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VACUUM AND ULTRAHIGH VACUUM FOR
PARTICLE ACCELERATORS AND STORAGE RINGS*

by

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Abstract

Particle accelerators operate at pressures of about 10^{-7} torr. Storage rings require 10^{-9} to 10^{-11} torr. The maximum permissible pressure is determined by many perturbing interactions between beam particles and gas molecules. Proton storage rings have additional problems from interactions with layers of gas adsorbed on the chamber walls. Most accelerators and storage rings have a tubular structure with pumps connected in regular intervals. The pressure behaviour in such a system can be calculated from a differential equation, which can be extended to include beam-wall interactions, readsorption and distributed pumps. The systems are pumped by sputter-ion pumps, pre-evacuated by turbopumps and controlled by computers. Radioactivity poses special problems.

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1. INTRODUCTION

Particle accelerators and storage rings for high energy physics are among the numerous applications of vacuum technology. Let us have a quick look at one of the largest laboratories in the field, that of CERN, the European Organization for Nuclear Research, in Geneva, Switzerland

Figure 1 shows very schematically the complex as it is in operation at present. Protons produced in a plasma ion source are at first accelerated through a linear accelerator (Linac) of 30 m length and about 1 m diameter to 50 MeV energy and then further accelerated in a so-called booster synchrotron to 800 MeV. From the booster the protons are transferred - always under vacuum - into the ring of the main synchrotron of 200 m diameter where they circulate in a vacuum chamber of $145 \times 70 \text{ mm}^2$ aperture at a pressure between 10^{-7} and 10^{-6} torr. They are kept in orbit and continually focussed by electromagnets, and are accelerated by RF cavities within one second to a maximum energy of 28 GeV. At several places the high energy protons, or secondary particles produced by protons hitting a target, are ejected from the ring into different channels and are available for the physicists doing fundamental research on elementary particles.

From one of these ejection points protons can be guided through two transfer tunnels into the Intersecting Storage Rings (ISR)¹⁾. The storage rings are installed in a tunnel of 300 m diameter and 15 m width. Two concentric chains of vacuum chambers of 160 mm diameter are arranged in such a way that they intersect at 8 point with an angle of 15° . Each ring can be filled with successive pulses of protons from the synchrotron to beam intensities of up to 20 A. After adjustments these two beams are kept circulating quietly in opposite directions for many hours. The necessary lifetime of the protons is only possible in ultrahigh vacuum. In fact, the average pressure in the ISR is 10^{-11} torr. The physicists have installed their equipment closely around the intersection points where they observe the head-on collision of protons with protons.

All the installations described so far form one interconnected vacuum system of 5 km total length with pressures varying between 10^{-5} and 10^{-12} torr.

This seems to be a very big vacuum system, but it looks almost insignificant on Figure 2 which shows an extension which is now under construction. On the right you can still recognize the synchrotron and the storage rings. The new big ring is a tunnel with a diameter of 2.2 km. It will house the Super Proton Synchrotron (SPS) which will be able to accelerate protons up to 400 GeV²⁾. Its vacuum chamber will have a length of 7 km and the design pressure is 3×10^{-7} torr. The old synchrotron will serve, through a new transfer tunnel, as injector for the SPS. More, but rather simple, vacuum lines are required for the two ejected beams leading to the experimental areas.

When the construction will be finished in 1978, the total length of all vacuum lines will be almost 20 km.

Other laboratories work with accelerators and storage rings for electrons. Since this subject is covered by two invited papers³⁾⁴⁾, I shall restrict myself to proton machines.

2. VACUUM REQUIREMENTS

For the determination of the vacuum requirements of a given accelerator, storage ring or transfer line one must take into account all conceivable interactions with the residual gas which can disturb the operation of the machine or the experiments. In this respect one should not forget that the gas adsorbed on the vacuum chamber walls also belongs to the residual gas.

2.1 Gas Scattering

One obviously important interaction is the scattering of the protons on the nuclei of the residual gas, since this shortens the lifetime or the free path. In elastic or inelastic nuclear scattering the angle of deflection or the loss of energy are almost always so large that the scattered particle is directly lost from the beam. More frequent is the electromagnetic Coulomb interaction with the nuclei. For protons this scattering is mostly elastic. The scattering angles at high energies are very small so that the protons are not lost but continue to oscillate

about the beam centre with increased amplitude. Consequently the beam is blown up, where the square of its diameter increases linearly with time. This leads, of course, eventually also to beam losses, when the beam dimension tends to exceed the chamber aperture.

The scattering probabilities and the scattering angles depend on the nature of the residual gas. Qualitatively speaking, hydrogen is a weak scatterer, argon a strong one. Based on the scattering theory one can calculate for each gas species a relative weight factor with respect to nitrogen as reference gas. One can then calculate from the partial pressures of all gases an equivalent nitrogen pressure by multiplying each partial pressure by the weight factor for the given scattering process and adding them all up. For nuclear scattering the weight factors are simply the total cross-sections divided by the cross-section of nitrogen. For Coulomb scattering the expression is more complicated. A maximum acceptable pressure is always given as nitrogen equivalent pressure.

The maximum acceptable pressure depends of course on the particle energy and finally on the distance the particles have to travel in a given beam. In a beam of high energy secondary particles, for instance, the distance between the target where they are produced and the detection apparatus is not more than a few tens or a few hundreds of metres and it is traversed only once. For such beams it is sometimes sufficient to pass them through bags of thin plastic foil filled with helium. In this case a "vacuum" of one atmosphere of helium is good enough.

The other extreme are the Intersecting Storage Rings where the protons have lifetimes of many days and have to traverse correspondingly astronomical distances. The pressure must, in this case, not exceed 10^{-10} torr of 90% hydrogen.

The requirements for accelerators are in between the two described extremes. The acceleration time in proton synchrotrons is of the order of one second and the path-length a few hundred thousand kilometres. This requires a pressure of less than 10^{-5} torr.

2.2 Ionisation

When a high energy proton interacts with an electron of a residual gas molecule the proton itself is very little disturbed but the molecule is ionised. The released electron is trapped by the positive electrostatic potential of the beam and the ion is projected by the same potential against the chamber wall where it can make disturbances which will be explained in the next section.

The creation of stationary or fluctuating negative space charge affects seriously the performance of a machine. The mechanisms are difficult to explain and not yet fully understood. They are a fascinating subject for theoreticians. In proton accelerators negative space charge effects are particularly disturbing at injection when the protons have still a low energy and are easily deflected. This effect requires a lower pressure than for gas scattering reasons and demands a pressure of less than 10^{-6} torr. In proton storage rings the presence of an electron space charge contributes to a number of mechanisms leading to beam instabilities. The requirement is that the ratio of trapped electrons to protons must nowhere exceed 1 : 1000.

There are two ways of fighting negative space charges which are complementary to each other: one is the installation of special high-voltage electrodes for the extraction of electrons; the other is to reduce the rate of ionisation by reducing the gas pressure. In proton storage rings this is one of the justifications for having ultrahigh vacuum.

2.3 Wall reactions

One of the biggest problems in electron ring accelerators and storage rings is the pressure rise provoked by the intense synchrotron light generated in these machines⁴⁾. Proton storage rings have also a wall reaction problem but of quite a different nature.

When the current of circulating protons is increased by repetitive injections, eventually an intensity is reached at which the pressure starts to rise, at first slowly, at one or several places. If one tries to increase the beam current further, the pressure rises so fast up to 10^{-7} or 10^{-6} torr that the beam is rapidly lost due to a multitude of disturbances.

At the ISR this critical current was initially around 4 A; now after many improvements, it is around 20 A. The mechanism behind this is gas desorption from the chamber walls under the bombardment by ions produced in the residual gas. This effect tends to become unstable because the pressure rise increases the rate of ionisation and with it the gas desorption. The effect is attenuated by the available pumping speed. The improvement for 4 to 20 A has, therefore, been achieved partly by installing many additional Ti sublimation pumps.

High pumping speed and very low base pressure alone, are, however, not enough. Equally or more important is the cleanliness of the walls. It is achieved by in situ bakeout at 300°C for 24 h after each exposure to air and by glow discharge cleaning of all new chambers before installation. This type of cleaning removes adsorbed CO and hydrocarbons from the surfaces, gases which are mainly responsible for the beam induced pressure rises. Surprisingly for us, a glow-discharge cleaned chamber remains clean even if it is exposed for several days to atmospheric pressure.

2.4 Other considerations

There are, of course, many other considerations which influence the determination of the design pressure of a machine. The main reason for the 3×10^{-7} torr chosen for the SPS was, for instance, the requirement that the life of the sputter-ion pumps must not be shorter than the expected life of the accelerator.

The cost factor plays, of course, also its role. However, I must point out that the vacuum system of a particle accelerator presents only a very small part of the budget. Even the 2 km of 10^{-11} torr of the ISR have cost only 8% of the total construction budget. The big money went into civil engineering, magnets and power supplies.

My advice : don't save on vacuum! The economies are negligible with respect to the total of the project and you will pay for them later in the form of technical trouble.

3. THE PRESSURE AS FUNCTION OF SPACE AND TIME

The vacuum system of all accelerators, storage rings and transfer lines consist of long tubes to which, in regular distances, pumps are connected. The behaviour of the pressure as function of time and of a longitudinal coordinate measured along the tube can be described very generally by a differential equation which is of first order in time and of second order in the longitudinal coordinate.⁵⁾ The pumping speed of the pumps appears in the form of boundary conditions. I resist the temptation to write down mathematical equations, but mention only qualitatively, that the differential equation can easily be extended to include a so-called linear pump, that is, a pump which offers pumping speed everywhere along the tube, as common in electron storage rings. It can also easily be extended to include beam induced desorption from ion bombardment in proton storage rings⁶⁾.

The equilibrium solutions of the differential equation are relatively simple. They give the static pressure profile along the tube. Measurements have shown good agreement theory⁷⁾.

If one tries to solve the differential equation for a particular place of the tube as function of time and compares it with actual dynamic pressure measurements, one finds enormous discrepancies in the sense that observed pressure changes are always orders of magnitude slower than those calculated. This can, however, be explained by adsorption and desorption to and from the chamber walls. Mathematically this leads to a set of differential equations, one for the pressure and one or several for the gas density on the chamber wall as function of time and tube length which includes such constants as sticking coefficient and sojourn time. These constants can easily be adjusted to bring the computations in fair agreement with experimental observations.

4. PUMPS

The main vacuum pump for all big accelerators and storage rings is, to my knowledge, without exception, the sputter-ion pump. This pump is so ideally suited for these machines that it seems as if it were invented for this application. The essential advantages are the simplicity of the design without moving parts, liquids or cold, the freedom of service and maintenance over many years and the possibility to use the pumps for pressure monitoring and as pressure transducers for control and interlock purposes.

Turbomolecular pumping stations are used almost everywhere for pre-evacuation down to the starting pressure of the sputter-ion pumps and - on storage rings - during a bakeout. A certain competition comes from 2-stage rotary pumps baffled with zeolite or activated alumina traps.

The very low pressure in the ISR has been obtained by adding titanium sublimation pumps to the sputter-ion pumps in a ratio of 2 : 1 to 3 : 1. This addition reduces the operating pressure from about 10^{-10} to about 10^{-11} torr, and in combination with better surface cleanliness makes the rings stable against beam induced pressure rises up to beam currents of 20 A.

5. COMPUTER CONTROL

All new accelerators and storage rings make use of computers for monitoring, logging, controlling, steering, alarm signals and interlocks. The vacuum systems with the huge number of pumps, gauges and valves are important customers to these computers.

It is always a controversial question to decide which function to entrust the computer with and which functions not. I believe a good guidance can come from a look at the nervous system of the human body. The cerebrum - the brain proper - is always and rightly compared with the control computer. Nature has not been so stupid to entrust all functions to the cerebrum. Many functions, like the well-known knee reflex, are autonomous and consist only in a small loop

up to the corresponding sector of the spinal cord. To remind you, the knee reflex is one of the many reflexes which makes walking semi-automatic. Other autonomous reflexes have a protection function. In analogy, all safety interlocks of vacuum systems should be "hardwired" in full independence from the computer. The computer may only receive a message that an interlock circuit has been activated and announce it by making an alarm print-out.

On the ISR the main task of the control computer is the monitoring of the pressure given by 250 Bayard-Alpert gauges. It presents upon request or repetitively all pressures of the machine in form of a complete or selective graphical display on a CRT screen, on a fast printer or stores them for later evaluation on a magnetic tape. The given pressures are already the result of some arithmetic. Starting from the ion current, the computer takes into account the emission current of the gauge, the zero reading of the electrometer, the residual pressure from X-ray effect, ion desorption and gauge outgassing and the change of gauge sensitivity by stray fields of the magnets. Special programmes permit to re-establish from time to time the respective correction values for each individual gauge and to store them in the computer's memory. So much about the elaborate sensory nervous system of the ISR. The motor ("control") part of its central nervous system is very limited. All the computer can do is to switch on pumps and gauges which had tripped off for some reason.

6. RADIOACTIVITY

The radioactivity during the operation of accelerators and storage rings is so high that elastomere seals for flanges and valves are excluded. Only all-metal seals can be used.

After the machine is stopped a residual radioactivity remains which decreases with time. This residual activity can become critically high on proton accelerators designed for highest intensity. Naturally, but unfortunately, the activity is mainly concentrated in the vacuum chamber. Since the tolerance dose for the personnel must be respected under all conditions, it becomes important that all unavoidable interventions

on the machine can be executed in the shortest possible time, and preferably by a man standing at a certain distance from the hot components.

A vacuum flange system has, therefore, been chosen for the SPS, which meets this condition very well. Figure 3 shows the conical flanges with the V clamps and the aluminium gasket. Please note the three little hooks on the gasket. Figure 4 shows more clearly the clamp which consists of four sectors connected by two elastic steel bands. Only two bolts are used for tightening and opening. The bolts are parallel and a special tool has been developed which turns both bolts simultaneously. The technician can do the complete operation, with the help of some additional tools, at a distance of 1 m from the vacuum chamber. The gasket, for instance, is put in place by means of a sort of fishing line and the hooks you have seen on Figure 3. If necessary the technician can even be standing behind a moveable radiation shield.

7. A TEST FIELD FOR VACUUM EQUIPMENT

There is one aspect of particle accelerators and storage rings which makes them particularly interesting for the development of vacuum and ultrahigh vacuum techniques in general : this is the enormous quantity of equipment employed. Let me quote some numbers for the Intersecting Storage Rings : 80 turbomolecular pumping stations, 300 sputter-ion pumps, 600 titanium sublimation pumps, 500 Bayard-Alpert gauges of the modulator type, 6000 all-metal flange seals, 3000 ceramic feedthroughs, 260 valves of all sizes, and all this bakeable up to 300°C and leak tight for operation at and below 10^{-11} torr. This requires a degree of reliability much superior to what is usual in other fields of vacuum applications. If a repair becomes unavoidable, a loss of machine operation for physics of at least 3 days is the sad consequence, because the repaired sector must be rebaked for 24 h at 300°C and reconditioned.

Here are some numbers for the Super Proton Synchrotron :
125 turbomolecular roughing stations, 815 sputter-ion pumps,
5000 flange seals, 400 gauges of different sorts, 250 all-metal
sector and roughing valves. A repair can be done quicker here,
because the system has not to be baked, but the size of the machine
is, on the other hand, so enormous that one must demand that most
of the vacuum equipment will work for many years without any
intervention.

The tough requirements are reflected in very detailed and
stringent technical specifications for the call for tenders. Vacuum
firms who win big contracts for our vacuum systems may not only gain
from the business itself but also - and sometimes more - from the
progress in know-how which they must develop in the manufacturing
of vacuum equipment of top performance and top reliability.

Acknowledgement

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Figure Captions

Figure 1 : General layout of the CERN Proton Synchrotron (CPS) and Intersecting Storage Rings (ISR) near Geneva.

Figure 2 : Layout of the Super Proton Synchrotron (SPS) under construction at CERN.

Figure 3 : Quick flange coupling for the SPS with aluminium gasket.

Figure 4 : Quick flange coupling for the SPS with special tool for opening and closing from 1 meter distance.

GENERAL LAYOUT OF SYNCHROTRON AND INTERSECTING STORAGE RINGS

Fig.1

SUPER PROTON SYNCHROTRON PROJECT

Fig. 2

QUICK COUPLING WITH AL GASKET

Fig. 3

QUICK COUPLING WITH TIGHTENING TOOL

Fig. 4