VACUUM CONDITIONS FOR PROTON STORAGE RINGS

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Summary

The stability of coasting beams in storage rings depends critically on the vacuum. The beam is perturbed both by scattering on the residual gas molecules and neutralisation effects resulting from gas ionisation. Historically, these considerations were the only ones employed in the design of the ISR vacuum system. The operational experience with the ISR has shown that the vacuum itself may be perturbed by desorbed gas resulting from beam induced ion bombardment of the chamber wall. This can lead to an unstable chain reaction and to the destruction of the stored beam. The dynamic vacuum equation including stimulated desorption is applied to the conduction limited case. This shows the importance of the effective pumping speed at every given point and demonstrates the value of good conductance or quasi-distributed pumps. A vital factor is the state of the vacuum chamber wall and its response to low energy ion bombardment. Results of investigations on different materials, cleaning methods and recontamination problems are discussed in the light of their applicability and relevance to the design of large machines.

1. Introduction

The vacuum conditions necessary for proton storage rings are determined by the numerous interactions the beams can have with the residual gas. Not only the gas present in the volume of the vacuum chamber is important in this respect but also the gas adsorbed on the chamber walls. Some of the interactions were known and taken into account when the Intersecting Storage Rings (ISR) of CERN were designed. Others became apparent during the running-in of the machine.

Nuclear scattering is an important interaction of the protons with the residual gas molecules.[1] A scattered particle changes its direction or energy so much that it is lost from the beam. Hence the beam decay is given by

$$\frac{1}{I}\frac{dI}{dt} = -c\,\sigma\,n \qquad (1)$$

where I is the beam current, c the proton velocity, σ the total nuclear cross-section and n the atomic density of the rest gas. The decay rate in the ISR for quiet beams of up to about 10 A agrees to within ± 20% of that calculated from equation (1).

Coulomb scattering represents a second type of interaction of the circulating protons with the rest gas. The scattering angles due to Coulomb interaction with the electrostatic field of the nuclei are very small, but many successive events, i.e. multiple scattering, lead to a gradual blow-up of the beam. The process can be described as diffusion in betatron phase space.[1] The mean square betatron amplitude, $\langle x^2 \rangle$, of the freely circulating beam increases linearly with time according to

$$\langle x^2 \rangle = \langle x^2 \rangle_o + 7.2\cdot10^{-14}\,\beta\,\beta_{av}\,p^{-2}\,Z^{-2}\,n\,t \qquad (2)$$

where $\langle x^2 \rangle_o$ is the initial amplitude at the time t = 0, β and β_{av} the β-value in m at the given place and the average value respectively, p the proton momentum in GeV/c, Z the charge number and n the density of the scattering gas in molecules cm^{-3}.

With the gradual blow-up by multiple scattering the beam will finally occupy the whole aperture, A(mm^2). In this limiting case the decay rate is

$$\frac{1}{I}\frac{dI}{dt} = -\pi^2\,A^{-1}\,\frac{d}{dt}\langle x^2 \rangle \qquad (3)$$

where $\langle x^2 \rangle$ is taken from Eq. (2).

In the ISR, with a residual hydrogen pressure of 10^{-11} torr the beam does not fill the available aperture after a long run of 36 hours. Even so, the observed beam blow-up rates of a freely circulating beam in the ISR are, under best conditions, about one order of magnitude faster than calculated from equation (2). Hence, other perturbations also causing diffusion in betatron phase space are more important. One possible cause is again linked with the vacuum conditions, namely with the ionisation of the residual gas.

2. Beam Neutralisation

Ionisation of the rest gas by high energy protons produces ions, which are repelled from the beam and hit the chamber walls, and electrons which may stay trapped in the potential well of the beam if their energy is too low to escape. The partial neutralisation of the space charge causes a shift of the betatron frequencies.[2] Defining a neutralisation coefficient ε as the ratio of the number of electrons to protons and neglecting image effects, the Q-shift can be expressed as

$$\Delta Q = \frac{2\,R^2 r_p}{e\beta^3 c Q\,\gamma}\,\frac{I}{b(a+b)}\cdot\Delta\varepsilon \qquad (4)$$

Here R (m) is the machine radius, r_p the classical proton radius, e the electron charge, β and γ are the usual relativistic factors and c the velocity of light. 2a and 2b are respectively the horizontal and vertical beam dimensions. With typical ISR parameters one obtains from (4) to a good approximation

$$\Delta Q/\Delta\varepsilon \approx I/\gamma.$$

In proton storage rings one uses Q values which vary across the aperture and hence a "working line", which must be positioned between resonances in the Q_V, Q_H diagram to obtain low decay rates. An uncontrolled tune shift such as can be caused by partial neutralisation varying with time must therefore be avoided. From permitted tolerances in working line shifts one can derive that the permissible variations of ε are of the order of 10^{-2} over a running period of, say, 24 h.

To keep the residual neutralisation low, the ISR have been equipped with an extensive system of electrostatic clearing electrodes.[3] Under stationary conditions ε can be expressed by the ratio of the electron production rate - in the ISR one finds a value of about $1.4\cdot10^9$ electrons/protons s^{-1} $torr^{-1}$ which is in good agreement

with calculation - and the clearing rate (s^{-1}). The latter depends on the longitudinal drift velocity of the electrons, the mean distance between clearing electrodes and, implicitly, also on ε. For small degrees of neutralisation it is sufficient to assume a constant clearing rate and one finds that ε is proportional to the residual pressure.[3] Hence changes in the residual pressure which can occur due to beam induced gas desorption from the vacuum chamber walls, may shift the working line on to resonances and cause an increased decay rate.

3. Coupled Electron-Proton Oscillations

A further known mechanism which can modulate the residual neutralisation, is coupled oscillations of electrons and protons. This system can be described by a set of coupled oscillators and it has been shown[4)5] that there exists a threshold value for ε above which the amplitudes become unstable and grow in a short time so that the electrons are lost on to the vacuum chamber. The calculated threshold neutralisation ranges from 10^{-3} to a few percent.[4)5] Apart from being a transport mechanism which can feed protons into non-linear resonances, successive electron-proton instabilities can also give rise to a gradual beam blow-up similar to multiple scattering on the residual gas.

Figure 1 shows a beam signal taken from a horizontal pick-up station, and one recognises the fast rise of the instability which lasts for about 5 ms. The repetition rate of this particular instability was 1.2 s. If one assumes that it was driven from a place in the ring with a pressure of 2×10^{-11} torr, a neutralisation of 3.5% can be estimated. This is in fair agreement with predicted values. Using equation (4) with the particular parameters I = 12 A and $\gamma = 28$, one finds a Q modulation of about $1.5 \cdot 10^{-2}$.

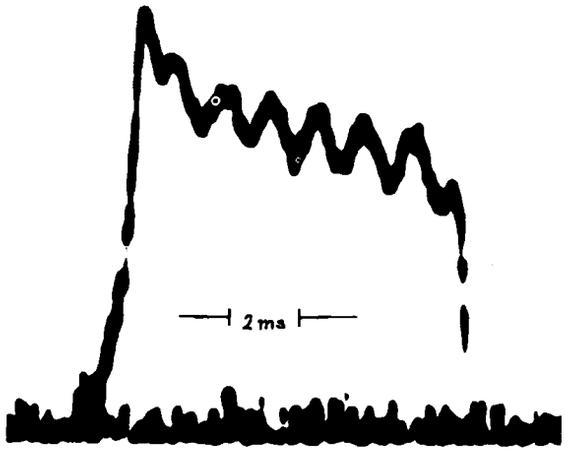

Fig. 1 Beam induced signal from a pick-up station showing a coupled electron-proton instability. Beam current is 12 A and a proton energy 26 GeV.

4. Beam Induced Pressure Rise

The most serious interaction between the proton beam of the ISR and its vacuum environment was only discovered during the early running-in period. When the beam current was increased beyond 4 A the static pressure of about 10^{-10} torr started to rise at several places around the ring until it reached 10^{-7} or even 10^{-6} torr and the beam was rapidly destroyed.

This pressure runaway has been explained by ion induced gas desorption from the vacuum chamber. A quantitative approach is obtained by solving a differential equation for the pressure in the vacuum tube as function of time and one-dimensional space[6], where one includes the desorption and readsorption of the residual gas on the walls. The gas density $n(x,t)$ and the surface coverage of adsorbed molecules $\theta(x,t)$ in an idealised module of the ISR vacuum system, are then described by

$$A \frac{\partial n}{\partial t} = a + C \frac{\partial^2 n}{\partial x^2} - w \frac{\partial \theta}{\partial t}$$

$$\frac{\partial \theta}{\partial t} = \left(\frac{\bar{v} s}{4} - \frac{\sigma}{ew} \eta I \right) \cdot n - \theta/\tau \qquad (5)$$

with the boundary conditions $C \frac{\partial n}{\partial x} \pm Sn = 0$ at the locations $x = \pm L$ where the pumps of speed 2S are connected to the system.

The vacuum chamber is characterised by its cross sectional area A, its perimeter w and a specific conductance C ($cm^4\ s^{-1}$). The wall is assumed to have a specific degassing rate a ($cm^{-1}\ s^{-1}$), and the gas molecules hitting the chamber wall a sticking probability s. The sojourn time of adsorbed molecules on the wall, which is a function of the binding energy in the adsorbed state is characterised by τ; furthermore $\bar{v}$ is the mean thermal velocity of the gas molecules, σ the ionisation cross section and e the electron charge. I is the stored beam current in amps and η the net desorption yield, defined as the number of released gas molecules per bombarding ion, minus the sticking probability of the ion itself.

In the presence of beam induced gas desorption from the walls, the gas density remains finite only as long as the product

$$\eta I < (\eta I)_{crit} = \frac{e}{\sigma} (C\omega^2 + w\bar{v}s/4 + A/\tau). \qquad (6)$$

Here, $\omega < \frac{\pi}{2L}$ is the first root of the transcendental equation[7]

$$\omega \tan \omega L = S/C.$$

In the limit where the reaction of the residual gas with the surface can be neglected, that is for $s \to 0$ and $1/\tau \to 0$, this stability criterion gives a simplified pressure bump criterion.[6)7] When considering the pressure stability in a machine like the ISR it is probably safer to neglect all surface-sticking effects. This may however be different for a storage ring with a cryogenic vacuum chamber, where s can easily approach unity and the resulting increase in the stability limit would then become very important. In case of a cold ISR ($s \to 1$) the term $w\bar{v}s/4$ would account for an increase of about 10^4 in terms of the critical product ηI, and a much larger desorption yield could be tolerated than at present.

It follows from equation (6) that the beam-vacuum limit can be increased either by the installation of additional and somewhat larger pumps, or by increasing the aperture of the vacuum pipe. Alternatively, the net desorption yield of the walls may be reduced. From the definition, η can have negative values, implying that molecules are removed from the gas phase by the action of the beam and hence the pressure is decreased. This beam pumping can indeed be observed at many places around the ISR either in chambers which are sufficiently clean, or in those which have been conditioned successfully by one of the special surface treatments to be discussed.

Figure 2 shows η as measured on a well baked ISR chamber versus the energy of the bombarding ions. At low energies one observes $\eta < 0$, hence beam pumping, while above 800 V, the yield becomes positive and almost proportional to energy. Figure 2 was obtained with a constant beam current of 6 A and the ion energy could be varied with the help of a biasing electrode. Under normal conditions the ion energy is determined by the space charge potential of the beam which increases in the ISR by about 100 V per amp of stored beam.

5. Improved bakeout and additional pumps

The first effort to counter these pressure rises was to reduce the amount of adsorbed gas and hence η by increasing the bakeout temperature from 200°C to 300°C and lengthening the bakeout time from 5 to 24 h.

The second stage in the improvement of the ISR vacuum system consisted in installing some 500 additional sublimation pumps to raise the vacuum limit to about 20 A and to obtain $(\eta I)_{crit}$ = 40 A at the weakest places. The sublimation pumps which have reduced the residual pressure by a factor of 10 to 100, gave at the same time also a reduction of η; from the observed pressure runaway at 20 A one concludes $\eta \simeq 2$ as compared to the previous value of 4.

Tests in the laboratory have shown that a desorption coefficient of 2 molecules per ion is only observed on a contaminated stainless steel surface. A carefully cleaned and baked sample of stainless steel shows η-values of 0.1 and even lower. One can,

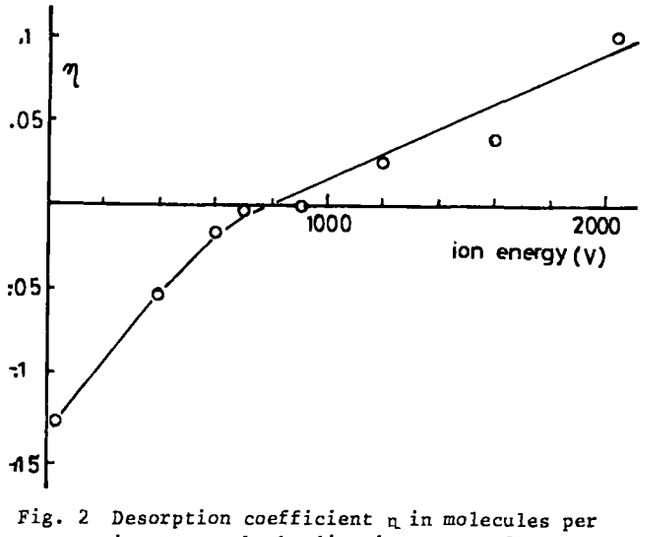

Fig. 2 Desorption coefficient η in molecules per ion versus bombarding ion energy for a stainless steel chamber after a 340°C bakeout of 24 h.

therefore, conclude that the vacuum limit is determined by that place around the one kilometre of circumference of an ISR ring where an accidental local contamination (high η) coincides with a low $(\eta I)_{crit}$, that is, with a place which is relatively poorly pumped.

6. Prevention of contamination

The most likely source of contamination in the present ISR, apart from the unavoidable leaks which are however surprisingly harmless as far as beam pressure bumps are concerned, seems to be from the roughing pumps. These stations, consisting of a rotary pump combined with a turbomolecular pump are used to provide the starting pressure for the ion pumps and provide also differential pumping for the double seal sector valves. The stations are valved-off from the main vacuum chamber except during the bakeouts. Nevertheless systematic measurements around the ISR have shown consistently increased desorption yields near the pumping stations and sector valves. To avoid or to reduce this source of contamination, the pumping stations are being prebaked before each use on the UHV system. It is furthermore planned to install titanium sublimators adjacent to all sector valves to stop any contamination from spreading out.

7. Results from surfaces and surface treatments with low ion desorption coefficient

As a third approach to overcome the beam vacuum limit, various methods yielding low desorption coefficients have been investigated. First results of this work have already been reported.[7]

The analysis of the beam desorbed gas shows primarily an increase of mass 28 (CO). This agrees with the results indicated by other methods of surface analysis (Auger spectroscopy or secondary ion mass spectroscopy, SIMS) which show consistently an excessive carbon contamination on the stainless steel surface.

Studies have since been pursued in two main directions, namely by experiments and surface analyses in the laboratory (work which is reported elsewhere) and by in situ experiments in the ISR in the presence of high intensity beams.

The aim of the latter is to test the desorption properties of various samples in a realistic environment. This is important since the desorption yield depends on parameters which cannot, or only with difficulty, be reproduced in the laboratory. The long term behaviour of a given surface treatment is, next to the immediate desorption yield, one of its principal characteristics should it be applied on a large scale.

Treatments which can be applied prior to the installation are very attractive from a practical point of view. They are based on the fact that once the strongly adsorbed molecules are removed, the surface remains clean even after subsequent air exposure. Hence the requirements are :

- the fresh surface must have a low outgassing rate to obtain a low residual pressure and a low ion desorption yield.
- it should be insensitive to contamination and maintain the low desorption yield for a sufficiently long period of time.

- in case of accidental contamination it must be possible to regenerate the surface in situ, e.g. by a 300°C bakeout.

Following this general guide-line bakeouts at 350°C have been very effective in reducing the desorption yield and in regenerating a contaminated surface. Unfortunately the general application to the ISR vacuum chamber is difficult because many elements are not designed to withstand this high temperature.

Glow Discharge Cleaning

Glow discharge cleaning was one of the first treatments studied and applied to the ISR vacuum chambers. Although it does not yield consistently negative η values, the desorption coefficient obtained is always very low. The procedure itself is rather straight forward: the chamber is filled with about 10^{-2} torr of argon and a discharge is initiated by applying a few hundred volts to a wire electrode which is stretched along the chamber axis. The positive argon ions strike the wall and cause very intense gas desorption. To enhance the process, and to help to prevent readsorption, including argon, the chamber is held at 300°C. During the treatment one maintains a continuous flow of argon gas through the chamber which effectively transports the desorbed gas out of the system. The total dose applied is of the order of 10^{18} ions per cm^2, but may be reduced to 5×10^{16} ions cm^{-2} without significant loss in performance. Surface analyses and laboratory experiments show that the low desorption yield obtained immediately after the treatment is indeed preserved during several weeks of exposure to atmosphere. It is therefore not necessary to treat the chambers in situ, but the surface conditioning can be done more conveniently as the last step before the installation. This has become standard practice on all new vacuum chambers and up to now some hundred metres of the ISR vacuum system have been conditioned in this way. Figure 3 shows the desorption yield obtained by glow discharge cleaning versus the bombarding ion energy. Up to the maximum energy, 2200 V, corresponding to a beam intensity of about 20 A, the yield remains negative and the surface exhibits beam pumping.

Surface Oxidation

A possible method of removing the carbon contamination found on the surface has been investigated by oxidising the chamber and by pumping out the gaseous end products. The desorption coefficients so far obtained were positive, see Figure 3, but nevertheless sufficiently small to increase the beam-vacuum limit well beyond 20 A. In principle it should be rather easy to apply the oxidation in situ and this could become even part of a normal bakeout procedure.

800°C bake under vacuum

To overcome the temperature limitation of the in situ bakeouts high temperature bakeouts in a special vacuum furnace up to 800°C have been investigated. While laboratory tests and surface analysis on small samples show a considerable improvement in surface cleanliness and in the specific outgassing rate, the results from in situ experiments were so far rather disappointing. Measured desorption yields are shown in Figure 3.

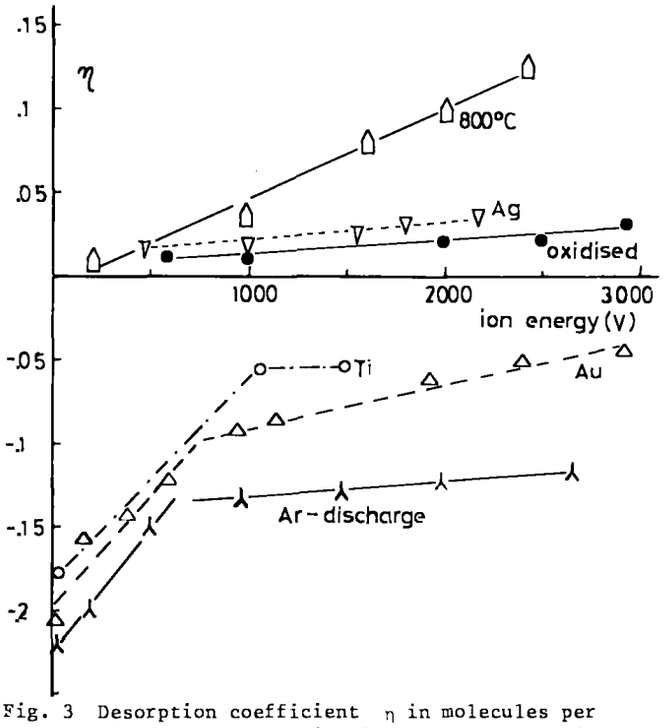

Fig. 3 Desorption coefficient η in molecules per ion versus bombarding ion energy as obtained by various surface treatments and surface coatings of stainless steel :

argon glow discharge cleaning,
oxidation at 400°C,
800°C bakeout under vacuum,
gold coating by evaporation,
layer of freshly sublimated titanium,
silver coating by sputtering.

Except for the titanium sample, all measurements were done after exposure to air and bakeout in the ISR.

Desorption yields of special surfaces

In the search for a surface material, other than stainless steel, we have investigated gold, silver and titanium. The latter material was tested in the form of an evaporated layer as well as in the form of liners made out of titanium alloy (13 Cr, 11 V, 3 Al). The coatings were produced by sputtering or sublimating the material under high vacuum on to the inner wall of a test chamber. The thickness of the layer, in some cases not very uniform, was of the order of 1 μm. In principle, this should be enough to cover the various contaminants on the stainless steel substrate and to protect them from the energetic bombarding ions. After the evaporation, the samples had to be exposed to atmospheric pressure before being installed in the ISR and baked at 300°C for 24 hours. The only surface which could also be deposited in situ under ultrahigh vacuum conditions and tested without prior exposure to air was the layer of sublimated titanium.[7]

Negative desorption yields were obtained for gold plating and for in situ deposited titanium; less favorable results were found with silver, see Figure 3. It could be shown that the gold and silver layers are fairly insensitive to recontamination by an air leak. After exposure their initial desorption properties could be reproduced, at least to a large extent, by a 300°C bakeout of 24 h. Figure 4 shows the desorption yields

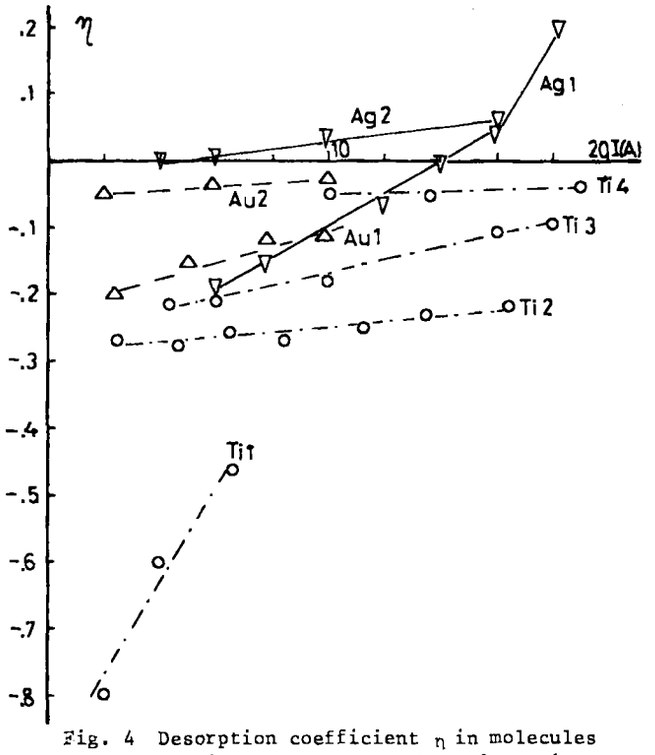

Fig. 4 Desorption coefficient η in molecules per ion versus proton beam intensity for titanium alloy (Ti(1) - Ti(4)), gold coating (Au(1) - Au(2)) and silver coating (Ag(1) - Ag(2)) each as measured after successive exposures to air and rebakes.

measured before and after exposure(s) to air and rebake. The same procedure, applied to the in situ deposited titanium layer which is shown in Figure 3, gave, however, different results and the yield increased and remained high after the bakeout.

This behaviour is in strong contrast with the results obtained from liners made out of titanium alloy mounted inside the ISR vacuum chamber. The only pre-treatment which was given to this test surface consisted of a 3 hour bakeout at 700°C under vacuum. It has been found that this high temperature bake reduces the outgassing rate of the titanium sheet metal to at least one tenth of the value for our normal degassed stainless steel, that is from about 2×10^{-13} to 2×10^{-14} torr ℓs^{-1} cm^{-2}. The initial desorption yield of these titanium liners, as measured after their first installation, turned out to be about - 0.3, see Figure 4, curve Ti(1). Hence this chamber was strongly pumping in presence of beam. However, contrary to the previous experience with sublimated titanium, the alloy proved to be rather insensitive to contamination and maintained its negative desorption yield irrespective of several exposures to air and rebakes. The reason for this striking difference is not completely understood.

8. Long term behaviour of clean surfaces

When investigating the usefulness of various materials or surface treatments for low ion desorption yields, an important characteristic is their long term behaviour in an environment like the ISR. The test surfaces studied so far occupy a rather short length of the ISR circumference and have standard vacuum chambers on either side. It is therefore not excluded that, in the long term, contaminants are transferred from the normal chambers, where they are desorbed by the beam, to the specially cleaned test surface. This effect may well account for at least part of the gradual increase in η which is observed on the various chambers.

In this respect, the titanium alloy appears to be particularly promising. Over a period of 10 months and despite several bakeout cycles, its desorption yield increased from about - 0.3 to - 0.03. It has therefore been decided to mount similar titanium liners in critical locations of the ISR where there is not enough space for additional pumps and a reduction of η remains the only possible way of obtaining stable vacuum. Effort goes, furthermore, into the development of titanium chambers for the intersecting regions to improve the vacuum conditions and to obtain chambers which are more transparent to high energy particles.

With the combined efforts of increasing the pumping speed and lowering the ion desorption yield η the ISR vacuum system has in the past steadily improved and the average pressure around the ring in the presence of stacked beams of up to 10 A has dropped to less than 10^{-11} torr. More important, however, the vacuum has become stable enough so that the original design aim of 20 A stable beams can now be obtained.

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