MEASUREMENTS OF HEAVY ION BEAM LOSSES FROM COLLIMATION

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Abstract

The collimation efficiency for $^{208}\mathrm{Pb}^{82+}$ ion beams in the LHC is predicted to be lower than requirements. Nuclear fragmentation and electromagnetic dissociation in the primary collimators create fragments with a wide range of Z/A ratios, which are not intercepted by the secondary collimators but lost where the dispersion has grown sufficiently large. In this article we present measurements of loss patterns caused by a prototype LHC collimator in the CERN SPS. The loss maps show a qualitative difference between $^{208}\mathrm{Pb}^{82+}$ ions and protons, with the maximum loss rate observed at different places in the ring. This behaviour was predicted by simulations and provides a valuable benchmark of our understanding of ion beam losses caused by collimation.

INTRODUCTION

The collimation in the LHC [1] of $^{208}\mathrm{Pb}^{82+}$ ions is expected to be less efficient than for protons [2], because ions have a high probability of fragmenting in the primary collimators. This produces isotopes (e.g. ^{207}Pb, ^{203}Tl and others) with a different charge to mass ratio from the main beam, and therefore a different magnetic rigidity $(B\rho)(1+\delta)$, if $(B\rho)$ is the rigidity of the original beam and δ is given by

$$\delta = \frac{Z_0}{A_0}\frac{A}{Z}(1+\delta_{\mathrm{kin}}) - 1 \qquad (1)$$

where (Z_0, A_0) are the charge and mass number of the original ion, (Z, A) those of the fragment and δ_{kin} the fractional momentum deviation per nucleon. These ions follow the dispersion function generated downstream from the collimator and may be lost later in the machine, outside the collimation insertion, possibly quenching superconducting magnets.

To study the LHC ion collimation inefficiency, a series of simulation studies have been done [2, 3]. Since a large fraction of the systematic error in those simulations comes from the generation and tracking of the fragmented ions, an experiment on ion collimation in the SPS has been performed. The results, presented in the following, have been compared to simulations, not only in terms of loss locations but with the goal of reproducing the absolute value of the losses measured by the SPS beam loss monitors (BLMs). We also make a brief comparison with protons.

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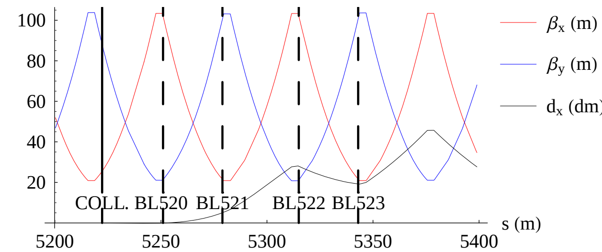

Figure 1: The β-functions of the SPS just downstream of the collimator together with the locally generated dispersion d_x from the collimator. The locations of the BLMs and the collimator are indicated by vertical lines.

EXPERIMENTAL SETUP

A prototype of a secondary LHC collimator has been installed in the SPS [4]. It consists of a pair of 1 m long CFC graphite jaws, which can be moved independently to intercept the beam in the horizontal plane. The optical functions in the vicinity of the installation are shown in Fig. 1 and the horizontal aperture in Fig. 2.

Moving the collimator into the beam creates losses, which are recorded by 216 BLMs placed around the ring. The BLMs are ionization chambers mounted close to lattice quadrupoles. Losses are read out and integrated over every machine cycle (18 s in the case of ions). Figs. 1 and 2 show the s-values of the four BLMs (called BL520, BL521, BL522 and BL523) immediately downstream of the collimator. Beam loss data were collected during $^{208}\mathrm{Pb}^{82+}$ dedicated ion runs in late 2007 with a 106.4 GeV/nucleon coasting beam. The transverse normalized RMS emittance was approximately 1 μm and the injected intensity around 6×10^7 ions. The collimator, kept parallel to the beam, was moved in steps, generally $0.1-1$ mm, but sometimes up to 10 mm. Data were also taken with tilted jaws and at lower energy, which we intend to present elsewhere.

SIMULATION SETUP

In order to simulate the particle propagation through the LHC lattice together with the particle-matter interactions in the collimators, a specialized program, ICOSIM [2], has been developed. ICOSIM tracks particles through a lattice, defined in external files, using a linear matrix formalism but chromatic effects at leading order and sextupoles in thin kick approximation are included. The collimator interactions are, for simulations in this article, treated by external calls to the Monte Carlo program FLUKA [5, 6].

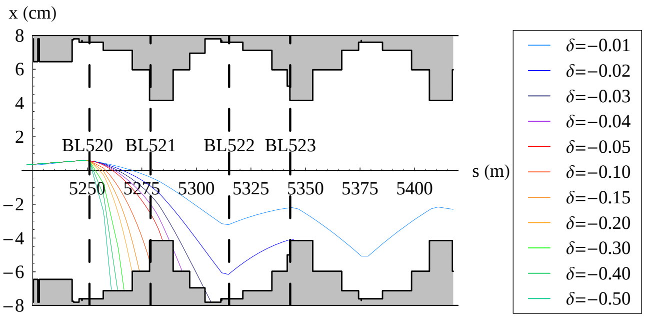

Figure 2: Dispersive orbits of fragmented ions produced in of one of the collimator jaws, shown together with the aperture. The vertical dashed lines indicate the location of the four BLMs closest downstream.

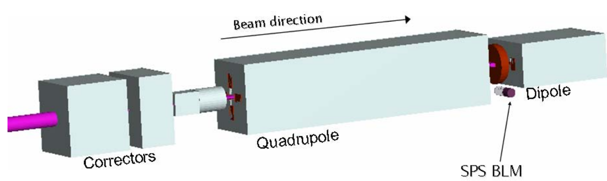

Figure 3: The geometry as implemented in FLUKA around the monitor BL520, which is located around 30 m downstream of the collimator in the SPS.

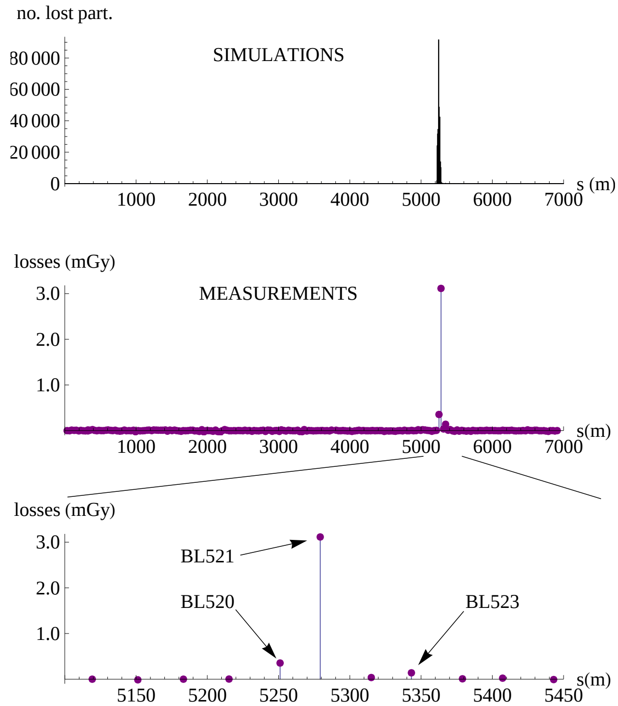

Figure 4: Example of simulated ICOSIM (top) and measured (middle) $^{208}\mathrm{Pb}^{82+}$ ion loss map for the whole SPS ring. The bottom part shows a closeup of the loss peak in the measurements, with the names of the BLMs with the highest signals indicated. The simulated losses were binned in 5 m intervals. The collimator is located at $s = 5222$ m, just upstream of the large loss peak.

The simulations done for the LHC were performed using a less detailed method based on tabulated cross sections. We intend to publish comparisons with this method elsewhere.

The BLM signals depend not only on the number of ions lost nearby, but also on the mass of the ions, the distribution of impact parameters and the amount and type of material they have to traverse before reaching the monitor. In order to accurately simulate this for a quantitative comparison with data, the particle-matter interaction of the lost ions needs to be taken into account.

As discussed later, the main loss location is right downstream of the collimator. Thus the 3D geometry of the magnetic elements around BL520, BL521 and BL523 was implemented in FLUKA, as illustrated for BL520 in Fig. 3. BL522 was not included, since the losses predicted and observed there were negligible. The momenta and impact coordinates of all particles lost within a 15 m interval of each BLM were recorded in ICOSIM and fed as starting conditions into FLUKA and the resulting energy deposition in the N_2 gas inside the BLMs was converted to dose in Gy.

RESULTS

A typical example of a loss map in the SPS ring, measured with coasting $^{208}\mathrm{Pb}^{82+}$ beam, is shown in Fig. 4, together with the corresponding simulated loss map. The detector background, consisting of noise and other beam losses that are not caused by the collimator movement, had to be subtracted. As background data we used the loss map from the machine cycle before the collimator movement. A similar approach was already used in Ref. [4]. The only stable loss locations, clearly separable from the background, are located right downstream of the collimator, both in simulation and measurement.

Fig. 5 shows the simulated and measured BLM signals around the maximum, normalized to 10^{10} lost particles and averaged over several machine cycles where the collimator jaws were kept parallel when moved into the beam. The pattern from the measurements is very similar to the simulation and is due to the dispersive orbits of ion fragments with different values of δ starting at the collimator jaws, as shown in Fig. 2. Fragments satisfying $-0.2 < \delta < -0.08$ are lost near the aperture limitation at $s = 5277$ m, close to BL521. Fig. 6, showing the spectrum of δ of all ions exiting the collimator, demonstrates that this corresponds to a large fraction of the fragments, so that this monitor is expected to show a high signal.

At BL523, only fragments with a magnetic rigidity much closer to the original $^{208}\mathrm{Pb}^{82+}$ ion are lost ($\delta \approx -0.02$). This is close to what can be expected in the cold regions of the LHC. In the vicinity of BL520, however, the losses are not only dispersive: light fragments with large vertical betatron angles are also lost there. Fig. 7 shows the mass spectrum of the particles lost close to each BLM.

The magnitudes of the simulated signals agree well with measurements, although they are lower. The discrepancies are however well within estimated error margins associ-

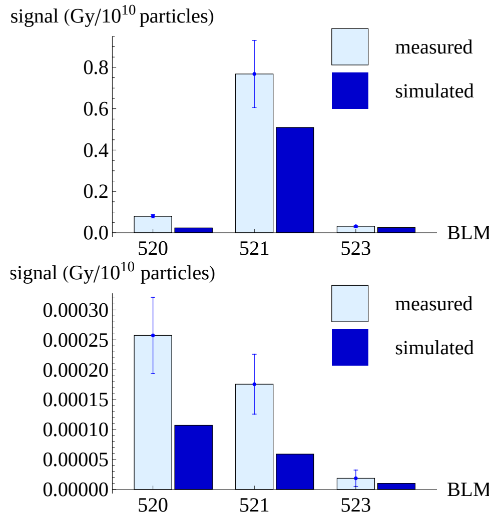

Figure 5: Average measured ion (top) and proton (bottom) loss map from the BLMs downstream of the collimator compared with simulations normalized to 10^{10} lost particles. The standard deviation between different measurements is indicated.

ated with the uncertainty in the shower simulation (approximately a factor 2) and the uncertainties in the tracking, the impact distribution of halo particles on the collimator and the fragmentation cross sections in the collimator, which are hard to quantify.

The simulated ratio between the losses at BL521 and BL523 shows an excellent agreement with measurements, while the expected relative loss at BL520 is lower. This could be due to the fact that BL520 is located only 30 m downstream of the collimator, meaning that it might see traces of shower particles from the collimator that are not properly taken into account in the simulation.

COMPARISON WITH PROTONS

For the sake of comparison, proton runs in the SPS were also simulated with ICOSIM and FLUKA and compared with measurements from 2007 with coasting beam at 270 GeV (emittances $\epsilon_x \approx 2.6\,\mu$m, $\epsilon_y \approx 4\,\mu$m, intensity $\approx 10^{12}$, typical jaw steps ≈ 0.2 mm). Measured and simulated loss maps are shown in Fig. 5. The ratio between the higher peaks agree well with measurements and it is clear that there is a significant qualitative difference between proton and ion loss patterns: the maximum signal for protons was found at BL520, while in the ion runs it was found on BL521. This can be understood from the fact that the δ of the protons is much lower, which means that large betatron angles caused by multiple scattering are the main loss mechanism instead of dispersion. This difference is a striking parallel to the expected behaviour in the LHC, and the ability of the simulations to quantitatively predict it in the SPS provides an extremely valuable benchmark.

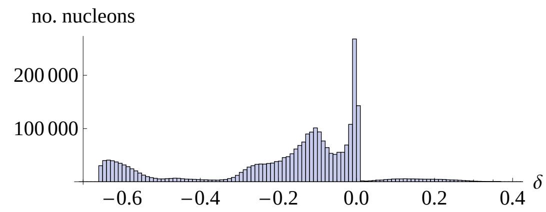

Figure 6: The distribution of δ of all ion fragments coming out of the collimator. The heights of the bars show the number of nucleons belonging to ions having δ within a certain interval.

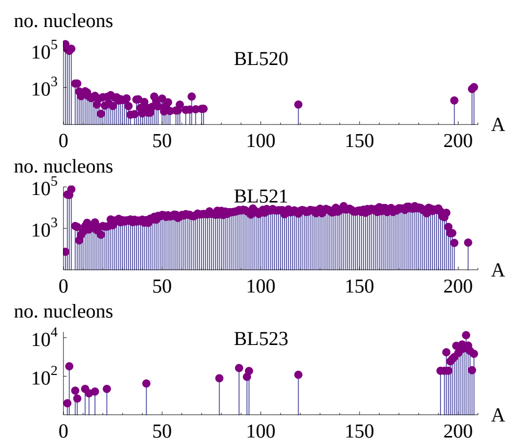

Figure 7: The A distribution of ion fragments lost within 15 m upstream of each BLM. The heights of the bars show the number of nucleons from ions having a certain A.

CONCLUSIONS

Measurements and simulations with ICOSIM and FLUKA show that beam losses induced by the collimator in the SPS are qualitatively different for $^{208}\mathrm{Pb}^{82+}$ ions and protons. Ion losses are mainly due to large values of δ and the protons' due to large angles, resulting in different loss patterns. Quantitatively, the simulated loss maps correspond well to the measured ones, both in the magnitude of the signal and the ratio of losses between different locations. This confirms and strengthens our knowledge of ion beam losses related to collimation, which is vital for our understanding of what to expect in the LHC.

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