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Photon stimulated desorption of an unbaked stainless steel chamber by 3.75 keV critical energy photons

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A stainless steel vacuum chamber, which had been going through a usual laboratory ultrahigh vacuum process, was exposed to a white synchrotron radiation photon beam, 3.75 keV critical energy, 70 W power at DCI. The vessel was however not baked ''*in situ*'' in order to test the necessity of this intermediate step. This is an issue with far reaching consequences for new synchrotron radiation sources. Beam scrubbing from a photon beam dose of 2.3×10^{23} photons m^{-1} was found to decrease the molecular yields from an initial value of 10^{-2} molecules per photon to below 10^{-5} for the main species CO and CO_2. The cleaning effect of the secondaries was clearly demonstrated, thus justifying the definition of the photon beam dose. It also explains the strong reduction of the static pressure. Wall pumping developed by the irradiation of the 3.6 m long tube was found to develop a pumping speed of, respectively, 750 and 1900 $\ell\,s^{-1}$ for CO and CO_2 and nil for H_2, CH_4, and N_2. The resulting pumping capacity amounts to an equivalent of 10^{-4} monolayer for both CO and CO_2 to be compared to a total of 2 monolayers removed by beam scrubbing. These results are finally applied to predict the gas beam lifetime for a new synchrotron radiation source SOLEIL. It appears that a reasonable lifetime can be reached in a short time in the absence of *in situ* bakeout. © *1999 American Vacuum Society.*
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I. INTRODUCTION

The present study aims at providing quantitative data so as to decide whether, in the absence of *in situ* bakeout, the beam scrubbing of vacuum vessels allows one to reach a comfortable gas beam lifetime for future synchrotron radiation (SR) sources.

The interest for such an issue was stimulated by a discussion which took place during a vacuum workshop held at Orsay in April 1996.[1] It concerns mainly two aspects. Savings on capital and running costs of the new sources is the first one. Machine stability threatened by beam induced thermal effects in the vacuum chamber is another one. The absence of bakeout jacket allows one a larger clearance with respect to the surrounding magnets, thus totally preventing any contact point.

Assuming a usual preparation of the vacuum vessels including laboratory bakeout, the question is in fact a threefold one:

(a) Can one ultimately reach a low enough static outgassing as well as a photon stimulated desorption (PSD) gas load which does not critically depend on local vacuum vessel details?

(b) Can this, together with a suitable distribution of pumping speed around the ring circumference allow one to reach the gas beam lifetime specifications needed usually?

(c) How long would it take with realistic conditions for a modern SR source to reach such a situation? In connection with this, what would be, in terms of recovery time, the impact of venting part of the ring to atmosphere?

Sections II–X of the present article are devoted to answer a number of problems raised by (a). Based on a new SR source ''SOLEIL,''[2] the Appendix is a first attempt to illustrate a practical situation[3,4] in answer to (b) and (c).

II. DESCRIPTION OF THE TESTS PRIOR TO THE IRRADIATION

A. Chamber

The chamber is a stainless steel tube 3.6 m long, 129 mm in diameter, 1.5 mm thick equipped with two 63-mm-diam outlets, one for a gauge, the other one for pumping. These are located on the central part of the tube.

On each side of the chamber, two square cooling copper tubes 8×8 mm^2 with an inner hole $\phi = 6$ mm are stuck in the midplane all along the chamber with Thermon cement. Thermostated water at 25 °C is run in the tubes. The heat conductivity of Thermon is close to that of stainless steel. With the above geometry and for a photon beam power of 70 W (300 mA) spread over 3.2 m, the temperature difference between the cooling water and the inner surface of the tube is smaller than 1.5 °C. A 3 mm glass wool insulation protects the tube from room temperature change. The temperature measured by a T.C. on the upper part of the tube, and for steady run-

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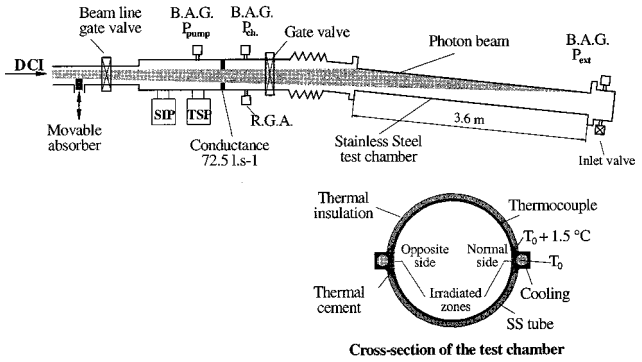


FIG. 1. Synopsis of the beamline for PSD studies at DCI.

ning conditions shows variations smaller than 1 °C, thanks in particular to the very large lifetime of the positron beam (200 h).

The chamber received the normal stainless steel surface treatment performed usually at CERN.

B. Laboratory bakeout

The chamber has been baked out at 200 °C for 20 h with a 160 $\ell\,s^{-1}$ turbo pump backed up with an Alcatel forepump. The system included two Bayard–Alpert (BA) gauges, a conductance, 50 $\ell\,s^{-1}$ for N_2, and a gas analyzer QMG 112 in order to evaluate the quantities of molecules desorbed. Using a special bench, the residual gas analyzer (RGA) was calibrated against a BA gauge in the pressure range 10^{-5}–10^{-3} Pa for the H_2, CH_4, N_2, and CO gas species.

The various quantities of molecules pumped down during the initial bake out are shown below.

Gas species	H_2	CH_4	H_2O	CO	CO_2	Total
mol $cm^{-2}\times10^{15}$	11	0.7	7	4.4	5.7	28.8

III. TESTS ON THE BEAMLINE

A. Installation and preliminary pumping

The beamline has been fully described in an earlier article.[5] The layout is reminded in Fig. 1. The test chamber was transferred to the site and installed, the active part of the beamline including the ion pump, the Ti sublimators, the two BA gauges the RGA, and finally the pumping hole being kept in ultrahigh vacuum.

The downstream part of the beamline was evacuated with the help of a turbomolecular pump, down to a pressure of 10^{-4} Pa and then pumped for about one week through the 72.5 $\ell\,s^{-1}$ conductance. By this time, the pressure in the test chamber reached 6.0×10^{-7} Pa, the RGA spectrum showing an important H_2O peak.

Later on, the vertical alignment of the chamber was checked against the photon beam direction. The chamber was finally oriented for irradiating the so-called ''normal side.''

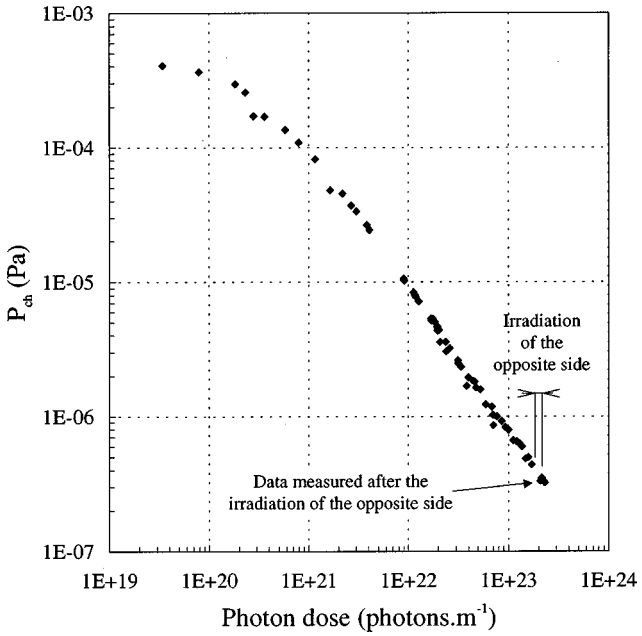


FIG. 2. Total pressure in the test chamber normalized to 300 mA vs photon beam dose.

B. Irradiation of the test chamber

1. Dynamic pressure

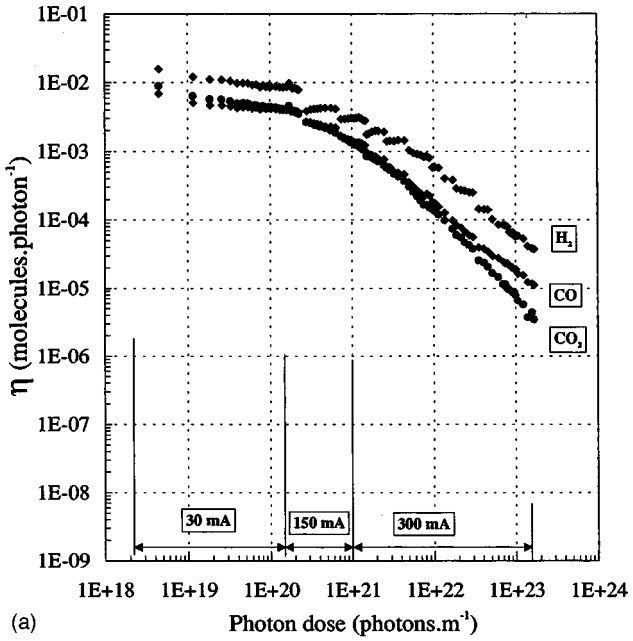
In order to limit the pressure to values below 10^{-4} Pa, the beam intensity was successively raised from 1.5 to 30 mA, 150 mA, and finally 320 mA, the normal starting current for a DCI beam fill. Thanks to its tremendous lifetime (larger than 200 h), the beam which is usually injected on Monday afternoon lasts until Saturday 4 a.m., whereby its intensity is around 220 mA. Such a beam sequence is repeated every week, except for accidental beam losses. During a week of irradiation, an average integrated beam dose of 27 A h is collected. In our units, a beam of intensity 1 A circulating during 1 h (1 A h) corresponds to a photon beam dose of 1.25×10^{21} photons per meter of the test chamber.

The normal side was irradiated for six weeks and the integrated photon beam dose thus reached 137 A h. Thanks to the upstream bellows, the chamber still under vacuum was then reoriented to a symmetric position with respect to the photon beam, so as to irradiate the so-called ''opposite side.'' An integrated photon beam dose of 28 A h was accumulated during one week. The normal side was then further irradiated during another week, the extra integrated photon beam dose being 19 A h.

During the whole period, the pumping speed in the upstream part of the beamline was reactivated from time to time, thanks to fresh sublimations. It was always kept at least an order of magnitude larger than the 72.5 $\ell\,s^{-1}$ conductance.

The results of the irradiation tests are presented below.

Figure 2 shows on a log–log scale the evolution of the total pressure measured in the test chamber as a function of



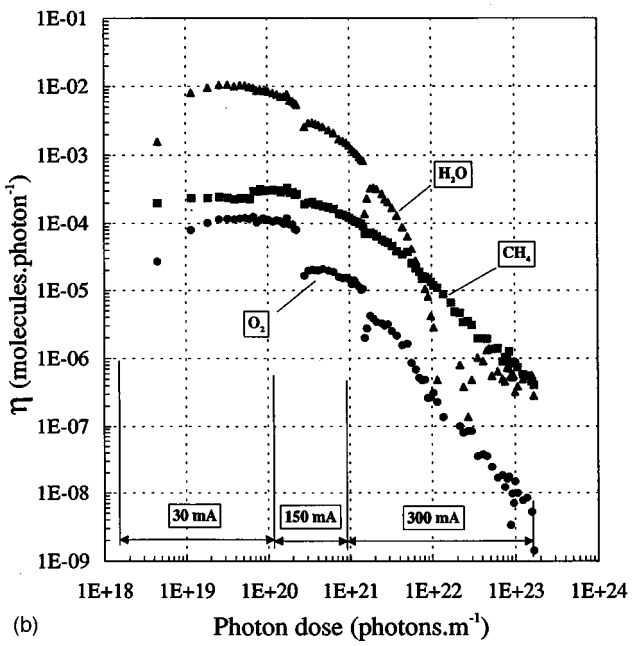


FIG. 3. (a) Molecular yield vs photon beam dose for H_2, CO, and CO_2. (b) Molecular yield vs photon beam dose for CH_4, H_2O, and O_2.

the integrated photon beam dose evaluated in photons m^{-1}.

Figures 3(a) and 3(b) show the variation of the η's, the molecular yields (molecules pumped through the conductance per incident photon) as a function of the integrated photon beam dose.

Figure 4 presents a linear fit of the η's at large integrated photon beam dose.

Figure 5 shows, as a function of the photon beam dose, the number of molecules desorbed and pumped through the conductance, normalized to 1 cm^2 area of the test chamber. The following illustrates the integrated numbers.

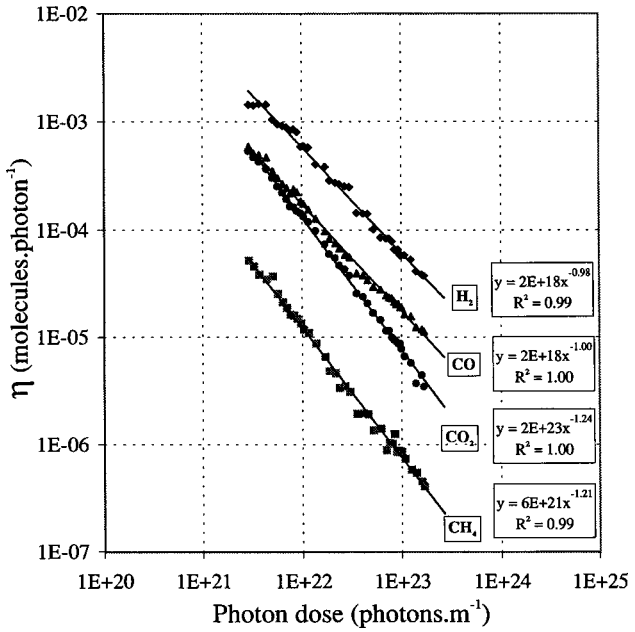


FIG. 4. Linear fit of the molecular yields vs photon beam dose for large beam doses.

Gas species	H_2	CH_4	H_2O	CO	CO_2	Total
mol $cm^{-2}\times 10^{15}$	5.6	0.2	2.0	2.0	1.7	11.4

2. Static pressure

The weekly sequence described above left the opportunity of a period of two and a half days without beam to record the evolution of the static pressure after beam abortion. The static pressure was defined as the one measured every week on Monday morning (52 h after beam abortion). Figure 6

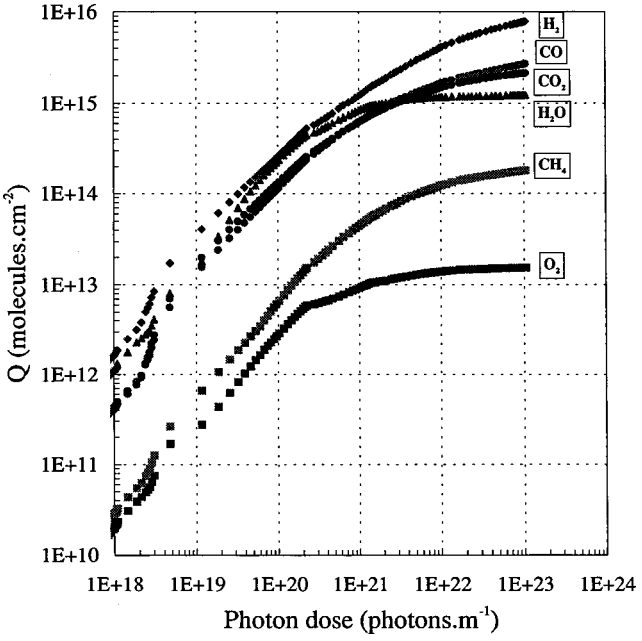


FIG. 5. Number of molecules desorbed per square centimeter of surface area as a function of the photon beam dose.

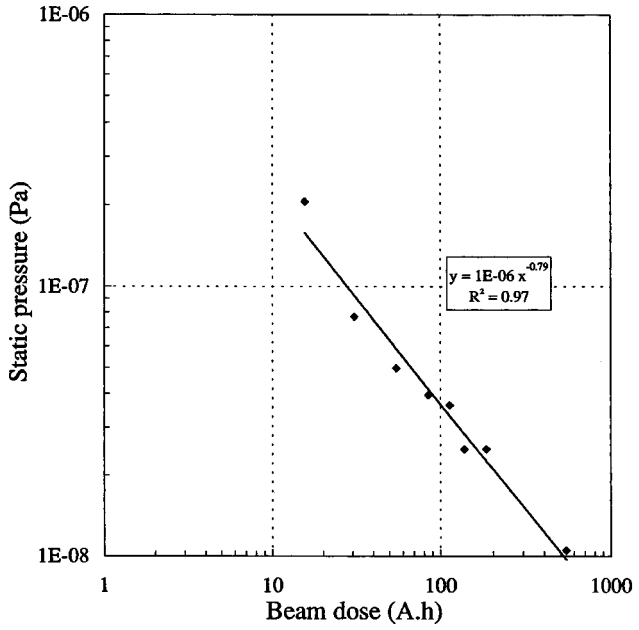


FIG. 6. Static pressure vs integrated beam dose evaluated in amperes per hour.

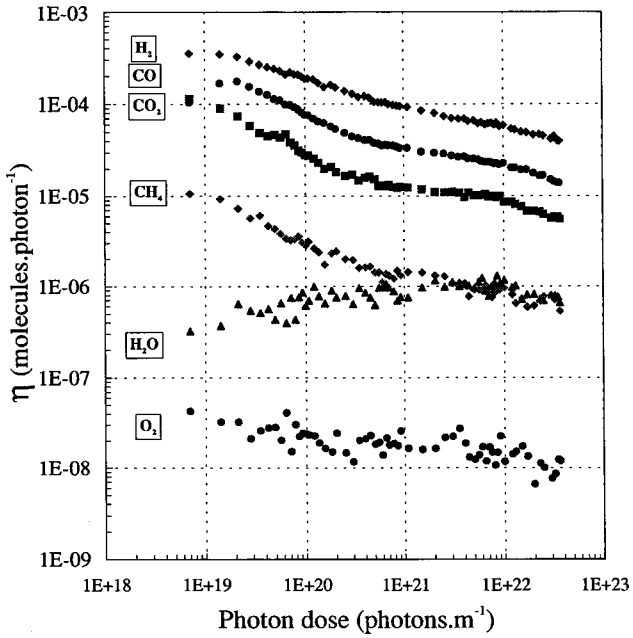


FIG. 7. Molecular yields vs photon beam dose for the irradiation of the opposite side.

presents on a log–log scale the decay of the static pressure as a function of the integrated beam dose measured over a period of two months. The slope of the curve is 0.80.

A final measurement recorded after reaching an integrated beam dose of 540 A h and with the RGA switched off, gave a value as low as 1.05×10^{-8} Pa. This is another important proof of the effectiveness of beam scrubbing.

IV. CONCLUSIONS OF THE IRRADIATION TESTS OF A CHAMBER "UNBAKED *IN SITU*"

The results can be appreciated as such and also in comparison with those from a very similar experiment performed at Orsay on a Cu chamber baked out *in situ*[5] and on a stainless steel chamber at Brookhaven National Laboratory (BNL).[6]

The main comments are: At small integrated photon beam dose, the values of η's are an order of magnitude larger for the present chamber; and water vapor photon stimulated desorption is dominant by a factor of 3 as compared to that of CO and CO_2 for small photon beam dose [see Figs. 3(a) and 3(b)]. However, rather soon, the situation is reversed and H_2O partial pressure becomes a small fraction (2%–3%) of that of CO and CO_2. At this point the dynamic pressure of H_2O shows practically no difference with the static value, a situation in contrast from that of other gas species.

The dependance of the molecular yields of H_2, CH_4, CO, and CO_2 with the photon beam dose D above 4×10^{21} photons m^{-1} (see Fig. 6) shows very good fits with a simple formula

$$\eta=\frac{1}{D^a}. \tag{1}$$

The exponent a, ranges between 0.98 and 1.24 for the different gas species.

These values are somewhat larger than those measured on the Cu chamber (0.80) in identical conditions.

At the end of six weeks, the photon beam dose being 1.7×10^{23} photons m^{-1} (137 A h), the comparative values of η's for CO and CO_2, the relevant species to the gas beam lifetime, are given below both for the Cu chamber and for the stainless steel chamber.

Cu chamber baked *in situ* CO: 7.0×10^{-6}, CO_2: 7.0×10^{-6}

Stainless steel chamber not baked *in situ* CO: 1.0×10^{-5}, CO_2: 4.0×10^{-6}

At this moment, the dynamic partial pressure of CO was 1.7×10^{-7} Pa and that of CO_2, 7.0×10^{-8} Pa for a photon beam power of 70 W (300 mA beam intensity). The total static pressure was 2.5×10^{-8} Pa.

V. IRRADIATION OF THE OPPOSITE SIDE OF THE CHAMBER

After an irradiation corresponding to 1.7×10^{23} photons m^{-1} (137 A h) of the so-called normal side, the chamber was reoriented symmetrically to the photon beam. The so-called opposite side was then irradiated for one week with a beam dose corresponding to 0.35×10^{23} photons m^{-1} (28 A h) in conditions strictly similar to the previous ones.

Figure 7 shows the dependance of the molecular yields with the new beam dose. The substantial reduction of the η's as compared to the values of the initial irradiation shows that

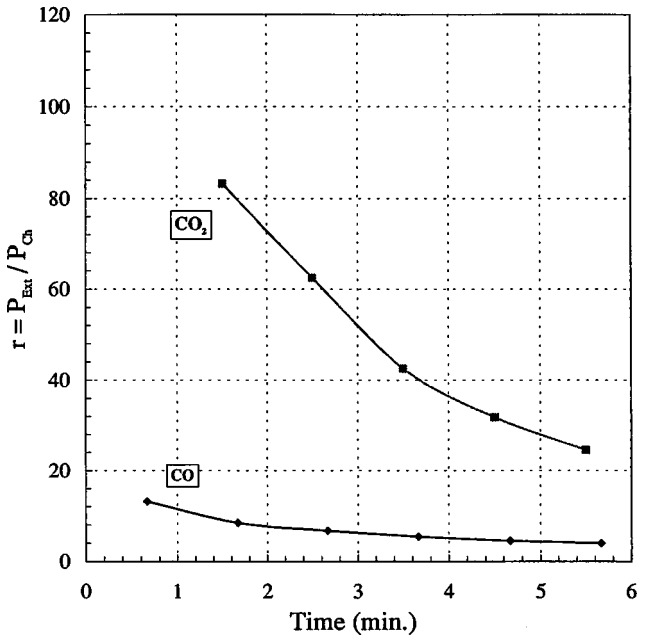


FIG. 8. Ratio of pressures at both ends of the test chamber as a function of time, displaying various aspects of wall pumping for CO and CO_2.

the opposite side was already conditioned to a large extent by the secondaries of the photon beam. Very similar results were obtained previously with an irradiation of a Cu chamber.[5]

Following this, the normal side was again irradiated for another week (19 A h). The decrease of the total pressure, see Fig. 2, shows no particular discontinuity with that of the initial irradiation provided the contribution of the dose of the opposite side is added.

VI. WALL PUMPING AFTER BEAM ABORTION

These measurements were carried out after the full photon beam dose of 2.3×10^{23} photons m^{-1} (184 A h) was collected.

In the absence of beam during a weekend, several gas species were injected one after the other through the adjustable leak at the chamber downstream end. The ratio P_{ext}/P_{ch} between the pressures at the two ends of the chamber (see Fig. 1) was evaluated after subtracting the base values. For the gas species H_2, CH_4, and N_2 the ratio has exactly the value calculated from the known conductances, namely 1.5. In contrast, the pressure ratio for CO and CO_2 was found to be much larger, thus indicating the presence of an extra pumping by the wall, see Fig. 8. However the pumping speed was found to decrease very fast. With a limited gas flow inlet pressure in the range of $1-2\times10^{-7}$ Pa, the decay of the pumping speed could be observed for at least 5 min.

A simple model using a uniformly distributed conductance and wall pumping speed, together with the pressure ratio extrapolated at time zero enable one to evaluate the pumping speed integrated over the tube length. It appears that the wall developed no pumping speed for H_2, CH_4, and N_2 in contrast with 750 and 1900 $l\,s^{-1}$ for CO and CO_2, respectively. The integrated quantity of gas which can be pumped by the walls is 1.3×10^{-5} and 1.4×10^{-5} Pa m^3, respectively, for the two gas species.

The prior results call for two remarks: The wall pumping speed measured for CO and CO_2 corresponds to a fraction of 5.2×10^{-3} and 1.8×10^{-2}, respectively, of a fully absorbing tube inner surface; and the amount of gas molecules pumped by the walls is in average 2×10^{11} molecules cm^{-2}, that is of the order of 2×10^{-4} monolayers.

In another test, the wall pumping experiment was repeated after an interruption of 40 min during which the system was pumped by the conductance C. Very similar results were obtained in the second measurement, thus showing that the adsorption of the molecules on the walls is a very quickly reversible process.

VII. WALL PUMPING SPEED IN THE PRESENCE OF IRRADIATION

When the photon beam is present, two processes are going on at the same time: photon stimulated desorption of molecules and partial reabsorption by the walls.

A simple model was worked out with a uniformly distributed conductance (total conductance of the test tube, C_0), a uniformly distributed desorption (λ per unit length) and a uniformly distributed pumping speed (integrated speed on the test tube length V_0).

The pressure differential equation is

$$P''(x)-\eta^2P(x)=\frac{-\lambda}{C_0 l} \quad \text{with} \quad \eta^2l^2=\frac{V_0}{C_0}, \quad l=\text{tube length}.$$

Solving it gives

$$P_{ch}=\frac{\lambda l}{V_0}\tanh\,\eta l\frac{(C_0V_0)^{1/2}}{C+(C_0V_0)^{1/2}\tanh\,\eta l} \tag{2}$$

and

$$P_{ext}=P_{ch}\cosh^{-1}\,\eta l+\frac{\lambda l}{V_0}\,\frac{\cosh\,\eta l-1}{\cosh\,\eta l}. \tag{3}$$

The ratio P_{ext}/P_{ch} is

$$r=\cosh^{-1}\,\eta l+\tanh\frac{\eta l}{2}\left[\frac{C}{C_0\eta l}+\tanh\,\eta l\right]. \tag{4}$$

For $V_0=0$, $r_0=1+\frac{1}{2}(C/C_0)=1.41$ and for $V_0=\infty$, $r_\infty=1$.

At small values of ηl

$$P_{ch}=\frac{\lambda l}{C+V_0}, \tag{5}$$

and for large values of ηl,

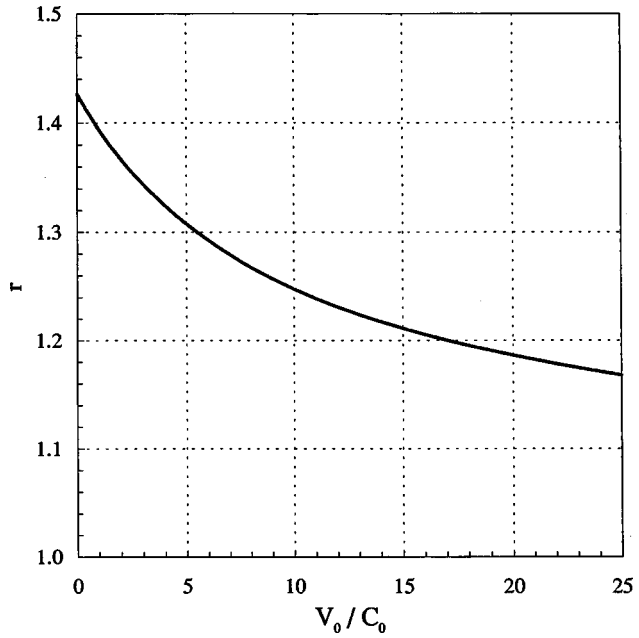


FIG. 9. Theoretical variation of the ratio of pressures at both ends of the test chamber as a function of V_o/C_o.

$$P_{\mathrm{ch}}=\frac{\lambda l}{V_0+C(V_0/C_0)^{1/2}}. \tag{6}$$

The quantity of gas pumped through the conductance, $q=CP_{\mathrm{ch}}$, which is used to evaluate the true desorption rate is

$$q=\lambda l\frac{C}{V_0+C(V_0/C_0)^{1/2}}. \tag{7}$$

One can therefore draw several conclusions from this simple model: The ratio r allows one to evaluate the pumping speed, at all stages of the conditioning. It is, however, not very sensitive to this value as shown by Fig. 9 which presents the dependance of r as a function of V_0/C_0; and the true desorption is reduced from the virtual desorption rate λl by the factor

$$k=V_0/C+(V_0/C_0)^{1/2}. \tag{8}$$

We have attempted to evaluate V_0 during the first period of irradiation of the chamber which cumulated with a beam dose of 137 A h. In the absence of a second RGA at the extreme end of the test chamber, only the total pressure measured by the two BA gauges was considered.

Figure 10 shows the measurements of the ratio r as a function of the integrated photon beam dose. Although the variation is small, 1.385–1.19, there is a clear evidence for the existence of wall pumping during irradiation. Figure 11 presents the value of the wall pumping speed deduced from the comparison with the theoretical ratio computed in the assumption of a single gas species, namely CO. This comparison is justified by the fact that hydrogen contribution to the BA gauge readings is small. Furthermore, the CO_2 contribution becomes comparatively smaller than that of CO at high beam dose. Wall pumping speed develops more or less linearly with the integrated photon beam dose. For the value corresponding to 137 A h it is in reasonable agreement with the measurements reported in Sec. VI, on account of the relative contributions of CO and CO_2, 1 and 0.4, respectively.

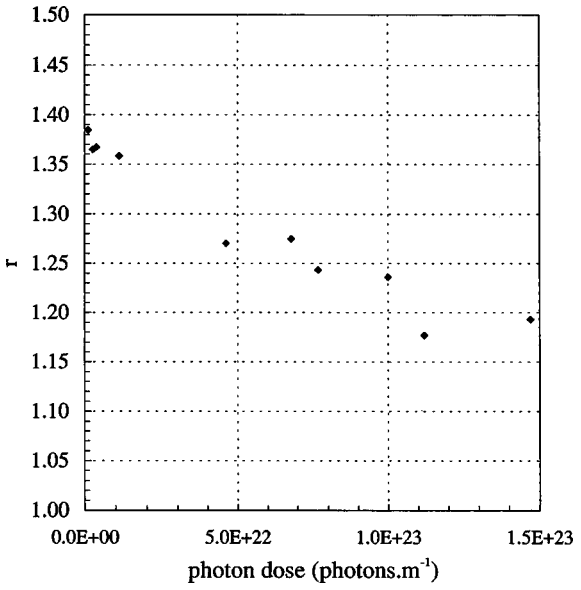


FIG. 10. Experimental variation of the ratio of the pressures at both ends of the test chamber as a function of the photon beam dose.

VIII. NEW IRRADIATION TESTS AFTER VENTING

A. Venting with dry N_2

This test aims at simulating a foreseen intervention on the ring vacuum system. After collecting a beam dose of 2.3

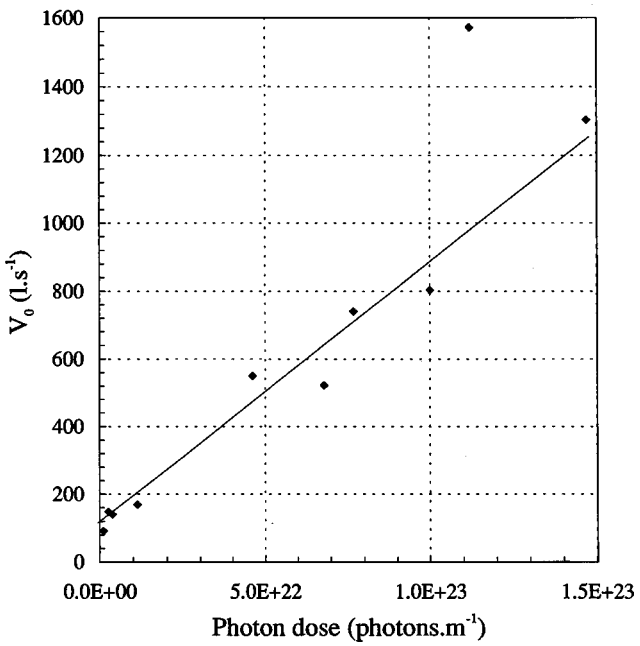


FIG. 11. Wall pumping speed during irradiation assuming CO dominance.

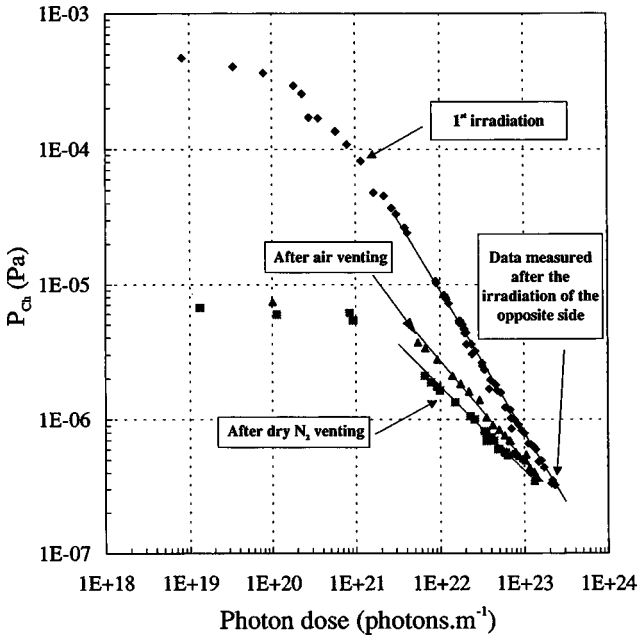


FIG. 12. The total pressure variation vs photon beam dose for the initial irradiation and after dry N_2 and air ventings.

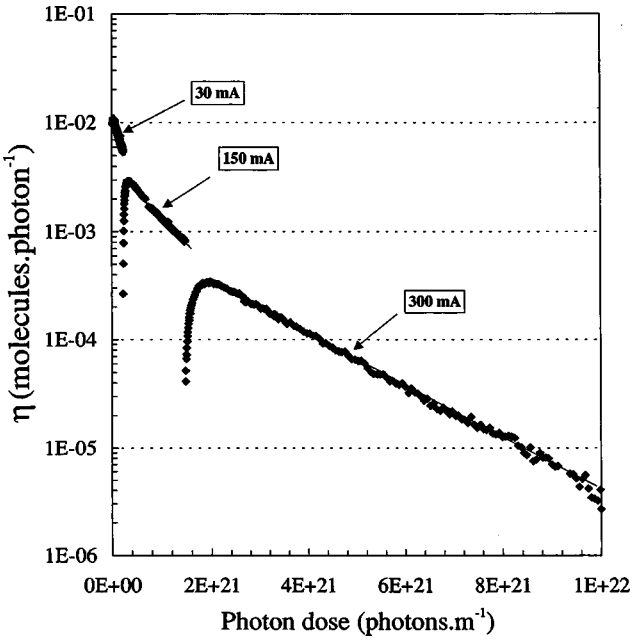


FIG. 13. Photon stimulated desorption of H_2O displaying an exponential behavior.

$\times 10^{23}$ photons m^{-1} (184 A h), the downstream part of the beamline was let to atmospheric pressure for a while. Dry N_2, 5 ppm purity, was used for refilling the system through a carefully evacuated duct arrangement. After pumping down until a pressure 10^{-6} Pa was reached, the chamber was again irradiated at full beam power during two typical weekly sequences.

Figure 12 shows the evolution of the pressure difference on both sides of the conductance *C*, as a function of the beam dose.

At small doses the molecular yield is strongly reduced in comparison with the values observed during the initial irradiation. The conditioning slopes are however correspondingly smaller. These observations are another illustration of the so-called memory effect of PSD.

They can be stated in precise terms: H_2, H_2O, CO, and CO_2 are desorbed in proportions similar to those measured at the beginning of the first irradiation. In absolute terms, the reduction factor is 60; the conditioning slope in the log–log plot is more or less reduced by a factor of 2; and the static pressure goes down ''rather rapidly.''

After two weeks, 0.62×10^{23} photons m^{-1} (50 A h), the dynamic and static conditions are not very far from those reached earlier with a beam dose of 137 A h.

In conclusion, the behavior is similar to that observed during the initial irradiation, except for general scaling factors.

B. Venting with air

This test aims at simulating a vacuum failure, however free from a strong pollution, such as oil for instance.

The results are very similar to those observed during N_2 venting (see Fig. 13). The desorption rate is however a factor of 1.7 stronger at the beginning, but the conditioning a little faster.

Altogether, after a four week conditioning, the system has more or less recovered both the dynamic and the static conditions.

IX. TENTATIVE INTERPRETATION OF SOME PSD ASPECTS

A. True and virtual molecular yields

The gas species desorbed under photon bombardment are mostly H_2, CH_4, CO, CO_2, and H_2O. We have seen in Sec. VII, that H_2 and CH_4 exhibit no wall pumping. Obviously for these molecules, there is no difference between true and virtual molecular yields. The same experiment has also demonstrated the existence of a large wall pumping speed for CO and CO_2 measured for a photon beam dose of 2.3 $\times 10^{23}$ photons m^{-1} (184 A h). However, we have seen that after a short while, a molecule of either gas species pumped by the wall will desorb and reach the pumping conductance thus disappearing from the test chamber. So, any molecule CO or CO_2, which was once desorbed through PSD will ultimately reach the pumping hole, whatever the number of sticking collisions it will have suffered before.

The paradoxical effect of the wall pumping is to reinforce the true molecular yield so as to give rise to the virtual molecular yield λl. The extra gradient arising from the wall pumping speed, combined with the virtual molecular yield gives again the true yield at the chamber output which is the basic figure to consider.

B. Virtual molecular yields

The molecules which were once desorbed through PSD and are for a while reattached on the surface, will either be naturally desorbed or suffer PSD events. There is however an important conclusion to be drawn from the occurrence of a large wall pumping speed in the presence of a photon beam, at a dynamic pressure above 10^{-7} Pa. In Sec. VI, it was shown that at such a pressure and without photon beam, the wall pumping would be saturated in a fraction of 1 h. The existence of a large pumping speed in the presence of the photon beam implies that the reabsorbed molecules will be mostly desorbed through PSD rather than thermally.

X. SUMMARY OF CONCLUSIONS ON THE PRESENT EXPERIMENT

As expected, surfaces not baked *in situ* have higher molecular yields than baked surfaces, in fact two orders of magnitude in the present experimental conditions.

However they display a faster cleaning rate with the photon beam dose. The ultimate dynamic vacuum turns out to be independent of the preparation before irradiation, namely *in situ*/no *in situ* bakeout. This is also true for the static vacuum (no beam) which goes down steadily with the photon beam dose.

Secondary radiations impinging on the whole inner chamber surface are quite active and dominant in the long run. This is an ''a posteriori'' justification for the use of the parameter photons m^{-1} instead of fluence for the beam dose.

Water vapor disappears exponentially that is much faster than other gas species. These exhibit a D^{-a} law over two decades of the molecular yields, with the parameter a ranging between 0.98 and 1.24.

At saturation, a rough 10 monolayers of different gas species are in average removed from all over the vacuum vessel inner surface.

For a photon beam dose of 2.3×10^{23} photons m^{-1}, a large wall pumping speed of the order of 1% of a fully adsorbing surface was measured for CO and CO_2, but none for H_2, CH_4, and N_2. The full pumping capacity which is developed is however very small, of the order of 10^{-4} monolayers. These adsorbed molecules display a fast reversible behavior. Furthermore a wall pumping speed is observed in the presence of the beam which develops proportionally to the photon beam dose. An important point is that a molecule, once desorbed through PSD, will ultimately be evacuated whatever the wall pumping is.

A new irradiation after venting shows that: Memory effect is rather strong; and final vacuum is again reached after more or less half the initial photon beam dose.

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APPENDIX: SCALING TO A 2.5 GeV SYNCHROTRON RADIATION SOURCE SOLEIL

SOLEIL is a 2.5 GeV ring, 336 m of circumference, which is supposed to run a 300 mA beam current, with a total beam power of 200 kW of 6.5 keV critical energy photons. The machine straight parts cover 90% of the ring circumference which absorb 41% of the emitted power from the dipoles. The total pumping speed ''on the beam'' installed on the ring will amount to 24000 $\ell\,\mathrm{s}^{-1}$. The gas beam lifetime for such a machine is supposed to be 30 h for an average gas pressure of 10^{-7} Pa, N_2 equivalent.[4]

In comparison, the present experiment was performed with 3.75 keV critical energy photons and a beam power of 70 W. After reaching an integrated beam dose of 2.3×10^{23} photons m^{-1}, a total pressure $CO+CO_2$ of 1.5×10^{-7} Pa was obtained for an effective pumping speed of 72.5 $\ell\,\mathrm{s}^{-1}$. (H_2 contribution to the gas beam lifetime is negligible.)

For a beam dose on the vacuum chamber identical to that reached in the present experiment, the gas beam lifetime would be

$$\tau = 30\,\frac{1.0\times10^{-7}}{1.5\times10^{-7}}\,\frac{6.5}{3.75}\,\frac{70}{200\,000}\,\frac{24\,000}{72.5} = 4\,\mathrm{h}.$$

The average number of photons impinging on the straight parts of the machine per day and per meter is

$$\frac{1.3\times10^{20} E I 2\pi\times.41\times.864\times10^{5}}{0.90\times336},$$

with E in gige-electron-volts and I in amperes.

This number would be 7.17×10^{22} photons $\mathrm{m}^{-1}\,\mathrm{day}^{-1}$, for a constant beam current of 0.3 A. It would therefore take of the order of 3.2 days to reach the assumed 2.3×10^{23} photons m^{-1} beam dose.

The above calculation neglects the contribution of the dipole vessel pressure. This is justified by the so-called local crotch absorbers which stop 59% of the beam power in sectors which should be degassed swiftly.

The above calculation is based on a photon flux uniformly distributed. This is substantiated by the fact that at a given location in a straight part, the product of the photon flux by the molecular yield (grossly proportional to the reciprocal of the photon beam dose) is roughly constant. This is fully exact for a $\eta = D^{-1}$ law.

In conclusion we see that after running a machine for several days, a reasonable 4 h lifetime is obtained for a beam intensity as large as 300 mA. For a photon beam dose ten times higher, a 40 h beam gas lifetime would be reached, but we have not investigated this region of parameters in our experiment. We note however that there is no sign of leveling off of the curves η_s' of D_s' in this experiment in the range of parameters investigated.

We are therefore confident in the above extrapolation.

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