Doubling the MI Power

May 20, 2014

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MI Department

Fermilab

Acknowledgments

- Headquarters
- Proton source Department
- Main Injector Department
- Operations
- External Beams Department
- Mechanical Support Department
- E/E Support Department
- RF Department
- Accelerator Controls Department
- Instrumentation Department
- Accelerator Physics Center
- Alignment & Metrology Department (PPD)
- Scientific Computing Division

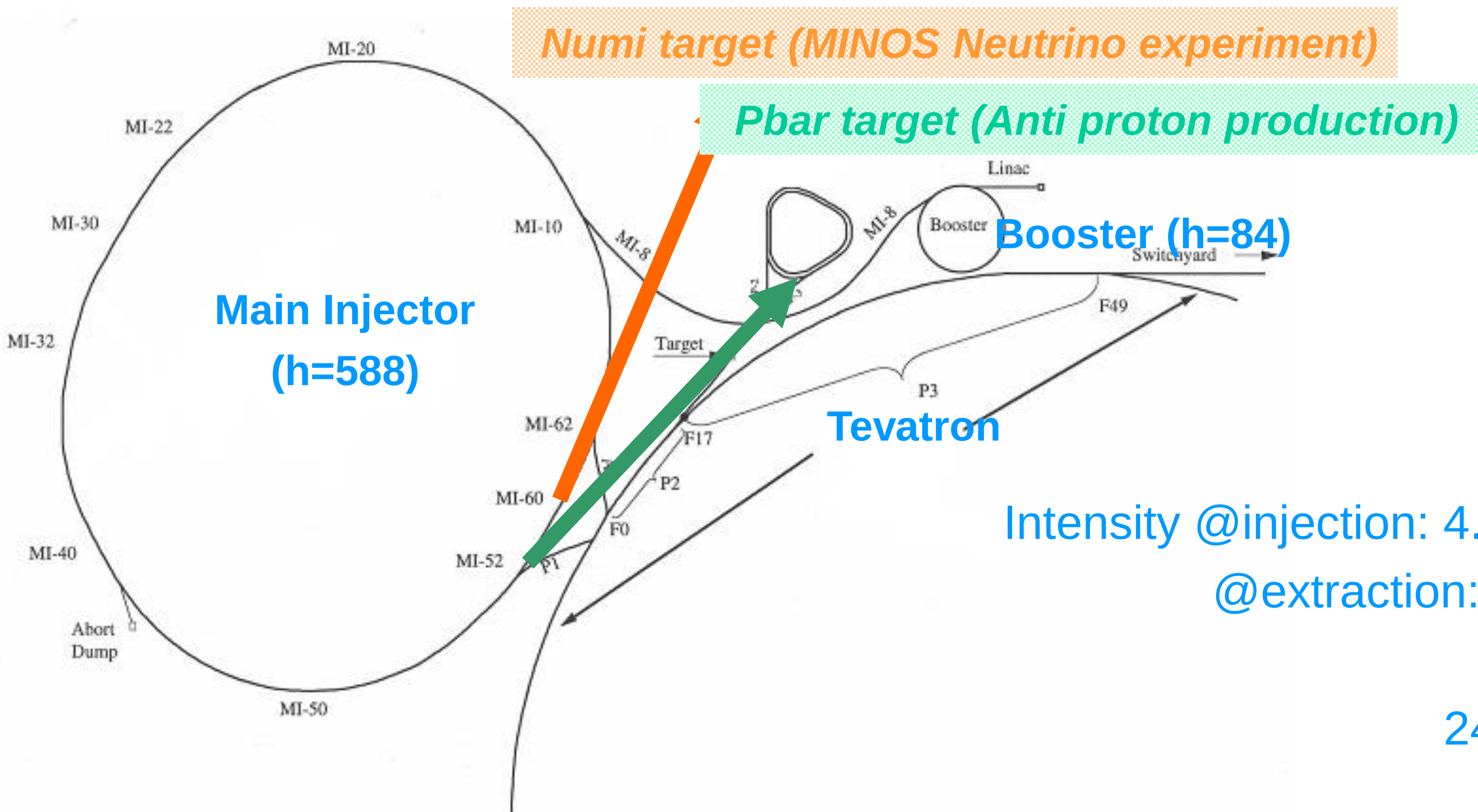
Outline

- Introduction.
- Review of past MI high power operations.
- Plan of doubling the MI Power.
- Progress on increasing the MI power.
- MI/RR requirements in PIP II.
- Conclusions

Introduction

- In MI TDR there was a provision for a "mixed mode" operation where five Booster batches will be injected first to be used for fixed target and then a sixth batch to be used for pbar production is injected in the center of the 3.2 micro-sec gap.
  - 3E13 p every 1.9 sec (~300KW!)
  - 20% loss in stacking rate!(assuming 1 booster batch every 1.5 sec)

MI 120GeV cycle operations in the Tev Era

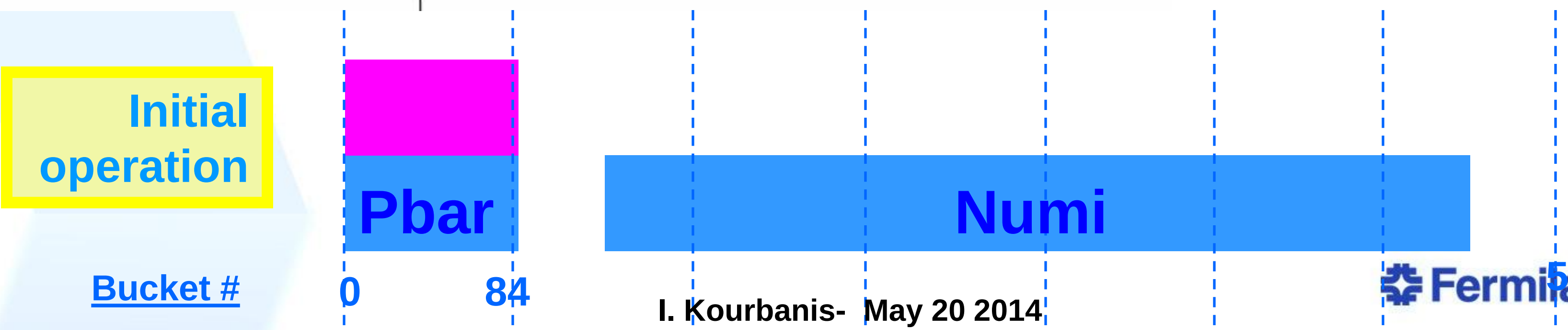


Intensity @injection: 4.8E12 ppp x 7

@extraction: 32.5E12 ppp

8.5E12(Pbar)

24.0E12(Numi)



Initial Mixed mode operations

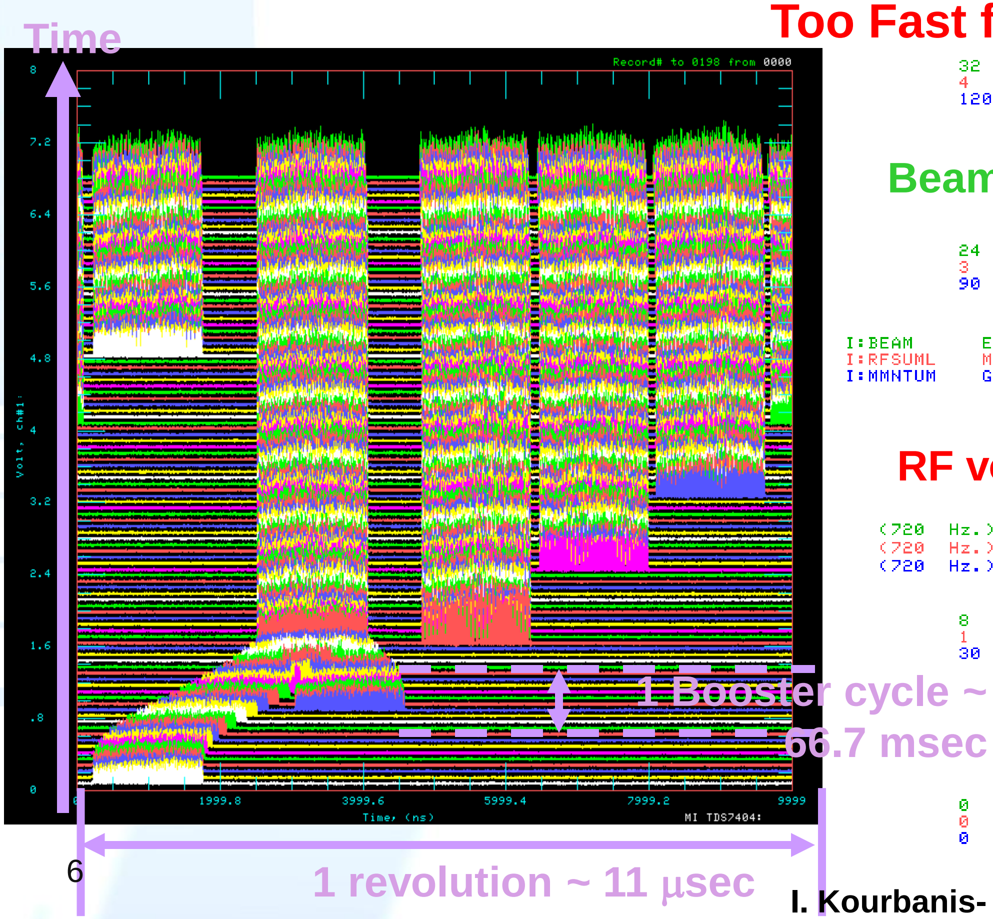
Intensity on Pbar target: 8.5E12 ppp

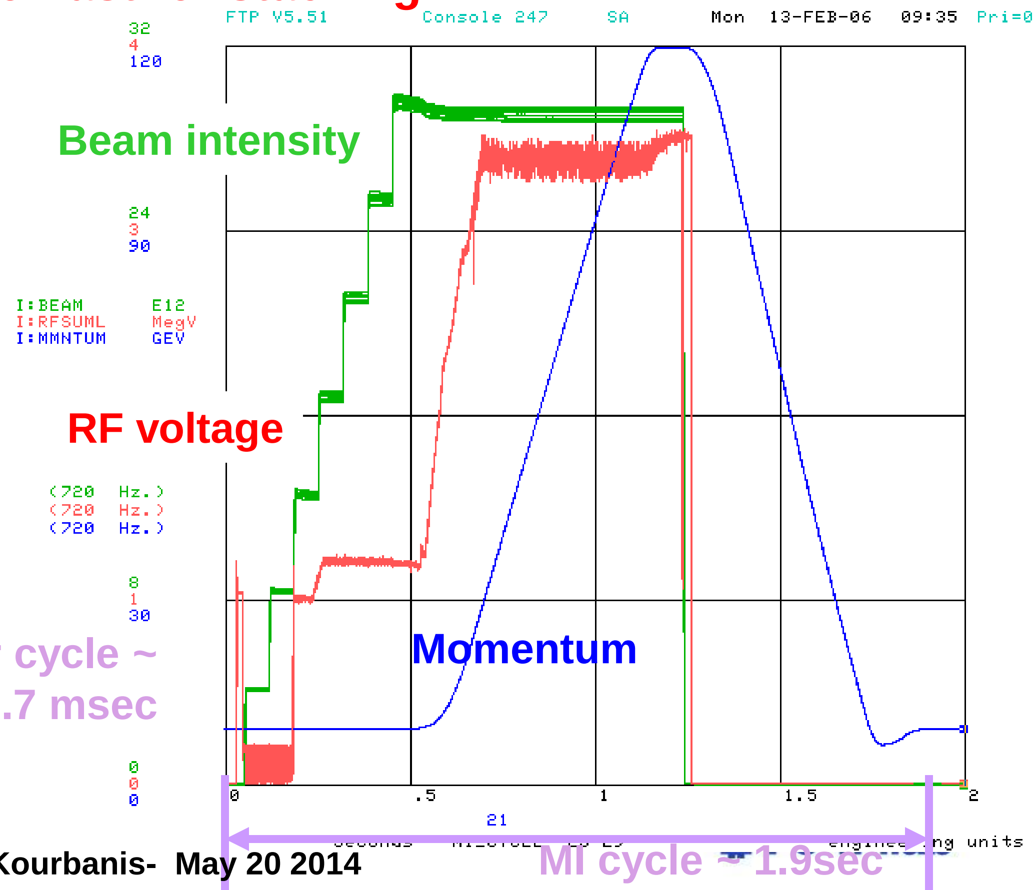
Acceleration efficiency: 95%

bunch length @ ext.< 1.8nsec after the bunch rotation

Slip stacking time < 2 Booster cycles

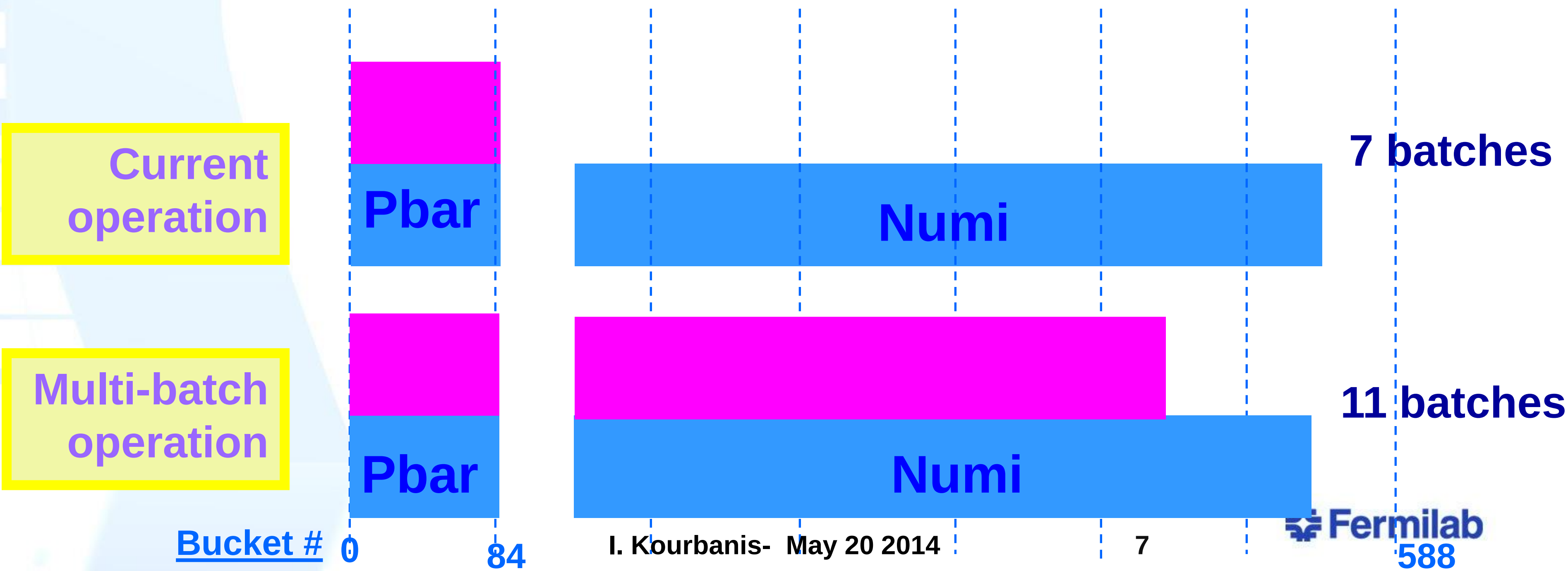
Too Fast for stacking!





Proton Plan Goal

- Intensity @ injection : 4.3E12 ppp x 11
  @ extraction: 4.5E13 ppp
- Total beam power: 400kW 80kW → Pbar
  320kW→ Numi
- MI cycle rate < 2.2 sec
- Total beam loss: < 5%



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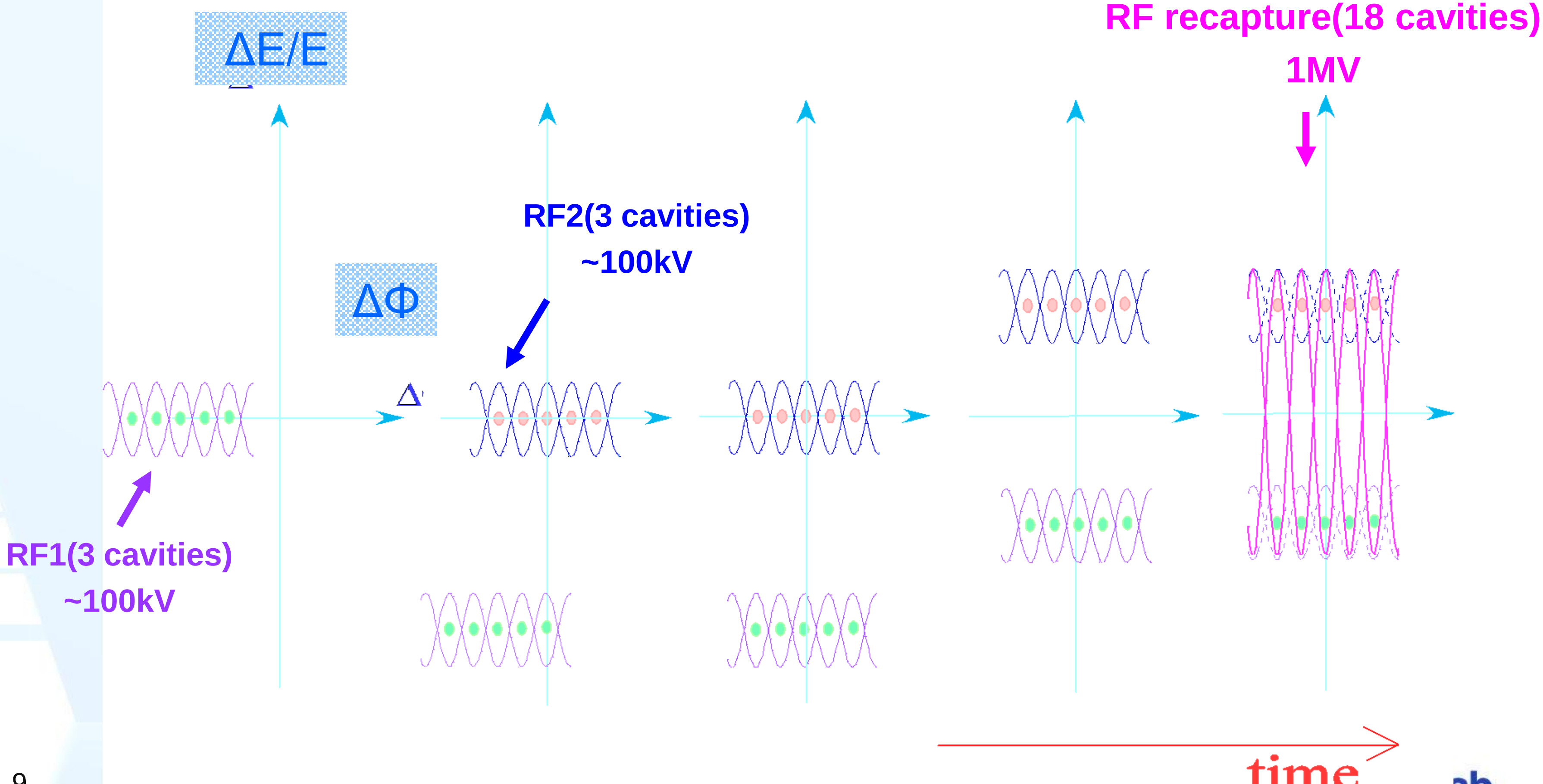
Slip Stacking

- Original idea dates back in 1970s
- Very difficult to implement in a fast ramping synchrotron because of the large beam loading voltages.
- Beam loading compensation is essential.
- Very sensitive to the longitudinal beam distribution inside the slip stacking buckets.
- Need momentum aperture.

Slip stacking procedure

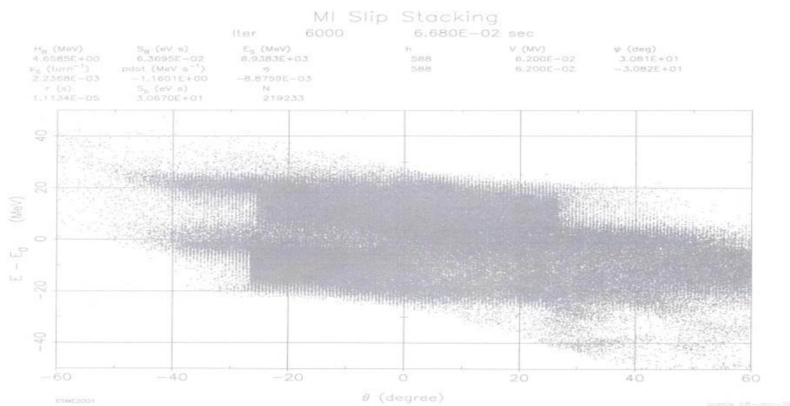
(MI has 18 53MHz RF cavities)

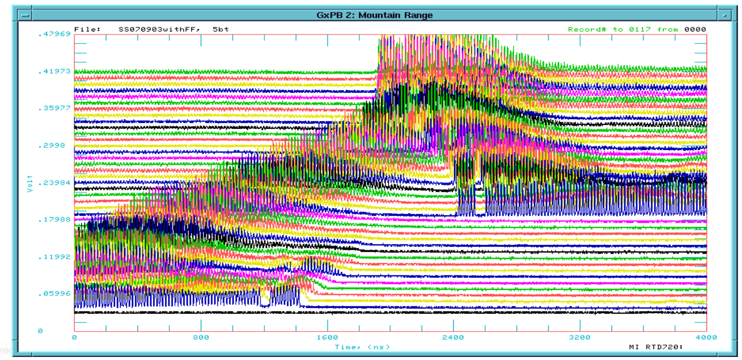


Slip Stacking and beam loading

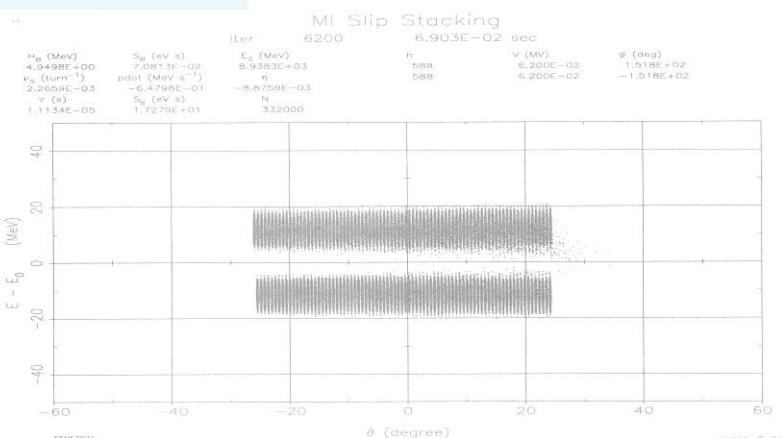
Simulation

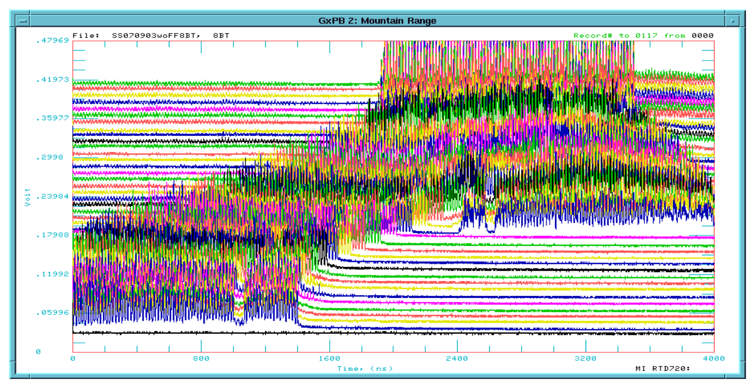
Beam





No Beam Loading Compensation





With Beam Loading Compensation

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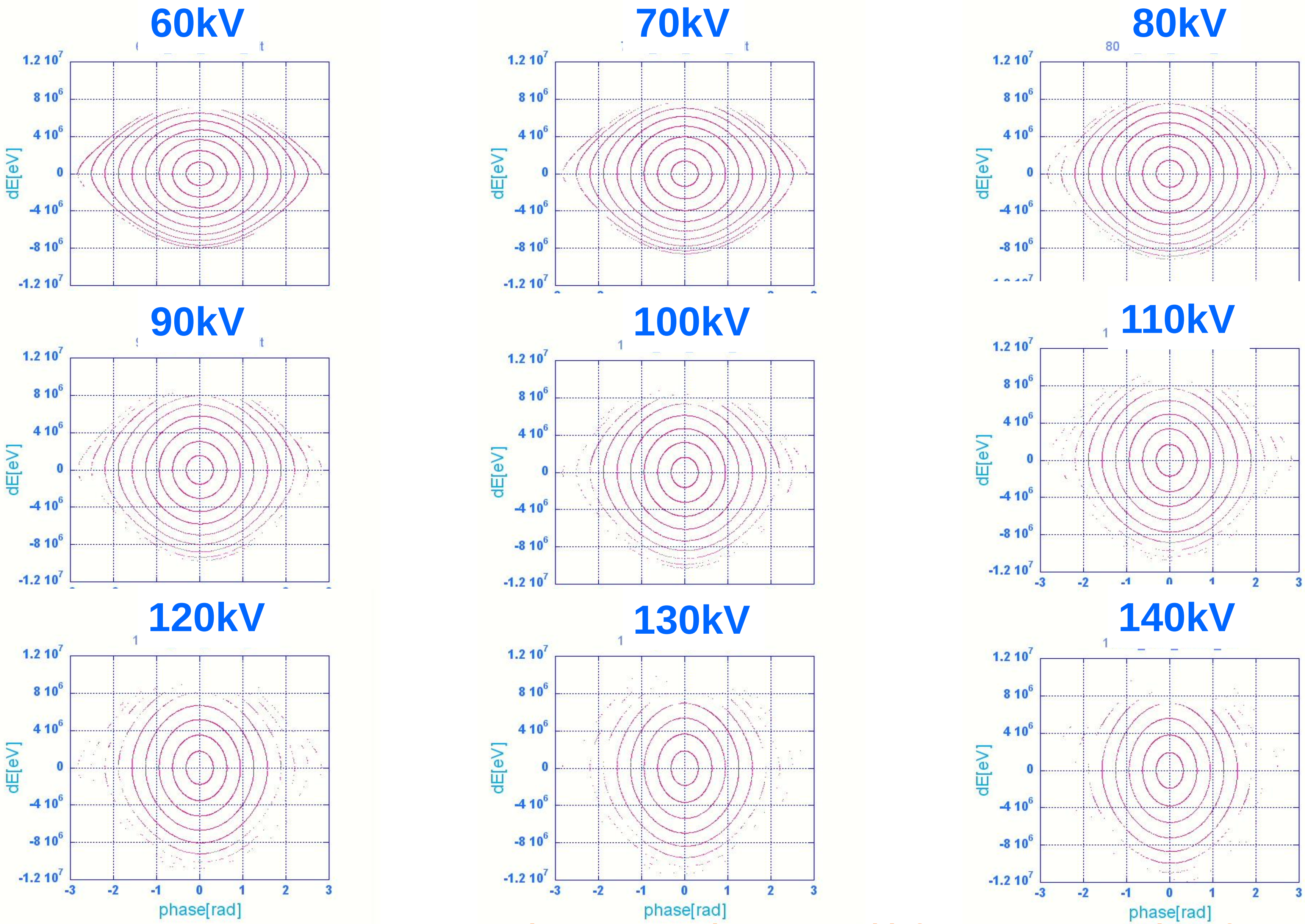
Particles which could survive after 120msec (df=1200Hz)



Maximum energy is ~ 6MeV with frequency separation of 1200Hz

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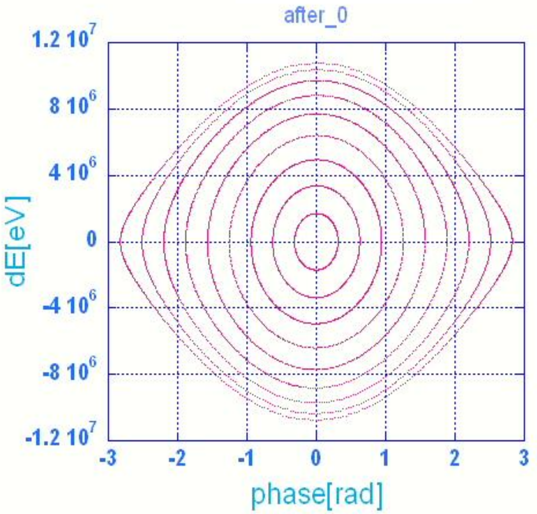
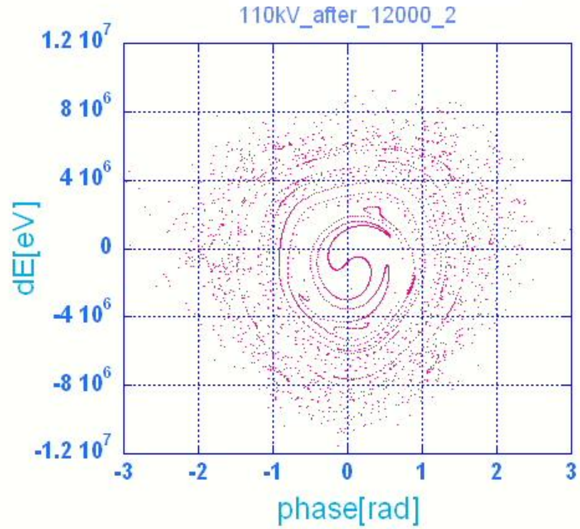
Longitudinal phase space
(Vrf= 100kV, df=1200Hz)

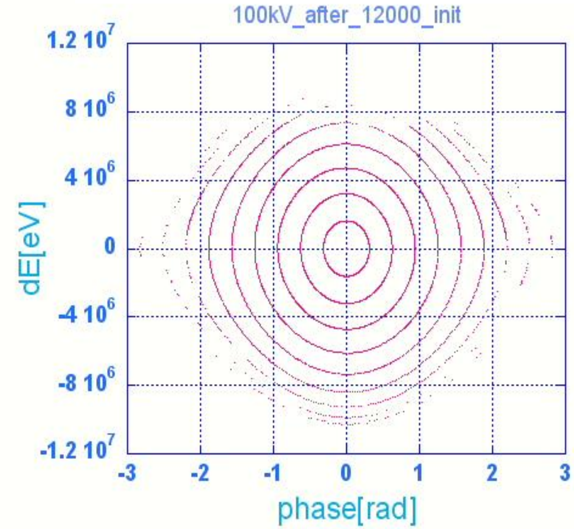
injection



12000turns

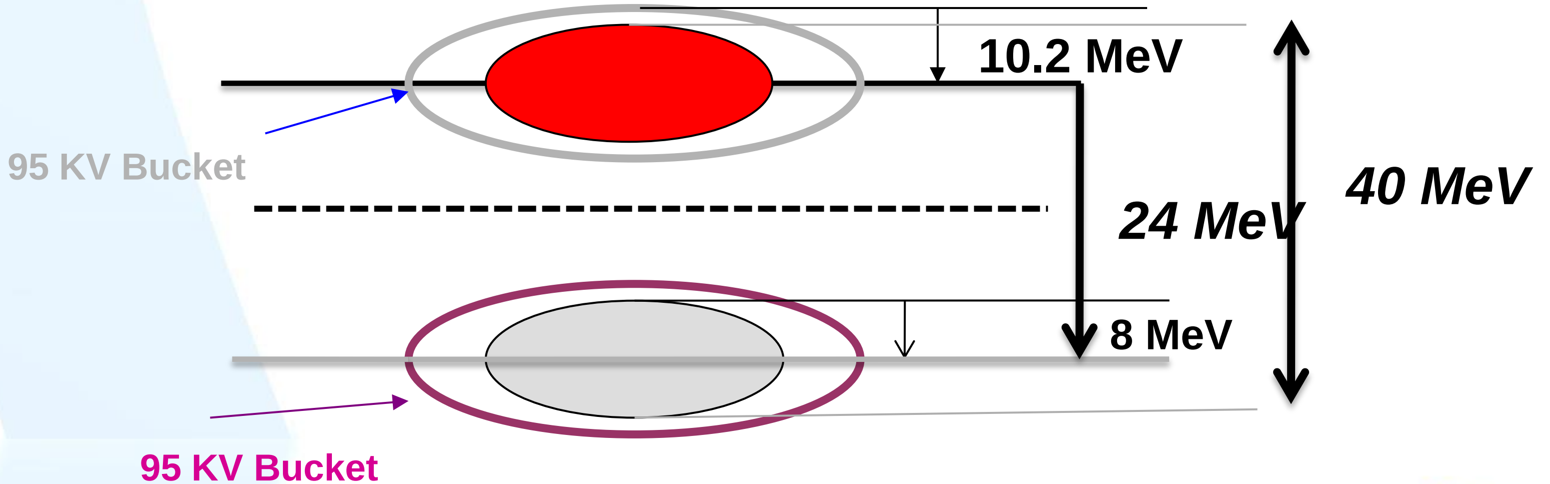


Survivors at injection



Momentum Aperture Requirements for Slip Stacking

- **The central frequency separation between the two beams is fixed**
  - Δf = 1260 Hz or Δp =24 MeV.
- **Assume Booster beam has momentum spread of ±8 MeV (95%)**
  - The min. momentum aperture required is 40 MeV or Δp/p = 0.45%



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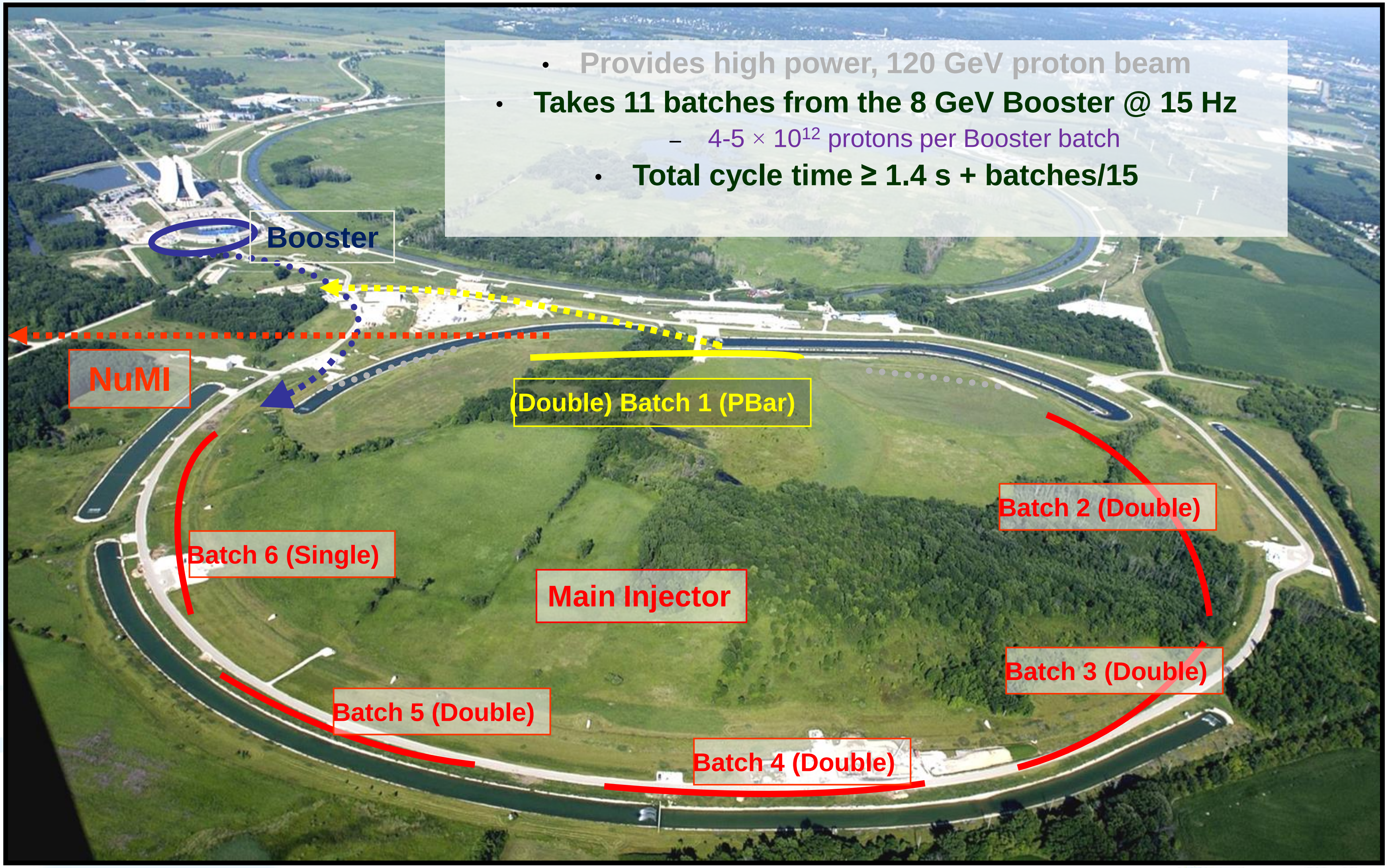
Main Injector High Power Operation (Mixed Mode)



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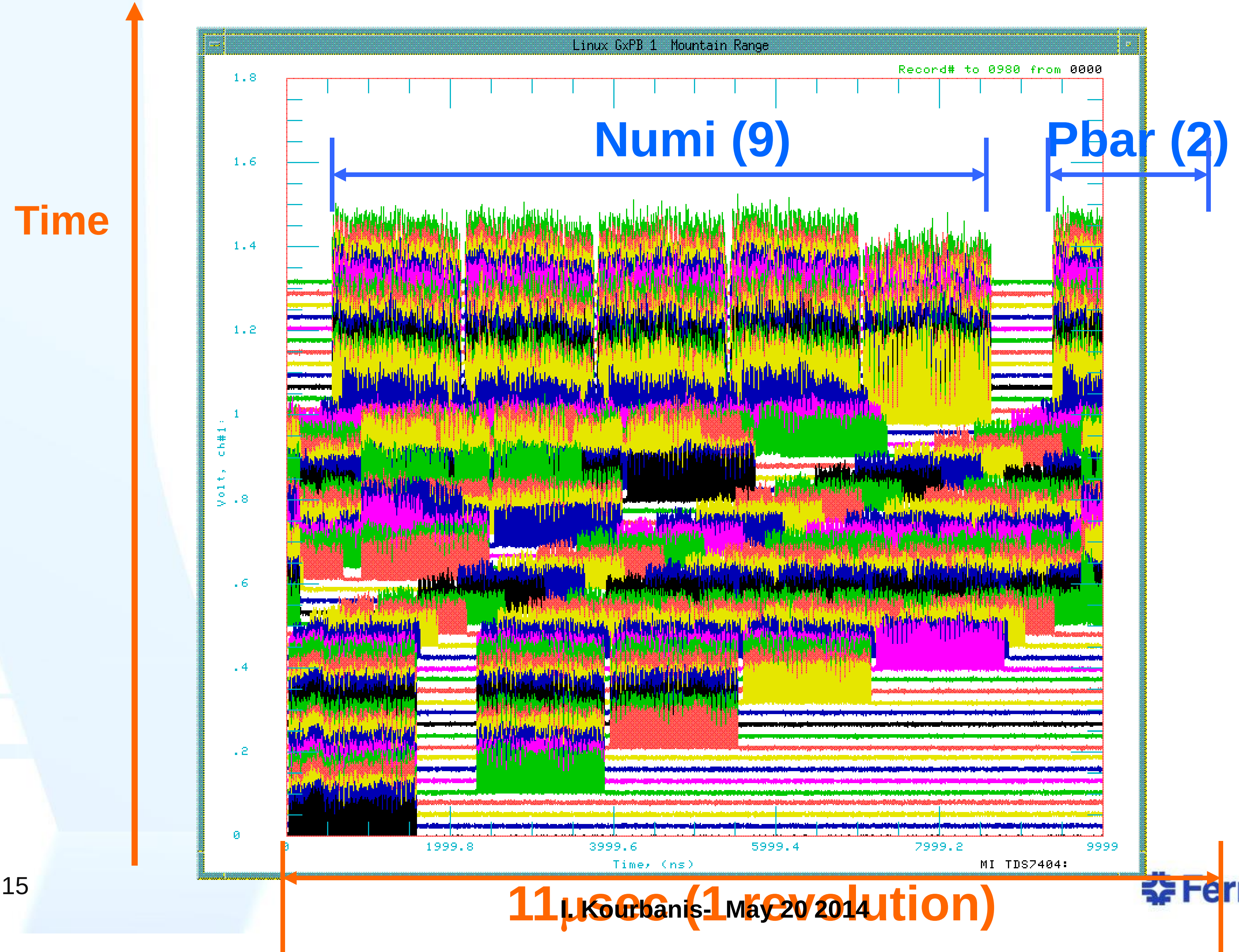
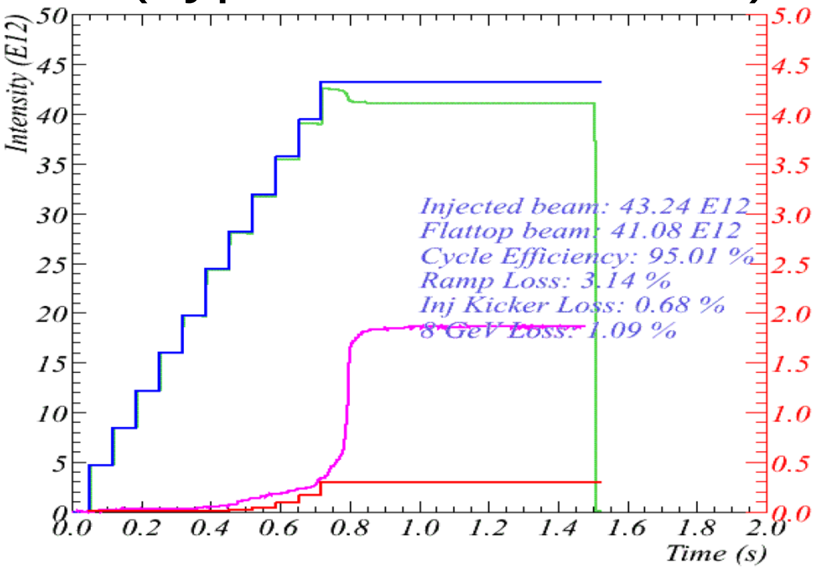
11 batch slip stacking on mixed mode cycle



Slip Stacking Losses

- Overall slip stacking efficiency is 95%
- Some “unavoidable” losses
  - Lifetime losses
    - Dampers don’t work for 2 RF frequencies
  - Other losses
    1. Re-captured in an extraction kicker gap
    2. Drift into an injection kicker gap.
    3. At re-capture time beam outside of the 1 MV bucket is not accelerated and lost on momentum aperture
- <W/m if distributed
  - However, losses 1,2 & 3 are localised and need to be controlled

Beam intensity vs. time (Typical Pbar & NuMI)



Blue - sum of the injected beam

Green - circulated beam

Red - loss from injection kicker

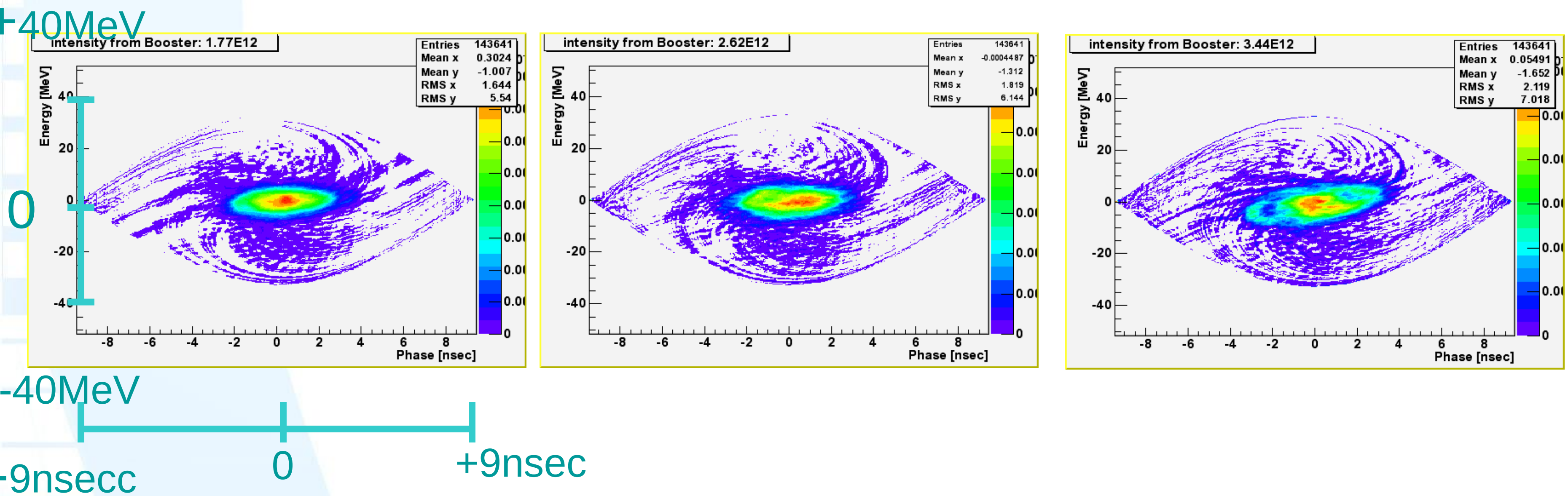
Magenta - total ring loss

Simulation for Injection kicker & Ramp losses

Use measured distributions as input to the simulations!

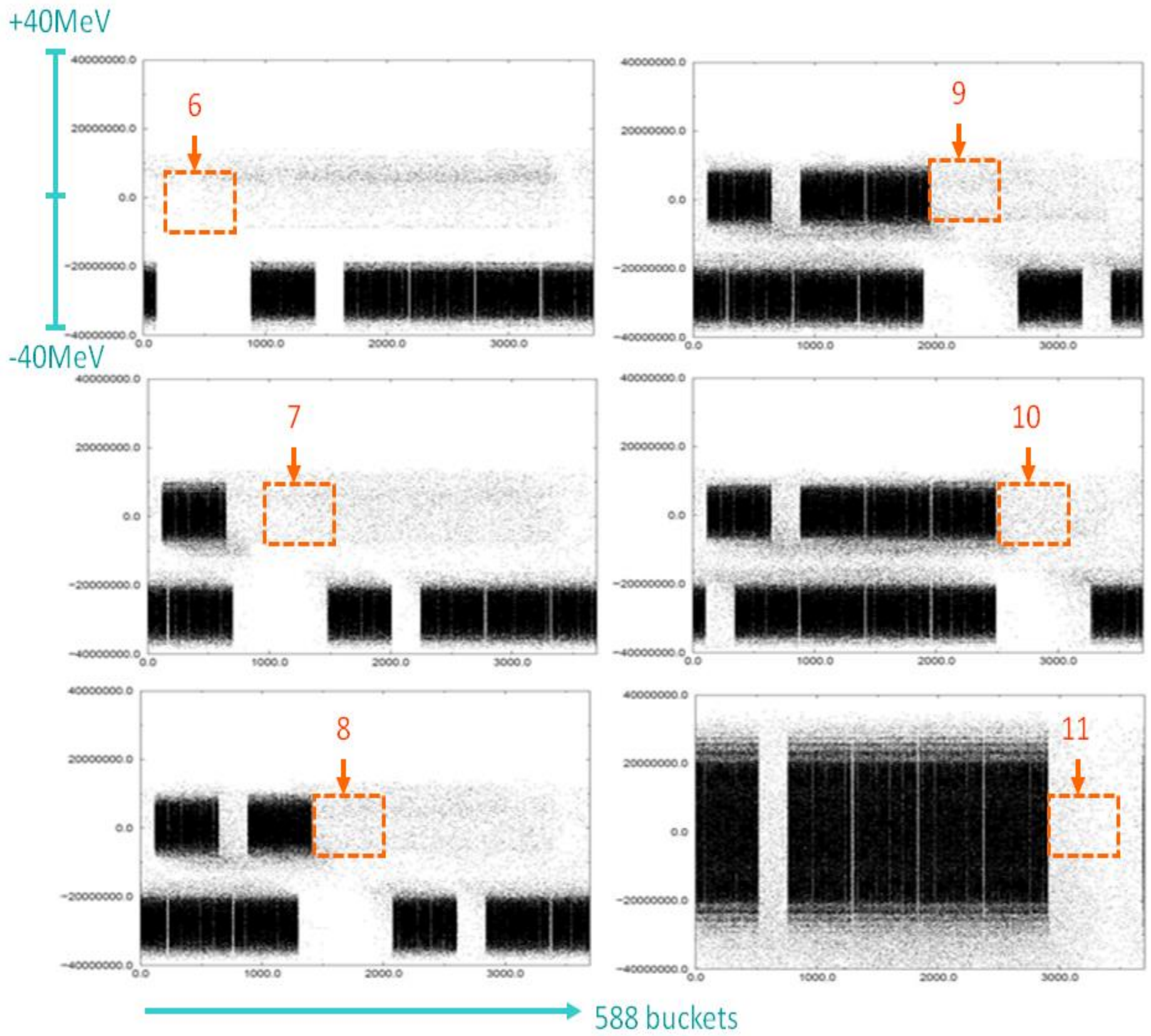
Longitudinal phase tomography with measurement results

1.77E12 ppp 2.65E12 ppp 3.44E12 ppp



Δϕ:	**+/-1.47nsec**	**+/-1.68nsec**	**+/-1.78nsec**
Δp/p:	**+/-6.88MeV**	**+/-7.62MeV**	**+/-8.99MeV**

Simulation of Multi-Batch Slip Stacking

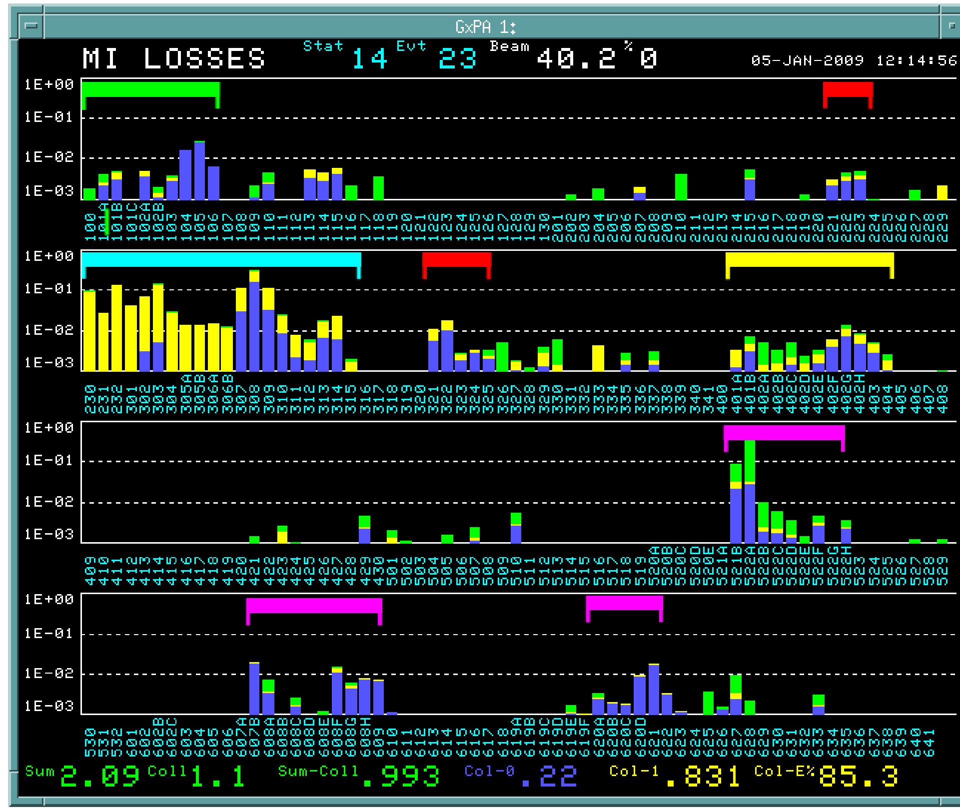


After the Injection of the first 5 Booster batches there is some beam left in the Injection Gap where the rest of the 11 batches are injected (orange squares). This amount of beam is relatively small (1% of total injected beam) but leads to localized beam loss (104-106 MI region)

Slip Stacking Losses

- MI Beam Loss Monitors (BLM) Display
  - Real time measurement on permanent display in MCR
  - Can be used to tune
  - Get spatial and temporal information
    - Blue - before acceleration
    - Yellow - after 1% acceleration
    - Green - end of cycle

Example display



Injection	Collimation	Abort	Extraction	RR Transfer

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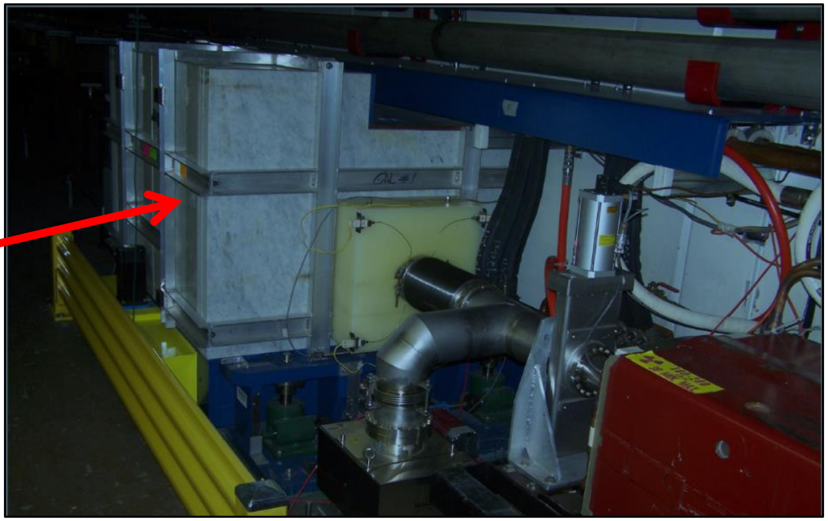
Un-Captured Beam Loss

- Uncaptured beam after slip stacking is not accelerated and lost on the momentum aperture and the Lambertsons!
  - ~5% of injected beam, Collimators required to absorb this beam
- 2-stage collimation system
  - One tungsten primary collimator to scatter
  - 4 20-ton secondary collimators to absorb
    - vacuum chamber surrounded by a steel absorber
    - Marble radiation shielding for personnel
    - Upstream polyethylene block reduces neutrons to upstream magnets



- **Collimator region absorbs 99% of the un-captured beam**
- **>50% of other 8 GeV losses (mainly lifetime) are also captured.**
- **The collimators enabled multi-batch slip stacking in MI**

Un-captured beam loss

- Uncaptured beam after slip stacking is not accelerated and lost on the momentum aperture and the Lambertsons.
  - ~5% of injected beam, Collimators required to absorb this beam
- 2-stage collimation system
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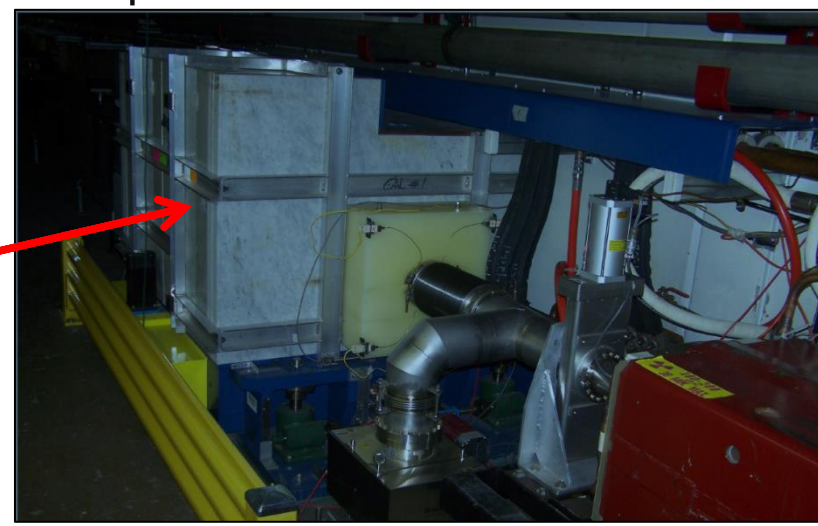
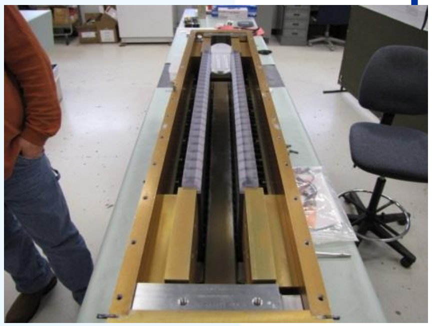


	Residual Radiation Ratio before/after collimators installed						
Location	113-221	Coll	40	405-521	52	60	62
RRR	**0.26**	**5.06**	**0.55**	**0.30**	**0.68**	**0.65**	**0.70**

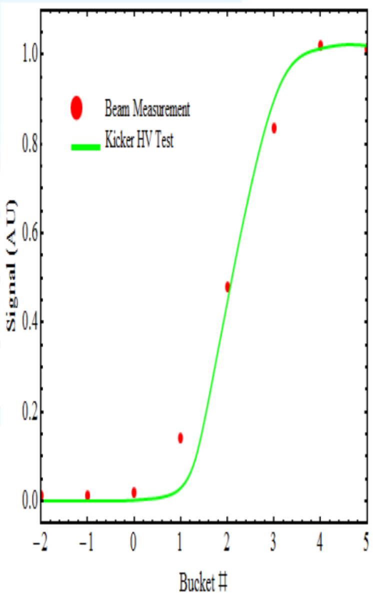
Injection Gap Losses

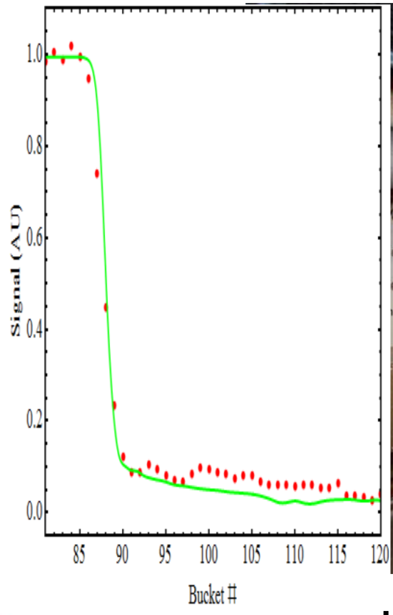
- Beam spills into the gap left open for injecting new batches,
  - Localised losses when injection kicker fires
- Build “gap-clearing” kickers to send this beam to abort instead
  - fast (3 bucket) rise and fall time to match injection kicker
  - kick horizontally
- kickers were moved to Recycler during the last shutdown

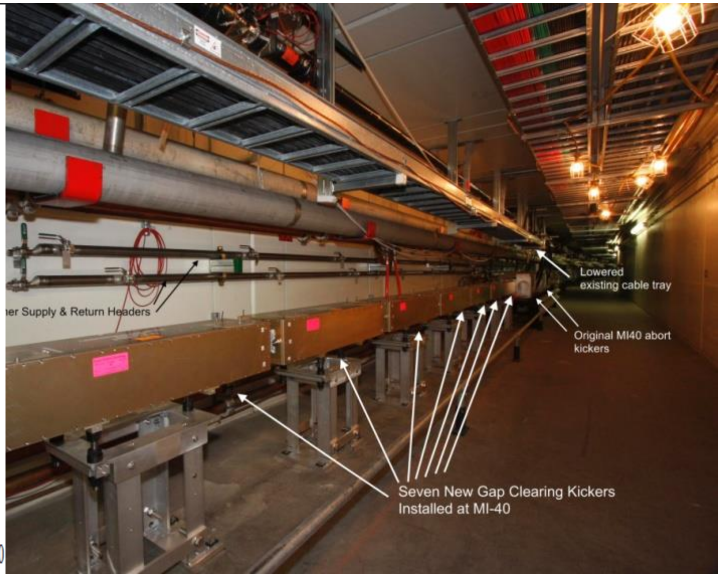
Gap Clearing Kickers



- Magnets built by TD
- Fast rise/fall time, so need short magnets
  - 7 magnets to generate necessary kick



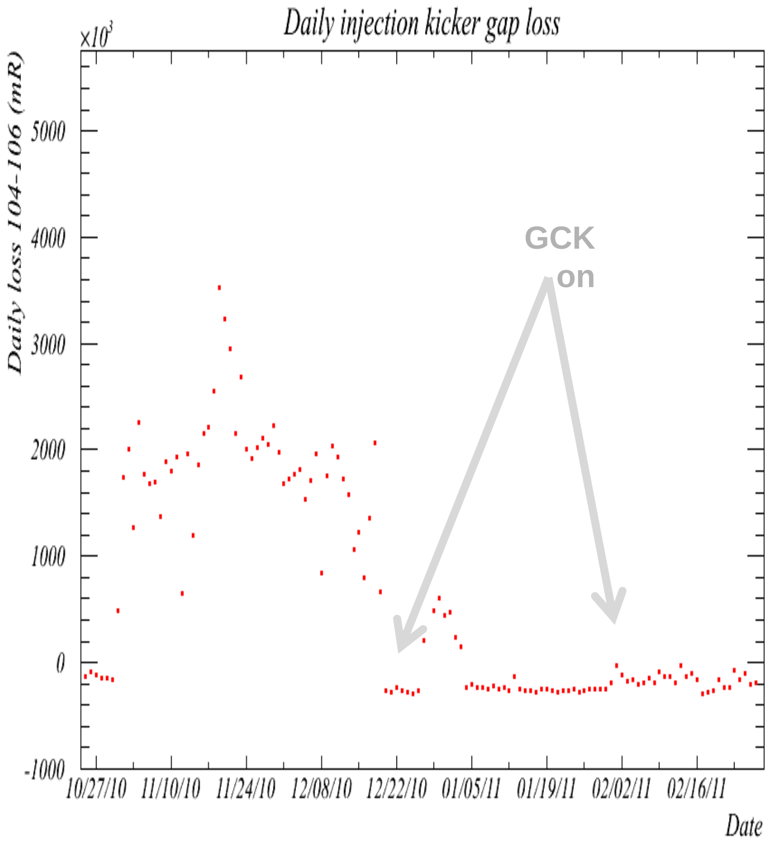


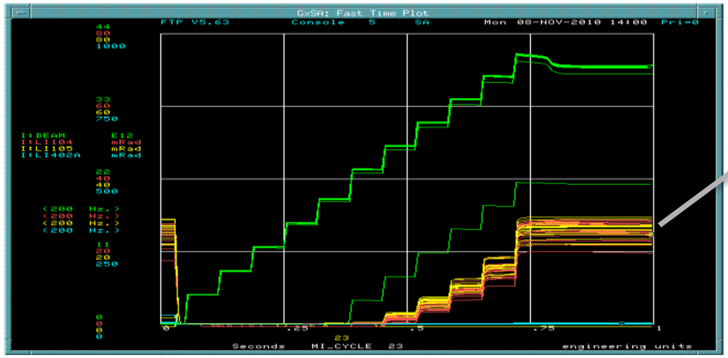


Installed summer 2009

Injection Gap Losses

Beam loss, 104-106 region



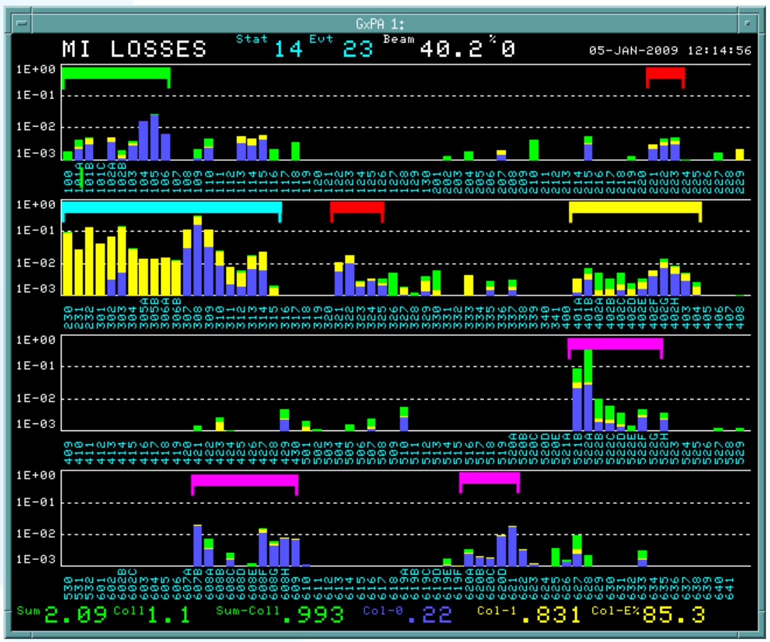


Injection losses

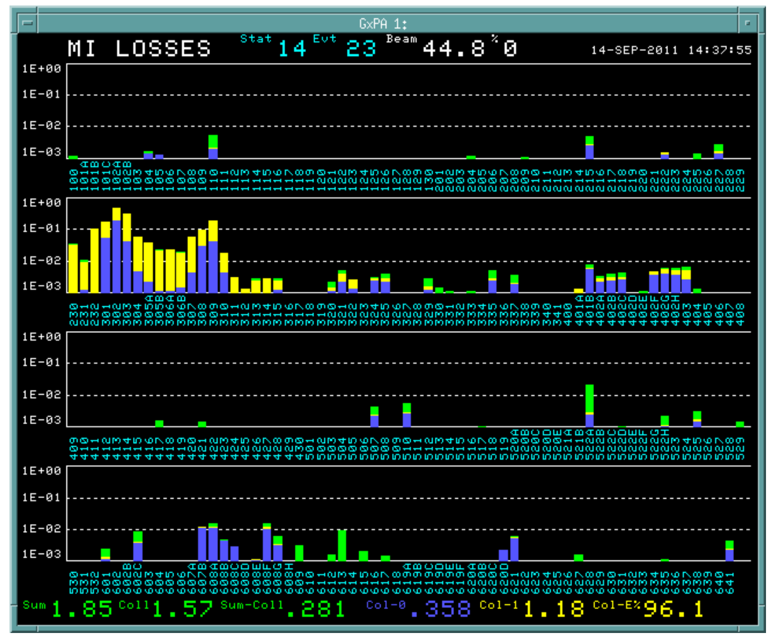
Loss Reduction

- **Compare 2009 to 2011, lower losses everywhere except collimators**

Injection	Collimation	Abort	Extraction	RR Transfer



2009



2011

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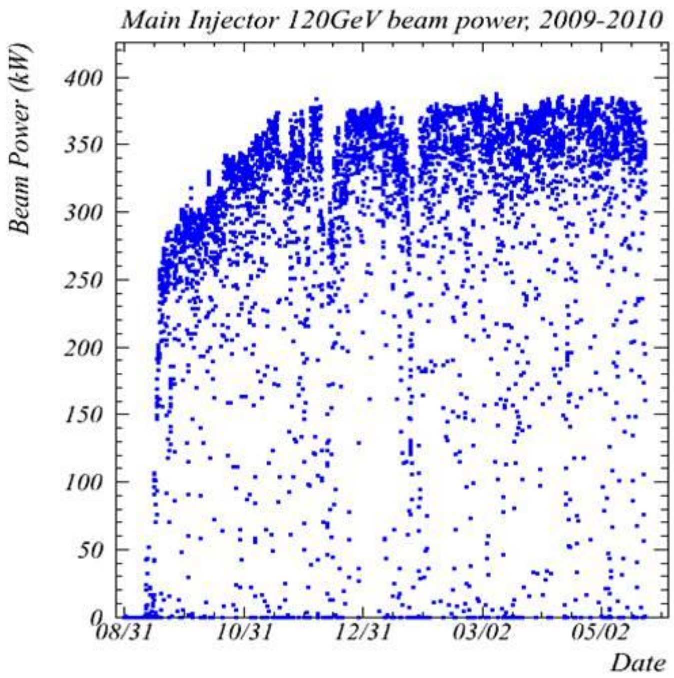
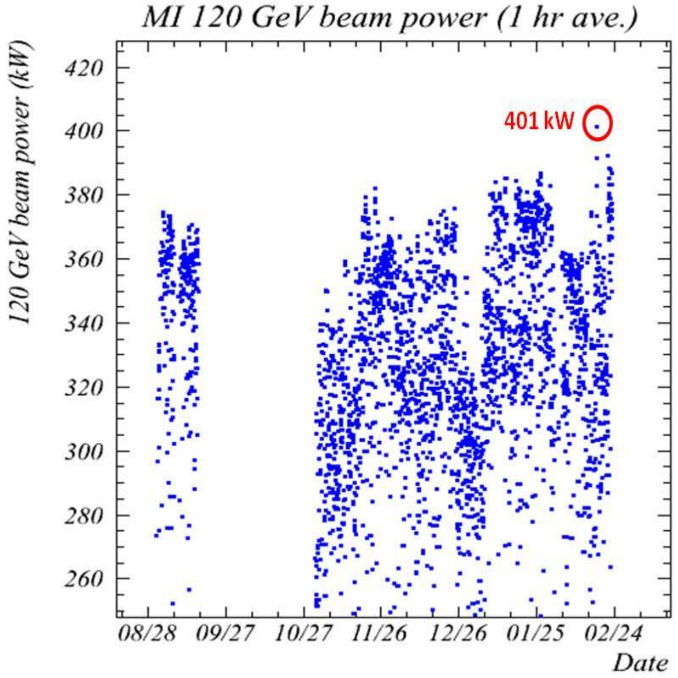
Main Injector beam power with multi-batch slip stacking 2009-2011



MI 120 GeV Beam Power 2009-2010 (MI Collimators operational)



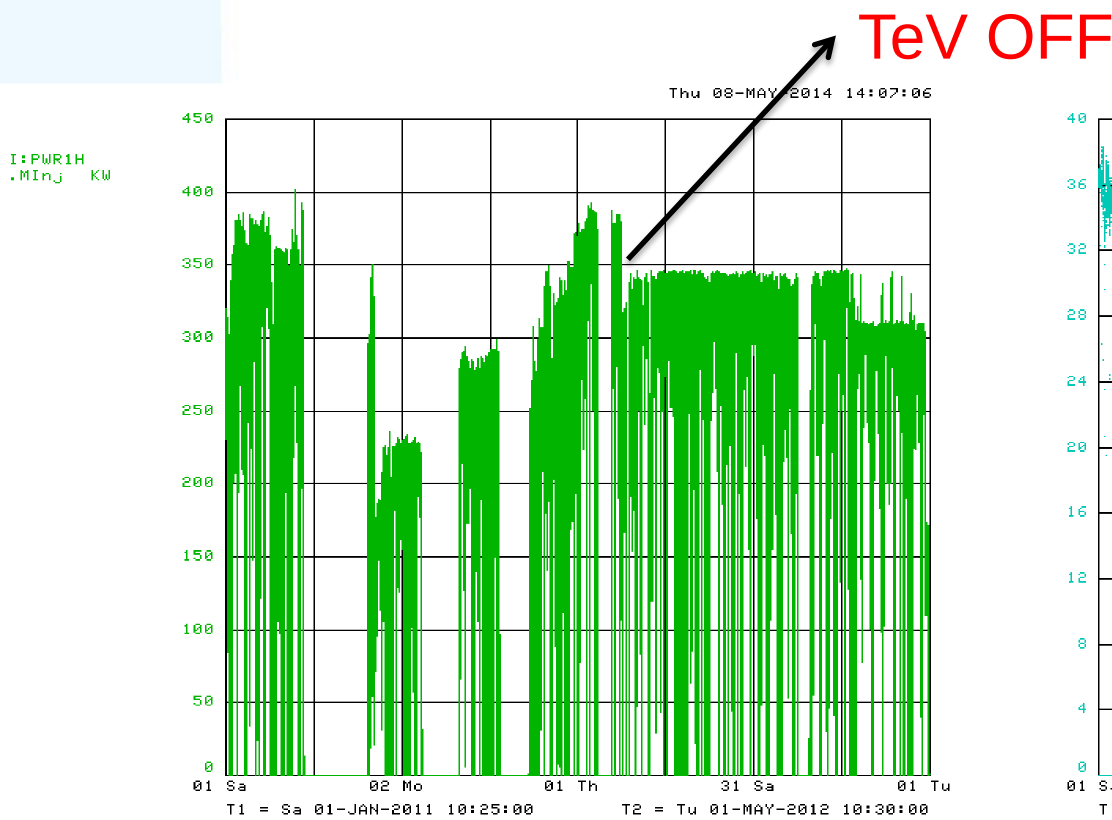
MI 120 GeV Beam Power 08/10-03/11 (Gap Clearing Kickers Operational)

Achieved a record beam power of 401 KW by running 4.6E13p in a mixed mode with 11 batches.

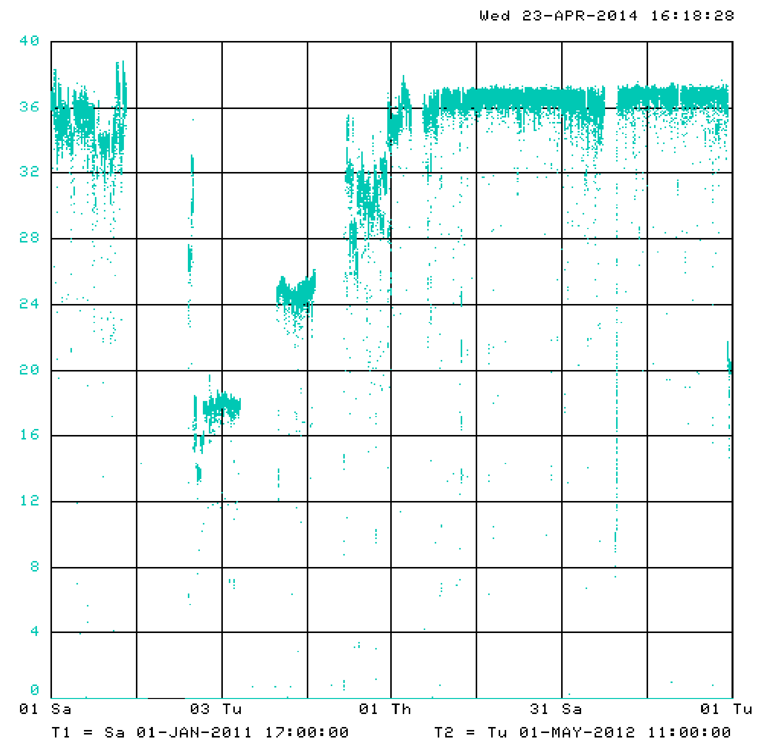
Last year of running

- After TeV was turned off the MI beam power was reduced (350KW instead of 390KW) because of NuMI target concerns.
  - The intensity at the NuMI target never exceeded 4.0E13p.
- We run 3.7E13 with 9 total batches (8+1) and with a 2.03 sec MI cycle time.
  - This also reduced our power loss.

Beam Power and NuMI target intensity 2011-2012



Main Injector beam power 01/11-05/12



NuMI Target Intensity 01/11-05/12

Summary of past MI High Power Operation

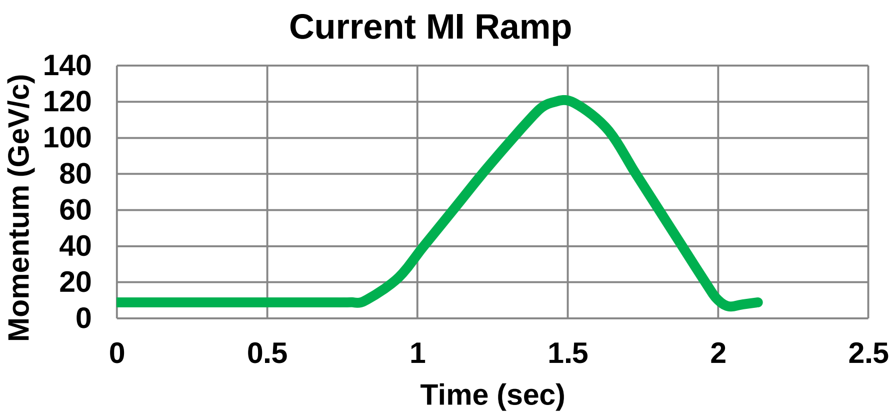
- After understanding the multi-batch slip stacking and implementing loss control measures we were able to achieve 380 KW of beam power with 11 batch slip stacking (10+1).
- The total cycle time was 2.2 sec with 0.8 sec spent at injection energy for stacking.

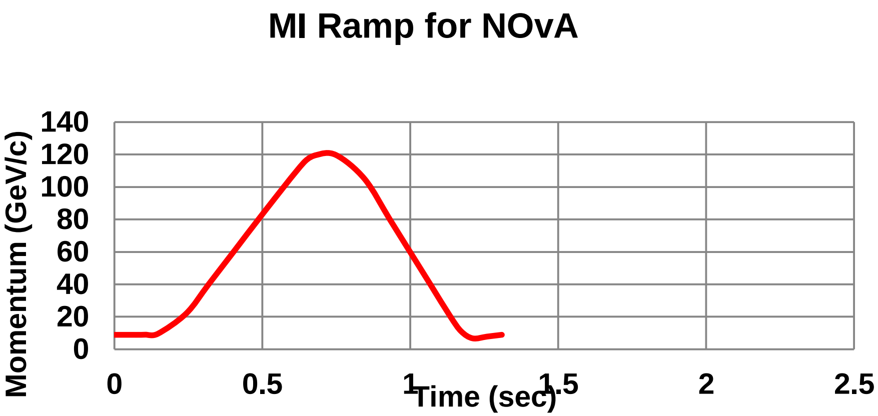
Plan for doubling the MI Beam Power

- Transform the Recycler into a proton injector ring for injecting and slip stacking the protons from Booster.
- Eliminate the long dwell MI time.
- Need a Project Plan to execute the required upgrades (ANU).
  - ANU stands for “Accelerator and NuMI Upgrades” and it was part of the NOvA Project.

MI 700 KW Operation

- MI Cycle Reduced from 2.2 sec (33 Booster Ticks) to 1.33 sec (20 Booster Ticks).
- MI Beam Intensity increased by 9% (49E12).
- The intensity per bunch remains the same.
- No Instability Issues are anticipated.
- Loss control is the major Issue (Power loss is increased by 80%).





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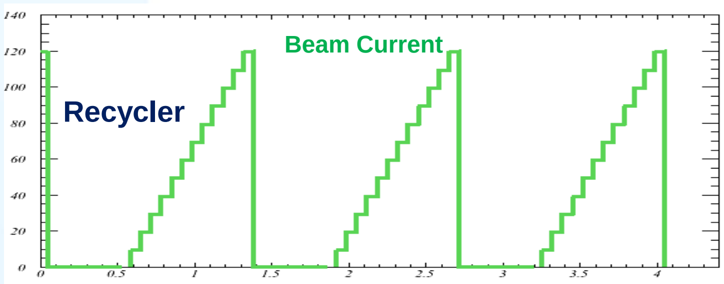
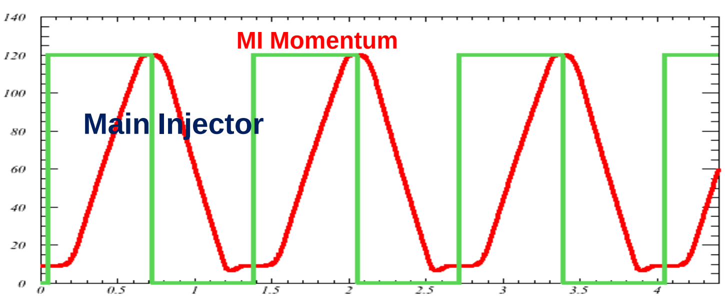
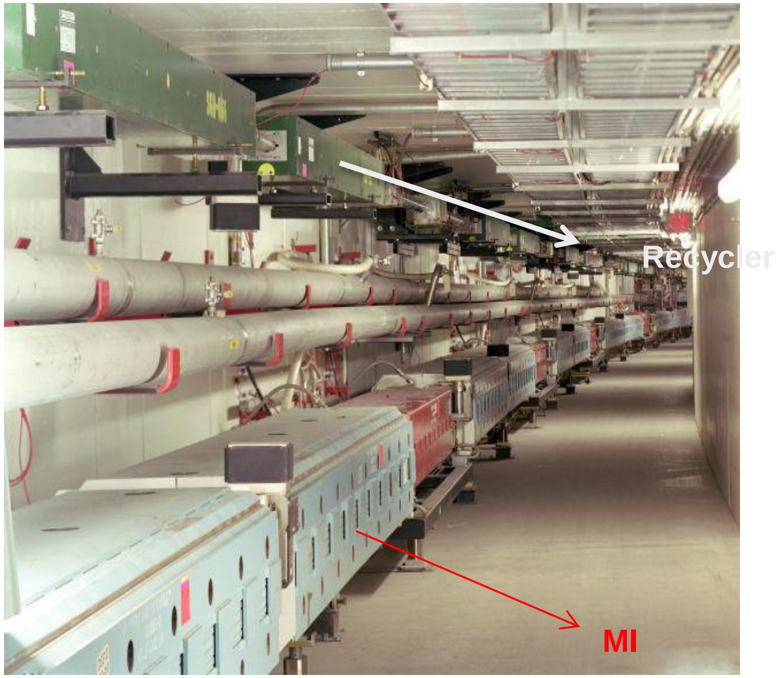
Recycler Operation

- Injection of 12 high intensity Booster Batches for slip stacking(4.3E12x12).







- Up to 8 additional Booster batches cab be injected in Recycler for delivery to the modified p-bar Rings (Mu2e, g-2 experiments)

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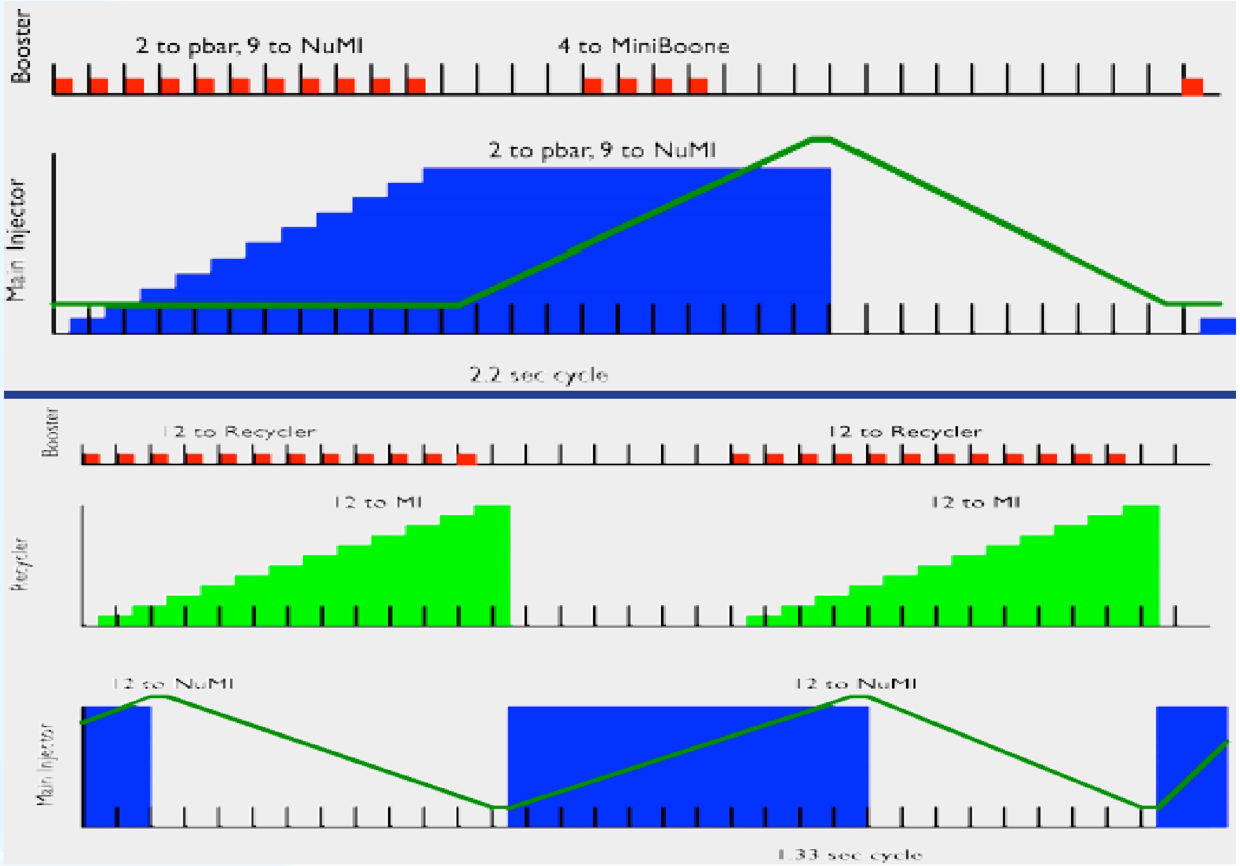
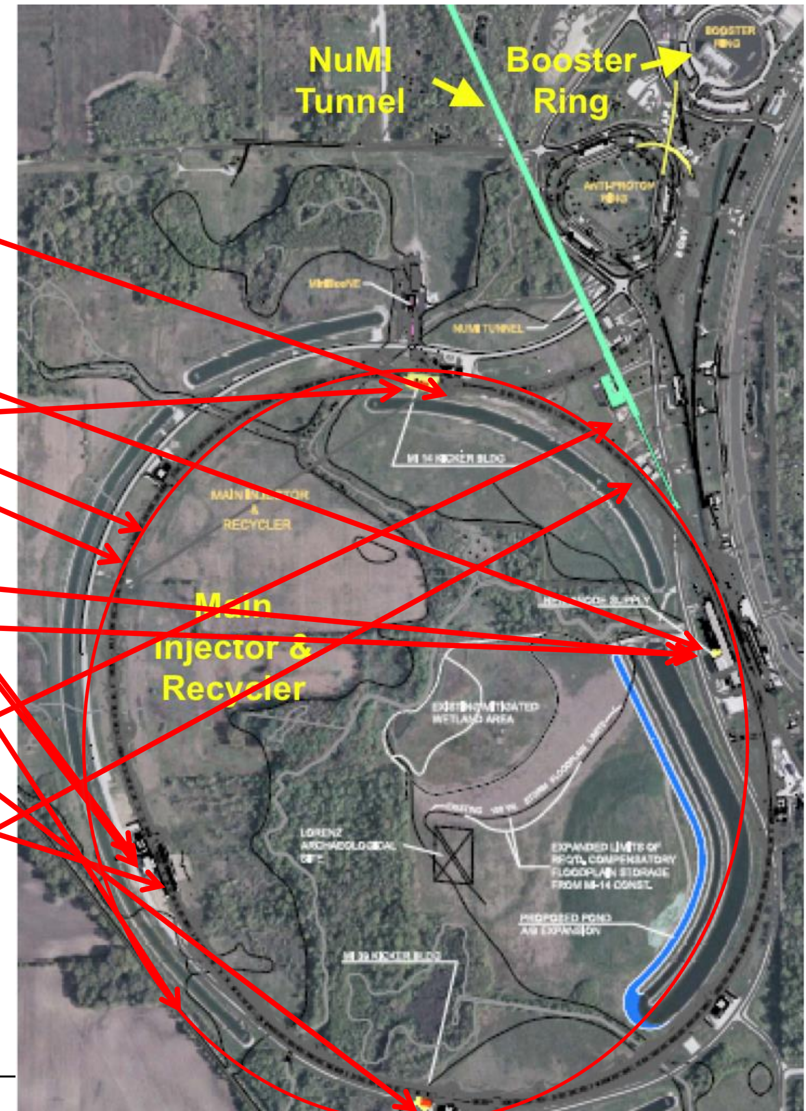


Tev Era Operation: 11 Booster batches (2 to pbar), 3.5E13, 2.2 second cycle.

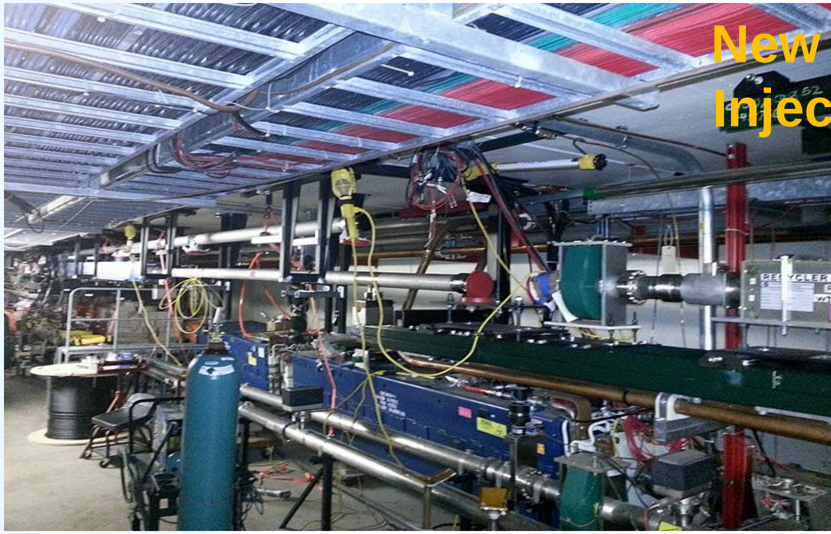
NOvA Era Operation: 12 Booster Batches, 4.9E13 to target, 1.33 sec cycle.

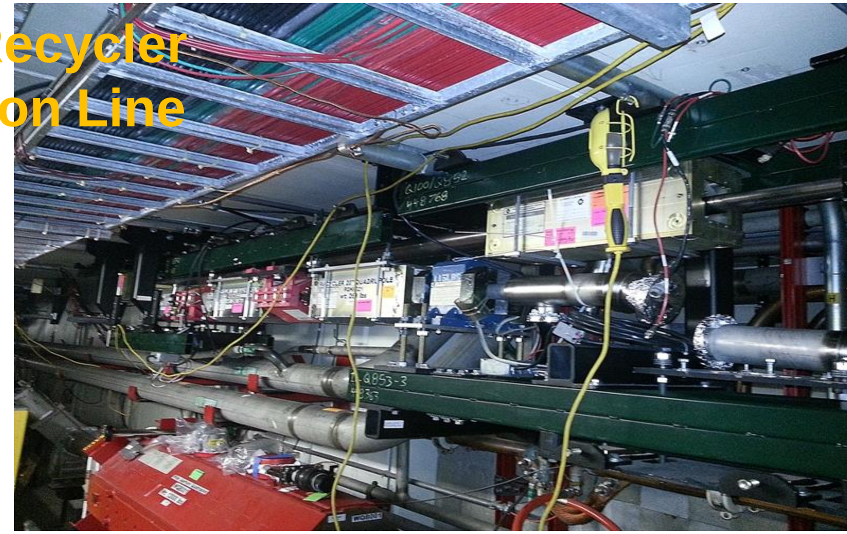
Accelerator and NuMI Upgrades for NOvA

- Recycler Ring, RR
  - New injection line into RR
  - New extraction line from RR
  - New 53 MHz RF system
  - Instrumentation Upgrades
  - New abort kickers
  - Decommissioning of pbar components
- Main Injector
  - Two 53 MHz cavities
  - Quad Power Supply Upgrade
  - Low Level RF System
- NuMI
  - Change to medium energy ν beam configuration (new target, horn, configuration)
  - Cooling & power supply upgrades



Pictures of Recycler ANU Installation





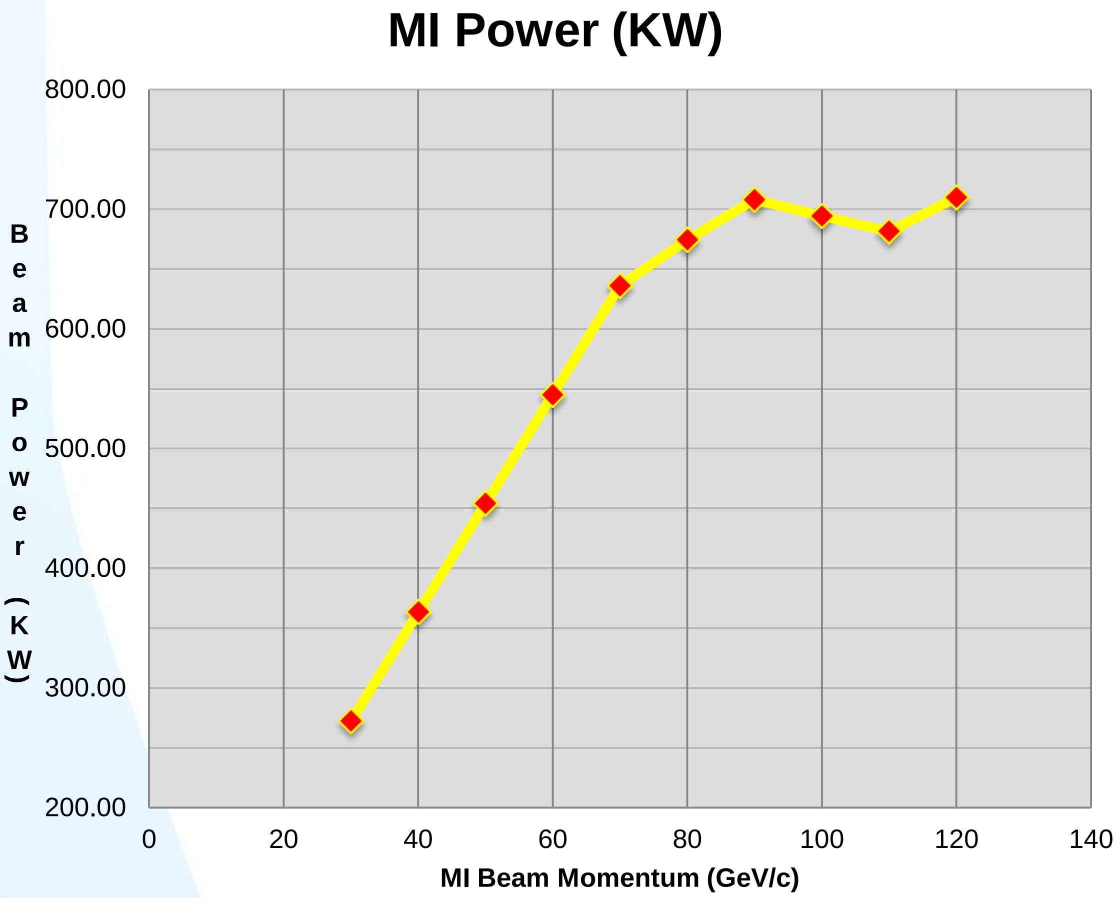
RR 53 MHz Cavities

D. Wildman

f_0	52.809 MHz
Z_0	10.2 Ω
Vpeak (max)	150 kV
Maximum power	150 kW
Rshunt	75 kΩ
Q	5800
R/Q	13 Ω
Outer conductor ID	32 in
Inner conductor OD	27 in
nominal gap width*	2.9 in
Inner conductor length**	49.75 in
Step up ratio	6

2Cavities instead of 18; R/Q 13 Ohms instead of 104 Ohms. 72 times less beam loading!

MI Injector Power vs. Energy after ANU Upgrades



Fermilab Accelerator Complex after ANU

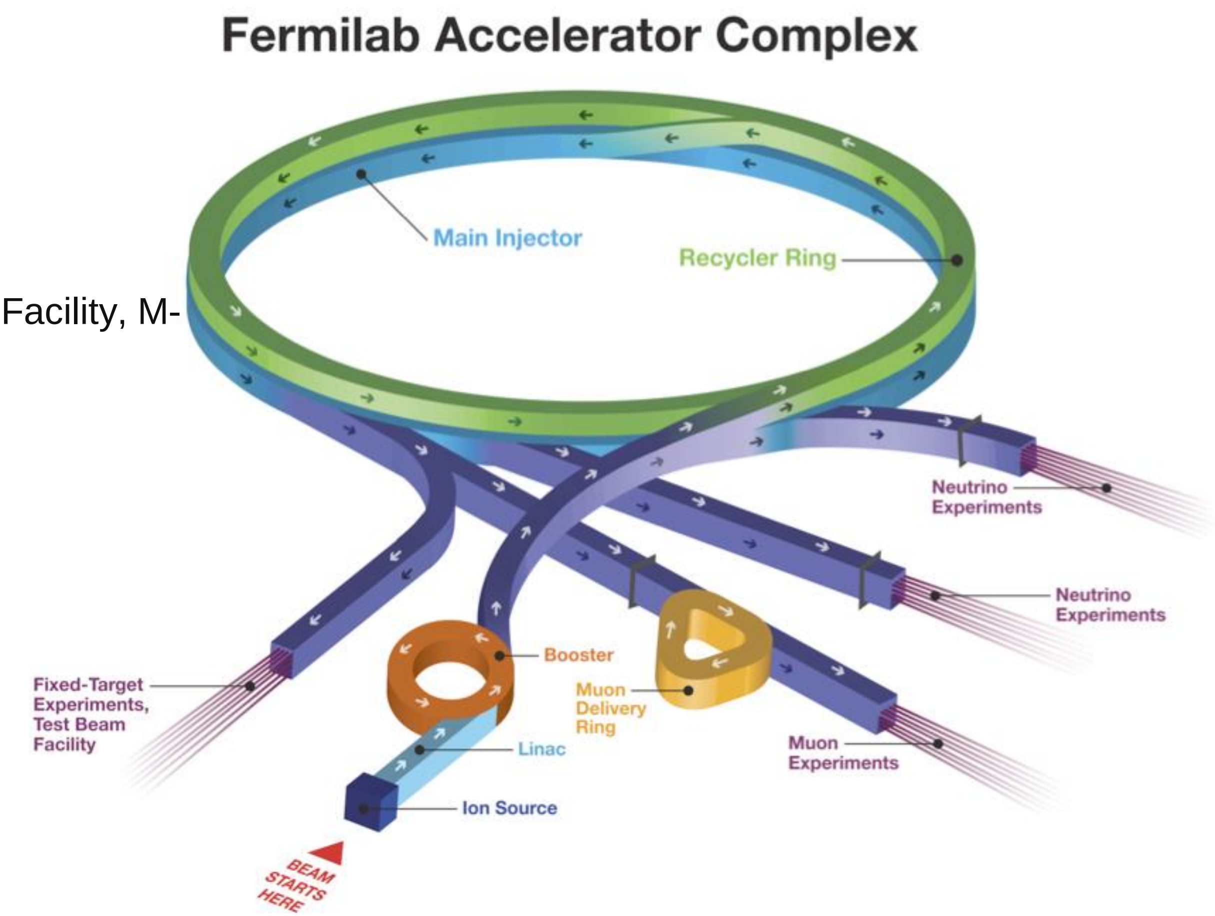
Linac: NTF, MTA

BNB: MicroBooNE

NuMI: MINOS+, MINERvA, NOvA

Fixed Target: SeaQuest, Test Beam Facility, M-Center

Muon: g-2, Mu2e (future)



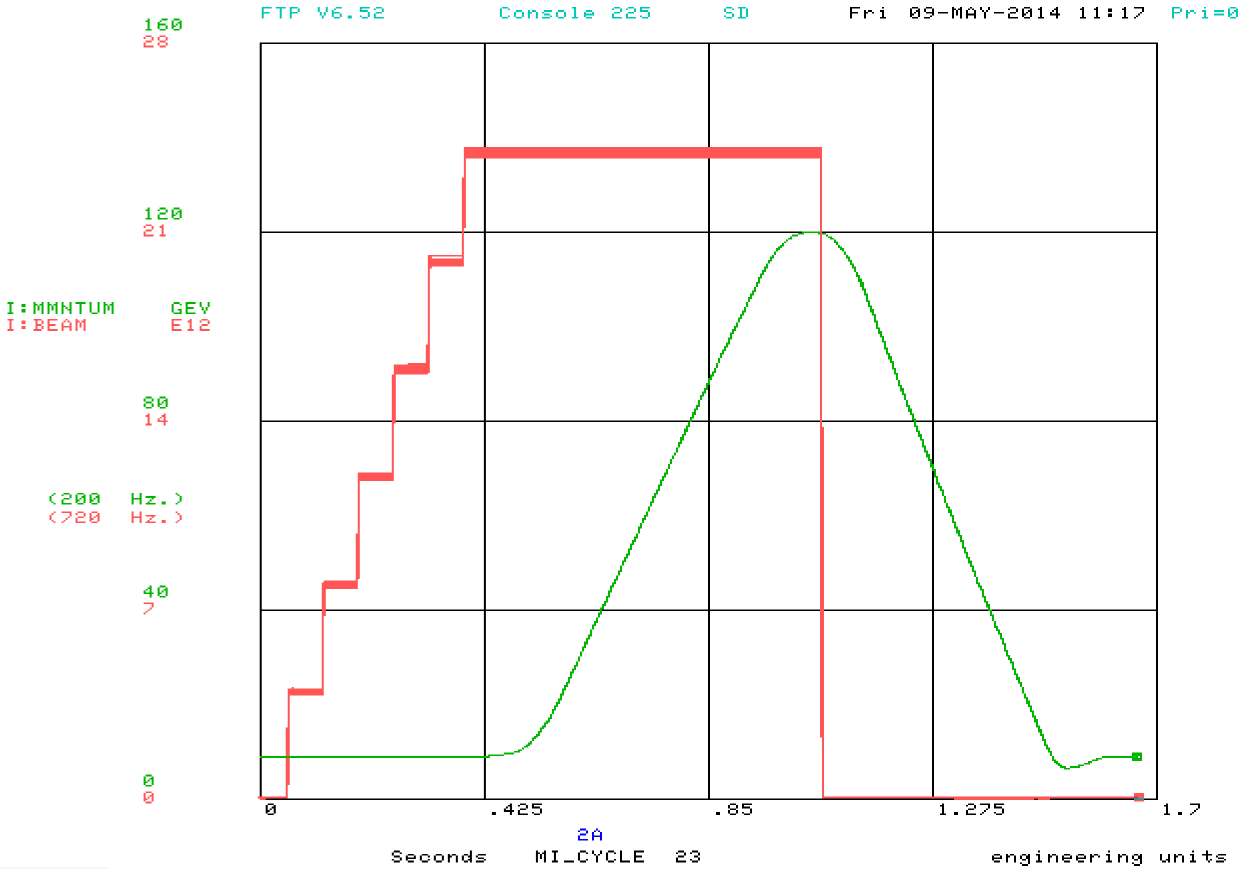
Recycler commissioning

- ANU only provided us with the capability to transform Recycler into a high intensity proton storage ring. Significant work is required to achieve this and integrate Recycler into operations.
  - Establish slip stacking
  - Establish high intensity beam
  - Condition the Recycler beam pipe
  - Open the Recycler Aperture
  - Run Recycler under the MI.
  - Commission the Recycler dampers

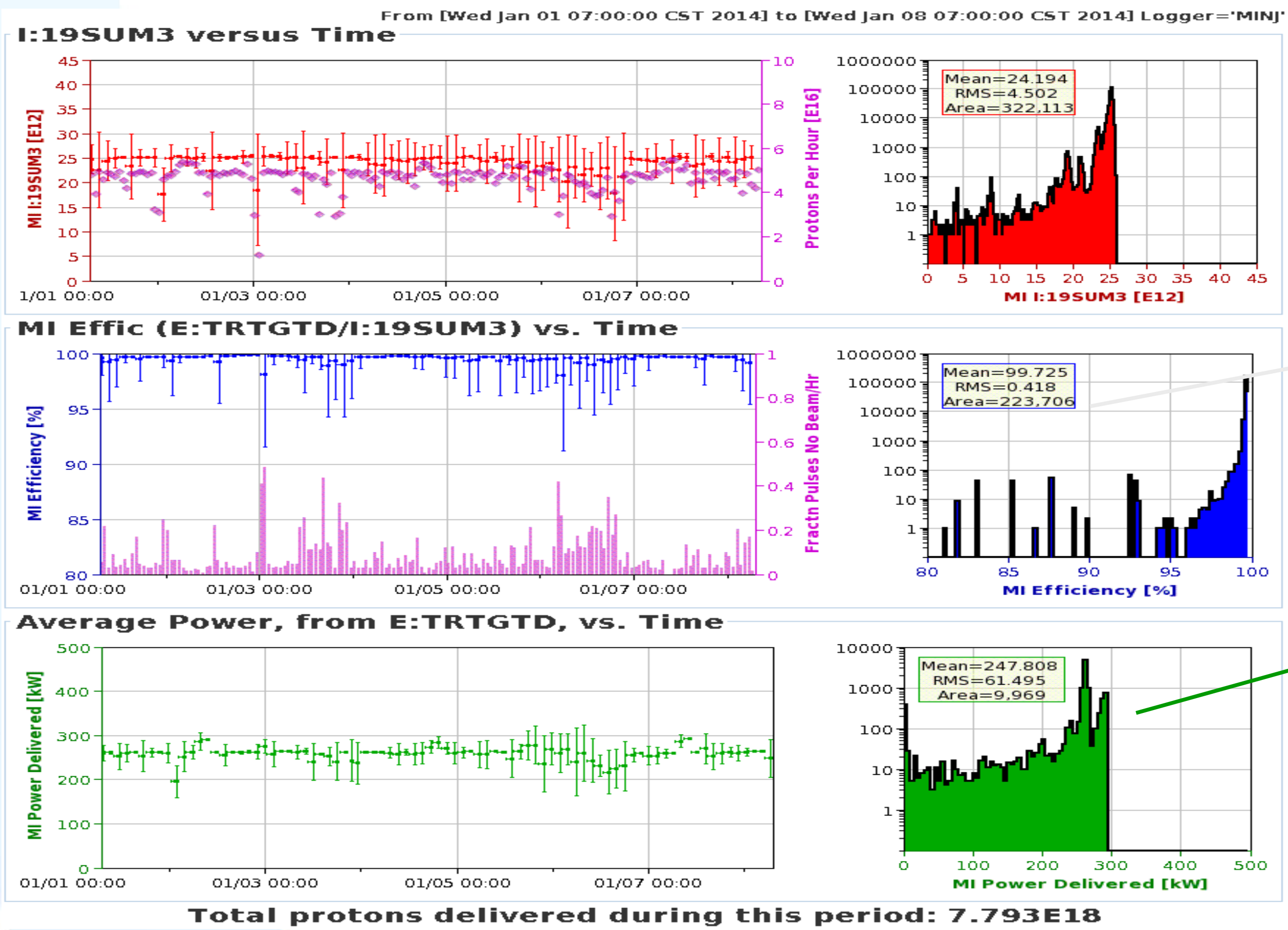
MI High Power Operation during Recycler Commissioning

- Using the existing Booster to MI injection line we are providing high beam power to NuMI without using the Recycler.
- We are able to provide about 280 KW to NuMI (250KW with SY120) with no slip stacking by utilizing a faster ramp (1.67 sec).
  - By not using slip stacking we are able to keep our tunnel loss free during the Recycler commissioning period.
- Since start-up we have provided ~22E19 protons to the NuMI target (20E19 in FY14).

Current MI high power running $23



Typical MI performance during NuMI operations



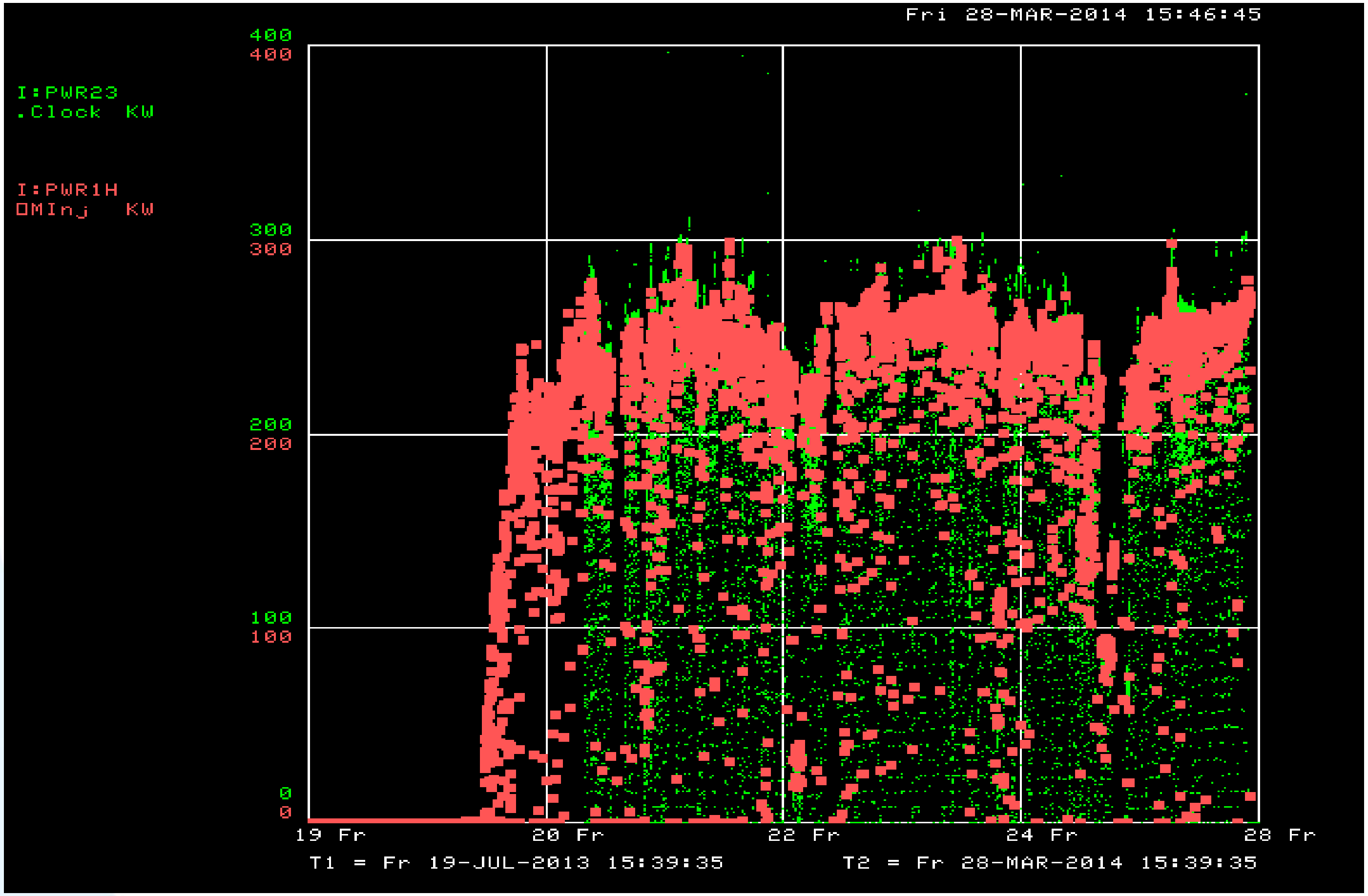
Very High MI Efficiency (99.8%)

248 KW NuMI Beam Power

Recycler Ring

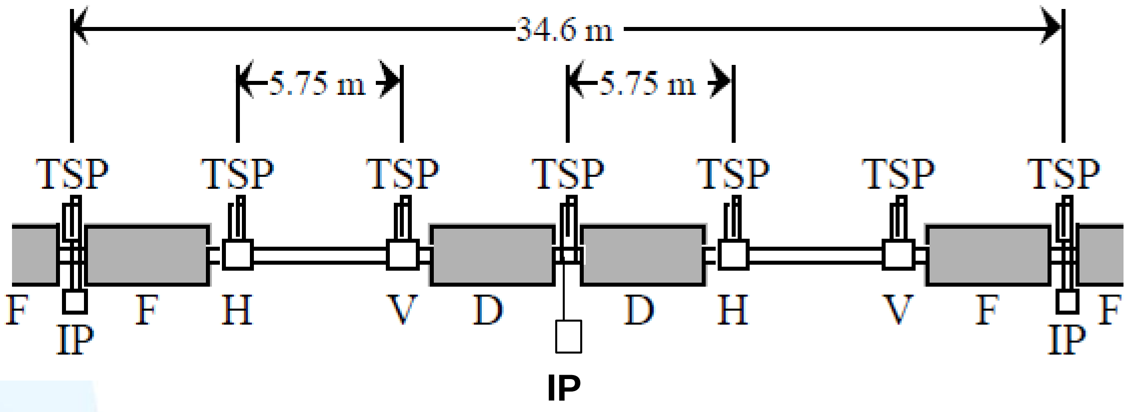
- The Recycler is a permanent magnet fixed energy (8 GeV) storage ring.
- Used magnet end-shims to adjust tunes and chromaticities close to our desired working point.
- Powered dipole correctors are used for orbit control.
- Tunes are adjusted without altering the ring wide lattice using two phase trombones (30,60 sectors).
- Powered sextupoles are used for adjusting the chromaticity.

NuMI Power during RR Commissioning



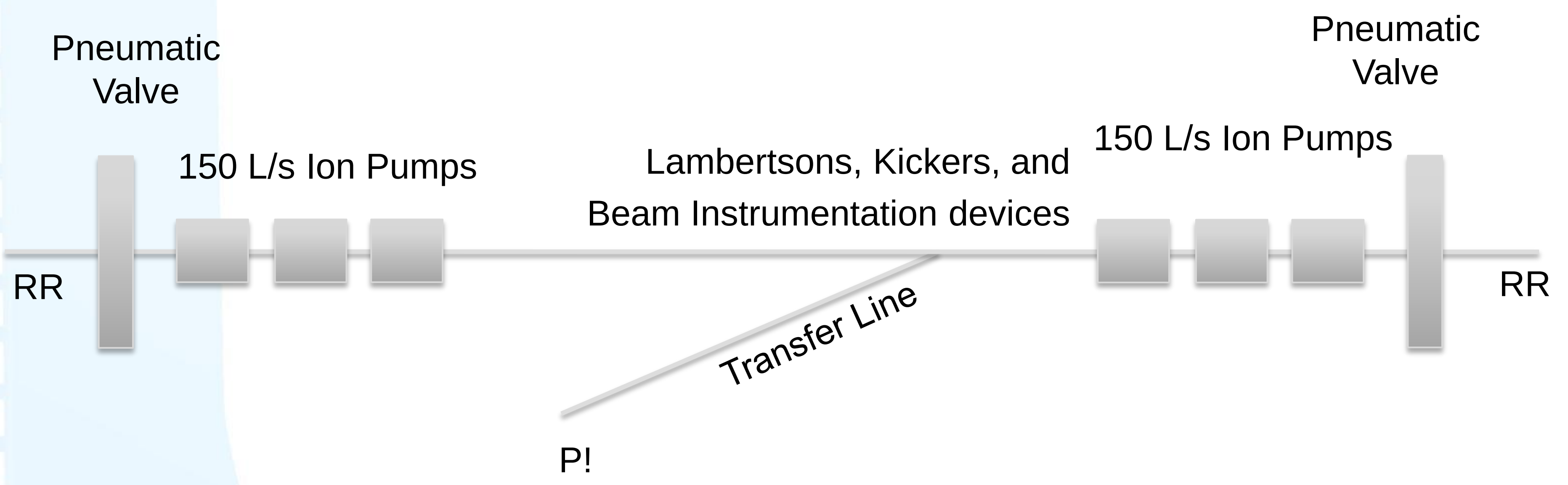
- **In this mode of operation the NuMI power depends on the Booster peak intensity.**

Recycler vacuum system



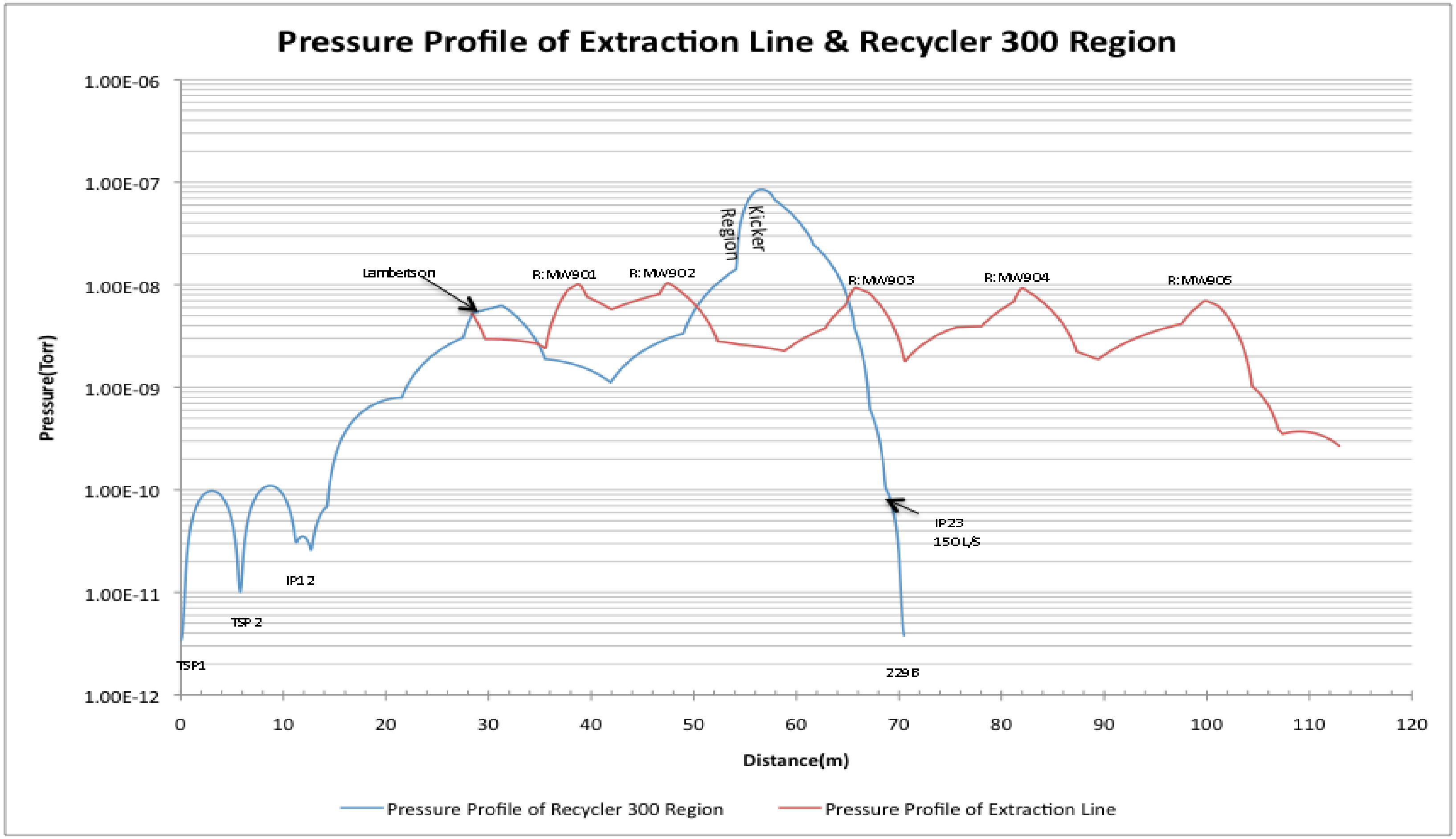
- In Recycler we have 2 ion pumps and 5 Ti sublimation pumps (TSPs) per cell.
- Can achieve very high vacuum E-10, but we need to bake (integrated coax heaters) each time we break vacuum.
- Need a design for the new injection/extraction areas.
- Very little lifetime left in the existing TSPs.

Schematic for Differential Pumping Regions



- RR regions beyond valves are unchanged. These sections will be baked, and normal TSP and ion pump spacing remains.
- Center region uses normal MI ion pump spacing (when possible) and no TSP's. This section will not be baked because kickers would have to be isolated, which is impractical. Dedicated ion pumps matched to each Lambertson and flanking the kickers.

Example of differential pumping pressure profile



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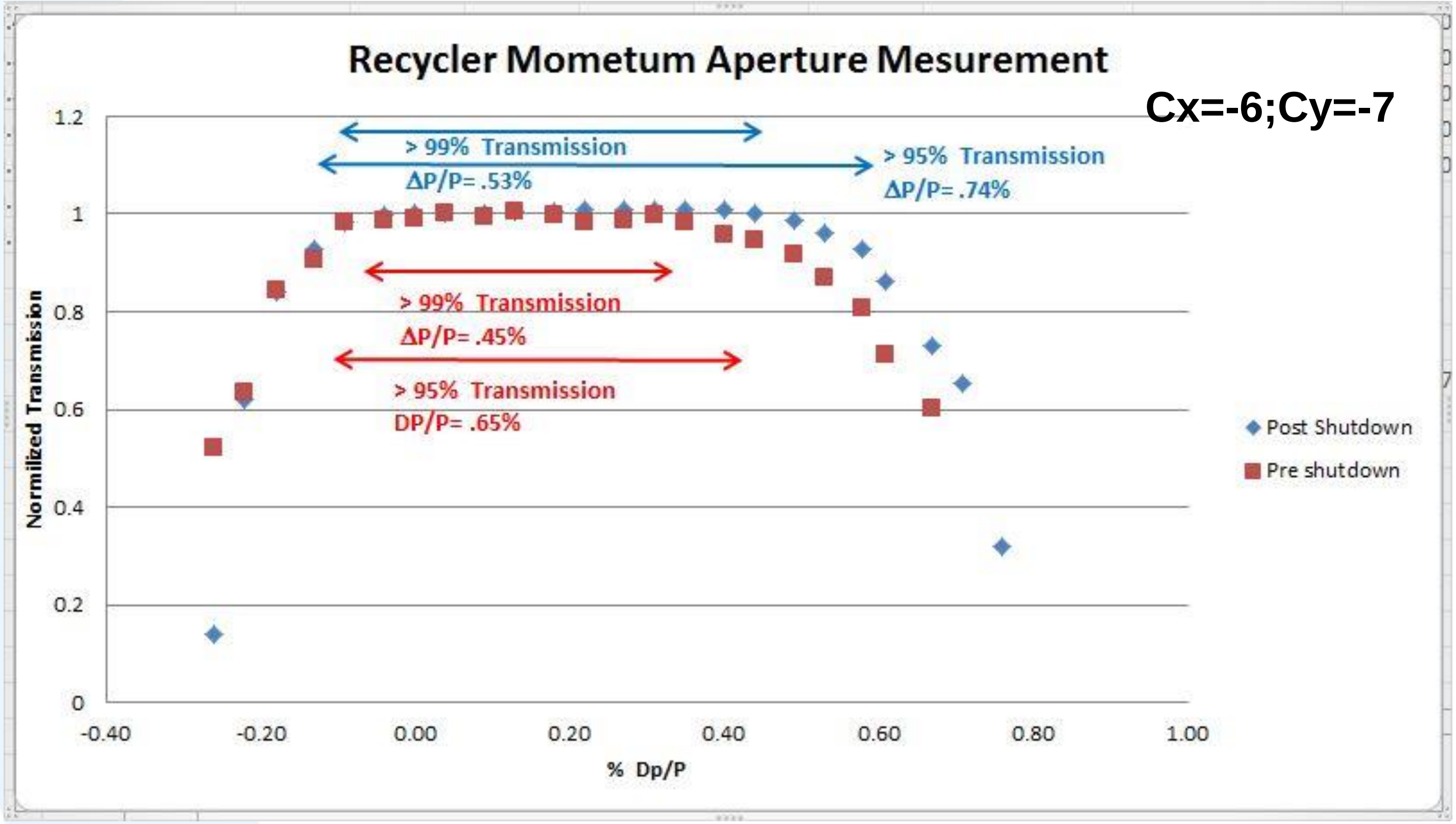
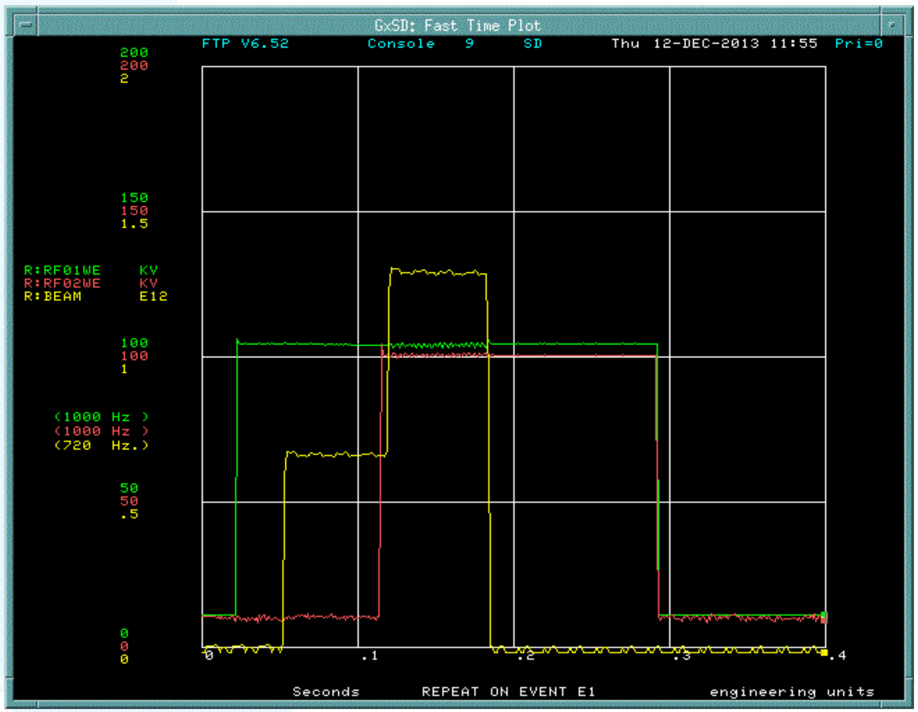
RR Momentum Aperture

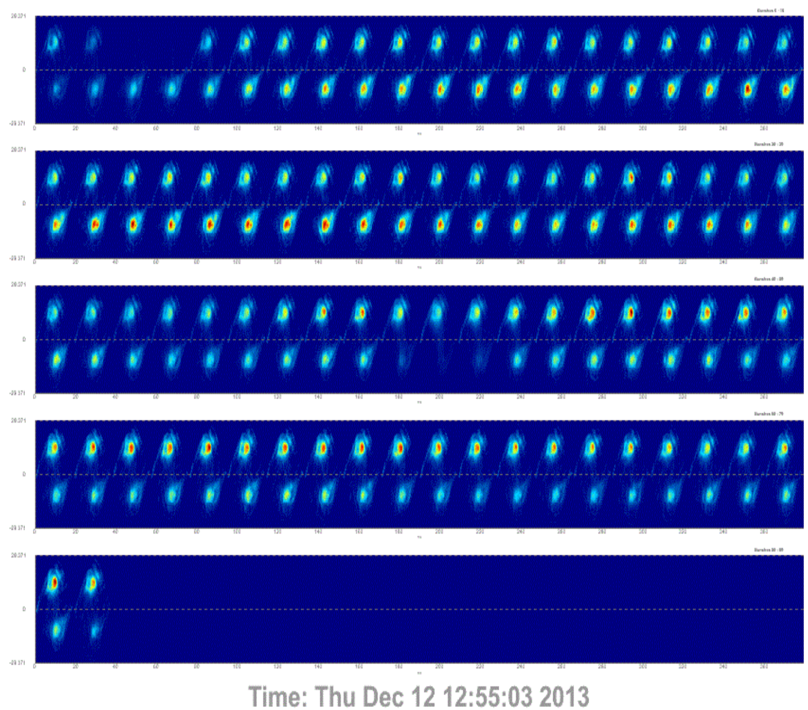


Momentum aperture required for SS 0.59% (min. 0.45%)

First slip stacking in Recycler

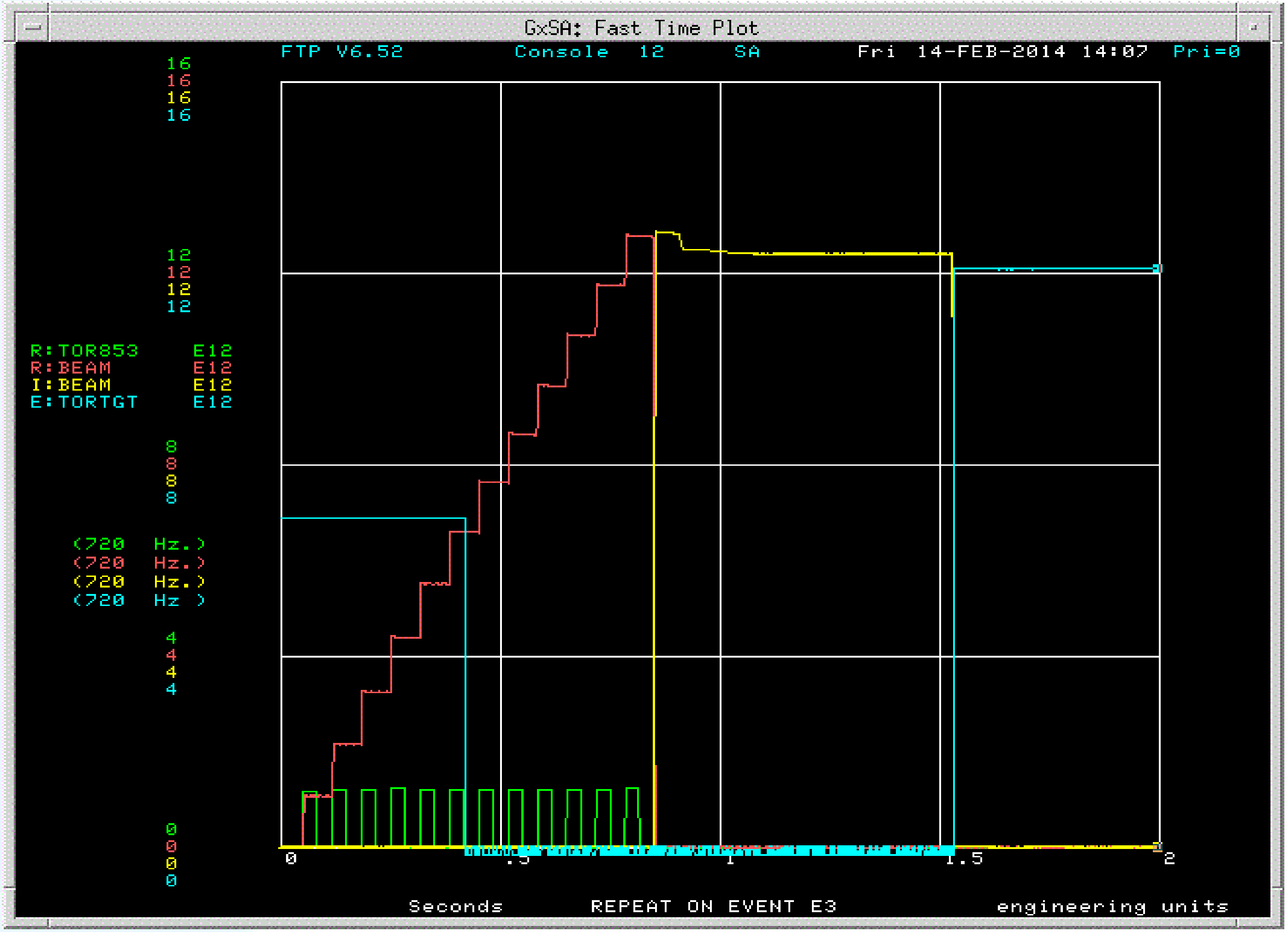


Beam intensity and RF voltage



2-D longitudinal picture of all 82 bunches

12-Batch Slip stacking to NuMI Target



Highest slipped stacked intensity in RR 24E12

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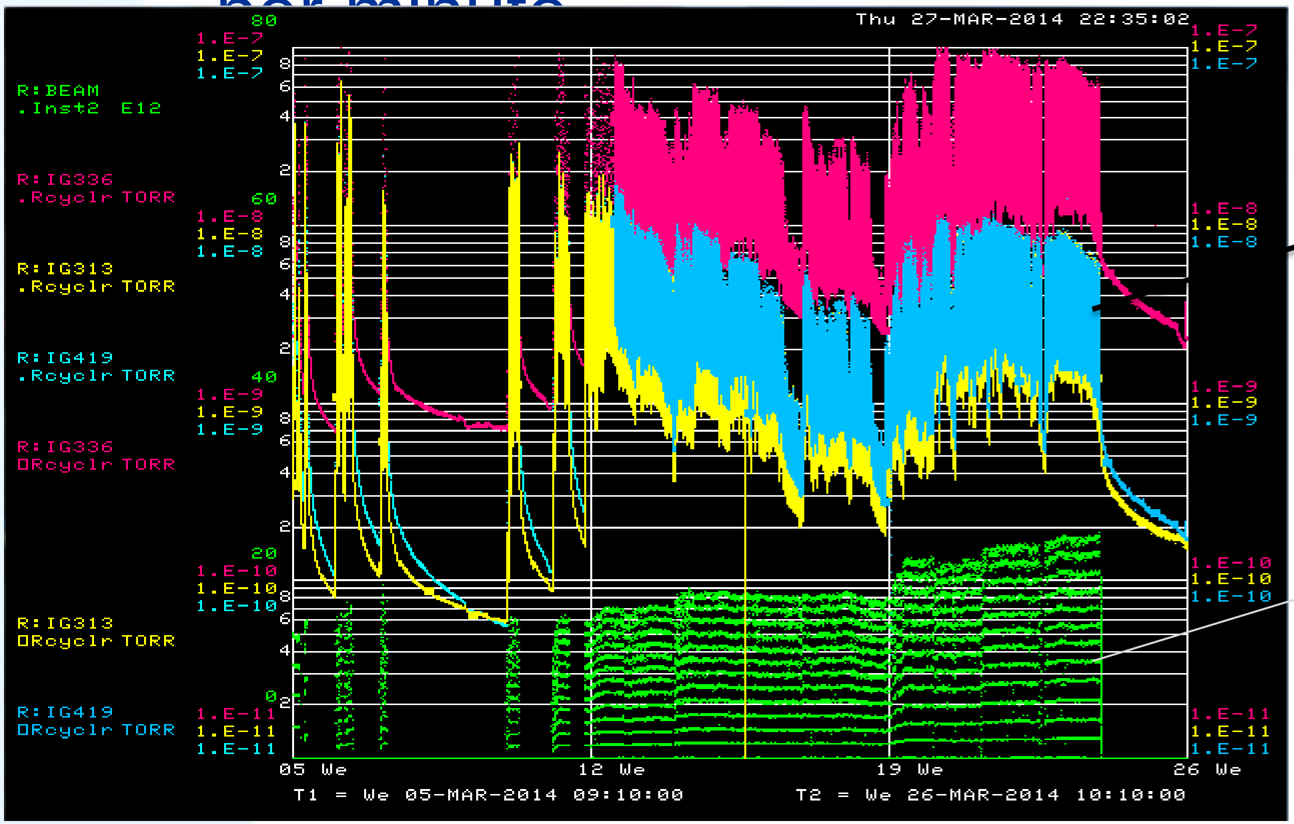
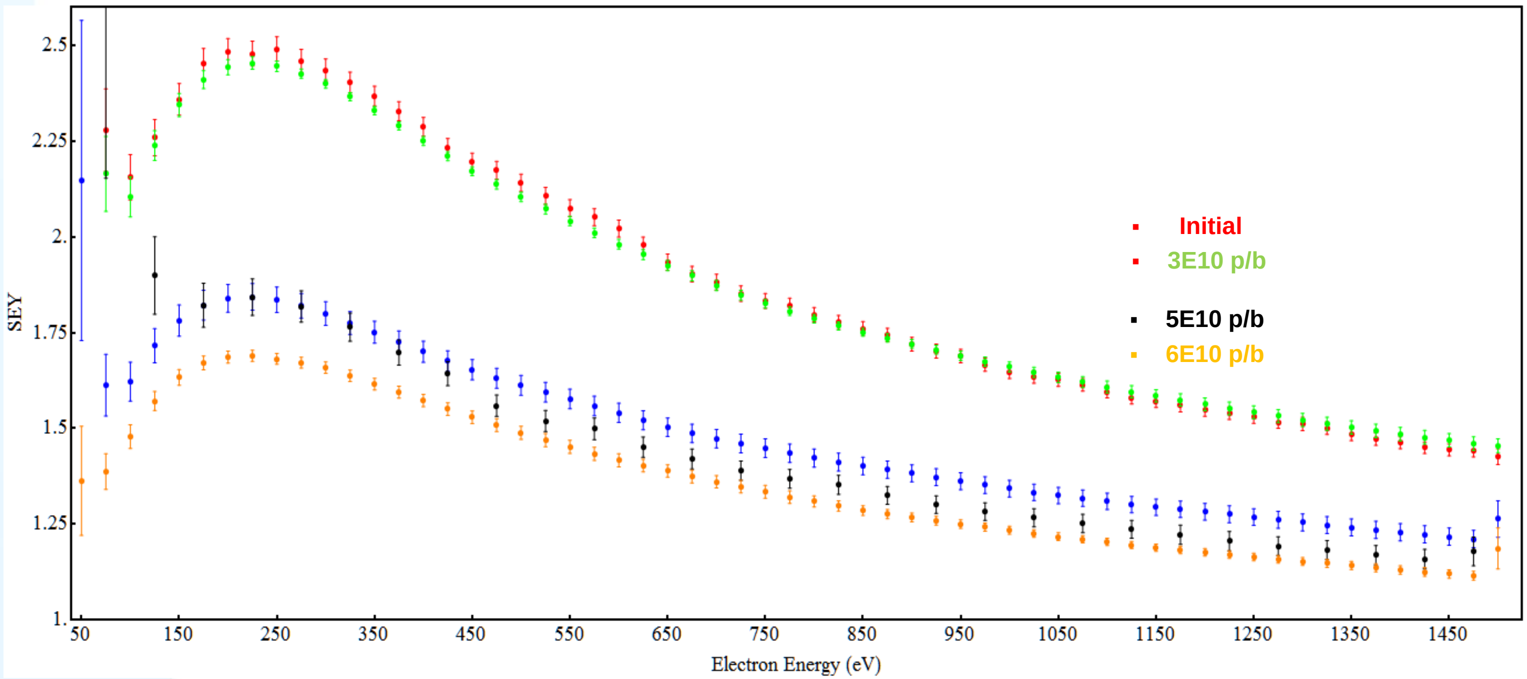
Beam Scrubbing with 1 and 2 $2A Cycles per minute



Pressure rises due to electron bombardment. The beam scrubbing effect characterizes a decrease of these pressure rises. This decrease results from both a cleaning of the surface (gas desorbsion and pumping) and a reduction of the electron cloud activity as a result of the decrease of the secondary electron yield of the inner chamber wall surfaces.

MI SEY Measurements

Effect of beam scrubbing on secondary emission yield (SEY)



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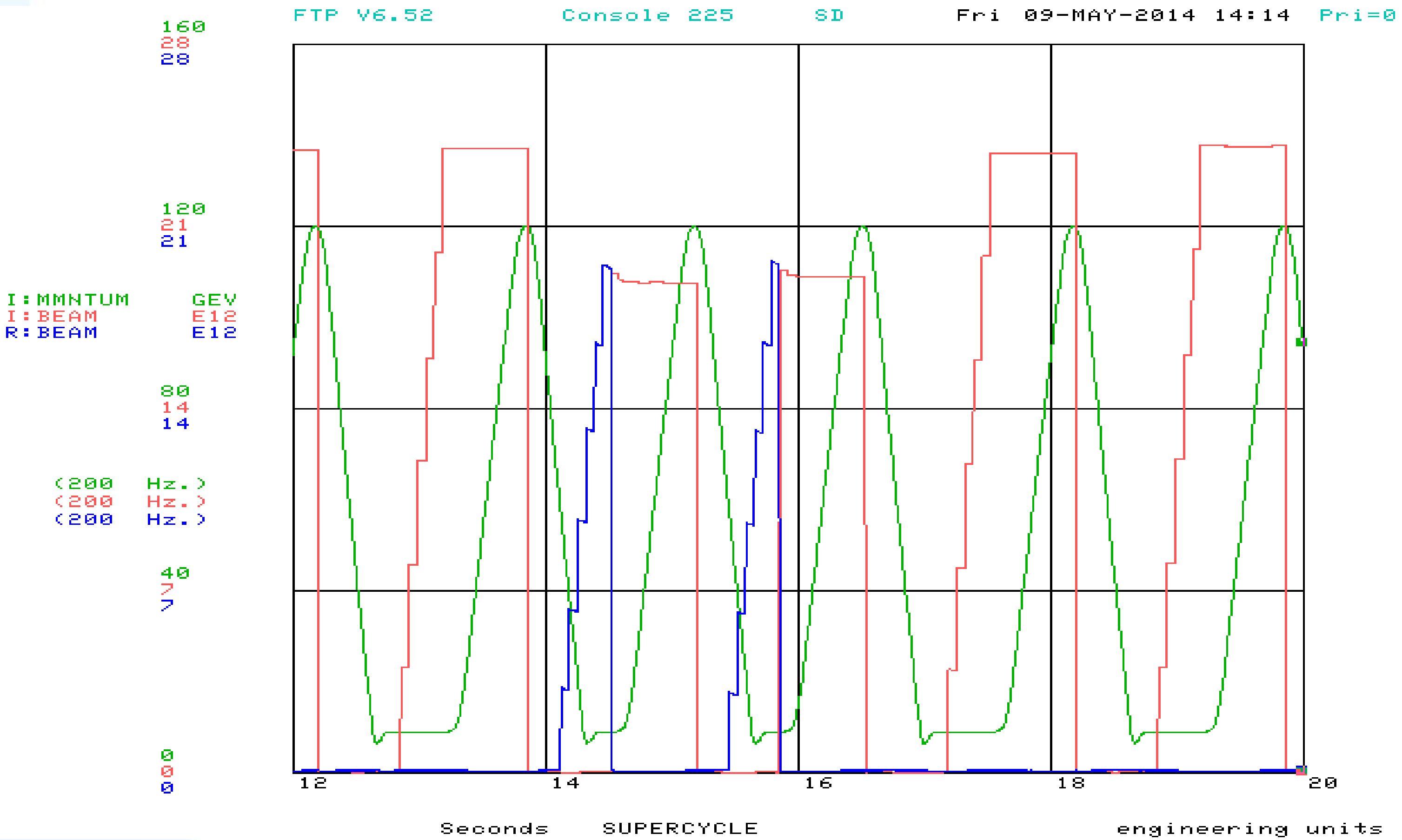
Running $23 (MI only) and $2A (MI+RR) cycles



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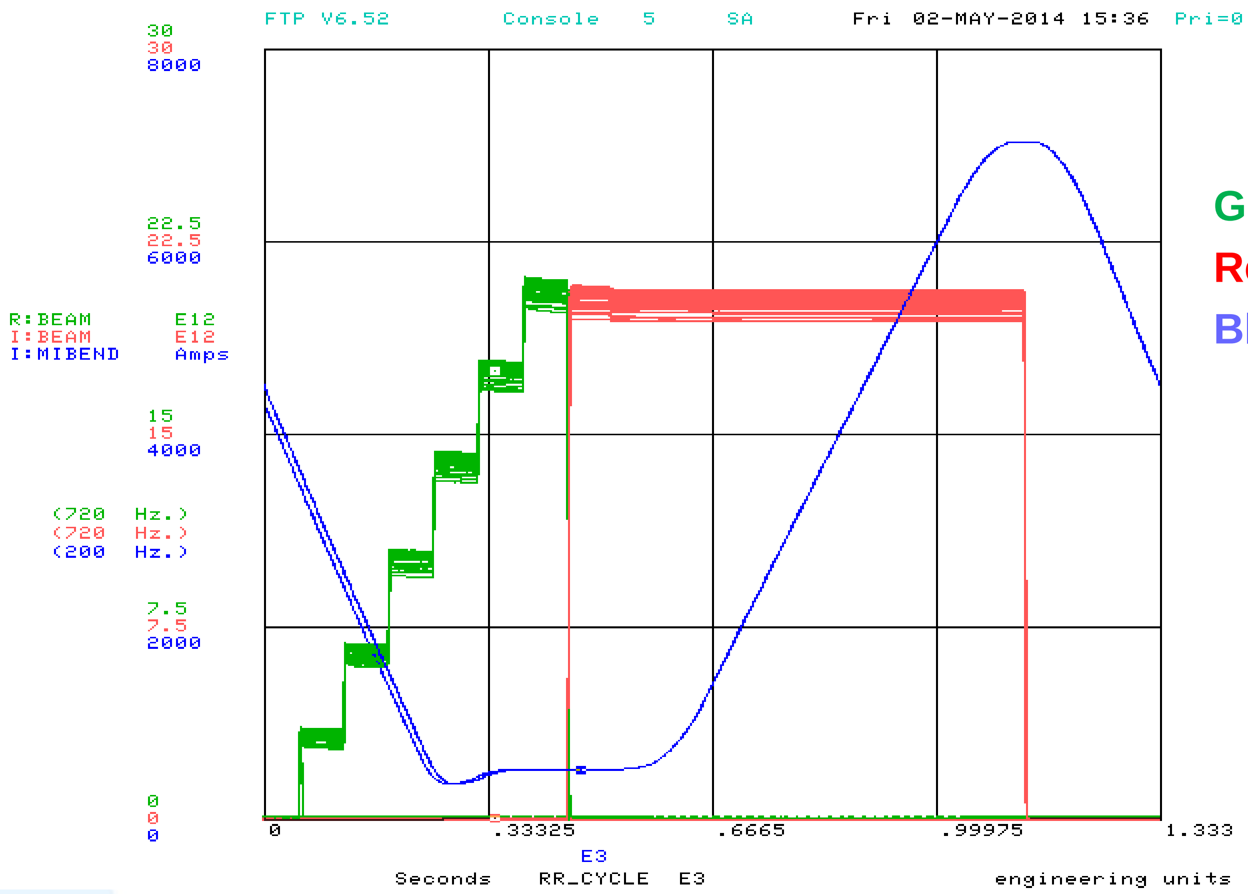
Running 2E13 with a 1.33sec MI Ramp



Green:RR Beam
Red: MI Beam
Blue:MI Ramp

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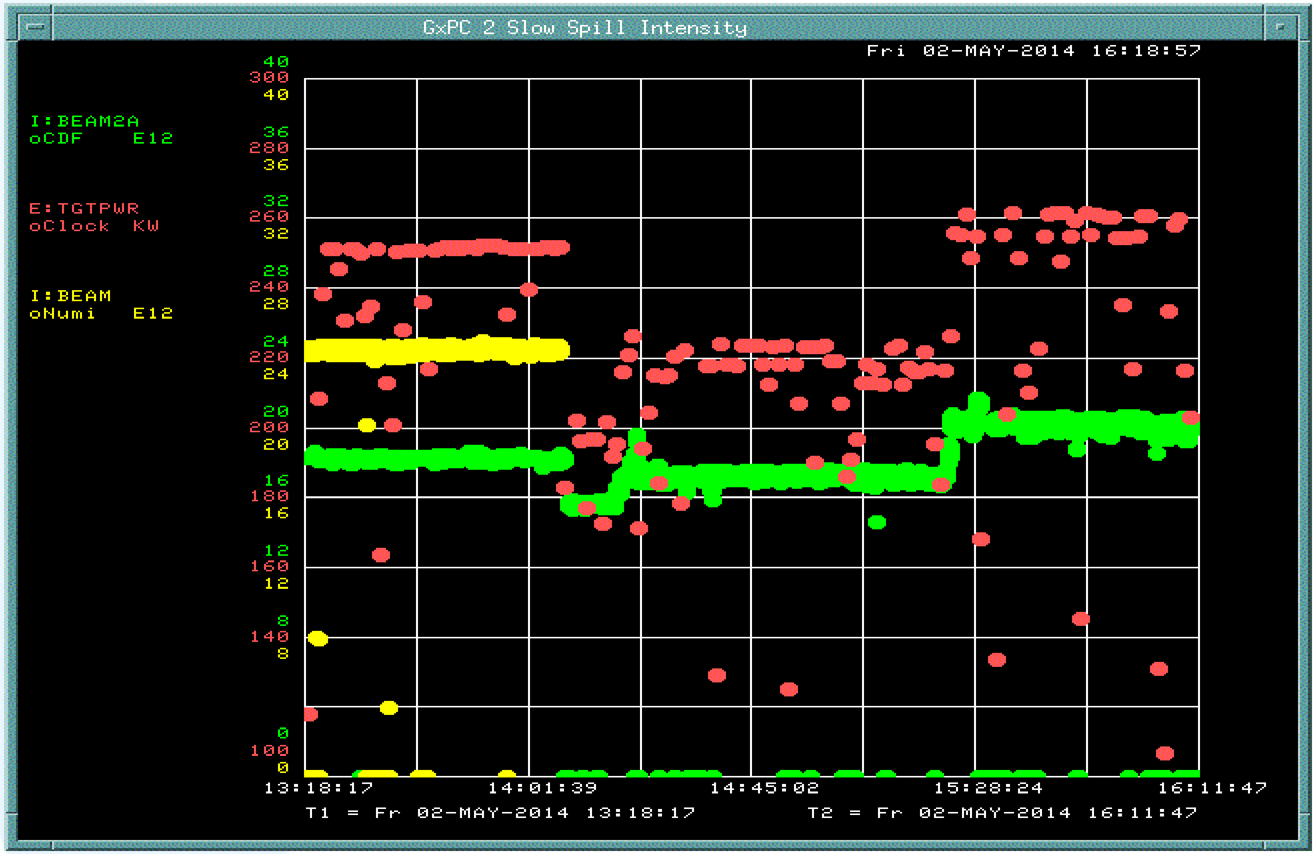
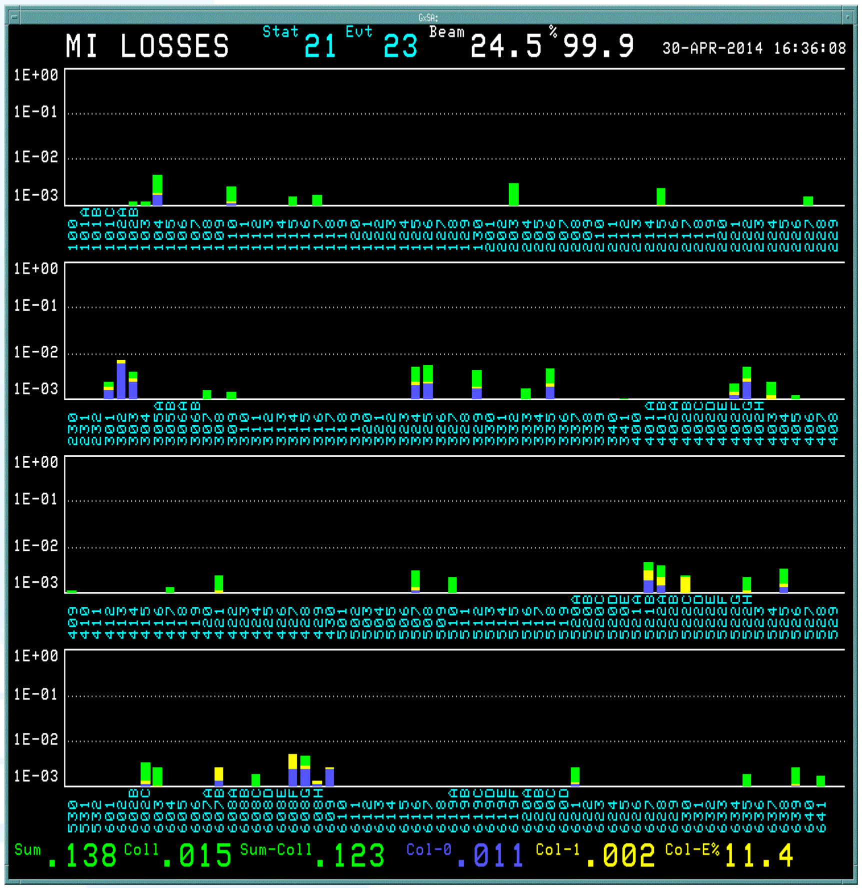
MI Beam power all $2As compared with $23s



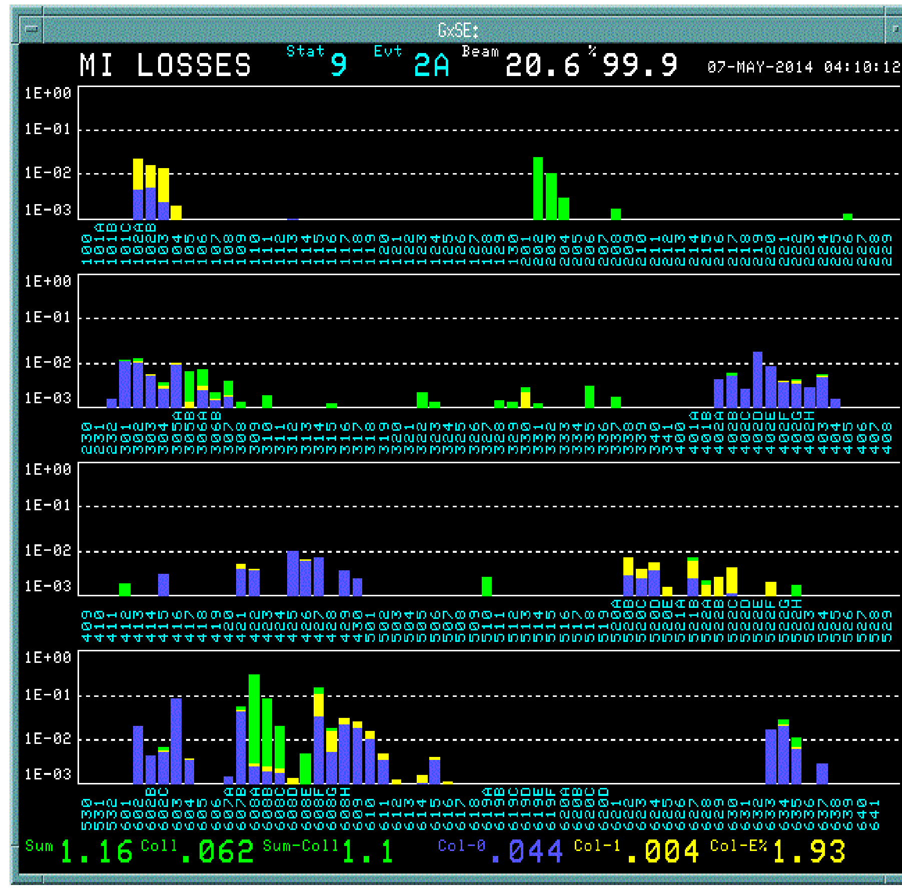
- $23 Beam intensity(E12)
- $2A Beam Intensity(E12)
- Beam Power (KW)

We can achieve the same beam power running with 20E12 in $2As or 25E12 in $23s!

$23 vs $2A Losses

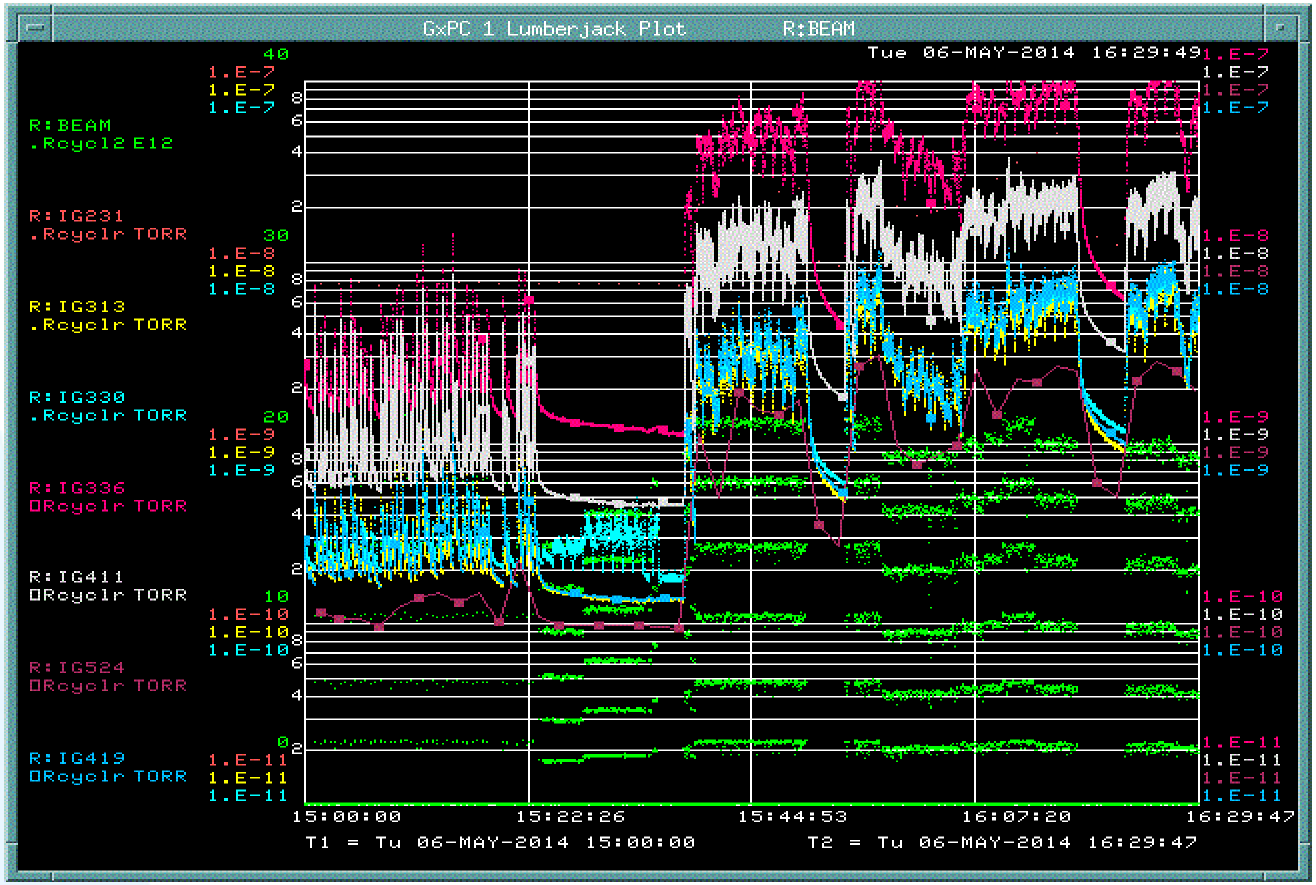


MI only losses with 25E13 ($23 cycles)



MI + RR losses with 20E13 ($2A cycles)

Recycler vacuum with 1.33 sec rep rate.



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Current status

- We are close to having Recycler operational.
  - Running all $2A cycles with 20E12p and 1.33 rep rate.
- We need to reduce the beam losses and improve the vacuum before this happens.
  - We will need to commission the bunch by bunch dampers.

Plan for the rest of the year

- Run all $2As with 20E12 and 1.33sec rep rate (280KW beam power)
- Increase the RR and MI intensity to 25E12 (350KW beam power).
- Start slip stacking in Recycler with 8 Booster batches (2+6). Total beam intensity 32E12 every 1.33sec (447 KW beam power). This requires 6 Hz Booster operation.
- Slip stack more batches as they become available.

PIP II MI/RR Requirements

Performance Parameter	Requirement	
Particle Species	Protons	
Injection Beam Energy (kinetic)	8.0	GeV
Extracted Beam Energy (kinetic)	60-120	GeV
Protons per Pulse (injected)	7.7×10^{13}	
Protons per Pulse (extracted)	7.5×10^{13}	
Slip-stacking Efficiency	97	%
Controlled 8 GeV losses to Abort	0.8	%
Controlled 8 GeV losses to Collimators	1.7	%
Uncontrolled 8 GeV losses	0.5	%
Transition Losses	0.2	%
Cycle Time	0.8-1.2	sec
Beam Power	0.9-1.2	MW
Beam Emittance (6σ, normalized)	20	π mm-mrad
Bunching Factor	0.5	
Laslett Tune Shift (Injection)	-0.06	

50% more beam intensity!

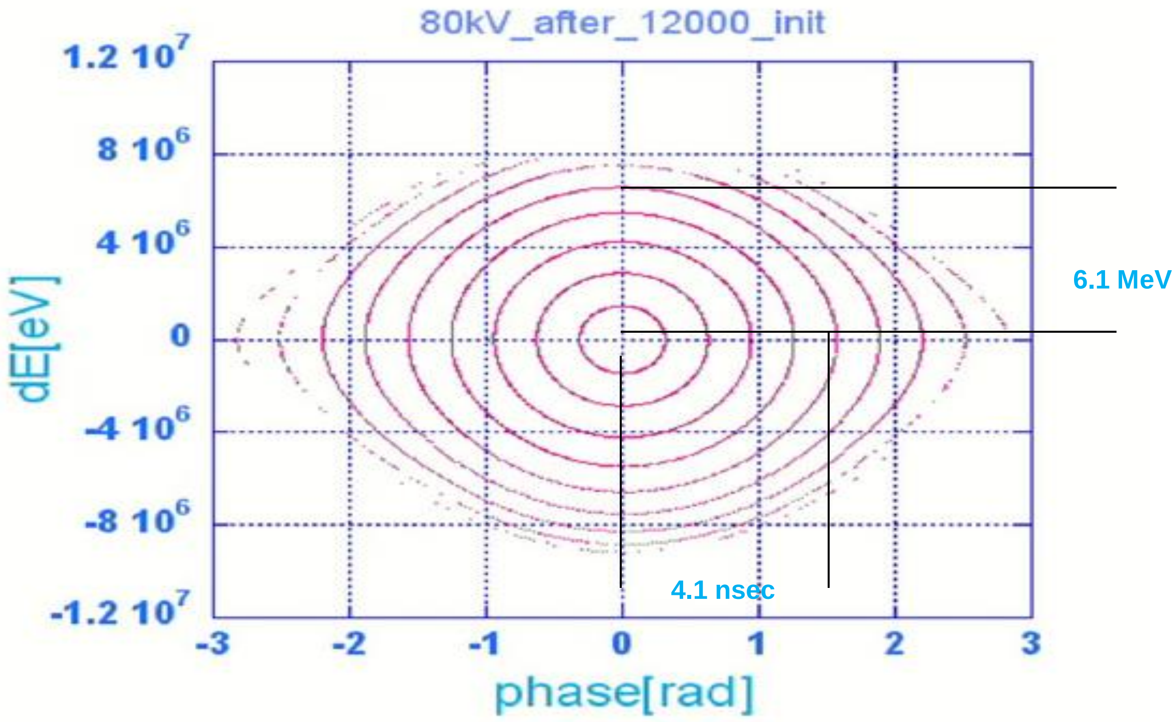
MI/RR Accelerator Issues

- Can we slip stack and accelerate 50% more intensity.
  - Power loss from slip stacking
  - RF Power
- Transition crossing
- Electron cloud
- Beam loss control/mitigation
- Running Recycler 53 MHz Cavities CW

Slip Stacking in the Recycler

- We need to maintain the same power loss from slip stacking with 50% more intensity per bunch.
- Increase the slip stacking efficiency from 95% to 97%.
  - Tighter beam specifications out of Booster.

Injected beam requirements for 97% efficiency.



Particles on initial matching contours in an 80 KV bucket after 120 msec of slip stacking with 1,200 Hz separation.

MI RF Capability/Requirements

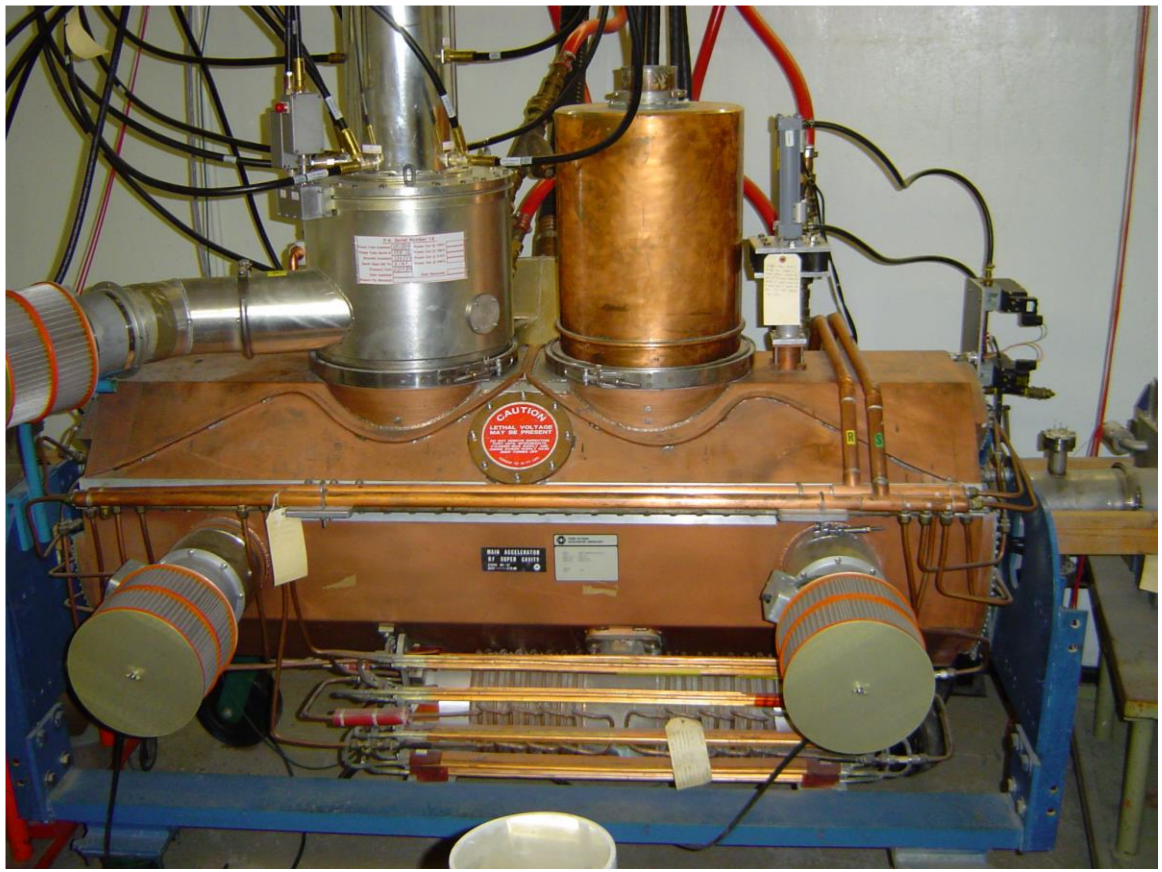
Performance Parameter	Present Capability	PIP-II Requirement	
Beam Intensity	6.2×10^{13}	7.5×10^{13}	
Harmonic Number	588	588	
Number of Filled Buckets	504	504	
RF Frequency Range	52.811-53.104	52.811-53.104	MHz
Acceleration Rate	240	240	GeV/s
Main Injector Ramp Rate:	1.2 s	1.2 s	
Accelerating Cavities	20	20	
Maximum Accelerating Voltage	235	235	kV/cavity
Total Available Accelerating Voltage	4.7	4.7	MV
Total Required Accelerating Voltage ($V\sin\phi_s$)	2.7	2.7	MV
Total Required Cavity Power	204	240	kVA/cavity
Robinson Stability Factor	4	4	

Current RF system does not have the power for 7.5E13

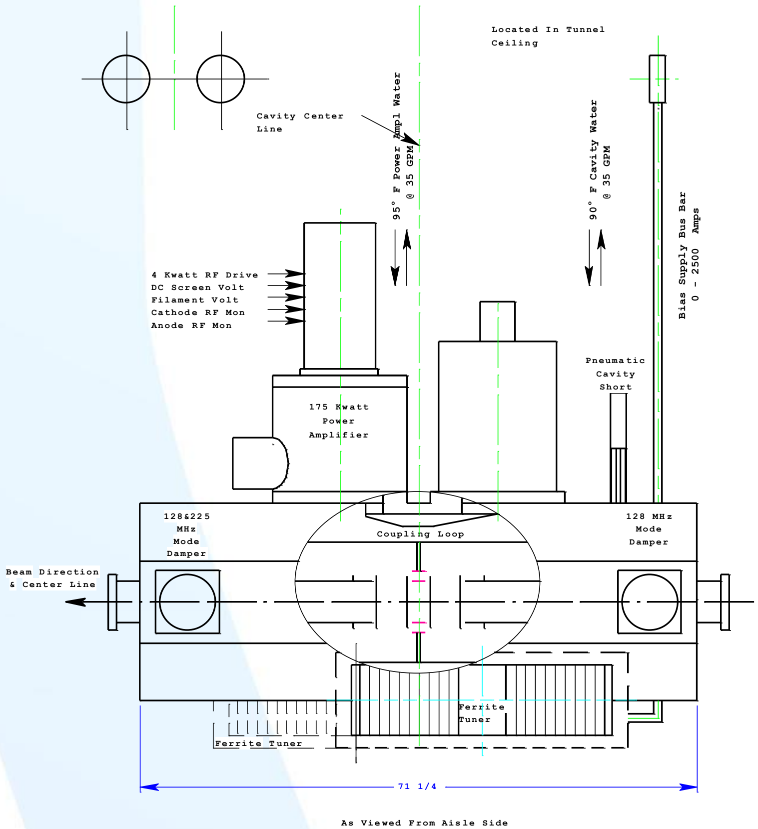
MI RF Options for higher power

- Operate the current rf cavities with two power tubes instead of one in a push-pull configurations.
  - Need to double the number of modulators and solid state drivers.
- Use a new more powerful power tube (EIMAC 4CW250,000B).
  - New mounting configuration (much longer tube).
  - New modulators and upgraded PA cooling.

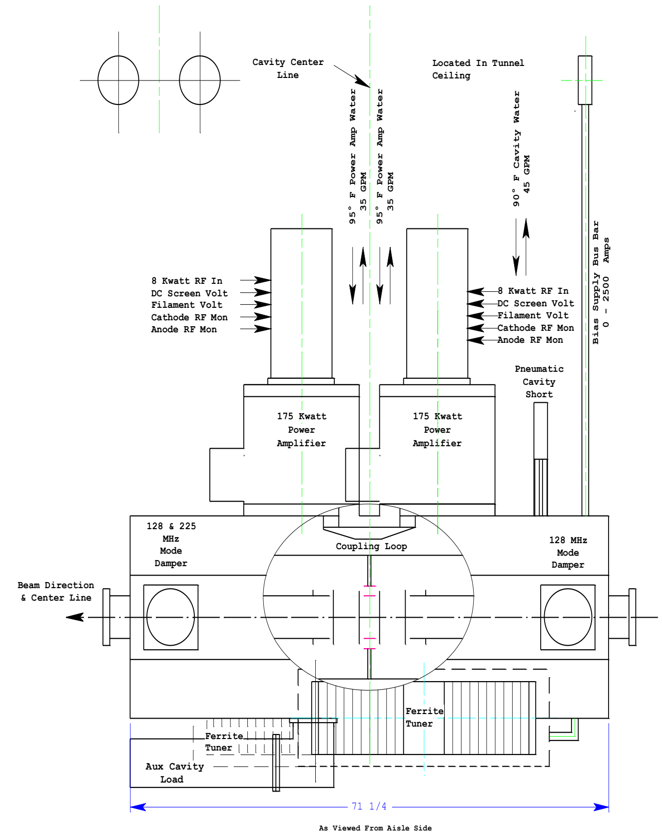
MI RF Cavity


CAUTION
LETHAL VOLTAGE MAY BE PRESENT
MAIN ACCELERATOR
RF SUPER CAVITY

Present and modified MI RF Cavity



Present Main Injector Cavity



Modified Main Injector Cavity for Two Power Amplifiers

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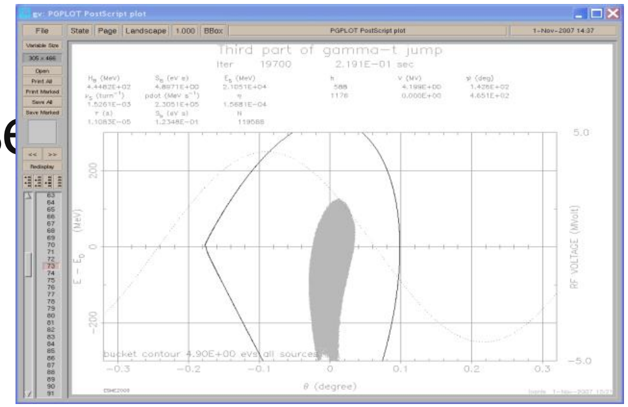
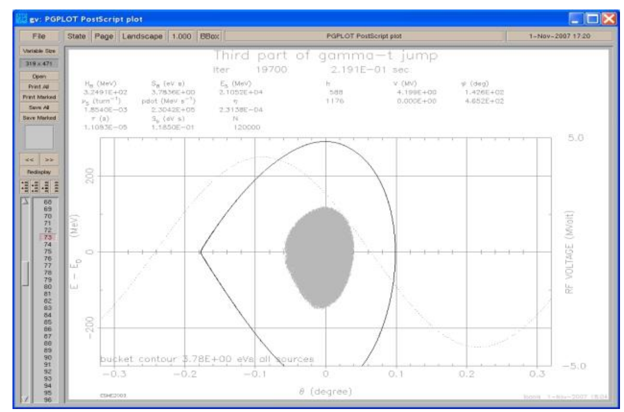
Transition crossing

- A design of a first order gamma-t jump system for the Main Injector was completed as part of the Project X Reference design. This system is required for 2.3 MW operation.
- Further simulations are needed to verify if this system is required for 1.2 MW operation.

MI transition jump

- A first order jump system with small dispersion increase (taking advantage of the dispersion free region)
- Design goal:
  - $\Delta\gamma_T = \pm 1$ within 0.5 ms
  - $d\gamma /dt = 4000$ 1/s
  - 16 times faster than the normal ramp (240 GeV/s)
- Components:
  - 8 sets of quad triplets
  - 8 sets of power supplies
  - Inconel beam pipe





Required R&D for RR RF Cavities

- The Recycler 53 MHz cavities used for slip stacking have a high power dissipation (90 KW, 60% DF) because of the low R/Q (13 Omhs).
- Running MI at energies as low as 60 GeV will require the slip stacking cavities to run CW.
- We will need a different cavity design with higher R/Q and active beam loading compensation.

Loss control

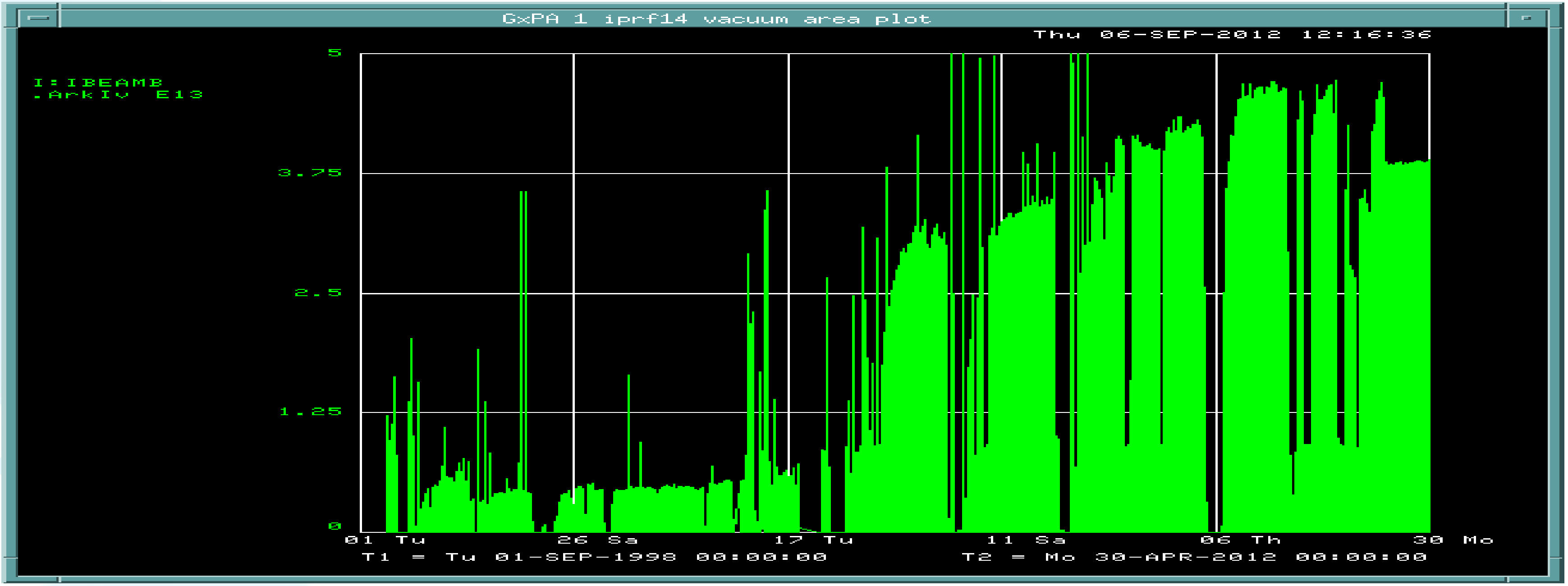
- Need to understand and control the space charge losses with the higher intensity beam in MI and Recycler.
  - In MI the collimators intercept most of these losses.
  - Do we need collimators in Recycler?
- Realistic space charge simulations using SYNERGIA are under way.

Conlusions

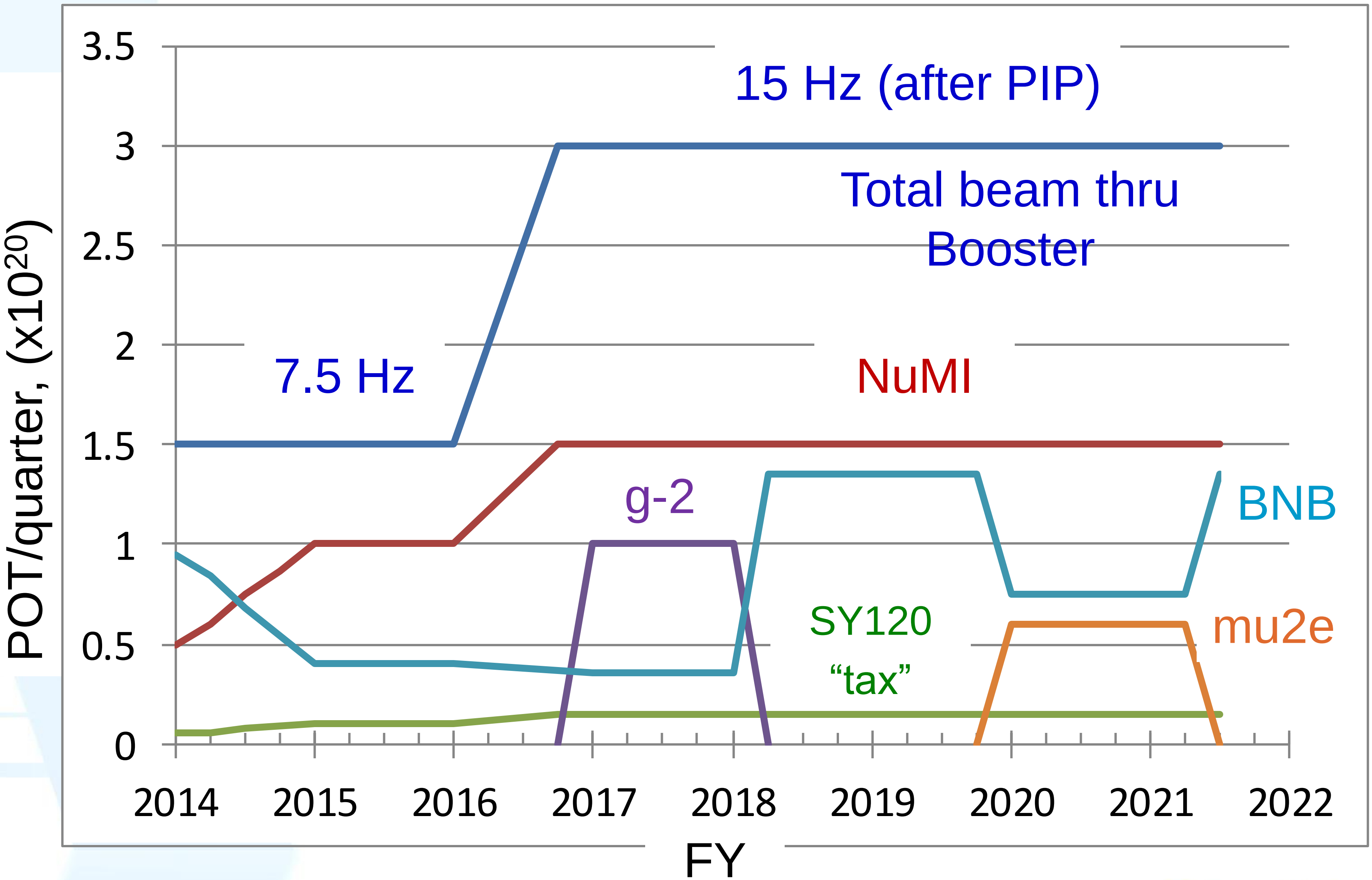
- With the ANU shutdown now complete we are getting ready to integrate Recycler in operations for delivering high beam power to NuMI target.
- We are expecting to be delivering 450KW of beam power before the end of the summer.
  - We will be increasing the beam intensity and power as more Booster pulses become available.
- PIP II requires slip stacking and accelerating 50% more beam.

EXTRA SLIDES

Main Injector Beam Intensity



Booster Proton delivery scenario



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Recycler Ring Modifications

- New Injection Line
  - Direct injection into the Recycler
    - Preserve 8 GeV injection into MI
    - Preserve 8 GeV Booster Neutrino Beam
  - Follow existing MI-8 Line
  - Vertical switcher magnet (at 848) inject at RR104

Apertures: $\pm 5\sigma$ for 20π

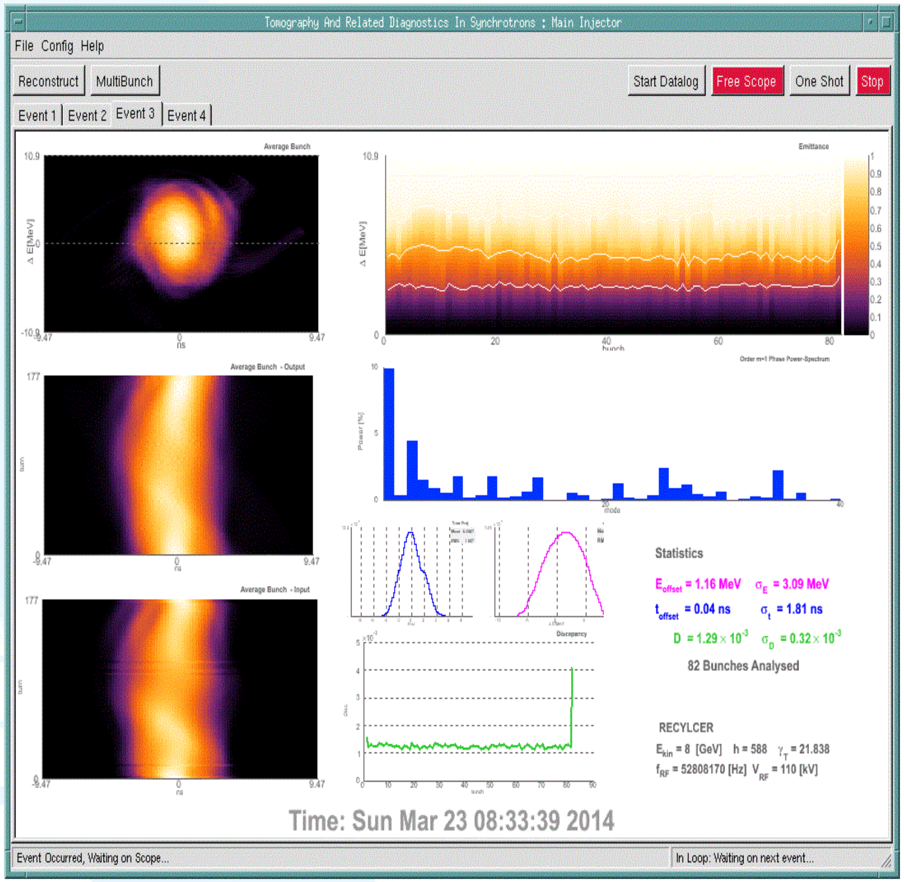
- New Extraction Line
  - Single turn extraction into MI
  - Kicker at RR230, extraction Lambertson at RR232
  - Injection Lambertson at MI306, Kicker at MI308
- Rework RR30 Straight Section
  - Removal of electron cooling
  - Rebuild as RR FODO

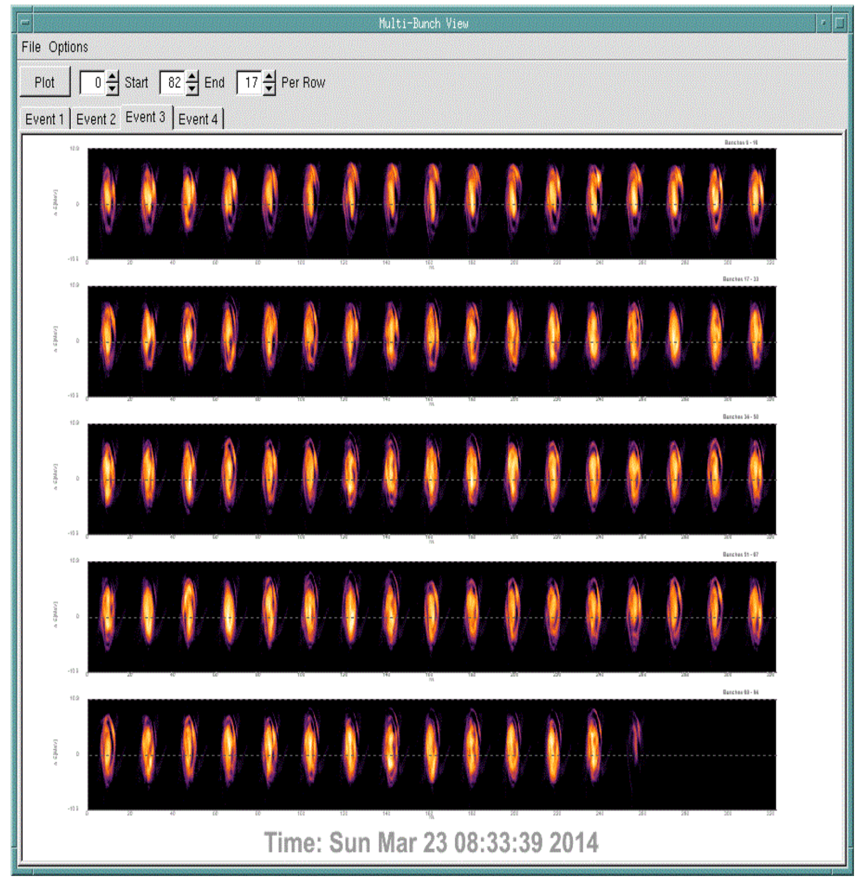
- RR Injection & Gap Clearing:
  - 57 nsec rise/fall time, 81 bucket flat top
- RR Abort
  - 1 μsec rise, 10.5 μsec flattop
- RR Extraction / MI Injection
  - 1 μsec rise, 10.5 μsec flattop, 1 μsec fall

Recycler Ring modifications (2)

- Recycler had no 53 MHz RF capabilities
  - fo = 52.809 MHz +/- 1.3 kHz necessary
  - Tunable over +/- 5 kHz range using fast (4 turns) garnet phase shifters developed for the Proton Driver
  - Vrf = 2 X 150 kVpeak for slip-stacking
  - Fast cavity tuning for Beam Loading Compensation
  - HOM dampers for 3rd & 5th harmonics on Cavities
- Built new cavities with new design
- New BPM system (53 MHz)
  - New cables to every Recycler BPM (~100km heliax)
  - New electronics : Modeled on existing MI system
- New DCCT
- New Multiwires in transfer lines

Longitudinal tomography





Integrated beam to NuMI