather low) due to the absence of HOM's and MC extensions for which the designs had to be upgraded to make them suitable for higher beam intensities. Results above 100 W correspond to use of thicker, shorter HOM cables without active cooling (+ 20 W!).

3. DISTRIBUTION OF COLD HELIUM

The way the cryogenic supply system for the LEP2 cavity programme was designed had been explained in [5] and a flow scheme shown. Per module an equivalent (liquefaction loads with warm gas return converted to entropy-equivalent refrigeration load) 4.5 K cooling power of 750 W will be available: Less than 90 W are accounted for static losses in each module, less than 60 W per module for transfer line losses, about 100 W for gas cooling (by a total gas flow of about 0.8 g/s) of cones, main couplers, HOM cables and tuners (see below), about 200 W for RF losses at LEP2 standard conditions (5 MV/m of acceleration field with resonator quality factor Q= 3.10^9) and a spare capacity of some 300 W for higher fields or a reduced quality factor in some modules due to an accidental surface contamination resisting to 'in-situ' conditioning.

The cold gas for all the heat intercepts (per cavity about 0.2 g/s or 10 cm^3/s at 4.5 K) is taken from the GHe manifold through a common capillary to keep the usual small pressure oscillations, which often occur in helium pipes with strong temperature gradients, from affecting the bath pressures The gas is then distributed to various cooling pipes which are partly connected in parallel and partly in series, in order to use its enthalpy in the most efficient way according to the temperature requirements of each component: 0.09 g/s is cooling in parallel the six half-branches of the thermal tuner system; the same amount is used first for parallel heat intercepts on the 4 HOM power extraction cables (4.5->20/30 K), is then, where applicable, cooling the cold side of the beam cones at the module ends (30->40 K), followed by the cooling of the solenoid coils for the excitation of the fast magnetostrictive tuner action (30/40->80/150K) before flowing inside of the main coupler antenna from the tip to the warm end (80/150->300K); finally there is a third branch with about 0.02 g/s for cooling the cold 'extension' of the warm outer conductor of the main couplers.

4. BEAM TUBE CONES

The beam pipe transition cones at both ends of each module consist of a 230 mm long cone made of 0.7 mm thick st.st., followed on the cold side by a 60 mm long bellows made of 0.15 mm thick st.st.. The smaller diameter is 100 mm, and the inner of the bellows 190 mm. In addition to heat conduction along the st.st. walls, there will be heating by beam particle image currents and those HOM fields excited in the cavities which are not well extracted by the HOM couplers and which cannot propagate into the 100 mm diameter pipe on the warm end. The inner surfaces of cone and bellows are copper-plated wherever possible to reduce RF heating, but recent calculation [6] predicted losses in excess of 50 W per cone at the highest beam intensities planned now for LEP2, and more if the bunch length is further shortened.

The cooling loop around the flange between bellows and cone was designed to extract a thermal flux of up to 10 W and could probably not handle more than 20 W, also depending on where most of the heat will be dissipated. Measurements on the modules already available in LEP should provide, with beam currents getting closer to the 8 + 8 mA limit given by the planned klystron power, the necessary input .for deciding whether more cooling is required on the cones.

5. MAIN COUPLERS

The main RF power coupler ("MC") is a special coaxial line of which the inner conductor ("antenna") is penetrating into the transition between cavity and beam cone and coupling to the fundamental mode of the cavity. The outer part of the outer conductor is at room temperature, and only the part inside the vacuum tank ("extension") connecting the 4.5 K of the flange on the cavity bath to the room temperature flange.

The extensions are 50 cm long, made of st.st. with a gas-passage between concentric cylinders; the total wall thickness is 2 mm. All parts exposed to the RF power are either made of copper or coated with a copper layer of 10-40 μm to reduce the RF heating.

It is not well known how the RF losses vary with temperature for the fundamental frequency of 352 MHz or the higher-order modes in the range 0.5 - 1.3 GHz to which HOM couplers, their power cables and beam cones are exposed. Using measurements done on copper of OFHC quality at 500 MHz for temperatures between 300 K and 4 K [7] as well as the formulas for the surface resistance with normal and anomalous skin effect, one can conclude that copper surfaces of good quality behave at 350 MHz as if their RRR value is limited to about 35 and to about 25 for frequencies around 1 GHz.

The cooling of the MC antenna by cold helium gas, mentioned already in chapt.3, is not as vital as for the other components; any temperature of the antenna tip below 300 K is considered as acceptable. Nevertheless the cold gas available from the tuner coil screens with temperatures of 80-150 K is conveniently warmed up in the antenna and is keeping there the thermal radiation load low.

6. HIGHER-ORDER MODE COUPLERS

During the prototype development if the LEP2 cavities various types of HOM couplers were used, starting with straight antennas (type "1") for the first modules, then moving to hook types ("5A"-"5M"). In all cases the basic scheme of cooling was retained, but also questioned again and again, each time limitations and quenches were observed during conditioning of contaminated cavities.Starting from the fact that the HOM coupler components see only moderate RF fields with surface loads of a few mW/cm^2 ,it proved normally sufficient to cool the outer bell-shaped conductor by heat conduction to the mounting flange and the cavity bath, and the hollow inner conductor simply by filling it with LHe, using free circulation of the liquid from a bypass line between the LHe manifold beneath the cavities and the gas manifold on their top.

This system worked surprisingly well, even for coupler of type "1", where the liquid had to find its way against escaping bubbles in a 20 cm long passage of only 6 mm inner bore.The only condition was that the liquid level in the bypass reached the level of the coupler tap, but the dynamic overpressure in the LHe manifold helped providing at least 3 mbar of static head or more than 20 cm of additional level height.

New problems were seen when the extraction of more and more HOM power to external loads had to considered; coaxial cables became thicker, shorter and doubled to handle up to 200 W per coupler. LHe bath cooling of the outer shell was tried, but finally preference was given to intercepting the heat on the cables with copper clamps which bridge the outer conductor braid to a gas-cooled pipe at 8 points between 10 and 55 cm from the cold end of the 80 cm long cables of type RG165U.

For the inner conductor doubts about the functioning of the cooling came up when about 20% of the HOM couplers "5C", which was widely used on Nb/Cu cavities, showed 'hard' quenches when cavities had to be conditioned. This blocked conditioning until power-pulse processing was applied. It could be shown experimentally that these quenches were related to electron emitters in the cavity next to the coupler and trajectories ending on the hook. Attempts to solve the problem on the cooling side, in particular using 'injector' pipes bringing LHe directly down into the hook had little effect, but made recovery faster. A temperature sensor on the cooling pipe became an essential tool to act as quench detector and to exclude overheating of the hook.

Cryogenic measurements on a model hook showed that surface temperatures go up quickly by several degrees as soon as heat loads on any part of the hook exceed 0.5 - 1 W; then bubbles accumulate and recovery of superconductivity is only possible if the typical specific load limit for film boiling in LHe (< 0.1 W/cm^2) is not exceeded.

7. TUNERS

The frequency tuning of the LEP2 cavities had not required any substantial change since the first prototypes [8]. It consists of 3 nickel (Ni) tubes of 2 m length which brace the structure defining the length of each 4-cell cavity. The resonance frequency of the cavity changes by 40 kHz per 1 mm of change of overall length. The length of the nickel tubes can be controlled by magnetic excitation from solenoid coils on both tube halves (fast tuning, max. range 1.5 kHz) and by change of the temperature profile (slow tuning, range about 50 kHz); to this end an electric heater in the tube center is acting against the cooling by conducting to the ends kept at 4.5 K by contact to the LHe bath and a gas flow guided from the ends along the inner tube walls.

The flow rate of 0.015 g/s per tube end is chosen such that the speed of frequency change is similar when increasing or decreasing the heater power around the 20 W value needed to keep the Ni tube center near 200 K in the middle of the frequency range.

8.OPERATIONAL ASPECTS

The nominal 'dynamic' heat load is close to the overall 'static' load, but as shown in chapt.2, there is an operational spare capacity built in of, on average, 150% of the nominal dynamic load. Experience showed that performances of individual modules will always have a considerable dispersion. The cryogenic circuits are designed to handle dynamic loads of at least 600 W per module and could probably even accept 800 W for a special case.

As cryogenic systems have usually parts with a wide range of time constants and many interacting control loops, there is always a contradiction between long-term stability and good reaction to fast perturbations, such as the RF loads can be. For this reason, the load seen by the cryogenics is stabilized using electric heaters of 0 - 200 W range in each of the cavity bath volumes.

Two modes of driving this heaters are kept available. The first one is used during cavity testing and conditioning; here a control loop is used to find the heater power required to stabilize a parameter depending on the total load, such as the position of the outlet valve which itself is controlling the bath pressure. The heater power found in this way can be used to display on-line the effective average quality factor of the cavities in the module.

The second heater mode is used in normal operation where the quality factors are well established in the working range of fields. Here a simple algorithm is calculating directly from the field strength signal the necessary compensation power It was shown on the modules running in LEP [5] that bath pressures and bath levels as well as their corresponding valve positions were kept perfectly stable even under wildly varying RF fields.

9. CONCLUSION

We consider the development of the cooling system of the LEP2 SC cavities as completed. However, the last verification can only be the operation in LEP at maximum beam current of double strings of 8 modules together with its 12-kW cryoplant system.

10. REFERENCES

[1] C.Wyss, "Progress of the LEP Energy Upgrade Project", these proceedings.

[2] G.Cavallari et al., "Status Report on SC RF Cavities at CERN", Fifth Workshop on RF Superconductivity at DESY, Hamburg, Germany, 19-23 August, 1991.

[3] G.Cavallari et al., "Status of the RF Superconductivity at CERN", Sixth Workshop on RF Superconductivity at CEBAF Newport News, USA, 4-8 October, 1993.

[4] D.Güsewell et al., "Cryogenics for the LEP200 Superconducting Cavities at CERN", Particle Accelerator Conference (PAC93), Washington D.C., USA, 17-20 May, 1993.

[5] Ph.Gayet et al., "First Operational Experience in Running a New 6 kW Cryoplant with Superconducting Cavities in LEP at 4.5 K", Sixth Workshop on RF Superconductivity at CEBAF Newport News, USA, 4-8 October, 1993.

[6] R.Baskaran and E.Haebel, "Estimation of the Power Deposited in Different Frequency Ranges for the LEP SC Cavity Module", LEP2 Note 93-06, CERN, 18 October 1993.

[7] W.Weingarten, "Radio-Frequency Superconductivity Applied to Large Electron Accelerators", in Particle World, vol. 1, No. 4, p.93-103, 1990.

[8] R.Stierlin, "Development of a Cryostat for the 4-Cell 352 MHz SC Accelerating Cavity for LEP", Third Workshop on RF Superconductivity at Argonne National Laboratory, USA, 1987.