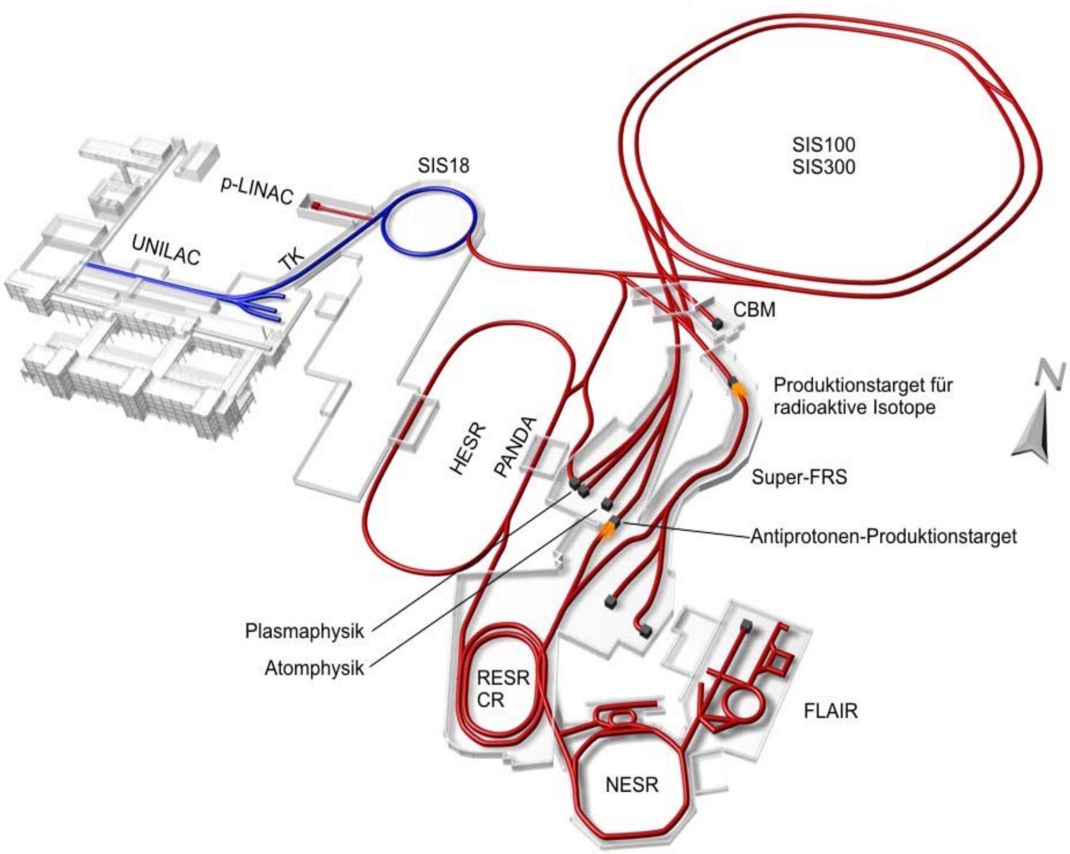
Collimation and Cleaning Systems of

SIS18 and SIS100

GSI / FAIR Overview



Blue: existing machines

Red: new machines

~1.2 billion € project

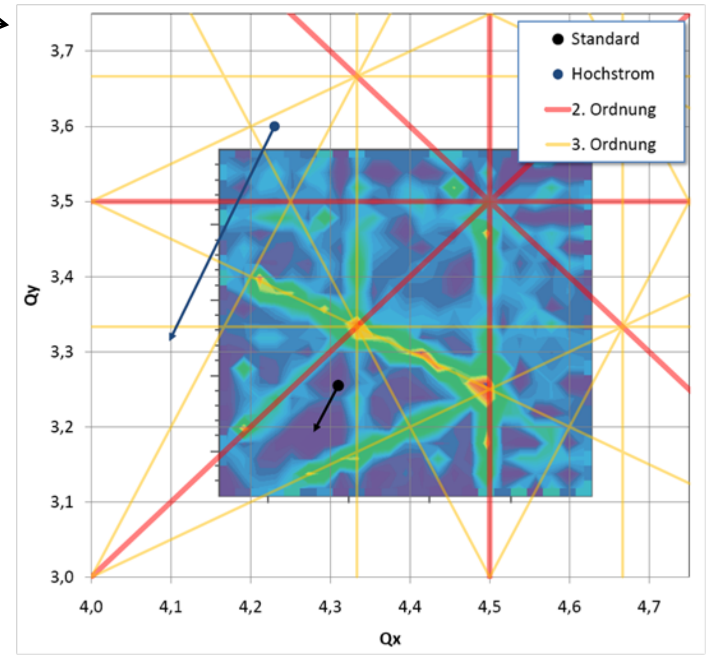
Relies on UNILAC/SIS18 as injector

FAIR is on the way!

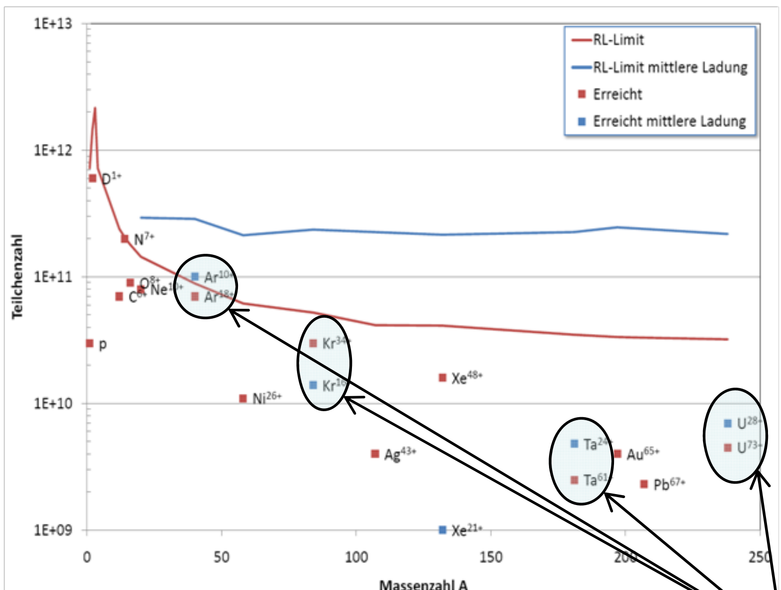
- started officially in November 2007
- Upgrade of machines started earlier

Motivation

- High current operation of heavy ions (^{238}U)
  - Space charge limit $\mathbf{N_{max} \sim A/q^2}$
  - Go to low charge states (U^{28+}) instead of U^{73+}
- Required number of particles for FAIR: $6*10^{11}$ / cycle
- Achieved Intensities:



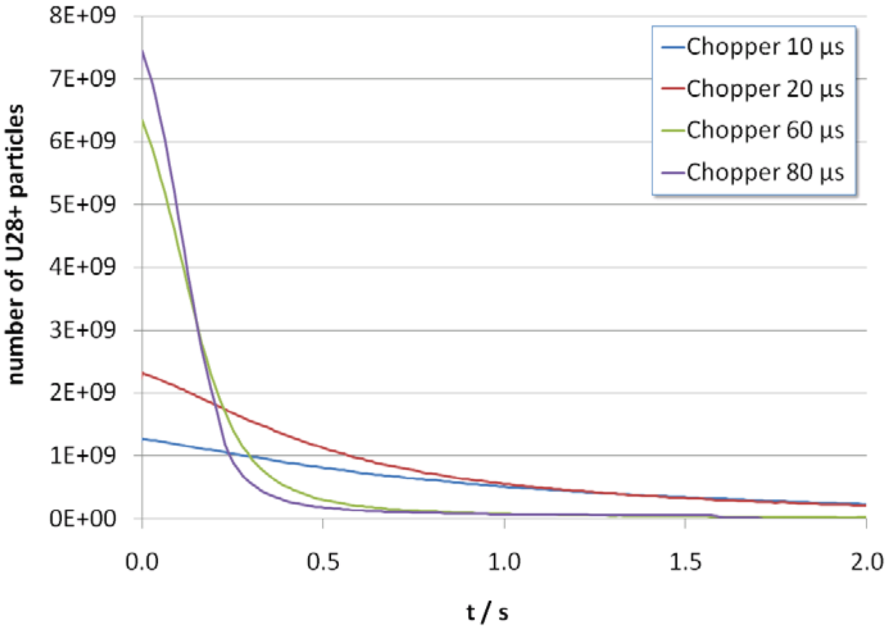
G. Franchetti, 2006



...something happens to the low charged ions!
Intensity should be much higher!

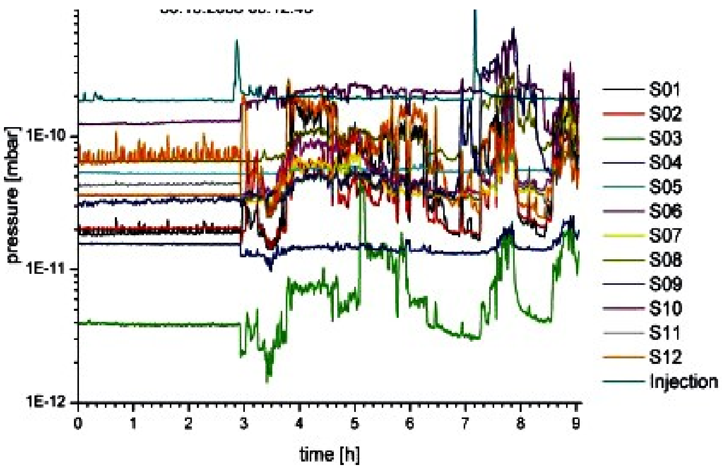
Introduction

- Observation of fast, intensity dependant beam losses during operation with low charge state heavy ions (U^{28+}) in synchrotron SIS18 (far below space charge limit). Strong pressure rise at the same time (> 1 order of magnitude).



P. Spiller, 2001

- Losses depend on:
  - Initial number of particles
  - Injection losses
  - RF-capture losses
  - Base pressure of vacuum
  - 1/energy (1st approximation)

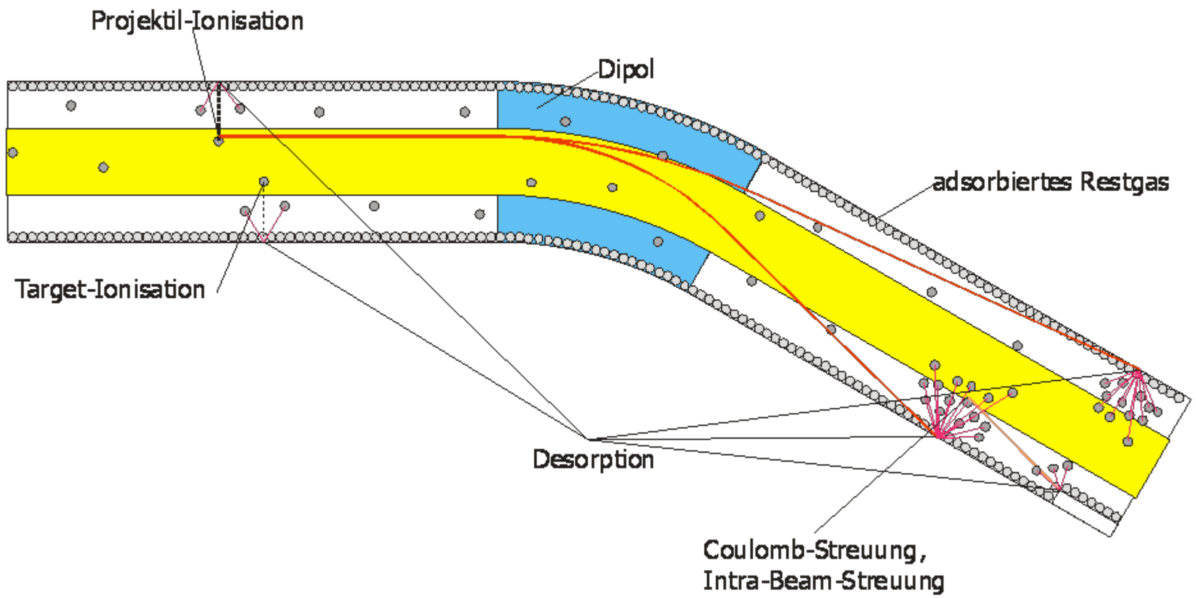


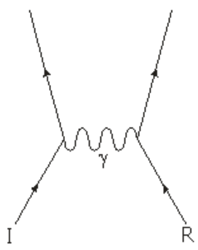
New effect?

- Seen in other accelerators before:
  - CERN
    - ISR 1974
    - PS
    - PS Booster
    - LEIR, limited intensity of Pb^{54+} a factor of 10 below design
  - BNL
    - AGS Booster, Au^{32+}
    - AGS
    - Not in RHIC → electron clouds pressure rise to 10^{-5} mbar
- What helps?
  - UHV upgrade (pumping power) reduces symptoms
  - Collimators in arcs (LEIR)
  - But: Vacuum in SIS18 is already very good (10^{-11} mbar)

Charge exchange process

- A beam ion hits residual gas atoms/molecules and looses or gains one or more electrons.
- This beam ion is separated behind the deflecting dipoles from the reference ion by his different magnetic rigidity ($\delta p/p \cong q_0/q - 1$, e.g. for $U^{28+} \rightarrow U^{29+}$ $\delta p/p = -3.45\%$!) and hits the beam pipe.
- A shower of residual gas atoms/molecules is produced by ion stimulated desorption at a typical rate of $\eta \geq 10^4$ mol/ion.
- Self-amplification may lead to avalanche-like pressure rise and consecutive beam loss!



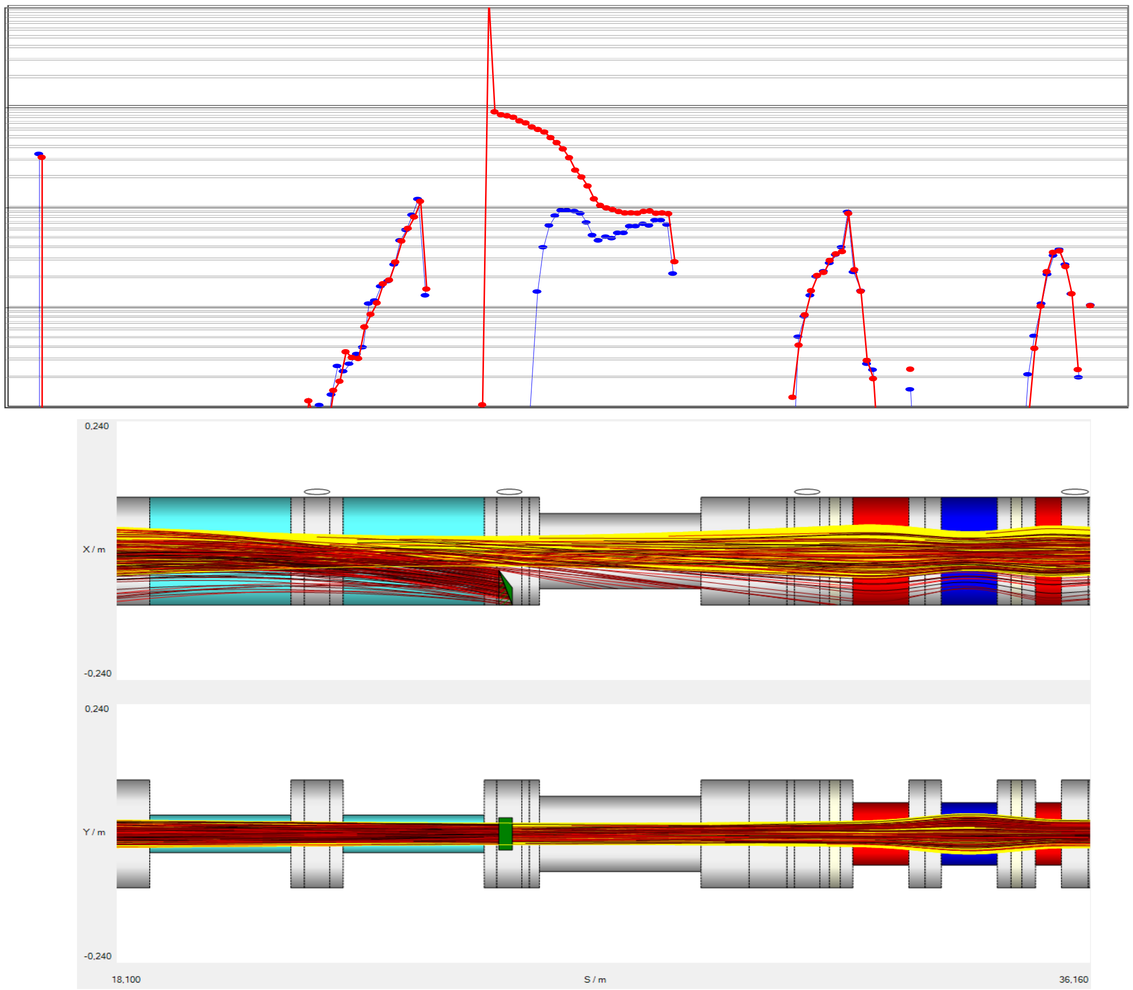


Collimator positioning in SIS18

Losses / a.u.

horizontal

vertical



Without collimators
With collimators

- SIS 18, Section S02
- E = 11.4 MeV/u
- $U^{28+} \rightarrow U^{29+}$
- 2.500.000 particles

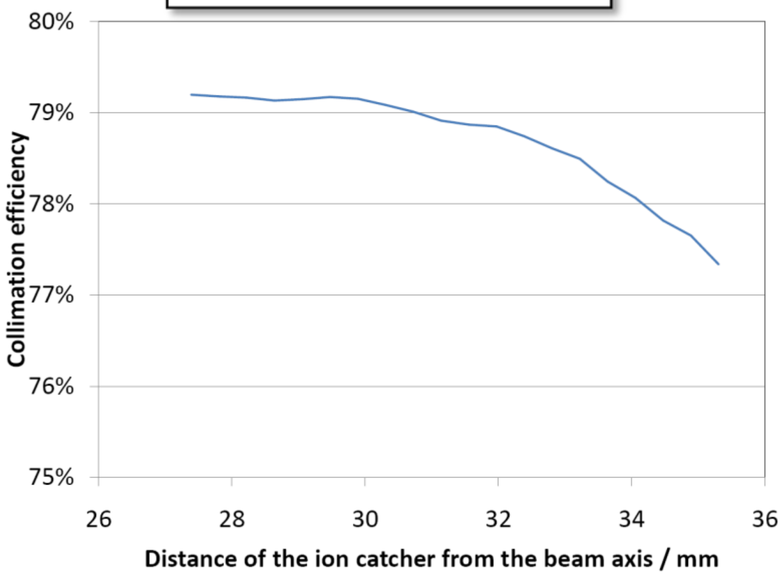
- Lattice is fixed
- Collimator position is predefined by dipoles.

Collimator positions in SIS18

- Transversal:
  - Acceptance of machine can not be reduced!
  - Optimise collimation efficiency for reference process ($U^{28+} \rightarrow U^{29+}$)!
  - Compromise always needed in existing machines!
- Optimal placement in lattice design of SIS100

$\eta_{coll} = N_{coll}/N_{total}$

(here at injection energy)



Calculated for 10/12 installed collimators. Two sections of SIS18 are blocked by installations (extraction septum and electron cooler).

Lattice-Optimization: Principles

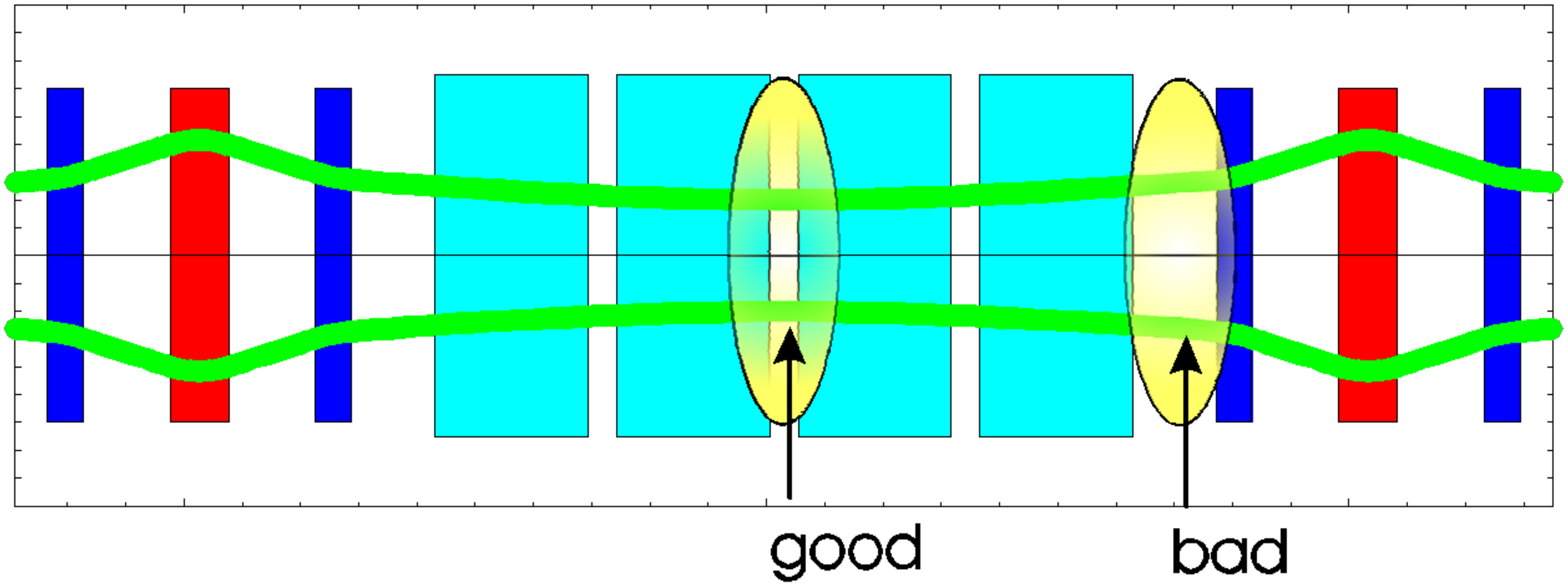
- Beam loss must be localised:
  - Machine protection – Radiation demage
  - Activation
  - Sufficient space for a collimation system at loss position needed
- Charge exchanged particles should have a good separation from the circulating beam at the place of the collimator.
- Collimators should not reduce acceptance!

Localised!

Separated!

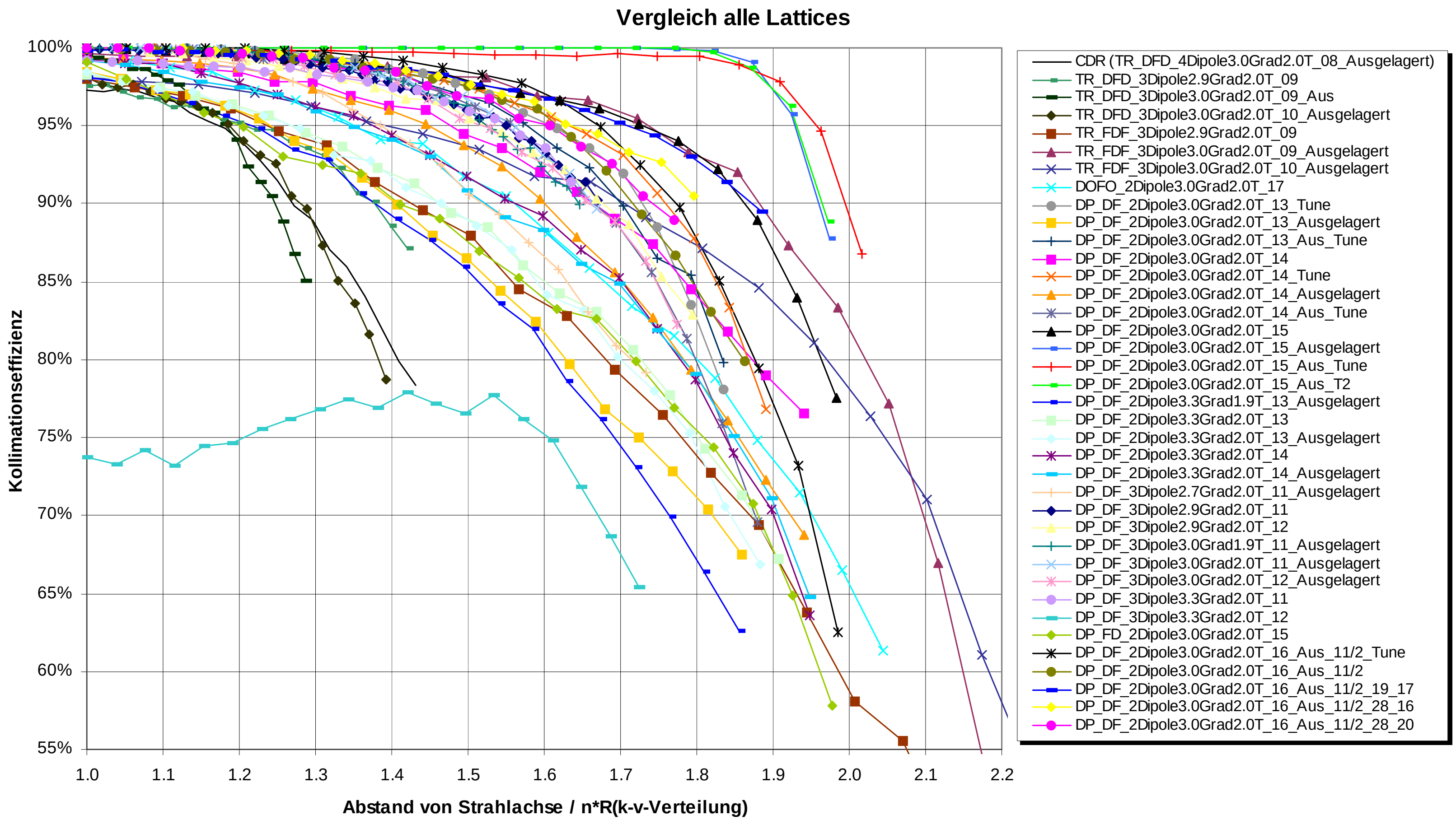
Acceptance!

SIS100: CDR lattice

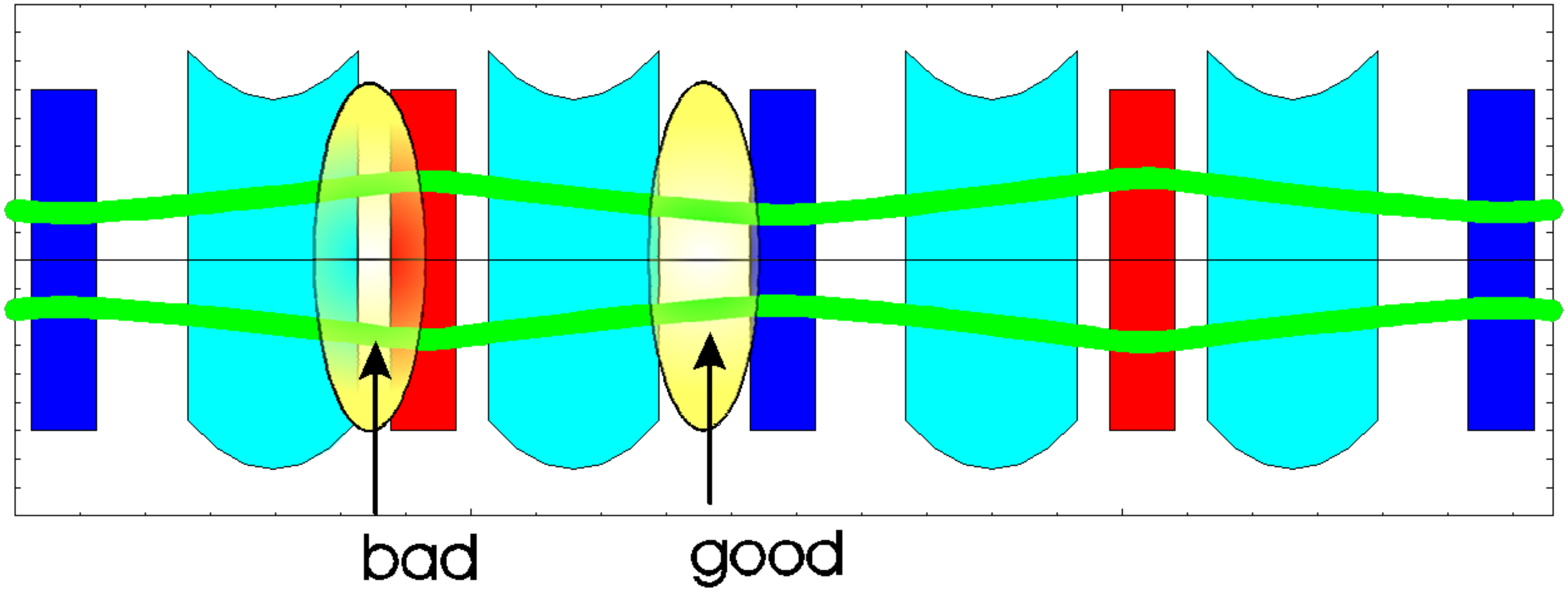


- Starting point of lattice design: Triplett structure (like SIS18), described in the conceptual design report
- Would work, if all dispersive elements were in the first half of the cell.

SIS 100 Design I: Lattice-Choice

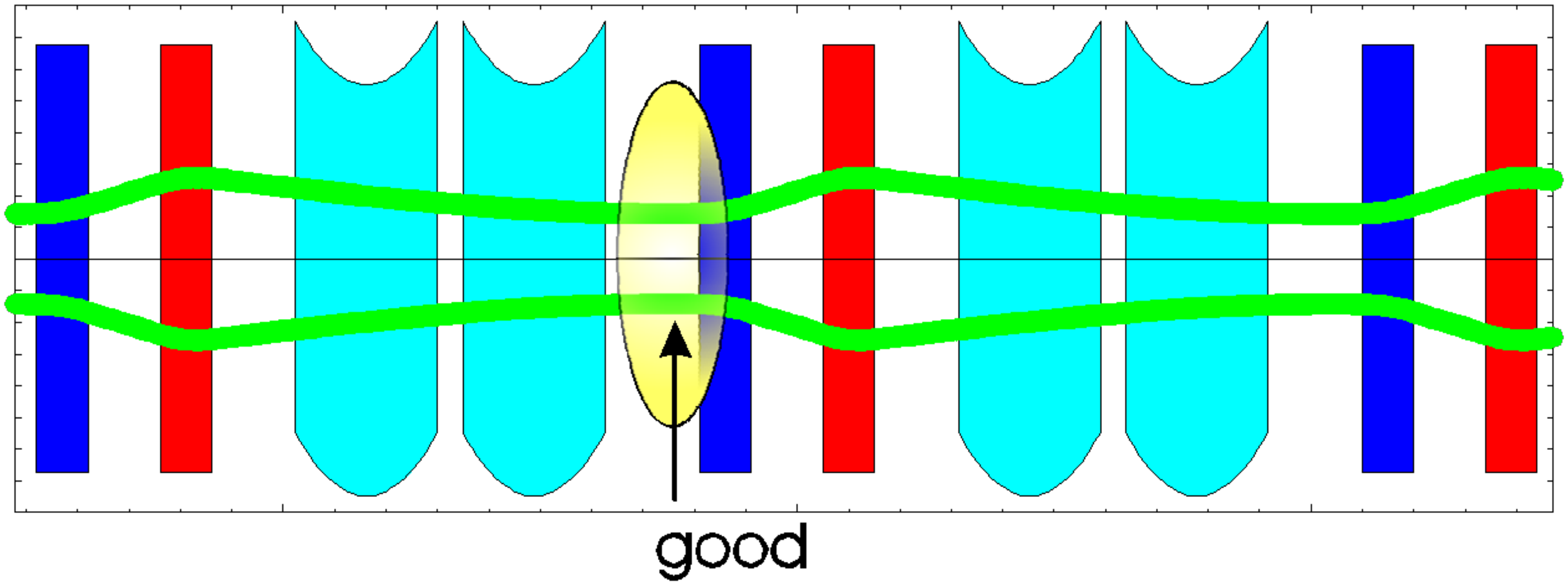


SIS100: FODO lattice



- FODO is quite common, but if the deflection angle of dipoles is large beam loss is not well concentrated.
- One half cell is ok, next one is bad.

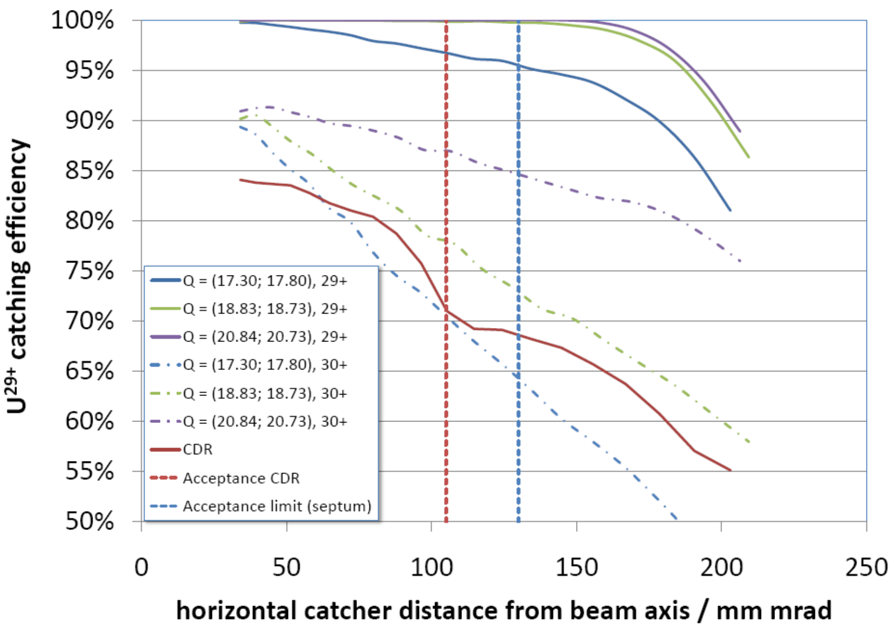
SIS100: doublet lattice (DF order)



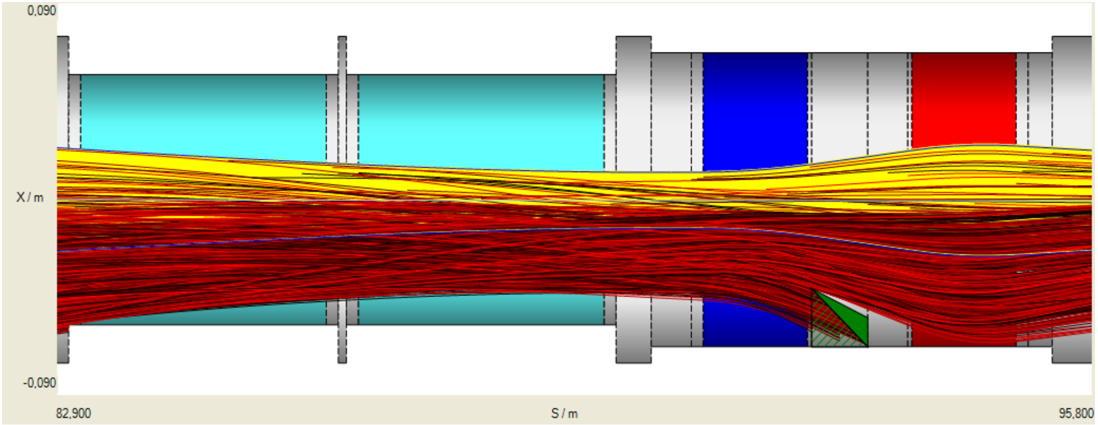
- Beam waist with good separation of U^{29+} from U^{28+}.

  Charge spectrometer lattice.
- Enough space for a collimator in front of or inside the quadrupole doublet.

SIS100: Maximum collimation efficiency

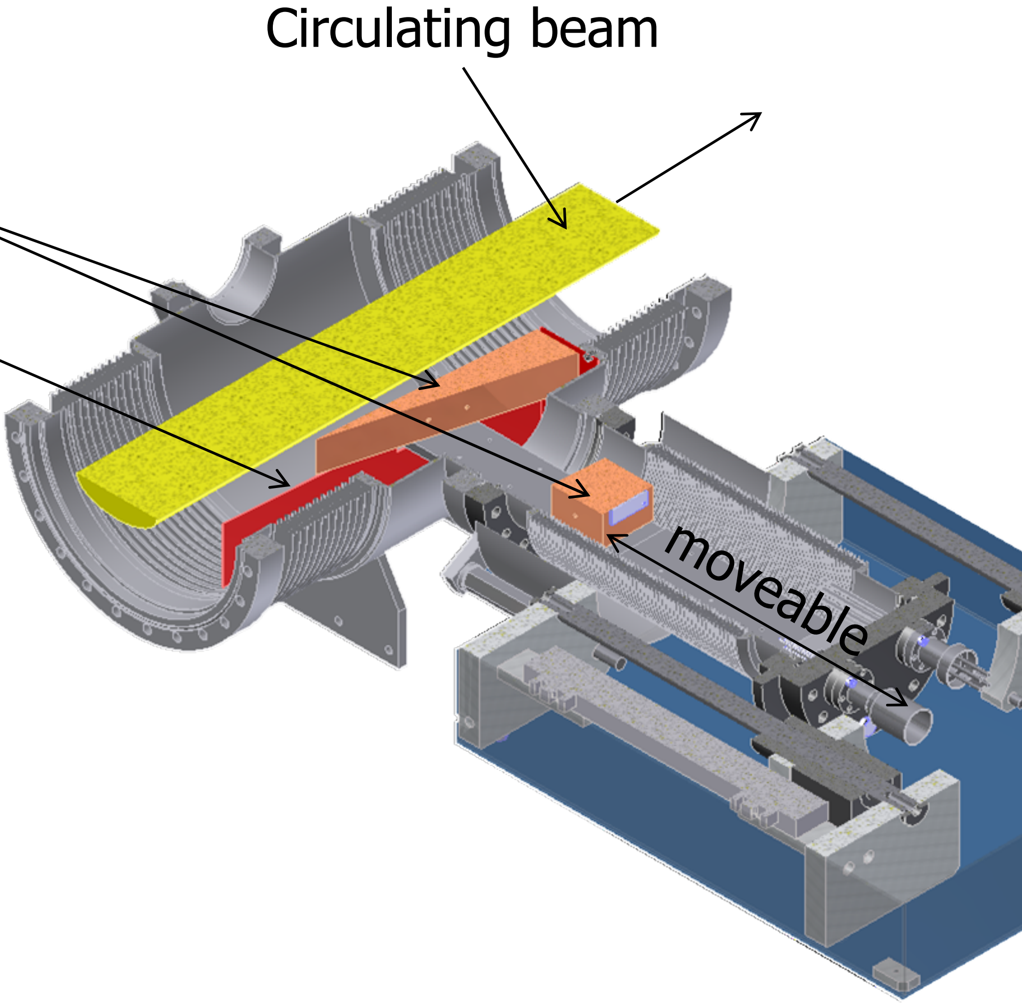


- Collimation efficiency can be enhanced further by quadrupole defocusing!
- Collimation works (to a reduced degree) for multiple ionisation, too.



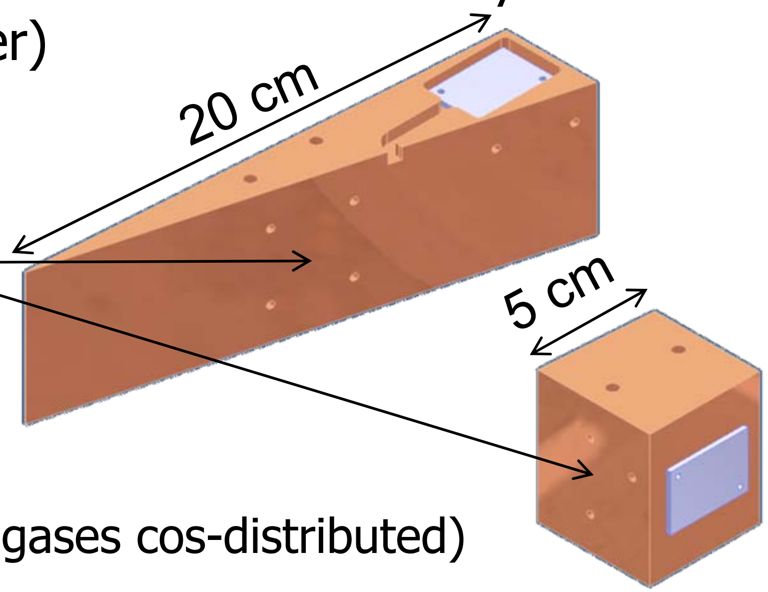
SIS18 Collimator system prototype

- Confine and control desorption gases
  - Absorber: Cu, Au-coated
  - Secondary chamber
  - As much pumping speed as possible
    - NEG-coating, where possible
    - Ionen-getter pump (not shown)
  - Lots of diagnostics
    - Total and partial pressures
    - Ion current of U^{27+} and U^{29+}
    - Temperature of absorber



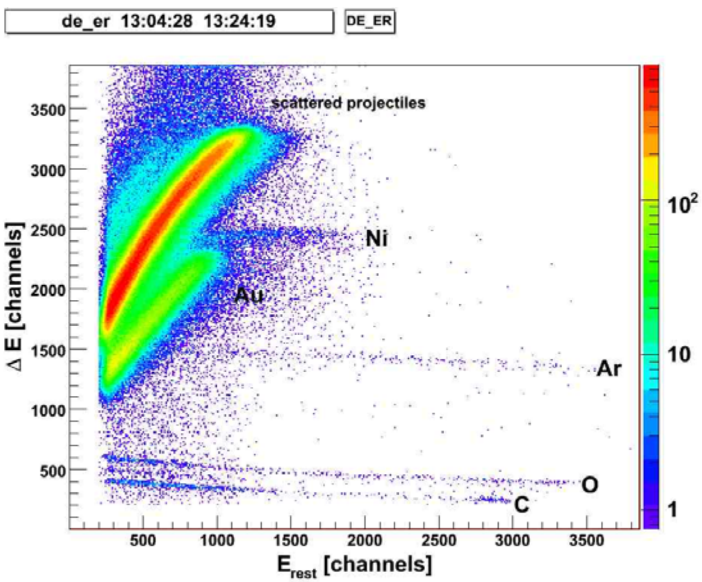
SIS18 absorber geometry

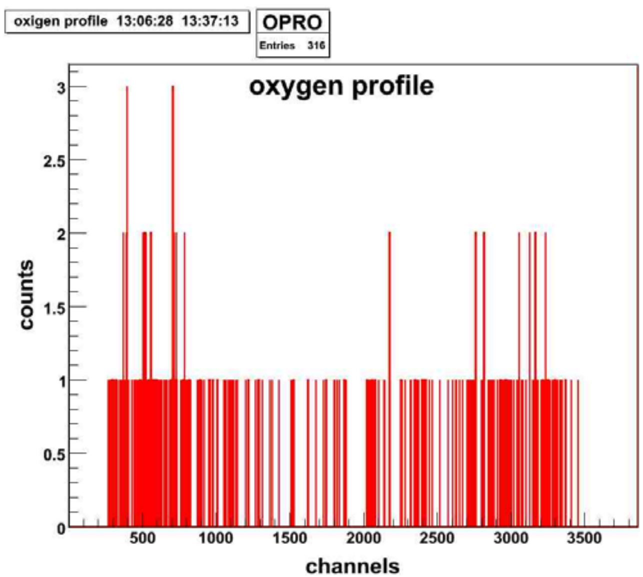
- Choice of material:
  - Must stop heavy ions at energies of up to 200 MeV/u → $^{238}U^{28+}$ range is ~ 1.5 mm (neglectible fragmentation, e.g. He up to 42 mm)
  - Surface should be made of a material with a low desorption rate
- Desorption rate measurements and surface characterisation by ERDA (UHV-group H. Kollmus / M. Bender)
- Result:
  - Cu core
  - Coating with a few 100 nm Au
  - Desorption rate is not 0!
  - In prototype: two geometries
    - Block better for effective desorption
    - Wedge better for control (desorption gases cos-distributed)



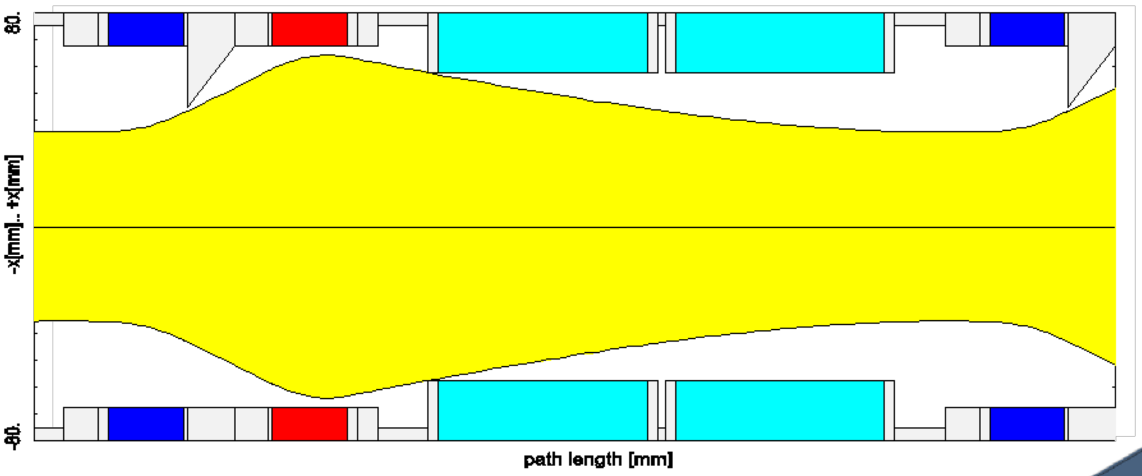
Absorber: Surface

- ERDA measurements (Elastic Recoil Detection Analysis) at HLI of GSI (H. Kollmus / M. Bender) of 29.9.2007 with 1.4 MeV/u $^{136}Xe^{18+}$ (dE/dx similar to ~10 MeV/u ^{238}U):
  - Au-coated surface has lowest desorption rate measured ever (under perpendicular angle of incidence)
    - ~ 90 mol/ion
    - ~ 25 mol/ion after thermal treatment / longer bombardment
  - Pure Au, mechanically treated: 1200 mol/ion (!)
  - 300 nm Au
  - 200 nm Ni as a diffusion barrier

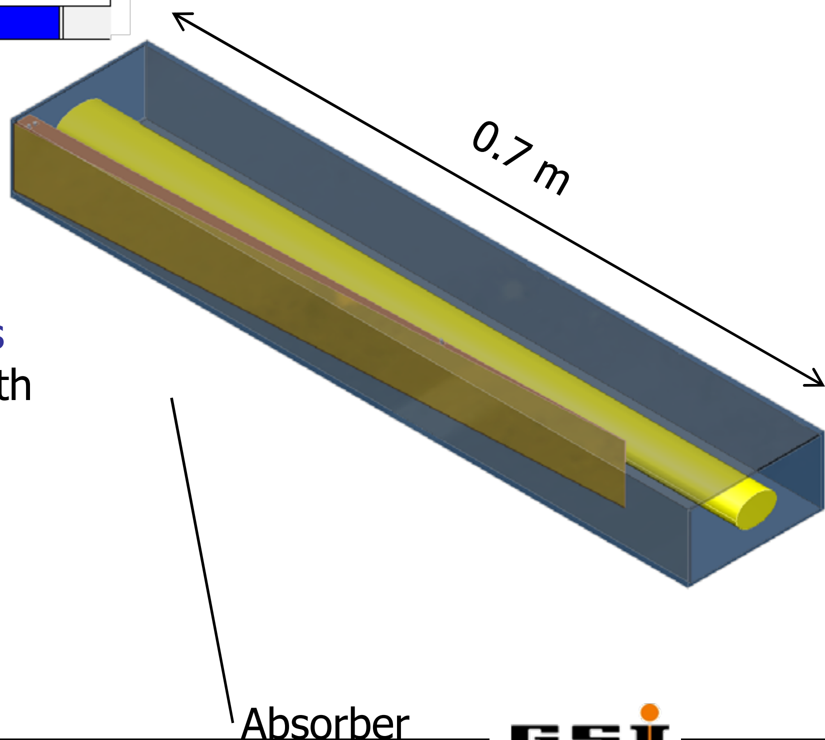




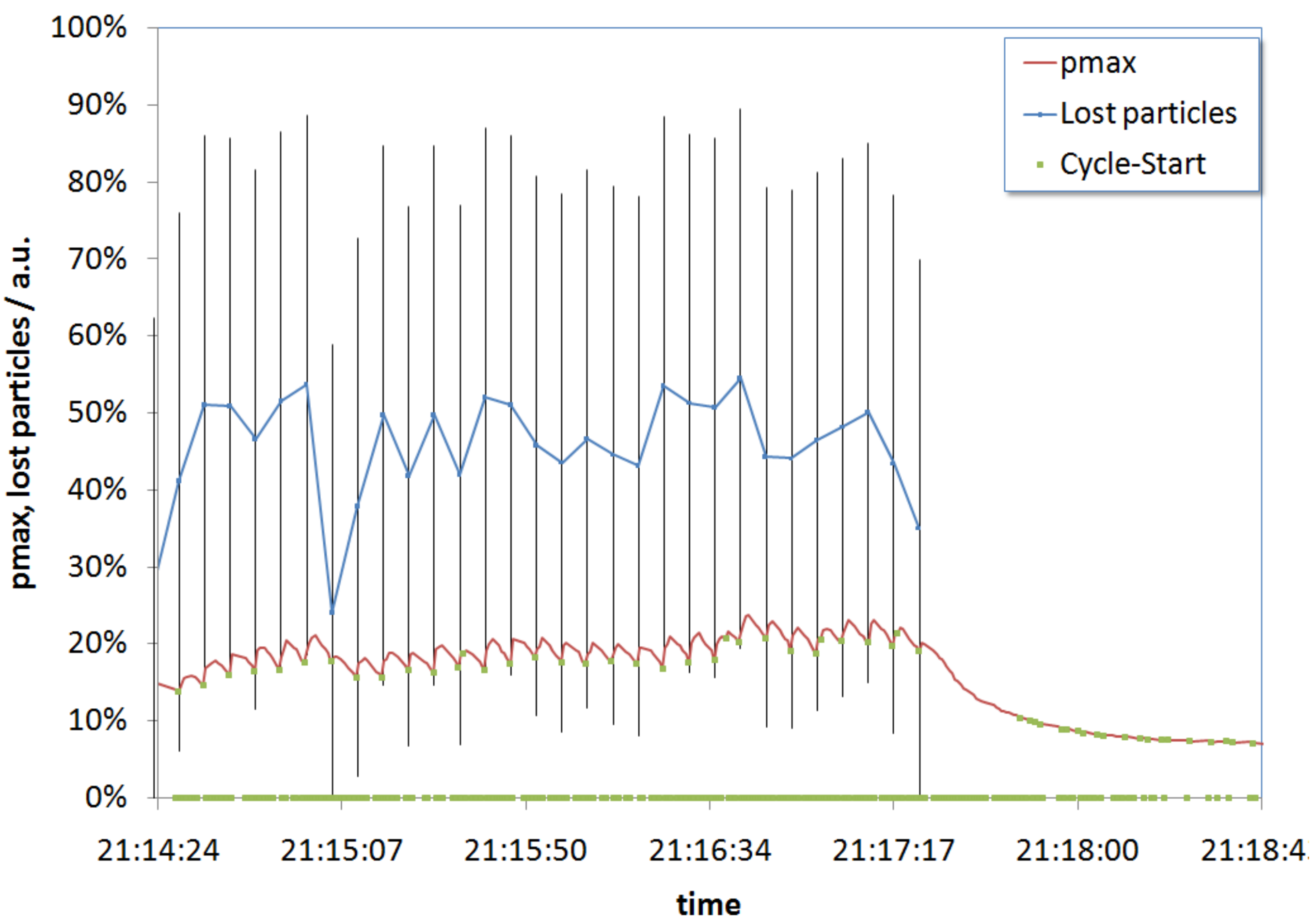
SIS100 Collimators



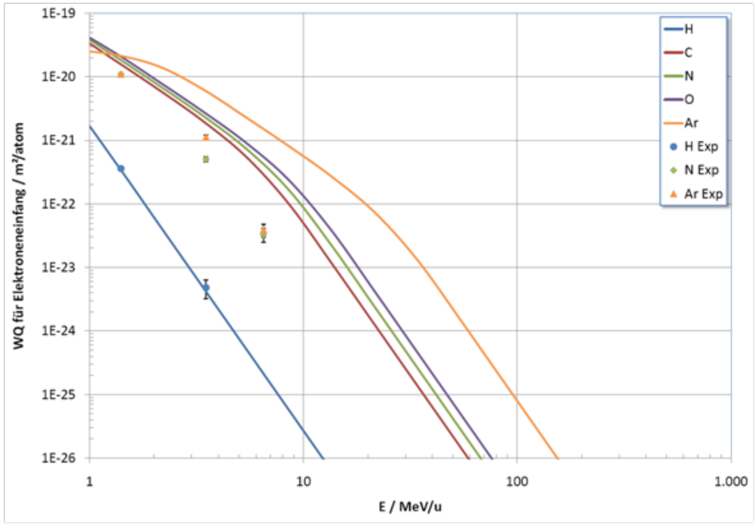
- Collimators do not reduce acceptance!
- No condensation of residual gas on absorbers!
    - Absorber-surface at ~50 K, chamber wall at 4.2…20 K
    - Need large absorber length to stop heavy ions and fragments (E=2.715 GeV/u, calculated with ATIMA)
    - U in Cu: 47.5 mm
    - He in Cu: 1.8 m

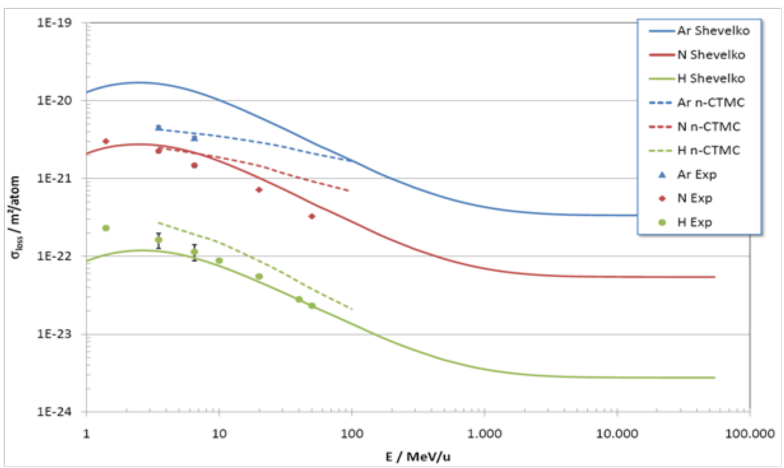


Residual gas pressure during experiments

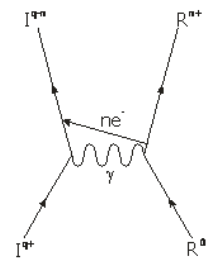


Charge exchange cross sections

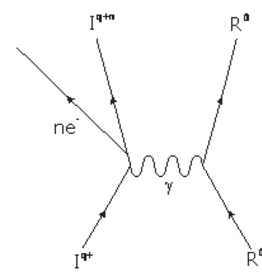




Experimental: 1,4 MeV/u (GSI, Franzke),
3,5/6,5 MeV/u (Texas A&M, Olson)



- Electron capture:
  - Schlachter formula gives sufficient agreement, but fails for U^{28+} (c.s. too high)



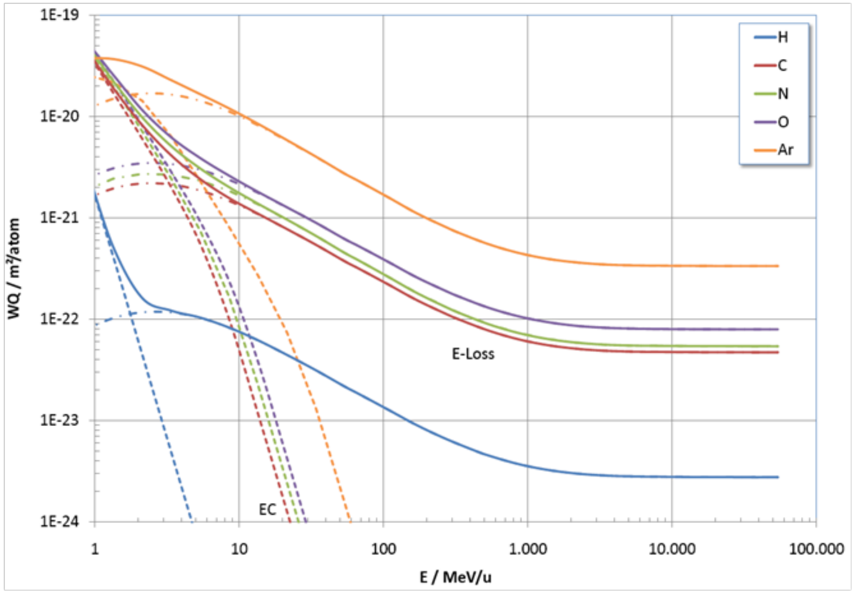
- Electron loss:
  - No empirical scaling law does exist
  - No high-energy experimental data exists
  - Rely on theory:
    - R. Olson 2003
    - V. Shevelko 2007/2008

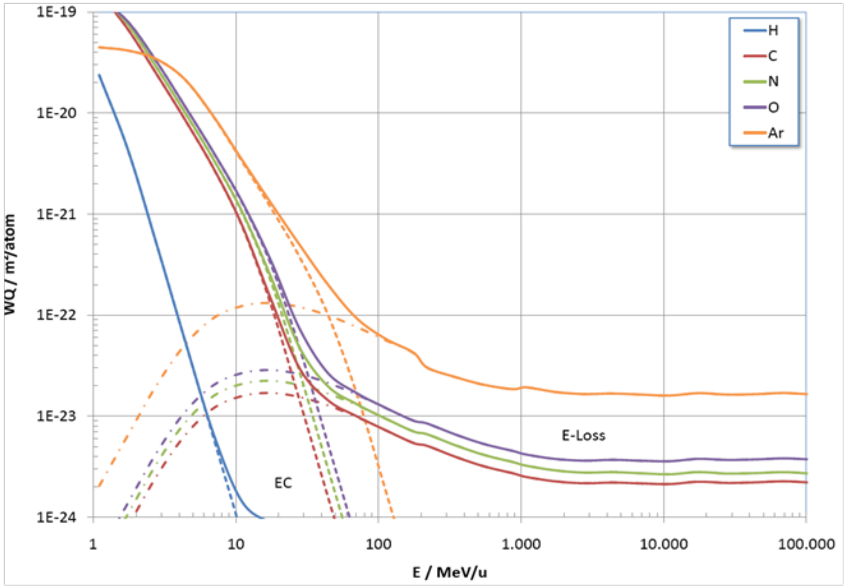
Sufficient agreement, but a factor of 2-3 too high for heavy targets.
Not much experimental data available!

Difference between U^{28+} and U^{73+}

U^{28+}:
- Loss dominated for E>10 MeV/u
- C.s. rather large at high energies

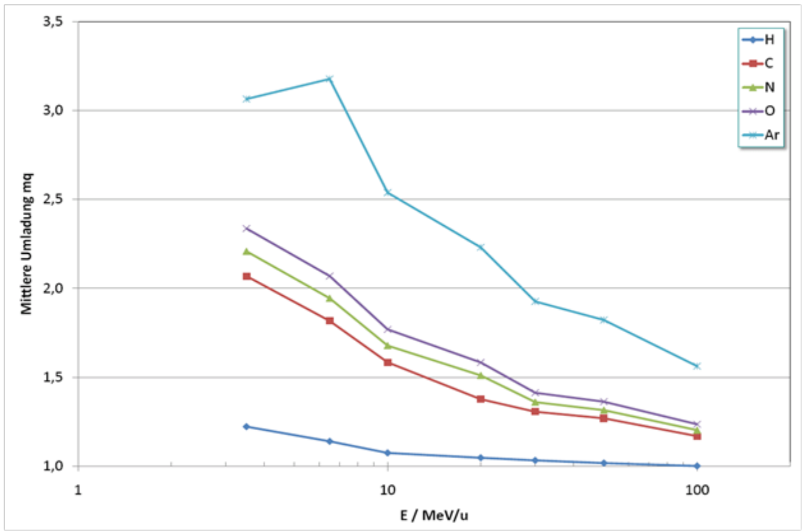
U^{73+}:
- Capture dominated until E~80 MeV/u
- C.s. vanish for high energies





Heavy residual gases have the largest c.s., so better pump them out!

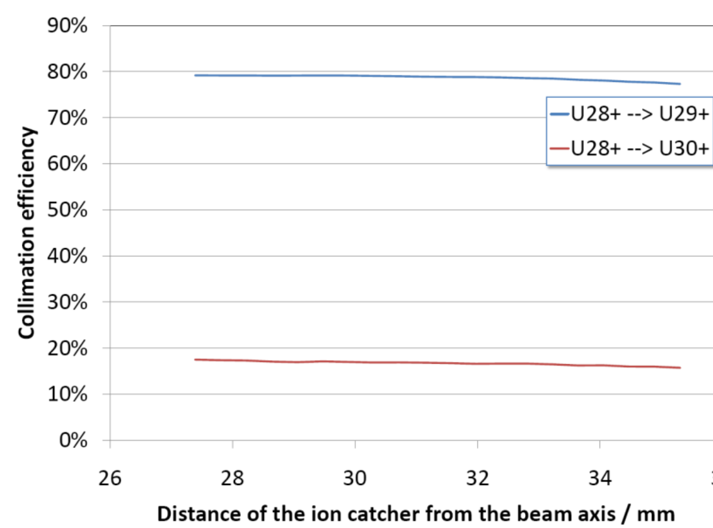
Multiple Ionisation?



R. Olson 2003

More than one electron can be lost during a collision…

$$\Gamma_{pl} = \beta \cdot c \cdot \sum_i n_i \cdot \sigma_i(E,q),$$



- Same as for c.s.:
  Heavy residual gas atoms have largest amount of multiple ionisation.
- Collimation efficiency lower than for single ionisation!

Charge-exchange process

- Projectile-ionisation of the circulating beam by rest-gas particles
  - charge-exchange cross sections $\sigma(E, q, \Delta q)$ acc. to Shevelko or experimentally determined ~ $10^{-23}...10^{-21}$ m²
  - single- and multiple ionisation possible
  - → desorption rate $\eta_{\angle}$~ $2...3*10^4$ (depends on angle and energy)

☑ collimation feasible

$$\Gamma_{PI} = \beta \cdot c \cdot \sum_k \sum_i n_i \cdot \sigma_i(E, q_k)$$

<u>StrahlSim publication:</u>

Charge change-induced beam losses under dynamic vacuum conditions in ring accelerators

C Omet *et al* 2006 *New J. Phys.* 8 284   doi:10.1088/1367-2630/8/11/284

Dynamic vacuum

$$\Gamma(n_t,\beta,\epsilon,t) = \sum_t [\Gamma_{CS}(n_t,\beta,\epsilon) + \Gamma_{EL}(n_t,\beta)] + \Gamma_{RZ}(\beta) + \Gamma_{IBS}(\beta,\epsilon,t) + \Gamma_{inj}(t) + \Gamma_{MF}(t),$$

- Beam loss rate

$$\Gamma_{TL}(n_t,\beta) = \beta \cdot c \cdot \sum_t n_t \cdot \sigma_{TL,t}(q,\beta).$$

- Production rate of ionised residual gas

$$\dot{n}_t = N \cdot \{\Gamma(n_j,\beta,\epsilon,t) \cdot \eta_{t,\angle}(\beta) + [\Gamma_{EL}(n_j,\beta,\Delta q < 0) + \Gamma_{TL}(n_j,\beta)] \cdot \eta_{t,\perp}(\beta,N)\} + \dot{n}_{t,A}(T) - \dot{n}_{t,P}(n_t,T).$$

- Dynamic vacuum pressure (here without collimators)

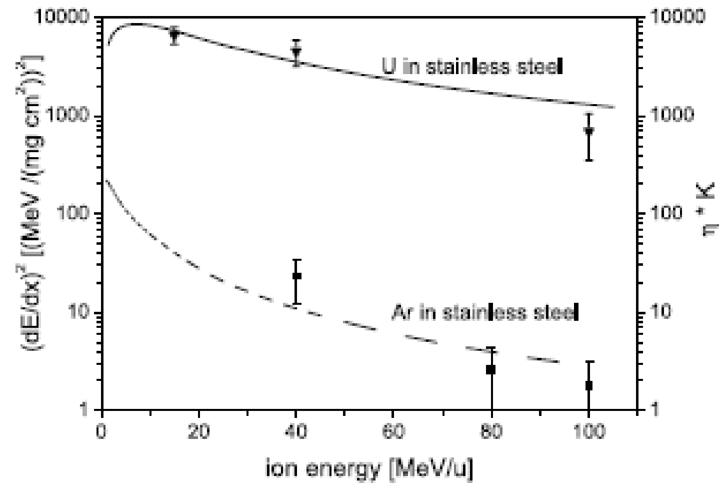
$$\dot{N} = -N \cdot \left[\sum_t [\Gamma_{CS}(n_t,\beta,\epsilon) + \Gamma_{EL}(n_t,\beta)] + \Gamma_{RZ}(\beta) + \Gamma_{IBS}(\beta,\epsilon,t) + \Gamma_{inj}(t) + \Gamma_{MF}(t)\right]$$

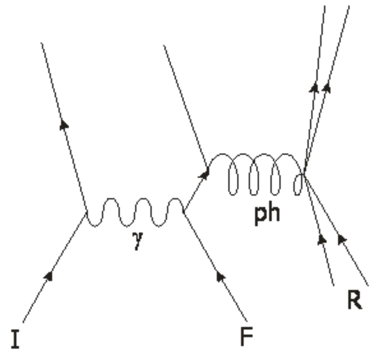
$$\Delta t = t_{rev}$$

- Numeric integration, turn by turn

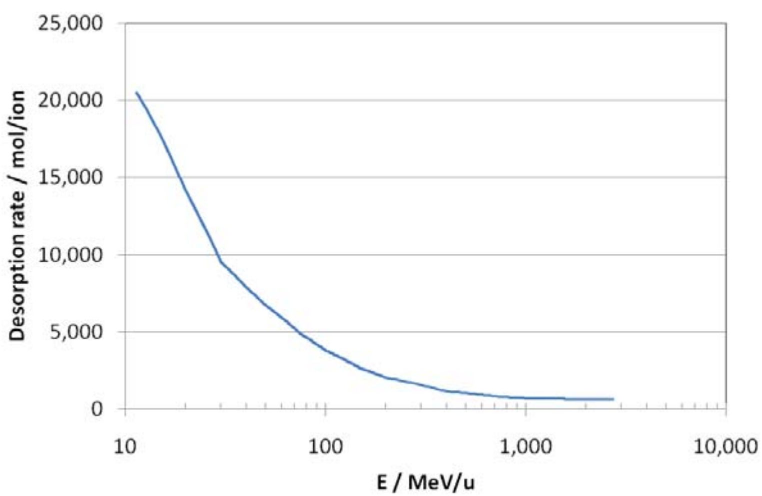
Scaling of the desorption rate

- Experimental hints:
  Desorption rate scales with $(dE/dx)^2$ of the incident ion.
  - A. Molvik, Electrons and gas versus high brightness ion beams, 25th International Workshop on Physics of High Energy Density in Matter
  - M. Bender et al, Energy-Loss Dependence of the Ion-Induced Desorption Yield Measured with Ar10+ Ions at GSI-HHT
- Implementation:
  - Calculate dE/dx with ATIMA and rescale desorption rate.



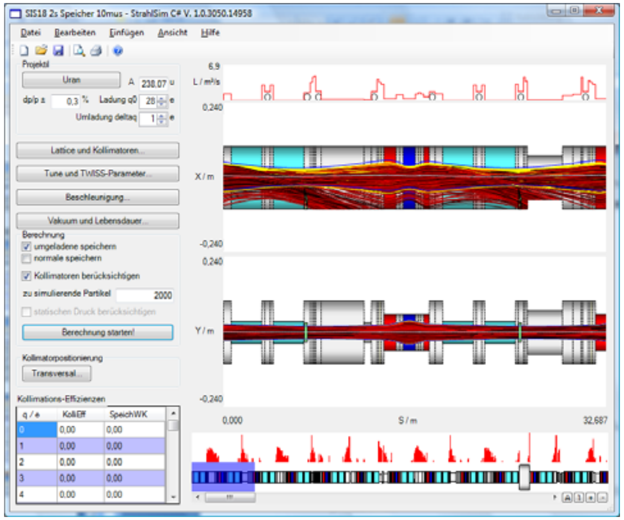


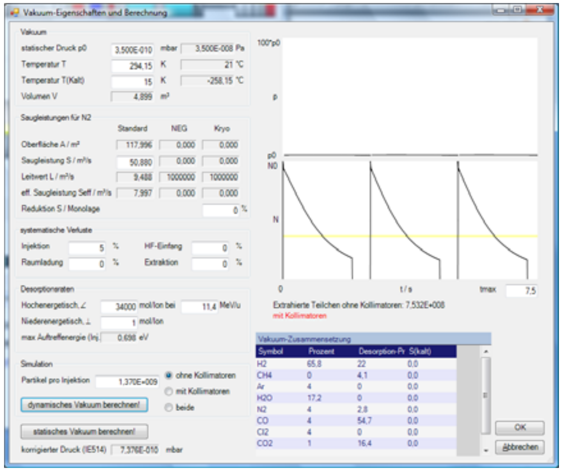
Molecule	Mass / u	Air / %	Desorbed Gas / %
H_2	2	0	18,1
N_2	28	78,084	2,3
O_2	32	20,942	8,5
Ar	40	0,934	
CO_2	44	0,038	13,6
H_2O *	18	0 ... 4	
CO	28	0	45,2
CH_4	16	0	9,0



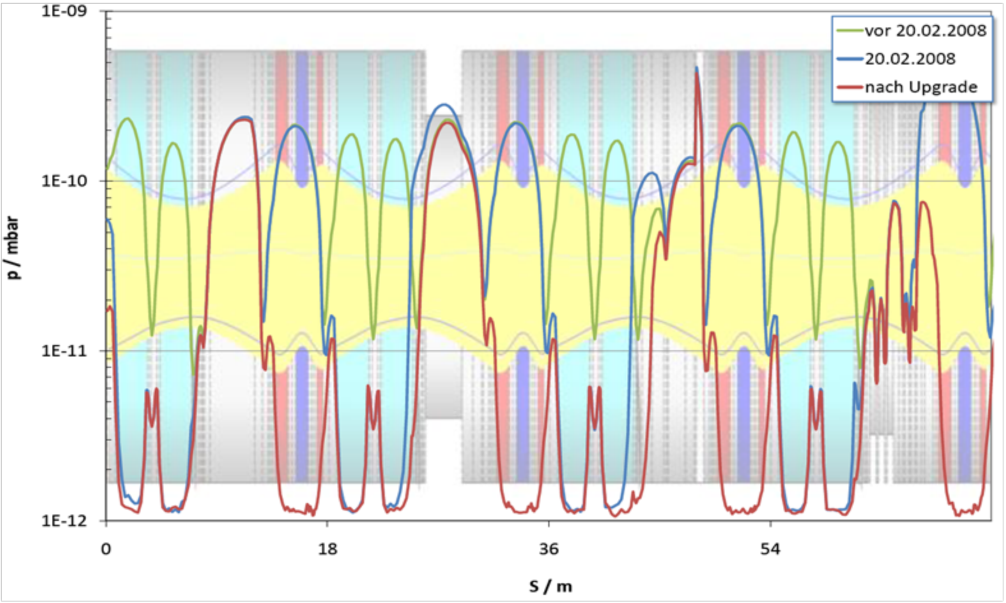
StrahlSim Code

- Vacuum calculations
  - Static
    - p_0, S_{eff}, vacuum conductance,
      NEG coatings, cryogenic surfaces,
      residual gas components
  - **Dynamic (source of beam losses)**
    - Synchrotron cycle
    - $S_{eff,cold}(p, T)$: analytical model
    - Systematic losses (injection, RF capture)
    - **Projectile ionisation** $\sigma_{pi}(E, \Delta q)$ from Shevelko, Olson, collaboration with AP
    - Coulomb scattering
    - Target ionisation
    - Intra beam scattering
    - **Ion stimulated desorption** (desorption rate η scaled with $(dE/dx)^2$) couples losses to residual gas pressure rise
- Linear ion optics
  - Loss distribution, catching efficiency
  - Reads and writes many formats (AML, MIRKO, MAD-X, WinAGILE)
- Benchmarked with many machine experiments and other accelerators





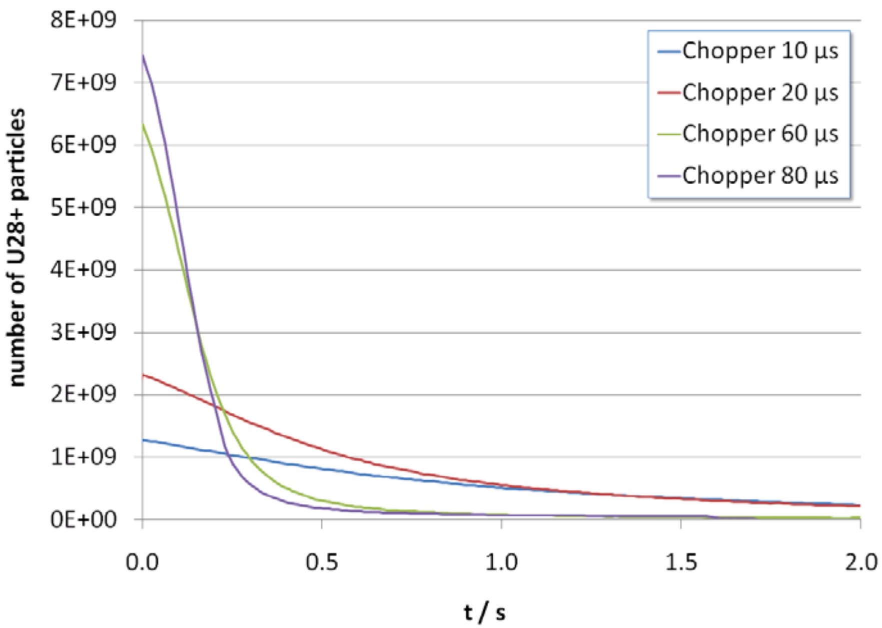
Longitudinal pressure profile

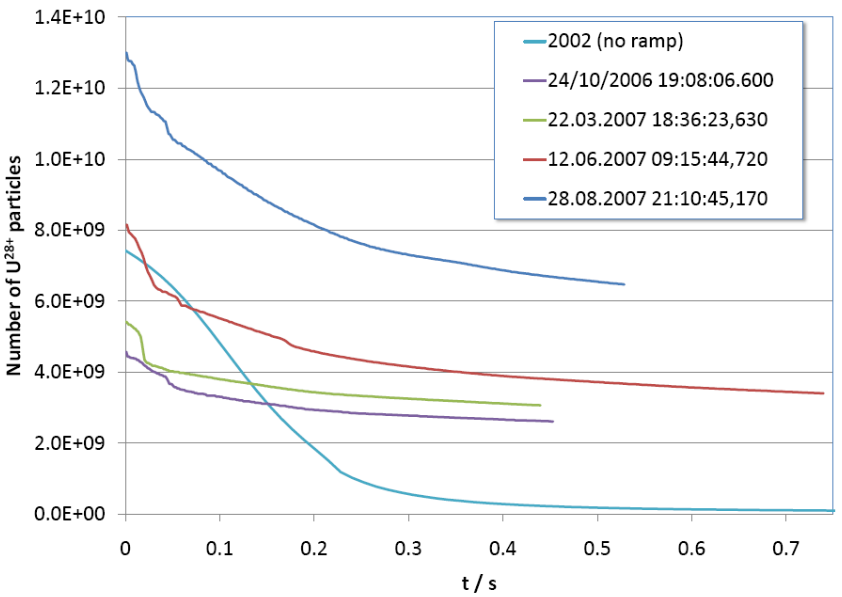


Section S01 of SIS18
at present and in future

- Needed for correction of measured pressures (pressure gauges are always situated beneath pumps, not at pressure maxima)
- Can be calculated by molecular flow method:
  - Raytracing of outgassing molecules until they reach a pump or pumping surface
  - No cunductance values needed
  - Full 3D, 4D (spatial+time dep.) possible, but very memory intensive: (N*N*M)
    N=Number of ion optical elements
    M=Number of time steps
  - Valid for UHV/XHV (always conductance limited, not pumping speed limited)
  - Need sticking factors for pumping surfaces

SIS18: Time dependant particle number (now)





December 2001

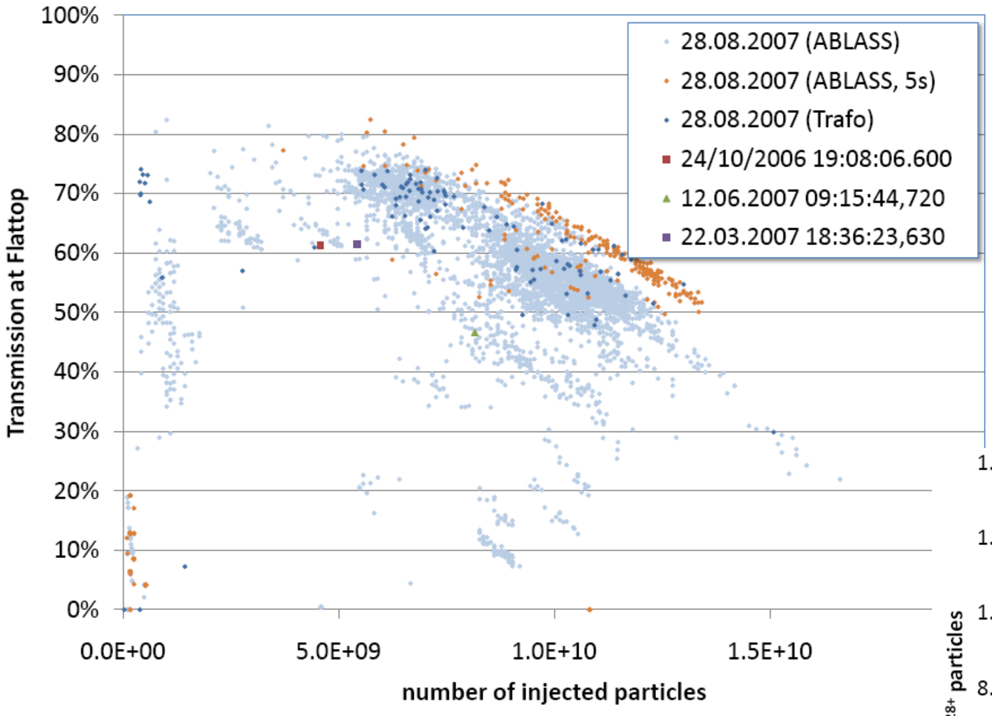
No acceleration, 8,6 MeV/u

Base pressure ~3*10^{-10} mbar

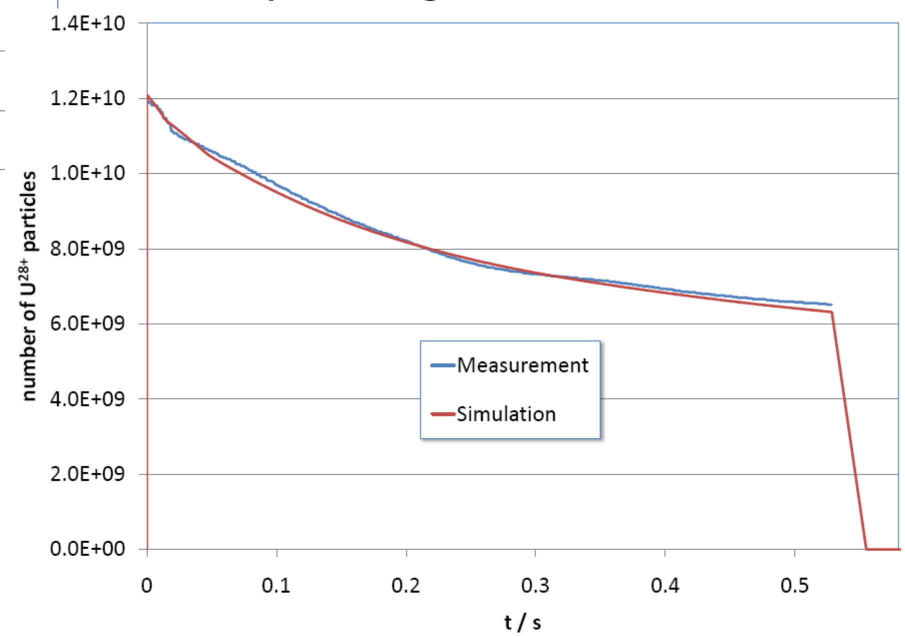
Extreme short lifetime!

- August 2007
- Ramp rate of 4 T/s
- Closed orbit corrected
- Enhanced pumping speed
  - NEG coating of one dipole- and three quadrupole chambers
  - Fired Ti-sub pumps

SIS18 Machine experiments



- Very delicate machine settings
  - 2 ½ days of dedicated optimization
  - Injection optimized
  - Closed orbit corrected
  - Introduced a 5 s break between cycles to give vacuum time

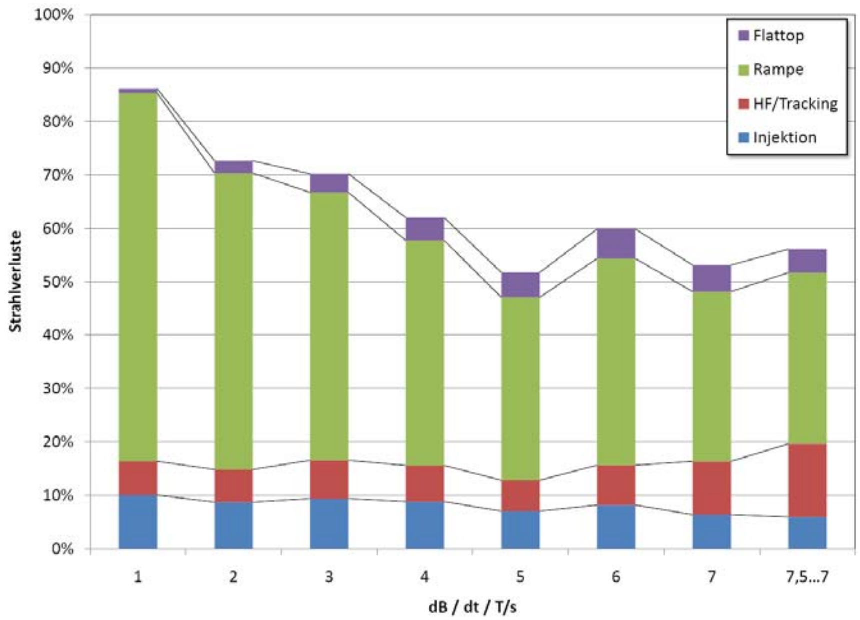


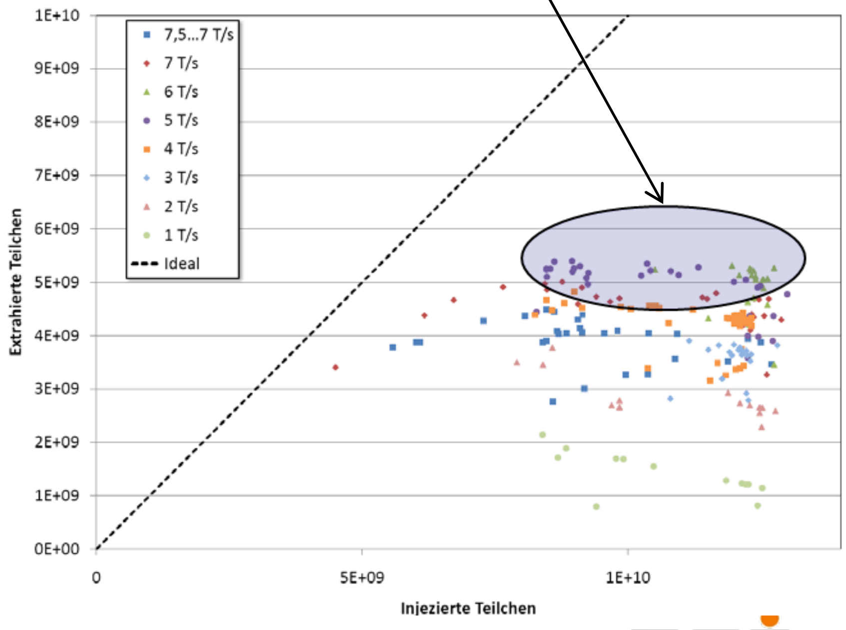
- Nice statistics, but a clear limit…
- Simulations with STRAHLSIM shows very good agreement with experiments.

SIS18 Machine experiments: fast ramping

- Special operation mode for ramp rates of up to 10 T/s.
- Beam loss on ramp reduces, but others enhance…

Best transmission with 4…5 T/s (sufficient RF acceleration voltage)

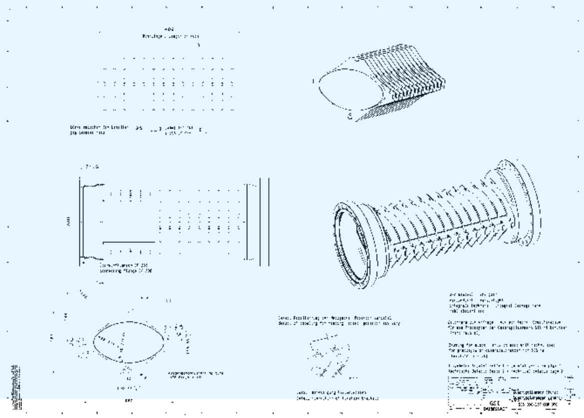




UHV system upgrade, NEG coating

- Generation of extremly low static pressures of $p_0 < 5 \times 10^{-12}$ mbar and increased average pumping speed by up to a factor of 100
- Stabilization of dynamic pressure to $p(t)_{max} < 10^{-9}$ mbar
- Removement of contamination with heavy residual gas components

- Replacement of all dipole- and quadrupole chambers by new, NEG coated chambers
- Improved bake-out system for operation up to 300K



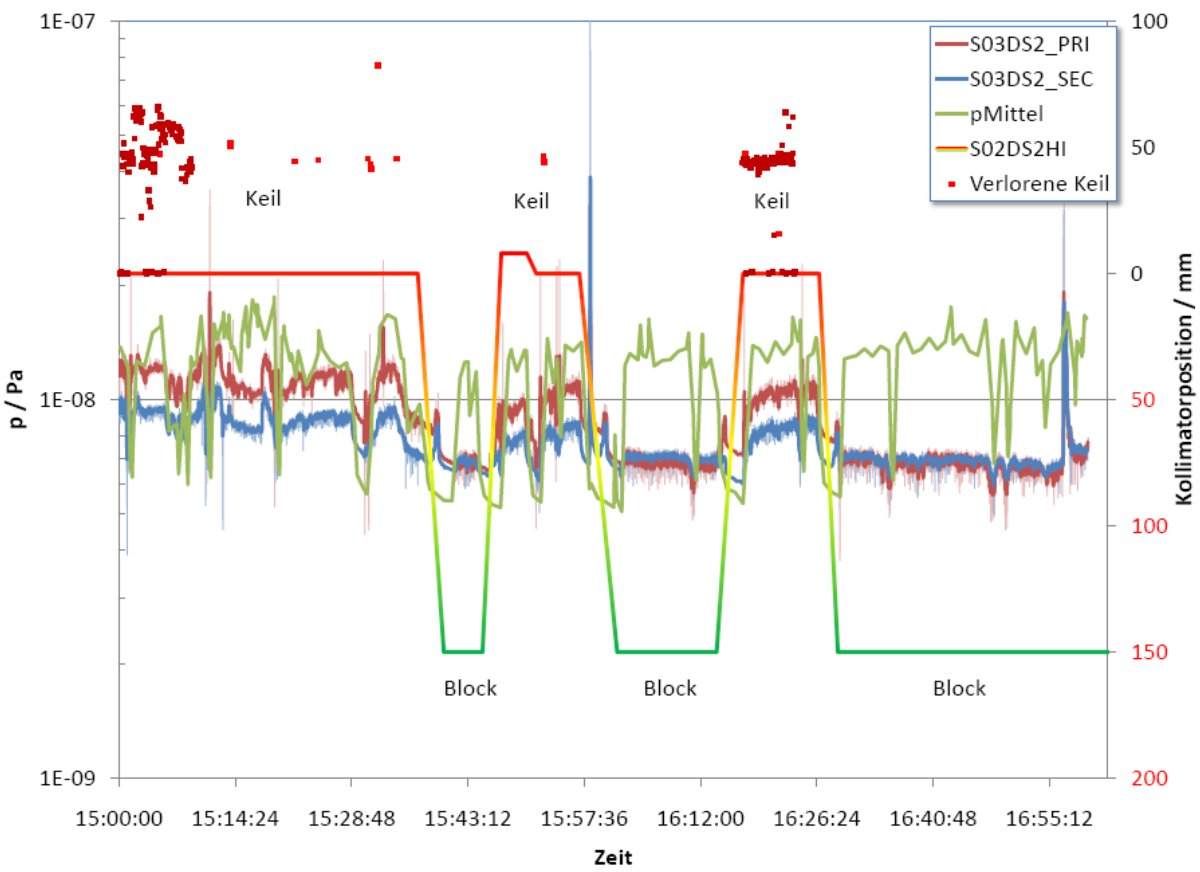
Collimator prototypes manufactured

(as seen from the beam)

Installation of two prototype collimators completed in last shutdown!

Residual gas pressure during experiments

(20.-22.02.2008, with 2 prototypes)



Surprise: Collimator block better than wedge!

Pressure rise in collimator chamber:

Wedge: 3.30^{-11} mbar

Block: $0.63*10^{-11}$ mbar

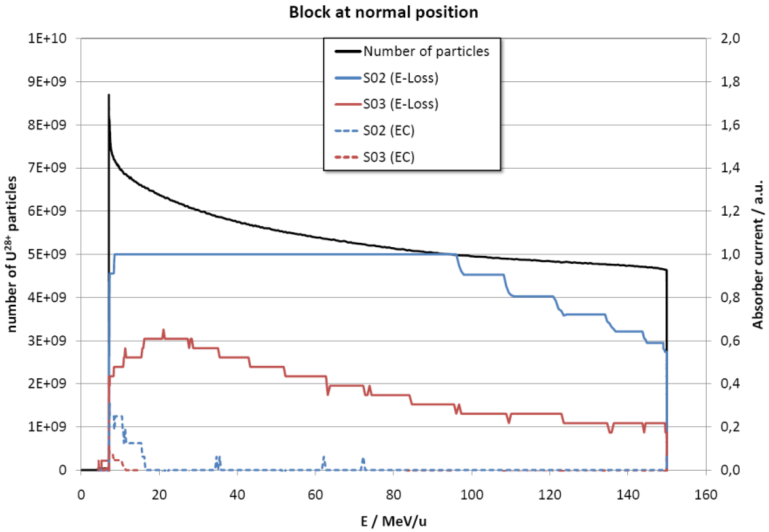
Measured desorption rates:

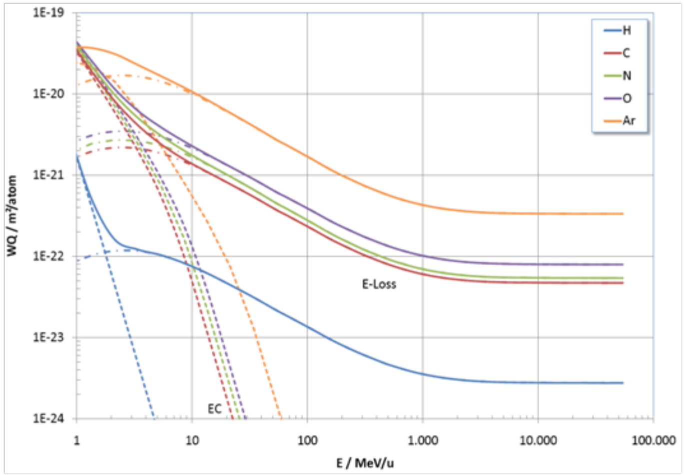
Keil: >119 mol/Ion

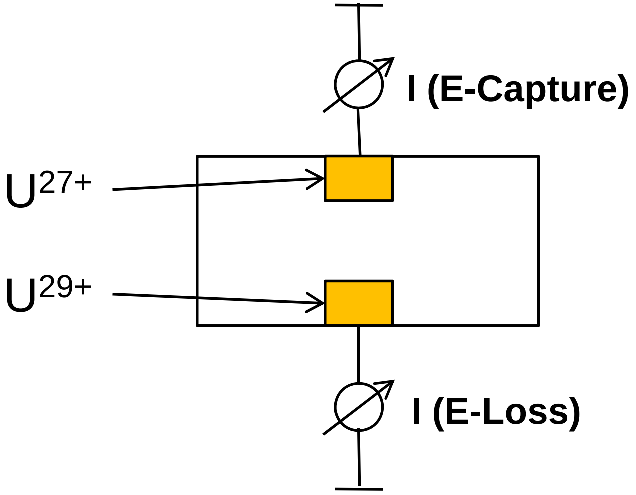
Block: >24 mol/Ion (!)

Global pressure dominated by other sections (e.g. injection)!

Ion current on absorbers







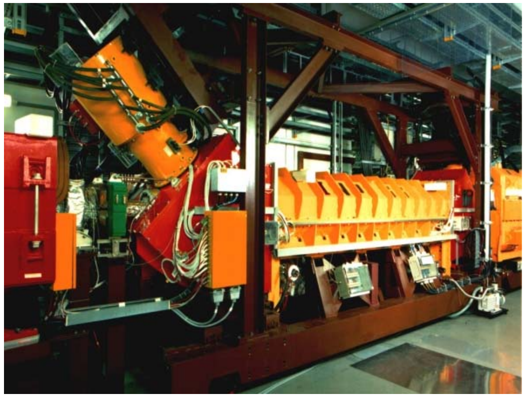
First measurement of real lost beam ions!

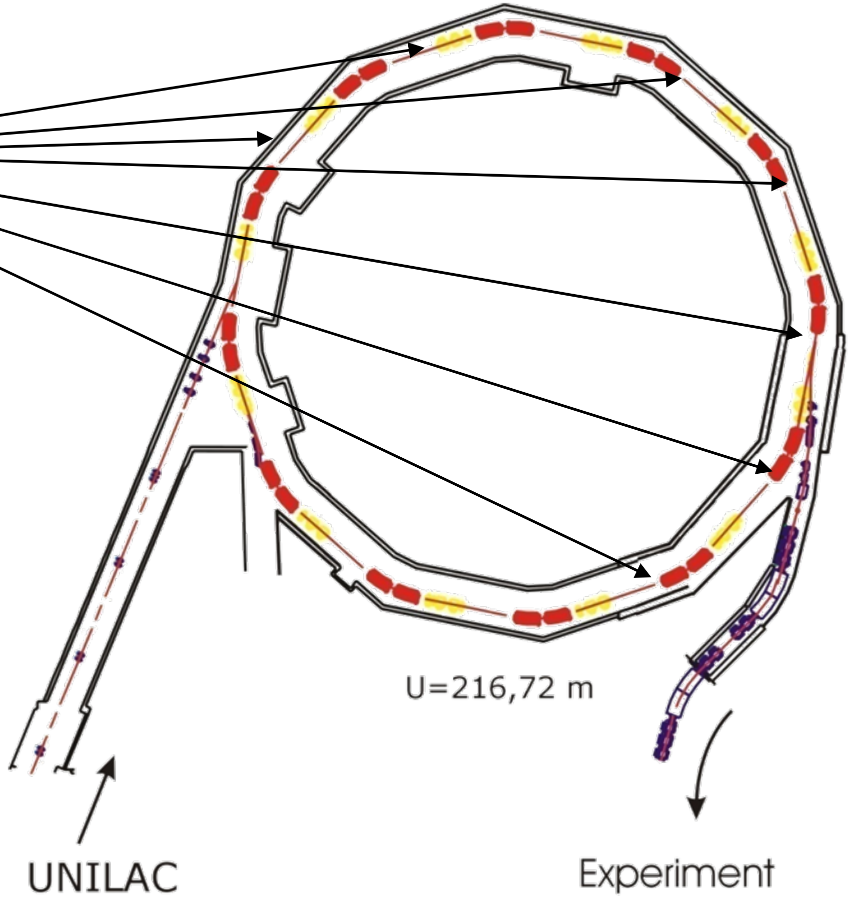
Agreement with theory:

- More electron loss than capture
- Energy-falloff

Position of Collimators (Charge Scrapers)

Installation behind each dipole group

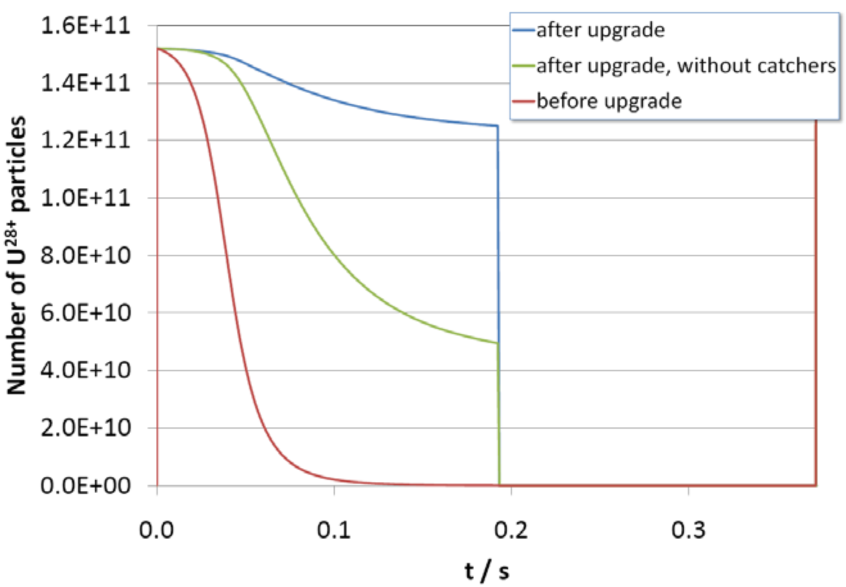


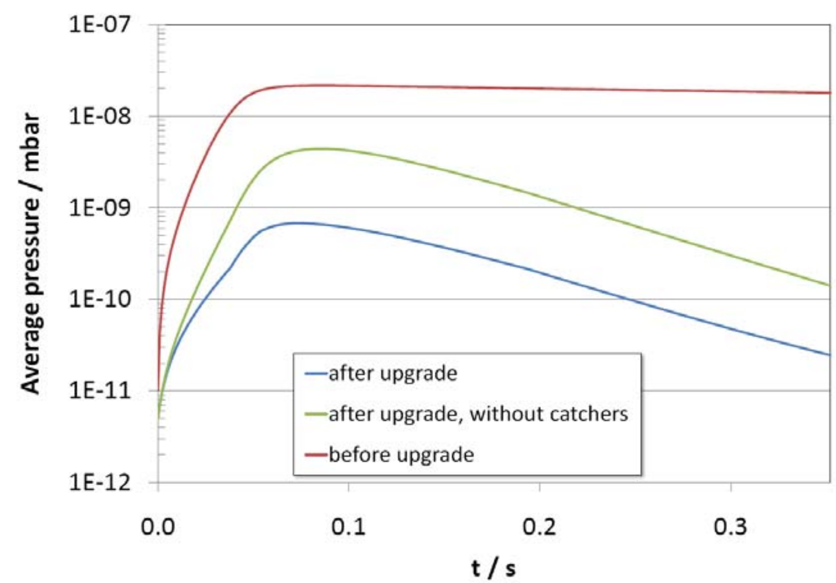


Electron cooler in S10, electrostatic septum in S06

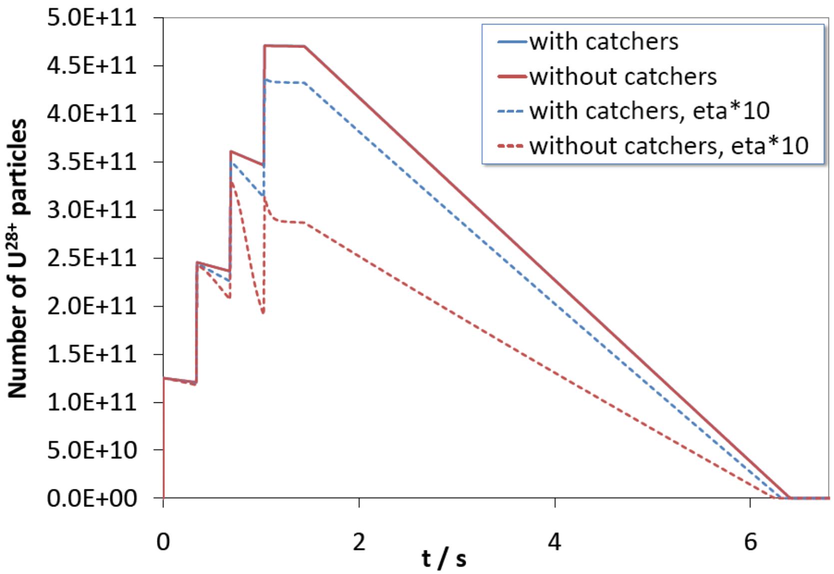
SIS18: Time dependant particle number (future)

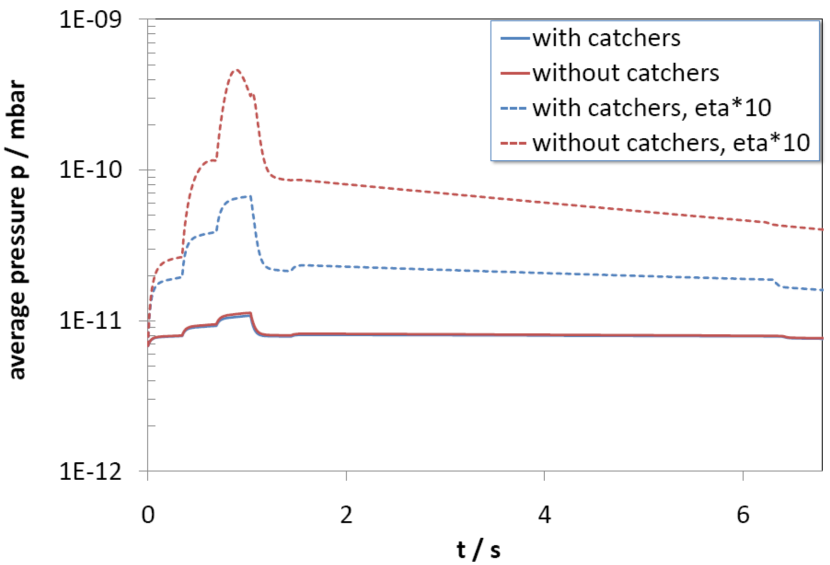
- Ultimative goal for FAIR: Accelerate 1.25*10^{11} U^{28+} particles from 11.4 to 200 MeV/u and inject 4 cycles of them into SIS100 in ~1.3 s
- Simulations with STRAHLSIM before and after SIS18 Upgrade:
  - Enhanced ramping rate of 10 T/s
  - Reduced injection- and RF-capture losses
  - Enhanced pumping speed by NEG-coating of all dipole and quadrupole chambers
  - Collimator system





SIS100: Time dependant particle number

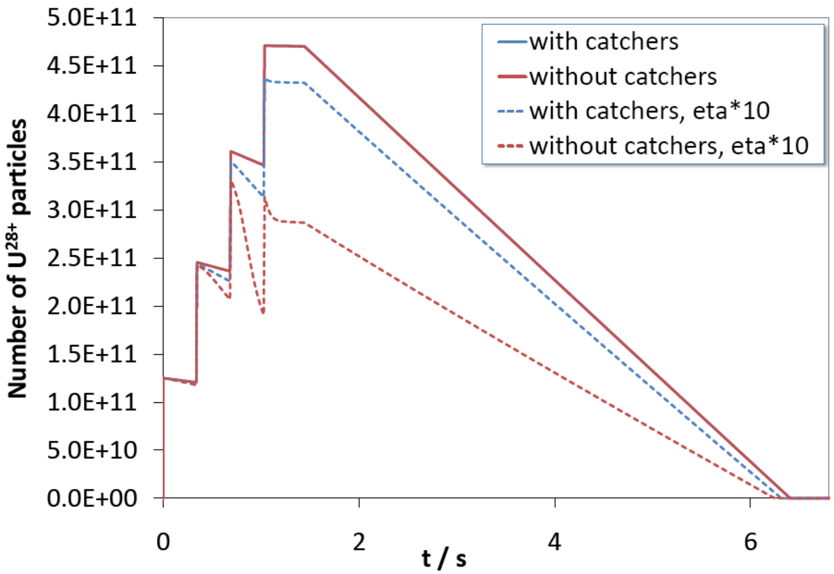


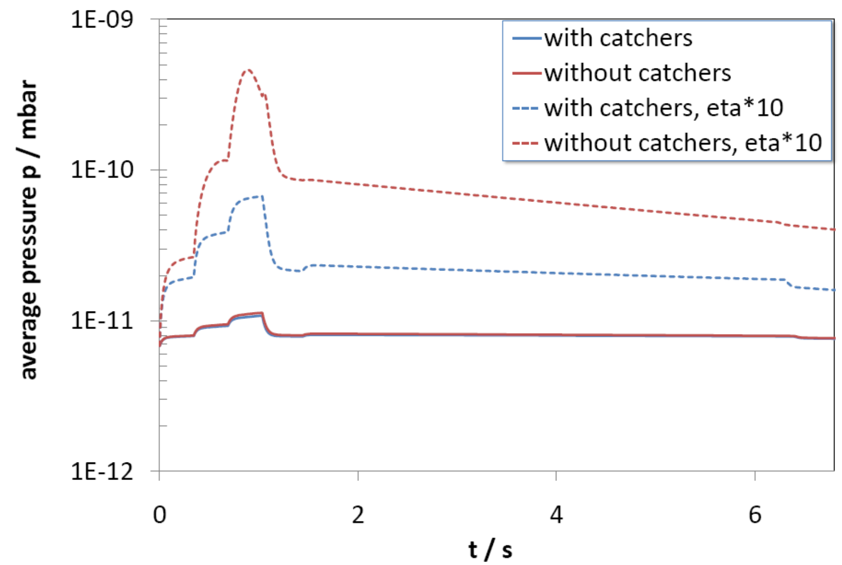


If physics of simulation is OK:

- Everything looks fine and quite relaxed (huge pumping speed of cryogenic surfaces pumps away ‘everything’)
- Ionization losses < 1 % ($4.7 \cdot 10^9$ particles)
- Pressure is more or less static
- Are Collimators useless? Without error bars, yes, but…

SIS100: Time dependant particle number





<u>If desorption rate is only a factor of 10 higher as assumed with (dE/dx)²-scaling law (e.g. cold surface, grazing angle of incidence):</u>

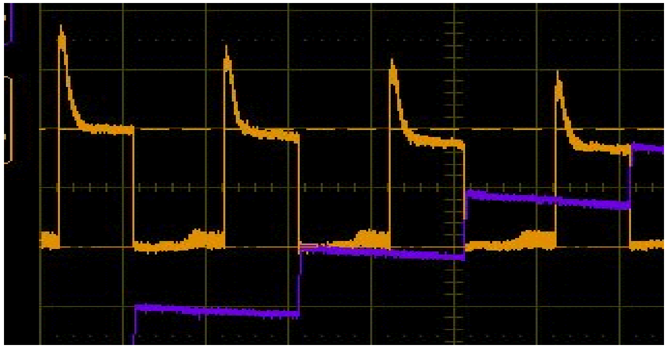
•Pumping speed will be reduced by adsorbing more than a monolayer of desorbed gas in a quite short time – 2.8 days (!), not 1 month

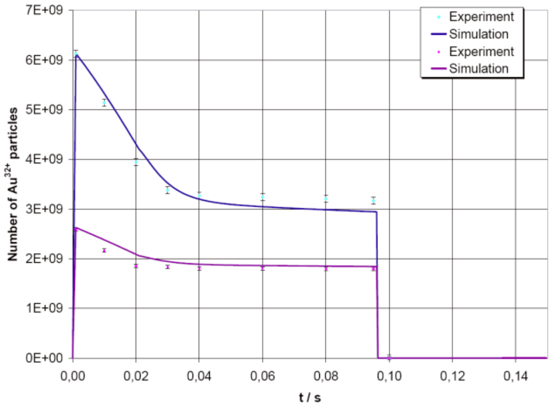
•Ionization losses > 9.18 % (4.6*10^{10} particles) and increasing from shot to shot

•Pressure will be very dynamic

•**Collimators are useful** (not talking about other errors)

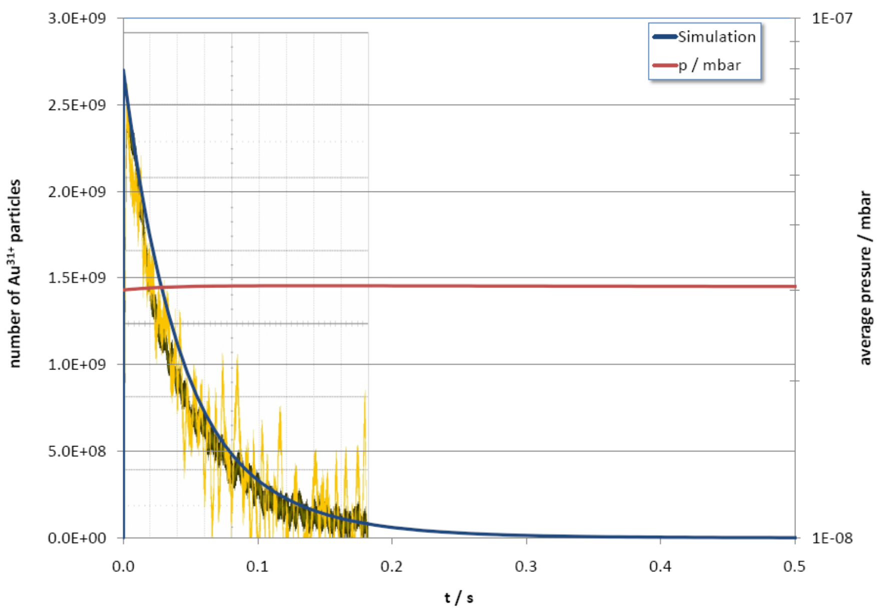
Benchmarks at other accelerators: AGS Booster

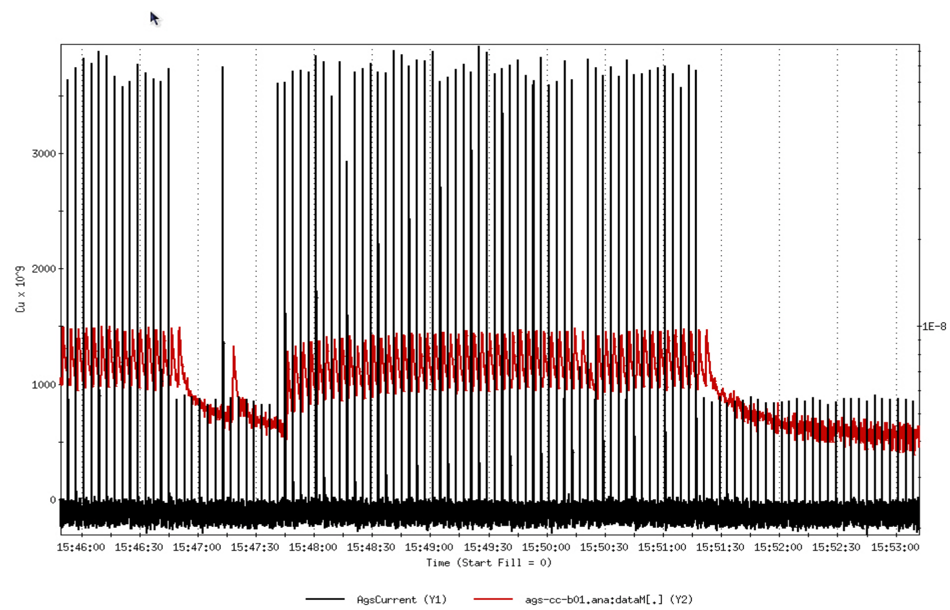




- AGS Booster (BNL) with Au^{32+}-Ions
- Electron capture dominated, but also restricted to ~6*10^9 particles per cycle
- Good agreement of simulation with experiments

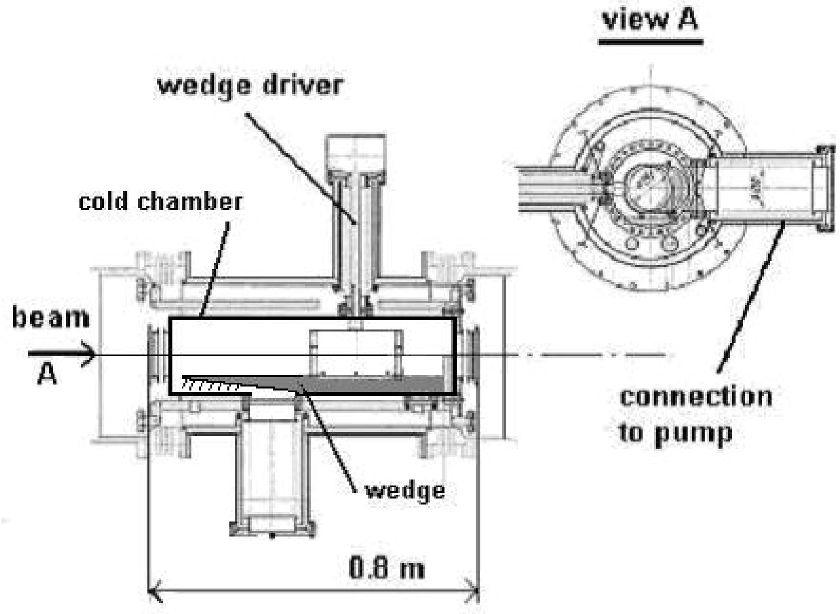
Desorption rate and beam life time test in AGS

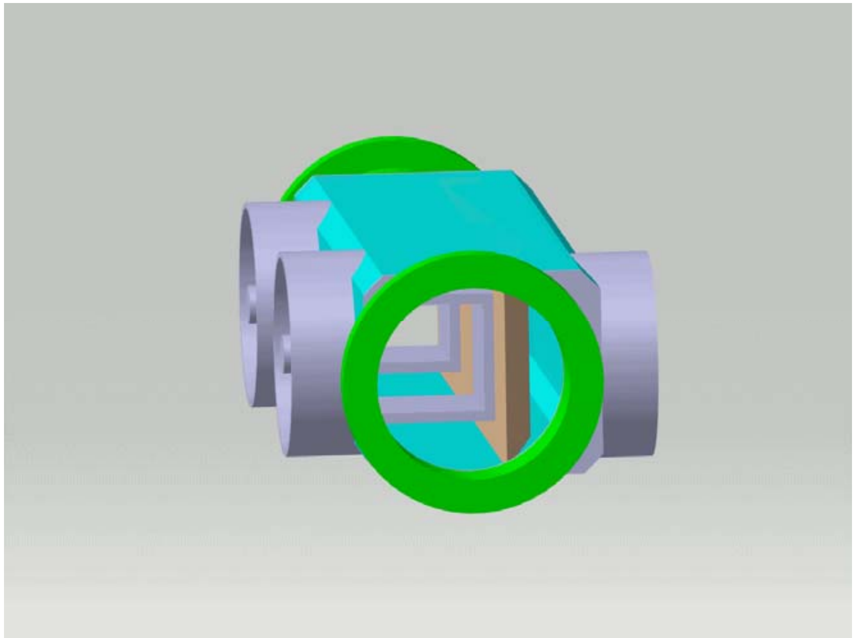




- Au^{32+} in BNL AGS 19.01.2008 (L. Ahrens, W. Fischer et. al.)
- Calculated desorption rate of η = 24.000 mol/ion at E=100...200 MeV/u
- Expected was η ~ 4.000, but the AGS is not baked, so the desorption rate is higher as in SIS18.

Cryo-collimator Design Study in FP7





Sketch of a SIS100 Cryo-collimator

Goals of the Design Study

- Set-up of a prototype cryo-collimator for SIS100 with identical technical design
- Set-up of the prototype at a HE beam line at GSI and beam tests
- Measurement of dynamic pressure in the primary and secondary chambers
- Determination of desorption rate of cryogenic surfaces
- Temperature measurement of collimator and chamber
- Measurement of required cooling power at different beam loads with the goal to stabilize the intermediate temperature level of 50 K

Outlook

- In preparation
  - 10 series collimators
  - SIS18 Upgrade will bring further enhancements for better machine control
  - Reduction of heavy residual gas components
  - Prototype of cryo-collimator for SIS100
- Further research at GSI and other institutes, e.g. CERN
  - Materials and desorption (UHV group - ERDA)
  - Simulation code STRAHLSIM
  - …

Summary

- Dynamic vacuum
  - Caused by charge exchange of low charged heavy ions at low energies (or beta decay)
  - All beam losses coupled to pressure by ion stimulated desorption
  - The specific desorption rate for baked, unbaked, warm, crogenic or coated surfaces has to be respected
  - SIS18:
    - Losses can be controlled partially: Collimator system, UHV, Injection- and RF Upgrade
    - Two prototypes manufactured and operating in SIS18 (Section S02, S03)
  - Simulation model does exist
- Other beam losses still exist at very high beam currents
  - Resonances, space charge
  - Closed orbit distortions
  - RF bucket area / UNILAC energy mismatch
  - ...

Summary

Collimation may not be needed for magnet protection but eventually to supress the residual gas pressure dynamics

Uncertainties of simulation

- Desorption rate:
  - At highest energies still not known precisely
  - Desorption rates of various surface properties
- Pumping speed:
  - Huge in cold and NEG coated machines
  - Temperature: lots of cold-warm transitions
  - Unknown reduction of the sticking factor by changing from cryosorption to physisorption
- Cross sections for charge change:
  - Only theoretical estimates (AP, Shevelko et al.) available at these high energies, error bar at least 30%
  - Rates for beta decay well known
- Losses by other effects (resonances, higher order fields, etc.) not included!