

FERMILAB RECYCLER COLLIMATION SYSTEM DESIGN

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Abstract

To provide 700 kW proton beams for neutrino production in the NuMI facility, we employ slip stacking in the Recycler with transfer to the Main Injector for recapture and acceleration. Slip stacking with 12 Booster batches per 1.33 sec cycle of the Main Injector has been implemented and briefly tested while extensive operation with 8 batches and 10 batches per MI cycle has been demonstrated. Operation in this mode since 2013 shows that loss localization is an essential component for long term operation. Beam loss in the Recycler will be localized in a collimation region with design capability for absorbing up to 2 kW of lost protons in a pair of 20-Ton collimators (absorbers). This system will employ a two stage collimation with a thin molybdenum scattering foil to define the bottom edge of both the injected and decelerated-for-slipping beams. Optimization and engineering design of the collimator components and radiation shielding are based on comprehensive MARS15 simulations predicting high collimation efficiency as well as tolerable levels of prompt and residual radiation. The system installation during the Fermilab 2016 facility shutdown will permit commissioning in the subsequent operating period.

INTRODUCTION

The flagship physics program at Fermilab for the next two decades requires a robust high energy, high intensity proton source [1]. Slip stacking in the Recycler Ring [2] is a central part of that plan. The similar lattices and apertures of the Recycler compared with the Main Injector suggested that similar per cycle beam intensities could be supported. The increase in delivered proton beam power at 120 GeV is largely due to a faster repetition rate due to using the Recycler for beam accumulation while the acceleration of intense proton beams occurs in the Main Injector. In Ref. [2] one finds a description of several limitations which are being addressed, this paper will focus on the need to provide beam loss localization (collimation) to limit activation and radiation damage in the Recycler Ring.

The beam emittance available from the Fermilab Booster is large enough to produce losses due to both longitudinal and transverse emittance tails when used for slip stacking. Slip stacking in the Recycler is accomplished by stacking in the Recycler Ring but transferring the aligned bunches to the Main Injector for capture in the high voltage RF. This allows the use of the Main Injector collimation system [3] to continue to protect from the uncaptured longitudinal tails. The vertical design aperture of the Recycler beam pipe is

22 mm (half height) whereas the Main Injector beam pipe design provides 23.9 mm (half height). We have shown [4] that losses in the Main Injector were seen when this design aperture was reduced by installation issues. Many of the observed loss locations are at vertical β_{max} when the vertical aperture is reduced from the design value by installation imperfections. Additional activation locations are found at the transfer points where Lambertson magnets limit both the horizontal and vertical aperture.

The transverse beam loss in the Recycler has not been resolved into components due to the tails on the injected beam or tails due to emittance growth. Construction of a collimation system is proceeding without a such understanding. We will construct a collimation system which defines a vertical beam boundary with a primary collimator which scatters beam into the limited available vertical aperture in the local region. Studies with SYNERGIA confirm that horizontal to vertical emittance coupling will allow this to control horizontal tails.

TUNNEL LOCATION

The nominal Recycler beam height is 84" (7' or 2.13 m) above the floor of the Main Injector tunnel. Most of the tunnel is constructed with 10' wide by 8' high concrete hoops. For beam transport to the Tevatron this 8' ceiling height transitioned to 9' and then 10' for the proton (P150 line at 520) and antiproton (A150 at 620) beam transfer tunnel sections. For the Main Injector secondary collimators, we found that 23" (584 mm) of steel was suitable to contain the radiation showers from 8 GeV proton loss. With only 12" available with 8' ceilings we looked around. The 9' ceilings might be marginally usable but in the MI520 region there is too much else involved in the Recycler (P150 kickers and electrostatic septa in the Main Injector and the transfer line from RR to P150). At MI620 we have lots of instrumentation and the 9' ceiling ends too soon to be helpful for most purposes. The 520 region has two accelerators and two transfer lines while details of the Recycler lattice add complications. At the 613 cell boundary (high vertical beta) between the G613A and G613B gradient magnets there is a 9' ceiling with the transition to 10' ceiling above the G613B gradient magnet. We have placed a primary collimator at 613 and two secondary collimators in this region as a Phase I installation in the 2016 Facility Shutdown with consideration for two additional secondary collimators for a Phase II installation later.

TWO STAGE COLLIMATION

We employ a 0.125 mm molybdenum (Mo) TZM foil to define the lower edge of both the injected beam and the beam decelerated for slipping. Since we use a location with

4: Hadron Accelerators

T19 - Collimation

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much higher β_v , we choose a smaller RMS scattering angle than in the Main Injector system and we use Mo since the corresponding tungsten (W) foil is so thin as to be of mechanical concern. Halo beam which is scattered down (outward) may strike the secondary collimator placed downstream of the G613B gradient magnet. Beam which is scattered up (inward) may strike the secondary collimator placed downstream of the G616B gradient magnet. The plan is to place the primary collimator at a 3σ boundary and the secondary collimators at a 3.5σ boundary. This will leave scattered beam between these boundaries to circulate and perhaps rescatter on the primary. Some beam will be scattered beyond the available aperture between the primary and the secondaries while other beam will circulate and perhaps strike the secondaries or the primary on subsequent turns. Some of the scattered beam may strike aperture limits around the ring. Detailed tracking studies are continuing.

MECHANICAL CONSIDERATIONS

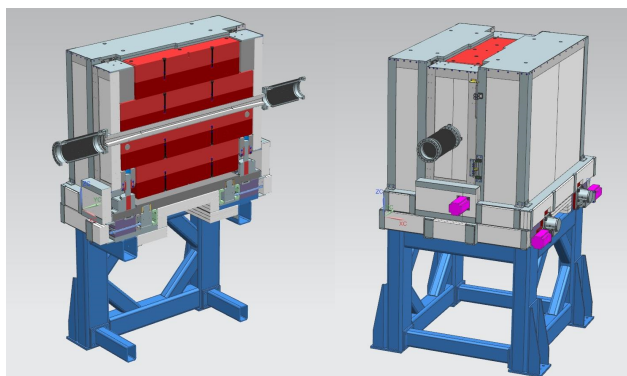


Figure 1: Mechanical Design Model for Secondary Collimator. Right figure is view from aisle side while left figure shows view with vertical cut through beam line. A stainless steel vacuum liner (grey) is surrounded by steel shielding (red) with marble absorber on the aisle side as well as on the upstream, downstream, and bottom.

The secondary collimators are designed to interact the protons deep in a large steel block so that the bulk of the shower energy is contained. A rectangular aperture with parallel sides 38.75" (0.984 m) long is preceded and followed by tapered portions 14" (355.6 mm) long. The apertures are selected to match the expected maximum beam size and the lattice β functions. With limited phase advance along the tunnel, we need to provide a way to position the interaction point (end of the tapered section) and the angle of the parallel section. Rather than employing a complex and powerful orbit correction, the secondary collimators provide precise control of the position and angle in both the horizontal and vertical planes. The vacuum portion is fabricated in stainless steel with an outer vacuum frame and removable inner liners to define the aperture. The vacuum liner is surrounded by steel to absorb the hadronic shower. An inner portion allows positioning of the aperture in vertical position and angle

(pitch) while this is mounted on a horizontal stage which allows control of horizontal position and angle (yaw). Additional iron outboard of the vertical portion completes the shielding. Stepper motors driving through a high gear ratio allow precise positioning (0.001") for each end of the secondary collimators (in both planes) far beyond any control requirements.

In order to absorb beam which showers toward or is scattered toward the beam aperture, we create collimation masks. These have a 38.25" (0.97 m) parallel portion with a 4" upstream tapered portion so that interactions will be buried in the body of the mask. These will protect the downstream magnetic elements and other components.

The primary collimator foil is supported on a 'C' frame with a free edge on the top. It is mounted on a precision motor drive which provides position accuracy of 0.001" (0.025 mm). The collimator system is illustrated in Figure 1.

The shielding around the primary collimator, the sides and bottom of the secondary collimators and masks are covered with 9 cm of marble. Marble does not become significantly activated but it absorbs the MeV gammas emitted by the activation products in the iron.

ANCILLARY SYSTEMS

To assure adequate vacuum performance, we employ large vacuum pumps downstream of the primary and upstream and downstream of each secondary collimator. We will add several channels of Beam Loss Monitor readout and place a gas filled loss monitor at the primary and upstream and downstream of each secondary collimator. Secondary collimator temperatures will be monitored using thermocouples.

In order to allow for injection errors to be damped by the bunch-by-bunch damper system we will use a fast vertical bump to move the beam edge to the collimation edges. After each of the 12 injections, a bump rising in 5 ms and staying flat until 5 ms before then next injection will be started after a delay of 2 - 5 ms. A set of 5 new trim dipoles will provide this orbit bump. The cooling water systems for the Main Injector and some of the high current bus work has been repositioned to permit this collimation system installation. To reduce degradation from radiation, some high current cables in the tunnel have also been repositioned.

SIMULATION STUDIES

In view of the physics program requirements, we have made conservative assumptions for proton losses. A loss of 2 kW of 8 GeV protons scattered by the primary collimator has been studied. Using MARS15, we study the important radiation fields (including prompt dose and residual dose both locally and for areas outside the tunnel and on the surface). Most studies employ a local model which follows particles scattered in the primary collimator. These interact in the secondary collimators and the showers are followed through the secondary collimators, masks as well as the other nearby material. Figure 2 shows the collimation system (primary collimator, two secondary collimators and two masks) as

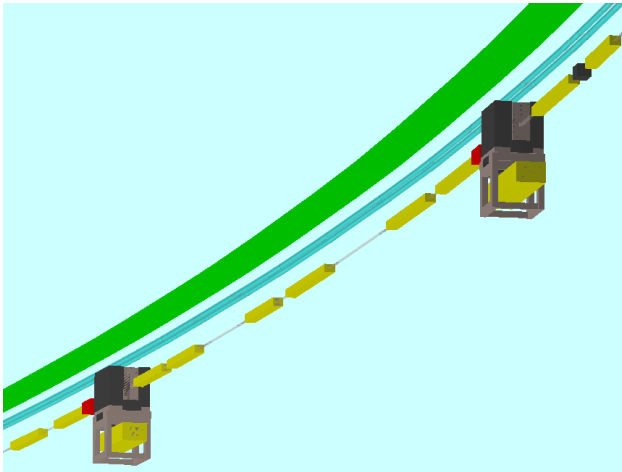


Figure 2: Geometry of MARS Model for Recycler Collimator System. Beam moves from right to left. PCOL613 appears between two gradient magnets at right. SCOL613 and MASK613 follow with SCOL616 and MASK616 further downstream. The MI Dipole beneath stand (only) is only component of Main Injector included in this view.

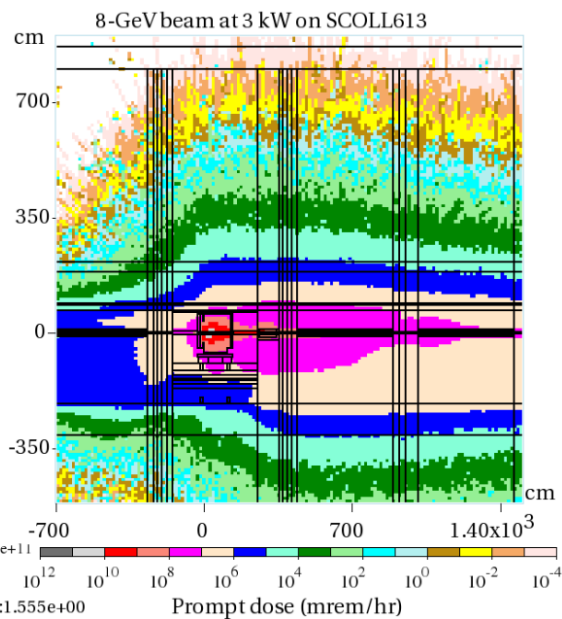


Figure 3: Prompt Dose for Secondary Collimator SCOL613 and MASK613. Beam from left to right in this view. One gradient magnet upstream and two downstream are shown.

described for MARS. Figure 3 shows one typical result of these MARS studies. We examine all interesting radiation results including prompt and absorbed and residual dose, air and water activation and material damage. Additional studies employing MARS and MAD-X/PTC study multi-turn performance of this collimation system.

STATUS AND PLANS

The installation will complete in October 2016 and commissioning will commence with beam start-up by November

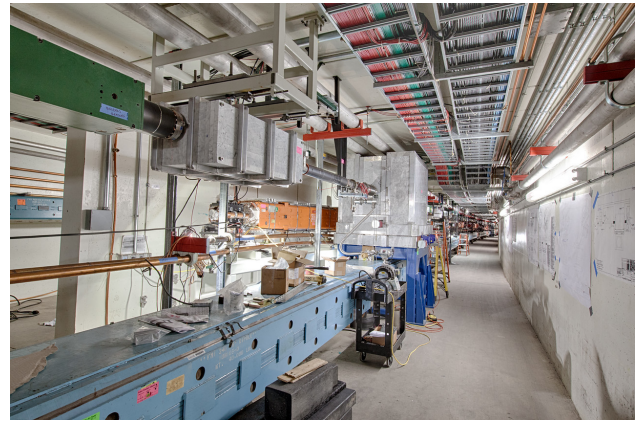


Figure 4: Photo of Secondary Collimator and Mask at 613 as construction is finishing.

2016. Figure 4 shows pictures of the collimation system as installed. Operation before the 2016 Shutdown provided a one minute demonstration of 700 kW proton beam power delivered to the NuMI facility. Plans call for continuous operations at 700 kW (when devoting all beam time to neutrino operations) after collimator commissioning.

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