Beam-loss induced pressure rise of Large Hadron Collider collimator materials irradiated with 158 GeV/u In^{49+} ions at the CERN Super Proton Synchrotron

E. Mahner, I. Efthymiopoulos, J. Hansen, E. Page, and H. Vincke

CERN, 1211 Geneva 23, Switzerland

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During heavy ion operation, large pressure rises, up to a few orders of magnitude, were observed at CERN, GSI, and BNL. The dynamic pressure rises were triggered by lost beam ions that impacted onto the vacuum chamber walls and desorbed about 10^4 to 10^7 molecules per ion. The deterioration of the dynamic vacuum conditions can enhance charge-exchange beam losses and can lead to beam instabilities or even to beam abortion triggered by vacuum interlocks. Consequently, a dedicated measurement of heavy-ion induced molecular desorption in the GeV/u energy range is important for Large Hadron Collider (LHC) ion operation. In 2003, a desorption experiment was installed at the Super Proton Synchrotron to measure the beam-loss induced pressure rise of potential LHC collimator materials. Samples of bare graphite, sputter coated (Cu, TiZrV) graphite, and 316 LN (low carbon with nitrogen) stainless steel were irradiated under grazing angle with 158 GeV/u indium ions. After a description of the new experimental setup, the results of the pressure rise measurements are presented, and the derived desorption yields are compared with data from other experiments.

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I. INTRODUCTION

An intense experimental program was started at the CERN Heavy Ion Accelerator (LINAC 3) in November 2000 to measure the beam-loss induced molecular desorption of Pb^{53+} ions at 4.2 MeV/u in order to prepare the Low Energy Ion Ring (LEIR) vacuum system for operation with heavy ions under Large Hadron Collider (LHC)-type conditions. Effective desorption yields of up to 2×10^4 molecules/ion were measured for standard stainless steel vacuum chambers [1]. Initial pressure rises depended strongly on the surface preparation of the vacuum chamber and could be reduced by polishing, noble-metal coating, and continuous bombardment (beam scrubbing) with heavy ions [2]. Similar high desorption rates and very strong pressure rises were also reported from GSI [3,4] and BNL [5,6]. At RHIC, a yield of 1.5×10^7 molecules/ion was reported for Au^{79+} ions with an energy of about 10 GeV/u [6]. This value is about 3 orders of magnitude higher than the yields measured previously at LINAC 3. This latter observation, indicating a strong effect of the ion energy on the desorption rate, motivated the Super Proton Synchrotron (SPS) experiment described in this paper. The measurements were done with In^{49+} ions at 158 GeV/u, an energy very close to the 177 GeV/u injection energy of Pb^{82+} into the LHC.

II. EXPERIMENTAL SETUP

At the CERN SPS an experiment was installed in October 2003 to measure the ion-induced desorption yields for In^{49+} at 158 GeV/u. An overview of the experimental setup is shown in Fig. 1.

The experiment consists of a rotatable 316 LN (low carbon with nitrogen) stainless steel vacuum chamber with an inner diameter of 400 mm and a height of 292 mm. This central chamber is pumped with a turbo molecular pumping (TMP) group, a 400 ℓ/s sputter ion pump (SIP), and a 1200 ℓ/s titanium sublimation pump (TSP). Pressure measurements are made with a Bayard-Alpert gauge (BAG) and a quadrupole residual gas analyzer (RGA), both calibrated. The RGA can be calibrated *in situ* via a gas injection valve.

Four identical 316 LN stainless steel vacuum chambers, with an inner diameter of 156 mm and a length of 300 mm, are connected symmetrically (90° between each) to the central vacuum chamber. Each chamber is equipped with a different collimator sample, which were prepared in the following way. Three commercially available graphite blocks [7], each 200 mm long, 65 mm wide, and 20 mm thick, were first snow jet cleaned with CO_2 to remove the dust from the graphite surface and afterwards vacuum fired at 1000 °C for 2 h. One bare graphite block was kept under vacuum, while the second block was sputter coated with a nonevaporable getter film of TiZrV (1.5 μm), and the third graphite sample was sputter coated with Cu (1.5 μm). The fourth sample was a machined 316 LN stainless steel block (same dimensions as the graphite) that was cleaned and vacuum fired at 950 °C for 2 h.

Each sample was mounted on a motorized manipulator. The manipulators enable a vertical sample displacement of $z = \pm 25.0$ mm with a resolution of 0.02 mm. The position $z = 0$ corresponds to the center of the vacuum system. All four collimators are fixed in the horizontal plane (x-y direction) and were carefully aligned in order to guarantee an ion impact angle of $\Theta = 35$ mrad. A picture of an assembled sample inside a collimator chamber is shown in Fig. 2.

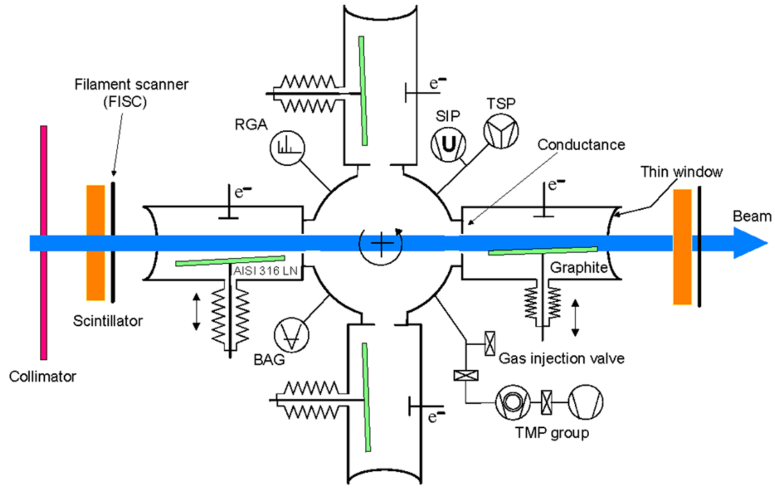

FIG. 1. (Color) Schema of the ion-induced desorption experiment at the CERN SPS.

Each sample chamber also contains one electron detector which is mounted on a port perpendicular to the collimator surface. A description of the functionality of these electron detectors, which were successfully used during electron cloud studies at the SPS, can be found elsewhere [8]. For the SPS ion-induced desorption experiment the standard electron detectors were modified and are now bakeable at 300 °C.

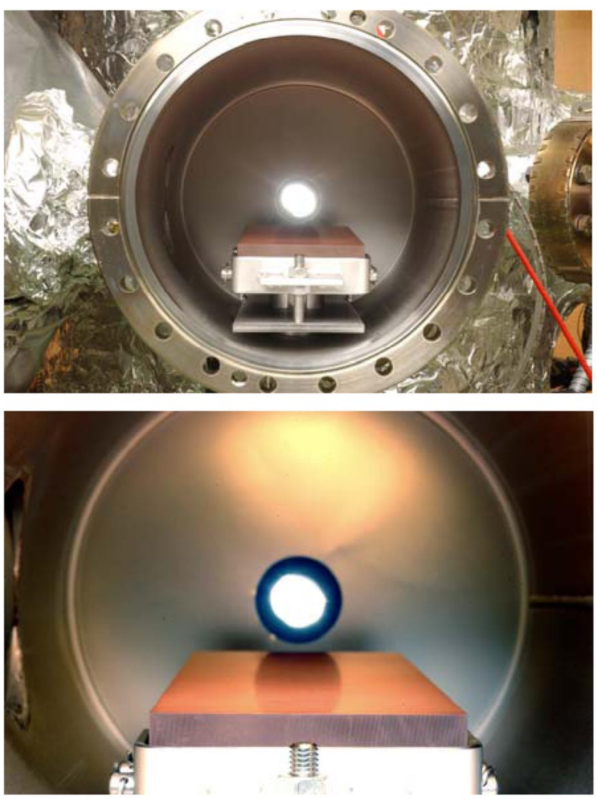

FIG. 2. (Color) Pictures of the inner part of one collimator chamber of the SPS desorption experiment. The aligned ($\Theta = 35$ mrad) Cu/graphite collimator is shown in its "parking position," i.e., 18.5 mm below the beam axis. The ion beam has to pass the centered conductance (diameter 30 mm), which is made of a vacuum fired 100 μm thick 316 LN stainless steel foil.

The sample chambers are closed with specially made 100 μm thick 316 LN stainless steel windows, which allow the 158 GeV/u ion beam to pass the experimental setup with negligible interaction. After assembly the vacuum system was baked at 300 °C for 48 h. A pressure of 7×10^{-12} Torr was achieved 72 h after cool-down to room temperature.

The experiment was then transported under vacuum to the SPS North Area, moved into the T4-H8 beam line, and fixed on a rail system, which allows the removal of the test stand from the beam axis. Two filament scanners, which are part of the SPS North Area beam line instrumentation, are used to measure the beam position. A picture of the experiment installed at the SPS is displayed in Fig. 3.

III. RESULTS

A. Pressure rise measurements

At the beginning of the experiment the In^{49+} ion beam was carefully aligned and passed the vacuum system without hitting the collimators, which were kept in their parking position, i.e., 18.5 mm below the beam axis. The pressure remained at about 6.2×10^{-12} Torr. The beam size was measured with the filament scanners to 2×2 mm^2 full width half maximum and 4×4 mm^2 full width.

For pressure rise measurements only one collimator was moved from its parking position into the beam axis and bombarded under 35 mrad grazing incidence with $\sim 1.5 \times 10^6$ In^{49+} ions/spill. The spill length was 6.2 s and the SPS cycle length 19.2 s. Pressure readings of the Bayard-Alpert gauge were taken every $\sim$150 ms. The

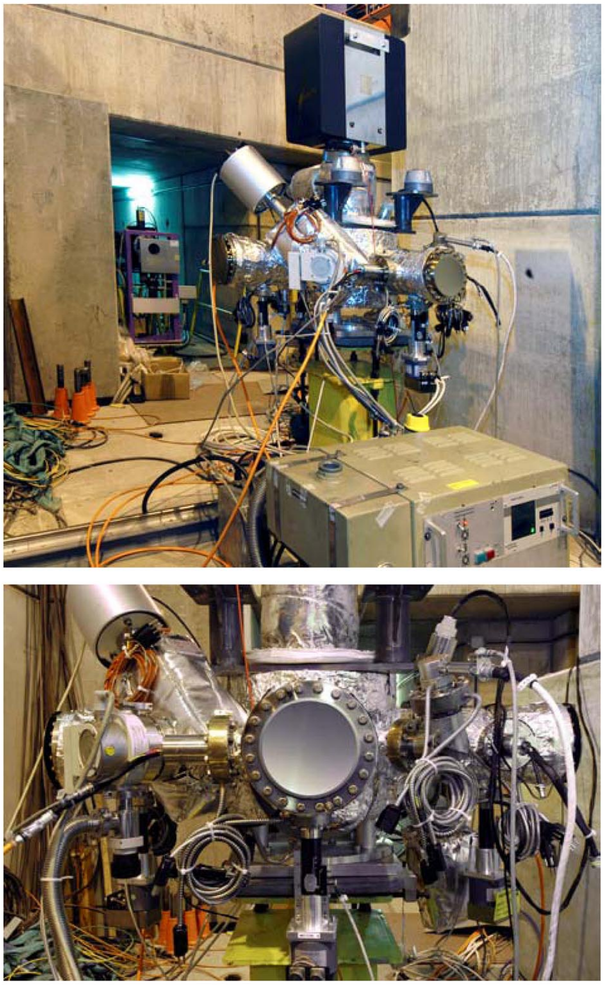

FIG. 3. (Color) Ion-induced desorption experiment installed on 31 October 2003 in the T4-H8 beam line at the CERN SPS (upper photo). Close view of one collimator chamber with the stainless steel window in the center, as seen by the ion beam, the collimator motorization at the bottom, and the electron detector on the left side (lower photo).

results obtained for the Cu/graphite sample are shown in Fig. 4.

A surprisingly small pressure increase was clearly identified when the 158 GeV/u indium beam was hitting the sample [see Fig. 4(a)]. The measured pressure rise pattern fits very well with the time the collimator is bombarded (6.2 s) and the period (13 s) without ion beam [see Fig. 4(c)]. Very similar pressure rises were measured for the other three collimator materials, i.e., for bare graphite, TiZrV/graphite, and 316 LN stainless steel. The results are summarized in Fig. 5.

B. Desorption yields

The measured pressure rises, shown in Figs. 4 and 5, are used to derive the desorption yields of the four LHC-type collimator materials. The effective desorption yield η_{eff} (molecules/ion) is given by

$$\eta_{\mathrm{eff}} = \frac{\Delta P \times S}{\dot{N}_{\mathrm{In}} \times k_B \times T} = G \times \frac{\Delta P \times S}{\dot{N}_{\mathrm{In}}},$$

where ΔP is the pressure rise under ion bombardment, S is the pumping speed in ℓ/s, $\dot{N}_{\mathrm{In}}$ is the number of impacting indium ions per second, k_B is the Boltzmann constant, T is the temperature (300 K), and G is a constant ($\approx 3.2 \times 10^{19}$ at 300 K), that converts gas quantities (Torr $\times\ \ell$) into number of molecules. It should be mentioned that partial pressure measurements were not successful during the beam time because the sensitivity of the secondary electron multiplier of the RGA was strongly reduced (due to aging) after the final 300 °C bakeout.

The pressure rises ΔP (N_2 equivalent), measured with the calibrated Bayard-Alpert gauge, had to be corrected (factor of 2.2) because of the time constant (10 s) of the used electrometer. This value is larger than the 6.2 s spill length which corresponds to the ion bombardment period. Both time constants explain the fact that the pressure rise curves (see Figs. 4 and 5) did not stabilize but show a nontypical "zigzag" behavior.

A pumping speed of $S \approx 1270\ \ell$/s (for CO) was measured *in situ* after the experiment. We obtain the following η_{eff} values for the different samples:

$$\eta_{\mathrm{eff}}\,(\text{graphite}) \approx 55\,800\,\text{molecules}/\text{In}^{49+}\,\text{ion},$$
$$\eta_{\mathrm{eff}}\,(\text{Cu/graphite}) \approx 111\,500\,\text{molecules}/\text{In}^{49+}\,\text{ion},$$
$$\eta_{\mathrm{eff}}\,(\text{TiZrV/graphite}) \approx 111\,500\,\text{molecules}/\text{In}^{49+}\,\text{ion},$$
$$\eta_{\mathrm{eff}}\,(316\,\text{LN stainless steel}) \approx 37\,200\,\text{molecules}/\text{In}^{49+}\,\text{ion}.$$

C. Temperature rise simulations

An important assumption for the ion-induced desorption yield estimation is the fact that a thermal contribution of the high energetic indium beam can be neglected, i.e., the 158 GeV/u heavy ions do not heat significantly the collimator surface. In order to verify this assumption, energy deposition calculations were performed with the Monte Carlo code FLUKA [9,10]. The whole electromagnetic and hadronic particle cascades, triggered by the impacting ions, were calculated. The computed energy deposition output has to be converted into a temperature rise of the material. The correlation between the temperature rise and the energy deposited can be calculated with

$$E_{\mathrm{dep}} = \int_{T_1}^{T_2} \rho \times c(T) \times dT,$$

where E_{dep} is the energy deposition per cm^3, ρ is the density, $c(T)$ is the specific heat capacity, and T is the temperature of the material. Since the expected temperature rise is small in our case, $c(T)$ can be set as constant. Therefore, the relation between the energy deposition and the temperature rise becomes linear. The formula leading

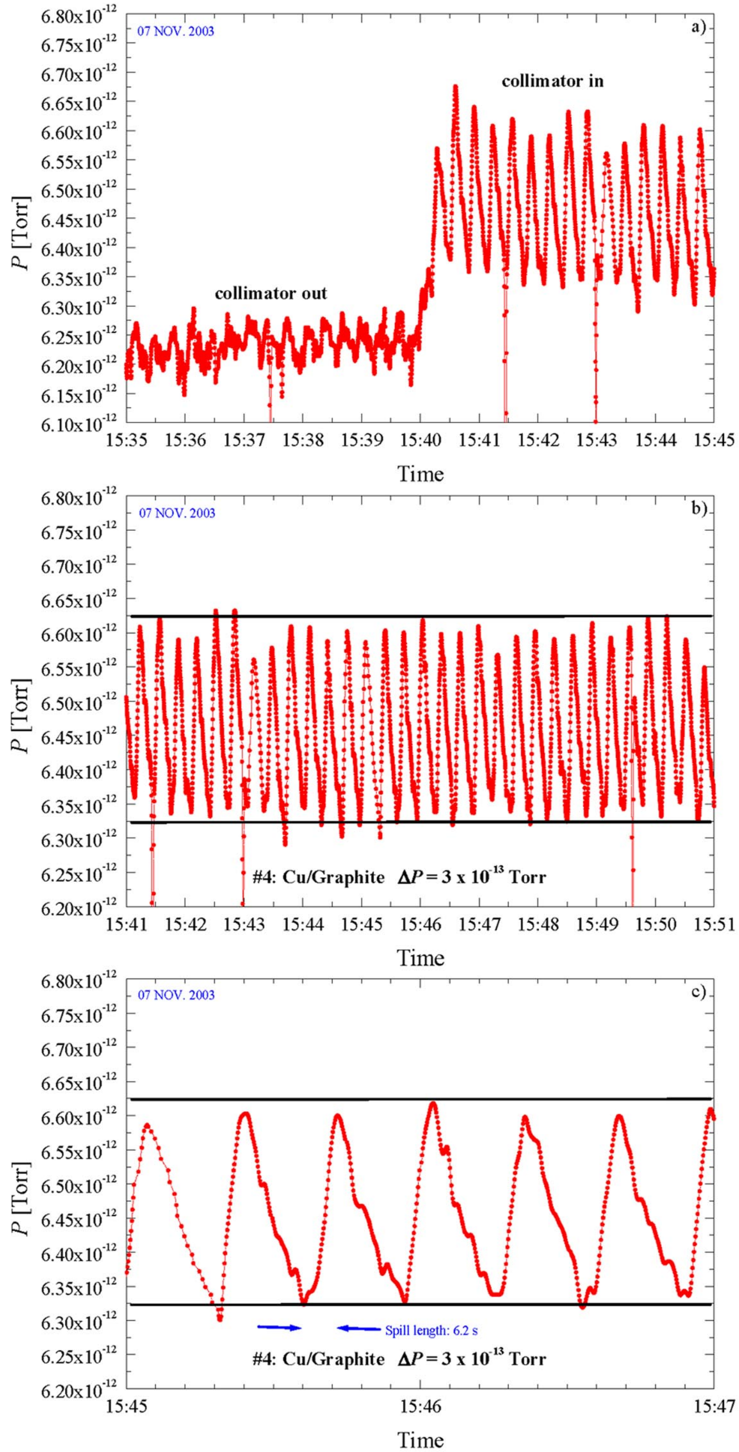

FIG. 4. (Color) Pressure rises of the Cu/graphite collimator bombarded under 35 mrad with 158 GeV/u In^{49+} ions at the SPS. The intensity was $\sim 1.5 \times 10^6$ ions/spill with a spill length of 6.2 s. (a) Pressure rise when the sample was moved at 15:40 h into the ion beam, (b) pressure rise during continuous bombardment, and (c) magnification of (b).

to the temperature rise ΔT is then given by

$$\Delta T = \frac{E_{\mathrm{dep}}}{\rho \times c}.$$

The bare graphite and the Cu/graphite collimators were chosen to study the heating effect. For the simulations and the subsequent temperature calculations carbon was taken into account with a density of 1.84 g/cm^3 and a specific heat capacity of 795 J/(kg K). Copper was simulated with a density of 8.96 g/cm^3 and a heat capacity of 385 J/(kg K). The ion beam parameters (energy, size, impact angle) and the collimator dimensions were taken

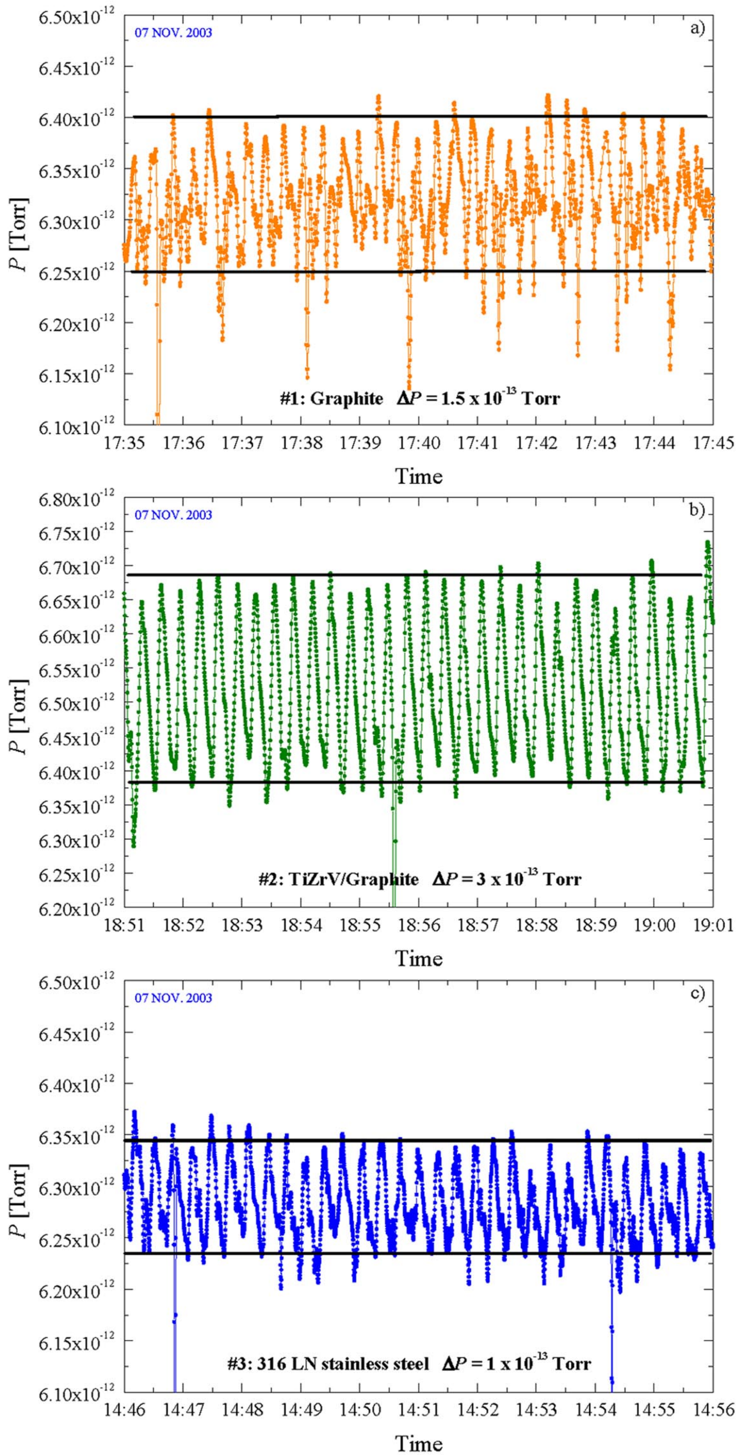

FIG. 5. (Color) Pressure rises of (a) the bare graphite sample, (b) the TiZrV/graphite sample, and (c) the bare 316 LN stainless steel sample bombarded under 35 mrad with 158 GeV/u In^{49+} ions at the SPS. The intensity was $\sim 1.5 \times 10^6$ ions/spill with a spill length of 6.2 s.

as described above. In Fig. 6 the simulated temperature rise of the bombarded Cu/graphite collimator is displayed.

One can conclude from the FLUKA simulations that the temperature increase of a Cu/graphite collimator, bombarded under 35 mrad angle with 1.5×10^6 In^{49+} ions of 158 GeV/u energy, is maximum 100 mK in the uppermost surface (1.5 μm) of the sample center [see Fig. 6 (left)]. For the collimator bulk the temperature rise ΔT is even several orders of magnitude lower [see Fig. 6 (right)]. Very similar temperature increases were obtained for the bare graphite sample. For comparison, the whole simula-

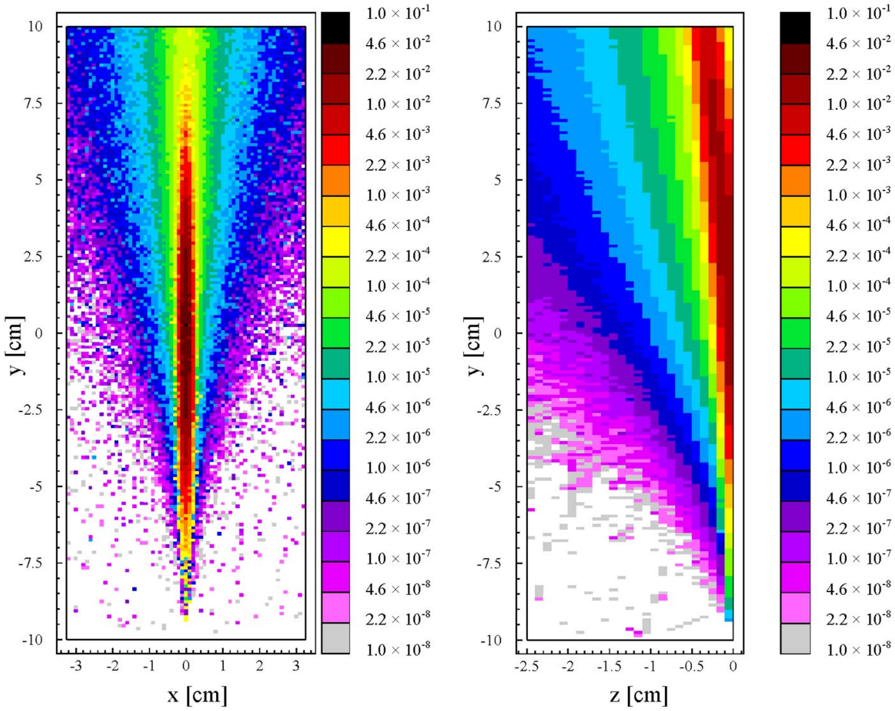

FIG. 6. (Color) Temperature increase ΔT (in kelvin) calculated for the Cu/graphite collimator bombarded under 35 mrad grazing angle with $\sim 1.5 \times 10^6$ In^{49+} ions at 158 GeV/u. Left: ΔT in the uppermost 1.5 μm copper layer (x-y plane); right: ΔT across the collimator (z-y plane) at $x = 0$.

tion procedure was repeated with protons as primary impacting particles. The results obtained, a temperature rise of about 2500 less than simulated for In^{49+} ions, confirmed the validity of the FLUKA simulations with indium ions. We conclude that the assumption to neglect a thermal contribution to the heavy-ion induced desorption process is fully justified for the intensities studied at the SPS.

We should mention that during collimator bombardment with 158 GeV/u indium ions no significant electron

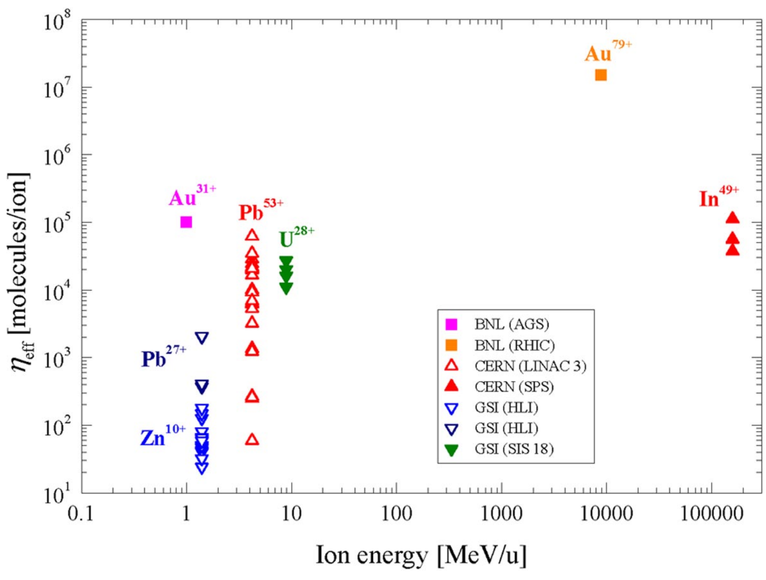

FIG. 7. (Color) Overview of heavy-ion induced desorption data including the SPS measurements with In^{49+} ions at 158 GeV/u. The measurements were made at CERN [1,2], GSI [3,4], and BNL [5,6]. The ion impact angles (perpendicular, mrad, μrad) of the experiments are different.

"activity" could be detected with the electron detectors, an observation which is currently not understood. The sensitivity of our electron detectors is about 10 nA.

D. Comparison with other desorption data

An overview of available data for heavy-ion induced desorption yields, measured as a function of the ion energy, is shown in Fig. 7.

Effective molecular desorption yields, derived from machine experiments (AGS: Au^{31+}; SIS18: U^{28+}; RHIC: Au^{79+}), are compared with dedicated "test-stand" experiments (LINAC 3: Pb^{53+}; HLI: Pb^{27+}, Zn^{10+}). We want to address the question of whether test-stand experiments give adequate answers to accelerator questions. The authors are convinced that one has to carefully distinguish between the low energy case (MeV/u) and the high energy case (GeV/u). For low energy machines, like AGS Booster, SIS18, and LEIR, charge-exchange processes (capture and loss) lead to beam losses onto the vacuum chamber with well-defined impact angles in the mrad range. Therefore, dedicated experiments with extracted beam (e.g., at LINAC 3, HLI, SPS) should give the right values for effective molecular desorption yields. The situation is different (no charge exchanges) for high energy machines, like RHIC and LHC, where losses are due to nonlinear dynamics and nuclear scattering, and result in very small impact angles in the μrad range or even less. Therefore, corresponding experiments are much more complicated. In addition, one cannot exclude contribution of other effects like electron or photon stimulated desorption.

The new SPS data (see Fig. 7) fit well with the low energy LINAC 3 data obtained for bulk 316 LN stainless steel and OFE (oxygen free electronic) copper vacuum chambers ($\eta_{\mathrm{eff}} \approx 2 \times 10^4$ molecules/Pb^{53+} ion). The wide spread of LINAC 3 desorption yields (see Fig. 7) is explained by the strong influence of the surface preparation (different polishing and coatings) of the stainless steel vacuum chambers [2]. We conclude that the effective molecular desorption yield of heavy ions does not depend strongly on the ion energy as suggested by the RHIC result. More ion desorption measurements in the range of ~10 MeV/u up to ~100 GeV/u are proposed to verify this conclusion.

IV. SUMMARY AND CONCLUSION

The present study represents the first ever desorption experiment with heavy ions at an energy well above 10 GeV/u. In^{49+} ions with 158 GeV/u bombarding LHC-type collimator material under 35 mrad only led to a very small pressure rise in the 10^{-12} to 10^{-11} Torr range. Effective beam-loss induced desorption yields of (4–11) $\times 10^4$ molecules/In^{49+} ion were measured for different materials. No dramatic pressure rise (several orders of magnitude) was observed and the reported RHIC desorption yield of 1.5×10^7 molecules/Au^{79+} ion is not confirmed. The influence of the ion type, ion charge state, and especially the impact angle on the desorption yield remains to be investigated.

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