Beam Induced Activation and Collimation

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HIC4FAIR Workshop Detectors & Accelerators, Hamburg, 2015

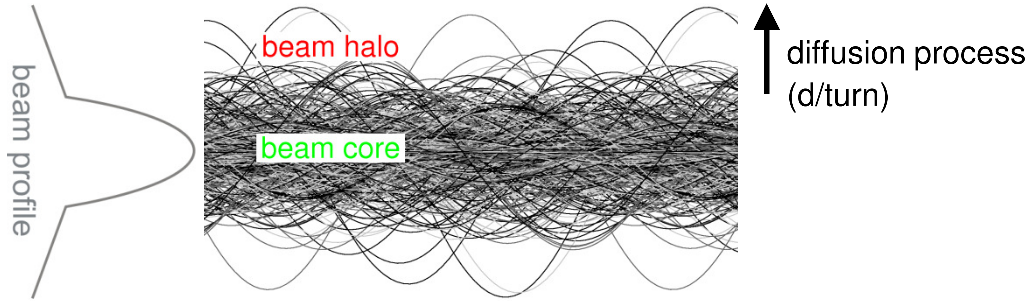
Overview

- Beam halo and regular beam losses
- Experimental studies and simulation of the residual activity
- Beam loss criteria for heavy ions and protons
- Halo collimation of fully stripped ions and protons in SIS100
- Halo collimation of partially stripped ions in SIS100
- Beam collimation in transfer lines

Beam halo & regular beam losses

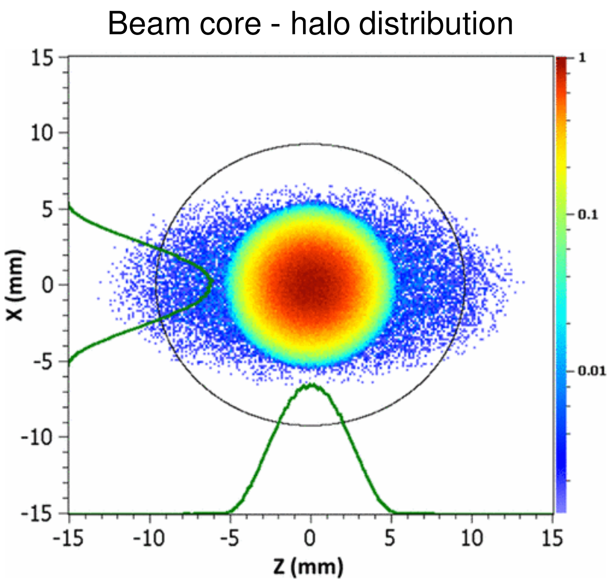
- Beam dynamics processes and machine errors → beam halo formation
  - General definition of the beam halo – difficult due to variety of machines and beams
  - Description – low density, large amplitudes of the betatron oscillations, diffusion speed

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



Diffusion speed can be very low: < 1 μm/turn (in synchrotrons)

[Ref] G. Valentino, Phys. Rev. ST AB 16, 021003 (2013)



[Ref] I. Hofmann, Phys. Rev. ST AB 16, 084201 (2013)

- Beam halo → uncontrolled regular beam losses (usually a few % of the beam)

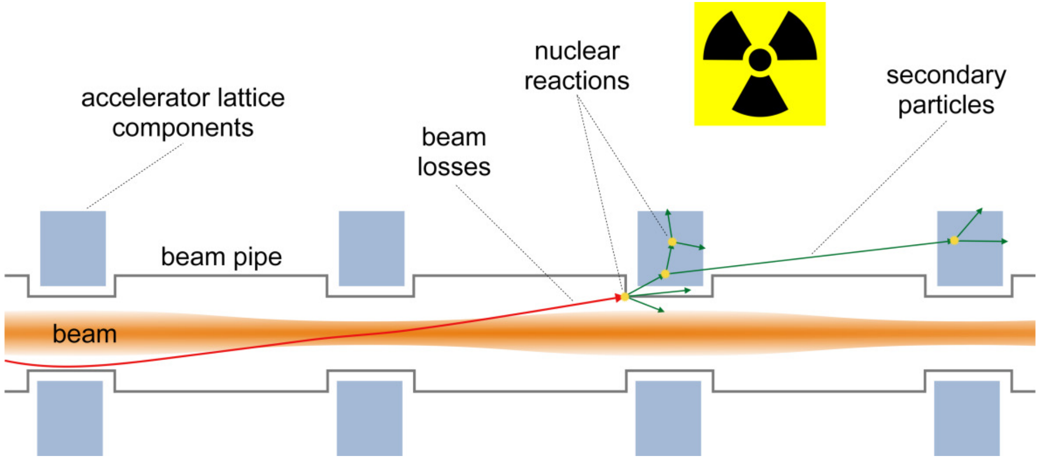
Beam losses & residual activation

- Consequences of the beam halo and uncontrolled beam losses
  - Residual activity induced in the accelerator structure
  - Radiation damage of the accelerator components
  - Vacuum degradation due to desorption process
  - Quench of the superconducting magnet

- Residual activation
  - Production of radioactive nuclei in construction materials of an accelerator
  - Important for "hands-on maintenance" (people who do installation or repair work)
  - High radiation in the area where a technical malfunction occurs → forbidden access → → cannot fix the machine → loss of time for operation

Residual activation process

- Mechanism of the residual activation

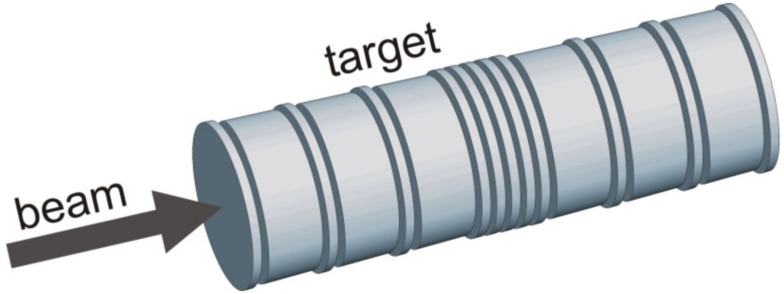


Radionuclides detected in the accelerator construction materials		
Material	Radionuclides	Half-life
Carbon, plastic	^{7}Be ^{11}C	53.1 days 20.4 minutes
Aluminum	Above plus: ^{22}Na ^{24}Na	 2.6 years 15.0 hours
Stainless steel	Above plus: ^{43}K ^{46}Sc ^{48}V ^{51}Cr ^{52}Mn ^{54}Mn ^{56}Co ^{57}Co ^{58}Co ^{59}Fe ^{60}Co	 22.3 hours 83.8 days 16.0 days 27.7 days 5.6 days 312.3 days 77.3 days 271.8 days 70.9 days 44.5 days 5.3 years
Copper	Above plus: ^{64}Cu ^{65}Zn	 12.7 hours 244.3 days

- Activation process - nuclear reactions
  - Spallation reactions
  - Radiative capture of low energy neutrons
  - Photonuclear reactions

Experimental studies of the residual activity @ GSI

- Irradiation of various materials using SIS18 heavy ion beams
- Compound targets for depth profiling of the residual activity
- Measurement of the activated samples using HPGe detector
- Gamma-spectroscopy analysis of the samples

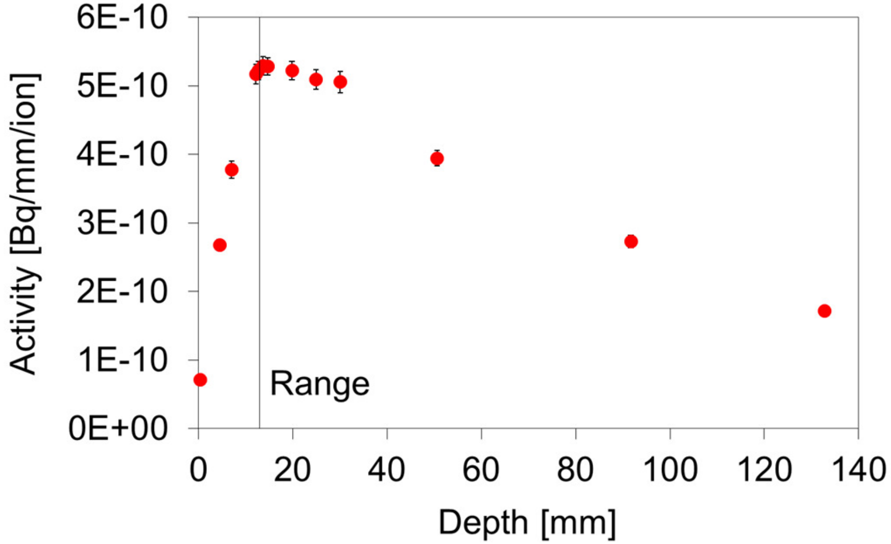


Year	Beam	Beam energy [MeV/u]	Target
2005 - 2006	^{238}U	950, 500	copper, stainless steel
2008	^{238}U	1000	stainless steel
2009	^{40}Ar	1000, 500	copper, alluminium
2010	^{238}U, ^{14}N	950, 500	alluminium, lead
2011 - 2012	^{238}U, ^{181}Ta	500, 100	graphite, carbon-composite
2014	^{238}U	950, 200	tungsten, copper, aluminium

Radioactive isotopes induced by ^{238}U ions

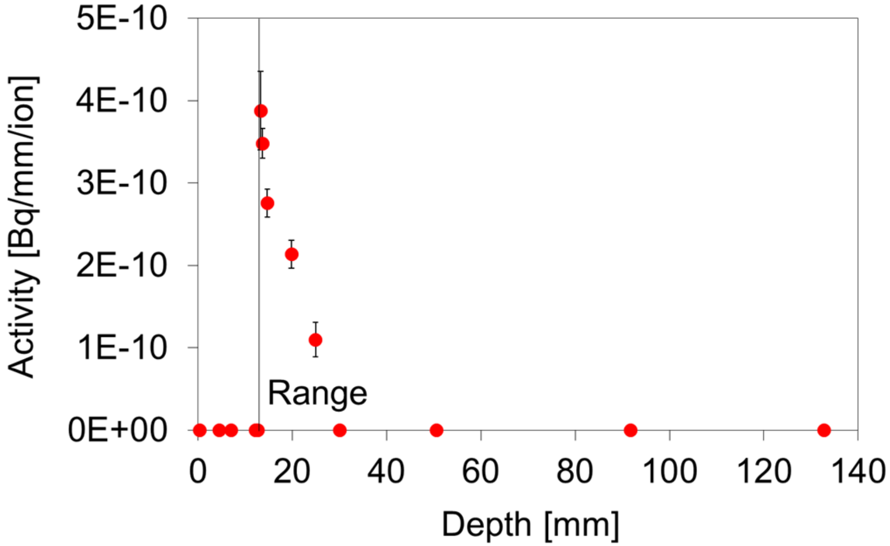
- Depth profile of ^{56}Co ($T_{1/2}$ = 77 d)
  target-nuclei fragment

  copper irradiated by 950 MeV/u ^{238}U ions



- Depth profile of ^{131}I ($T_{1/2}$ = 8 d)
  primary ion fragment

  copper irradiated by 950 MeV/u ^{238}U ions



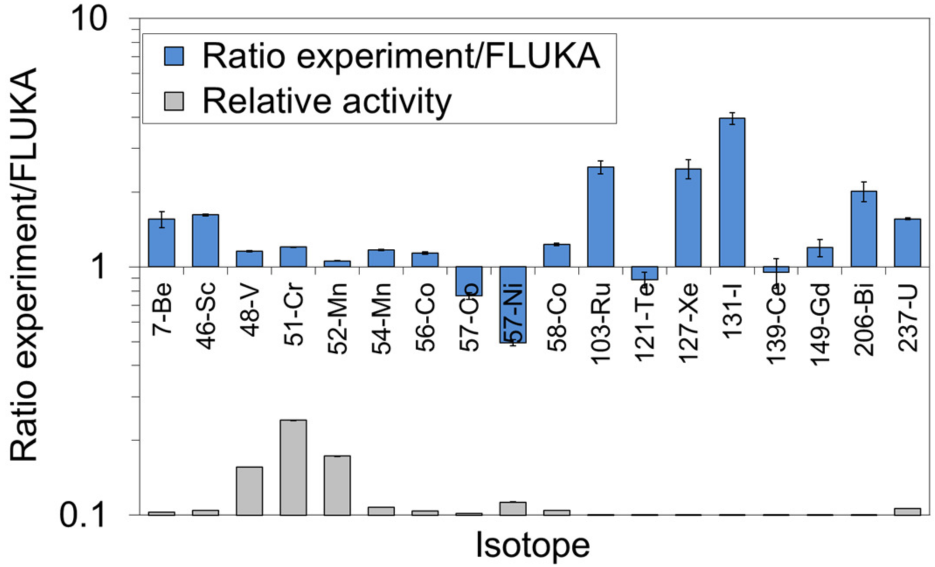
Validation of the simulation codes (FLUKA)

- FLUKA – Monte Carlo code for the simulation of particle transport in matter

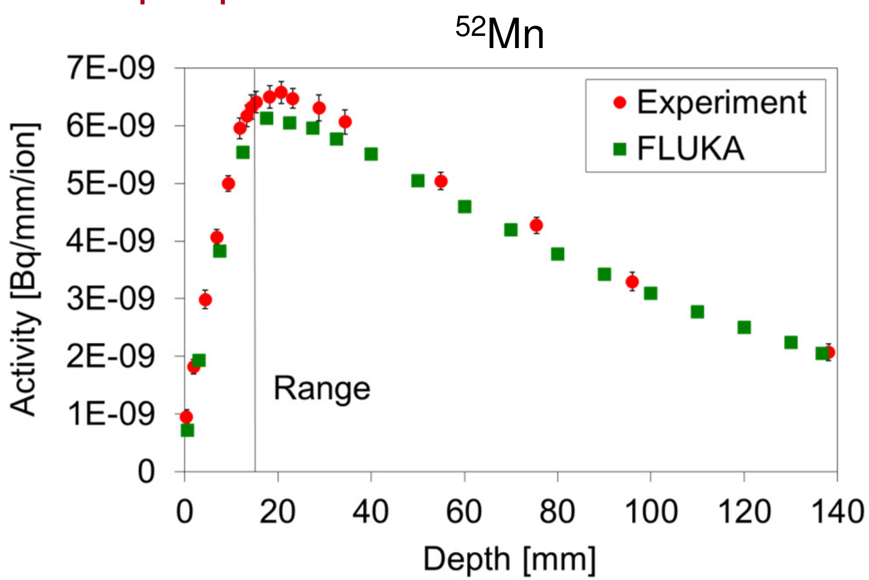
- Irradiation conditions

  Target material: stainless steel
  Beam: ^{238}U
  Beam energy: 950 MeV/u

- Residual activity of the isotopes



- Depth profiles

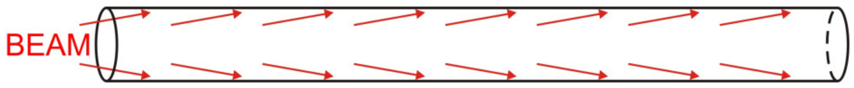


Tolerable beam losses of the proton beam

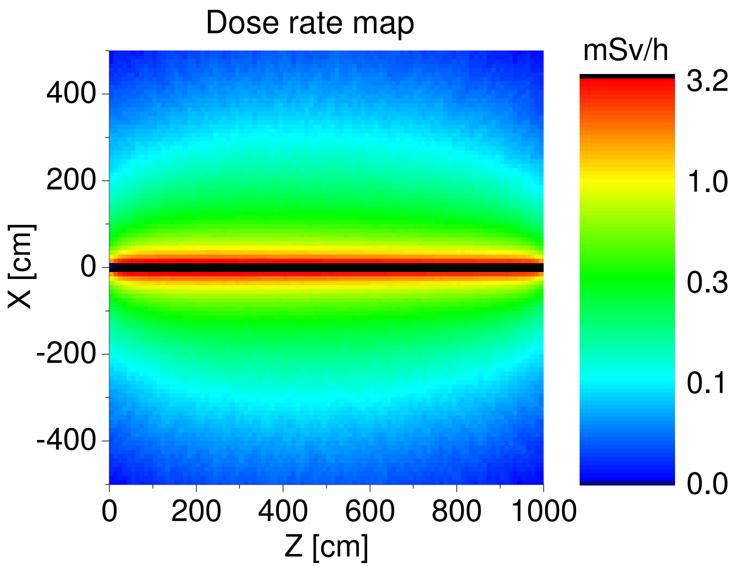
"uncontrolled beam losses of 1 W/m should be a reasonable limit for hands-on maintenance"

[Ref] N.V. Mokhov and W. Chou, The 7th ICFA Mini-workshop on High Intensity High Brightness Hadron Beams, USA, 1999.

- 1 W/m → 6.2×10^9 protons/(m·s) of energy 1 GeV (uniformly distributed)
- Simulation of the steel beam pipe residual activity induced by beam losses of 1 W/m
  - Simulation tool: FLUKA
  - Irradiation time: 100 days
  - Cooling time: 4 hours



Effective dose rate at 30 cm is about 1 mSv/h



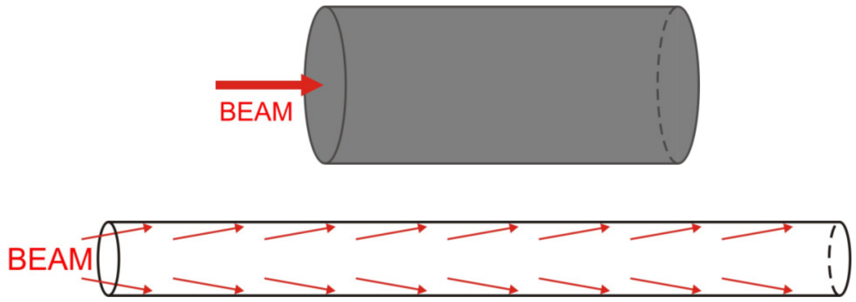
Natural background radiation (annual dose)	2 mSv
Medical radiation sources (e.g. CT scan)	10 - 20 mSv
Limit for radiation workers (annual dose)	20 mSv

Beam loss criteria for heavy ions

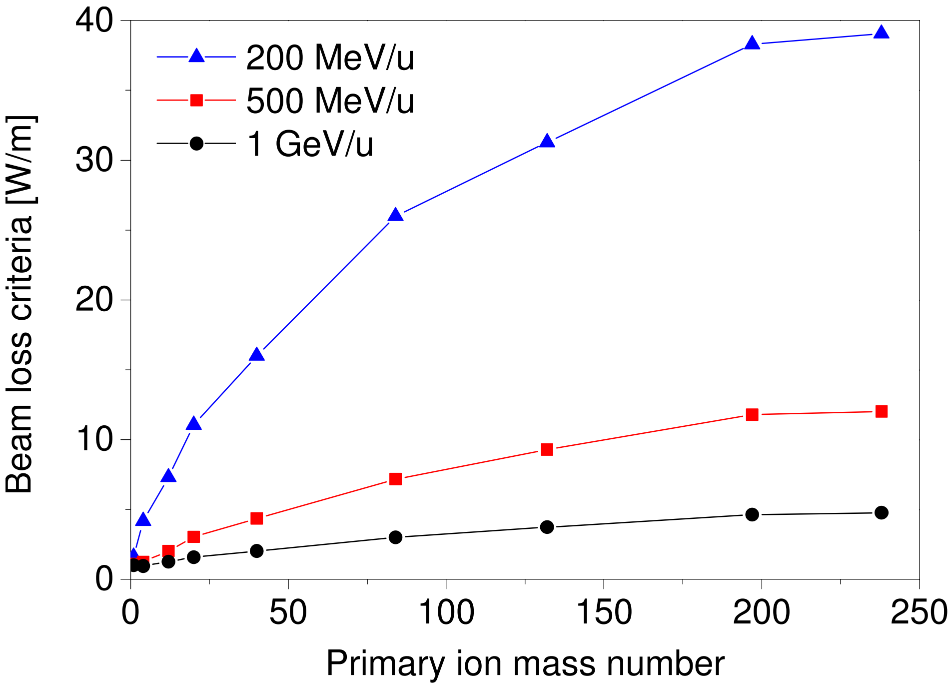
- Simulation performed by using FLUKA
- Beam loss criteria: A_p/A_i

  A_p – activity induced by 1 W/m of protons

  A_i – activity induced by 1 W/m of ions



Primary ions (E = 1 GeV/u)	Equivalent to 1 W/m [ions/(m·s)]
^{1}H	6.2×10^{9}
^{4}He	1.6×10^{9}
^{12}C	5.2×10^{8}
^{20}Ne	3.1×10^{8}
^{40}Ar	1.6×10^{8}
^{84}Kr	7.4×10^{7}
^{132}Xe	4.7×10^{7}
^{197}Au	3.2×10^{7}
^{238}U	2.6×10^{7}



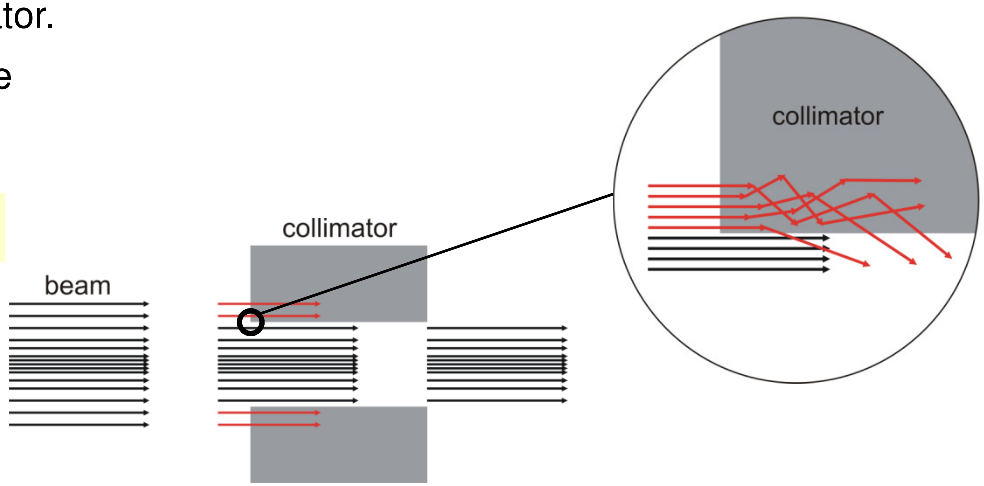
Halo collimation in high energy accelerators

- Collimation system - devices which intercept halo particles (future lost particles)
- Provides well defined and shielded storing location for the beam losses
- Residual activity is much higher (hot spot) compared to other components
- Collimation system design - two simulation tools of different types are needed
  - Particle interaction with the collimator material (e.g. FLUKA)
  - Particle tracking through the accelerator lattice (e.g. MAD-X)

- Simple idea of the halo collimation
  - Naively, the particles are stopped in the collimator.
  - In reality, due to small impact parameter are the particles scattered out of the collimator!

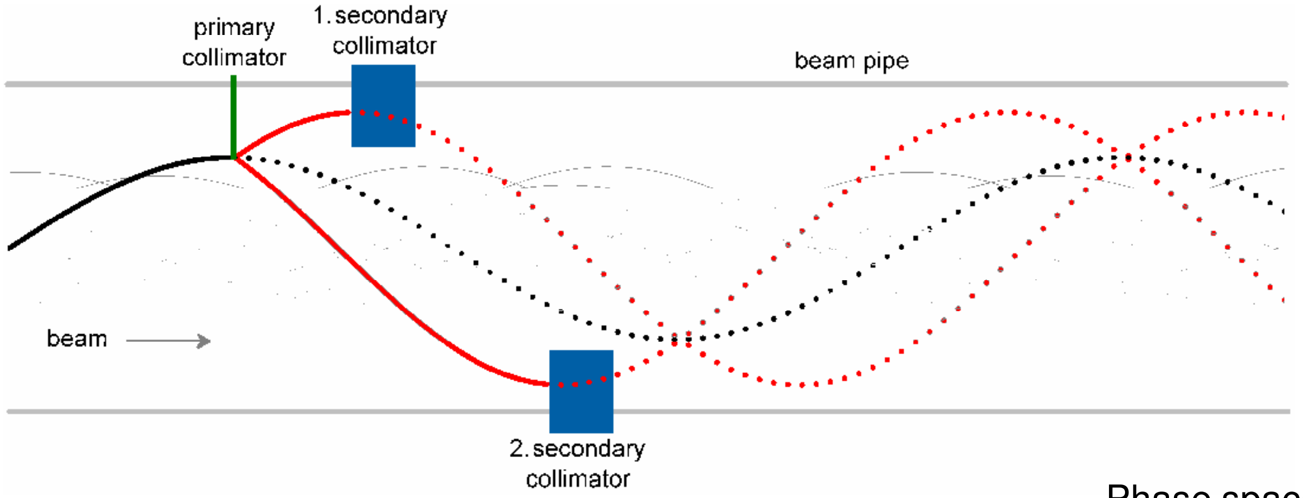
Impact parameter is usually very small: nm - µm

[Ref] G. Valentino, Phys. Rev. ST AB 16 (2013)



Two stage betatron collimation system

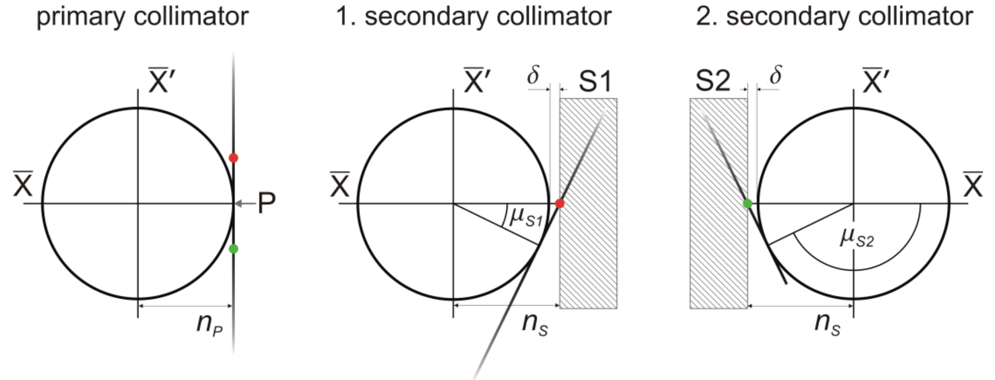
- Two stage collimation system consist of:
  - Primary collimator (thin foil) – scattering of the halo particles
  - Secondary collimators (bulky blocks) – absorption of the scattered particles



Very robust concept and well established in many accelerators.

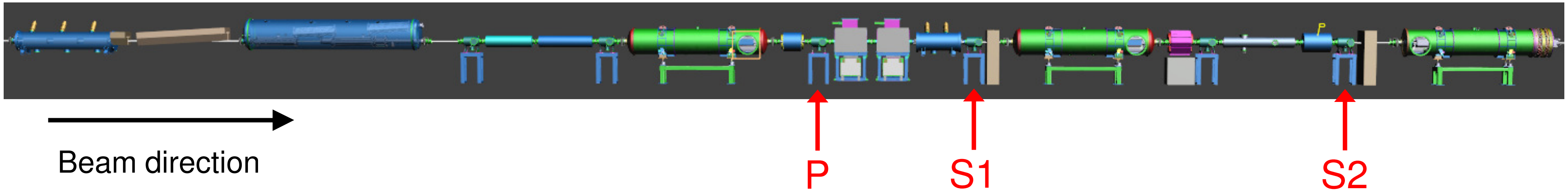
[Ref] J.B. Jeanneret, Phys. Rev. ST AB 1 (1998)

Phase space plots



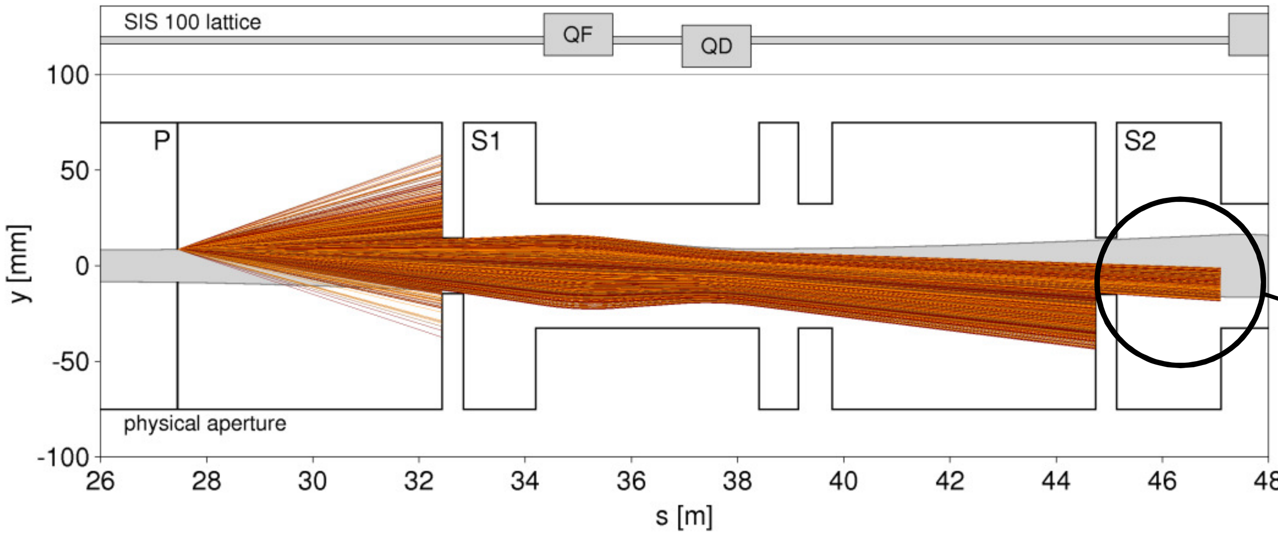
Collimation system for protons in SIS100

- Location in SIS100: Sector 1, straight section



P – primary collimator
S1 – 1st secondary collimator
S2 – 2nd secondary collimator

- Simulation of the proton beam collimation in SIS100 using FLUKA and MAD-X codes



What happens with the particles that escape?

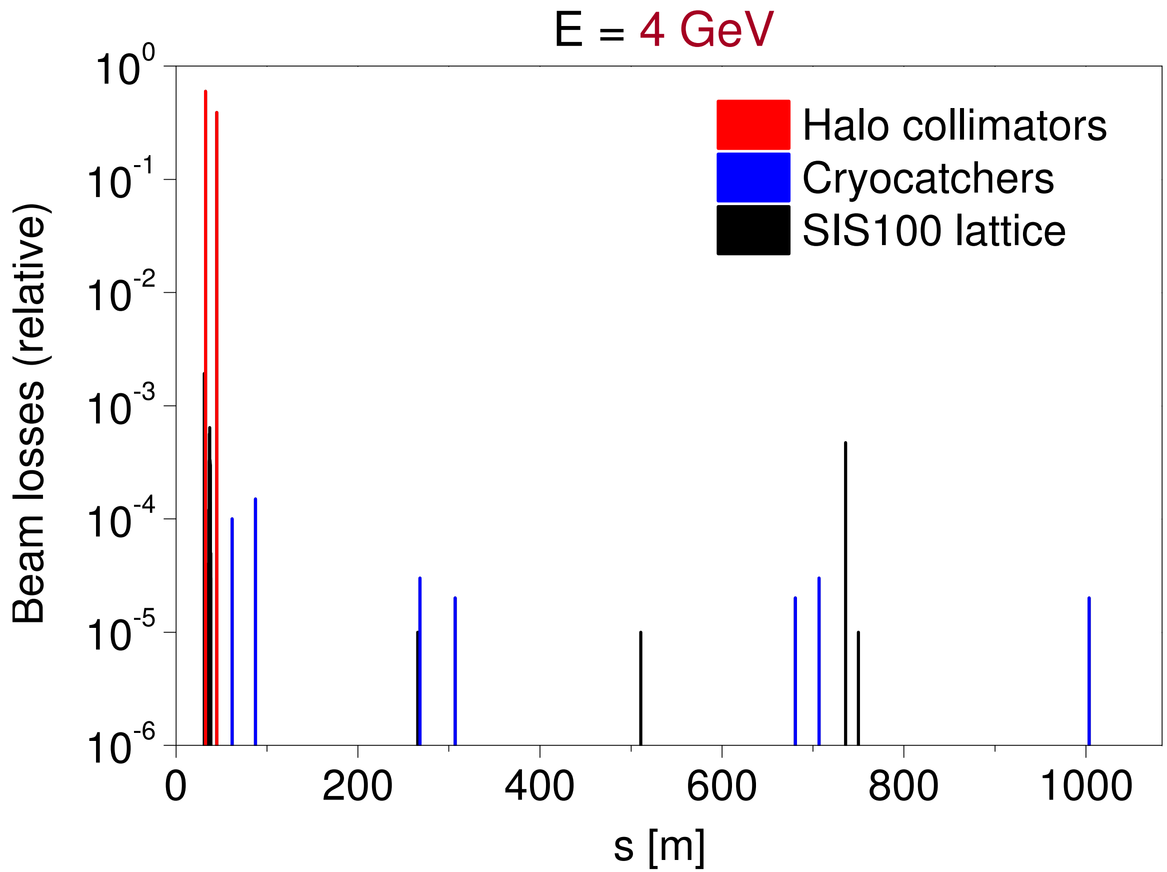
Efficiency of the proton collimation in SIS100

Beam-material interaction: FLUKA

Particle tracking in the SIS100 lattice: MAD-X

Statistics: 100 000 particles

Collimation efficiency: ~ 99 %



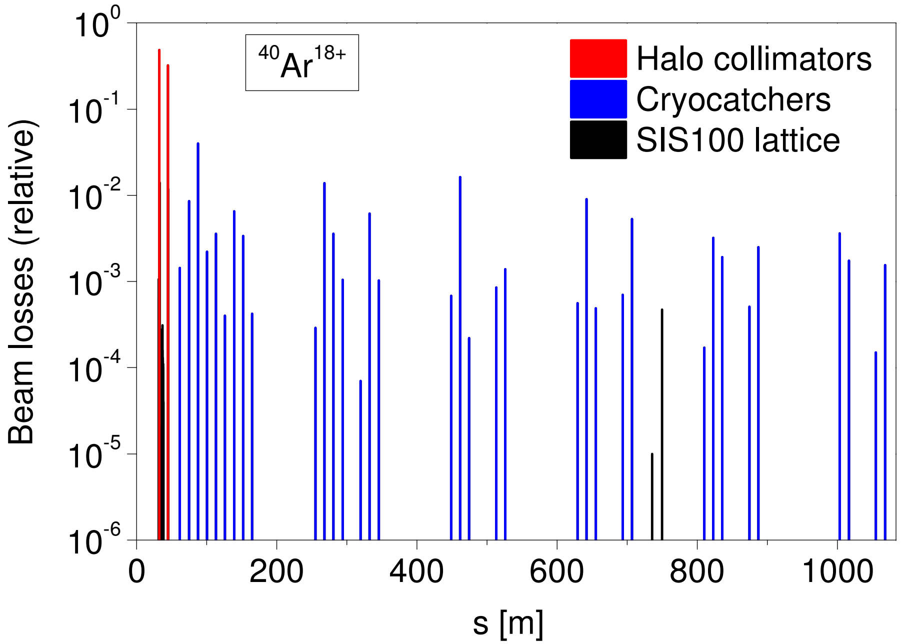
Collimation of fully stripped ions in SIS100

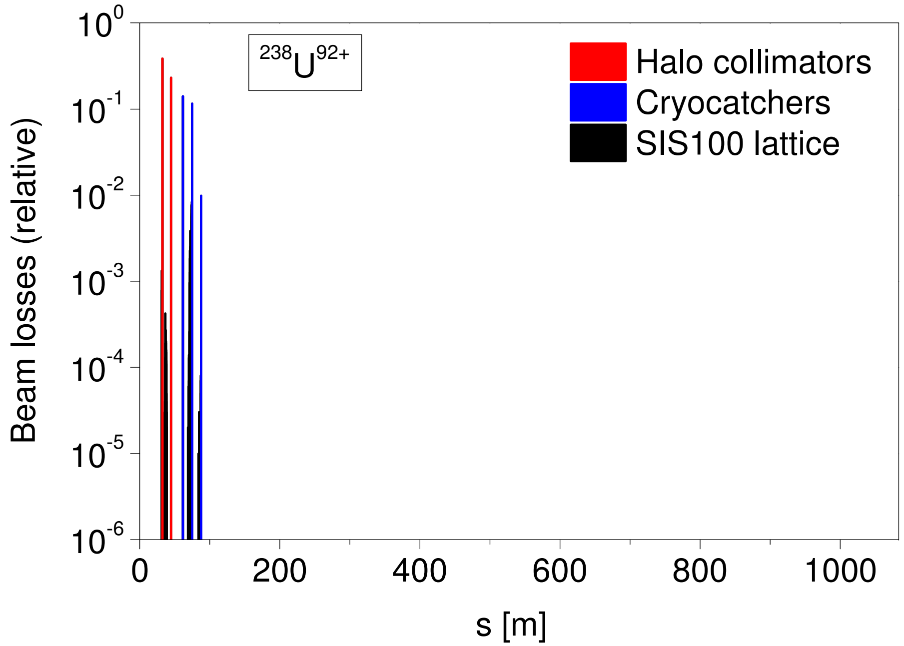
- Proton collimation system in SIS100 is used also for the fully stripped ions

Beam-material interaction: FLUKA

Particle tracking in the SIS100 lattice: MAD-X

Statistics: 100 000 particles



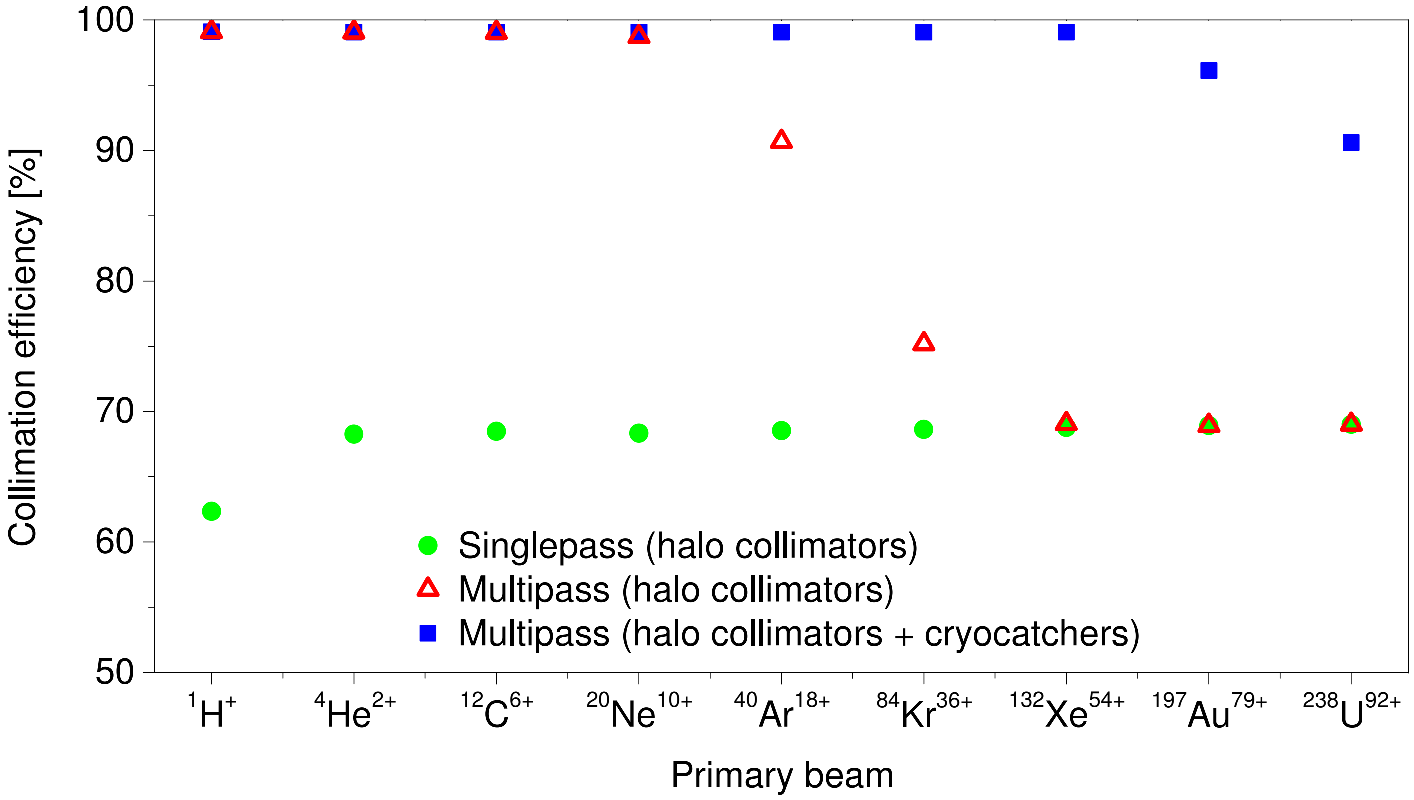


Collimation efficiency for the fully stripped ions

Beam-material interaction: FLUKA

Particle tracking in the SIS100 lattice: MAD-X

Statistics: 100 000 particles

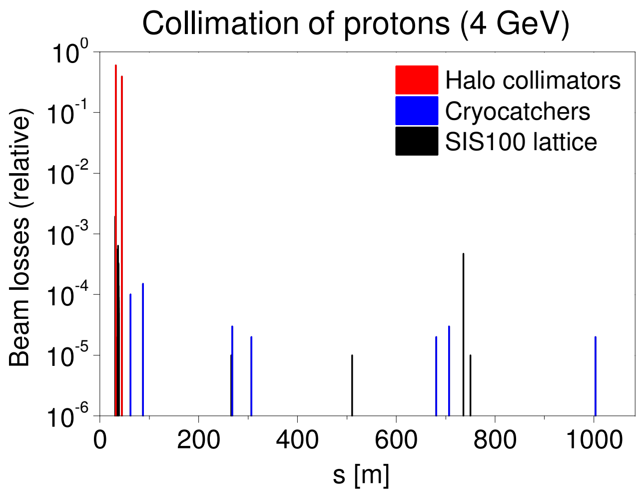


Tolerable beam losses in SIS100

- SIS100 beam parameters and equivalent to 1 W/m (number of particles)

Beam	Injection energy	Extraction energy	1 W/m equivalent (injection)	1 W/m equivalent (extraction)	Beam intensity
Protons	4 GeV	29 GeV	1.5×10^9	2.1×10^8	2×10^{13}
$^{40}Ar^{18+}$ ions	1.6 GeV/u	12 GeV/u	1×10^8	1.3×10^7	1×10^{11}
$^{238}U^{92+}$ ions	1.3 GeV/u	10 GeV/u	2×10^7	2.5×10^6	1.5×10^{10}

- From the beam loss maps tolerable beam losses (% of the beam) can be identified.

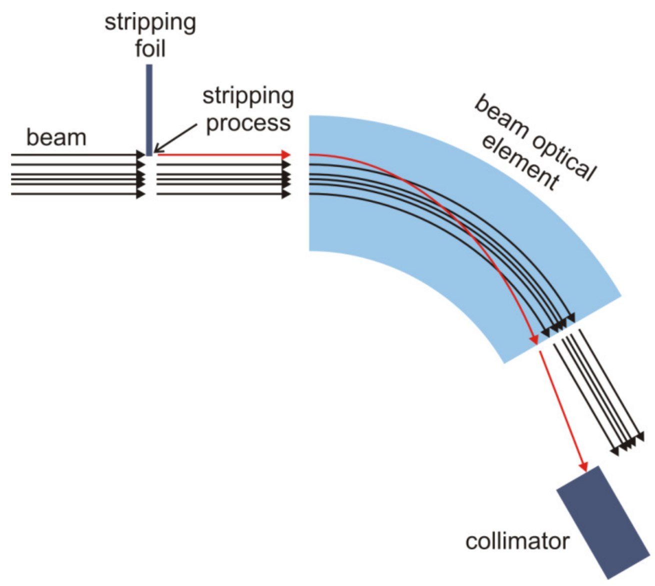


Beam	Loss criteria (injection)	Loss criteria (extraction)	Tolerable losses (injection)	Tolerable losses (extraction)
Protons	1 W/m	1 W/m	10 %	5 %
$^{40}Ar^{18+}$ ions	2 W/m	1 W/m	30 %	6 %
$^{238}U^{92+}$ ions	4 W/m	2 W/m	20 %	10 %

Collimation of partially stripped ions in SIS 100

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

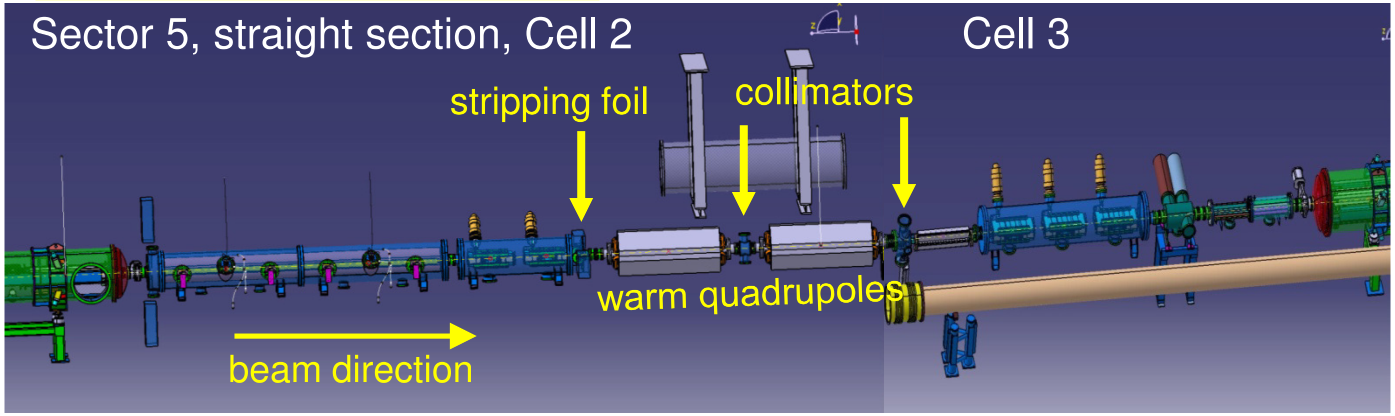
  $^{238}_{92}U^{28+}$, $^{197}_{79}Au^{25+}$, $^{181}_{73}Ta^{24+}$, $^{132}_{54}Xe^{22+}$, $^{84}_{36}Kr^{17+}$, $^{20}_{10}Ne^{5+}$



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

- Collimation of the partially stripped ions in SIS100

Slow extraction area in SIS 100

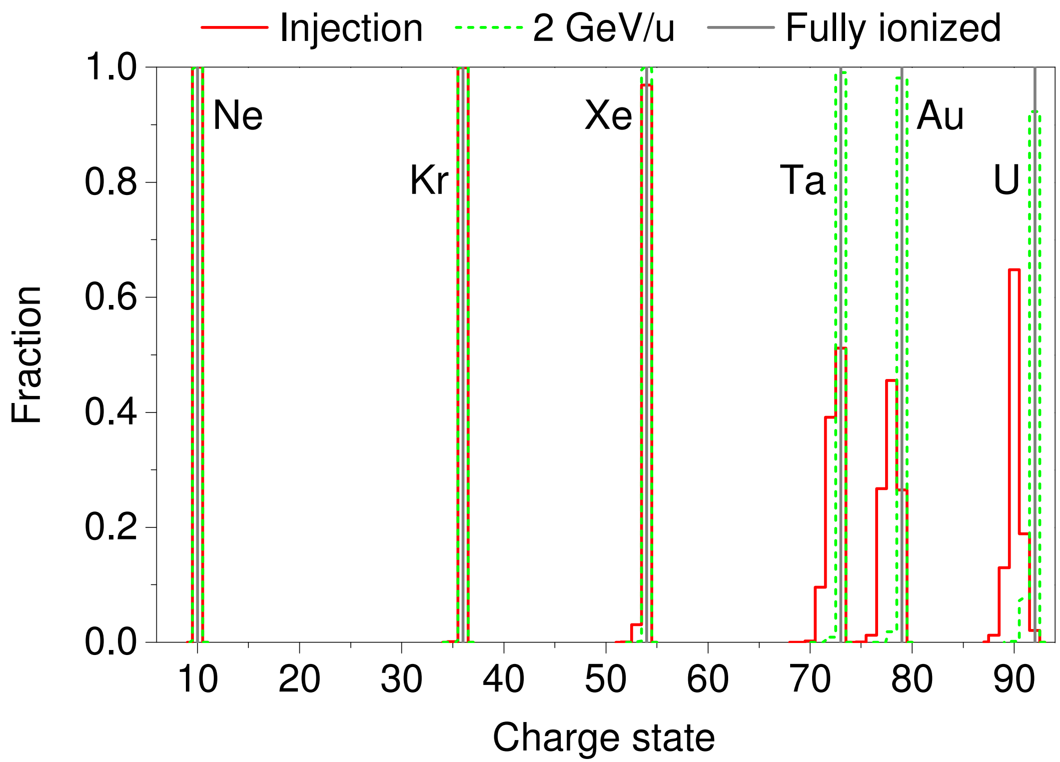


Charge state distribution after stripping

Electron capture and electron loss → Equilibrium charge-state distribution

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

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



Stripping foil: 500 μm thick, titanium

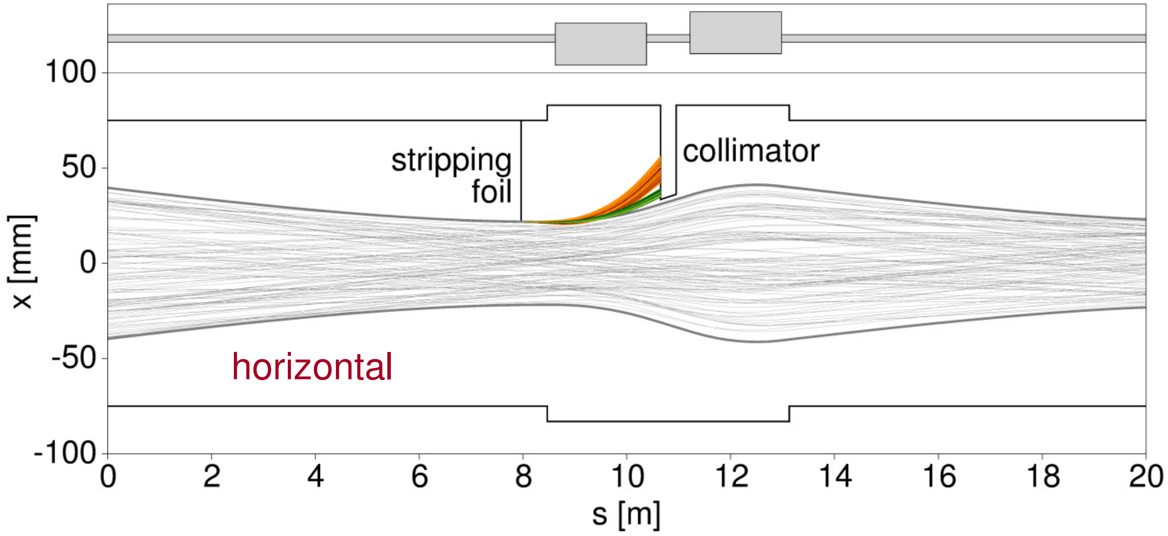
Particle tracking of stripped ions

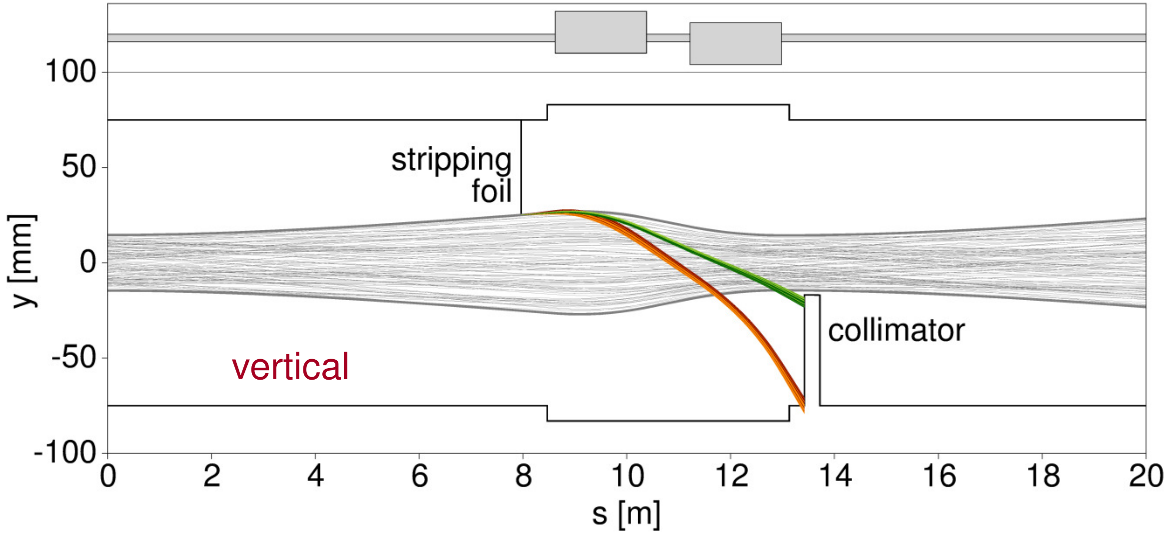
Orange tracks

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

Green tracks

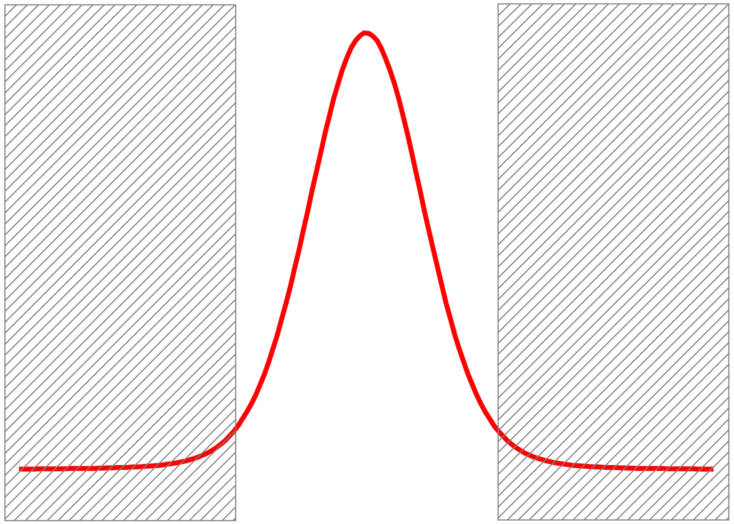
$^{20}_{10}Ne^{5+} \rightarrow ^{20}_{10}Ne^{10+}$





Collimation in the beam transfer lines

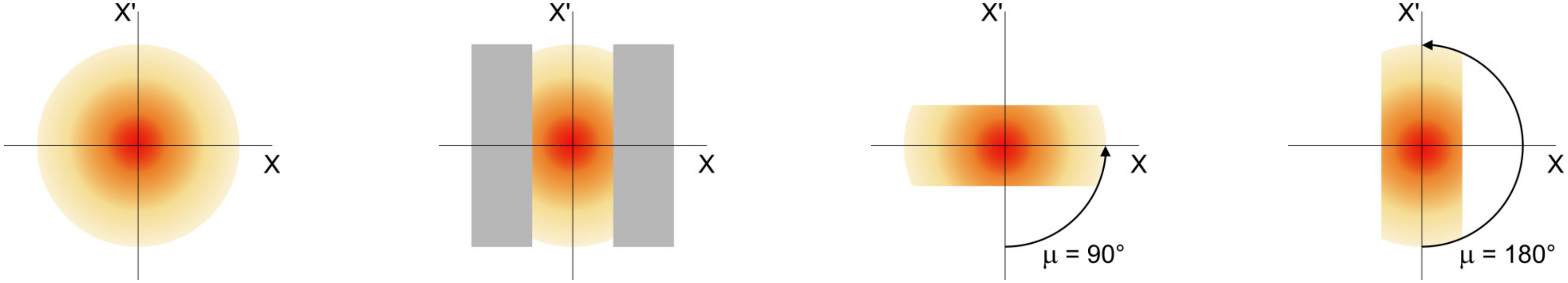
- Halo collimation or cut the tails?
  - Beam halo – unstable particles with diffusion speed assumed to be lost
  - Beam tails – part of the beam distribution larger than certain n×σ



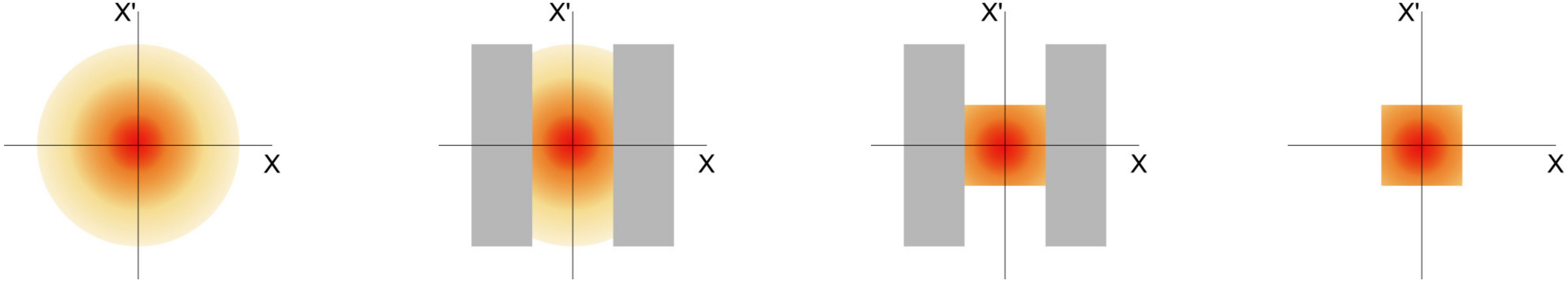
- Collimation in the beam transfer lines
  - Prevent background in experiments
  - Single pass process
  - Using of thick absorbers (two stage system is not useful)
  - Different beam size → variable aperture of the collimators (stepping motors)

Outline of the collimation in the transfer lines

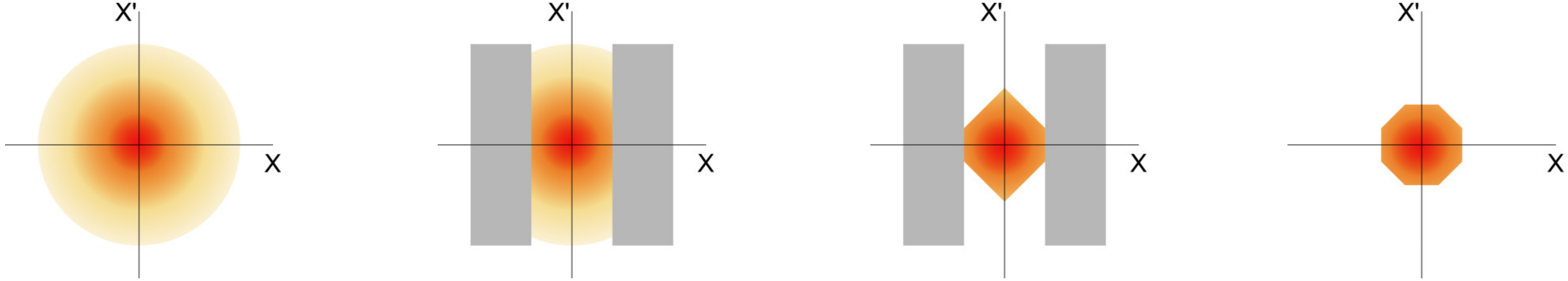
- 2 collimators at 1 position (phase advance between the collimator and detector is crucial)



- 4 collimators at 2 positions (phase advance between the positions is 90°)



- 8 collimators at 4 positions (phase advance between the positions is 45°)



Summary

- Residual activation in heavy ion accelerators
  - Experimental studies of the residual activity induced by heavy ions performed at GSI
  - Simulation of the residual activity – validation of the simulation codes (FLUKA)
  - Beam loss criteria for heavy ion beams are less strict (in W/m) than for protons

- Halo collimation in heavy ion accelerators
  - Halo collimation of fully stripped ions and protons
  - Halo collimation of partially stripped
  - Collimation efficiency in SIS100 can be 99 % in the most of the cases

- Detailed information
  - Residual activation in heavy ion accelerators

    [Ref] I. Strašík, E. Mustafin, and M. Pavlovič, Phys. Rev. ST AB 13 (2010)
  - Beam halo collimation in heavy ion accelerators

    [Ref] I. Strašík, I. Prokhorov, and O. Boine-Frankenheim, Phys. Rev. ST AB 18 (2015)

Thank you for your attention