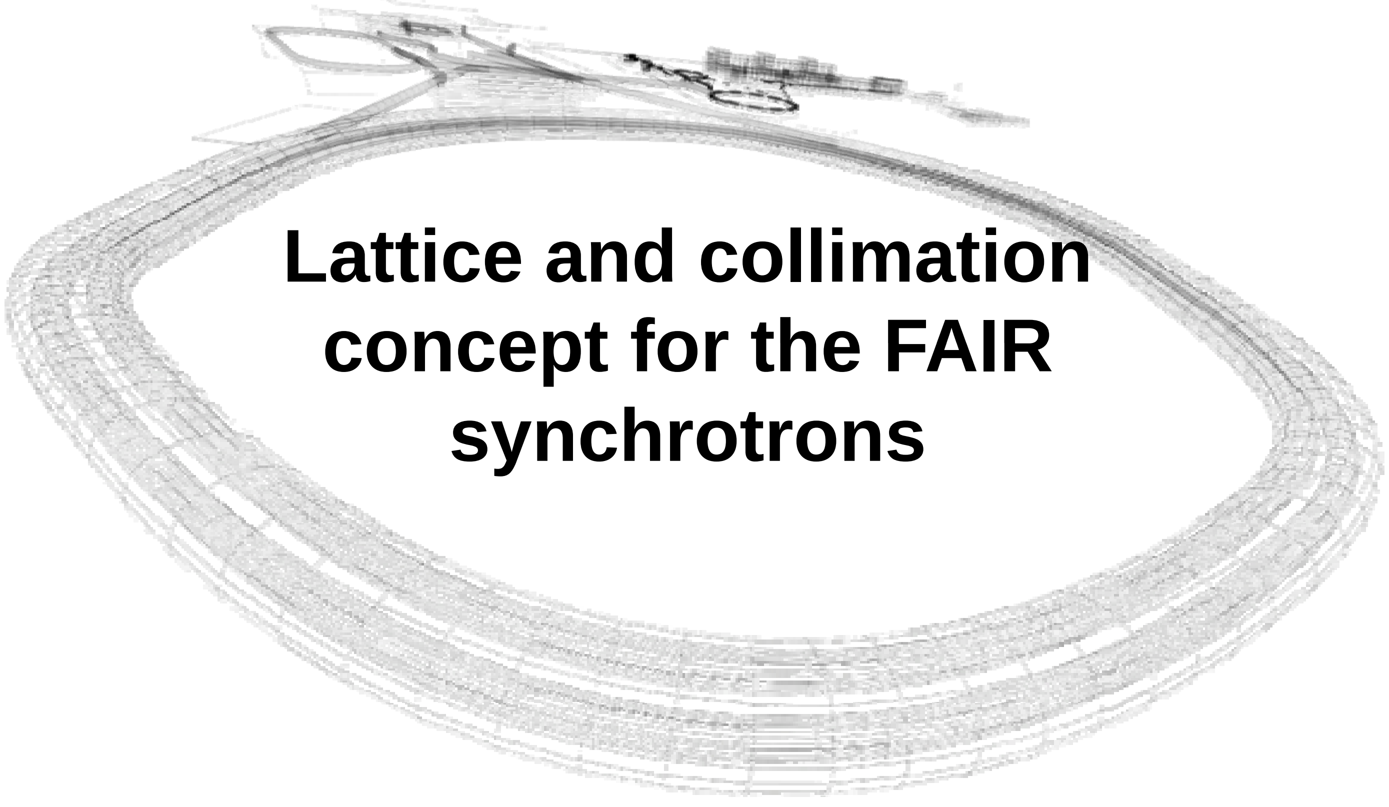


Lattice and collimation concept for the FAIR synchrotrons

CARE-HHH-APD BEAM’07, CERN October 02nd 2007

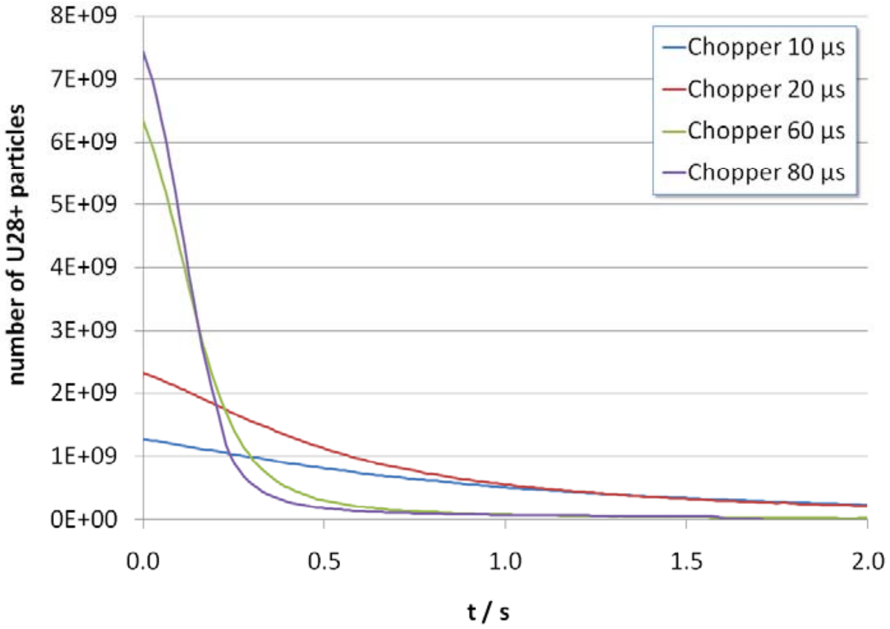
C. Omet, FAIR Synchrotrons

Contents

- Introduction
- Charge change losses of heavy ions
- Collimator placement
- Lattice optimization
- Collimator system design
- Absorber surface
- Measurements and simulations of beam life time
- Outlook

Introduction

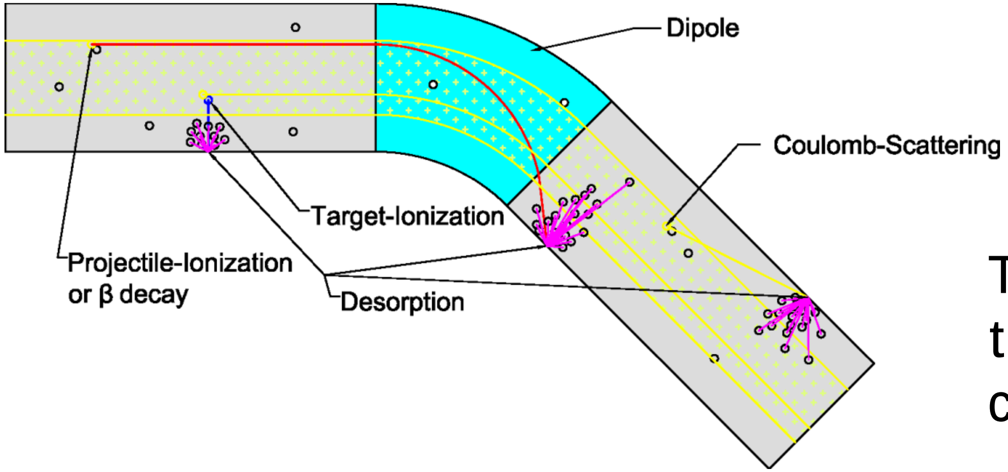
- Observation of fast, intensity dependant beam losses during operation with low charge state high intensity heavy ion beams in our synchrotron SIS18 (well below space charge limit).
- A large residual gas pressure rise was observed the same time.



- Losses depend on:
  - injected beam intensity
  - injection losses
  - RF capture losses
  - residual gas pressure
  - 1/energy (1st approx.)

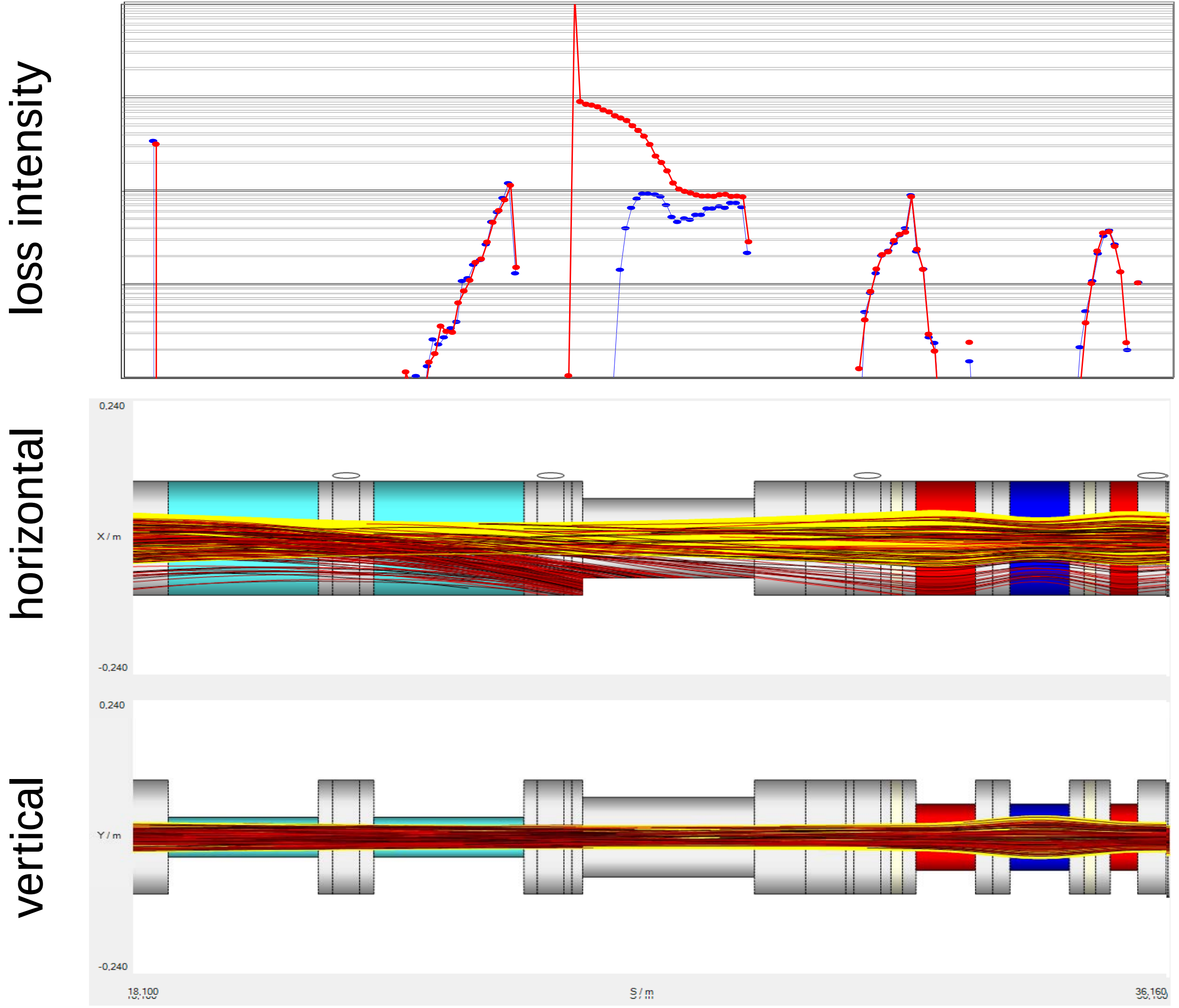
Charge change loss mechanism

- A beam ion hits residual gas atoms/molecules and loses one or more electron(s)
- This ion is lost after the next dipole by different magnetic rigidity ($\delta p/p \cong q_0/q - 1$, e.g. for $U^{28+} \rightarrow U^{29+}$ $\delta p/p = -3.45\%$!)
- There, a shower of secondary particles is produced by ion stimulated desorption with a rate of $\eta \geq 10^4$ mol/ion.
- An avalanche process can be initiated!



There are more loss processes, but this one can be controlled with collimators / catchers!

Collimator placement in SIS18



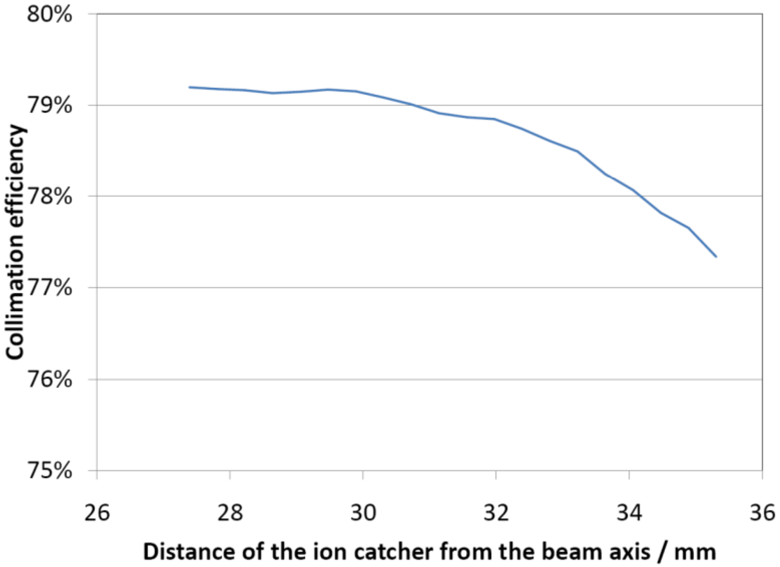
without collimators
with collimators

- SIS 18, section S02
- E = 11.4 MeV/u
- $U^{28+} \rightarrow U^{29+}$
- 2,500,000 particles

- Lattice is fixed
- Collimator position is ‘forced’ by dipole position

Collimator placement in SIS18

- Transversally:
  - Do not reduce acceptance of the machine!
  - Maximise collimation efficiency for reference ion (U^{28+})
  - Have to make a compromise always in existing machines!
- Optimal placement and lattice design: SIS100 lattice



Calculated for only 10 installed collimators, two sections cannot be used because of non-moveable insertions (extraction septum and ion cooler).

Lattice optimization: Principles

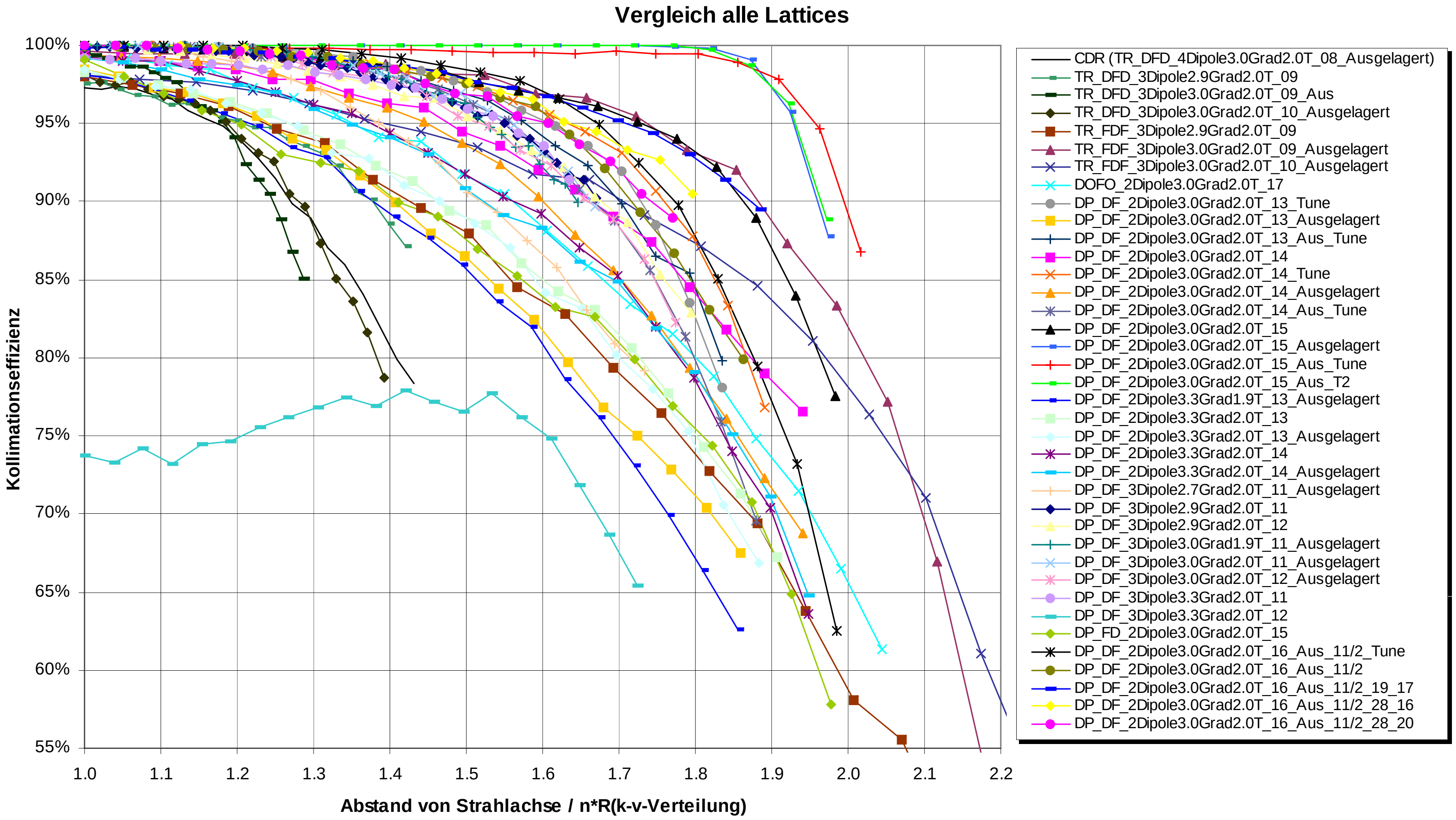
- Ions should not be lost at arbitrary positions:
  - Machine protection (magnets, electronics)
  - Activation should be peaked
  - Losses should be in sections with sufficient space for a dedicated scraper system
- Circulating beam and daughter products should be clearly separated at the positions of the scrapers.
- Scrapers should not reduce the acceptance.
- Ideally all unwanted ions which are produced downstream of one scraper should be transported at least to the next scraper (high tune or increased aperture).

Peaked!

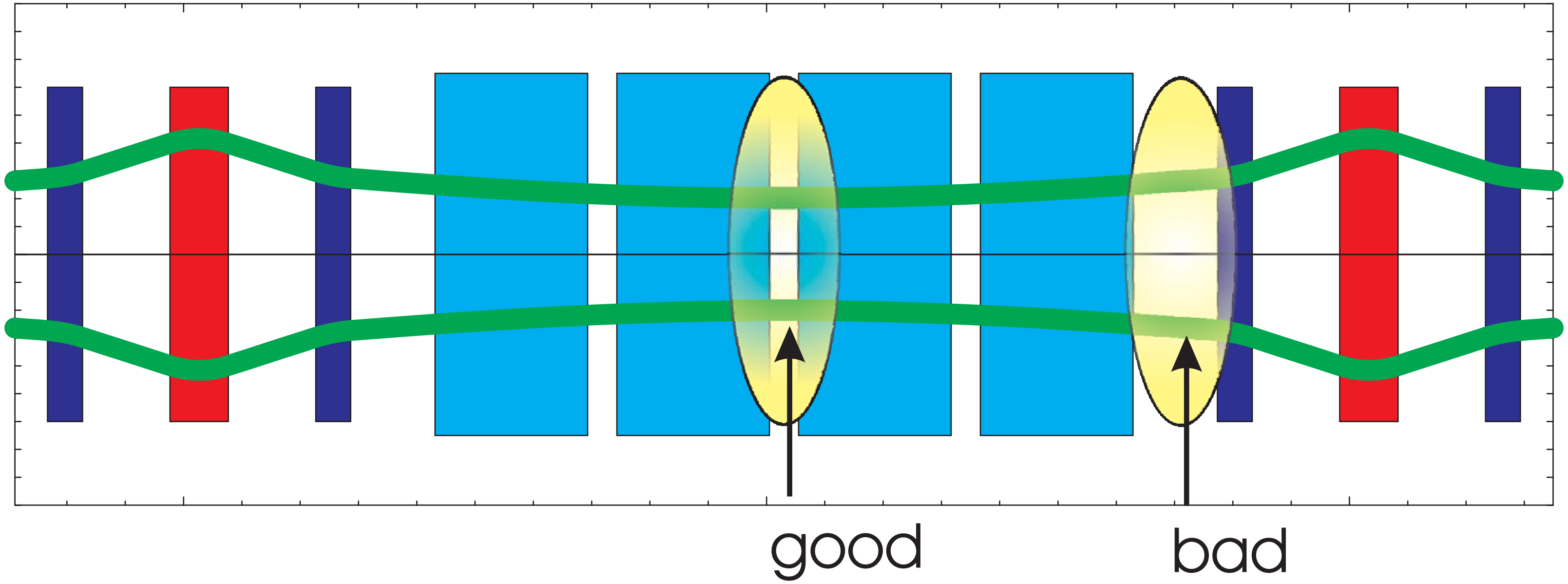
Separated!

Acceptance!

SIS 100 Design I: Lattice choice and optimization

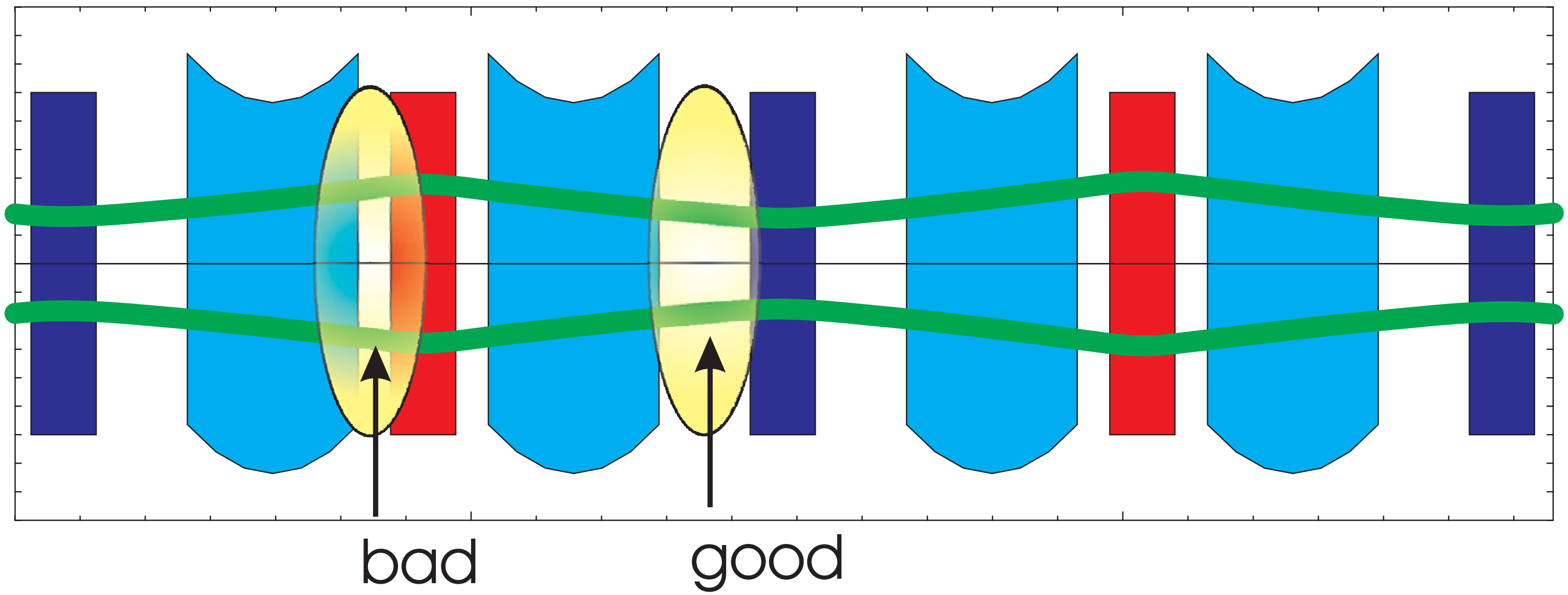


SIS100: CDR lattice



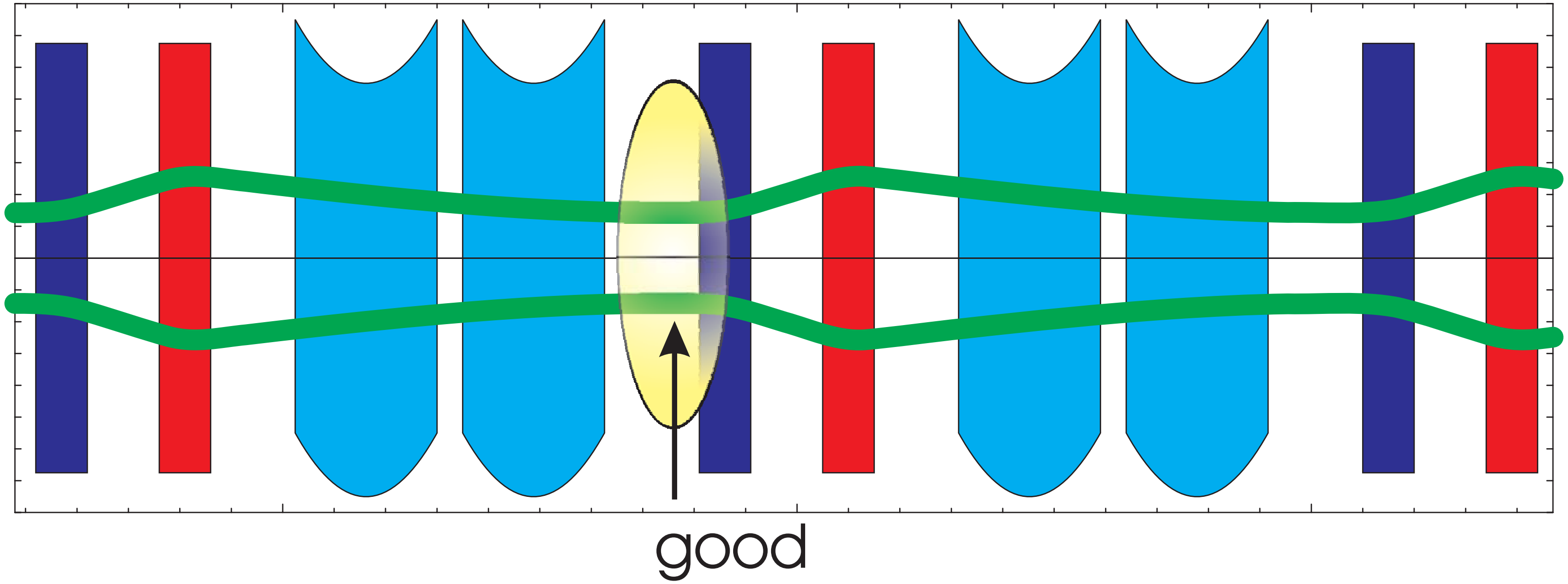
- Starting point of lattice design: Triplett structure (like SIS18), described in the conceptual design report
- Would work, if all dispersive elements were in the first half of the cell.

SIS100: FODO lattice



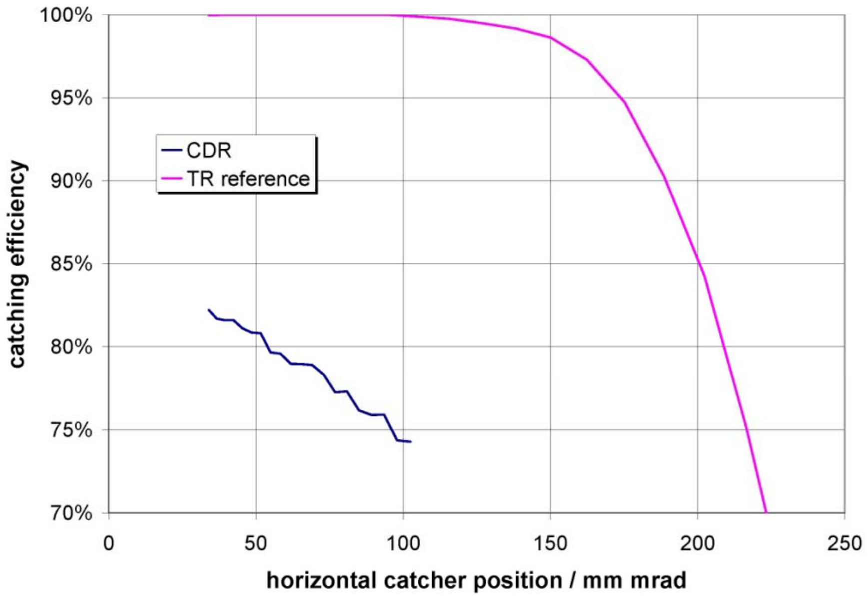
- FODO is quite common, but if the deflection angle of dipoles is large not suitable for collimation.
- One half cell is ok, next one is bad.

SIS100: doublet lattice (DF order)



- Beam waist with good separation of U^{29+} from U^{28+} together with beam waist.
- Enough space for a collimator before or inside the quadrupole doublet.

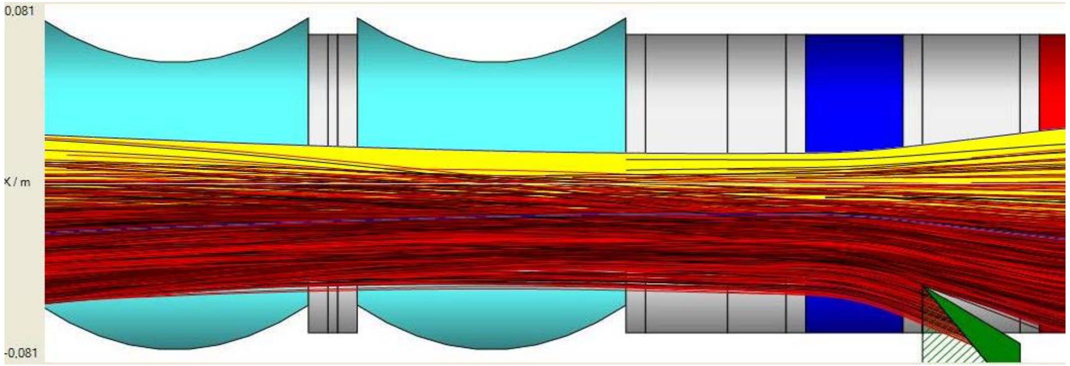
SIS100: Maximum collimation efficiency



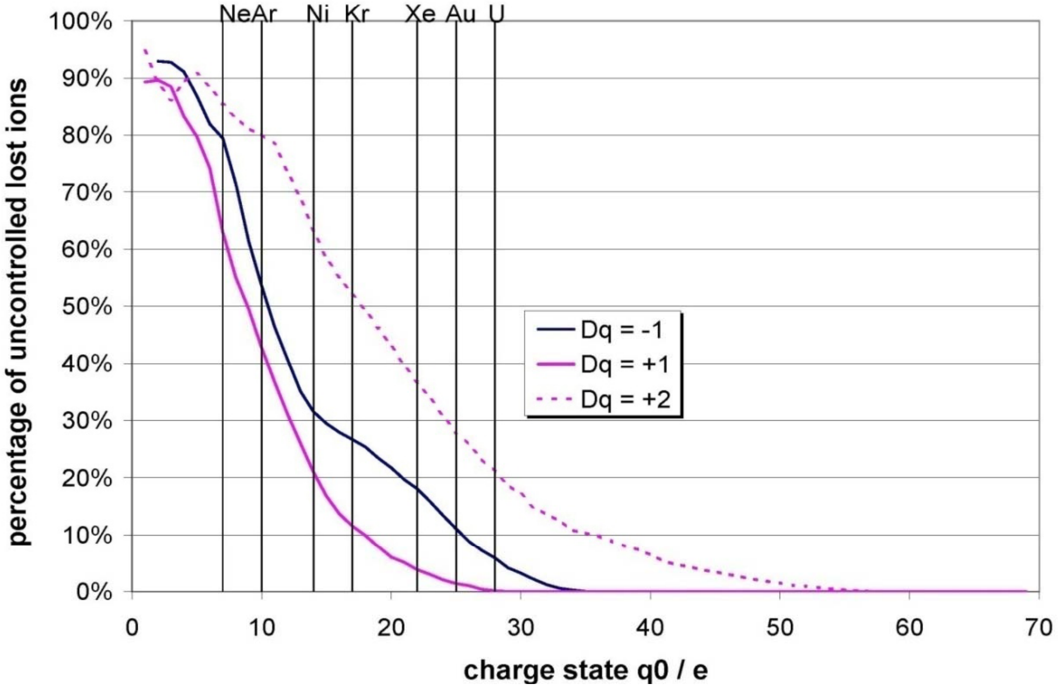
$\eta_{coll} = N_{coll}/N_{total}$

(here shown at injection energy)

Collimation efficiency can be further enhanced using the quadrupole defocusing!

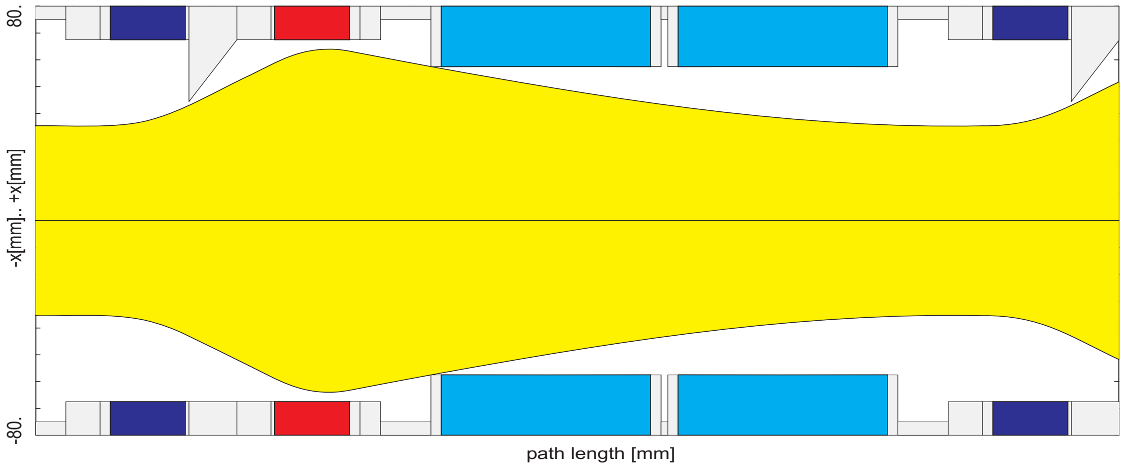


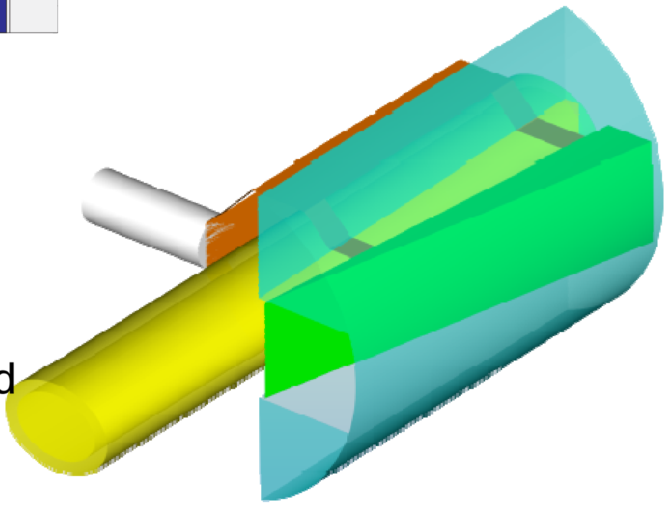
SIS100: Behaviour of lighter ions



- The scraper system is optimized for heavy ions (U^{28+}).
- Lighter ions miss the scraper and are lost in the beam pipe upstream of the collimators.
- The loss rate of light ions is low, since the cross sections are considerably lower.

SIS100 scrapers

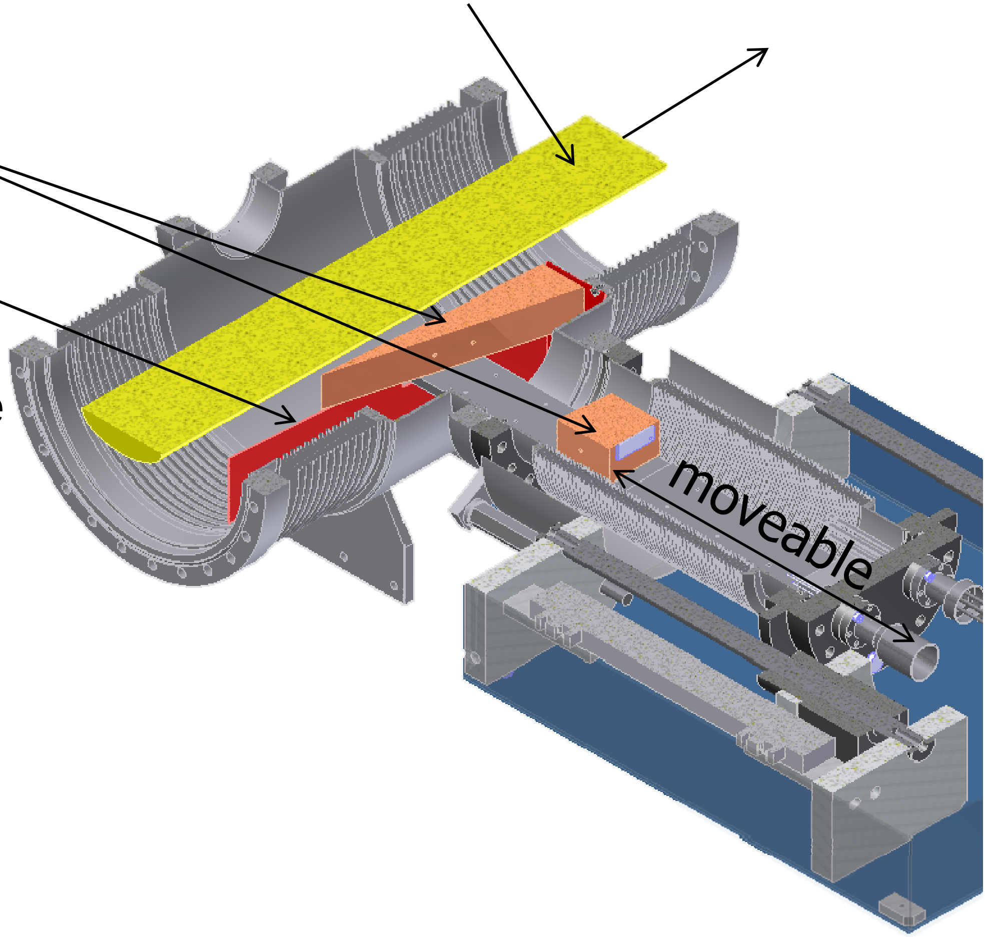




- The catchers do not interact with the stored beam!
- Do not freeze out particles at absorber!
  - Absorber surface will be at ~50 K, beam pipe at 4.2...20 K
- Need large length to stop heavy ions and their fragments at high energies (E=2715 MeV/u, calculated with ATIMA)
  - U in Cu: 47.5 mm
  - He in Cu: 1.8 m

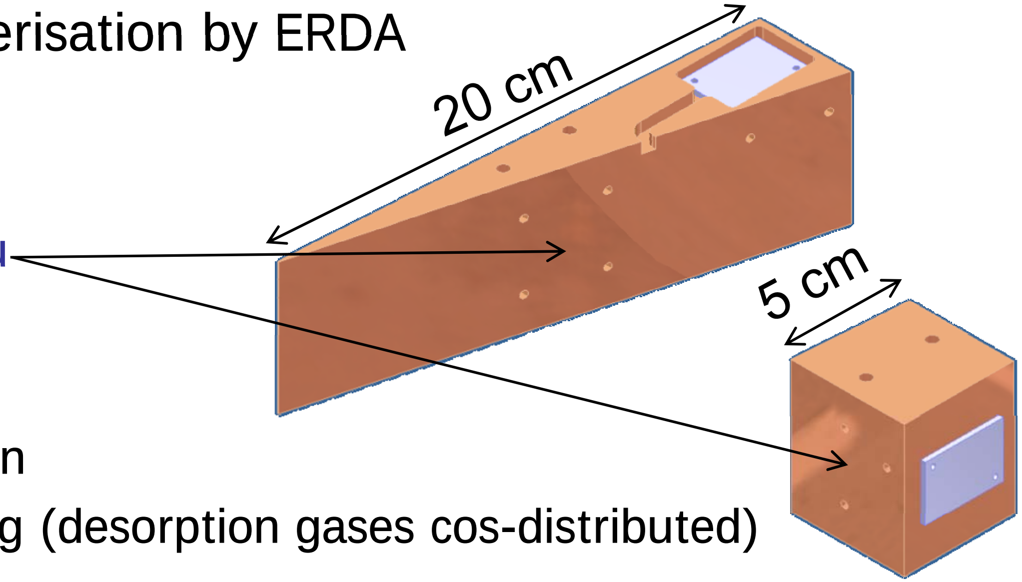
SIS18 collimator system

- Control and confine desorption gases where they are produced
- Absorber: Cu, Au coated
- Secondary chamber
- Need as much pumping speed as possible
  - NEG coating, wherever possible
  - Flanged ion pump (top mounted, not shown)
- Lots of diagnostics
  - total and partial pressures
  - ion current of U^{29+}
  - temperature of absorber



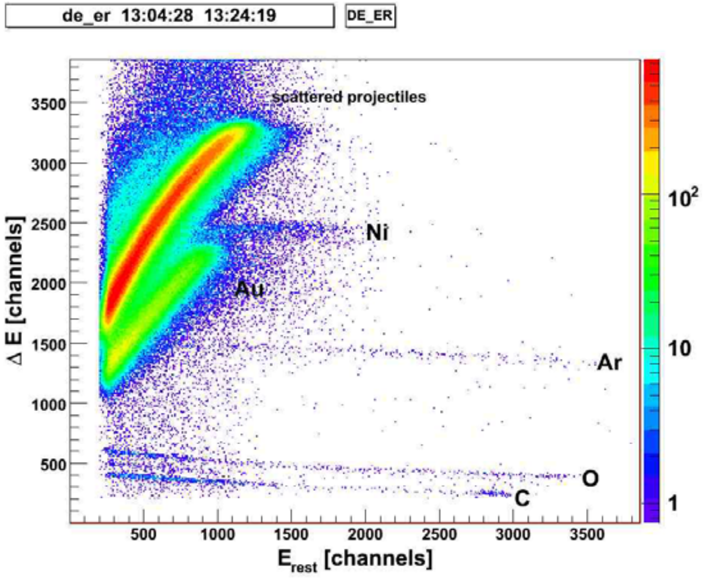
SIS18 beam absorber: Geometry

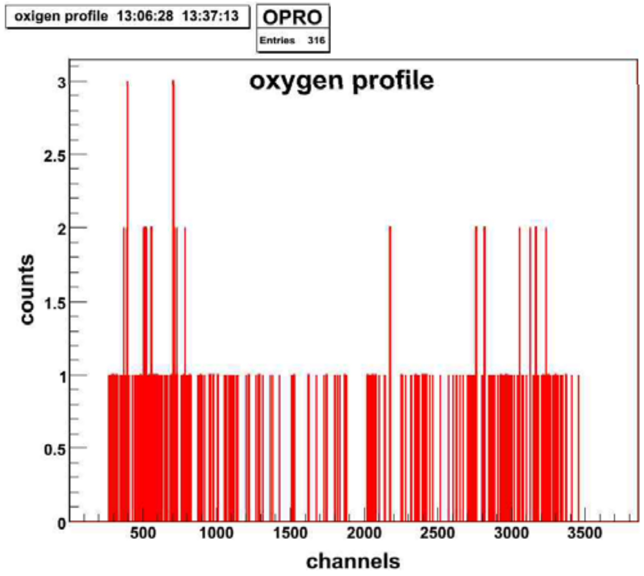
- Material choice:
  - Has to stop heavy ions at energies up to 200 MeV/u → $^{238}U^{28+}$ range is ~ 1.5 mm (fragments, e.g. He up to 42 mm)
  - Should have a low desorption rate at the active surface
- Use ion range calculations (ATIMA) and desorption measurements together with surface characterisation by ERDA
- Result:
  - Cu core
  - Coated with a few 100 nm Au
  - Desorption rate is not 0!
  - In prototypes: Two shapes
    - Block better for desorption
    - Wedge better for pumping (desorption gases cos-distributed)



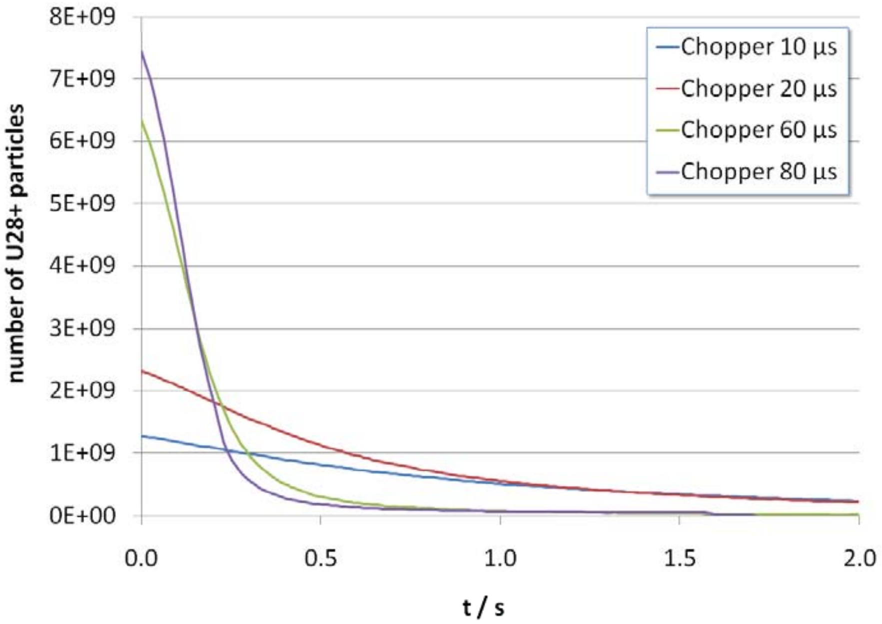
Beam absorber: Surface

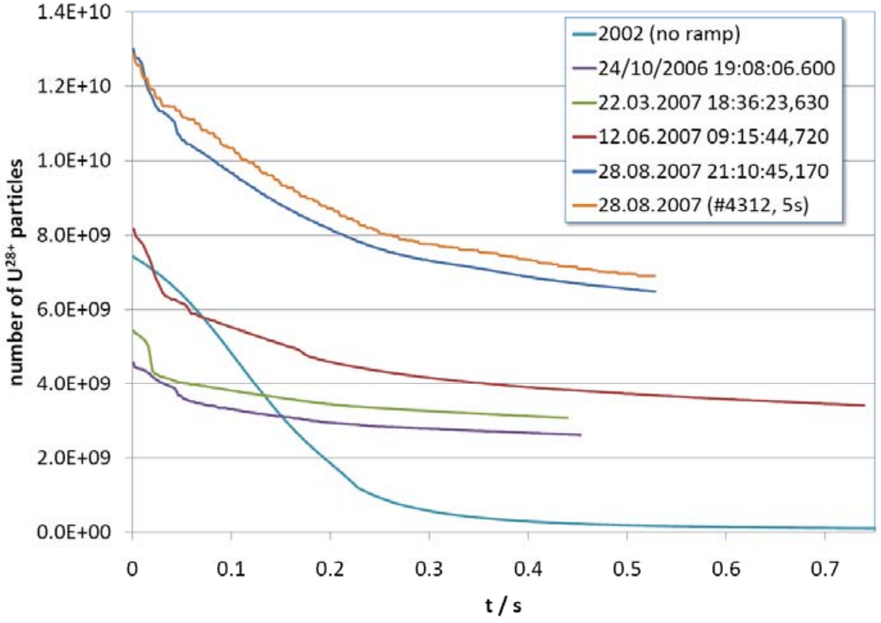
- ERDA measurements (Elastic Recoil Detection Analysis) taken at the HLI in GSI (H. Kollmus / M. Bender) 29th of September with 1.4 MeV/u $^{136}Xe^{18+}$ (dE/dx similar to ~10 MeV/u ^{238}U):
  - Au coated surface has lowest desorption rate (tested under perpendicular angle of incidence)
    - ~ 90 mol/ion
    - ~ 25 mol/ion after thermal treatment
  - pure Au, mechanically treated: 1200 mol/ion (!)
  - 300 nm Au
  - 200 nm Ni as a diffusion barrier





SIS18: Time dependent particle number (now)





December 2002

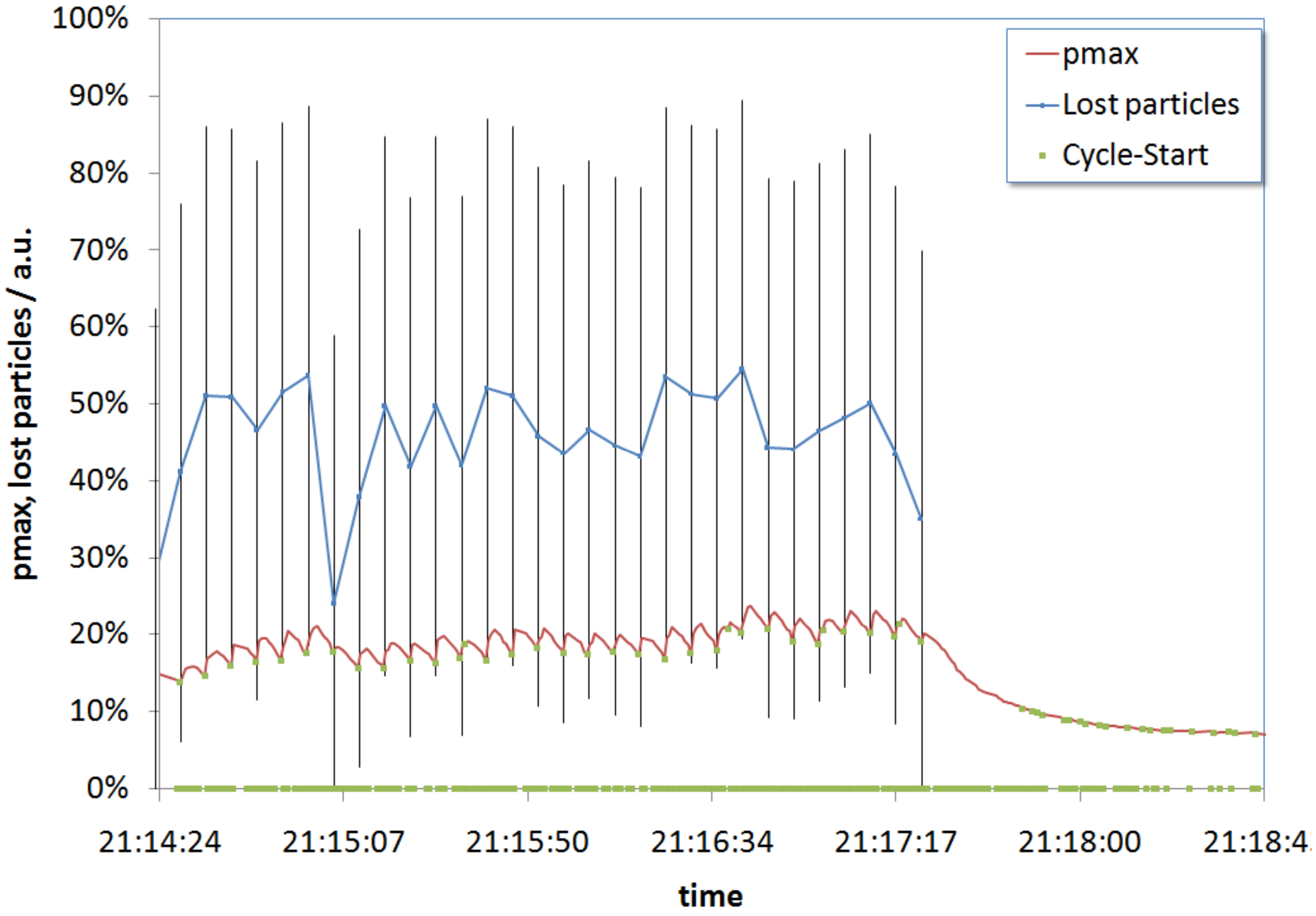
No ramping, 7.1 MeV/u

Base pressure ~1*10^{-10} mbar

Extreme short lifetime!

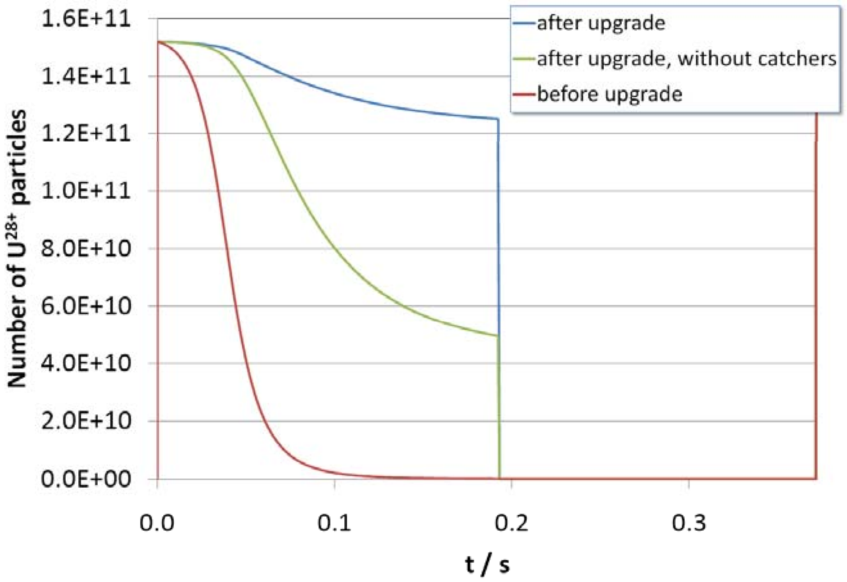
- August 2007
- Ramp rate of 4 T/s
- Closed orbit corrected
- Enhanced pumping speed
  - NEG coating of one dipole and three quadrupole chambers
  - Fired Ti-sub pumps

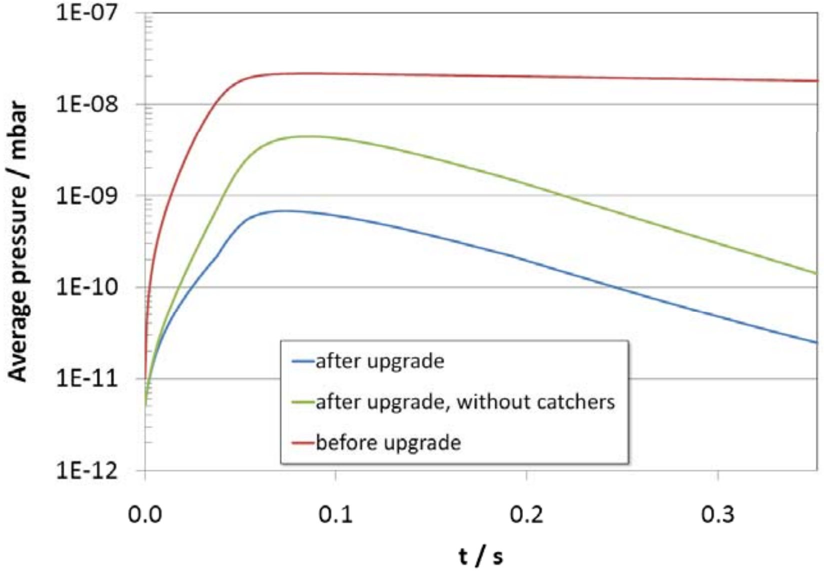
Residual gas pressure during experiments



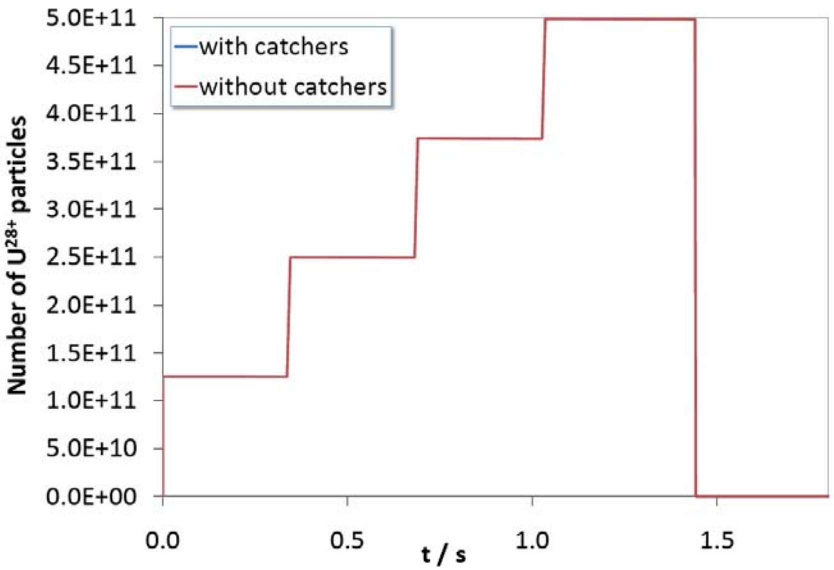
SIS18: Time dependant particle number (future)

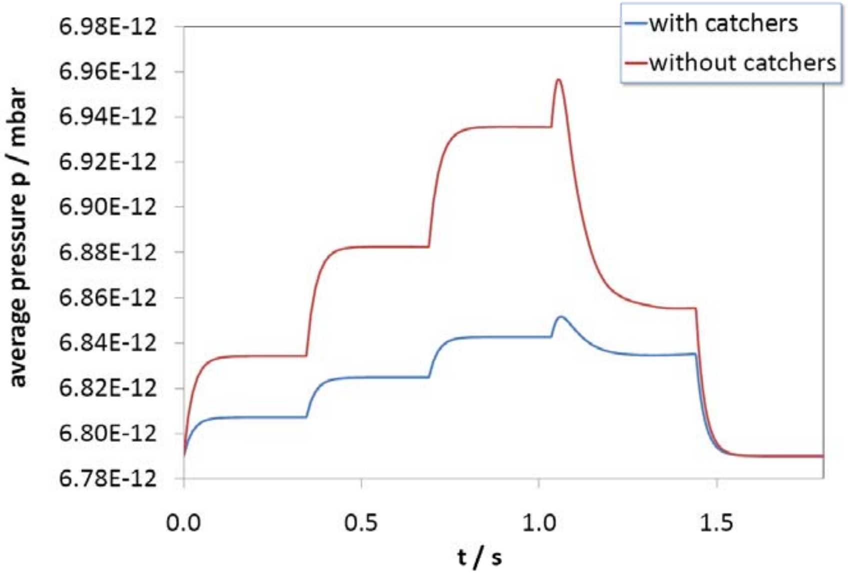
- Ultimate goal for FAIR: accelerate $1.25*10^{11}$ U^{28+} particles from 11.4 to 200 MeV/u and inject 4 of them into SIS100
- Simulations using StrahlSim before and after SIS18 upgrade:
  - Enhanced ramp rate of 10 T/s
  - Reduced injection and RF capture losses
  - Enhanced pumping speed by NEG coating of all dipole and quadrupole chambers





SIS100: Time dependant particle number

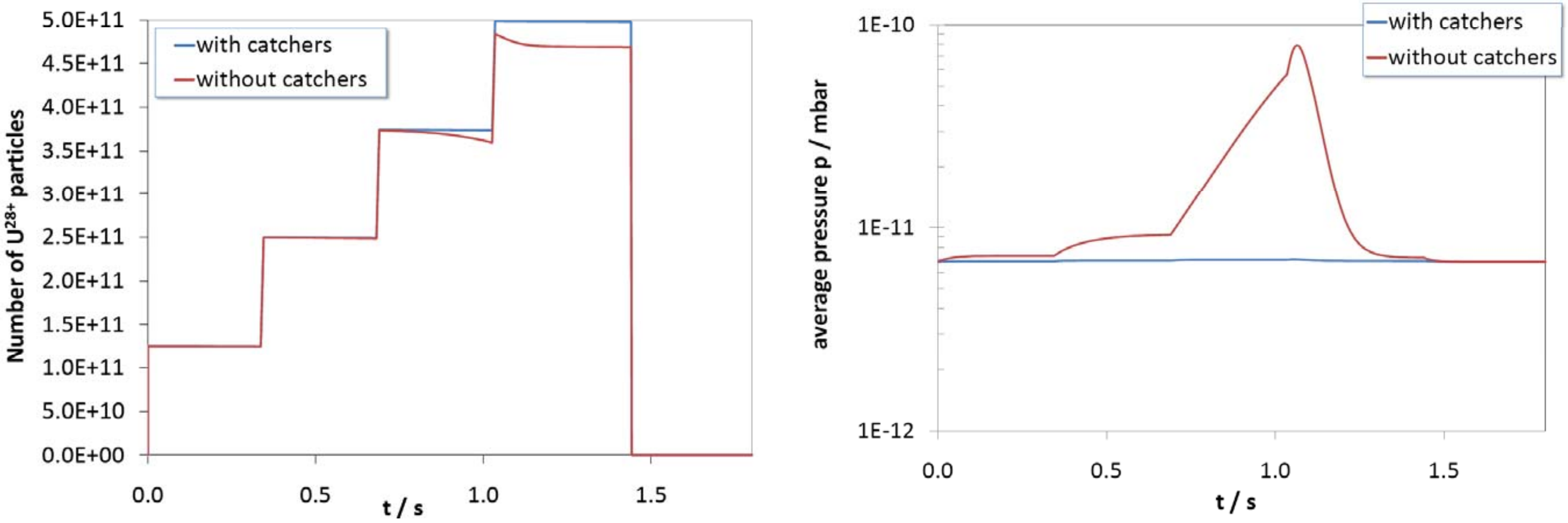




If physics of simulation is OK:

- Everything looks nice and quite relaxed (huge pumping speed of cryogenic surfaces pumps away ‘everything’)
- Losses < 0.4 % (1.75*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 days (!), not 1 ½ month
- Losses > 6.42 % ($3.11 \cdot 10^{10}$ particles) and increasing from shot to shot
- Pressure will be very dynamic
- **Collimators are useful** (not talking about other errors)

Simulation remarks

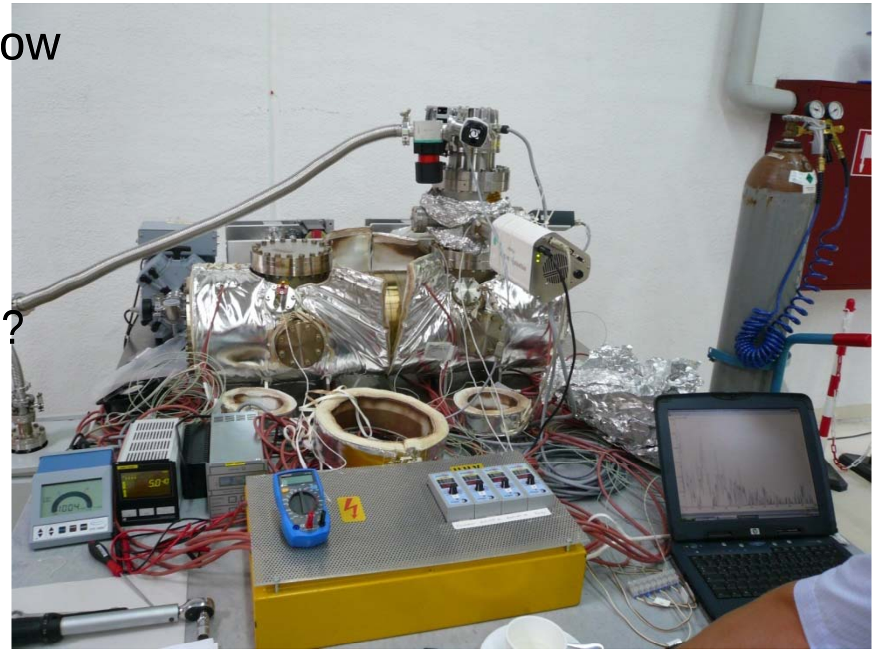
- Desorption rate:
  - Behaviour at high energies quite unknown
  - Cold surfaces will desorb more molecules/ion!
- Pumping speed:
  - Huge, large surface area
  - Temperature: lots of cold-warm transitions
  - Unknown reduction of the sticking factor by changing from cryosorption to physisorption
- Cross sections for charge change:
  - Only theoretical estimates (AP, Shevelko et al.) available at these high energies, error bar at least 30%
- Losses by other effects (resonances, higher order fields, etc.) not included!

Conclusions

- Dynamic vacuum problems
  - Caused by charge change process of low charged ions at low energies
  - Coupled to ion stimulated desorption
  - SIS18:
    - Can be partially solved by a suitable collimator system, UHV, injection and RF systems upgrade
  - SIS100:
    - Losses can be held under control quite well with the collimation system
    - Error bars are large
  - Simulation model does exist
    - Including Coulomb scattering, target ionisation
- Other beam losses remain (esp. at high intensity operation)
  - Resonances, space charge
  - Closed orbit distortions
  - RF bucket size / energy mismatch from LINAC / pre-acc.
  - ...

Outlook

- In preparation
  - Civil construction of two collimator prototypes finished
  - Installation into SIS18 during winter shutdown 2007 (section S02, S03)
  - Measurement campaign Jan/Feb 2008 with U^{28+}
  - If successful, 8 collimators will follow
- Ongoing effort in GSI
  - Materials and desorption (ERDA)
  - Simulation codes
  - Measurements with Au at the AGS?
  - ...

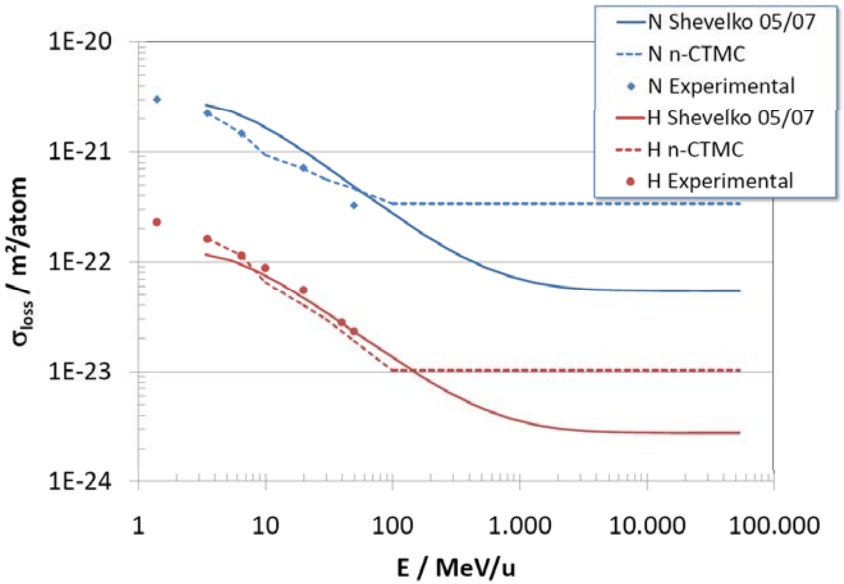


Questions?

Acknowledgements:

- GSI vacuum group
- GSI FSY group

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
    - **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

Charge-exchange process

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

☑ collimation feasible

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

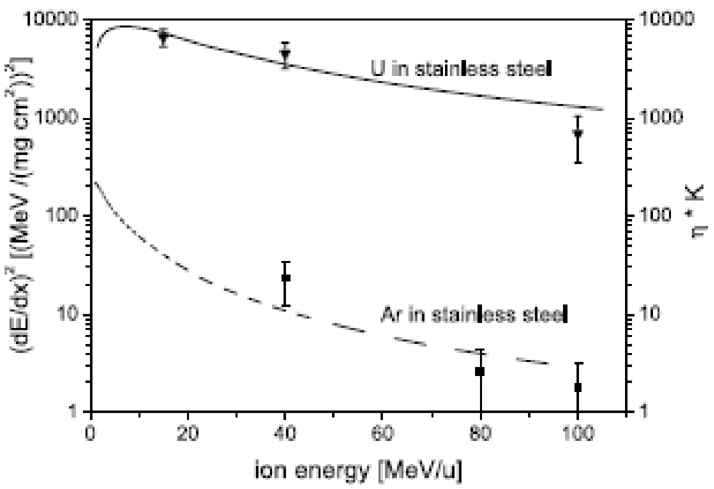
<u>StrahlSim publication:</u>

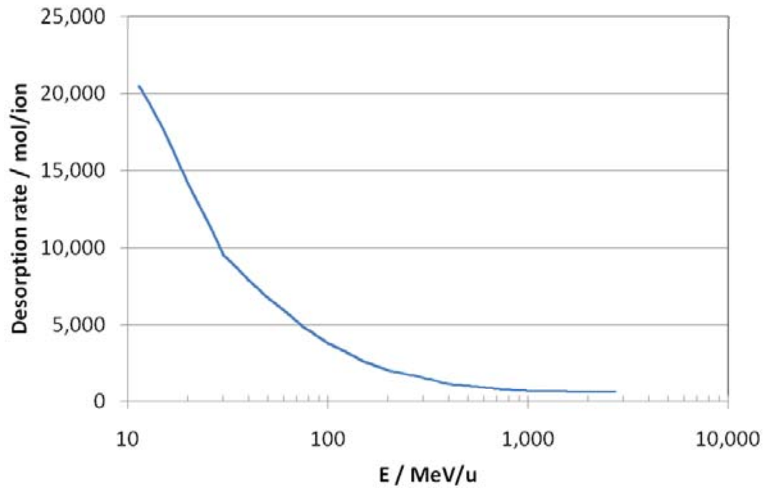
Charge change-induced beam losses under dynamic vacuum conditions in ring accelerators

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

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.





Dynamic Vacuum

- Loss rate of the beam

$$\Gamma_P = \Gamma_{CS}(n_i, \beta) + \Gamma_{PI}(n_i, \beta, E)$$

- Production rate of ionised residual gas

$$\Gamma_T = \Gamma_{TI}(n_i, \beta)$$

- Dynamic vacuum (here shown without collimators)

$$\dot{n}_i = -\dot{N} \cdot \eta_{i,\angle}(E) + \Gamma_T(n_i, \beta) \cdot \eta_{i,\perp} + Q_{i,Outgas} - Q_{i,Pump}(n_i)$$

- Numeric integration, turn by turn

$$\dot{N} = -N \cdot \Gamma_P(n_i, \beta) \qquad \Delta t = t_{rev}$$