Collimation System for Beam Loss Localization with Slip Stacking Injection in the Fermilab Main Injector

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Fermilab Main Injector Collimation

Outline:

- The Problem: Uncaptured Beam
- Constraints: Available Locations
- Design:
  - Simulations
  - Primary/Secondary Collimation
  - Mechanical Design
- Hardware/Commissioning
- Loss Measurements
- Status and Results

Fermilab Main Injector

Goal: High Intensity (PBar and Neutrino)

Problem: Limited Booster Intensity

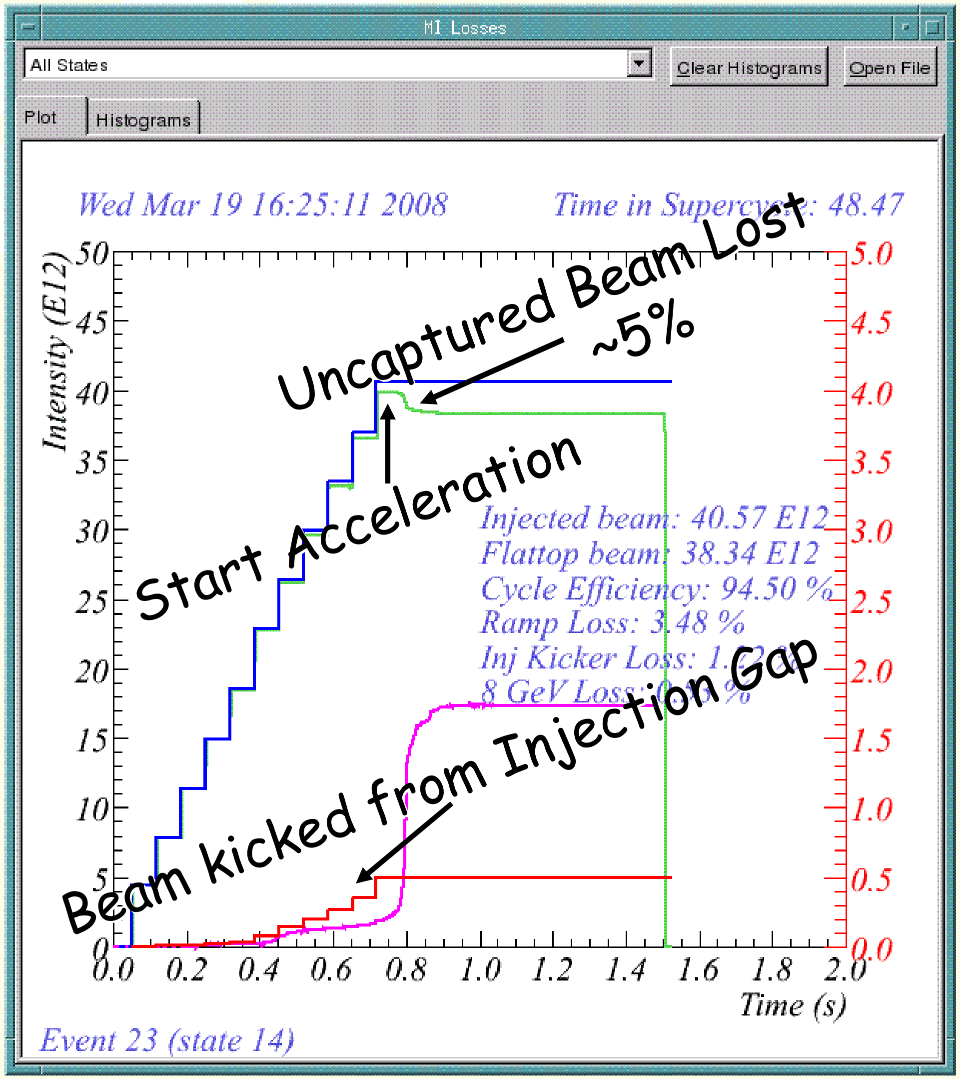
(Length=6 Booster Batches + Abort Gap)

Solution: Momentum Space Slip Stacking

(Slip together two sets of 5 batches then add one more)

Problem: Booster emittance not quite small enough for MI Bucket size so some beam uncaptured or captured in wrong RF buckets

Fermilab Main Injector



Operation with recent conditions

Injected Beam

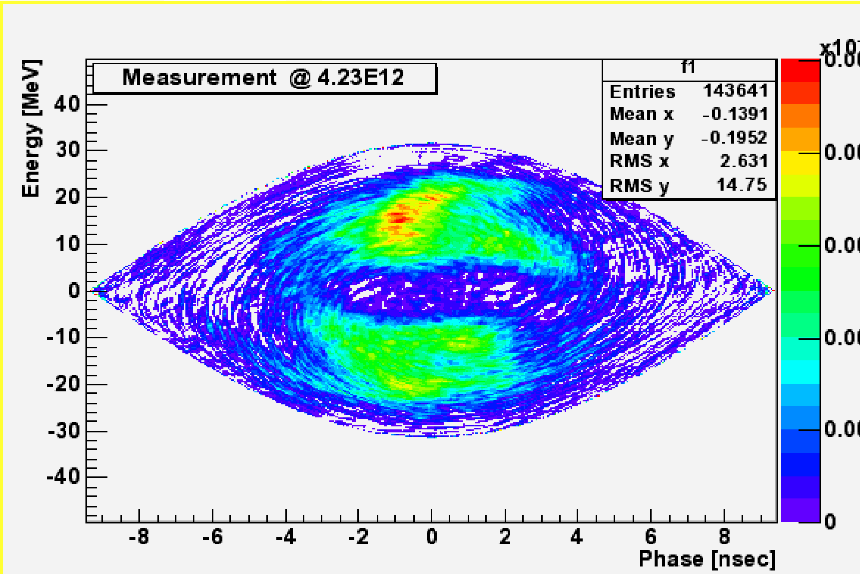
(slip 5 on 5 then inject 1 more)

Beam vs. time

Injection Loss

Lost Beam Energy

Main Injector Slip Stacking



Beam Captured in 1 MV Bucket
(Tomography Reconstruction)

Slip Stack Injection

Inject 5 Booster Batches
Decelerate to clear injection orbit
(bunches will slip vs. central orbit)
Inject 5 additional Batches using different rf system
Accelerate to symmetric orbits
When bunches are aligned, replace two low voltage rf systems with regular high voltage rf to capture
Inject 11th Batch
Accelerate as usual

New Loss Issues

Uncaptured beam drifts to injection gap (kicked by injection kicker)
Uncaptured Beam not Accelerated (Lost at Momentum Aperture)
Beam Captured into Extraction Gap (kicked by extraction kicker)

MI Collimation – Uncaptured Beam

Slip Stack Injection Losses:

- [Before recapture some uncaptured beam kicked from injection gap]
- After slipping and recapture, some particles are
  - In unwanted buckets (extraction kicker gaps)
  - **Not in buckets – uncaptured – so not accelerated.**
- Uncaptured beam hits momentum aperture during acceleration – about 1% dp/p
- The lost beam is separated from accelerated beam by dispersion of lattice

MI Collimation - Where

MI32
RR->MI 1.5 Cells →

MI22
← MI->RR 1.5 Cells

MI40 2 Cells
Abort

MI30 4 Cells
ECOOL + Collimation

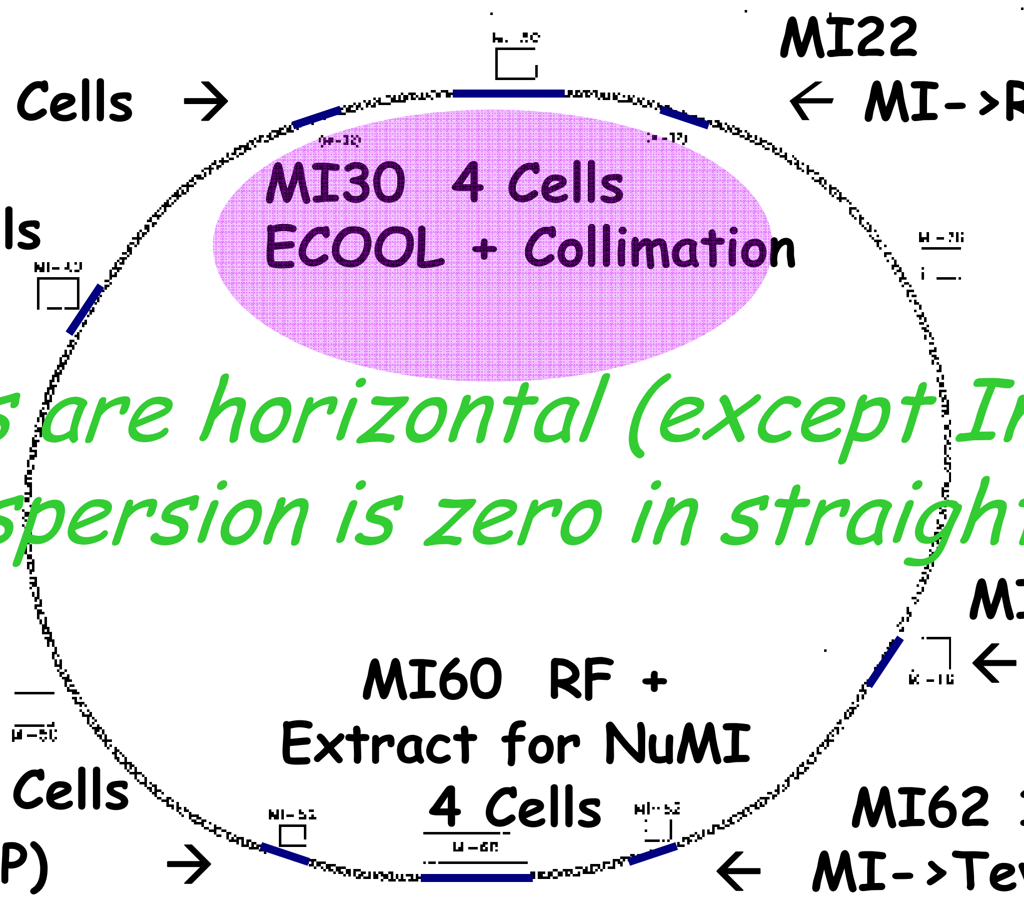


Figure 2.1-1. Main Injector Geometric Layout Showing Locations of Service Buildings and Straight Sections.

Transfers are horizontal (except Injection)
Design dispersion is zero in straight sections

MI10 2 Cells
← Injection

MI60 RF +
Extract for NuMI
4 Cells

MI52 1.5 Cells
MI->TeV(P) →

MI62 1.5 Cells
← MI->Tev(PBar)

MI Collimation Simulation

Slip Stack Injection/Capture/Acceleration

- Injected Beam Parameters
- Apertures of Ring Components
- RF manipulations
- Linear **and Non-linear** Magnetic Fields

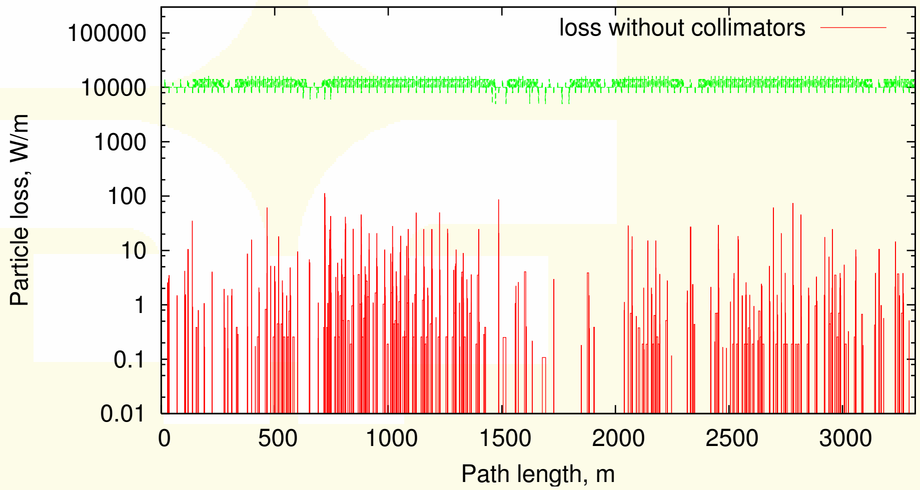
STRUCT Tracking Code

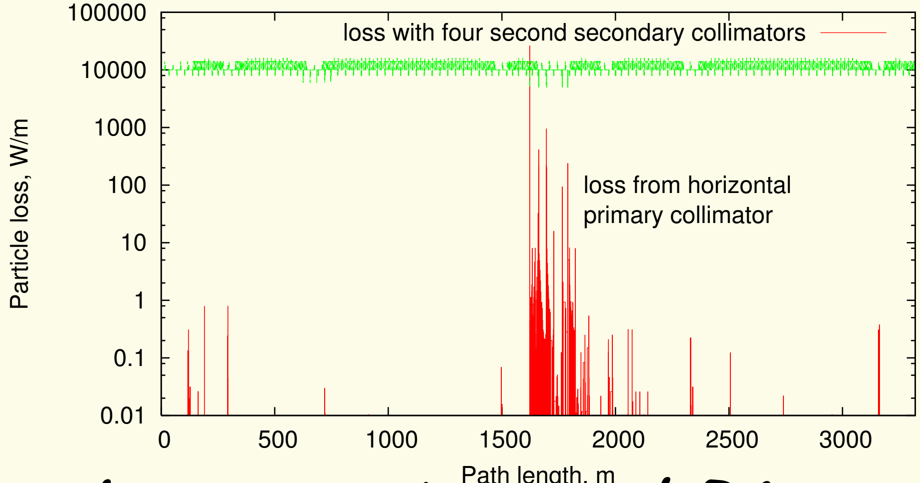
Compare Simulations with Observed

- Time Pattern of Lost Beam
- Distribution of Loss Around Ring

As momentum aperture is explored by uncaptured beam, non-linear fields are critical to understanding loss distribution.

MI Collimation -Simulation

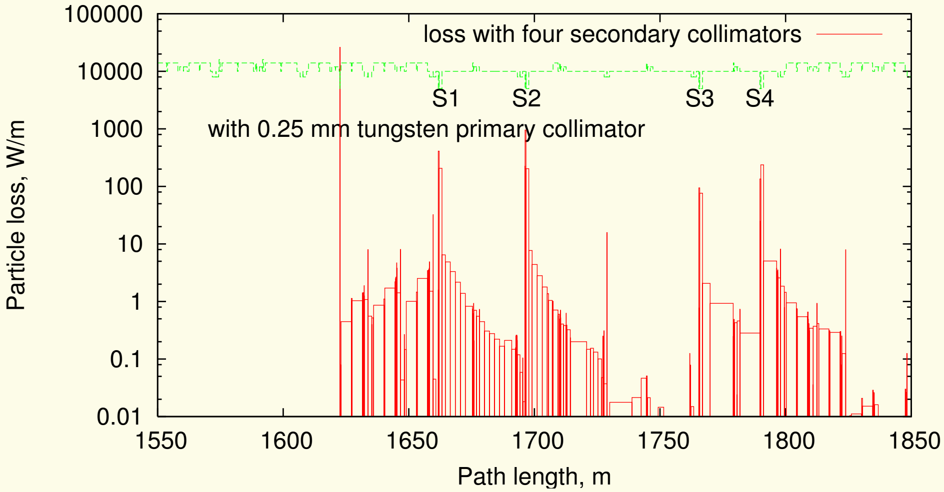




Losses Around Ring

Describe:

- *slip stacking,*
- *apertures,*
- *non-linear magnetic fields*



Losses in Collimator Region

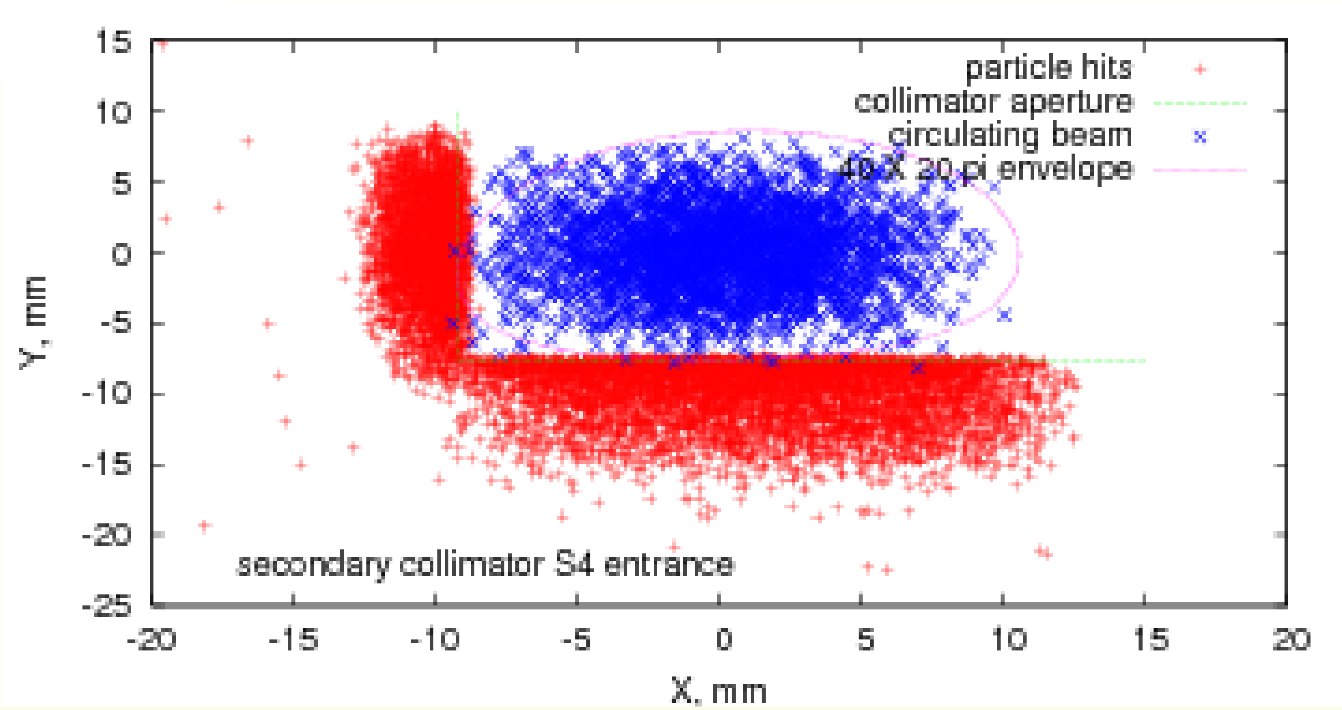
MI Collimation Concept

Collimate loss due to uncaptured beam:

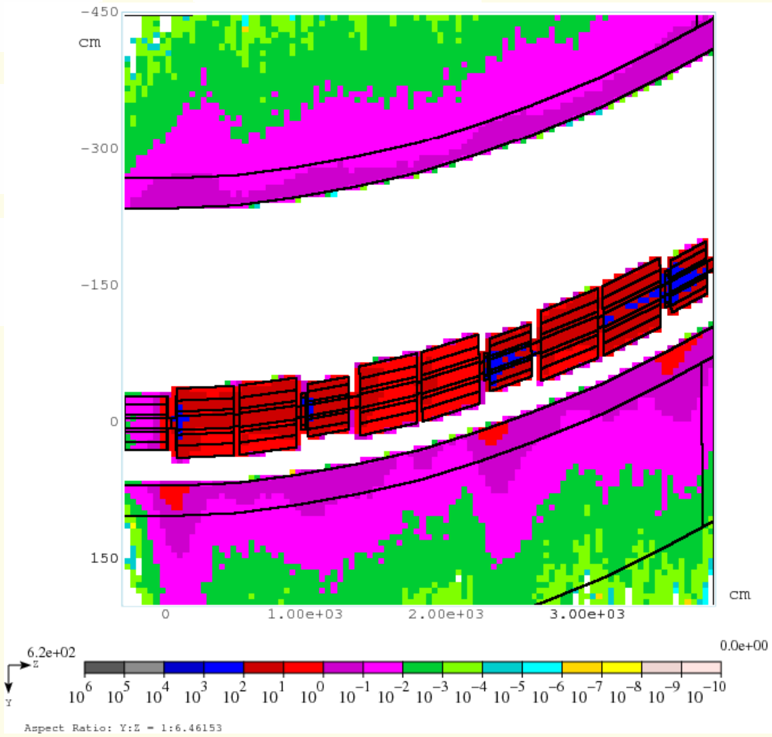
- Horizontal primary collimator at normal dispersion as near to open straight section as possible. Use 0.25 mm Tungsten sheet on radial inside (scatter).
- Massive (20 Ton) secondary collimators with fixed aperture which can be aligned radially and vertically. Limited angle control vertically an no angle control radially. Thick stainless steel vacuum tube absorbs primary shower. Available tunnel space filled with steel to absorb rest of shower. Marble used to shield aisle side.
- Mask of steel (and concrete) blocks opening left by moving secondary collimator. Absorbs shower and neutrons immediately downstream.
- Mask of steel and marble shields next magnet downstream from far forward particles.

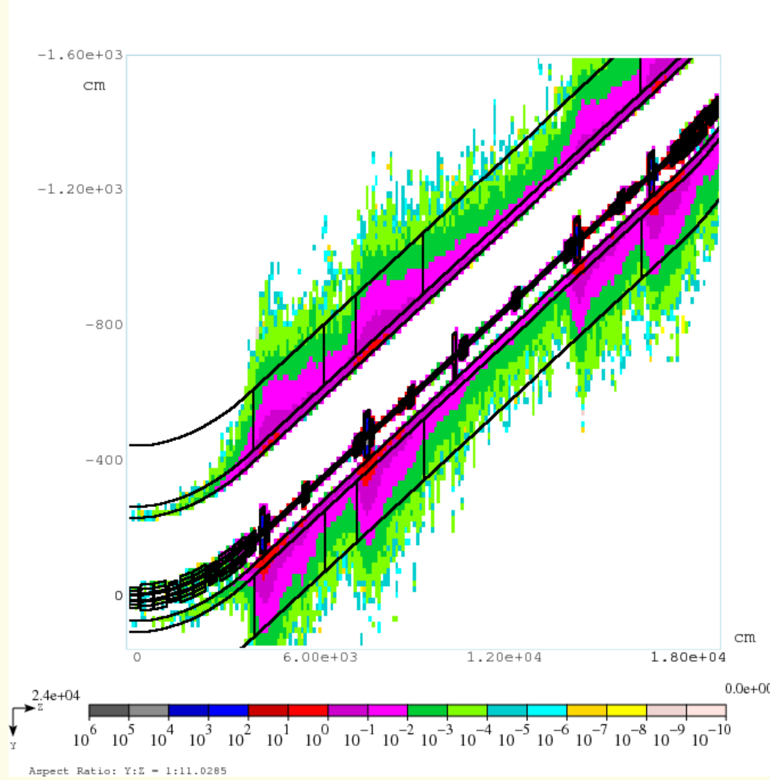
MI Collimation

Collimator positioned to scrape beam halo on horizontal edge and vertical edge, i.e. in corner



MI Collimation - Simulate Radiation



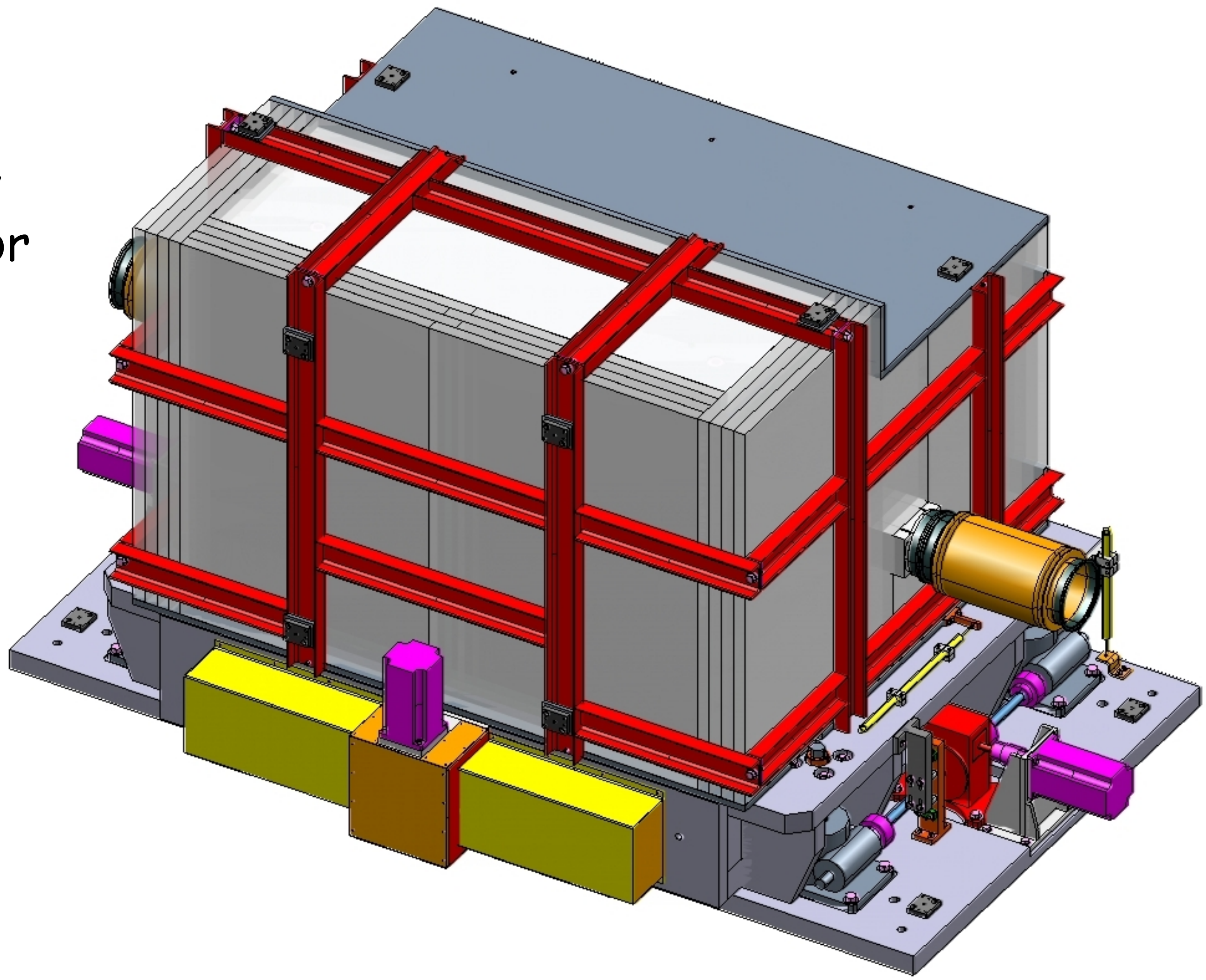


MI230 to MI301   *MI301 to MI309*

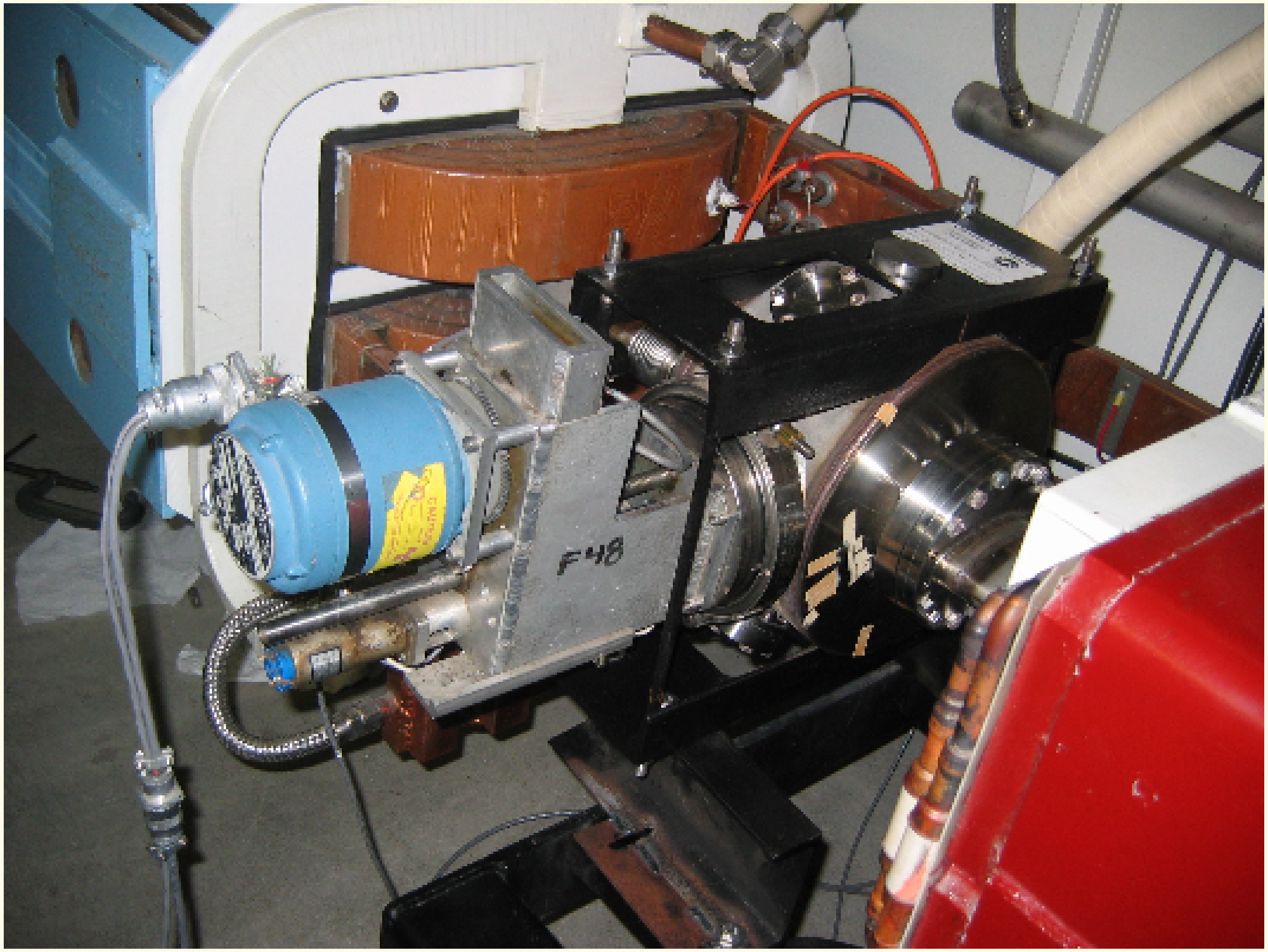
MARS Simulation for Slip-stacking Loss

MI Collimation Hardware

20 Ton Primary Collimator



Primary Collimator - MI230



20 Ton Secondary Collimators

Aperture
4" x 2"

Includes Precise Radial and Vertical Motion

How Big? --- Fill Available Space

Steel/Concrete Mask

This captures outscatter and neutrons

Steel/Marble Mask

To Protect Downstream Magnets

Concrete Wall at 304

Reduce Neutrons at ECOOL

MI Collimator Criteria

Thermal capacity up to 2 kW

(each collimator has sufficient capacity)

Position to fraction of mm

(control achieves 0.025mm least count)

Radiation Concerns:

- o Activation of soil outside of tunnel
- o Residual Radiation (maintenance)
- o Radiation Damage(motion system, magnets)
- o Air Activation

MI Collimator Design

The secondary collimators are in a region of 'zero' dispersion. The scattering from the primary collimator reaches them only when they are near the beam boundary (modest scattering angles). Boundaries in radial plane clip scattered particles at appropriate phase advance from primary. Collimators are placed with beam in 'corner' to also capture vertically scattered beam.

MI Collimator Design

Injection Process Loss Collimation

Since the collimators are near the emittance boundary to catch 'uncaptured' beam loss, they are also near enough to catch losses from the injection process.

This system is an aperture limit during entire injection process and captures much of the beam lost during injection.

MI Collimator Commissioning

Primary Collimator:

Confirm collimation of un-captured beam

[Compare position vs. time (momentum) of loss]

Select radial position for primary collimation

[This is combination of physical position and orbit time bump]

Secondary Collimators:

Design orbit for collimation (separately horizontal and vertical)

Angle at collimation edge function of collimation emittance.

[want edge of collimated beam parallel to collimator]

Create orbit time bump to achieve design orbit

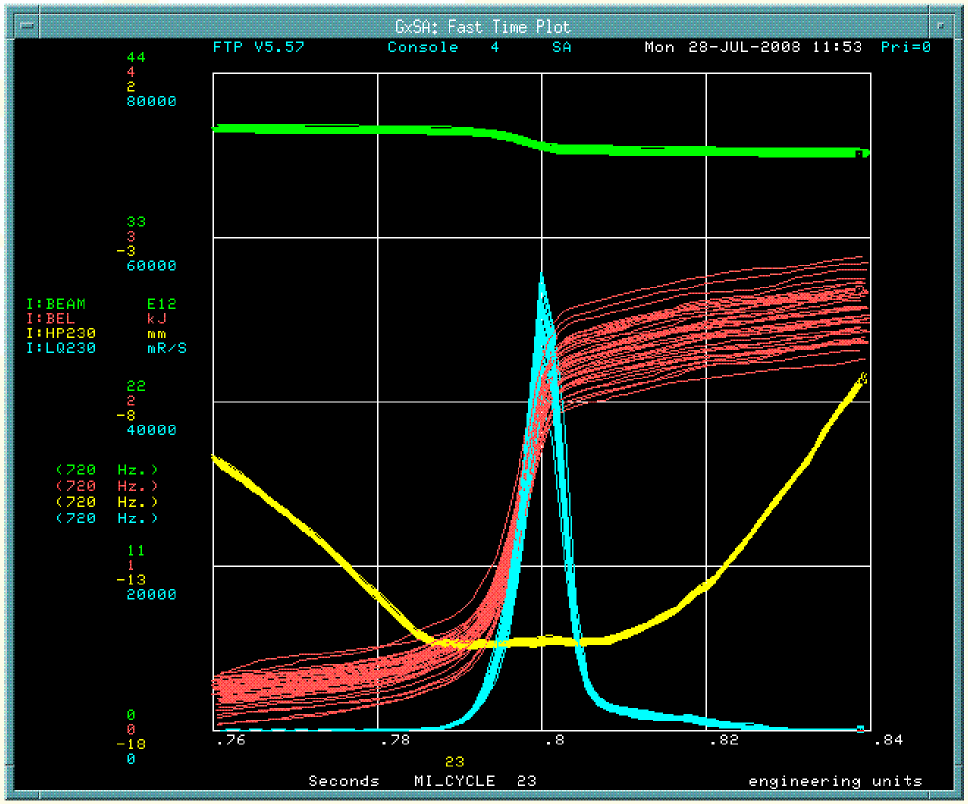
Place collimators to achieve collimation

In practice scan position and observe resulting loss time profile

Measure losses around ring

Observe both injection and un-captured beam loss

MI Collimator Commissioning



Beam Intensity

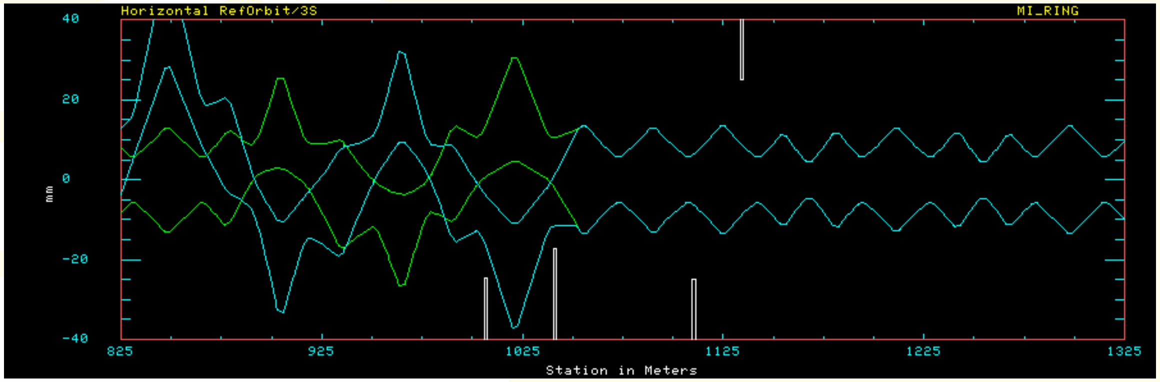
Energy Loss

Horizontal Position at Primary Collimator

Loss Monitor at Primary Collimator

Time in Cycle
(20 ms per box)

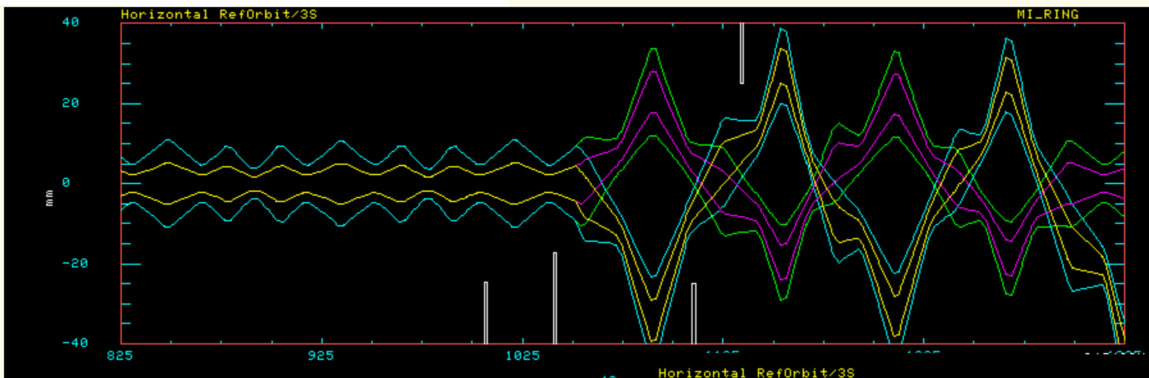
MI Collimator Commissioning



Acc => RR

Transfer Orbits

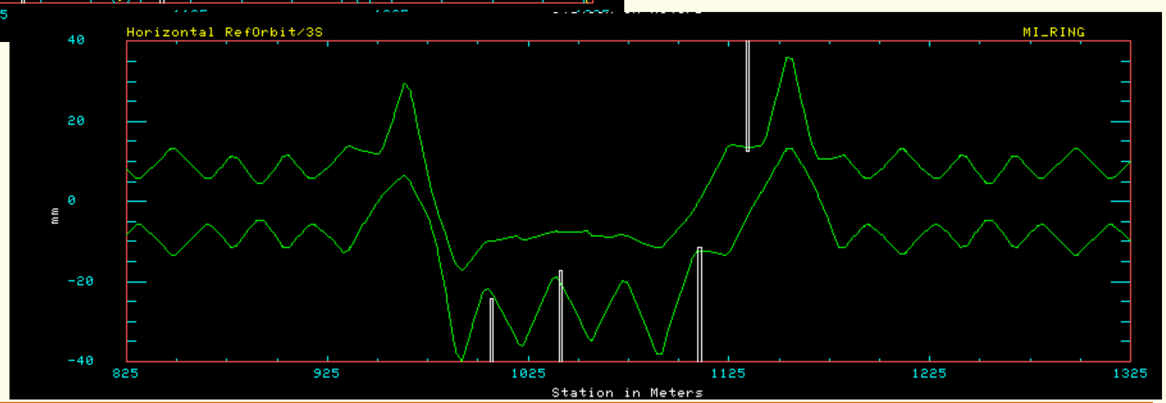
and counterwaves



RR => TeV

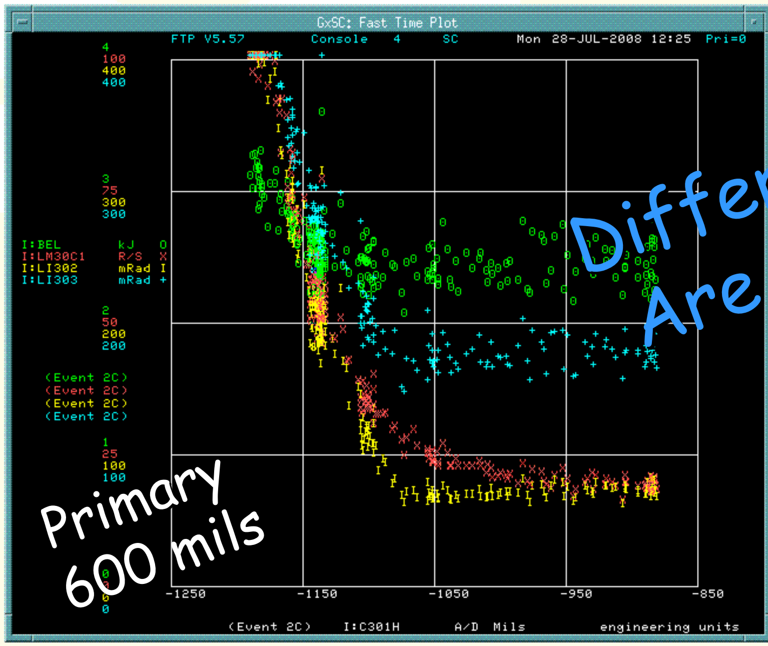
Collimation Orbit

(time bump)



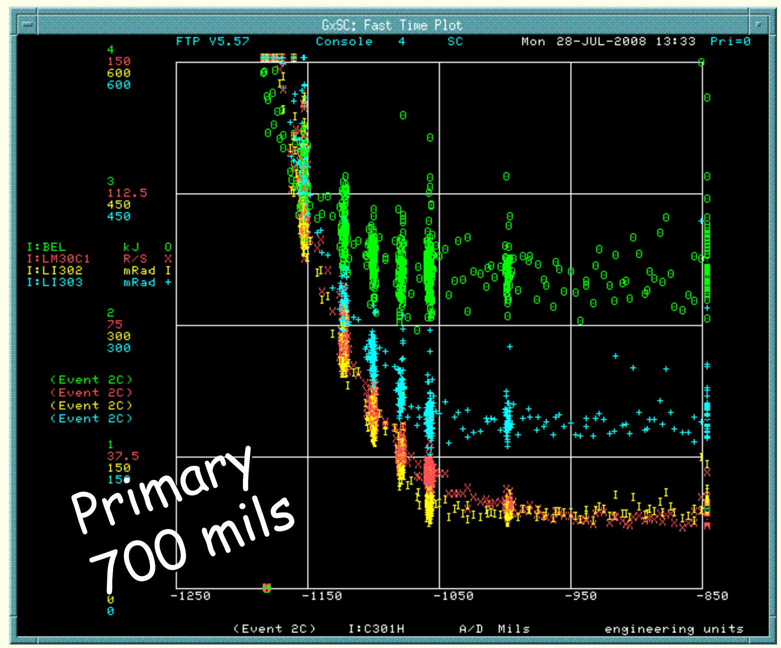
MI Collimator Commissioning

Scan Collimator Positions – C301H



Differences
Are Subtle

Horizontal Offset (mils)
BEL (Energy Loss)
Beam Pipe Loss Monitor
Loss Monitor at Q302
Loss Monitor at Q303



Horizontal Offset (mils)
BEL (Energy Loss)
Beam Pipe Loss Monitor
Loss Monitor at Q302
Loss Monitor at Q303

Main Injector Losses

Loss Monitor Readings on PROFILE Times
Individual Readings to Database, Sums Here

Collimator Region
Injection
34%
Efficiency

Values in Rads

Values as Fraction Of Column

Groups of Monitors

GxPB 1 None

Collimation Analysis

Data Date: 12-AUG-2008 11:04:34, Grouping ID: 0 , Average cycles: 1

Profile #:	0	1	2	3	4	5	6	7	GrpSum
Time:	.7549	.82815	.85952	.90649	.98463	1.1887	1.4468	1.5269	
Zero Suppressed Group Losses:									
105 - 106	.05112	.00033	.00005	.00008	.00008	.00022	.00025	.00008	.05221
112 - 116	.01969	.00188	.00758	.0009	.00153	.00019	.00016	.00003	.0319[illegible]
221 - 222	.00704	.00076	.0042	.00033	.00019	.00008	.00014	.00005	.01279
229 - 309	.1767	.87092	.02597	.00469	.00486	.00218	.00109	.0004[illegible]	1.0869
321 - 322	.01413	.00505	.00044	.00005	.00022	.00019	.0003	.00008	.02046
401A - 403	.02114	.00985	.00155	.00041	.00235	.00027	.00055	.01058	.0467
520A - 523	.04375	.00668	.00155	.00052	.0048	.00338	.01279	.26312	.33661
607A - 608H	.03164	.00311	.00655	.00063	.00109	.0013[illegible]	.00224	.00183	.04847
619E - 623	.03625	.00175	.00046	.00005	.00469	.00033	.00049	.00035	.04438
Rest	.1207	.04604	.01399	.00346	.07136	.0272	.01566	.00636	.30477
PfSum	.52218	.94637	.06236	.01113	.0[illegible]116	.03543	.03366	.28295	1.9852
Fractions:									
105 - 106	.09789	.00035	.00087	.00735	.0009	.00616	.00729	.00029	.0263
112 - 116	.03772	.00199	.12161	.08088	.01676	.00539	.00486	.0001	.0161
221 - 222	.01348	.00081	.00737	.02941	.00209	.00231	.00405	.00019	.00644
229 - 309	.3384	.92027	.41645	.42157	.05326	.06159	.03242	.00164	.54748
321 - 322	.02706	.00533	.007	.0049	.00239	.00539	.00891	.00029	.01031
401A - 403	.04048	.01041	.02493	.03676	.02573	.0077	.01621	[illegible]	.0[illegible]352
520A - 523	.08379	.00706	.02493	.04657	.05266	.09546	.38006	.92991	.16955
607A - 608H	.0606	.00329	.10499	.05637	.01197	.03926	.06645	[illegible]	.02442
619E - 623	.06942	.00184	.00744	.0049	.05147	.00924	.01459	.00125	.02236
Rest	.23115	[illegible]	.22441	.31128	.78276	.76751	.46515	[illegible]	.15352
PfSum	.26303	.4767	.03141	.00561	.04592	.01785	.01696	.14253	1

Collimator Region
Uncaptured
92% Efficiency

Extraction Region
Extraction
92% of loss

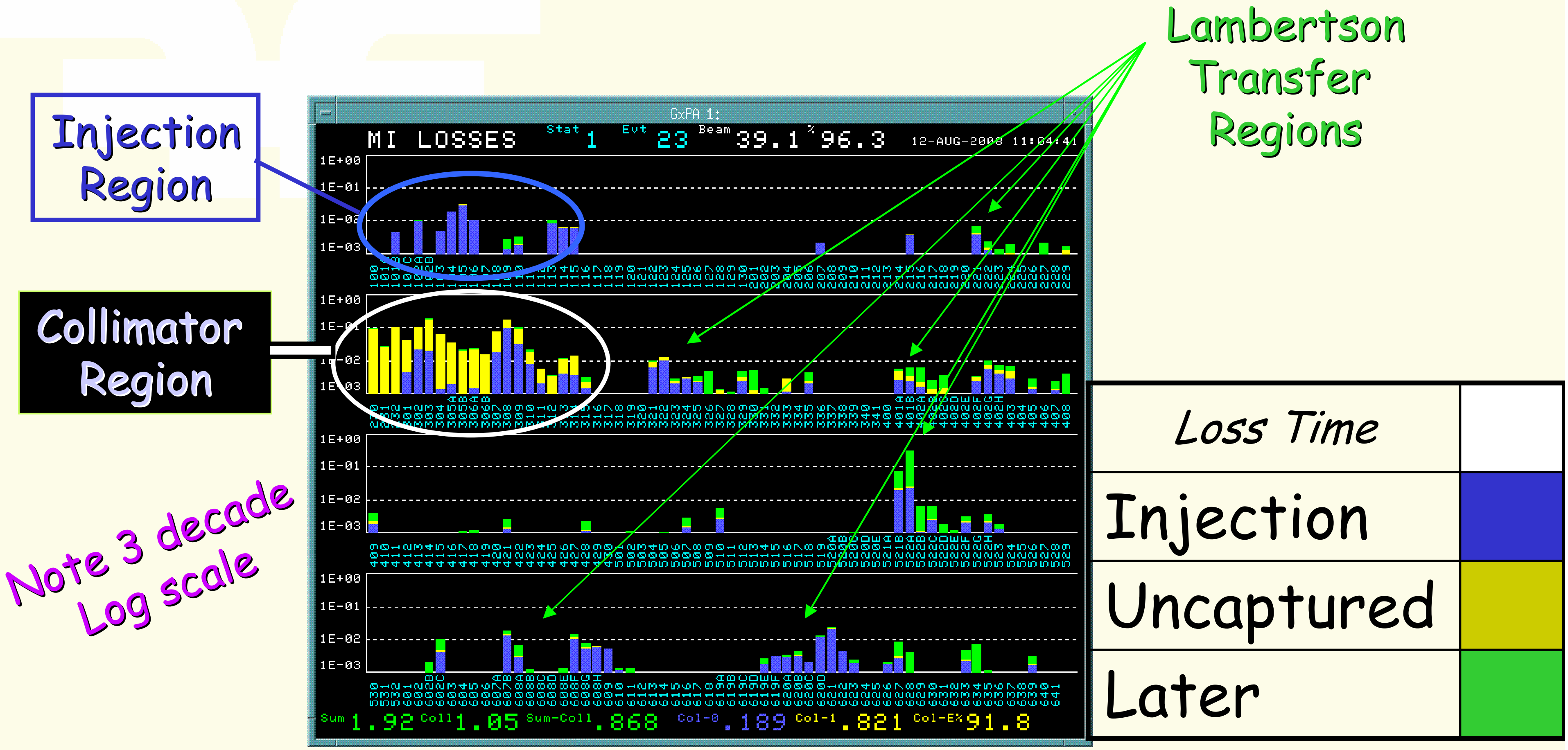
Ring Sum
Extraction
14% of Total

Ring Sum
Uncaptured
48% of Total

Times: Inj, Uncap, ...later..., Extraction

Main Injector Losses

Loss pattern of 11-Batch Operation
[This display runs continuously in Main Control Room]



MI Collimation

Interesting Issues Not Discussed Fully:

- Injection Line Collimation (PAC07)
- Residual Radiation
  - Residual Radiation Measurements
  - Comparison with Activation (Al Tag Study)
  - Comparison with MARS
    (Residual, Activation, Loss Monitors)
- Loss Monitor Geometry and Response

Questions posed for HB2008

Does the system perform as expected?

Engineering Answer:

The system reduces losses from uncaptured beam (as considered for design) by x10. It also reduces injection losses by about x2. OK !

Physics Answer:

The losses not captured in the collimation region are x10 greater than predicted by simulation. Why?

Questions posed for HB2008

What are the major limitations in performance? Were they known in the design stage?

Machine Irradiation:

The region between primary collimator (last place with useful dispersion) and first secondary collimator (in straight section) contains magnets which will suffer radiation damage (expect life of few years).

This was known. Alternative of using trim magnets to create dispersion in straight section (only few quads which would be irradiated) was rejected as complex.

Questions posed for HB2008

What are the major limitations in performance? Were they known in the design stage?

Limited angle control for collimators:

The design was based on the successful Fermilab Booster collimators which used slip plates to allow horizontal angle control but they have some evidence of sticking problems.

The present design provides precise remote control of horizontal and vertical position but no horizontal angle and limited vertical angle control. It was assumed that orbit control was sufficient.

It is difficult to provide an orbit with beam edge parallel to collimator with existing (limited) set of correctors. Not appreciated at design stage. Can add correctors if needed.

Still Assessing significance.

Questions posed for HB2008

What are the major limitations in performance? Were they known in the design stage?

Our performance is sufficiently good that there may be a dominant limitation which we have not yet identified.

Questions posed for HB2008

If someone were to begin now designing the same type of system for a similar machine, what is the one piece of advice that you would give them?

For an existing facility:

Be sure to employ good simulation tools and do the details.

[The option of creating a low energy lattice modification for providing dispersion could be reviewed.]

For a new facility:

Design in a cleaning section

Main Injector Collimation:Summary

- Collimation Simulation
  - Tracking (STRUCT) and Energy Loss (MARS) studies
  - Aperture Geometry, Linear plus higher harmonics fields
  - Slip Stack Injection and RF Manipulations
  - Predict loss times and locations
    [Only losses at large dispersion before higher harmonics]
  - Designed primary-secondary collimation system
- Collimator Hardware
  - 0.25 mm primary, 1.5 m – 20 Ton Secondary at 4 locations
- Collimator Commissioning
  - Orbits defined, positions scanned, losses studied
  - Greater than 90% loss control achieved
- Plans
  - Slipping in Recycler – few changes needed.

MI Collimation

Fermilab Main Injector Lattice

The Fermilab Main Injector contains eight straight sections
Their numbering and functions are as follows:

- MI-10 - 8 GeV proton injection
- MI-22 - Transfers to Recycler Ring
- MI-30 - Electron Cooling (in Recycler Ring)
- MI-32 - Transfers to Recycler Ring
- MI-40 - proton abort
- MI-52 - 150/120 GeV proton extraction; 8 GeV antiproton injection
- MI-60 - rf section
- MI-62 - 150 GeV antiproton extraction

All straight sections are obtained by omitting dipoles while retaining the standard 17.29-m quadrupole spacing. There are three different lengths of straight sections. Straight sections MI-10 and MI-40 are 69 m long (two cells), straight sections MI-22, -32, -52, and -62 are 52 m long (one and one half cells), and straight sections MI-30 and MI-60 are 138 m long (four cells). Straight section MI-60 is used for the rf; its length will allow flexible spacing of the rf cavities and provide generous free space for diagnostic beam pickups.

MI Lattice Straight Sections

Location (cells)	Original	Recycler + NuMI	Collimate	Future
MI10(2)	8 GeV Inj	-	-	-
MI22(1.5)	Unused	+ RR Trans		-
MI30(4)	Unused	+ ECool & Kickers	Collimate	Transfer
MI32(1.5)	Unused	+ RR Trans		-
MI40(2)	Abort	-	-	-
MI52(1.5)	P8/P150	-	-	-
MI60(4)	RF	+ NuMI	-	-
MI62(1.5)	A150	-	-	Available?