IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

NEW VACUUM TECHNIQUES FOR SMALL APERTURE PROTON STORAGE RINGS

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The pressure and stability limit was measured in long and thin pipes after bakeout, glow discharge cleaning and sputter-coating with Ti in situ. In situ-treatments provide a better vacuum performance than any particular choice of pipe material. An average pressure $\sim 10^{-11}$ Torr and a critical current > 100 A can be achieved in small aperture proton storage rings with these treatments.

Introduction

The use of superconducting magnets for high energy proton storage rings can impose considerable constraints on the vacuum system design as it may be desirable to make long magnets having a small coil diameter. Therefore only small diameter beam pipes with low vacuum conductance can be used with a large distance between possible locations of lumped pumps. If the pump speed is high compared with the pipe conductance, an average pressure (Torr)

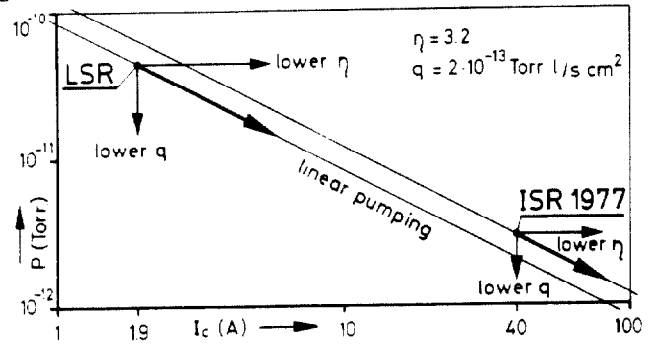
$$\bar{p} \simeq p_o + 50 \cdot qL^2/r^2 \qquad (1)$$

could be achieved, whereas the vacuum stability limit due to the well known pressure bump phenomenon is given by the critical current (A)

$$I_c \simeq 10 \cdot r^3/\eta L^2, \qquad (2)$$

where p_o is the low pressure limit of the pumps, q the specific thermal outgassing rate (Torr ℓ/s cm^2), L the distance between lumped pumps (m), r the pipe aperture radius (cm) and η the net ion-induced molecular desorption yield (molecules/ion).

The vacuum system of the CERN-ISR is made of stainless steel and baked in situ at 300-350°C. For this machine, $q \simeq 2 \times 10^{-13}$ Torr ℓ/s cm^2 and $\eta \simeq 3.2$ are rather well established figures. Hence, for the CERN-LSR [1] with superconducting magnets, $\bar{p} = 5 \times 10^{-11}$ Torr and $I_c = 1.9$ A would have to be expected for L = 5.1 m and r = 2.5 cm from Equs. (1) and (2), assuming $p_o = 3 \times 10^{-12}$ Torr. However, $\bar{p} < 2 \times 10^{-11}$ Torr and $I_c > 10$ A are required to meet the specified low beam-gas interaction rate and high luminosity.



In Fig. 1, the ISR and LSR vacuum systems are shown in a diagram with respect to their average pressure and critical current, assuming $p_o = 0$. Any performance improvement in these lumped pumping vacuum systems must be obtained by decreasing both q and η. Thus, to meet the LSR design figures is as difficult as to upgrade the present ISR to $\bar{p} = 4 \times 10^{-12}$ Torr and $I_c = 850$ A.

With a distributed pumping system, however, a large improvement is possible even at a low linear speed S (ℓ/s m). Then, Equs. (1) and (2) become

$$\bar{p} \simeq p_o + 630 \cdot qr/S \qquad (3)$$

and

$$I_c \simeq S/\eta \; . \qquad (4)$$

Thus, with q and η as in the ISR, the specified LSR-performance could be achieved with S ≃ 35 ℓ/s m only.

Since a small aperture would most certainly not accommodate conventional distributed pumps, linear getter pumping was considered. This method implies an in situ preparation of the inner pipe surfaces. It would also be required for a strong reduction of q and η, since the benefit of surface treatment is almost completely lost when the pipe is exposed to air.

In situ glow discharge cleaning, hereafter referred to as ISGD, is expected to diminish q and η considerably through removing the surface contamination by the ion bombardment and flushing it away with the discharge gas, usually argon. As the discharge anode, a wire would have to be installed within the pipe, which might be retractable. The major drawback of this method is that large quantities of Ar are implanted in the beam pipe wall, giving rise to an enhanced thermal outgassing. The high bakeout temperature to remove it, ≳ 300°C would be undesirable within a cryostat.

With this wire, it is only a small step to obtain distributed getter pumping, since it could be made of titanium and used as the sputter-cathode in a gas discharge. During this process, hereafter referred to as ISSP, Ti is sputtered in situ onto the beam pipe wall which is simultaneously cleaned by electron bombardment, whereas the ion implantation in the wire is negligible because of its high temperature provided for by the impinging ions. Over 4000 ℓ/s m are expected with a molecular sticking factor of ~ 0.06 for H_2 at RT [2]. However, quite similar to the "cold bore" [3], any increase of η might compensate some of the gain in linear pumping speed.

Within the cryostat, the temperature distribution along the pipe is determined by the thermal conductivities of the pipe and the superinsulation. It can be as low as LNT, without external heating. In distinction to a "cold bore" [3], where the pipe is at about LHT, this option has been referred to as a "cool bore" [4]. Its linear pumping is poor for H_2, but thermal outgassing is almost negligible also. Furthermore it offers a high degree of independency of the vacuum system and magnet cryostat.

Method of Measurement

All measurements were carried out in a full size test system for a long LSR dipole. From the pressures at the middle and the end of the pipe, p_m and p_e :

$$\bar{p} = p_e + \frac{2}{3}(p_m - p_e) \qquad (5)$$

was obtained, i.e. assuming that q was constant over the length of the pipe and a parabolic pressure profile. With some linear pumping in addition, Equ. (5) would

give just the upper limit to $\bar{p}$. No correction for the low pressure limit of the gauges, $\lesssim 5 \times 10^{-12}$ Torr has been attempted.

It was obviously impossible to install test chambers of LSR dimensions in the ISR to measure critical currents, as well as it was excluded to carry out a test series with so many different materials and various treatments in situ within a reasonable time. A new method has therefore been used to predict the critical current for a particular system in the laboratory [5].

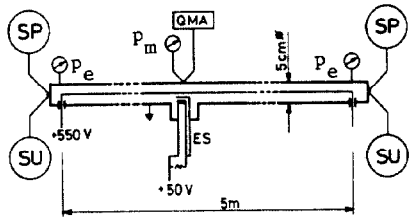


Fig. 2 shows the experimental set-up. The test pipe is equipped with a sputter-ion and a Ti-sublimation pump of 400 ℓ/s ans 2000 ℓ/s, respectively, on either side. Electrons, injected by a small source ES (mounted halfway between the pumps) into the field created by a long axial anode wire (the same as used for ISGD and ISSP) orbit around this anode over a considerable length. With argon injected at high pressure ($\sim 10^{-4}$ Torr), each electron ionizes just one Ar-molecule, whereafter it leaves its stable orbit. The ions are accelerated in a similar type of electric field as produced by the proton beam, impinge at the pipe wall and desorb gas. With a calibrated residual gas analyser QMA at the middle of the pipe, the corresponding partial pressure rise could be measured for the different gas species as a function of increasing electron emission. I_c is inversely proportional to the slope of this (linear) function. It is given for the particular gas component that would be responsible for vacuum breakdown, taking account of the respective residual gas ionisation cross-section of the beam.

Treatment Procedures

The sequence of treatments was identical for all the test pipes, as well as the procedure within each individual step, in order to allow an unambiguous comparison of the results. After each individual step, $\bar{p}$ and I_c were measured in situ, some 24 h after its completion. Prior to installation, each pipe was cleaned following the standard ISR-procedure [6].

The first three steps were :

a) installation and pumpdown for 3 days;
b) bakeout at 300°C for 24 h (190°C for Al alloy);
c) ISGD with argon, total dose > 10^{18} ions/cm^2, followed by step b) to remove the implanted argon.

These steps are referred to as "laboratory treatment" hereafter, because a 300°C bakeout would be undesirable within the cryostats, but also because it is relatively more difficult and time-consuming to carry out an ISGD than an ISSP. The bakeout is indispensable prior to ISGD (and ISSP) as it removes most of the gas contaminating the surface, predominantly H_2O, whose presence would of course be deleterious.

After having the test pipe exposed to air for at least 3 days, the "machine treatment" followed :

d) pumpdown for 3 days;
e) bakeout at 150°C for 30 h;
f) ISSP with argon, total coverage $\sim$ 50 monolayers of titanium. During sputtering, the pipe was heated to 150°C, to prevent burying of Ar under the Ti film, but the rest of the system remained at RT.

After another venting for 3 days, the "machine treatment" was repeated to check whether the application of the previous one has some permanent effect on the vacuum performance, despite the exposure to air.

Test Pipes

Altogether 8 test pipes have been investigated :

- 4 stainless steel tubes (304 L, made for the Swiss dairy industry). This choice was made to provide a sound basis for comparison of results with other laboratory measurements and ISR operational experience, as well as to give an idea of reproducibility of results from different pipes of the same material;
- 1 tube of the same material, but electropolished and subsequently heat-treated at 950°C in vacuum furnace. The objective was mainly to see whether in situ treatments, like bakeout, ISGD and ISSP are more efficient on a smoother surface;
- 1 tube of untreated stainless steel as above, but cooled to LNT over its entire length during the measurements. This "cool bore" is supposed to be a more realistic approach to a vacuum system for a superconducting magnet machine, than a "warm bore";
- 1 tube made from aluminium alloy 6351, and
- 1 tube made from pure titanium, both chosen in order to check whether the vacuum performance obtained with these materials is so much better than stainless steel, thus compensating for some of their obvious mechanical disadvantages.

With the exception of the electropolished tube, no test pipe has been given any pre-treatment apart from the above mentioned standard ISR procedure [6].

Results

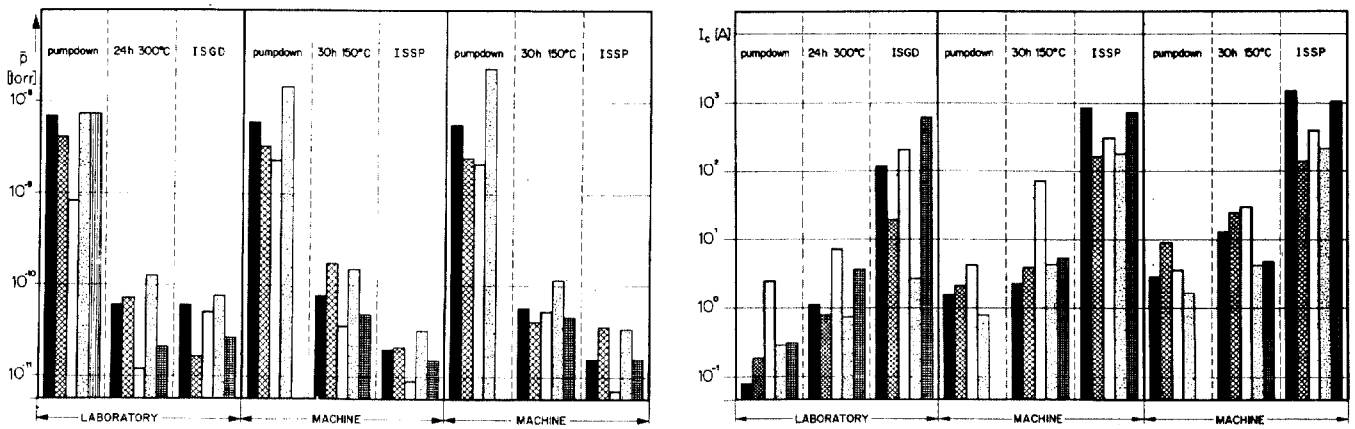
Fig. 3 is a histogram of the average pressure or its upper bound in case of some linear pumping, measured after the different steps of treatment. Fig. 4 is the corresponding critical current. The results from the four stainless steel tubes all agreed within a factor of two, for both $\bar{p}$ and I_c, this may also be considered as the error margin for the other pipes.

Untreated stainless steel

After the first bakeout, $\bar{p} > 5 \times 10^{-11}$ Torr, as expected from Equ. (1) with $q = 1.6 \times 10^{-13}$ Torr ℓ/s cm^2 which is in perfect agreement with the commonly accepted figure. After ISGD, the pressure was still about the same, to some extent due to enhanced outgassing of argon. No evidence for linear pumping was found. Using Equ. (2) $\eta = 76$, $\eta = 5.1$ and $\eta = 0.05$ is obtained from the corresponding measured I_c value. These figures are a little higher than those found with a different method [6]. Scaling to ISR geometry, critical currents of about 1.7 A, 25 A and over 2500 A would be expected before and after bakeout and after ISGD, respectively.

Whereas the effect of the "laboratory treatment" on $\bar{p}$ is lost with exposure to air, the critical current has already doubled after only a 150°C bakeout. For the ISR, the "laboratory treatment" is actually applied, but the beam pipes are baked at 300°C in the machine. Its actual stability limit is $\sim$40 A, whereas $\simeq$ 49 A can be deducted from these laboratory measurements. The ISSP improves the vacuum performance drastically, better than the LSR design figures : $\bar{p} < 2 \times 10^{-11}$ Torr and $I_c \simeq 1000$ A.

Results obtained during the second "machine treatment" indicate a beneficial effect of the previous one, most certainly due to ISSP : after the corresponding steps, $\bar{p}$ is a little lower, but I_c is three times higher during the second cycle. For the ISR, $I_c = 260$ A would



be expected after a 150°C bakeout in situ, if the chamber was previously glow-discharge cleaned and titanium sputtered onto its surface.

Electropolished and heat-treated stainless steel

Before a bakeout, $\bar{p}$ was typically less than in an untreated steel pipe, but higher thereafter. The lowest $\bar{p}$ after ISGD was measured in this test pipe, after ISSP, however, it was not better than in a normal steel pipe, and even higher after the second ISSP.

Before and after each bakeout, I_c was slightly above the corresponding figures for normal stainless steel. After ISGD and after ISSP, however, I_c was far below those for steel and titanium and about equal to that of the Al-alloy pipe, which was a smooth surface also. Apparently, smoother surfaces provide less linear pumping if they are sticky, than rugged ones, but also have a lower specific outgassing rate.

Stainless steel "cool bore"

As expected, $\bar{p}$ was considerably lower in the "cool bore" before and after bakeout, than in any other pipe. Before the first ISSP, I_c was about ten times higher than in the steel tube at RT. In contrary with the result in warm pipes, I_c had diminuished after the first "machine treatment" for no obvious reasons.

After ISGD, $\bar{p}$ and I_c in the "warm bore" and the "cool bore" were about equal. After ISSP, I_c was not as high as in the warm pipe, however, the average pressure was well below 10^{-11} Torr, probably adulterated by the thermal outgassing of the hot gauges.

Aluminium alloy

This test pipe gave the poorest results, after almost every step of treatment. It seems unlikely that a more sophisticated chemical pre-treatment would have given better results as it is difficult to believe that the glow-discharge cleaning which stirs up the surface so tremendously is less effective. There was also no permanent improvement by ISSP, unlike to other pipes. The performance immediately after ISSP is very similar to the electropolished stainless steel tube.

A faint luminous glow could be observed during I_c-measurements, together with erratic, short and local discharges causing pressure bursts. The ISSP eliminated this phenomenon completely, which did not reappear even after exposure to air, whereas it was persistent after ISGD. The high ion-induced secondary electron yield of oxidised aluminium might be responsible for this observation. Electron multipactoring has recently been suspected to provoke the strongly enhanced gas desorption in the aluminium-alloy test chamber of the ISR when high intensity bunches were stacked in this machine [7].

Titanium

In this test pipe, $\bar{p}$ was about the lowest after all corresponding treatments, except from the "cool bore" and from the electropolished tube after ISGD. After the 300°C bakeout, $q = 6 \times 10^{-14}$ Torr ℓ/s cm^2. Before the first ISSP, I_c was typically three times higher than for stainless steel. After ISGD, the I_c-value was the highest achieved in all tubes, it was about the same as found in stainless steel after ISSP. This is expected, as ISGD and ISSP should have the same effect in a titanium pipe and a Ti wire.

Conclusions

The various in situ treatments like bakeout, ISGD and ISSP are much more efficient in improving the vacuum performance than is any particular choice of beam pipe material. These treatments have some permanent beneficial effect if applied to a stainless steel "warm bore". ISGD and ISSP give - in this order of preference - a drastic improvement in vacuum performance, ISSP by the provision of linear pumping. In situ treatments also offer the advantage that they can be carried out where ever a local recovery is required, without breaking the vacuum and exposure of adjacent sections to air. The technical complications arising from ISGD and ISSP are comparable to those from using Al or Ti alloy, but the performance obtained is far better. ISSP also makes conventional, i.e. lumped Ti sublimation pumps superfluous.

The adoption of a "cool bore" design reduces the average pressure and also increases the critical current, in comparison with a "warm bore", the relative gain after ISSP, however, is small. Without ISSP, a "cool bore" is certainly the best choice, in case of a "warm bore", electropolished stainless steel should be used.

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