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IN-SITU CONDITIONING FOR PROTON STORAGE RING VACUUM SYSTEMS

by

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Abstract: Average pressure and vacuum stability limit as expected in the presence of a proton beam were measured after in-situ treatments such as bakeout under various conditions, argon glow-discharge cleaning and sputter-deposition of titanium. Measurements were carried out for test pipes made of stainless steel (untreated, electropolished or cooled to 77 K), pure titanium and aluminium alloy. The measurement method to obtain the vacuum stability limit in the laboratory and in a prototype system is described. The results can be applied also to other systems of different geometry by use of scaling laws. In-situ conditioning has generally a stronger influence on vacuum performance than a particular choice of material. Bakeout gives low average pressures and rather good vacuum stability. Glow-discharges also increase the vacuum stability but have only a small effect on the static pressure. Coating the beam pipe wall with titanium by in-situ sputtering provides large linear pumping, thus a lower pressure and an extremely good vacuum stability.

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INTRODUCTION

Various high energy proton storage rings have been studied in the last few years which could provide the high energy physics community with a new facility of very high c.m. energy /1/. Experience with the only so far existing machine of this type, the Intersecting Proton Storage Rings ISR at CERN /2/, has shown that the average residual gas pressure has to be very low. This is mainly necessary in order

- to avoid a high neutralisation of the proton beam by trapped electrons, which could lead to beam instabilities by coherent plasma oscillations,
- to keep the scattering rate of the circulating protons with residual gas molecules below an acceptable limit.

Another problem are positive ions which are created by these collisions. They are accelerated in the space charge field of the beam and impinge at the beam chamber wall where they desorb gas. This feedback process /3/ leads to a breakdown of the vacuum with consequent loss of the stored proton beam, if the proton beam current is high enough and the resulting local gas release not attenuated by sufficient pumping speed. The beam current at vacuum breakdown is also referred to as the critical current.

The ISR which are operated at a proton energy of typically 26 GeV are the only existing source of experimental data for average pressure and vacuum stability limit on a large scale. The total length of the vacuum system is about 1 km for each of the two rings /4/. It has a lumped pumping system with a maximum distance of about 240 cm between lumped pump stations and a beam pipe conductance of $\geq 8.5 \times 10^6 \text{ cm}^4/\text{s}$. The average pressure is about 7×10^{-12} Torr, the critical current approximately 40 A. This performance is obtained by conditioning the vacuum chambers before installation (chemical cleaning, followed by a heat-treatment in a vacuum furnace and high vacuum, and by glow-discharge cleaning in a mixture of argon and 10 % oxygen /5/), followed by an in-situ bakeout at 300°C for at least 24 h.

Storage rings for protons of more than 100 GeV energy are most likely to be built with superconducting magnets to minimise the machine diameter. For obvious reasons, these magnets have to be long and slim. Therefore, they define beam pipe conductance and distance between possible locations of lumped pumps. The only free parameters to achieve a low average pressure together with a high critical current are thus the thermal and the ion-induced desorption from the beam chamber.

It seems unlikely that more sophisticated pre-installation treatment procedures than those already being used at the ISR, could much improve these two parameters. In addition, a bakeout temperature of 300°C is very likely too high within a superconducting cryostat.

The installation of a conventional distributed pumping system might be a solution, however, it is often inconvenient or even impossible within the available aperture.

We have therefore investigated a few possibilities of conditioning beam chambers in situ in a full size prototype model built for a particular machine project /6/. For some of these treatments, a discharge electrode must be installed within the beam pipe, for example a wire strung along the beam pipe axis by a special manipulator shown in Fig. 1. This wire can be retracted after conditioning of the pipe and before protons are injected.

The results presented in this work can generally be used to predict the vacuum performance of proton storage rings. When applied to the particular case of the ISR, this prediction is in good agreement with the actually observed performance. At present, another retractable wire system of ~5 m length has been installed in the ISR and seems compatible with normal machine operation. We hope to confirm all the laboratory measurements presented here but with a "real" proton beam and in a different vacuum system geometry.

THEORY

The equilibrium pressure profile $P(x)$ along the beam path x in a tubular vacuum system (Fig. 2) can be obtained from

$$qU + \sigma Y P(x) I / e - s P(x) + c d^2 P(x) / dx^2 = 0 \quad (1)$$

where

- q = specific thermal outgassing rate (Torr cm/s)
- U = beam pipe perimeter (cm)
- Y = net ion induced desorption yield (molecules/ion)
- σ = beam-gas ionisation cross section (cm^2)
- I = stored proton beam current (A)
- e = elementary charge (As)
- s = speed of distributed pumping (cm^2/s)
- c = beam pipe conductance per unit length (cm^4/s)

Equ. (1) can be integrated with lumped pumps of speed S_0 (cm^3/s) and low pressure limit P_0 (Torr) mounted at $x = \pm L/2$ (cm):

$$P(x) = P_0 + \frac{qU}{ck^2} \left\{ \frac{\cos(kx)}{\cos(kL/2) - (kc/S_0)\sin(kL/2)} - 1 \right\} \quad (2)$$

with

$$k = [(\sigma Y I / e - s) / c]^{1/2}, \quad (3)$$

where k can also be imaginary. In the latter case, $\cos$ and $\sin$ in Equ. (2) have to be replaced by $\cosh$ and $i \sinh$, respectively. The well known parabolic pressure profile in a tubular vacuum system with lumped pumps only is then found for $k \rightarrow 0$:

$$\lim_{k \rightarrow 0} P(x) = P_0 + \frac{qU}{2c} \left\{ \frac{cL}{S_0} + \left(\frac{L^2}{4} - x^2 \right) \right\}. \quad (4)$$

Now we can derive the two basic parameters to the vacuum system:

- the average pressure from Equ. (2):

$$\langle P \rangle = \frac{2}{L} \int_0^{L/2} P(x) dx = \frac{qU}{ck^2} \left\{ \frac{2}{kL [\operatorname{ctg}(kL/2) - ck/S_0]} - 1 \right\} \quad (5)$$

- and the critical current from Equ. (3):

$$I_c = e(ck_c^2 + s) / \sigma Y. \quad (6)$$

If the denominator in Equ. (5) goes to zero, the vacuum breaks down; hence, k_c is found as the first root of the transcendental equation

$$ck_c \tan(k_c L/2) = S_0. \quad (7)$$

It is usually much more difficult to provide sufficient pumping speed to obtain the desired vacuum stability limit than it is to achieve the specified average pressure. The low average pressure in the ISR, for example, is just the consequence of the large pumping speed which was installed to improve the stability limit. This most would certainly also apply to other proton storage rings where the proton energy is comparable or higher than at the ISR where the pumping system is aperture limited. Hence, the local effective pumping speed per unit length of beam pipe (cm^2/sec) at the most critical location which is midway between the lumped pump stations, must be at least

$$s_{\text{eff}} = \sigma Y I_c / e \quad (8)$$

to prevent a vacuum breakdown. Therefore, with Equ. (6):

$$s_{\text{eff}} = s + ck_c^2. \quad (9)$$

Equ. (7) is not very practical for scaling purposes or for the design of a pumping system. A convenient method, however, is to chose

$$z = S_0 L / 2c \quad (10)$$

thus, from Equ. (6)

$$I_c = \frac{e}{\sigma Y} \left[s + \frac{c}{L^2} F(z) \right]. \quad (11)$$

Equ. (11) gives the vacuum stability in a system of known geometry and pumping speed. It can also be used to scale the performance from one vacuum system to another. Fig. 3 is a plot of $F(z)$, obtained from

$$\left[\frac{F(z)}{4} \tan \left\{ \frac{F(z)}{4} \right\} \right]^{1/2} - z = 0. \quad (12)$$

It is obvious from Equ. (11) that there is a limit to the critical current in a purely lumped pumping system ($s=0$), since $F(z)$ goes to π^2 for $S_0 \gg 2c/L$. In this case, i.e. for purely aperture limited lumped pumping, we have

$$I_c = e c \pi^2 / \sigma Y L^2 \quad \text{and} \quad \langle P \rangle = P_0 + q U L^2 / 12c \quad (13)$$

whereas in the case of purely distributed pumping ($s \neq 0$), we have $F(z) = 0$, thus

$$I_c = es / \sigma Y \quad \text{and} \quad \langle P \rangle = P_0 + q U / s \quad (14)$$

with the low pressure limit of the pump P_0 .

TEST SYSTEM

The set-up of the test system is sketched in Fig. 2. It had the dimensions of a vacuum section within a long superconducting bending magnet for the LSR design project /7/. The total length and the diameter of the test pipes were 5.1 m and 5 cm, respectively.

Pump stations were mounted at either end, each comprising a 80 lit/s sputter-ion pump and a 1000 lit/s sublimation pump. This pumping speed was large compared with the conductance across the pipe ($z > 150$), giving at least 95 % of the maximum possible effective pumping speed at the centre, see Fig. 3. The system could be pumped by a 100 lit/s turbomolecular pump backed by a roughing pump. It was used before and during bakeout and also for the evacuation of the argon used for in-situ conditioning and critical current measurements. It could be separated from the rest of the system by a bakeable UHV valve.

The test system was all metal and could be baked up to 300°C. Pressures were measured with gauges mounted at the pump stations (modulated BA-type gauges /8/), and at the centre (special, calibrated extractor type gauge /9/). Their useful range covered about 5×10^{-4} to below 5×10^{-12} Torr. A quadrupole mass spectrometer /10/ was installed halfway between the pump stations. It could be shut off by a bakeable UHV valve for protection during in-situ glow-discharge conditioning.

A small thoria coated tungsten filament was mounted within the test pipe, it was the electron source required for critical current measurements. A 1 mm diam. titanium wire was strung along the test pipe axis and served as

- the anode for critical current measurements,
- the anode during glow-discharge cleaning,
- and as the sputter-cathode to coat the test pipe with titanium.

Argon gas for in-situ conditioning and critical current measurements was injected by a special valve mounted on the pump station opposite to where the turbomolecular pump was installed.

MEASUREMENT METHOD

Both, the average pressure and the critical current were measured before and after each conditioning cycle and in situ.

(A) Average Pressure

A closer inspection of Equ. (5) shows that the average pressure increases only when the stored beam current is already very close to the critical current. The vacuum system should be so designed that this situation ideally never occurs, therefore, we have determined the average pressure in the test system for $I = 0$. Furthermore, since it is very difficult to determine the linear pumping speed s with sufficient accuracy, we have made the pessimistic assumption $s = 0$.

Hence with Eqs. (4) and (5) for gauges mounted at the positions shown in Fig. 2, i.e. at $x = \pm L/2$ and at $x = 0$:

$$\langle P \rangle = P_0 + P(\pm L/2) + (2/3)\{P(0) - P(\pm L/2)\} \quad (15)$$

Thus, the average pressures quoted hereafter are pessimistic figures, they are given in N_2 -equivalent.

(B) Critical current

To measure the critical current, the sputter-ion pumps are switched off; clean argon gas ($> 99.999\%$) is then injected into the system up to a pressure of some 5×10^{-6} Torr. Then, a potential of $+700$ V was applied to the axial wire and the small cathode filament mounted halfway between the pump stations, see Fig. 2, was switched on. It provides electrons up to a current of 2 mA, most of which are placed onto stable orbits in the radial electric field between the wire and the test pipe wall. The electrons produce argon ions from the injected gas, which are accelerated in the field and bombard the pipe wall like in a real machine. The ion current density is hereby rather uniform over the length of the test pipe, because the electron mean free path is long in this orbitron-like set up, typically some 10 m at the chosen argon pressure.

The partial pressure variation Δp_i of gas species i was then measured with the mass spectrometer versus the change of argon ion current ΔI^+ collected at the beam pipe wall. The ion induced desorption of gas species i per unit length of test pipe is then

$$\Delta Q_i = (Y_{L,i}/e\gamma L)\Delta I^+ = s_{\text{eff},i}\Delta P_i, \quad (16)$$

where $\gamma = 3.53 \times 10^{16}$ molecules/Torr cm^3 . Thus we have with Equ. (8)

$$I_{C,i} = (Y_{L,i}/Y_{M,i})/[\sigma_i\gamma L\Delta P_i/\Delta I^+]. \quad (17)$$

The molecular desorption yield of gas species i by argon ions, $Y_{L,i}$ is related to the net desorption in the real machine

$$Y_{M,i} = Y_{L,i} - a_i \quad (18)$$

where the incident ions are generated from the residual gas molecules. The probability that the primary ion is not returning into the gas phase is denoted by a_i .

We have assumed that all ions are equally effective in desorbing gas from the beam pipe surface. This is obviously a rather pessimistic assumption, since argon ions are heavier than most of the other gas components in the system.

Another, less pessimistic simplification is to set α_i to zero. The ratio $R_i = y_{L,i}/y_{M,i}$ can then be obtained from a measurement of the ion desorption yield versus the energy of the incident energy. This energy is about 200 eV in the laboratory, whereas it can be much higher in a real machine where it is determined by the beam space charge potential.

Eqs. (16) and (17) can be combined

$$I_{c,i} \geq 1/[\sigma_i \gamma L \Delta P_i / \Delta I^+] \quad (19)$$

This relation was used to determine individual critical currents for different gas species where $\Delta P_i / \Delta I^+ \geq 0$. Critical currents $I_{c,i}$, as given hereafter are the lowest amongst all individual critical currents measured, the corresponding residual gas component determines the vacuum stability limit. A different method to investigate vacuum stability in the laboratory has recently been reported elsewhere /11/.

The partial pressure diminished with increasing electron emission, i.e. the argon ion density for some gas species, like methane in a system at ambient temperature, water vapour and argon. They will contribute to a total pressure reduction in presence of a coasting beam. This phenomenon is observed at some places around the ISR and is referred to as "beam pumping" /12/.

TEST PIPES AND CONDITIONING CYCLES

Nine different test pipes have been tested; the in-situ conditioning cycles to which they were subjected are described in Table I. The pipes had the following characteristics:

- (a) one tube made of pure titanium;
- (b) four stainless steel tubes (304 L made for the Swiss dairy industry),
- (c) one tube made of aluminium alloy 6351;
- (d) one stainless steel tube as (b), which was, however, electropolished and subsequently baked in a vacuum furnace at 950°C and at a pressure of $\leq 10^{-5}$ Torr;
- (e) one tube of stainless steel as (b) but cooled to liquid nitrogen temperature over its entire length during the measurements;
- (f) one stainless steel pipe as (b), which was used to test a

- (f) one stainless steel pipe as (b), which was used to test a different sequence of in-situ conditioning treatments, cycles (10)-(14) than to all the others, cycles (1)-(9);

The measurements on four different stainless steel pipes were made to obtain a good average value which can be checked against results from other laboratory measurements and from ISR experience. Furthermore, this choice also gives an idea of the reproducibility of the measurements. Electropolished stainless steel pipes were expected to give a better vacuum performance than untreated ones due to their smoother surface which appears to be cleaned easier and where probably less gas is adsorbed on the surface.

The pipe cooled to liquid nitrogen temperature ("cool bore") is a more favourable solution to a vacuum system that is enclosed by cryomagnets over a large fraction of the total machine circumference. Titanium and aluminium alloy tubes were selected because they were earlier proposed for the construction of proton storage rings or as a part of it /13/.

RESULTS AND DISCUSSION

Fig. (4) is a summary of all the results. It is a diagramme of the average pressures and the critical currents measured in the different test pipes before and after the in-situ conditioning cycles shown in Table I. Different test pipes are identified by the shape of their plot symbol. Results obtained before and after a particular treatment procedure are combined in groups and linked up with lines. Critical current measurements could generally be reproduced within a factor of less than two.

In practically all cases, the lowest individual critical currents were found for CO. Only after exposure to air and before the first bakeout, hydrogen generally gave the lowest figures. The predominant partial pressure in the system after bakeout was always hydrogen.

Cycle (1) :

The lowest critical currents and high average pressures were, as expected, measured in an unbaked system, quite independent of the material. Cooling the test pipe to about 77 K gave an improvement of about an order of magnitude on both figures.

Cycle (2) :

After the first bakeout, the lowest average pressure together with highest critical current was found with the "cool bore" (pipe at 77 K). The second best results were obtained with the titanium test pipe. Lower average pressures are predicted for titanium systems also from outgassing rate measurements /14/. All the other pipes gave much worse

results which were not very different from one another.

Cycle (3) :

A large spread in the critical currents for different test pipes was found after glow-discharge cleaning in situ, hereafter referred to with ISGD. The effect on the average pressure was small. The reason for this observation is not quite clear. It seems as if the discharge provides a weakly pumping wall not only in the case of a pure titanium wall, where it is expected, but also with untreated stainless steel, the apparent surface area of which was much larger than that of electropolished steel or aluminium alloy.

The highest critical current was measured with the titanium tube: since the ion bombardment scrubs off the walls, it opens a large chemically active titanium surface which is an ideal linear pump for gas species like H_2 , CO and CO_2 . The second best were the untreated stainless steel pipes either at room temperature or at 77 K: for which the results were almost identical. ISGD had only a minute effect on the critical current in the aluminium alloy test pipe. Better results were obtained with electropolished stainless steel.

Cycle (4) :

After venting and pumpdown, roughly the same average pressures as before the very first bakeout were achieved. For some test pipes, however, the critical currents had increased by about an order of magnitude. The gain was particularly good for both, the untreated and electropolished stainless steel pipes. For aluminium alloy and the "cool bore" pipe, the improvement was poor. For this cycle, the measurements of the titanium tube were, unfortunately, useless.

Cycle (5) :

It can be seen that the previous 300°C bakeout and glow-discharge cleaning results in a permanent improvement of the critical current, i.e. despite the fact of having the system exposed to air and of the lower bakeout temperature of 150°C. This effect is already known /5/ and made use of in the ISR, where all the newly installed beam chambers are glow-discharge cleaned before they are installed.

For the "cool bore", the electropolished stainless steel and aluminium tubes, we found a great improvement. The "cool bore" again gave the highest critical current. The average pressures were generally a little higher than after the first bakeout, most likely due to the lower bakeout temperature.

Cycle (6) :

In-situ sputter deposition of titanium, hereafter referred to as ISSP, had a drastic effect. Practically all the critical currents had increased by almost two orders of magnitude, apart from the result for the "cool bore", where it was already high before. The average pressures had also dropped. Again, there is a similarity in the results obtained with aluminium alloy and electropolished stainless steel, which had already been observed after the first and second bakeout.

Results are also very much the same for titanium and untreated stainless steel. This can probably be explained in terms of surface roughness, since a rougher wall has a larger apparent surface area and hence a higher distributed pumping speed for a given molecular sticking factor. The "cool bore" gave the lowest average pressure (about 7×10^{-12} Torr), however not the highest critical current.

Cycles (7) to (9) :

These treatments are a repetition of cycles (4) to (6). Their purpose was mainly to find out whether the beneficial effect from the ISSP will be completely lost upon exposure to air or whether there is also some permanent improvement as after ISGD.

For the unbaked system, we found about the same average pressure as after cycle (4), and only a small increase in critical current. The results were slightly better for untreated or electropolished stainless steel. Even after the second bakeout at 150°C , i.e. following cycle (8), there was practically no improvement for aluminium and titanium with respect to the results obtained after the analogous cycle (5). However, the critical currents for untreated or electropolished stainless steel were considerably higher than before.

All results obtained after the second ISSP were practically the same as after the previous one. Aluminium alloy and electropolished stainless steel again gave the worst results, untreated stainless steel and titanium the best.

Cycle (10) :

The effect of the following five cycles was only tested for a stainless steel pipe (f). This test pipe was in a "virgin" condition at the time of its first installation, i.e. before cycle (10), apart from having been electropolished and heat treated.

After cycle (10), the critical current was about the same as in a system where a bekeout was preceding the ISSP. The average pressure had decreased by only an order of magnitude due to the sputtering. A residual gas analysis after cycle showed that water vapour and methane were the dominating gas components, i.e. gas species which are practically not pumped by the titanium film.

Cycle (11) :

After exposure to air and another pumpdown, the test pipe was cleaned by ISGD, again, as in cycle (10) without a bakeout neither during nor after the glow-discharge conditioning. The average pressure and critical current were about the same as obtained in the test pipe after a pumpdown only.

This disappointing result is probably due to the large quantities of loosely adsorbed gas, like water vapour on the surface. During the discharge, it contaminates the cleaning agent, i.e. the argon gas flushed through the pipe. Thus, an ISGD cannot replace the in-situ bakeout, as was hoped for some time. The effect of ISGD is obviously based on a reduction of small quantities of rather tightly bound gas species, like CO. They do not contribute much to the thermal outgassing at ambient temperature due to their high binding energy, but they can enhance the ion induced desorption.

Cycle (12) :

ISSP after cycle (11), i.e. without exposing the system to air and after glow-discharge cleaning and without bakeout, slightly improves the figures obtained after the last sputtering before the ISGD. The predominant gas species in the residual gas spectrum are still water vapour and methane.

Cycles (13) and (14) :

This combination is also referred as "quick cycle", because the UHV is achieved only some 8 hours after installation of the pipe. It practically gives the same results as a bakeout under vacuum. An air bakeout at reduced temperature (some 150°C) has earlier been investigated for an ISR section /15/, with promising results from the average pressure point of view. Our measurements confirm this. In a virgin tube, however, the critical currents could be higher. The vacuum stability was a little higher than after a vacuum bakeout, but the average pressure too. After ISSP, almost the same performance was obtained as for the other electropolished steel pipe after the corresponding cycles (6) or (9).

Other observations

For each test pipe, a faint luminous glow was observed during the critical current measurements and before the very first bakeout. It was associated with short, spontaneous local discharges and pressure bursts. The phenomenon was persistent in the "cool bore" also after a bakeout, until it was glow-discharge cleaned. In the aluminium chamber, however, it could only be eliminated by the sputtering cycle. In all the other test pipes it vanished already after the first bakeout.

This effect might be connected to a high ion-induced secondary electron emission yield. We have recently observed massive pressure bursts in an aluminium test chamber mounted in the ISR machine when protons were stored. It was suspected that electron multipactoring /16/ could be the reason for this phenomenon. The fact that this has never been observed in stainless steel or titanium chambers, supports this hypothesis.

Fig. 5a shows a typical pumpdown curve after a 150°C bakeout, without having the lumped sublimation pumps activated. A base pressure of about 4×10^{-10} Torr and a critical current of 1.7 A were achieved. Fig. 5b shows the pumpdown after ISSP, again without lumped sublimation pumps. A base pressure of 2×10^{-11} Torr and a critical current of over 300 A was then reached; the total pressure at the centre was smaller than at the pump stations.

This shows that lumped sublimation pumps are superfluous in a system where the in-situ sputtering technique is applied. Scaling from these critical current figures to ISR geometry, using Eqs. (13) and (14) for the case without and with linear pumping, respectively, we could expect 42 A or 500 A, before and after sputtering /17/. The first figure is in perfect agreement with ISR operational experience, the second is far beyond other limits to the beam current.

CONCLUSIONS

Conditioning of beam pipes in-situ, such as bakeout - whether at 300°C or only at 150°C -, glow discharge cleaning, or sputter deposition of titanium onto the beam pipe wall, are suitable to improve the design performance of a vacuum system of proton storage rings. These methods are much more effective than the choice of a particular beam pipe material. They also have a beneficial effect, even if they are not carried out in situ. Particularly glow discharge cleaning and titanium sputtering improve the vacuum stability permanently.

If a special type of beam pipe is to be chosen, then the order of preference depends on the treatment given. If a high temperature bakeout is possible but no discharge in situ, the best is a "cool bore", i.e. with the beam pipe at about liquid nitrogen temperature during normal machine operation. The highest performance after in-situ glow discharge is obtained in a titanium tube. If an in-situ sputtering system can be implemented, untreated stainless steel should be preferred. Electropolished and heat-treated stainless steel, glow discharge cleaned, then covered with a thin film of titanium should be used where only a 150°C bakeout is possible.

The purpose of an in-situ bakeout is mainly to remove the mass of loosely adsorbed gas, in particular H_2O and CO_2 , i.e. to reduce the average pressure. By the in-situ glow discharge stronger bound gas species such as CO for example are removed. This minimizes the ion induced molecular desorption and hence increases the vacuum stability limit, rather than improving the average pressure. In-situ sputtering of titanium provides large linear pumping for chemically active gas species, this reduces the net thermal desorption of getterable gas species and improves the vacuum stability drastically.

In-situ treatments offer the advantage of a relatively quick and local recovery. Sputtering of titanium makes conventional, i.e. lumped sublimation pumping superfluous. The necessity of a discharge electrode for the glow discharge or sputtering process in situ is a technical complication, in particular if this electrode must be retractable. However, a rather simple solution exists, which seems competitive in view of technical problems encountered with titanium or aluminium alloy.

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- /17/ It is assumed that the distributed puming speed scales linearly with the pipe circumference.

TABLE I

Cycle	In-situ conditioning procedure
1	Vapour degreasing, installation and 3 days pumping; at first with the turbomolecular pump (1 day), then with sputter-ion and sublimation pumps;
2	Bakeout under vacuum at 300°C for 24 h, at only 190 °C for aluminium alloy;
3	Glow discharge cleaning in pure argon; gas flow rate about 10 std. cm ³ , discharge gas pressure 0.06 Torr, discharge current 120 mA, anode potential + 300 V, ion dose > 10 ¹⁸ ions/cm ² ; bakeout at 300°C (for Al-alloy at 190°C) during and 2 h after the discharge;
4	Exposure to air at atmospheric pressure for 3 days; pumpdown for 3 days as cycle (1);
5	Bakeout under vacuum at 150°C for 30 hours;
6	Sputter coating of the pipe with about 100 monolayers titanium in argon gas; with the system closed after argon injection, discharge gas pressure about 0.2 Torr; discharge current 120 mA, cathode potential about - 500 V;
7	Repetition of cycle (4);
8	Repetition of cycle (5);
9	Repetition of cycle (6);
10	Cycle (1) followed by cycle (4), no bakeout;
11	Cycle (1) followed by cycle (3), no bakeout before, during or after cycle (3);
12	Repetition of cycle (6);
13	Exposure to air for 3 days, bakeout at 150°C for 6 h with the system up to air at atmospheric pressure;
14	Repetition of cycle (6);

FIGURE CAPTIONS

- Fig. 1: Manipulator of the in-situ conditioning wire.
- Fig. 2: Experimental layout. (SU = sublimation pump, SP = sputter-ion pump, QMA = quadrupole mass analyser, ES = electron source)
- Fig. 3: Function $F(z)$, see Equ. (11), to calculate critical currents with $z = S_0 L / 2c$.
- Fig. 4: Diagramme of average pressure and critical current, measured after the various in-situ conditioning cycles (1) - (14), see Table I. Results from the same test pipe are plotted with symbols of the same contour: T = titanium, S = untreated stainless steel, A = aluminium alloy, E = electropolished stainless steel and C = "cool bore", see text.
- Fig. 5a: Pumpdown curve after 150°C bakeout using sputter-ion pumps only.
- Fig. 5b: Pumpdown curve after in-situ sputtering following this bakeout.

FIG. 1

Figure 2

Figure 3

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Figure 4

Figure 5