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I. R. Collins, O. Gröbner, O.B. Malyshev, A. Rossi, P. Strubin and R.Veness

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LHC Division
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VACUUM STABILITY FOR ION INDUCED GAS DESORPTION

I. R. Collins, O. Gröbner†, O.B. Malyshev, A. Rossi, P. Strubin and R.Veness, CERN, Geneva, Switzerland

Abstract

Ion induced vacuum instability was first observed in the Intersecting Proton Storage Rings (ISR) at CERN and in spite of substantial vacuum improvements, it remained a limitation of the maximum beam current throughout the operation of the machine. Extensive laboratory studies and dedicated machine experiments were made during this period to understand the details of this effect and to identify ways of increasing the limit to higher beam currents. Stimulated by the recent design work for the LHC vacuum system, the interest in this problem has been revived with a new critical review of the parameters which determine the pressure run-away in a given vacuum system with high intensity beams.

1 INTRODUCTION

One of major concerns in the design of the warm sections of the LHC vacuum system is the so–called ion–induced pressure instability. This phenomenon was first encountered in the ISR machine and was hence named the 'ISR pressure–bump' [1]. It occurs in proton and positron storage rings when the particle beam ionizes the molecules of the residual gas. These positive ions are then repelled by the positive space charge of the beam and bombard the vacuum chamber walls with energies up to a few hundred eV depending on the beam current. The energetic ions desorb tightly bound surface gas that increases the pressure and hence, in turn, the ion bombardment. Thus a positive feedback process exists which may result in a pressure runaway. One important parameter, therefore, contributing to the stability of the vacuum is the ion induced desorption yield, η, which is defined as

$$\eta = \frac{number of\ emitted molecules}{incident\ ion} . \qquad (1)$$

Since in an actual vacuum system of an accelerator, the ions are created from the residual gas, it is appropriate to use a net desorption yield, η, which takes into account the probability, κ, that the incident ion is implanted in the vacuum chamber surface. In most of the past studies, this probability has been assumed to be unity. However, when comparing measurements from a laboratory system using an external ion beam, η_{lab}, with observations in the ISR, it would have been more correct to use the general relation

$$\eta = \eta_{lab} - \kappa \qquad (2)$$

and to consider that κ may depend on the incident ion energy and on the conditions of the vacuum chamber surface.

For the vacuum stability in a room temperature vacuum system it turns out that CO is the most critical of the gas species, due to its relatively large ionisation cross–section, its relatively poor pumping speed but mainly due its relatively high ion–induced desorption yield as compared with the other gases H_2, CH_4 and even CO_2, commonly found in a UHV system.

1.1 Historical Background

The ISR was high energy facility in which two counter-rotating beams of 28 GeV protons were accumulated and circulating in separate beam pipes; each ring being approximately 1 km in circumference and intersecting at 8 equally spaced points. The vacuum system was entirely fabricated from stainless steel and was initially baked to 200˚C for 5 hours in order to achieve UHV conditions [2].

In the early running–in period of the ISR, when the beam current, I, increased beyond 4 A the initially stable pressure, P_0, of about 10^{-10} Torr started to rise at several places around the machine until it reached 10^{-7} or even 10^{-6} Torr and the beam was rapidly destroyed [3]. Figure 1 shows a typical example of this vacuum effect from the early operation period of the ISR.

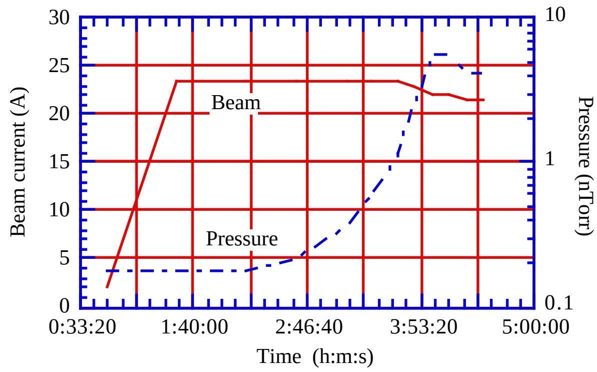

Figure 1: Pressure instability during beam accumulation in the ISR

The total flux of molecules into the vacuum system per unit length is:

$$Q = \eta \sigma P \frac{I}{e} + Q_o$$

† E-mail: oswald.grobner@cern.ch

where σ is the ionisation cross section of the residual gas molecules, P the pressure, e the unit charge and Q_o the thermal outgassing rate from the wall. The balance of molecules desorbed by the beam and removed by external pumps, S_{eff}, can be written as :

$$P S_{eff} = \eta\, \sigma\, \frac{I}{e} P + Q_o$$

and thus the original pressure bump equation

$$P = \frac{Q_o}{S_{eff} - \eta\sigma \frac{I}{e}}$$

was obtained. One finds that the pressure increases with beam current and that above a critical value

$$(\eta I)_{crit} = \frac{e\, S_{eff}}{\sigma}$$

no equilibrium pressure exists. At half this critical value, the initial pressure doubles. This limiting product depends on the effective linear pumping speed ($m^3s^{-1}m^{-1}$) of the vacuum system.

Since the configuration of vacuum chambers and pumps was given, the effective pumping speed in the ISR could be calculated from which in turn, an ion–induced desorption yield could be inferred by observing the maximum current at which the pressure could be maintained stable. It turned out that for the 200˚C baked vacuum chambers η's of between 2 and 4 molecules per ion were deduced. Subsequently, by installing additional pumping (titanium sublimation pumps), special ex–situ glow discharge cleaning and in–situ baking to 300˚C for 24 hours it was possible to increase the critical current product $(\eta I)_{crit}$ and simultaneously to reduce the desorption yield to acceptable levels (η's of close to zero and even negative) such that beam currents of up to 60A could be stored in the ISR.

Over many years an intensive program of measurements was performed on the ISR vacuum system itself using a dedicated vacuum test section, the results of which have been documented in a large number of internal 'ISR-Performance Reports' but with few exceptions [4], have remained largely unpublished. In view of the regained interest in the vacuum performance with recent high intensity machines, in particular the LHC, it seems an appropriate moment to review the main aspects of this work.

2 ION INDUCED PRESSURE INSTABILITY

Until now the ISR has been the only machine which has shown the ion induced pressure instability. For future high intensity machines, particularly for the LHC, the machine parameters are such that this vacuum effect is likely to affect the performance and specifically the maximum stored beam current. For this reason an intensive study has been initiated to identify possible ways of overcoming the vacuum instability in various parts of the ring, mainly in the sections where the vacuum system of the LHC is at room temperature and hence relies on conventional pumps. Parameters which influence vacuum stability will be reviewed in the following sections but the only two quantities which are under the control of the vacuum system designer are the pumping speed (S_{eff}) and the cleanliness of the vacuum system (η).

2.1 Residual gas ionisation

Ionisation cross sections for some common gas species are listed in Table 1. The values have been calculated for the proton beam energies in the ISR and for LHC using the formulae from Ref. [5]. For high energy particles the ionisation cross section depends on the relativistic speed and on the charge rather than on the type of the particle. Hence these cross sections may be used for electrons, protons and also for a beam of relativistic lead ions in the LHC.

Table 1: Ionisation cross sections

	Ionization cross-section (in 10^{-22} m^2)	
Gas	26 GeV	7000 GeV
H_2	0.22	0.37
He	0.23	0.38
CH_4	1.2	2.1
CO	1.0	1.8
Ar	1.1	2.0
CO_2	1.6	2.8

In addition to the ionisation cross section due to collisions, photo-ionisation of residual gas molecules by synchrotron radiation may become important not only in positron storage rings but also in the LHC machine with its large photon flux. The effect of photo-ionisation has been studied for the PEP-II vacuum system where it was shown that for ions produced close to the beam, this effect may be of the same order of magnitude as the rate of ionisation due to collisions.

2.2 Effective linear pumping speed

The pumping speed which is required to compensate the desorption by ions depends strongly on the configuration of the vacuum system. For a periodically pumped, linear vacuum system the vacuum stability condition can be calculated as shown below [6]. The addition of distributed pumping, e.g. by a continuous, linear getter pump or by cryo-pumping in a cold bore vacuum system can be implemented as a straightforward extension of this mathematical formalism.

In stationary conditions, the pressure in a linear vacuum system is described by :

$$c\frac{d^2P}{dx^2} + bP + q = 0 \ .$$

with :

q (Torr m^2 s^{-1}) specific linear outgassing rate

c (m^4 s^{-1}) molecular conductance per unit length.

The ion induced desorption is described by the parameter b (m^2 s^{-1})

$$b = \sigma\eta \ \frac{I}{e} \ .$$

Boundary conditions for the most relevant case of a uniform, periodic vacuum system with pumps (each pump with the speed 2S) placed at a regular distance 2L are given by :

$$c\left[\frac{dP}{dx}\right]_{x=\pm L} = \mp\, SP[\pm L]$$

Three types of solutions exist for this system, which depend on the range of the parameter b:

For $b = 0$, one obtains the usual parabolic pressure distribution for a periodically pumped system :

$$P(x) = q\left(\frac{2Lx - x^2}{2c} + \frac{L}{S}\right)$$

For $b > 0$, the solution has the form

$$P[x] = \frac{q}{b}\left[\frac{\cos[\sqrt{b/c}\ x]}{\cos[\sqrt{b/c}\ L] - \frac{\sqrt{bc}}{S}\sin[\sqrt{b/c}\ L]} - 1\right]$$

A finite solution exists as long as :

$$\cos[\sqrt{b/c}\ L] - \frac{\sqrt{bc}}{S}\sin[\sqrt{b/c}\ L] > 0 \ .$$

The limit of vacuum stability, i.e. the largest stable value for the parameter b corresponds to the first root of the transcendental equation

$$L\sqrt{b/c}\ \tan[L\sqrt{b/c}\,] = \frac{SL}{c}$$

which can be computed numerically. Nevertheless, an upper limit for b exists when the vacuum system is strongly conductance limited (S and L very large or c small), which can be obtained simply from the argument when the tangent tends to infinity :

$$b_{\max} = \frac{\pi^2}{4}\frac{c}{L^2}$$

The critical beam current for this limiting condition is

$$(\eta I)_{crit} = \frac{\pi^2}{4}\frac{e\,c}{\sigma\,L^2} \qquad (3)$$

For any practical case, the critical current will be lower but any 'well designed' vacuum system should fall to within 30% of this approximate condition.

Finally for $b < 0$, that is in case of $\eta_{lab} < \kappa$, the pressure decreases and the beam acts like an ion-pump -> beam pumping. The pressure has a hyperbolic distribution and remains always stable. The maximum value of the 'linear pumping speed' of the beam can be calculated from the expression

$$S_{beam} = \frac{\sigma\kappa}{e} I \ \ (\mathrm{m^2\,s^{-1}}) \ .$$

Beam pumping increases with the beam current and has been observed frequently, but not systematically, in the ISR with currents of up to 60 A [1]. The pumping depends strongly on the capture probability of the ions on the wall and a rough estimate of this effect may be derived from the pumping speed of a commercial ion pump as κ~0.1 [7].

2.3 Ion induced molecular desorption yield

Molecular desorption yields obtained by laboratory measurements [8, 9] and derived from observations with beam in the ISR can be found in [10]. Incident ion energy and surface cleanliness are important parameters for the desorption rate. The net yield in a machine, where ions are produced from the residual gas and the corresponding yields measured in the laboratory using an external ion source have been evaluated frequently assuming κ =1. [8] However, for a more correct and conservative estimate it would be appropriate to assume that incident ions may predominantly (>90%) be reflected as neutrals rather than implanted and trapped in the vacuum, chamber surface with a unit probability.

Values for η which are considered to be representative for an accelerator vacuum system and their dependence on ion energy are shown in Figure 2 for unbaked stainless steel [8]. For energies above 3 keV the yield shows saturation and this maximum value has been used to estimate the vacuum stability in those cases where the ion energies are above this maximum.

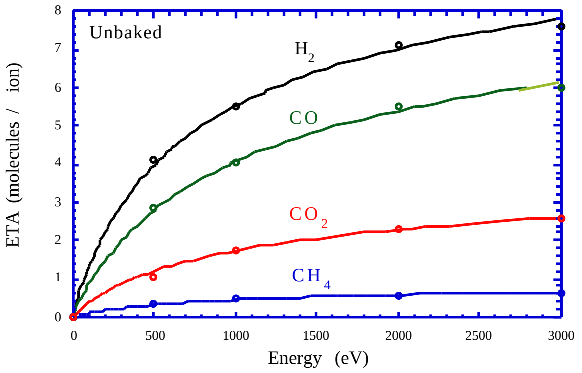

Figure 2: Desorption yield for unbaked stainless steel

Among the various vacuum conditioning procedures which were studied the first which has been applied successfully in the ISR machine was an *in-situ* bakeout at 300°C for 24 hours which results in an average reduction of the desorption yields by a factor of 3 and thus increasing the current limit from about 6 A to nearly 20 A. Further studies have shown that a bakeout combined with an argon ion glow discharge and in turn followed by an *in-situ* bakeout [11] results in a further significant reduction of the desorption yield. Figure 4 summarises the effect of various treatments and highlights the importance of the final *in-situ* bakeout to preserve the beneficial effect of any *ex-situ* treatment for obtaining a low desorption yield [12].

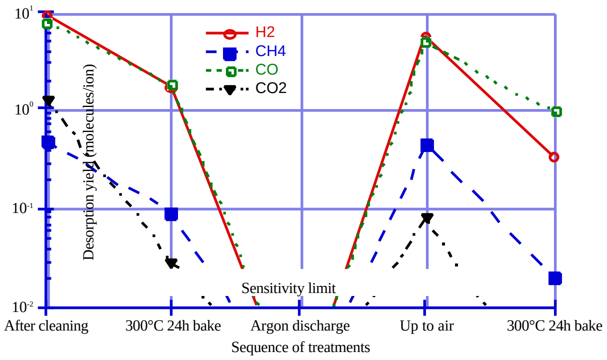

Figure 4: Effect of successive treatments on the ion induced desorption yield.

A glow discharge treatment, when it can not be performed *in-situ* and which is not followed by an *in-situ* bakeout of the vacuum system results only in a small, often insufficient improvement [13].

2.4 Ion impact energy

Ions created from the residual gas are repelled by the positive space charge of the beam either due to the kicks of successive bunches or, as in the case of the ISR with coasting beams, by the time independent electric field. For the ISR, typical ion energies have been measured as 200 eV per Ampere reaching a maximum of about 2 keV at the highest beam currents [14]. In the bunched-beam case, light ions experience more strongly the peak electric field and thus gain more energy than heavier ions. In the regular arc of LHC, the ion impact energy for CO is close to 300 eV while H_2 ions can gain up to 400 eV. Near the beam crossing points where the beams are tightly focussed, the ion energy may even increase to several keV [15]. Inspection of Figures 2 and 3 shows that such ion energies are by far sufficient to generate significant gas desorption yields.

3 COLD BORE SYSTEM WITH CRYO-SORBING WALLS (LHC)

In a cryogenic vacuum system with cold walls molecules are cryo-pumped with high efficiency directly onto the cold bore.

The pumping speed per unit length is

$$S_{eff} = \frac{1}{4} \bar{v}\, sF$$

with $\bar{v}$ the mean molecular velocity, s the sticking probability of molecules on the wall and F the surface area per unit length.

With a cold beam pipe of radius r_p, the stability limit is

$$(\eta I)_{crit} = \frac{\pi}{2} \bar{v}\, s r_p \frac{e}{\sigma} \ .$$

For $s\sim1$ the critical current can be very large, of the order of kA [16]. However, this large stability limit may again be offset by two factors:

Firstly, the sticking probability can be much smaller than unity

Secondly, the molecular desorption yield for condensed gas, specifically for H_2 accumulating on the cold bore, can become very large and values of up to 10^4 molecules per ion have been measured in the laboratory [17]. Fortunately, in the LHC, the strong recycling of cryosorbed molecules by synchrotron radiation counteracts the accumulation of hydrogen on the wall of the beam screen [18] and effectively limits the surface density to well below a monolayer and hence indirectly also the desorption yield to an acceptable value. A detailed discussion of ion induced vacuum stability in a cold vacuum system can be found in Ref. [15].

4 ISR OBSERVATIONS

Up to now, the ISR has been the only machine where the ion induced pressure instability has been observed, initially at very low beam currents of only a few amperes. Following many years of an intensive effort this limit could be increased to about 60A partly by installing additional pumps, thus reducing L and increasing S, but primarily by improving systematically the surface cleanliness of all vacuum chambers [2]. A typical example of the build-up of an unstable pressure during beam stacking is shown in Figure 5. A remarkable feature of the ISR pressure bumps was their very long time constant and the slow build-up of the pressure over many hours following the stacking of the beam. This characteristic behaviour could not be expected from the simple stability condition derived above. To understand the observed very slow time response of the pressure a more advanced model, which involves the interaction of the volume gas with an adsorbed surface phase had to be developed [19]. This model is in many details very similar to the more recent treatment for the LHC cold bore vacuum system [18].

A further important observation has been that while the pressure instability develops, the gas composition slowly evolves from a hydrogen dominated rest gas to a gas dominated by CO [20]. Since for this gas species the desorption yield is larger (larger ion mass) and the effective pumping speed smaller (smaller vacuum conductance) as compared to hydrogen, the stability limit of the system can be significantly reduced (a factor of up to 4 has been estimated for such a gas mixture [21]).

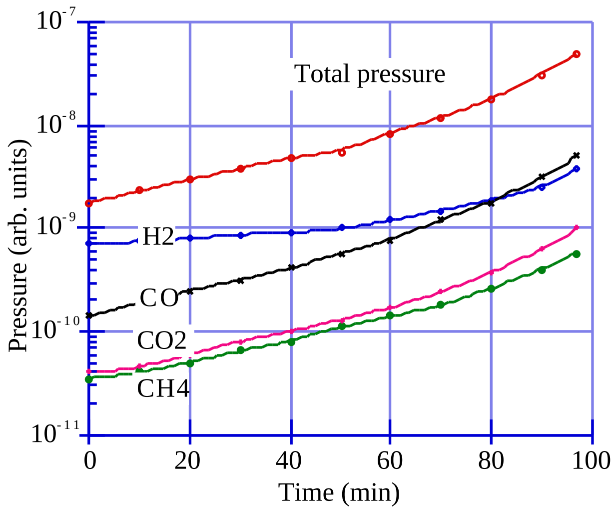

Figure 5: Pressure instability developing over a period of hours showing a gradually changing gas composition.

An extension of the one-gas model discussed above to a mixture of two [22] or even more gas species [15] has been made. Unfortunately, to apply this model to a real vacuum system, it would be necessary to know the matrix of desorption yields, $\eta_{i,j}$, for a gas species i desorbing species j, with a much better precision than at present available. A limited set of measurements of desorption yields for cryosorbed gas molecules and their dependence on the incident ion mass can be found in Ref [23]. This data set has been used for the study of the ambient temperature sections, i.e. the vacuum systems for the experiments of the LHC.

Machine experiments in the ISR on a large variety of surfaces, specifically prepared for these studies, have shown that the net η values were not constant but would depend rather strongly on the machine conditions. While the net desorption yield could be small and even negative at low beam intensities, the net yield had a systematic tendency to increase with the beam current (i.e. with increasing bombarding ion energy) and to become progressively larger and even positive. This characteristic behaviour is illustrated in Figure 6 for different types of beam pipes installed in a test section of the ISR machine. Among the many vacuum chamber materials and vacuum treatments studied, baked stainless steel with and without argon glow discharge (GDC) treatment [24] are presented. One of the best results in terms of low molecular desorption yields could be obtained with a baked titanium liner which was inserted inside the standard stainless steel chambers [25].

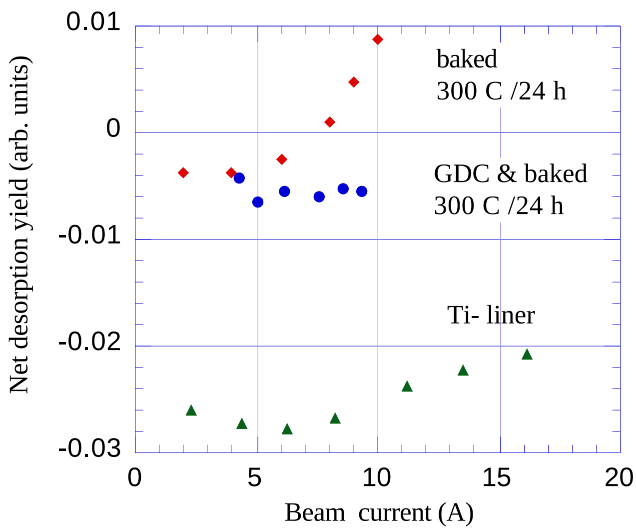

Figure 6: Net desorption yield as a function of the beam current in a test section of the ISR for different types of beam pipes.

A frequently observed behaviour was that following the first appearance of a pressure bump in a given location of the machine, the pressure rise developed at a progressively lower beam intensity for each subsequent beam storage. This was indicative of the fact that the critical current of the system was gradually reduced due to the accumulation of weakly bound molecules on the vacuum chamber walls. Furthermore, in strong contrast to the experience with synchrotron radiation, no cleaning effect of the vacuum system could be observed in spite of extended runs at high beam currents and by attempting to operate the machine as close to the critical current as was practical.

5 SUMMARY

The design of a vacuum system to guarantee vacuum stability requires high pumping speed and a low desorption yield. The effective linear pumping speed scales with the conductance between pumps, i.e. with the third power of the beam pipe radius, and with the inverse square of the pump distance as shown in equation [3].

Typical values of desorption yields were found to range between unity up to 10 molecules per ion for as received, unbaked surfaces. *In-situ* bakeout to 300°C lowers the yields to values below 2 to 4 while a glow discharge cleaned surface which is baked *in-situ*, provides in a reliable way η values below unity .

ISR machine experiments have shown that the simple stability criterion should be used with great caution since it only provides a very approximate value of the critical current. The real vacuum system behaves in a more complicated way with a gas mixture and re-adsorption of weakly bound molecules on the surface, giving rise to a weakly bound surface phase. The overall result is that the initially stable vacuum could evolve into an unstable condition with a slow pressure rise during a beam coast. To account for this uncertainty, a safe design must include an appropriate current margin of at least a factor of 4 with respect to the simple stability criterion. The importance of such a design margin is underlined by the fact that in the ISR, once an unstable pressure bump had been triggered, it always reappeared at a lower beam intensity during the following beam storage.

For the time being, the full set of input parameters for the desorption yields that would be required for an optimised design are not available. Indeed, only few elements of the matrix η_{ij} are known and until more of these important data become available, most of them can only be obtained by scaling [21].

Special surface coatings of vacuum chambers are a promising option but have been studied only very incompletely in the ISR. In the past the best results were obtained with bulk Ti-liners and with thin evaporated films of titanium deposited on the inner wall of vacuum chambers [4]. Following this approach, it is proposed to coat the experimental beam pipes for LHC with a getter film which can be activated by an *in-situ* bakeout of the beam pipe [26]. Tests are in preparation to evaluate the vacuum stability of vacuum systems which use this novel design concept.

REFERENCES

[1] O. Gröbner, R. Calder, PAC 73, San Francisco, 760, March 5-7, 1973

[2] R. Calder, 4th Annual Vacuum Conference, Liverpool, England 17th-19th April, 1974

[3] K. Johnsen in ‘The Rise of the Standard Model’, pp. 285-298, Cambridge University Press, 1997

[4] R. Calder, E. Fischer, O. Gröbner, E. Jones, 9th Int. Conf. on High Energy Accel., Stanford, California, 2nd-7th May 1974

[5] F. Rieke, W. Prepejchal, PR A6, 1507, (1972)

[6] E. Fischer, K. Zankel, CERN/ISR-VA/73-52, (1973)

[7] J.M. Laurent, private communication 1998

[8] A. G. Mathewson, CERN-ISR-VA/76-5, 1st March 1976

[9] M-H. Achard, R. Calder, A. Mathewson, CERN-ISR-VA/78-2, January 1978

[10] E. Fischer, CERN-ISR-VA/EF/sm (1975)

[11] R. Calder, A. Grillot, F. Le Normand, A. G. Mathewson, Proc. 7th Intern. Vac. Congr. Sept. 12-16, Vienna, 1977

[12] A. G. Mathewson, Vuoto, Vol. 17, No. 3, 102, July-September (1987)

[13] R. Veness et. al., EPAC-98, Stockholm, (1998)

[14] O. Gröbner, P. Strubin, IEEE Trans. Nucl. Science, Vol.NS-24, No 3, June 1977

[15] W. C. Turner, J. Vac. Sci. Technol. A 14 (4) , 1996

[16] C. Benvenuti, R. Calder, N. Hilleret, IEEE Trans. on Nucl. Sci. Vol, NS-24, No. 3, June (1977)

[17] J. C. Barnard, I. Bojko, N. Hilleret, Vacuum 47, No. 4, 347, (1996)

[18] R. Calder et al. J. Vac. Sci. Technol. A 14(4), p2618, 1996

[19] O. Gröbner, CERN/ISR-VA/76-25, 8th June, (1976)

[20] A. G. Mathewson, P. Strubin, ISR Performance Report, Run 1196, ISR/VA/AM/sm, 17th August (1981)

[21] O. B. Malyshev et al., LHC Report in preparation.

[22] O. Gröbner, CERN/ISR-VA/76-25, 1976

[23] N. Hilleret, R. Calder, Proc. 7th Int. Vac. Congr. Vienna, 227, 1977

[24] R. Calder, O. Gröbner, ISR-Performance Report Run 199 and 204, 1972

[25] E. Jones, J-C. Brunet, ISR Performance Repot, Run 312, 316. 23. May, 1973

[26] C. Benvenuti, P. Chiggiato, F. Cicoira, V. Ruzinov, VACUUM, Vol 50, No 1-2, 1998