FERMILAB-CONF-09-167-AD

FERMILAB MAIN INJECTOR COLLIMATION SYSTEMS: DESIGN, COMMISSIONING AND OPERATION *

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Abstract

The Fermilab Main Injector is moving toward providing 400 kW of 120 GeV proton beams using slip stacking injection of eleven Booster batches. Loss of 5% of the beam at or near injection energy results in 1.5 kW of beam loss. A collimation system has been implemented to localize this loss with the design emphasis on beam not captured in the accelerating RF buckets. More than 95% of these losses are captured in the collimation region. We will report on the construction, commissioning and operation of this collimation system. Commissioning studies and loss measurement tools will be discussed. Residual radiation monitoring of the Main Injector machine components will be used to demonstrate the effectiveness of these efforts.

ACHIEVING HIGH INTENSITY

The Fermilab Main Injector provides high intensity 120 GeV proton beams for production of anti-protons and neutrinos[1]. Protons are injected from the 8 GeV Booster which can provide intensities $> 5 \times 10^{12}$ per batch. The gaps needed for injection and extraction limit one to acceleration of 6 batches of Booster length. To increase the intensity above 30×10^{12} requires stacking. Slip-stacking[2] has been developed to permit acceleration of 11 Booster batches. Operation with 2.2 second cycles has produced more than 350 kilowatts of 120 GeV beam power with intensity limited by operational loss limits.

The most significant losses are directly related to the limitations of the slip stack process. Limits to the RF bucket sizes during slipping are specified by the available momentum aperture while the momentum spread of the Booster beam includes tails beyond that which can be captured. This beam which is uncaptured during the slipping process may be captured in unwanted locations (kicker gaps) when the acceleration RF system is turned on or it may remain outside the RF bucket and not be accelerated. The Main Injector Collimation System is designed to efficiently absorb losses due to unaccelerated beam.

COLLIMATION SYSTEM

As the acceleration ramp begins, the captured beam is accelerated on the central orbit while the uncaptured beam follows the dispersion orbit at greater and greater momentum offset. However, the straight sections, where one can place absorbers, were designed with low dispersion. The collimation system is designed using secondary collimators in the MI300 straight section and a primary collimator in the last half cell (MI230) ahead of that region where there is sufficient dispersion. The 0.25 mm Tungsten primary collimator is set to define the momentum aperture with a vertical edge. The secondary collimators are located downstream at horizontal phase advances of 156^o, 245^o,423^o and 476^o. The secondary collimators are thick-walled stainless steel vacuum boxes surrounded by a massive absorber system. Each of them is placed so that the circulating beam is in a corner and the beam scattered by the primary collimator will strike one radial and one vertical aperture limit.

The collimation design was based on an extensive simulation of slip stacking in the Main Injector[3] using the STRUCT code. We found that, after careful description of the lattice and the slip stacking process, the time structure of the loss and the quantity of beam lost could be simulated. However, simulation with only the linear fields predicted losses only at points of high dispersion. Simulation including the measured higher harmonic components of the magnetic fields predicted losses at transfer points (Lambertson magnets) where the aperture restriction is mostly vertical and dispersion is low. The comparison with losses during slip stacking operation was much better. The above collimation concept was then added to the simulation and optimized. It predicted that particles lost due to the uncaptured beam would be absorbed by the collimation system (from the primary collimator to the end of the MI300 straight section) with more than 99% efficiency.

The collimation system was installed in the 2007 Fermilab Facility Shutdown and was ready to begin commissioning in November 2007. The hardware[4][5] and commissioning[5] have been described previously. Since the MI300 straight section also includes the Recycler Electron Cooling system, one wishes to limit the radiation exposure of those devices. In order to limit radiation of the materials outside of the concrete tunnel enclosure, the secondary collimators were constructed to fill the available transverse aperture. The length is sufficient to capture the bulk of the induced shower. The face of the collimator is placed parallel to the centerline of the straight section while a taper on the upstream collimator end permits the absorption of the shower with minimum outscattering.

Figure 1 pictures the 20-Ton secondary collimator at

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

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Figure 1: 20-Ton Secondary collimator

MI301. The residual radiation in the aisle is reduced by addition of marble to shield the MeV gamma rays due to activation of the steel. The motion system provides horizontal and vertical positioning with 25 μm step size. The beam pipe adjacent to the downstream end of the collimator and again upstream of the next corrector magnet has been provided with a ‘mask’ by surrounding the pipe with iron blocks which are in turn surrounded by concrete or marble. Outscattered beam remanents and shower tails are captured by these devices. This system was not provided for the third collimator as low losses was expected from uncaptured beam but high loss is observed before acceleration and as a result, the next corrector magnet is very radioactive. Comparison with comparable locations suggests that these masks provide about a times ten reduction in residual activation. The upstream end of the collimators is shielded by a polyethylene block to reduce the flux of neutrons which impact the nearby quadrupole magnet.

COMMISSIONING AND LOSS MEASUREMENT

A kicker near the middle of the MI300 straight section is employed to transfer anti-protons from the Main Injector to the Recycler and back. The positioning of the collimators is restricted by the orbits employed for these transfers. In order to employ the collimators, a time bump distorts the closed orbit. This orbit is designed so that, at the desired emittance boundary, the edge of the beam is parallel to the collimator, causing unwanted particles to strike the upstream tapered portion. Since no dipole corrector magnets were added for the collimation project, there is only a minimal set and the possible orbit offsets at the four secondary collimators are coupled. Some flexibility is achieved by employing correctors outside of the collimation region to induce an incoming distortion.

The Main Injector is equipped with a loss monitor system consisting of sealed glass ion chambers filled with argon. New electronics was commissioned in 2007 to provide high resolution recording and flexible readout. Applications to display this data for monitoring and studies has been developed in order to optimize collimation.

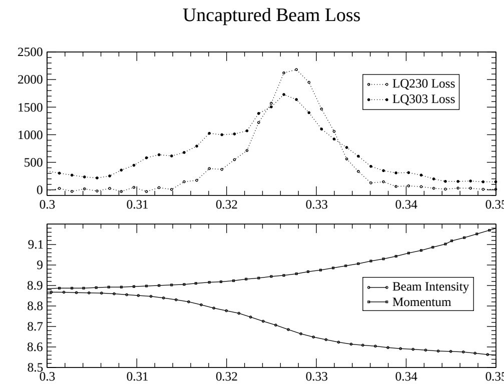

Figure 2: Loss monitor readings, momentum and beam intensity during uncaptured beam loss on PBar production cycle. Loss at primary and one secondary collimator are shown. Loss peak occurs when captured beam has been accelerated by 0.82%

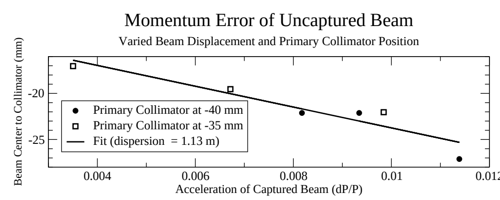

Figure 3: To confirm that loss is due to un-accelerated beam we vary distance from beam center to primary collimator and observe time and momentum of loss peak. We plot distance *vs.* momentum change, finding that it matches expected dispersion.

Commissioning has proceeded by creating an orbit distortion at a time before the uncaptured beam reaches a momentum aperture outside the collimation region. One then defines the momentum aperture with a combination of the primary collimator position and a position bump at that location. This defines a point for scattering the particles, setting their orbit downstream. Figure 2 shows the loss recorded at the primary collimator (and the 2nd secondary collimator) as well as the beam intensity and the momentum to which the capture beam has been accelerated. Using this technique, Fig. 3 shows that the dispersion for lost beam is similar to that measured in other ways.

The secondary collimator positions are optimized by studying loss patterns recorded by the loss monitor system. Collimators are moved toward the beam edge where the scattered beam is expected. Moving too close will result in decreasing the accelerated beam. Collimation orbits and the four collimator positions, both horizontal and vertical, are adjusted to achieve high collimation efficiency for the uncaptured beam. Despite using significant collimation orbit bumps as acceleration starts, the collimators can still be moved close enough to provide a significant limiting aperture for the injected beam. This results in capturing a large fraction of the pre-acceleration losses in the collimation region also.

Figure 4: Logarithmic display of losses around the Main Injector. Integrated loss at the end of the cycle are displayed in green. Losses after the uncaptured beam loss overlay this in yellow. Losses at the end of injection overlay this in blue. Various sums and intensities are displayed at the top and bottom. For this display, the collimation region includes 229 - 309.

RESULTS

Using a three decade logarithmic display of all loss monitors, we observed the loss patterns during each cycle of Main Injector operation. For normal operation we display this continuously in the Main Control Room. Figure 4 illustrates typical operation since an orbit and collimation adjustment in April 2009.

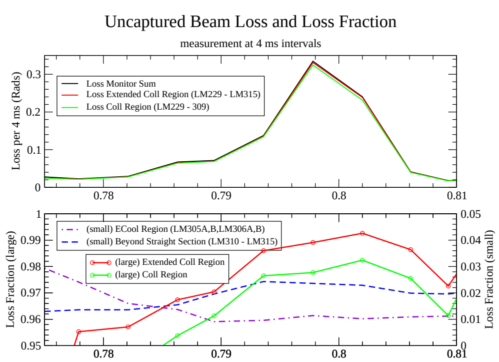

Figure 5: Loss at collimators compared to loss sum around the ring. The STRUCT simulation reported losses from LM229 - LM309. The orbit distortion added loss at LM228. We observe small loss from LM310 - LM315 which we continue to study.

The efficiency calculated for the display in Fig. 4 integrates losses over a 74 ms interval. The uncaptured beam is lost in about 12 ms. In Fig 5, the loss measurement hardware was configured so all loss monitors record the integral loss in 4 ms intervals. We have taken differences to get the loss in that interval, taken sums of all loss monitors and various groups to see the efficiency of collimation. We see that other loss mechanisms continue as acceleration begins.

If we observed losses at the peak of uncaptured beam loss, we find that the collimation captures $>99\%$ of the losses in the region of the collimators. If we include only the region which was included in the simulation, the efficiency is more than 98%. These results are simple sums of the measured signal in the ionization loss monitors. Variations in the sampling density and geometry limit our precision for precisely evaluating the efficiency.

A program to monitor residual radiation at selected locations in the Main Injector has monitored activation since 2005. To demonstrate the impact of collimation we averaged the ratio after (2/2009, 4/2009) to before (12/2007, 1/2008) we began using collimation for groups of locations in major arcs, the collimation region and transfer points at LAM40, LAM52, LAM60/61 and LAM62. Table 1 shows these results. Since some long-lived isotopes have been produced, further improvements are expected at some locations.

Table 1: Residual Radiation Ratio: 2009 vs 2008

113-221	**Coll**	**40**	**405-521**	**52**	**60**	**62**
0.26	5.06	0.55	0.30	0.68	0.65	0.70

ACKNOWLEDGMENTS

We would like to thank the Fermilab Accelerator Division Mechanical Support Group, Controls Group and Operations Group for assistance in constructing, commissioning and operating this system.

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