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FIRST STUDIES OF ION COLLIMATION FOR THE LHC USING BDSIM*

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Abstract

At the Large Hadron Collider (LHC) at CERN ion physics runs are performed in addition to proton physics runs. In ion operation the cleaning efficiency of the collimation system is lower than in the case of protons and the ion showering process is more complicated and produces a larger variety of secondary particles. In particular, lighter ion species can be produced as fragmentation products in the collimation system and specialised physics lists are required to simulate their production and propagation in matter. The Geant4 toolkit offers comprehensive physics process lists that extend to the case of arbitrary ion species at high energies. First results from a study of ion collimation for the LHC using the Geant4 physics library in BDSIM are presented here. These include simulations of a full ring loss map and particle spectra for collimator leakage for a Pb beam at injection energy in the LHC.

ION COLLIMATION AT THE LHC

The LHC has a multi-stage collimation system that is designed to protect the machine and the experiments by removing the halo in high-energy, high-power proton beams in the standard mode of operation [1]. The collimation of ion beams when the LHC operates as a heavy ion collider involves additional challenges as a result of the additional nuclear interactions that ions can undergo in the collimators [2]. In the multi-stage collimation system of the LHC, the collimators are arranged in a hierarchy based on their opening and the material they are made of. This is because the energy is sufficiently high that no single collimator can stop a particle as the length is limited by beam divergence and impedance. The primary collimators have the smallest openings and are designed to intercept particles in the beam halo and disrupt their trajectories. The particles scattered by the primary collimators should be diverted into the secondary collimators where further scattering and shower development occurs [3]. In the case of ions, the interaction cross-section is much larger and it is likely that an ion undergoes nuclear fragmentation or electromagnetic dissociation before it leaves the collimator. The secondary ion fragments produced in those interactions can leave the collimator at a small angle, but have altered rigidity. Fragments that are found within the geometrical acceptance of the machine, but outside of the magnetic rigidity acceptance are likely to be lost in the dispersion suppressor downstream, where they cause an increased heat load to the superconducting magnets and increased risk of quenches.

In order to accurately the simulate collimation system performance for ions, nuclear fragmentation and hadronisation must be fully simulated. One of the tools that does this is the heavy ion SixTrack-Fluka active coupling [4]. In such simulations, the heavy ion beam is tracked with SixTrack in the magnetic lattice of the machine and passed on to Fluka for shower simulation in the collimators. The fragments resulting from interactions in the collimator are passed back to SixTrack for further tracking [5]. Using this technique, a qualitative agreement is seen between simulations and measurements [6]. In this work the aim is to further improve the accuracy of simulation predictions by taking into account fragmentation and showering processes in the whole accelerator, not just the collimators.

BEAM DELIVERY SIMULATION (BDSIM)

BDSIM [7] is a program that combines particle tracking routines and radiation transport to simulate energy deposition and charged particle background in a 3D model of an accelerator. The model is built using the description of the machine in MADX [8] and the physics processes for radiation transport are provided by the Geant4 library [9]. The particles in the beam are tracked through the magnetic lattice of the machine using BDSIM's thick-lens tracking algorithms until an aperture or any other solid mass is encountered. At this stage, the Geant4 physics processes are invoked to simulate the shower development and the secondary particles produced are tracked further using numerical integration until they deplete their energy. Information about the trajectory and the history of interactions is saved for each particle, which allows the position of energy deposition to be accurately traced back to where the particle first interacted. This is of particular interest for ion collimation studies, where secondary ion fragments can travel significant distances and produce further showering before finally depleting their energy. BDSIM has full native support for ion species both in terms of tracking and physics that makes the presented study possible.

SIMULATION SETUP

The chosen configuration for this pilot study of ion collimation using BDSIM is the LHC at injection wth lead ions. The model used for this study is based on the LHC 2015 injection optics [10] and collimation settings.

Beam 1 is used and the starting primary distribution is a horizontal halo beam starting at the surface of the horizontal primary collimator (TCP.C6L7.B1). Only a fraction of the halo on the boundary of the collimator jaw that is likely to interact is selected. No energy spread is included in the simulation. Some of the main parameters are summarised in Table 1.

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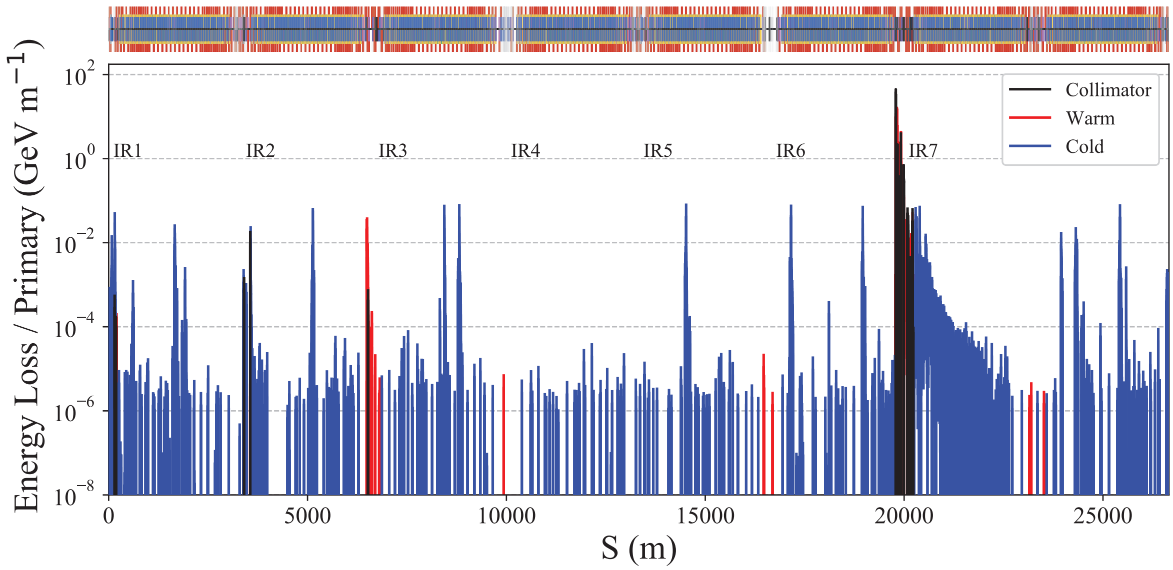

Figure 1: Normalised energy deposition around the whole ring. The machine elements are shown on top.

Table 1: Summary of beam and collimator parameters

Parameter	**Value**
Particle	Pb-82-208
E / Z	450 GeV
ϵ_N	1.4 µm
Primary collimator opening (H)	5.7 σ
Secondary collimator opening (H)	6.7 σ

Table 2: Summary of production cuts and corresponding energy cuts in materials

	Range Cut	**Energy cut** C	Cu	W
e^-	1 m	777 MeV	10 GeV	10 GeV
p	1 m	100 MeV	100 MeV	100 MeV
γ	1 m	4.5 MeV	10 GeV	10 GeV

The physics processes in the simulation includes nuclear, hadronic and electromagnetic interactions provided by the following Geant4 physics lists and processes: *G4EmStandardPhysics*, *G4HadronPhysicsFTFP_BERT*, *G4DecayPhysics*, *G4IonPhysics*, *G4IonElasticPhysics*, *G4RadioactiveDecayPhysics*, *G4HadronElasticPhysics*, *G4EMDissociation*.

For computational efficiency, secondary production cuts are in place to control the infrared divergence of the simulation. As the energy beam is very high in comparison to the rest mass of basic particles, a very large number of secondaries can be generated that would dominate the simulation time. Moderate use of production cuts vastly improves the efficiency whilst maintaining the physical accuracy of energy deposition and stopping location. If a secondary particle is not expected to travel a minimum distance in the material defined by the range cut, it will not be produced and its energy will be deposited at that location instead. A summary of the range cuts used and the energy cuts they correspond to in several materials is provided in Table 2.

The simulation includes 100,000 primaries over up to a maximum of 100 turns and it is executed on a computer cluster of 500 cores at Royal Holloway, University of London.

RESULTS

The results from the simulation are analysed in an event-by-event basis. Using this approach, the energy deposition histograms presented here are prepared individually for each event and are then averaged to provide the correct statistical uncertainty. The loss maps presented show binned energy deposition. The full ring loss map can be seen on Fig. 1 and a zoomed in view of the betatron collimation system in Interaction Region 7 (IR7) can be seen on Fig. 2.

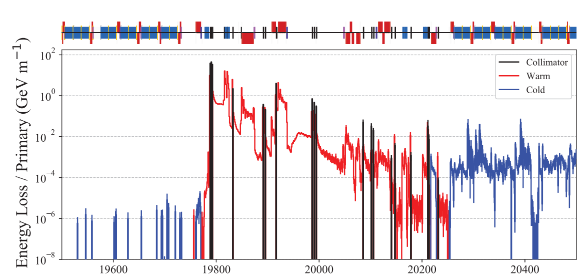

Figure 2: Zoom in of the betatron collimation section in IR7. The machine elements are shown on top.

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As the energy deposition maps include contributions from the passage and interaction of all secondary particles in the simulation, it is difficult to benchmark these simulations against existing collimation simulations. Current simulations record only the impact location of primary particles on the aperture, or in the case of ions, the energy of the ion or fragment at its impact location on the aperture. Preliminary qualitative observation shows collimator losses in the IR7 that correspond to the collimator hierarchy and losses in the dispersion where secondaries with differences in magnetic rigidity relative to the primary beam are lost. There are distinct loss peaks identified in the cold aperture of the regular arcs between interaction regions. The origin of those losses will be investigated further by tracing back the losses to primary particles and recreating their coordinates in a dedicated simulation.

The abundances of secondary particle species produced in the primary collimator and the rigidity spectra of the secondary ion fragments were also investigated. The ion fragment mass distribution is shown in Fig. 3. Light ion fragments dominate the mass distribution, with heavier fragments being produced in smaller fractions. Fragments with a mass similar to the primary particles make up a small fraction of the spectrum. Such fragments are produced in electromagnetic dissociation interactions and further investigation is needed to determine what the mean free path in the collimator is for ions at injection energy for the LHC. Simulation with more primary particles and a refined input distribution to more accurately match current simulations will also be performed to validate the preliminary results presented here.

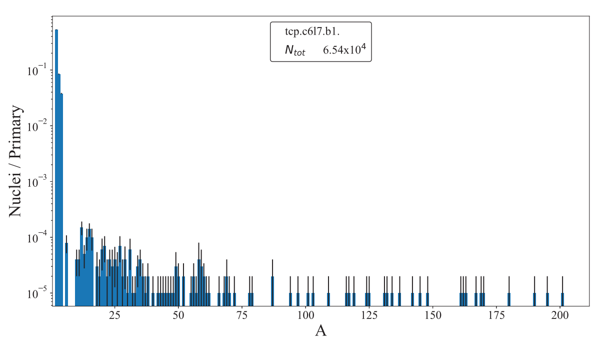

Figure 3: Abundances of nuclear fragments observed after the primary collimator in terms of the atomic number A.

The rigidity spectrum on Fig. 4 show that a significant fraction of the hydrogen isotopes and alpha particles produced are found near the nominal beam magnetic rigidity. Those secondaries can potentially travel long distances in the machine, depending of the angle they leave the collimator at, and can cause losses around the whole ring. In addition to light ion fragments, protons and pions can also be found near the nominal rigidity as shown in Fig. 5.

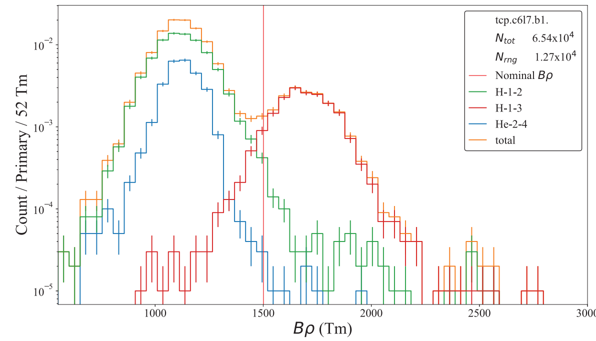

Figure 4: Rigidity spectrum of secondary nuclear fragments observed after the primary collimator. N_{tot} is the total number of fragments and N_{rng} is the number inside the range shown in the figure.

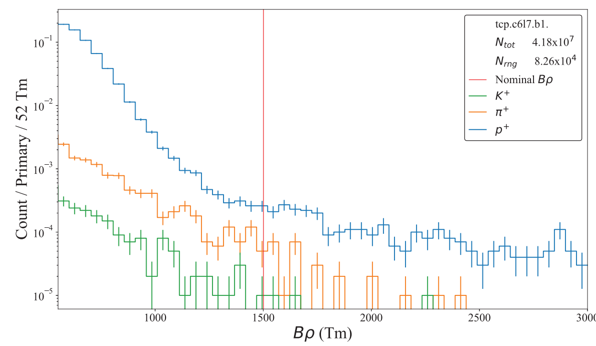

Figure 5: Rigidity spectrum of non-ion particles observed after the primary collimator. N_{tot} is the total number of secondaries and N_{rng} is the number inside the range shown in the figure.

CONCLUSION AND OUTLOOK

The study presented demonstrates the application of a 3D radiation transport simulation using Geant4 through BDSIM for collimation efficiency studies over the entire LHC ring with a complete Geant4 physics library. Following the recent addition of ion support, BDSIM has been shown to be a promising tool in future ion collimation simulations. Currently, the main limitation in studying the LHC ion collimation at nominal energy is the limited energy range of the electromagnetic dissociation model in Geant4.

The results presented here show qualitative agreement with the expectations for loss location and relative magnitude. The spectra of particles leaking from the primary collimator clearly show the presence of light nuclear fragments and other secondaries near nominal magnetic rigidity that lead to dangerous losses in the cold aperture of the dispersion suppressor. The next step is to compare the results obtained with the loss pattern measured by Beam Loss Monitors (BLMs) at the LHC. Because of the full treatment of nuclear fragmentation and hadronisation in BDSIM it is possible to compare to measurements in a more quantitive way and ultimately to derive operational limits of the signal recorded by the BLMs.

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