ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA29

SECOND GENERATION FERMILAB MAIN INJECTOR 8 GeV BEAMLINE COLLIMATION PRELIMINARY DESIGN

K.J. Hazelwood*, P. Adamson, B.C. Brown, D. Capista, R.M. Donahue, B.L. Klein, N.V Mokhov, V.S. Pronskikh, V.I. Sidorov, M.C. Vincent
Fermi National Accelerator Laboratory, Batavia IL, USA†

Abstract

The current Fermilab Main Injector 8 GeV beamline transverse collimation system was installed in 2006. Since then proton beam intensities and rates have increased significantly. With the promise of even greater beam intensity and a faster repetition rate when the PIP-II upgrade completes later this decade, the current collimation system will be insufficient. Over the past 18 months, multiple collimation designs have been investigated, some more traditional and others novel. A preliminary design review was conducted and a design chosen. Work is underway to finalize the chosen design, prototype some of its novel components and procure parts for installation Summer 2023.

NEW COLLIMATION SYSTEM NEED

The Fermilab Main Injector 8 GeV (MI8) beamline is the transfer line for proton beam from the Booster to the Recycler Ring and Main Injector (MI) accelerator as well as the Booster Neutrino experiments (BooNE). The existing transverse collimation system is used to remove beam tails that would otherwise be lost in an uncontrolled fashion at multiple points along the aforementioned machines. The collimators, installed in 2006 [1], were designed to handle beam intensities and repetition rates that were beyond the ability of the Booster to provide then. However, with the end of the Tevatron collider program in 2011, Fermilab has focused on increasing beam power for its neutrino program [2]. Per pulse beam intensity and repetition rates now approach and can exceed the original design expectations of the MI8 collimation system [3]. Later this decade, the PIP-II linear accelerator will provide beam intensities far exceeding the existing collimators abilities [4].

DESIGN SPECIFICATIONS

As seen in Table 1, multiple constraints were specified for the new MI8 collimator system. In addition to these specifications it was also desirable to find a location in the MI8 beamline where the lattice function is at minimal dispersion. The existing MI8 collimators were installed at locations were dispersion was less than ideal, resulting in collimation of higher momentum beam, an undesired effect. The current collimators also happen to be installed adjacent to a tunnel alcove where cables are fed through penetrations to the upstairs service building. Having such high dose rates where personnel often have to work is not ideal. Locations 825 and 827 were chosen to be the ideal installation locations because of their low dispersion and distance from any radiation sensitive areas in the tunnel.

* kjh@fnal.gov
† Operated by Fermi Research Alliance, LLC under Contract No.De-AC02-07CH11359 with the United States Department of Energy, Batavia, IL USA.

Table 1: Collimation Design Specifications [5]

Name	Value	Unit
Maximum Beam Intensity [4]	6.5 E12	Protons
Maximum Beam Rate [4]	20	Hz
Maximum Total Collimation	2	%
Maximum Temperature	200	C
Minimum Aisleway Width	4.5	ft
Maximum Power	2	kW
Maximum Total Power	2	kW
Jaw Position Resolution	0.25	mm
Maximum Shielding Dose Rate [6]	0.05	mrem/Hr
Maximum Average Vacuum	1.0 E−7	Torr
Maximum Vacuum	1.0 E−5	Torr

TRADITIONAL DESIGN CANDIDATE

Three existing 8 GeV transverse collimation systems have been designed and installed over the last couple decades, a two stage system in the Recycler Ring [7], another two stage system in Main Injector [8, 9] and the single stage system in the MI8 beamline [3]. All three systems are similar in design; fixed jaws inside a vacuum chamber, encapsulated in tons of steel to absorb lost protons and secondary particles, wrapped in marble to protect personnel from the activated steel. All designs adjust the collimation by moving the entire collimator body. It's because of the success of these operational systems that the first design candidate for the new MI8 collimation system followed this traditional design concept (Fig. 1).

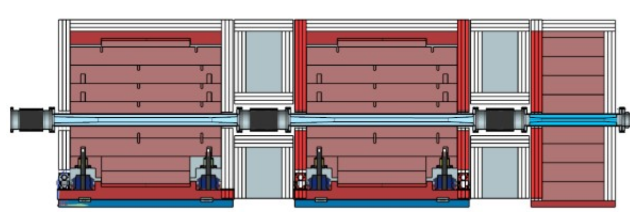

Figure 1: Traditional collimator design candidate elevation cross section. Beam travel is left to right.

Collimator Size

The first improvement implemented in the the Traditional design concept is its size. The current MI8 collimators simply do not have enough steel both transversely and longitudinally to efficiently capture most of the lost protons from collimation, the Traditional design, along with all designs considered, maximized the amount of steel possible in the planned installation locations.

Tapered Jaws

The second improvement was to add tapered jaw apertures. First implemented in the Recycler collimation system installed in 2016 [7] and later retrofitted to the MI collimators in 2019 [10], tapered jaws allow the collimation interaction to occur deeper in the collimator on the upstream end, creating the highest residual doses deeper inside the collimator and helping to lower exposure to personnel later accessing the tunnel. Likewise, a taper on the downstream end of the jaw ensures less exposure to personnel on that end. The jaw aperture is designed to be 5σ the transverse beam emittance at the interaction point. Likewise, the taper angle of each jaw is designed to follow the beta progression of the MI8 lattice function.

Masks

The third improvement was to add a mask to the downstream end of each collimation location. The existing MI8 collimators do not have significant masks, only small concrete and marble masks were added later. The Recycler Ring transverse collimation system installed significant steel and marble masks to their design which proved to be helpful in containing loss [7]. No actual beam collimation occurs in the masks, their beam apertures are larger than the collimating jaw apertures. The masks are intended to capture secondary particles that may escape.

Vacuum Bellows Shielding Plugs

The last significant Traditional design improvement was to create so called vacuum bellows shielding plugs. Due to the collimation edge being controlled by moving the entire collimator body, vacuum bellows are needed at either end of each body to allow travel. To increase the amount of steel the collimated particles encounter, steel plugs wrapped in marble were designed that could be removed during maintenance and repairs.

NOVEL MULTI-JAW DESIGN CANDIDATE

A second conceptual design came about when trying to maximize the amount of steel in the MI8 collimator. In order to maximize steel, it was decided to try and eliminate the vacuum bellows and alter the collimation jaw positions without moving the entire collimator body. What resulted was an idea for 4 jaws, 2 horizontal and 2 vertical, that move independent of each other within a fixed vacuum chamber (Fig. 2). The collimator nearly fills each installation location with as much steel as possible, both longitudinally and transversely. This multi-jaw design, while maximizing absorption steel, has many components that warranted further investigation and simulation.

Figure 2: Novel multi-jaw collimator design candidate Elevation cross section. Beam travel is left to right.

Multiple Independent Jaws

Each jaw in the Novel design is able to move along an axis, horizontally or vertically, such that either side of the beam can be collimated or not at all when the jaw aperture is positioned directly in the center of the vacuum vessel. Two linear actuated plungers are attached to each jaw and driven by motors on the aisle side or atop the collimator. The entire plunger is part of the vacuum vessel with a small vacuum bellows located at the coupling between the plunger and motor. Horizontal jaws remain in contact with the bottom of the vacuum vessel via bronze slip pads that ensure thermal contact while reducing movement friction (Fig. 3). Vertical jaws are also kept in thermal contact with the vacuum vessel via bronze slide pads (Fig. 3), however since gravity can not be used to provide sufficient thermal contact, additional force is applied to the aisle side of the vacuum vessel using a spring tuned to provide the desired contact. Each jaw aperture also features the taper from the updated Traditional design concept.

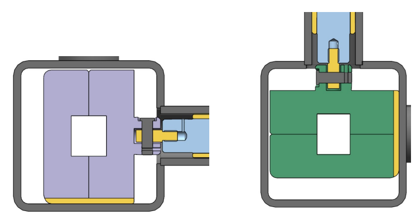

Figure 3: Left: Cross-section of Novel design horizontal jaw. Right: Cross-section of Novel design vertical jaw.

Integrated Masks

Both the Traditional and Novel design concepts have masks, however the Novel design features masks that reside in the vacuum vessel itself. This again maximizes the amount of steel at each location while still protecting against secondary particle loss.

PRELIMINARY DESIGN REVIEW

In March 2022, the project underwent a preliminary design review. At the review both the Traditional and Novel collimation design candidates were presented. The reviewers were also presented with the project's preferred design choice, the Novel design.

Motion Control Comparison

The most substantial difference between the design candidates is the mass being moved by the motion control systems.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA29

The Traditional design moves the full mass of the collimator bodies, estimated to be approximately 25 tons each, while the Novel design moves only the jaws, weighing approximately 98 lbs each. The Novel design jaws do not require as large motors nor does it need screw jacks to handle the load. Some advantages to not requiring screw jacks are the omission of oil to lubricate the jacks and the speed of jaw travel. Faster possible jaw travel would allow much faster collimation tuning and studies.

Thermal Analysis Comparison

The Traditional design is superior for heat dissipation caused by collimated beam power. The Traditional design collimator jaws are affixed to the vacuum vessel thus there exists an excellent heat sink. ANSYS simulations were done for the Novel design to determine if these could also handle the beam power. The jaws of the Novel design were found to not exceed 165 C when 350 W of beam power (approximately twice more than anticipated operationally) [11] was deposited on the jaw interaction point. Two bronze contact pads, covering 20 in^2 of the contact area of the jaw was sufficient to dissipate the heat and keep the jaw within the project specifications of 200 C (Table 1). Another thermal concern was expansion of the motion plungers. Simulations showed that the plungers, an integral path to dissipating heat, would only expand 0.1 mm when constructed of Invar, well within our jaw position tolerance of 0.25 mm (Table 1).

Vacuum Comparison

As the MI8 beamline is single pass, the vacuum levels are not as high of a concern as in the accelerators. Both the Traditional and Novel designs meet the minimum requirements for vacuum. Vacuum simulations show the Traditional design would pump down faster and maintain a static pressure lower than the Novel design. However, the difference in vacuum between the two designs was not significant enough to consider.

Collimator Efficiency Comparison

Both collimators were simulated using MARS [12]. Scenarios using each collimator jaw edge were simulated using 6.5 E11protons/second, twice the design specifications maximum beam intensity rate per jaw edge (Table 1). Overall, both collimators exceeded the design requirements for maximum inter-shielding dose rate (Table 1) and contained losses similarly (Fig. 4). With both collimators performing well, from an ALARA standpoint the Novel design was preferred because it did not require the use of the removable plugs.

Engineering and Fabrication Comparison

The vacuum vessel of the Novel multi-jaw design presents a fabrication challenge. The vacuum vessel box tube will be approximately 5 in square by 4.52 m long. The inside surface of the vacuum vessel must be machined to ensure sufficient thermal contact. Large tubes must be welded to the mutli-jaw vacuum vessel for the motion control plungers. In contrast, the Traditional design fabrication is very well understood.

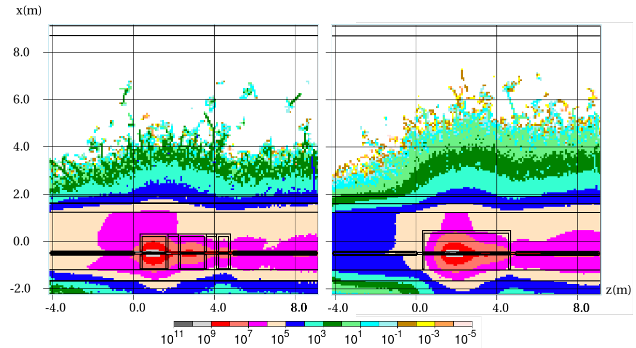

Figure 4: Single scenario MARS simulations prompt dose (mrem/Hr) elevation view charts. The tunnel enclosure shielding berm is denoted by the red line at approximately 8.5 m. Left: Traditional design, Right: Novel design; the Novel simulations have increased statistics thus the more low dose plume protruding into the berm area.

However, the removable plugs designed to better capture collimation losses are not trivial. Each plug would contain nearly 3 tons of steel and marble and since the plug would be significantly radioactive, it would have to transported away from personnel working on the collimator bellows during repairs and maintenance. Moving such a large, heavy, radioactive piece presents its own challenges and risks.

Reviewers Comments

Overall, the preliminary design reviewers agreed with the projects choice of the Novel multi-jaw design [11]. The reviewers echoed concerns with the removable plug on the Traditional design and agreed the removal of the vacuum bellows, as in the Novel design, should make for a more reliable and efficient collimation system. However, the reviewers did express concerns with a few of the Novel designs components.

First, the reviewers thought the presented design for a spring mechanism to keep the vertical jaws in contact with the vacuum vessel was not sound and recommended it be replaced with a Inconel Belleville washer system in use for many years in some of our beam target systems that also experience considerable amounts of radiation and heat [11]. Second, as the thermal conduction of the jaws to the vacuum is critical to the Novel designs ability to collimate the designed beam power, they suggested this aspect be tested by prototyping a full jaw and vacuum vessel assembly [11].

SUMMARY

Two design candidates, one traditional, the other novel, were investigated as improved replacements for the insufficient existing MI8 beamline transverse collimation system. After an extensive preliminary design review, the Novel multi-jaw candidate was chosen as the design to pursue. Work is underway to finalize the novel design and prototype some of its components. If all prototype testing succeeds, the project plans to install this design during the summer 2023 Fermilab accelerator complex shutdown with commissioning the following fall.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA29

REFERENCES

[1] B. Brown, P. Adamson, D. Capista, D. Morris, and M.-J. Yang, “First results from MI8 collimator use,” Tech. Rep., 2007. https://beamdocs.fnal.gov/cgi-bin/sso/ShowDocument?docid=2618

[2] B. C. Brown *et al.*, “The Fermilab Main Injector: high intensity operation and beam loss control,” *Phys. Rev. ST Ac-cel. Beams*, vol. 16, no. 7, p. 071 001, 2013. doi:10.1103/PhysRevSTAB.16.071001

[3] B. C. Brown, D. Capista, I. Kourbanis, N. V. Mokhov, and V. Sidorov, “Collimation for the Fermilab booster to main injector transfer line,” *Conf. Proc. C*, vol. 070625, p. 1673, 2007. doi:10.1109/PAC.2007.4440860

[4] M. Ball *et al.*, “The PIP-II conceptual design report,” Tech. Rep. FERMILAB-DESIGN-2017-01; FERMILAB-TM-2649-AD-APC 1516858, 2017. doi:10.2172/1346823

[5] K. Hazelwood, P. Adamson, D. Capista, D. Morris, N. Chelidze, and M. Murphy, “Second generation MI8 collimators design specifications,” Tech. Rep., 2022. https://beamdocs.fnal.gov/cgi-bin/sso/RetrieveFile?docid=8965&filename=mi8_collimators_specifications.pdf

[6] M. Gerardi, “Main injector and 8 GeV complex shielding assessment (1998),” Tech. Rep., 1999. https://fermipoint.fnal.gov/org/eshq/sa/Shared%20Documents/Main%20Injector%20and%208%20GeV%20Complex%20Shielding%20Assessment%20(1998)/MAIN%20INJECTOR%20SHIELDING%20ASSESSMENT%20V1.pdf

[7] B. Brown *et al.*, “Fermilab Recycler Collimation System Design,” in *Proc. of North American Particle Accelerator Conference (NAPAC’16)*, Chicago, IL, USA, 2016, pp. 726–728. doi:10.18429/JACoW-NAPAC2016-WEPOA16

[8] B. C. Brown *et al.*, “Fermilab Main Injector Collimation Systems: Design, Commissioning and Operation,” in *Proc. PAC’09*, Vancouver, Canada, May 2009, pp. 2841–2843. https://jacow.org/PAC2009/papers/WE6RFP025.pdf

[9] A. I. Drozhdin *et al.*, “Collimation system design for beam loss localization with slipstacking injection in the Fermilab Main Injector,” *Conf. Proc. C*, vol. 070625, p. 1688, 2007. doi:10.1109/PAC.2007.4440865

[10] B. C. Brown *et al.*, “Design Considerations and Operational Features of the Collimators for the Fermilab Main Injector and Recycler,” in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, paper WEYBB6, pp.642–645. doi: 10.18429/JACoW-NAPAC2019-WEYBB6

[11] K. E. Anderson, R. Bushek, S. Chaurize, E. Gianfelice-Wendt, K. Hazelwood, and R.Ridgway, “Second generation MI8 collimation preliminary design choice review report,” Tech. Rep., 2022. https://beamdocs.fnal.gov/cgi-bin/sso/RetrieveFile?docid=8965&filename=mi8_collimators_preliminary_design_choice_review_report.pdf

[12] N. V. Mokhov and C. C. James, “The MARS Code System User’s Guide Version 15, 2016,” Tech. Rep. FERMILAB-FN-1058-APC, 2017. doi:10.2172/1462233