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SIMULATION STUDY OF BEAM HALO COLLIMATION IN THE HEAVY-ION SYNCHROTRON SIS 100 *

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Abstract

The FAIR synchrotron SIS 100 will be operated with high-intensity proton and heavy-ion beams. The collimation system should prevent beam loss induced degradation of the vacuum, activation of the accelerator structure and magnet quenches. A conventional two-stage betatron collimation system is considered for the operation with protons and fully-stripped ions. Particle tracking and ion-collimator interaction simulations of the collimation system were performed. The angular and momentum distributions of the scattered halo particles were described using analytical models and numerical tools like ATIMA and FLUKA. MADX was used for the multi-pass tracking simulations. The results obtained for the collimation cleaning efficiency as a function of the ion species and beam energy together with the detailed beam losses distributions along the ring circumference are presented. This work highlights the main aspects of the collimation of fully-stripped ion beams in the intermediate energy range using conventional two-stage systems.

INTRODUCTION

The FAIR heavy ion synchrotron SIS 100 will utilize a conventional multi-stage collimation system for light (e.g. $^{12}C^{6+}$) and heavy (e.g. $^{238}U^{92+}$) ion beams in the range of beam rigidities from 18 to 100 Tm. The collimation system is designed to keep the machine hands-on maintainable and to not exceed the tolerable level of uncontrolled beam losses of 1 W/m [1]. Although conventional collimation systems are a well-developed concept applied in a variety of high-power circular accelerators [2], the collimation of relativistic heavy ions requires additional understanding of particle-material interaction processes. Since the injection is the longest part of the machine cycle we are concerned mostly about collimation at the injection energy.

We start this paper with the description of the SIS 100 collimation system design. We briefly discuss the relevant physics of ion-material interaction in the second part. The results of the simulations of cleaning efficiencies for different scenarios in SIS 100 are presented in the last section.

SIS 100 COLLIMATION SYSTEM

We propose to use 1 mm thick tungsten foil as the first stage – primary collimator (scatterer) and two 400 mm blocks as the second stage – secondary collimators (absorbers). Tungsten has been chosen as a material for primary collimator because it provides significantly wide scattering within comparably small thickness. The choice of the material for the secondary collimators is still the matter of investigation. For the simulation studies we assumed the secondary collimators being an ideal absorbers. The collimators have a rectangular aperture – two vertical and two horizontal jaws. The jaws are supposed to be movable.

The longitudinal distances between the primary and one of two secondary collimators are 5 m and 17 m, respectively. The location of the collimators in the lattice is selected due to the space limitations in the machine. The phase advance between collimation stages depends on the working point of the accelerator and can not be adjusted. However, these positions provide similar phase advances close to the required optimum.

INTERACTION OF HEAVY IONS WITH COLLIMATORS

For an adequate simulation of the halo collimation we need to know the angular and momentum distributions of the halo particles after the first collimation stage, namely after scattering in a thin tungsten foil. Fragmentation of the primary beam is also a point of interest. We used ATIMA [3] and FLUKA for the simulations of aforementioned processes.

Angular Scattering

A charged particle passing matter experiences multiple Coulomb scattering. According to Moliere theory, the angular distribution of scattered particles is roughly Gaussian with the r.m.s. angle θ_0 (Eq.1), $B\rho$ is the magnetic rigidity and x is the foil thickness.

$$\theta_0 = \frac{0.47}{\beta\,(B\rho)\,[Tm]}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln\left(\frac{x}{X_0}\right)\right], \qquad (1)$$

here X_0 is radiation lengths, tabular value for tungsten is $X_0 = 3.504$ mm. Moliere theory predicts Gaussian distribution in the range $10^{-3} < x/X_0 < 100$.

Figure 1 shows r.m.s. angle as a function of beam magnetic rigidity for different ion species being accelerated in SIS 100. For relativistic particles with $\beta \approx 1$ the r.m.s. angle decreases hyperbolically with beam rigidity. The outcome of this fact is that the same transverse collimation system geometry can be used for all ion species including protons. FLUKA simulation of the angular distribution shows non-gaussian tails starting at 2.7 σ and containing roughly 1% of the total amount of particles.

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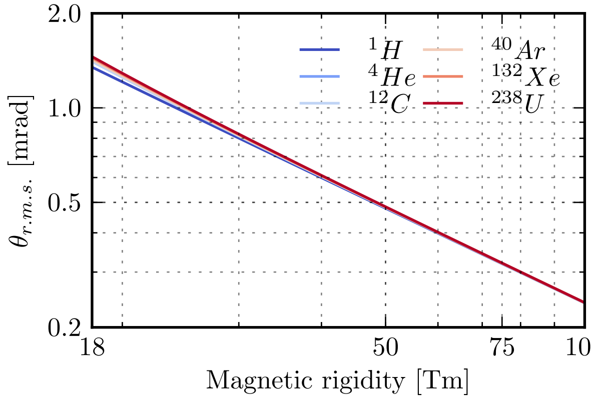

Figure 1: Angular scattering of different ions in 1 mm tungsten foil as a function of beam magnetic rigidity. Simulated by ATIMA.

Momentum Losses

Momentum losses (see Figure 2) are described by (Eq.2) with the following corrections to standard Bethe-Bloch term L_0: δL_{shell} correction represents the motion of electrons in the matter, δL_{Barkas} is proportional to Z^3 and δL_{LS} takes into account the finite radii of heavy nuclei [4].

$$-\frac{\delta p}{p} = \frac{K}{\beta^4}\frac{Z_t}{A_t}x\,[L_0 + \delta L_{shell} + \delta L_{Barkas} + \delta L_{LS}], \tag{2}$$

here $K = 3.07 \cdot 10^{-4} GeV g^{-1} cm^2$.

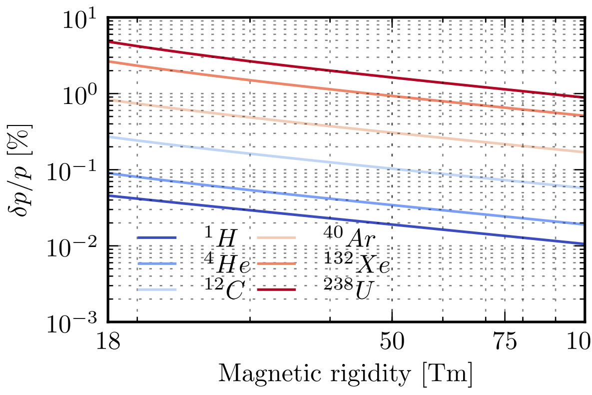

Figure 2: Momentum losses for different ions in 1 mm tungsten foil as a function of beam magnetic rigidity. Simulated by ATIMA.

According to [4], momentum straggling has Gaussian distribution for ions heavier than $^{40}Ar^{18+}$ at SIS 100 injection energy.

Inelastic Nuclear Interaction

Cross-sections and, hence, probabilities of the inelastic nuclear interaction for light and heavy ions passing through the tungsten foil were calculated using Tripathi formula [5] and simulated with FLUKA (see Table 1).

Table 1: Probability of inelastic nuclear interaction of beam ions at different energies passing through 1 mm tungsten foil.

Beam	**Tripathi** ≥18 Tm	**FLUKA** 18 Tm	**FLUKA** 100 Tm
$^{1}H^{1+}$	0.011	0.011	0.011
$^{40}Ar^{18+}$	0.031	0.032	0.044
$^{238}U^{92+}$	0.057	0.114	0.236

SIMULATION STUDIES OF CLEANING EFFICIENCY

For the simulation studies MADX was used as a main particle tracking tool, distributions of the halo particles were obtained with the help of ATIMA and FLUKA. We define cleaning efficiency as the ratio of halo particles intercepted by the secondary collimators to the initial amount of halo particles. We also distinguish the cleaning efficiency of the first turn – *singlepass* efficiency, and the overall efficiency gained after many turns when all the halo particles are lost – *multipass* efficiency. In the SIS 100 there are special installations – *cryocatchers* – for collimation of partially-stripped ions [6], we consider halo particles lost in these elements as collimated, see Figure 3.

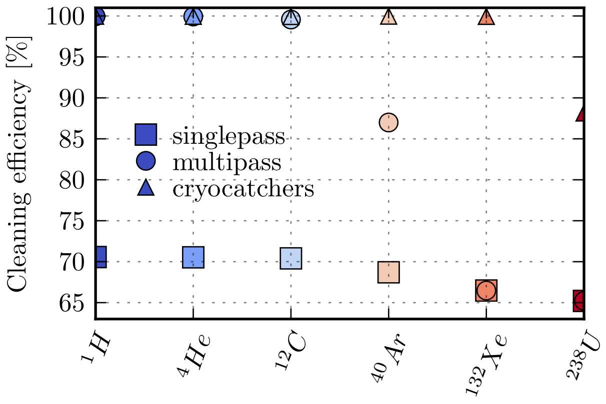

Figure 3: Cleaning efficiency at the SIS 100 injection energy ($B\rho$ = 18 Tm) for light and heavy ions. Primary collimator placed at 4.5 σ, secondary collimators are retracted by 10 %.

The cleaning efficiency decreases with the mass number due to the increasing momentum losses in the primary collimator. Strongly off-momentum heavy particles are unable to make one turn in the accelerator and are lost in the high-dispersion regions of the lattice.

With the increasing beam energy singlepass efficiency goes down drastically (2% at 100 Tm) because of significant decrease of angular scattering. However, multipass collimation becomes possible for heavy ions at high energies due to relative momentum losses smaller than momentum acceptance, see Figure 4.

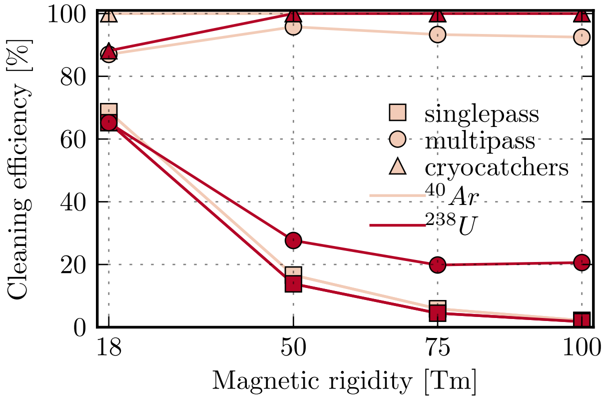

Figure 4: Collimation efficiency as a function of beam energy.

An impact parameter of the halo particles on the primary collimator is an entity related to the diffusion speed of the halo particles. Since we don't know the exact value of the diffusion speed, a series of simulations for different impact parameters has been done. In SIS 100 a halo particle with the impact parameter $\leq 1\ \mu$m does not pass through the full thickness of the primary collimator.The simulation studies shows (see Figure 5) that for heavy ions with small impact parameter the multipass regime of collimation is possible.

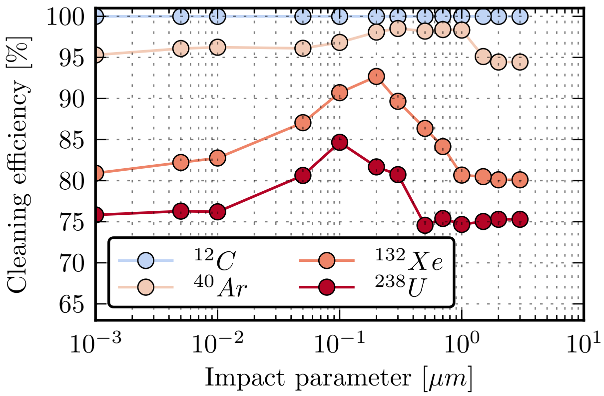

Figure 5: Cleaning efficiency of halo particles with different initial impact parameters on the primary collimator. Beam at injection energy.

In order to check the robustness of the designed collimation system we studied the influence of the closed orbit distortion on the collimation performance. Transversal misalignments of quadrupole magnets were assumed to be the main source of the closed orbit distortion (COD). Lattice imperfections have no effect on the singlepass collimation efficiency and thus do not affect the collimation efficiency for heavy ions. For light ions collimation efficiency decreases by 5 % when r.m.s. COD is 6.75 mm. Lattice imperfections also lead to the additional spikes on the loss maps.

Figure 6 shows an example of the beam losses distribution along the ring circumference. For all ion species losses outside of collimators are concentrated in cryocatchers. For the heaviest ions main locations of losses are the cryocathers in the first straight section of the machine.

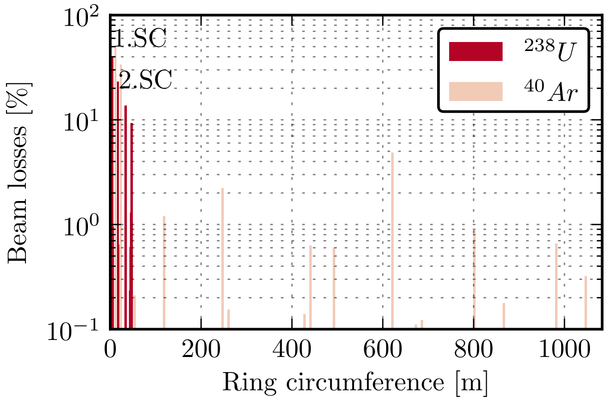

Figure 6: Simulated beam loss locations along the SIS 100 circumference.

CONCLUSION

We have performed a series of simulations of light and heavy ion beam collimation system using MADX for tracking and ATIMA and FLUKA for ion-material interaction simulations. Based on the obtained results we can conclude that conventional collimation system can be used for efficient cleaning of variety of ion beams at energies available in SIS 100. The momentum losses of the heavy ions in the primary collimator at the injection energy are considered as the main limitation of high cleaning performance. However, heavy ion beam losses outside of the collimation system are mostly concentrated in the cryocatchers. In these studies we assumed that products of inelastic nuclear interaction are lost in the collimators, the detailed simulations of the fragments trajectories in the collimation system is foreseen.

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