Collimation Concept for Beam Halo Losses in SIS 100

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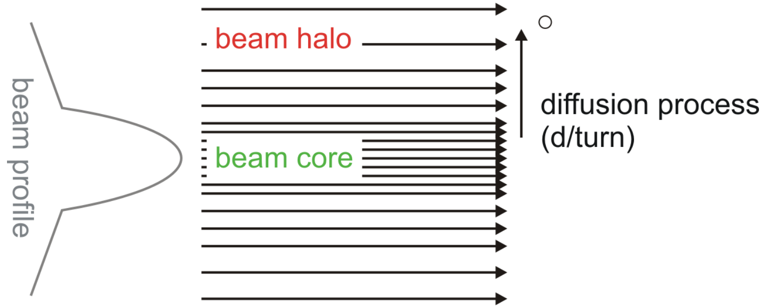
Introduction

- Beam dynamics processes → beam halo formation

  (*sources of the halo: space charge force, mismatched beam, nonlinear forces, RF noise, magnet errors, scattering, resonances, electron clouds...)*

- Beam halo → uncontrolled beam losses



- Beam losses can cause:
  - Superconducting magnets quenches
  - Vacuum degradation due to desorption process
  - Activation of the accelerator structure
  - Radiation damage of the equipment and devices
  - Background in experiments

[Ref] K. Wittenburg, CERN Accelerator School: Course on Beam Diagnostics, 557 (2008).

- Purpose of the halo collimation:
  - To remove the halo → prevent or reduce above mentioned problems
  - To provide a well defined (and shielded) storing location for the beam losses

Halo collimation in SIS 100

- FAIR project at GSI
  - Future SIS100 synchrotron ↔ present SIS18 synchrotron

    beam intensity increase: ~ factor of 100

    beam energy increase: ~ factor of 10

- SIS 100 will accelerate:
  - various ion species from proton up to uranium
  - fully-stripped ions (e.g. ${}^{40}_{18}\mathrm{Ar}^{18+}$)
  - partially-stripped ions (e.g. ${}^{238}_{92}\mathrm{U}^{28+}$)

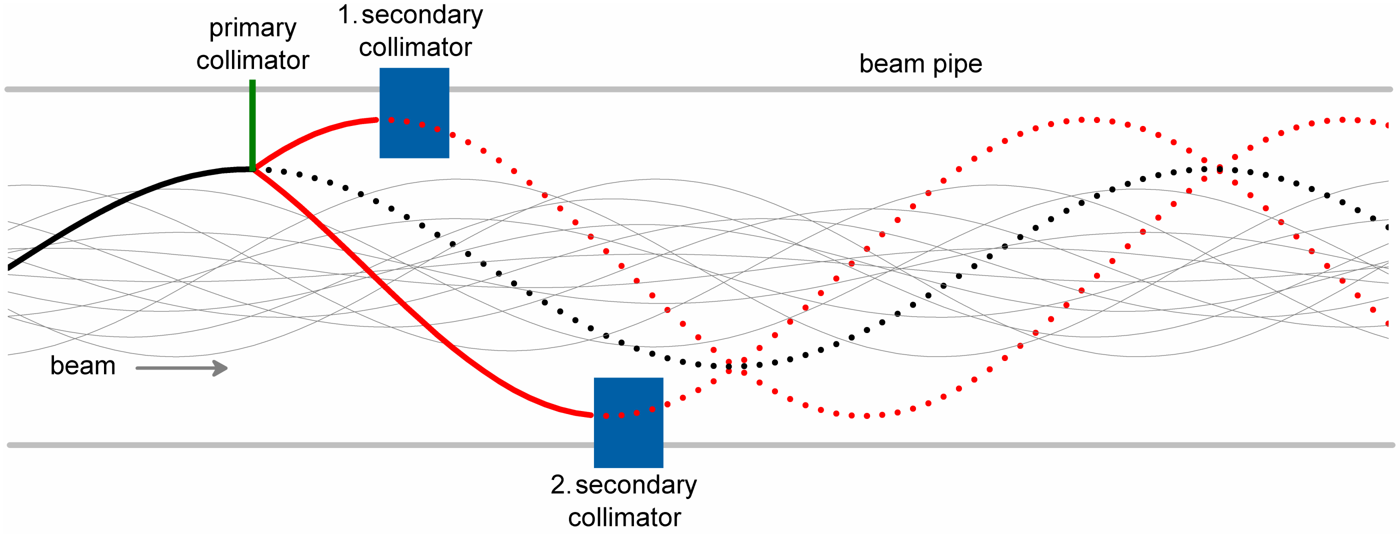
- Need for halo collimation in SIS 100
  - Proton and light ion operation

    residual activation ("hands-on" maintenance limit 1 W/m), quenches
  - Heavy ion operation

    vacuum degradation due to desorption, radiation damage

Two-stage collimation system

- Primary collimator (thin foil) – scattering of the halo particles
- Secondary collimators (bulky blocks) – absorption of the scattered particles



- Particles have small impact parameter on the primary collimator.
- The impact parameter on the secondary collimator is enlarged due to scattering.

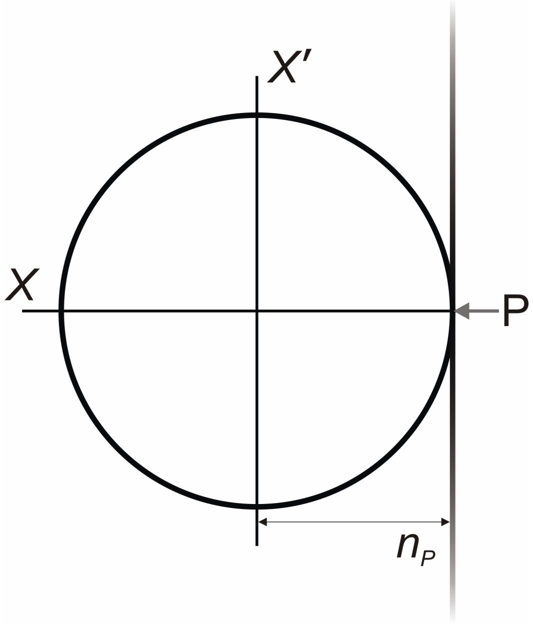
Well established in proton accelerators

[Ref] M. Seidel, DESY Report, 94-103, (1994).
[Ref] T. Trenkler and J.B. Jeanneret, Particle Accelerators 50, 287 (1995).
[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998).
[Ref] K. Yamamoto, Phys. Rev. ST Accel. Beams 11, 123501 (2008).

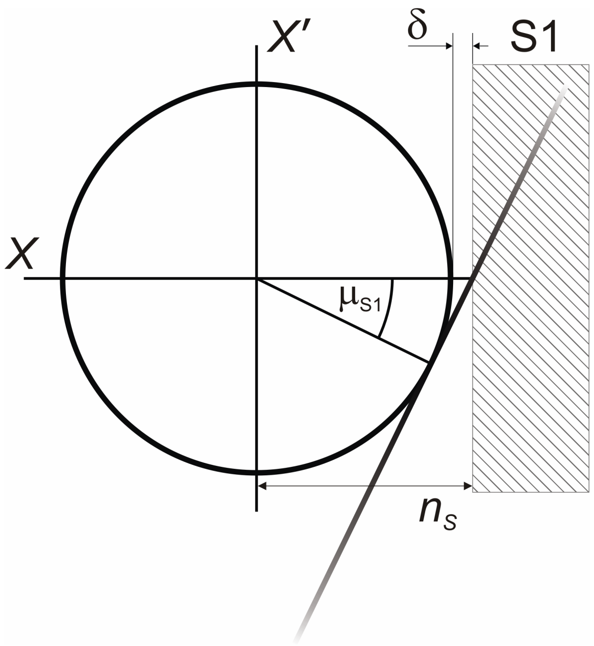
Intended for proton and light ion (fully-stripped) collimation in SIS 100

Normalized phase space plots at the collimators

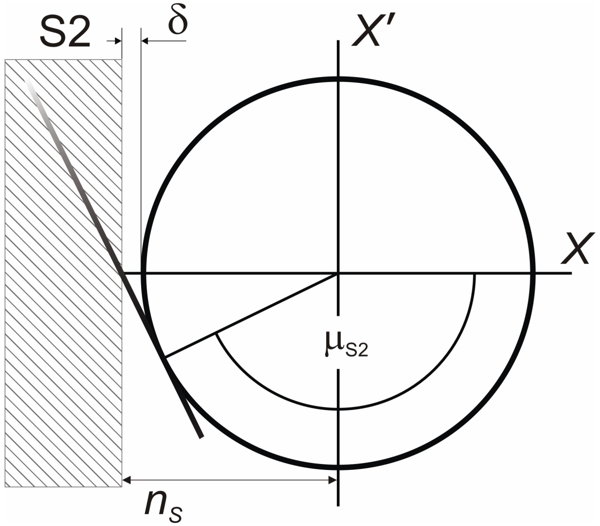
primary collimator



1. secondary collimator



2. secondary collimator



$$\begin{pmatrix} X \\ X' \end{pmatrix} = \frac{1}{\sigma_x} \begin{pmatrix} 1 & 0 \\ \beta_x & \alpha_x \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix} \qquad \sigma_x = \sqrt{\beta_x \varepsilon_x}$$

particle coordinates at the primary collimator

$$X_P = n_P \qquad X'_P = 0$$

particle transport

$$\begin{pmatrix} X_S \\ X'_S \end{pmatrix} = M \begin{pmatrix} X_P \\ X'_P \end{pmatrix}$$

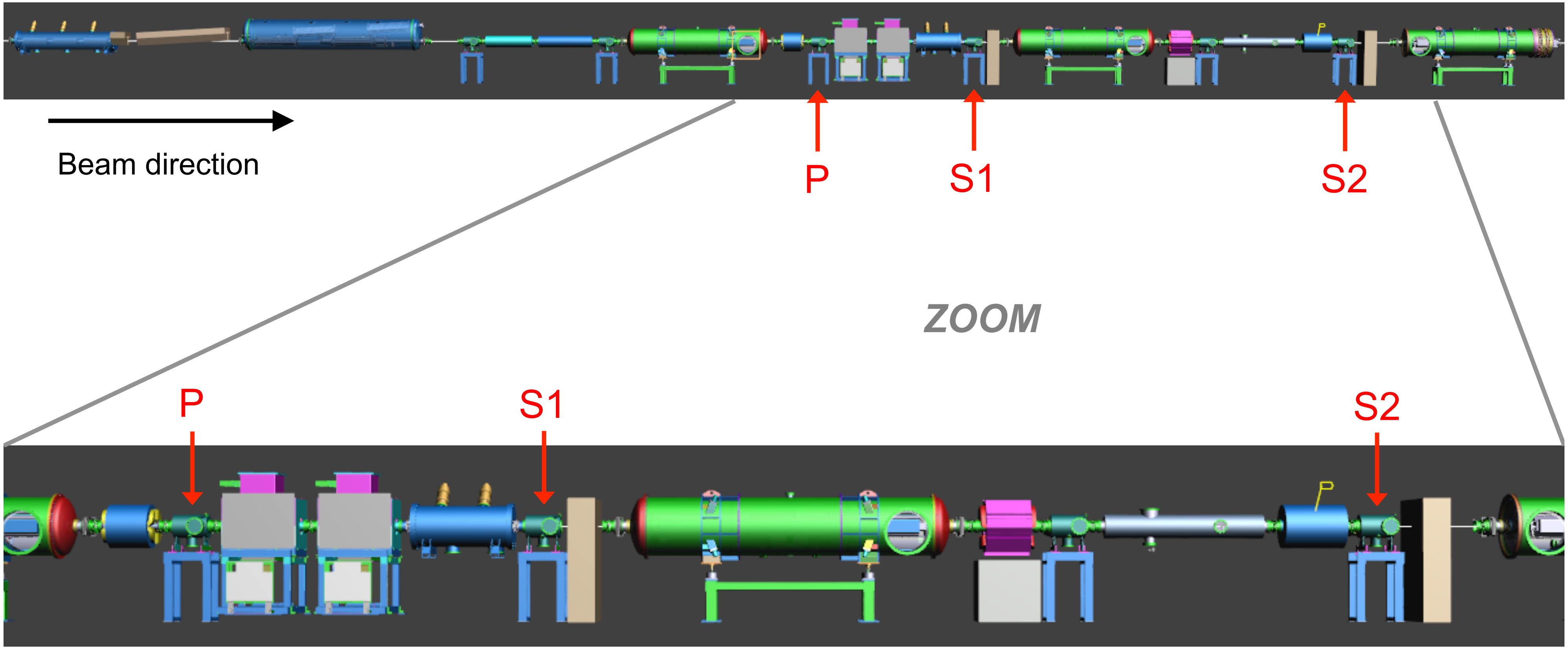
$$\mathrm{M} = \begin{pmatrix} \cos\mu_S & \sin\mu_S \\ -\sin\mu_S & \cos\mu_S \end{pmatrix}$$

[Ref] T. Trenkler and J.B. Jeanneret, Particle Accelerators 50, 287 (1995).
[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998).

Halo collimation of protons in SIS 100

Sector 1, straight (SIS100 → SIS300 transfer)

Position of the halo collimation system for protons and light fully-stripped ions



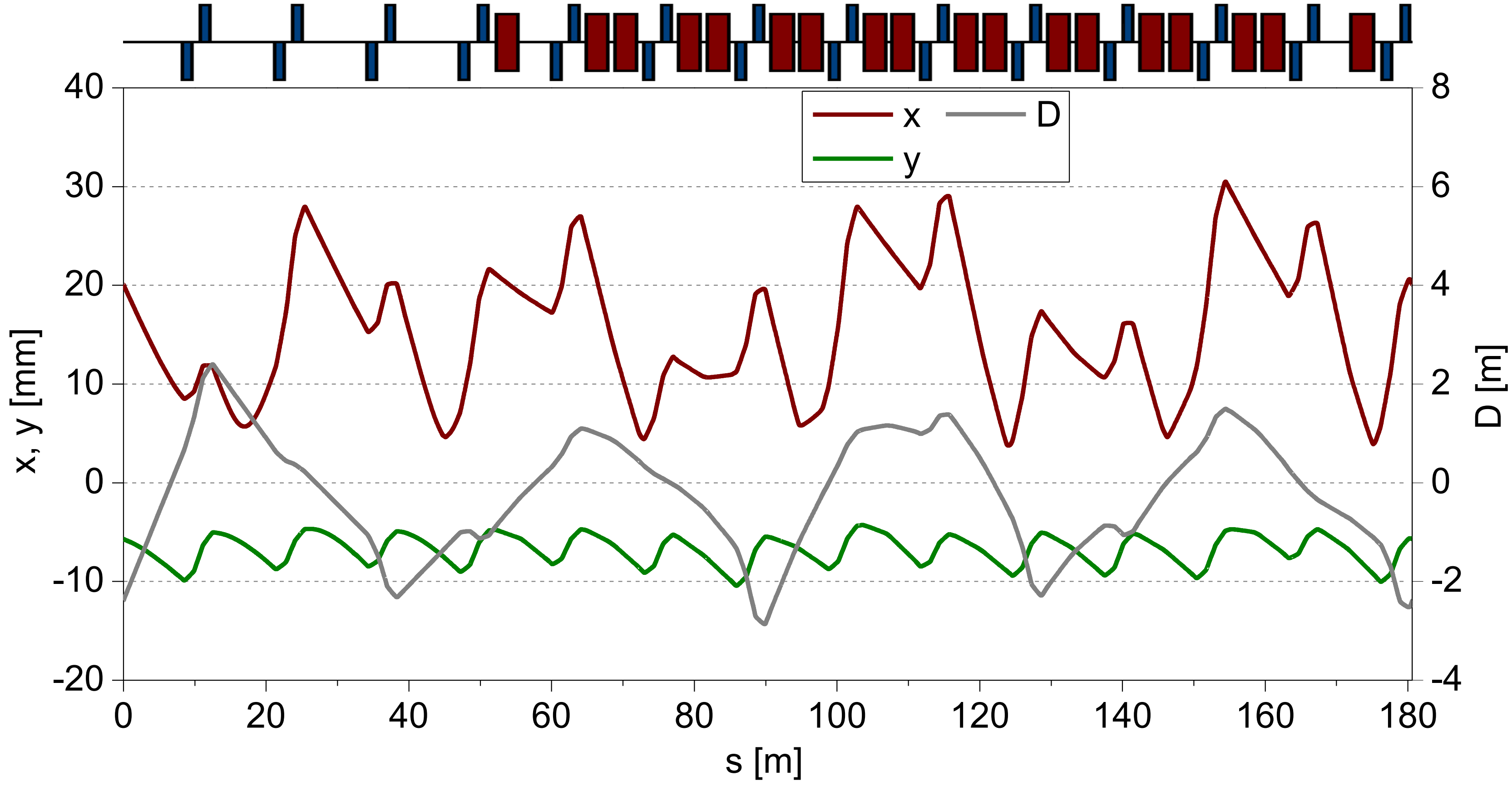
P – primary collimator S1 – 1. secondary collimator S2 – 2. secondary collimator

SIS100 lattice for the proton operation

$Q_x = 21.78$

$Q_y = 17.40$

$\gamma_{tr} = 45.5$



Collimator acceptance

Primary collimator acceptance

ε_x = 40 mm·mrad

ε_y = 13 mm·mrad

Secondary collimators acceptance

larger than primary collimator acceptance

depends on the retraction distance

Beam emittance

ε_x = 13 mm·mrad

ε_y = 4 mm·mrad

SIS 100 proton lattice acceptance

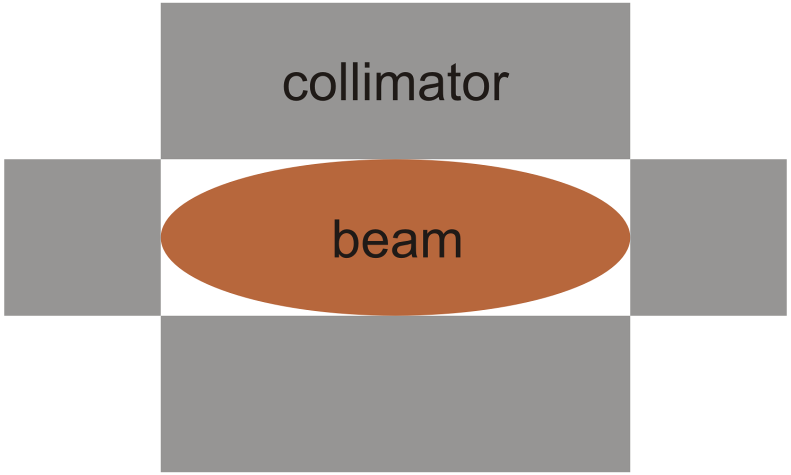
ε_x = 49 mm·mrad

ε_y = 36.3 mm·mrad

Parameters of the collimation system

Aperture of the collimators

rectangular



Primary collimator (scattering foil)

material: tungsten (high-Z materials are preferable)
thickness: 1 mm

Secondary collimators (bulky absorbers)

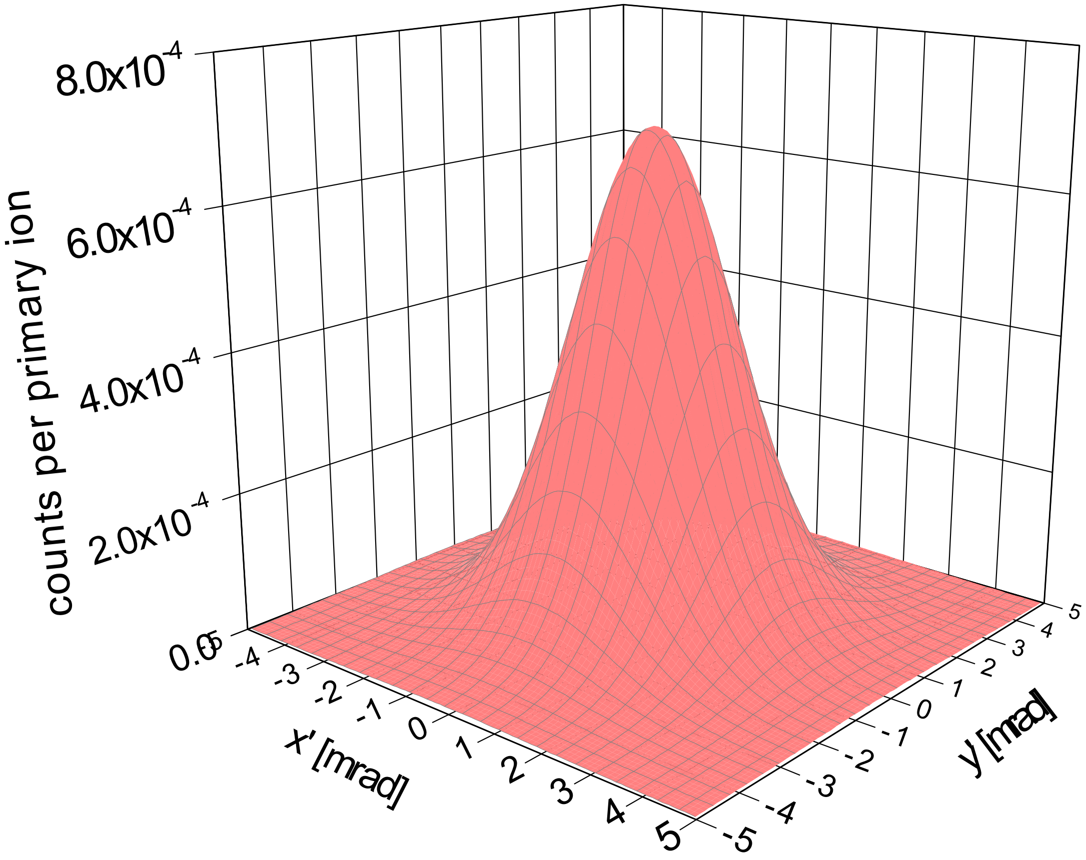
material: ??? (FLUKA simulation required)
thickness: ~ 40-50 cm (restricted by the size of the chamber)

Angular distribution after scattering

4 GeV protons → 1 mm thick tungsten foil (FLUKA simulation)

‹-10mrad; 10mrad› ~ 98.5 % of the particles
‹-π; -10mrad) ∪ (10mrad; π› ~ 0.4 % of the particles
Inelastic nuclear interaction ~ 1.1 % of the particles

angular distribution of the particles downstream of the foil

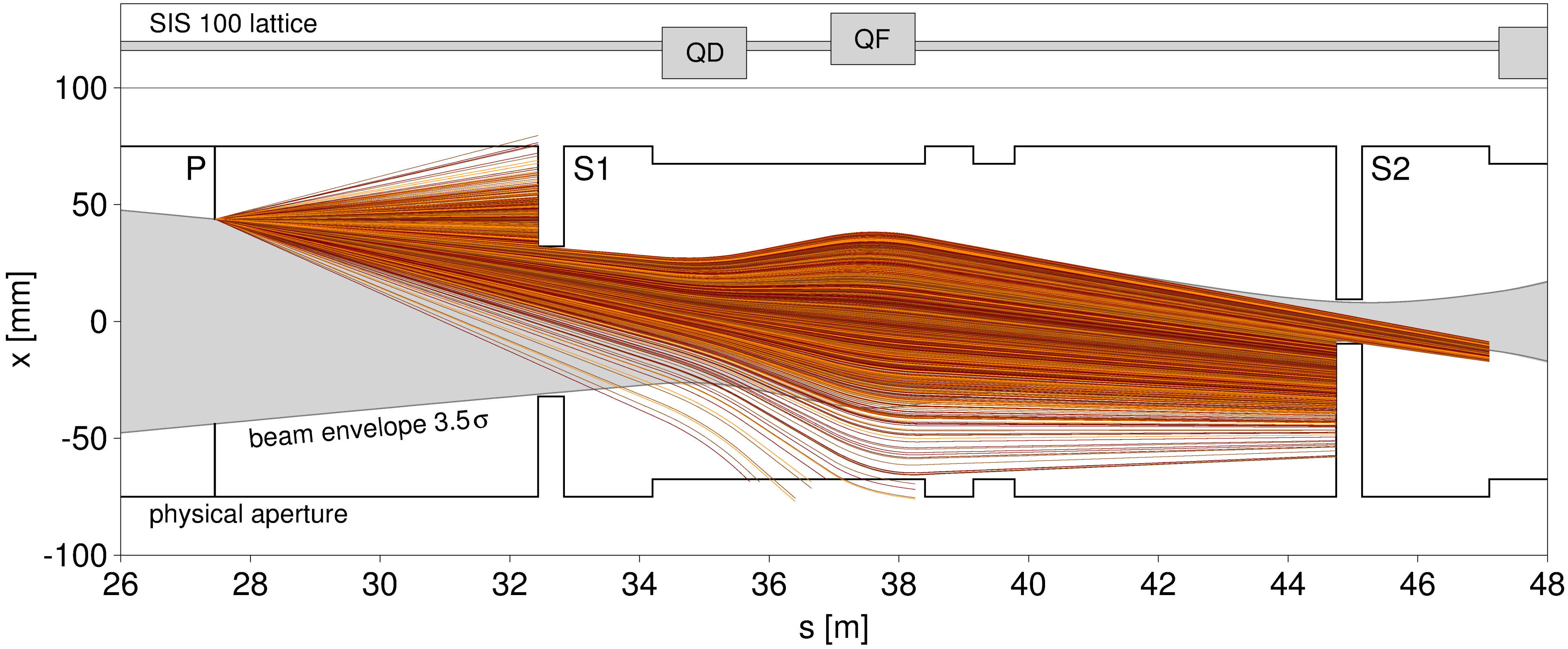


Particle tracking (horizontal)

Particle tracking: MADX code

Scattering process: FLUKA code

Statistics: 100 000 particles



Collimation efficiency (single-pass) > 75 %

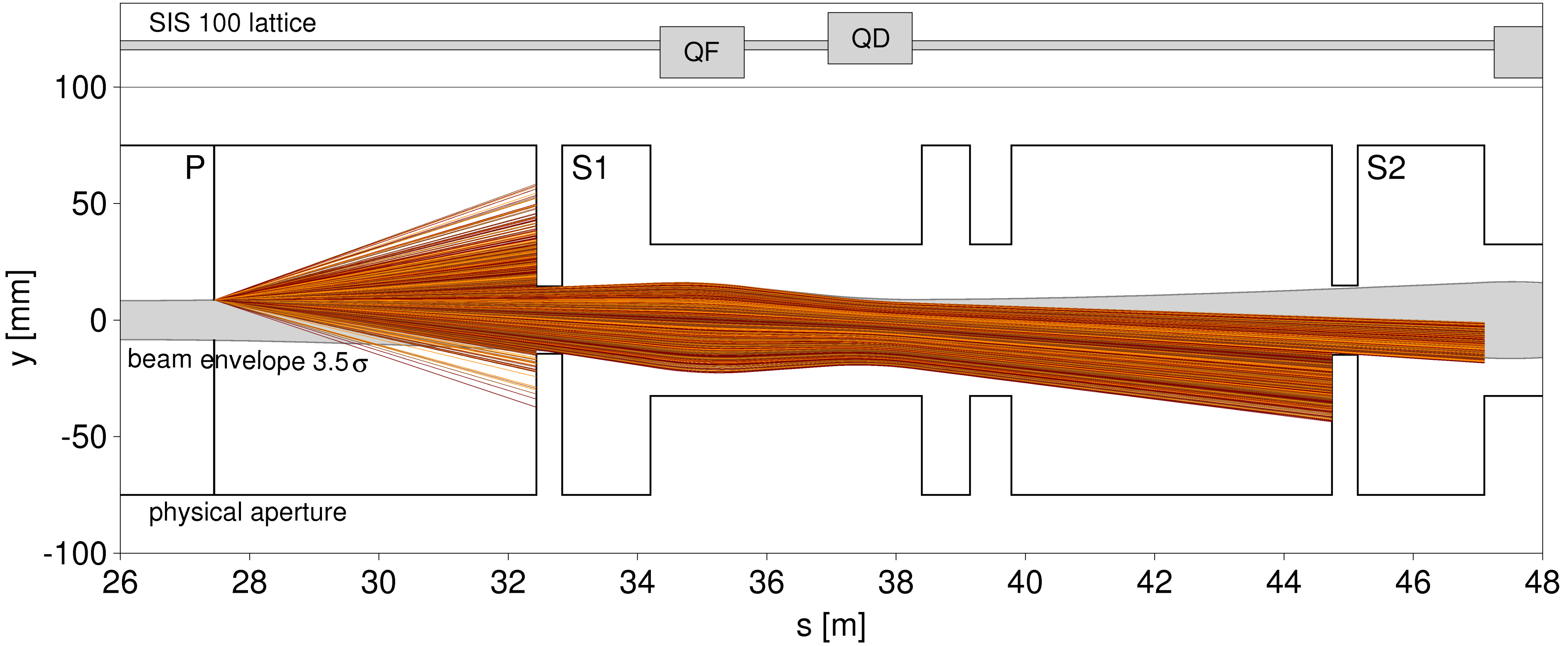
Calculation of the multi-pass efficiency is in progress

Particle tracking (vertical)

Particle tracking: MADX code

Scattering process: FLUKA code

Statistics: 100 000 particles



Collimation efficiency (single-pass) > 75 %

Calculation of the multi-pass efficiency is in progress

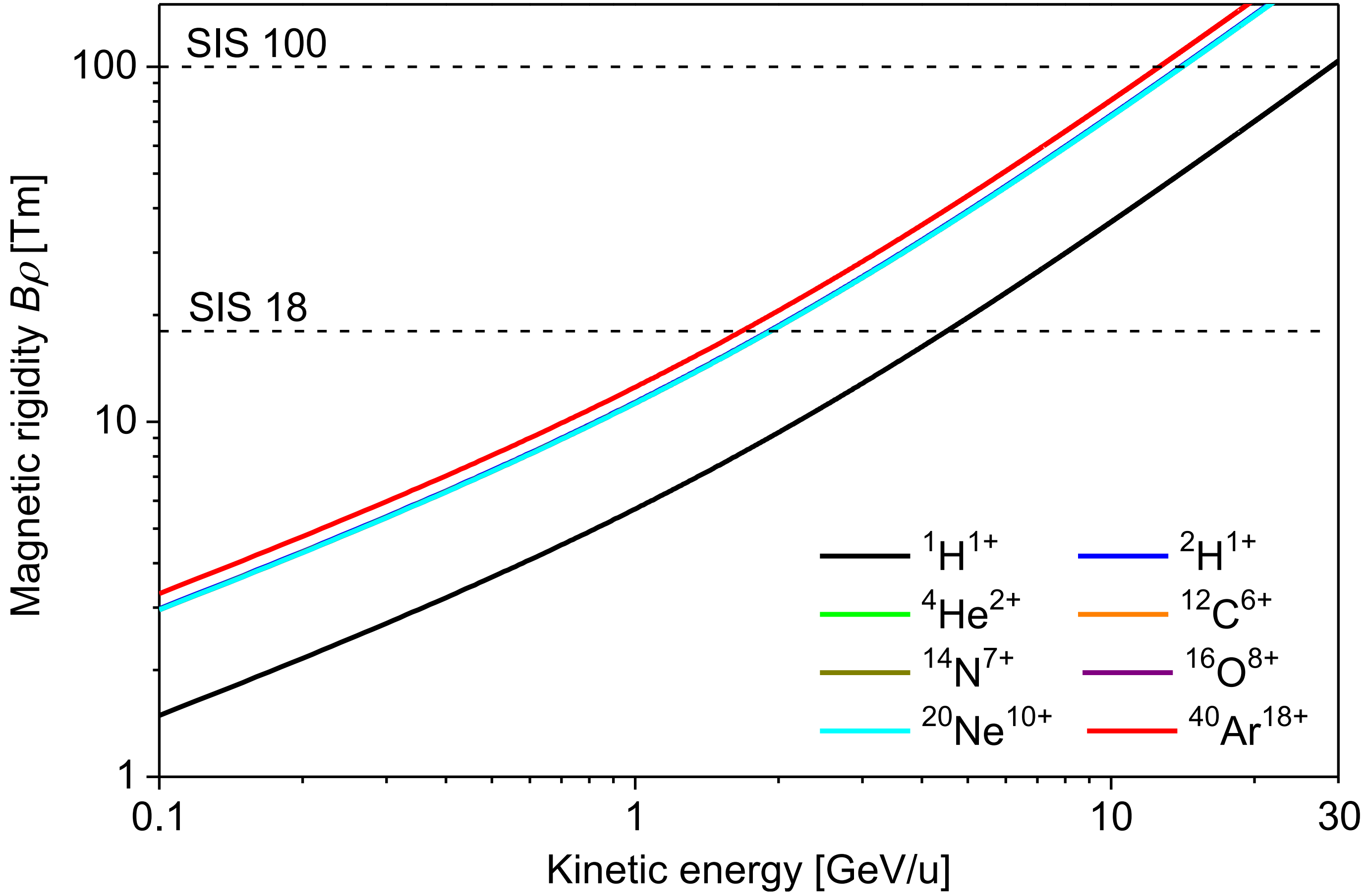
Collimation of the fully-stripped light ions

- Two-stage collimation system can be utilized also for fully-stripped ions
- Reference quantity - magnetic rigidity
  Injection and extraction energy
- Scattering in the primary collimator
  Molière theory (multiple Coulomb scattering)
- Inelastic nuclear interactions in the primary collimator
  Sihver formula
- Energy (momentum) losses in the primary collimator
  Bethe formula
- Collimation efficiency
  Dependence on the ion species

Magnetic rigidity

Reference quantity → magnetic rigidity $B\rho = \frac{p}{q}$

Magnetic rigidity → injection and extraction energy of the beam



Scattering in the primary collimator

Molière theory of multiple Coulomb scattering

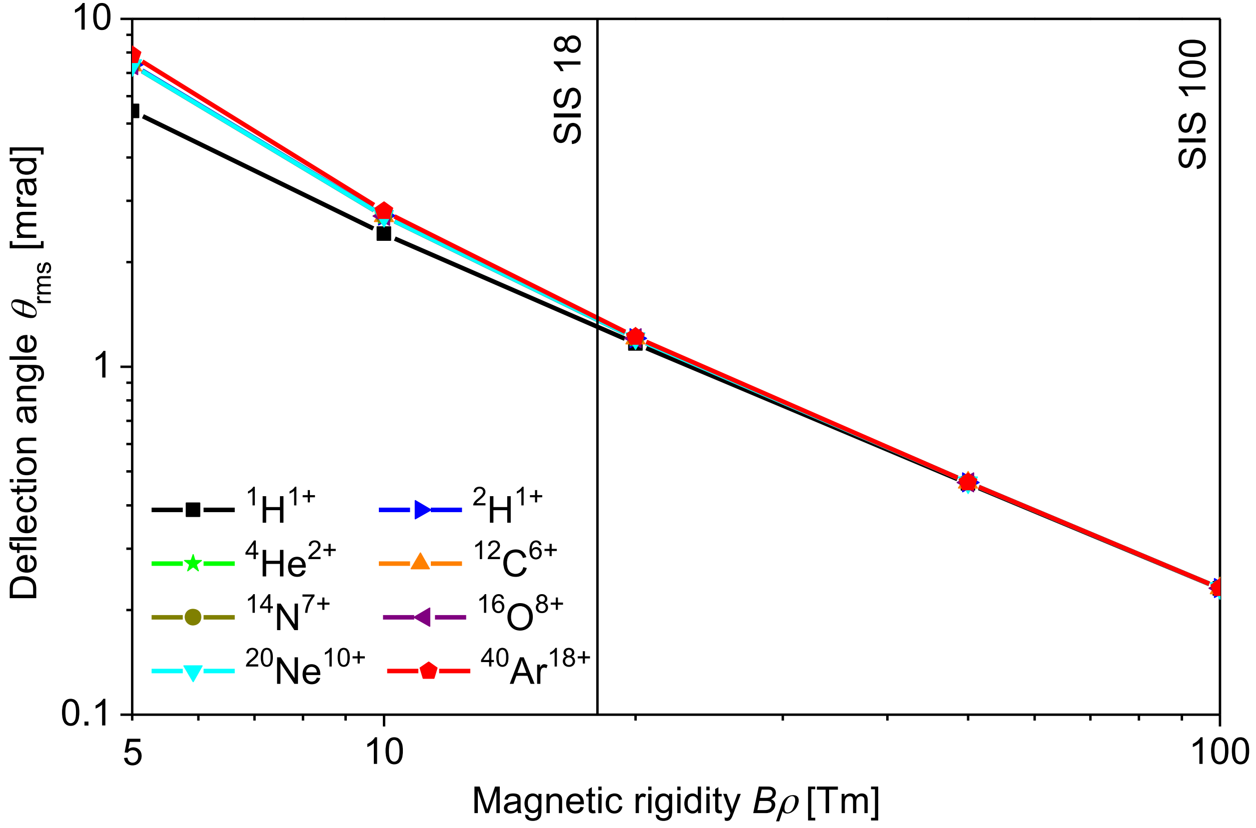
$$\theta_{rms} = \frac{13.6}{\beta cp} Z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0} \right) \right]$$

roughly Gaussian for small deflection angles

[Ref] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

Scattering foil

material: tungsten
thickness: 1 mm



Inelastic nuclear interactions

Cross section for inelastic nuclear interaction

Sihver formula (E > 100 MeV/u)

$$\sigma_{in} = \pi r_0^2 \left[A_p^{1/3} + A_t^{1/3} - b_0 \left(A_p^{-1/3} + A_t^{-1/3} \right) \right]^2$$

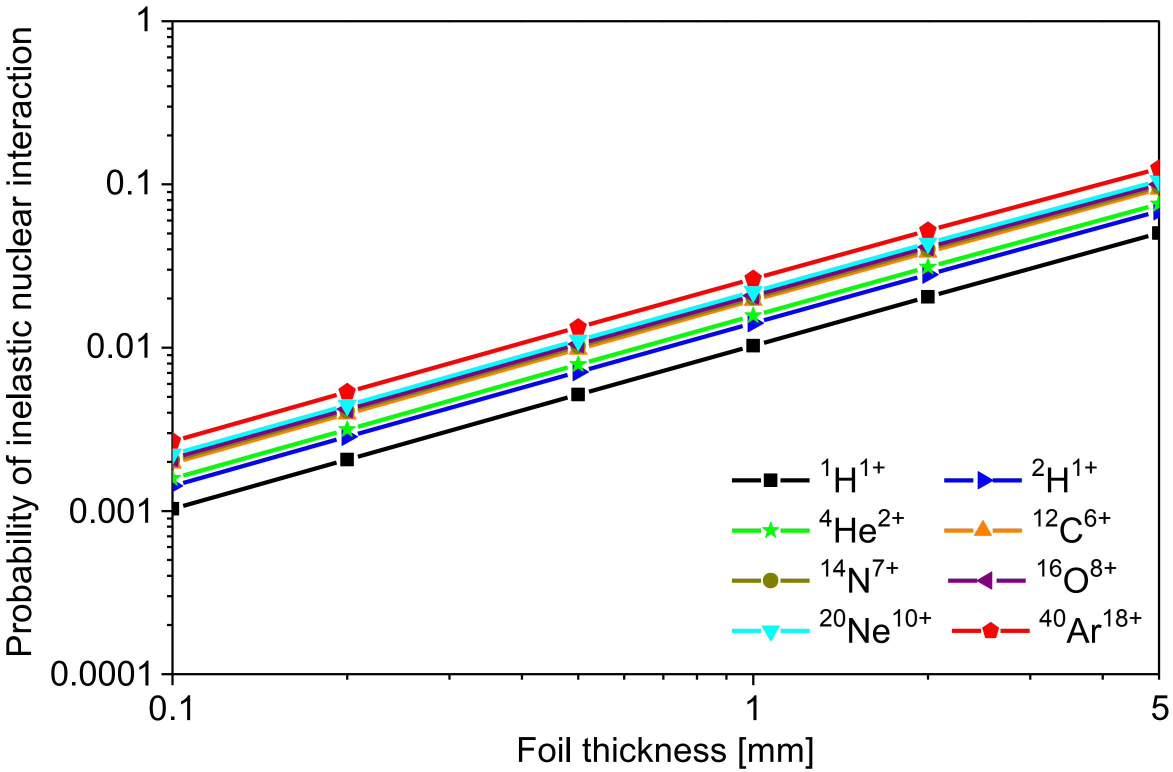
$$b_0 = 1.581 - 0.876 \left(A_p^{-1/3} + A_t^{-1/3} \right)$$ Ions

$$b_0 = 2.247 - 0.915 \left(A_p^{-1/3} + A_t^{-1/3} \right)$$ Protons

[Ref] L. Sihver et al., Phys. Rev. C47, 1225 (1993).

Scattering foil

material: tungsten
thickness: 1 mm



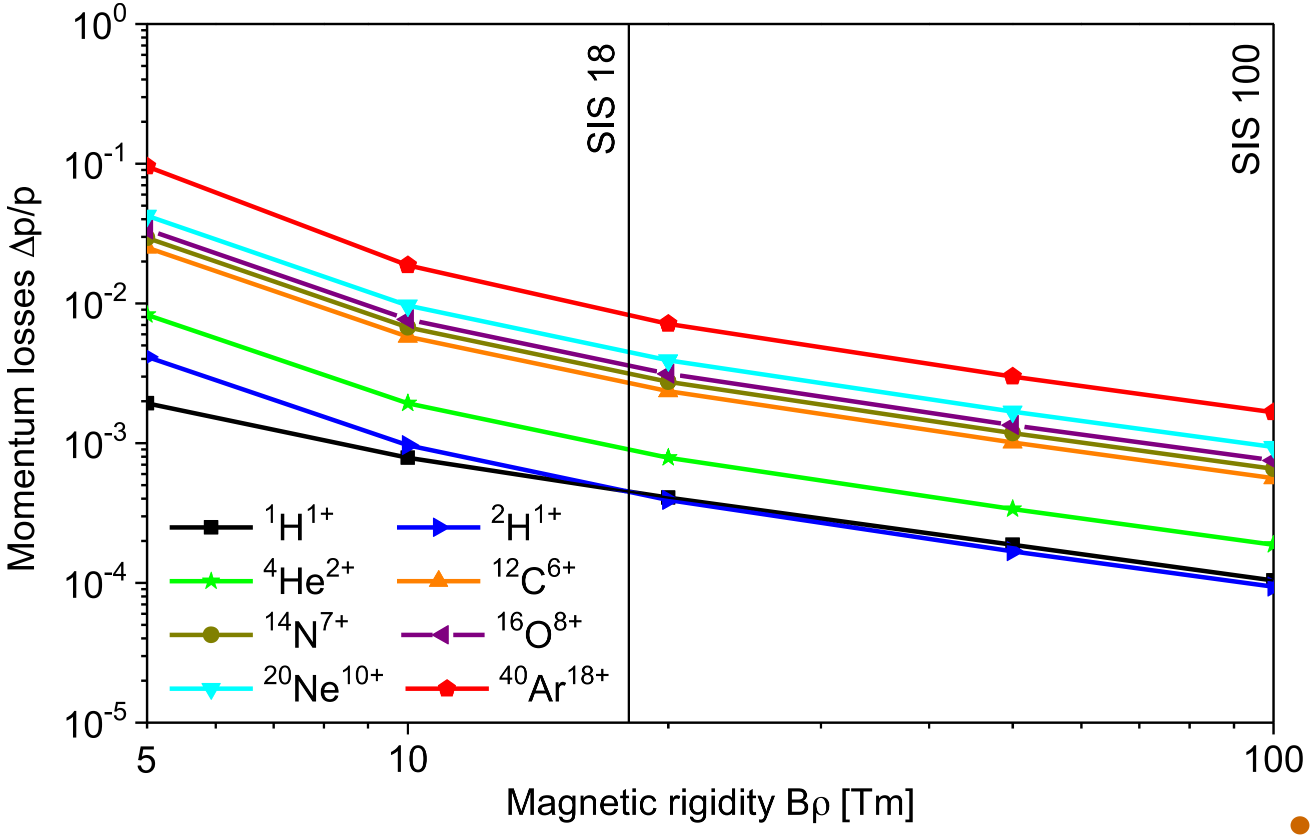
Momentum losses in the scattering foil

Bethe formula

$$-\frac{dE}{dx}=\frac{nZz^2 4\pi\alpha^2\hbar^2}{m_e\beta^2}\left[\ln\left(\frac{2m_ec^2\beta^2}{I\left(1-\beta^2\right)}\right)-\beta^2\right]$$

Scattering foil

material: tungsten
thickness: 1 mm



Material choice of the scattering foil

Material	Graphite	Titanium	Copper	Tungsten
Protons (Bρ = 18 Tm)				
Thickness [mm]	66.5	10.4	4.2	1.0
Scattering angle [mrad]	1.30	1.30	1.30	1.30
Probability of inel. nuclear int.	0.127	0.036	0.027	0.010
Momentum losses dp/p	0.0044	0.0014	0.0011	0.0005
^{40}Ar ions (Bρ = 18 Tm)				
Thickness [mm]	66.5	10.4	4.2	1.0
Scattering angle [mrad]	1.35	1.35	1.35	1.35
Probability of inel. nuclear int.	0.593	0.132	0.091	0.026
Momentum losses dp/p	0.0803	0.0249	0.0193	0.0079

High-Z materials are preferable.

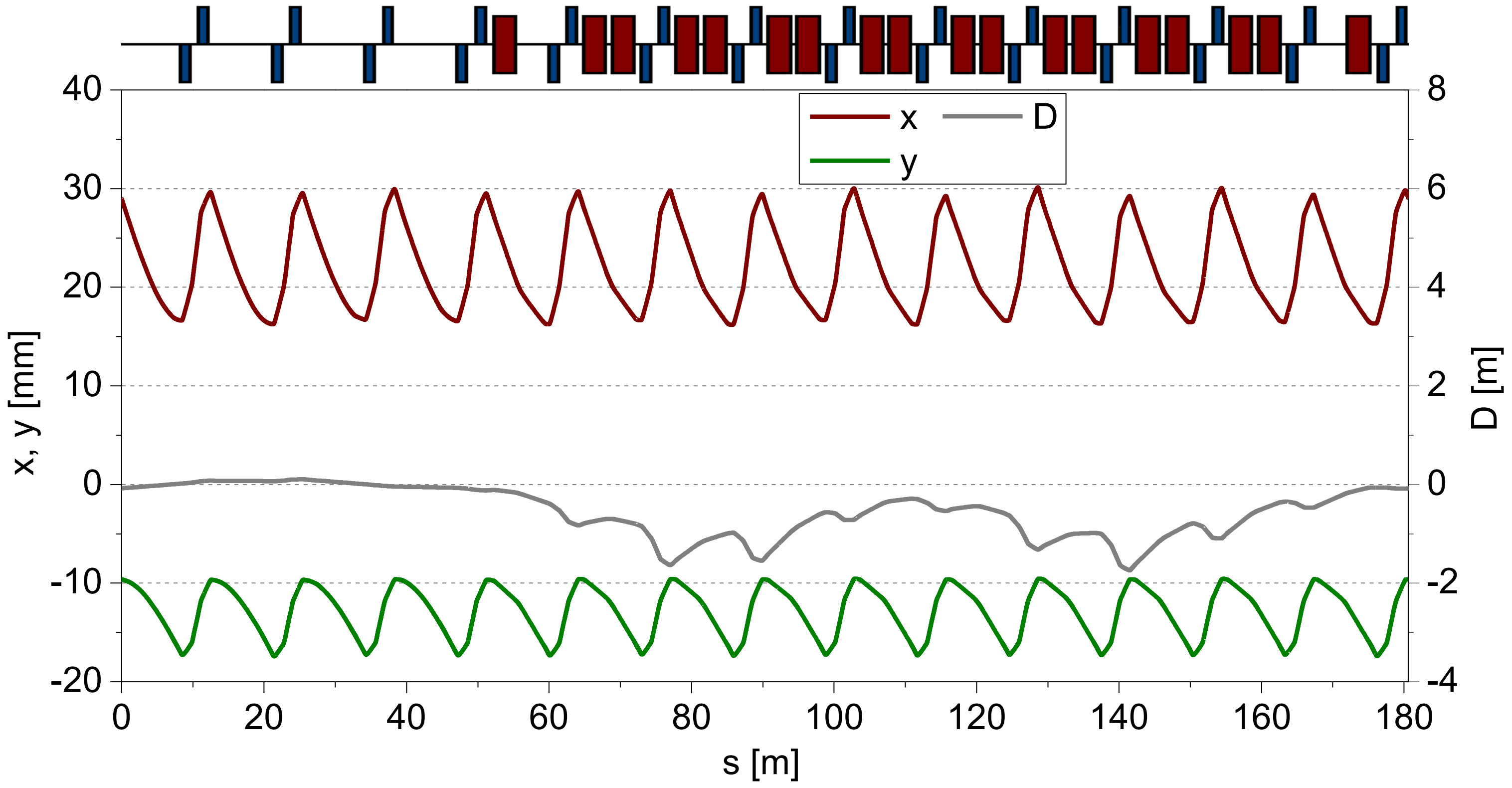
Halo collimation of the partially-stripped ions

Intermediate charge-state ions will be accelerated in SIS 100.

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

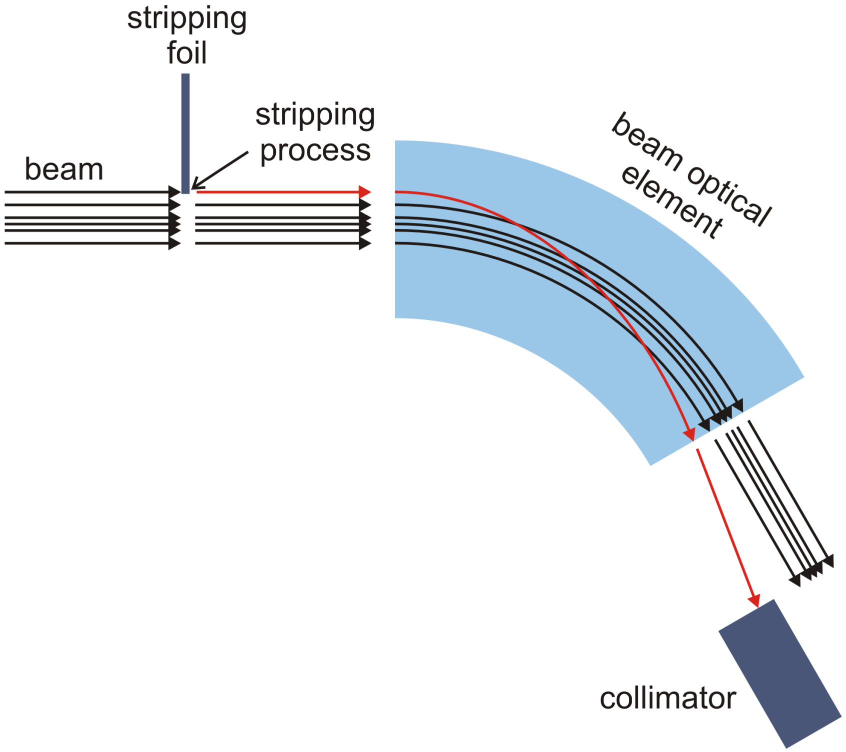
[Ref] FAIR - Baseline Technical Report, GSI Darmstadt, (2006).

SIS100 lattice for the ion operation



Collimation concept for partially-stripped ions

Stripping foil $^{238}_{92}\mathrm{U}^{28+} \rightarrow {}^{238}_{92}\mathrm{U}^{92+}$ → Deflection by a beam optical element



Lost particles during the slow extraction in SIS 100 → intercepted by two warm quadrupoles

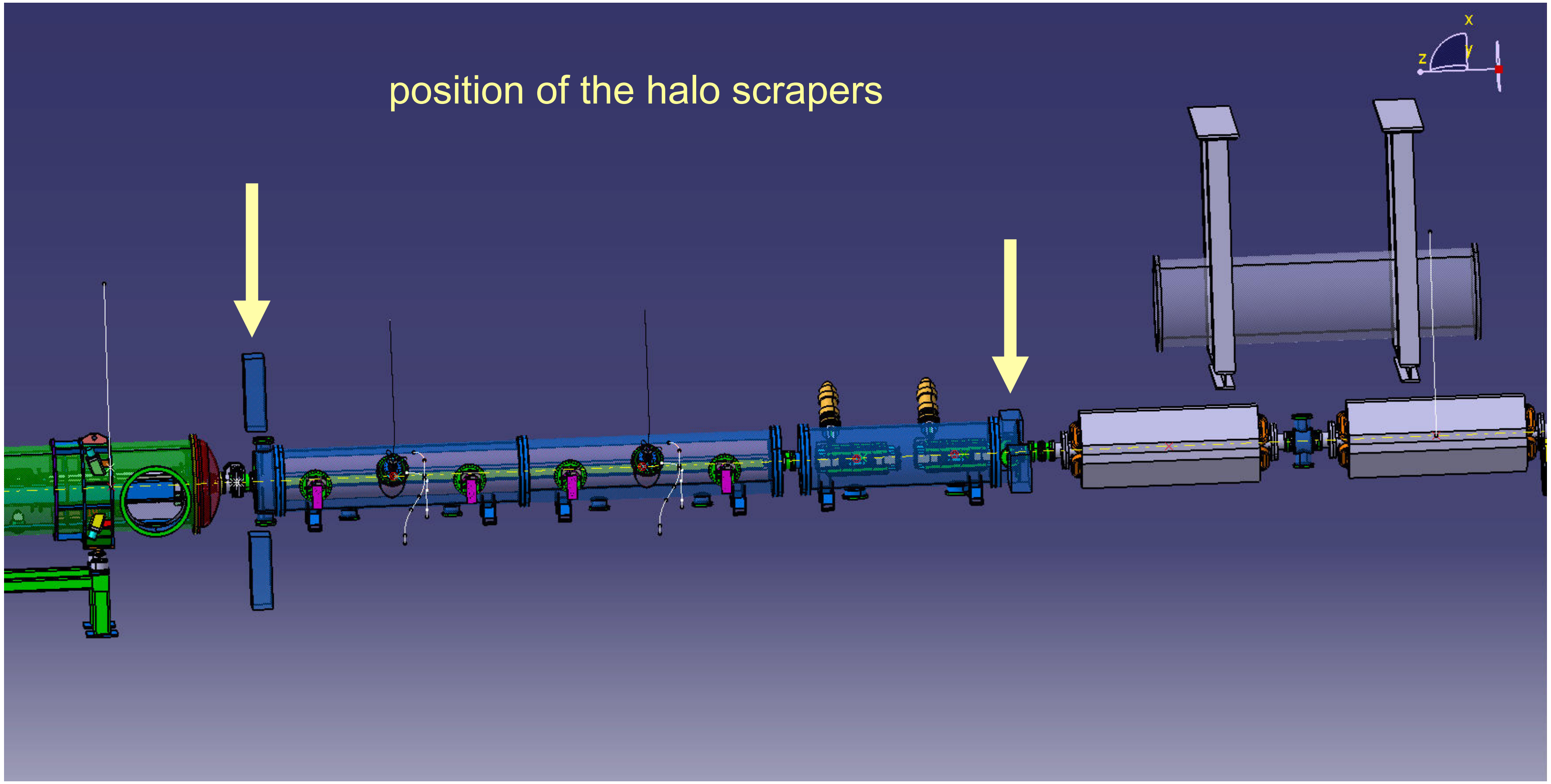
[Ref] A. Smolyakov at al, EPAC2008, 3602 (2008).

The two warm qudarupoles will play the role of the absorbers also for the halo collimation

Two stage system: 1. the stripping foil → 2. the two warm quadrupoles

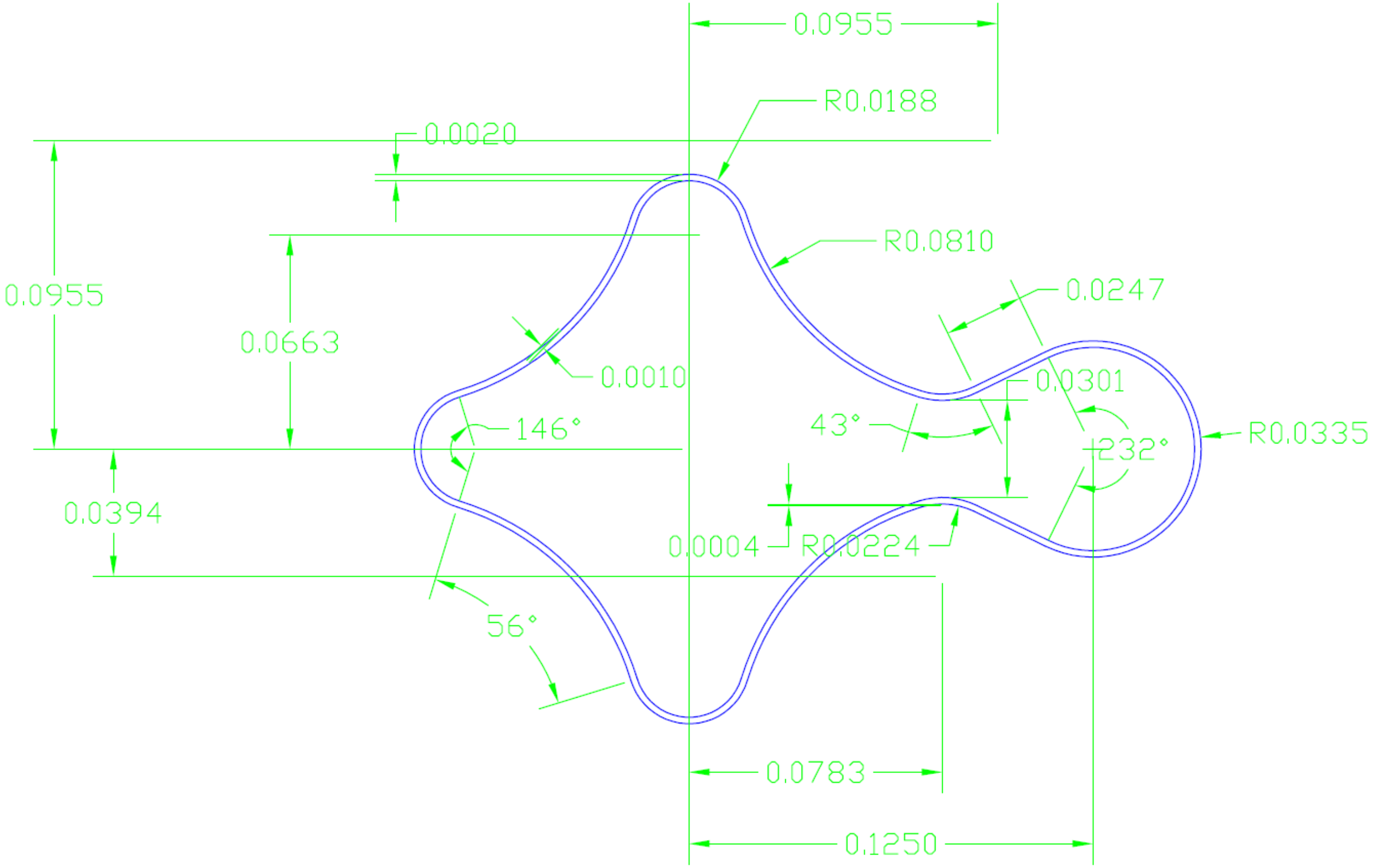
Slow extraction area

SIS 100 / Sector 5 / Cell 2



Beam pipe in the slow extraction area

Low desorptive material; pipe: Ti (90%), Al (6%) V, (4%)



Charge state distribution after stripping

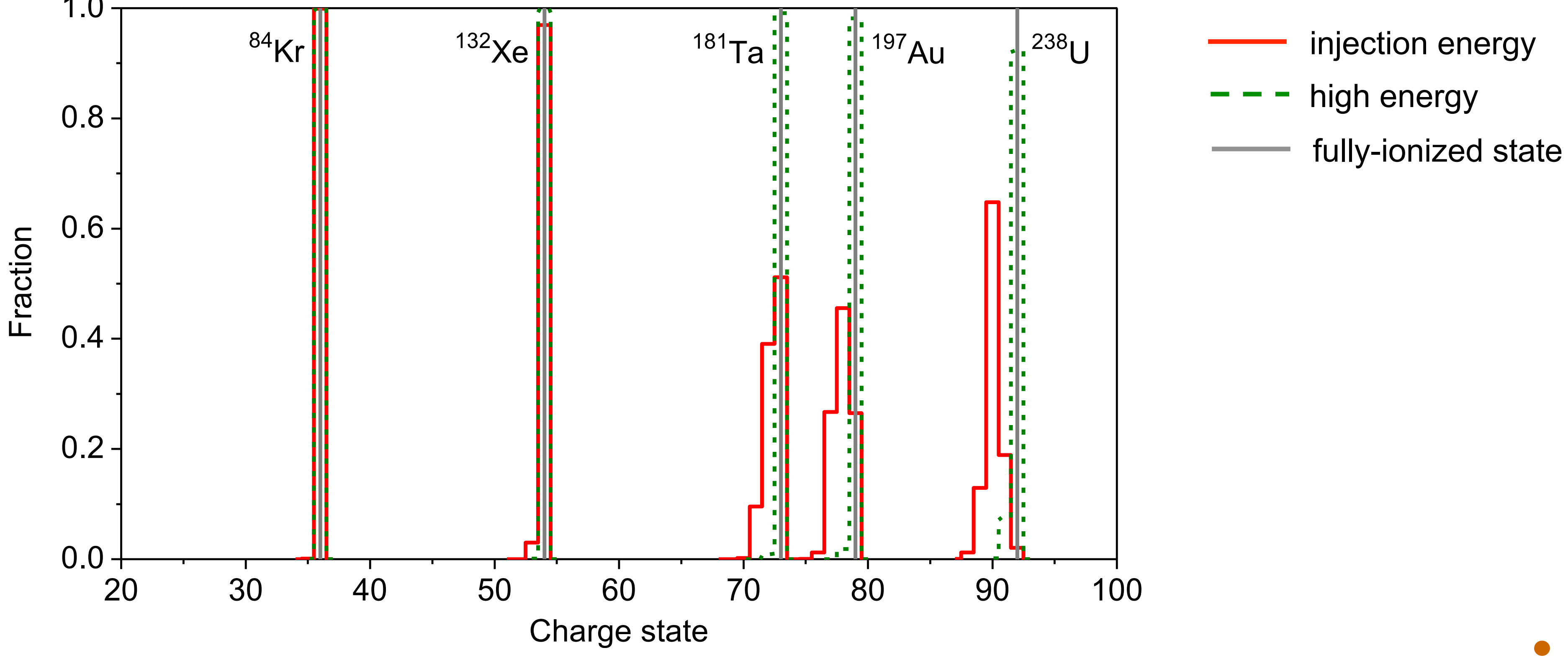
Medium-Z materials (Al – Cu) → optimal for efficient stripping for wide range of projectiles and beam energies

[Ref] C. Scheidenberger et al., NIMB *142 (1998) 441.*

code GLOBAL

Electron capture and electron loss → equilibrium charge-state distribution

stripping foil: titanium, 500 μm thick



Conclusion

- Halo collimation for proton and ion operation in SIS 100 was studied.

- Proton operation – two stage collimation system.
  Single-pass collimation efficiency > 75%
  Multi-pass efficiency – calculation in progress

- Light-ion operation (^{2}H - ^{40}Ar, fully stripped) – two stage system.
  Single-pass efficiency ≈ proton operation
  Multi-pass efficiency < proton operation due to larger momentum losses

- Heavy-ion operation (^{84}Kr – ^{238}U, partially stripped) – stripping foil and interception by the two warm quadrupoles in the slow extraction area.

- Detailed particle tracking and calculation of the beam loss distribution in the synchrotron using simulation codes is in progress.

Thank you for your attention