COLLIMATION OF HEAVY ION BEAMS IN LHC

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Abstract

The LHC collimation system is designed to cope with requirements of proton beams having 100 times higher beam power than the nominal LHC heavy ion beam. In spite of this, specific problems occur for ion collimation, due to different particle-collimator interaction mechanism for ions and protons. Ions are subject to hadronic fragmentation and electromagnetic dissociation, resulting in a non-negligible flux of secondary particles of small angle divergence and Z/A ratios slightly different from the primary beam. These particles are difficult to intercept by the collimation system and can produce significant heat-load in the superconducting magnets when they hit the magnet vacuum chamber. A computer program has been developed to obtain quantitative estimates of the magnitude and location of the particle losses. Hadronic fragmentation and electromagnetic dissociation of ions in the collimators were considered within the frameworks of abrasion-ablation and RELDIS models, respectively. Trajectories of the secondary particles in the ring magnet lattice and the distribution of intercept points of these trajectories with the vacuum chamber are computed. Results are given for the present collimation system design and potential improvements are discussed.

INTRODUCTION

The LHC collimation system has been conceived for proton beams of high intensity. To deal with these beams a two stage collimation concept is implemented [1,2] with short primary collimators (called TCPs in LHC notation) and long secondary collimators (TCSs) downstream of the TCPs. The gap widths of the TCPs and TCSs are set to 2×6σ and 2×7σ beamsize respectively. The betatron amplitudes of halo particles are increased by multiple scattering in the TCPs. This can happen during multiple turns and several TCP passages. Once betatron amplitude larger than 7σ is reached the particles hit the TCS, where they dissipate their energy in a hadronic shower. In order to withstand the high beam power density of the LHC beam graphite has been chosen as the material for the TCP and TCS due to its low stopping power and good heat handling capabilities.

The condition for a halo particle hitting a TCP to be scattered onto the TCS can, in 1 dimensional approximation, be written as

$$\delta x' > \sqrt{\frac{\left(N_S^{\ 2} - N_P^{\ 2}\right)\varepsilon_N}{\gamma_{REL.}\ \beta_{TWISS}}} \qquad (1)$$

with $\delta x'$ the scattering angle in the TCPs, ε_N the nominal and normalised r.m.s. emittance, N_P and N_S the gap-width of the TCP and TCS in units of 1σ beam-width, β_{TWISS} the β-function at the TCP and γ_{REL} the relativistic factor.

The difference between protons and heavy ion beams comes from the fact that heavy ions have a roughly 20 times higher probability for nuclear interactions than protons, while the angles due to multiple Coulomb scattering are almost the same for both particles at given magnetic rigidity $B\rho$. As a consequence the heavy ions have a very high probability to undergo nuclear interactions with the TCP material before condition (1) is reached. The most probable interactions are the loss of a few nucleons in nuclear fragmentation (NF) and electromagnetic dissociation (ED). The residual ion has a different Z/A ratio, while the direction and amount of momentum per nucleon is hardly changed. In consequence many of these ions are not intercepted by the TCSs but are lost downstream in the superconducting magnets of the dispersion suppressor, because of their different $B\rho$ values. This effect can cause significant heat loads on the superconducting magnets, which make the heavy ion collimation difficult despite a beam power two orders of magnitude less than the nominal proton beam.

HEAVY ION-MATERIAL INTERACTIONS

In the context of beam collimation the important interaction types are multiple Coulomb scattering, energy loss due to ionisation, NF and ED. Table 1 gives the strength of these effects for fully stripped ^{208}Pb ions in graphite. For comparison the values for protons are shown as well. Typical distances for electron stripping of partially stripped ions are very short compared to electron pick-up length; therefore electron pick-up can be neglected. Table 1 shows that multiple scattering is the same for heavy ions and protons of same $B\rho$, while ionisation energy loss is increased roughly in proportion to the Z value of the projectile. The probability of nuclear

Table 1 Physics processes in collimators. The upper values are for injection energy, the lower for maximum collision energy.

Physics process	Proton	^{208}Pb
$\frac{dE}{Edx}$ due to ionisation	-0.12 %/m -0.0088 %/m	-9.57 %/m -0.73%/m
Mult. Scattering (projected r.m.s. angle)	73.5µrad/m^{½} 4.72µrad/m^{½}	73.5µrad/m^{½} 4.72µrad/m^{½}
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

interactions is much greater for ions than for protons. The important interactions for heavy ions are NF and ED.

NF leads to a large variety of residual nuclei. The probability of producing a specific Z,A combination in a single interaction is computed with our Monte Carlo program based on the abrasion-ablation model [3]. The typical transverse momentum transferred to the residual nuclei by NF is estimated with the Goldhaber formula [4] to be of the order of 1 A·MeV/c. This is small compared with the transverse momentum due to the beam emittance, which is in the order of 10 A·MeV/c at collision energy at the location of the collimators. The cross sections for (ED) are computed with the RELDIS model [5]. ED leads predominantly to the loss of one neutron (probability 59%) or two neutrons (probability 11%), i.e., the production of ^{207}Pb and ^{206}Pb. The transverse momentum transfer in ED is less than in NF as can be seen in Fig. 1, which shows the transverse momentum distribution for ED as computed by RELDIS. An ion moving through a

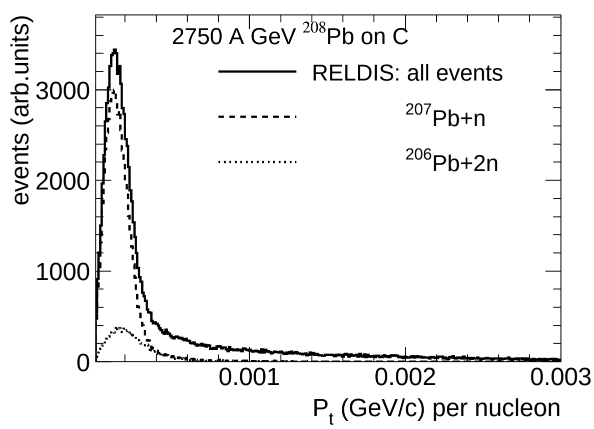

Figure 1 Transverse momentum distribution due to ED as computed by RELDIS

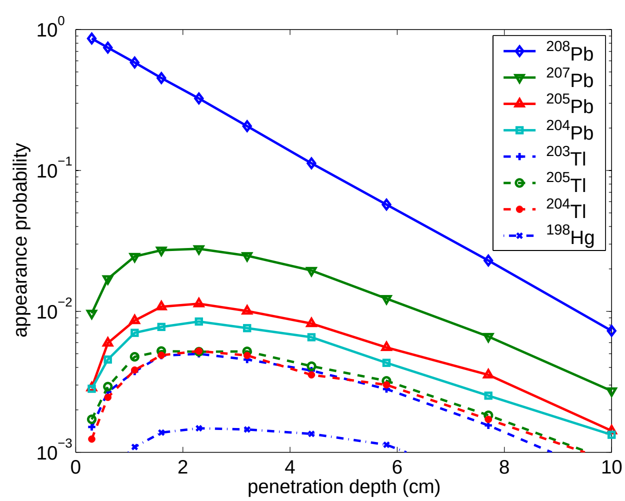

Figure 2 Probability of appearance of isotopes as a function of penetration depth in graphite for a primary ^{208}Pb beam of 2750 A GeV

collimator can be subject to several NF and ED processes, leading to a large probability distribution of isotopes as a function of penetration depth. These probabilities have been computed in a simple transport code based on cross-section tables generated with the abrasion-ablation and RELDIS codes mentioned above. The result of such a calculation is shown in Figure 2.

THE ICOSIM TRACKING CODE

In order to study the specific problems of ion collimation a new code called ICOSIM (for Ion COllimation SIMulation) has been developed. The purpose of ICOSIM is to treat particle tracking in the lattice of a storage ring together with heavy ion specific interactions with collimator materials in a single program and to predict the locations, types and intensities of particle losses on the collimators and the vacuum chamber.

The lattice for the particle tracking as well as the aperture data are retrieved from MAD-X Twiss tables [6]. This allows straightforward implementation of the lattice for any machine with a MAD-X optics description. Tracking is for the five coordinates x,x',y,y' and $\Delta p/p$. Synchrotron oscillations are neglected, because the typical timescales for synchrotron oscillations are long (T_{RF}≈500 turns for LHC) compared to the time between a first interaction of an Ion with a collimator and the final loss (1—100 turns). Chromatic effects are accounted for in leading order, this means that for bending magnets linear dispersion is taken into account and for quadrupoles a strength correction in first order of $\Delta p/p$ is applied. Sextupoles are treated in thin element kick approximation. Higher order multipoles are ignored. A check whether particles are outside the vacuum aperture is made at the end of each element. For particles that are outside, the precise impact position within the element is found by interpolation. Aperture cross sections are approximated by ellipses, except for the collimators, where the complete geometry is taken into account. All these choices are made as a compromise between tracking precision and tracking speed. Tracking speed is at prime since a large number of particles (typically 10^4) have to be tracked for typically 100 turns through the LHC lattice with about 4000 transformations per turn.

For the description of the beam collimator interactions a simple Monte Carlo transport code has been implemented, which uses cross section tables for NF and ED generated by the abrasion-ablation and RELDIS codes discussed above. Ionisation energy loss is treated by the Bethe-Bloch formula with the usual corrections and multiple scattering is described using a Gaussian approximation of the scattering distribution. Transverse momentum transfer in NF and ED is neglected for the reasons explained above.

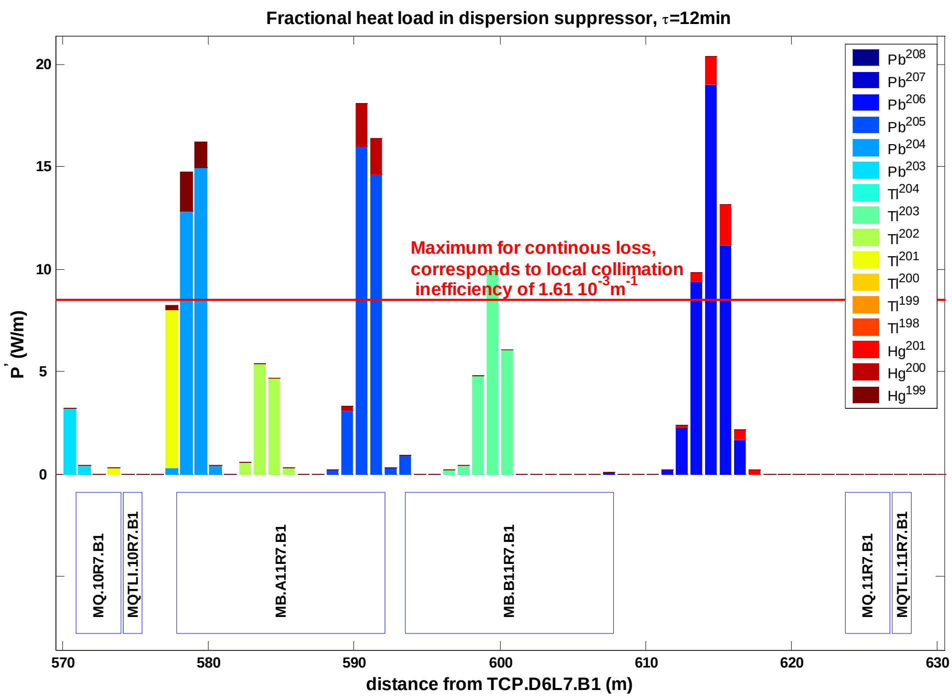

Figure 3, Heat deposition in the dispersion suppressor due to isotopes produced in collimators.

In Figure 3 a loss map of particles as generated by ICOSIM is shown. Beam parameters are for a nominal LHC heavy ion beam [7] at collision energy and the picture covers the region of the dispersion suppressor downstream of the betatron collimation section. The collimation rate corresponds to a beam lifetime of 12 min, specified as the minimum beam lifetime the collimation system has to accept. It can be readily seen that the heat load exceeds the expected quench limit of the SC magnets by about a factor 2.

CONCLUSIONS AND OUTLOOK

The present design of the LHC collimation system has a cleaning efficiency which falls short by about a factor two for the nominal ^{208}Pb heavy ion beam at collision energy. Consequences are magnet quenches due to heating by ions lost in the dispersion suppressor magnets. For the early beam with a beam intensity reduced by one order of magnitude the collimation efficiency is sufficient. For the various accident scenarios affecting the collimation system which have been analysed for proton beams, the consequences with heavy ion beams are more relaxed. This has been verified with preliminary FLUKA calculations not shown here [8]. However, because of the much higher initial stopping power for ions on material one has to beware of assuming that the effects scale with the ratio of beam powers. In fact a nominal LHC ion beam hitting a material surface produces at the impact surface a local heating comparable to a nominal proton beam, although the proton beam carries a two orders of magnitude higher beam power. Presently there is an effort to include the ED process in the FLUKA program (so far only NF is implemented). This will allow more precise estimates of the heat loads and radiation generated by ion beam losses in the collimation and downstream systems. Studies are ongoing to use thin spoilers of high Z material to improve the cleaning efficiency, but results are not conclusive yet.

Furthermore, more work is needed to verify for ion beams the effectiveness of the beam loss monitors for machine protection [9].

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