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DESIGN CONSIDERATIONS AND OPERATIONAL FEATURES OF THE COLLIMATORS FOR THE FERMILAB MAIN INJECTOR AND RECYCLER *

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Abstract

The Fermilab Main Injector system delivers 700 kW of 120 GeV Proton beam for neutrino experiments. Since 2013 this has been achieved using slip stacking accumulation in the Recycler with up to 12 batches from the Fermilab Booster per Main Injector Ramp Cycle. To control activation from beam loss, collimation systems in the Booster to Recycler transfer line, in the Recycler and in the Main Injector are employed. Residual radiation measurements around the ring with detailed studies at the collimators are required to maintain adequate loss control. We will review design considerations, operational parameters and activation results for more than ten years of operation. Simulations with MARS15 are used to explore the activation rates and the isotopic composition of the resulting activation.

OVERVIEW

Since preparations began in 2004 for high intensity operation of the Fermilab Main Injector for the neutrino program, an intensive effort has been required to control activation and radiation damage to devices in the accelerator tunnel. An overview of the efforts through the Tevatron era is provided in [1]. Peak power delivered in that era reached 400 kW using slip stacking in the Main Injector. By using the Recycler as a stacking ring [2] [3] beam power of 700 kW of 120 GeV protons have been delivered. These have been achieved with about 1% loss at collimators in the MI8 Booster to Recycler transfer line, >97% transmission in the Recycler and >97% transmission in the Main Injector. A gap-clearing kicker system [4] delivers some unwanted beam to the abort while collimators in the MI8 line [5], in the Main Injector [6], and in the Recycler [7] localize most of the remaining losses. Acceleration from 8 GeV to 120 GeV with very low losses is normally achieved.. Residual radiation at some critical locations are now ten times lower than their peak. Table 1 introduces these collimation systems.

Examination of the residual radiation for the Main Injector found patterns which suggested [8] that the transverse emittance of Booster beam was not cleanly accepted into the Main Injector aperture. At the same time, plans for higher intensity using slip stacking [9] assured that a few percent of the injected beam would not be captured into rf buckets for acceleration. A modest collimation system for the MI8 Booster to Main Injector Transfer Line [5] was developed quickly (installed in Spring 2006) while we designed and built a collimation system for the Main Injector [6] which would capture the beam from Main Injector slip stacking which was not accelerated and also define aperture limits to localize transverse losses from either injected beam or emittance growth from any source. This system was installed in Fall 2007 and commissioned in 2008.

Plans to employ the Recycler Ring for proton stacking [10] deferred collimation considerations. It was understood that the uncaptured beam from slip stacking would transfer cleanly to the Main Injector where the existing collimation system would contain the loss. Although other improvements solved many problems, the usefulness of a collimation system for localizing transverse emittance issues (injection, beam growth, and instabilities) was determined to demand a Recycler Collimation system. It was installed in the 2016 Facility Shutdown [7]. We will describe some features of these systems and report various issues which remain.

COLLIMATOR DESIGN

Collimation is achieved with thick-wall stainless steel vacuum boxes with a taper on the upstream end. Beam starts interacting downstream at the end of the taper. Welded vacuum bellows permit the required motion. This is surrounded by a massive steel shield to absorb the interaction products. Since the stainless and steel becomes highly radioactive, a layer of marble surrounds the steel to shield the outside from the residual gamma radiation. Marble is highly resistant to activation. This design allows the motion control and readout to be placed in low radiation areas near the floor for MI8 and MI Collimators.

Simulations for the energy deposition design of these collimators employed MARS [11]. The MI8 and Main Injector tunnel depth is sufficient to reduce concerns about prompt dose on the surface. Considerations for hands-on maintenance, radiation damage to accelerator components, air activation and activation of ground water (important) were explored [12].

Transfer Line Collimation

Collimation of the Booster beam halo was achieved using a 2” x 2” collimation aperture with horizontal and vertical motion. A pair of collimators provides scraping of four sides of the beam in a half cell. After a 90^o phase advance

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Table 1: Collimation Systems for 8 GeV to 120 GeV Fermilab Accelerators

Item	MI8 Transfer Line	Main Injector	Recycler
Installation	Spring 2006	Fall 2007	Summer 2016
Design Concept	One-Stage	Two Stage	Two Stage
Design Function	Transverse (H&V)	Uncaptured Beam (Momentum)	Transverse
Hardware	Four 4-Ton Collimators	Four 20-Ton Secondaries	Two 20-Ton Secondaries
	Taper Upstream	Taper Upstream	Taper Upstream and Downstream
	Pairs at 90^o	Primary - Radial Outside	Primary - Vertical Bottom
	(or one cell) phase	Eight Masks	Two Masks
	H & V Motion	H & V Motion	H & V, Yaw & Pitch
Capability	~1% (at design limit)	~3%	~3%
Plans	Add Collimation Upstream	Reduce Forward Aperture	Performs as needed

(two half cells), the emittance edge which was at large angle is at large offset. A second collimator pair completes halo removal for this single pass beam. These collimators are installed in a low/zero dispersion section of the lattice. Each absorber employs a 4-Ton shield. MI8 system design in 2005-6 assumed Booster upgrades to 10 Hz beam operation whereas the Proton Improvement Plan (PIP) recently achieved 15 Hz delivery of protons at a comparable per pulse intensity.

Main Injector Collimation

A two-stage collimation system was implemented to capture the out-of-bucket protons which are not captured in the high voltage buckets at the end of slip stacking. Magnets occupy the lattice except in low dispersion straight sections. The primary collimator is located at the last (nearly) normal dispersion cell upstream of the MI300 long straight section. Four 20-Ton secondary collimators are arranged in the subsequent 10 half cells. The 0.25 mm tungsten foil (vertical edge) primary collimator is positioned on the radial inside downstream of a focusing quadrupole. An orbit bump combined with the foil radial position define a momentum aperture limit. After the captured beam has accelerated by about 1%, the unaccelerated protons reach that foil. They scatter to larger transverse emittance. Four 20-Ton secondary collimators are positioned so that the beam is in a suitable corner. Protons scattered by the primary may strike one of the secondary collimators at the end of the upstream taper and interact or they may continue to circulate. Since they have a larger emittance than other protons, they will either strike some secondary collimator on a subsequent turn (as their phase advance changes) or after a few turns they will strike the primary again and receive an additional emittance increment.

Since these secondary collimators are so close to the circulating beam, they are the limiting transverse aperture for almost all beam halo (any source) so they will also collimate other sources of beam loss. The positioning systems provide horizontal and vertical offsets to the 4” wide by 2” high vacuum aperture. A complicated orbit bump is imposed to steer the beam so that the edge to be collimated is parallel to the collimator for best absorption of halo while also setting the position. This bump is imposed just while the beam starts acceleration.

The protons which interact inside the secondary collimators produce a cone of secondary particles in the forward direction. Much of this develops into a shower which is absorbed but a portion of the shower escapes down the beam pipe. By surrounding the downstream beam pipe with a steel mask (which was in turn surrounded by concrete or marble), an important part of the forward shower was contained. A mask was placed just downstream of the secondary collimator and again just upstream of the next trim magnet. Failure to include the masks for the third secondary collimator in the initial implementation resulted in a very radioactive trim dipole.

Recycler Collimation

To contain the shower in a secondary collimator for 8 GeV protons requires 58 cm of absorber. Since the Recycler beam circulates 30 cm from the ceiling except in special locations, we designed a collimation system to scrape transverse tails which could be placed in one of those special places. The aperture is much more limited for vertical beam halo so we addressed that by employing a primary foil to define a vertical boundary (horizontal edge). The available β_y was large so a smaller scattering angle was desired. A 0.125 mm molybdenum (TZM) foil serves as the primary. Two 20-Ton secondary collimators with a forward mask for each provides the absorption for this system. The vacuum liner has a taper at both the upstream and downstream end for these secondary collimators.

The available orbit control was more limited so the mechanical system was provided with both position (H & V) and angle (yaw and pitch) control. The weight is supported on roller plates to allow yaw control. We find that the motion control is not as precise but still very adequate. The orbit bumps required to employ these collimators are invoked for each of the 12 injections into the Recycler for each Main Injector cycle.

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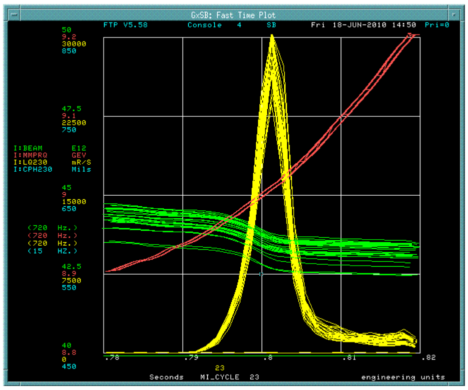

Figure 1: Loss Monitor Signal (yellow) at the primary collimator along with the Main Injector Momentum (red) and the beam intensity. (green) for a 40 ms period centered after 1% acceleration

PERFORMANCE

Operation of the Main Injector complex for ever higher intensities has successfully employed these collimation systems. Following a few months of system tune-up, excellent localization of losses were achieved.

Collimation Efficiency

As and example, we explore Main Injector collimator performance by examining the time structure of losses around the ring with a Beam Loss Monitor (BLM) system as shown in Fig. 1. We define the collimation region as the loss monitors group in the 14 half cells beginning at the primary collimator. When looking at the losses in time with the loss at the primary, we find that >99% of the loss are recorded in the collimation region. This is achieved after imposing the orbit bump described above and incrementally moving the secondary collimators closer to the beam in both the horizontal and vertically to achieve best containment. MARS studies suggest that ~80% of the lost proton power is absorbed into the secondary collimators. In the same efficiency definition, we find that >93% of losses for the whole cycle were contained in the collimation region. These measurements were carried out during Main Injector slip stacking since it is more tedious to explore losses when both rings have beam. Efficiency of the Recycler collimators has received less scrutiny following the successful control of instabilities by the diode damper system [13], [14]. With losses in two rings in the same tunnel, the measurement is more challenging.

Chlorine-induced Corrosion

During the 2012-3 shutdown for the Recycler upgrade, several sections of beam pipe were found to have severe corrosion, such that rough vacuum could no longer be achieved. Electron microscopy confirmed that chlorine was present in the corrosion pits. We ascribe this to the release of chlorine from the multitude of cables in the area with polyvinyl chloride (PVC) jackets. Some of the 316L vacuum pipe has been replaced with high molybdenum content 2205 Duplex stainless steel for sections which do not require a non-magnetic vacuum system. Additional dehumidification has also been provided in this area.

Destruction of High Voltage Cables

The cable system was in place from the initial installation of the Main Injector in the 1990's. In the vicinity of the Main Injector collimation system is a variety of power and signal cables. Above the aisle adjacent to the collimators there are red RG58 cables for vacuum pumps (5 kV) and beam loss monitors (2 kV). No cable failures were observed until about 10 years of operation. However between 2016 and 2019, all the vacuum (5 kV) cables in this area have shorted. Using BLM calibrations of the lost protons and MARS simulations for the absorbed radiation dose, we conclude that the failures require about 5000 grays. Replacement cables are being provided during the 2019 Facility Shutdown. MARS studies indicate that 10 cm of polyethylene or borated polyethylene shielding will provide a significant reduction in the absorbed dose to cables.

FUTURE PLANS

Future operation to deliver 900 kW beam in the near term and 1.2 MW of 120 GeV protons after the PIP-II upgrade will demand attention to the collimation systems. Locations are available in the MI8 transfer line where additional (and more capable) collimators can allow transverse scraping of higher intensity beams. Using MARS, we have explored the impact of reducing the 4" by 2" aperture in the Main Injector secondary collimators. We expect to achieve better containment of the lost power by providing inserts there.

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REFERENCES

[1] B. C. Brown *et al.*, "The Fermilab Main Injector: High Intensity Operation and Beam Loss Control," *Phys. Rev. ST Accel. Beams*, vol. 16, p. 071001, Jul 2013. doi:10.1103/PhysRevSTAB.16.071001.

[2] R. Ainsworth *et al.*, "High Intensity Proton Stacking at Fermilab: 700 kW Running," in *Proceedings, 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2018)*, Daejeon, Korea, June 17-22, 2018 doi:10.18429/JACoW-HB2018-TUA1WD04.

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[3] P. Adamson, "Reuse Recycler: High Intensity Proton Stacking at Fermilab," in *Proc. of ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, pp. 463–467, Malm , Sweden, July 2016. doi:10.18429/JACoW-HB2016-THAM1X01.

[4] I. Kourbanis *et al.*, "A Gap Clearing Kicker for Main Injector," in *Proceedings of the 2011 Particle Accelerator Conference*, pp. 1870–1872, New York, NY, 2011.

[5] B. C. Brown *et al.*, "Collimation System for the Fermilab Booster to Main Injector Transfer Line," in *Proceedings of the 2007 Particle Accelerator Conference*, p. 1673, Piscataway, NJ, 2007.

[6] B. Brown *et al.*, "Fermilab main injector collimation systems: Design, commissioning and operation," in *Proceedings of the 23rd Particle Accelerator Conference*, pp. 2841–2843, Vancouver, BC, Canada, May 2009.

[7] B. C. Brown *et al.*, "Fermilab Recycler Collimation System Design," in *Proceedings, 2nd North American Particle Accelerator Conference (NAPAC2016)*, Chicago, IL, USA, 2017. doi:10.18429/JACoW-NAPAC2016-WEPOA16.

[8] B. C. Brown, "Residual Radiation Hints for Aperture and Alignment Issues in the Main Injector," Beams-doc 1382 v2, Fermilab, January 2005.

[9] K. Seiya *et al.*, "Multi-batch slip stacking in the Main Injector at Fermilab," in *Proceedings of the 2007 Particle Accelerator Conference*, pp. 742–744, IEEE, Piscataway, N.J. 08855-1331, 2007.

[10] P. Derwent, "Accelerators for Intensity Frontier Research," in *Proceedings of the 2012 International Particle Accelerator Conference (IPAC2012)*, pp. 4185–4189, New Orleans, LA, USA, 2012.

[11] N. V. Mokhov and C. C. James, "The MARS Code System User's Guide Version 15(2016)," FN 1058-APC, Fermilab, 2017. doi:10.2172/1462233.

[12] I. Rakhno, "Radiation shielding for the Main Injector collimation system," TM 2391-AD, Fermilab, 2007.

[13] A. Burov, "Coupled-Beam and Coupled-Bunch Instabilities," *Phys. Rev. Accel. Beams*, vol. 21, no. 11, p. 114401, 2018. doi:10.1103/PhysRevAccelBeams.21.114401.

[14] N. Eddy *et al.*, "Transverse Damper Using Diodes for Slip Stacking in the Fermilab Recycler," in *Proceedings, 6th International Beam Instrumentation Conference (IBIC2017)*, 2018. doi:10.18429/JACoW-IBIC2017-TUPCF21.