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VACUUM FOR PARTICLE ACCELERATORS AND STORAGE RINGS

by

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ABSTRACT

Accelerator vacuum systems must be measured in kilometres rather than metres and operate down to or below 10^{-8} Pa. Vacuum requirements and design constraints are reviewed for different machines using, as examples, the Intersecting Storage Rings (ISR) for protons, the Large Electron Positron (LEP) machine for electrons and the 'cold-bore' Large Hadron Collider (LHC) again for protons. Various dynamic interactions between the particle beam and the vacuum system which are specific to accelerators are described. This is followed by a general discussion on pumping, especially distributed NEG pumping, cold-bore design and certain operational aspects of large systems.

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VACUUM FOR PARTICLE ACCELERATORS AND STORAGE RINGS

1. INTRODUCTION

Particle accelerators and storage rings are frequently very large, some tens of kilometers length being characteristic of today's machines and, if the Super-conducting Super Collider (SSC) project in the USA is completed the length of its vacuum system will approach the 100 km mark. Apart from the sheer size, which renders both access and control complicated, the large number of components (e.g. ~ 20'000 all-metal UHV flange pairs in the Large Electron Positron (LEP) machine¹⁾ now being constructed at CERN) places a very high premium on reliability. Thus some degree of sectorization using gate valves is usually necessary to bring the vacuum system into units of manageable proportions. Other general characteristics of the vacuum system follow from the required performance of the machine and its environment and will often include complete UHV and bakeout compatibility together with resistance to radiation and corrosive atmospheres. The small cross-section of the chamber, imposed by cost considerations of the machine aperture, leads to a low gas conductance, typically $< 0.1 \text{ m}^3 \text{ s}^{-1} \text{ m} (\text{N}_2)$ and the need for a large number of relatively small pumps and, in some cases, the installation of distributed pumping. The present trend is towards the use of superconducting magnets to give higher field strengths and smaller bending radii for proton machines. With the vacuum chamber integrated in the magnet cryostat this leads to a 'cold-bore' vacuum system which takes on the characteristics of one huge cryopump. This will be the case both for the Large Hadron Collider (LHC) project²⁾ at CERN and the SSC project³⁾ in the USA.

The level of vacuum required will depend on the degree of beam degradation which can be tolerated during the passage through the machine - geometrical degradation and intensity loss by Coulomb and nuclear scattering on the residual gas, and energy losses (again via the Coulomb interaction) through molecular excitations and, especially for electrons, by Bremsstrahlung radiation.

Beam degradation will be more severe the higher the charge of the particle and/or the atomic number(s) of the residual scattering gas (both give an increased Coulomb interaction) and, again, more severe the lower momentum (or 'stiffness') of the beam. Other things being equal, the beam degradation will depend directly on the product of residual gas pressure and particle path length which for storage rings should typically reach a light-day or $\sim 10^{13}$ m - so without doubt UHV is a must.

In addition to these more obvious effects of scattering, which depend directly on the 'static' residual gas density, there are other indirect effects by which the performance of the machine may be limited by the quality and design of the vacuum system. The particle beam may stimulate gas desorption from the inner surfaces of the vacuum chambers via ion bombardment from residual gas ionisation in the case of proton beams or via synchrotron radiation from electron beams - both giving rise to a beam dependent 'dynamic' pressure.

Many accelerators are designed these days to profit from the large increase in centre-of-mass energy available for particle interactions by operating as storage ring 'colliders' with two opposing beams. The particles constituting the beams may be similar (e.g. proton-proton as for the CERN Intersecting Storage Rings), circulating in opposite directions in two separate magnet and accelerating structures with beam paths (and vacuum systems) which intersect at a few selected collision points (the 'experiments') around the circumference. Alternatively, and today more usual and economic on hardware, opposing beams of a particle and its antiparticle (e.g. $p\bar{p}$ in the CERN Super Proton Synchrotron and e^-e^+ in the CERN Large Electron

Positron machine) are counter-circulated in the same magnet structure and side by side in the same vacuum system except at the experimental points where they are steered into collision. In either case, any upstream beam - gas collision may give rise in an experiment to unwanted background, and a pressure over some tens or hundreds of meters much lower than that dictated by simple considerations of beam degradation may be requested. One may note in passing that the particle beams remain entirely within the vacuum system of a collider whereas experimental detectors, frequently complex arrays of counters etc., must be almost entirely outside the vacuum. Vacuum chamber transparency to secondary particles, the collision products, becomes vital and results in the use of extremely thin (e.g. 0.1 mm stainless steel) and/or low atomic number material (e.g. Be or Al lined carbon fibre) vacuum chambers⁴⁾.

Further constraints of an electromagnetic nature will be imposed by the machine on the design and hardware of the vacuum system - especially the 'beam-pipe' which is "seen" directly by the beam. This must present a low impedance to the image current of the particle beam which is frequently concentrated into short discrete bunches and will present harmonic components up to some tens of gigahertz.

An attempt will be made to discuss some of the more important facets of accelerator and storage ring vacuum systems by using a few specific machines to illustrate the similarities and differences between the two broad categories, namely those machines for protons and those for electrons. Detailed reference will therefore be made only to a very limited selection of high energy particle machines at CERN, namely the Intersecting Storage Rings⁵⁾ for protons (ISR: 2 x 1 km, albeit now dismantled), the Large Electron Positron¹⁾ (LEP: 27 km) collider now under construction with completion planned for 1989, and the projected superconducting cold-bore Large Hadron Collider²⁾ (LHC: 27 km) for protons. This selection, while covering the main machine types, has the advantage of giving a glimpse of the past, the present and, maybe, the future while still remaining with projects which we, the authors, have been personally involved.

2. VACUUM REQUIREMENTS

It is convenient to consider the vacuum requirement of a particular machine in terms of a lifetime for the beam, for example, the time of a given beam to increase ('blow-up') its transverse dimension by a certain factor, or to fall to $1/e$ of its original current, etc. One can distinguish several basic processes by which the residual gas density will simultaneously and in parallel contribute to the degradation of the beam.

In this section we will identify and briefly discuss the quantitative relation between lifetime and pressure for these processes. We will accept the residual gas pressure in the vacuum system as an independent and adjustable parameter while leaving for later sections both the physical description of the vacuum system and the discussions on the dynamic inter-dependence of pressure and beam.

2.1 Proton machines

The important beam degrading interactions between high energy protons (or heavier ions) and residual gas molecules result both from the Coulomb force and from the strong force in nuclear proton encounters.

2.1.1 Multiple (small angle) Coulomb scattering

The deviation of charged particles via the Coulomb interaction is described by the Rutherford scattering formula and results predominately in successive small angular displacements of the particle trajectory.

This blow-up of the beam cross-section will eventually cause beam loss and scattered background radiation when the aperture limit of the machine vacuum system is reached. More seriously, for colliders like the ISR with the opposing beams intersecting in

the horizontal plane, the luminosity L (interaction rate) of the machine for two equal beams varies as the square of the beam current and inversely as the beam height z . The relative decay rate (or inverse lifetime) of the luminosity,

$\frac{-1}{L} \frac{dL}{dt}$ is therefore equal to the relative beam growth rate which

is given by⁶⁾

$$\frac{1}{\tau_z} = \frac{1}{z} \frac{dz}{dt} = 1.61 \cdot 10^2 a^2 p^{-2} \sum_i P_i G_i \quad (s)$$

where a is the particle charge ($a = 1$ for protons), p is the particle momentum in GeV/c, P is the (molecular) partial pressure (at 20°C) in Pascal of the residual gas, $G (=Z^2 [10.6 - 0.33 \ln ZA])$ is the absolute atomic gas factor for atomic number Z and atomic weight A . The sum is taken over all constituent atoms of each molecular species. The numerical factor contains basic atomic constants and some parameters concerning the beam optics of the specific (here, ISR) machine. Since G varies essentially as the square of the nuclear charge Z , one readily appreciates the importance of minimising contamination by heavy atomic species, for example the accumulation of argon via small air leaks which may frequently be aggravated by a low pumping speed for this gas. It is also clear that both multiply charged ion beams ($a > 1$) and beams of lower momentum (i.e. less 'stiff') will be degraded more rapidly.

At the design momentum of $p = 26.6$ GeV/c for the ISR an initial relative blow-up lifetime in P_{N_2} Pa of nitrogen gas ($G_N = 442$) of $\tau_z = 1.41 \cdot 10^{-6} P_{N_2}^{-1}$ hours is obtained. Thus to fulfil the requirement of useful running periods of a day or more between proton refills and/or operation at lower momenta, a design pressure of 10^{-8} Pa nitrogen (suitably scaled for other gases) was adopted to achieve a $1/e$ lifetime of ~ 100 hours. That the ISR in fact operated at or below 10^{-9} Pa of hydrogen resulted essentially as a by-product of measures adopted to control the dynamic ion induced pressure bumps which are described in section 4.

For completeness, two other effects due to the Coulomb interaction with the residual gas may be mentioned.^{7,8)} Firstly, a few beam particles will be scattered by this same process through angles greater than the machine angular acceptance Θ_M and will be immediately lost from the beam. The effect is small amounting to $\sim 5\%$ and 15% of the loss via nuclear scattering from H_2 and N_2 respectively (see section 2.1.2) and, although scaling as $a^2 Z^2 p^{-2} \Theta_M^{-2}$, can be neglected here. Secondly, there is small energy loss via the residual gas excitation and ionisation resulting in a 0.1% effect after 10^4 hours at 10^{-9} Pa N_2 in the ISR. This energy loss rate scales as $a^2 Z$. Both effects, as for the beam blow up, are proportional to pressure (residual molecular density) and are aggravated by heavy atoms with large Z and/or for ion beams with $a > 1$. These effects are the proton counterparts of 2.2.2 (e) and 2.2.2 (c+d) respectively as discussed later for electrons (see Table 1).

2.1.2 Nuclear scattering

Protons or other particles making a direct nuclear collision with a residual gas atom will be lost immediately from the beam via a large angle scattering or other nuclear event. If a total nuclear cross-section σ_{nj} for j -type atoms is defined for such processes the exponential time constant τ_{nj} for beam decay due to nuclear scattering from these j atoms is given by

$$1/\tau_{nj} = \beta c \sigma_{nj} n_j$$

where βc is the particle velocity and n_j the relevant atomic number density. In the general case of polyatomic gases and gas mixtures the losses are additive giving, in terms of the molecular partial pressures P_j (Pa at 20°C), for σ_n in m^2 and $\beta \approx 1$

$$1/\tau_n = 7.44 \cdot 10^{28} \sum_j P_j \sigma_{nj} \quad (\text{s}^{-1})$$

where the sum extends over all constituent atoms of each molecular species. The experimental nuclear cross-sections for high

energy proton scattering are almost independent of proton energy and may be approximated⁹⁾ to within 10% (except $\sigma_n(H) \approx 4 \cdot 10^{-30} \text{ m}^2$) by $\sigma_{nj} = (1.5 \cdot 10^{-15} A_j^{1/3})^2 \text{ m}^2$. Using the experimental value of $\sigma_n(N) = 39 \cdot 10^{-30} \text{ m}^2$ yields a more than adequate lifetime at the ISR design pressure of 10^{-8} Pa (see section 2.1.1) of 4800 hours. Nevertheless, this implies some $3 \cdot 10^4$ nuclear scattering events per second and per meter from each beam at the ISR design current of 20 Amp. Although the experimental detectors were designed only to 'look at' the approximately one meter length over which the two opposing beams interacted, and could partially discriminate against such spurious background events, there was a great interest to reduce the residual gas pressure in these experimental regions by one or two orders of magnitude. This indeed was achieved by a variety of techniques¹⁰⁾ including the use of liquid helium cooled cryopumps and, frequently, by sublimating Ti over large areas of the inner surface and turning the vacuum chamber into an large getter pump.

2.2 Electron/positron machines

The important beam-gas interactions in high energy electron and/or positron machines seem just the opposite to those in proton machines. Although the primary effect is still via the Coulomb interaction, it is now energy loss which becomes the dominant cause of beam degradation (by loss of particles) while beam blow-up via scattering becomes unimportant.

Accelerated charged particles, for example those constrained to move on a curved orbit, lose energy by emitting synchrotron radiation at a rate proportional both to the fourth power of their total to rest energy ratio and to the orbit curvature (see section 4). This explains both the large radius of LEP, a compromise between cost and energy dissipation, and why, for comparable total energy, the radiation loss has been neglected for proton machines but becomes of paramount importance in electron machines. This energy loss must be

replaced, e.g. every half or quarter turn, by an r.f. accelerating system to prevent the electron spiraling into the vacuum chamber. Even so, those particles which by statistical chance lose more than a certain limiting energy ΔE (the machine energy acceptance) in a 'one-shot' or single photon emission will be lost before re-acceleration can occur and give rise to the inherent quantum fluctuation lifetime of the beam¹¹⁾. Similarly, and our primary concern here, that fraction of beam-residual gas encounters which give rise to Bremsstrahlung photons of energy $>\Delta E$ will cause a pressure dependent beam loss (see 2.2.2. a), while the smaller energy losses (see 2.2.2. b) will be continuously replaced. It is important to note for electron machines¹¹⁾, in contrast to those for protons, that the r.f. accelerating system not only replaces (via the so-called energy damping) the quasi-continuous part of synchrotron and Bremsstrahlung radiation losses, and also the corresponding part lost to molecular excitations (see 2.2.2 d), but more importantly, it also damps the otherwise continuous transverse and longitudinal blow-up of the bunched beam due to multiple small angle scattering (see 2.2.2 f), as discussed in 2.1.1 for protons.

2.2.1 Bremsstrahlung lifetime due to residual gas

The rate of energy loss by relativistic electrons (velocity c) of energy E traversing an elemental material (j) with density ρ_j is given by¹²⁾

$$-\frac{dE}{dt} = \frac{c\rho_j E}{X_j}$$

thus defining the radiation length X ($= \left[4\alpha r_e^2 Z(Z+1) N_0 A^{-1} \ln(183/Z^{1/3}) \right]^{-1}$) in (kgm^{-2}) with the fine structure constant, r_e the classical electron radius, Z the atomic number, N_0 Avogadro's number and A the atomic weight. Further, the probability W per radiation length of radiating a photon of energy $>\Delta E$, i.e. of being lost from the machine, is given approximately by¹³⁾ $W = \ln(E/\Delta E)$. Since the rate of traversing material is $c\rho_j / X_j$ radiation lengths per unit time the relative loss rate from a

beam of N particles, and hence the Bremsstrahlung decay time constant τ_B , is given by

$$\frac{1}{\tau_B} = -\frac{1}{N} \frac{dN}{dt} = cW \sum_j \rho_j / X_j$$

where the sum has to be taken over the atomic components of all residual gases. Inserting the LEP value of $\Delta E/E = 5.10^{-3}$ and expressing the atomic densities ρ_j in terms of the molecular partial pressures P_i and atomic weights A_j , the lifetime becomes

$$\tau_B = \frac{4.24.10^{-7}}{\sum_i P_i \sum_j A_j / X_j} \quad (s)$$

and the sum has to be taken over the j atomic components for each molecular partial pressure P_i expressed in Pa. In nitrogen ($X_N = 393 \text{ kg.m}^{-2}$) this Bremsstrahlung lifetime is given by $\tau_B(N_2) = 5.95.10^{-6}/P_{N_2}$ hours showing that average pressures in the 10^{-7} Pa range are required. The $Z(Z+1)$ factor in $1/X$ shows yet again the importance of avoiding high atomic number contaminants.

2.2.2 Further electron-residual gas interactions

A range of related electron beam-residual gas effects, all mediated by the Coulomb interaction, can be identified and for completeness are listed in Table 1. Processes labelled c) and e) (see Table) give rise to exponential beam intensity decays due to particle loss by, respectively, losing more than the permitted machine energy spread E through individual residual gas excitations¹⁴⁾ and being scattered out of the machine angular acceptance Θ_M ¹⁵⁾. Both for LEP are negligible in comparison with the single photon Bremsstrahlung discussed in 2.2.1, although the dependence of scattering on (momentum)² means that this effect can become important in lower energy situations. Processes b) and d) cause a more or less continuous energy loss and times

to lose the limiting energy E are shown to be long in comparison to the LEP machine energy damping time (~ 20 ms) whereby the accelerating cavities restore any such energy losses. Finally in f) the time constant determining the initial beam blow-up rate due to multiple Coulomb scattering⁶⁾ (the most important effect for protons in the ISR) is seen to be long compared with the transverse damping in the machine (~ 40 ms) due, again, to the action of the accelerating cavities.

Table 1

Summary of electron beam interactions with residual gas calculated for LEP at $E = 50$ GeV, ($p = 50$ GeV/c), $\Delta E/E = 5 \cdot 10^{-3}$, $W = \ln(E/\Delta E)$, $\Theta_M = 0.22 \cdot 10^{-3}$ and $P = 1 \cdot 10^{-7}$ Pa of nitrogen ($Z = 7$).

Electron residual gas interaction	Time (s) τ	Scaling of τ	Remarks
a. Single Bremsstrahlung (Photons $>\Delta E$; particle loss) See section 2.2.1.	$2.14 \cdot 10^5$ (τ_B)	$\frac{1}{Z(Z+1)W} \times \frac{1}{P}$	Dominant in LEP (also in most machines)
b. Continuous Bremsstrahlung (Photons $<\Delta E$; energy loss)	$5.67 \cdot 10^3$	$\frac{\Delta E/E}{Z(Z+1)} \times \frac{1}{P}$	Unimportant ; $\tau \gg$ energy damping time
c. Excitation of gas molecules ($>\Delta E$; particle loss)	$9.59 \cdot 10^7$	$\frac{\Delta E}{Z} \times \frac{1}{P}$	Unimportant ; $\tau \gg \tau_B$
d. Excitation of gas molecules ($<\Delta E$; energy loss)	$1.87 \cdot 10^6$	$\frac{\Delta E}{Z} \times \frac{1}{P}$	Unimportant ; $\tau \gg$ energy damping time
e. Single Coulomb scattering ($\Delta\theta > \Theta_M$; particle loss)	$6.85 \cdot 10^6$	$\left(\frac{P\Theta_M}{Z}\right)^2 \times \frac{1}{P}$	Unimportant ; $\tau \gg \tau_B$
f. Multiple Coulomb scattering ($\Delta\theta < \Theta_M$; blow-up)	$1.70 \cdot 10^3$	$\left(\frac{P}{Z}\right)^2 \times \frac{1}{P}$	Unimportant : $\tau \gg$ transverse damping time

3. VACUUM CHAMBER CONSTRAINTS AND DESIGN IMPLICATIONS

The vacuum system for a high energy particle accelerator is very closely linked to the design of the magnet system for bending and focussing of the particle beam. Magnet cost increases rapidly with the gap width and hence the aperture of the vacuum chamber is closely fitted to the size of the beam. The direct consequence is a very low conductance of the vacuum chamber and, because of the construction of the magnets, very limited access for pump connections.

Apart from acting as a vacuum vessel, the beam pipe must also satisfy the requirements of the beam for an electrically conducting and smooth wall much the same as the outer conductor of a coaxial line which carries the image current of the central conductor (here the beam current). Hence, any variation of the vacuum chamber cross section must be made gradual and tapered to reduce the resulting loss factor for the beam. Infact the energy loss of the beam, which will actually be deposited via ohmic losses in the particular element, is proportional to a geometrical factor and to the square of the electric charge in the particle bunch of the beam. Because of this power dissipation the convolutions of vacuum bellows must be electrically shielded from the beam. This is achieved for the LEP vacuum system by inserting a set of flexible, sliding spring contacts with the shape of the oval vacuum chamber cross section into the otherwise circular bellows¹⁾.

Similarly, all pump ports require a perforated electric screen to minimise the disturbance to the particle beam. The linear pump structure, as will be shown later, must also be shielded from the beam by mounting it in a separate duct parallel to the beam channel and communicating only through small slots with the main beam duct of the machine.

The choice of the most appropriate material for the beam pipe and hence for the vacuum chamber is a very important starting decision¹⁶⁾.

The machine design requires a non-magnetic material in order not to disturb the external guiding field of the beam. For electron machines good thermal conductivity is essential to cope with the high power density of the synchrotron radiation. The bakeout of the system needs a material with good mechanical strength up to high temperature. The material should also be inexpensive and lend itself for easy production in large quantities and with well established manufacturing processes. For the reasons outlined, stainless steel has become the most widely used material for proton machines whereas aluminium is favoured for electron machines¹⁷⁾ for thermal conductivity and, to a large extent, because the complex beam pipe section with pumping and cooling ducts can be produced very economically by continuous extrusion.

For machines of large size the saving which may be obtained by careful detail design is more important than for smaller machines. Further encouragement to detail optimisation is derived from the longer duration of the project. Additional unit cost reduction results from large series production which favours the use of industrial processes and methods.

In a large machine project, reliability of components is essential. A failure rate which would be unnoticed on a small machine may have catastrophic consequences when the vacuum system is tens of kilometres long. On the LEP vacuum system, about 20'000 pairs of flanges will be present. A flange failure rate of 0.1% after bakeout, which would be excellent for a small machine, may result in rebaking a large fraction of the machine. Similarly, a failure rate of a few per cent for ceramic feedthroughs, which may be considered satisfactory in usual conditions, would not be tolerable for LEP where about 4000 high current feedthroughs for powering the NEG pumps, about 1800 high voltage feedthroughs for ion pumps and about 2000 feedthroughs for beam monitors will be installed. Similar considerations also apply for welds, particularly in the case of LHC where in addition they will be submitted to thermal fatigue resulting from the cooldown to liquid helium temperature and to pressure variations inside the magnet cryostats.

Whenever a component fails and it must be replaced the difficulty of the intervention increases with longer vacuum sectors which, for instance for LEP, tend to become longer due to the lack of space for inserting sector valves and their unit cost. On this machine, a compromise was found at 474 m, which could represent the length of a whole machine of medium size. In the case of LHC the vacuum sectors will be 1.6 km long, i.e. as long as cryogenic sectors. Cryogenic and vacuum sectors must be of equal length, otherwise venting of a vacuum sector would become problematic.

For electron machines, a large fraction of the synchrotron radiation may penetrate the vacuum chamber wall and be released in the machine tunnel. This radiation may have detrimental effects on machine components, either directly on any organic material, or indirectly via production of nitrous oxide and nitric acid which may result in corrosion of metals and in particular, at any junction of dissimilar metals. For this reason the LEP vacuum system will be all-metal (Al and stainless steel) and combinations of dissimilar metals like Al/Cu are proscribed. Corrosion considerations also ask for special brazing alloys (Au-Ni) for ceramic to metal joints in electric feedthroughs. For similar reasons, the turbomolecular pumping stations cannot be left permanently in the LEP tunnel but will be mobile and removed as soon as a vacuum sector has reached its ultimate pressure. This strategy would in any case be recommendable for a large machine, in view of the large capital saving.

4. DYNAMIC ASPECTS OF ACCELERATOR VACUUM SYSTEMS

The vacuum of high energy particle accelerators and storage rings can be affected in a number of ways by the interaction of the circulating beam with the vacuum system. For this reason it is frequently referred to as the dynamic vacuum as opposed to the static vacuum of a machine - the latter being determined by the normal thermal outgassing of the vacuum chambers.

4.1 Synchrotron radiation outgassing and beam cleaning

In accelerators for electron and positron beams, intense synchrotron radiation is emitted in a forward directed, narrow cone producing strong outgassing from the vacuum chambers in all curved sections of the machine. The description of this desorption process is made complex because incident primary photons undergo repeated reflections before they effectively illuminate the whole internal vacuum chamber surface. Desorption of gas molecules is generally considered to occur in a two stage process whereby in a first instance the primary photons produce photoelectrons which subsequently desorb gas by electron stimulated desorption^{18, 19}).

The power W , emitted in the form of synchrotron radiation is given by

$$W = 6.03 \cdot 10^{-12} (E/E_0)^4 I/R \quad (W)$$

(with the beam current I expressed in mA and the magnetic bending radius R in m) i.e. it increases with the 4th power of the ratio of the particle energy E (GeV) to its rest energy E_0 (0.511 MeV for electrons). The photon spectrum emitted in a high energy accelerator extends from visible light to hard X-rays and is identified by a critical (centre of power spectrum) energy

$$\epsilon_c = 2.22 \cdot 10^3 E^3/R \quad (eV)$$

The present generation of high energy accelerators have critical photon energies ranging from a few keV to close to 1 MeV. In terms of the absorbed synchrotron radiation power the vacuum chamber has to accept levels from a hundred W/m to several kW/m, implying a corresponding cooling capacity of all components.

The total number of emitted photons per second in a machine is

$$\frac{dN}{dt} = 8.08 \cdot 10^{17} IE \quad (s^{-1})$$

increasing linearly with the circulating beam intensity and with the particle energy. The desorbing photon flux per unit length ℓ of the vacuum system $1/(2\pi R) dN/dt$ for some typical machines is summarised in the table.

Machine	R(m)	E(GeV)	ϵ_c (keV)	$\frac{1}{I} \frac{d^2N}{d\ell dt}$ (mA ⁻¹ m ⁻¹ s ⁻¹)
DCI (Orsay)	3.82	1.72	2.95	5.8 10 ¹⁶
PETRA (DESY)	192	19	79	1.3 10 ¹⁶
LEP (CERN)	3096	50	89	2.1 10 ¹⁵

The resulting flux of desorbed gas is related to the photon flux by the desorption yield η . However, instead of quoting the molecular desorption yield the vacuum performance of an electron machine is frequently expressed by the specific pressure rise $\Delta P/I$ which includes implicitly also the installed pumping speed of the system.

When beam first circulates in a new machine, the dynamic pressure rise will normally exceed the static pressure by several orders of magnitude and the resulting beam lifetime may be very short. Fortunately this situation improves initially very fast and later on more gradually with the time the machine is operated with beam. This training of the vacuum system, or as it is commonly called 'beam cleaning', typically reduces the dynamic outgassing rate by 2 to 3 orders of magnitude to acceptable low values.

Gas species desorbed from Al systems by synchrotron radiation²⁰⁾ are in order of importance predominantly hydrogen, followed by carbon monoxide and carbon dioxide and to a lesser degree methane. Water, even if present in the residual gas of an unbaked system, is not desorbed as such by synchrotron radiation.

A typical clean-up test run in DCI of an aluminium vacuum chamber for the new LEP machine is shown in Figure 1. The molecular desorption yield η (molecules desorbed per incident photon) is plotted as a function of the accumulated photons per m.

For the given example about 10^{21} photons per m result in a reduction of the initial desorption yield by about a factor of 10.

An important aspect for the operation of electron machines is the need of retraining the vacuum system following any exposure to atmospheric pressure because of a repair or other intervention on the system. Fortunately, the system keeps a memory, at least partially, of the previous cleaning and the training starts at a lower initial desorption level. Obviously, whenever such an intervention is planned in advance, it is good practice to vent the system with dry and very clean nitrogen. Under such conditions the previous cleaning is preserved much better.

4.2 Ion induced desorption

The emission of synchrotron radiation is practically absent in high energy proton machines because of the 4th power dependence on the ratio of the particle energy to its rest energy. Nevertheless the next generation of proton machines are planned with such high energies - between 10 and 20000 GeV, that synchrotron radiation will begin to influence the vacuum performance.

So far the main problem of beam - vacuum system interaction in proton machines has centered around ion induced desorption from the walls of the vacuum chamber²¹⁾. The circulating high energy protons ionise residual gas molecules and under the positive space charge potential of the beam these ions are accelerated towards the wall. Typically such ions may gain an energy of 100 eV to several keV and are, therefore, very efficient to desorb molecules from the wall.

The flux of desorbed molecules Q per unit length of the machine can be expressed in terms of a desorption yield η , here in molecules per incident ion,

$$Q = \eta \sigma_i PI/e$$

where e is the charge of the electron, σ_i is the ionisation cross section for high energy protons (i.e. in the 10^{-22} m^2 range), I the circulating beam current and P the pressure.

By writing the balance between the total in-flow of desorbed molecules, including the thermal outgassing Q_0 , in the system and the molecules pumped with an effective pumping speeds per unit length, S , one obtains

$$P.S = P\eta\sigma_i I/e + Q_0$$

thus
$$P = Q_0 / (S - \eta\sigma_i I/e)$$

and one finds that no stable equilibrium pressure exists for values of the product

$$(\eta I) > Se/\sigma_i$$

First observed on the ISR vacuum system²²⁾, this pressure instability (pressure bump) has been a severe limitation for the maximum circulating beam current which could be accumulated in this machine.

Since the stability depends on the local values of the desorption coefficient i.e. on the local degree of cleanliness of the vacuum chamber and on the local value of the pumping speed, the pressure run-away will always develop at the weakest place in the machine. Therefore a significant improvement can be obtained only by systematically improving the whole of the machine. Contrary to the training

with synchrotron radiation where the desorption coefficient can be strongly reduced, it was not possible to obtain any significant improvement for the ion induced desorption by merely running the machine with beam for long periods. This negative result can be attributed to the much lower integrated ion dose which can be obtained under practical conditions.

In the ISR, the vacuum stability was increased not only by installing larger pumps at reduced distance, which counteracts the conductance limitation of the vacuum chamber, but also by better cleaning of the vacuum chambers. This was achieved by a combination of high temperature pre-bakeout (950°C under vacuum) and argon ion glow discharge, systematically applied to all stainless steel vacuum chambers.

Future proton machines, both under construction²³⁾ and planned^{2,3)}, will exploit the very high effective pumping speed which is achieved in a cryopumped vacuum system. Profiting from the presence of the cryogenic system, which is required for the now indispensable superconducting magnets, the vacuum chamber will be brought into direct contact with the liquid helium of the magnet cryostat and thus form an inner cold bore of the magnet.

The cold bore design offers the advantage of extreme simplicity for the construction of the vacuum system together with a very large pumping speed. However, it still had to be proven by theoretical as well as practical work, that the large desorption yield which occurs on ion bombardment of the condensed gas layer is adequately compensated by the pumping action²⁴⁾. The pressure stability of the cold bore system can be expressed as²⁵⁾.

$$(\eta I) < \pi e r s v / (2 \sigma_i)$$

with r the vacuum chamber radius, s the sticking probability and v the mean molecular velocity. Effectively, the stability limit

depends on the time a gas molecule spends in the gas phase traversing the beam pipe when it can be ionised, hence on the mean molecular velocity.

The energy of the ions hitting the wall, and hence the desorption yield η , is determined by the positive space charge potential of the beam, which, in turn, depends on the chamber/beam geometry and on the electric charge density. In the ISR where the average circulating beam current could be increased above 50 A the energy of the ions could reach several keV. More recent machine designs are based on lower average currents and hence also much reduced ion energies.

4.3 Bunch induced multipactoring

Electrons produced by ionisation of the residual gas may, under certain conditions involving bunched beams, gain a significant amount of energy from the passage of the bunches. Electron multipactoring occurs if the electric field of the bunch has a resonant relation with the movement of the electrons in the vacuum chamber. Electrons may then strike the vacuum chamber wall and produce secondary electrons which are subsequently picked up by the electric field of the next beam bunch and are again accelerated across the beam pipe to the opposite wall. This transverse back and forth bouncing of the secondary electron cloud can give rise to very strong electron induced gas desorption and vacuum degradation.

In high power accelerating cavities this effect is well known but in the ISR it has also been observed in a simple beam pipe²⁶⁾. For a concentric circular geometry of the beam bunches and the vacuum chamber the threshold current I' above which the resonance condition occurs is

$$I' = (1/30)(m/e)(r/T)^2$$

where e/m is the charge to mass ratio of the electron, r the radius of the beam pipe and T the time between beam bunches. Furthermore, the average secondary electron yield during this process must be above unity. In this respect aluminium as vacuum chamber material is more critical than stainless steel - it was in a section of aluminium beam pipe installed in the ISR for test purposes where this effect has been observed. A remedy against electron multipacting is the use of materials or surface treatments giving a low secondary electron yield (e.g. titanium nitride coating) or avoiding the resonant condition by a proper choice of the relevant parameters.

5. PUMPING

5.1 Pumping speed, conductance limitations and linear pumping

The vacuum requirements for the various types of machines, which are discussed in chapter 2, refer to average pressures. In the case of a vacuum system with pumps located at a regular distance from each other, the pressure presents a parabolic distribution with minima at the pump location. The pressure difference between a pump and the mid-position maximum is given by

$$\Delta P = qUD/8C$$

and the average pressure is

$$P_{av} = P_o + qUD(1/S + 1/12C)$$

Here D is the distance between pumps (m), C the conductance of the pipe between pumps (m^3s^{-1}), S the pumping speed of a pump (m^3s^{-1}), P_o the base pressure of a pump (Pa), U the perimeter of the vacuum chamber (m), q the specific degassing rate of the chamber walls ($Pa\ ms^{-1}$). The conductance for nitrogen of a circular pipe of radius r ($\ll D$) may be approximated by the Knudsen formula for molecular flow

$$C = r^3/10D$$

These formulae indicate that, even for reasonably large vacuum chamber cross sections, the average pressure which may be obtained inside an accelerator quickly becomes determined by the chamber conductance when increasing the spacing between the pumps. The benefit of increasing S under these circumstances is minimal. Rather, it is more efficient to increase the number of pumps i.e. to decrease their spacing. This solution clearly becomes very expensive due to the large number of pumps and connecting ports to the vacuum chamber. The obvious remedy to the problem is to use distributed linear pumps whenever the pumping speed required per metre of vacuum chamber exceeds a few hundredths of m^3 per second.

5.2 Electron colliders

In these machines, dynamic degassing may exceed thermal degassing by some orders of magnitude. To cope with this large degassing induced by synchrotron radiation a large and evenly distributed pumping speed is required (typically $0.05 \text{ m}^3\text{s}^{-1} \text{ m}^{-1}$). Historically, electron colliders were the first accelerators to be equipped with distributed pumps in the form of a linear sputter-ion pump inserted in a channel parallel to and in good vacuum contact with the beam channel. These 'integrated' pumps²⁷⁾ are more cost effective than a large number of appendage pumps and they can also make use of the magnetic field of the machine bending magnets. Integrated sputter-ion pumps were adopted both in PETRA²⁸⁾ and in PEP²⁹⁾.

This elegant solution, however, is not free of disadvantages. During the initial pumpdown the magnets are not powered and additional appendage pumps are required to obtain and maintain the vacuum ('holding' pumps). Furthermore, the magnetic field intensity is lower when the electrons are injected, resulting in a reduced pumping speed. This feature is particularly important for LEP, as it would also be for other machines of this size, for which the injection

energy is limited by the size of the injector to a value much lower than the operating energy of the machine. In the case of LEP, only 200 gauss are available at injection, a value which is dangerously close to the limit at which the discharge extinguishes in the sputter-ion pump and the pumping speed falls to zero.

These inconveniences were overcome in the design of the vacuum system of LEP by using a distributed Non-Evaporable Getter (NEG) strip^{30, 31}). It consists of a constantan ribbon 0.2 mm thick and 30 mm wide, coated by cold sintering with a powder layer of Zr 84% Al 16% alloy. The thickness of this coating, applied on each side of the strip, is about 0.1 mm. This NEG is commercially available under the tradename of St 101 from SAES Getters (Milano, Italy)^{32, 33}). Upon heating under vacuum at an appropriate temperature (about 700°C for about 1 h) the NEG surface becomes chemically active and able to fix gaseous molecules in the form of stable chemical compounds. This surface activation by heating is achieved by diffusing the gases from the surface into the getter bulk. After activation, a new NEG strip provides pumping speeds as high as about $2.5 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ for CO and CO_2 , $1.5 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ for H_2 and $1.0 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ for N_2 .

Inside the LEP vacuum chamber the NEG is attached to a rigid stainless steel carriage via insulating ceramics as shown in fig. 2. At each end of the 12 m long LEP dipole chambers the NEG pump is connected to electric current feedthroughs to permit activation by ohmic dissipation.

During LEP operation, the normal continuous heating of the NEG is not feasible because the magnetic field produced by heating current would upset the stored beams. After the first activation, the NEG will be kept at ambient temperature and, now in the absence of diffusion, its surface will progressively saturate and the pumping speed decrease correspondingly. When the pumping speed falls below a pre-defined value ($\sim 0.05 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ for LEP), the NEG must be heated again to restore the pumping speed. Since now the surface coverage

is much lower than after exposure to atmospheric air, lower temperatures and shorter heating times than for full activation are sufficient. Typically, heating for a few minutes at a temperature of the order of 450°C is sufficient³⁰). On the basis of the foreseen gas load (section 4) and measured NEG performance, it may be estimated that the NEG should be heated between 10 and 20 times for 20 years of LEP operation, depending on actual degassing rates and desired pumping speed, as well as on the number of ventings to atmospheric pressure.

Since the NEG's do not pump the rare gases or methane, some other pumping for these gases must be supplied. For LEP, appendage sputter-ion pumps of about $0.03\text{ m}^3\text{ s}^{-1}$ pumping speed will be installed at a distance of about 20 m from each other (4 such pumps per cell 80 m long). According to the results obtained on the approximately 500 dipole chambers which have been tested so far, the LEP pumping system should be able to produce an average static pressure of about 10^{-9} Pa one day after bakeout (about 24 h at 150°C) and a pressure in the low 10^{-10} Pa after a few weeks.

In addition the appendage sputter-ion pumps will also supply valuable pressure indications during operation. Using the pump current for pressure monitoring results in a saving on measuring equipment which is particularly attractive for such large machines. For most sputter ion pumps existing today on the market, the pump current remains proportional to pressure down to 10^{-7} Pa.

5.3 Proton colliders

The modest energy loss via radiation makes proton machines particularly attractive for reaching very high energies. This quest for high energies has two important implications for the design of the vacuum system. The first is that very high magnetic bending fields are desirable, a feature which calls for superconducting magnets. The second is that the required vacuum chamber aperture becomes very

small (typically 2 to 4 cm in diameter), therefore rendering distributed pumping impossible.

The obvious choice for pumping such a proton machine consists therefore in transforming the vacuum chamber itself into one large cryopump by cooling it to liquid helium temperature together with the superconducting magnet. This solution, which may be adopted because of the proven pressure stability of a 'cold bore' based vacuum system²⁵⁾ (see section 4), offers many advantages. In addition to providing a linear pump of the maximum possible pumping speed (it may be assumed that a molecule hitting the wall of the vacuum chamber has a probability of approximately unity of being adsorbed), a 'cold bore' based solution results in a drastic design simplification (and cost reduction of the vacuum system). The ultimate pressure can also be expected to be extremely low.

A typical example of this solution is depicted in Fig. 3 which represents the schematic view of the vacuum chamber and superconducting magnet assembly proposed for the LHC at CERN²⁾.

As in the case of NEG pumping, some appendage sputter-ion pumps are required to pump He. Helium may leak in from the cryostat of the magnet and can be adsorbed on the chamber walls only in limited amounts due to its high vapour pressure. The appendage pumps are again useful for pressure monitoring purposes, both before and after magnet cooling.

6. OPERATIONAL ASPECTS

The behaviour of the machine is the best monitor of its vacuum condition. The beam lifetime measured on the ISR was found to present the expected dependence on pressure down to the 10^{-10} pa range. However, only average values are obtained in this way which therefore does not help to define and localise a problem. Precise information could be supplied by locally installed pressure

monitoring instruments, but their installation with useful spacing on a large machine is prohibitively expensive.

The compromise approach which tends to be followed to overcome this problem covers two different aspects. First, information is required on the behaviour of the vacuum system in general. In this respect it may be assumed that the situation is the same at seemingly identical regions of the machine, a few of which may therefore be identified as 'pilot' regions and fully equipped with total and partial pressure gauges. This same approach may also be followed for vital regions like the experiment interaction regions of a storage ring. Second, it must be possible to localise an anomalously high pressure as produced for instance by a leak. In this case extensive use may be made of the pressure readings from the sputter ion pumps which may indicate an increase above the specified average pressure. This strategy has been adopted for LEP and proposed for LHC.

When the evidence for the presence of a leak is indicated by the current profile from adjacent sputter ion pumps, the leak must be localised for repair. To do so, leak detectors are usually used. In some cases, however, traditional detectors should not be connected directly to the vacuum system in order to avoid the risk of oil backstreaming from the diffusion pump - such is the case for LEP. In even more stringent vacuum conditions as for the ISR, the detector was not connected to the vacuum chamber even through a turbomolecular pump. For leak detecting on the ISR a method was developed which consisted in observing the variation on the pressure indicated by an ionisation gauge when testing the doubtful regions with argon. Replacing in-leaking air by argon always produces an increase of the gauge signal because the gauge sensitivity is higher and the pumping speed lower³⁴). Pressure enhancement by argon is particularly important on systems where the available pumping speed is mostly supplied by getter pumps, either Ti sublimation or NEG, because these pumps do not pump rare gases at all. Argon leak detecting may then result in a pressure increase of more than an order of

magnitude. This method, unfortunately, is not applicable to 'cold bore' machines, because argon is very effectively cryopumped at liquid helium temperature. Only leaks located on the lateral connections, as shown by Fig. 3, may be localised in this way. Fortunately, these connections are the only possible origin of air leaks, because all other cold parts of the main vacuum system are protected by the insulation vacuum of magnet cryostats. In this vacuum only He is likely to be present, because all other gases are effectively pumped on the cold walls. Helium leaking in from the insulation vacuum into the main vacuum of the machine will be physisorbed up to a coverage of a fraction of a monolayer and cause a front of increased pressure which will propagate from the leak along the main vacuum chamber, finally resulting in a noticeable increase on the sputter ion pump current. It must be noted that for leak detection purposes it is convenient to have base pressure monitoring as low as possible, because this may result in earlier indication of a leak. Upon obtaining this indication, and whenever the consequent pressure increase cannot be tolerated, leak localisation may require heating up and opening a magnet cryostat.

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FIGURE CAPTIONS

- Figure 1: The molecular desorption yield η (molecules per incident photon) as a function of the accumulated photons per m for a LEP sample vacuum chamber exposed to synchrotron light at DCI (Orsay).
- Figure 2: Cross section of the LEP dipole vacuum chamber with the NEG pump.
- Figure 3: Schematic view of the LHC magnet cryostat with the cold-bore vacuum chamber.

Figure 1

Figure 2

Figure 3