Review of heavy-ion induced molecular desorption studies for particle accelerators

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Outline

• Introduction
  – CERN accelerators and vacuum systems overview, vacuum instabilities at the ISR, LEAR, SIS18.

• Heavy-ion desorption experiments
  – Ion desorption test-stands at CERN, GSI, LBNL, RHIC, ion beams and energies, target materials studied.

• Review of results
  – How we measure desorption, pressure rise measurements, surface characterizations with XPS & ERDA, impact angle & charge state dependence, energy scaling, thermal spike model, overview of desorption yield data.

• Mitigation techniques
  – Coatings, collimators, beam scrubbing.

• Conclusions, future studies, acknowledgements
Introduction: CERN Accelerators

ALICE\(^1\)  
\(\text{Pb}^{82+}\text{Pb}^{82+}\)

ATLAS\(^2,\) CMS\(^3\)  
\(\text{pp, Pb}^{82+}\text{Pb}^{82+}\)

LHCb  
\(\text{pp}\)

CERN Accelerator Complex

LEIR dynamic vacuum: \(10^{-12}\) Torr

Refs. for Heavy Ion Physics @ LHC

## CERN Accelerator Vacuum Systems

<table>
<thead>
<tr>
<th>Machine</th>
<th>Type</th>
<th>Year</th>
<th>Energy</th>
<th>Bakeout</th>
<th>Pressure (Pa)</th>
<th>Length</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linac, Booster, ISOLDE, PS, n-TOF and AD Complex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>LINAC 2</td>
<td>linac</td>
<td>1978</td>
<td>50 MeV</td>
<td>Ion pumps</td>
<td>$10^{-7}$</td>
<td>40 m</td>
<td>p</td>
</tr>
<tr>
<td>ISOLDE</td>
<td>electrostatic</td>
<td>1992</td>
<td>60 keV</td>
<td>-</td>
<td>$10^{-4}$</td>
<td>150 m</td>
<td>ions: 700 isotopes and 70 (92) elements</td>
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<tr>
<td>REX-ISOLDE</td>
<td>linac</td>
<td>2001</td>
<td>3 MeV/u</td>
<td>partly</td>
<td>$10^{-6} - 10^{-10}$</td>
<td>20 m</td>
<td></td>
</tr>
<tr>
<td>LINAC 3</td>
<td>linac</td>
<td>1994</td>
<td>4.2 MeV/u</td>
<td>Ion pumps</td>
<td>$10^{-7}$</td>
<td>30 m</td>
<td>ions</td>
</tr>
<tr>
<td><strong>LEIR</strong></td>
<td>accumulator</td>
<td>1982/2005</td>
<td>72 MeV/u</td>
<td>complete</td>
<td>$10^{-10}$</td>
<td>78 m</td>
<td>pbar, ions</td>
</tr>
<tr>
<td>PSB</td>
<td>synchrotron</td>
<td>1972</td>
<td>1-1.4 GeV</td>
<td>Ion pumps</td>
<td>$10^{-7}$</td>
<td>157 m</td>
<td>P, ions</td>
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<td>PS</td>
<td>synchrotron</td>
<td>1959</td>
<td>28 GeV</td>
<td>Ion pumps</td>
<td>$10^{-7}$</td>
<td>628 m</td>
<td>P, ions</td>
</tr>
<tr>
<td><strong>AD</strong></td>
<td>decelerator</td>
<td>1998</td>
<td>100 MeV</td>
<td>complete</td>
<td>$10^{-8}$</td>
<td>188 m</td>
<td>pbar</td>
</tr>
<tr>
<td>CTF3 complex</td>
<td>linac/ring</td>
<td>2004-09</td>
<td>26 GeV</td>
<td>partly</td>
<td>$10^{-8}$</td>
<td>300 m</td>
<td>e</td>
</tr>
<tr>
<td>PS to SPS TL</td>
<td>Transfer line</td>
<td>1976</td>
<td>26 GeV</td>
<td>-</td>
<td>$10^{-6}$</td>
<td>~1.3 km</td>
<td>P, ions</td>
</tr>
<tr>
<td><strong>SPS Complex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td>synchrotron</td>
<td>1976</td>
<td>450 GeV</td>
<td>Extractions</td>
<td>$10^{-7}$</td>
<td>7 km</td>
<td>p, ions</td>
</tr>
<tr>
<td>SPS North Area</td>
<td>Transfer line</td>
<td>1976</td>
<td></td>
<td></td>
<td></td>
<td>~1.2 km</td>
<td></td>
</tr>
<tr>
<td>SPS West Area</td>
<td>Transfer line</td>
<td>1976</td>
<td></td>
<td></td>
<td></td>
<td>~1.4 km</td>
<td></td>
</tr>
<tr>
<td>SPS to LHC T12/8 Line</td>
<td>Transfer line</td>
<td>2004/2006</td>
<td></td>
<td></td>
<td></td>
<td>2 x 2.7 km</td>
<td></td>
</tr>
<tr>
<td><strong>LHC Accelerator</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~730 m</td>
<td></td>
</tr>
<tr>
<td>LHC Arcs (Beam x2, Magnets &amp; QRL insulated)</td>
<td>collider</td>
<td>2007</td>
<td>2 x 7 TeV</td>
<td>complete</td>
<td>$&lt; 10^{-8}$</td>
<td>~2 x (2 x 25 km)</td>
<td>p, ions</td>
</tr>
<tr>
<td>Beam Dump Lines TD62/68</td>
<td>Transfer line</td>
<td>2006</td>
<td>7 TeV</td>
<td>-</td>
<td>$10^{-6}$</td>
<td>2 x 720 m</td>
<td></td>
</tr>
<tr>
<td><strong>High Vacuum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~20 km</td>
<td></td>
</tr>
<tr>
<td><strong>UHV w/wo NEG</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~57.5 km</td>
<td></td>
</tr>
<tr>
<td><strong>Insulation vacuum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~50 km</td>
<td></td>
</tr>
</tbody>
</table>

E. Mahner
27.05.2011
Some history: CERN Intersecting Storage Rings (ISR)

O. Gröbner and R.S. Calder (1973)

Ion desorption yield \( \eta \) (molecules/ion) strongly depended on the cleanliness of the vacuum chamber walls.

Cures that helped to stabilize the ISR vacuum system:
- increased pumping speed
- improved bakeouts
- special vacuum chamber surface treatments: argon glow-discharge cleaning,
- coatings (gold, silver, titanium), and oxidation.

ISR design study (May 1964)
- pp collisions (26 GeV)
- \( L \sim 2 \times 1 \) km (double ring)
- Average pressure: \( 10^{-9} \) Torr
- Material: stainless steel
- Bakeout: 300°C

First observation of a so called ion-induced vacuum instability

R. Calder, E. Fischer, O. Gröbner, E. Jones (1974)
**Pb\(^{54+}\) accumulation test (1997) in the Low Energy Antiproton Ring (LEAR) at CERN**

**LEAR** static vacuum was good: \(10^{-12}\) Torr
Dynamic pressure rises up to \(10^{-11}\) Torr
Direct limit for beam intensity and lifetime.
LEAR achieved: \(~ 3 \times 10^8\) ions, \(\tau \sim 6.5\) s
LHC requests: \(9 \times 10^8\) ions, \(\tau = 30\) s

First observation of beam-loss ion-induced vacuum instability

Other pressure rise observations of similar type reported in:
U²⁺ operation with the heavy-ion synchrotron (SIS18) at GSI

Pressure rise during a high-intensity U²⁺ run at SIS18, triggered by ion injection losses onto vacuum chamber walls and aperture limiting devices. Lifetime no longer independent of injected current.

- Direct limit for beam intensity and lifetime

First fast pressure measurements and proof of desorption process at SIS 18 (2001).

A. Krämer et al., EPAC 2002, 2547 (2002),
U. Weinrich, GSI internal report (2002),
E. Mustafin et al., NIM A510, 199 (2003).
GSI/FAIR accelerator facility – challenges

GSI/FAIR accelerator facility
Primary beam intensity $\times 10^2 - 10^3$
Secondary beam intensity: $\times 10^4$
Heavy-ion beam energy: $\times 30$

P. Spiller, CARE-HHH Workshop 2008 - Scenarios for the LHC upgrade and FAIR, 24.-25.11.2008

Existing facility (blue) serves as injector for the new FAIR complex (red).

For FAIR: reach a SIS18 intensity of $10^{12} U^{28+}/s$ @ 4Hz
R&D program in collaboration with CERN on heavy-ion desorption experiments since $\approx 2003$. 
Large pressure rises and high desorption yields observed with heavy-ion accelerators worldwide and reported at the 2003 "Pressure Rise Workshop" in Brookhaven.

A different type of vacuum instability induced by the loss of heavy ions

many open questions at that time.... how can 1 ion desorb 10000 molecules?


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27.05.2011
Experimental setup at CERN-LINAC 3

Particles: $1.5 \times 10^9 \text{ Pb}^{53+}$ or $10^{10} \text{ Pb}^{27+}$ @ 4.2 MeV
Repetition time: 1.2 s
Impact angles studied: $\theta = 89.2^\circ, 84.8^\circ, 0^\circ$ (perpend.)

E. M. et al., EPAC 2002, p 2568;
PRST-AB 6, 013201 (2003);
PRST-AB 8, 053201 (2005).

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Experimental setup #1 at GSI-HLI
GSI-CERN collaboration

Ions: C\(^2^+\), Cr\(^7^+\), Zn\(^{10^+}\), Pb\(^{27^+}\) @ 1.4 MeV/u
Intensities: 10\(^9\) - 10\(^{11}\) ions/pulse
Impact angles studied: \(\theta = 0\) (perpend.)
Targets: stainless steels, Cu, Ag/Cu, Si, Al

Diploma thesis M. Bender (GSI)

June 2003
Experimental setup #2 at GSI-HLI
GSI-CERN collaboration

Ions: Zn$^{10+}$ @ 1.4 MeV/u
Intensities: $10^9 - 10^{11}$ ions/pulse
Impact angles studied: $\theta = 0$ (perpend.)
Targets: Nb, Mo, Ta, W, Re, stainless steel w/wo coatings of Au, Ag, Pd, TiZrV

October 2003

1.4MeV/u Zn$^{10+}$

Experiment by:
M. Bender (GSI)
H. Kollmus (GSI)
A. Krämer (GSI)
E. M. (CERN)
Experimental setup at the CERN-SPS

Accelerator: SPS North Area (T4-H8)
Ions: In^{49+} @ 158 GeV/u
Intensities: 1.5 \times 10^6 \text{ ions/spill}; \text{spill length: 6.2 s}
Impact angles studied: \theta = 35 \text{ mrad}
Targets: graphite, Cu/graphite, TiZrV/graphite,
Targets: stainless steel (316 LN)


Limit pressure after bakeout: \(6 \times 10^{-12} \text{ Torr}\)
Rotatable setup with 4 different samples, each mounted on a motorized manipulator.

Aligned Cu/graphite collimator in its parking position 18.5 mm below the beam axis.

Experiment by:
E.M., J. Hansen, E. Page,
I. Efthymiopoulos, H. Vincke

27.05.2011
Experimental setup at GSI-SIS 18
GSI-CERN collaboration

Cave HHT
September 2004

Figure 1: Schematic drawing of the ion-induced desorption experiment mounted in the HHT Cave of SIS18.

Experiment by:
M.C. Bellachioma, M. Bender, H. Kollmus, A. Krämer (GSI), E. M. (CERN), O. Malyshev (Daresbury, UK), L. Westerberg, E. Hedlund (TSL, Sweden)

Ions: U$^{73+}$ @ 15 - 1000 MeV/u
Intensity: $7.2 \times 10^7$ ions/s, ($2.4 \times 10^8$ ions/pulse every 3.9 s)
Impact angles studied: $\theta = 0$ (perpend.)
Targets: stainless steels (316LN, P506), Al 6028, Cu-OFE

beam alignment onto Al$_2$O$_3$ screen
Ion pumps (P1-P4); vacuum gauges (G1-G4); vacuum valves (V1,V2) baked (24h @ 200°C);
Rest Gas Analyzer (RGA), NEG (2h @ 250°C).

Beam in both directions; beam injected into closed valves to measure ion-impact desorption.
Four measurements (2 valves, 2 beam directions) for each projectile

Projectiles: $^{197}$Au$^{79+}$ (9 GeV/u), $^{65}$Cu$^{29+}$ (10 GeV/u), $p^+$ (23 GeV)
Avg. bunch intensities (Au; Cu; p): $7 \times 10^8$; $5 \times 10^9$; $2 \times 10^{11}$
Static pressures (Au; Cu; p): $5 \times 10^{-11}$; $2 \times 10^{-11}$; $1 \times 10^{-9}$
Impact angles studied: perpendicular
Target type/material: vacuum valves/stainless steel

Measurement place inside the Relativistic Heavy Ion Collider (RHIC)

W. Fischer et al., in Proc. ECLoud’07 (2007)
Experimental setup at Uppsala-TSL

Fig. 1. The experimental installation: KB—K beamline with last quadrupole doublet, TC—test chamber, C—conductance, PC—pump chamber, V1-V5—valves, RGA1 and RGA2—residual gas analysers, E1 and E2—extractor gauge, SIP—sputter ion pump, TSP—titanium sublimation pump, TMP—turbo molecular pump, CP—cryogenic pump, W—viewport, R—sample rotator, FC—Faraday cup.

Ions: $\text{Ar}^{8+}$ (5 MeV/u), $\text{Ar}^{9+}$ (9.7 MeV/u), $\text{Ar}^{12+}$ (17.7 MeV/u)

Intensities: $\approx 2 - 8 \times 10^9$ ions/s

Impact angles studied: perpendicular & grazing

Target types: flat, tubular, cone samples

Target materials: ss (316 LN), Au/ss, Cu, Ta, TiZrV/ss


High-CURRENT Experiment at Berkeley (LBNL)

The HCX is a small, flexible heavy-ion accelerator at LBNL (A. Molvik)

A.W. Molvik et al., PRST-AB 7, 093202 (2004); NIM A577, 45 (2007); PRL 98, 064801 (2007)
L.R. Prost et al., PRST-AB 8, 020101 (2005)
M. Kireeff Covo et al., PRL 97, 054801 (2006)
F.M. Bieniosek et al., PRST-AB 10, 093201 (2007)
J.E. Coleman et al., PRST-AB 11, 050103 (2008)

Ions: K$^+$ @ 1 MeV (0.025 MeV/u)
Intensities: 180 mA, t ≈ 4 μs, 4.5 × 10$^{12}$ ions/pulse
Pulse repetition rate: 10 s
Beam potential: +2 kV
Impact angles studied: $\theta$ ≈ 80-88°, perpend.
Targets: stainless steel
One "highlight" of LBNL results: optical measurements of gas expansion

Optical measurements of the gas cloud: view at a right angle (to the beam) onto a ‘paddle’ which is inserted into the K$^+$ ion beam path.

K$^+$ beam ions interact with the gas cloud → generates light as the beam excites states in the atoms and molecules in the gas cloud. By varying the time gating of the camera, → possible to construct a time history of the gas cloud during the ion beam pulse.

Color-coded images of the gas cloud taken at 0.5 μs delay intervals

Ion beam-induced pressure rises may also limit the performance of future high-intensity heavy-ion linear accelerators which could be used as drivers for heavy-ion inertial fusion.

Good overview in:
G. Logan et al., NIM-A 544, 1 (2005); NIM-A 577, 1 (2007)

F.M. Bieniosek et al., PRST-AB 10, 093201 (2008)
How we measure desorption yields?
pressure rise method

\[ \eta = \frac{\Delta P \times V}{N \times k_B \times T} \]

\[ \eta = \frac{\Delta P \times S}{N \times k_B \times T} \]

Beam cleaning (scrubbing)

1.4 MeV/u Zn\textsuperscript{10+}

4.2 MeV/u Pb\textsuperscript{27+}/ Pb\textsuperscript{53+}

Total pressure [Torr]

Time [min.]

Need of baked ultra-high vacuum system
with a low static pressure for a high $\Delta P$ sensitivity

H. Kollmus et al., Vacuum 82 (2008) 402

CERN LHC/VAC Note 2001-007
Summary of LINAC 3 pressure rise measurements

Vacuum chamber

316 LN (Ar-O₂ glow discharged)
Si (0.4 µm evaporated)
316 LN (Ar-O₂ glow discharged)
Mo (127 µm foil)
Cu
Al
316 LN (He-O₂ glow discharged)
316 LN (LEAR type, not polished)
316 LN (50 µm electropolished)
316 LN (50 µm electropolished)
316 LN (50 µm chem. polished, getter purif.)
316 LN (50 µm chem. polished)
316 LN (vented after scrubbing)
C#2
K
C#1
L
C#2
TiZrV (1.5 µm sputtered)
TiZrV (1.5 µm sputtered)
Pd (0.6 µm sputtered)
St707 (getter strips)

21 different surfaces (15 different vacuum chambers)
Pb⁵³⁺, 4.2 MeV/u, grazing angle impact

PRST-AB 11, 104801 (2008)
E. Mahner
27.05.2011
Carbon & oxygen evolution during UHV bakeout

E. M. et al., PRST-AB 8, 053201 (2005)
Carbon+oxygen surface content after UHV bakeout vs. pressure rise

XPS carbon + oxygen concentration [at%] after bakeout in UHV

LINAC 3 pressure rise $\Delta P$ [Torr]

TiZrV (200°C)
St707 (400°C)

getter

TiZrV (300°C)

Ag (300°C)
Au (300°C)
Pd (300°C)

noble metals

XPS results
M. Taborelli

E. Mahner
27.05.2011
Elastic Recoil Detection Analysis (ERDA): sample results on cutted LINAC 3 chambers

Correlation between surface oxygen + carbon content and pressure rise $\Delta P$, which is proportional to $\eta$.

316 LN, Ar-O$_2$ glow discharged (950° C, 2 h)

316 LN, getter purified

304 L

not vacuum fired

Munich Tandem Accelerator (Jan. 2003)

$Au^{+30}$ @ 1 MeV/u, $p \approx 1 \times 10^{-7}$ mbar

W. Assmann, H. Kollmus, E. M.

PRST-AB 11, 104801 (2008)
Material studies with UHV-ERDA at GSI

ERDA: element-specific depth profiling up to ~ 1 \( \mu \)m, resolution of a few nm.

Question: How are the target properties (surface, oxidation, bulk properties) correlated to the heavy-ion induced desorption?

A typical \( \Delta E - E_{\text{rest}} \) spectrum for 316LN stainless steel measured with 1.4 MeV/u Xe\(^{18}\) projectile ions.

M. Bender, PhD thesis 2008; H. Kollmus, Vacuum 82 (2008) 402
Impact angle dependence

A.W. Molvik et al., PRST-AB 7, 093202 (2004); NIM-A544 (2005) 194

Roughened target surface eliminates grazing collisions to reduce desorption for low-energy ions with short penetration depths.

Conclusion: rough/smooth surfaces are often not defined. Effect on gas desorption depends on surface morphology, impact angle, and ion range; difficult to predict.


A rough surface increases the desorption, high-energy ions can enter and exit the surface morphology desorbing molecules each time.

Topographic view of a $1 \times 1$ mm$^2$ part of the inner surface of the RHIC beam pipe; measured with an optical profilometer.
Impact angle & charge state dependence: LINAC 3 lead ions with 4.2 MeV/u

Impact angle (89.2°/perpendicular) for 316 LN stainless steel
Factor 2 (Pb$^{53+}$) reduced $\eta$ at $\theta = 0$ $\rightarrow$ special collimators or saw-toothed chambers

Ion charge state (53+/27+) for 316 LN stainless steel
Factor 10 reduced $\eta$ at $\theta = 0$ $\rightarrow$ no impact for LEIR

Conclusion: The heavy-ion induced molecular desorption yield scales with the electronic energy loss as $\eta = k \cdot (dE_{el}/dx)^n$ of the projectile/target system with $n \approx 2-3$, $k$ is a scaling factor. The power of $n \geq 2$ indicates a microscopic thermally moderated desorption process as introduced many years ago by the Thermal Spike Model.
**Ion dose dependent evolution of the oxide layer (top) and the desorption yield (bottom).**

**Electronic sputtering of the surface oxide**

1.4 MeV/u Xe\(^{18+}\) → 316LN st.st.

**Different dose behavior**

**Pressure decrease**

Conclusion: measured $\Delta p$ is not due to sputtering of the st. steel components, but it is a surface effect, the adsorbed gas is released by the heavy-ion impact.

How can 1 heavy-ion stimulated the desorption of up to several 1000 gas molecules?

1. Projectile ion loses energy (mainly to the electronic system)
2. Electrons carry energy away from the ion track
3. The hot electrons transfer the energy to the lattice by e-p coupling
4. Thermal desorption due to enhanced lattice temperature

**M. Bender, PhD thesis 2008**
Thermal Distribution as a function of time and space (radius) for 1.4MeV/u Xe → Cu

Temperature of the electronic system (top) and the lattice (bottom).

M. Bender et al., GSI Scientific Report 2007, 103 (2008)

Desorption from one single projectile

<table>
<thead>
<tr>
<th>Proj. (1.4MeV/u)</th>
<th>Xe</th>
<th>Xe</th>
<th>Xe</th>
<th>C</th>
<th>Pb</th>
<th>Pb (4.2MeV/u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Cu</td>
<td>Au</td>
<td>Rh</td>
<td>Cu</td>
<td>Cu</td>
<td>Au</td>
</tr>
<tr>
<td>Experiment</td>
<td>290</td>
<td>90</td>
<td>1280</td>
<td>10</td>
<td>800</td>
<td>800 (prel.)</td>
</tr>
<tr>
<td>Calculation</td>
<td>185</td>
<td>165</td>
<td>3400</td>
<td>5</td>
<td>525</td>
<td>750</td>
</tr>
</tbody>
</table>

"...the extended inelastic Thermal Spike Model is the first approach to calculate ion induced desorption yields in the investigated energy regimes. The experimentally found (dE/dx)^2 scaling is reproduced by the model."
Overview of heavy-ion desorption experiments at accelerators

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Ion energy</th>
<th>Impact angle</th>
<th>Target material, Stainless steel = ss</th>
<th>Lab-Accelerator</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au$^{31+}$</td>
<td>1 MeV/u</td>
<td>Grazing</td>
<td>Stainless steel</td>
<td>BNL-AGS</td>
<td>[4,5]</td>
</tr>
<tr>
<td>Au$^{79+}$</td>
<td>8.9 GeV/u</td>
<td>Grazing</td>
<td>Stainless steel</td>
<td>BNL-RHIC</td>
<td>[22]</td>
</tr>
<tr>
<td>Au$^{79+}$</td>
<td>9 GeV/u</td>
<td>Perpendicular</td>
<td>Stainless steel</td>
<td></td>
<td>[23]</td>
</tr>
<tr>
<td>Cu$^{29+}$</td>
<td>10 GeV/u</td>
<td>Perpendicular</td>
<td>Stainless steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p$^+$</td>
<td>23 GeV</td>
<td>Perpendicular</td>
<td>Stainless steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb$^{53+}$/Pb$^{27+}$</td>
<td>4.2 MeV/u</td>
<td>Grazing and perpendicular</td>
<td>ss (316LN, 304 L), Au, Ag, Pd, TiZrV/ss (316LN), Cu, Al, Mo, Si/ss (316LN)</td>
<td>CERN-LINAC 3</td>
<td>[30,31]</td>
</tr>
<tr>
<td>In$^{49+}$</td>
<td>158 GeV/u</td>
<td>Grazing</td>
<td>ss (316LN), graphite, Cu/graphite, TiZrV/graphite</td>
<td>CERN-SPS</td>
<td>[32,43]</td>
</tr>
<tr>
<td>C$^{2+}$/Cr$^{7+}$/Pb$^{27+}$/Zn$^{10+}$/Xe$^{18+}$...$^{21+}$</td>
<td>1.4 MeV/u</td>
<td>Perpendicular</td>
<td>ss (304 L, 316LN), Cu, Si, Al</td>
<td>GSI-HLI</td>
<td>[33,44]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19° (ERDA)</td>
<td>ss (304 L, 316LN), Cu, Au/316 LN, Au/Cu, Rh/Cu</td>
<td></td>
<td>[45]</td>
</tr>
<tr>
<td>U$^{28+}$</td>
<td>8.9 MeV/u</td>
<td>Grazing</td>
<td>ss (316LN)</td>
<td>GSI-SIS 18</td>
<td>[7]</td>
</tr>
<tr>
<td>U$^{73+}$/Ar$^{10+}$</td>
<td>15, 40, 100 MeV/u</td>
<td>Perpendicular</td>
<td>ss (316LN, P 506)</td>
<td>GSI-HHT</td>
<td>[36]</td>
</tr>
<tr>
<td></td>
<td>40, 80, 100 MeV/u</td>
<td></td>
<td>ss (316LN, Cu, Al)</td>
<td></td>
<td>[46]</td>
</tr>
<tr>
<td>K$^+$</td>
<td>0.002–0.025 MeV/u</td>
<td>Grazing</td>
<td>Stainless steel</td>
<td>LBNL-HCX</td>
<td>[37,41]</td>
</tr>
<tr>
<td>LLNL-STSS500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar$^{8+}$/Ar$^{9+}$/Ar$^{12+}$</td>
<td>5, 9.7, 17.7 MeV/u</td>
<td>Perpendicular</td>
<td>ss (316LN), Cu, Ta</td>
<td>Uppsala-TSL</td>
<td>[47]</td>
</tr>
</tbody>
</table>
Review of heavy-ion induced desorption data

PRST-AB 11, 104801 (2008)

E. Mahner
Some applicable mitigation techniques for heavy-ion accelerators

**Mitigation:** Coatings with non evaporable getter (NEG) films like TiZrV.

*Why:* to obtain very clean surfaces after *in situ* bakeout and low dynamic gas loads under ion bombardment, provides high distributed pumping speed as close as possible to the beam.

*Where:* implemented in LEIR, LHC, RHIC, SIS 18 (ongoing), FAIR (planned).

*Remark:* should (or must) be considered in the design of new ion accelerators, is maybe more complicated (cost, time) for the upgrade of operational machines.

**Mitigation:** Special collimators with low outgassing under heavy-ion impact.

*Why:* concept to intercept lost beam ions, prevent these ions from grazing angle impact onto the vacuum chamber walls, lost ions should bombard collimators under perpendicular impact to minimize the desorption yields. Loss areas need to be known.

*Where:* implemented in LEIR, started in SIS 18, tests in RHIC.

*Remark:* important to consider for new machines, can be retrofitted in existing accelerators.

**Mitigation:** Beam cleaning (scrubbing).

*Why:* Cleaning of the vacuum chamber walls or any other machine device to decrease the pressure rise with time

*Where:* mostly tested in experimental setups, much less observed in LEIR, SIS 18, and RHIC.

*Remark:* the feasibility has been demonstrated in LINAC 3 tests (for LEIR) and at GSI test stands, needs either long scrubbing time or high ion doses.
During LEIR machine commissioning in 2006, no evidence has been found that the accumulated Pb\textsuperscript{54+} ion intensity was limited by a dynamic vacuum degradation. The design beam lifetime was achieved!

**Conclusion:** applied mitigation techniques of NEG coating and perpendicular ion-loss onto gold coated, oxide layer free collimators are successful. Beam-loss induced desorption is no operational issue for LEIR since the 2006 run!
Antigrazing rings in BNL-RHIC

Idea (P. Thieberger 2004) is to mitigate grazing angle projectile collisions in RHIC.

A set of bare stainless steel rings was installed in a warm section of the machine and tested with protons in 2005. Result: rings were effective in raising the electron cloud threshold and in reducing the dynamic pressure rise.

Further improvements were expected for gold beams due to their larger secondary electron and desorption yields but not experimentally verified.

Decision: not to install more anti-grazing rings in the machine and to avoid the potential risk to increase detector background signals in the experiments, RHIC relies mostly on vacuum system upgrade with NEG coated beam pipes. More refs: P. Thieberger et al., PRST AB 7, 093201 (2004); S.Y. Zhang et al., PRST AB 8, 123201 (2005)
Scrubbing in LINAC3 (1)

Pb$^{53+}$ @ 4.2 MeV/u
\[\Theta = 89.2^\circ\] (grazing)

LEAR-type chamber

Etched/polished chambers

Ag, Au coated

E. M. et al., PRST-AB 8, 053201 (2005)
Scrubbing in LINAC3 (2)

Pb$^{53+}$ @ 4.2 MeV/u
$\Theta = 89.2^\circ$ (grazing)

LEAR-type chamber

Pd coated

TiZrV (NEG) coated

E. Mahner

27.05.2011
How to achieve 10^{-12} Torr dynamic vacuum for heavy-ion accelerators (LEIR, FAIR)

- **Design + strategy for 10^{-12} Torr dynamic vacuum**
  - **In general:** very strict choice of materials, vacuum pumps, instrumentation, cleaning procedures and elaborated bakeout systems are necessary to reduce the total dynamic outgassing rate to the 10^{-13} Torr.l.s^{-1}.cm^{-2} range (or less) with negligible amount of leaks.
  - **For particle accelerators:** bakeable vacuum systems (300°C) with “special” machine components (kicker, septa...)
  - "Conventional" pumping + NEG coating where possible, cryogenic systems (?)
  - Low ion-loss design of the machine especially at injection/extraction,
    - collimator design to stop charge exchanged particles onto low-outgassing absorbers
  - Beam scrubbing to reduce pressure rises if necessary

- **Challenges & unknowns**
  - dynamic vacuum is difficult to obtain (not the static...)
    - very high desorption rate for lost high-energy ions
  - ion desorption of cryogenic surfaces recently studied at CERN, GSI
  - measure \( p \leq 10^{-12} \) Torr, influence of gauges & analysers?
  - accelerator environment \( \neq \) laboratory conditions!
Conclusions, future studies, and acknowledgements

During the last decade intense experimental studies on the heavy-ion induced molecular desorption were performed in several particle accelerator laboratories worldwide. A lot of progress has been made in the physics understanding of the ion desorption process and several mitigation techniques were developed and implemented in some synchrotrons.

For ambient temperature targets only some few but important questions remain to be answered. Future studies should probably focus on at least two aspects. First, more particle accelerator relevant experiments are needed to investigate the heavy-ion induced molecular desorption of NEG coatings, which are by now used in several machines. It is proposed to further research the ion desorption behavior TiZrV films and to compare fully activated with saturated getter films. First experiments have already been done at CERN and in Uppsala.

A second domain is the ion-induced desorption of cryogenic surfaces. With the exception of one recent experiment at CERN#, cold surfaces are nearly unstudied using high-energy ions. Cryogenic experiments are motivated by the heavy-ion operation of the LHC and later at FAIR.

I want to acknowledge many colleagues from different laboratories (Berkeley, Brookhaven, CERN, GSI, and Uppsala) for their collaboration during the last years. The shown results are based on their hard and dedicated work.

#E. Mahner, L. Evans, D. Küchler, R. Scrivens, M. Bender, H. Kollmus, D. Severin, M. Wengenroth
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