Fig. 7.11. The test laboratory of the LEP chambers. About 2000 aluminium chambers were tested in batches of 12. Only those providing a pressure lower than 2 × 10^{-9} Pa after bake-out were accepted.

7.4 Superconducting Skin Boosts Accelerator Cavity Performance

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If the walls of radiofrequency (RF) accelerator cavities are superconducting (SC), the resistive RF losses on the cavity walls are orders of magnitude less than those of normal conducting cavities. However, some power is still absorbed and it increases proportionally to the square of the accelerating field [Box 7.4]. When this field is increased, a value is reached at which the internal surfaces of the cavity exceed the transition temperature T_c (9.3 K for niobium), and the cavity becomes normal conducting (it “quenches”).

Among the various factors which contribute to the temperature of the cavity surface, the thermal conductivity of the cavity wall material plays a major role. Niobium (Nb), the usual SC metal of choice for these cavities, is not a good thermal conductor, and it becomes even worse in the SC state, because the paired electrons do not transport heat. Copper would be a much better choice. Although copper is not a superconductor, it can be coated with a superconducting film [20]. This film does not need to be thick: About 10^{-3} mm would suffice to shield the underlying copper from the RF power. Copper would also provide the additional bonus of a much lower cost.

RF behaviour of superconductors **Box 7.4**

In the presence of radio frequency (RF) fields the electrical impedance of a superconductor (SC) is not zero, as it is for DC applications (e.g. magnets). The reason is that not all the conduction electrons are coupled in resistance-free Cooper pairs, even at temperatures lower than the SC transition temperature T_c. While in DC applications the current carried by the Cooper pairs [Box 8.1] short-circuits that carried by unpaired electrons, in RF conditions the unpaired electrons behave as electrons in a normal conductor and experience resistive losses. The population of normal conducting electrons decreases exponentially with the ratio of the temperature of operation to T_c, so materials with a high T_c represent a better choice. The negative role of the normal electrons is further reduced by choosing metals with low resistivity at low temperature.

While high T_c and low resistivity in the normal state are desired characteristics of a superconductor for RF accelerating cavities, essential practical features are ductility and weldability, required for manufacturing cavities from sheet metal. Niobium (Nb), with T_c = 9.3 K, reasonable electrical conductivity and mechanical behaviour similar to that of copper is the most widely used material for this application.

The "figure of merit" Q of an accelerating cavity is proportional to the ratio of the RF power stored in the cavity to the power dissipated resistively on the cavity walls in one RF cycle. At liquid helium temperature Nb offers a Q value about 5 orders of magnitude greater than that of copper. This difference more than compensates for the thermodynamic cost of helium liquefaction and the complexity of cryogenics.

Niobium is a good choice in spite of its very modest critical magnetic field (about 0.2 T) compared to that of the Nb-Ti alloy used for SC magnets (about 14 T). This is because the field of 0.2 T is only reached for accelerating gradients of over 40 MV/m, greater than that needed for circular e^+e^- colliders and linear colliders such as the ILC.

The real limitation of Nb lies in its modest thermal conductivity which defines the temperature gradient through the cavity wall and may result in a cavity "quenching" whenever T_c is exceeded locally. This was the main justification for developing a Nb-coated copper cavity. An added bonus of this approach is that it makes possible the manufacture of cavities using SC materials not suitable for forming from bulk.

For these reasons a vigorous development program was undertaken in parallel to that of the traditional bulk Nb approach in view of exploring the possible use of Nb film technology for the cavities to be used for the LEP upgrade from the initial energy of 50 GeV to about 100 GeV. When this work was started in 1980 little information on thin Nb films was available, and no one had succeeded in obtaining T_c = 9.3 K. A deeper analysis showed that all these films had been produced in sputtering systems with poor vacuum (10^{-4} to 10^{-5} Pa). Niobium is very reactive and during coating its purity is spoiled by trapping residual gas molecules. By improving the process vacuum and adopting standard UHV procedures the nominal T_c was immediately obtained on small samples. However, this was only the first difficulty. Since the cavity is an almost closed vessel of ellipsoidal geometry, obtaining a coating of uniform thickness is far from trivial. Furthermore, the copper surface cleanliness is crucial to ensure good film adhesion. Finally, the coating process requires clean room conditions to avoid surface defects produced by trapping particles floating in the ambient air.

Test cavities were initially coated by bias diode sputtering, which was later replaced by cylindrical magnetron sputtering [35]. The test cavity was a single cell of 500 MHz frequency shown in Fig. 7.12. The cathode was a stainless steel cylinder covered with a Nb liner, from which atoms were sputtered off during the coating by positive ion bombardment. These ions were produced by triggering a discharge in argon or krypton gas at about 10^{-2} Pa, thanks to a negative bias of 400 V on the cathode. The cylindrical cathode contained a solenoid producing an axial field of about 1.4 T at 20 mm from the its surface. This field imparted a circular motion to the discharge electrons, increasing their ionisation efficiency and the sputtering rate. During operation the solenoid was cooled using Freon.

A nice feature of this cathode structure is that by adjusting the cathode diameter and the length of the magnet it is possible to obtain a very uniform coating thickness, because at the cavity equator the higher perpendicular Nb emission compensates for a lower deposition rate due to the larger distance from the cathode.

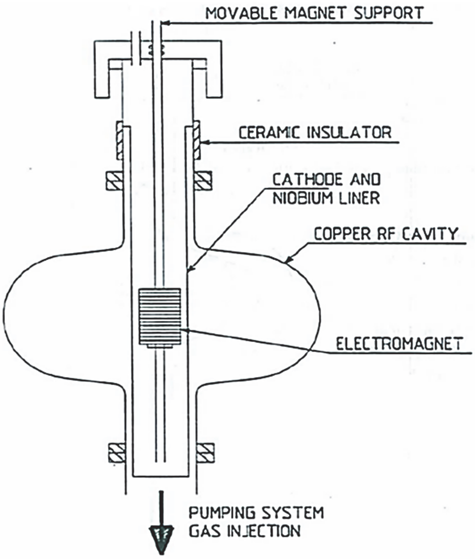

Fig. 7.12. The sputtering configuration.

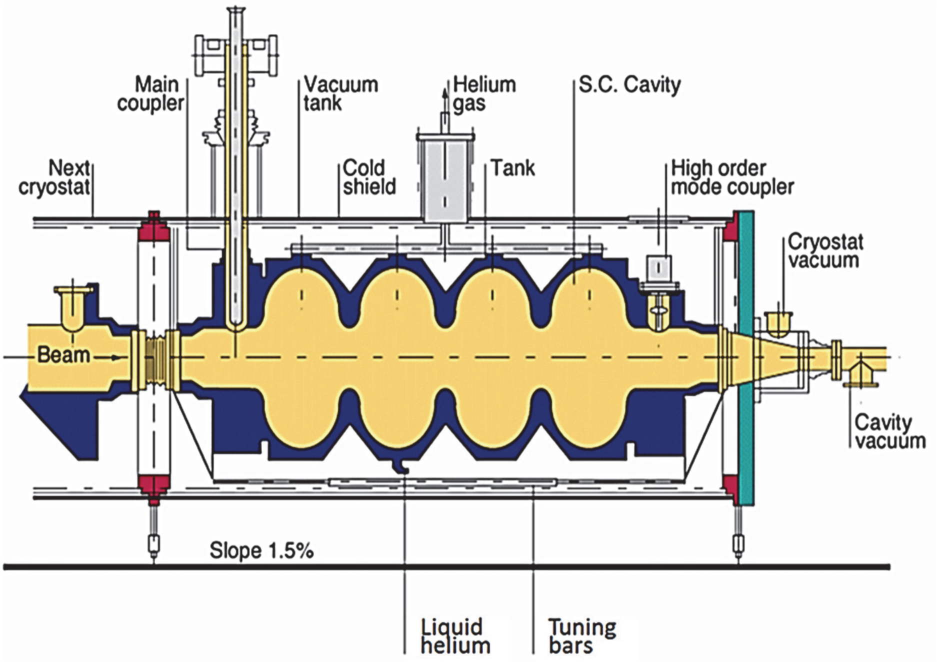

Fig. 7.13. The LEP accelerating RF cavity in the cryostat. The cell diameter is 752 mm and the mid-cell spacing is 0.43 m ($\lambda_{RF}/2$).

After the initial development on single cell test cavities, the coating process was applied to LEP 4-cell 352 MHz cavities (Fig. 7.13) quickly exceeding the 5 MV/m field initially specified for bulk Nb cavities, so as to allow the specified field to be raised to 6 MV/m [36]. A total of 288 cavities were produced by three European manufacturers to whom the CERN know-how had been transferred. Finally, these cavities reached very reliably an average accelerating field of 7.5 MV/m, and the LEP energy was gradually increased up to the maximum achieved value of 104.5 GeV [37].

The coating approach could be extended to other materials of superior superconducting properties. Promising results were obtained with Nb_3Sn coating, but it was too late to envisage its application to LEP. These studies have since also been taken over by other laboratories [38].