Dynamic vacuum challenges for heavy-ion accelerators

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W.E. Heraeus Seminar 17.10.2012

Outline

Introduction

- CERN accelerator complex, vacuum instabilities at ISR, LEAR, SIS18

Overview of heavy-ion induced desorption experiments

- Test stands at CERN, GSI, RHIC, Uppsala, LBNL

Review of results

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

Mitigation techniques

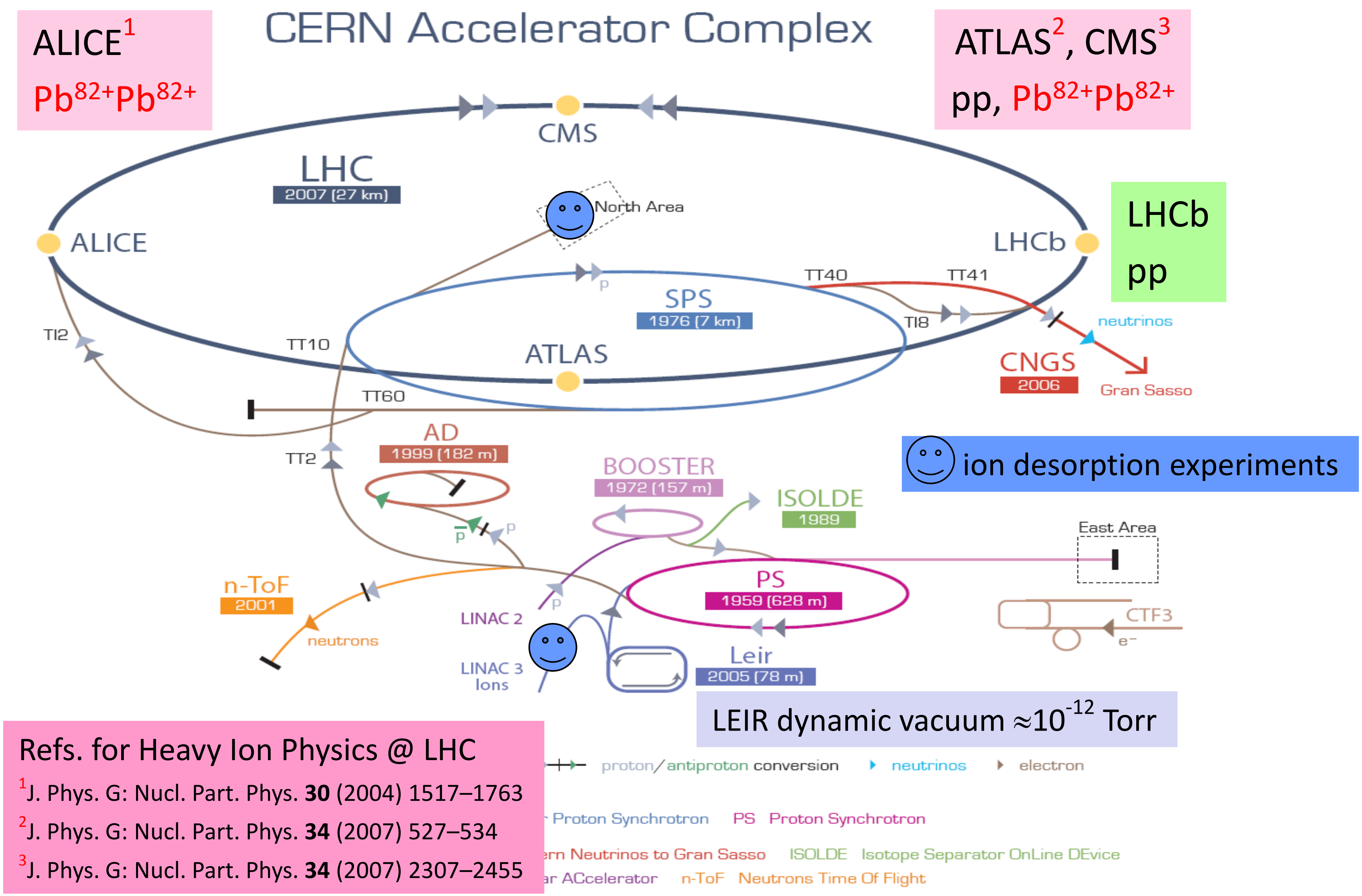
- Coatings, collimators, scrubbing

Cryogenic target experiments

- CERN & GSI test stands, prototypes, and results

Conclusions

Introduction: CERN Accelerators



Refs. for Heavy Ion Physics @ LHC

[1]J. Phys. G: Nucl. Part. Phys. **30** (2004) 1517–1763

[2]J. Phys. G: Nucl. Part. Phys. **34** (2007) 527–534

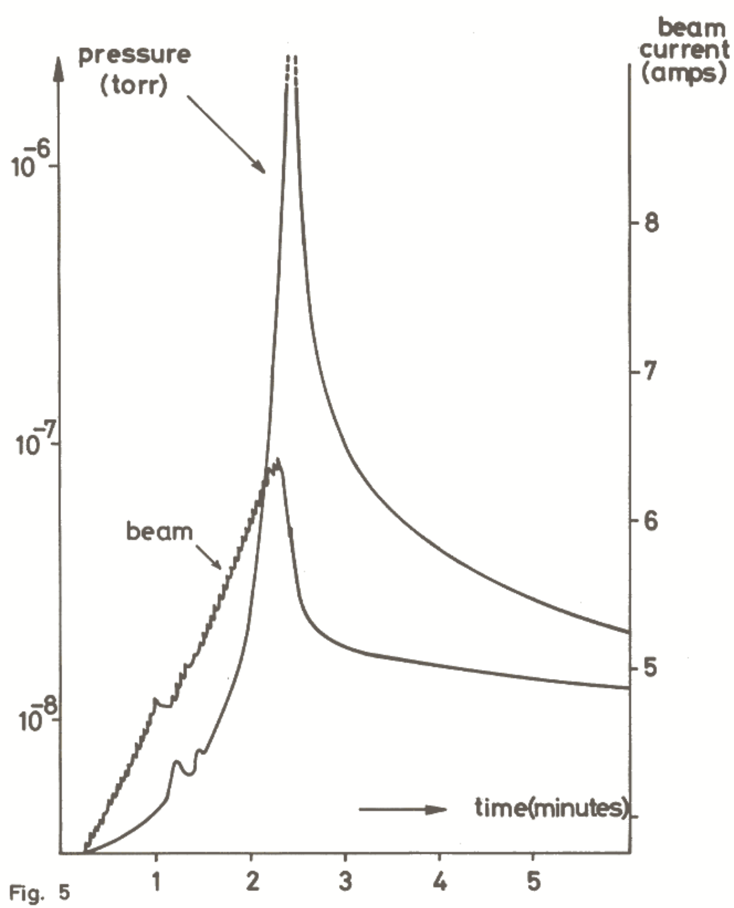
[3]J. Phys. G: Nucl. Part. Phys. **34** (2007) 2307–2455

CERN Accelerator Vacuum Systems

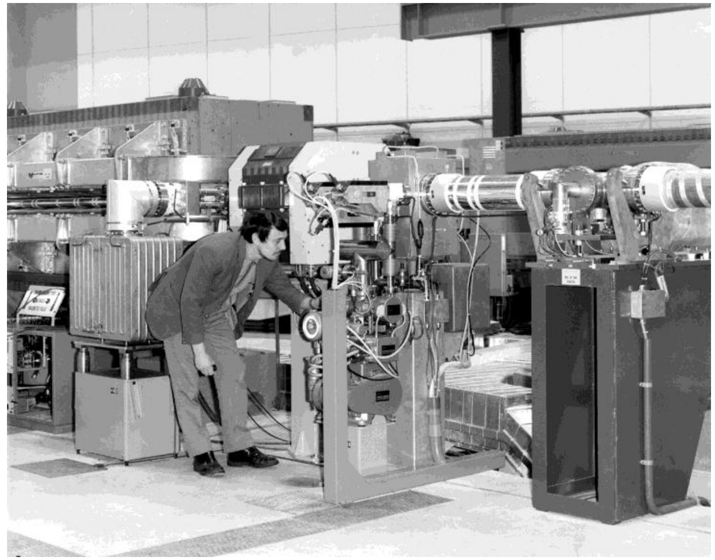
Machine	Type	Year	Energy	Bakeout	Pressure (Pa)	Length	Particles
Linac, Booster, ISOLDE, PS, n-TOF and AD Complex						**2.6 km !**	
LINAC 2	linac	1978	50 MeV	Ion pumps	10^{-7}	40 m	p
ISOLDE	electrostatic	1992	60 keV	-	10^{-4}	150 m	ions: 700 isotopes and 70 (92) elements
REX-ISOLDE	linac	2001	3 Mev/u	partly	10^{-5} - 10^{-10}	20 m	
LINAC 3	linac	1994	4.2 MeV/u	Ion pumps	10^{-7}	30 m	ions
LEIR	accumulator	1982/2005	72 MeV/u	complete	10^{-10}	78 m	pbar, ions
PSB	synchrotron	1972	1-1.4 GeV	Ion pumps	10^{-7}	157 m	P, ions
PS	synchrotron	1959	28 GeV	Ion pumps	10^{-7}	628 m	P, ions
AD	decelerator	1998	100 MeV	complete	10^{-8}	188 m	pbar
CTF3 complex	linac/ring	2004-09		partly	10^{-8}	300 m	e
PS to SPS TL	Transfer line	1976	26 GeV	-	10^{-6}	~1.3 km	P, ions
SPS Complex						**15.7 km !**	
SPS	synchrotron	1976	450 GeV	Extractions	10^{-7}	7 km	p, ions
SPS North Area	Transfer line	1976		-	10^{-6} - 10^{-7}	~1.2 km	
SPS West Area	Transfer line	1976				~ 1.4 km	
SPS to LHC TI2/8 Line	Transfer line	2004/2006				2 x 2.7 km	
CNGS Proton Line	Transfer line	2005				~730 m	
LHC Accelerator						**~109 km !**	
LHC Arcs (Beam x2, Magnets & QRL insul.)	collider	2007	2 × 7 TeV	-	< 10^{-8}	2 x (2 x 25 km)	p, ions
LSS RT separated beams				complete		2 × 3.2 km	
LSS RT recombination						~ 570 m	
Experimental areas						~ 180 m	
Beam Dump Lines TD62/68	Transfer line	2006	7 TeV	-	10^{-6}	2 × 720 m	

High Vacuum	~20 km	**~128 km !**
UHV w/wo NEG	~ 57.5 km	
Insulation vacuum	~ 50 km	

Some history
CERN Intersecting Storage Rings (ISR)



O. Gröbner and R.S. Calder (1973)



ISR design study (May 1964)

pp collisions (26 GeV)

L ~2 × 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

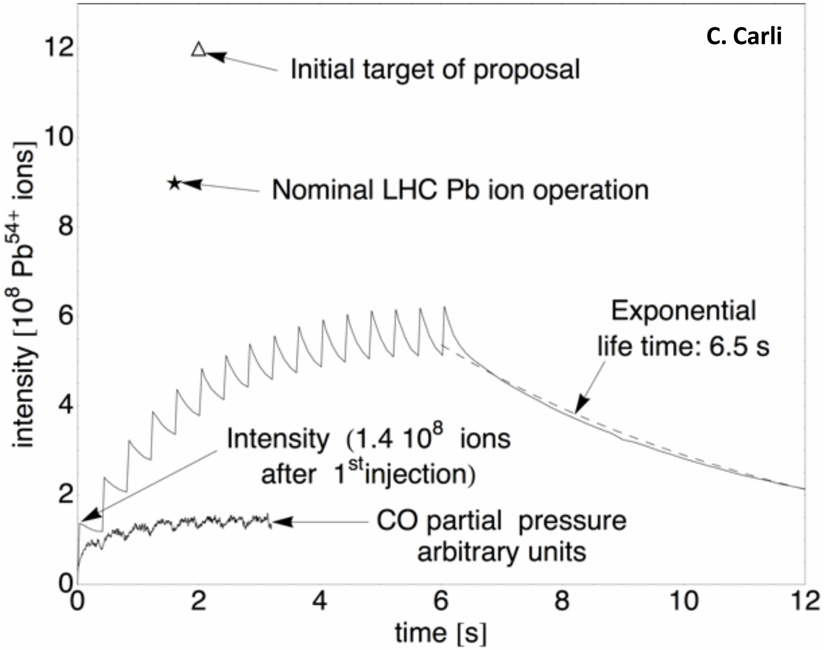
Ion desorption yield η (molecules/ion) strongly depended on the cleanliness of the vacuum chamber walls.

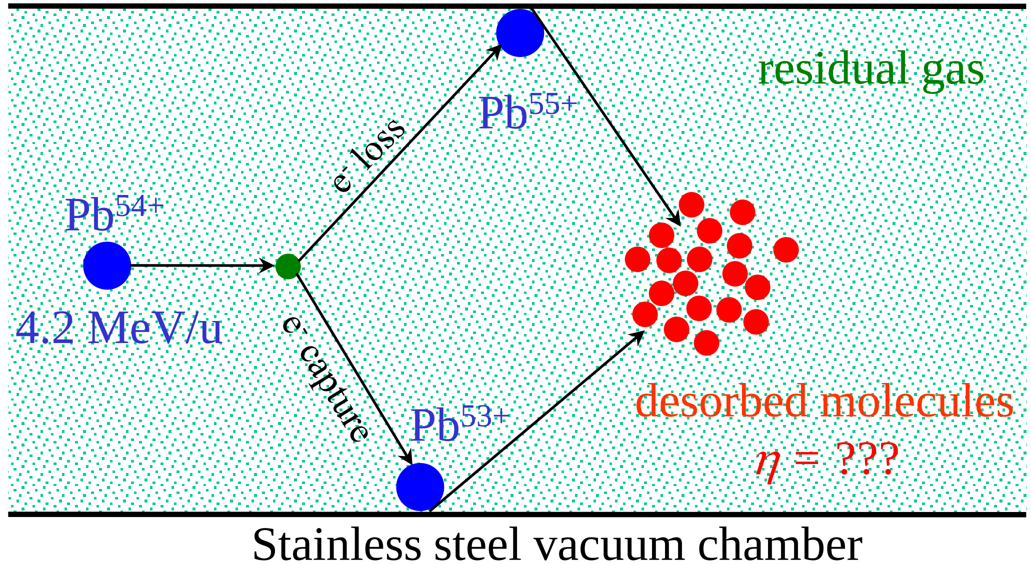
Cures that helped to stabilize the ISR vacuum system:

increased pumping speed, improved bakeouts, special vacuum chamber surface treatments: argon glow-discharge cleaning, coatings (gold, silver, titanium), and oxidation.

R. Calder, E. Fischer, O. Gröbner, E. Jones (1974)

Pb^{54+} accumulation test (1997) in the Low Energy Antiproton Ring (LEAR) at CERN





First observation of beam-loss ion-induced vacuum instability

"The LEAR static vacuum was of the order of 5×10^{-12} Torr, but local pressure bumps up to 10^{-9} Torr occured with continuous injection of about 10^8 ions/s."

Direct limit for beam intensity and lifetime.

LEAR achieved: $\approx 3 \times 10^8$ ions, $\tau \approx 6.5$ s

LHC requests: 9×10^8 ions, $\tau = 30$ s

Other pressure rise observations of similar type reported in:

LEAR (1997): J. Bosser et al., Part. Accel. 63, 171 (1999)

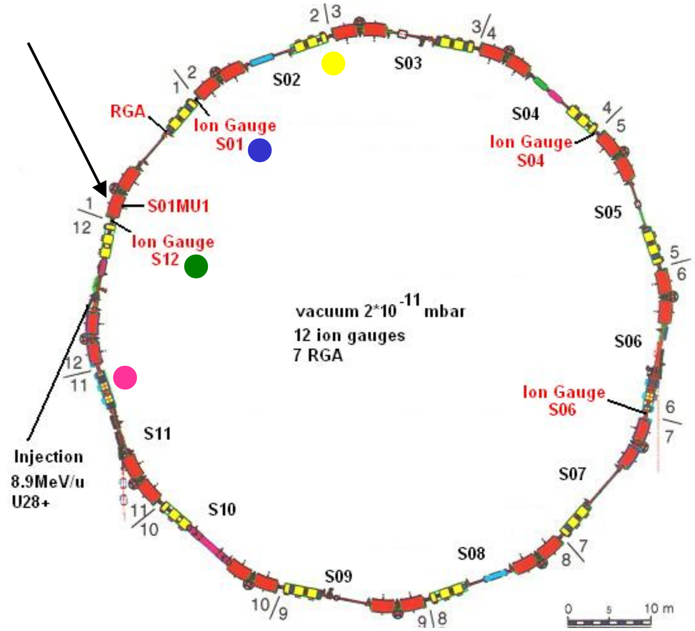
AGS-Booster (1998): S.Y. Zhang et al., EPAC 1998, 2149 (1998)

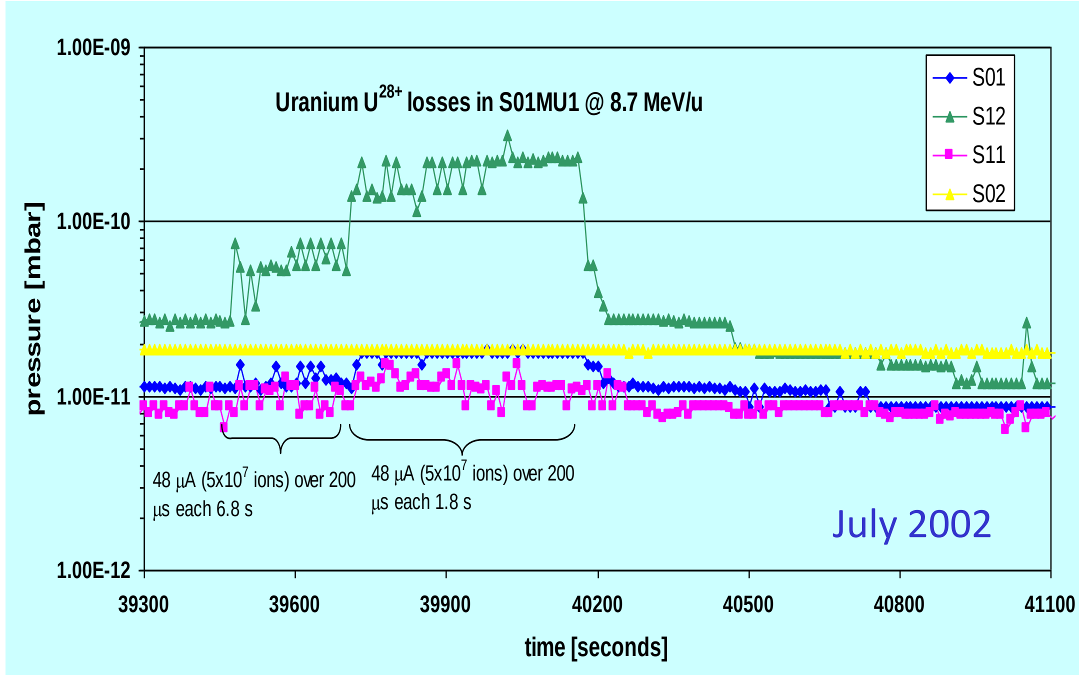
Studies at LINAC 3 (2000): M. Chanel et al., PAC 2001, 2165 (2001)

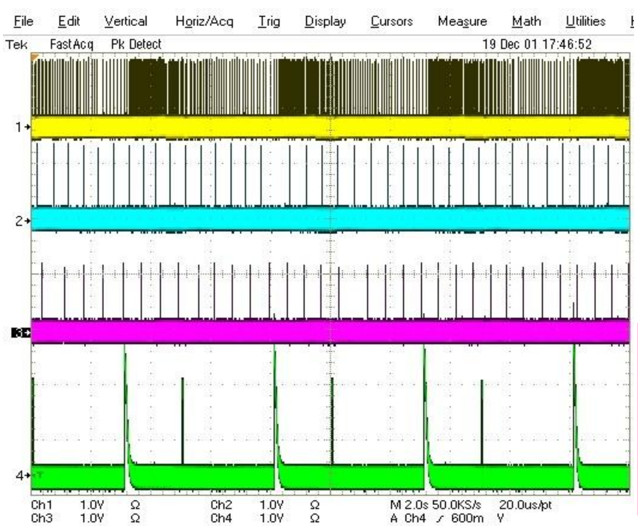
SIS 18 (2002): A. Krämer et al., EPAC 2002, 2547 (2002)

RHIC (2002): W. Fischer et al., EPAC 2002, 1485 (2002)

U^{28+} operation with the heavy-ion synchrotron (SIS18) at GSI







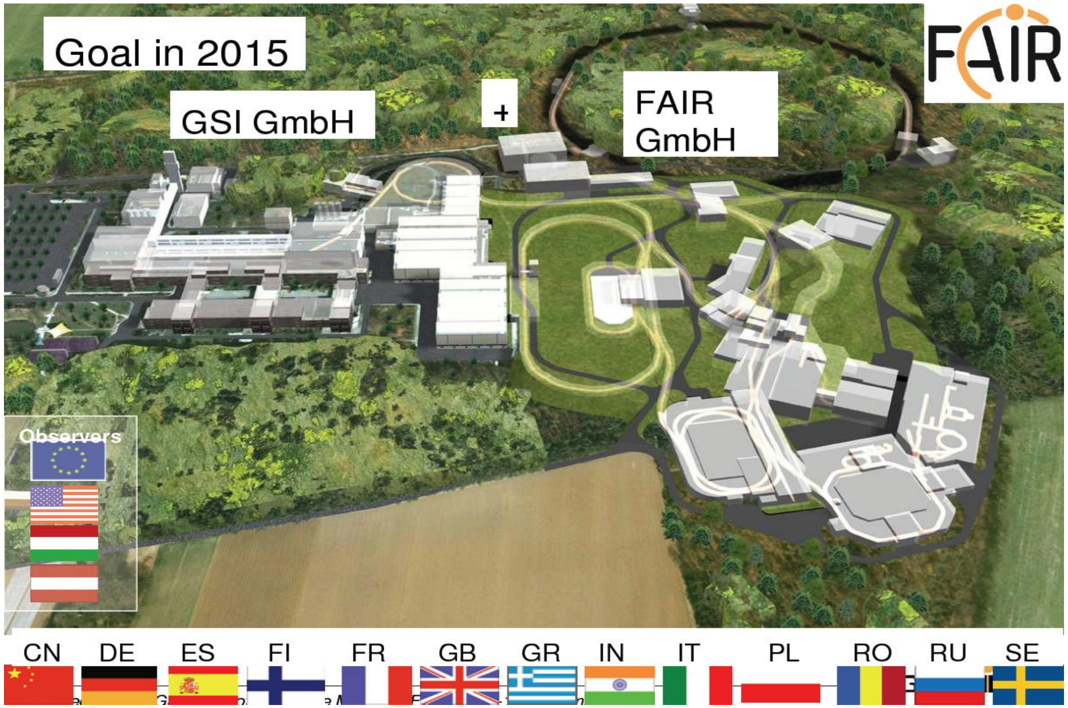
Pressure rise during a high-intensity U^{28+} run at SIS18, triggered by ion injection losses onto vacuum chamber walls and aperture limiting devices. Lifetime no longer independent of injected current.

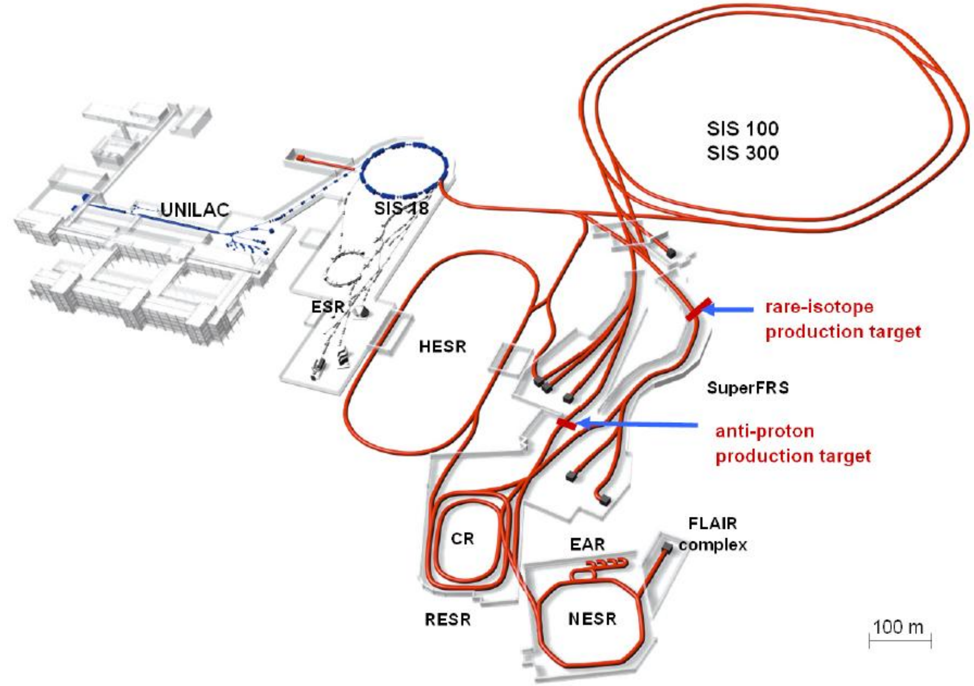
➡ Direct limit for beam intensity and lifetime

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 x $10^2 – 10^3$

Secondary beam intensity: x 10^4

Heavy-ion beam energy: x 30

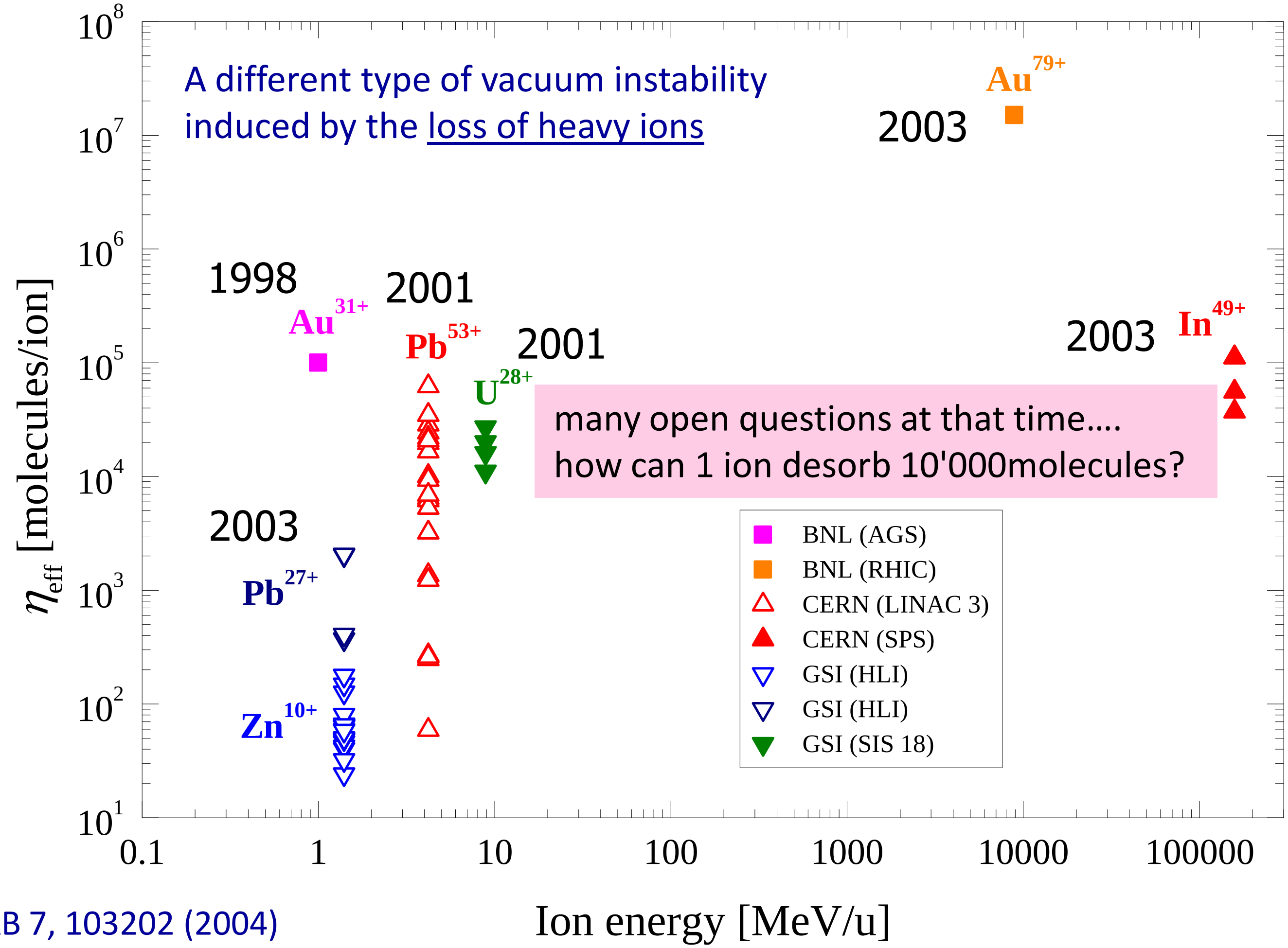
Existing facility (blue) serves as injector for the new FAIR complex (red).

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 ≈ 2003.

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

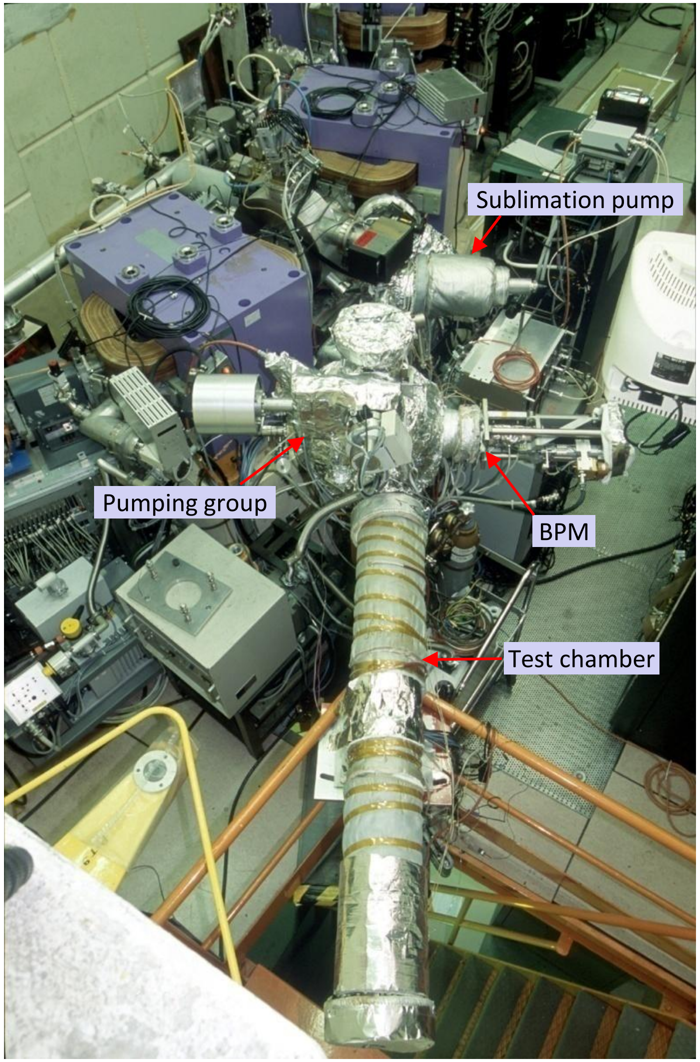
About 30 years after the ISR…

Large pressure rises and high desorption yields observed with heavy-ion accelerators worldwide and reported at the 2003 "Pressure Rise Workshop" in Brookhaven



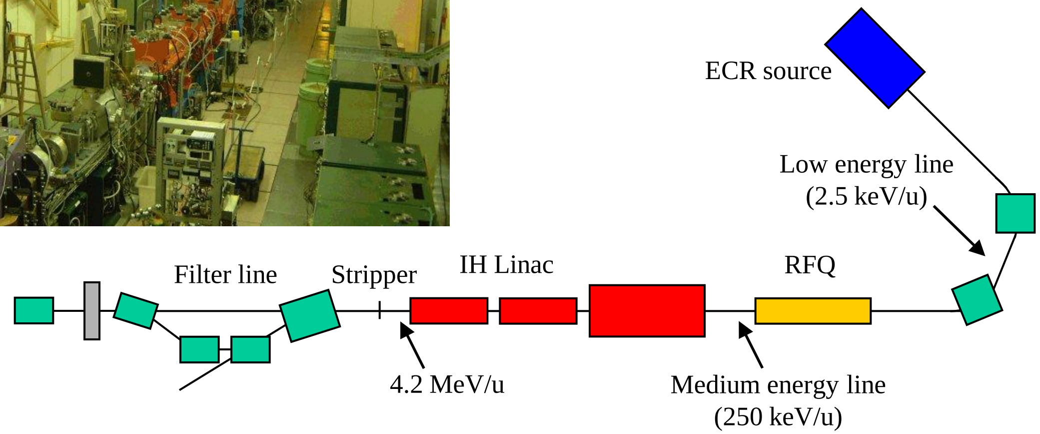
E. M. et al., PRST-AB 7, 103202 (2004)

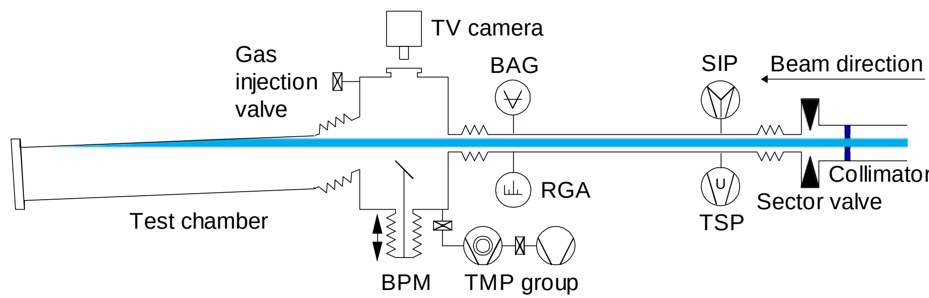
Experimental setup at CERN-LINAC 3



Experiments from Nov. 2000 - July 2010

J. Hansen et al., CERN Report No. LHC/VAC-TN-2001-07 (2001).
E. M. et al., EPAC 2002, p 2568; PRST-AB 6, 013201 (2003);
PRST-AB 8, 053201 (2005).



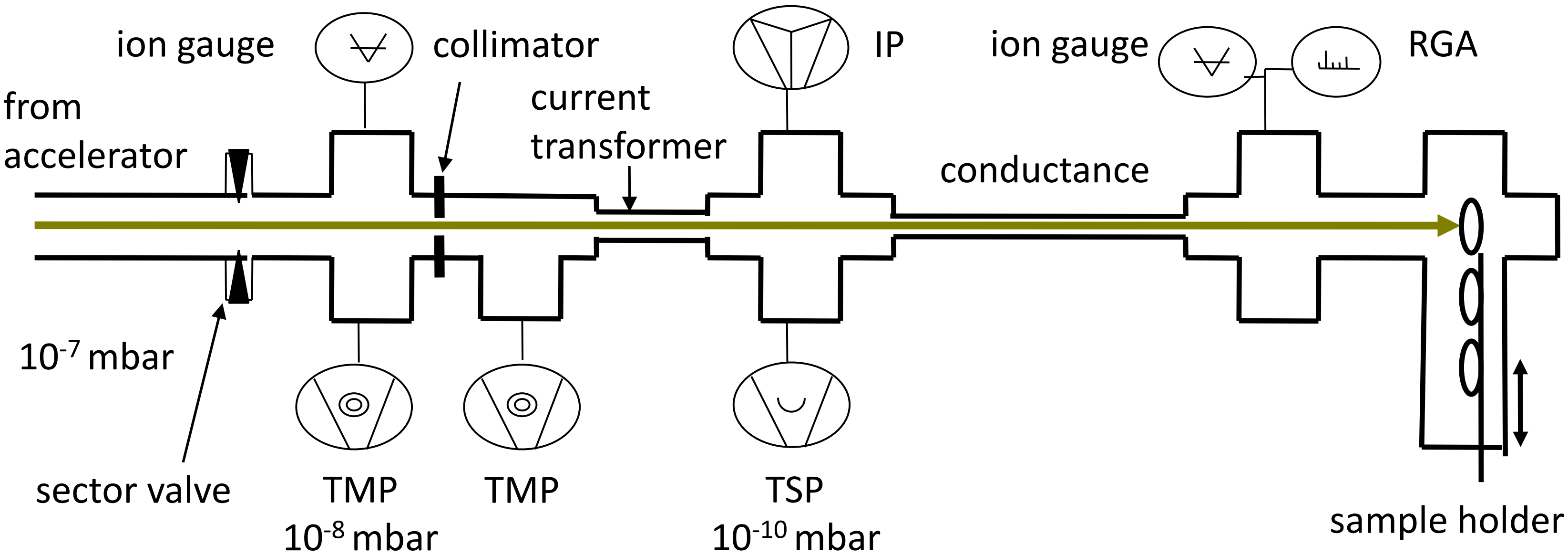


Particles: 1.5×10^9 Pb^{53+} or 10^{10} Pb^{27+} @ 4.2 MeVu

Repetition time: 1.2 s

Impact angles studied: θ = 89.2 , 84.8 , 0 (perpend.)

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



June 2003

Ions: C^{2+}, Cr^{7+}, Zn^{10+}, Pb^{27+} @ 1.4 MeV/u

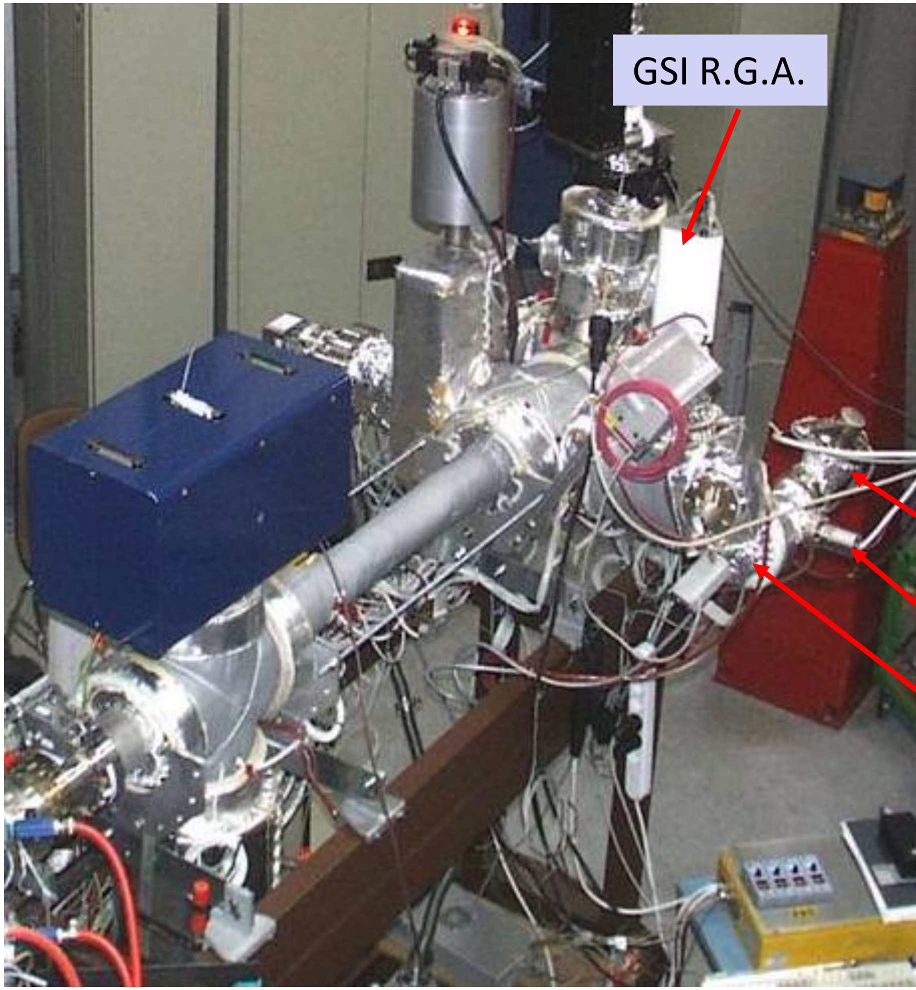
Intensities: 10^9 - 10^{11} ions/pulse

Impact angles studied: $\theta = 0$ (perpend.)

Targets: stainless steels, Cu, Ag/Cu, Si, Al

Diploma thesis M. Bender (GSI)

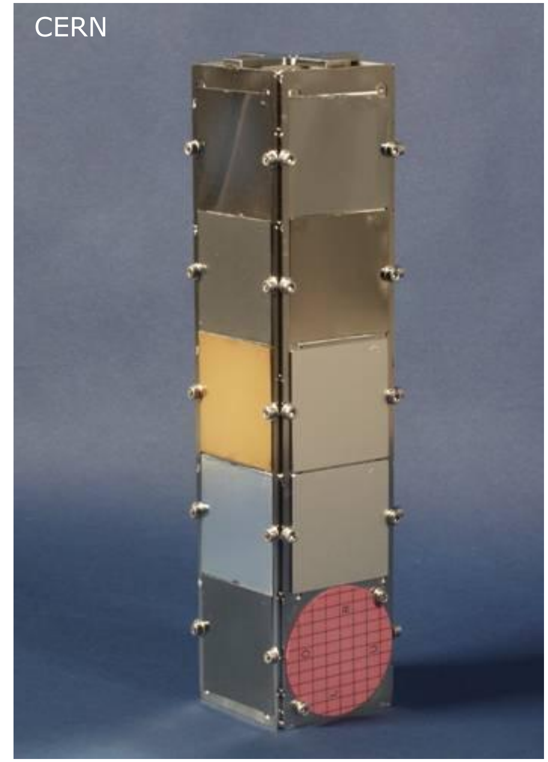
Experimental setup #2 at GSI-HLI
GSI-CERN collaboration



October 2003

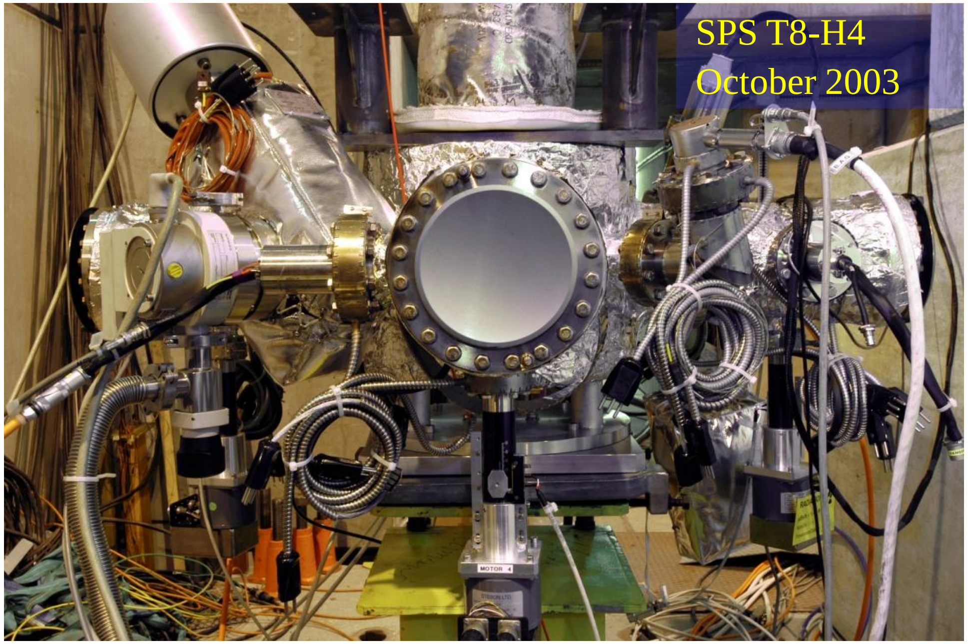
<u>1.4MeV/u Zn^{10+}</u>

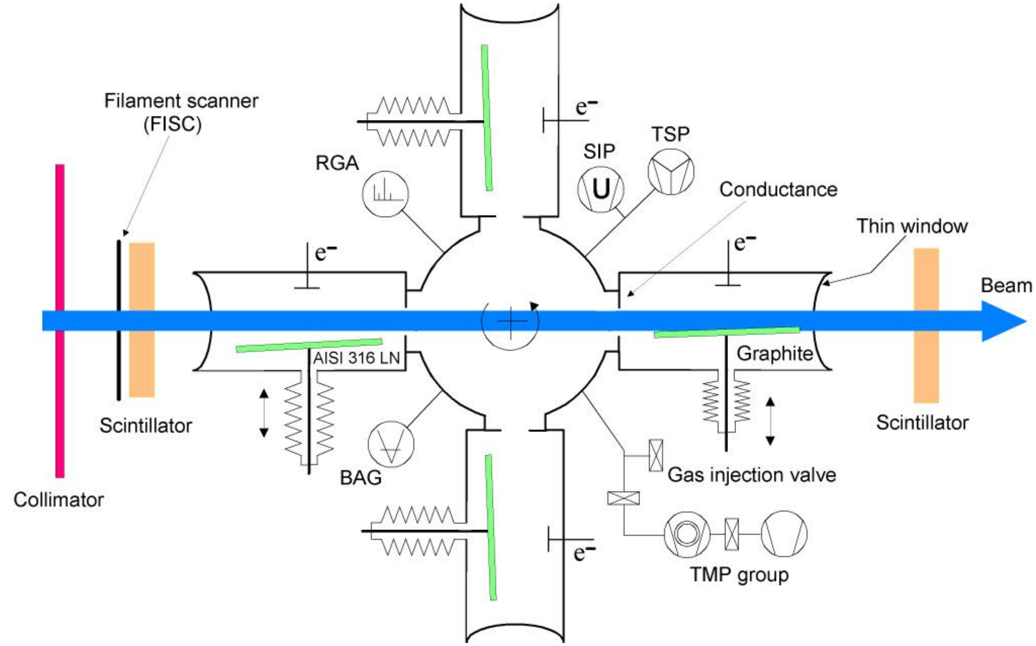
Experiment by:
M. Bender (GSI)
H. Kollmus (GSI)
A. Krämer (GSI)
E. M. (CERN)



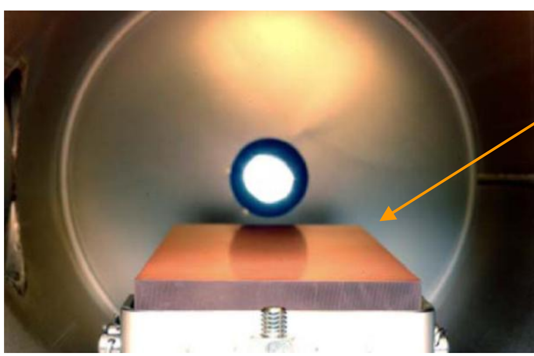
Ions: Zn^{10+} @ 1.4 MeV/u
Intensities: 10^9 - 10^{11} ions/pulse
Impact angles studied: $\theta = 0$ (perpend.)
Targets: Nb, Mo, Ta, W, Re, stainless steel
w/wo coatings of Au, Ag, Pd, TiZrV

Experimental setup at the CERN-SPS





Limit pressure after bakeout: 6×10^{-12} 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

Accelerator: SPS North Area (T4-H8)

Ions: In^{49+} @ 158 GeV/u

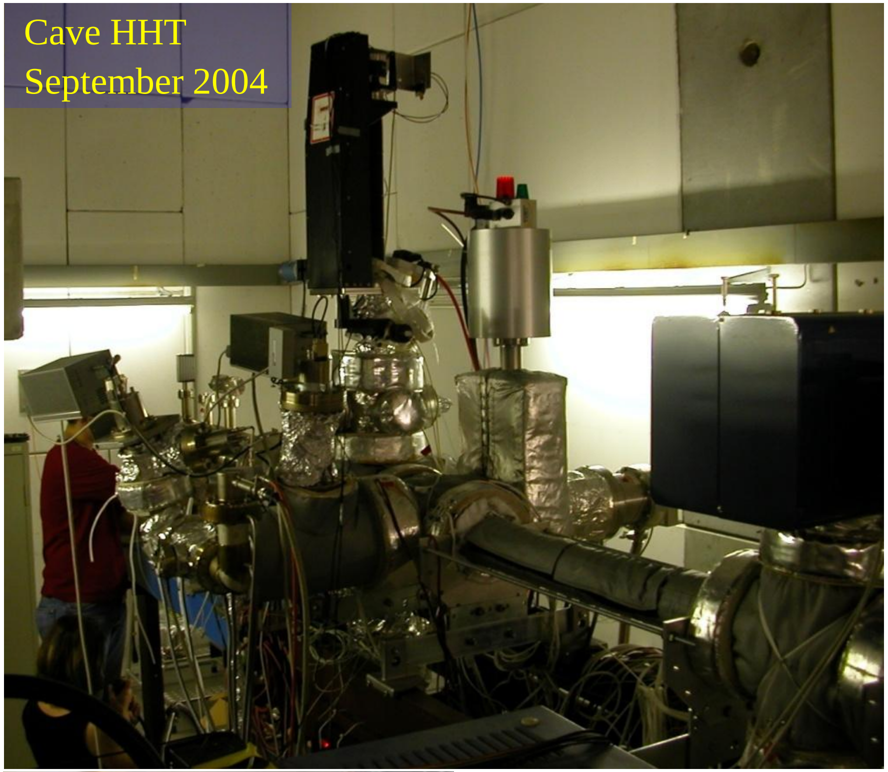
Intensities: 1.5×10^6 ions/spill; spill length: 6.2 s

Impact angles studied: $\theta = 35$ mrad

Targets: graphite, Cu/graphite, TiZrV/graphite, stainless steel (316 LN)

E. M. et al., PRST-AB 7, 103202 (2004)

Experimental setup at GSI-SIS 18
GSI-CERN collaboration



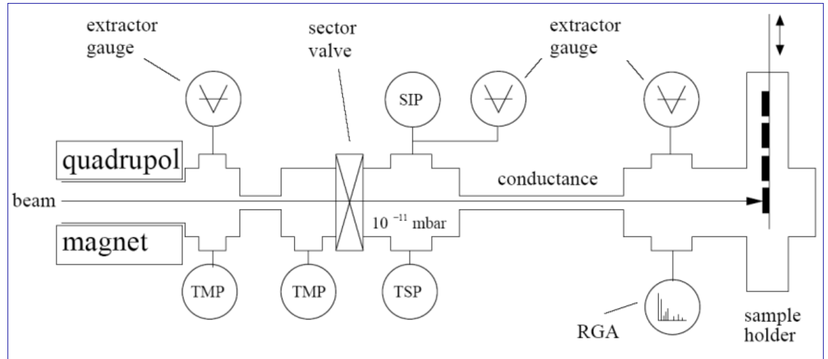
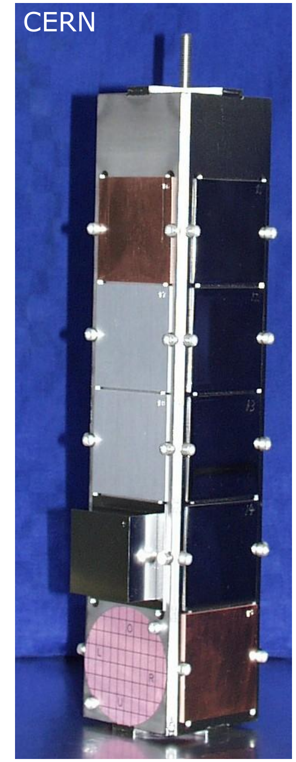
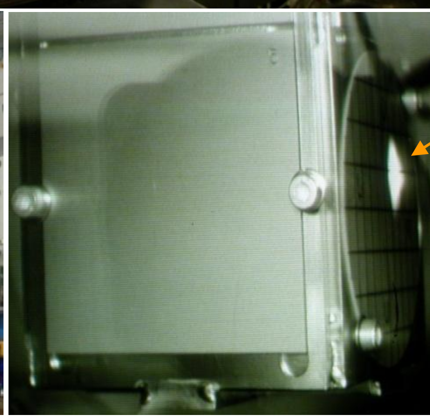


Figure 1: Schematic drawing of the ion-induced desorption experiment mounted in the HHT Cave of SIS18.



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)



beam alignment onto Al_2O_3 screen

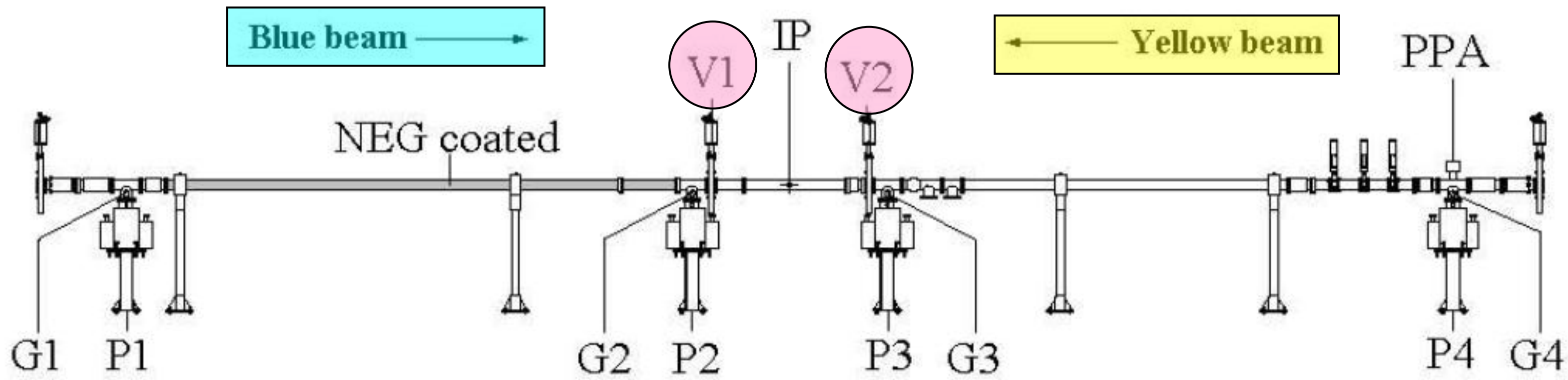
Ions: U^{73+} @ 15 - 1000 MeV/u

Intensity: 7.2×10^7 ions/s, (2.4×10^8 ions/pulse every 3.9 s)

Impact angles studied: $\theta = 0$ (perpend.)

Targets: stainless steels (316LN, P506), Al 6028, Cu-OFE

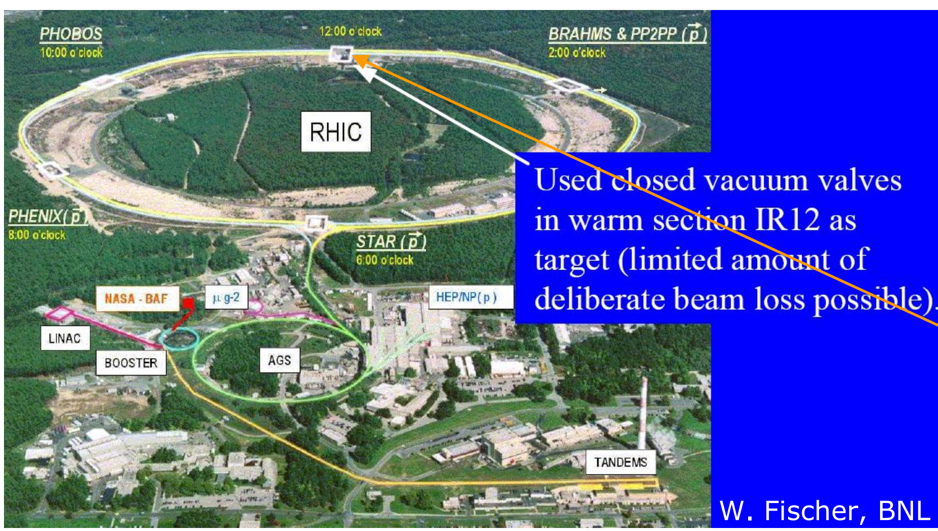
RHIC machine experiment



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: Au^{79+} (9 GeV/u), Cu^{29+} (10 GeV/u), p^+ (23 GeV)

Avg. bunch intensities (Au; Cu; p): 7×10^8; 5×10^9; 2×10^{11}

Static pressures (Au; Cu; p): 5×10^{-11}; 2×10^{-11}; 1×10^{-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

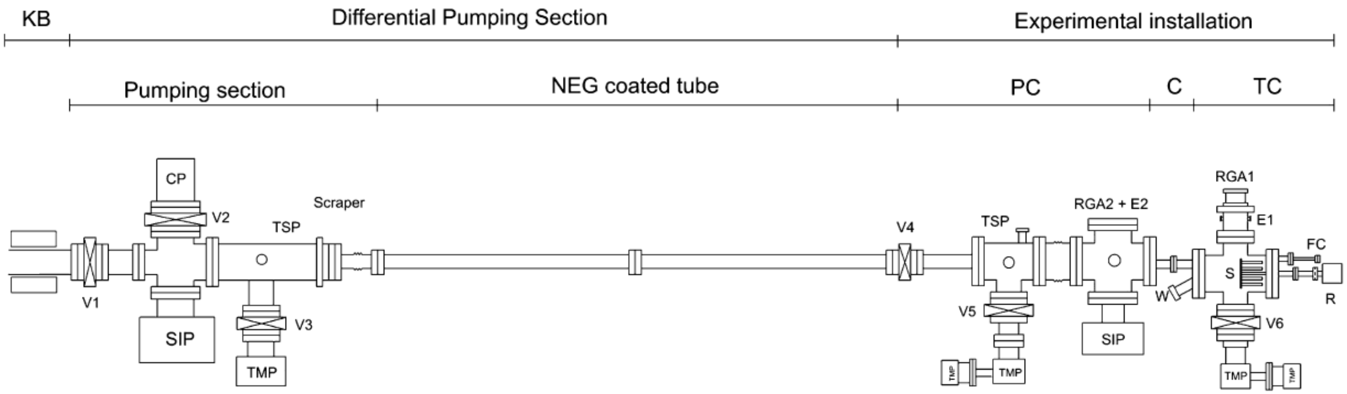


Fig. 1. The experimental installation: KB—K beamline with last quadrupole doublet, TC—test chamber, C—conductance, PC—pump chamber, V1-V5—valves, RGA1 and RGA2—residual gas analysers, E1 and E2—extractor gauge, SIP—sputter ion pump, TSP—titanium sublimation pump, TMP—turbo molecular pump, CP—cryogenic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

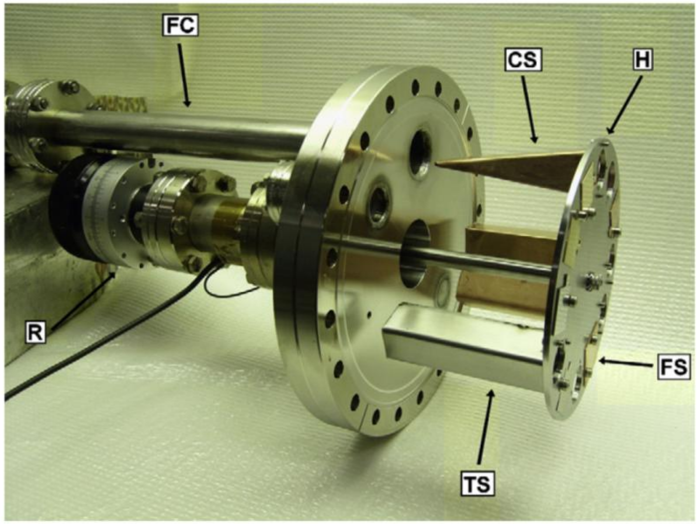


Fig. 2. The sample holder assembly: a sample holder (H) with flat (FS), tubular (TS) and cone (CS) sample, a rotator (R) and a Faraday cup (FC).

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

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

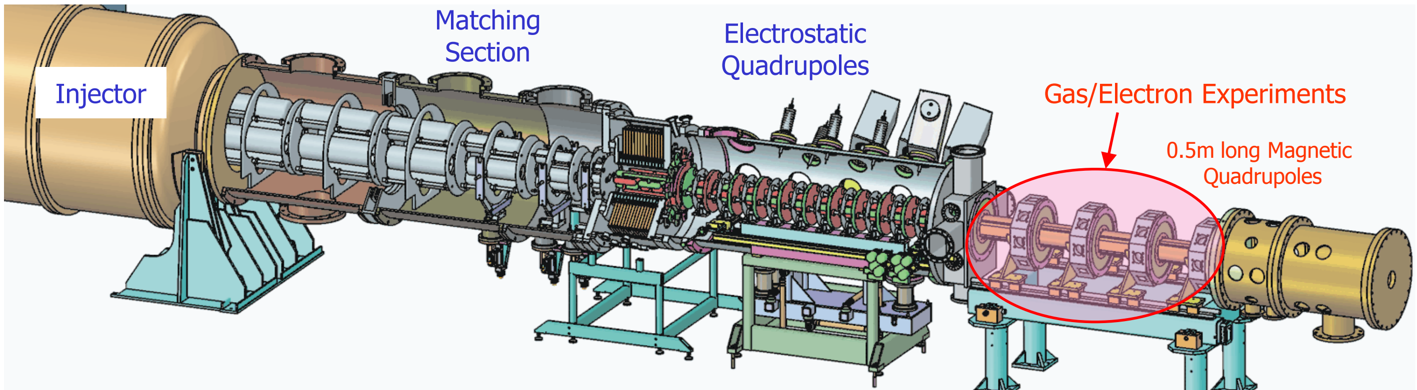
Impact angles studied: perpendicular & grazing

Target types: flat, tubular, cone samples

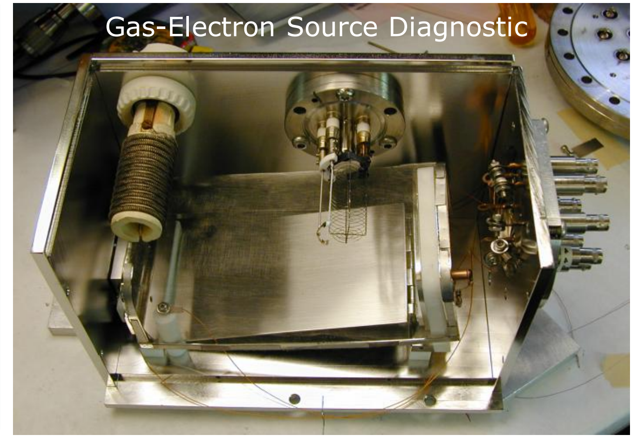
Target materials: ss (316 LN), Au/ss, Cu, Ta, TiZrV/ss

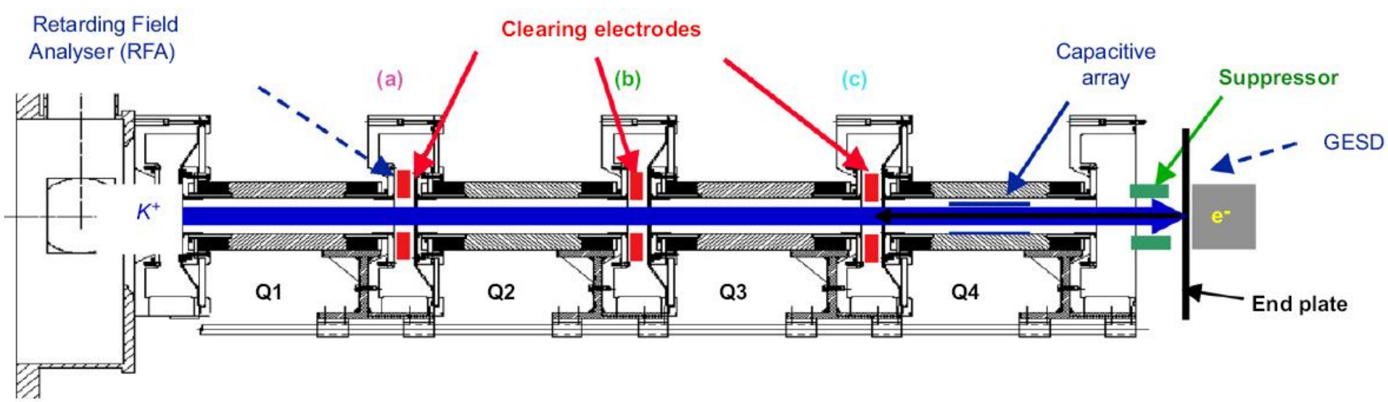
E. Hedlund et al., NIM A586, 377 (2008)
E. Hedlund, PhD thesis 2008.

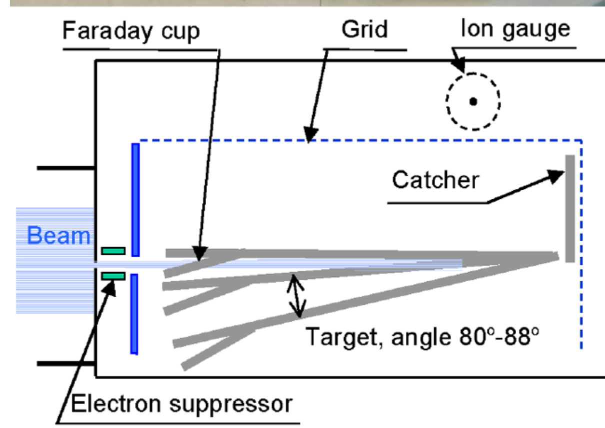
High-Current Experiment at Berkeley (LBNL)



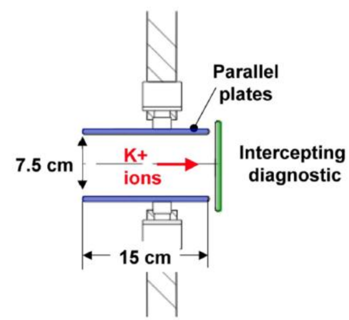
The HCX is a small, flexible heavy-ion accelerator at LBNL (A. Molvik)





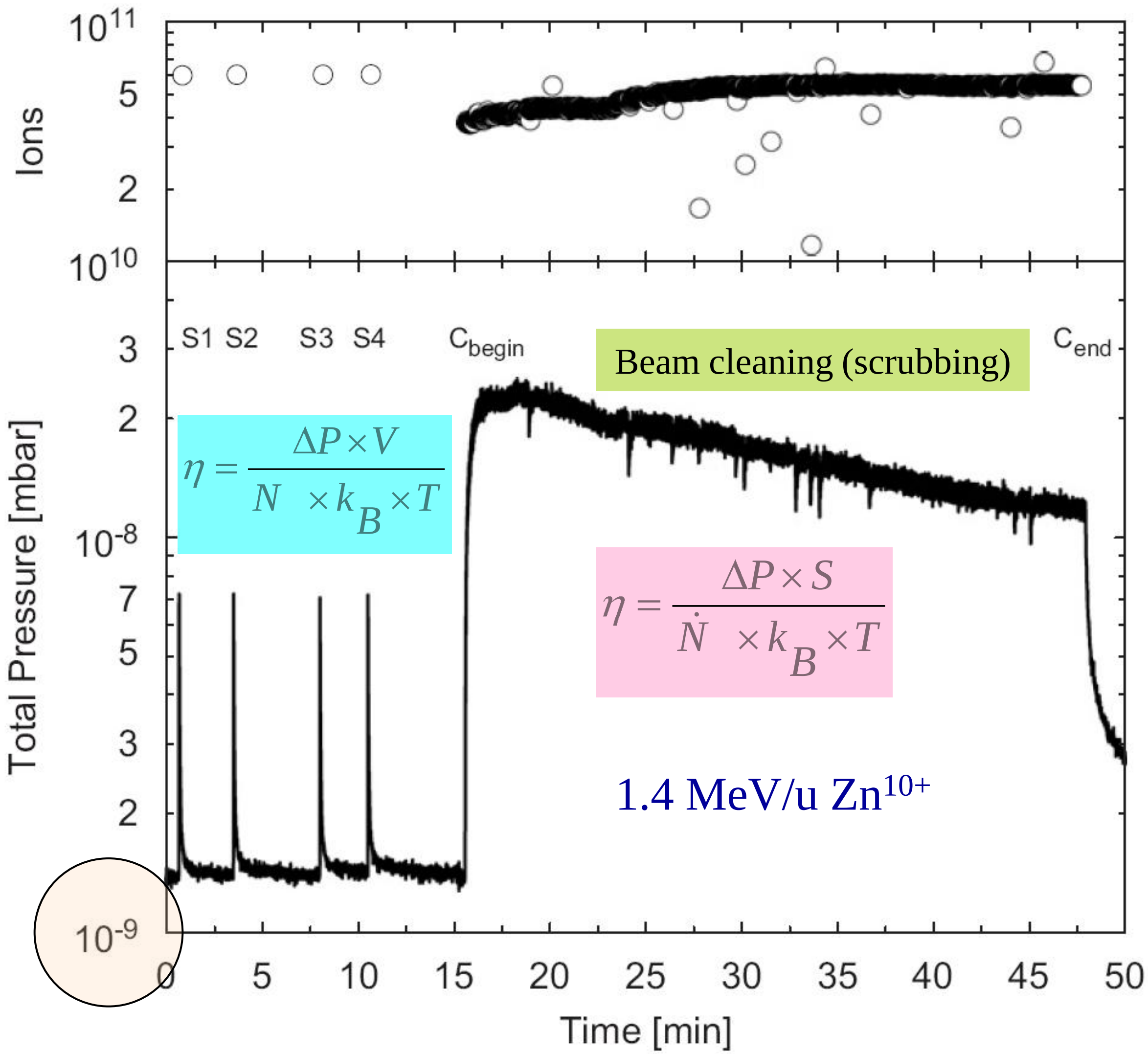


A.W. Molvik et al., PRST-AB 7, 093202 (2004); NIM A577, 45 (2007); PRL 98, 064801 (2007)
L.R. Prost et al., PRST-AB 8, 020101 (2005)
M. Kireeff Covo et al., PRL 97, 054801 (2006)
F.M. Bieniosek et al., PRST-AB 10, 093201 (2007)
J.E. Coleman et al., PRST-AB 11, 050103 (2008)

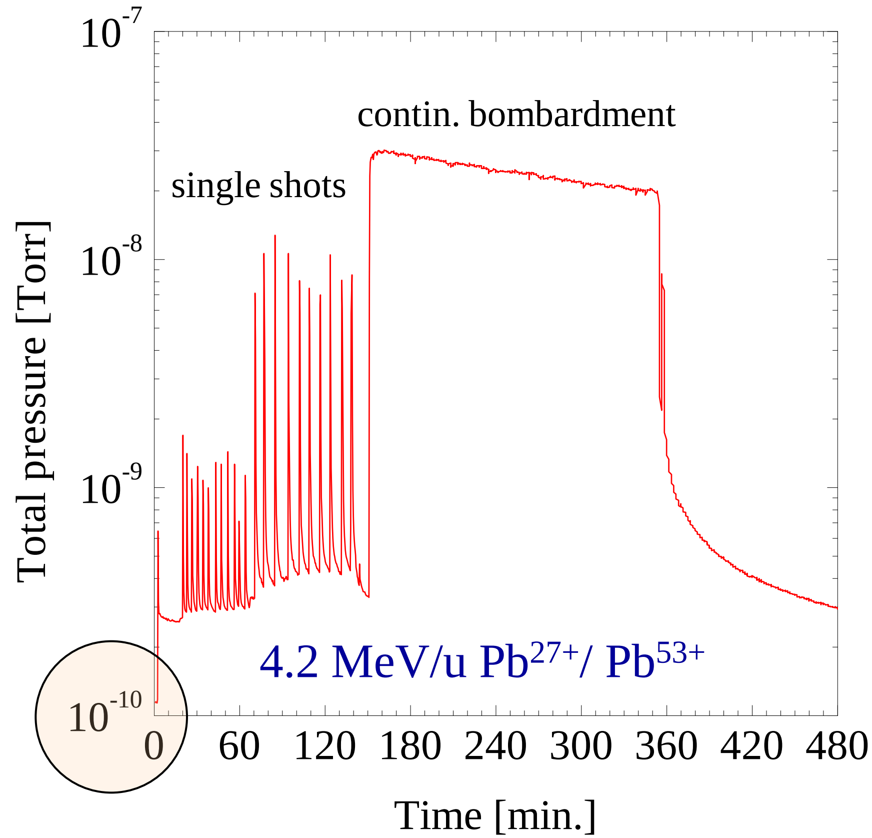


Ions: K^{1+} @ 1 MeV (0.025 MeV/u)
Intensities: 180 mA, t ≈ 4 µs, 4.5 × 10^{12} ions/pulse
Pulse repetition rate: 10 s
Beam potential: +2 kV
Impact angles studied: $\theta \approx$ 80-88°, perpend.
Targets: stainless steel

How we measure desorption yields?
Pressure rise method



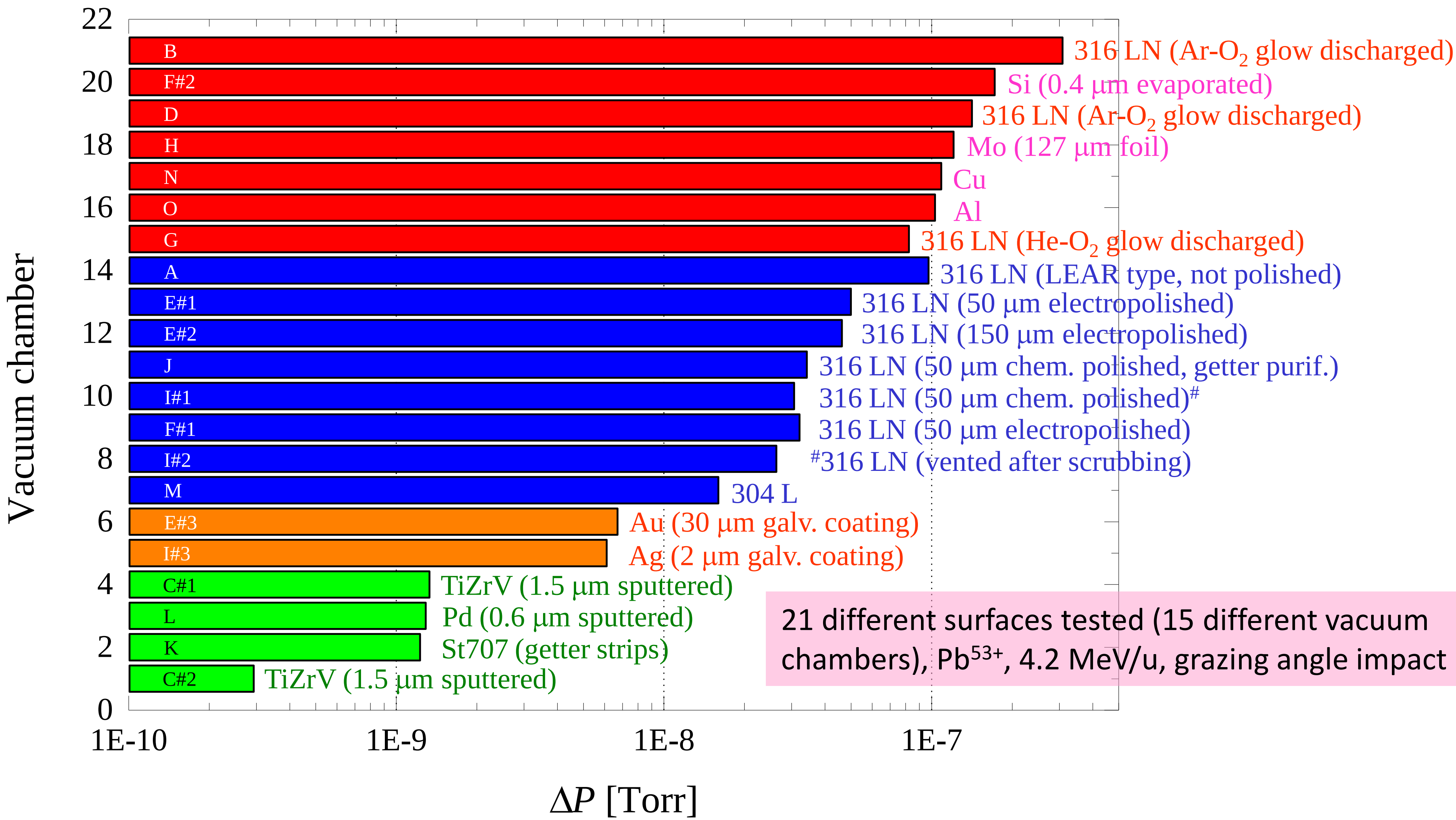
H. Kollmus et al., Vacuum 82 (2008) 402



Need of baked ultra-high vacuum system with a low static pressure for a high ΔP sensitivity

CERN LHC/VAC Note 2001-007
E. M. et al. PRST-AB 6, 013201 (2003)

Summary of LINAC 3 pressure rise measurements

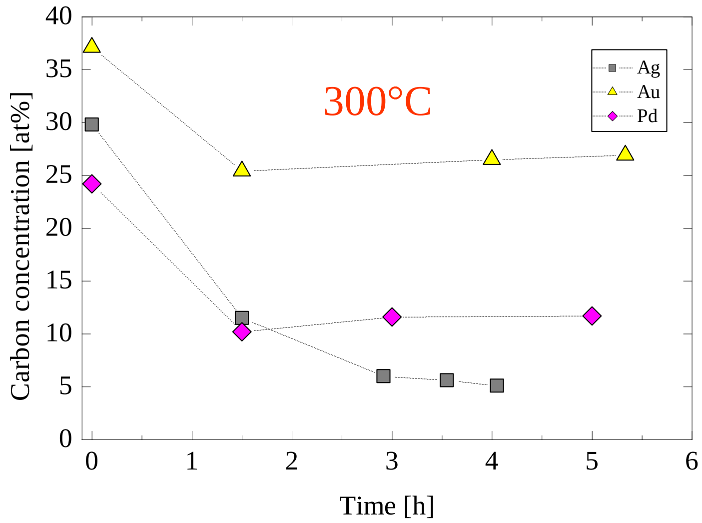


21 different surfaces tested (15 different vacuum chambers), Pb^{53+}, 4.2 MeV/u, grazing angle impact

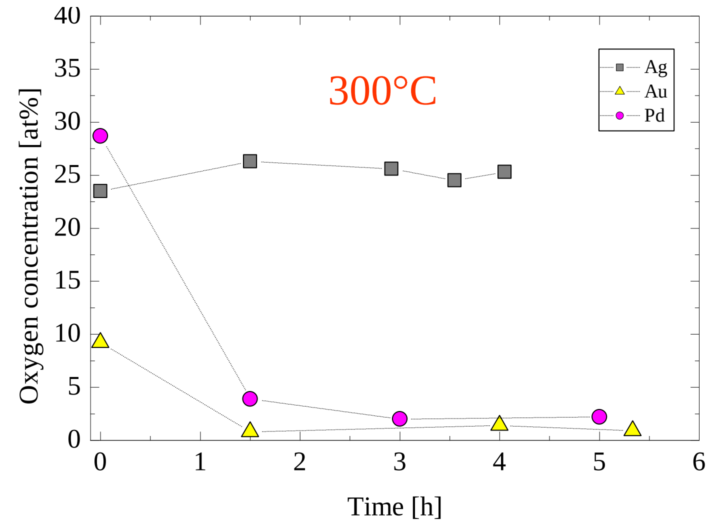
PRST-AB 11, 104801 (2008)

Carbon & oxygen evolution during UHV bakeout

Carbon surface concentration

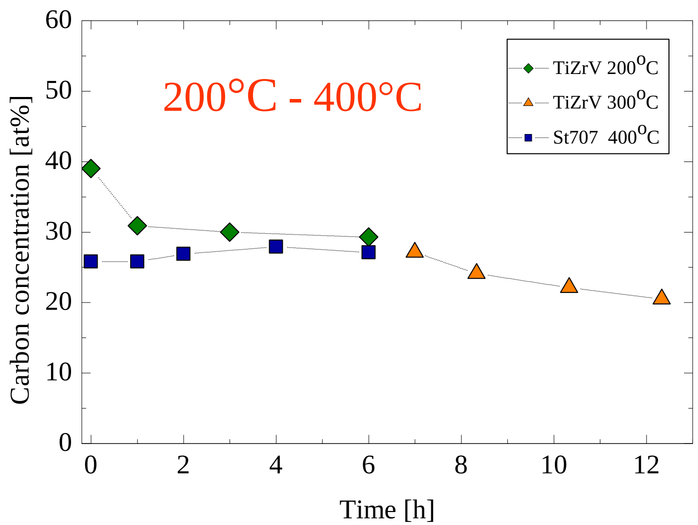


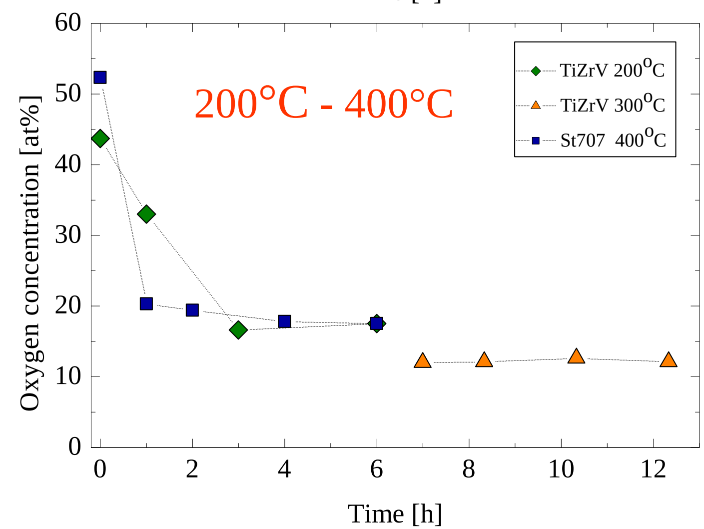
Oxygen surface concentration



Au/ss
Ag/ss
Pd/ss

XPS results
M. Taborelli

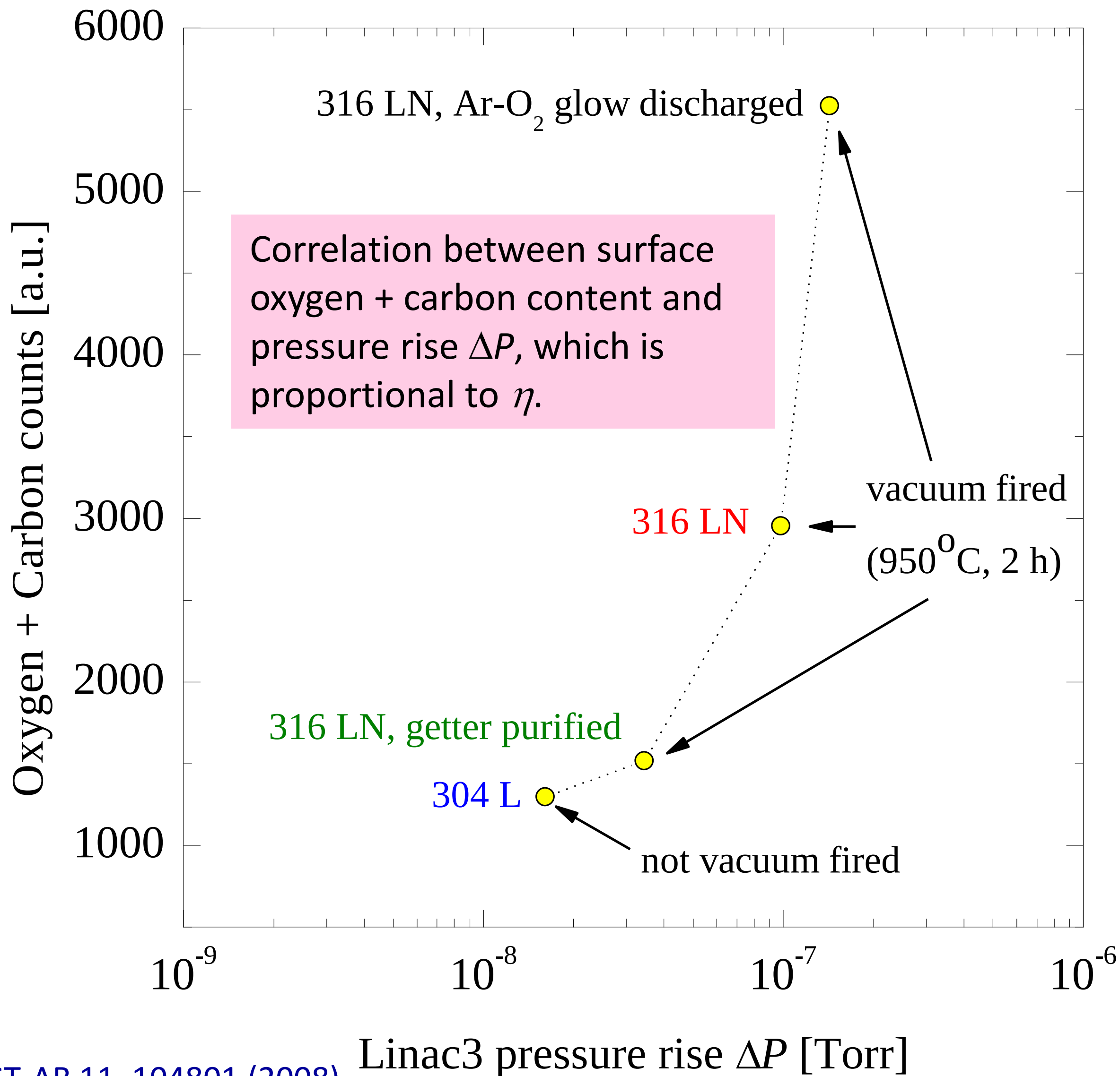


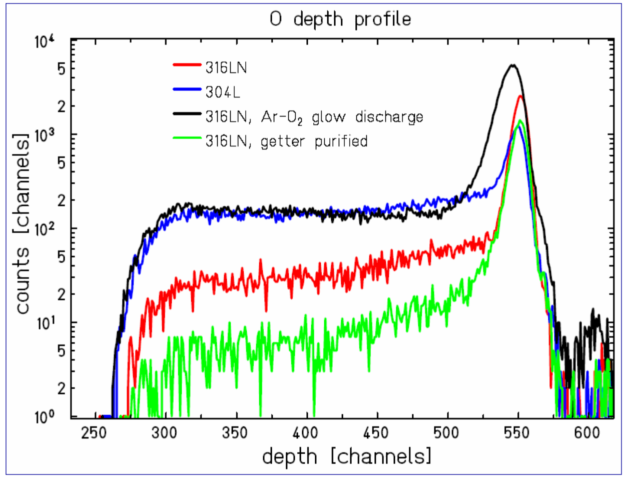


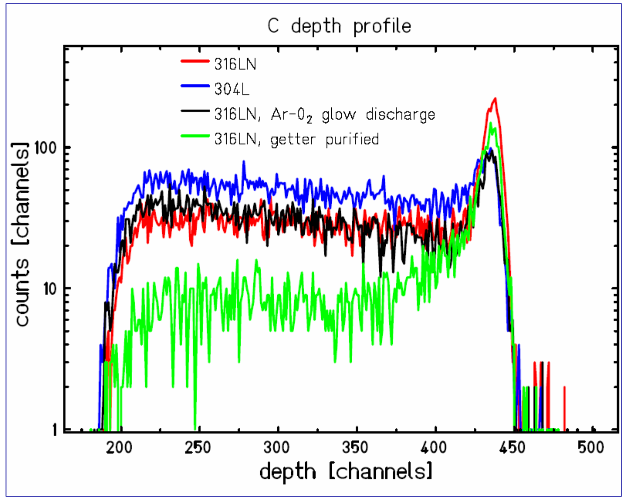
TiZrV/ss
TiZrV/ss
St707

E. M. et al., PRST-AB 8, 053201 (2005)

Elastic Recoil Detection Analysis (ERDA) sample results on cutted LINAC 3 chambers



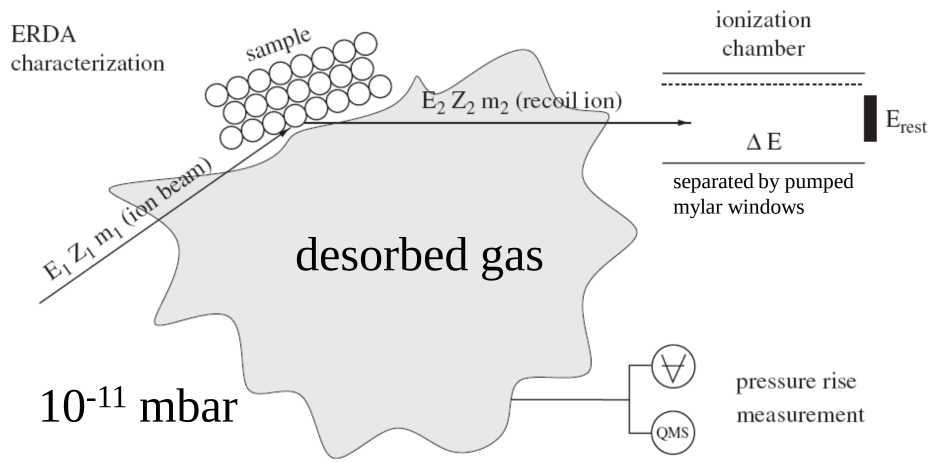


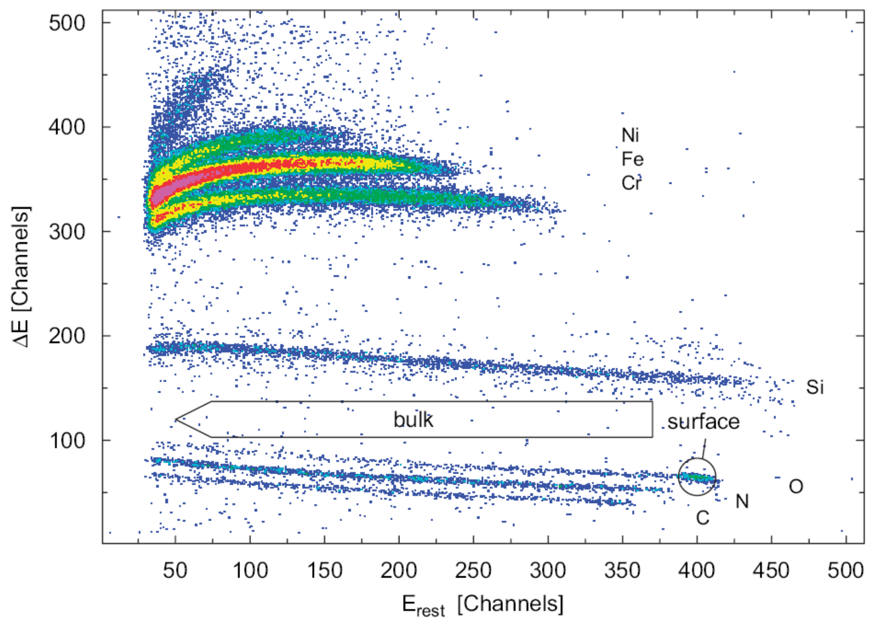


PRST-AB 11, 104801 (2008)

Munich Tandem Accelerator (Jan. 2003)
Au^{+30} @ 1 MeV/u, $p \approx 1 \times 10^{-7}$ mbar
W. Assmann, H. Kollmus, E. M.

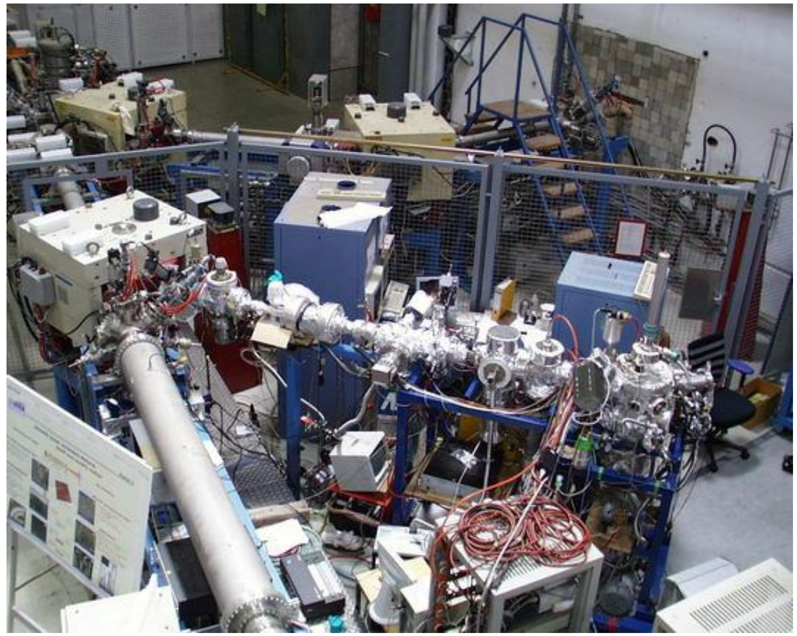
Material studies with UHV-ERDA at GSI





ERDA: element-specific depth profiling up to ≈ 1 μm, resolution of a few nm.

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

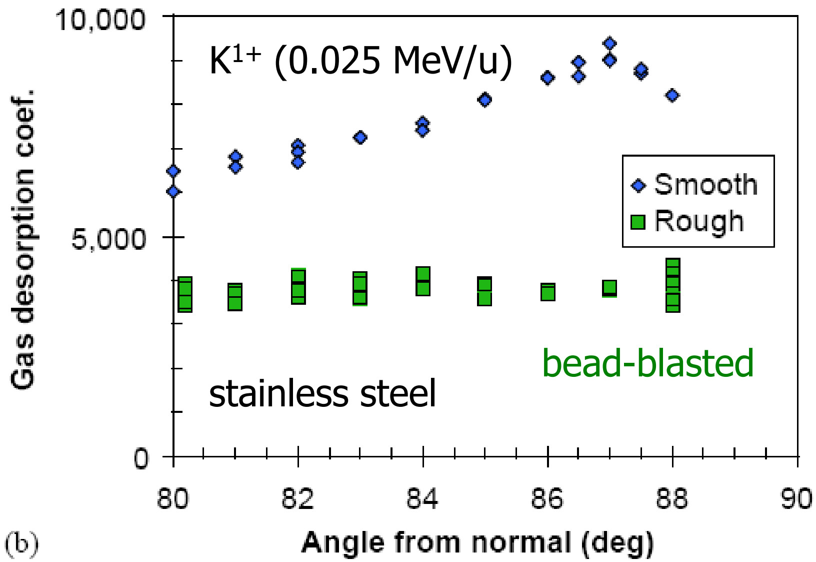


A typical ΔE -E_{rest} spectrum for 316LN stainless steel measured with 1.4 MeV/u Xe^{18+} projectile ions.

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

Impact angle dependence

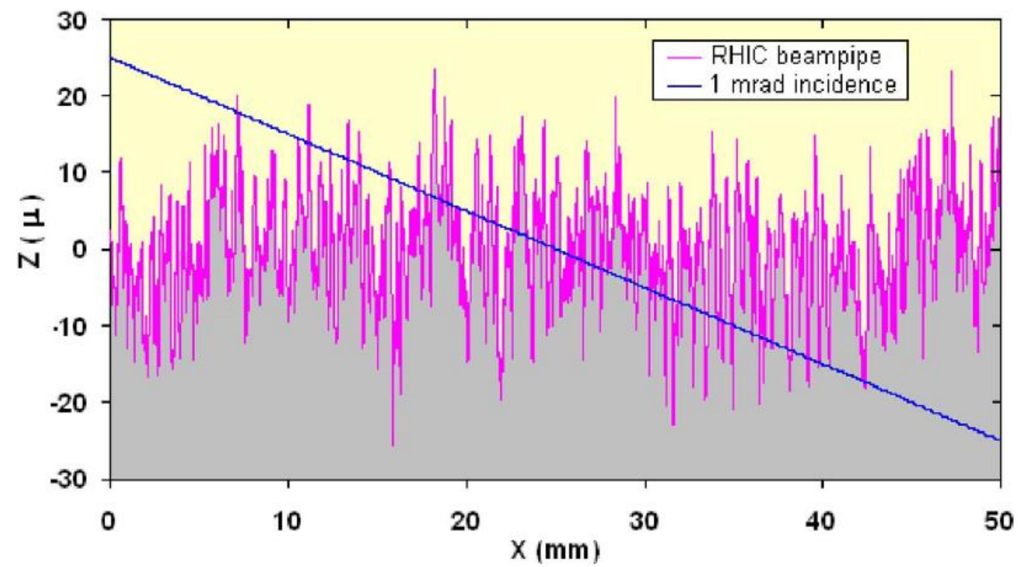
A.W. Molvik et al., PRST-AB 7, 093202 (2004); NIM-A544 (2005) 194



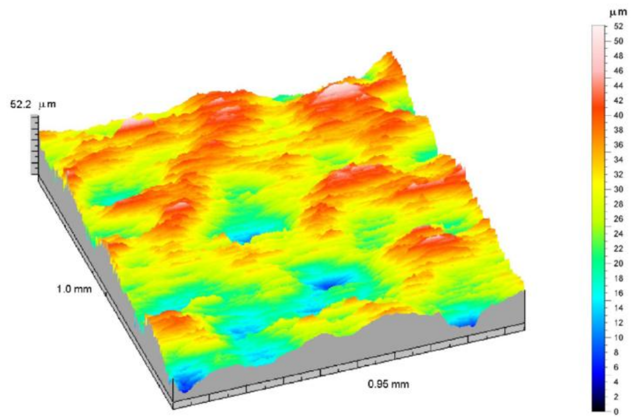
Roughened target surface eliminates grazing collisions to reduce desorption for low-energy ions with short penetration depths.

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

P. Thieberger et al., PRST-AB 7, 093201, (2004)

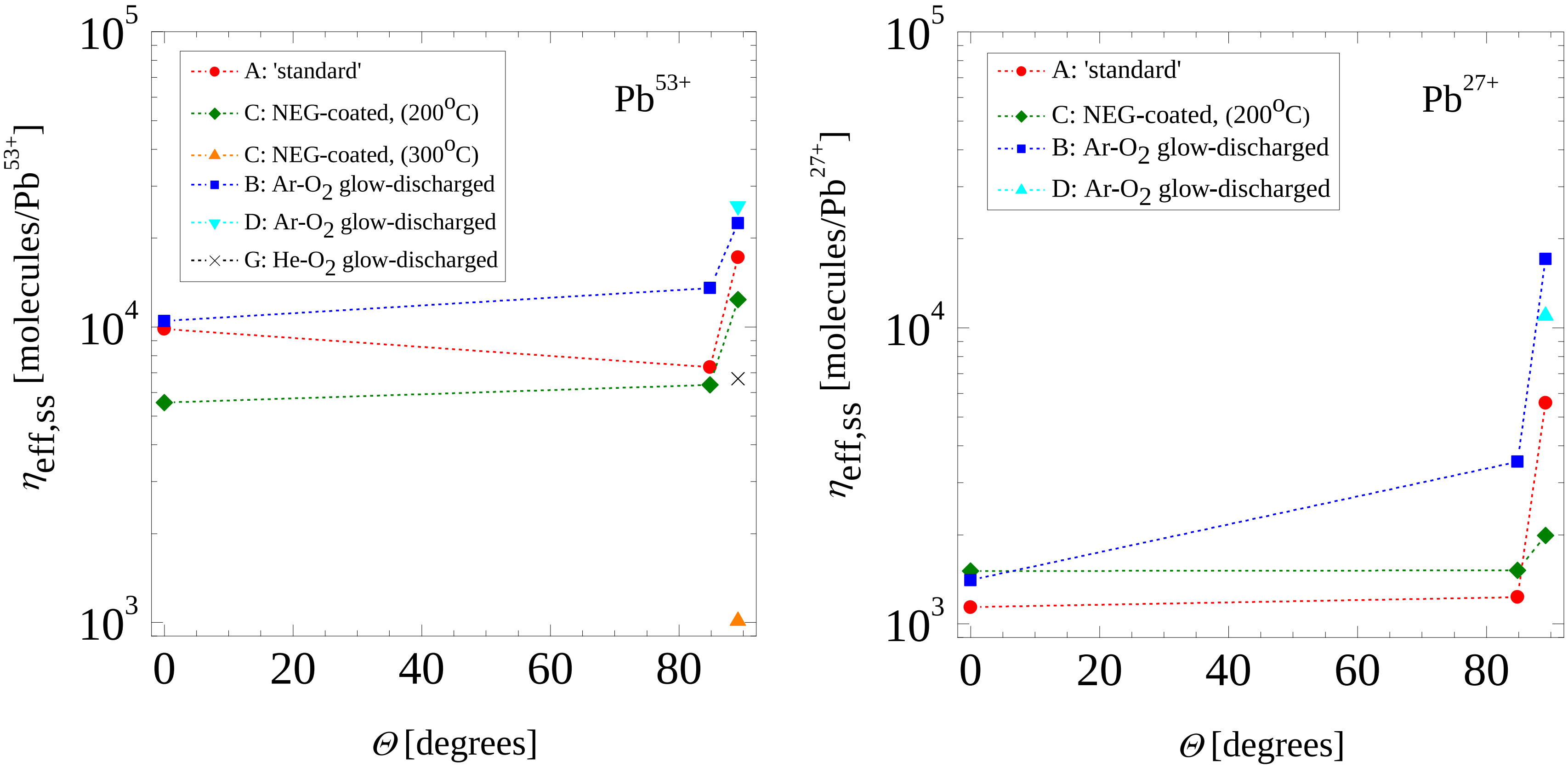


A rough surface increases the desorption, high-energy ions can enter and exit the surface morphology desorbing molecules each time.



Topographic view of a 1 × 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

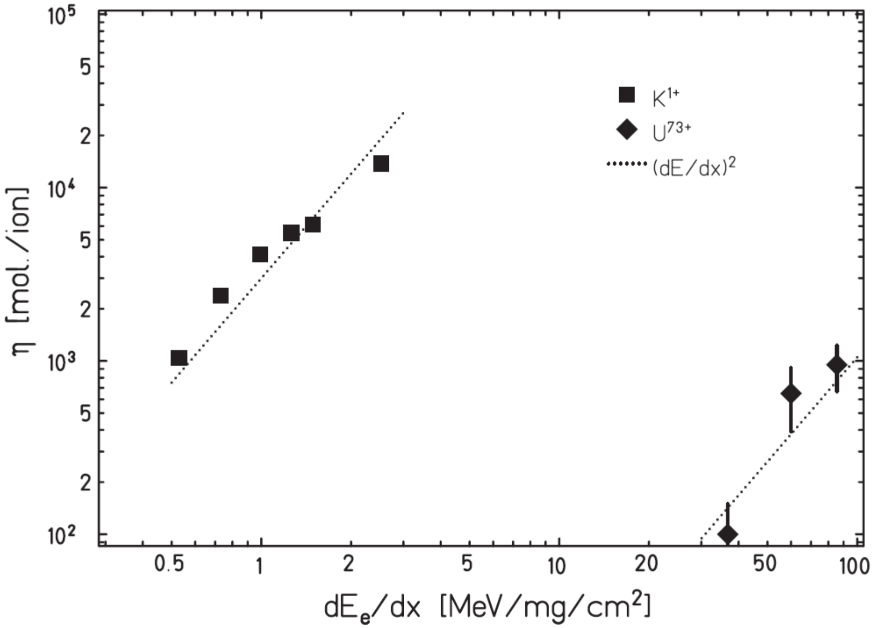
Factor 2 (Pb^{53+}) reduced η at $\theta = 0$ → **special collimators (chosen for LEIR)** or or saw-toothed vacuum chambers

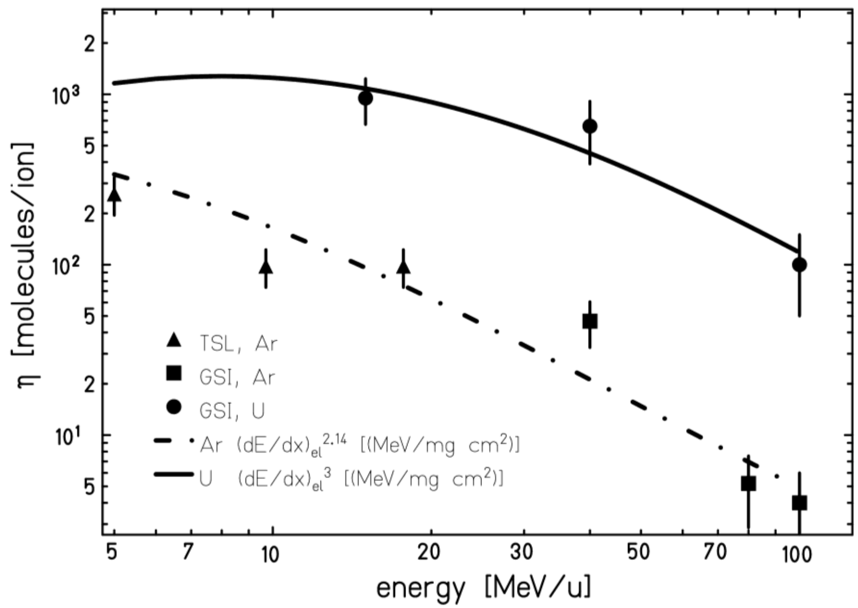
Ion charge state (53+/27+) for 316 LN stainless steel

Factor 10 reduced η at $\theta = 0$ → no impact for LEIR

E. M. et al., PRST-AB 6, 013201 (2003)

Energy scaling
GSI-CERN-LBNL-Uppsala results



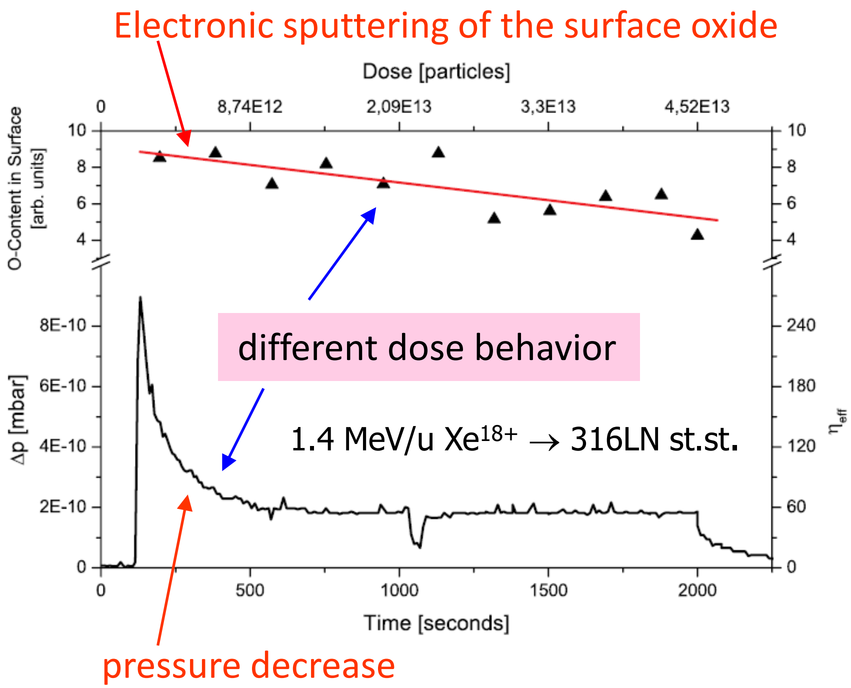


Conclusion: The heavy-ion induced molecular desorption yield scales with the electronic energy loss as $\eta = k \cdot (dE_{el}/dx)^n$ of the projectile/target system with $n \approx 2\text{-}3$, k is a scaling factor. The power of $n \geq 2$ indicates a microscopic thermally moderated desorption process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

A.W. Molvik, H. Kollmus, E. Mahner, M. Kireeff Covo, M.C. Bellachioma, M. Bender, F. M. Bieniosek, E. Hedlund, A. Krämer, J. Kwan, O.B. Malyshev, L. Prost, P.A. Seidl, G. Westenskow, and L. Westerberg
Phys. Rev. Lett. 98, 064801 (2007)

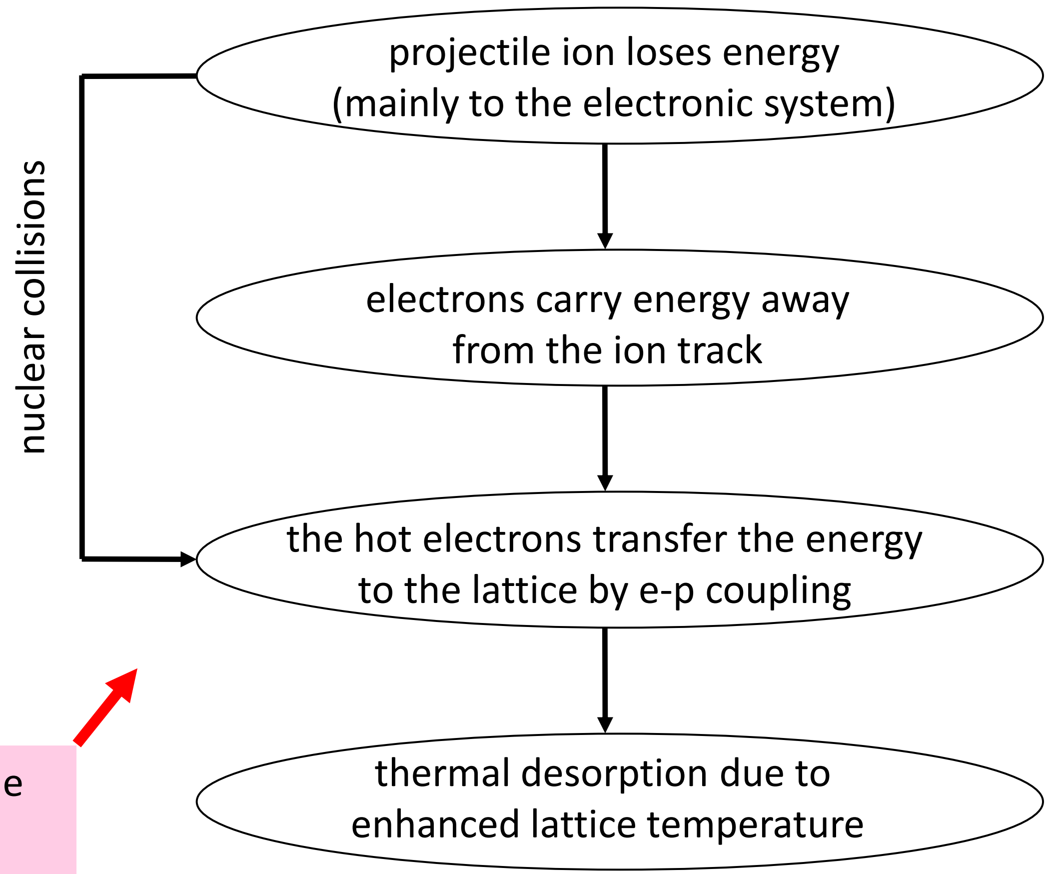
H. Kollmus, A. Krämer, M. Bender, M.C. Bellachioma, H. Reich-Sprenger, E. Mahner, E. Hedlund, L. Westerberg, O.B. Malyshev, M. Leandersson, E. Edquist
J. Vac. Sci. Technol. A27, 245 (2009)

Experiment, theory, calculations, first quantitative model



Ion dose dependent evolution of the oxide layer (top) and the desorption yield (bottom).

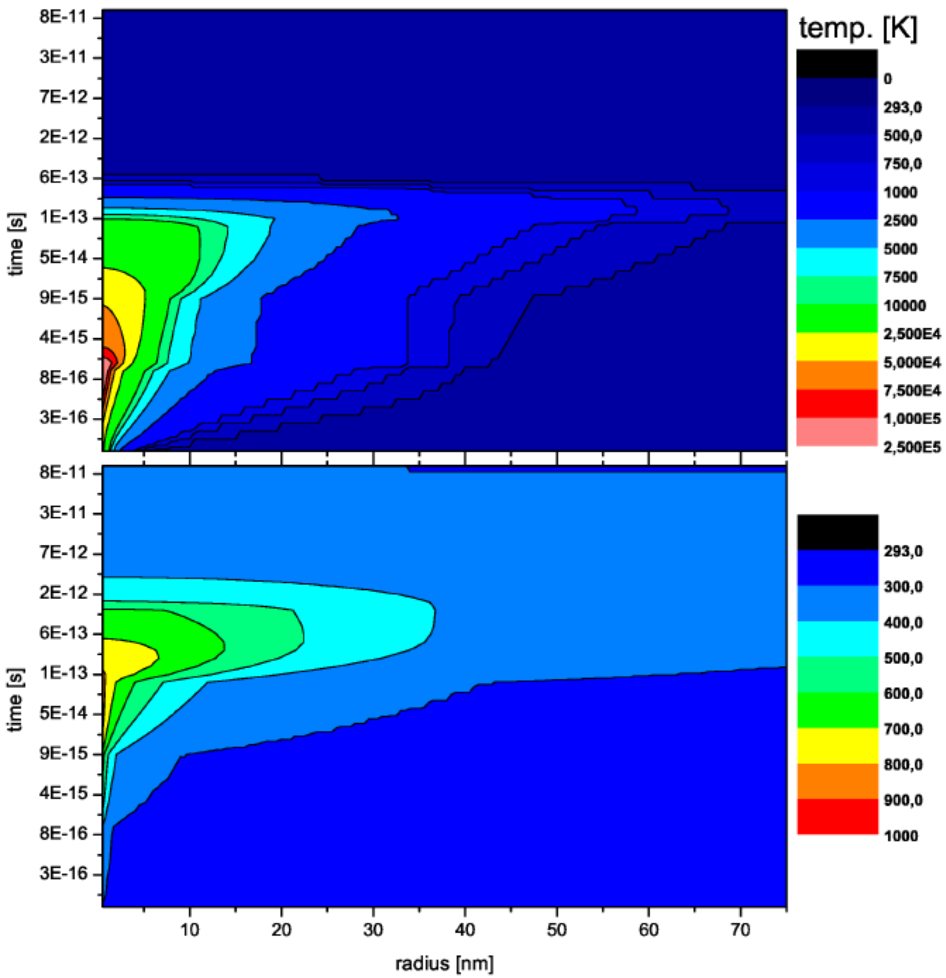
How can 1 heavy-ion stimulated the desorption of up to several 1000 gas molecules?



Conclusion: measured Δp 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.

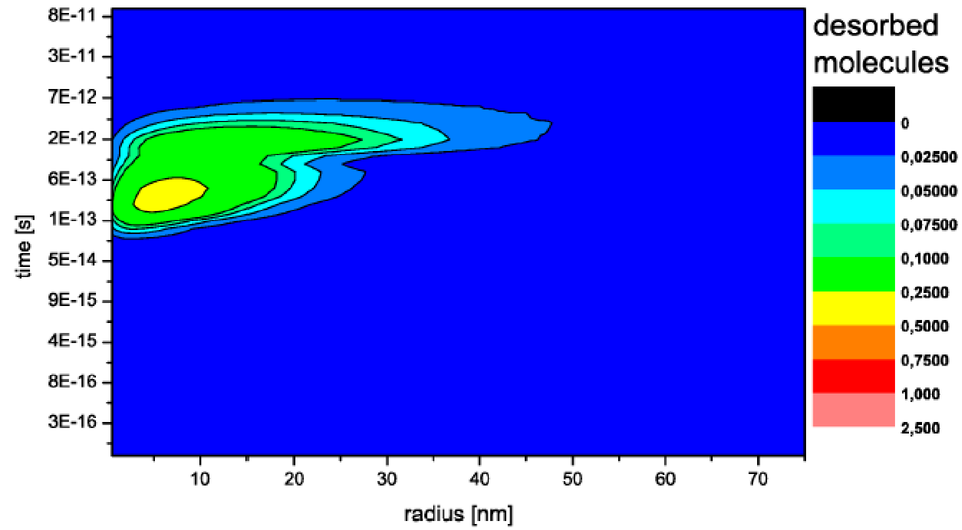
M. Bender, PhD thesis 2008

Thermal Distribution as a function of time and space (radius) for 1.4 MeV/u Xe → Cu



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

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



Desorption from one single projectile

Proj. (1.4MeV/u)	Xe	Xe	Xe	C	Pb	Pb (4.2MeV/u)
Target	Cu	Au	Rh	Cu	Cu	Au
Experiment	290	90	1280	10	800	800 (prel.)
Calculation	185	165	3400	5	525	750

"...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."

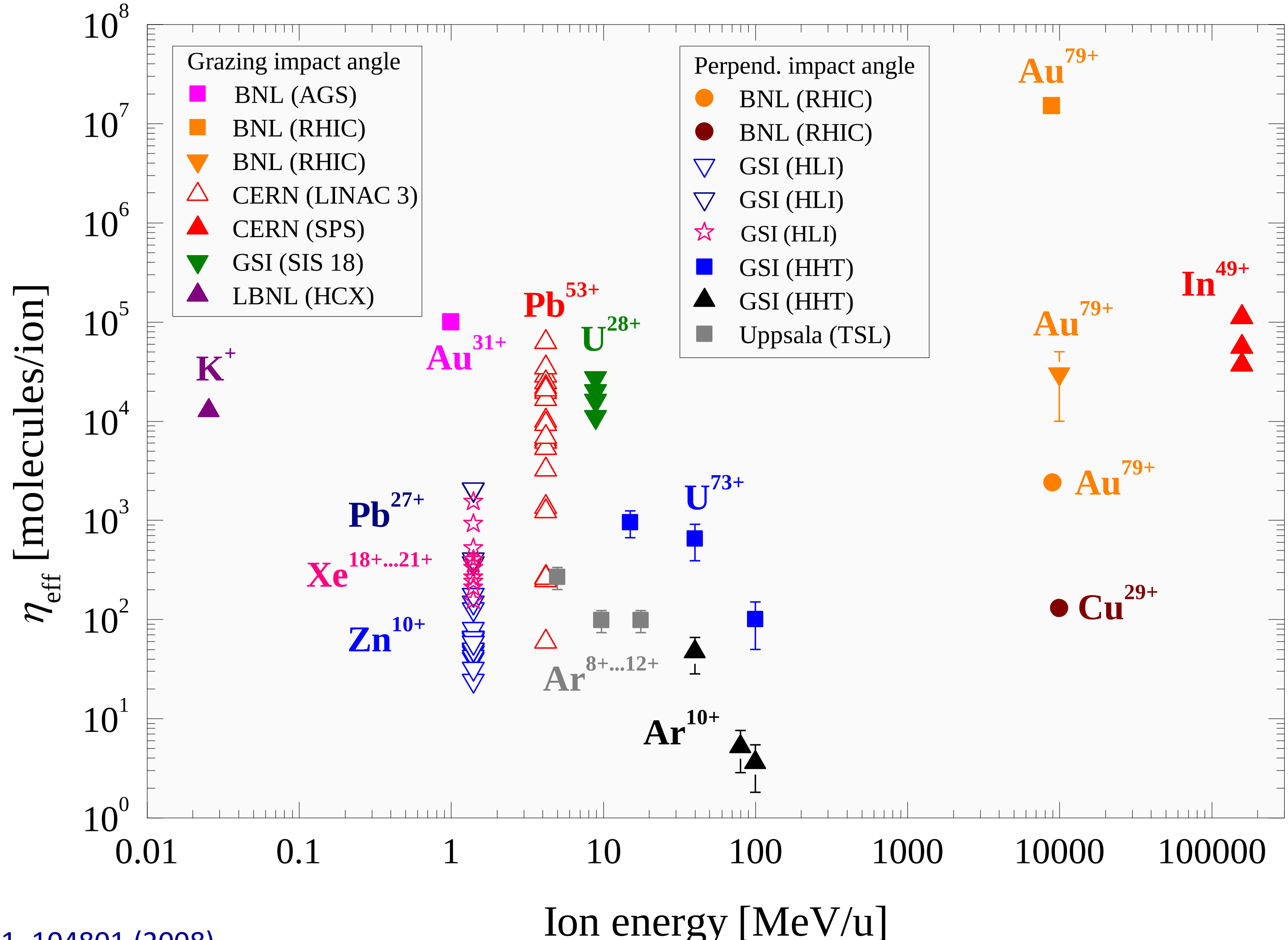
Overview of heavy-ion desorption experiments with ambient temperature targets at accelerators

TABLE I. Overview of heavy-ion-induced desorption experiments at particle accelerators worldwide. The different types of ions, charge states, energies, impact angles, and target materials are compared between the different laboratories. Desorption experiments were performed between 1998 and 2008.

Projectile	Ion energy	Impact angle	Target material, Stainless steel = ss	Lab-Accelerator	Reference
Au^{31+}	1 MeV/u	Grazing	Stainless steel	BNL-AGS	[4,5]
Au^{79+}	8.9 GeV/u	Grazing	Stainless steel	BNL-RHIC	[22]
Au^{79+}	9 GeV/u	Perpendicular	Stainless steel		[23]
Cu^{29+}	10 GeV/u	Perpendicular	Stainless steel		
p^{+}	23 GeV	Perpendicular	Stainless steel		
Pb^{53+}/Pb^{27+}	4.2 MeV/u	Grazing and perpendicular	ss (316LN, 304 L) Au, Ag, Pd, TiZrV/ss (316LN) Cu, Al, Mo, Si/ss (316LN)	CERN-LINAC 3	[30,31]
In^{49+}	158 GeV/u	Grazing	ss (316LN), graphite, Cu/graphite, TiZrV/graphite	CERN-SPS	[32,43]
C^{2+}, Cr^{7+} Pb^{27+}, Zn^{10+} $Xe^{18+\cdots 21+}$	1.4 MeV/u	Perpendicular	ss (304 L, 316LN), Cu, Si, Al	GSI-HLI	[33,44]
		19° (ERDA)	ss (304 L, 316LN), Cu, Au/316 LN, Au/Cu, Rh/Cu		[45]
U^{28+}	8.9 MeV/u	Grazing	ss (316LN)	GSI-SIS 18	[7]
U^{73+}	15, 40, 100 MeV/u	Perpendicular	ss (316LN, P 506)	GSI-HHT	[36]
Ar^{10+}	40, 80, 100 MeV/u		ss (316LN), Cu, Al		[46]
K^{+}	0.002–0.025 MeV/u	Grazing	Stainless steel	LBNL-HCX LLNL-STS500	[37,41]
$Ar^{8+}/Ar^{9+}/Ar^{12+}$	5, 9.7, 17.7 MeV/u	Perpendicular	ss (316LN), Cu, Ta	Uppsala-TSL	[47]

PRST-AB 11, 104801 (2008)

Review of heavy-ion induced desorption data



PRST-AB 11, 104801 (2008)

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, 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, SIS 18, tests in RHIC, in preparation for SIS 100 (FAIR).
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.

CERN-LEIR with collimators +…

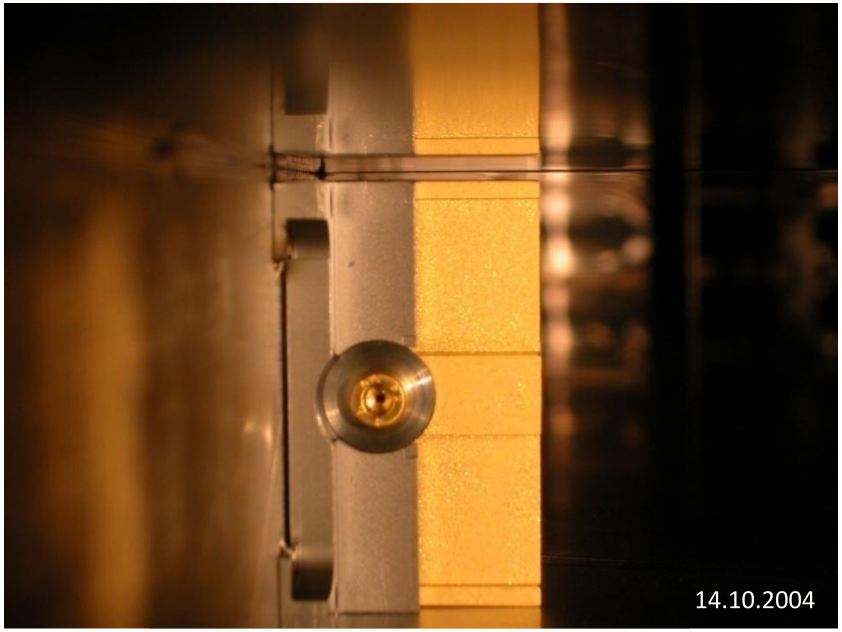
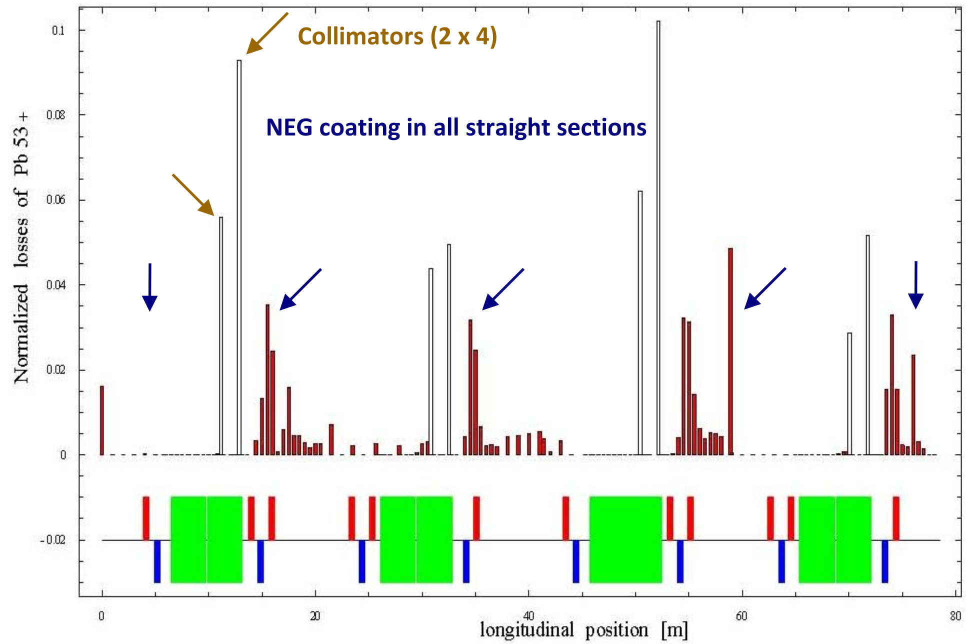


Fig. 2. Photograph of a 30 μm gold-coated 316LN stainless steel collimator to collect lost 4.2 MeV/u Pb^{53+} ions. The collimator is screwed on the back face onto a stainless steel support which is spot-welded at the end of each LEIR bending magnet vacuum chamber.

E. Mahner, CERN Report AT-2005-013 (2005)



Ions hitting 8 gold-coated collimators placed in 4 main bending vacuum chambers. NEG coated chambers in all straight sections.

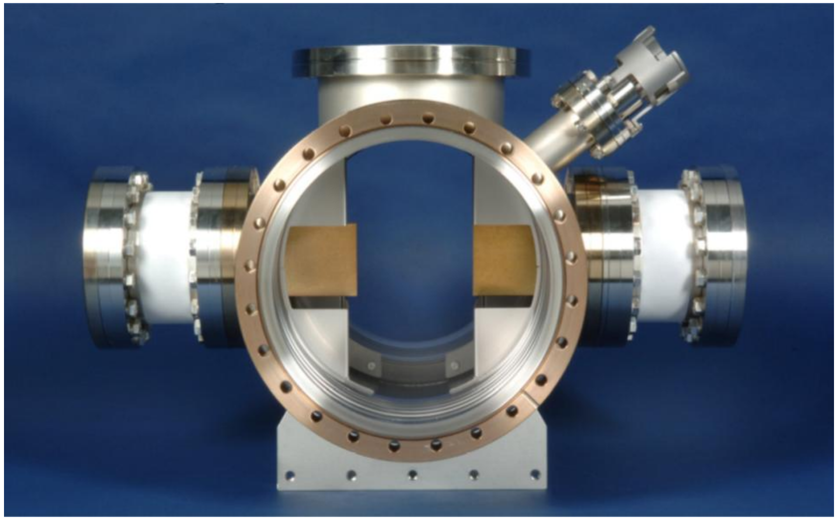
J. Pasternak et al., PAC 2005

During LEIR machine commissioning in 2006, no evidence has been found that the accumulated Pb^{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**.

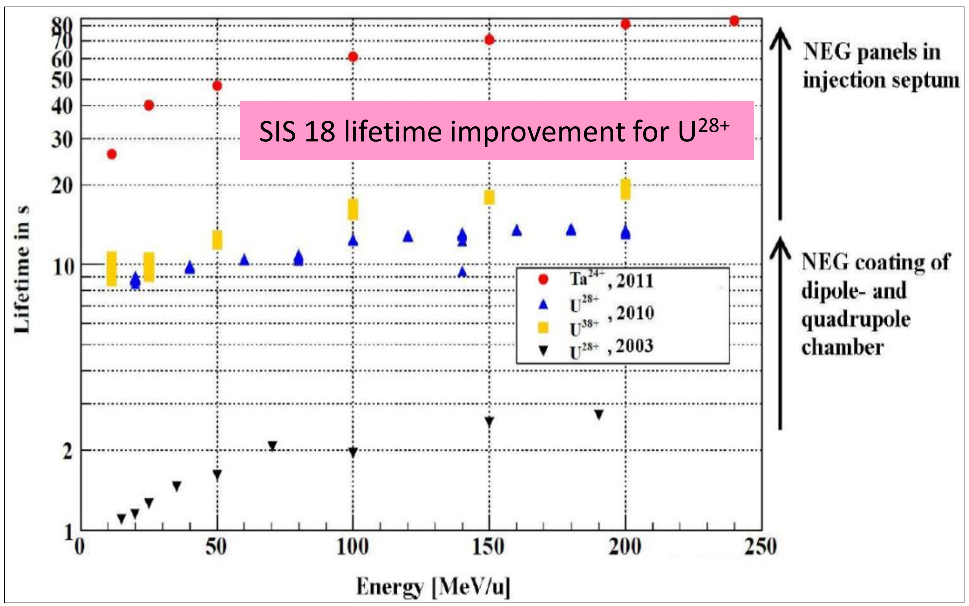
Beam-loss induced desorption is no operational issue for LEIR since the 2006 run!

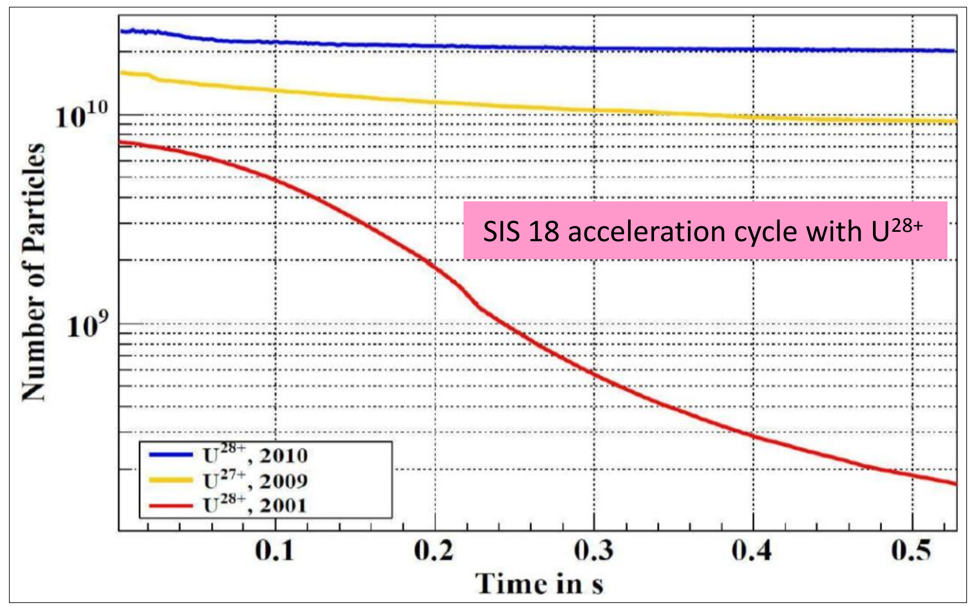
GSI-SIS18 upgrade with collimators +…



SIS18 ion-catcher vacuum chamber with 2 gold-coated copper catchers, for ionization and capture losses.

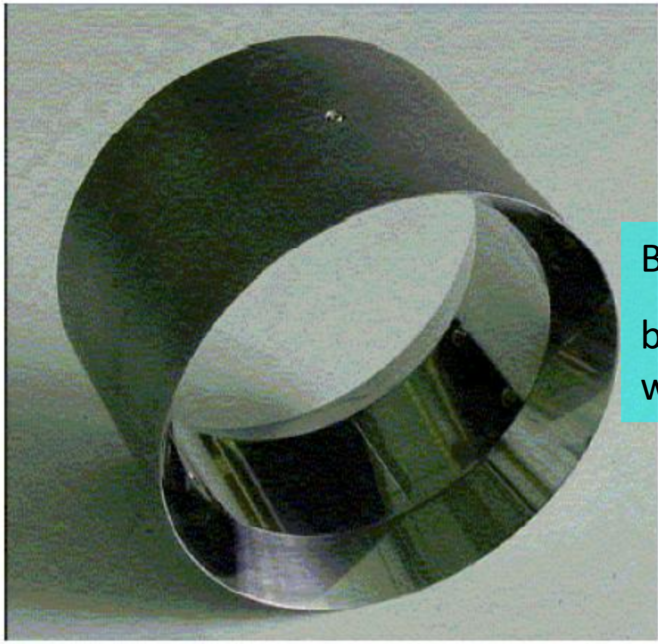
- Ion-catcher system behind each SIS 18 dipole group
- Replacement of all magnet chambers by new, NEG coated chambers
- Injection at higher energy of 11.4 MeV/u instead of 7.1 MeV/u with lower ionization cross sections
- Acceleration with higher ramp rates (shorter cycle times)





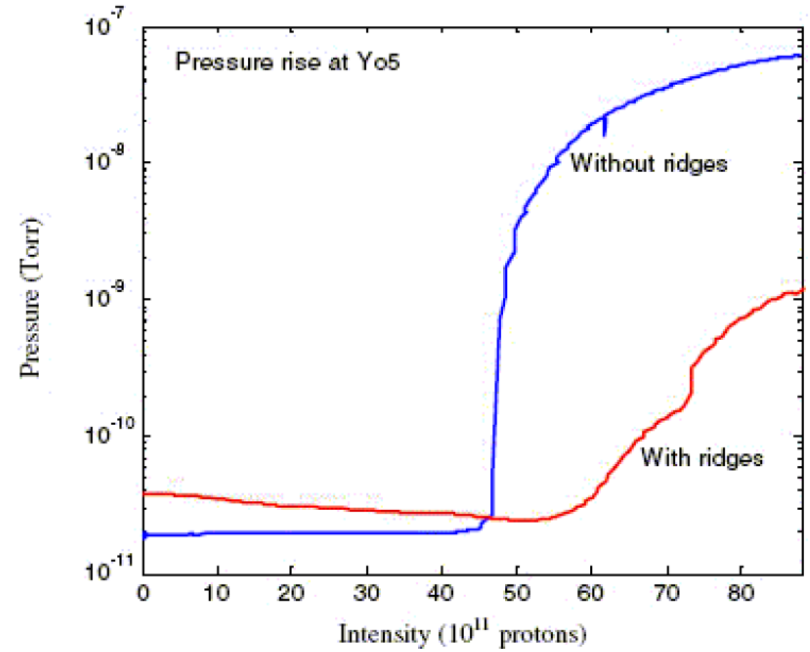
P. Spiller et al., IPAC'10/11 (2010/11)

Antigrazing rings in BNL-RHIC



BNL-RHIC (installed)

bare stainless steel without coating



W. Fischer et al., PRST-AB 11, 041002 (2008)

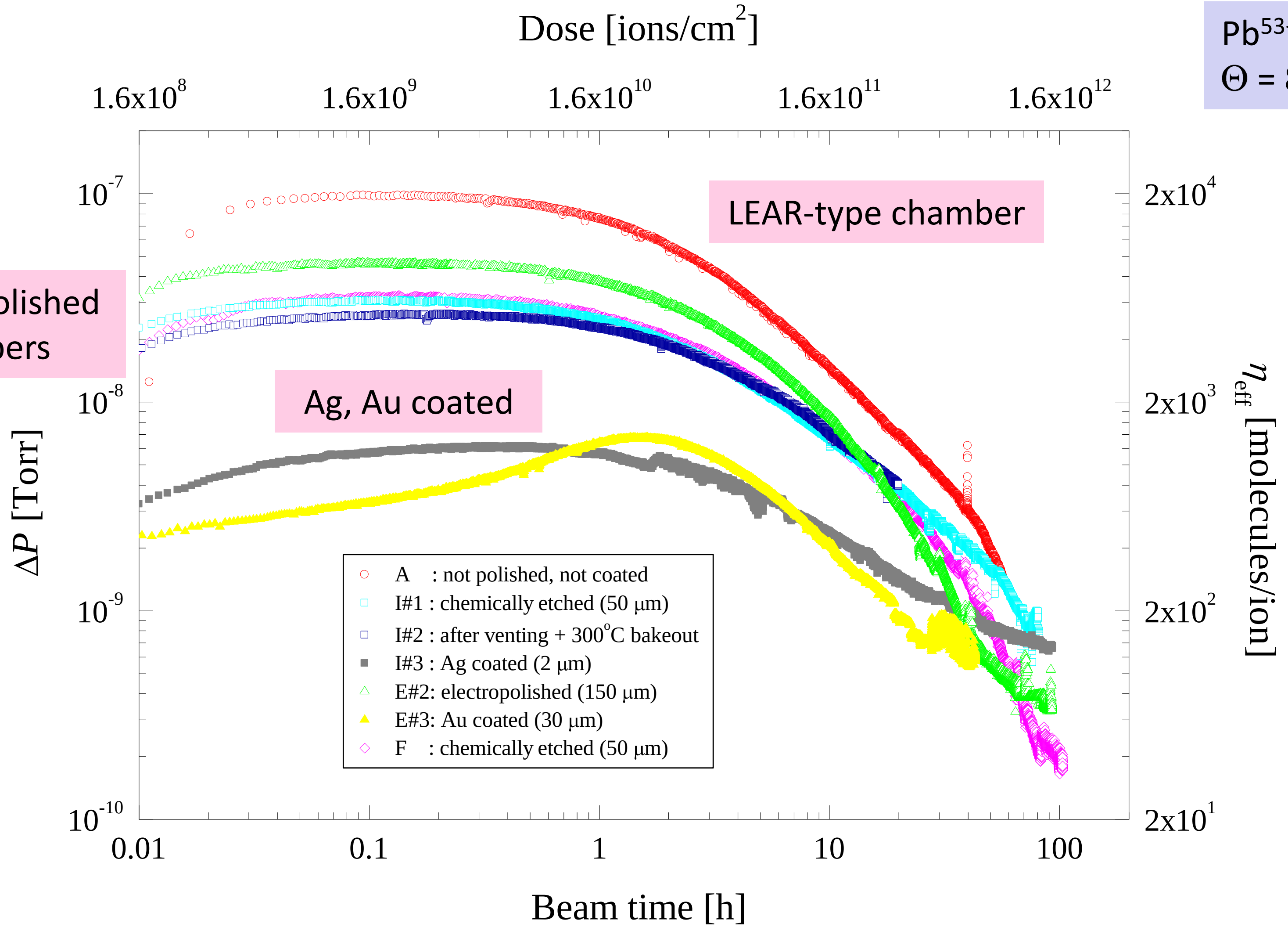
Idea (P. Thieberger 2004) is to mitigate grazing angle projectile collisions in RHIC.
A set of bare stainless steel rings was installed in a warm section of the machine and tested with protons in 2005.

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)

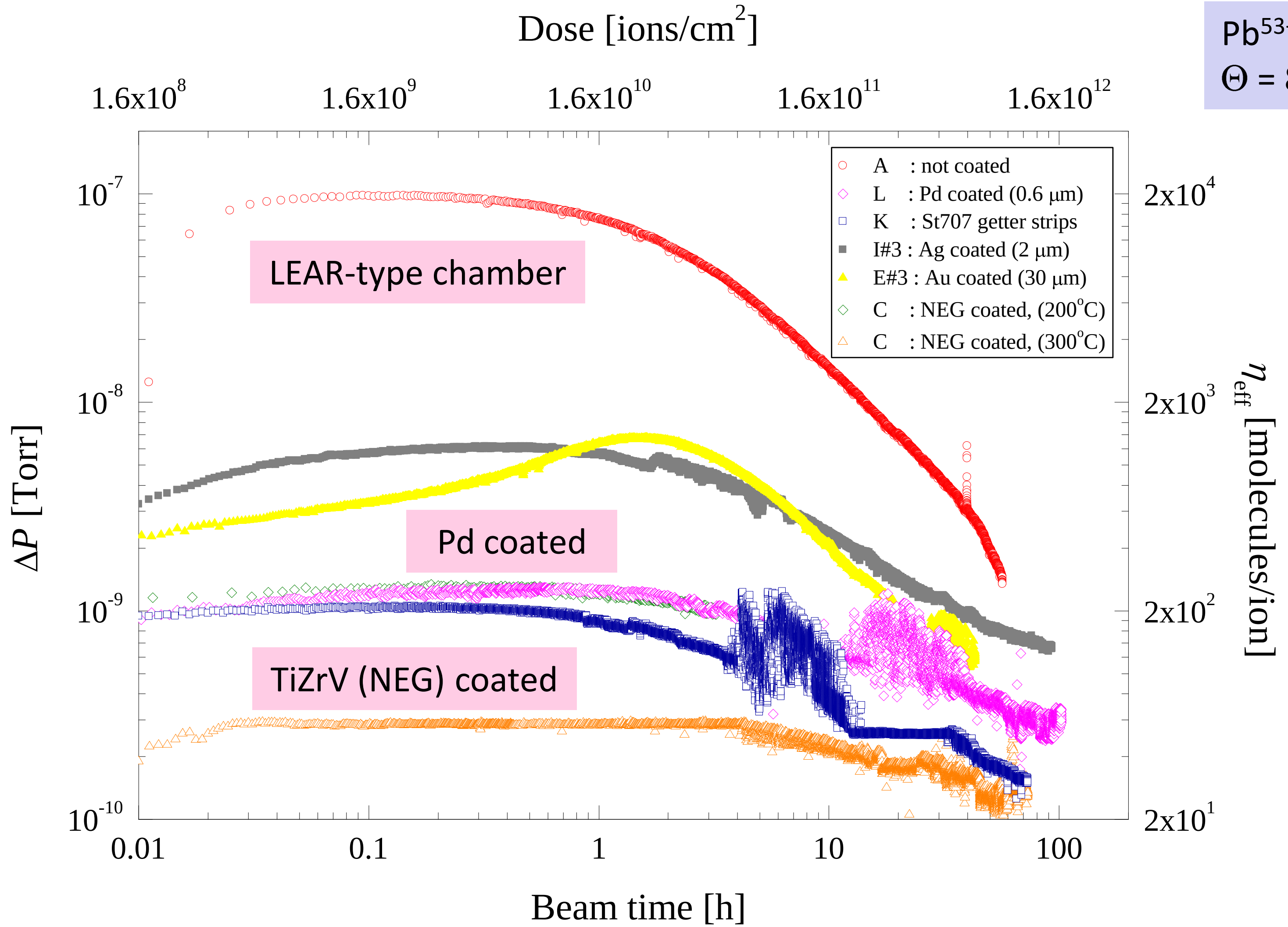
Pb^{53+} @ 4.2 MeV/u
Θ = 89.2° (grazing)



E. M. et al., PRST-AB 8, 053201 (2005)

Scrubbing in LINAC3 (2)

Pb^{53+} @ 4.2 MeV/u
Θ = 89.2° (grazing)



E. M. et al., PRST-AB 8, 053201 (2005)

Cryogenic targets…

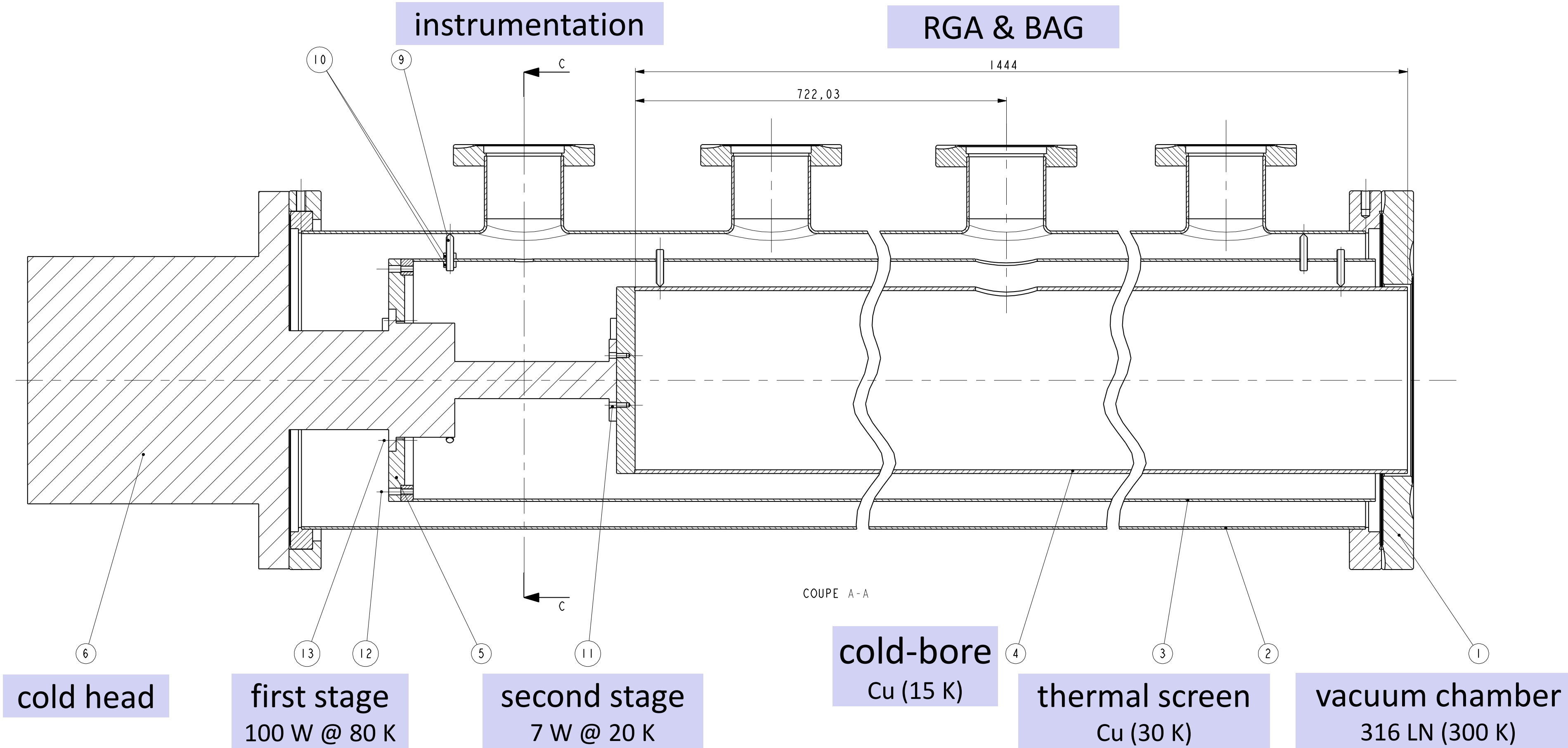
…a significant challenge for future synchrotrons

so far, only a few accelerator relevant experiments were performed at

CERN-LINAC 3 (2004, 2009)

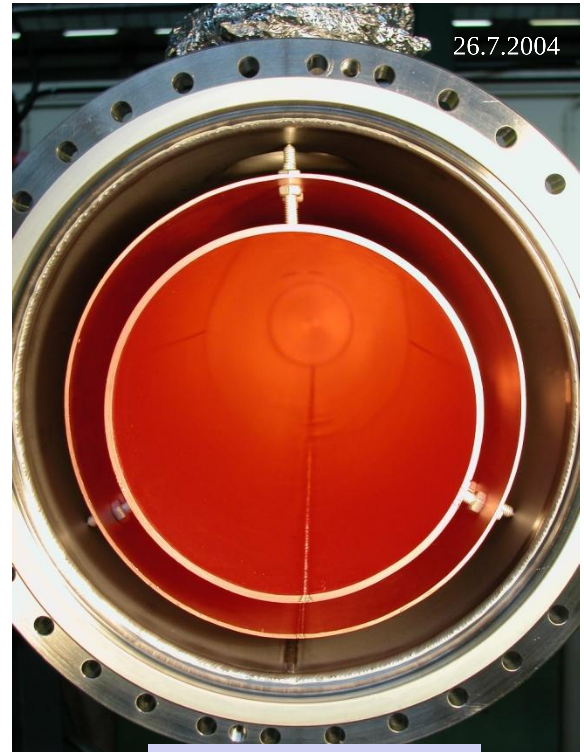
GSI-HLI (2011), GSI-HHT(2011)

LINAC 3 cold-bore experiment 2004
design



E. M., M. Bender, H. Kollmus, AIP CP773, 219 (2005)

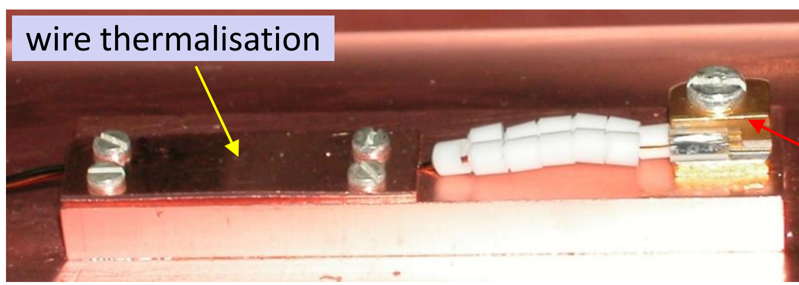
LINAC 3 cold-bore experiment 2004
components



as seen by the Pb^{53+} ion beam

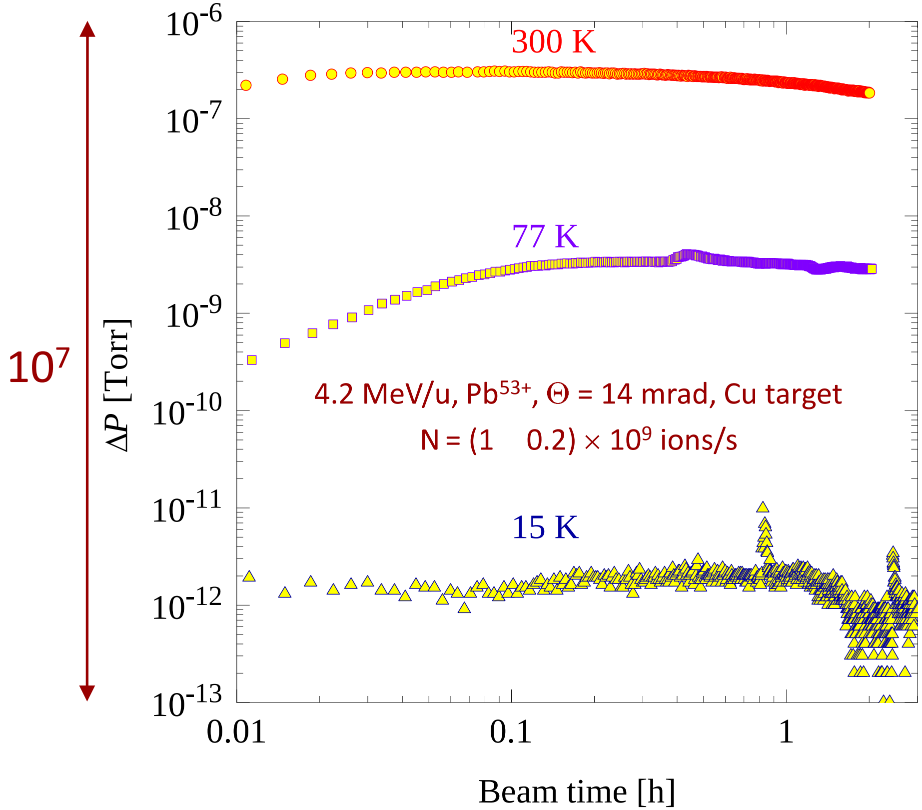
E. M., M. Bender, H. Kollmus, AIP CP773, 219 (2005)

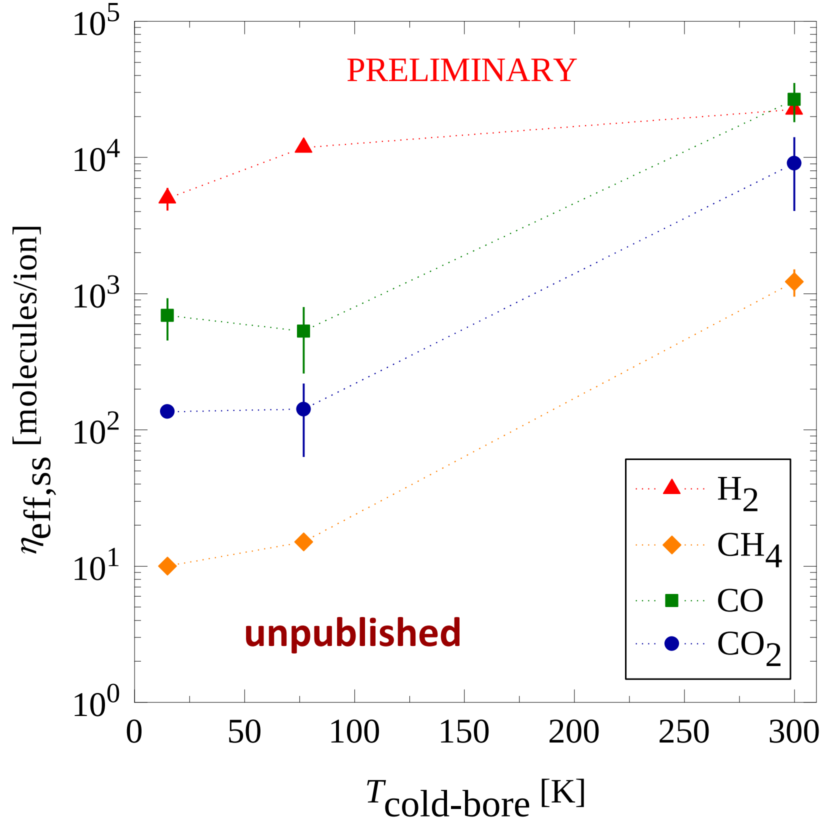
cold head (5/100 T)



silicon diode (DT-670B-BO)

LINAC 3 cold-bore experiment 2004 results



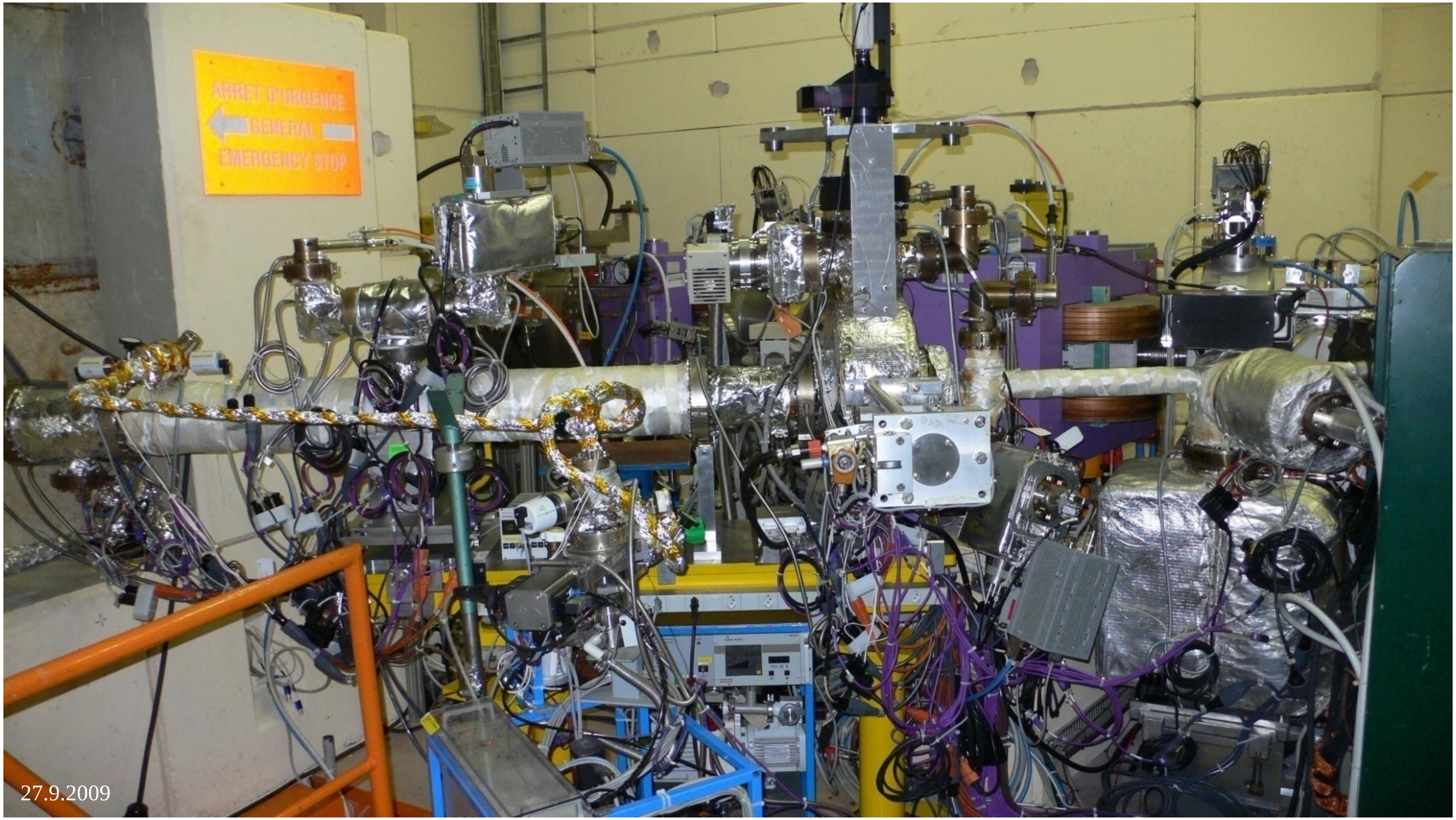


During these first cryogenic target experiments in 2004 very low absolute and partial pressure rises were measured for the bare copper at 15 K. During beam scrubbing a temperature rise of 203 ± 13 mK was measured along the cold bore.

The ambient temperature desorption yield of $\eta = 4 \times 10^4$ molecules/ion confirmed previous results obtained at LINAC 3. A temperature dependence of η was derived but remained unpublished.

E. M., M. Bender, H. Kollmus, AIP CP773, 219 (2005)

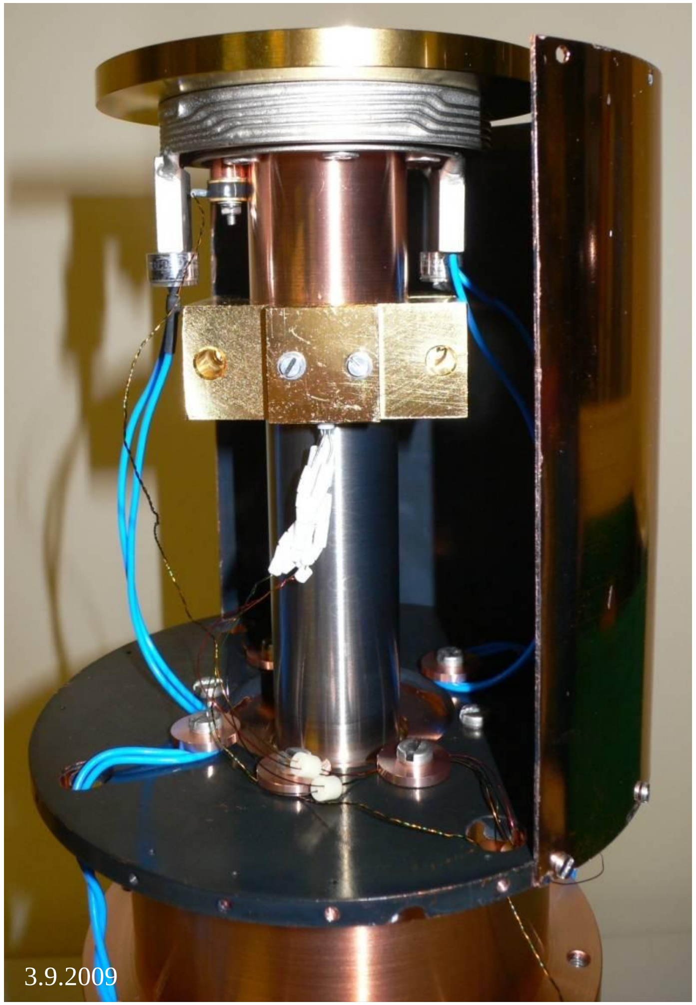
LINAC 3 cryogenic target experiment 2009

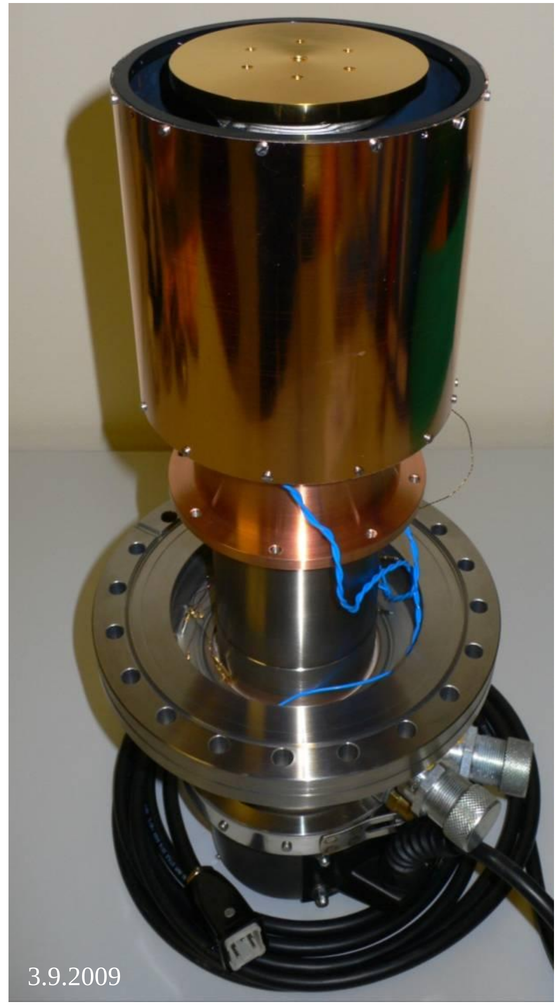


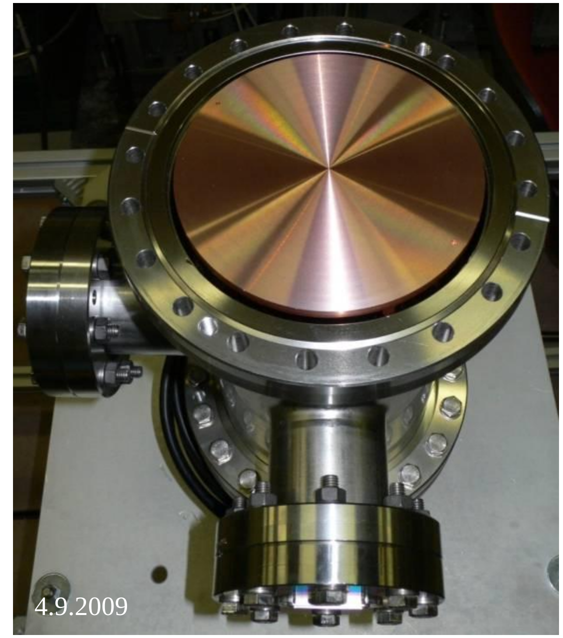
Bakeable UHV system with 2 RGA's, 2 BAG's, gas injection system, MTV, linac beam control
Cryogenic target assembly developed
Static pressure: low 10^{-11} Torr

LINAC 3 cryogenic target assembly 2009

E. M. et al. PRST-AB 14, 050102 (2011)







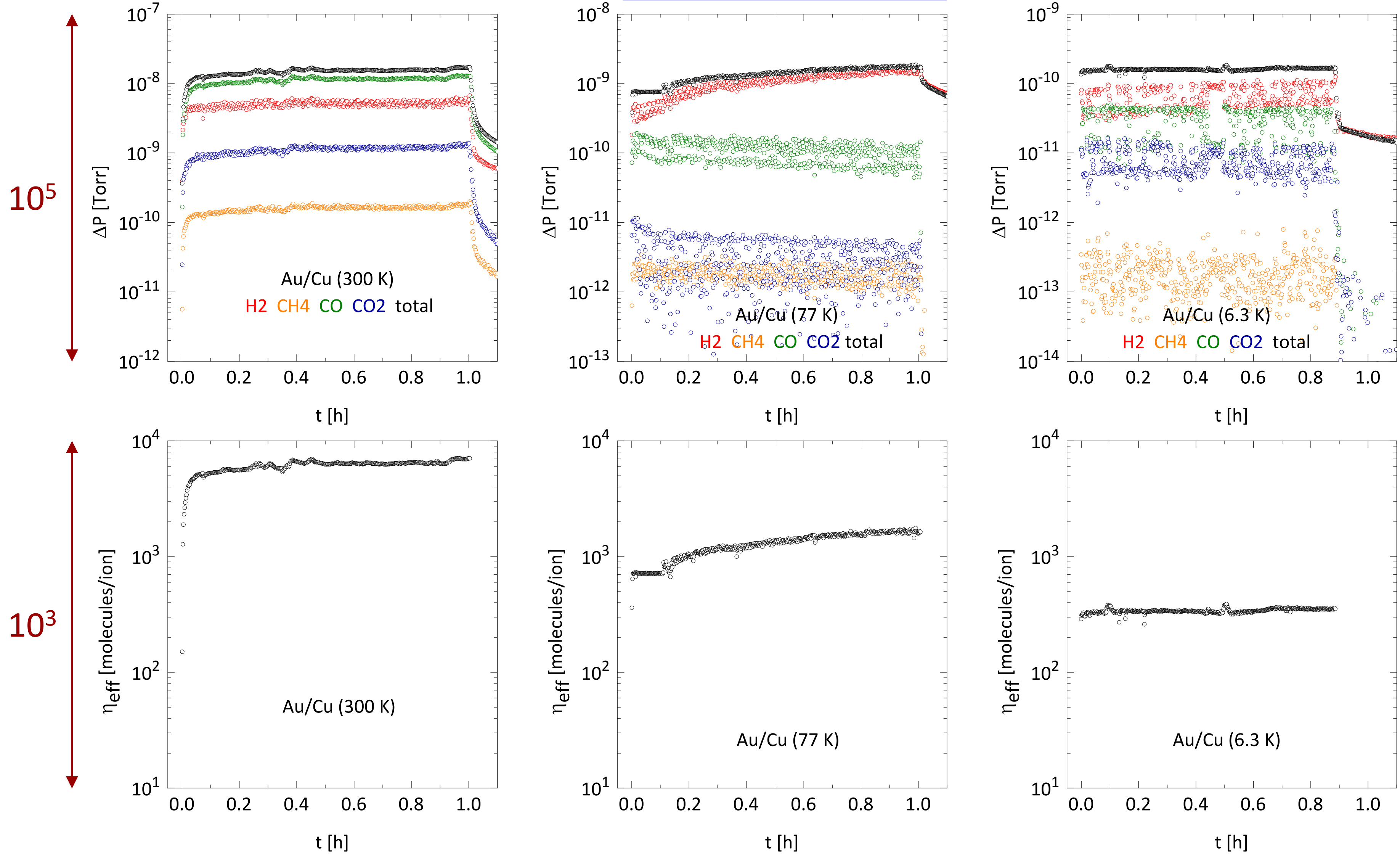
Assembly with bare Cu target and instrumentation feedthroughs

Ions: Pb^{54+} @ 4.2 MeVu,
Impact angle: $\theta = 0$
Intensity: 1.1 - 1.5 × 10^9 ions/pulse
Targets: bare Cu, Au/Cu
Target temp.: 300, 77, 6.3 K

Cryogenic targets: ∅ 141 mm, mounted on a cold-head, 2 samples tested: bare Cu and Au/Cu
Temperature control: 3 sensors (PT100, RhFe, Si diode) + 2 heaters (25 W)
Cu radiation shield: electro-polished outside, coated inside. Lowest target temperature achieved: 6.3 K

LINAC 3 pressure rises and desorption yields
Au/Cu target at 300, 77, 6.3 K

Pb^{54+} (4.2 MeV/u), Θ = 0°



E. M. et al. PRST-AB 14, 050102 (2011)

LINAC 3 temperature and CO gas adsorption
Desorption yields for Au/Cu and Cu

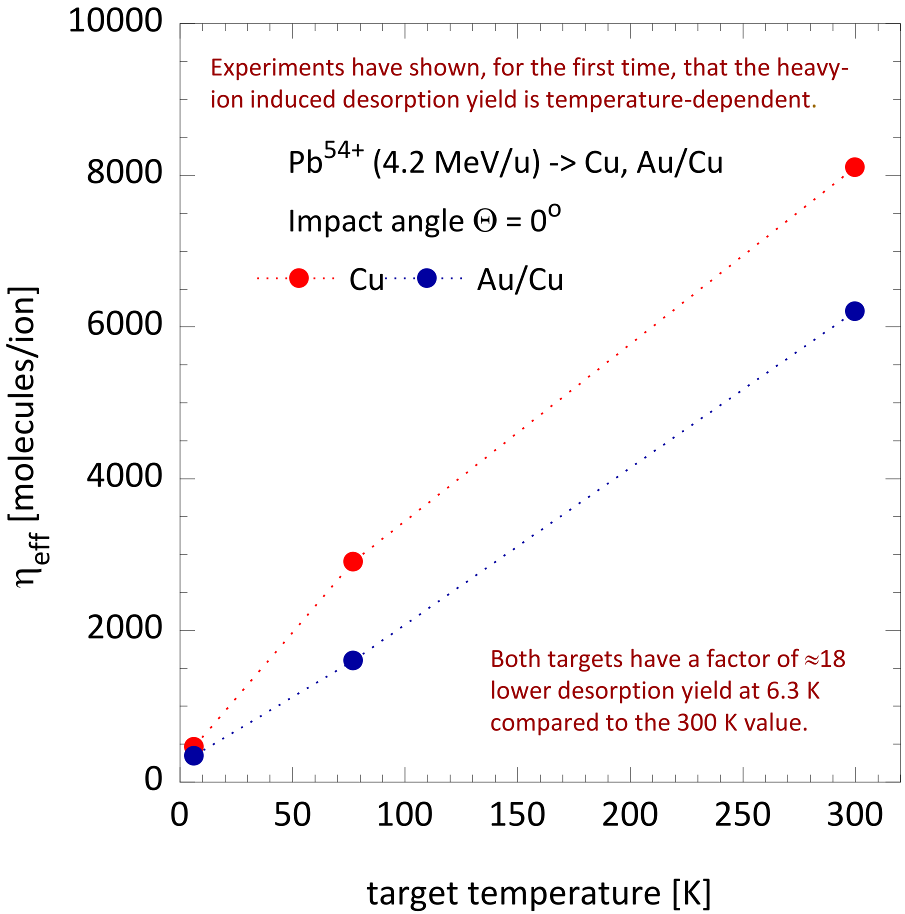


FIG. 5. Temperature dependence of the heavy-ion-induced desorption yield of bare and gold-coated surfaces bombarded under $\Theta = 0°$ with 4.2 MeV/u Pb^{54+} ions.

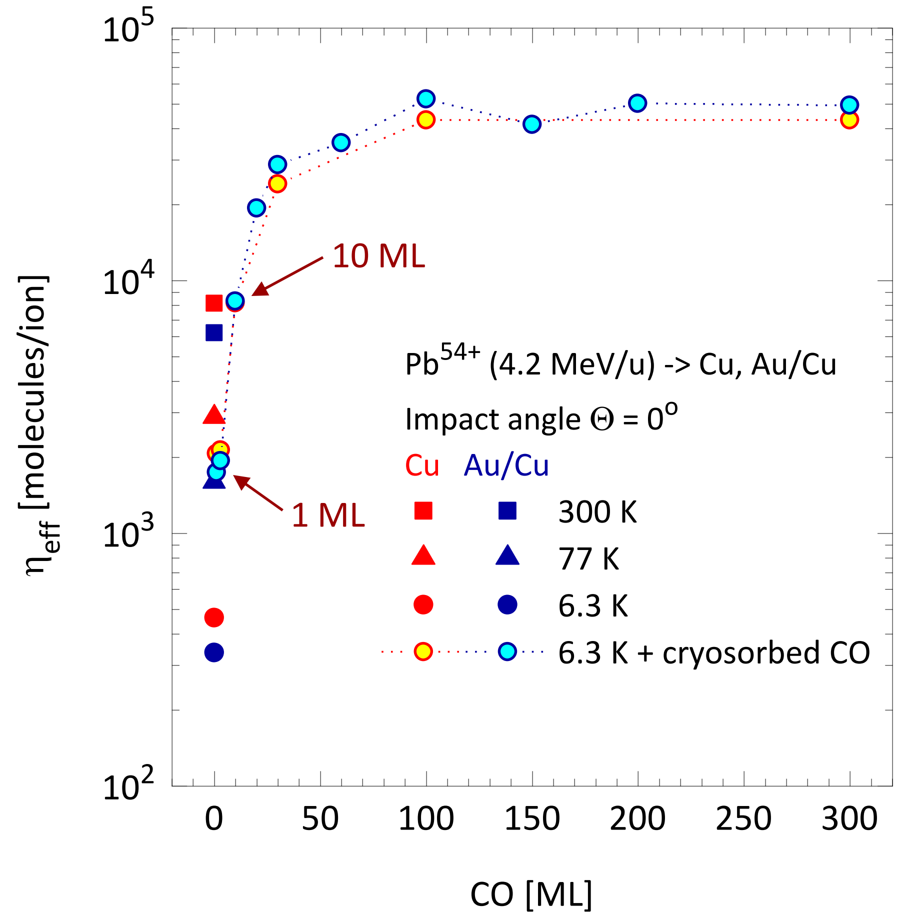
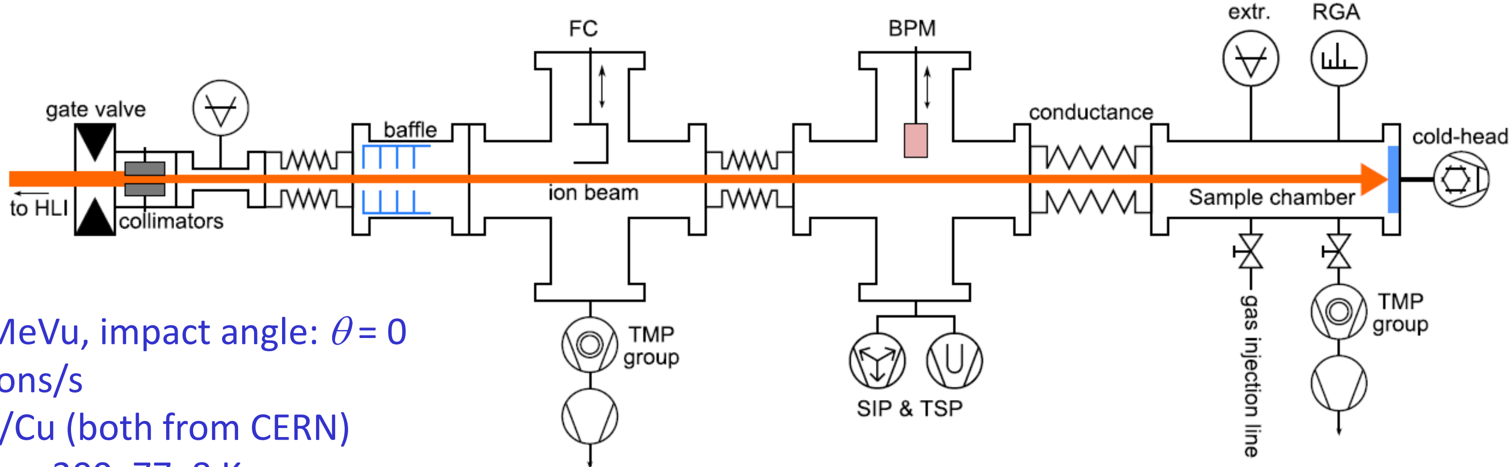


FIG. 6. Dependence of the heavy-ion-induced desorption yields on CO gas adsorption. Full symbols: 300, 77, and 6 K yields without gas injection. Open symbols: yields measured at 6.3 K as a function of cryosorbed CO monolayers.

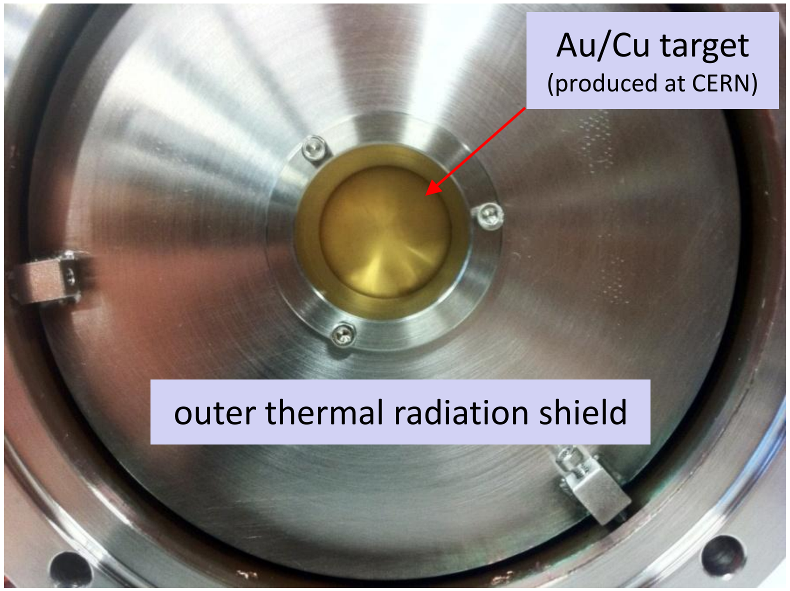
E. M., L. Evans, D. Küchler, R. Scrivens, M. Bender, H. Kollmus, D. Severin, M. Wengenroth, PRST-AB 14, 050102 (2011)

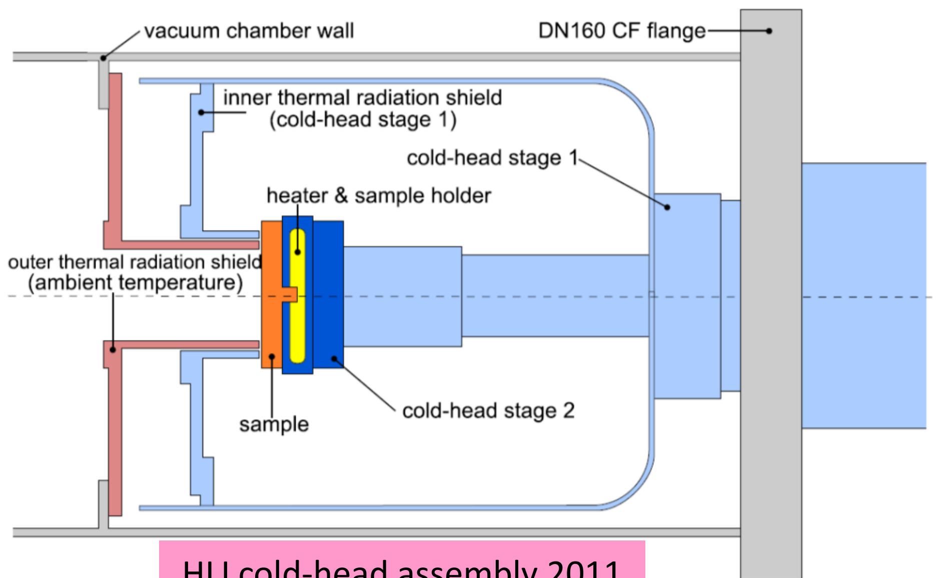
HLI cryogenic target experiment 2011 setup



Ions: Xe^{18+} @ 1.4 MeVu, impact angle: $\theta = 0$
Intensity: 2×10^9 ions/s
Targets: Au/Cu, aC/Cu (both from CERN)
Target temperatures: 300, 77, 8 K

Experimental setup installed at GSI High Charge State Injector (HLI) for heavy-ion induced desorption experiments at 1.4 MeV/u.





HLI cold-head assembly 2011

HLI CO gas adsorption at 8 K vs LINAC 3 at 6.3 K
Desorption yields for Au/Cu, aC/Cu, Cu

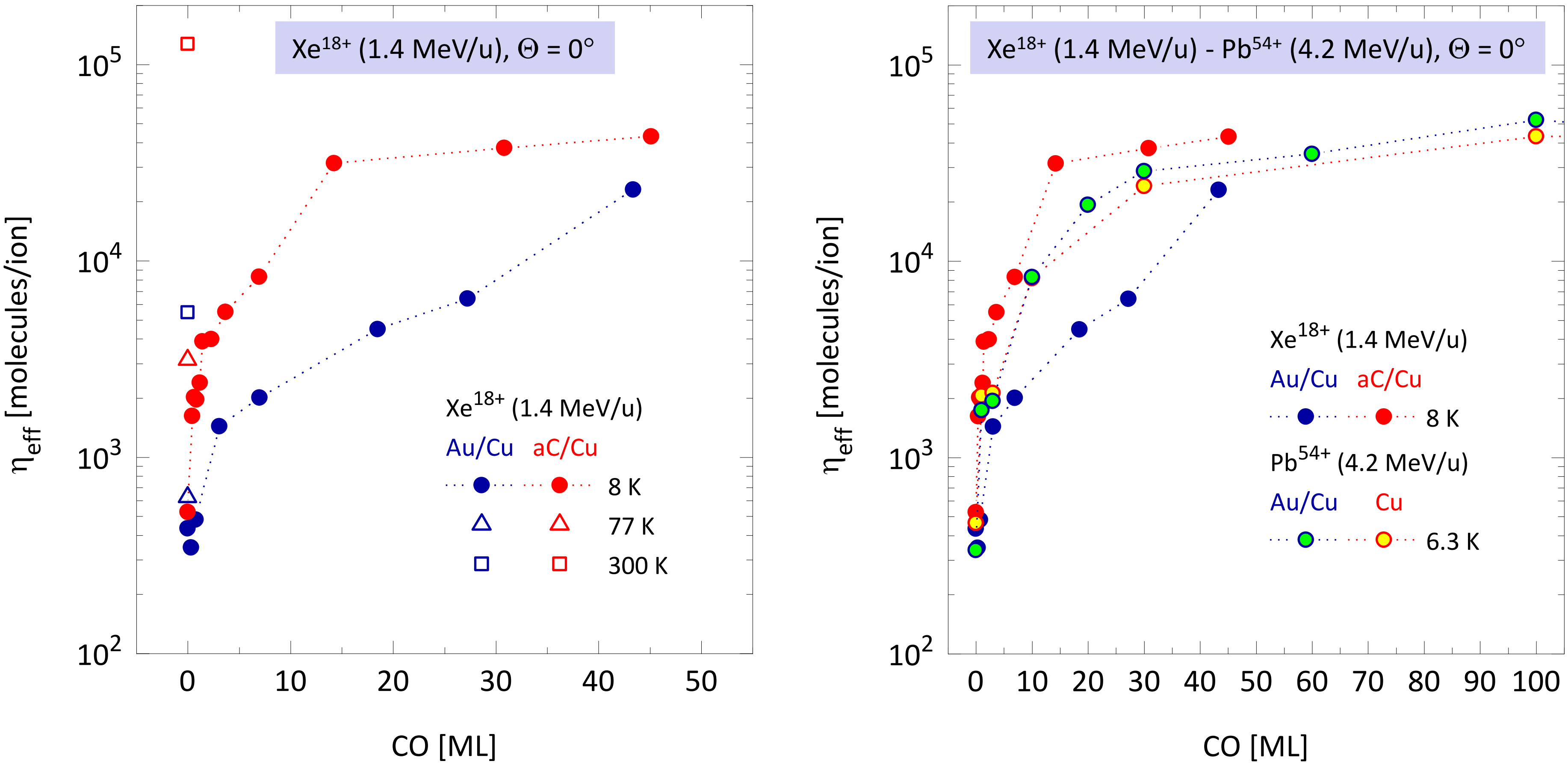
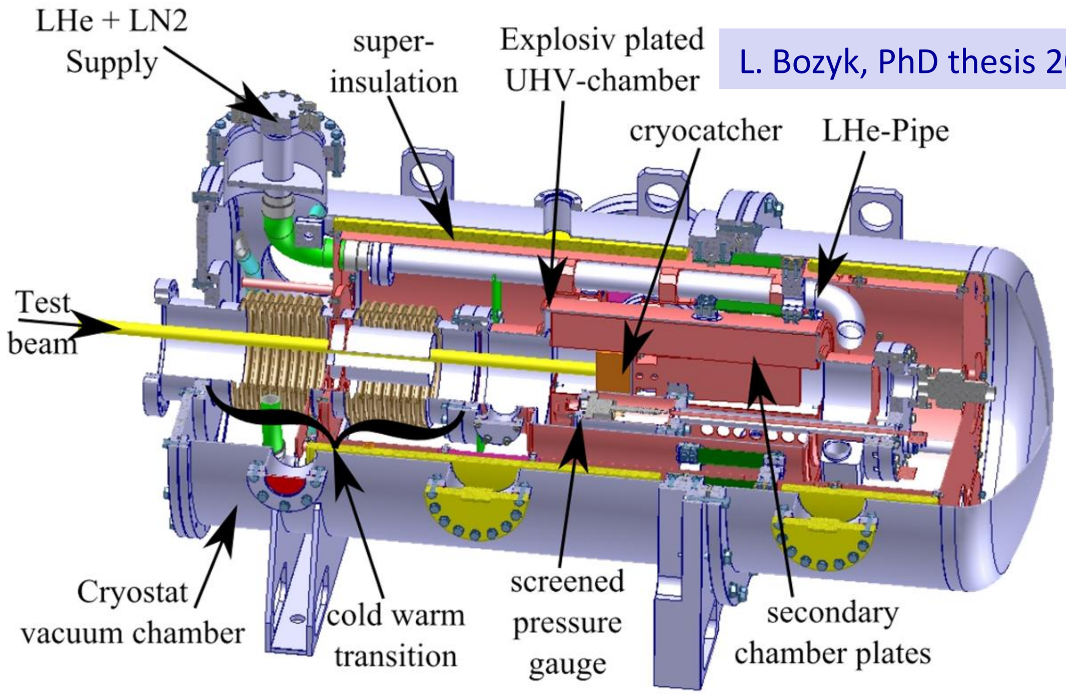


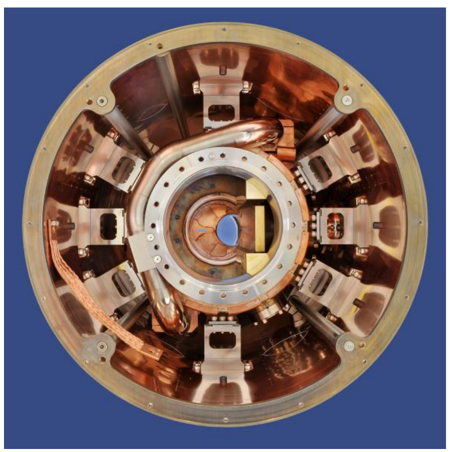
FIG. 9. Left: Heavy-ion-induced desorption yields as a function of adsorbed CO monolayers on gold-coated and amorphous-carbon-coated copper surfaces bombarded at 8 K with 1.4 MeV/u Xe^{18+} ions under $\theta = 0°$. Right: comparison with LINAC 3 desorption data obtained for 4.2 MeV/u Pb^{54+} ions bombarding under $\theta = 0°$ bare and gold-coated copper targets at 6.3 K [5].

D.P. Holzer, E. M., H. Kollmus, M. Bender, D. Severin, M. Wengenroth, submitted to PRST-AB (2012)

Cryocatcher prototype for SIS 100 (FAIR)

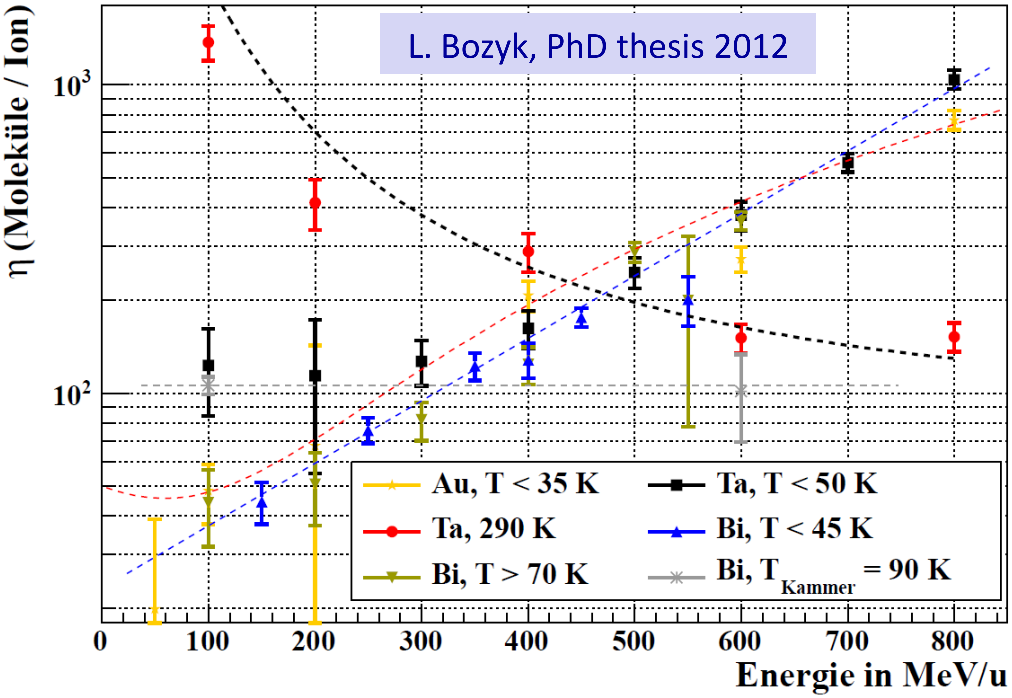
L. Bozyk, PhD thesis 2012





Accelerator: SIS18 - HHT
Ions: Au^{65+}, Ta^{61+}, Bi^{68+}
Energy: 50 – 800 MeV/u
Intensity: 1 - 2 $\times$ 10^9 ions/pulse
Impact angle: $\theta = 0°$
Target: Au/Cu

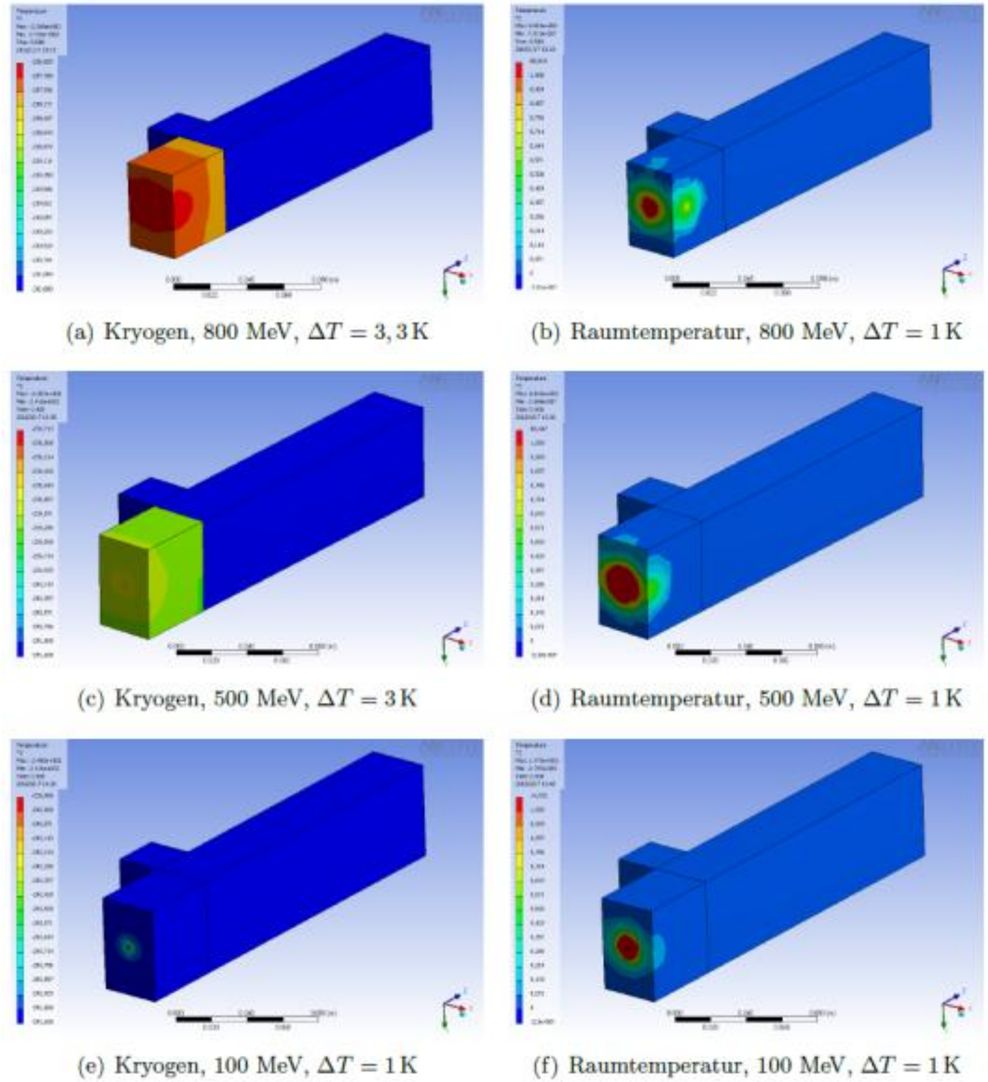
Cryocatcher prototype results



Beam-loss induced desorption of a cryogenic target increases with ion energy, against expectation and results obtained for ambient temperature targets.

Possible explanation: at cryogenic target temperatures the heated part of the sample surface increases with beam energy -> higher ion-induced desorption yields.

My proposal: study collimator blocks with lower heat conductivity (than copper) at cryogenic temperatures, *e.g.* Au/stainless steel



Calculated temperature distribution (ANSYS) of the collimator after impact of 1.1 x 10^9 Ta ions as a function of beam energy and target temperature.

How to achieve 10^{-12} Torr dynamic vacuum for heavy-ion accelerators

Design + strategy for 10^{-12} Torr dynamic vacuum

What is needed:

In general, a 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.

In particle accelerators, bakeable vacuum systems (up to 350°C) with "special" machine components as kicker, septa is sometimes complex

How to do it:

Conventional pumping + NEG coating where possible, cryogenic systems only if necessary
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 as an option

Challenges for accelerators

Dynamic vacuum is difficult to obtain (not the static…), high desorption rate for lost high-energy ions
Ion desorption of cryogenic surfaces is an important issue for FAIR-SIS 100; needs more experiments
Measure $p \leq 10^{-12}$ Torr, influence of gauges & analysers?
Accelerator environment $\neq$ laboratory conditions!

Conclusions, future studies, 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 some first experiments at CERN and later at GSI, cold surfaces are not systematically studied with high-energy ions. Today, cryogenic experiments are mainly motivated by the near-future heavy-ion operation of SIS 100 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.