Halo Collimation of Ion Beams

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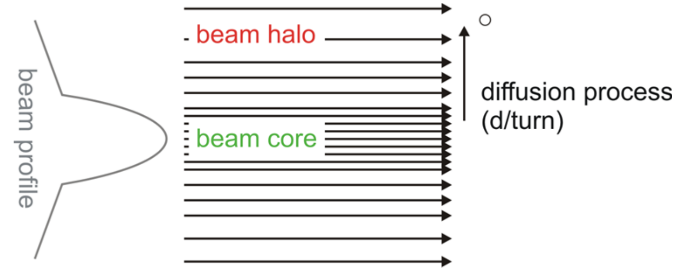
Introduction

- Beam dynamics processes → halo formation → 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



[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 beam losses

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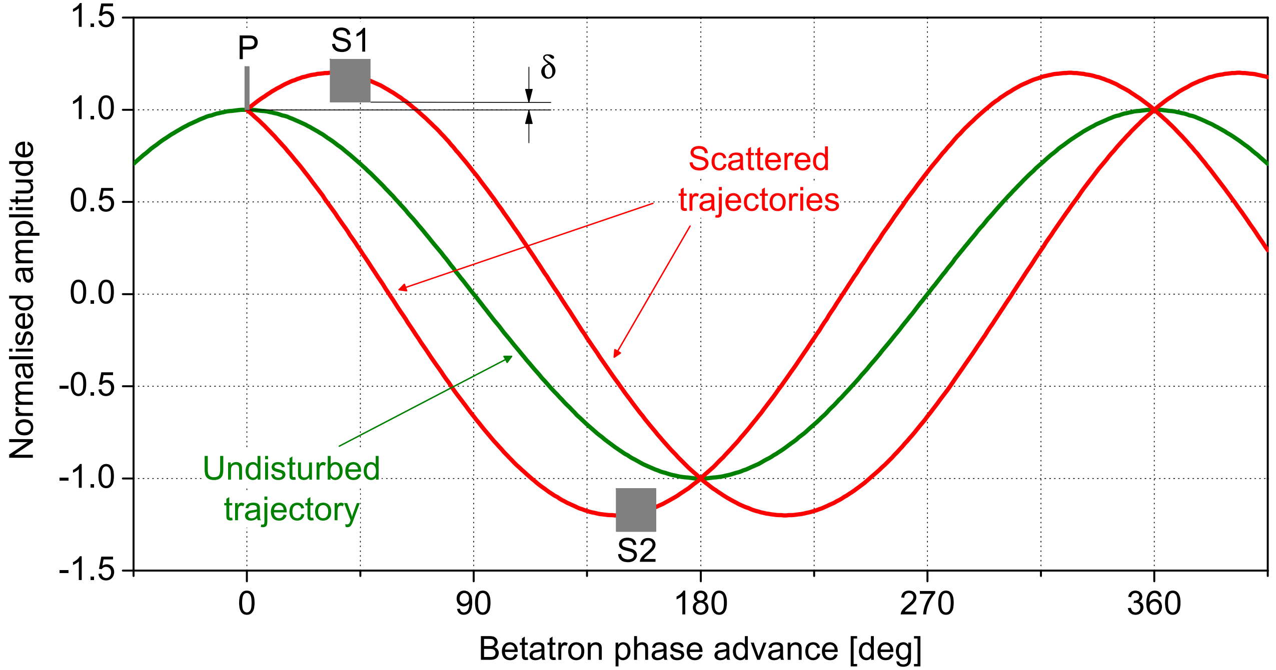
- FAIR project (Facility for Antiproton and Ion Research) at GSI
  - Future SIS100 synchrotron ↔ present SIS18 synchrotron
    beam intensity increase: ~ factor of 100 , beam energy increase: ~ factor of 10
  - SIS100 will accelerate various ion species from proton up to uranium
    fully-stripped ions (e.g. ${}^{40}_{18}Ar^{18+}$) , partially-stripped ions (e.g. ${}^{238}_{92}U^{28+}$)
- Need for halo collimation in SIS 100
  - Protons and light ions – activation ("hands-on" maintenance limit 1 W/m)
  - Heavy ions – vacuum degradation due to desorption, radiation damage

Two-stage betatron collimation system

Well established in proton accelerators

- 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 at the secondary collimator is enlarged due to scattering → reduced leakage of the particles.

[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).

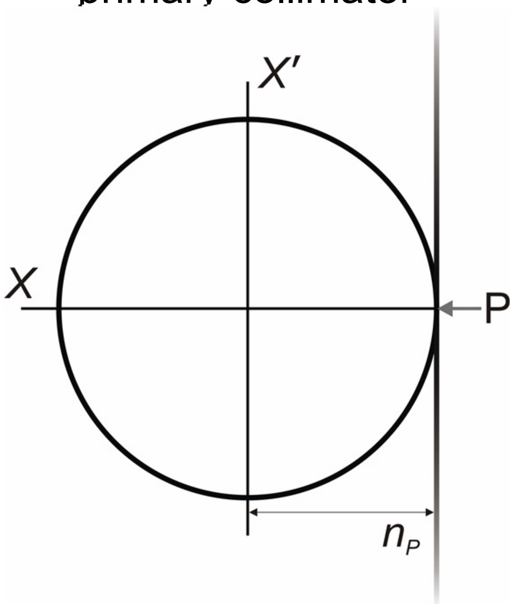
[Ref] T. Wei and Q. Qin, Nucl. Instrum. Methods Phys. Res. Sect. A 566, 212 (2006).

[Ref] K. Yamamoto, Phys. Rev. ST Accel. Beams 11, 123501 (2008).

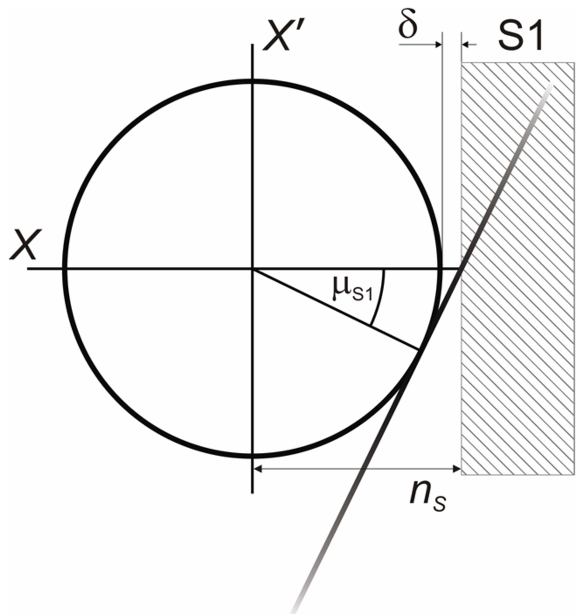
[Ref] N. Mokhov et al., Fermilab-Pub-11-378-APC (2011).

Normalized phase space plots at the collimators

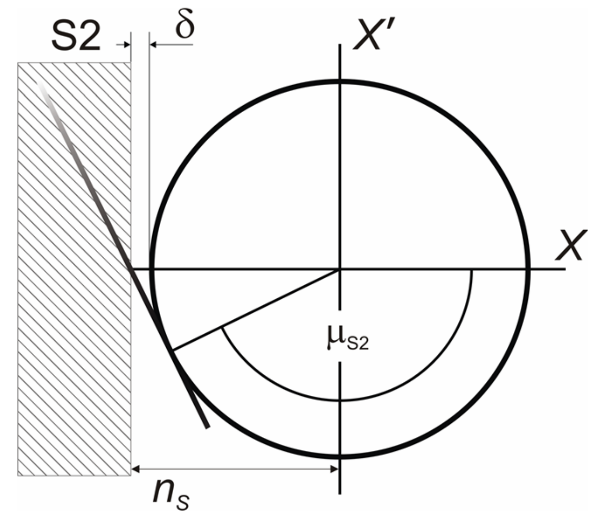
primary collimator



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

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

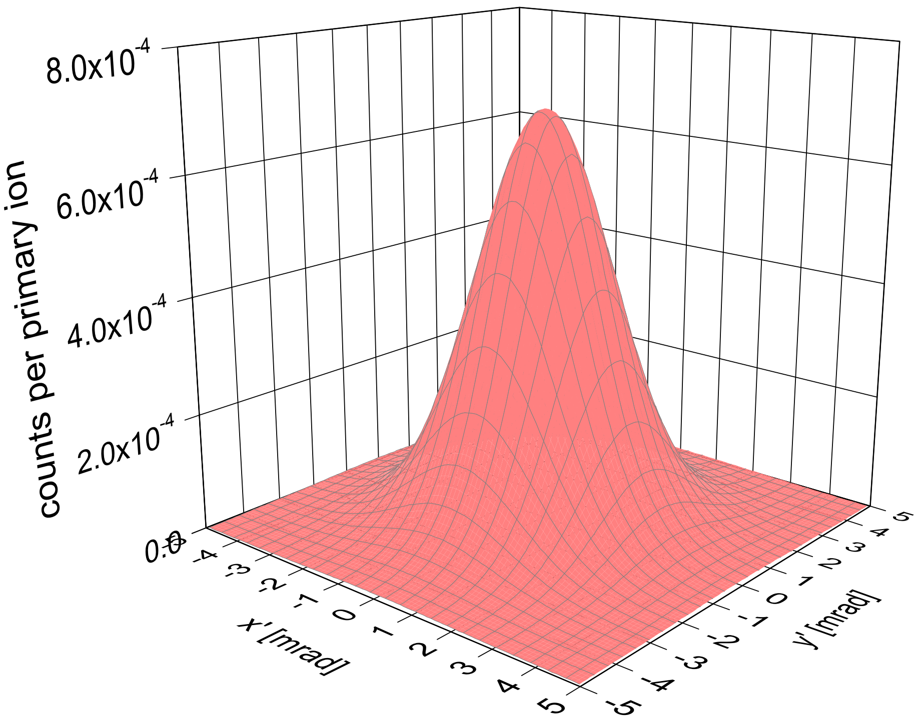
$$M = \begin{pmatrix} \cos\mu_S & \sin\mu_S \\ -\sin\mu_S & \cos\mu_S \end{pmatrix}$$

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

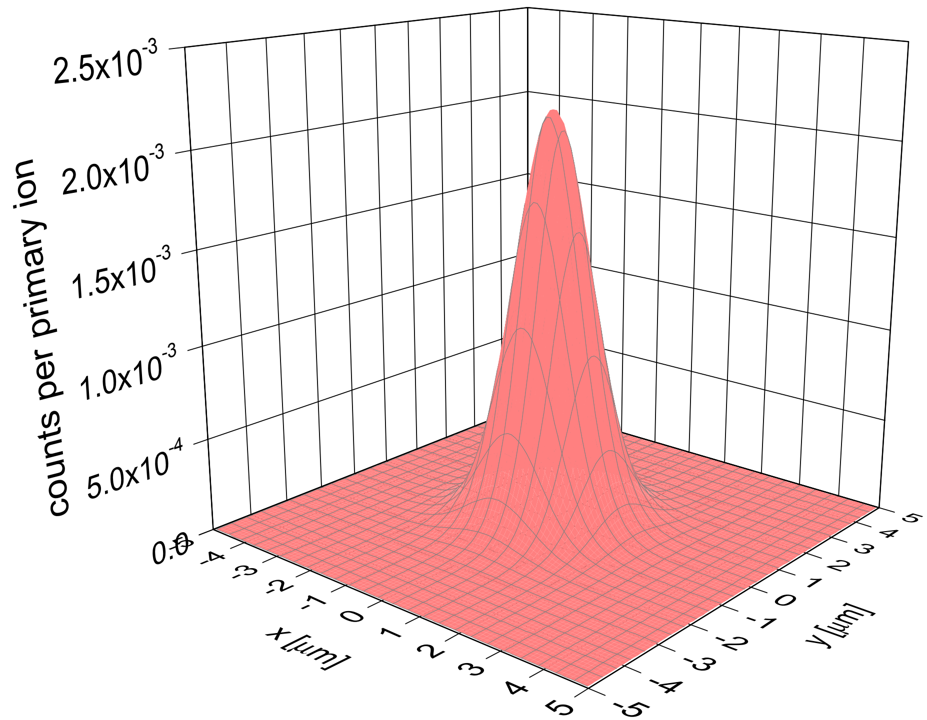
Angular and position distribution after scattering

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

distribution of the particles downstream the foil

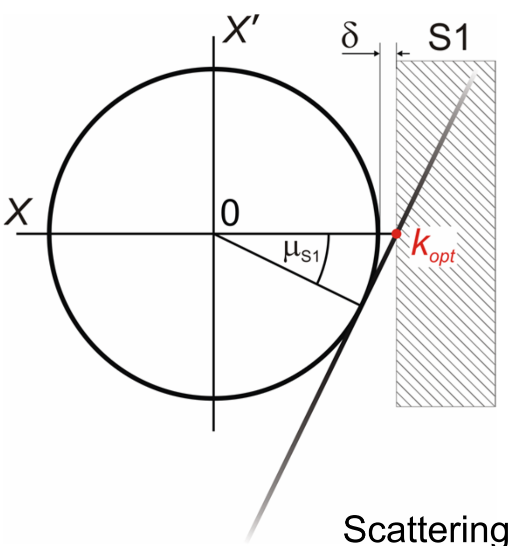


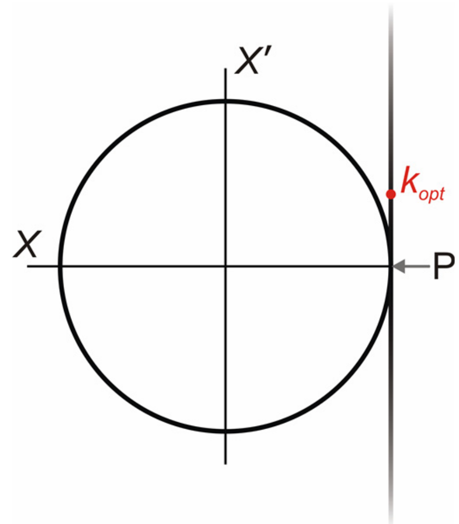
angular distribution [mrad]



position distribution [µm]

Scattered particles in the phase space





$$\begin{pmatrix} X_{S1} \\ X'_{S1} \end{pmatrix} = \begin{pmatrix} \cos\mu_{S1} & \sin\mu_{S1} \\ -\sin\mu_{S1} & \cos\mu_{S1} \end{pmatrix} \begin{pmatrix} X_P \\ X'_P \end{pmatrix}$$

Scattering angle k

$$k = \frac{n_S - n_P \cos\mu_S}{\sin\mu_S}$$

Scattering angle k_{opt} (optimal phase advances)

$$\mu_{S1} = \arccos\frac{n_P}{n_S} \qquad \mu_{S2} = \pi - \mu_{S1} \quad \longrightarrow \quad k_{opt} = \sqrt{n_S^2 - n_P^2} = n_P\sqrt{2\delta + \delta^2} \qquad n_S = n_P(\delta + 1)$$

2D optics

Scattering is an isotropic process and occurs in both planes hor. & ver. → 2D description is required

Optimal geometry for the efficiency of the collimation system → circular aperture

Circular aperture → mechanical problems with movable aperture → octagonal approximation

$$n_P = \sqrt{X^2 + Y^2} \qquad X' = Y' = 0 \qquad \vec{V} = (X, X', Y, Y') \qquad k_{opt} = k_{X,opt}\cos\phi + k_{Y,opt}\sin\phi$$

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

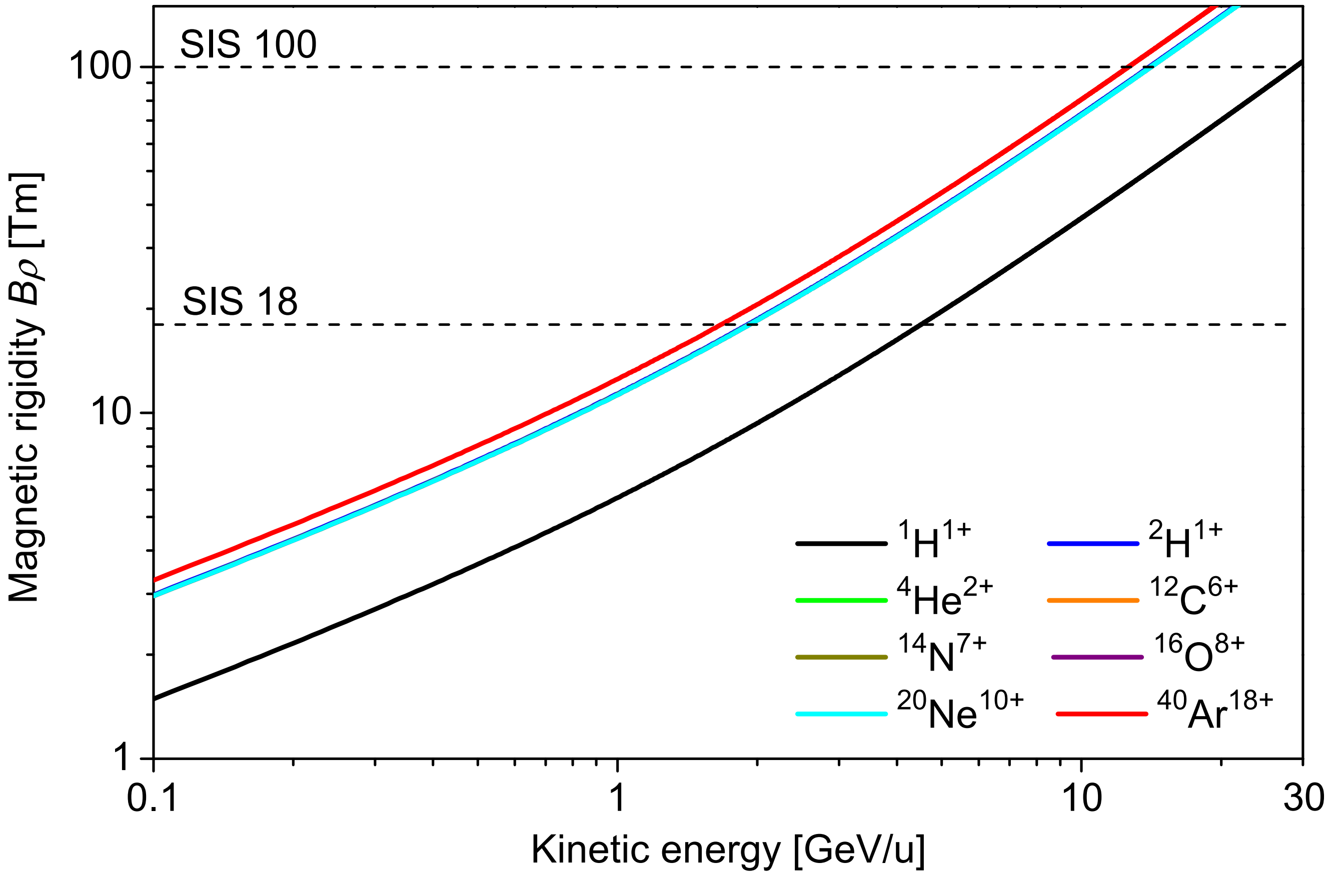
Collimation fully-stripped ions

- Two-stage collimation system utilize also for fully-stripped ions
  - Study of the following processes for various ion species
- 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

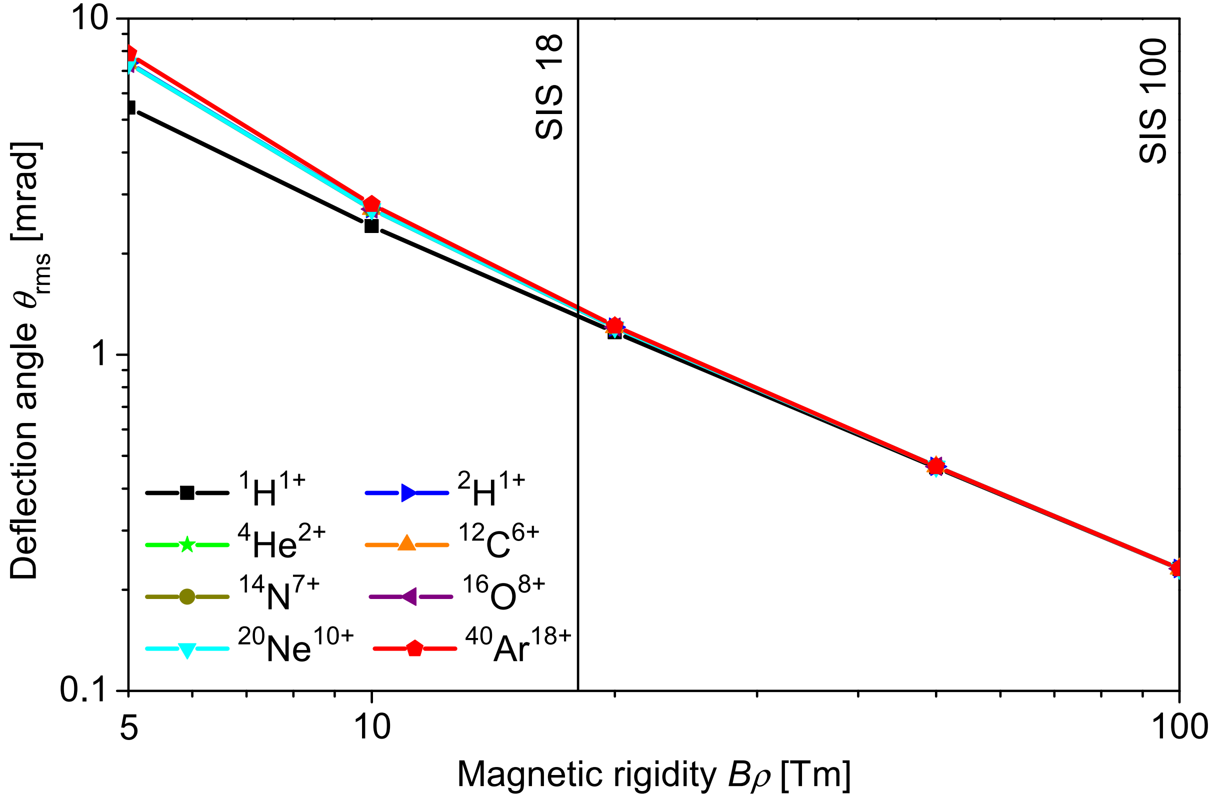
$$\theta_{rms} = \frac{13.6}{\beta cp} Z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0} \right) \right]$$

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)

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

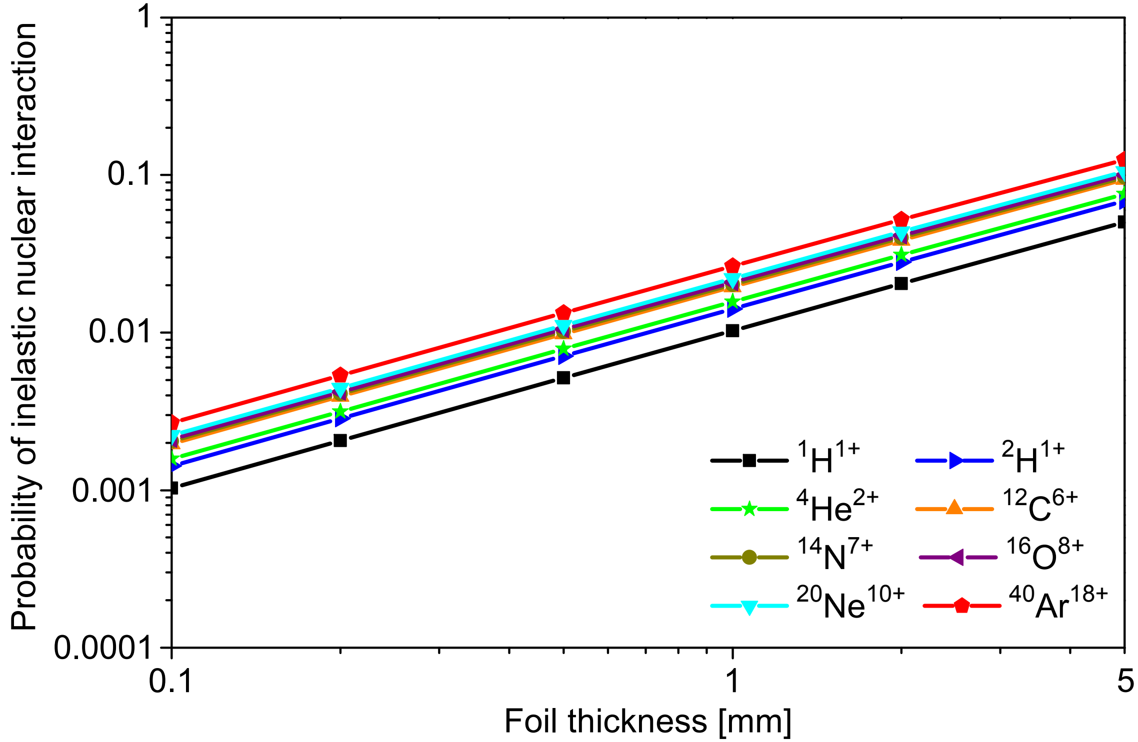
$$b_0 = 1.581 - 0.876\left(A_p^{-1/3} + A_t^{-1/3}\right)$$ Ions

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

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

Other formulae (E > 10 MeV/u)

- Tripathi formula
  [Ref] R. Tripathi et al., NIMB117, 347 (1996).
- Kox formula
  [Ref] Kox et al. Phys. Rev. C35, 1678 (1987).
- Shen formula
  [Ref] Shen et al. Nucl. Phys. A491, 130 (1989).



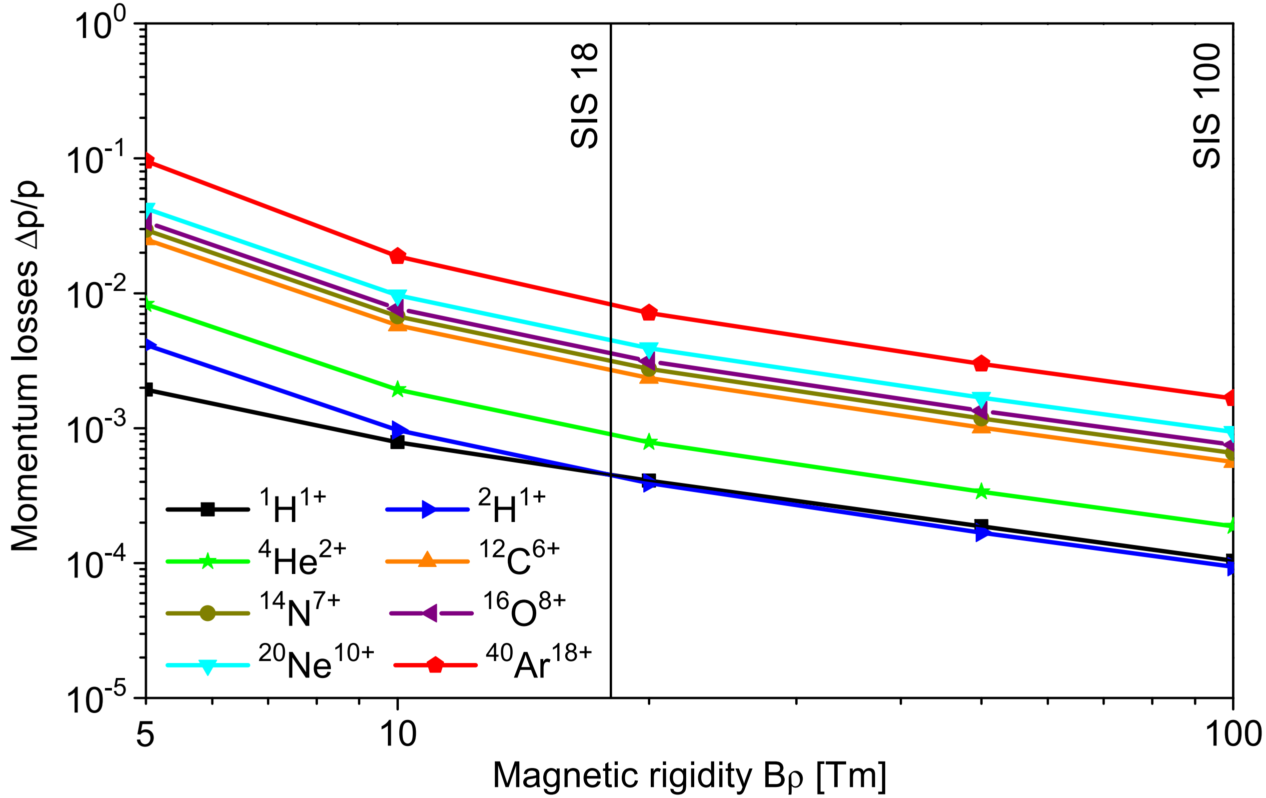
Foil material: tungsten

Momentum losses in the primary collimator

Bethe formula

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

Scattering foil: tungsten, 1 mm



Momentum losses in the primary collimator

Collimation system is localized in a straight section with no dipoles.

Normalized dispersion

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

Coordinates at the primary collimator

Before scattering $X_P = n_P$, $X'_P = 0$ → $\frac{dp}{p} = \delta$ After scattering $X_P = n_P - \delta\chi_P$, $X'_P = k - \delta\chi'_P$

Momentum losses

Transport of the particles

$$X_S = X_P \cos\mu_S + X'_P \sin\mu_S + \delta\chi_S$$

Scattering angle

$$k = \frac{n_S - n_P\cos\mu_S}{\sin\mu_S} + \delta\frac{\chi_P\cos\mu_S - \chi_S}{\sin\mu_S} + \delta\chi'_P$$

Dispersion vector

$$\chi_S = \chi_P\cos\mu_S + \chi'_P\sin\mu_S$$

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

Scattering angle for the optimal phase advances

$$k = \frac{n_S - n_P\cos\mu_S}{\sin\mu_S} \qquad k_{opt} = \sqrt{n_S^2 - n_P^2} = n_P\sqrt{2\delta + \delta^2}$$

k_{opt} does not depend on the momentum losses if the collimation system is localized in a stright section

Material of the primary collimator

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.

Collimation of partially-stripped ions

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

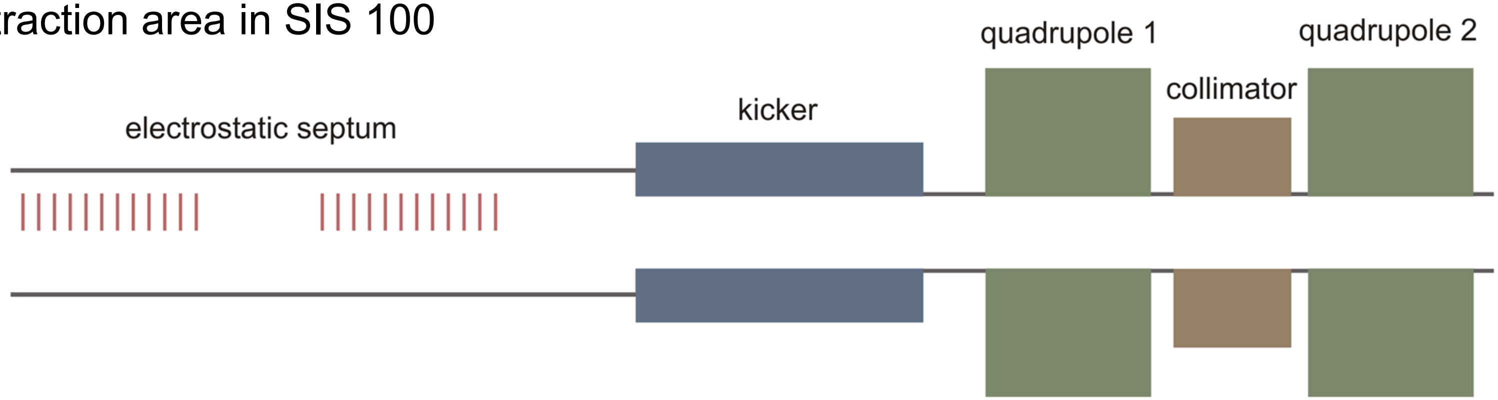
$^{238}_{92}U^{28+}$, $^{197}_{79}Au^{25+}$, $^{181}_{73}Ta^{24+}$, $^{132}_{54}Xe^{22+}$, $^{84}_{36}Kr^{17+}$

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

Colimation concept

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

Slow extraction area in SIS 100



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

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

The stripping foil for halo collimation is placed in the slow extraction area in SIS 100

Charge state distribution after stripping

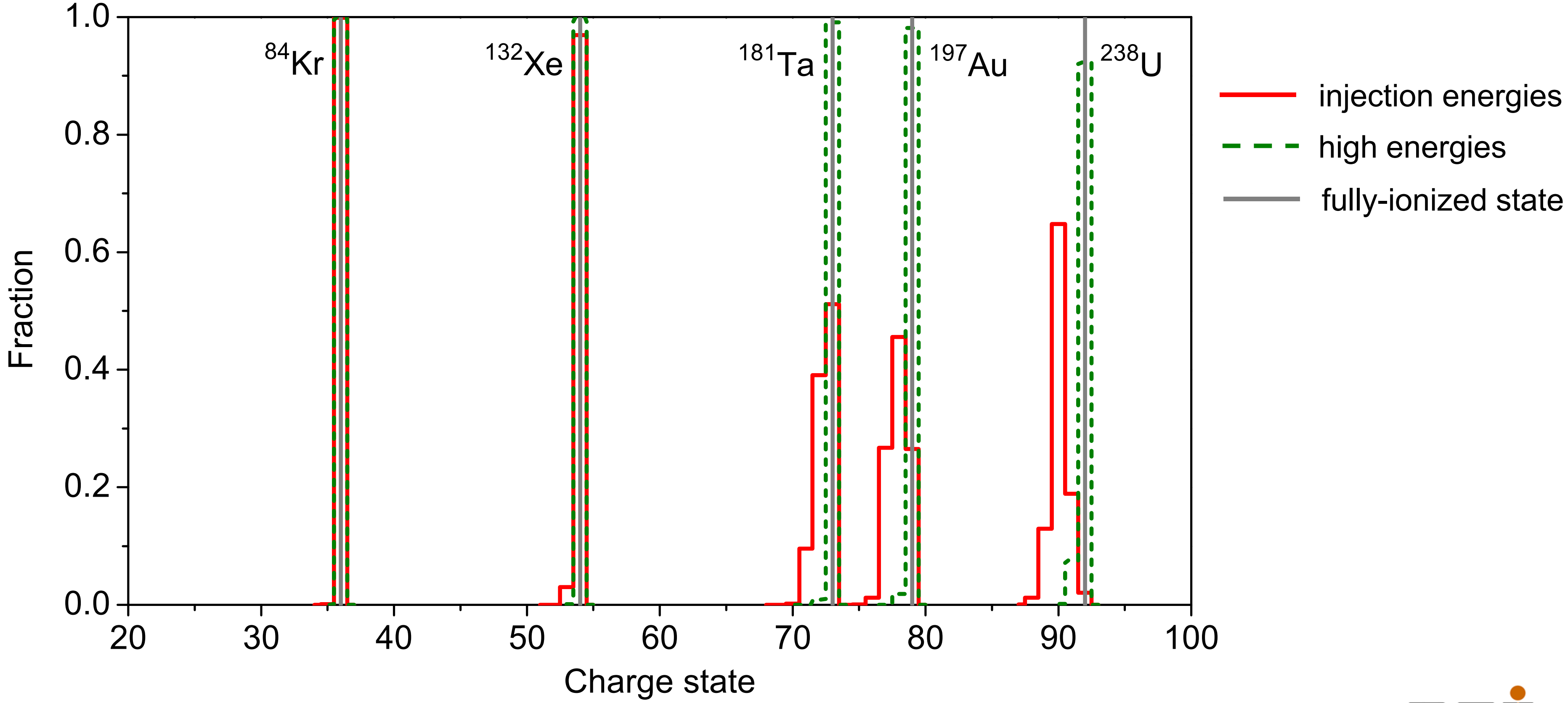
Medium-Z materials (Al – Cu) → optimal for efficient stripping for wide range of projectiles and beam energies

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

code GLOBAL

Electron capture and electron loss → equilibrium charge-state distribution

Stripping foil: 500 µm thick, titanium



Conclusion

- Halo collimation of partially- and fully- stripped ions was studied.
- Dependence of the collimation efficiency on the scattering, inelastic nuclear interaction and momentum losses in the primary collimator was investigated.
- Above 20 Tm the scattering angle for protons and ions is almost the same.
- The probability of inelastic nuclear interaction for ^{40}Ar ions is less than 3 % in the considered primary collimator.
- Influence of the momentum losses in the primary collimator to the efficiency is also not significant if the collimation system is localized in a straight section.
- The particles with large momentum losses which are not intercepted by the secondary collimators will be likely lost in the following arc section.
- The concept for the partially-stripped ions is based on the stripping of their electrons and consequently their interception by two warm quadrupoles.
- Detailed particle tracking and calculation of the beam loss distribution in the synchrotron using simulation codes is needed.

Thank you for your attention