# RADIO FREQUENCY SUPERCONDUCTIVITY AT CERN: A STATUS REPORT

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## 1. INTRODUCTION

Up to 1984 the efforts in superconducting (s.c.) cavity development at CERN were mainly concentrated on 500 MHz cavities [1], leading to the test of a 5-cell, 500 MHz cavity at PETRA [2]. The results confirmed that the achievable accelerating fields do not decrease at lower frequencies as strongly as previously suspected. Therefore, it was decided in 1984 to concentrate efforts on 352 MHz cavities [3,4]. This frequency choice is suggested by the fact that LEP will be equipped at the beginning with 128 Cu cavities at 352 MHz which will bring up energies to 55 GeV/beam [5]. There is an obvious interest to install at a later stage s.c. cavities with the same frequency and to use at maximum the existing installation of radio frequency (r.f.) power sources. With the installed r.f. power of 16 MW, LEP could be upgraded to ~ 90 GeV by using s.c. cavities [6]. This will require the construction, testing and installation of several hundred of s.c. cavities, therefore arguments of economy and reliability are of outstanding importance.

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The LEP programme asks for many additional items and substantial work has gone into the development, construction and testing of cryostats, main couplers, Higher-Order Mode (HOM) couplers and frequency tuners.

Besides the main line based on Nb-cavities another development has been pursued and that is the deposition of a thin niobium layer on copper cavities [9-12]. Results look very promising but more efforts will be needed to reach the same level of know-how as for Nb cavities.

## 2. RESULTS WITH 350 MHz-Nb CAVITIES

In the following the main experimental results are given which led us to the final layout of a LEP prototype cavity.

A new cavity geometry (fig. 1) has been developed with the following features [13] in comparison to our previous 500 MHz, 5-cell design:

- The iris thickness and diameter have been modified to obtain a higher cell-to-cell coupling for all modes yielding a lower sensitivity to manufacturing tolerances.
- A "multimode" end-cell compensation for the most important HOM assures a sufficiently high field at the coupler location on the cut off tubes.

We decided to use 4-cell units for the application in LEP. This results in cavities which fit into the existing machine lattice [6] and which do not show significant mechanical tolerance problems.

A few cavity parameters are collected in table 1. For testing this design five mono-cell cavities and three 4-cell cavities [7,8] have been constructed. They are fabricated from 3 different types of Nb material (RRR = 40, 110 and 156).

A great effort has since been devoted at CERN to develop new and improved facilities for cavity spinning, welding, surface treatments and to test installations. With the know-how accumulated at CERN several LEP prototype cavities have been designed and constructed [7,8]. Two more cavities with cryostats of our design have been ordered at industry.

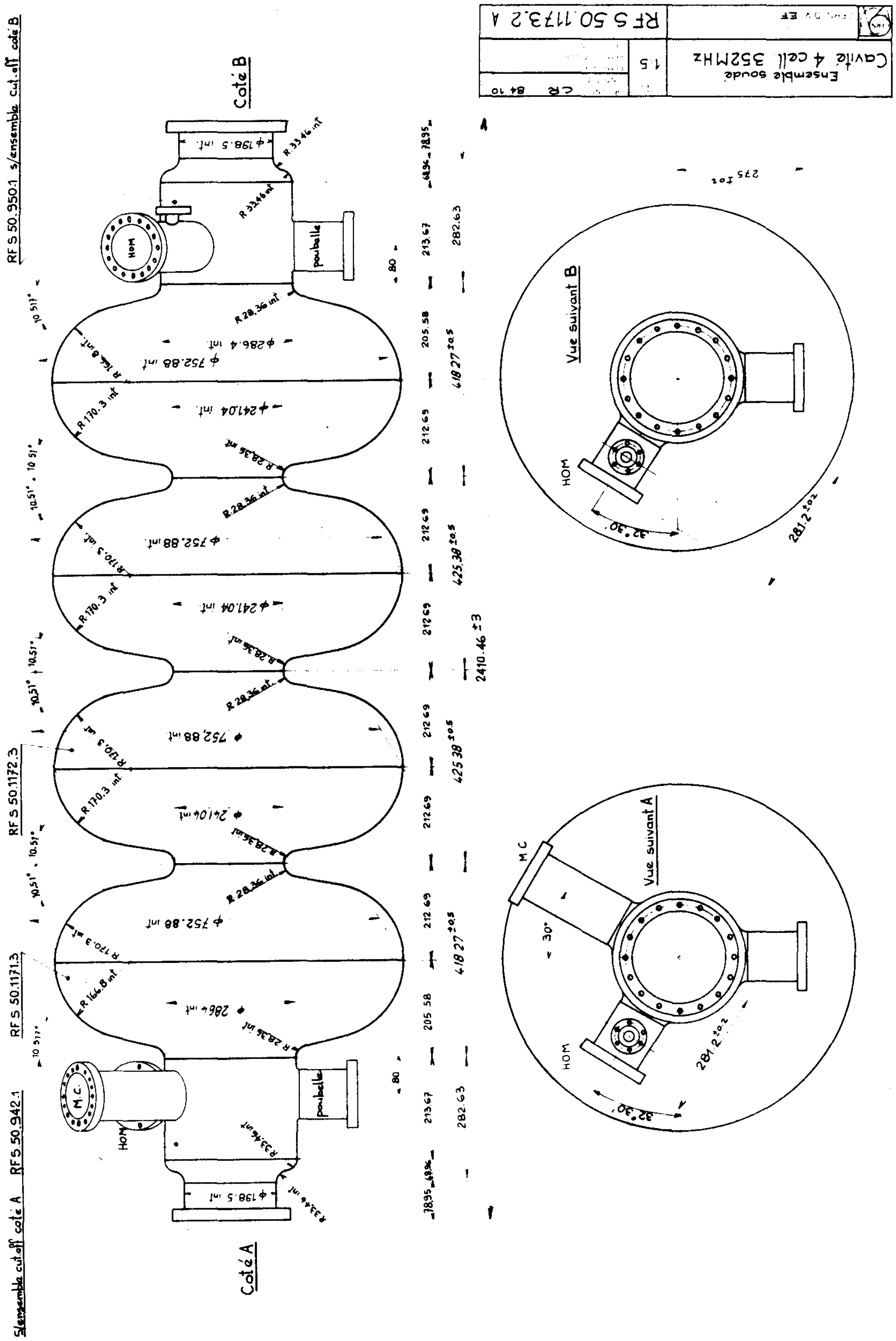


Fig. 1 Geometry of a LEP 4-cell cavity with end-cell compensation and with one main coupler port, 2 higher-order mode coupler ports and two auxiliary ports

**TABLE 1**

A few parameters of 4-cell LEP cavities

| | |
|---|---|
| Frequency f | 352.209 MHz |
| Cavity active length | 1.70 m |
| Iris hole diameter | 241 mm |
| Shunt impedance/quality factor r/Q | 276 Ohm/m |
| $E_p/E_{acc}$ | 2.3 [(a)] |
| $H_p/E_{acc}$ | 39 G/(MV/m) |
| Geometry factor G | 280 Ohm |
| $2(f_\pi - f_o)/(f_\pi + f_o)$ | 1.76% |
| $- \Delta f/\Delta p$ | ~ 2 Hz/mbar [(b)] |
| $\Delta f/\Delta \ell$ | 45 Hz/µm |
| f (low field) - f (5 MV/m) | < 200 Hz |

(a) 2.13 at beam-tube iris,
(b) Inside prototype cryostat.

In table 2, the main results obtained with mono-cell and 4-cell cavities are presented.

In fig. 2 the final Q values as a function of accelerating field are given for the 4-cell cavities LEP 0 and LEP 2. They have been obtained with a shielding of the external magnetic field compensated to $H_{ext} \leq 140$ mG. This increases low field Q values at 4.2°K typically by more than a factor 2 compared to the uncompensated case.

From the measured Q curves at different bath temperatures, $Q_{BCS}$ and residual resistances could be derived. Values[(*)] obtained with LEP 0 (RRR = 112) are

$$Q_{BCS} = (6.5 \pm 0.3) \times 10^9 \text{ at } 4.2°K,$$

$$R_{res} = 17 \text{ nOhm for } H_{ext} < 100 \text{ mG}.$$

(*) Measured values at 500 MHz for similar material are $Q_{BCS} = 3.1 \times 10^9$, $R_{res} = 18$ nOhm [14].

**TABLE 2**

A few typical results for 350 MHz cavities(*)

| Cavity type | Material RRR | $Q_o (\times 10^9)$ at 4.2°K | | $E_{max}$ at 4.2°K (MV/m) | Most common field limitation | Remarks |
|---|---|---|---|---|---|---|
| | | Low field | 5 MV/m | | | |
| Mono-cell | 40 | 3.1÷4.1 | 2.2÷2.9 | 5.8÷10.3 | Localised defect | Results obtained with 5 mono-cell cavities, 2 with and 3 without coupling ports |
| Mono-cell | 110 | 2.9÷6 | 1.6÷3.1 | 5.4÷9.4 | NREL | |
| 4-cell | | | | | | |
| LEP 0 | 112 | 4÷5.5 | 3.1÷4.7 | 7.5 | NREL | |
| LEP 2 | 156 | 5÷5.8 | 3 | 7.3 | NREL | |
| LEP 1 | 40 | 6 | - | 3.4 | q at weld | Poor material, no push for higher fields |

(*) Standard surface treatments

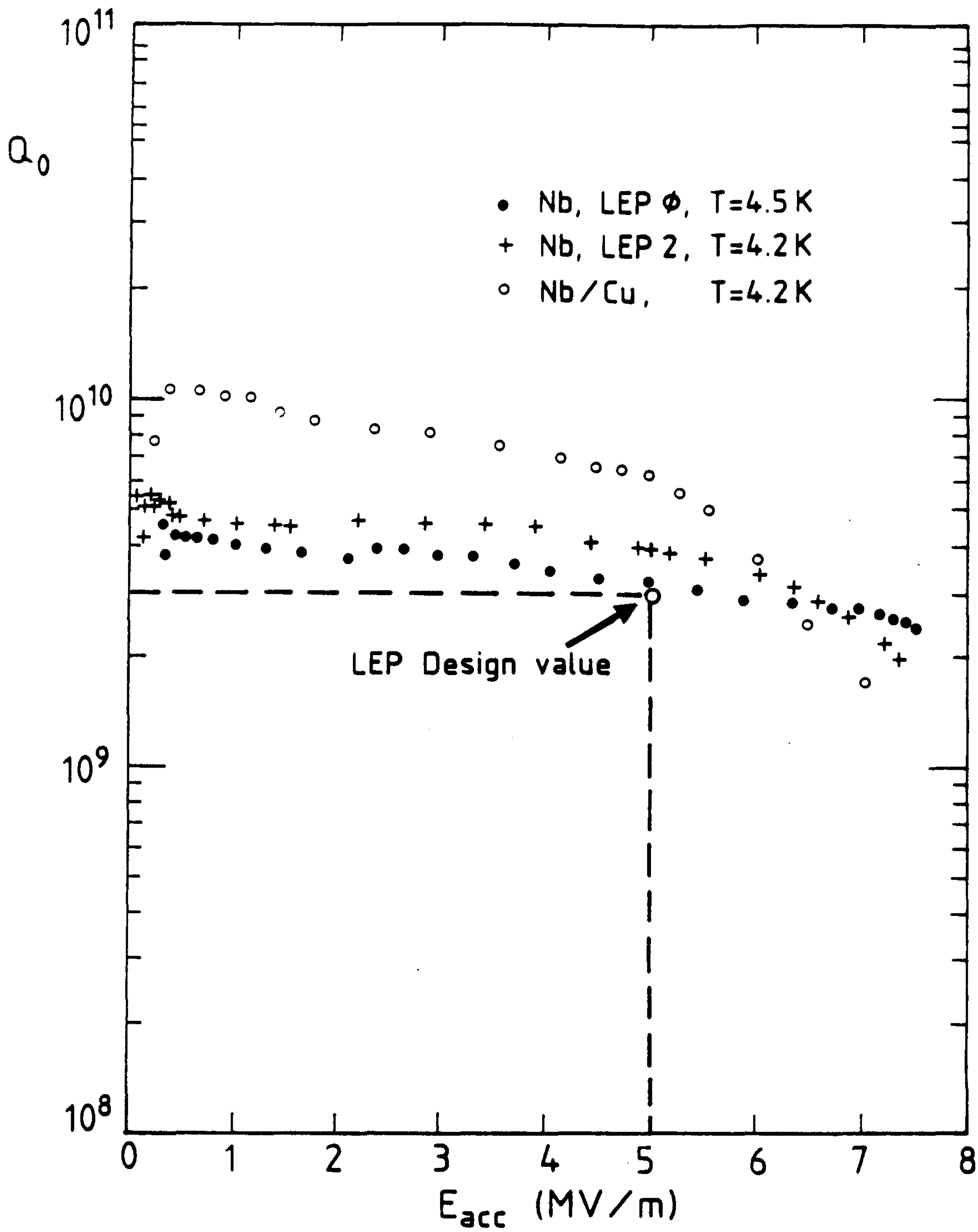


Fig. 2 Dependence of Q values on $E_{acc}$. Final values for 4-cell cavities LEP 0 and LEP 2 with $H_{ext} \leq 160$ mG and for a 350 MHz 4-cell Cu-cavity with a magnetron sputtered Nb-layer.

In fig. 3 the measured temperature dependence of $R_{BCS}$ is shown. The measured Q values at 5 MV/m reaches ~ 50% of the value of $Q_{BCS}$ = 280 Ohm/$R_{BOS}$.

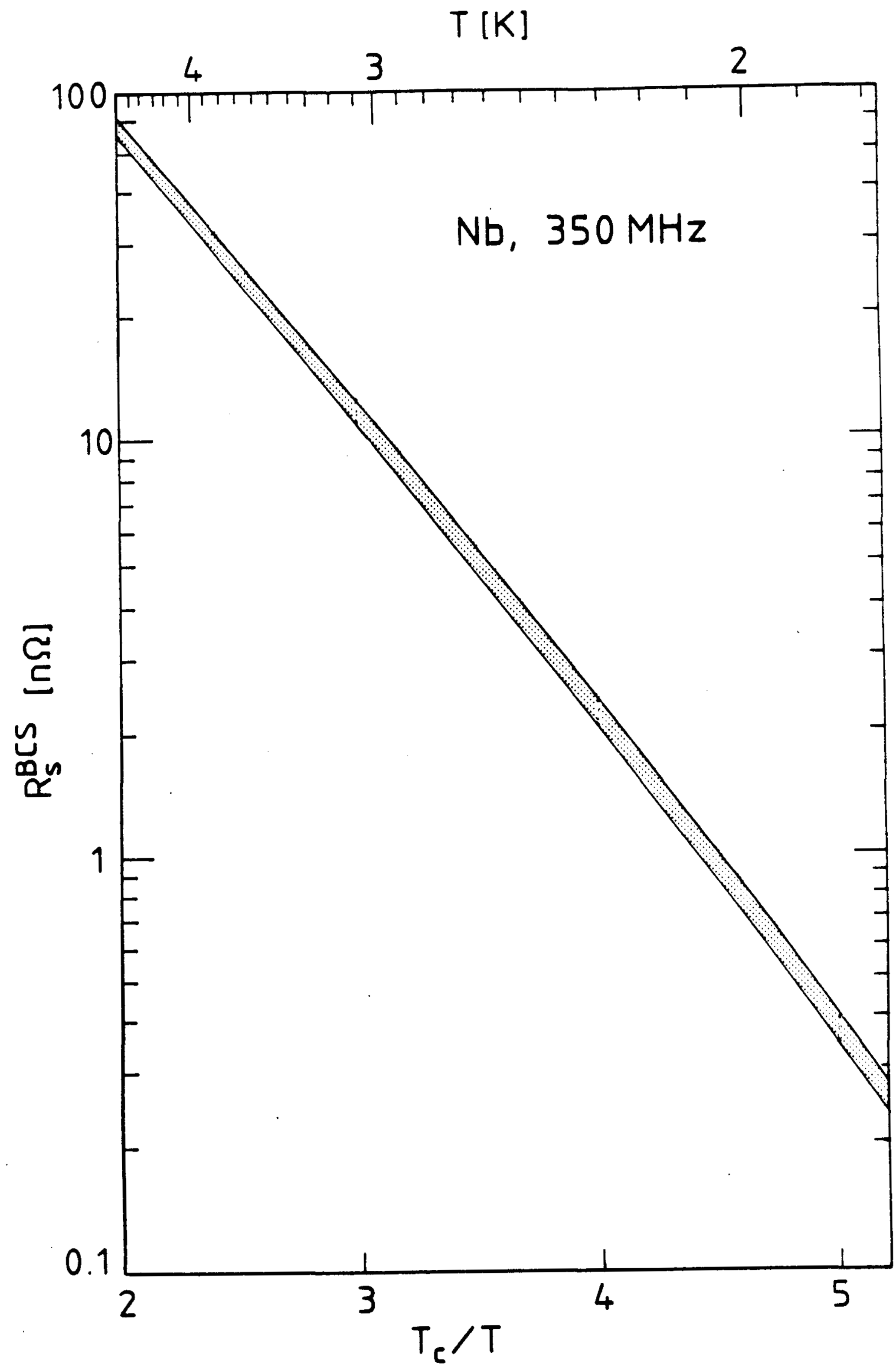


Fig. 3 Measurement of $R_{BCS}(T)$ for 4-cell cavity LEP 0 (RRR = 112, G = 280). For 4.2°K one has $R_{BCS}$ = 45 nOhm, $Q_{BCS}$ = 6.2 x $10^9$.

The long-term performance of the cavity LEP 0 (without power and HOM couplers) was tested in the laboratory for:

- a high field operation (CW) of 2200 h.
- an estimated total radiation dose at the cavity surface (during 73 h of He processing) of ~ 1 Mrad.
- a few short warm up cycles to ~ 300°K.

No degradation of Q values and fields have been found during this long-term test (fig. 2).

A test of a fully equipped cavity is under way in the CERN SPS accelerator.

All cavities fabricated from Nb material of RRR ≳ 110 needed no guided repair of defects to reach fields above 5 MV/m. We therefore believe that one can get with our present fabrication methods and surface treatments in a reliable way fields well in excess of the design value of 5 MV/m for LEP 4-cell cavities equipped with all coupling ports.

Fields reached after exposure to dry dustfree air or nitrogen lie in the range of 6 to 9 MV/m and were almost always limited by non-resonant electron loading (NREL) and/or by the available r.f. power.

In fact, accelerating fields in 350 MHz cavities are very often limited by NREL and very long He processing is sometimes needed to reach high enough fields. A review of all our measurements shows that coupling ports on the beam tubes influence this behaviour strongly.

For mono-cell cavities without coupling holes fields above 9 MV/m have been reached after a short (< 1 h) r.f. processing demonstrating that our surface treatment and assembly methods and in particular the final rinsing with ultrapure water is satisfactory. For cavities with coupling ports at the beam tubes, high fields could only be achieved after a He processing of many hours and whose duration increased also with the number of cells.

The most plausible explanation is the increased risk of contamination by dust particles in cavities with coupling ports (which need additional assembly procedures) and/or a less efficient rinsing.

Multipactor has been observed nearly always starting sometimes at field levels as low as 0.1 MV/m and up to ~ 7 MV/m. Besides the well known localisation of two side multipactor near the equator [15], multipactor has also been localised at the coupling ports, but has never been a serious field limitation.

The room temperature field flatness of the two 4-cell cavities LEP 0 and LEP 2 was after fabrication in the range of $\Delta E/E \leq \pm 10\%$ and could be easily corrected by inelastic deformation of individual cell lengths to values below ± 4%.

These results convinced us that the cavity design is now mature for industrial production.

## 3. NIOBIUM COATED COPPER CAVITIES (Nb-Cu)

Besides the development of cavities made from Nb sheet material, another line has been pursued: the deposition of a thin (0.7-2 μm) Nb layer on Cu cavities [9-12].

This solution presents several advantages. The high heat conductivity of Cu (typically 450 W/m • K versus 40 W/m • K for our best Nb material) ensures a better thermal stabilization of defects. In these cavities fast breakdown up to accelerating fields of 10 MV/m has never been observed. This is an obvious advantage for the LEP acceleration system where one klystron will feed 16 superconducting cavities. Another argument in favour of the Nb-Cu solution is a possible reduction in cavity costs. This reduction may be substantial for the large LEP cavities where the Nb material costs represent 25% of the total costs (cavity, cryostat, couplers, tuners and vacuum systems).

Both diode [9,10] and magnetron [11,12] sputtering have been chosen for coatings and excellent results, comparable to those of solid Nb cavities, have already been obtained in 500 MHz single-cell cavities. At present magnetron sputtering is preferred because of its simpler layout and higher deposition rate (> 1 μm/h). Typical layer thicknesses range from 0.7 to 2 μm.

Accelerating fields up to ~ 11 MV/m and low field Q values even higher than those ones obtained with solid Nb cavities have been reached. However, the decrease(*) of Q values towards higher fields is stronger than in Nb cavities and "Q switches" due to localised blistering of the sputtered Nb surfaces are still a problem. The sputtered layers contain relatively large impurity contents (between 0.1 and 2 at% of H, C, O, Cu reflecting itself in the low RRR values measured; RRR = 7 ÷ 25).

An interesting aspect of Nb coatings is the small dependence of residual r.f. losses from the surrounding magnetic fields [14] which makes shielding of the earth magnetic field superfluous.

Recently magnetron sputtering has also been applied to 350 MHz single-cell and 4-cell cavities of LEP geometry [12]. As for 500 MHz cavities, Q values at low field are higher than for solid Nb cavities and a strong decrease of Q values at higher fields is observed.

In fig. 2 the Q curve of a magnetron sputtered LEP 4-cell cavity is shown. Low field Q values reach values of $10^{10}$. The Q value at the LEP design field of 5 MV/m is still $6.2 \times 10^9$ i.e. more than a factor 2 above design value. A maximum field of 7 MV/m has been reached after 32 h of He processing and no quench due to a localised surface defect has so far been observed, nor a "Q switch" due to blistering (for a total surface of ~ 6 $m^2$).

It appears that the requirements for weldings of Cu cavities are at least as demanding as for Nb cavities if porosities and blistering of the Nb layers are to be avoided. Requirements for surface cleanliness [16] before sputtering of thin layers also present a considerable challenge. It is suspected [11] that already impurities of microscopic sizes (down to tens of μm) can produce blistering or at least a poor thermal contact of the sputtered layer with the copper substrate.

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(*) It can be approximated by $Q(E_{acc}) = Q_o \exp(-\alpha\ E_{acc})$ [14]; the normalised decrease $\alpha/Q_o$ is comparable.

One should note that the sputtering approach will also be very interesting for the application of alloys like $Nb_3Sn$ and NbN or of the new high $T_c$ superconductors based on oxide materials which can reach $T_c$ in the 90°K range. The mechanical properties of these materials make construction of cavities from solid material impossible and deposition methods will be a necessity.

## 4. OTHER MATERIALS AND CAVITIES

### 4.1 $Nb_3Sn$ cavities

$Nb_3Sn$ layers have been grown by diffusion from tin vapour on a 500 MHz single-cell cavity treated at 1025-1050°C for a period of 2 x 8 h [17,18]. The low temperature applied has limited the $Nb_3Sn$ thickness to ~ 0.9 µm, nevertheless $Q_o = 2.4 \times 10^{10}$ at 4.2°K, (corresponding to $R_{res}$ = 11 nOhm) has been reached. This is an improvement of $Q_o$ by a factor 7 with respect to Nb at 4.2°K. The result confirms that $R_{res}$ of $Nb_3Sn$ decrease with decreasing frequency [17]. Accelerating fields up to 5 MV/m have been reached. Q curves are still characterised by a strong decrease towards higher fields and by "Q switches" which seem to be caused by weak spots with critical temperatures well above 4.2°K and which appear already at very low fields. A dependence on external magnetic fields similar to the one observed in Nb cavities is also found.

### 4.2 68 GHz cavities

Four 68 GHz Nb cavities for application in a two-photon transition maser have been fabricated, surface treated and tuned to a definite frequency [19]. First maser experiments have been made recently at Ecole Normale Supérieure (Paris).

### 4.3 Material characterisation

For the characterisation of thermal conductivity of Nb, Cu and other metals at He temperatures a fully automatized test set-up has been developed [20] as well as a test set-up for determining $H_{c2}(T)$ dependencies of s.c. sheet material and thin layers and for evaluating inhomogeneities [21].

## 5. ADDITIONAL ITEMS FOR SC LEP cavities

The LEP programme asks for many additional items and in the past years a considerable effort has gone into their design, development and testing.

### 5.1 Cryostats [22]

The length of LEP cavities has been chosen to place eight 4-cell cavities [6] in each r.f. cell (24 m total length) of the LEP straight sections. It has been foreseen to install up to eight s.c. cavities with their He tank in one common insulation vacuum tank. A tunnel slope of up to 1.5% has to be accomodated.

The design of cryostats [22] has been guided by the following requirements: cryostats should be modular in order to allow a lateral (and not axial) removal of individual cavities and He tanks from a string of cavities. Good access to all critical parts like couplers, tuners and beam tube connections should be guaranteed. Assembly of cavities, connections to the beam vacuum system and local repairs should be possible under clean and dustfree conditions and by keeping cavities under a slight overpressure of dry, dustfree protective gas. Finally, the choice of materials and layout should aim for low costs.

The He vessel (fig. 4) is made of a thin stainless steel sheet and is welded around the cavity. It has a corrugated shape which reduces the liquid helium volume to ≃ 200 ℓ and which can be easily matched to the requirements of the coupling port geometry. The main coupler and HOM couplers which are of a coaxial type are mounted on Conflat type flanges to which the He vessel is welded. The longitudinal rigidity of the He vessel is kept small enough to allow tuning by changing the cavity length. The cold shield is made of removable Cu sheets thermally linked to a copper tube frame by means of mechanical clamping devices. It is cooled by He gas deviated from the main boil-off flow.

The vacuum vessel consists of a supporting frame with reinforcing staves wrapped in a thin stainless steel sealing envelope. Vacuum tightness is obtained by rubber gaskets. The sealing skin, staves and cold shield can be removed laterally and provide full access to the cavity and to all critical parts. Frequency tuning is achieved by changing the length of three tubes anchored to the cavity end flanges and located inside the insulation vacuum.

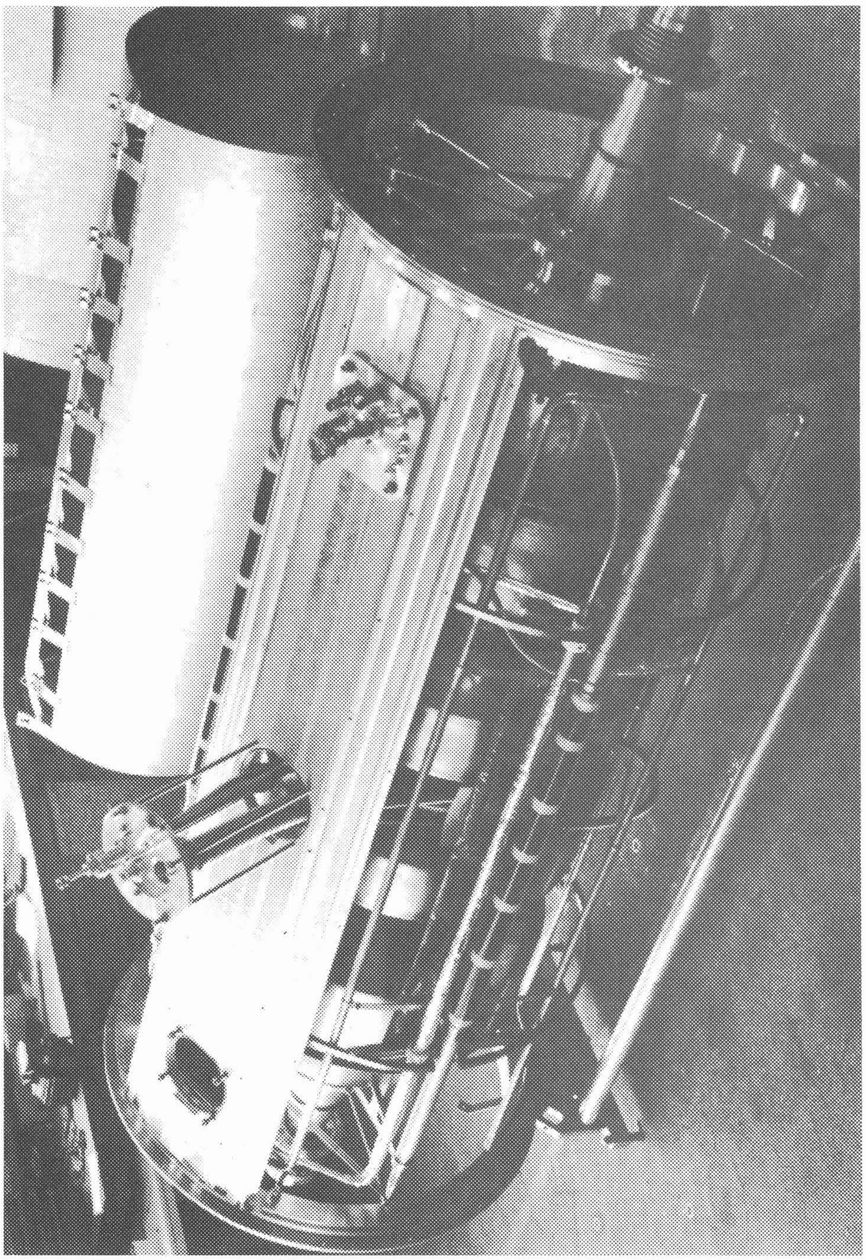

Fig. 4 Photography of the cryostat for 350 MHz 4-cell LEP cavity

The cryostats are equipped with small domes for the main coupler, the He transfer lines and for electrical and r.f. connections. They are turned by ~ 30° from the vertical plane. In this way room for a later installation of a proton storage ring in the LEP tunnel is left.

Two cryostats have been constructed at CERN. They have been cooled down with a s.c. cavity a number of times and a total operation time of 9 months has been accumulated without any major failure. For one cryostat and cavity with beam tube connections to room temperature, but without main coupler, static losses of ≤ 14 W at 4.2°K have been measured. During this measurement the cold He gas flow across the thermal shield amounted to < 0.1 g/s.

At present improvements of the cryostat design are under study and will be tested very soon. In particular one aims at a better understanding of static losses and at a suppression of thermo-acoustic vibrations. The final layout of the He transfer geometry and phase separation geometry depends on the chosen He supply system which is presently under study.

5.2 Frequency tuners [23]

The tuning requirements for operation in LEP are a.o. determined by the bandwidth B of the loaded cavity: for a main coupler matched to the LEP design values ($E_{acc}$ = 5 MV/m, $i_{beam}$ = 2 x 3 mA) this gives $Q_{ext} = 4 \times 10^6$ and B = 90 Hz.

Rapid frequency changes due to beam loading, He pressure changes or vibrations and the requirements of a fast detuning in case of a cavity quench require a fast tuning system with a range of at least some hundred Hz.

It is anticipated that cavities can be pretuned at room temperature so that their frequency will be within ± 10 kHz of their design frequency at low temperature. Tuning is achieved by a change of total cavity length (45 kHz/mm).

A combined system for fast and slow tuning has been proposed [24] and developed [23] using three Ni tubes located inside the insulation vacuum and connected to the beam tube flanges of the cavity (fig. 4). By choosing a very rigid and symmetric construction it was possible to push up the first longitudinal resonance of the cavity-tube system to ~ 100 Hz and to suppress transverse oscillations to a negligible amplitude.

Fast tuning uses the magnetostrictive effect of the support tubes: Ni has been chosen as tube material for its proven cryogenic properties although its magnetostrictive effect is smaller than for specially developed magnetostrictive materials. A tuning range of ~ 2 kHz, and a step recovery time of 20-50 ms have been measured.

For slow tuning the mean temperature of the Ni tubes is changed by an electric heater at their centre which counteracts the cooling action of cold He gas injected into the ends of the tubes and which flows from there with good heat exchange towards the tube centre. A tuning range of 50 kHz is achieved. Tuning speeds depend on the mean temperature and lie in the range of 2 ÷ 10 Hz/s.

At present this system is used on a 4-cell cavity installed at the CERN 450 GeV Proton Synchrotron. Further refinements and improvements are under study.

5.3 Main coupler [25]

Following the decision to locate all couplers at the beam tube an antenna type, coaxial main coupler had to be developed. Its r.f. window has been located at room temperature. A cylindrical window integrated in the coaxial to waveguide transition as developed for the LEP Cu cavities [26] is used. Inner and outer conductors are fabricated from stainless steel tube plated with a thin layer of Cu. They are cooled by cold boil-off He gas. The r.f. window and inner conductor can be replaced without opening the cryostat vacuum tank.

A few couplers have been constructed and tested on cold cavities up to a power level of 40 kW, Continuous Wave (CW), needed for LEP operation. Great care has been taken to reduce contamination of the s.c. cavity by gases desorbed from the warm coupler and window parts. Prior to final installation and cool down couplers are baked out and conditioned (in pairs) at room temperature on a special automatic test set-up. It takes typically 24 h of conditioning to reach a power level of 40 kW. Coupler losses at 4.5°K havebeen measured at the design field of 5 MV/m. For a transfer of 40 kW under TW conditions the losses are 2.5 W.

### 5.4 Higher-order mode (HOM) couplers [25]

As for the main coupler, the location of couplers on the beam tubes triggered the developments of new types of HOM couplers. It has been tried to keep them compact, demountable, tunable at room temperature and easy to cool. Several types [27-29] have been designed and tested on cold cavities at accelerating fields exceeding 5 MV/m. For LEP operation it is considered sufficient to evacuate the HOM losses via type N connectors and cables to room temperature r.f. loads. For an antenna-type coupler this scheme has been tested with two HOM couplers on a cold cavity up to power levels of 200 W. Coupler losses are estimated to remain below 1 W and no measurable influence on $Q_0$ values has been found.

Other coupler types based on a "lunar guide" [28] have been developed in view of special requirements of Nb sputtered Cu cavities [29] or of high-current linacs where a strong damping of dipole modes is essential [30]. These types rely to a large extend on cooling by heat conduction. The use of these couplers allows to reach for the dangerous HOM modes cavity dampings better than naturally found in Cu cavities and specific modes can be attenuated to $Q_{ext}$ between $10^3$ and $10^4$.

## 6. FABRICATION AND SURFACE TREATMENTS OF CAVITIES

The large size of 350 MHz cavities raises special problems for cavity fabrication. Many changes and improvements were necessary to adapt existing facilities which had previously been used for the fabrication of 500 MHz cavities.

### 6.1 Spinning of Nb half-cells

Spinning of half-cells has been applied for the fabrication of 350 MHz Nb and Cu cavities. For the spinning of 3 mm sheet material a semi-automatic procedure using an Al alloy dye and a template (but no numerically controlled lathe) is used. The final shape refinements at the equator region are performed with the help of a second hard wood dye. The required mechanical tolerances at the equator and the iris of a few tenth of a millimeter can be obtained as well as an adequate surface quality. Up to now more than 30 Nb half-cells and more than 40 Cu half-cells have been produced.

### 6.2 Electron beam welding [31,32]

Electron beam welding of Nb and Cu cavities has been improved by now to a quality and reliability level which is satisfactory for our large multi-cell cavities. The large openings of 350 MHz cavities allow to use an internal electron gun. This method presents, with respect to the normally used internal-external welding, definite advantages especially for material thicknesses exceeding 2 mm. A full penetration of the welding is not essential and much lower beam powers are sufficient. This decreases the danger of damages in case of gun failure or errors. Also a larger range of welding parameters can be tolerated. Welding seams are of higher quality at the side where the electron beam impinges, in particular there is less danger for projections. Mounting rigs can be simpler (fig. 5) and welding of multi-cell cavities in a single pumping cycle becomes easier. A horizontal position of the electron beam increases seam quality by a better stabilisation of the welding pool.

At CERN TIG welding of Nb parts has been abandoned nearly completely because of the insufficient reliability of inert gas protection systems for Nb welding seams.

### 6.3 Brazing of Nb with stainless steel

Vacuum brazing [33] has been adopted at CERN as a standard method for joining stainless steel flanges to Nb tubes. At present OFHC copper wires are used as brazing alloy. Extensive tests have been performed confirming the excellent mechanical properties and the resistance to low temperature shock of such brazings. UHV requirements of CERN storage rings are taken into account by using conflat flanges of forged AISI 316 LN material. It has also been chosen because it develops particularly small remanent magnetic field after heat treatments and cool-down cycles.

### 6.4 Surface treatments and assembly conditions for Nb cavities

A great effort has been made for enabling surface treatments [16] of large 4-cell cavities under safe and reproducible conditions.

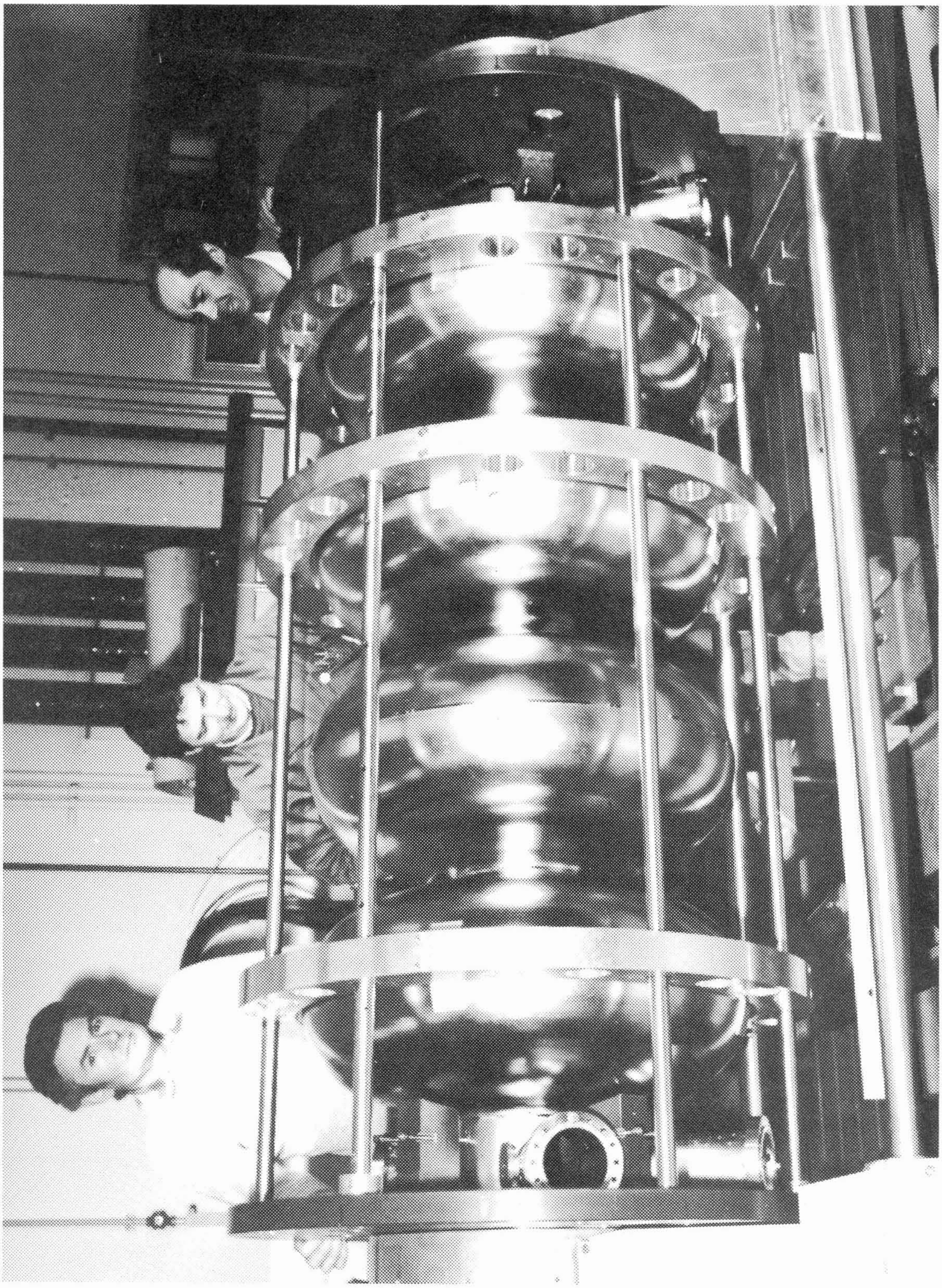

Fig. 5 A mounting rig for cavity EB welding

Prior to all weldings, Nb parts are degreased, chemically polished (80 μm in a standard 1:1:1 solution), anodised, inspected and eventually reground. Welding is done in a sequence allowing inspection of all welding seams and good access for a possible regrinding of welding seams and their surrounding.

The sequence of final treatments of 4-cell cavities is the following:

- Degreasing.
- Chemical polishing in a 1:1:2 solution (~ 30 min. at ~ 1 μm/min; filling and emptying time ~ 50 s).
- Thorough rinsing with demineralised water.
- Final rinsing with ~ 600 ℓ of ultrapure water ($\rho$ = 18 Mohm/x cm; resistivity decrease controlled at outflow).
- Drying of cavity by a roughing pump with baffle to avoid oil back streaming. The cavity is dried with a 45° inclination of its axis and heated to ~ 50°C.

For the chemical treatments a dedicated installation is used (fig. 6). The process is controlled by a microprocessor and is done without human intervention inside the treatment pit. Safety aspects have been of prime importance for the design of the whole installation.

The mounting of HOM couplers, r.f. probes, coupling port and beam tube covers is done in a dustfree laminar air flow room of class 100. Final connections of the cavity with its vacuum system and/or with beam tubes is performed in front of another large laminar flow installation of class ~ 1000.

In the course of cavity tests, repairs of leaks at covers and r.f. probes or additional mountings of HOM couplers were sometimes necessary. These were done by exposing the cavity slowly (~ 1 h) to dry dustfree air or $N_2$. Repairs were made in front of a mobile laminar air flow unit and at a slight overpressure inside the cavity. If properly done, this procedure did not affect $Q_o$ values and maximum fields but an increase of multipactor and NREL was often observed. It is foreseen to use a similar method for the mounting or removal of cavity units within a string of cavities and cryostats at LEP and for "in situ" replacement of main couplers.

Fig. 6 Installation for chemical treatments

6.5 Inspection devices [16]

For a detailed inspection of cavity surfaces and of welding seams a telescope on a stand equipped with a rotatable mirror is used. A direct illumination source located near the mirror completes the layout. The optics and mirror are far away from the inner walls and there is little risk to damage surfaces. Defect identification however is sometimes difficult. In particular, small holes in the surface are hard to distinguish from protrusions. For a closer view of very small defects a non-contaminating stereo optics located near to the surface would be of great utility.

## 7. UPGRADING OF LEP BY SC CAVITIES [6]

As already mentioned before, the frequency for the s.c. LEP cavities and their cell number have been chosen so as to require a minimum of changes in the existing r.f. layouts (with klystrons, waveguides, controls) and in the machine lattice (8 cavities per r.f. cell, fig. 7).

It is foreseen to install and operate four 4-cell cavities, two fabricated by industry and two by CERN, at the earliest possible date in LEP. The design values for these cavities are $E_{acc}$ = 5 MV/m and $Q_o$ (5 MV/m) = $3 \times 10^9$.

A cost optimization [6] has been made for the s.c. acceleration system including cavities, r.f. and cryogenic systems as well as operating costs for 5 years showing that the total costs corresponding to $E_{acc}$ = 5 MV/m exceed minimum costs (reached at ~ 10 MV/m) by only 10%. For this accelerating field and for beam currents up to 2 x 4 mA, 16 s.c. cavities can be powered with one of the existing 1 MW klystrons installed in LEP.

The LEP upgrading will ask for very large refrigeration and He distribution systems. These systems are at present under study [34].

Various possible scenarios have been worked out for the upgrading programme of LEP. In a first stage one could install 32 cavities near one interaction region with two 1 MW klystrons and two refrigerators. Operation with these cavities alone would allow to reach particle energies (per beam) slightly above 50 GeV, i.e. nearly as much as obtainable with the 128 Cu cavities and their sixteen 1 MW klystrons. In combination with the Cu cavities an energy of ~ 65 GeV can be reached. This is just below the energy limit where some machine components have to be upgraded. The concentration of all s.c. cavities near one interaction region would allow to test to which extent LEP operation with a single acceleration station is

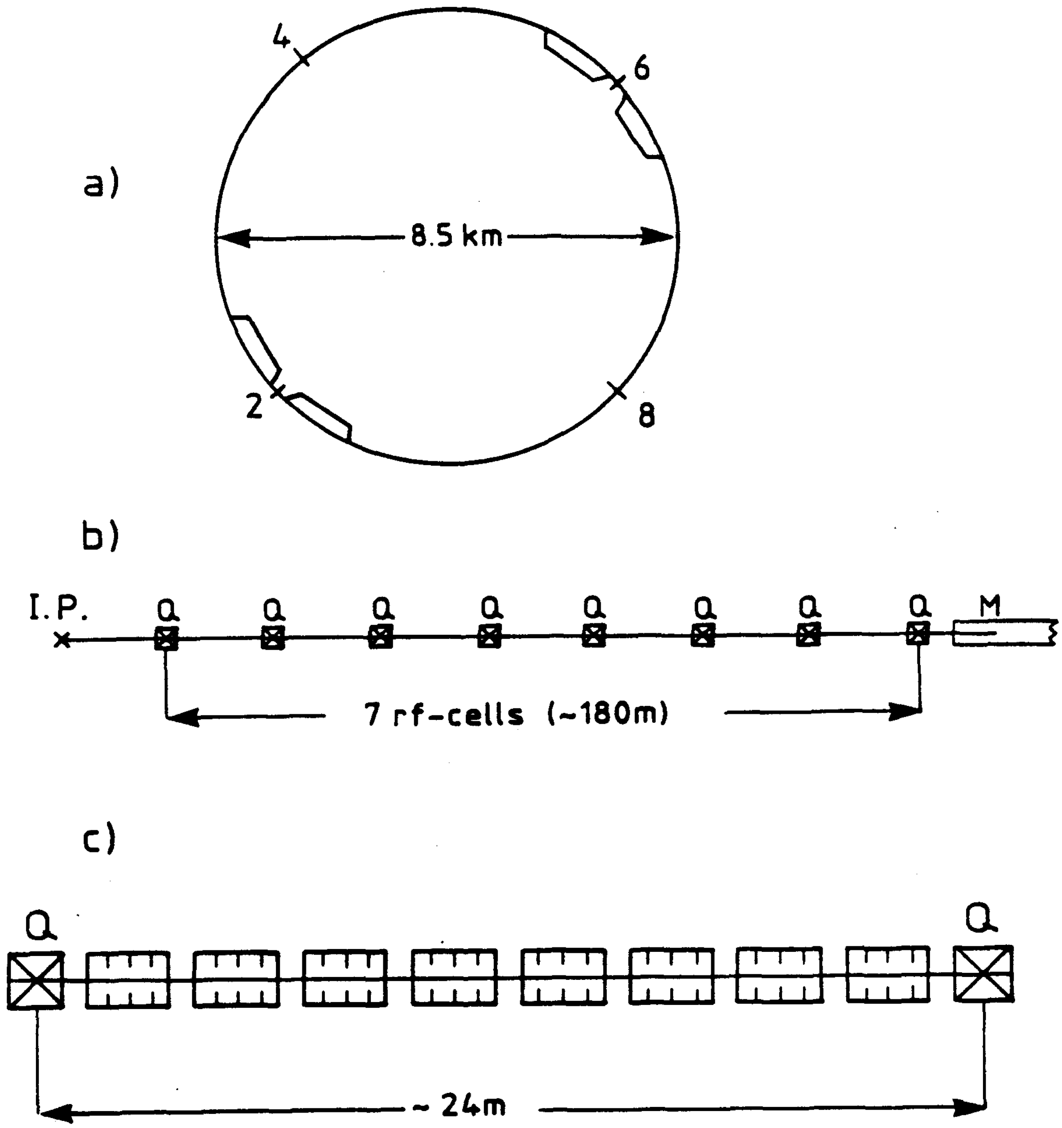


Fig. 7 General r.f. layout for LEP:
(a) LEP with two r.f. stations for Cu cavities (interaction regions 2 and 6);
(b) Layout of r.f. cells at one side of an interaction point;
(c) Layout of eight s.c. 4-cell cavities in one r.f. cell ($\ell_{eff}$ = 13.6 m, $E_{acc}$ = 5 MV/m).

possible and could give valuable information on whether two or four r.f. stations will be needed at the LEP design energy of ~ 100 GeV.

Two scenarios can be envisaged for the final upgrading. The first one foresees installation of a total of 192 s.c. cavities near two interaction regions with twelve 1 MW klystrons and four 6 kW refrigerators at 4.2°K. This would bring up LEP energies to 84 GeV (for $E_{acc}$ = 5 MV/m) i.e. just above the threshold energy for $W^{\pm}$ pair production ($m_W$ = 82 GeV).

The second scenario would be necessary if it turns out that LEP cannot be operated with two acceleration stations only. A total of 256 s.c. cavities with sixteen 1 MW klystrons and eight refrigerators could be installed at 4 interaction regions and would bring up LEP energies to 90 GeV. This scenario would need additional klystron galeries and facilities near the two new r.f. stations.

Given adequate financing, construction and installation time will extend over a period of 5-6 years. This includes a period of 2 years for transfer of know how to industry and for preparing fabrication and testing at a very high rate (2 cavities/week).

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REFERENCES

[1] C. Benevenuti et al., Proc. 2nd Workshop on RF Superconductivity, Geneva, Editor H. Lengeler (1984) 25.

[2] Ph. Bernard et al., Proc. 12th Int. Conf. High-Energy Acc., Fermilab (1983) 244.

[3] Ph. Bernard, G. Cavallari, E. Chiaveri, H. Lengeler and W. Weingarten, Internal Note CERN/EF/RF 83-6 (1983).

[4] D. Bloess et al., Internal Note CERN/EF/RF 85-2 (1985).

[5] LEP design report, CERN/LEP 84-1 (1984).

[6] Ph. Bernard, H. Lengeler and E. Picasso, Proc. ECFA Workshop on LEP 200, Aachen (1986) 29.

[7] G. Arnolds-Mayer et al., IEEE, NS-32 (1985) 3587.

[8] Ph. Bernard et al., Internal Note CERN/EF/RF 85-6 (1985).

[9] C. Benvenuti, N. Circelli and M. Heuer, Appl. Phys. Lett. 45 (1984) 5.

[10] C. Benvenuti, N. Circelli, M. Heuer and W. Weingarten, IEEE Trans. MAG 21 (1985) 153.

[11] G. Arnolds-Meyer et al., Internal Note CERN/EF/RF 86-1 (1986).

[12] C. Benvenuti, D. Bloess, E. Chiaveri, N. Hilleret, M. Minestrini and W. Weingarten, this Workshop.

[13] E. Haebel, P. Marchand and J. Tückmantel, Proc. 2nd Workshop on RF Superconductivity, Geneva, Editor H. Lengeler (1984) 281.

[14] G. Arnolds-Mayer and W. Weingarten, IEEE Trans. Mag. MAG-23 (1987) 1620.

[15] W. Weingarten, Proc. 2nd Workshop on RF Superconductivity, Geneva, Editor H. Lengeler (1984) 551.

[16] D. Bloess, this Workshop.

[17] G. Arnolds-Mayer and E. Chiaveri, Internal Note CERN/EF/RF 86-2 (1986).

[18] G. Arnolds-Mayer and E. Chiaveri, this Workshop.

[19] E. Chiaveri, J. Tückmantel, M. Brune, P. Goy, and J.M. Raimond, Internal Note CERN/EF/RF 87-3 (1987) and this Workshop.

[20] A. Schopper and W. Weingarten, Internal Note CERN/EF/RF 83-7 (1983).

[21] W. Weingarten, G. Müller and A. Welti, Internal Note CERN/EF/RF 87-2 (1987).

[22] R. Stierlin, this Workshop.

REFERENCES (Cont'd)

[23] G. Cavallari, E. Haebel, R. Stierlin, J. Tückmantel and W. Weingarten, this Workshop.

[24] E. Haebel, R. Stierlin and J. Tückmantel, Internal Note CERN/EF/RF 85-7 (1985).

[25] G. Cavallari, E. Chiaveri, E. Haebel, P. Legendre and W. Weingarten, this Workshop.

[26] J.P. Boiteux and G. Geschonke, LEP note 570 (1986) and CERN/LEP/RF 86-33 (1986).

[27] E. Haebel, Proc. 2nd Workshop on RF Superconductivity, Geneva, Editor H. Lengeler (1984) 299.

[28] E. Haebel, Internal Note CERN/EF/RF 85-3 (1985).

[29] E. Haebel and P. Legendre, Internal Note CERN/EF/RF 87-1 (1987).

[30] E. Haebel, Internal Note CERN/EF/RF, in preparation.

[31] E. Chiaveri and H. Lengeler, Proc. 2nd Workshop on RF Superconductivity, Geneva, Editor H. Lengeler (1984) 611.

[32] E. Chiaveri, D. Lacarrere, B. Thoeny, L. Verot and D. Vion, to be submitted to 4th Int. Symposium on welding and melting by electron and laser beams, Cannes (1988).

[33] J.P. Bacher, E. Chiaveri, R. Jacobs and B. Trincat, Internal Note CERN/EF/RF, in preparation.

[34] Ph. Bernard, W. Erdt, H. Lengeler, G. Passardi, J. Schmid and R. Stierlin, 11th Int. Conf. Cryogenic Engin. Conf., Berlin-West (1986) and CERN/EF 86-7 (1986).