SUPERCONDUCTING RF CAVITIES FOR LEP

Status Report

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Abstract

For the upgrading of LEP to energies beyond 55 GeV, s.c. cavities will be used and it is planned to install 4 s.c. cavities in LEP after a first running in period. Results obtained with 350 MHz prototype 4-cell cavities are presented. Besides the s.c. cavities a great effort has gone into auxiliary items like cryostats, main couplers, higher-order mode couplers and frequency tuners. Their layout and test results obtained in s.c. cavity measurements will be shortly presented. Some implications of the use of s.c. cavities in LEP will be discussed.

Introduction

Already at an early stage of LEP design [1] it was considered to upgrade energies to the design value of LEP (~ 100 GeV) by installing superconducting (s.c.) cavities.

In 1979 a development programme for s.c. cavities was started at CERN and after an initial phase where efforts were mainly concentrated on 500 MHz cavities it was decided in 1984 to change to 352 MHz cavities. There is an obvious interest to install s.c. cavities with this frequency because it will allow to use at maximum the existing installation of radio frequency (r.f.) power sources.

At high frequencies and for temperatures below the critical temperature T_c the r.f. resistance of a superconductor decreases exponentially with temperature and its value can be made typically 10^4 to 10^6 times smaller than for copper at room temperature. The corresponding decrease of r.f. losses in s.c. cavities has attracted accelerator constructors because much higher acceleration efficiencies and higher CW accelerating fields than in Cu cavities can be reached (table 1). The sixteen 1-MW klystrons needed for operation of LEP at 55 GeV with Cu cavities are sufficient to obtain 90 GeV when using s.c. cavities.

The advantage of an extremely high shunt impedance $r = (R/Q)\ Q_o$ for the accelerating mode turns out to be a disadvantage for higher-order modes (HOM) because of the danger of resonant build-up by the beam. For LEP cavities, this type of build-up is kept to a tolerable level by using HOM couplers with external quality factors Q_{ext} for the most dangerous modes comparable to the natural Q_o of Cu cavities (table 1). Once resonant built-up is avoided the main current limit for LEP is given by transverse instabilities linked to the internal modes of individual bunches [2]. The total transverse loss factor responsible for this type of instability is small due to the large iris opening (table 1). For comparison we give the most important contributions to this loss factor in LEP (for a bunch length of 40 mm) [3].

- 2880 bellows: 0.4×10^5 V/pC;
- 128 Cu cavities: 1.1×10^5 V/pC;
- 256 s.c. cavities: 0.2×10^5 V/pC.

Transient beam loading which can be characterised by the ratio of r.f. energy removed by one bunch of charge q from the cavity and the stored energy $\eta = q\omega(R/Q)/E_{acc}$ is also low due to the small R/Q and the large E_{acc} (table 1).

Status of Nb cavities at CERN

At CERN two development lines for Nb cavities are pursued [4], one using Nb sheet material for cavity fabrication and another one using Cu cavities covered with a thin layer of Nb (~ a few µm) [5].

Table 1 - A few LEP cavity parameters

	Cu cavities	s.c. cavities
Frequency	352.209 MHz	352.209 MHz
Number of cells	5	4
Cavity active length	2.13 m	1.70 m
Iris hole diameter	100 mm	241 mm
Shunt impedance/ quality factor	650 Ohm/m (a) 1000 Ohm/m (b)	276 Ohm/m
Q_o	4×10^4	3×10^9 (Nb, 4.2 K) 2.6×10^6 (loaded)
Design acceleration field	1.5 MV/m	5 MV/m
Total loss factor/ unit length	$403 \frac{V}{pC \bullet m}$	$46 \frac{V}{pC \bullet m}$
Q_{ext} for TM_{011}		2.7×10^4
TM_{110}	$\sim 3 \times 10^4$	4×10^4
TM_{111}		1.4×10^4
Percentage of stored energy taken by two bunches	12.8%	1.6%

(a) Without storage cavity. (b) With storage cavity.

In the following we will review only results obtained with Nb cavities but we note that both types of cavities have the same geometry and will therefore be fully interchangeable.

The development programme of 352 MHz Nb cavities at CERN was started with the construction and testing of a few monocell cavities. The important role of high thermal conductivity (or high Residual Resistance Ratio (RRR)) Nb material for stabilising surface defects was confirmed and accelerating fields up to 10 MV/m could be reached.

A new design for a LEP 4-cell cavity [6] was developed and three cavities were constructed from Nb material with RRR = 112, 40 and 156 resp. (the last one being used only for cryogenic tests).

After standard CERN surface treatments cavities were tested in a vertical cryostat. A He tank was welded around the cavities which were then installed in a LEP type horizontal cryostat and retested.

The results obtained with the two cavities fabricated from high RRR material (LEP 0 and LEP 2) can be summarized as follows:

- a correct operating frequency and a field unflatness < ± 4% could be reached by simple inelastic deformation of cavity cells;
- cavities needed no repair of defects;
- resonant electron loading (multipactor) presented no serious problem;

- accelerating fields reached values up to 7.5 MV/m;

- Q-values well above the design value of 3×10^9 at 5 MV/m have been reached (fig. 1);

- electron loading due to localised field emitters set in already at 2-3 MV/m. Very long He processing (50 ÷ 70 h) was needed to bring up fields from 5 to 7.5 MV/m, the maximum value reached;

- cavity performances did not degrade after:
  - a high field operation of 2200 h, CW at 7.2 MV/m;
  - an estimated total radiation dose (e^- and X-rays) of ~ 1 Mrad;
  - a few warm-up cycles to 300°K,

- short exposures to clean and dust free air at room temperature did not increase electron loading substantially and maximum fields and Q-values could be reached again after a short processing. Similarly exposure to a typical accelerator residual gas mixture at He temperature (up to an equivalent of 5 monolayers) did not affect cavity performances notably [7].

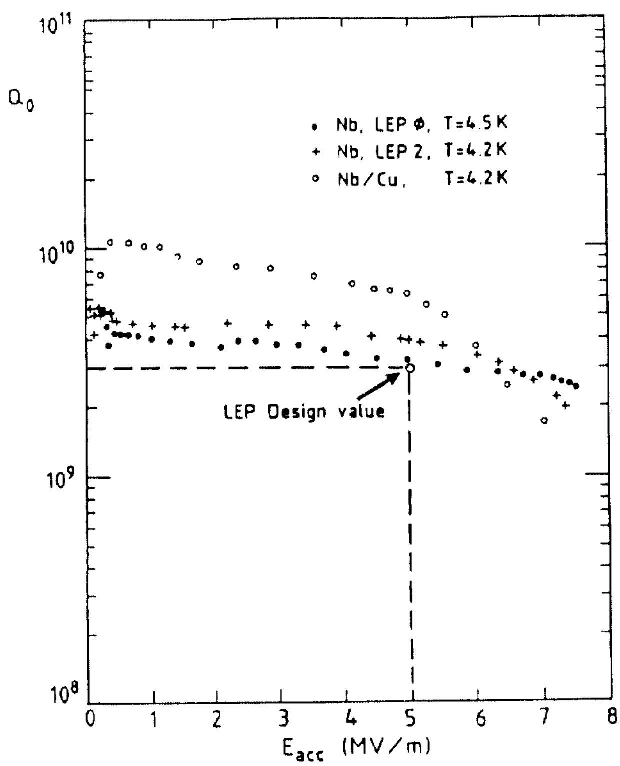

Fig. 1 Dependence of Q-values on E_{acc}. Final values for 4-cell Nb cavities LEP 0 and LEP 2 and for a 350 MHz 4-cell Cu cavity with a magnetron sputtered Nb layer.

Cavity LEP 2 is at present installed in the CERN SPS for a long-term test [7]. Four more Nb cavities with all auxiliaries are now under construction, 2 at CERN and 2 at industry.

Auxiliary equipment for s.c. cavities

During the last years a considerable effort has gone into the design, construction and testing of auxiliary equipment like cryostats, couplers and tuners which present ~ 50% of the total cost of the s.c. cavity system. Details can be found in the references cited. All auxiliaries are presently mounted to the LEP-type cavity, undergoing a long-term test at the SPS [7].

Cryostats

It is foreseen to locate up to eight s.c. cavities with their welded He tank inside a common vacuum tank [8]. Installation will be done in basic modules containing 2 s.c. cavities with a total length of ~ 6 m, allowing installation through the normal machine pits and without removal of machine components.

As it is intended to assemble cavities under clean conditions while still under dustfree protective gas, good accessibility to the assembly regions is required. This is achieved by a removable sealing skin around the vacuum tank and by removable cold shields. It allows also an easy repair of elements like e.g. main couplers. Two cryostats have been constructed at CERN (fig. 2) and have been operated with cavities and all auxiliaries in a number of tests. Static cryogenic losses of the cryostats at 4.2 K amount to ~ 12 W.

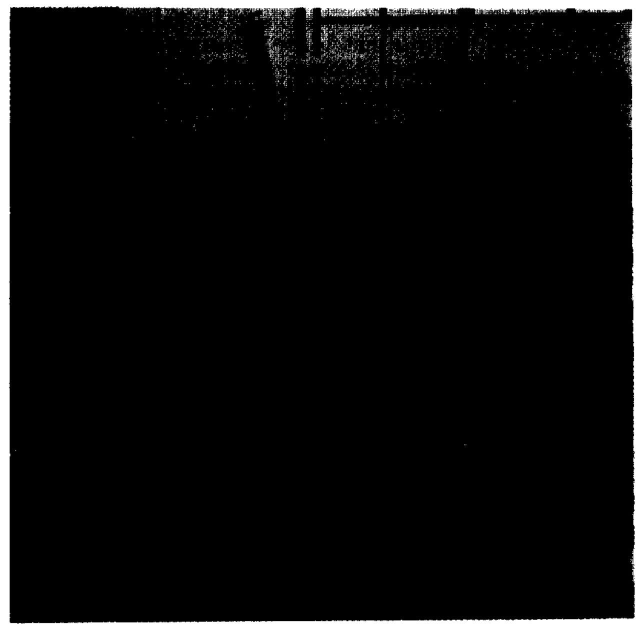

Fig. 2 Photography of cavity with welded He vessel inside its vacuum vessel. The outer sealing skin and the cold shield are removed.

Main couplers

An antenna-type coaxial coupler, located at one of the beam tubes of the cavity has been developed [9]. The cylindrical r.f. window, of the type developed for the LEP Cu cavities [10], is placed outside the cryostat at room temperature and can be easily replaced without opening the cryostat.

A few couplers have been constructed and tested up to power levels exceeding the maximum 60 kW (CW) foreseen for LEP operation. Cryogenic losses at 4.2 K remain below 2.5 W. It is foreseen to match couplers at a power level of 60 kW ($Q_{ext} = 2.6 \times 10^6$).

Higher-order mode (HOM) couplers

Various types of compact HOM couplers [9] of coaxial and compact design and located at the beam tubes have been designed, constructed and tested and have given completely satisfactory results with respect to mode attenuation, cryogenic losses and easy demountability. The Q_{ext} reached in a number of cavity tests are given in table 1 and satisfy the criteria adopted for operation in LEP.

Frequency tuners

Frequency tuning [11] of the cavities is achieved by a change of total cavity length (40 kHz/mm). Two tuning modes are used in parallel: a fast one based on magnetostriction of Ni bars supporting the cavity with a range of ± 1 kHz and a speed of 1 kHz/50 ms and a slow one based on temperature changes of the same Ni bars with a range of 50 kHz and with a speed of ~ 8 Hz/s.

Possible layout of s.c. cavity systems in LEP

For the first stage of LEP, 128 Cu cavities will be installed in interaction regions 2 and 6 and will occupy on each side of the interaction point 4 r.f. cells, each r.f. cell containing eight 5-cell cavities. Two 1 MW klystrons are needed for powering 16 cavities [1].

In order to keep changes to a minimum one should keep the number of 8 cavities per r.f. cell. However, because of the large iris and beam tube openings the distance between neighbouring s.c. cavities has to be increased from $\lambda/2$ (for the Cu cavities) to $2\lambda/2$ in order to avoid coupling of the accelerating mode between cavities. In addition, space has to be foreseen at both ends of a cryostat for a transition between the 4.2 K and 300 K temperature level. Even with eight 4-cell cavities housed in a common vacuum tank, the available space in the standard r.f. cells (ℓ = 24,26 m) will be marginal and it will be impossible to locate additional items like e.g. correction magnets, tilted quadrupoles and collimators. Therefore, it is proposed to increase the length of standard r.f. cells for installation of s.c. cavities.

The high acceleration efficiency of s.c. cavities allows to power 16 cavities with one 1 MW klystron so that ~ 60 kW will be available for each cavity. With a beam power $P_b = i_b \times E_{acc} \times \ell \times \sin\phi_s$ (ℓ = 1.7 m, $\sin\phi_s$ = 0.87) one can accelerate up to ~ 2 x 4 mA at E_{acc} = 5 MV/m or alternatively with a readjusted coupling ~ 2 x 3 mA at E_{acc} = 7 MV/m. For higher beam power P_b, the number of klystrons has to be increased.

It is proposed [12] to install one refrigerator cold box on each side of the interaction points inside the klystron tunnel. The available space in the tunnel will limit the refrigeration power at 4.2 K to ~ 6 kW for each cold box. This should be sufficient to operate s.c. cavities in (at least) 4 r.f. cells up to a gradient of 7 MV/m. If accelerating fields have to be increased beyond 7 MV/m, additional cold boxes (and compressors) have to be installed unless Q-values well above the design values of 3×10^9 can be obtained at these fields.

Studies for the layout of the LHe distribution system between cold boxes and cavities are under way. At present a combination of parallel and series supply (involving 2 phase flow of He) is considered [12]. Safety aspects for the large quantities of LHe inside the LEP tunnel (~ 200 ℓ/cavity) have been studied. The problem is alleviated by the fact that the electromagnetic field energy stored in s.c. cavities is much smaller than the magnetic field energy stored in a magnet. Heat loads are mainly due to r.f. losses and can therefore be switched off instantaneously. The 300 mm diameter suction lines between cold boxes below ground and compressors located at the surface can be used as a large rate evacuation line to atmosphere in case of catastrophic LHe loss due e.g. to a beam vacuum failure.

The first 4 s.c. cavities in LEP

It is foreseen to install in the LEP ring during the second half of 1989 and after a first running-in period, four s.c. Nb cavities with their auxiliary equipment. Two separate cryostats with 2 s.c. cavities each (and later on extendable to 4 s.c. cavities) will be located in cell 245 near interaction region 2. The foreseen layout of cavities, waveguide and He distribution systems are shown in fig. 3. Cavities will be powered by one 1 MW klystron standard system and will be cooled by a 1 kW refrigeration plant (modified ex-ISR liquefier).

With 4 cavities and with a gradient of 5 MV/m a total acceleration voltage of 34 MV is obtained. This should give an interesting possibility for storing and accelerating LEP beams up to ~ 30 GeV with the s.c. cavities alone.

Upgrading of LEP by s.c. cavities

Scenarios for the upgrading of LEP by s.c. cavities have been presented for a first time in ref. [3] where costs and time schedules are also discussed. An updated version will be presented at this Conference [13].

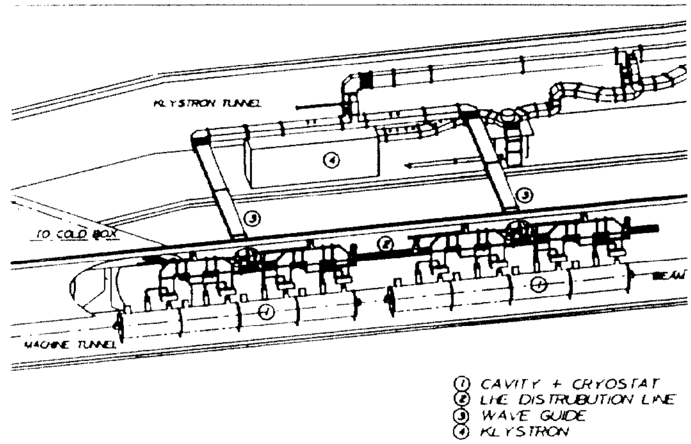

Fig. 3 Proposed layout of the first 4 s.c. cavities with a klystron inside LEP. The 1 kW cold box is located at the klystron tunnel.

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