Energy Deposition Simulations and Measurements in an LHC Collimator and Beam Loss Monitors

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Abstract

The LHC collimators are protected against beam-caused damages by measuring the secondary particle showers with beam loss monitors. Downstream of every collimator an ionisation chamber and a secondary emission monitor are installed to determine the energy deposition in the collimator. The relation between the energy deposition in the beam loss monitor and the collimator jaw is based on secondary shower simulations. To verify the FLUKA simulations, the prototype LHC collimator installed in the SPS was equipped with beam loss monitors. The results of the measurements of the direct impact of a 26 GeV proton beam injected in the SPS onto the collimator are compared with the predictions by FLUKA simulations. In addition, simulation results from parameter scans for mean and peak energy deposition with its dependencies are shown.

INTRODUCTION

The main function of the LHC collimators is the limitation of losses on sensitive beam-line components. Movable collimators are placed in vicinity of the beam (about 6 to 10σ) to intercept particles from the beam halo. Collimators of various types, depending on their protective purpose, are placed at appropriate positions along the LHC ring and its transfer beam lines. Losses on these exposed elements are individually surveyed by BLM detectors [1]. The abundance of collimators (about 80% for initial Phase I collimation) are placed in the LHC loss-intensive cleaning insertions [2]. They contain three types of collimators: primaries (TCP) and secondaries (TCSG) both with carbon jaws, and active absorbers (TCLA) with tungsten jaws, each monitored by a pair of BLM detectors as shown in Fig. 1. The scenario of impact on the collimator can vary

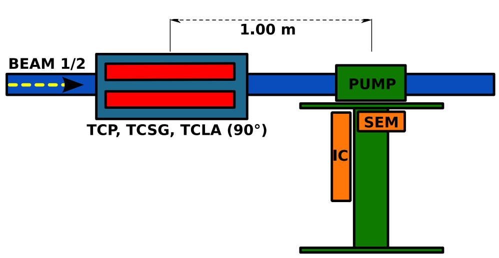

Figure 1: Side view of a "collimator-detector cell" composed of a collimator, an IC, and a SEM, as installed in the LHC cleaning insertions. A vertical collimator is shown.

considerably. For the protection of the collimators there is the need to estimate damage limits for the collimators as a function of the BLM detector signals. Depending on the time-scale of beam losses, total energy deposition in the movable collimator elements and maximum energy density in the collimator jaws were chosen for steady-state and transient losses, respectively, as meaningful quantities for damage limits in the collimator components. First, the accuracy of predicting BLM detector signals at collimators with Monte Carlo (MC) simulations is investigated by a comparison with measurements in an LHC-like setup mounted in the Super Proton Synchrotron (SPS). Secondly, dependencies of the energy deposition-to-signal ratio on parameters of the beam impact scenario are investigated. This paper is based on [3], details can be found therein.

METHODS

The multi-purpose MC code FLUKA [4, 5] was employed (FLUKA version 2006.3b) for the modeling of particle showers and energy deposition scoring in the relevant beam line geometries. Simulations were made with the NEW-DEFAULTS physics settings. Dependence of results on different cut values for production and transport of particles were investigated and chosen to reduce computation time while not influencing the results. Statistical errors were kept about or below 5%.

ACCURACY OF SIMULATION OF BLM SIGNALS

Experimental data, acquired in an LHC collimation-like installation in the SPS ring, are compared to the predictions of detector signals by simulations with FLUKA.

Experimental Setup

An LHC prototype secondary graphite collimator (TCSG) is mounted in the SPS Long Straight Section 5. About 1.9 m downstream of this collimator a set of BLM detectors is installed, consisting of two ICs (IC1A, IC1B) and one SEM as shown in Fig. 2. IC1A and the SEM are located in a similar position with respect to the collimator as in the standard LHC collimation installation.

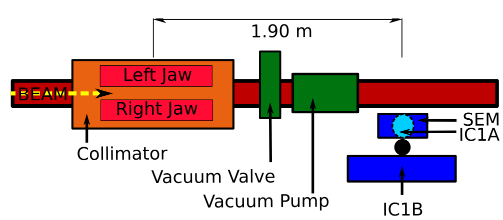

Figure 2: Top view of the horizontally mounted secondary collimator (TCSG) in the SPS and the BLM detectors.

Measurements

Three measurement sessions resulted in sets of data allowing to derive BLM signals per proton lost on the collimator. Measurements were conducted at SPS injection energy of 26 GeV. Measurements were taken in two different modes: one with high dose rates at larger impact parameters and a second one with low dose rates at small impact parameters. High dose rates at the collimator caused the ICs to enter in a saturation regime, consequently only data with lower intensities could be used for comparison. Assuming the collimator to be the limiting aperture on which beam particles are lost, the number of protons lost on the collimator was derived from beam current transformer measurements. The position of the beam with respect to the collimator jaws was calibrated by moving the collimators into the beam and monitoring the drop in beam current. The beam width at the collimator was determined with wire scanner measurements of the beam profile.

Simulations

The SPS section containing the collimator and the BLM detectors was modeled with a special focus on the collimator, the beam line and the BLM detectors. Materials and material properties of the collimator and the BLM detectors were carefully chosen in the simulation and are in agreement with the used equipment. Instrumentation and supports in vicinity were included making some simplifications in geometry and assuming standard materials. The influence of simplifications, such as for the collimator support, and uncertainites of the geometry on the results was assessed by variation studies and found to be below 15%.

Results and Discussion

The responses of the BLM detectors, measured as signal per proton lost on collimator, were compared with simulations. Simulations could reproduce IC measurements within $\pm 21\%$. For SEM simulations the agreement was worse and maximum deviations of $+73\%$ and -30% were found. Deviations between measurements and simulations are attributed to several sources. These include uncertainties of parameters of the experimental setup for reproduction by simulation, i.e., the precise impact scenario on the collimator (impact parameter distribution), the surface structure of the collimator, the beam-jaw angle, space-charge effects for the IC, and the calibration uncertainty of the IC and SEM. Additionally, the fraction of returning protons which are not removed from the beam after an initial impact on the collimator was only estimated roughly.

LHC SETUP

FLUKA simulations of a "collimator-detector cell" as shown in Fig. 1 were employed to calculate the ratios of BLM-signal to energy deposition in the collimator and BLM-signal per proton on collimator, called normalized BLM signal, depending on different beam impact scenarios. Implementation of geometry and materials was done similarly as described in the previous section. Simulations for all collimator types (i.e., TCP, TCSG, and TCLA) were done at LHC injection and top energy, 450 and 7000 GeV, respectively.

Results

Relative particle fluence spectra through the BLM detector volumes differential in energy were found to be alike at 26, 450, and 7000 GeV. Thus, simulations of BLM detector responses are expected to have a similar level of accuracy as determined in the previous section, given that the simulation of secondary shower propagation through the components is of the same precision for all relevant energies.

Collimator jaws are installed with different tilt angles (horizontal, vertical and about 45 degree). Variations of these angles with respect to a collimator with horizontal jaws resulted in signal changes of maximum -36% and -19% for IC and SEM detector, respectively.

Following simulations were done for collimators with horizontal jaws. Typical misalignment of BLM detectors is within ± 3 cm (transversal), and ± 5 cm (longitudinal). BLM detectors are most sensitive to a displacement in height. Maximum changes for both LHC injection and top energy are 21%. The impact of omitting the collimator support in the simulation was assessed by introducing a simplified model and yielded changes of maximum 16%.[1] The response of the BLM detectors for different impact parameters was simulated. Fig. 3 shows the normalized BLM signal and the signal-to-energy deposition ratio versus impact parameter of a pencil beam. The carbon density in a $1\,\mu$m surface layer of the collimator jaws was set to one-half of the regular density to assess effects of the surface roughness of the jaws. The signal-to-energy deposition ratio was found to be virtually constant for graphite-jaw collimators (TCP, TCSG). For the TCLA collimator an increase for smaller impact parameters of about 50% was found for the relevant range. Fig. 4 shows the BLM-signal ratios versus beam-jaw angle for a TCP collimator. A pencil beam with an impact parameter of $2\,\mu$m was used. Beam-jaw angles were varied between $\pm 300\,\mu$rad. The normalized signal was found to vary about 2 to 3 orders of magnitude for both LHC injection and top energy. The ratio of BLM signal to total energy deposition in the jaws is nearly constant for negative angles and rises by a factor of about 2.5 and 4.0 for ICs and SEMs, respectively.

Not only protons, also mixed particle showers generated at collimators upstream impinge on the collimators. An exemplary simulation of second and third order halos impinging TCP collimators resulted in ratios of BLM signal to energy deposition which were lower by a factor of up to 4 compared to ratios for impinging protons.

An assessment of the ratio of BLM signal to peak energy

[1] Differences to values presented in [6] are a consequence of re-analysing variations with more realistically chosen parameters.

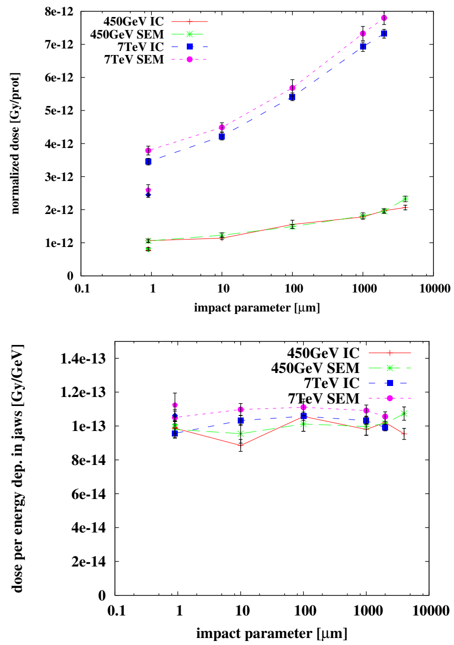

Figure 3: Top: Normalized BLM signal versus impact parameter is shown for a horizontal TCP collimator. Bottom: BLM signal-to-energy deposition ratio versus impact parameter for a horizontal TCP collimator. Isolated points are calculated reducing carbon density in a 1 μm surface layer of the collimator jaws .

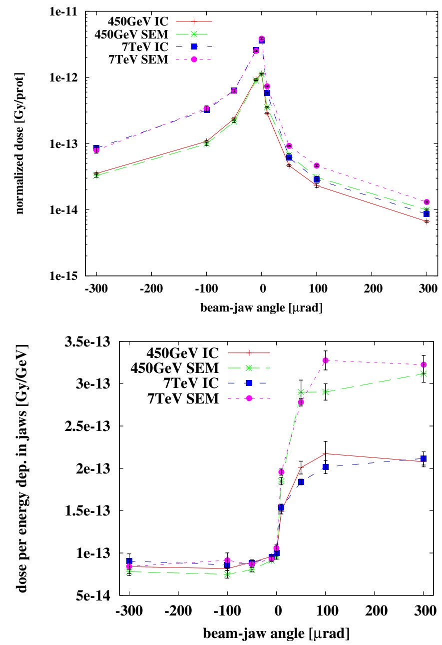

Figure 4: Top: Normalized BLM signal is plotted for a TCP collimator versus beam-jaw angle between $\pm 300\,\mu$rad. Bottom: Ratio of BLM signal to total energy deposition in the jaws is plotted for a TCP collimator versus beam-jaw angle.

deposition for protons impact in the collimator jaws was done assuming impact parameter distributions for typical failure cases having the form of a Gaussian tail, see [7, 8]. For graphite collimators a maximum variation by a factor of about 10 was found.

CONCLUSIONS

Measured BLM signals were compared in an LHC-like setup to simulations. Larger deviations were found for SEM detectors. The comparison should be repeated for the LHC setup. In order to interpret BLM detector signals for the protection of the collimators, a relation between energy deposition in the collimator due to impacting beam particles and signals of the BLM detectors were studied by simulations. The variation of the impact parameters and the beam-jaw angle for beam protons show that the ratio of BLM signal to energy deposition in the collimator jaws can be safely assessed for protons by using the lowest calculated ratios. Ratios of BLM signal to energy deposition in the collimator jaws from mixed particle spectra were found to be lower. They should be investigated systematically to allow for a safe assessment. Peak energy densities in collimator jaws were investigated for beam impact distributions of typical failure cases. The ratios of BLM signal to peak energy density decrease for TCPs and TCSGs for smaller mean impact parameters by a factor of maximum 10.

ACKNOWLEDGEMENTS

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