To evaluate such "cold bore" behaviour, a cryostat containing a 1.3 m long vacuum chamber cooled at temperatures from 2 K to 200 K was installed in the ISR. Various quantities of different gases were condensed on the chamber surfaces while beams up to 40 A were circulating [15]. The vacuum was found to remain stable even in the most severe conditions thanks to the large pumping speed provided by cryopumping.

These positive results and the solid experience gained provided the confidence to propose cryopumping on a large scale in LHC where it is now used successfully in the cold sectors stretching over about 18 km (Chapter 8).

4.3 How to Measure Almost Nothing

Cristoforo Benvenuti

In the technology of Ultra High Vacuum, pressure is usually measured by means of ionization gauges. In such gauges the electrons emitted by a hot filament (cathode) are accelerated by the positive potential of a grid (anode) and ionise the residual gas molecules, which are then collected by a third electrode, the ion collector. The current reaching the collector is proportional to the pressure. However, at low pressure, the performance of this gauge is limited due to X-rays produced by electrons striking the grid. This radiation extracts electrons from the ion collector resulting in a current (I_x) that falsifies the result.

A major improvement was achieved by Alpert in 1950 who replaced the ion collector surrounding the grid with a thin wire at its centre (Fig. 4.5a). The large reduction of the collector area resulted in a decrease of I_x, and the low pressure limit of the gauge (called the Bayard-Alpert gauge, B.A.) was reduced by a few orders of magnitude, down to the 10^{-9} Pa range. Alpert himself remarked a few years later that it might not be possible to reduce I_x indefinitely by reducing the collector diameter because "there may be a critical size below which the probability of collecting ions reduces as rapidly as does the X-ray effect" [16]. This was because the tangential component of the velocity of the ions inside the grid would prevent a fraction of them from reaching the collector when first approaching it, and — assuming the electric field inside the grid to be perfectly radial — they would never be collected. Decreasing the collector diameter below about 0.1 mm would decrease I_x, but the ion current would also decrease in the same proportion and the performance of the gauge would not improve. This was confirmed by theoretical calculations and some experiments, and became vacuum technology dogma.

But such ideal conditions are always rare. The radial field inside the grid is perturbed both by the potential of the nearby filament and by space charge due to the accumulation of ions, which being fully enclosed by the grid are, in time, bound to be collected. This effect was confirmed by experiment at CERN showing that in fact ion collection efficiency remains constant for collector diameters down to 0.025 mm, extending the low pressure range of the B.A. gauge to 10^{-10} Pa [17].

This study had been motivated by the need to measure pressures much lower than that originally specified for the ISR (10^{-8} Pa), resulting from the vacuum system upgrade referred to in the introduction. Based on this work some 500 B.A. gauges of improved design were produced by industry and installed in the ISR, where they measured pressures typically in the low 10^{-10} Pa range. After the dismantling of the ISR these same gauges were used for LEP and later for LHC, some 40 years after their production.

For the ISR experimental areas, a few gauges were needed to measure pressures lower than 10^{-10} Pa, so a type was required that performed better than the improved B.A. gauge at such low pressures. Outside CERN and due to the above-mentioned dogma, all development of low pressure gauges was based on the same approach of moving the ion collector to outside the grid volume and properly shielding it from the detrimental X-rays. Various commercial gauges were tested, all of the

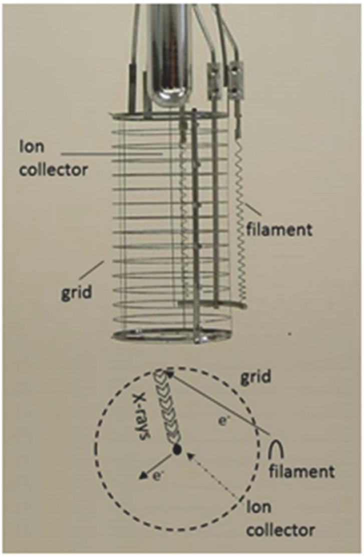

Fig. 4.5a: The Bayard-Alpert gauge, with an illustration of the X-ray effect.

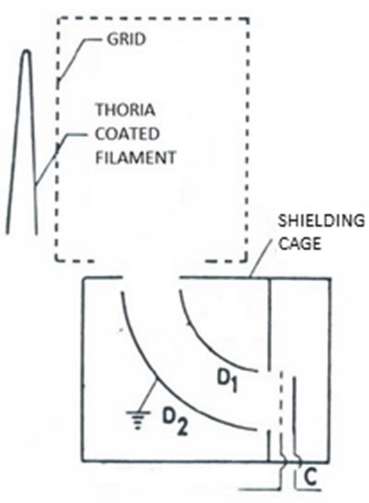

Fig. 4.5b: Schematic view of the Helmer gauge: D_1, D_2 electrostatic deflector, C ion collector [20].

"external collector" type, the most promising model being one that was marketed under the trade name of the Helmer gauge [18], with a power supply adapted for the 10^{-11} Pa range. The design of this gauge is shown in Fig. 4.5b. The ions produced inside the grid are extracted and driven by an electrostatic deflector to the ion collector, which is well shielded from X-rays. A thorough analysis of the gauge performance [19] showed that the atoms sublimating from the electron filament at ~ 2000 °C were producing a local parasitic pressure in the low 10^{-10} Pa range, in spite of the extremely low vapour pressure of tungsten, the material of the filament. By coating the filament with a better electron emitter (thoria) the filament temperature could be reduced to about 1000 °C, low enough to avoid atomic sublimation. By enlarging the grid diameter the length of the path of electrons inside the grid was increased, so extending the access of the gauge to the low 10^{-12} Pa range, which was and still is the lowest pressure ever measured inside a vacuum system [20].

4.4 Superconducting Magnets: Squeezing Beams to Extract More Collisions

Romeo Perin

The two main parameters of a colliding beam machine are the beam energy and luminosity [Box 2.1]. The energy is given by the size of the rings and the magnetic bending field: it cannot be altered, but there are ways of increasing luminosity. At a crossing point of the ISR the luminosity, inversely proportional to the height of the particle beams, can be increased by inserting a local focusing structure consisting of a pair of quadrupole magnets on either side of the interaction region (a quadrupole produces zero field on the axis and a linear gradient of field across the aperture). The concept was first validated with normal magnets, but stronger field gradients would be needed to increase luminosity by the desired factor of at least five. This would require superconducting quadrupoles — but of greater size, strength and quality than had been previously attained [Box 4.3]. In 1973 an R&D effort was initiated to verify the feasibility that culminated in the successful test of a prototype built at CERN [21, 22]. On this basis, specifications were written and orders placed in 1977–8 for critical components and for manufacture of eight quadrupoles. The high luminosity insertions (one per beam) started regular operation in 1981, as the first ever superconducting magnet system in an operating accelerator.

Cross-sectional views of the cryo-magnet are shown in Fig 4.9 [Highlight 4.5]. The main components of the quadrupole are: the room temperature bore, a stainless steel tube supporting 6-pole and 12-pole correction windings (which also