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Design Considerations and Operational Features of the Collimators for the Fermilab Main Injector and Recycler

[12 years in 12 minutes]

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Outline

Purpose

Design

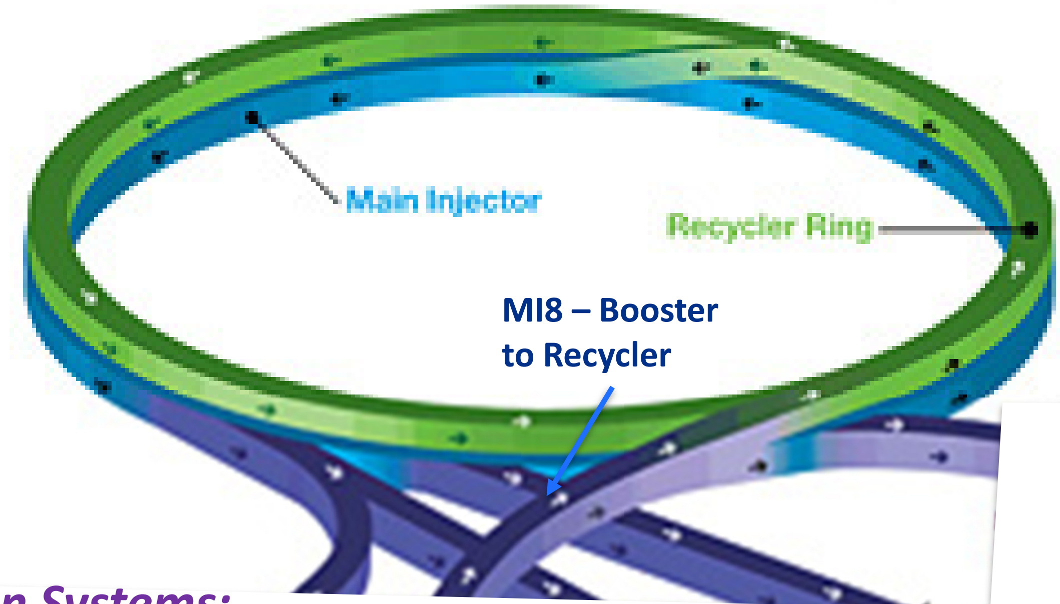
Implementation

Operation

Results

Lessons Learned

Fermi National Accelerator Lab -- Accelerators



Collimation Systems:

MI8 Transfer Line –

Four 4-Ton Collimators - Installed Spring 2006

Main Injector –

Primary + Four 20-Ton Secondary + 6 Masks – Installed Fall 2007

Additional Masks added in subsequent shutdowns

Recycler –

Primary + Two 20-Ton Secondary + 2 Masks – Installed Summer 2016

Why Collimate?

Purpose for Collimation

Localize beam loss in a dedicated region, reducing activation and component degradation in the rest of the ring

Radiation damage proportional to kinetic energy of lost protons.
700 kW of 120 GeV protons delivered. 50 kW of 8 GeV protons
With ~1% loss (500 W) in transfer line, ~3% loss (1500 W) in Recycler, ~3% loss (1500 W) in MI.
All loss at or near 8 GeV injection energy. Losses must be localized.

Beam Losses occur at aperture restrictions due to

- Transverse Tails
- Beam out of RF Acceleration Bucket
- Instabilities

Beam properties change, apertures remain until changed.

Loss Monitoring

Why do losses change?

1. Booster emittance changes (transverse or longitudinal)
2. RF System performance (insufficient bucket area)
3. Instabilities

How do we know?

1. Beam Loss Monitors are at each quad plus at transfer points
2. Residual Radiation is in proportion to nearby BLM signal
3. Loss Monitors are displayed in control room
4. Residual Radiation is recorded during accesses

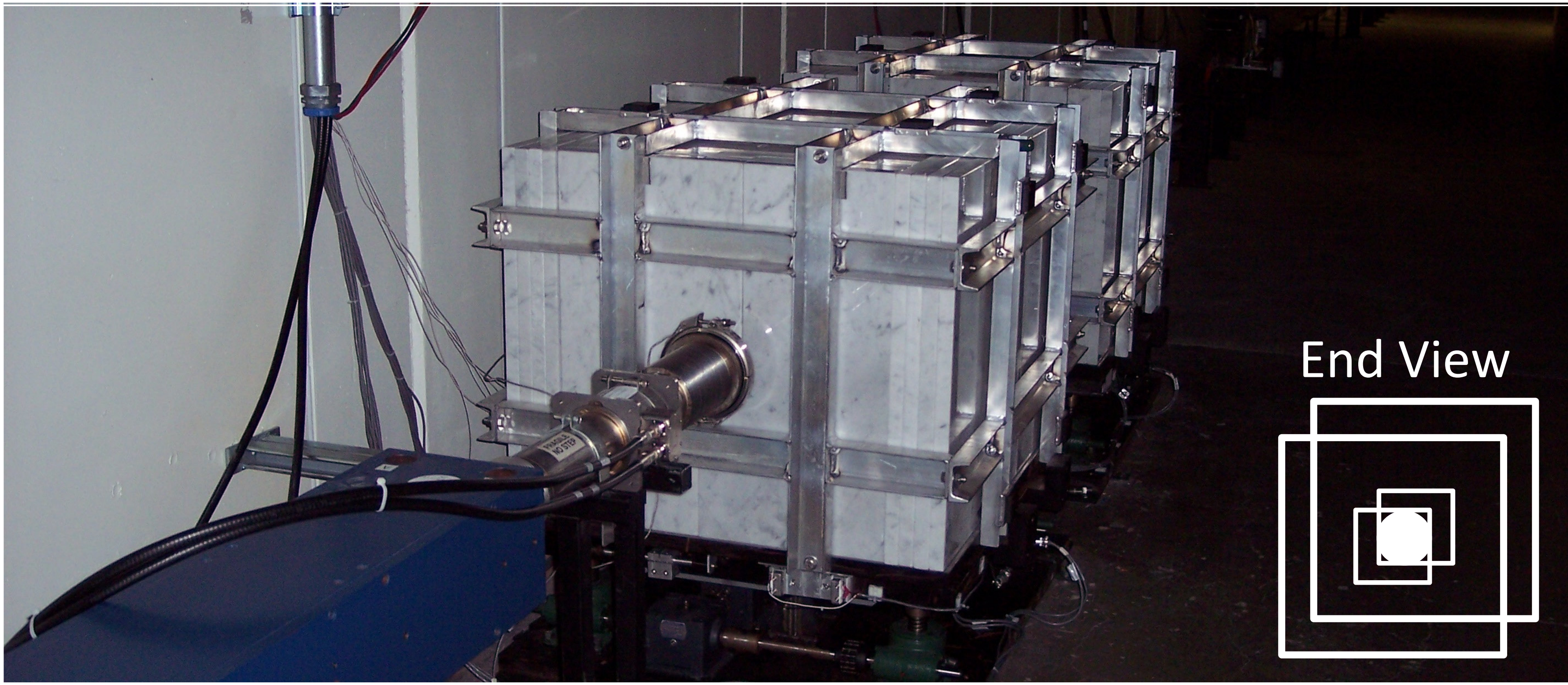
Loss History defines Radiation History (***HB2010 Paper***)

1. *At any loss point, activation is proportional to nearby BLM*
2. *Residual Radiation predicted by half life weighted BLM history*
3. *MARS studies identify isotopes to include in weighted history*

Design

Transfer Line Collimators	Main Injector Collimators	Recycler Collimators
• One-Stage • Transverse (H&V) • Four 4-Ton Collimators • Each Pair Scrapes in Two Opposite Corners • Pairs are one cell (90^o) apart • ***Taper Upstream***	• Two Stage • Uncaptured Beam • Off-Momentum at ~1% $\delta p/p$ + H&V Radial Edge Primary • Four 20-Ton Secondaries • Near and Far Masks (fixed outside pipe) • ***Taper Upstream***	• Two Stage • Transverse Tails • Vertical Edge • Two 20-Ton Secondaries • Near Masks • Some Coupling for Horizontal Tails • ***Taper Upstream & Downstream***

MI8 Transfer Line 4-Ton Collimator Pair

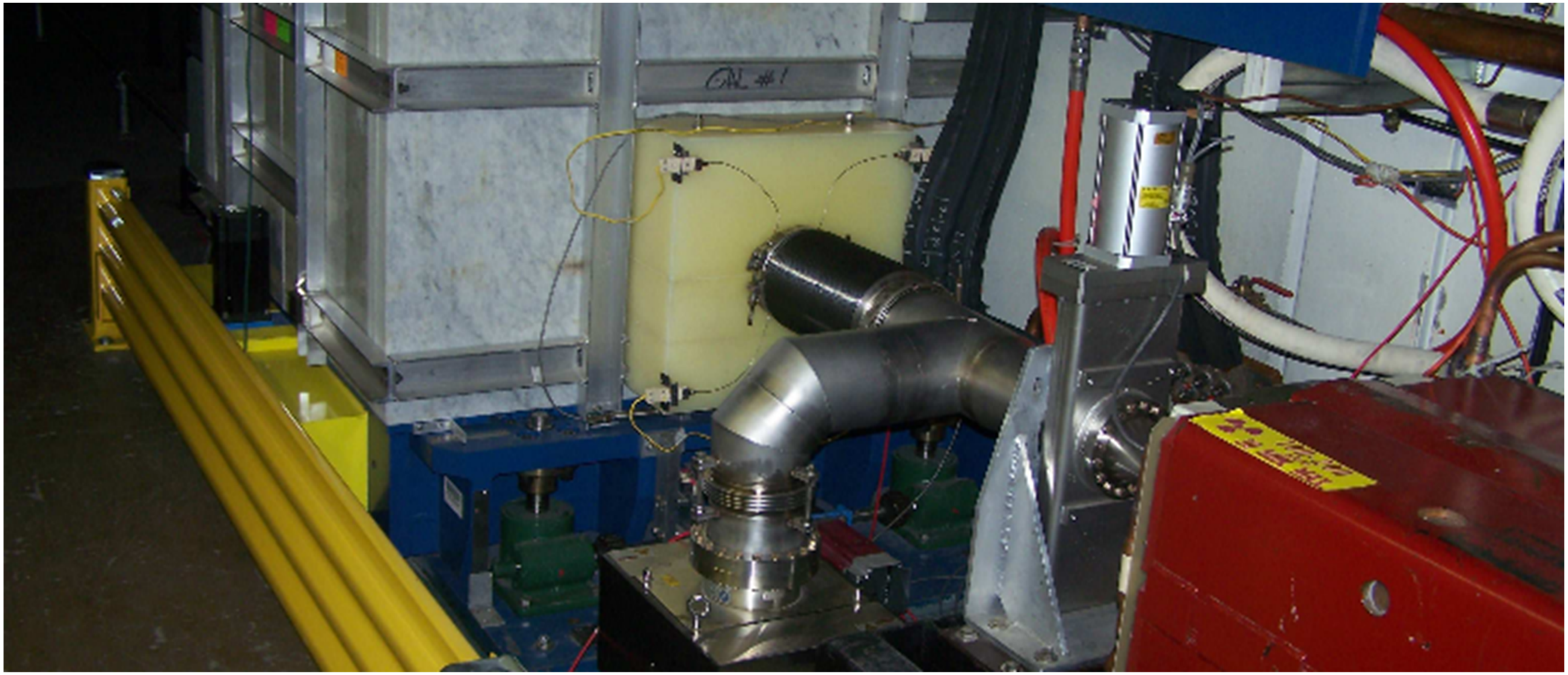


One collimator is positioned so that beam is in a corner to scrape H edge and V edge.

Next Collimator is positioned to scrape the opposite corner.

Next Collimator Pair is 90° phase advance away - angle edge becomes position edge.

Main Injector 20-Ton Secondary Collimator



C301 20-Ton Secondary Collimator from Upstream.

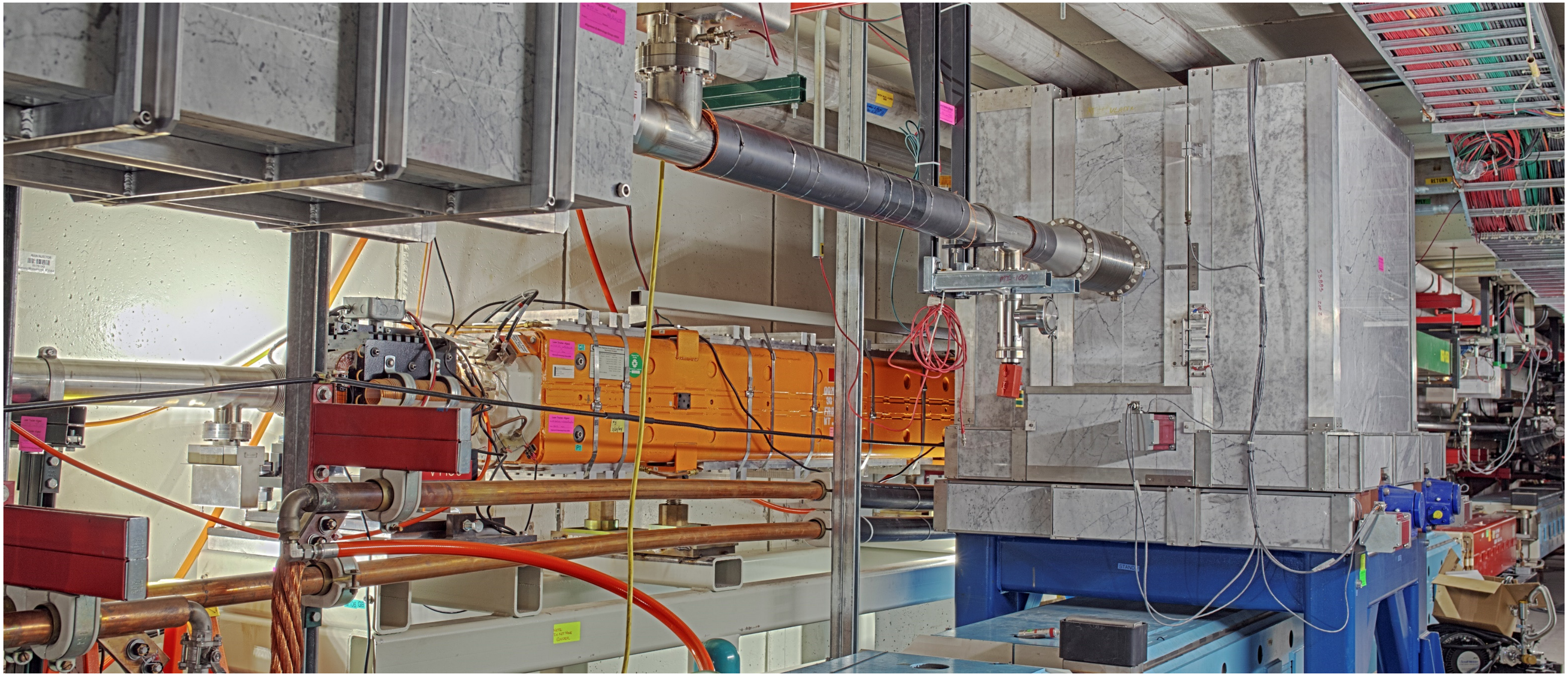
Motion in H and V directions (no H angle, have not used V angle)

Transverse positions controlled by stepping motors with high precision

~12 cm of Marble surrounds steel to absorb residual radiation during access

>23" (>58 cm) transverse space required to absorb shower with steel absorber

Recycler Collimators – Secondary and Mask



C613 20-Ton Collimator with mask. Primary Collimator visible upstream.

Horizontal and Vertical Motion with V angle (pitch) and H angle (yaw using roller plates).

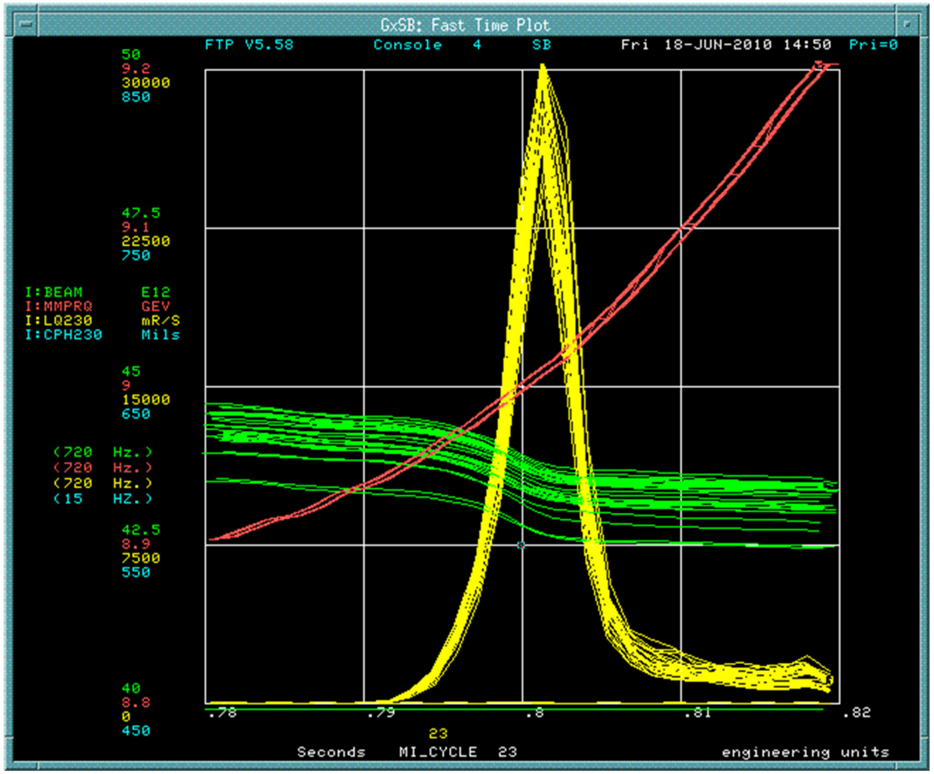
Stepping motors for precision motion.

>23" (>58 cm) transverse space required to absorb shower with steel absorber

Main Injector Collimation – Uncaptured Beam

Slip Stacking provides double intensity but with some beam which is not in RF buckets.

As magnets ramps and beam Is accelerated, uncaptured beam is left to drift inside



BLM Loss at Primary Collimator

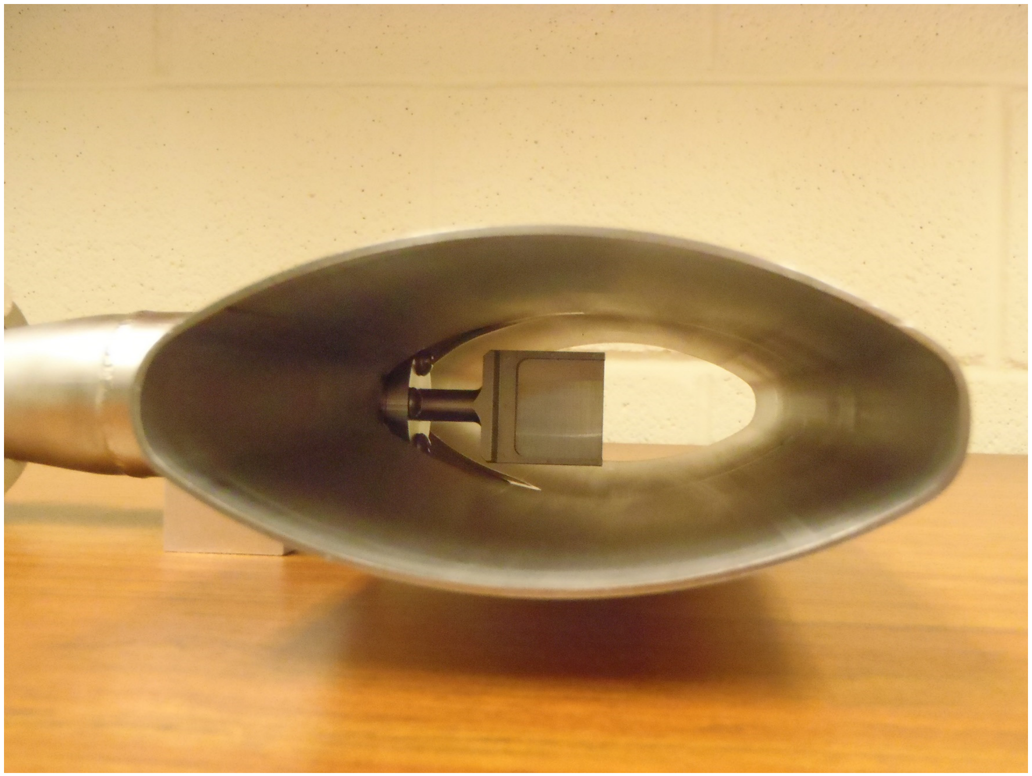
A scattering foil is positioned to interact after ~1% acceleration. An orbit bump moves beam into it.

Here we see **Beam intensity**, **Momentum**, and Loss at Primary

2 – 3% loss **1% acceleration** in ~5 mSeconds

Design–Primary-Secondary (two-stage) collimation

Main Injector Two-Stage Collimation

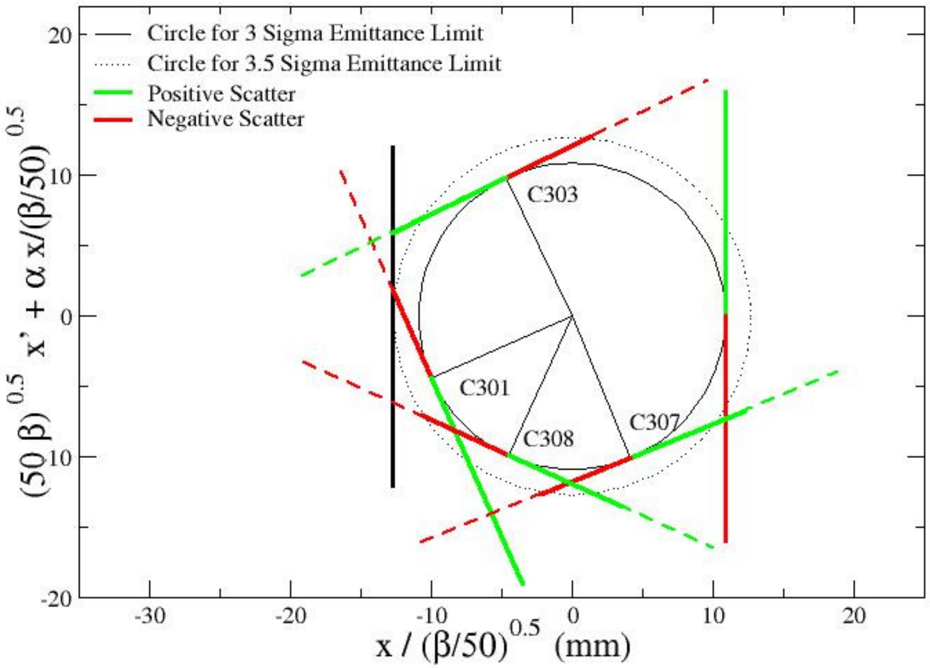


Primary Collimator (0.010" W) at 3 sigma on inside to scatter from x edge.

Design–Primary-Secondary (two-stage) collimation

Main Injector
Two-Stage
Collimation

On Average
Lost Protons
Strike Primary
2.5 Times



Two Stage Collimation in Reduced Coordinates (which preserve emittance of beam).
Primary Collimator (0.010” W) at 3 sigma on inside to scatter from x edge.
Secondary collimators at C301, C303, C307, C308 to scrape at either plus or minus x edge
Tune collimation to place secondary collimators at about 3.5 sigma.

Operational Tuning

MI8 –

Move Collimators to Beam Edge

Auto-tune to keep orbit.

MI –

Place beam edge parallel to collimator

(Complicated Orbit Bump)

Move collimators to achieve containment.

RR –

Pitch and yaw provided (Simple orbit bump)

Move collimator to scrape edges in both planes

(but vertical scattering from primary)

Beam Loss Monitors (glass tubes with argon gas)

record losses to allow tuning and monitoring

Results: Excellent Loss Containment

MI8 – Good Orbit stability for MI/RR Beam

Scrape ~1% (at design limit)

Needed to correct 8 GeV to Booster Neutrino Beam (BNB) to avoid excess loss

MI - Use loss monitors to record loss – Study Uncaptured Loss

>99% Containment of Uncaptured (off momentum) beam loss recorded in Collimation Region in Main Injector (16 half cells out of 208 half cells)

>93% Containment of all loss

MARS ~80% of lost power absorbed in 20-Ton secondaries

RR - Good containment. Damping of instabilities reduced loss.

Other Results -- Stainless Steel Pipe Damage

Inserted collimators into an existing tunnel with cable plant. This included cables for the Electron cooling system.

During the 2012-13 upgrade and Subsequently we found chlorine-induced pitting corrosion. We ascribe that to the release of Cl from PVC cable jackets which are about 50% Cl.

Design Features to Reconsider

Secondary Collimators Contain Shower Maximum Completely.

Tunnel depth is sufficient to contain Muon prompt dose

Muons from 8 GeV showers do not create activation.

One might consider motion control options which require space in the region with higher fluxes of hadrons.

We kept the mechanical system simple and rugged.

Vertical Angle (pitch) is easy enough if needed.

Horizontal Angle (yaw) required roller plates. Not as precise.

One Must Plan to Remove Secondaries without exposing high radioactivity portions

Further Progress -- Still learning – Cable Failure

These collimators were inserted into an operating accelerator so only minimal allowance was made for accommodating them.

The cable plant includes signal cables, RG58 Red high voltage cables for beam loss monitors (2 kV) and ion pumps (5 kV).

Cables are in trays above the aisle but near the Main Ring.

We had no failures until ~2016. By 2019, all 5 kV cables have failed somewhere in the collimator region.

MARS studies combined with BLM integral loss suggest that failure occurred after 5500 Gy (0.55 Mrad) of absorbed dose.

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