MODELING AND SIMULATION OF LHC BEAM-BASED COLLIMATOR SETUP

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Abstract

In the 2011 Large Hadron Collider run, collimators were aligned for proton and heavy ion beams using a semi-automatic setup algorithm. The algorithm provided a reduction in the beam time required for setup, an elimination of beam dumps during setup and better reproducibility with respect to manual alignment. A collimator setup simulator was developed based on a Gaussian model of the beam distribution as well as a parametric model of the beam losses. A time-varying beam loss signal can be simulated for a given collimator movement into the beam. The simulation results and comparison to measurement data obtained during collimator setups and dedicated fills for beam halo scraping are presented. The simulator will then be used to develop a fully automatic collimator alignment algorithm.

INTRODUCTION

The Large Hadron Collider (LHC) collimation system is designed to provide beam cleaning with an efficiency of 99.998% and protect the machine against quenches in the superconducting magnets [1]. The high level of performance is maintained by positioning the collimator jaws symmetrically around the beam to form a four-level hierarchy. The primary collimators (TCP) are set closest to the beam, followed by the secondary collimators (TCSG), the tertiary collimators (TCT) and the absorbers (TCLA).

The correct hierarchy is achieved when the beam centers and sizes at the collimator locations are known. These parameters can be determined through beam-based alignment of the collimators. In the 2011 LHC run, alignment was performed using a semi-automatic setup algorithm [2]. It automatically stopped the jaws from moving towards the beam when the losses detected on a beam loss monitor (BLM) downstream exceeded a pre-defined threshold. The typical beam loss signal during collimator setup is similar to the example in Fig. 1. The loss pattern can be divided into three components: the steady-state signal, the loss spike and the temporal loss decay.

In this work, a model of the beam losses is developed by combining the Gaussian properties of the beam with a parametric study of the temporal decays. The model serves as the basis of a simulator that provides a realistic BLM signal response for a given collimator movement. This would allow adequate training for a fully automatic setup algorithm before it is deployed with real beam.
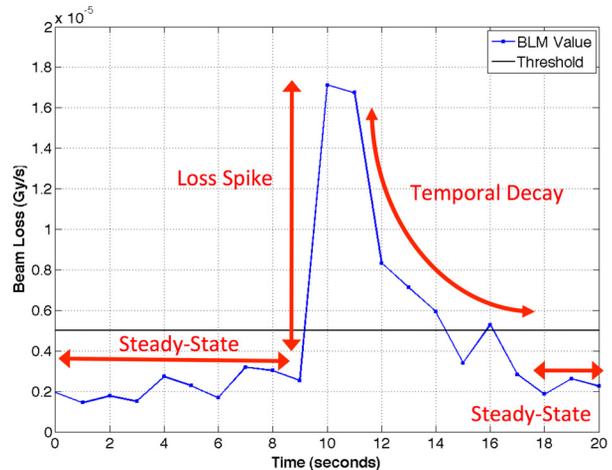
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Figure 1: The components of a typical clear BLM signal when the collimator jaw touches the beam halo.

BLM STEADY-STATE SIGNAL MODEL

The steady-state BLM signal is a measure of the particle loss rate. The further a jaw cuts into the beam, the more the average BLM signal increases as the particle density at the cut increases (see Fig. 2). An empirical model for this component of the BLM signal can be developed. In the simulator, random BLM values can be generated from the log-normal distribution (example shown in Fig. 3) depending on the distance of the jaw from the beam center.
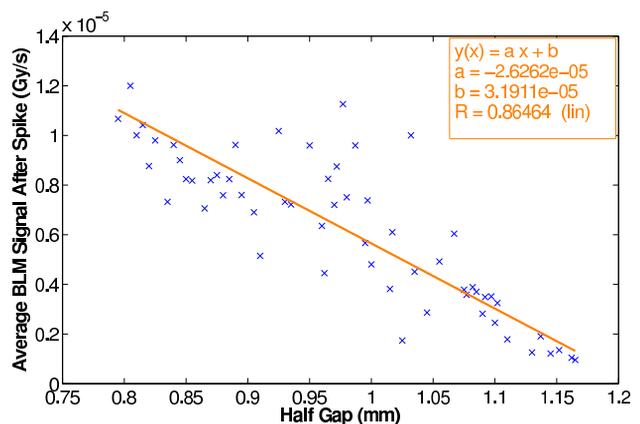

Figure 2: Average BLM signal after a loss spike.

Table 1: Measured Beam Scraping Parameters

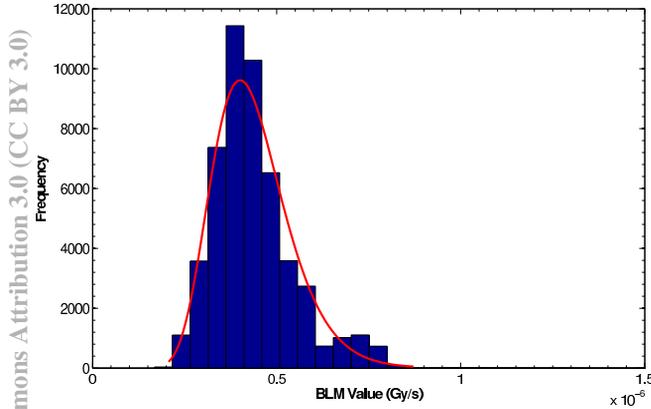| Collimator	Model Parameters				
	Emittance (μm)	σ_x (mm)	x_0 (mm)	N_0 (p)	f_i^{calib} (p/Gy)
TCP.C6L7.B1	1.4	0.663	- 0.280	1.37E11	1.25E12
TCP.C6R7.B2	1.8	0.730	- 0.160	1.18E11	1.26E12
TCP.D6L7.B1	1.4	0.478	0.470	1.24E11	1.20E12
TCP.D6R7.B2	1.9	0.542	0.650	1.32E11	1.13E12
TCP.B6L7.B1	1.3	0.540	- 0.640	1.25E11	1.94E12
TCP.B6R7.B2	2.0	0.654	- 0.635	1.10E11	1.75E12

Figure 3: Log-normal distribution of the background BLM signal at collimator parking positions.

GAUSSIAN BEAM MODEL

In the transverse plane the particles follow a normal distribution, and hence values for the number of particles lost for a given cut and the resulting particle distribution can be calculated. A full derivation of the following formulae is available in [3]. The fraction of particles lost after scraping can be expressed in terms of the collimator jaw position x and the beam center x_0, which is the co-ordinate in the collimator plane, as follows:

$$F_{lost}(n_\sigma) = e^{-n_\sigma^2/2} = e^{\frac{-\frac{1}{2}(x-x_0)^2}{\sigma_x^2}} \quad (1)$$

The distribution of the beam after a cut of n_σ in terms of the collimator jaw position x and the 1 σ beam size in mm is then:

$$y = \frac{e^{\frac{-x^2}{2\sigma_x^2}}}{\sqrt{2\pi}} erf\left(\frac{\sqrt{n_\sigma^2 - \frac{x^2}{\sigma_x^2}}}{2}\right) \times N_0 \quad (2)$$

where N_0 is the beam intensity. As the model assumes that there are no losses before the jaw movement, and the summation is performed from $-\infty$, the measured data can be approximated further by subtracting some losses from the fraction of lost particles given by the model:

$$F_{lost}(n_\sigma) = e^{-n_\sigma^2/2} = e^{\frac{-\frac{1}{2}(x-x_0)^2}{\sigma_x^2}} - e^{\frac{-\frac{1}{2}(x+a-x_0)^2}{\sigma_x^2}} \quad (3)$$

Table 2: Parametric Modeling of the Temporal Decay at 450 GeV and 3.5 TeV

Parameter	450 GeV	3.5 TeV
Δx (μm)	10 - 20	5 - 10
T_{decay} (s)	5.22 ± 2.71	7.86 ± 2.59
a (μGy/s)	12.9 ± 17.0	12.2 ± 17.8
n	- 0.747 ± 0.367	- 0.571 ± 0.257
R	0.887 ± 0.121	0.927 ± 0.103

The best fit to the measured data was found with $a = 0.15$. Comparisons of the error-compensated simulated intensity to the measured data are shown in Fig. 4(a) and Fig. 4(b). The BLM signal (Gy/s) can then be obtained from the loss rate (p/s) using the calibration factor [4]:

$$S_i(t) = \frac{R_i(t)}{f_i^{calib}} \quad (4)$$

The simulated decrease in intensity is therefore given by:

$$N_i = N_{i-1} \times (1 - F_{lost}(n_\sigma)) \quad (5)$$

Typical values for σ_x, x_0, N_0 and f_i^{calib} can be found in Table 1.

TEMPORAL LOSS DECAY MODEL

The temporal decrease in the losses over a period of a few seconds was parametrically modeled. The fit parameters are:

- Amplitude a
- Power coefficient n
- Error between fit and data R

A number of loss spike samples were collected (299 at 450 GeV and 262 at 3.5 TeV), and an exponential curve of the form $y = ax^n$ was fit to each sample. All samples were visually examined to determine the decay time T_{decay}, which is the time taken for the losses to decrease to reach steady-state. The results shown in Table 2 indicate that the loss decay time is larger at higher energy.

SIMULATOR ALGORITHM

The setup simulator was based on the existing GUI developed for the operational collimator application. However, the collimator and BLM data acquisition modules
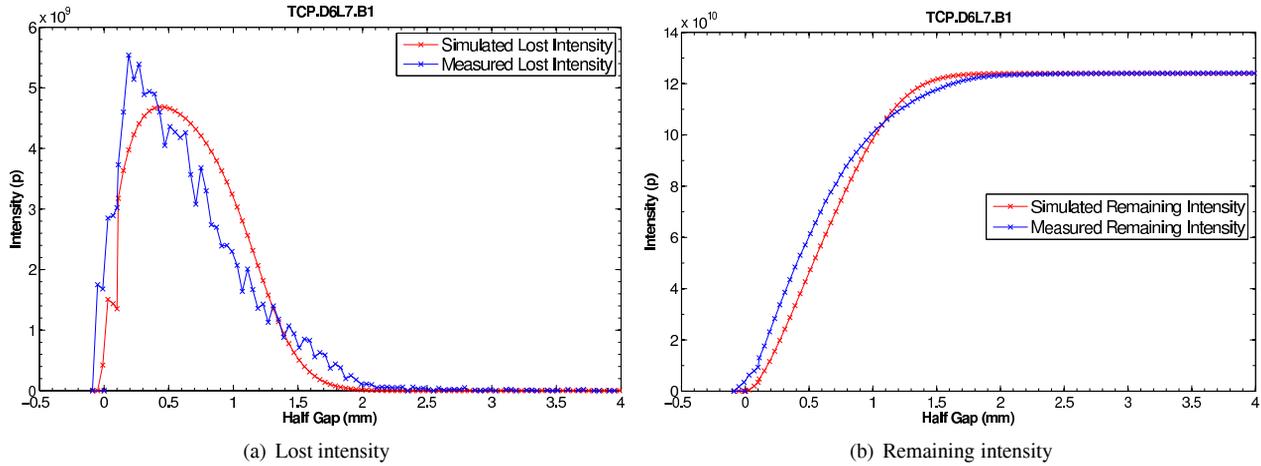
(a) Lost intensity

(b) Remaining intensity

Figure 4: Measured and simulated intensity every 4 seconds as a function of the collimator jaw half gap (TCP.D6L7.B1).

were adapted to transmit and receive data to and from the simulator engine. The simulator algorithm first initializes some parameters:

- Randomize beam centers from real data by $\pm\,200\,\mu$m.
- Calculate beam size at the collimators for a given emittance.
- Initialize the BLM signals for each collimator to the steady-state signals for the starting jaw positions.

For every collimator jaw movement:

1. Calculate $F_{lost}(n_\sigma)$ from Eq. (3).
2. Convert $F_{lost}(n_\sigma)$ into a BLM signal using Eq. (4).
3. Obtain the new beam distribution using the error function and calculate the new value for $1\,\sigma$ from the fit.
4. Decrease the intensity from Eq. (5).
5. Randomly choose a power coefficient from the log-normal distribution to generate the BLM decay for a stationary jaw.
6. Revert to the steady-state signal generation when the decay decreases below the average steady-state signal.

SIMULATION RESULTS

A comparison of the simulated data to measurement data for a beam scraping test is provided in Fig. 5. The scraping test was performed with a primary collimator (TCP.D6L7.B1) at 450 GeV, with a jaw step size of 40 μm every 4 seconds (the same data used to generate the calibration factor in [4]). The simulated losses start to increase with a larger half-gap in mm than expected. This is because the tails of the beam distribution are in fact more populated than the approximation provided by the Gaussian distribution. In addition, the simulated losses do not decay as fast as the measurements. A more detailed empirical analysis is required to study the loss decay for better accuracy.

CONCLUSION

A model for beam losses during collimator setup has been developed, based on the Gaussian beam distribution
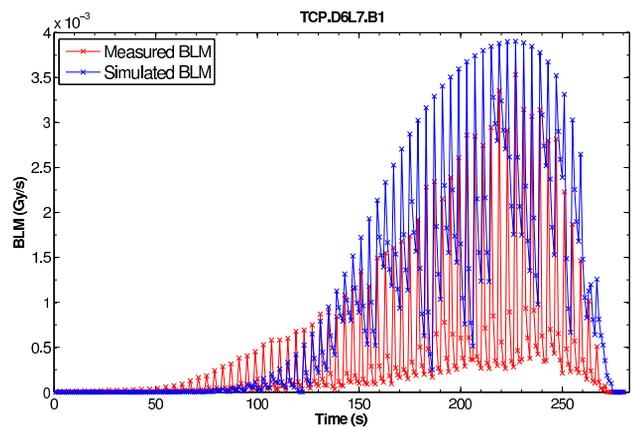

Figure 5: Simulation results of the BLM signal for the TCP.D6L7.B1 collimator.

model and a parametric model for the temporal loss decay. The simulator uses this model to generate beam losses which would occur during collimator alignment. An accurate simulator would allow for new collimator alignment algorithms to be tested without requiring costly beam time. A comparison of the simulation results to measured data obtained during beam scraping and collimator alignment is provided. The simulated losses start to increase with a larger half-gap in mm than expected. Further work will investigate the heavily-populated tails to improve the accuracy of the simulator.

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