bars and its field measured. Results met specifications. However, when these measurements were repeated some months later there was a bad surprise: despite the use of a mortar carefully chosen for its low shrinkage, some residual shrinkage was occurring long after the cores were dry. The longitudinal effect of shrinkage had been anticipated in the design of the core, the supports and the excitation bars. But the shrinkage also had an unforeseen effect: it put the laminations into transverse compression. Such stress decreases the magnetic permeability of the steel, affecting the field in the gap [31]. Such a drift was unacceptable for an accurate energy calibration of LEP. The solution was to submit every core, one year after manufacture, to five cycles of a slight opening/closing of the gap, to provoke micro-fissures in the mortar and relieve the compression in the back leg. In addition, each core was equipped with a flux loop embedded in the lower pole. These loops, which were connected in series in the ring, were used to monitor the field in situ so that the influence of temperature variations, and eventual further ageing of the mortar, could be taken into account when determining beam energy.

7.3 Pumping LEP: Sticky Tape for Molecules

Cristoforo Benvenuti

Storage rings need a low residual gas pressure to minimize beam–gas interactions and keep the particles circulating for hours. For an electron storage ring, such as LEP, the problem is aggravated by the synchrotron radiation produced by the beams, which hits the vacuum chamber walls and desorbs a large amount of gas.

The small conductance of the vacuum chamber limits the flow of the gas molecules to the pumps, so reducing their pumping efficiency. At LEP, pumps with one metre spacing would have been needed to circumvent this problem. An elegant alternative solution adopted in similar previous projects consists in replacing the lumped pumps by a linear sputter-ion pump inserted in the dipole bending magnets. In this case pumping is ensured by ionizing the gas by a discharge ignited between two electrodes, and burying the ions in the cathode. The discharge is maintained at low pressure thanks to a high voltage and a high magnetic field applied to the pump. However, the field of the bending magnets at the LEP injection energy was too low to ignite the gas discharge in the pumps. Another solution had to be found. Finally, a getter strip [Box 7.3] inserted all along 23 km of the LEP chambers was adopted, as shown in Fig. 7.9 [32].

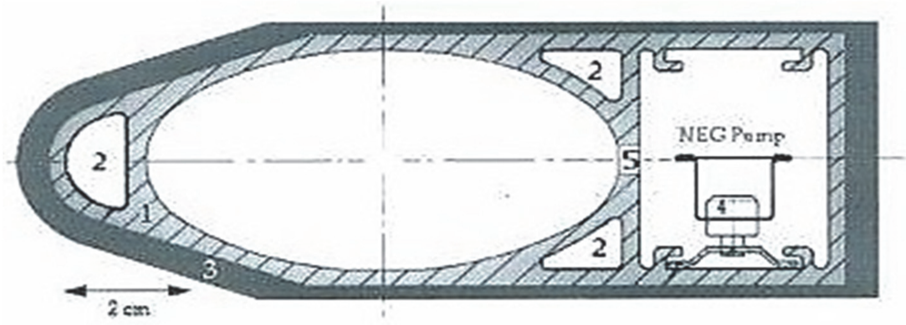

Fig. 7.9. Cross-section of the LEP dipole chamber with the getter pump. 1: extruded Al profile, 2: cooling channels, 3: lead shielding for synchrotron radiation, 4: ceramic insulators, 5: pumping slots.

Getters **Box 7.3**

Most metals and metal alloys display chemical reactivity with some gases, at least with oxygen (which is responsible for their surface oxidation). Materials able to trap the majority of gases in the form of stable chemical compounds are called getters and are widely used in vacuum technology. However, rare gases and methane do not react with getters, so additional pumping of a different nature must be added.

Getter applications were pioneered by D. G. Fitzgerald (England, 1883) and A. Malugnani (Italy, 1894), both for use in incandescent lamps. Since then getters have been inserted in all vacuum sealed devices to continuously pump the gas produced by components of the device.

A clean getter surface traps gas molecules, but in doing so its reactivity decreases and finally vanishes at saturation. To restore pumping two different strategies may be adopted, which define two different getter families. Evaporable Getters (EG), for which pumping is restored by coating the saturated layer by a fresh getter film, and Non-Evaporable Getters (NEG), for which the surface is cleaned by heating. Heating provides the energy needed to diffuse the trapped gas molecules from the surface into the getter bulk. The two important practical characteristics of NEGs are the surface area, which defines how much gas may be pumped before saturation, and the activation temperature (Ta) required for cleaning the NEG surface.

EG s have been used for Ultra High Vacuum (UHV) applications since the 1950s in the form of Titanium sublimation pumps, but these could not be adapted to provide linear pumping. On the other hand, NEGs were used only at relatively high pressures ($10^{-4}/10^{-6}$ Pa), at which the fast surface saturation imposes continuous NEG heating, not applicable in the case of LEP because it would upset the circulating beams. LEP required pressures lower than that, and the NEG behaviour at low pressures without continuous heating remained to be demonstrated at the time (it has since been confirmed).

Following the approval of the LEP project, vigorous development work was undertaken to explore the possibility of Non-Evaporable Getter (NEG) pumping. At that time only one NEG type was commercially available, in the form of a metal strip coated on both faces with 0.1 mm of getter powder. The getter material was a Zr-Al alloy with a daunting activation temperature of 750°C. The strip width chosen for performance evaluation was 30 mm.

Very quickly after the beginning of the experimental investigation it became clear that pressures as low as 10^{-10} Pa could be obtained by this NEG kept at room temperature. Since in this case gas diffusion does not take place, it was vital to ascertain how much gas could be pumped before reaching saturation.

The answer to this question is given in Fig. 7.10 [33]. The results were reassuring. About 10% of the initial performance was still available after pumping, per metre of NEG strip, 10 Pa litre of H_2 and CO, the most important components of the accelerator residual pressure. In practical units, 10 Pa litre of gas corresponds to about 0.1 cc of gas at atmospheric pressure, a huge amount by UHV standards. This result is a consequence of the active NEG surface area being about 100 times larger than its geometrical area, due to the high NEG porosity.

Although these results were comforting, the wide performance difference for different gases was puzzling and this poor understanding was not acceptable for a multi-billion project. For this reason, a large effort was invested in understanding

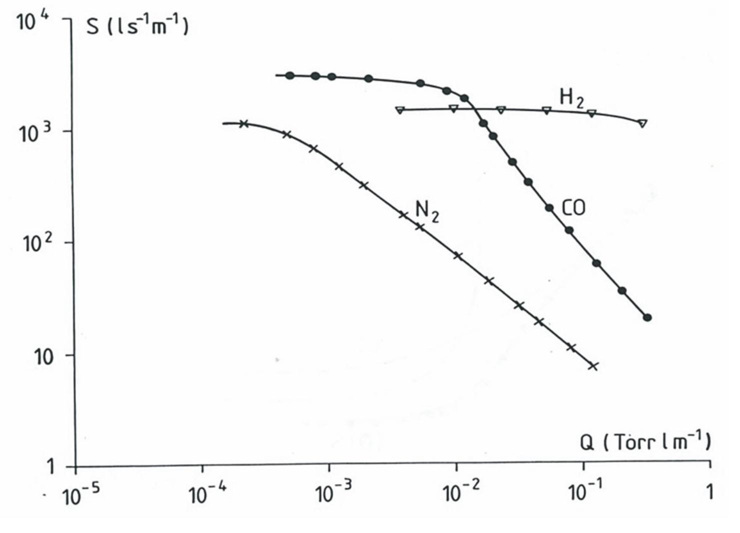

Fig. 7.10. Variation of the pumping speed S as a function of the pumped quantity of different gases. The measured sample is the strip (1 m long, 30 mm wide) adopted for the pumping of LEP. The getter is a Zr-Al alloy. (1 Torr = 133 Pascal)

the NEG pumping behaviour for individual gases and gas mixtures [34]. It was found that H_2 diffuses into the NEG bulk even at room temperature, while for heavier gases, which stick to the surface, pumping at room temperature depends on the NEG porosity and on the number of getter atoms needed to trap a gas molecule. The large difference of the pumping curves shown for CO and N_2 in Fig. 7.10 is a consequence of the fact that a CO molecule occupies one NEG atom, while six adjacent, free atoms are required to adsorb a molecule of N_2, for which the surface saturation is therefore much faster.

The strategy resulting from these studies was to rely on NEG pumping at room temperature and to apply regeneration heating whenever the remaining pumping was too low for the desired performance of the accelerator. Based on this strategy, a few LEP chambers were equipped with different prototypes of NEG pumps and finally the model shown in Fig. 7.9 was adopted. In this pump the NEG strip is electrically isolated from the chamber with ceramic pins inserted into a metal frame. At the two ends of each chamber the NEG strip is connected to electric feedthroughs which allow the NEG to be heated up to the temperature of 750°C by applying an electric current of about 100 A.

The last point to be clarified was the NEG pump behaviour in real accelerator conditions. How often would the NEG have to be heated to restore its pumping? Would the required heating frequency upset LEP operation?

To answer these questions a chamber equipped with a linear NEG pump was installed in PETRA, an electron storage ring similar to LEP already in operation at DESY (Hamburg). The test was conclusive: the behaviour of the NEG pump was fully satisfactory, leading to its adoption for the LEP project.

About 2000 chambers, most of which were 12 m long, were equipped with a NEG pump as shown in Fig. 7.9. The vacuum pressure after a 24 h baking cycle at 150°C was specified to be less than 2×10^{-9} Pa. Acceptance testing was done in a dedicated laboratory (Fig. 7.11) where many units were tested simultaneously.

At LEP the average pressure in the absence of beams was below 10^{-9} Pa. Pumping of rare gases and methane, at the level of 1% of the NEG pumping, was supplied by locally installed sputter-ion pumps. Fortunately, degassing induced by synchrotron radiation at an electron storage ring decreases with operation due to surface cleaning. For this reason, the frequency of the NEG heating cycles quickly became so low that they only had to be applied when the accelerator was stopped for maintenance.

The NEG pump worked perfectly during the entire ten years of LEP operation.