Progress Towards Doubling the Beam Power at Fermilab's Accelerator Complex

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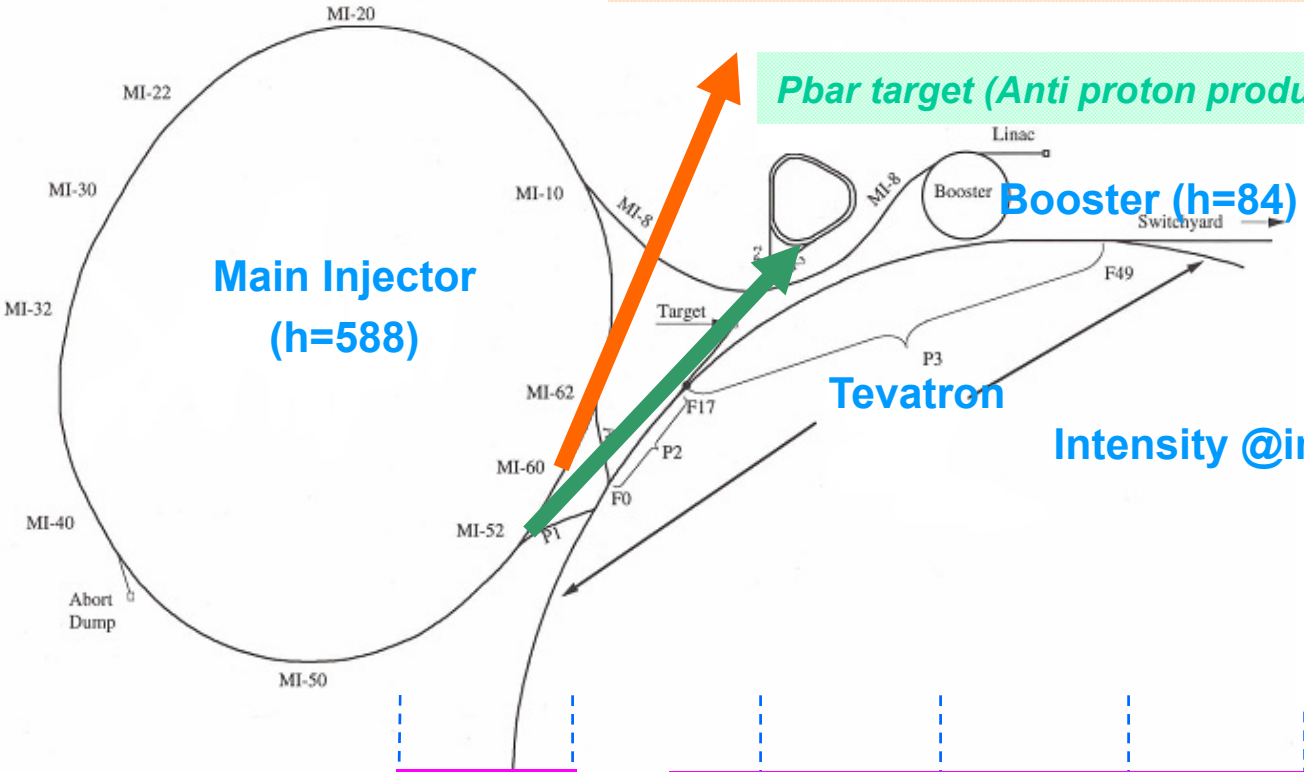
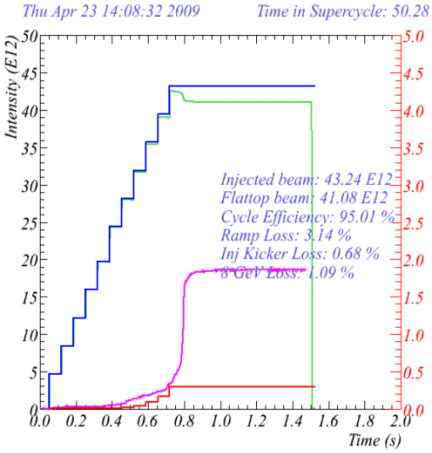
Outline

- Introduction.
- Review of past MI high power operations.
- Plan of doubling the MI Power.
- Progress on increasing the MI power.
- Conclusions

MI 120GeV cycle operations in the Tev Era





Intensity @injection: 4.3E12 ppp x 11

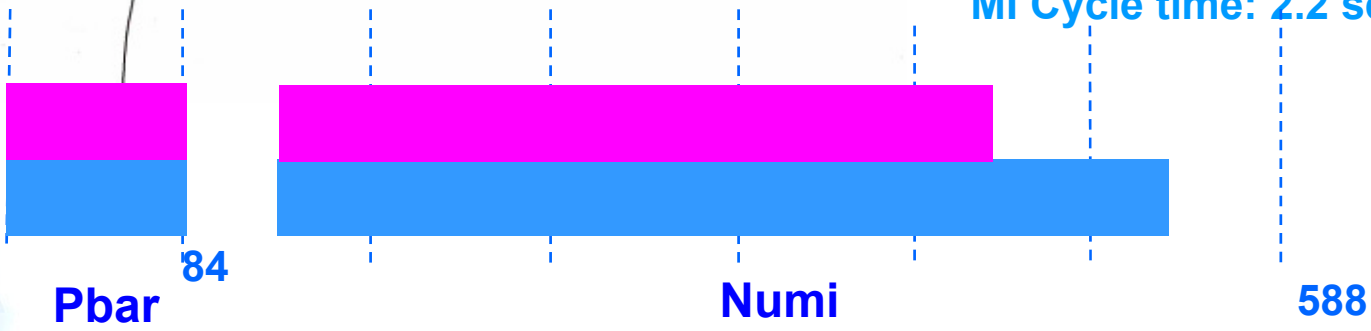
@extraction: 45E12 ppp

8.5E12(Pbar)

24.0E12(Numi)

MI Cycle time: 2.2 sec

Multi-batch operation



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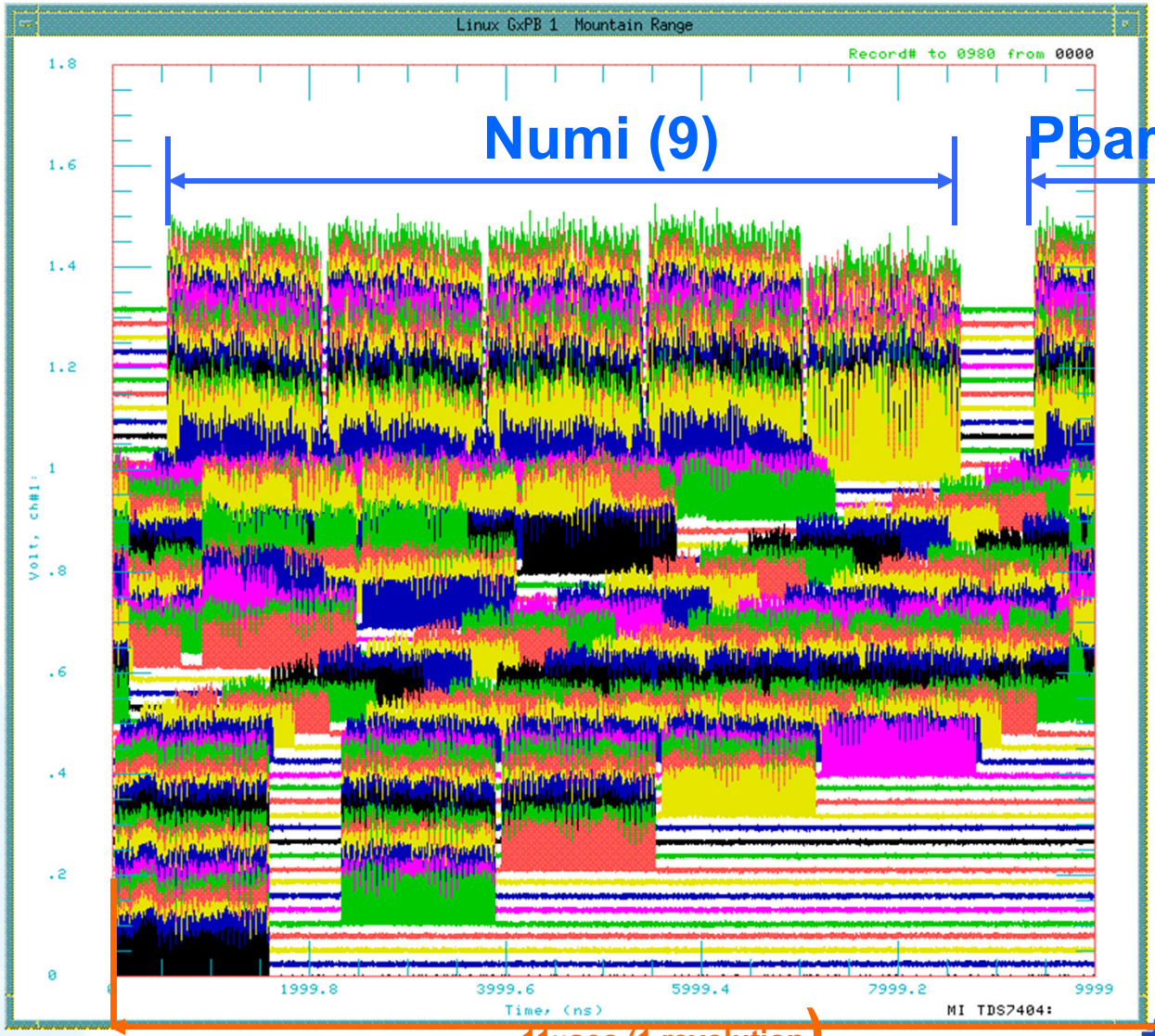
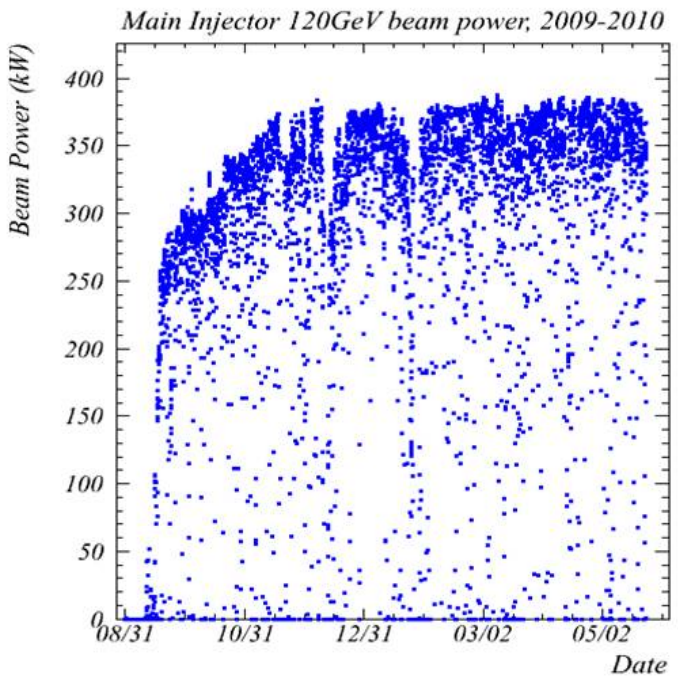
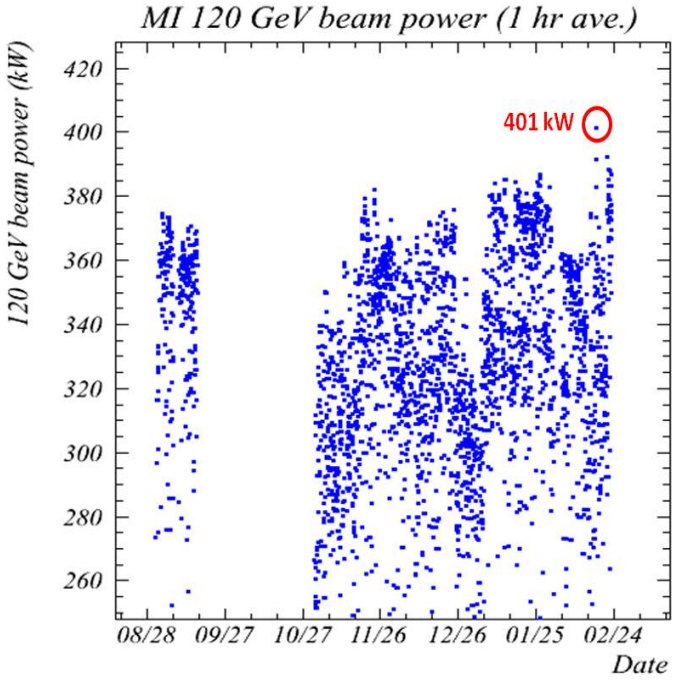
11 batch slip stacking on mixed mode cycle



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



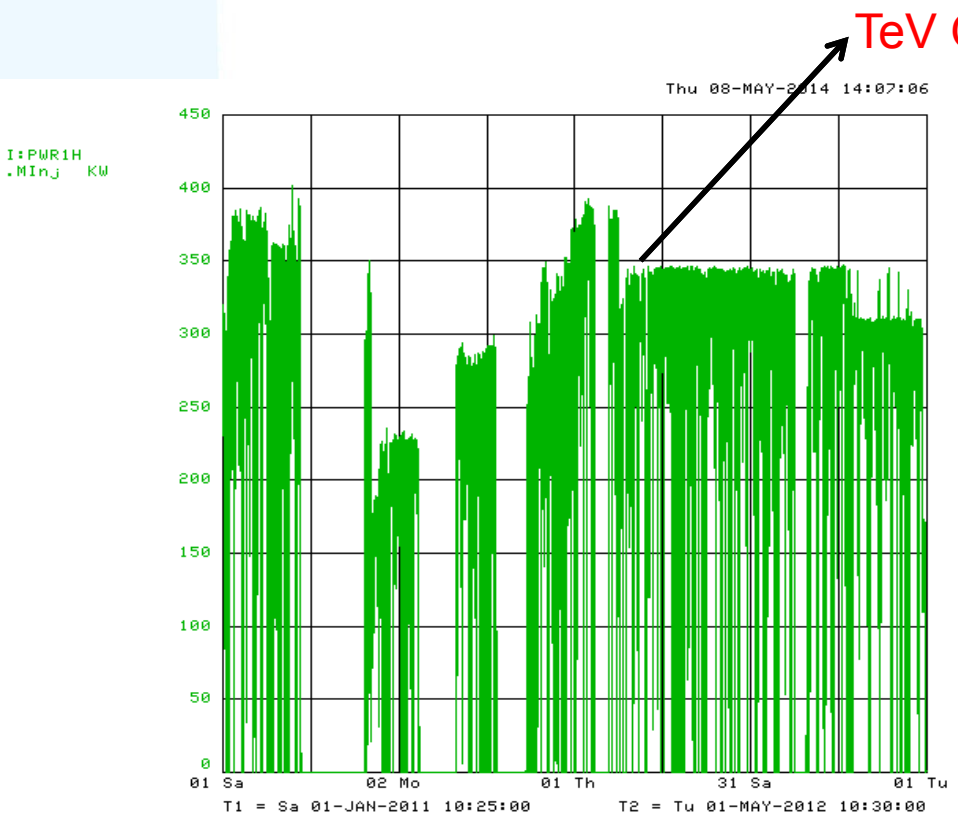
MI 120 GeV Beam Power 2009-2010 (MI Collimators operational)



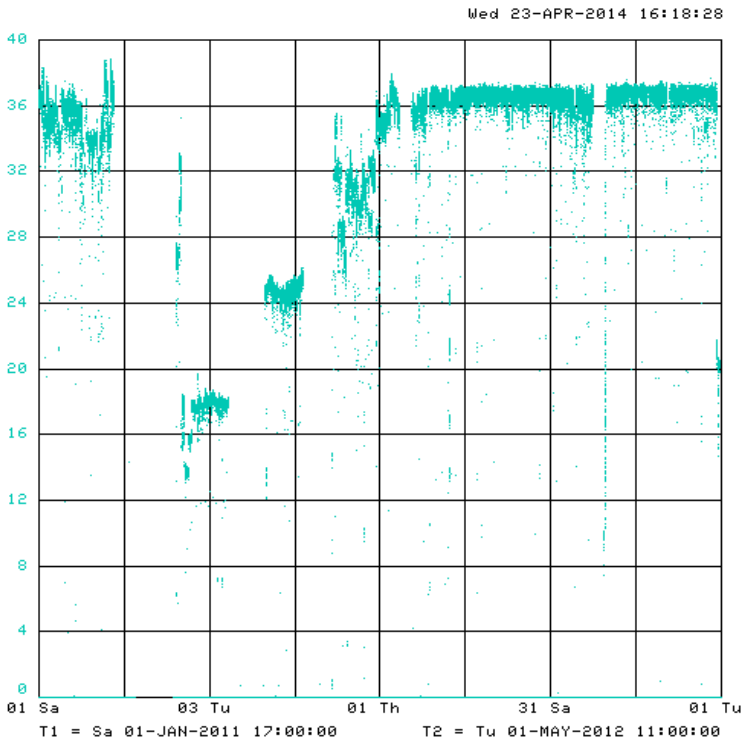
MI 120 GeV Beam Power 08/10-03/11 (Gap Clearing Kickers Operational)

Most of downtimes to neutrino beam were due to target failures. The accelerator operating efficiency was 72%-75%.Typically 290KW were delivered to NuMI and 75 KW to the pbar target.

Beam Power and NuMI target intensity 2011-2012



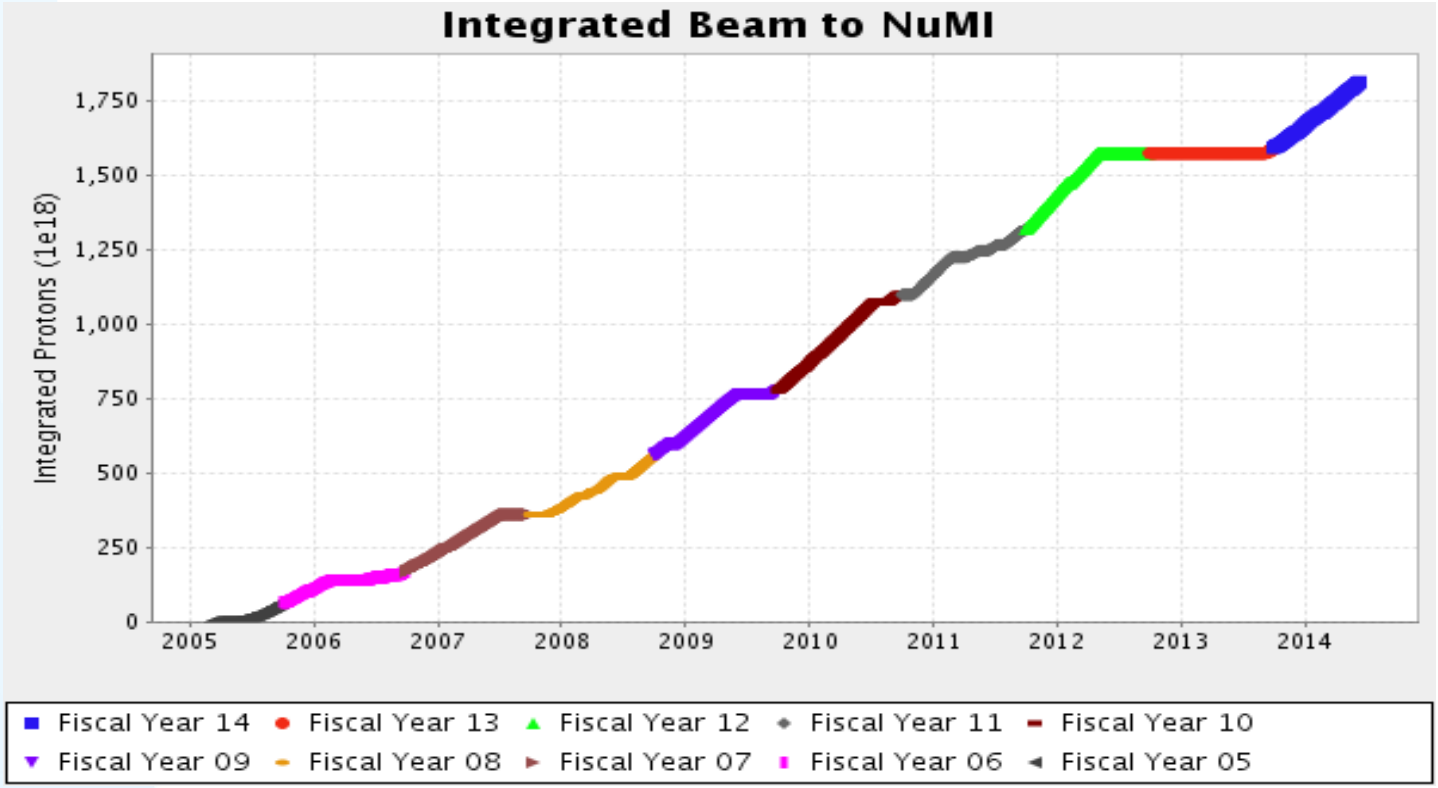
Main Injector beam power 01/11-05/12



NuMI Target Intensity 01/11-05/12

After TeV was turned off the MI power was reduced because of NuMI target concerns.

Accelerator performance for NuMI



Started delivering protons to NuMI in 2005

~1.55e21 in 7 years: NOvA goal is 3.6e21

Most intense high energy neutrino beam in the world

Summary of past MI High Power Operation

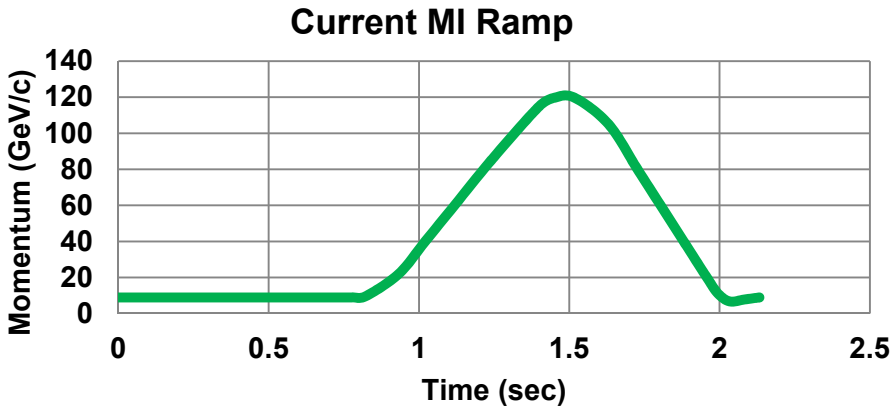
- After understanding the multi-batch slip stacking and implementing loss control measures we were able to achieve 380 KW of beam power with 11 batch slip stacking (10+1).
- The total cycle time was 2.2 sec with 0.8 sec spent at injection energy for stacking.
- Accelerator operational efficiency was ~75%.

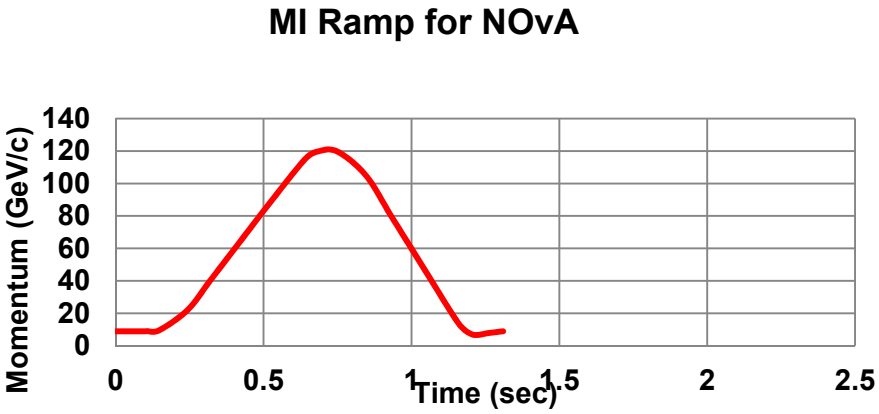
Plan for doubling the MI Beam Power

- 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

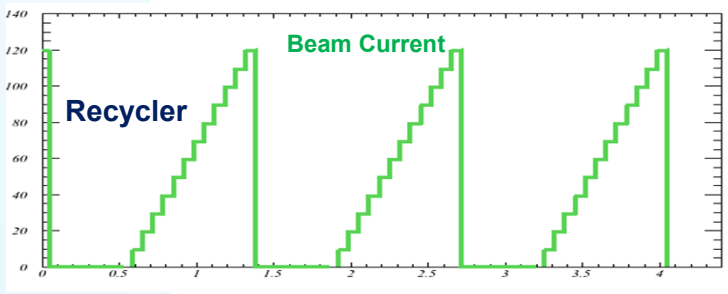
- MI Cycle Reduced from 2.2 sec (33 Booster Ticks) to 1.33 sec (20 Booster Ticks).
- MI Beam Intensity increased by 9% (49E12).
- The intensity per bunch remains the same.
- No Instability Issues are anticipated.
- Loss control is the major Issue (Power loss is increased by 80%).

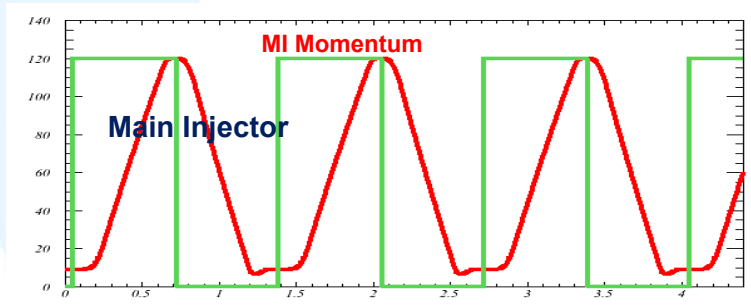


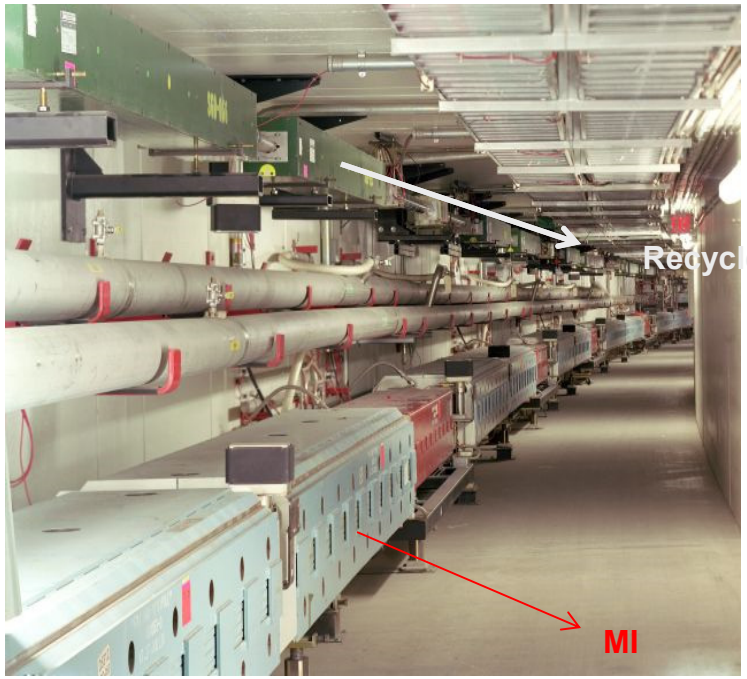


Recycler Operation

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



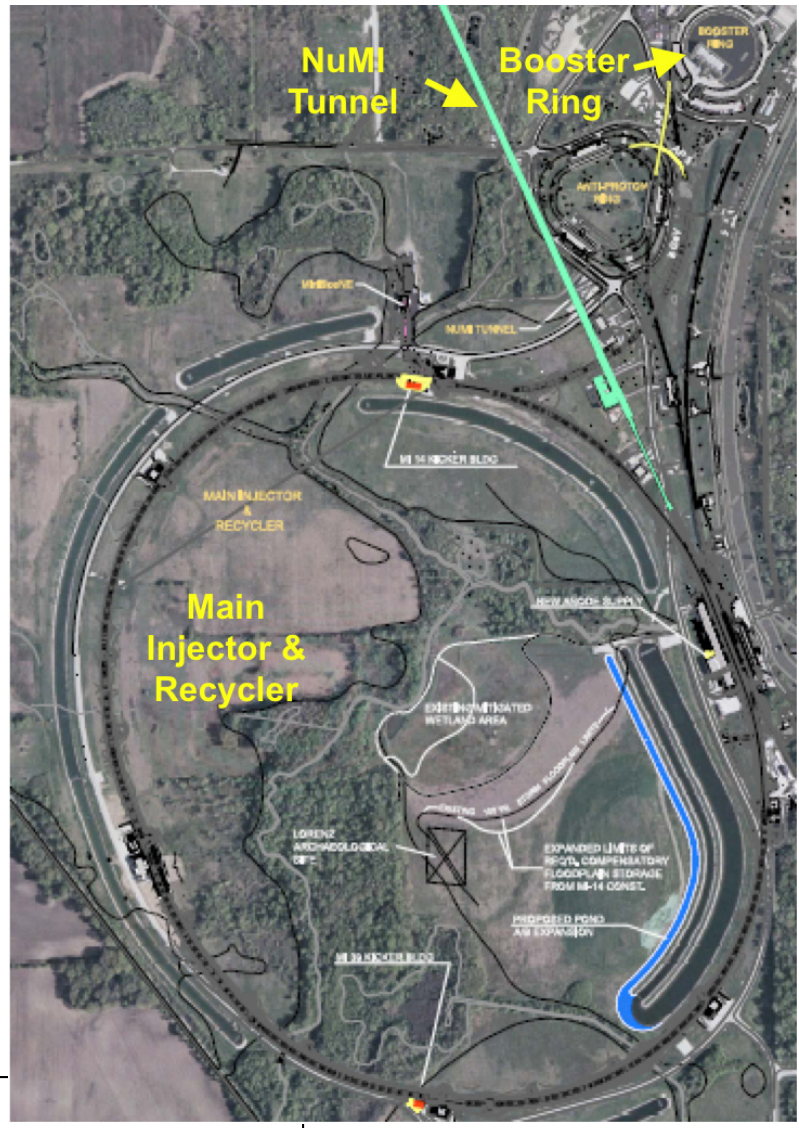




- Up to 8 additional Booster batches cab be injected in Recycler for delivery to the modified p-bar Rings (Mu2e, g-2 experiments)

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



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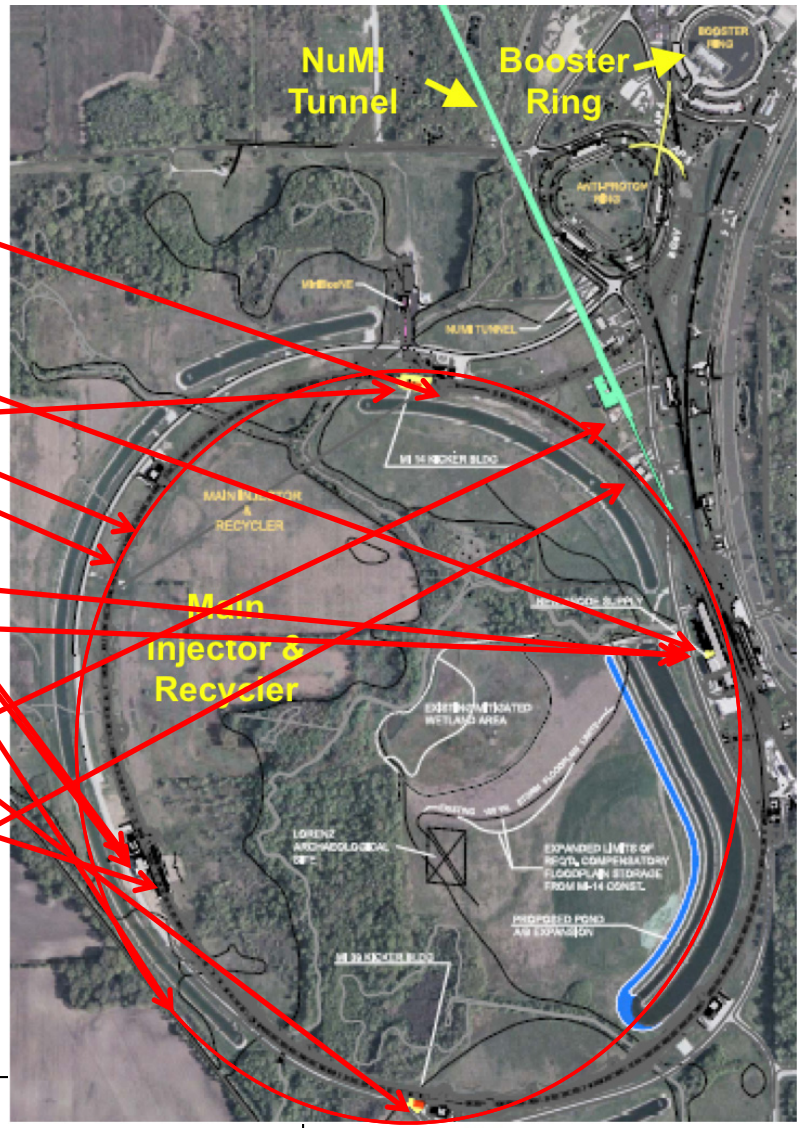


Fermilab Accelerator Complex after ANU

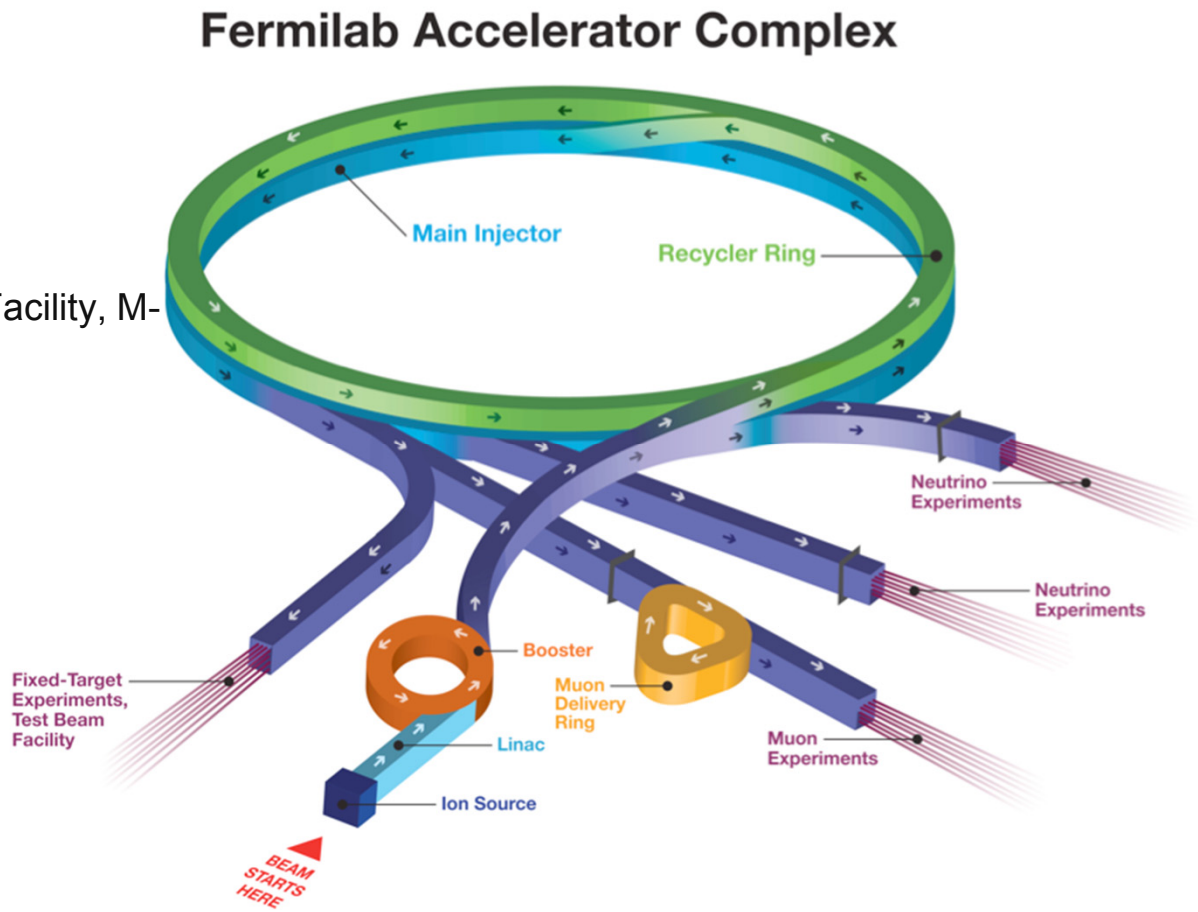
Linac: NTF, MTA

BNB: MicroBooNE

NuMI: MINOS+, MINERvA, NOvA

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

Muon: g-2, Mu2e (future)



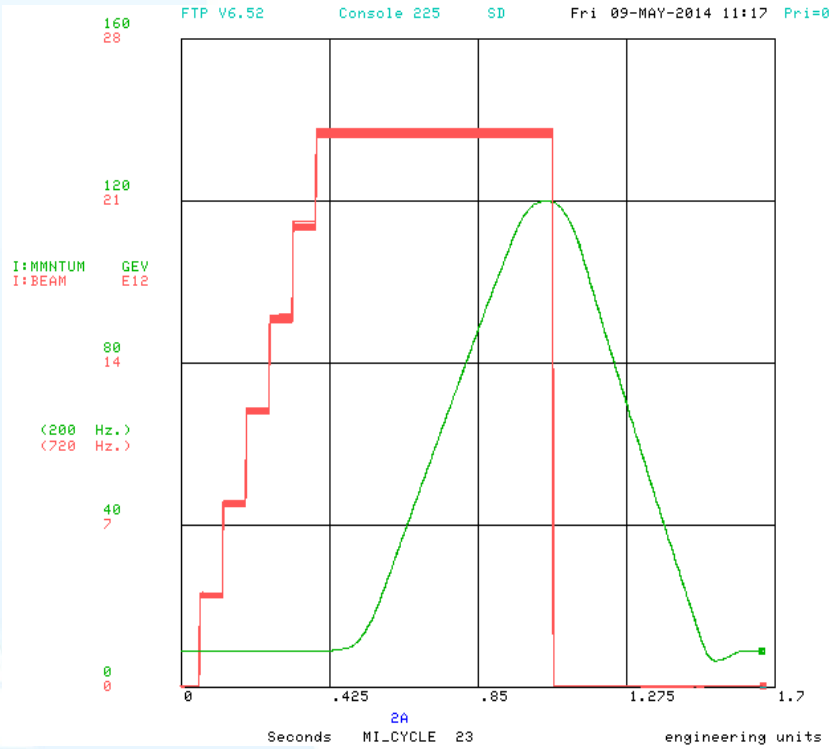
Recycler commissioning

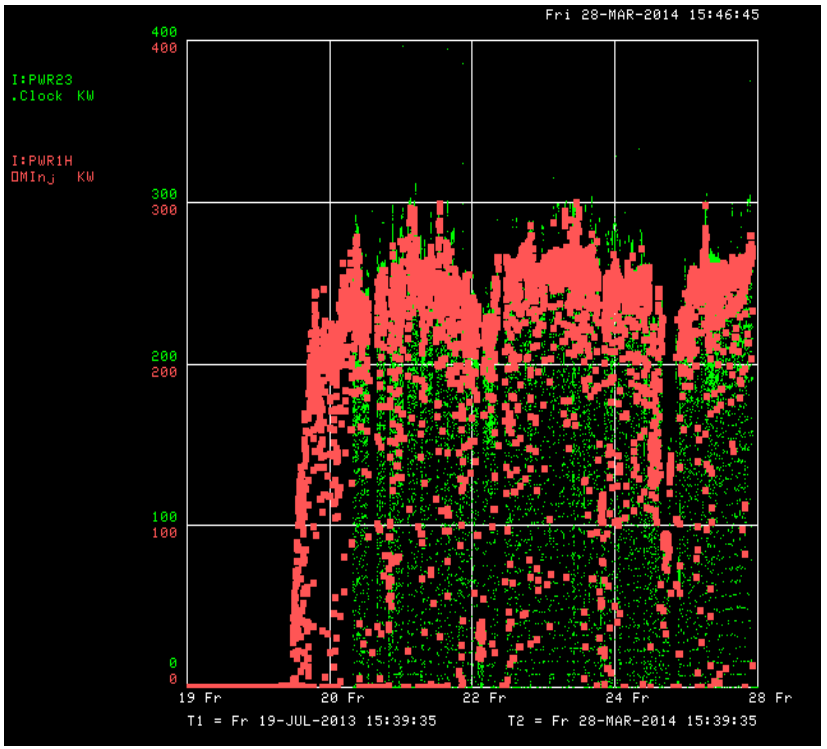
- ANU only provided us with the capability to transform Recycler into a high intensity proton storage ring. Significant work is required to achieve this and integrate Recycler into operations.
  - Establish slip stacking
  - Establish high intensity beam
  - Condition the Recycler beam pipe
  - Open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

NuMI beam and Power during Recycler Commissioning



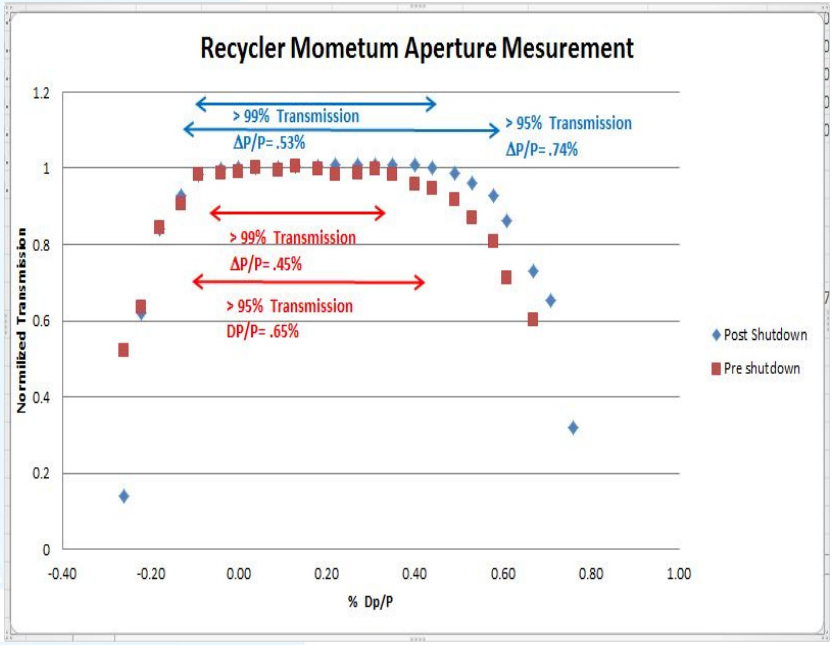


Running MI only with six Booster batches and 1.7 sec cycle time

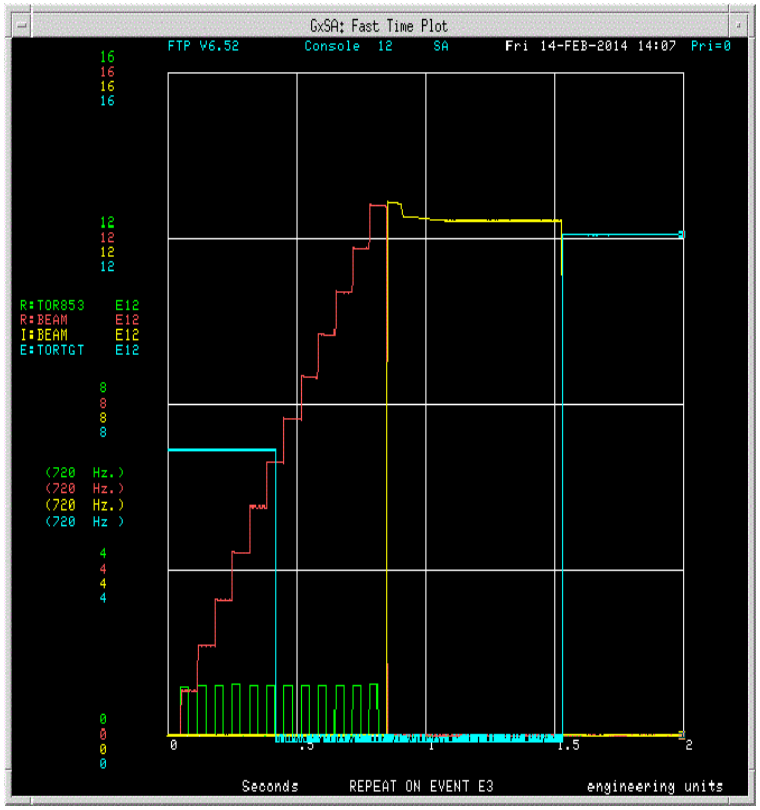
Recycler Ring

- The Recycler is a permanent magnet fixed energy (8 GeV) storage ring.
- Vacuum system based on titanium sublimation pumps (TSPs).
- 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.

12-Batch Slip stacking to NuMI Target

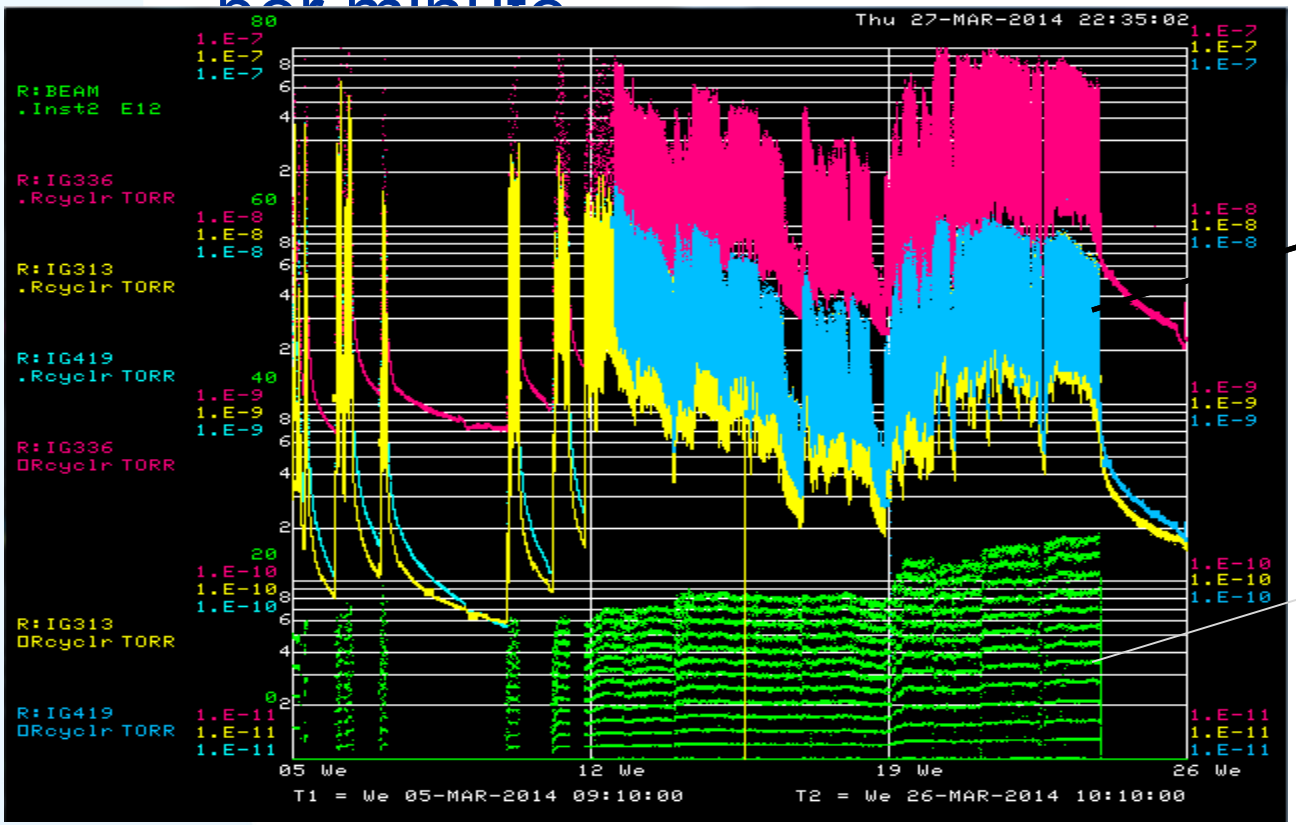


Momentum aperture required for SS 0.59% (min. 0.45%)



Highest slipped stacked intensity in RR 24E12

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

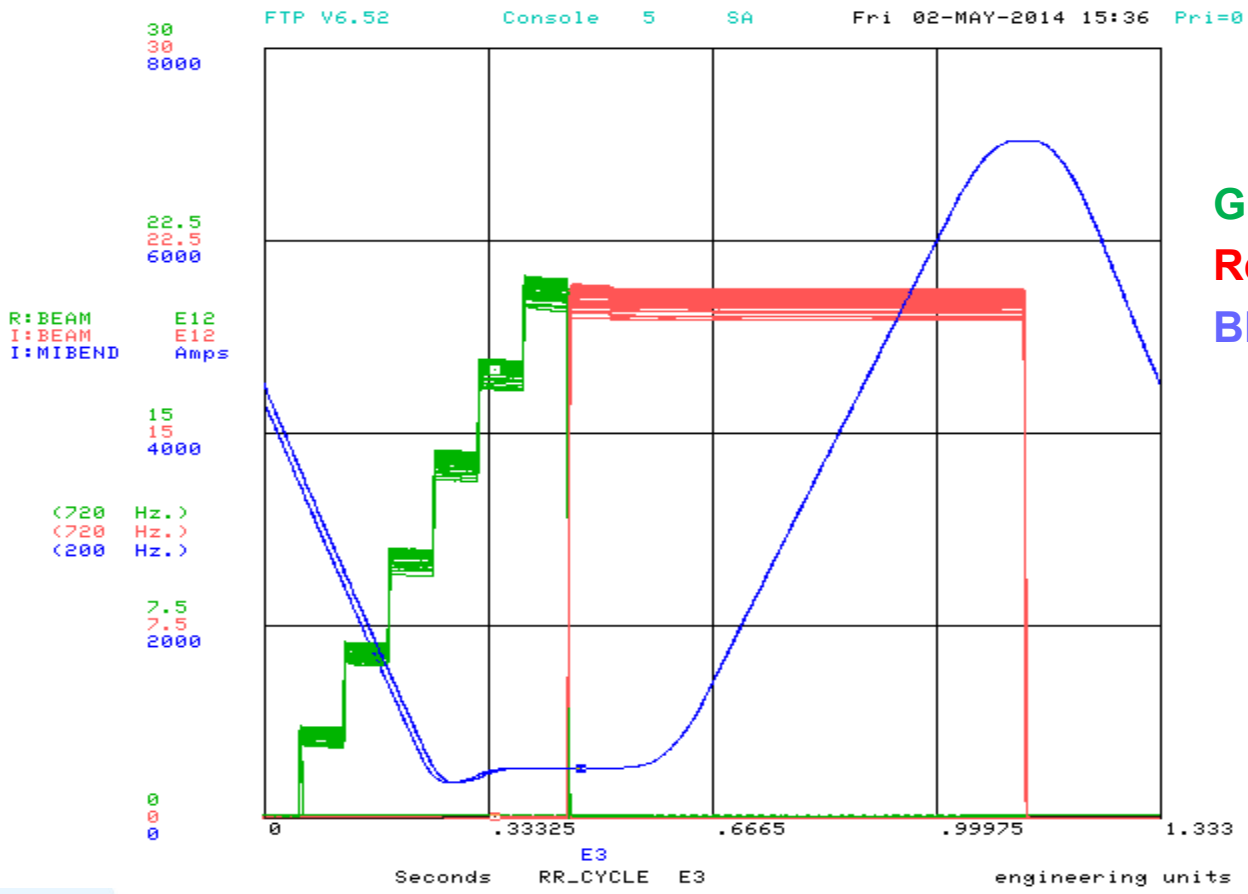


Recycler vacuum

Recycler Beam Intensity

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.

Running 2E13 with a 1.33sec MI Ramp



Green:RR Beam

Red: MI Beam

Blue:MI Ramp

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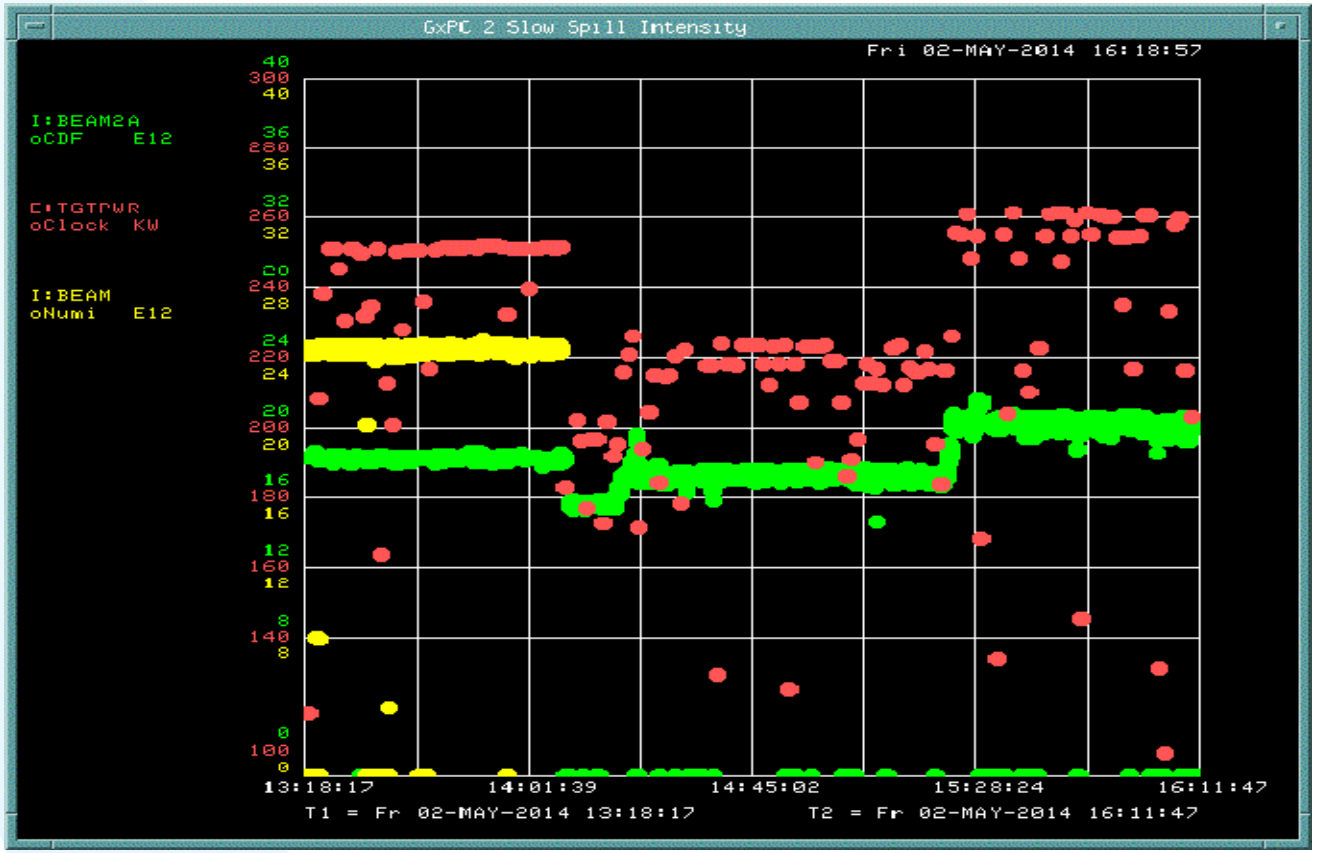
MI Beam power all $2As compared with $23s (MI only)



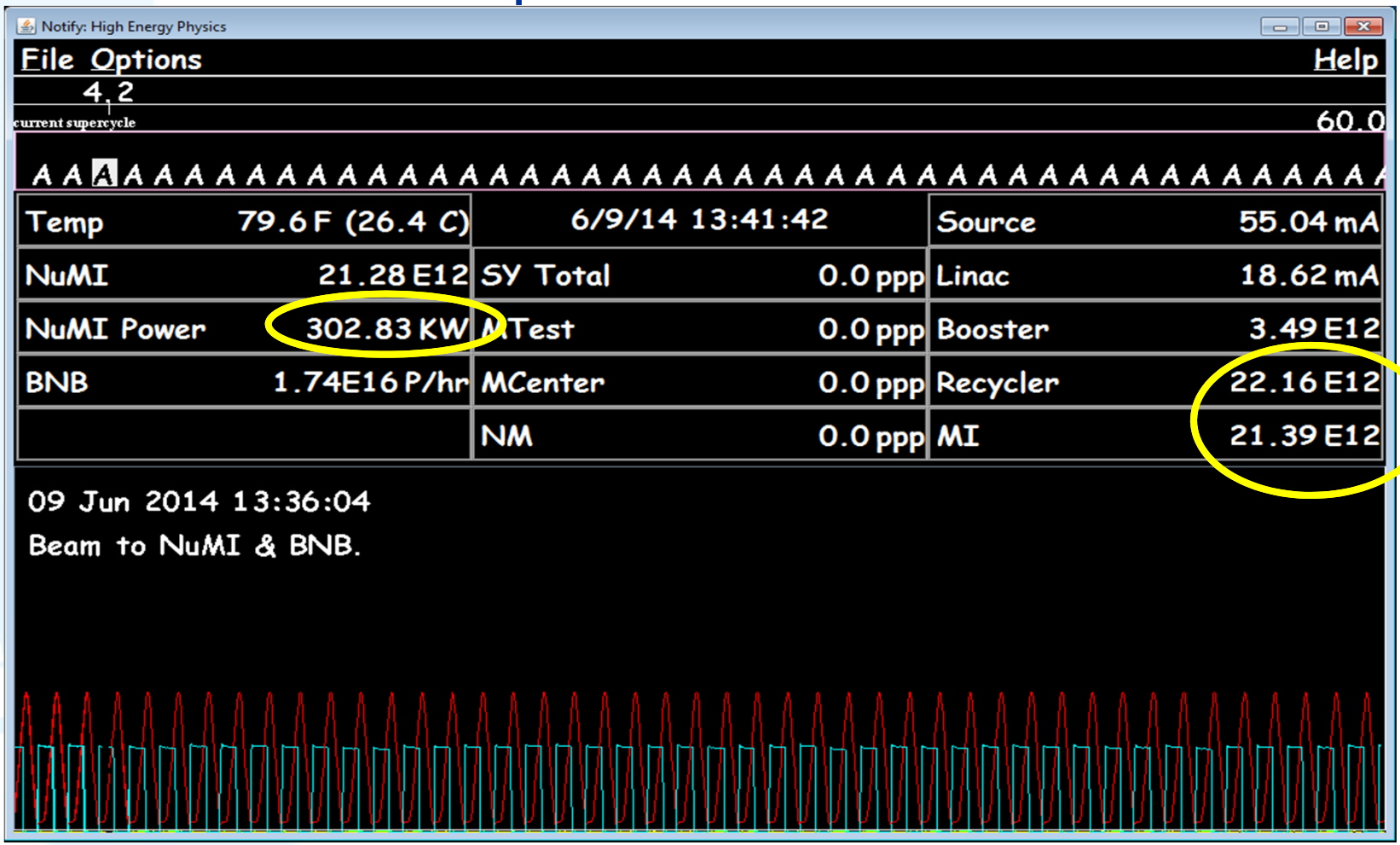
- $23 Beam intensity(E12)
- $2A Beam Intensity(E12)
- Beam Power (KW)

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

Current status and Plans

- We can currently run the Recycler with 22E12 p every 1.33 sec (300 KW or 270 KW with one slow spill event).
  - 6 Booster batches (no slip stacking)
  - Run in this mode a few hours every day. Need to finish damper commissioning before we can run 100% like this.
- Increase the beam intensity to 25E12 p delivering 345 KW (beginning of July).
- Plan to reach 450 KW by the end of summer by using 8 Booster batches (4 slipped stacked plus 4 single).

Running Recycler and MI with 22E12 and 1.33sec rep. rate.

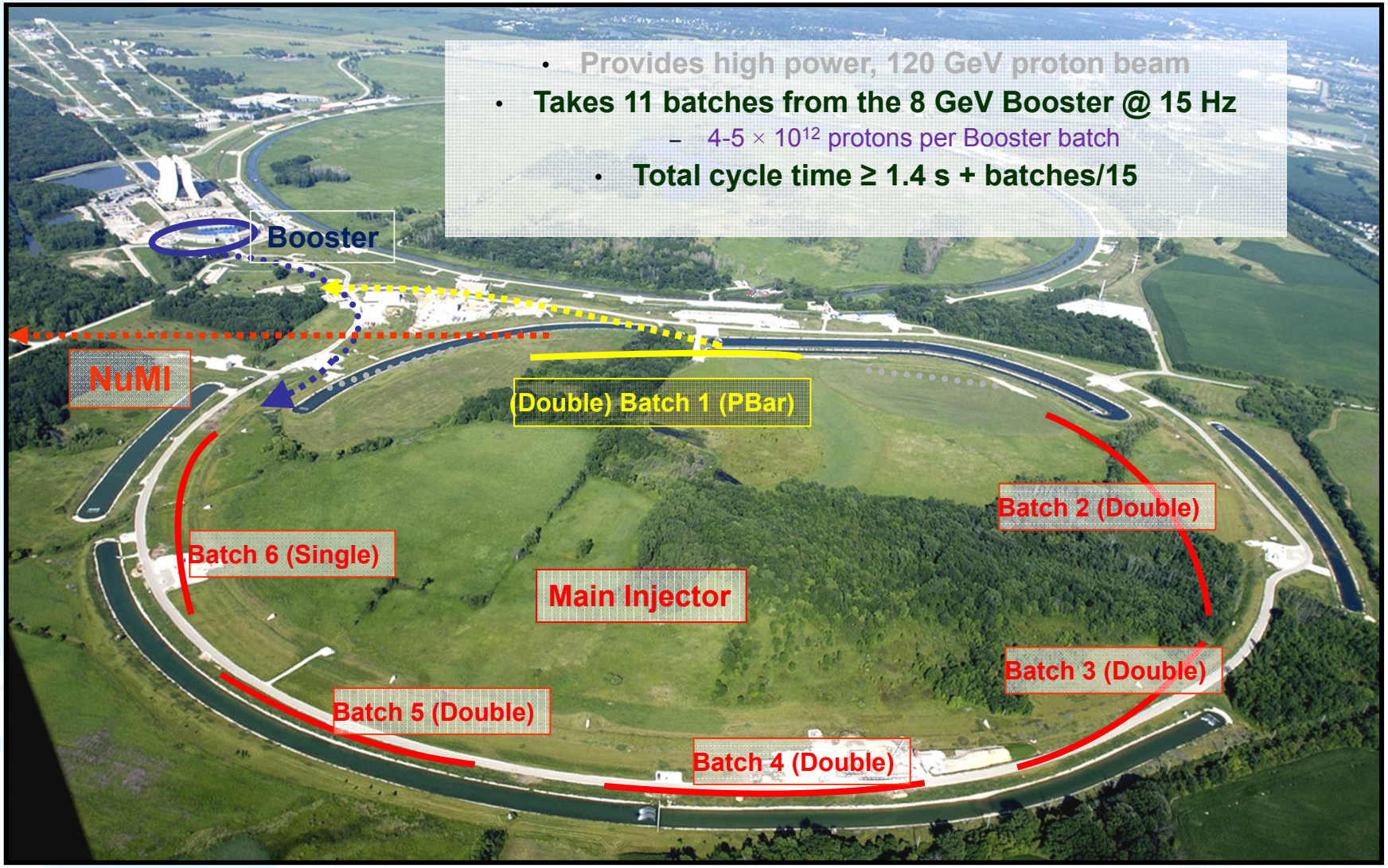


Conclusions

- All Accelerator upgrades (ANU) required for doubling the beam power are now in place and are working.
- Recycler is operational and we can achieve 300 KW with half the beam intensity.
- Plan to achieve 450 KW by the end of the summer.
- Expect to be ready to run at 700 KW when the Booster RF modifications are complete (Summer 2015).

EXTRA SLIDES

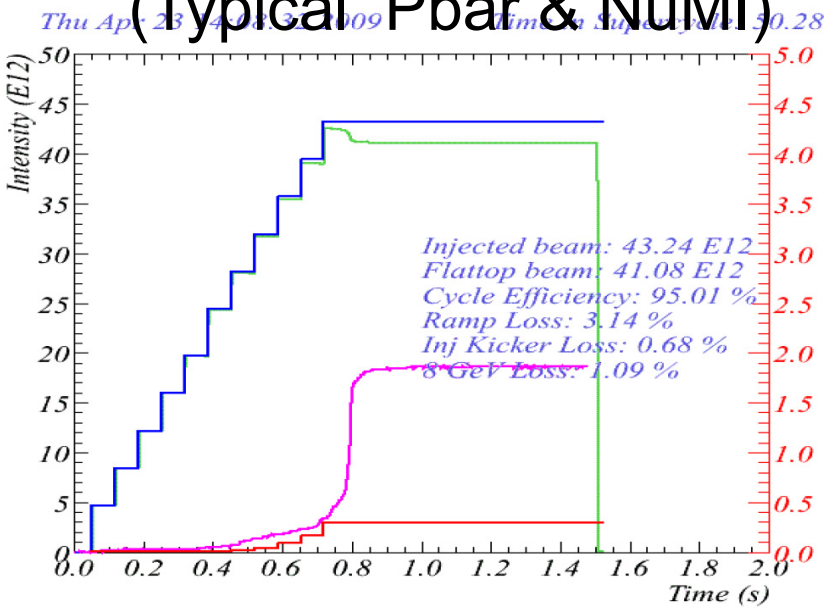
Main Injector High Power Operation (Mixed Mode)



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

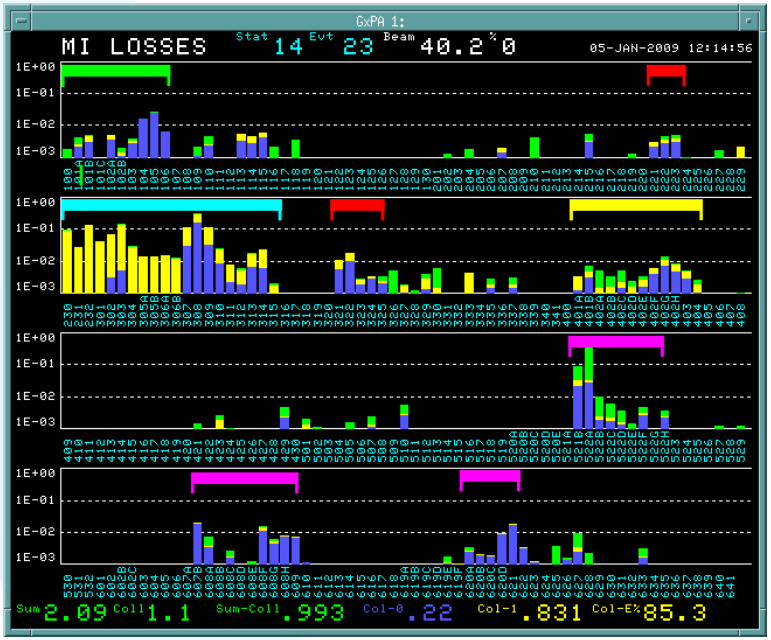
Green - circulated beam

Red - loss from injection kicker

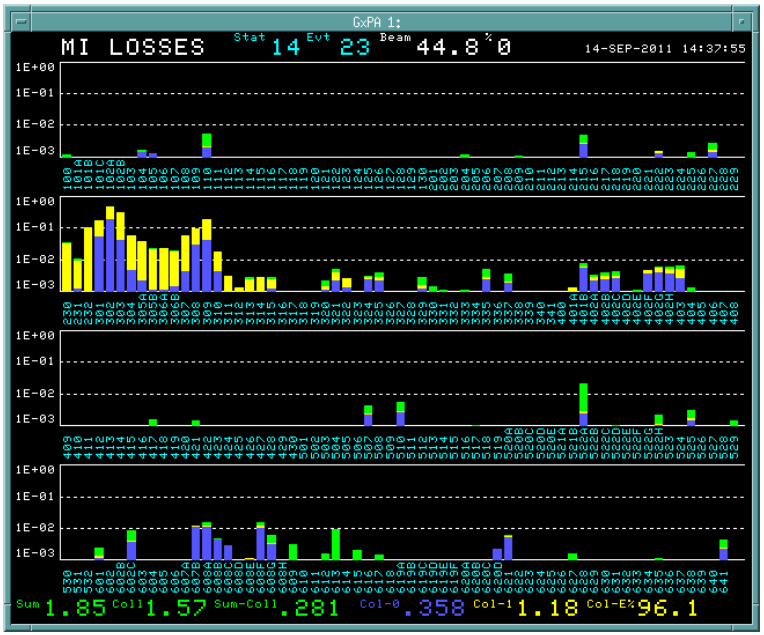
Magenta - total ring loss

Loss Reduction

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

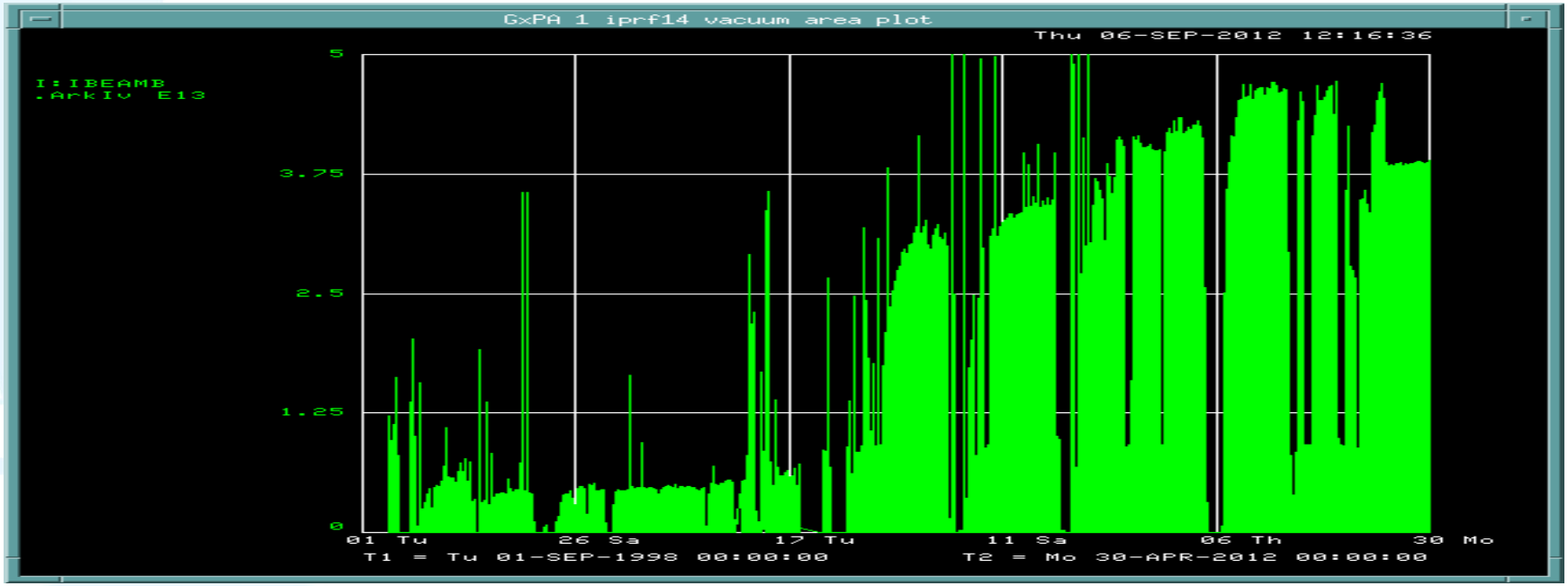


2009

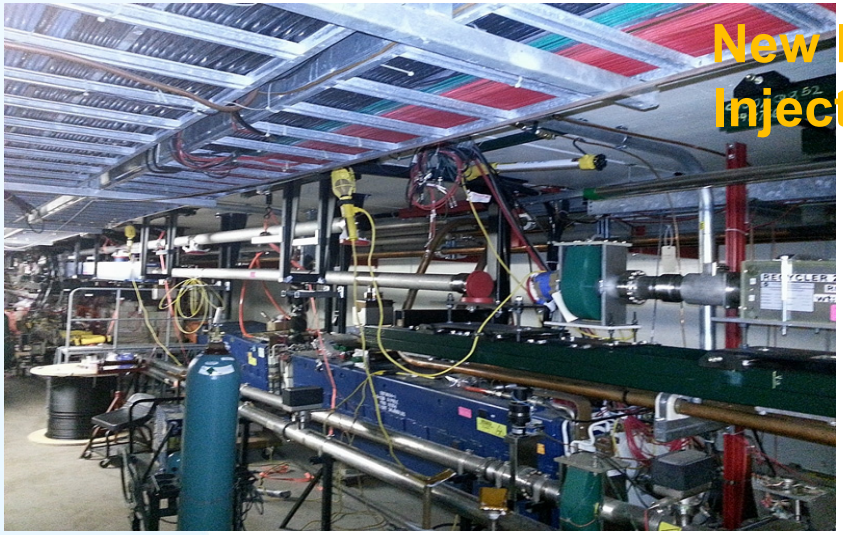


2011

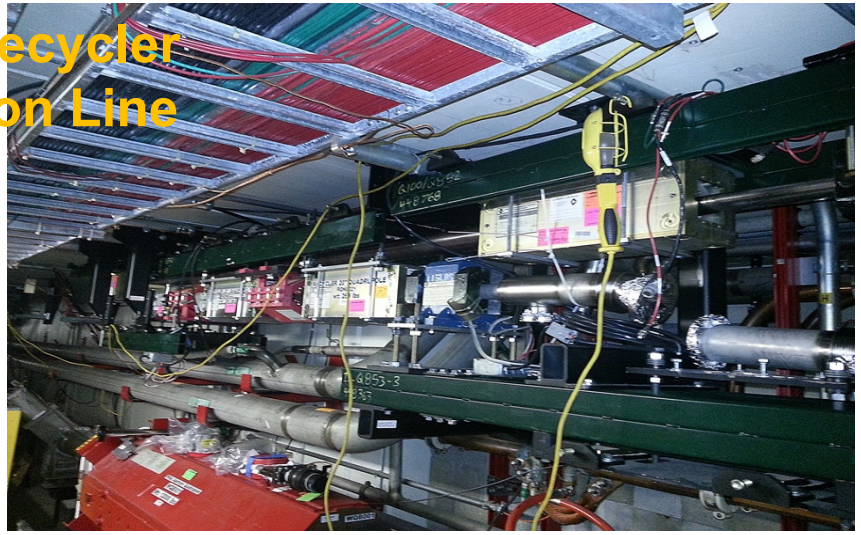
Main Injector Beam Intensity

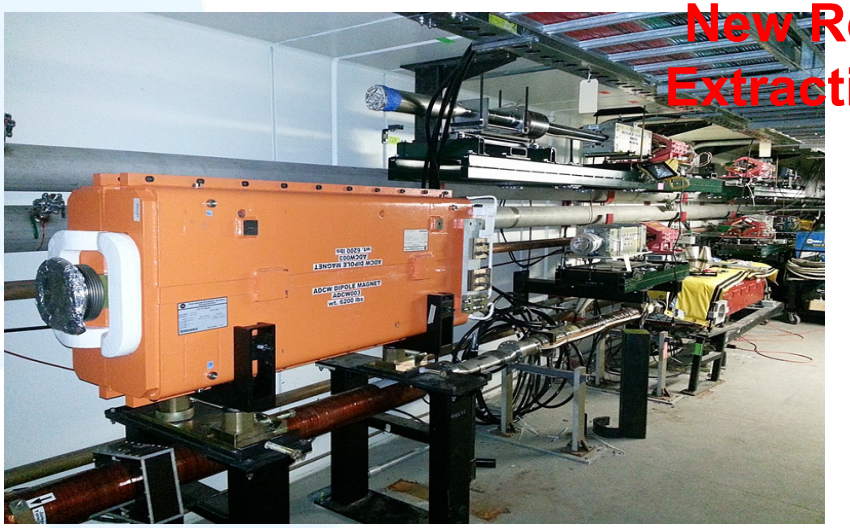


Pictures of Recycler ANU Installation



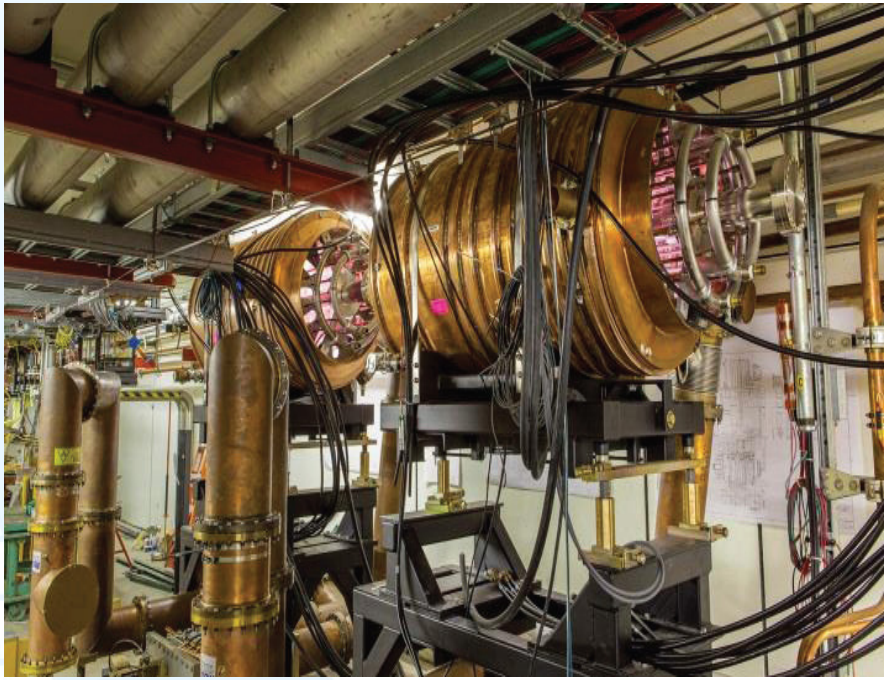
New Recycler Injection Line





New Recycler Extraction Line

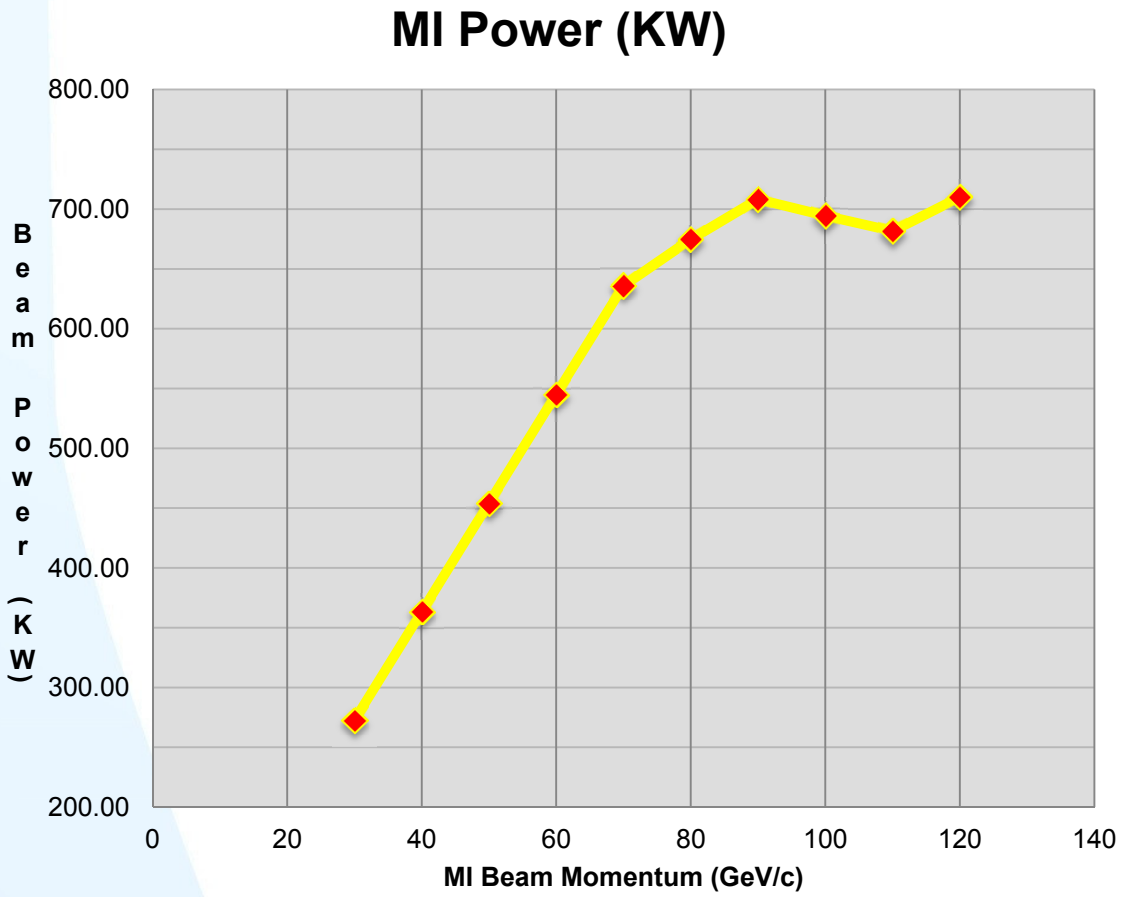
RR 53 MHz Cavities

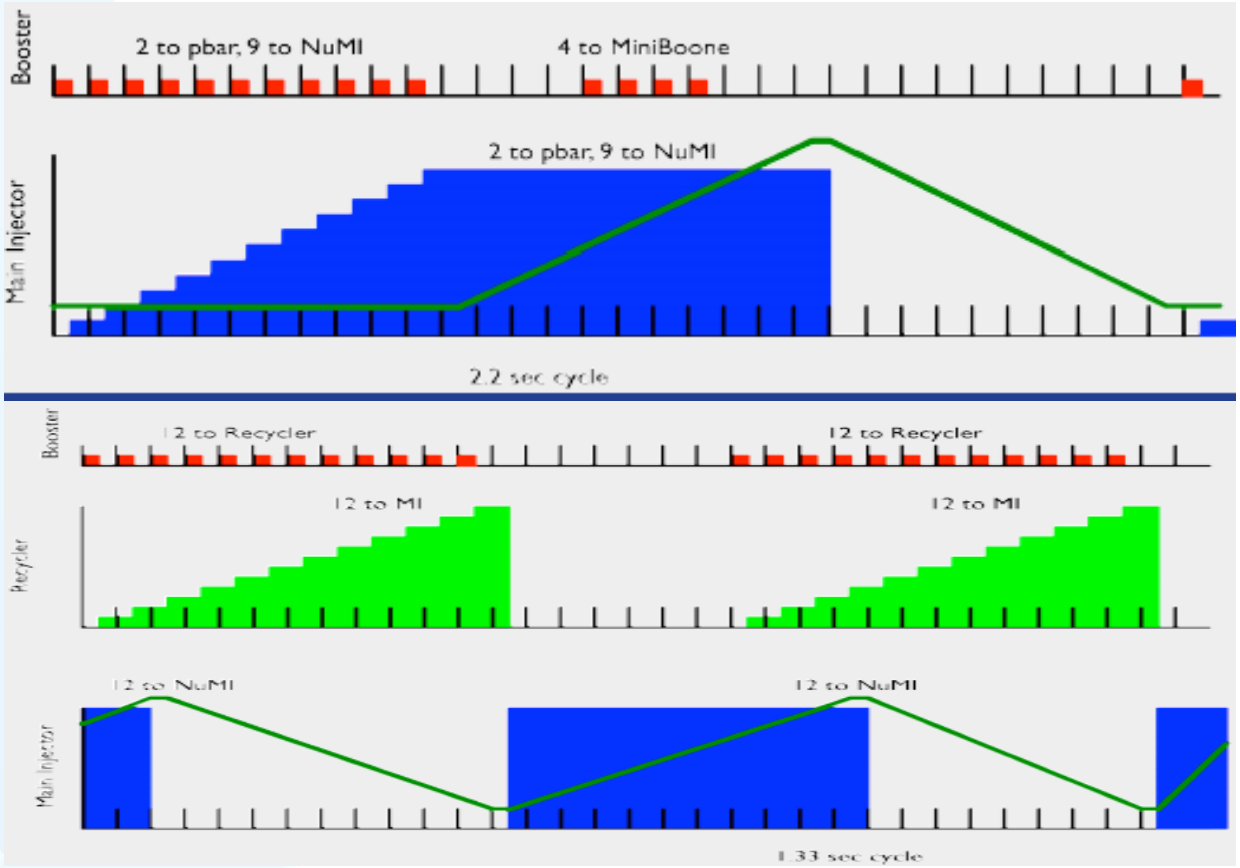


f_0	52.809 MHz
Z_0	10.2 Ω
Vpeak (max)	150 kV
Maximum power	150 kW
Rshunt	75 kΩ
Q	5800
R/Q	13 Ω
Outer conductor ID	32 in
Inner conductor OD	27 in
nominal gap width*	2.9 in
Inner conductor length**	49.75 in
Step up ratio	6

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

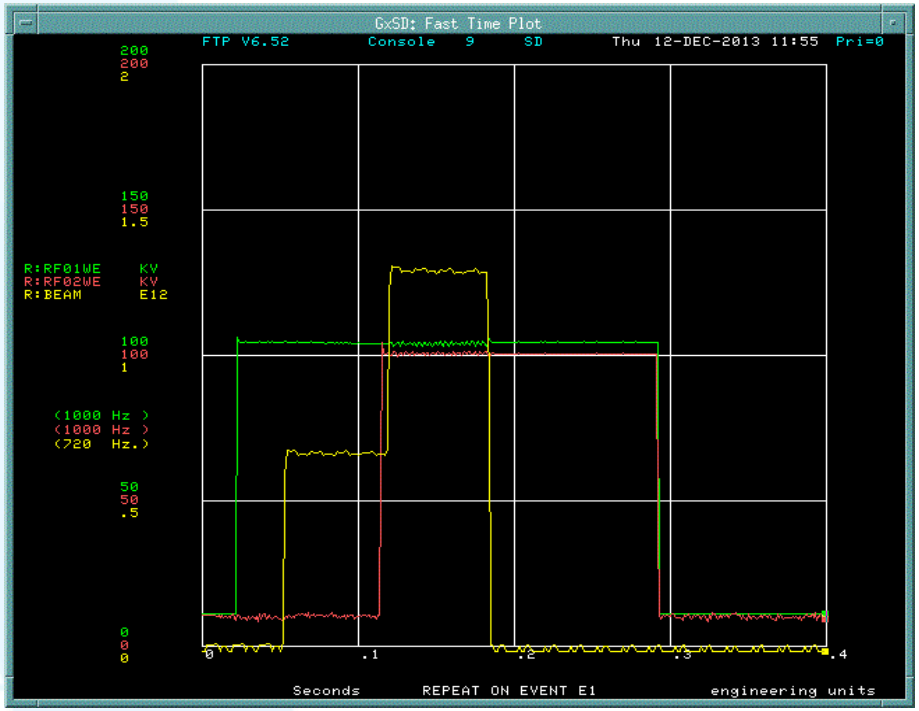




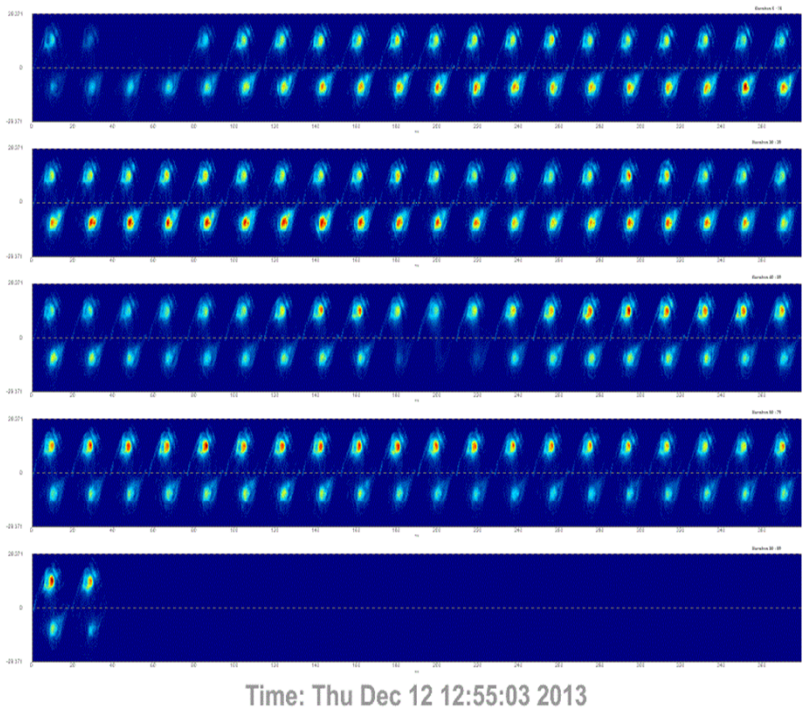
Tev Era Operation: 11 Booster batches (2 to pbar), 3.5E13, 2.2 second cycle.

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

First slip stacking in Recycler

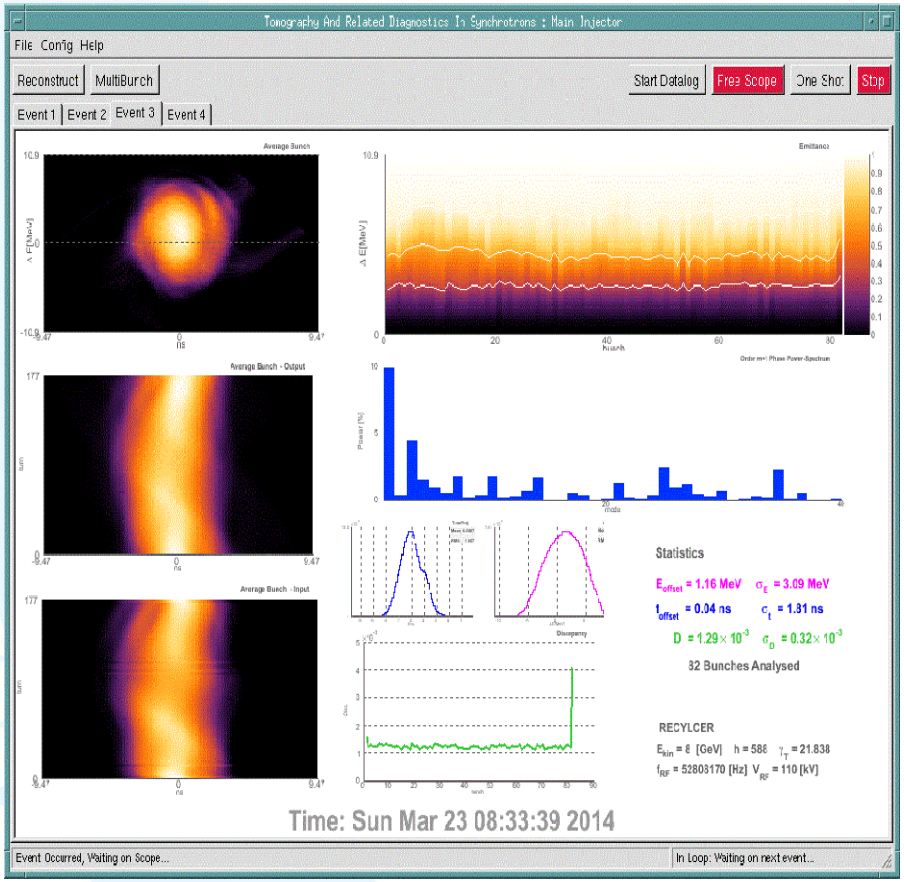


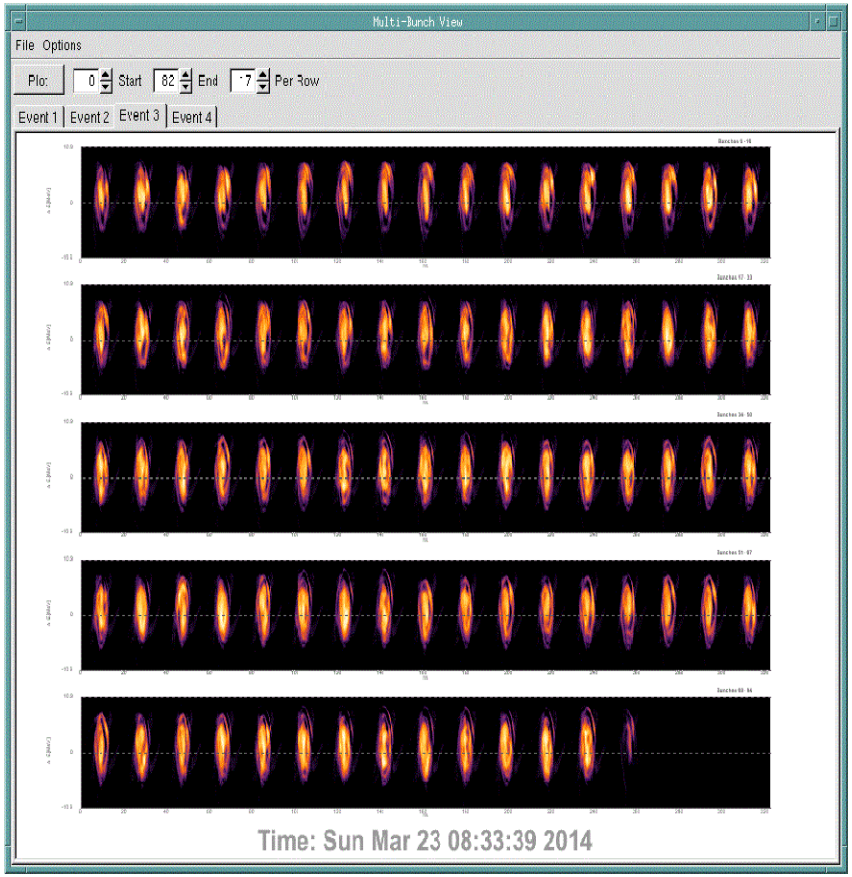
Beam intensity and RF voltage



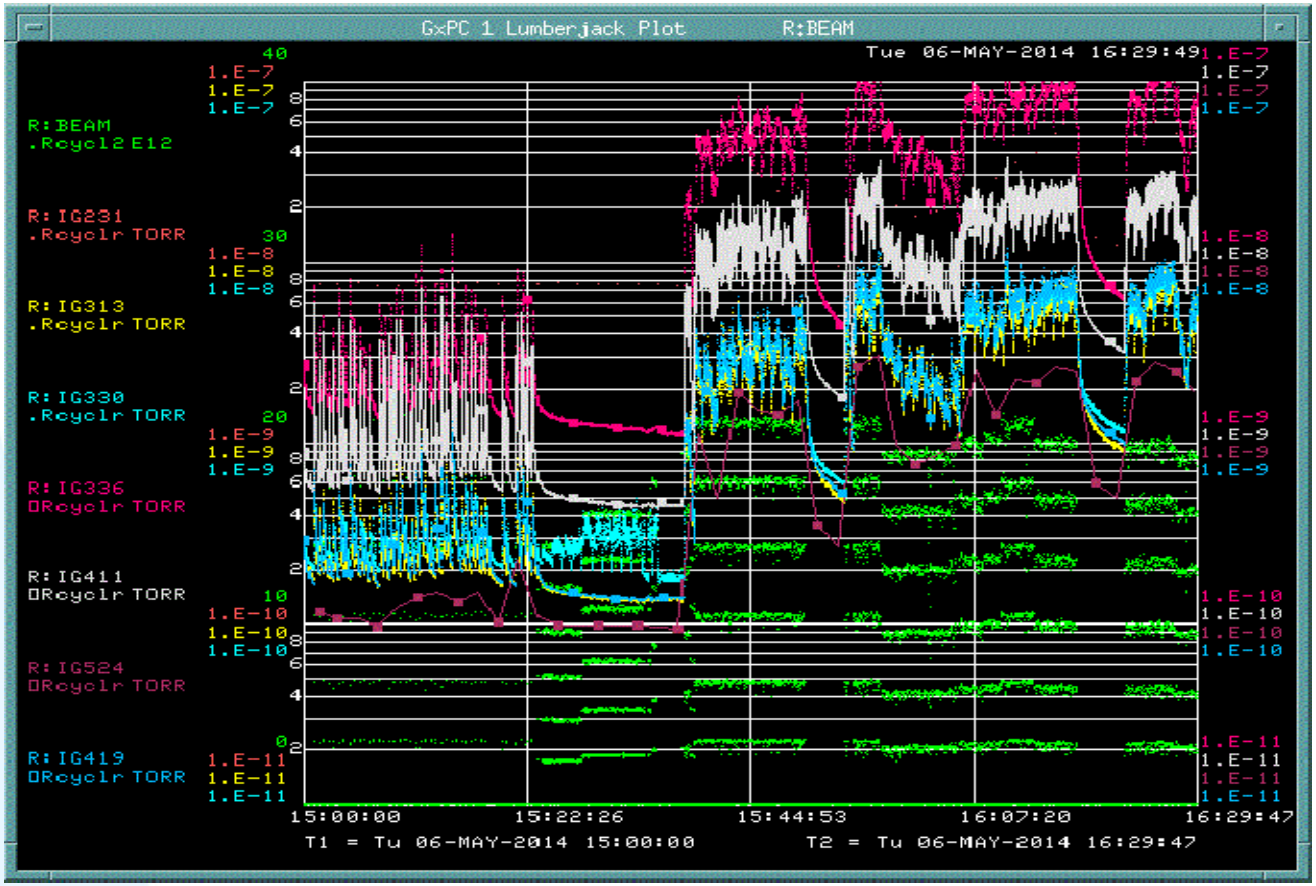
2-D longitudinal picture of all 82 bunches

Longitudinal tomography



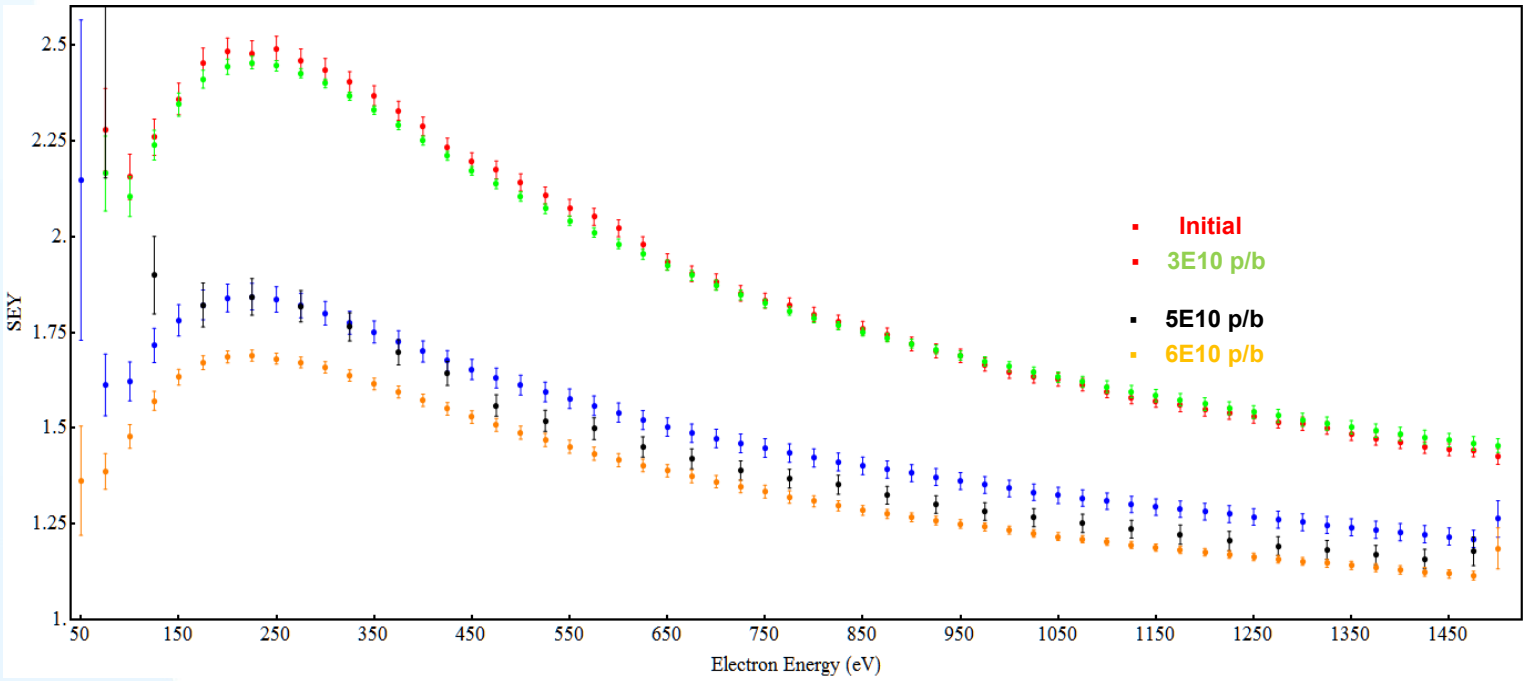


Recycler vacuum with 1.33 sec rep rate.

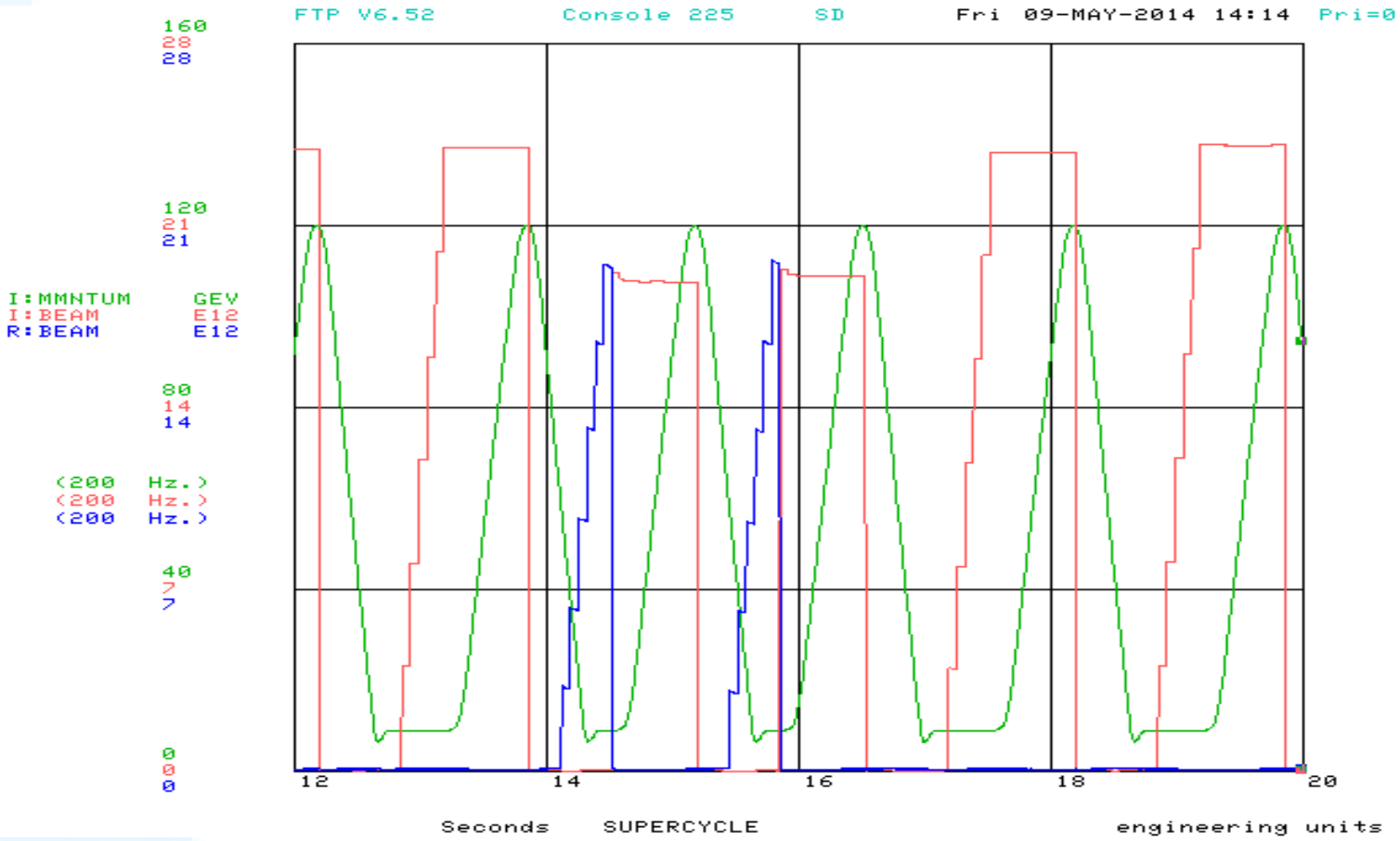


MI SEY Measurements

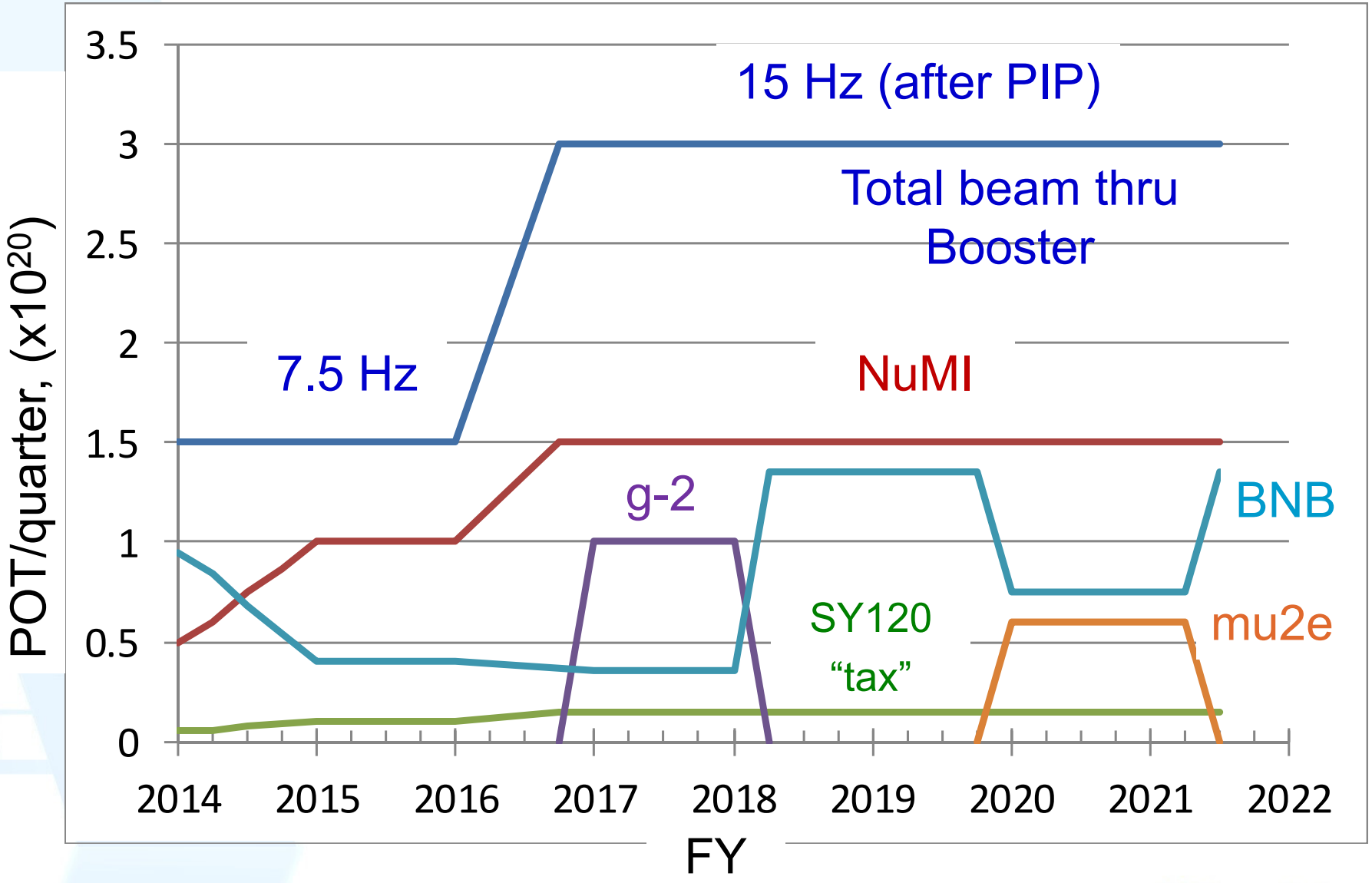
Effect of beam scrubbing on secondary emission yield (SEY)



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



Booster Proton delivery scenario



Fermilab