Beam Halo Collimation Over Wide Range Charge-to-Mass Ratio

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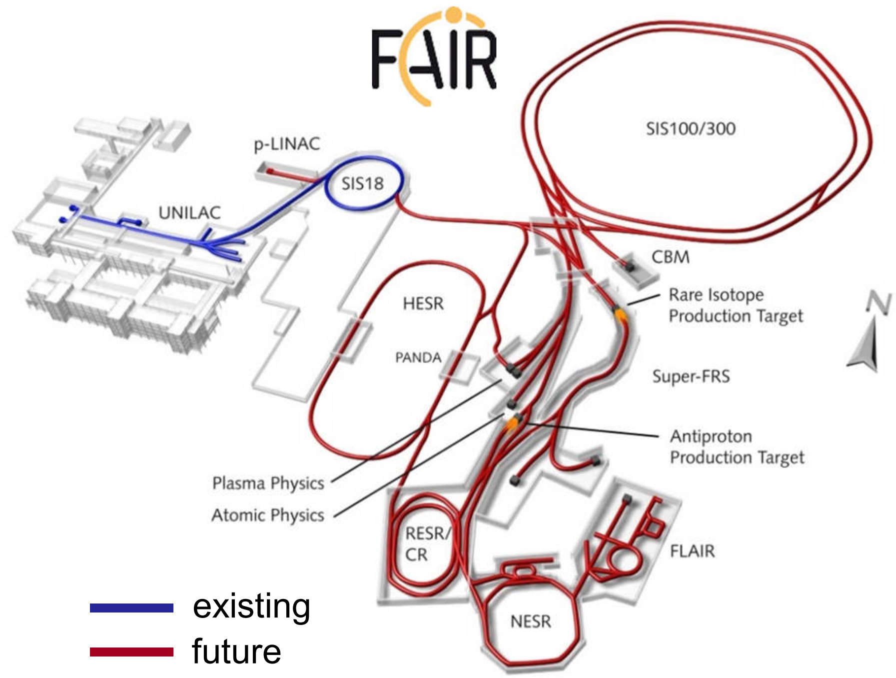
Introduction

- FAIR – Facility for Antiproton and Ion Research at GSI
- Synchrotron SIS100 (fixed target)
  - Lattice
    - circumference ~ 1.1 km
    - hexagonal shape (six superperiods)
    - quadrupole doublet structure (superconducting)
  - Beams
    - proton (antiproton production)
    - fully stripped ions (e.g.: ${}^{238}_{92}U^{92+}$, ${}^{40}_{18}Ar^{18+}$)
    - partially stripped ions (e.g.: ${}^{238}_{92}U^{28+}$, ${}^{40}_{18}Ar^{10+}$)



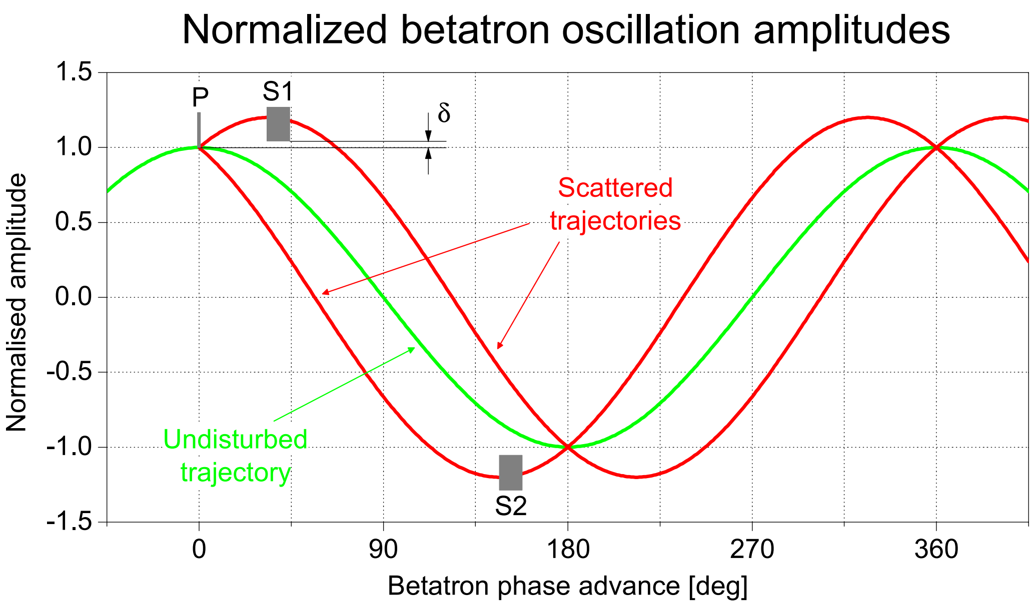
- Reference beams parameters

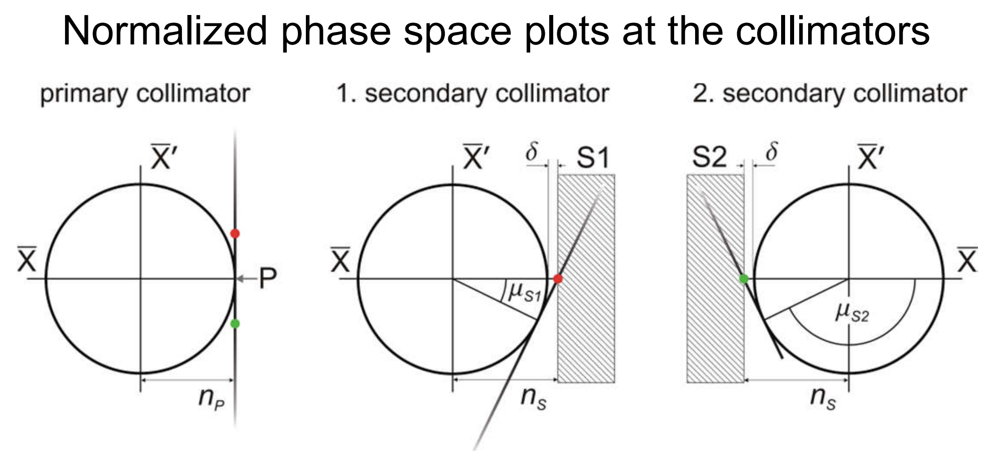
$B\rho$ = 18 - 100 Tm

Beam	Energy range	Beam intensity / cycle
protons	4 - 29 GeV	2×10^{13}
${}^{238}_{92}U^{92+}$	1.3 – 10 GeV/u	1.5×10^{10}
${}^{238}_{92}U^{28+}$	0.2 – 2.7 GeV/u	4×10^{11}

Two stage collimation system

- Intended for proton and fully stripped ion collimation in SIS100
- Primary collimator (thin foil) – scattering of the halo particles
- Secondary collimators (bulky blocks) – absorption of the scattered particles





$$\mu_{S1} = \arccos\frac{n_P}{n_S}$$

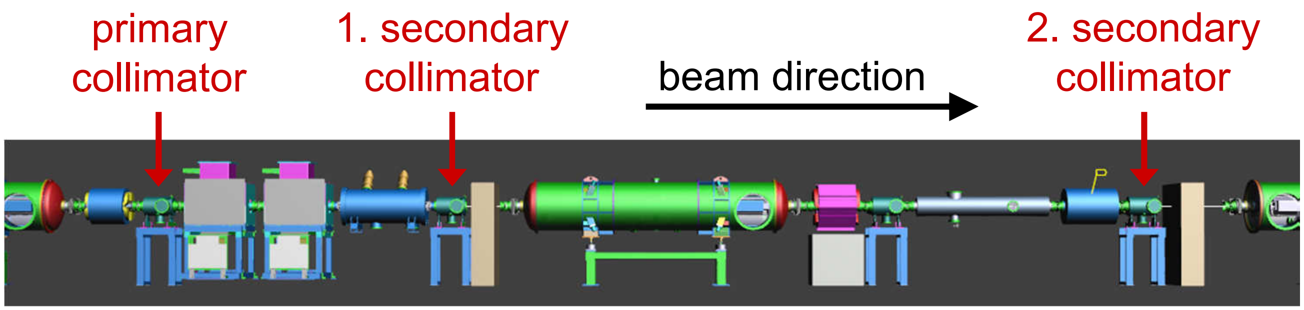
$$\mu_{S2} = \pi - \mu_{S1}$$

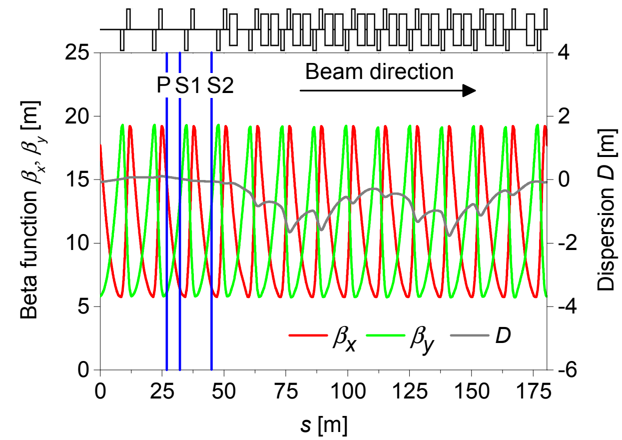
[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998).
[Ref] M. Seidel, DESY Report (Dissertation), 94-103, (1994).

- Very robust concept applied in many machines
- Singlepass and multipass collimation efficiency

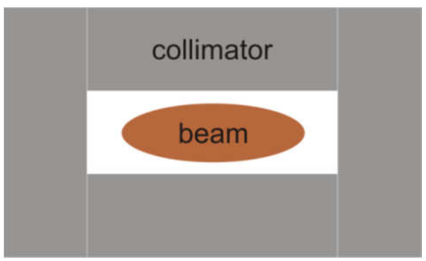
Parameters of the collimation system in SIS100

- Halo collimation system





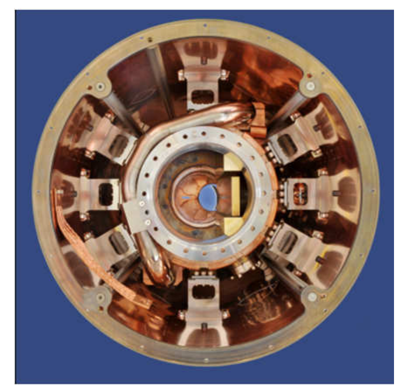
rectangular aperture



Collimator stage	primary collimator	secondary collimators
Material	tungsten	tungsten
Thickness	1 mm	40 cm
Transverse position	~ 4.5 σ	~ 5 σ

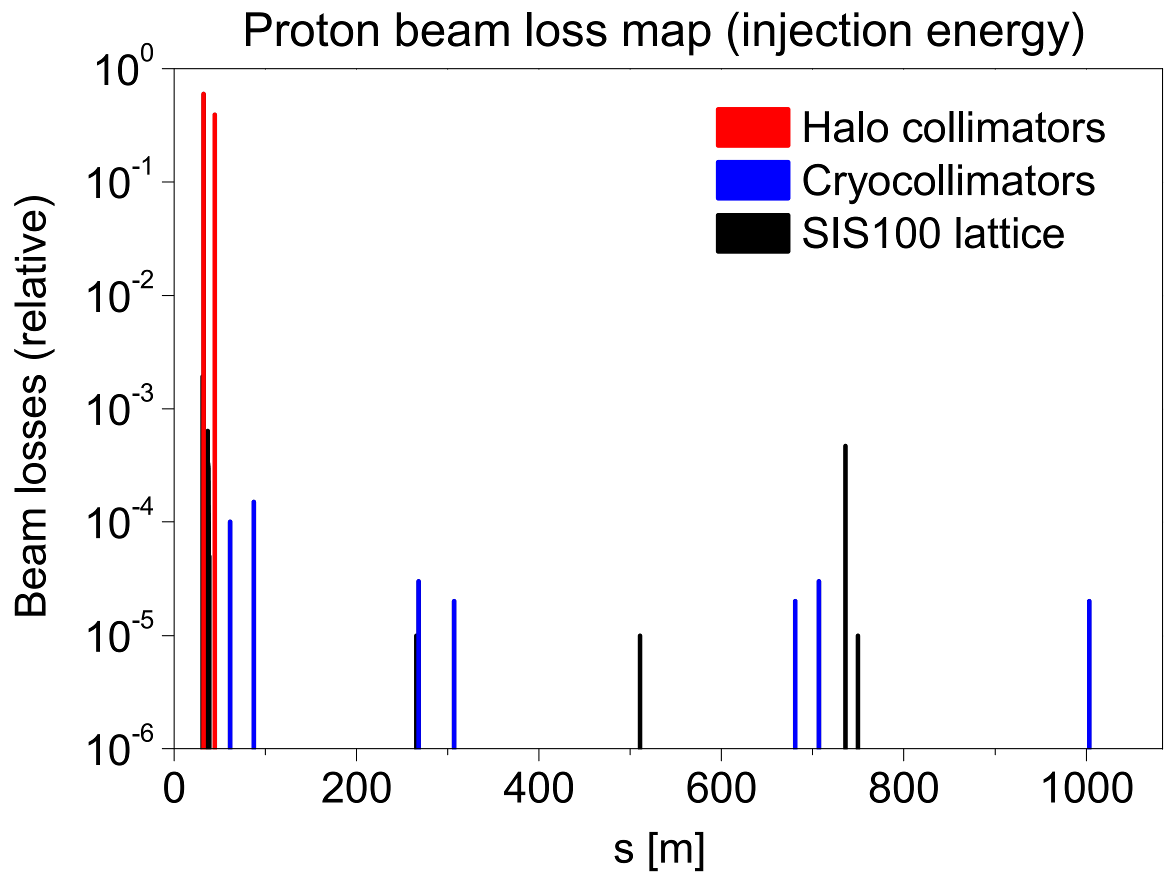
- Cryocollimators
  - Combined collimation and pumping system, in total 60 cryocollimators in SIS100
  - Interaction of the partially stripped ions with residual gas, $U^{28+} \rightarrow U^{29+}$
  - Minimize desorption of the molecules and prevent vacuum degradation

[Ref] L. Bozyk et al., IPAC'12, USA


cryocollimator prototype

Simulation of the proton collimation in SIS100

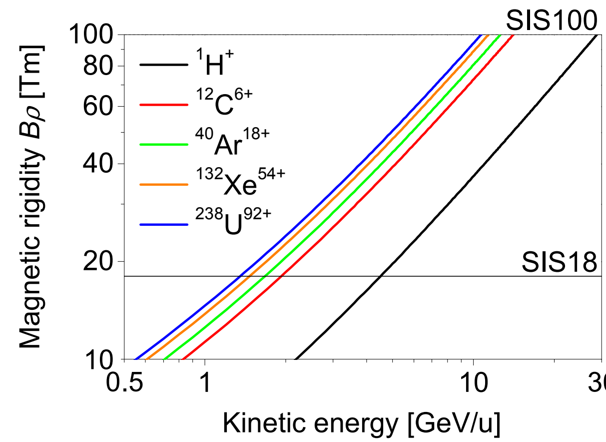
- Simulation tools used for the collimation design studies
  - Beam – material interaction: FLUKA code
  - Particle tracking through the lattice: MAD-X code
  - Statistics: 10^5 primary particles



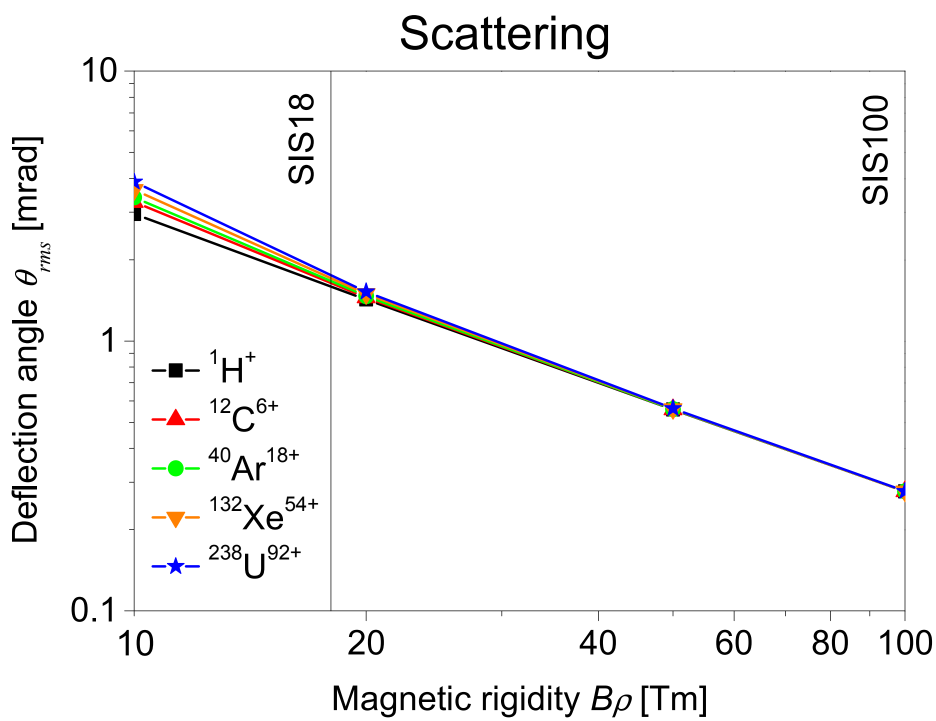
- Multipass collimation efficiency
  - 4 GeV (injection) – 29 GeV (extraction): eff. ≥ 99 %

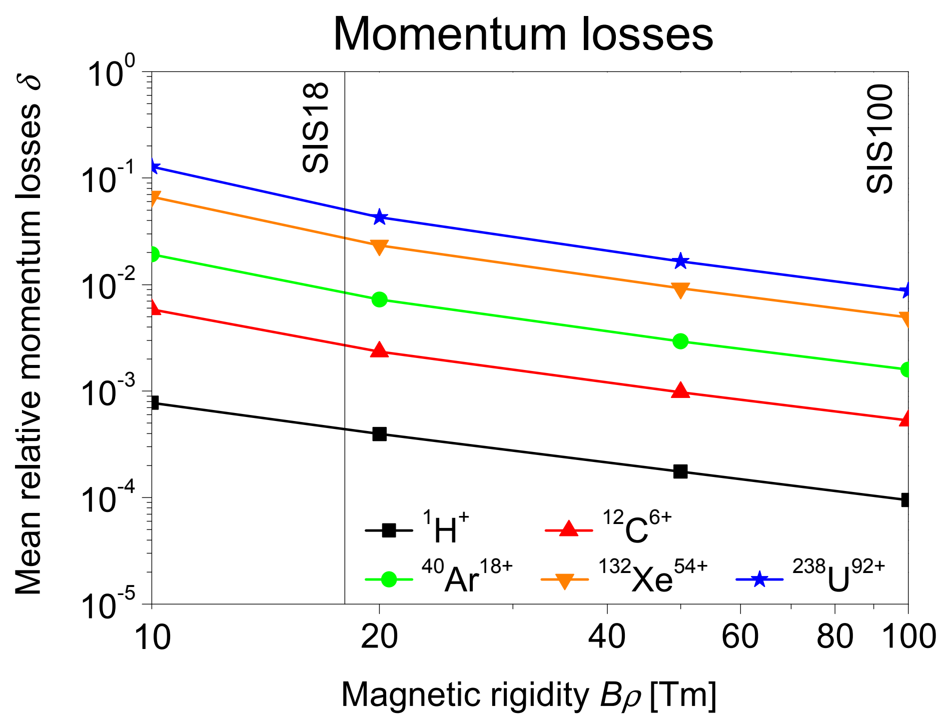
Interaction of ions with the primary collimator

- The same collimation system for protons and fully stripped ions in SIS100



- Interaction of the fully stripped ions with the primary collimator - FLUKA code

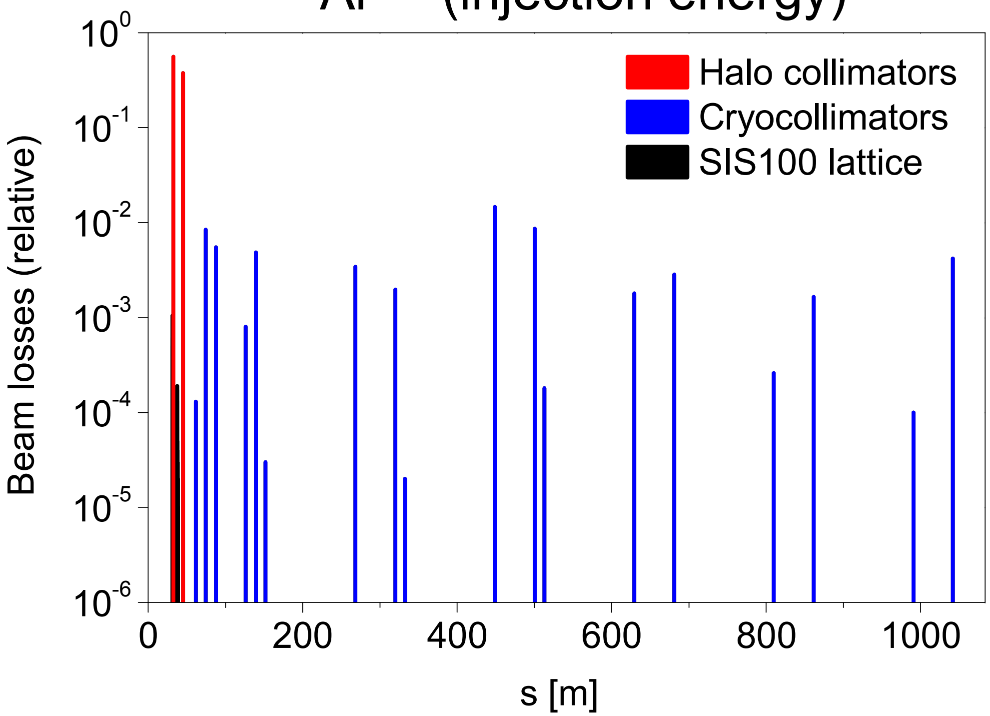




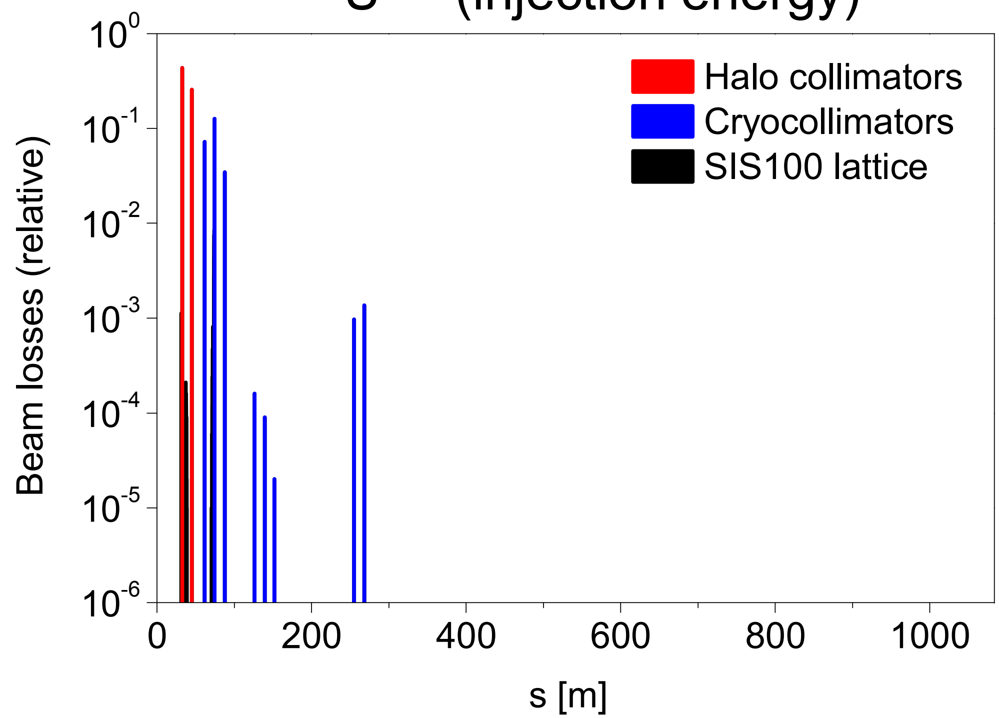
Beam loss maps of the fully stripped ion beams

- Simulation tools
  - Beam – material interaction: FLUKA code
  - Particle tracking through the lattice: MAD-X code
  - Statistics: 10^5 primary particles

$^{40}Ar^{18+}$ (injection energy)



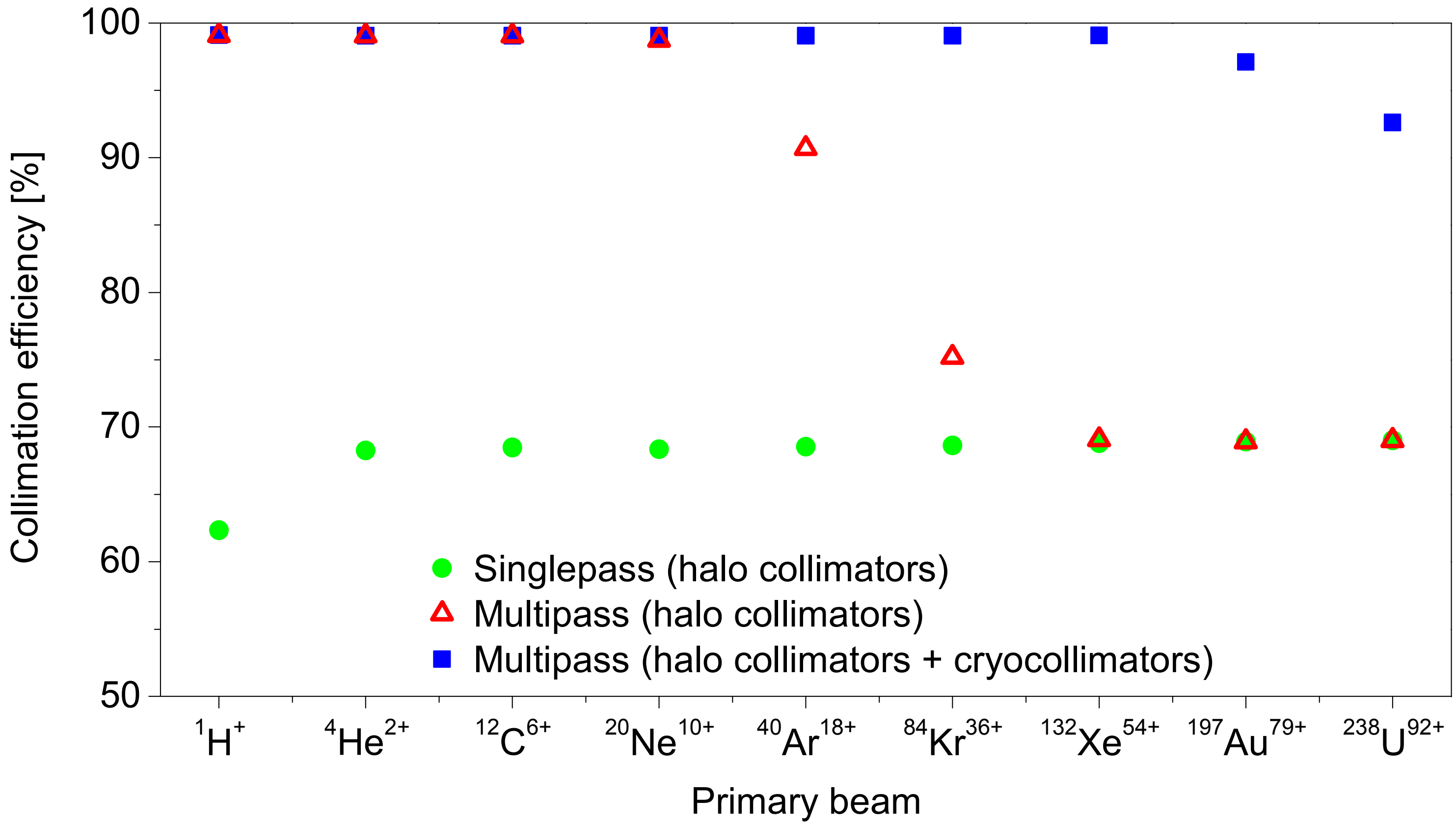
$^{238}U^{92+}$ (injection energy)



- Beam loss maps include only primary ions (secondary fragments are excluded)

Collimation efficiency of the fully stripped ions

- Collimation efficiency of the fully stripped ions in SIS100 from proton up to uranium
- Decrease of the multipass efficiency starting from $^{40}Ar^{18+}$ is due to high momentum losses of heavy ions in the primary collimator.
- The multipass efficiency is significantly improved with the help of the cryocollimators

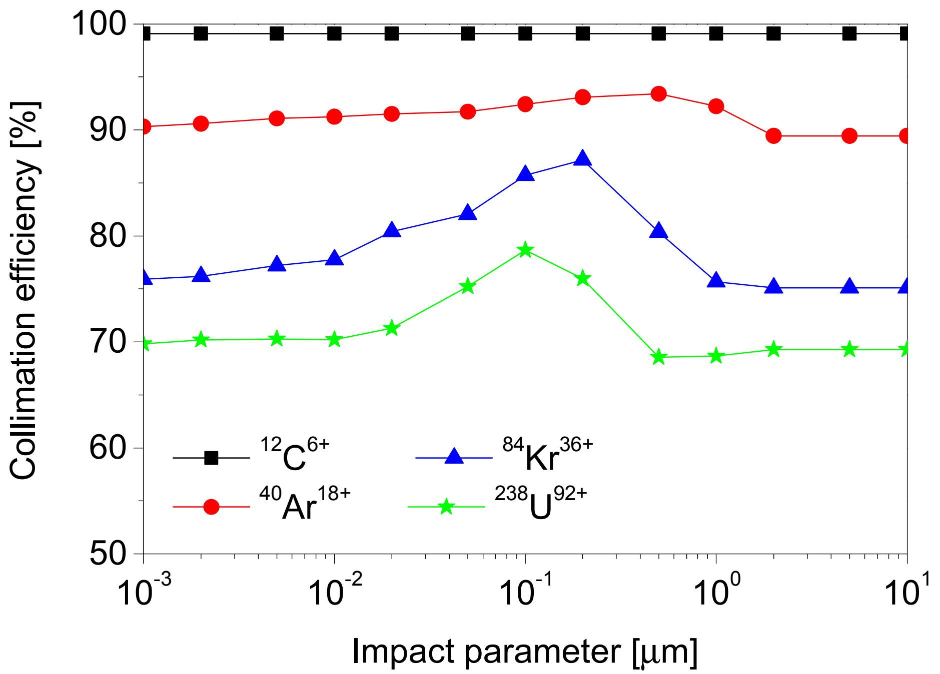


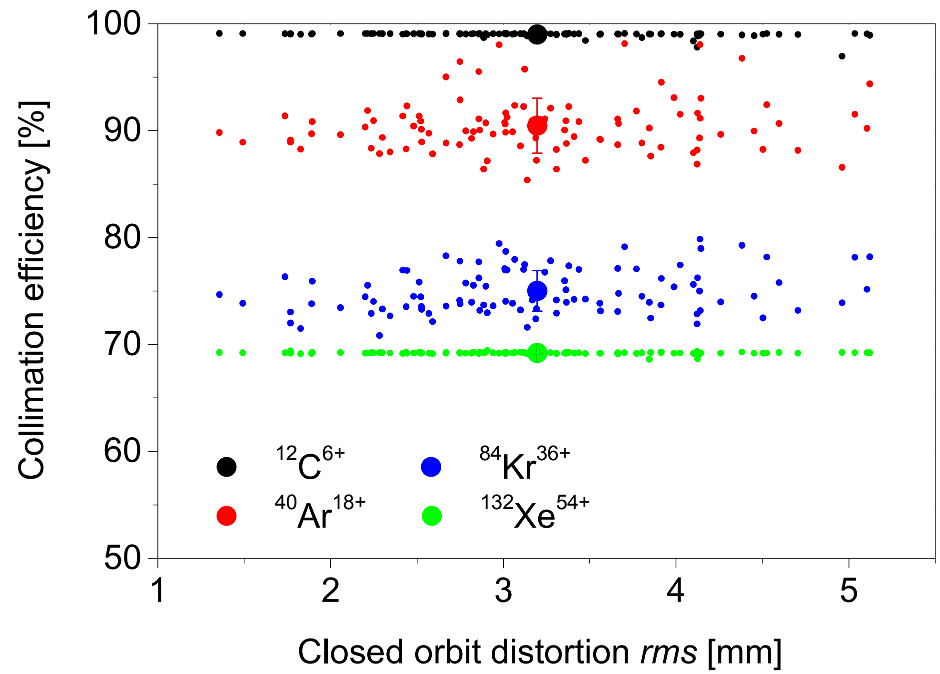
- Again only primary ions are included (without secondary fragments)

Imperfections and lattice errors

- Impact parameter on the primary collimator is affected by the halo diffusion speed
  - Range of the calculated impact parameters: $10^{-3} – 10^{1}$ μm
- Closed orbit distortion due to misalignment of the magnets and field errors
  - Number of error seeds: ~100 (for each beam particle)
  - Misalignment of the magnets: 1 mm (rms)
  - Corrected COD in SIS100: ~1.6 mm

G. Franchetti, I. Hofmann, S. Sorge, and V. Kapin, PAC09

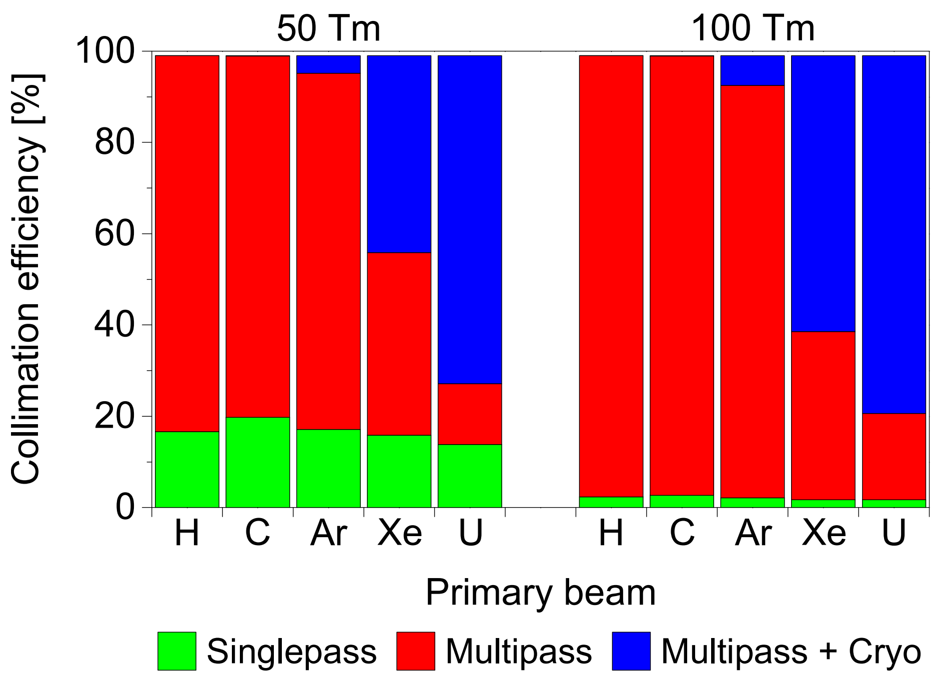




Beam energies and momentum spread

- Collimation efficiency was calculated also for the intermediate beam energies ($B\rho$ = 50 Tm) and for the extraction energies ($B\rho$ = 100 Tm)
- Higher energies → smaller scattering angles and relative momentum losses

$\delta = -dp/p$



- Momentum spread
  - Three values of dp/p = 1×10^{-3}, 3×10^{-3}, and 5×10^{-3} (Gaussian distribution truncated at ±2σ)
  - Almost no effect of the considered momentum spread values on the calculated collimation efficiency was observed

Inelastic nuclear interaction

- Two main interaction processes
  - Hadronic fragmentation or fission (through strong nuclear force)

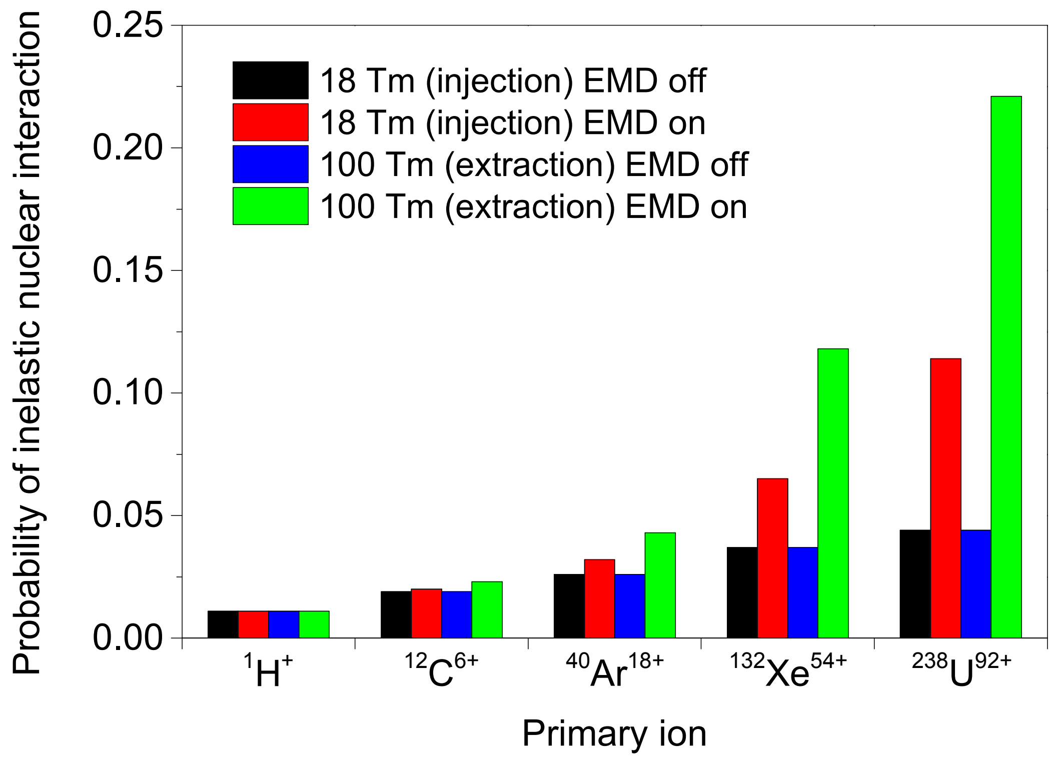
$$ {}^{a}_{b}X \rightarrow {}^{c}_{d}Y + {}^{e}_{f}Z + n + n + n + p + p + \dots $$

  - Electromagnetic dissociation (EMD) (through electromagnetic force)

$$ {}^{a}_{b}X \rightarrow {}^{a-1}_{b}X + n \qquad \left(\text{e.g. } {}^{238}_{92}U \rightarrow {}^{237}_{92}U + n\right) $$

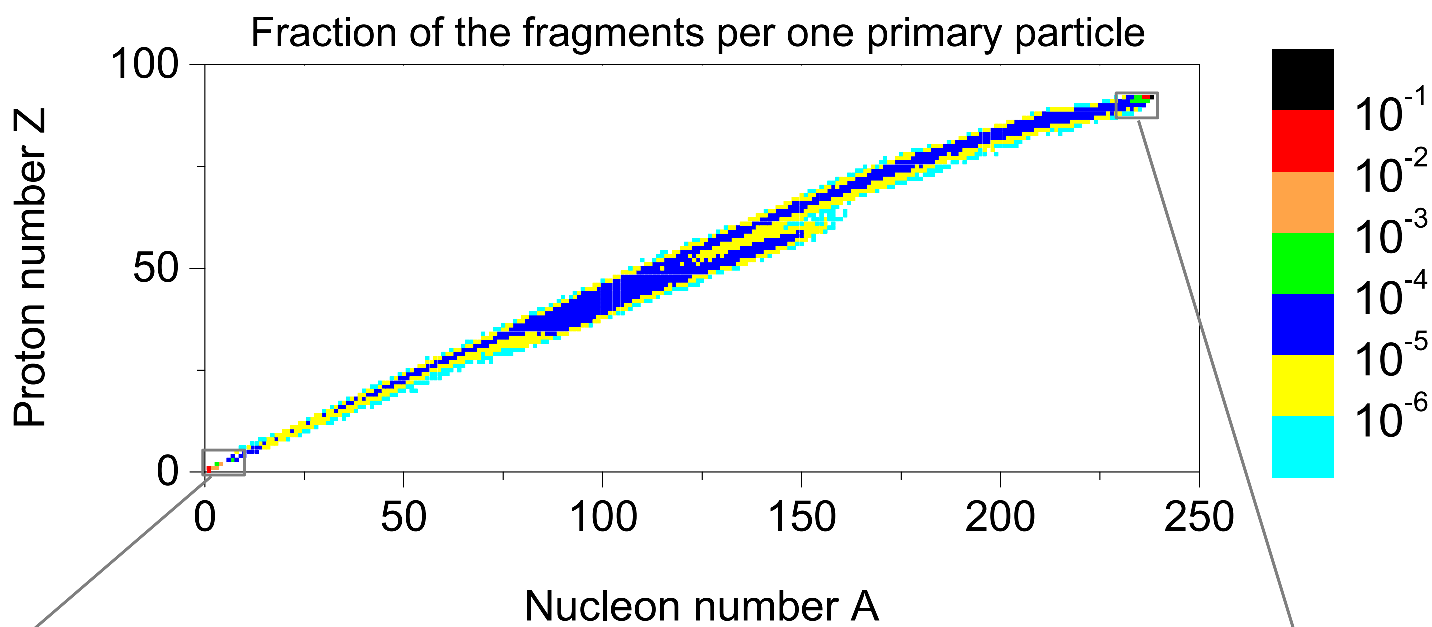
H. H. Braun et al., Phys. Rev. ST AB 17, 021006 (2014)

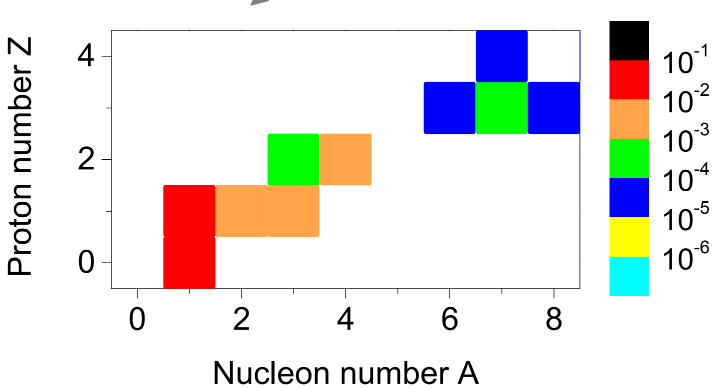
FLUKA simulation

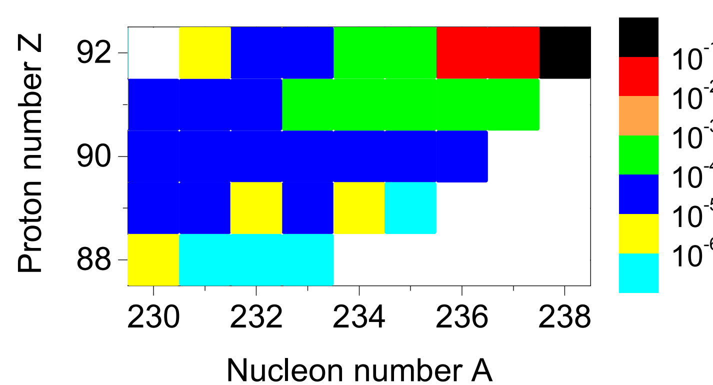


Products of the ^{238}U inelastic nuclear interaction

- FLUKA simulation, 10^7 primary particles
- The values are normalized by A/238

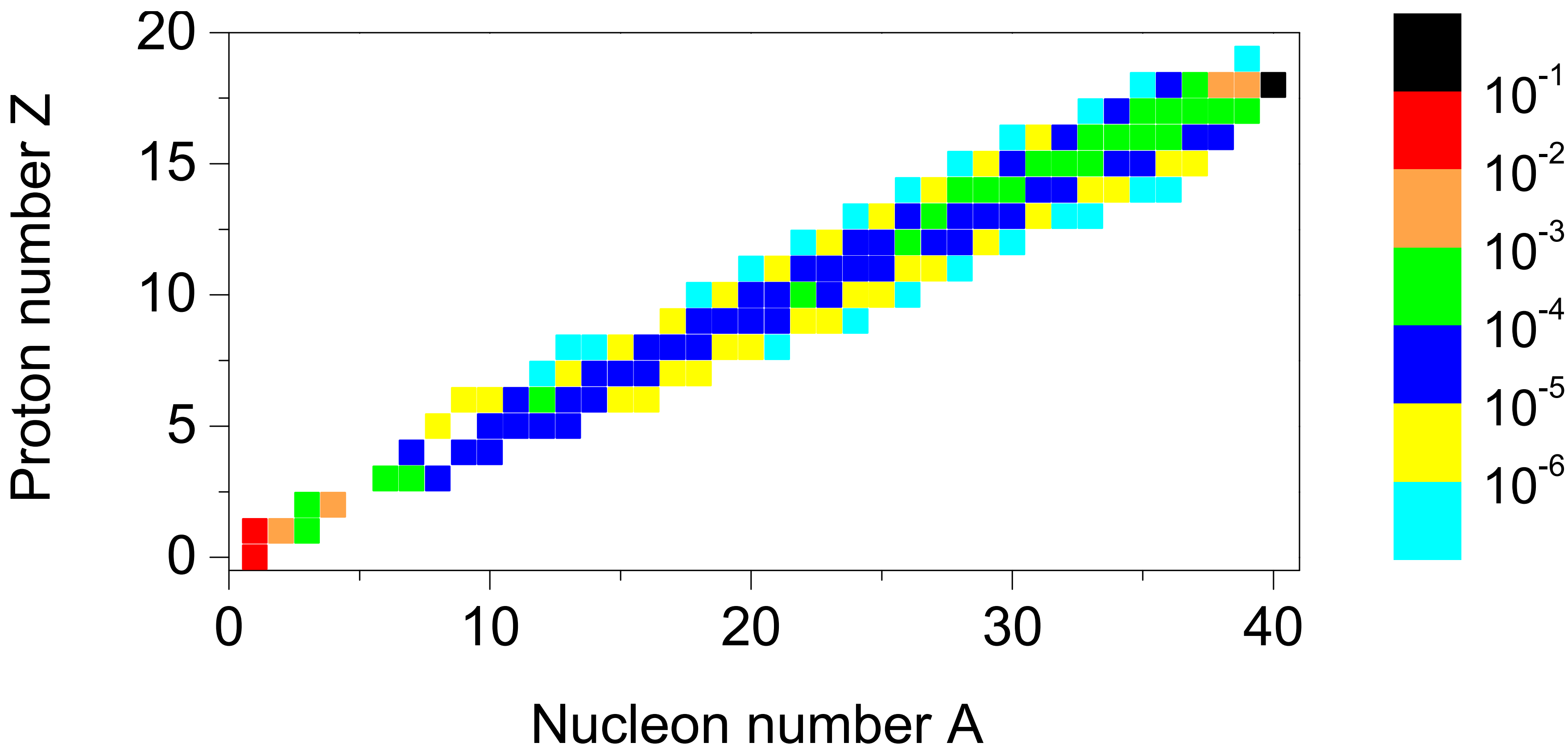






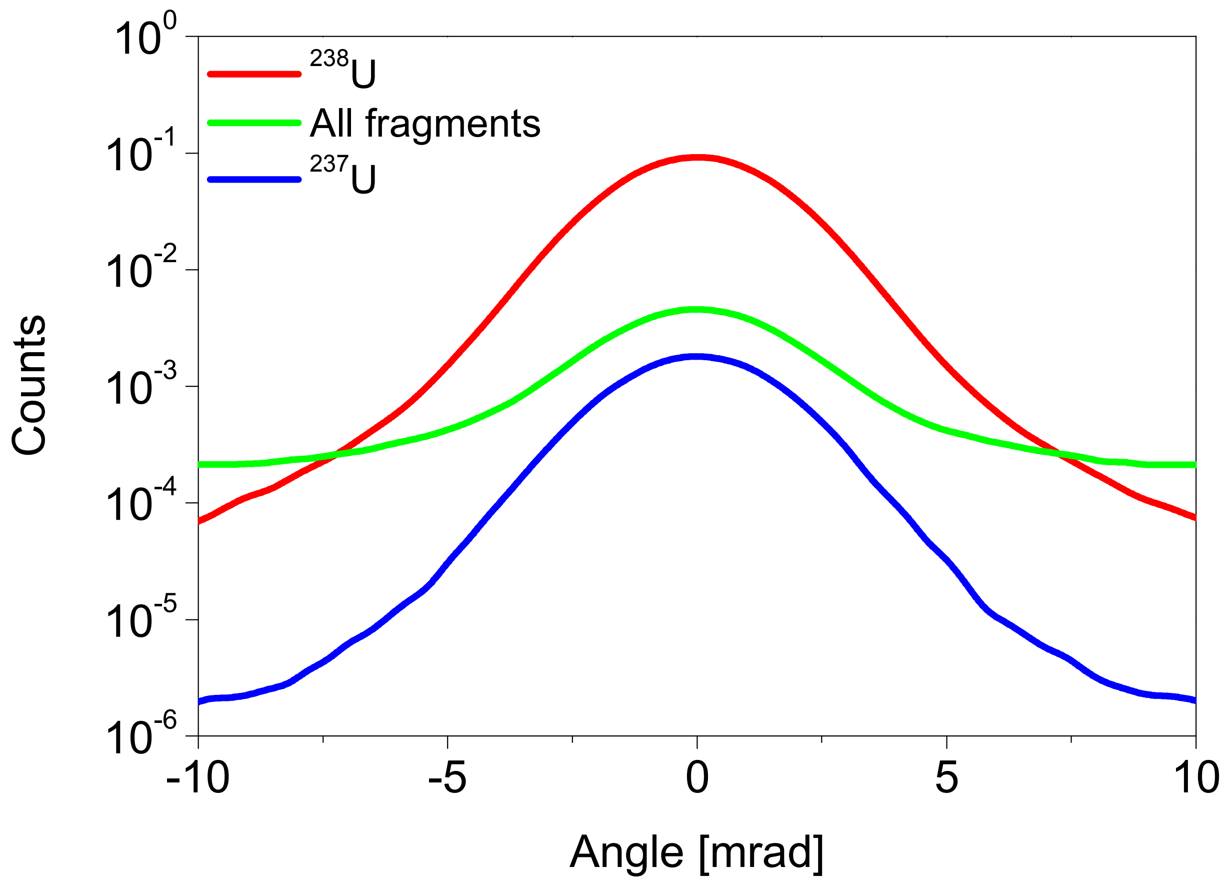
Products of the ^{40}Ar inelastic nuclear interaction

- FLUKA simulation, 10^8 primary particles
- The values are normalized by A/40
- Cross section of the EMD is significantly lower than in case of ^{238}U



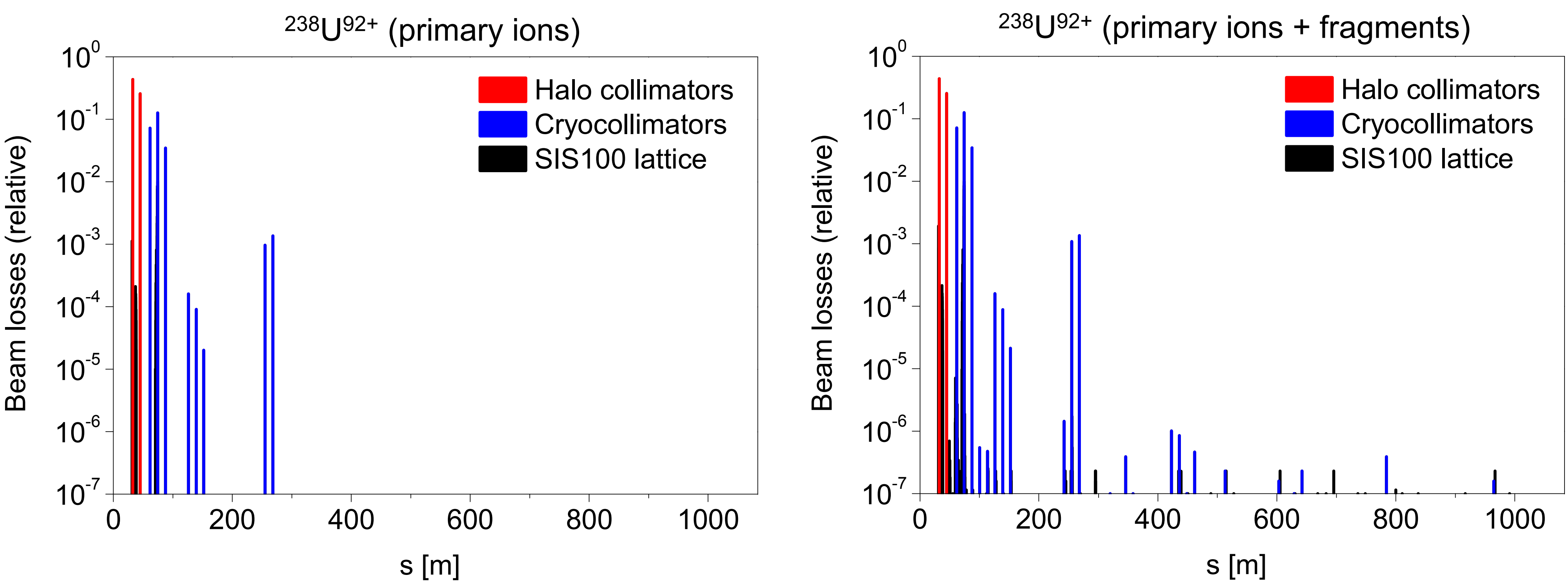
Angular distribution of the ^{238}U fragments

- FLUKA simulation, 10^7 primary particles
- Momenta of the fragments per nucleon are very similar
- Standard deviation of the angular distribution is for the fragments higher than for the primary particles (except the very heavy EMD products e.g., ^{237}U)



$^{238}U^{92+}$ beam loss distribution including fragments

- Particle tracking performed for the fragments with the abundance $> 10^{-4}$
- Motion of the fragments in the magnetic field differ from the primary ions depending on the changed A/Z ratio
- However, the heavy fragments coming from the EMD process have the magnetic rigidity very close to the rigidity of the primary ions



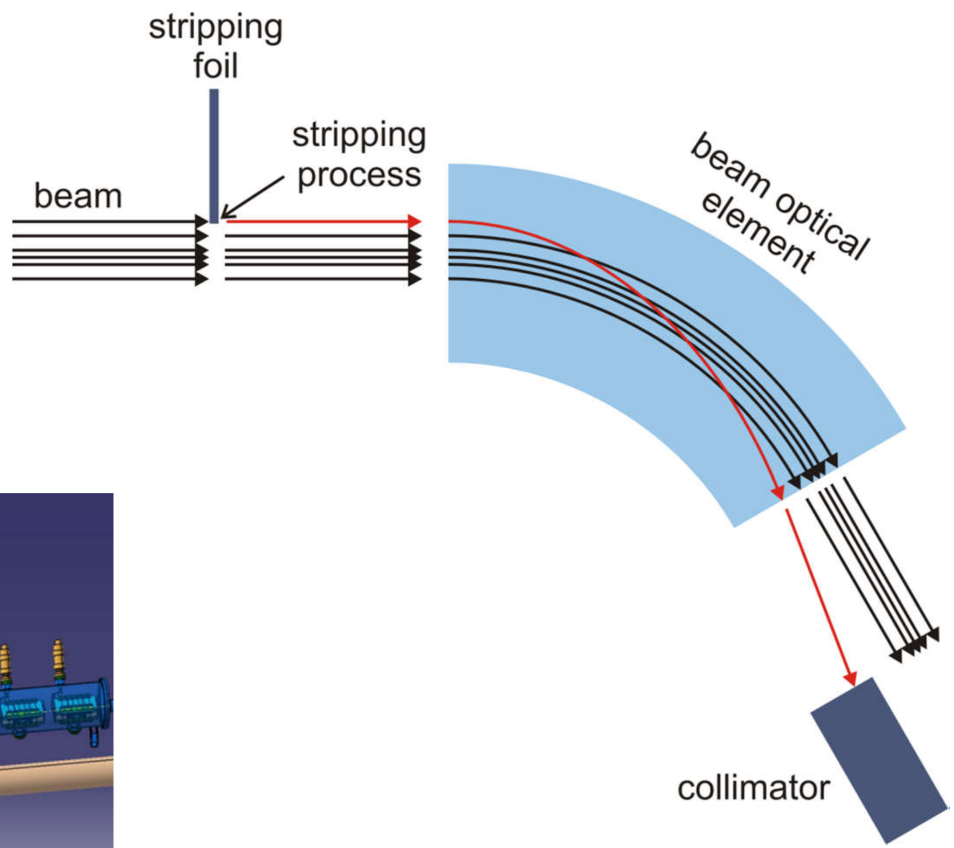
Collimation of the partially stripped ions

- **Intermediate charge-state** ions will be accelerated in SIS100

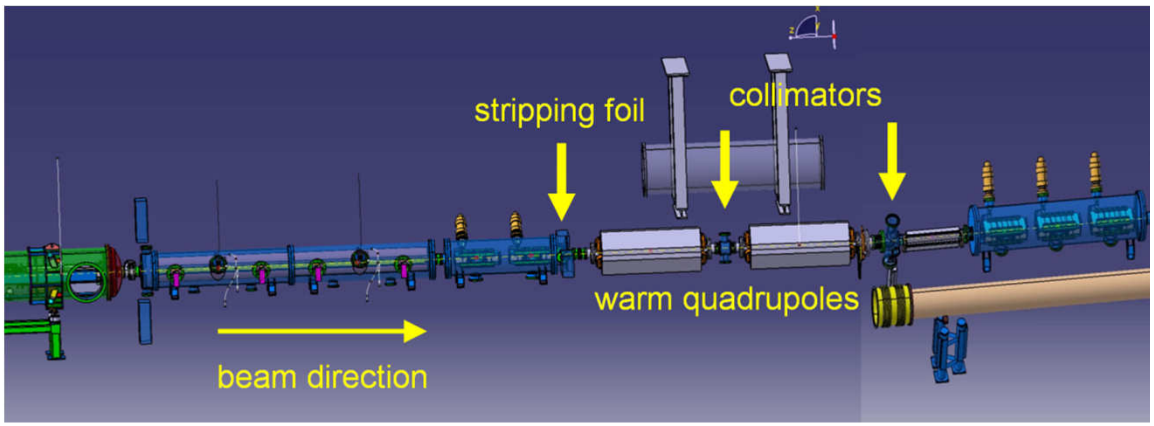
$^{238}_{92}U^{28+}$, $^{197}_{79}Au^{25+}$, $^{181}_{73}Ta^{24+}$, $^{132}_{54}Xe^{22+}$, $^{84}_{36}Kr^{17+}$, $^{20}_{10}Ne^{5+}$

[Ref] FAIR - Baseline Technical Report, GSI Darmstadt, (2006).

- Collimation concept
  - Stripping foil: $^{238}_{92}U^{28+} \rightarrow ^{238}_{92}U^{92+}$
  - Deflection by a beam optical element

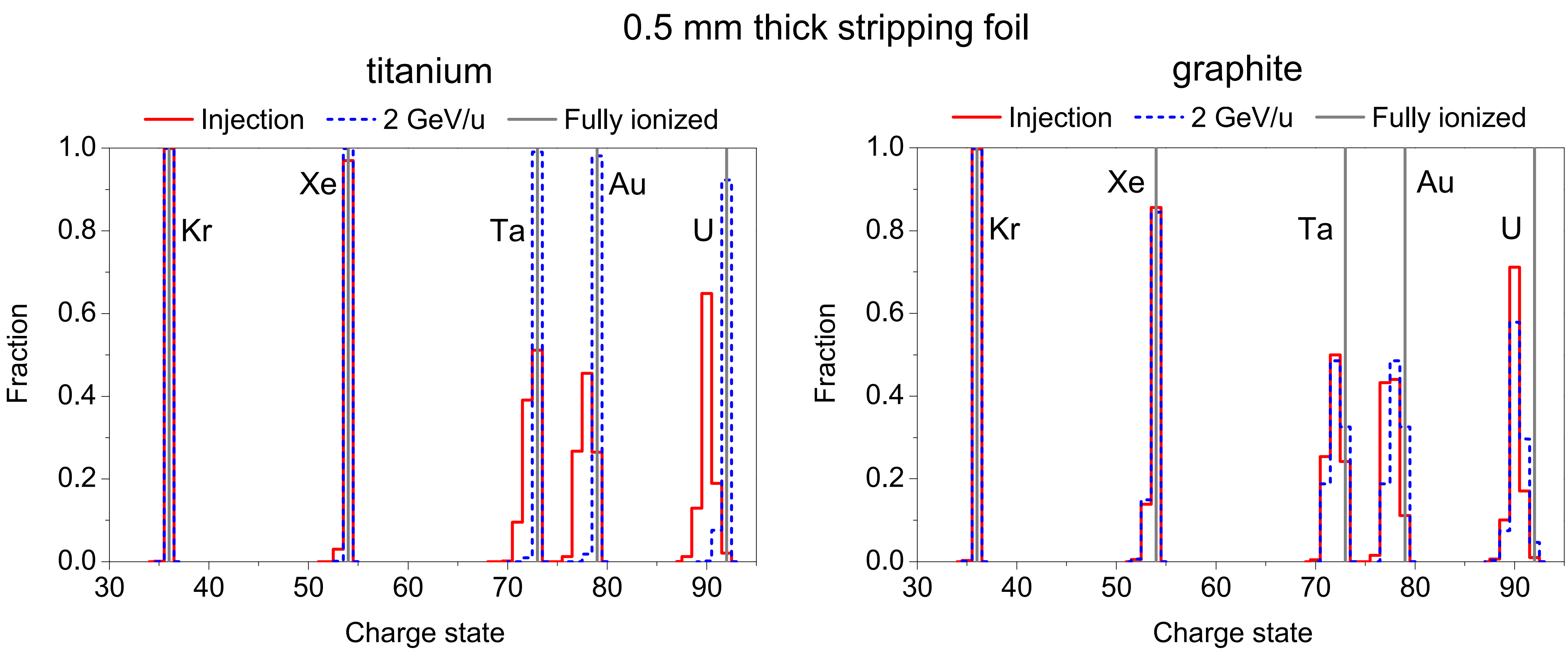


Slow extraction area in SIS100



Charge state distribution after stripping

- ➢ Electron capture and electron loss → equilibrium charge-state distribution
  - code GLOBAL (implemented also in LISE++) *[Ref] C. Scheidenberger et al.,* NIMB *142 (1998) 441*
  - Medium-Z materials (Al – Cu) → suitable for efficient stripping for wide range of primary ions and beam energies (0.5 mm thick titanium foil is optimal for SIS100 beams)
  - Thermomechanical calculation for fast beam losses → titanium can be melted



Particle tracking of the stripped ions

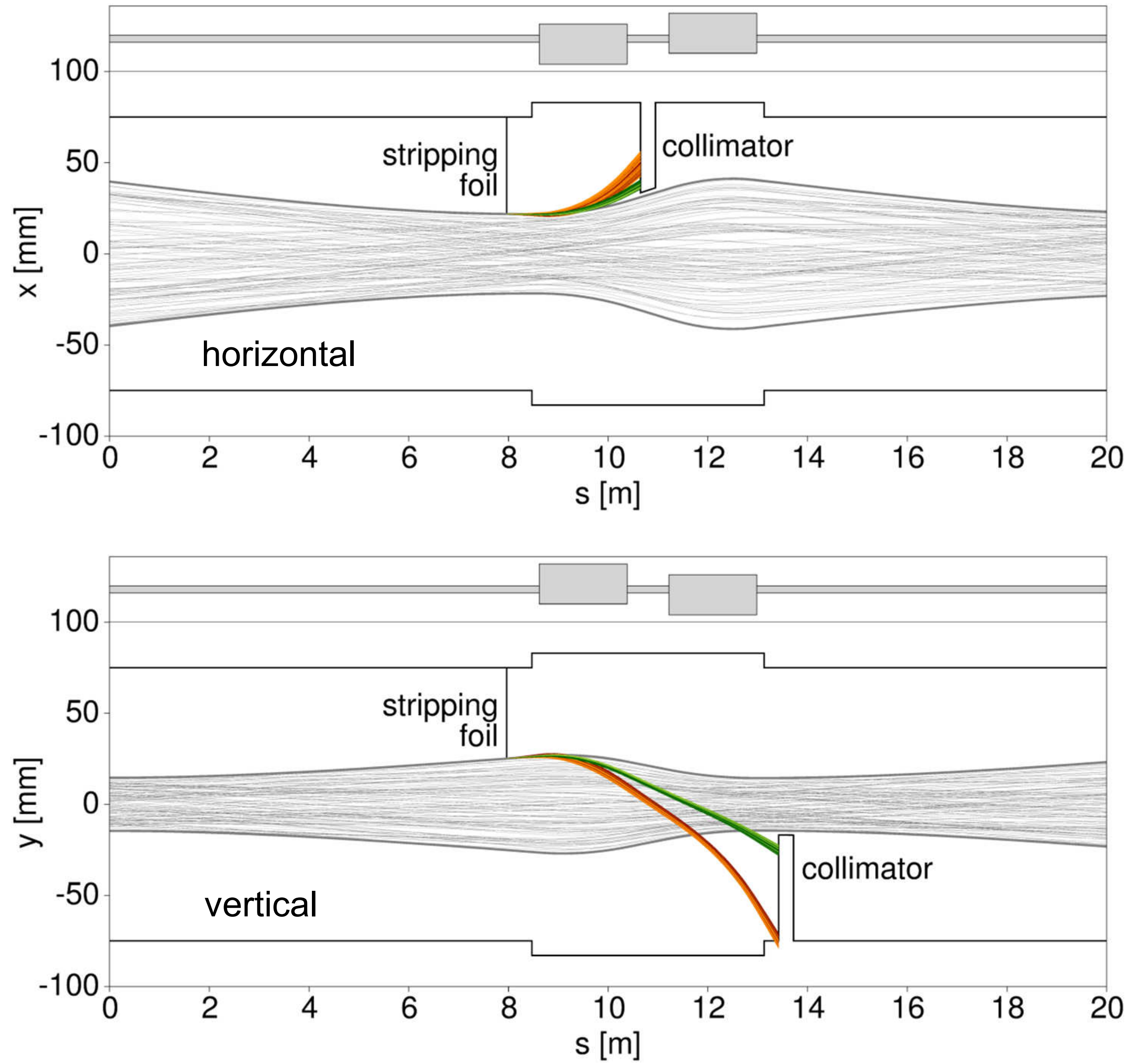
Orange tracks

$^{238}_{92}U^{28+} \rightarrow ^{238}_{92}U^{92+}$

Green tracks

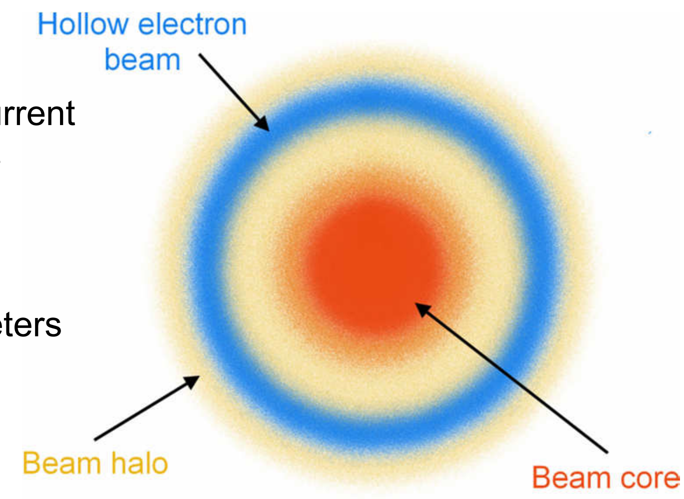
$^{84}_{36}Kr^{17+} \rightarrow ^{84}_{36}Kr^{36+}$

Inelastic nuclear interaction (^{238}U)	
$B\rho$ = 18 Tm	$B\rho$ = 100 Tm
0.015	0.018



Collimation using the hollow electron beam

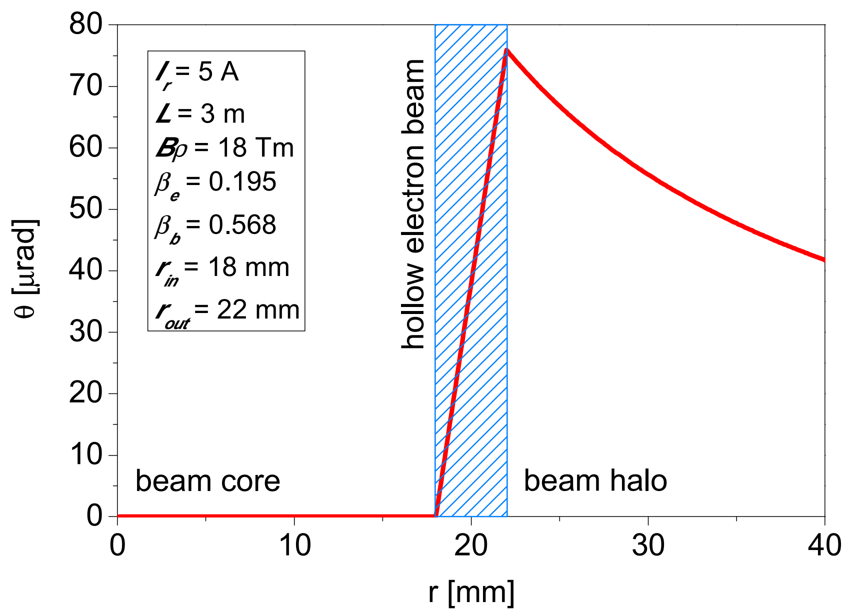
- Based on electromagnetic field generated by the hollow electron beam (HEB)
- Halo particles experience nonlinear transverse kicks



$$\theta_r = \frac{1}{4\pi\varepsilon_0} \times \frac{2I_r L(1 \pm \beta_e \beta_b)}{r\beta_e\beta_p c^2 (B\rho)_b} \begin{cases} 0 & r < r_{in} \\ \dfrac{r - r_{in}}{r_{out} - r_{in}} & r_{in} \le r \le r_{out} \\ \dfrac{r_{out}}{r} & r > r_{out} \end{cases}$$

I_r – enclosed electron current
L – length of the e-lens
r – radial distance
r_{in} – inner radius
r_{out} – outer radius
β_e, β_b – beta rel. parameters
$B\rho$ – magnetic rigidity

[Ref] G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
[Ref] V. Shiltsev, Electron Lenses for Super-Colliders (book), ISBN 978-1-4939-3317-4



- Enhances diffusion speed of the halo particles → larger impact parameter
- Primary stage of the collimation system might be, for the partially stripped ions, replaced by the HEB (range of the 200MeV/u ^{238}U in copper ~ 1.5 mm)

Summary and conclusion

- Various aspects of the halo collimation in heavy ion synchrotron SIS100 were studied
- Two stage collimation system applied on proton and fully stripped ion beams
- Fully stripped ions: the multipass collimation efficiency ≥ 99% from proton up to $^{20}Ne^{10+}$, with the cryocollimators up to $^{132}Xe^{54+}$
- Multipass collimation efficiency of the $^{238}U^{92+}$ is equal to the singlepass one (75%) however with the cryocollimators ≥ 90%
- The collimation of partially stripped ions relies on the change of the charge state using a stripping foil
- The ions can be, after the stripping, effectively deflected by the quadrupole field towards the collimators
- Fragmentation in the primary collimator has no significant effect on the efficiency
- Possible improvements using novel techniques are considered

Thank you for your attention