Proceedings of the Tenth International Conference on Cyclotrons and their Applications, East Lansing, Michigan, USA

RECENT ADVANCES IN VACUUM TECHNIQUES FOR ACCELERATORS

C. Benvenuti
CERN, 1211 Geneva 23, Switzerland

Summary

The stringent vacuum requirements of particle accelerators result both in better understanding of basic vacuum processes and in the development of new and more suitable vacuum techniques. A description of the vacuum problems of electron and proton storage rings will lead to the illustration of a few of these advances, such as linear NEG pumps, materials for vacuum, degassing of unbaked systems, argon discharge cleaning, cold bore stability and helium cryopumping. The potential interest of some of these examples for cyclotrons will be discussed.

1. Introduction

The last two decades of this century are characterized by the planned construction of very large particle accelerators. Fundamental research in high-energy physics calls for machines of higher and higher energy such as for instance LEP (an electron-positron collider with a developed length of about 27 km), the construction of which has begun at CERN (Geneva), HERA (an electron-proton collider consisting of an electron ring and a proton ring both of 6.4 km circumference), the construction of which has started at DESY (Hamburg) and SSC (a proton collider with a developed length still to be defined but ranging from 80 to 200 km), which is presently being studied in the USA.

The increasing size of these machines implies both longer design and construction times and higher costs. These two features encourage the accelerator community to undertake, either directly or in collaboration with specialized industries, technological developments which may lead to industrial production. For these reasons high-energy physics act as a driving force for some technologies, such as for instance vacuum, magnets and radio-frequency, and often makes available to other users cheaper products of better performance.

In the race for high energy, electron and proton machines presently share the interest of the physics community. To increase the energy available in the centre of mass of the colliding particles, both types of machine tend to be used as colliders, i.e. to produce interactions between particles travelling in opposite directions. All the machines listed above as well as the majority of the existing ones [PETRA at DESY (Hamburg), ISR at CERN (Geneva), PEP at SLAC, (Stanford), SPS at CERN (Geneva) and TEVATRON at Fermilab (Batavia)] are of this type or have been converted to this operating mode.

Although vacuum is essential to the survival of particles circulating inside any type of accelerator, storage rings require better vacua because the particles may undergo collisions with residual gas molecules not for seconds, as in accelerators, but for hours or days. Furthermore, stored beams of high energy and/or intensity interfere with the vacuum chamber walls via various mechanisms, which all lead to enhanced outgassing. This beam-induced degassing introduces a new dimension in the design of vacuum systems, to the extent that often it represents the major obstacle to obtaining the required pressures and renders the pumping requirements very stringent.

For all these reasons vacuum technology plays a very important role in the construction of high-energy accelerators, as will be shown below. The vacuum features of electron and proton machines are different and they will be discussed here separately. The relevance of the content of the next two sections will then be discussed in view of its possible interest for cyclotrons.

2. Electron-positron colliders

Particles which undergo radial acceleration in the bending field of the magnets emit electromagnetic radiation, or synchrotron light. The average power emitted per metre of trajectory may be written as[1]

$$P \propto E^4/\rho^2 m^3 \qquad (1)$$

where E is the particle energy, ρ the radius of curvature and m the mass of the particle. The mass dependence of the emitted power indicates that the effect is much more pronounced for electrons than for protons. To limit the power dissipated in an electron collider, the energy must be limited and the bending radius increased. For instance, in LEP Phase 1 at 51 GeV, P will be less than 60 W/m, at 86 GeV about 1.4 kW/m and several kW/m above 100 GeV.[2] These considerations explain why large electron machines are limited to reaching energies much lower than those of proton machines of similar size, in spite of very powerful accelerating systems.

The emission of synchrotron radiation is very important also for the design of the vacuum system. Upon impinging on the vacuum chamber walls, radiation induces gas desorption which may produce pressure rises many orders of magnitude above the obtained base pressure. This effect was noticed in the early days of electron machines and discussed since by many authors[3,4,5]. A typical composition of desorbed gases is 75% H_2, 24% Co and CO_2, 1% CH_4.[2] The surface coverage decreases with increased beam dose, and consequently the degassing is progressively reduced. For PETRA the following relation is quoted for the dynamic pressure rise per mA of circulating beam with a linear pumping speed of 50 l/sm.[6]

$$dp/dI = 6.7 \cdot 10^{-8}\ D^{-0.63}\ \text{Torr/mA} \qquad (2)$$

where D is the integrated beam dose in mA hours.

Residual gas molecules in electron machines result in losses of circulating particles mainly due to bremsstrahlung on nuclei. The beam lifetime therefore depends not only on the total pressure but also on the partial pressures of the various gases, their molecular weight M and their radiation length X_0 (g/cm^2). The product of beam lifetime τ and partial pressure p is

$$\tau p = 2.12 \cdot 10^{-8}\ X_0/M\ \text{(hTorr)} \qquad (3)$$

This product is shown in the first column of Table 1, which also shows in the second column the maximum permissible partial pressures of the different gases for τ = 20 h.[2]

Gas	τp hTorr	P_{max} Torr
H_2	$666 \cdot 10^{-9}$	$33 \cdot 10^{-9}$
CH_4	62	3
H_2O	43	2
CO, N_2	29	1.5
Ar	10	0.5
CO_2	18	1

Table 1

The design figure for LEP is a total pressure, nitrogen equivalent, of $3 \cdot 10^{-9}$ Torr.

2.1 Linear Pumps

Maintaining such pressure in spite of the usually small vacuum chamber cross-section and of the large degassing induced by synchrotron radiation requires high and evenly distributed pumping speed. Traditionally, the main pumping for electron machines has always been provided by sputter-ion pumps, either in the form of appendix "lumped" units at small distance from each other or as continuous elements inserted all along the vacuum chamber, in a channel specially designed for this purpose. These "integrated" pumps make use of the magnetic field of the bending magnets and provide an attractive solution when the large size of the machine and the conductance limitations would require a large number of appendix pumps. Integrated sputter-ion pumps were recently adopted both in PETRA at DESY[6,7] and in PEP at SLAC.[8].

The obvious disadvantage of these pumps is their direct dependence on the field of the magnets. During the initial pump-down the magnets are not powered and additional appendix pumps are required to obtain and maintain the vacuum. Furthermore, the magnetic field is lower when the particles are injected, and this implies a reduced pumping speed. This feature is particularly important for LEP, as it would be for other machines of this size, because at injection only about 200 G are available, a value which is dangerously close to the limit at which the discharge extinguishes in the sputter-ion pumps.[9] Mainly for this reason, but also for its intrinsic mechanical simplicity and potentially high pumping speed, a linear pump based on the use of a non-evaporable getter has been chosen for LEP.[10,11]

Any material which can provide a pumping action when introduced in bulk into a vacuum system is called a non-evaporable getter (NEG), as distinct from materials which only provide pumping when sublimated. The NEG's form thermally stable chemical compounds with the majority of the active gases (O_2, CO, N_2, CO_2, H_2O etc.), while the sorption of H_2 is thermally reversible[12]. When exposed to air, the gettering surface is saturated and loses its pumping activity.An essential operation is, therefore, activation. This consists of producing by heating the diffusion of the saturated surface layer into the bulk of the material. The heating also reduces the H_2 content in the getter whenever the H_2 dissociation pressure of the getter exceeds the H_2 pressure in the vacuum system. After activation, the gettering action depends on the amounts and molecular species of the gases which have been pumped. If large quantities of gases producing stable compounds are to be pumped, the getter operating temperature must be high enough to keep the rate of diffusion of the compounds into the bulk sufficiently high to prevent surface saturation. The diffusion rate of H_2 is much higher, and consequently much lower temperatures are required for continuous H_2 pumping. All these temperatures depend, of course, on the particular getter, and we will therefore limit ourselves henceforth to the NEG which has been chosen for LEP, i.e. a Zr-16% Al alloy bonded in a powder form on an iron or konstantan (non-magnetic) ribbon. This alloy is known by the trademark ST 101 and is produced by SAES Getters (Milano, Italy). The ST 101 has already been studied extensively and its relevant characteristics may be obtained from the published literature.[13,14]

The getter is available as a ribbon in various widths. The linear pump for LEP is obtained by attaching a 30 mm wide ribbon to a rigid stainless steel support via insulating ceramics. The cross-section of the LEP vacuum chamber with the NEG pump inserted in the pumping channel is shown in Fig. 1.

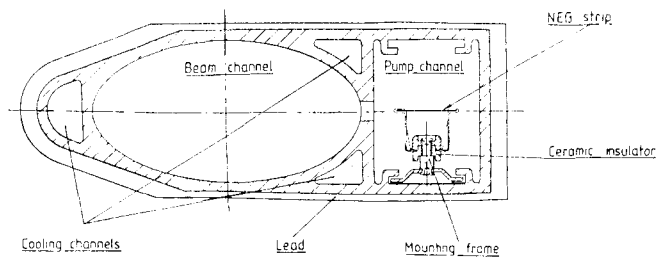

Fig. 1. Cross-section of the LEP dipole vacuum chamber with the NEG pump

Heating is achieved by circulating an electric current in the NEG strip. For the activation a temperature of about 700°C must be maintained for approximately one hour, corresponding to a heating current of about 95 A.

Since continuous NEG heating at 400°C is not feasible in LEP because the electric current circulating in the getter would upset the stored electron beam, it is important to know how the pumping speed varies as a function of the gas quantities pumped at room temperature. This variation is depicted in Fig. 2 for the most common gases, i.e. H_2, CO and N_2.[11]

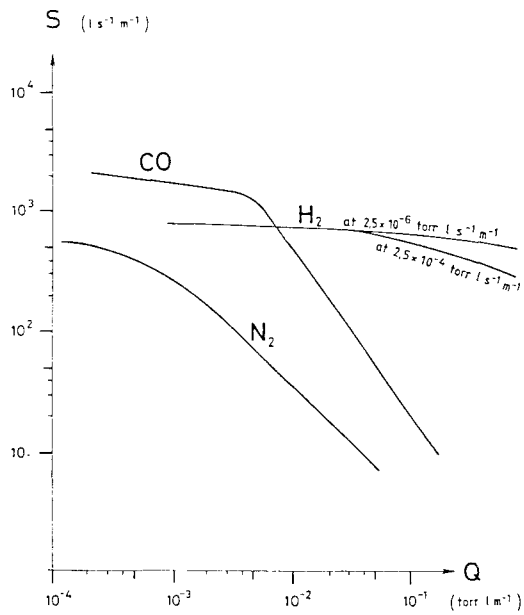

Fig. 2 Variation of NEG's pumping speed S at room temperature as a function of pumped quantities Q of gas. Both S and Q refer to 1 m of getter strip 30 mm wide. Spread from different samples is about ± 10%.

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The pumping characteristics for CO_2 closely approach those of CO. Pumping speed measurements for gas mixtures are also available and will be published soon. Note that for H_2 the initial pumping speed shows small variation with pumped quantity, because of the appreciable diffusion of this gas at room temperature. On the contrary, for heavier gases the variation is important and independent of the rate of gas uptake (i.e. there is no diffusion). When the pumping speed decreases to below a predefined value, the NEG must be heated to restore pumping speed. Since in this case the surface coverage is much lower than after venting to air, lower temperatures and shorter heating times than for activation are sufficient. It was determined experimentally that heating for a few minutes at about 400°C is enough to recover the initial pumping speed. This operation is referred to as conditioning.

In the LEP configuration the standard lattice vacuum chambers are about 12 m long and contain 10.83 m of NEG strip. Ten prototype chambers were built and tested in 1983. The ultimate pressures obtained after 24 bakeouts are typically represented in Fig. 3.

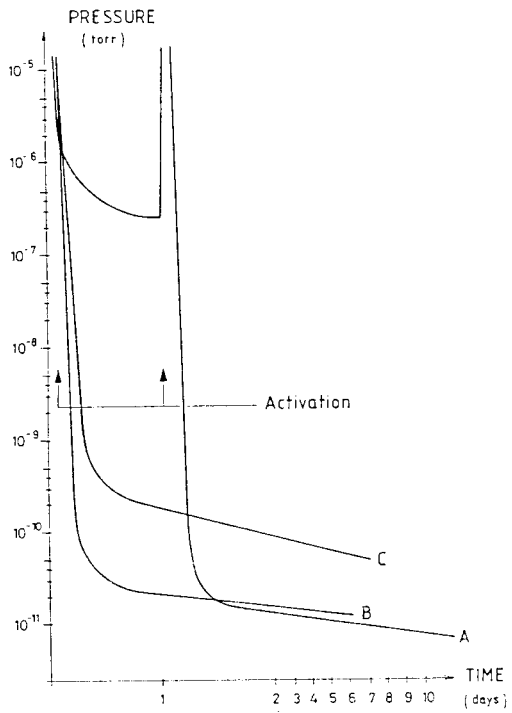

Fig. 3 Pumpdown curves for a LEP chamber equipped with a linear NEG pump. The chamber is baked at 120-150°C for 24 h (curve A) or 2 h (curves B and C) before NEG activation. For curve C the pumping speeds of both auxiliary pumps are reduced, by interposed diaphragms, to 2.3 ls^{-1}.

Fore-pumping is carried out during bakeout by means of a 70 l/s turbomolecular pump which is usually valved off after NEG activation, when a 30 l/s sputter-ion pump is switched on. Sputter-ion pumps are essential for pumping non-reactive gases such as rare gases and methane. In the LEP vacuum system sputter-ion pumps of about 30 l/s pumping speed will be installed at about 20 m intervals.

If the vacuum chamber is not baked, the pump-down curves shown in Fig. 4 are obtained.

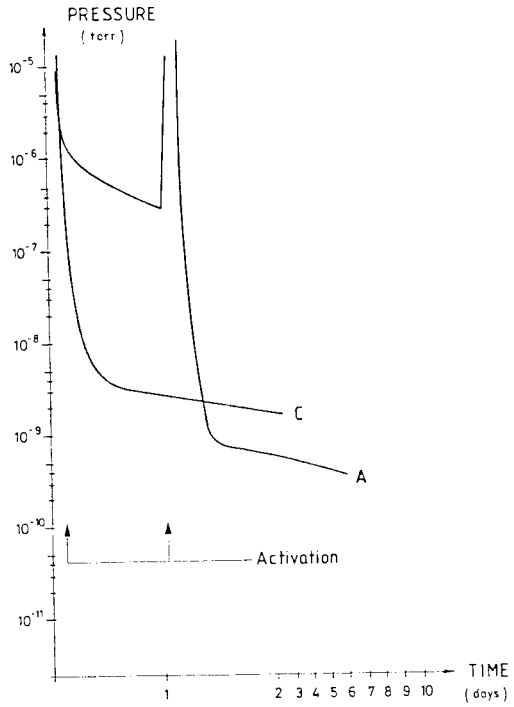

Fig. 4 Pumpdown curves for the same chamber as in Fig. 3 unbaked. The pumping time before NEG activation is 24 h for curve A and 2 h for curve C. For curve C the pumping speeds of both the auxiliary pumps are reduced, by interposed diaphragms, to 2.3 ls^{-1} and the turbomolecular pump is valved off before NEG activation.

The behaviour of these NEG pumps in real operating conditions of an electron machine has been tested at DESY. One standard PETRA chamber in which the integrated sputter-ion pump was replaced by NEG was installed in this machine in 1981. The results obtained during the initial 10^4 mAh of operation after this installation are condensed in Fig. 5. A more detailed description of this experiment is given in ref. 11.

2.2 Materials

For many years stainless steel has been the standard material for UHV. In addition to good mechanical properties and ease of welding, stainless steel offers the important feature of being bakeable at temperatures up to 450°C. Very high baking temperatures were assumed to be essential for the achievement of low pressures, to the extent that in vacuum catalogues "bakeable" usually meant bakeable at 450°C. Heating at this temperature reduces effectively the wall degassing consequent to three different physical processes. Firstly, the water vapour adsorbed on the surface is removed. Secondly, the contaminating hydrocarbons, which may otherwise release their volatile components (such as H_2, CO, CH_4, CO_2) for very long times, are cracked. Thirdly, the H_2 which is present in the bulk of stainless steel and is responsible for the ultimate pressure after bakeout is depleted from the surface layers . However, it was shown that this H_2 content may be reduced more efficiently by treatment at 950°C in a vacuum furnace[15] and that better surface cleaning may be obtained either chemically or by bombarding

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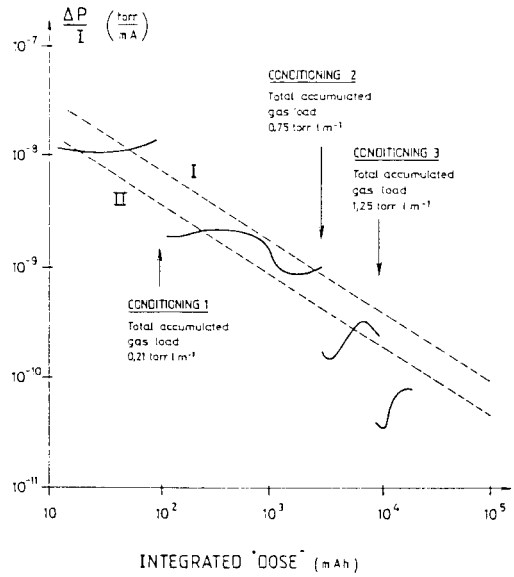

Fig. 5 Variation of the specific pressure rise as a function of the integrated beam dose for the NEG pumped chamber at PETRA (full line). Also shown (dotted lines) are the same variations for another new chamber pumped by ISP (I) and the reference curve (II) expressed by equation (2). The gas loads reported in the figure are obtained by integrating eq. (2) up to the beam dose corresponding to the various conditionings.

the surfaces with the argon ions produced by a glow discharge[16,17] (see Section 2). The essential function of baking in situ a vacuum system remains the removal of the water vapour for which, however, a baking temperature of 150°C is sufficient. This diversification of the treatments enlarges the choice of materials for UHV. Aluminium is particularly attractive for electron machines because of its high thermal conductivity (which is essential for high and very localized synchrotron radiation loads), low residual radioactivity and extrudability. Long vacuum chambers with a convoluted profile as shown in Fig. 1 may be obtained easily and cheaply by extrusion.

Extruded vacuum chambers made of aluminium alloys were used for PETRA[7] and PEP[8]. In both these machines stainless steel flanges of Conflat type (Varian tradename) were welded onto the aluminium by means of special transitions. Also, LEP will use aluminium alloy extruded chambers, both for the arcs and for the long straight sections. These chambers will be equipped with aluminium flanges which may be joined to aluminium or stainless steel flanges via aluminium gaskets of special profile[18]. More recently aluminium alloys have been used at TRISTAN (KEK-TSUKUBA) to produce vacuum chambers, elliptical bellows, fittings, flanges, bolts, gaskets, nuts, washers, feedthroughs, gauges, optical windows, sputter-ion pumps, turbomolecular pumps and valves.[19]

After baking at 150°C the H_2 degassing rate of aluminium alloys was found to be lower than 10^{-12} Torr l/s cm^2[20] and in some cases even below 10^{-13} Torr l/s cm^2.[19] These figures compare favourably to those of stainless steel, which requires high-temperature vacuum firing to reach degassing rates lower than 10^{-12} Torr l/s cm^2.

2.3 Degassing of unbaked metal surfaces

At the beginning of the pumping cycle metal surfaces mainly degas water vapour. The results of a critical review of available date were summarized in 1978[21] and are condensed in Fig. 6. Further

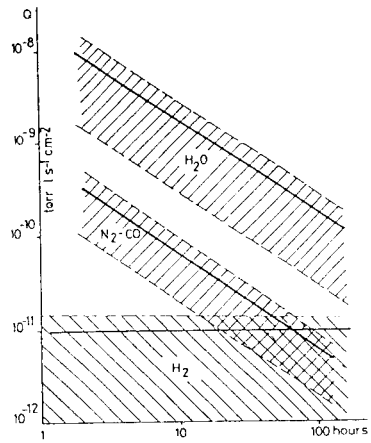

Fig. 6. Variation of the rate of degassing of various gases from stainless steel as a function of the pumping time. The dashed areas represent the spread of the data and the full lines the plausible values on which one could base the estimates of the required pumping speeds.

confirmations of the linear decrease of water vapour degassing with increasing time may be found in refs. 22, 23 and 24. To describe the observed variation a physical model was proposed which links this variation to the presence on metal surfaces of sites where water molecules are adsorbed with different binding energies.[24]

In electron machines the dynamic pressure rise exceeds the pressure produced by thermal degassing of water provided that pumping for a few days is allowed before operation. On the other hand, the presence of water molecules on the chamber walls does not much affect the radiation-induced gas desorption.[7] Therefore it is conceivable to operate electron machines without in situ baking. This is in fact the case both for PETRA and PEP.

Fig. 4 shows that acceptably low pressures may be obtained inside unbaked LEP chambers pumped by NEG and the results of Fig. 5 were obtained without baking. Nevertheless it was decided to bake the LEP vacuum system at 150°C so as not to load the getter unnecessarily with O_2 and to reduce the initial need of conditioning. However, experiments are in progress to ascertain what is the amount of water molecules on the walls of the vacuum chamber after different pumping times and how water vapour may affect the pumping speed of NEG for other gases. This work is not yet complete but some interesting results are already available. A further confirmation was obtained of the reported time-dependence of water vapour degassing rate Q, which may be expressed as $Q = k/t$. For a series of chambers produced from the same extrusion batch, k was found to vary between 0.15 and 0.3 Torr l/m (surface area per metre of chamber about 5000 cm^2) with the exception of two chambers for which the measured values were about ten times higher. These two chambers had been exposed to water vapours at 150°C. This fact is important to

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show that the degassing of unbaked metal surfaces does not depend only on their chemical nature. Any treatment which may reduce the effective area of surfaces exposed to vacuum should provide a beneficial effect in this respect. On the other hand, materials not presenting a stable surface, as for instance mild steel, necessarily present a large scatter of results and do not offer any guarantee of reproducible behaviour.

3. Proton storage rings

Interaction with residual gas molecules via nuclear scattering and multiple Coulomb scattering results in the loss of circulating protons and decay of beam intensity. Theoretical estimates[25] and past experience with the operation of proton storage rings[26] show that an average nitrogen pressure of about $5 \cdot 10^{-10}$ Torr is required to provide the stored beams with a lifetime of 24 h. In spite of having reached a better vacuum, the operation of the ISR (Intersecting Storage Rings for protons) at CERN was initially disturbed by pressure rises in the presence of intense circulating beams. As was later understood, ions produced by the interactions of circulating protons with residual gas molecules are accelerated by the positive beam potential to the vacuum chamber walls, producing degassing there. Degassing may yield a finite pressure increase or trigger an avalanche process which finally results in pressure runaway and the loss of the beam. This process (described in detail in ref. 27) is defined by the balance of degassing and pumping. For a given desorption yield of the impinging ions, which depends on wall cleanliness, the degassing rate increases with the intensity of the circulating beam. Above a certain beam intensity the degassing rate exceeds the available pumping throughput and the pressure runs away.

A large increase of the stored proton current was obtained upon increasing the pumping speed and improving surface cleanliness. About 700 titanium sublimation pumps were added to the 300 sputter-ion pumps of 400 l/s nominal speed already installed on the 2 km long ISR vacuum system. Furthermore, all the vacuum chambers were demounted and submitted to argon discharge cleaning. This cleaning process[16,17] consists of stretching a wire (+ 400 V) in the middle of the vacuum chamber (ground potential) and igniting a glow discharge by introducing argon at about 10^{-2} Torr. To remove more easily the gas released by the ions bombarding the vacuum chamber walls, the chamber is kept at 300°C and about 10% oxygen is added to the argon. Oxygen combines with desorbed carbon and produces CO which is evacuated by continuous pumping with a turbomolecular pump.

By this method impressive amounts of carbon are removed, equivalent to what are required to form about 70 monolayers on the vacuum chamber wall. These improvements resulted in an average ultimate pressure in the ISR, after in situ bakeout at 300°C, of about $3 \cdot 10^{-12}$ Torr. Beams of 55 A intensity were stored with stable vacuum.

3.1 Cold bore design

Since protons are only marginally affected by emission of synchrotron light, the energy of proton machines is only limited by the obtention of very high magnetic fields. This implies using superconducting magnets.

An important decision to be taken when designing superconducting proton storage rings is whether the vacuum chamber should be maintained at room temperature or cooled down with the magnets. A cold vacuum chamber is advantageous because it does not need thermal insulation and therefore allows for smaller magnet aperture. Furthermore it does not degas but on the contrary it becomes a large cryopump. The disadvantages of this solution are the rigid link between vacuum and magnets (venting the vacuum system requires warming the magnets up to room temperature) and the difficulty of precise alignment.

Besides these important considerations a necessary condition to be fulfilled is that of vacuum stability. The cold vacuum chamber provides very high pumping speed, but the pumping action of the walls may lead to large gas coverages and consequently to large ion-induced desorption.

The vacuum stability criterion, according to ref. 27, indicates that vacuum becomes unstable when degassing equals pumping, i.e. for a cold bore design, when

$$\frac{\sigma}{e}(\eta I)_{crit} = \frac{\pi}{2} r \bar{v} s \qquad (4)$$

where

- σ = ionization cross-section of the considered gas (cm^2)
- e = charge of electron (As)
- η = number of molecules desorbed per incident ion
- I = circulating beam current intensity (A)
- r = radius of the vacuum chamber (cm)
- $\bar{v}$ = average speed of the desorbed molecules (cms^{-1})
- s = sticking probability of the desorbed molecules.

Laboratory measurements of η are available[28,29], but $\bar{v}$ may only be obtained from experiments carried out in real machine conditions. To obtain information on this quantity, to check the validity of the physical model leading to equation (4) and directly to observe the behaviour of a cold bore chamber, the cryostat shown in Fig. 7 was installed in the ISR.[30,31]

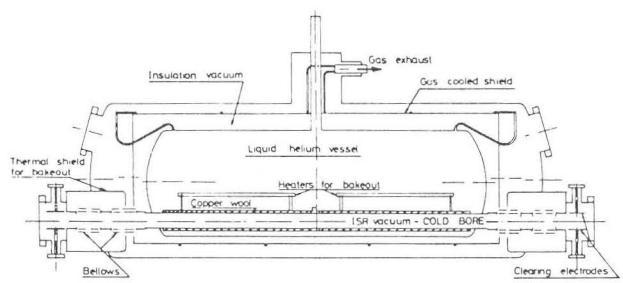

Fig. 7 The cryostat used for "cold-bore" experiments in the ISR

The main results obtained by means of this cryostat which provides a cold length of 1.3 m and an elliptical cross-section of 160 × 54 mm may be summarized as follows.

The cold section was run unbaked for 19 days with circulating beams of intensities up to 38 A[32] with stable pressure.

A few monolayers of H_2 were condensed on the cold chamber, resulting in an η value of 4×10^4. Also in this case the pressure was stable in presence of beams of 40 A intensity. A similar result was obtained by condensing a much thicker layer of H_2, i.e. about 100 monolayers.[33]

Also, helium present on the cold surfaces did not affect the stability of vacuum. The ISR test section was stable with a He coverage of about 10^{15} molecules/cm^2.[34]

Condensed nitrogen, such as could result from air leaks, showed a different behaviour.[31] Pressure spikes were produced by circulating beams, which were attributed to electrical breakdown across the condensed gas layer and consequent to charging up of the latter layer by impinging ions. Due to the unpredictable nature of leaks and lack of precise quantitative information on the process, this observation leads only to stress once more the importance of the leak-tightness reliability of a cold-bore vacuum system.

These results are sufficient to prove the feasibility of unbaked cold-bore proton storage rings.

A cold-bore-based design is presently being considered both for the SSC (USA) and for a hadron collider which may be installed in future in the LEP tunnel.

3.2 Cryosorption pumping of helium

The presence of liquid helium in the proximity of the vacuum chamber of superconducting accelerators originates the risk of helium leaks. These leaks may result in a pressure rise in the main vacuum chamber and/or spoil the insulation vacuum of the magnet cryostats. It therefore becomes important to know how the helium pressure varies as a function of the quantity adsorbed at 4.2 K on bare metal surfaces, and also how this helium may be pumped. Since liquid helium is available in this case, cryosorption pumping is very attractive. Adsorption isotherms for helium on molecular sieve 5A at 4.2 K were measured at Brookhaven National Laboratory.[35] The results obtained are compared in Fig. 8 to those relative to polished copper[36] and porous silver[37].

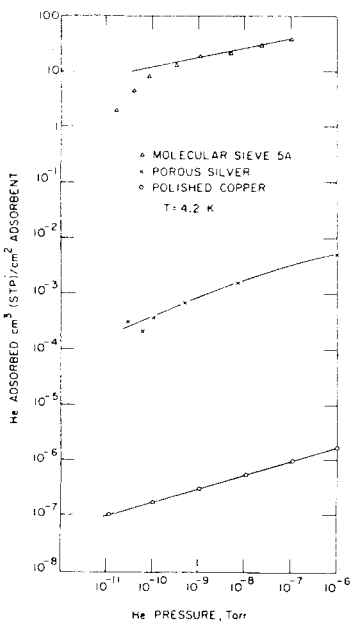

Fig. 8 Adsorption isotherms of helium at 4.2 K. Δ Halama and Aggus[35], ○ Danilova and Shal'nikov[36], × Hobson and Williams[37]. Reproduced from ref. 35.

Note that on bare copper 10^{14} He atoms/cm^2 are sufficient to produce a pressure increase to about 10^{-7} Torr, a value which in a proton collider may be tolerated only over a very short distance. The molecular sieve results in about eight orders of magnitude increase of the He quantity which may be adsorbed at equal pressure. Pumping speeds of a few litres per second and cm^2 of adsorbing area may be obtained by this method. The large specific pumping speed and pumping capacity make this type of pumping particularly attractive for the insulation vacuum of the magnet cryostats.

4. Conclusive remarks: implications for cyclotron vacuum systems

Only a few of the arguments developed in Sections 1 and 2 are relevant for cyclotrons. As a complement to the discussion presented a few years ago on this subject[21], the following points are worth being mentioned.

- Further evidence exists that the rate of degassing of water vapour, the main desorption product from unbaked metal surfaces at the beginning of pumping, varies according to the equation $Q = k/t$.

  Water vapour degassing is strongly dependent on the surface conditions of the materials considered. It may be reduced by selecting materials with smooth and stable surfaces.

- Aluminium and its alloys are suitable for UHV applications.

- Large pumping speeds and capacities may be provided for helium by physisorption at 4.2 K on porous materials.

- As already stated[21], NEG does not appear very suitable for being inserted in a cyclotron as the main pumping element. Cyclotrons always make use of demountable couplings of large and complicated geometry, which are more prone to leak than small flanges sealed with metal gaskets. Large leaks may result in rapid N_2 saturation of NEG pumps at room temperature and require venting for repair.

  Venting with dry nitrogen before opening the machine would not prevent NEG from being exposed to atmospheric air because of the large size of the opening ports. Since the openings are usually frequent on cyclotrons, this would imply a relatively fast NEG deterioration.

  Very large quantities of NEG would be required to obtain the same ratio of vacuum chamber wall to NEG surface area as provided by linear pumps in electron colliders. This implies a larger specific load of water vapour on the getter, the effect of which is not yet completely known.

  However, NEG may in some cases become a useful pumping complement if used as an appendix pump which may be valved off from the cyclotron vacuum. The valve would protect the getter from air during venting and from high loads of water vapour during the initial phase of pumping. This solution would also partially circumvent the leak problem by operating the getter at 400°C. A proper cooling of the NEG pump envelope might very efficiently reduce the power dissipated in the machine.

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