Relating Beam Loss, Activation and Residual Radiation for 400 kW Operation of the Fermilab Main Injector

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Abstract

In 2008 - 2012 the Fermilab Main Injector ramped up beam intensities to provide up to 400 kW of proton beam power at 120 GeV. Successful loss localization efforts resulted in transmission of nearly 95% of the beam with most proton losses at or near the 8 GeV injection energy. To document loss patterns, beam loss monitor (BLM) and transmission measurements were examined during selected beam acceleration cycles. Transmission and BLM Loss integrals were also recorded for each beam cycle. Activation measurements of Al tags and residual radiation measurements at designated locations identified with bar coded tags provide us with information to relate losses to MARS simulations of the loss control (collimation) system. We normalize these measurements using beam transmission measurements with toroids on beam injection and extraction checked against dc current transformer (DCCT) measurements of circulating beam intensity. Results will describe operational achievements in the 400 kW operational era and expectations for planned higher beam power operation.

1. Overview

The High Energy Physics programs at the Tevatron Collider and Neutrinos at the Main Injector (NuMI) neutrino beam line required operation of the Fermilab Main Injector at high intensity [1]. This was achieved by utilizing the Fermilab 8 GeV Booster at $4.3 \times 10^{12}$ protons per Booster batch and accelerating 11 batches from 8 GeV to 120 GeV in a slip stacking mode. Two batches were slipped together for acceleration as one for antiproton production while an additional (4+4) batches were slipped to form 4 and another batch was injected to provide a total of 9 to be delivered to the neutrino target. The longitudinal emittance (momentum spread) of the injected beam was too large to be fully captured after the slip stacking process. A transmission efficiency of 91% was typical for the higher intensity batches destined for the antiproton production target while 95% was typical for the neutrino (NuMI) batches.

In order to localize the losses, a system of primary/secondary collimators was constructed [2]. It was commissioned in winter 2008 while the 11 batch slip stacking was also being commissioned. Losses at 8 GeV were localized to the collimation region with this system and other tools reduced or eliminated losses at higher energies and at other locations. As a result, the important radiological concerns for Main Injector operation are the radiation damage to accelerator components and limitations for hands-on maintenance due to residual radiation for components in the tunnel, activation of air which escapes from the tunnel, and activation of materials outside the concrete walls of the tunnel where water carrying activation products might be pumped to the surface. The collimation system design was evaluated with MARS [3] and found to be within guidelines for the operating parameters that were achieved.

In order to document the successful operation of this system at 400 kW beam power and to prepare for planned operation at 700 kW and perhaps higher intensities, we are studying the injected, and extracted beam intensities measured with toroids and circulating beam intensity measured with DC current transformers (DCCT) to determine transmission and losses. We have beam loss measurements (BLM) using gas-filled...
ionization monitors\[4],[5]. We have measured the activation at 15 locations in the collimator area using Al Tags[6] which were removed after 1, 2, or 3 years exposure (with one location measured after a 4th year). Residual radiation was measured as needed for hands-on maintenance but in addition a program to monitor the residual radiation at up to 142 bar-coded locations[7] has provided measurements during beam off periods for more than 50 times per location.

We wish to relate the loss of beam and the activation it has produced to compare with simulations with MARS[8],[9]. We find that the data logging systems have bookkeeping limitations which require us to examine and inter-compare various measurements in order to have a useful results. In this work we will show the status of that effort. Our principal result will be to provide a calibration of the BLM signal in terms of the protons lost near to the loss monitor. With this calibration and with careful examination of the BLM loss record, we will have a history of the loss. Our study will extend through the long run until 30 April 2012. This will include running for the Tevatron and antiproton production until 30 September 2011.

2. Collimation System Overview and Loss Control

The major goal of the Main Injector collimation system was to localize losses of beam which is not captured and accelerated after slip stacking. That beam is distinguished by failing to remain on orbit but follows a dispersion orbit to the low momentum side. No longitudinal space is available in the Main Injector lattice except in straight sections where the dispersion is designed to be zero. Collimation begins at a location in the last half cell upstream of the MI300 straight section where the dispersion is large enough. By placing a 0.25 mm tungsten foil to form a vertical edge on the radial inside, particles which are not being accelerated will strike this foil and be scattered. Four 20-Ton secondary collimators are placed through the following 10 half cells to capture the scattered protons and contain the resulting shower of secondary particles. Ramped orbit bumps place the beam edges parallel to the straight section centerline for collimation with the collimators being positioned at suitable displacement from the centerline. Uncaptured beam accounts for about 5% of the injected beam. This system localizes 99% of this uncaptured beam loss with about 80% of the lost beam power being absorbed in the 20-Ton collimators.

In addition to the 20-Ton secondary collimator, fixed steel masks are placed to capture forward scattered secondary particles. One mask is just downstream of the associated secondary collimator while a second is placed just upstream of the next trim dipole magnet. The importance of these masks was demonstrated by examining the activation pattern downstream of the third collimator where the masks were only added after two years of operation. The downstream trim dipole was highly activated (2.5 R/hr on contact) but the activation dropped by \( \times 10 \) after installation of a two-mask system at that location. Activation further downstream was also impacted as discussed below.

Control of instabilities using dampers and aperture improvements were also important in controlling activation. Gaps in the beam which are needed for extraction magnet (kicker) rise time were kept clear using the dampers in antidamping mode. Beam which was lost due to antidamping and additional beam losses from injection and transverse loss mechanisms are partially contained by the collimation system. Slip stacking resulted in some beam in the gaps required for injection kickers. This created radiation in the injection area until Gap Clearing Kickers were installed and commissioned. The collimation system was installed in 2007. Collimator commissioning along with damper improvements continued during operations through June 2009. Gap Clearing Kicker operation began in 2010. Subsequent operation found beam loss at the collimation system to account for most transmission inefficiency.

Figure 1 shows transmission efficiency calculated by comparing beam delivered to antiproton and neutrino targets to the injected beam. The inefficiency is corrected for beam to the abort due to whole ring aborts or to beam removed by the gap clearing kickers. We calculate a transmission inefficiency by subtracting this beam sum from the injected beam sum. Transmission efficiency is then one minus the inefficiency. Prior to the Gap Clearing Kicker commissioning in 2010, beam lost from the injection gaps created activation in the MI104-106 area. We account for this by calibrating the loss in the loss monitors in that area. Using techniques described below, we then calibrate the loss at the collimators from loss monitors adjacent to the primary and each of the four secondary collimators. We see that the characterization of the transmission

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Figure 1: Weekly beam transmission inferred from Toroids and from Collimator losses. Beam sent to the abort is subtracted and accounting is made for beam lost from injection gaps
by the loss matches well to the transmission calculated by the toroids in the era when other losses are well controlled. Changes in the transmission mark the operational changes in the high energy physics program such as the improved transmission when antiproton production stopped in October 2011 and the total intensity was reduced to protect the NuMI neutrino target. Further details on the loss and activation control are available in Ref [1].

3. Beam Loss Monitor System

The beam loss monitor system created for the Tevatron[4] was applied for the Main Injector. Argon-filled glass tubes were installed in a regular pattern on the outer wall and above the beam height at the downstream end of the quadrupole which defines each half cell in the Main Injector. Additional monitors were liberally applied to observe losses at the original proton transfer locations. The response of the BLM system to the ionization deposit in Rads is well documented. Despite the regular structure, it must be assumed that details of the proton loss pattern will allow variations in the response in Rads per proton lost. An improved electronics package and associated software[5],[10] were commissioned in 2006. Using data logged from this system, we will derive careful calibrations for the BLM response in protons lost for the special case of the BLM’s near the four secondary collimators. This is possible because nearly all protons lost in the ring are lost at these collimators.

4. Monitoring with Al Tags

One can monitor an important portion of the activation spectrum produced by loss of 8 GeV protons by measuring the production of $^{22}\text{Na}$ in Al samples. Al tags were placed at 15 locations in the region of the Main Injector collimation system prior to system commissioning. Tags were removed on intervals of about one year. Using the nearby beam loss monitors (BLM’s), decay corrections allow one to normalize the measured activation to a half life weighted BLM signal. Ref [6] provides details of the aluminum activation study. Here we will use data from the Al Tags placed on the aisle side of each of the four secondary collimators to provide calibration for the nearby BLM.

The activation was quite similar for the aluminum tags placed at the first three collimators when normalized to their nearby BLM. When plotted as shown in Figure 2, it became apparent that the third year of activation for the fourth collimator also matched the pattern. We realized that in earlier years that activation was dominated by radiation produced by the protons lost in the third collimator. Collimation masks were installed downstream of the third secondary collimator only after the 2nd year of collimator operation. This then protected the fourth collimator from the activation produced by the third collimator. We assign a calibration for BLM’s near the four secondary collimators by assuming that all lost protons from the 3rd year interact in one of the four secondary collimators with the Al Tag activation being used to allocate the ratio between the four collimators. A small correction is required for protons lost at the primary collimator. We then use the tag activation to calibrate the BLM loss in Rads to a loss in protons.

5. Using Residual Radiation for BLM Normalization

One tool used in the loss control and monitoring program was frequent measurements of residual radiation. In addition to checking all high activation locations, a systematic program of measurements at up to 142 bar-coded locations[7] is available for study. A simple fit[11] of the recorded residual radiation (in mR/hr) to the BLM signal matches the data. Half life weights of the BLM signal using three Manganese isotopes ($^{54}\text{Mn} (312.2\text{ days})$, $^{52}\text{Mn} (5.591\text{ days})$, $^{56}\text{Mn} (2.58\text{ hours})$) are adequate for many purposes. Measurements of the activation of magnet steel samples[12] finds that $^{59}\text{Fe} (44.5\text{ days})$ and $^{51}\text{Cr} (27.7\text{ days})$ are observed but fits with more isotopes are not well constrained. When we examined measured data compared to various fits we find that for times when the beam is off for weeks, the fits are a few percent high which is likely due to failing to include appropriate longer half life isotopes.

Plots for fits to the residual radiation at each of the four secondary collimators are shown in Fig 3. During commissioning of the collimation system, the large variations are not adequately described by the

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Figure 2: Al Tag activation normalized to nearby BLM. Upper figure is cumulative for three years. Lower figure shows difference for each year. The observed activation is normalized to the beam loss weighted by the $^{22}\text{Na}$ half life.
fit. Fig 4 shows this data and fit after June 2011 and extending into the long shutdown which began on April 30, 2012. Here we can select data when the radiation from $^{54}$Mn dominates. Normalizing to the BLM signal weighted by the 312.2 day half life provides a residual radiation to BLM calibration. If we assume that all the protons were lost in the four secondary collimators (with a small correction for the primary) and we assign the losses in proportion to the residual radiation, we can normalize both the residual radiation and the BLM signal to the number of protons lost. We identify this normalization as the calibration from Residual Radiation. Here we employ the $^{54}$Mn coefficient from the fit but fits to alternative time periods or using the measured residual radiation after sufficient cooldown are options we will explore in achieving a final calibration.

6. Calibration from Fits to BLM Loss Measurements

As we see in Figure 1, the weekly transmission after the improvements in 2009 are well explained by the collimator losses. Either the Al Tag or the Residual Radiation calibration would be useful. As a further check and to study loss at the primary collimator, we have fit the calibrations to match toroid-measured loss to BLM-measured loss using Solver in Excel. The data is not suitable for straightforward Simplex fits and the data range must be carefully selected to get helpful results from GRG nonlinear fits. However between January and June 2009, we had a collimation tuneup which created large losses at the primary collimator. This technique allows one to determine the calibration for the BLM near the primary collimator. Further exploration provided the calibration identified as Fit Calibration. We employed weekly loss data for this fitting. We see in Figure 1 that the weekly transmission results are helpful. This same information is replotted in Fig 5 as the difference between the toroid loss measure and the loss determined by the BLM signals. The 4 week average is less confusing so we employ that in Figure 5. We will continue to examine these results to see if further understanding will improve the agreement of various techniques.

The resulting calibration values are specific to the system in the Fermilab Main Injector and will ac-
Figure 4: Residual Radiation Fit to Nearby BLM at each Secondary Collimator for later times.

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Figure 5: Beam Loss as measured by toroids is compared to Beam Loss at collimators using three options for proton loss calibration of collimator BLM readings.
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The software we have developed for relating residual radiation to the BLM history required techniques to remove a variety of spurious data from the datalogger history. The comparisons with MARS calculations will be done for time periods specific to the various situations we were in as the loss control system developed. To normalize the MARS calculations which begin with definite assumptions on the protons lost, we will apply BLM calibrations developed as we have the ones in Table 1.

References


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