PRELIMINARY COMPARISON OF THE RESPONSE OF LHC TERTIARY COLLIMATORS TO PROTON AND ION BEAM IMPACTS*

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Abstract

The CERN Large Hadron Collider is designed to bring into collision protons as well as heavy ions. Accidents involving impacts on collimators can happen for both species. The interaction of lead ions with matter differs to that of protons, thus making this scenario a new interesting case to study as it can result in different damage aspects on the collimator. This paper will present a preliminary comparison of the response of collimators to proton and ion beam impacts.

INTRODUCTION

The Large Hadron Collider (LHC) mainly operates with proton beams. However, heavy ion collisions have been included in the conceptual design of the LHC from an early stage and collisions between beams of fully stripped lead ($^{208}Pb^{82+}$) ions have been successfully carried out during the first years of operation of the LHC. The main beam parameters for protons and heavy ions are listed in Table 1. While the major hardware systems of the LHC ring are compatible with both proton and heavy ion operation, the physics of ion beams is qualitatively and quantitatively different from that of protons, resulting in different beam dynamics and performance limits for the two types of beams [1].

With a stored proton beam energy of 362 MJ (Table 1), the two counter-rotating LHC beams are highly destructive. Beam losses can cause both quenches of superconducting magnets as well as material damage [2, 3]. Therefore, the machine aperture must be protected and beam losses tightly controlled. Thus, these issues established the need for the development of a powerful multi-stage collimation system [4] to protect the accelerator against unavoidable regular and irregular beam losses as well as to ensure the proper functionality of the LHC.

The LHC collimation system consists of 100 movable collimators placed in 7 out of 8 LHC IPs (interaction points), having the two essential functions of beam cleaning and machine protection. The LHC collimation system is primarily optimized for proton operation but it is also used during the heavy-ion runs. Although the stored energy of the nominal ion beam is only 1% of that of the nominal proton beam (Table 1), it is important to study ion collimation because of the different characteristics of the beam-matter interactions.

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This paper gives a brief overview of the physics processes occurring when particles (heavy ions and protons) traverse the collimator material, together with a comparison of the response of tertiary collimators to proton and ion beam impacts.

Table 1: Design Parameters for the LHC's Proton and $^{208}Pb^{82+}$ Beams in Collision Conditions [1]

Particle	p	$^{208}Pb^{82+}$
Energy/nucleon	7 TeV	2.759 TeV
Number of bunches	2808	592
Particles/bunch	1.15×10^{11}	7×10^{7}
Transverse normalized emittance (1σ)	3.75 μm	1.5 μm
RMS momentum spread	1.13×10^{-4}	1.10×10^{-4}
Stored energy per beam	362 MJ	3.81 MJ
Design luminosity	10^{34} cm^{-2}s^{-1}	10^{27} cm^{-2}s^{-1}
Horizontal and vertical β*	0.55 m	0.50 m

PHYSICS OF PROTONS AND HEAVY IONS IN COLLIMATORS

Similar to a proton beam, a nominal ion beam hitting a surface, in our case a collimator, produces a local heat deposition inside the material. The final energy deposition in the material is to a large extent due to the number of secondary particles that are created in each interaction and that constitute the hadronic shower [5].

The ion-matter interaction in collimators results in ion-specific beam losses. The physics of the particle-matter interactions of heavy ions is however qualitatively different from protons, since ions undergo nuclear fragmentation and electromagnetic dissociation (EMD). Once the ions have fragmented, the resulting hadronic shower behaves similarly for both particle species (protons and heavy ions) and the heat deposition is in proportion to the beam energies. It can be expected that the heat deposition of the ions on the collimators nowhere exceeds that of the protons [1].

A short review of the passage of charged particles through matter can be found in [6]. Two important processes will be highlighted here: the energy loss through ionization, and the change of direction through many small-angle scattering events, so-called multiple Coulomb scattering (MCS). These processes are present for all charged particles. However, the ionization energy loss is much higher for ions compared to protons. The energy loss through ionization, which is described by the well-known Bethe-Bloch formula, rises proportional to

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the square of the particle's atomic number (Z), which means that a lead ion will lose more energy per unit path length in a material than for instance a proton. Consequently, this means that the energy deposition from a lead ion will be much more concentrated.

There are some other processes that apply only to heavy ions. For instance, an impinging nucleus may lose one or several nucleons, in particular neutrons, through electromagnetic dissociation (EMD), which is a process with a logarithmic energy dependence taking place in ultra-peripheral collisions. The nuclei may also split up in smaller fragments through nuclear inelastic reactions. Table 2 gives a summary of the main interaction mechanisms of high energy ions in the collimator material together with the differences between $^{208}Pb^{+}$ ion/matter interactions and proton/matter interactions in collision.

Table 2: $^{208}Pb^{+}$ Ion/Matter Interactions in Comparison with Proton/Matter Interactions. Values are for particle impact on graphite [1]

Physics process	p collision	$^{208}Pb^{+}$ collision
Ionisation energy loss *dE/Edx*	0.0088 %/m	0.73%/m
Multiple scattering projected RMS angle	4.72 μrad/m$^{1/2}$	4.72 μrad/m$^{1/2}$
Electron capture length		312 cm
Electron stripping length		0.018 cm
ECPP interaction length		0.63 cm
Nuclear interaction length (inc. fragmentation)	38.1 cm	2.2 cm
Electromagnetic dissociation length		19.0 cm

ACCIDENT SCENARIOS

Being in close proximity to the beam, the collimator jaws are continuously exposed to direct interaction with high-energy particles. In the worst accident case corresponding to an asynchronous trigger of the beam dumping system [7], one or more high-energy density bunches might directly impact on a collimator with possible serious consequences. Even though the machine configurations are chosen to minimize this risk in a way that it can only occur in case several unlikely combined failures occur at the same time [8], it is important to understand the implications of the catastrophic event on a tertiary collimator. Such studies have already been carried out for protons [9, 10].

This paper presents some general cases based on these realistic, although not so probable, combined error scenarios for which general inputs have been used to investigate what happens to the collimator structure. The purpose is to provide a preliminary comparison between proton and lead ion beams together with their effects in case of beam impact with a horizontal tertiary collimator (TCTH).

NUMERICAL ANALYSIS

Tools

The fast and complex thermo-mechanical phenomena induced by the interaction of beam particles with matter, as well as the complexity of the collimator structure, make the implementation of a numerical approach through finite element analysis highly necessary [11]. Non-linear, transient analyses were thus performed to correctly evaluate the temperature distribution and other thermally-induced effects due to beam impact. Such sequential analyses were conducted using the ANSYS® Finite Element code.

FLUKA [12, 13] models were set up and full shower simulations provided energy deposition distributions for the defined accident cases. These 3D maps were then loaded in the ANSYS 3D model through dedicated subroutines in order to provide the input thermal load in terms of power density distribution.

Simulations

Simulations were performed on the lower symmetrical half of a TCTH jaw (Fig. 1) since the considered beam impact leads to a symmetrical energy deposition in the longitudinal plane (x-z plane in Fig. 1). In the studied cases presented in this paper, the bunch has a beam size of 0.3 mm (σ_x) × 0.3 mm (σ_y) (RMS values) and an impact parameter of 0.5 mm. This means that the beam will graze the surface of the jaw inserts that are made of a tungsten heavy alloy known as INERMET 180, but which are simulated as pure tungsten.

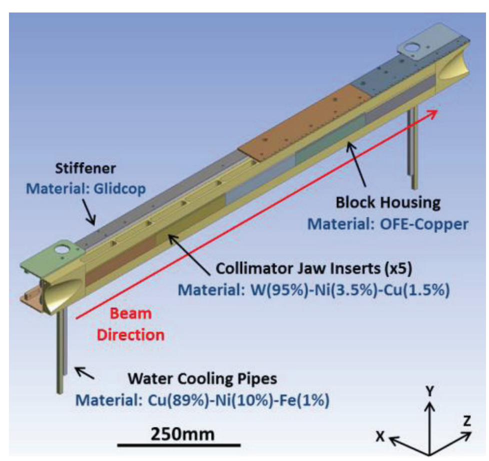

Figure 1: Left jaw assembly of a TCTH.

RESULTS

A first, preliminary comparison between lead ions and protons can be done by evaluating the energy deposited by 1 nominal bunch of each species on the collimator jaw inserts. It is observed from Fig. 2 and Fig. 3 that the energy deposited by a nominal proton bunch is around two orders of magnitude smaller than that for a nominal ion bunch as follows from the fact that the stored energy of the nominal ion beam is only 1% of that of the nominal proton beam.

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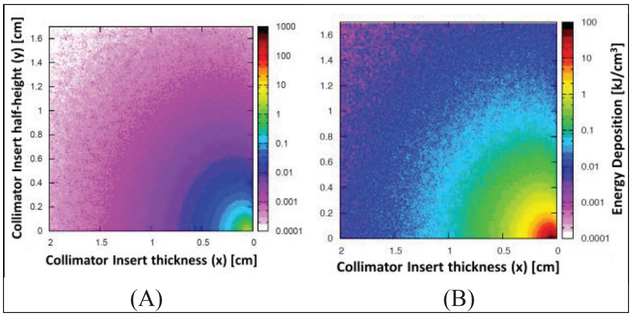

Figure 2: Energy deposition cuts in the x-y plane at the location of T_{max} in z. (A) 1 nominal bunch of lead ions (7×10^7 ions, 2759 GeV/n) with T_{max} occurring at z = 6.5 cm. (B) 1 nominal bunch of protons (1.15×10^{11} p) at 7TeV with T_{max} occurring at z = 7 cm.

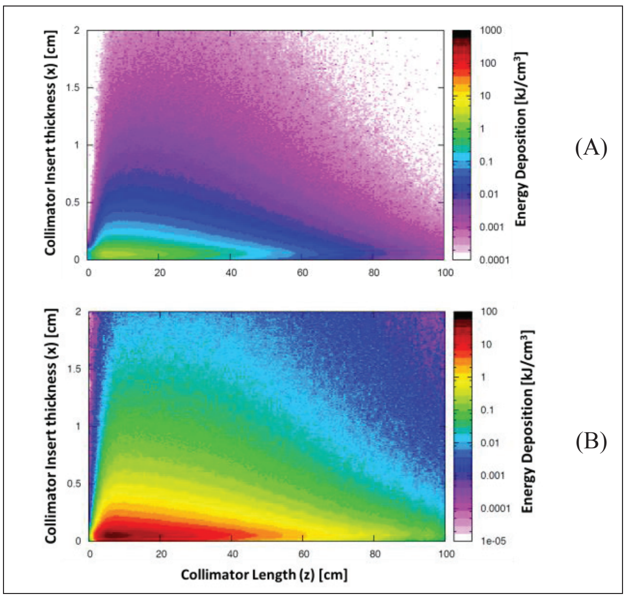

Figure 3: Energy deposition cuts in the x-z plane at collimator insert half-height (plane of symmetry). (A) 1 nominal bunch of lead ions (7×10^7 ions, 2759 GeV/n). (B) 1 nominal bunch of protons (1.15×10^{11} p) at 7TeV.

Another interesting aspect was to simulate the number of protons/bunch that would give the same temperature peak as 1 nominal ion bunch considering the same beam size and the same impact parameter. The graph in Fig. 4 shows that 4.93×10^9 protons/bunch would give the same temperature peak as 1 nominal ion bunch. However, some differences between the two temperature profiles can be observed. The first observable difference is the discrepancy between the energy deposition values at the beginning. This is caused by ionization. As shown in Table 1, the relative energy loss due to ionization is two orders of magnitude larger for heavy ions than for protons. This means that ions lose their energy to the target material over a shorter distance than protons.

Another difference between the profiles can be observed after the peak is reached. This difference is due to electromagnetic dissociation which plays an important role in the behaviour of heavy ions. In case of heavy ions, peripheral collisions with collimator nuclei lead to nucleon losses by hadronic fragmenatation and electromagnetic dissociation.

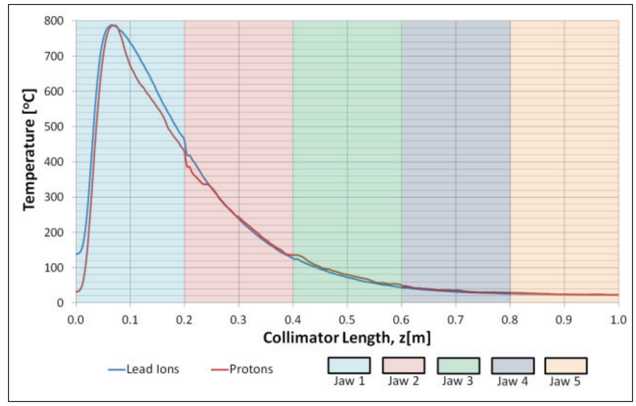

Figure 4: Temperature peak profiles within the jaw inserts along the beam direction for ions and protons.

CONCLUSIONS

The physics of ion beams is qualitatively and quantitatively different from that of protons, resulting in different characteristics for beam-matter interaction for the two types of beam. It has been shown that the heat deposition of the ions on tertiary collimators nowhere exceeds that of the protons. However, further studies are foreseen to investigate how the differences in energy deposition presented in this paper might result in a different mechanical response of the collimator structure.

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