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THE OPERATION OF THE ISR FACILITY IN RELATION TO THE UHV ENVIRONMENT

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by

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ABSTRACT

At CERN Geneva, two kilometres of UHV at 10^{-10} torr is in daily use at the Intersecting Storage Ring (ISR) facility. An appreciable fraction of the stainless steel vacuum chamber, some 200 metres in fact, is continuously at 10^{-11} torr.

Nature, we have been told, abhors a vacuum. Nature, in the guise of 25 GeV protons, persists in her abhorrence even when confronted with the brazen face of modern technology.

Beams of many ampères of 25 GeV protons circulate for many hours inside the ISR vacuum chambers. A vacuum of 10^{-10} torr is essential if the protons are to remain unperturbed by collisions with the residual gas molecules.

However, when the beam current is allowed to exceed about 5 ampères, certain regions of the vacuum chamber surface appear to desorb gas molecules and the pressure rises to values in excess of 10^{-7} torr. Mechanisms which might give rise to such pressure increases are discussed along with general problems related to the production and maintenance of large scale UHV systems.

THE OPERATION OF THE ISR FACILITY IN RELATION TO THE UHV ENVIRONMENT

INTRODUCTION

The ISR Facility has been described in detail in many publications¹; Fischer² recently described the UHV system in its entirety at the last International Vacuum Congress. In this paper the emphasis will be on the problems of designing the vacuum chamber and maintaining the vacuum in the presence of two major and sometimes conflicting requirements. These are :

1. The vacuum chamber must contain many ampères of circulating 28 GeV/c protons whilst creating a minimum of disturbance to the beam. At the same time the vacuum over the whole 2 km length of the machine should stay down at about 10^{-10} torr;
2. The vacuum chamber in the intersecting regions, where experiments on colliding beam physics are carried out, should create a minimum of interference with the particular experiment. The particles resulting from collisions of the high energy protons have to traverse the vacuum chamber before any detection and subsequent measurement of their properties can be carried out. Furthermore the vacuum in these regions should be at least an order of magnitude better than the average of 10^{-10} torr; this in order that the high energy protons in the circulating beam do not suffer too many unwanted collisions with the molecules of the residual gas and so create intolerably high "background" levels of particles scattered at random.

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The beam should circulate for typically twelve hours inside the vacuum chamber. This means that each proton which survives this time has travelled for 12 light hours or 1.44×10^{10} kms. During this time it should not have deviated from its intended path by more than a few millimetres. Otherwise the proton would have been lost because of the constricted nature of the aperture presented by the finite size of the vacuum chamber. This aperture is roughly an ellipse of major and minor axis 160 mm by 55 mm respectively. The beam itself has an elliptic cross section of about 50 mm by 10 mm. There are many perturbing factors which can lead the protons away from their curved but narrow path. Not least is the electromagnetic nature of the vacuum chamber. Its stainless steel walls can sustain image charges and induced currents produced in the "wake" of small perturbations which exist in the beam. Changes in cross section of the vacuum chamber can act like the resonant cavities of a klystron and are able to sustain electromagnetic fields. These wake and resonant fields can act back upon the beam and amplify the initial perturbances leading eventually to a blow-up in effective cross section and a subsequent loss of beam due to the limitations in aperture presented by the vacuum chamber.

Two approaches have been used to damp out the effects of electromagnetic interaction with the vacuum chamber. One is to introduce lossy material, namely resistors, in the form of thin nichrome films supported by a ceramic base, into the suspect regions. The other approach consists of making the geometry of the vacuum chamber appear electromagnetically "smooth" as far as the beam is concerned.

Fig. 1 shows an example of the first technique and Fig. 2 the second. In Fig. 2 such "sleeves" or "underpants" made out of stainless steel mesh may be used to reduce the volume of the "resonance cavity"

that a vacuum chamber with an enlarged cross section presents to the beam. The vacuum, materials and mechanical engineering problems presented by these complex ancillaries to the UHV system are considerable. The materials are chosen, cleaned and tested carefully to ensure that the additional outgassing load does not exceed the few $\times 10^{-13}$ torr litres/sec cm^2 specified for the stainless steel making up most of the ISR vacuum chamber.

F Figure 3 shows that even with these precautions such electromagnetic effects still exist. The figure shows a picture of the spectrum of frequencies picked up from the beam by means of a micro-wave loop.

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The residual pressure of 10^{-10} torr does not present too much of an obstacle to the circulating beam. Nevertheless each molecule encountered can scatter the high energy protons by virtue of its nuclear mass and charge. The effect of a nuclear scattering is usually catastrophic in that the high energy proton is immediately kicked out of the beam and lost. The decay rate of the beam from this effect is nevertheless quite small and of the order of five parts per million per minute at about 10^{-10} torr (all pressures are quoted as equivalent nitrogen pressure). The charge on the nucleus of the residual gas molecules has a more gentle effect and tends to increase the beam dimensions by multiple encounters, each encounter pushing a small amount of longitudinal momentum into the transverse plane so that the amplitude of the transverse oscillations about the longitudinal circular path of a proton in the guiding magnetic field is gradually increased. Particles will be lost when the edges of the beam start to scrape along the walls of the vacuum chamber. In practice this should only happen after about 100 hours of storage time have elapsed.

Neither of these primary effects of encounters with residual gas molecules are particularly disturbing at present. Much more serious are the secondary effects due to the ionisation of the residual gas. The electrons so produced may be trapped inside the positive space charge of the beam whereas the ions are thrown out quite vigorously - the beam-wall potential at 10 amps circulating current can amount to a kilovolt or so.

The ISR is equipped with many pairs of steel plates called "clearing electrodes" between which are applied electrostatic fields of up to + 10 KV. These drag out the electrons which otherwise get trapped in the beam. The static effect of these electrons is to change by modifying the space charge forces, the configuration of the focussing fields which are applied to keep the beam within the vacuum chamber. Small changes in these focussing fields have large effects on the decay rate of the beam intensity. The dynamic effects of these electrons oscillating within the beam and in conjunction with the transverse oscillations of the protons are less well understood but this effect is thought to be illustrated in Figure 4. There the decay rate is plotted as a function of the pressure over a very limited region of the ISR, not more than about 10 m in extent. The copper gasket of one of the 6000 conflat type flange seals had sprung a leak which was quickly sealed with varnish. The pressure in this region had already recovered to 1.1×10^{-9} torr by the time a 4.7 amp beam was stacked and throughout the following ten hours gradually sank to 7×10^{-10} torr. It is clear from Figure 4 that the decay rate decreases dramatically as the vacuum improves. This particular 10 metres of the ISR vacuum chamber is not yet equipped with an adequate amount of electron clearing electrodes so that the effect of this particular "pressure bump" was considerably larger than normal.

The elimination of "pressure bumps" is nevertheless the major activity of the ISR vacuum group at present. The frequency of occurrence of small leaks is reasonably low; it constitutes a nuisance but as yet no more than a slight headache. The major "malaise" that besets and inhibits the performance of the ISR is the production of large pressure bumps of up to 10^{-6} torr. These are produced, almost certainly, by desorption of gas molecules from the walls of the vacuum chamber by those ions produced by ionization of the residual gas and so vigorously rejected by the positive space charge of the beam.

The pressure bumps were first noticed at about 3 amps or so and were quickly attributed to ion bombardment. Unfortunately as the current circulating in the ISR is pushed upwards, the potential difference between the proton beam and the walls of the vacuum chamber increases almost linearly. The kinetic energy of the bombarding ions increases correspondingly making desorption easier and its elimination more difficult. Nevertheless, by more thorough bakeouts with as much as possible of the whole ISR kept at 300°C for about 10 hours or more, as well as installing many more titanium sublimation pumps to increase the pumping speed, the maximum current stacked to date in the ISR has reached 11.1 ampères. At this current level we still get pressure bumps. A typical pressure bump distribution along the circumference of one ring of the ISR is illustrated in Figure 5. In the presence of such large pressure bumps the ISR are inoperable but if the current stacked is reduced somewhat it is then possible to do useful physics experiments with currents of up to 6 amps circulating in each ring. The final design aim is 20 ampères however, so that we are in the position of Thursday's child - having far to go!

Baking and pumping apart, a search has begun for other methods of reducing the desorption from the vacuum chamber walls.

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The experiments referred to are, of course, those for which the ISR were built - experiments which study the results of collisions between high energy protons in the intersecting regions of the storage rings.

The particles emerging from the regions where the beams collide are studied with all the paraphernalia of high energy physics. Before they can be studied however, they have to traverse the material of the vacuum chamber. The stainless steel of the normal ISR vacuum chamber is only 2 mm thick. Thus a singly charged particle emerging from the interaction region at an angle of say 10 mradians and traversing such 2 mm thick walls encounters 200 mm of stainless steel. This is enough matter to deflect a singly charged particle of 10 GeV/c momentum by about 6 mradians on the average. Furthermore, since the collision length of iron is around 130 mm such a particle only has about a 50% chance of survival in its original form. The normal vacuum chamber thus constitutes a formidable obstacle to the accurate measurement of the essential physical parameters. Thus in the intersection regions special vacuum chambers are needed which are either extremely thin everywhere or are "custom built" to suit the needs of a particular physics experiment.

Figures 6 and 7 are illustrations of the latter approach. Figure 6 shows the vacuum chamber that was designed for a CERN-Rome collaboration who set out to study Coulomb scattering at very small angles. It consists essentially of 0.2 mm thick stainless steel re-entrant pots mounted on bellows which enable counters inside the pots to be moved to within 1 mm of the circulating beam to a precision of ± 0.2 mm.

Figure 7 shows a much larger vacuum chamber with 1 mm stainless steel "windows" mounted on the ends of twin cones and at right angles to the emerging particles which here are studied at larger angles. The large volume of this vacuum chamber was such that it needed to be equipped with the "underpants" illustrated in Fig. 2 to combat electromagnetic effects. Liquid helium cryopumps are also to be seen mounted on top of the cones because of the large volume and the requirement that the vacuum should be at least 10^{-11} torr in these regions. These cryopumps each have a pumping speed of about 20,000 litres/sec and the outgassing rate from the walls is about 2×10^{-13} torr litres/sec cm^2 so that the final outcome was somewhat overdone. The pressure in this region is thought to be about 2×10^{-13} torr but is proving rather difficult to measure.

A more universal approach to vacuum chamber design for physics experiments is illustrated in Figures 8 and 9. Here the trend is towards small chambers with very thin walls, 0.15 mm at their thinnest, with the actual crossing region consisting of a bi-conical arrangement out of which spring the four arms of the intersection region. The arms can be made out of corrugated stainless steel pipe as is illustrated in Fig. 9. These just stand one atmosphere external pressure at 300°C without collapsing and are made by a hydroforming technique similar to that employed for bellows.

Even these chambers present electromagnetic problems and can as well act like electrostatic straps for secondary electrons so that they all have to be equipped with damping resistors and electron clearing electrodes.

The next step in the development of these universal chambers, since they cannot be made thinner without collapsing, is to change to materials which are lighter and have fewer charges on their nucleus. The first choice for the future chambers was titanium and the new

carbon-fibre technology is also being pursued with somewhat less zeal but equal optimism.

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The physicist carrying out experiments at the ISR is usually very worried about "background" due to beam-gas and beam-wall collisions. Although coincidence techniques are widely used to discriminate against these effects, these collisions, if there are enough of them, can destroy an experiment by producing too many "random" coincidences. The solution to the "background" problem is to stop the beam from encountering both the walls of the vacuum chamber and the residual gas of the vacuum. The beams in the intersecting regions can be steered away from the walls by means of manipulating the magnetic fields but there always remains the beam-gas effects and this problem can only be solved by better UHV, at least 10^{-11} torr usually over lengths of the order of 50 metres.

All intersecting regions used for physics experiments are equipped with titanium sublimation pumps usually of the heated filament type and sublimating directly onto the walls of the vacuum chamber. These pumps perform remarkably well and pressures of the order 10^{-11} torr have been sustained over many months. The pumps are usually sublimated only once every few weeks so that we have no problems with lifetime of the filaments.

Work on cryopumping has been carried out at CERN over the last few years and has culminated in the design of the large pumps illustrated in Figure 7. Work along these lines is continuing so that smaller cryopumps can be made which are suitable for use with the reduced size of the more universal thin-walled vacuum chambers. In this way pressures of $\leq 10^{-12}$ torr are hopefully expected in the experimental regions of the ISR in the not too distant future.

ACKNOWLEDGEMENTS

Too many words and yet so few of substance for vacuum physicists. No apology is offered, however, since without the diversions into accelerator physics and the motivation given by high energy physics, the study of the vacuum at CERN would not be as interesting as we find it.

UHV on this almost industrial scale would not be possible without the devoted and sometimes inspired efforts of all fifty members of the vacuum group at CERN. Nature may abhor our vacuum but it seems that people can get to like it.

Fig. 3 is published with the kind permission of the Radio-Frequency Group of the ISR Department.

REFERENCES

1. Proceedings of the VIIIth International Conference on High Energy Accelerators 1971.
2. E. Fischer, Proceedings of the Vth International Vacuum Congress, Boston, 1971.

Figure 1

"Lossy" Damping Resistors mounted inside the Vacuum Chamber

Figure 2

"Underpants" for eliminating electromagnetic interaction
between the beam and large vacuum chambers.

Figure 3

Part of the electromagnetic spectrum emanating from the circulating beam. This may be called the microwave "thumb print" of the ISR Vacuum Chamber.

Figure 4

The decay rate as a function of a "pressure bump" produced by a leaking flange.

Figure 5

Pressure bumps around the ISR at 6 Amps.

Figure 6

"Roman Pots" : re-entrant vacuum chambers in the form of pots mounted on bellows which can be moved very near to the beam to study those particles scattered at very small angles.

Figure 7

A large "custom built" cryopumped vacuum chamber with stainless steel "windows" at right angles to the scattered particles emerging at large angles.

Figure 8

A Bi-cone; the thin-walled intersection point vacuum chamber for all types of physics experiments.

Figure 9

Thin-walled circular pipes for the long arms of intersection regions.