Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

700 kW Operations for NOvA at FNAL

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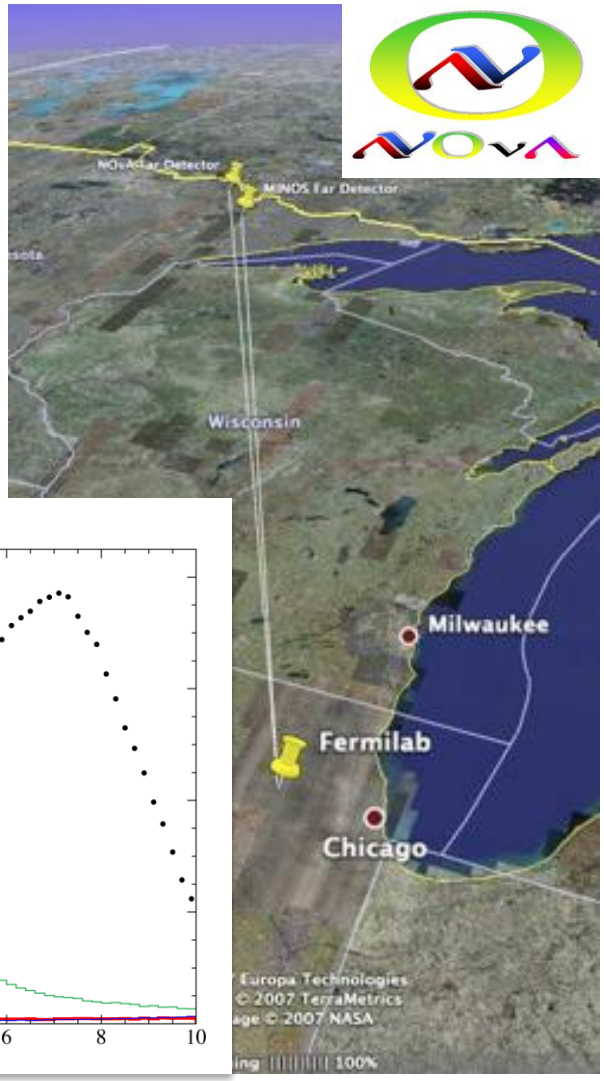
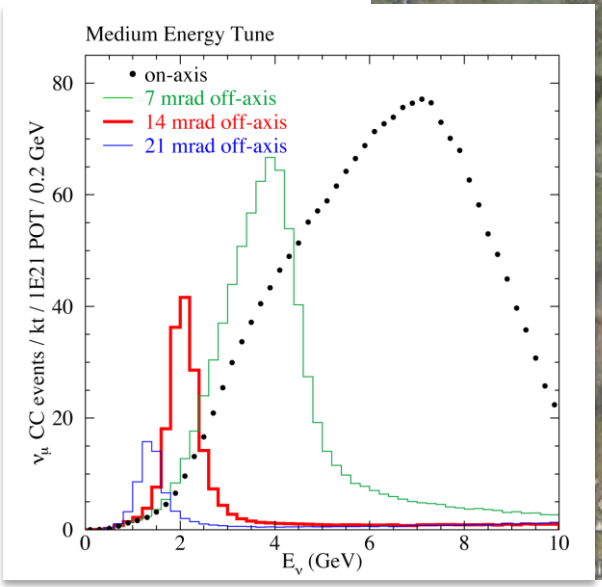
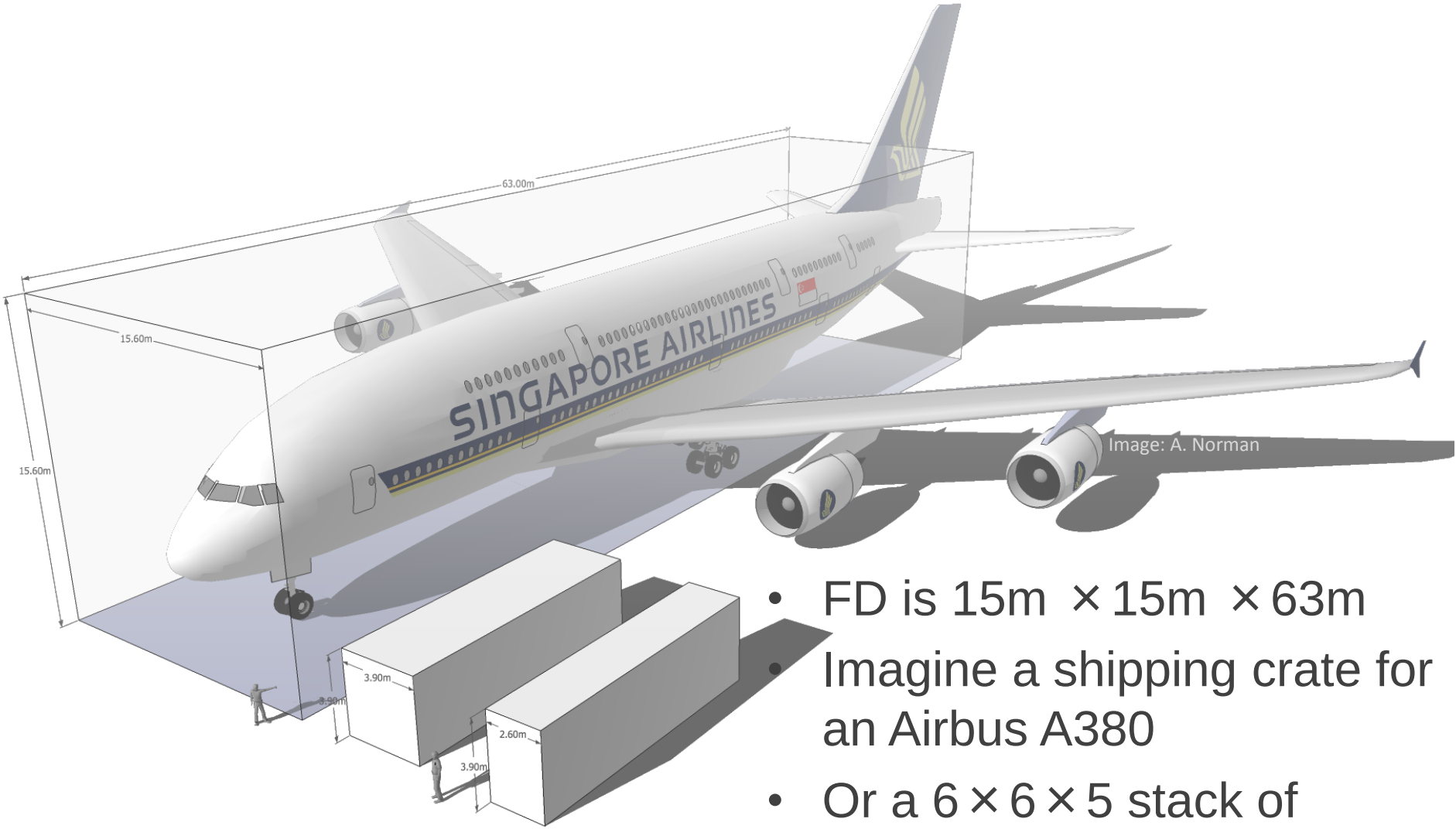
NuMI Off-axis ν_e Appearance Experiment

- Second generation experiment in existing NuMI neutrino beamline
  - 14,000 ton Far Detector
    - World's largest free-standing plastic structure
  - Off-axis (14 mrad): narrowband beam for precision measurements
    - θ_{13}
    - θ_{23} octant
    - Mass hierarchy
    - CP violation
    - Improved precision for θ_{23} and $\left|\Delta m^2_{32}\right|$





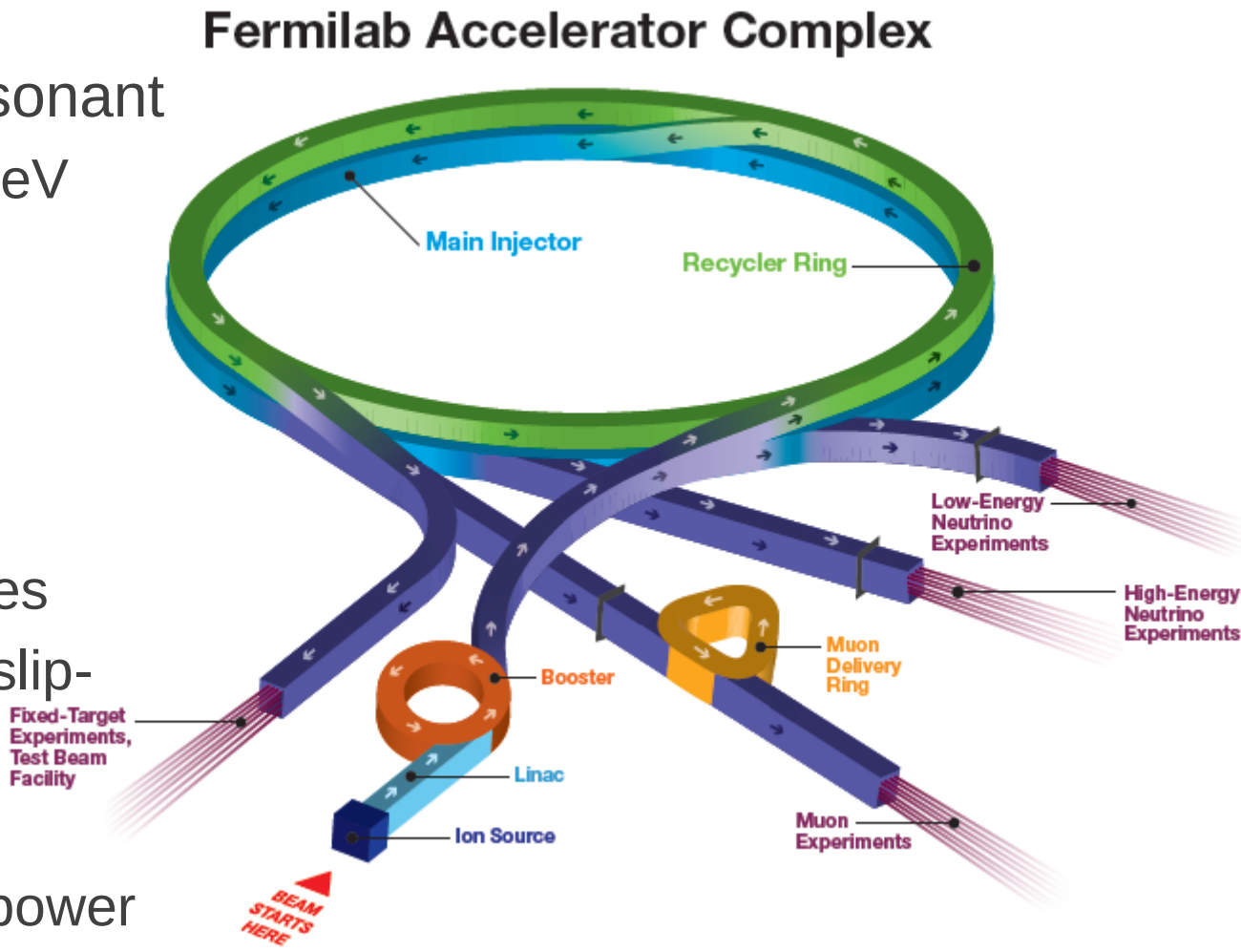
How big is NOvA far detector?



- FD is 15m × 15m × 63m
- Imagine a shipping crate for an Airbus A380
- Or a 6 × 6 × 5 stack of shipping containers

Providing beam to NuMI

- H^- linac
- Booster: 15Hz resonant
  - 400 MeV -> 8 GeV
  - h=84
- Main Injector
  - 8 -> 120 GeV
  - h=588 (7*84)
  - 6 booster batches
  - Double up with slip-stacking
- NOvA project
  - Increase NuMI power
  - 400 kW -> 700 kW

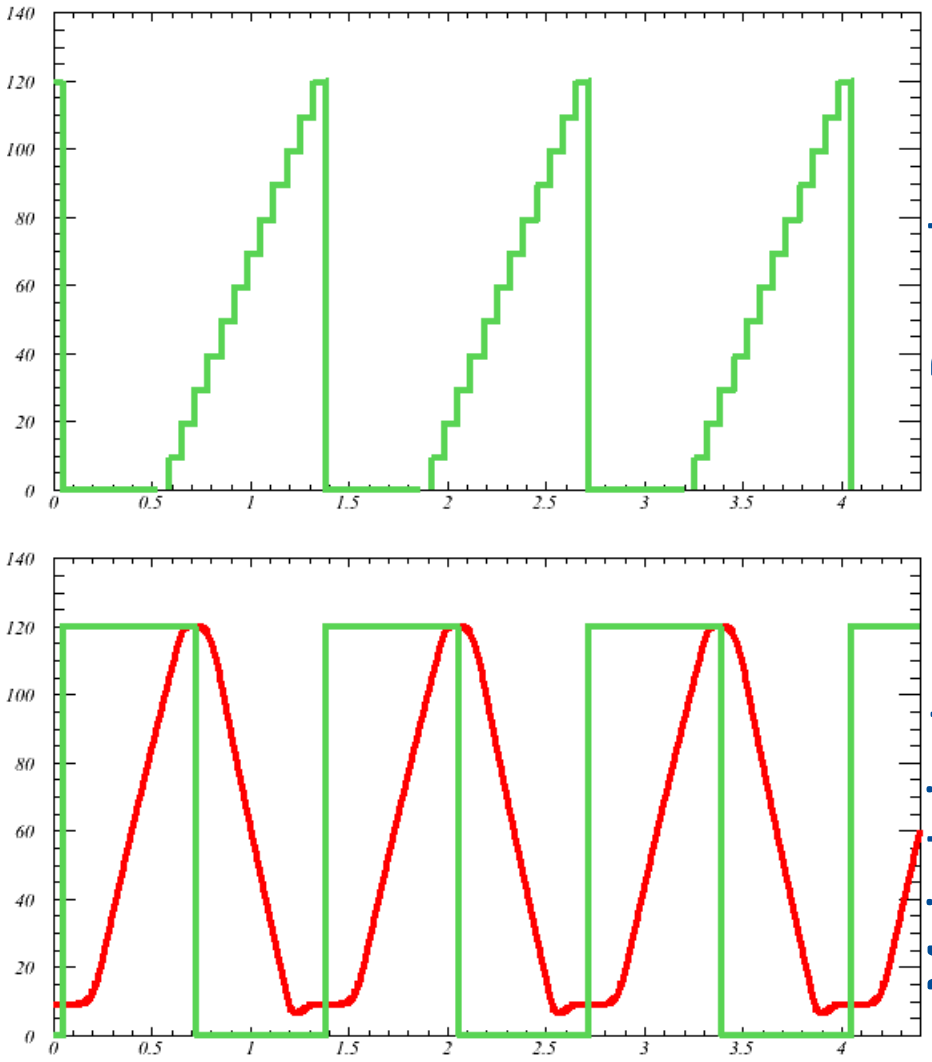


Recycler after the Tevatron

- Recycler is a permanent magnet 8.9 GeV/c storage ring in the Main Injector tunnel
  - Combined function strontium ferrite magnets, FODO lattice
    - Strontium ferrite quads in straight sections
    - Powered trim dipoles / quads / sextupoles
  - TSP vacuum $< 10^{-10}$ torr

Scheme to increase beam power

- Move slip-stacking to Recycler
  - 11 batch -> 12 batch
    - (faster kickers)
- Increase MI ramp rate (204 GeV/s -> 240 GeV/s)
  - 1.33s cycle time
- 380 -> 700 kW with only ~10% increase in per-pulse intensity
  - Don't expect new beam physics issues
  - ~ double protons through Linac / Booster: need PIP

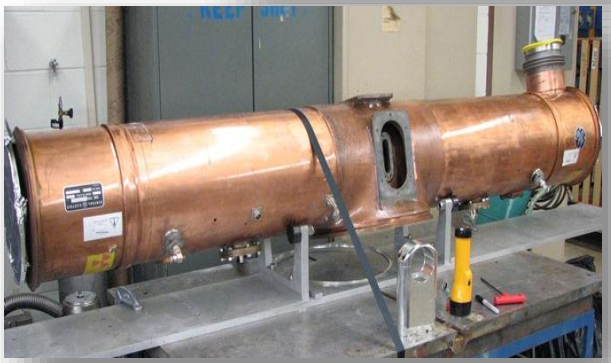


Proton Improvement Plan

- Linac / Booster deliver 2.3E17 protons per hour at 15 Hz
  - Factor 2 increase in pulse rate and proton throughput
- Operate Linac through 2023 / Booster through 2030
- Project contains many elements throughout proton source:
  - Reduce beam losses
    - Notching / Magnetic Cogging / Apertures / Dampers
  - Increase reliability (old equipment)
    - rf solid state drivers / power distribution / LCW / linac modulator
  - Eliminate risk of unavailability of spares (old equipment)
    - 7835 inventory / replacement modulator / klystron prototype
  - Enable 15 Hz operation (Tevatron era: limit ~7.5 Hz)
    - rf cavity refurbishment / tuner cooling upgrade
    - 700kW NOvA requires 9.8 Hz, then add BNB and g-2/mu2e

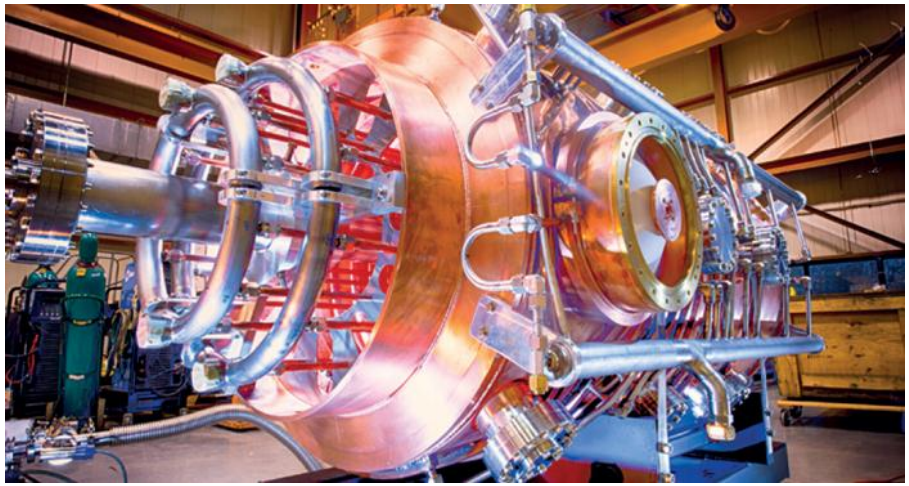
Booster Cavity Refubishment

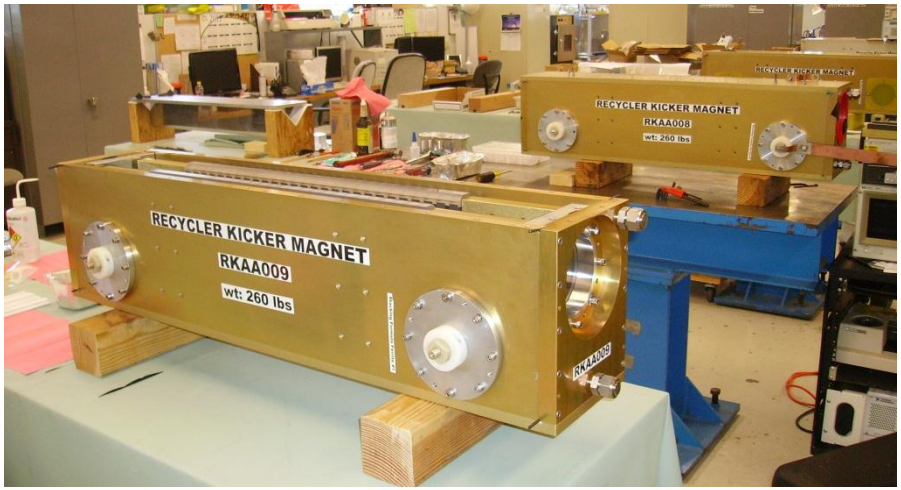
- Booster cavities were new in 1969
- Refurb began Jan 2012
- Booster had 19 cavities
  - Remove two at a time for upgrade
  - 17 is minimum for 4.3E12 ppp
- 17th cavity installed last week
  - Begin 15 Hz commissioning
- 20 cavities by end 2015



Necessary Recycler Upgrades

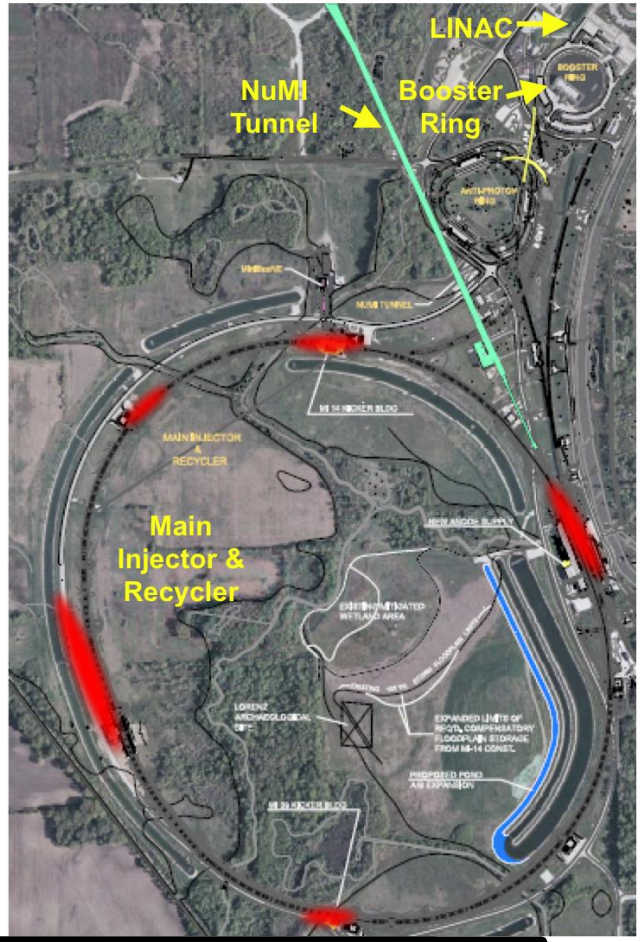
- Remove pbar era hardware
- Shim gradient magnets
  - Change base tune and chromaticity
- New injection line MI8 -> RR
  - Short, fast kickers
    - ~50ns full rise/fall
- New RR -> MI transfer line
- 53 MHz RF (slip-stacking)
  - 2 cavities at ~100kV each, plus one spare
- More trim quads / sextupoles
- Instrumentation
  - BPMs
  - Low-mass Ti multiwires
  - IPMs
  - Dampers
- Maintain TSP vacuum

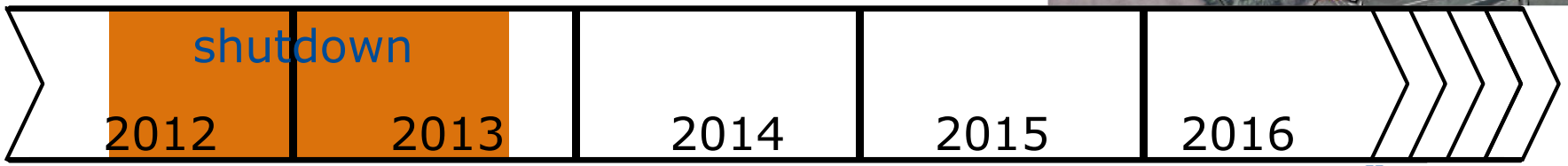




Long shutdown

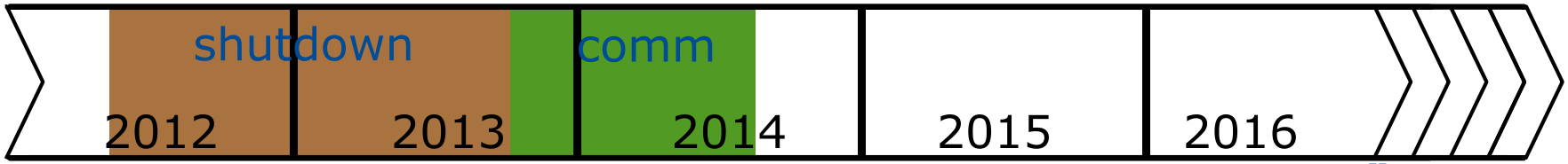
- Shut down from May 2012 to September 2013
  - Recycler upgrades
  - Faster MI ramp rate
    - Add 2 MI RF stations (maintain bucket area)
    - MI quad power supply / transformer upgrade
  - Install 700kW target / horns in NuMI target hall



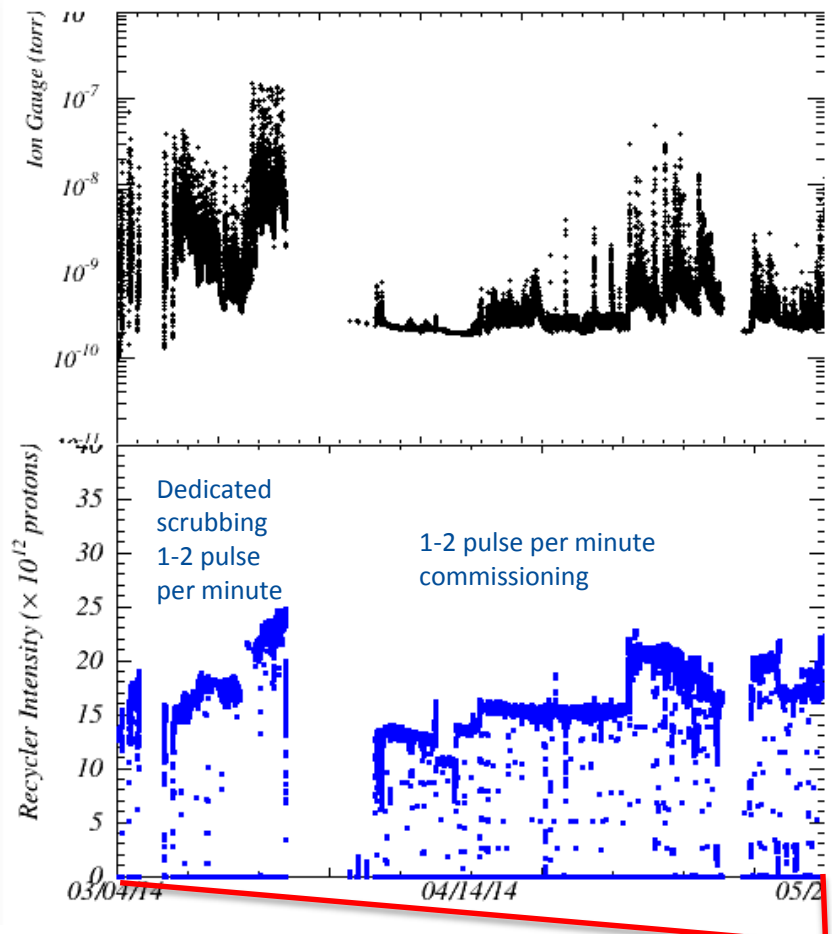


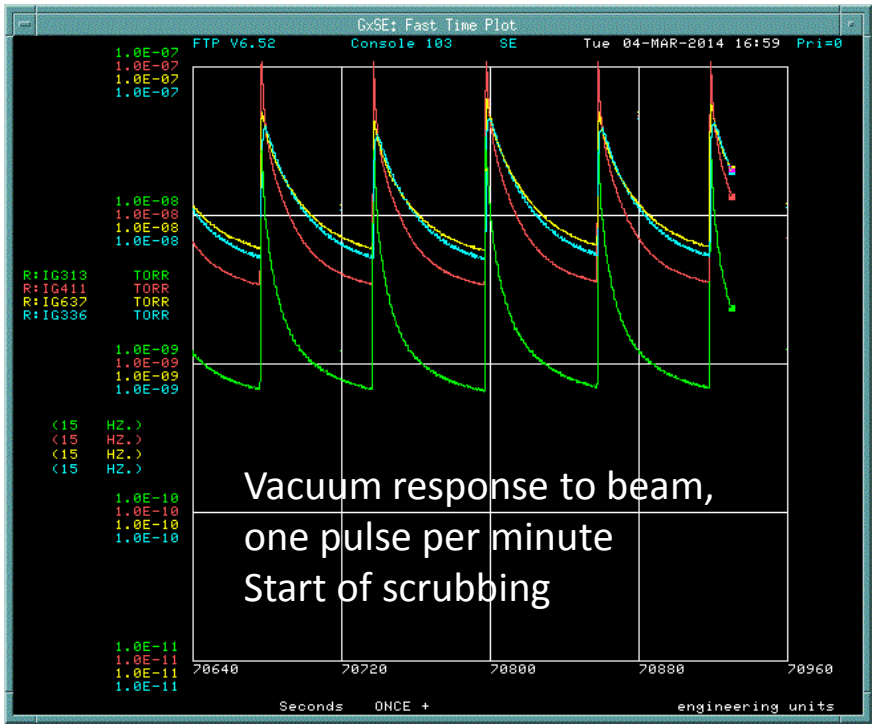
Recycler Commissioning

- Turn on after shutdown with Main Injector
  - NuMI at 240 kW
  - SY120 (SeaQuest / Test Beam): Reduces NuMI power by 10% (program planning choice)
- Commission recycler in parallel (effectively a brand new machine)
  - Open up apertures (sequential!)
    - Some issues with new installation
    - Some pre-existing issues (pbars ~6π, protons 15-20π)
  - Commission Recycler RF system and transverse dampers
  - BLM soft/firmware upgrade: no dead time
  - Orbit and tune corrections while MI is ramping
  - Condition beam pipe (scrubbing)

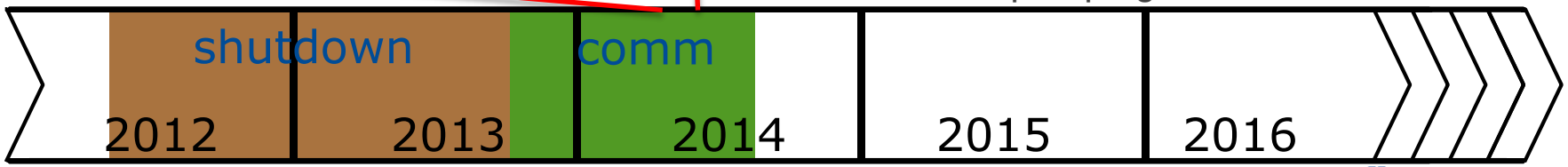


Vacuum Scrubbing

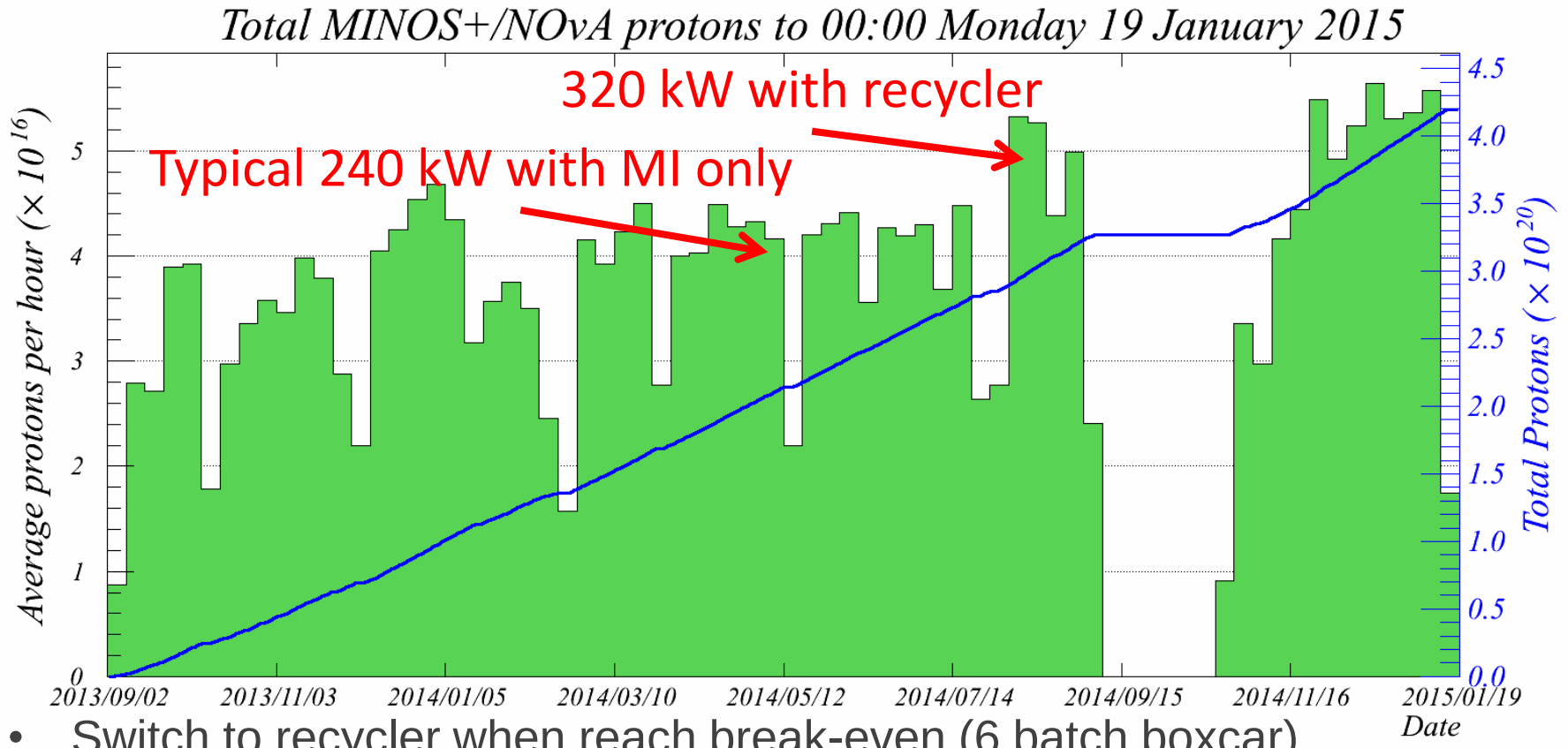




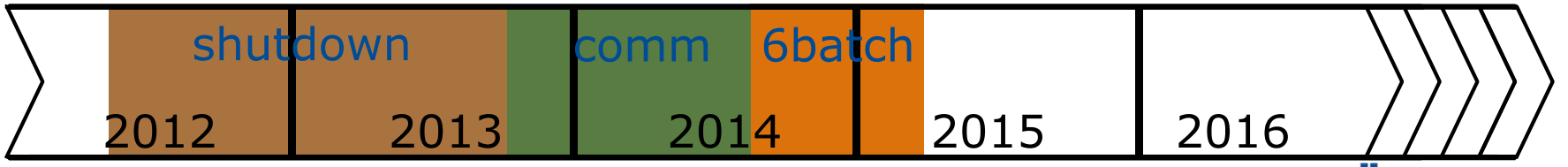
- Electron bombardment of beam pipe surface liberates adsorbed gasses
- Pressure reduction from gas desorbtion/pumping and SEY decrease



Recycler Commissioning

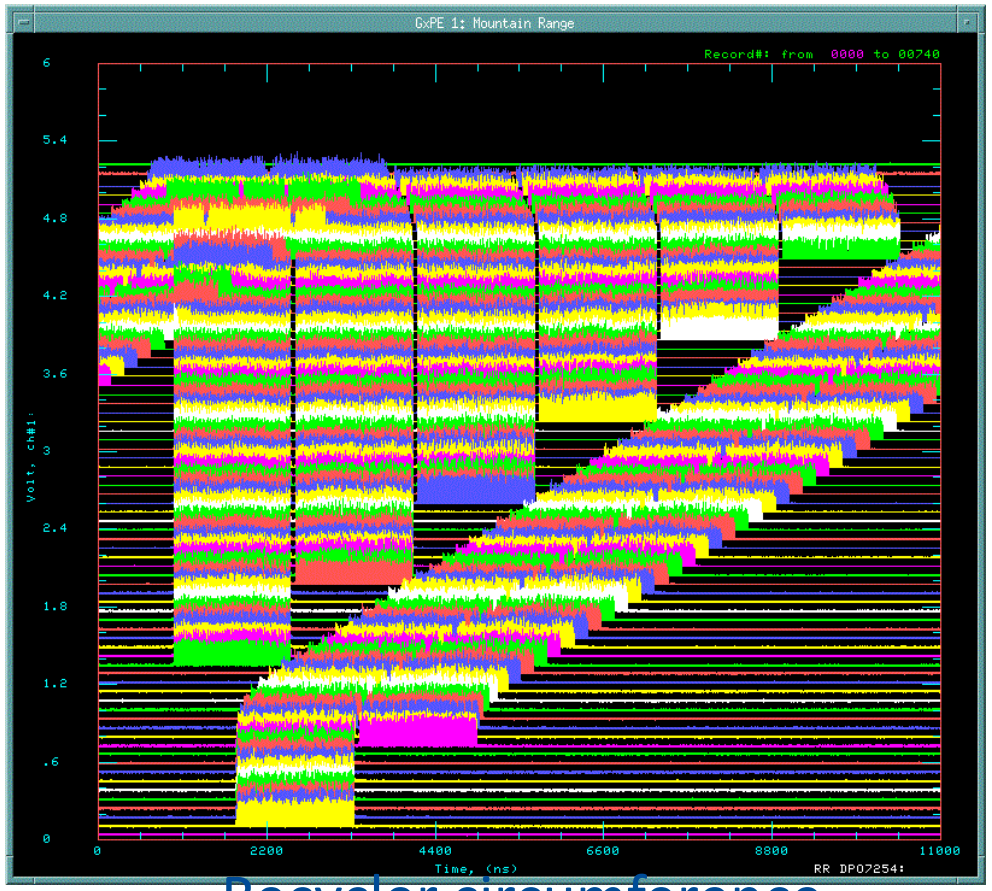


- Switch to recycler when reach break-even (6 batch boxcar)
  - Discovered horizontal instability (more later)



2+6 slip-stacking

- Can operate without upgraded Booster rep rate
- 2+6 ->
  - Decelerate 2 batches
  - Inject 6 more
  - Recapture by firing transfer kickers at right time
    - Into ~1MV MI bucket
  - Recycler injections on MI downramp



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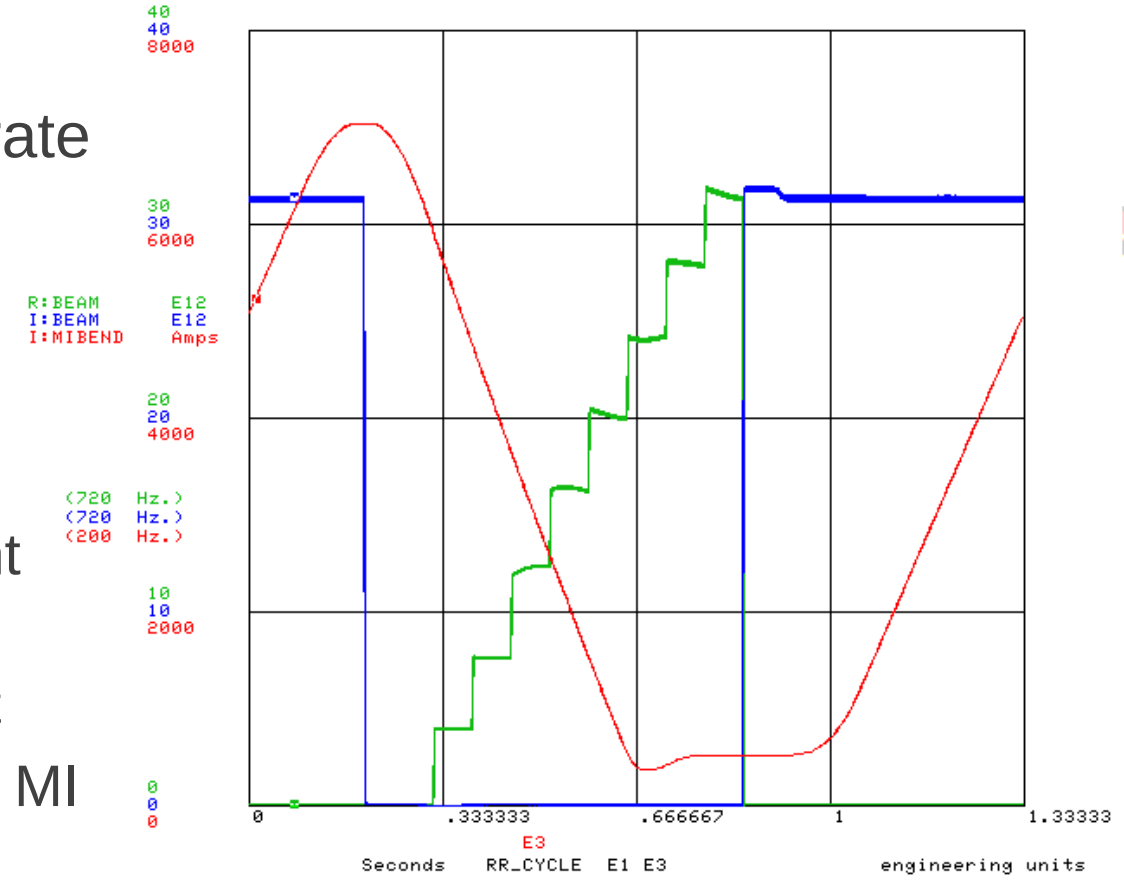

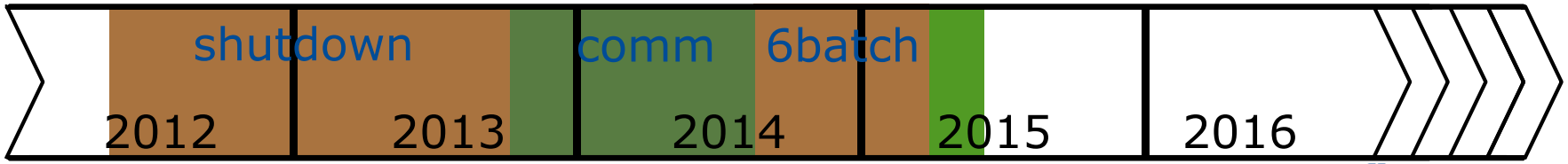

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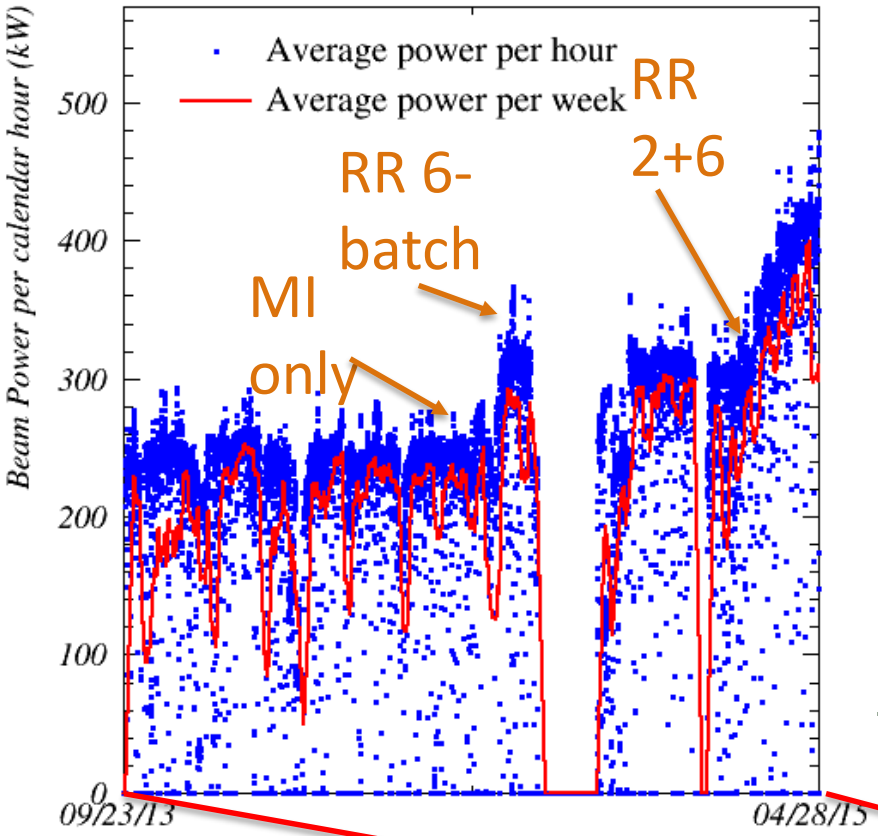

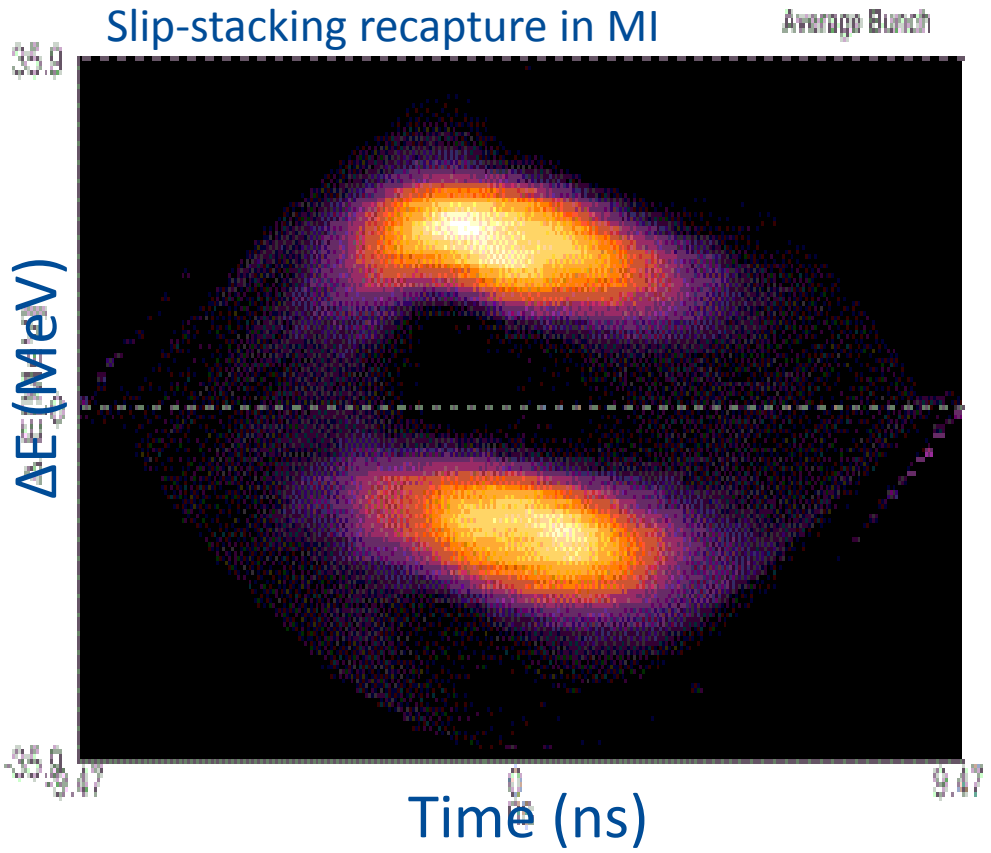

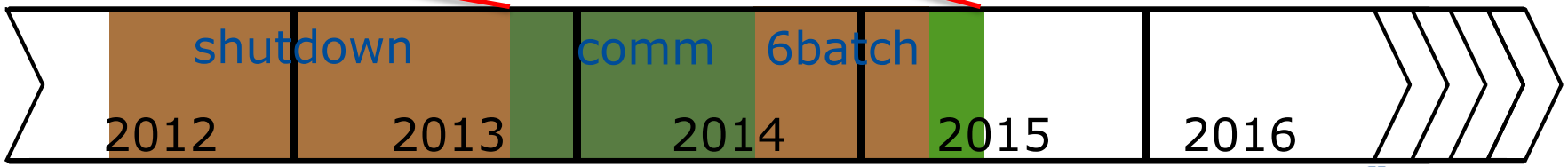

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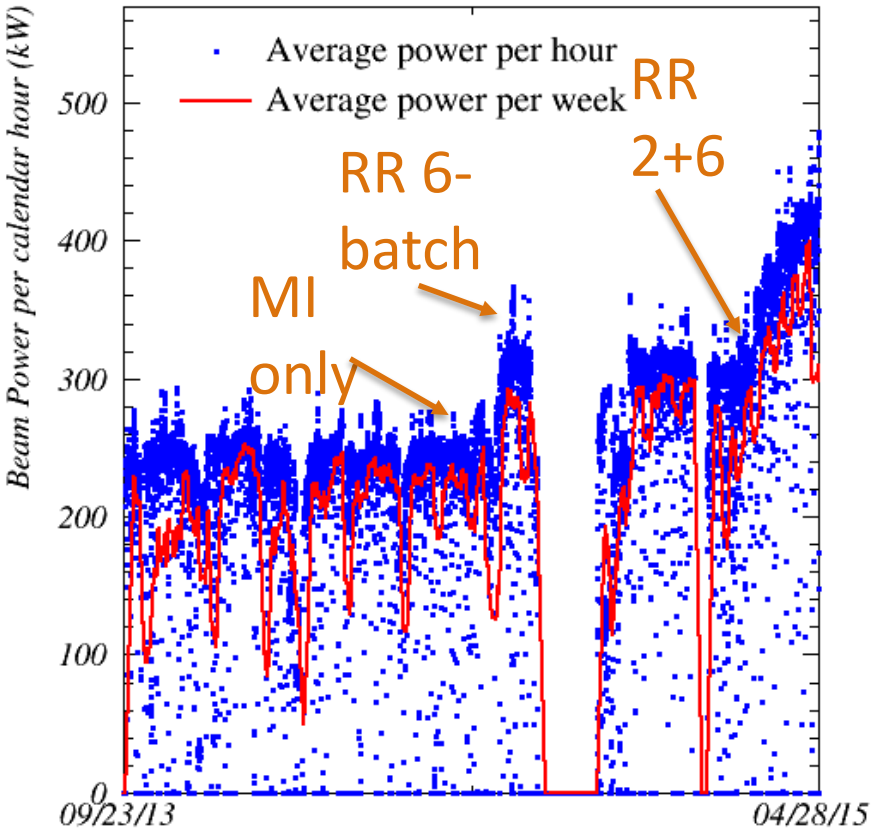
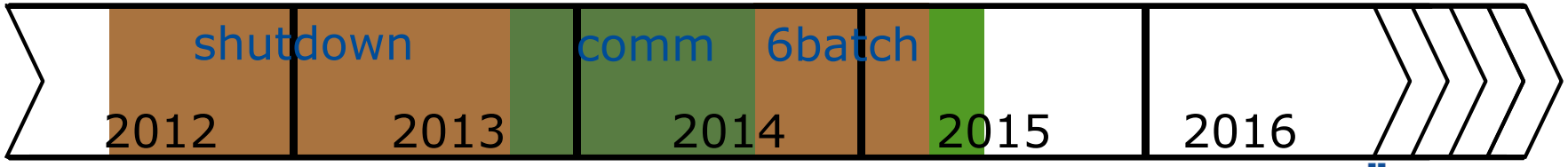
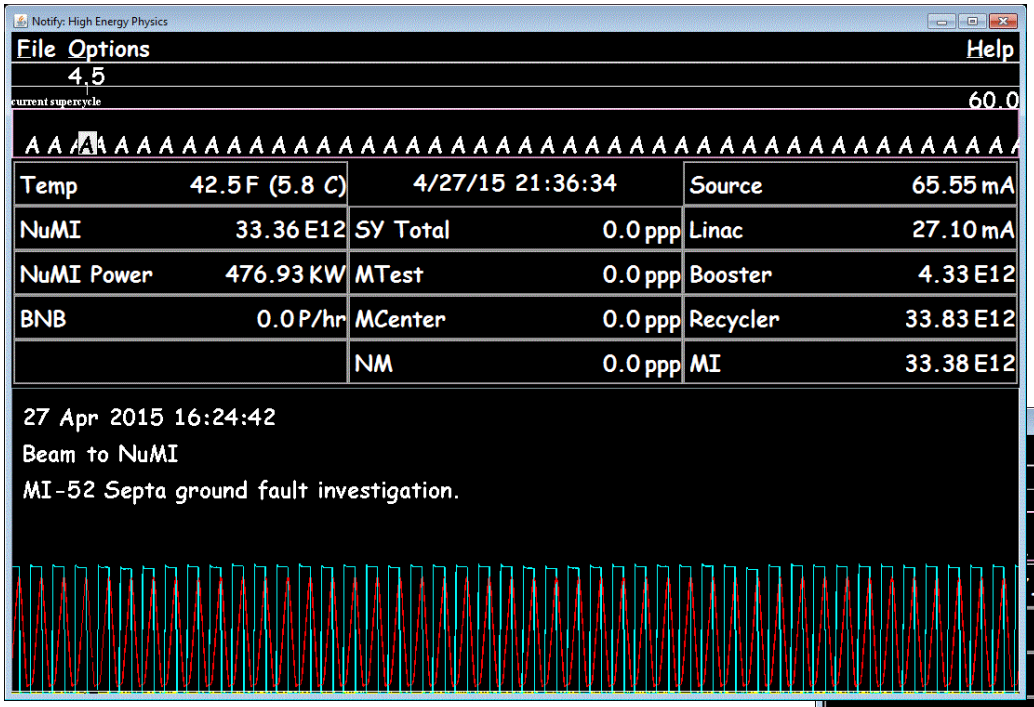
2+6 slip-stacking



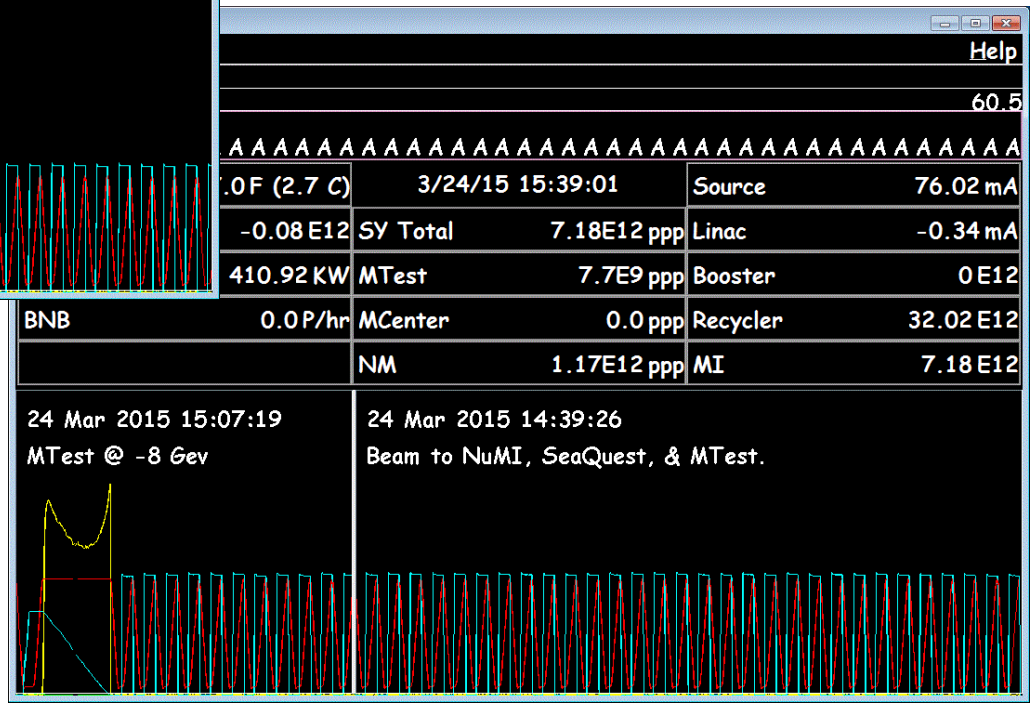
- Shown is beam power per calendar hour (blue) and per rolling 168 hour week (red)
  - Peak hour 482.8 kW
    - No SY120
  - Best continuous week average 400.4 kW
    - With SY120



Normal Operation

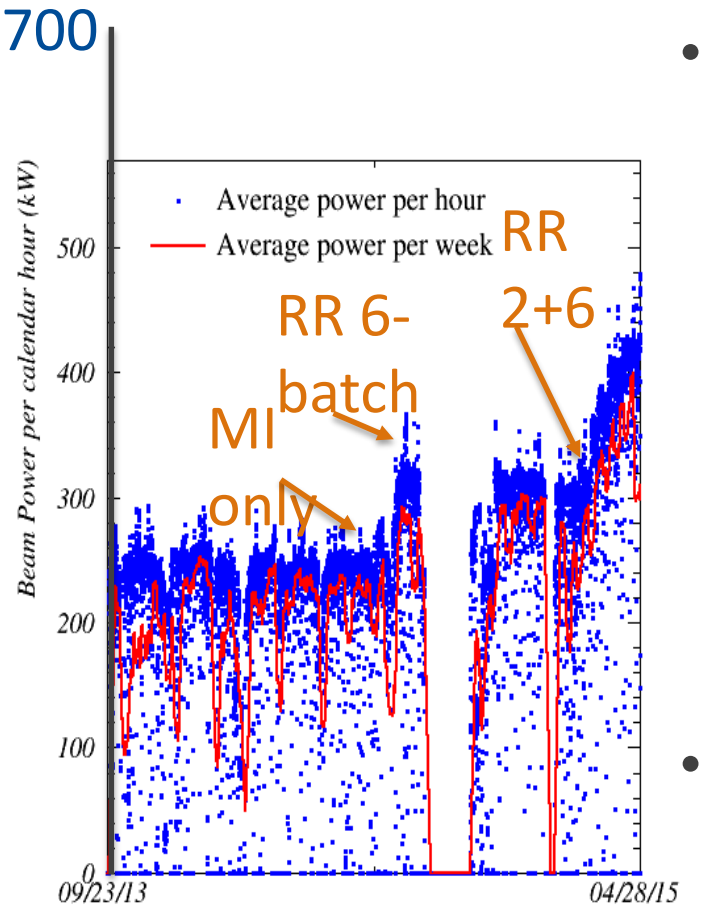


SY120 not running

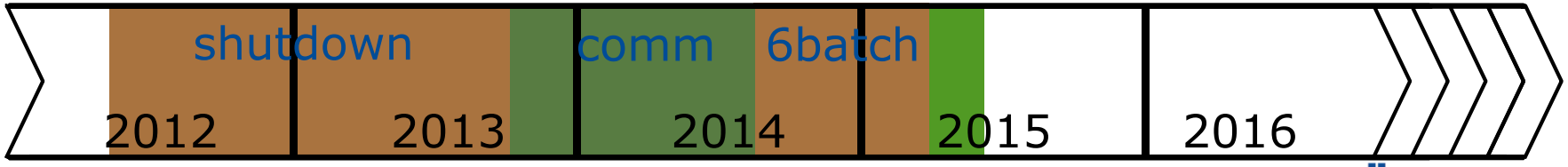


SY120 running

Roadmap to 700kW



- Current Operation
  - 2+6 slip-stacking
  - 460-480 kW (without SY120 in timeline)
  - 4.3E12 per booster batch
  - 6.8 Hz booster pulsing
- Met 2+6 milestones in March



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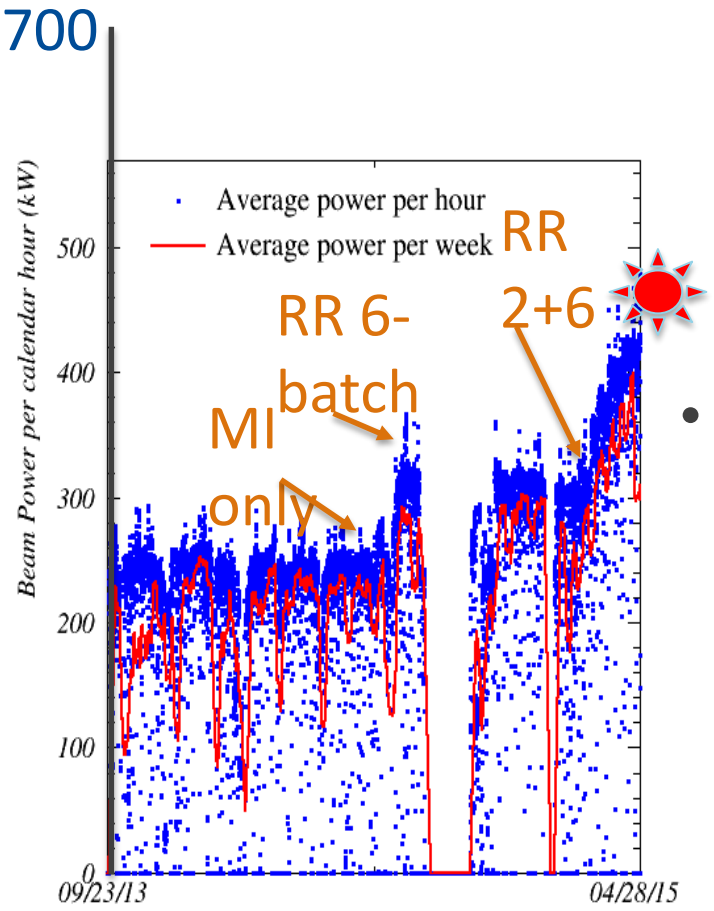
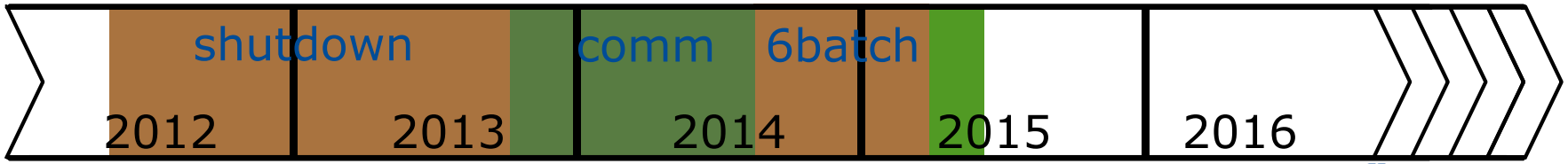


- May 2015
  - Run 4+6 slip-stacking for 1 hour
  - Needs 8.3 Hz booster pulsing



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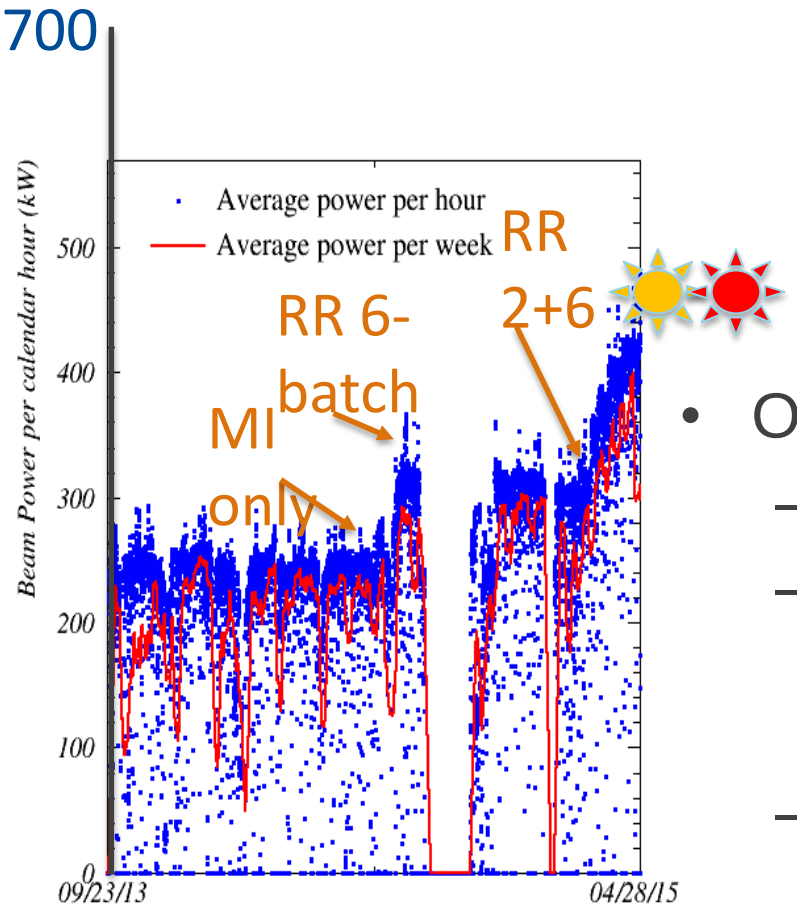
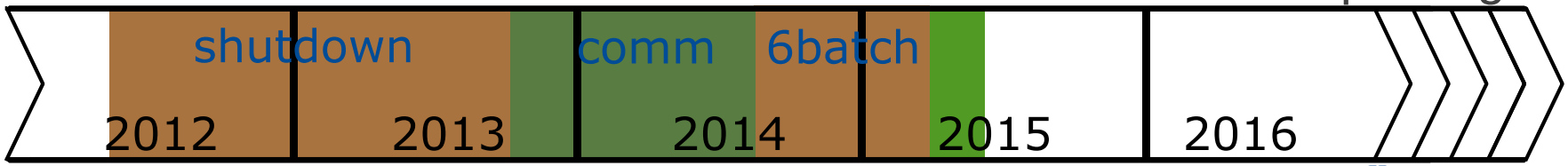


- October 2015
  - After shutdown
  - 4+6 slip-stacking operational at current 460 kW
  - Needs 8.3 Hz booster pulsing



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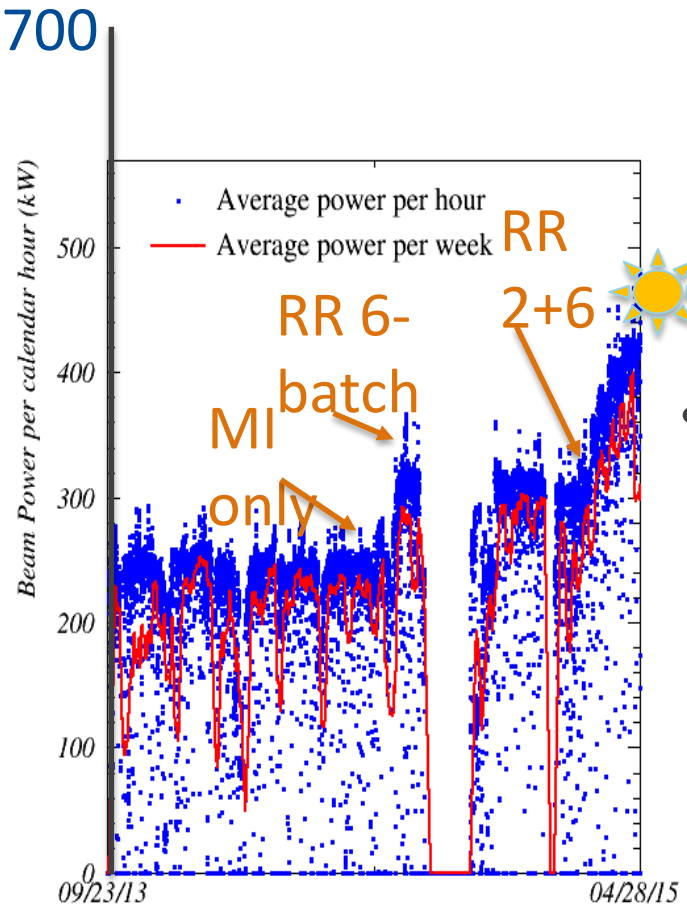
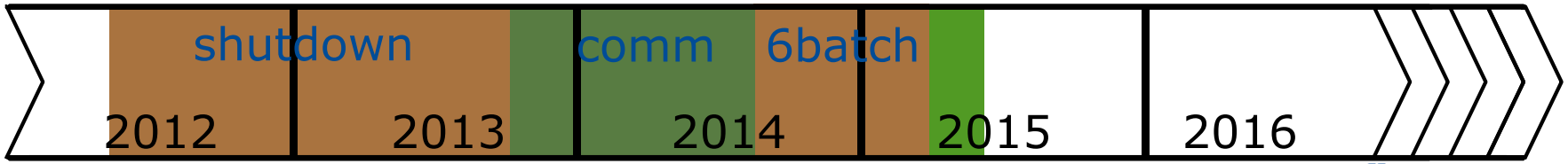
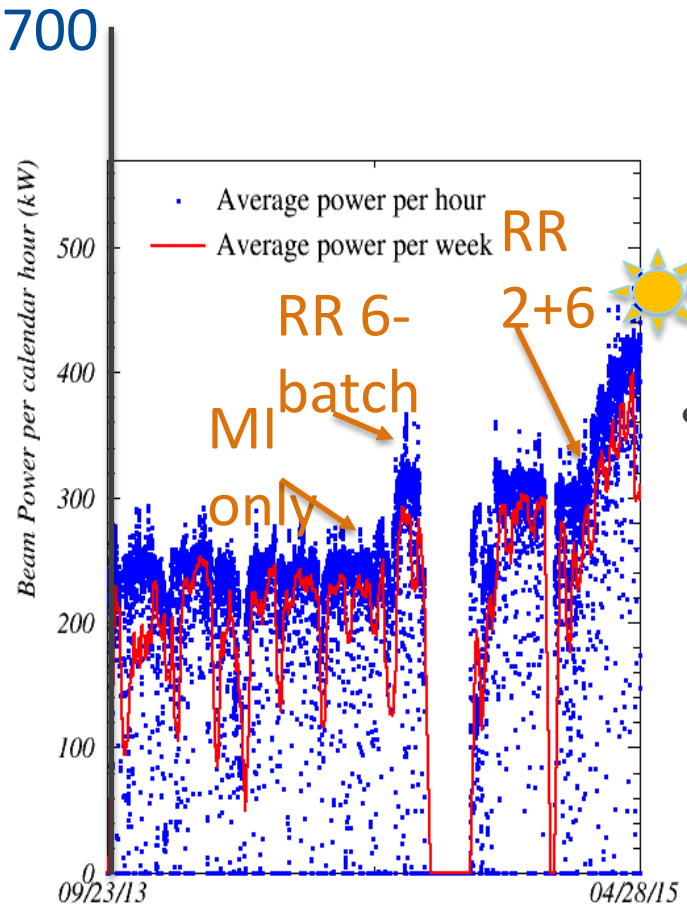


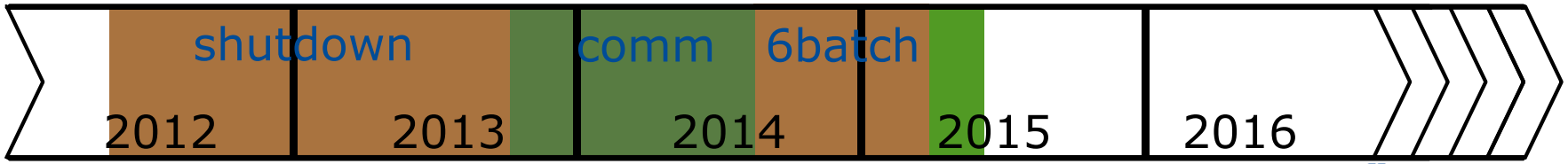
- November 2015
  - 4+6 slip-stacking operational at 575kW (4.3E12 per booster batch)
  - Needs 8.3 Hz booster pulsing



Roadmap to 700kW



- January 2016
  - 6+6 slip-stacking operational at 575kW
  - Needs 9.8 Hz booster pulsing



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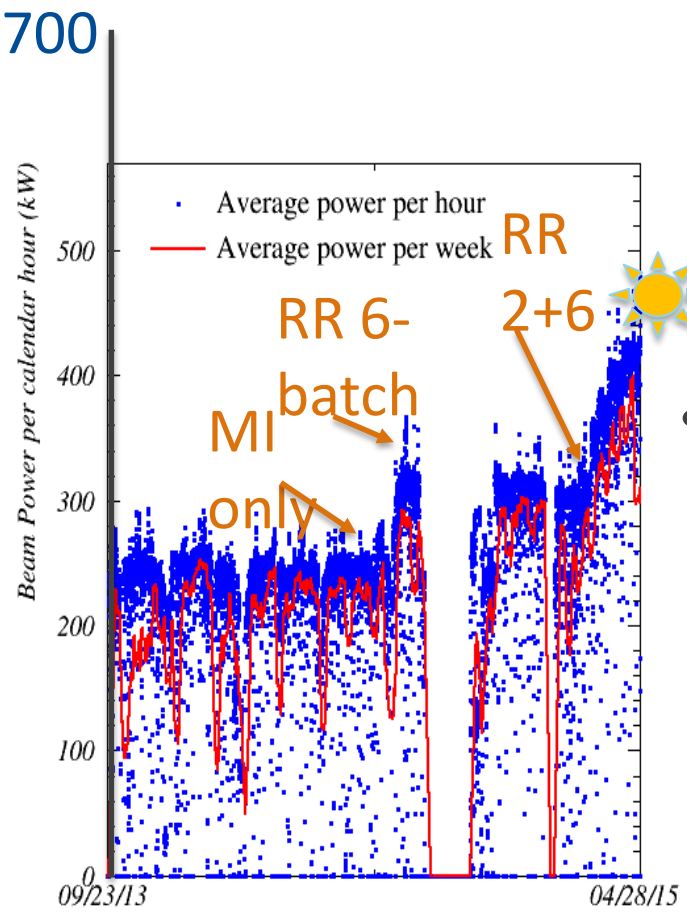
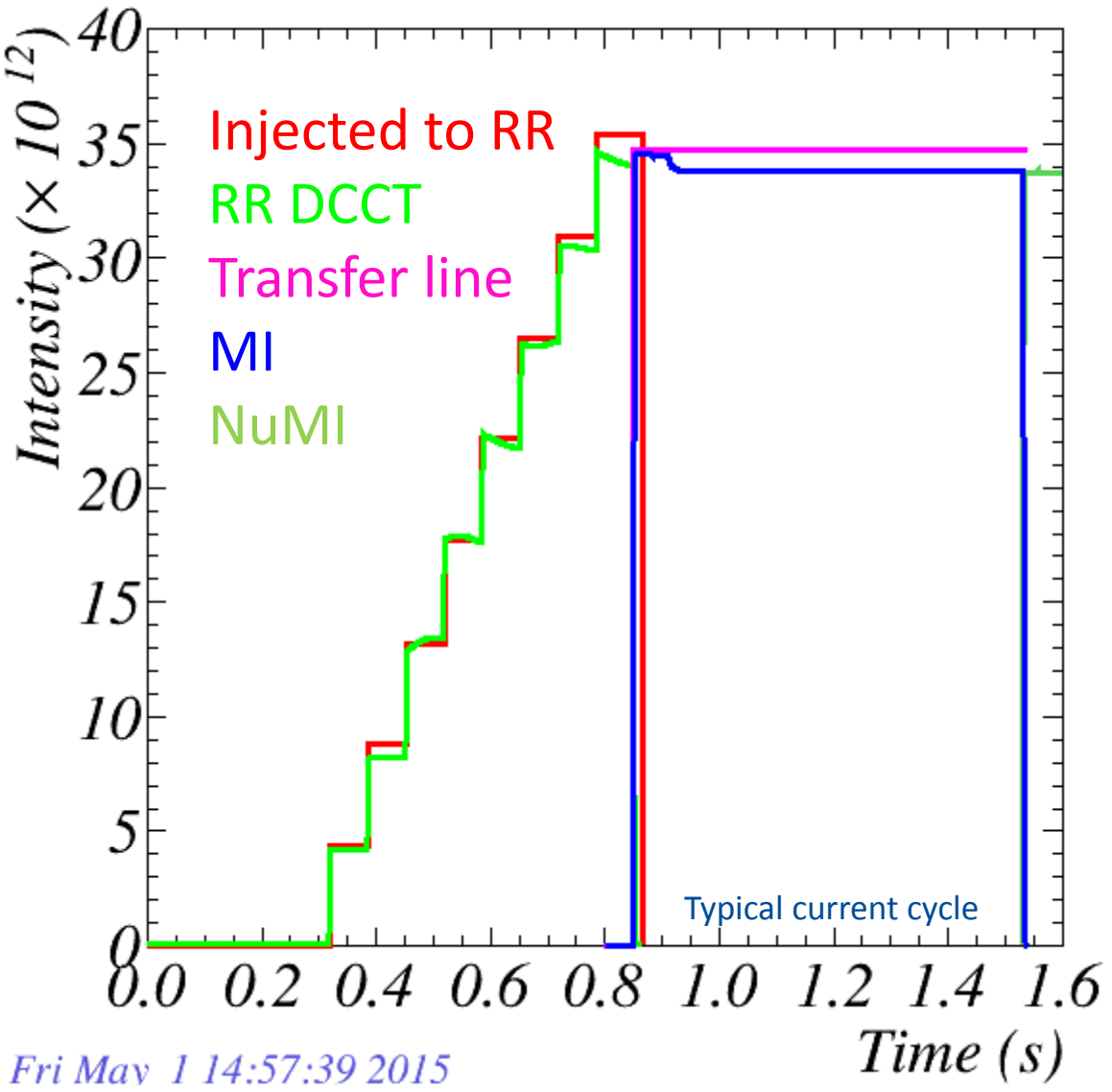


- February 2016
  - 6+6 slip-stacking operational at 700kW (4.3E12 per booster batch)
  - Needs 9.8 Hz booster pulsing

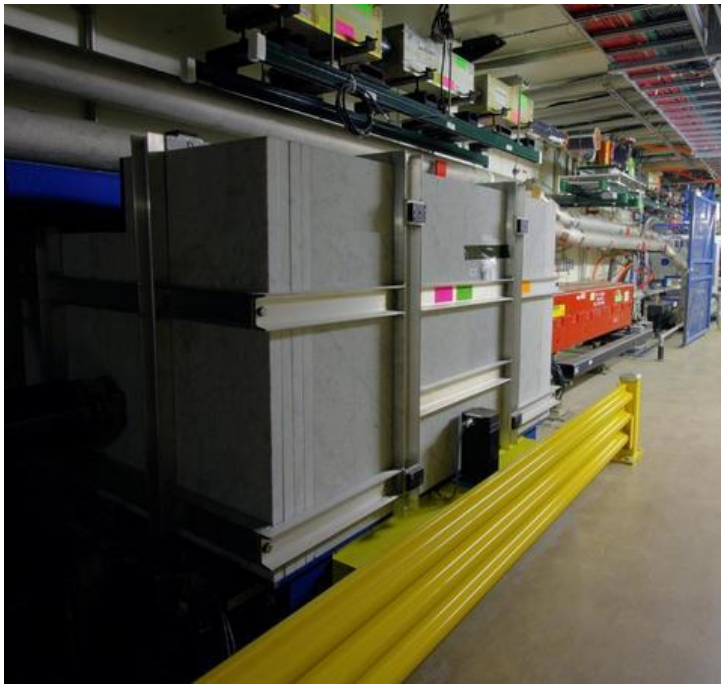
Current Beam Losses (400kW + sustained operation)

- Recycler efficiency 98.5% -> 440W loss
  - cf. MI transverse loss in Tev era
- MI start of ramp loss 2% -> 670W loss
- MI transition 40W loss
- Total tunnel loss 1.2kW
  - 360 mW/m
- But it's not distributed round the ring



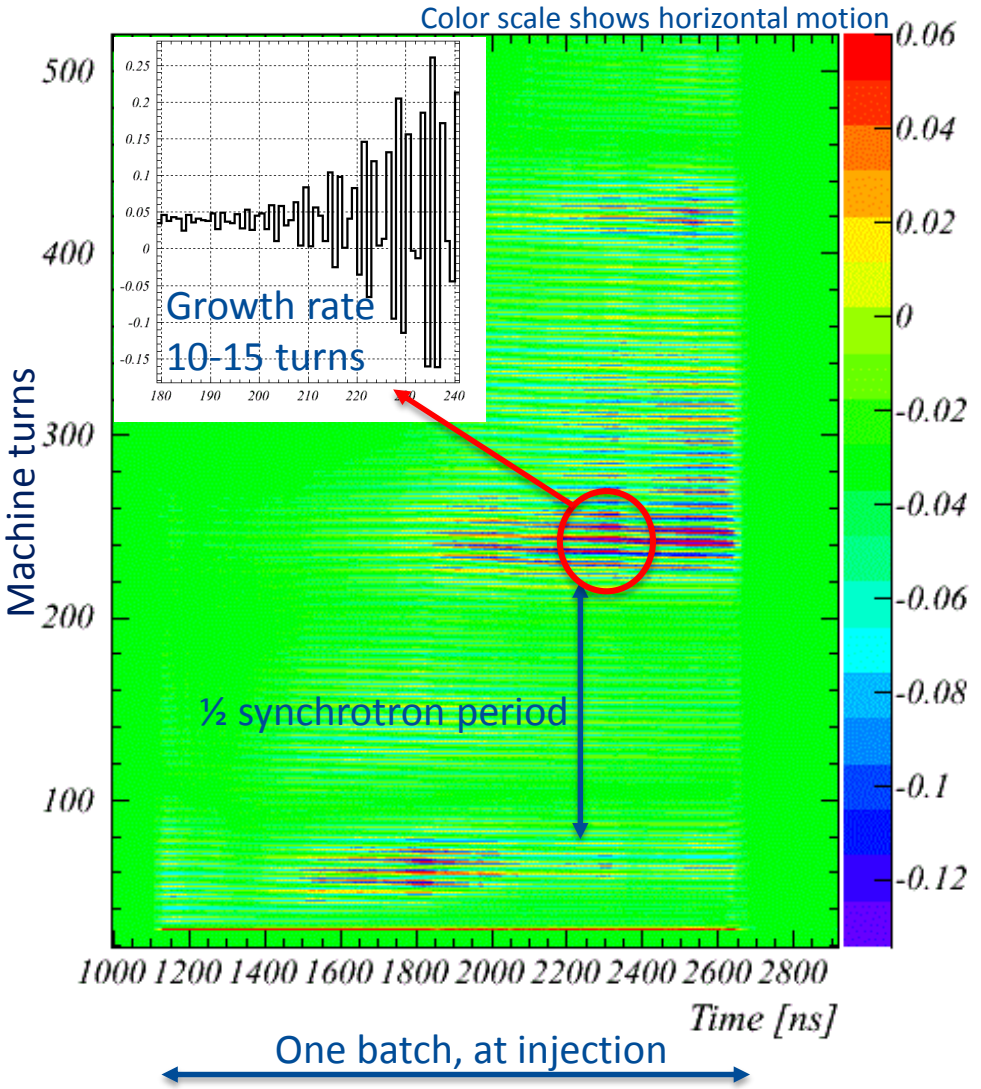
Collimating losses

- MI start of ramp loss 670W, but ~95% captured by MI ring collimators
  - 30W loss elsewhere (Lambertsons)
  - 40W transition loss (few spots in arcs)
- RR 440W loss mostly at a few locations with poor aperture
  - Build recycler collimators to trap these losses
    - Only a couple of high-ceiling spots suitable (RR usually less than 1 foot from ceiling)
    - Design in progress (like MI, but vertical only?)
    - Aim to install in 2016 shutdown



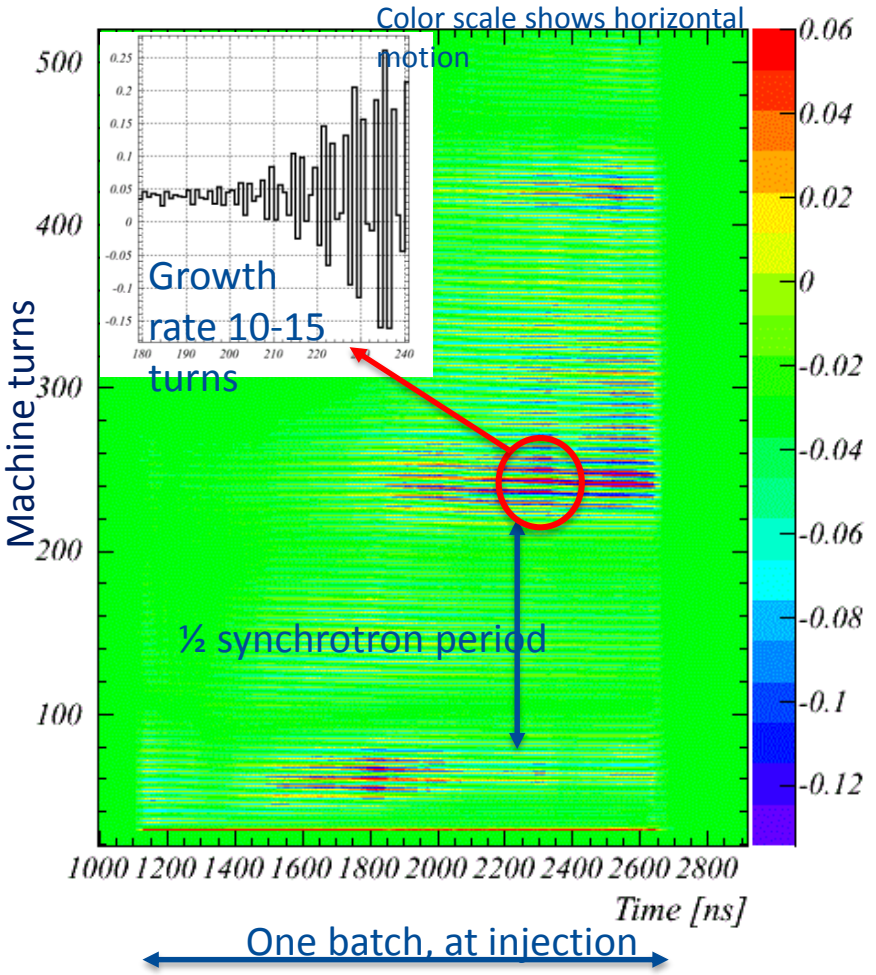
Recycler Horizontal Fast Instability: a surprise

- When we started to run the six-batch boxcar cycle at high intensity
- Fast instability at injection for high linear charge density
  - Only in horizontal plane
  - Single batch effect – not made worse by more beam in machine
    - In fact, the opposite
    - Before 2014 shutdown, first batch intensity ~80% of others
  - After shutdown, can run full intensity without instability
  - Hints that threshold increased with vacuum scrubbing



Recycler Horizontal Fast Instability: a surprise

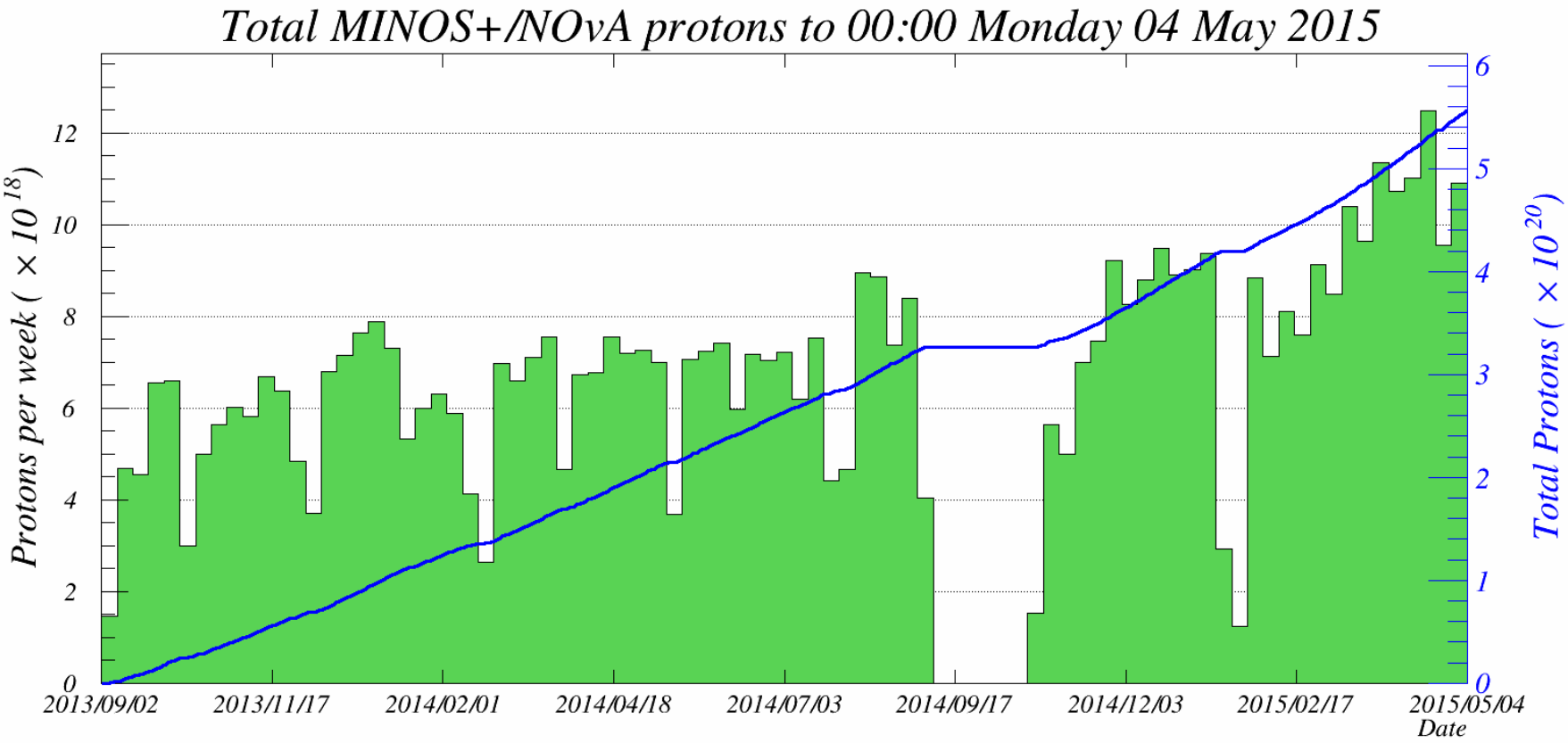
- Doesn't occur in Main Injector at same intensity
  - (even with shorter bunches)
- Differences between RR and MI
  - Combined function magnets?
  - RR beam tube a little smaller
  - Studies and simulations in progress
    - E-cloud is a popular explanation given the fast growth rate, but we can't yet explain all the details
  - Similar instability seen at extraction in CERN PS?
    - R. Steerenberg et al., PAC07
  - **Does not occur for 700kW operations**
    - Potential issue at PIPII intensity



Outlook for Main Injector / Recycler

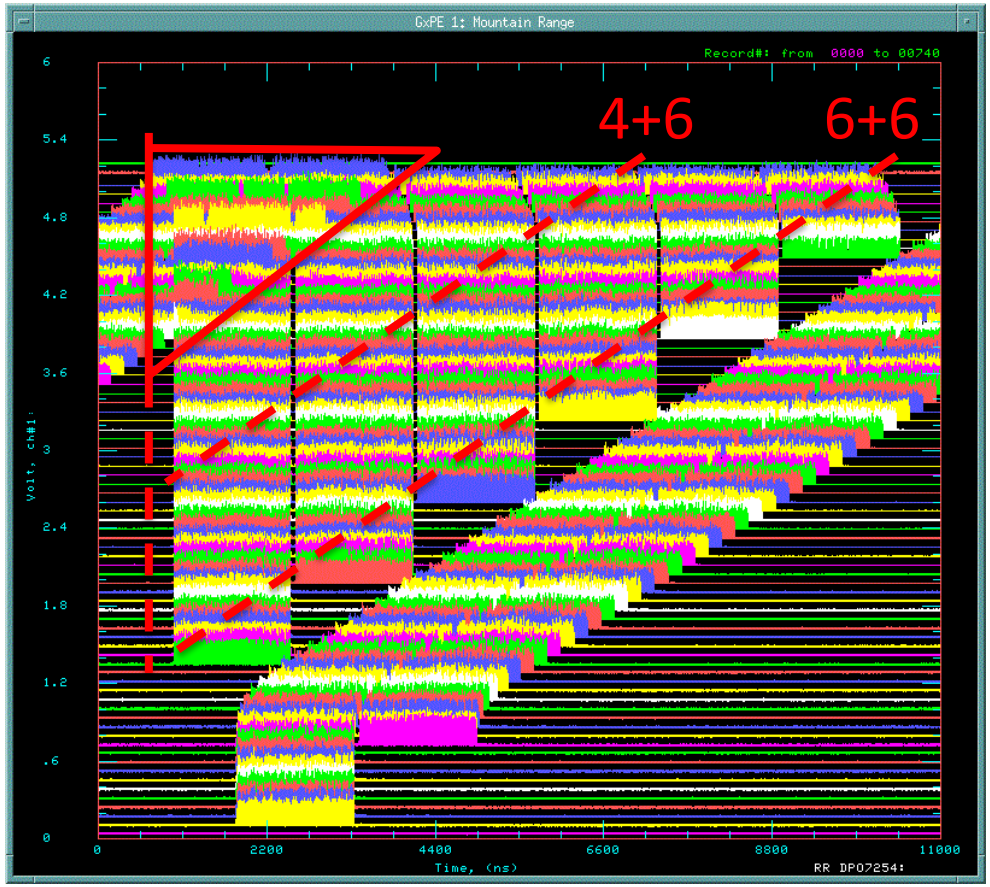
- This decade
  - Current peak hour 482.8 kW / 400.4 hour continuous week
  - Deliver 700 kW to NuMI to support NOvA physics
    - 700 kW milestone next February
  - Install Recycler collimators
  - Replace TSPs with ion pumps (next 3 years)
  - Install 2.5 MHz rf, extraction line in Recycler for g-2/mu2e
- Next decade: more power. PIP -> PIP-II
  - Initial 1.2 MW to LBNF/DUNE
  - Same slip-stack scheme as current 700 kW, but 50% more beam per pulse (and small rep rate increase)
    - New rf in RR, MI
    - New beam physics issues?
  - End of the road for lossy slip-stacking – replace Booster to go higher

Backup Slides

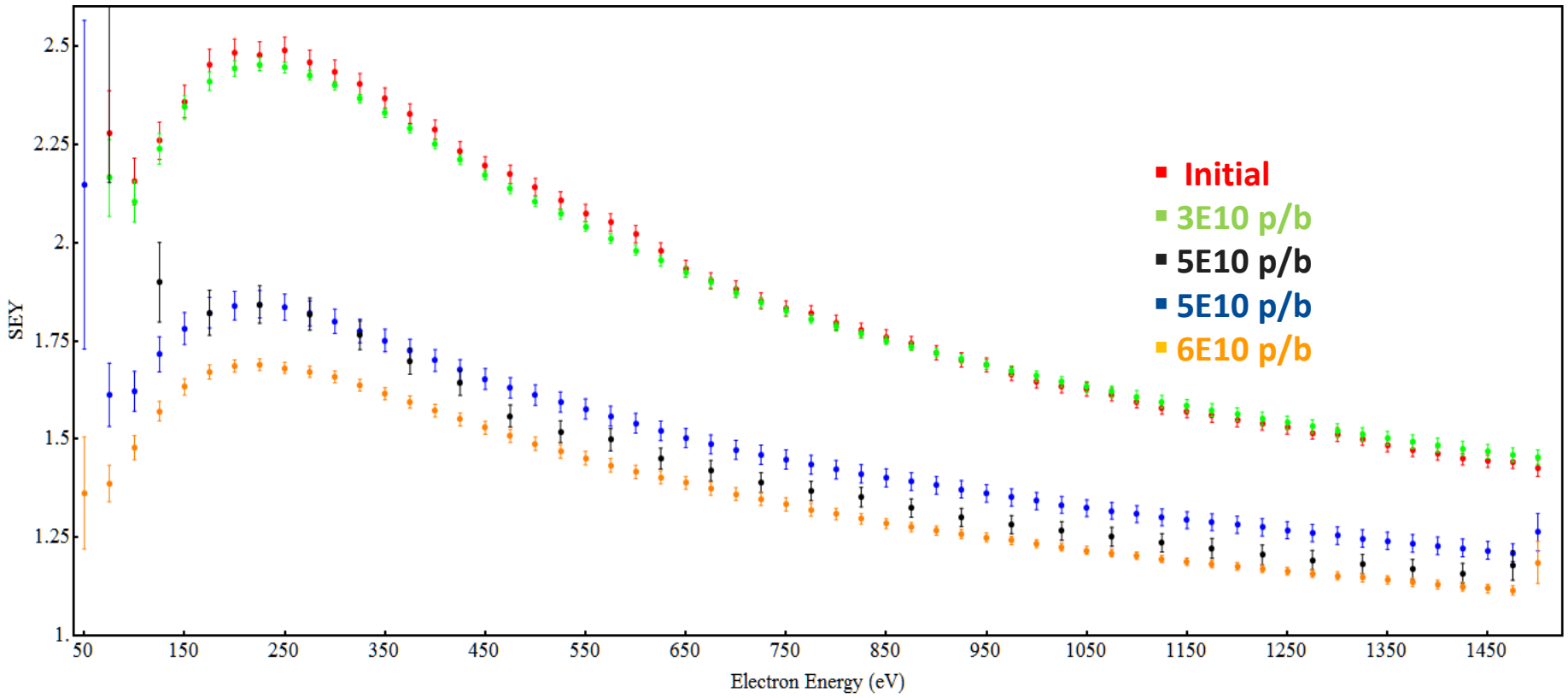


Challenges for 4+6 and 6+6

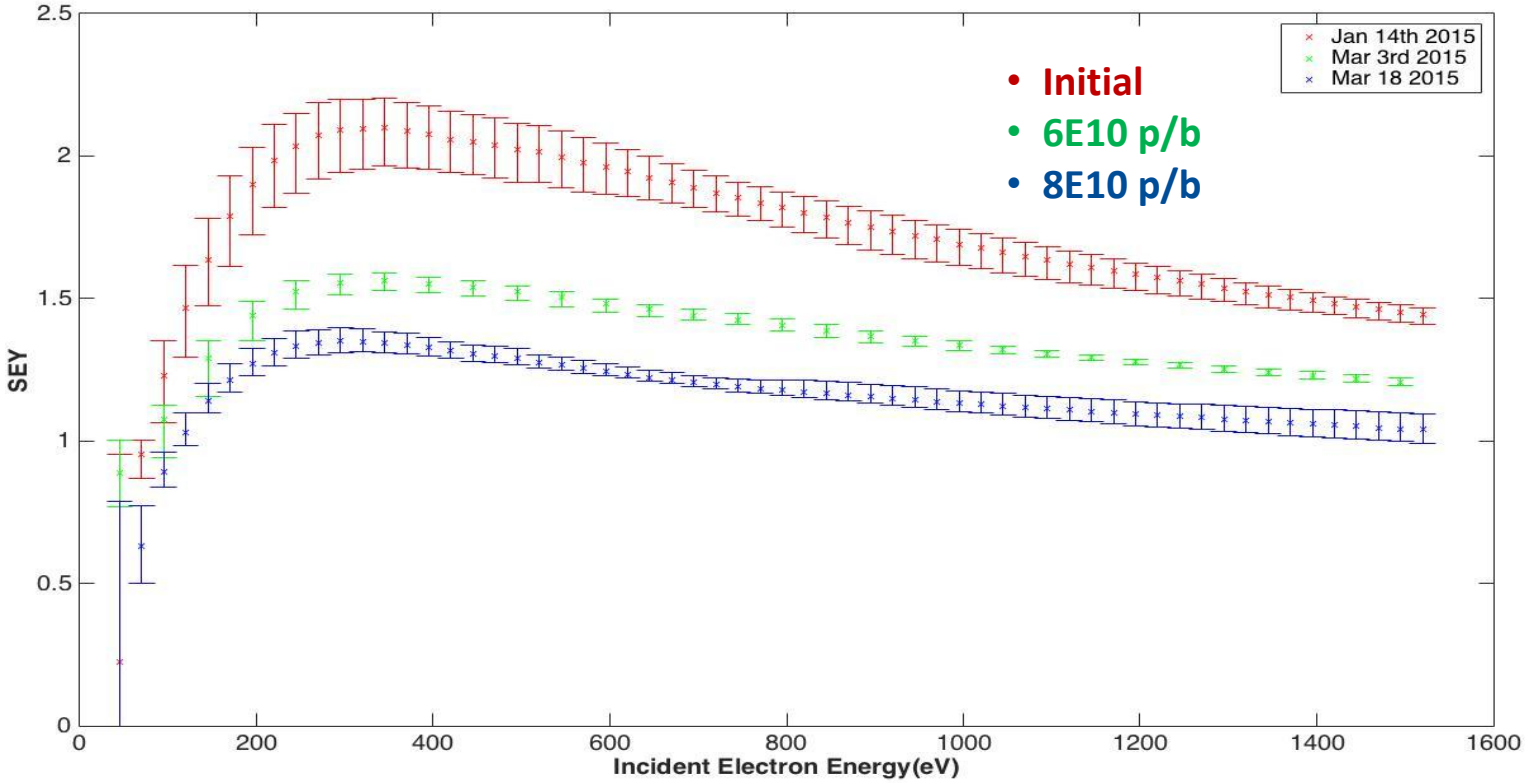
- Transverse damping challenging for region where beams overlap
  - Small for 2+6, larger for 4+6 and 6+6
  - Need to run with larger chromaticity to gain stability
    - Expect to be a little lossier, but ran like this in MI



MI SEY (316L SS) for different intensities

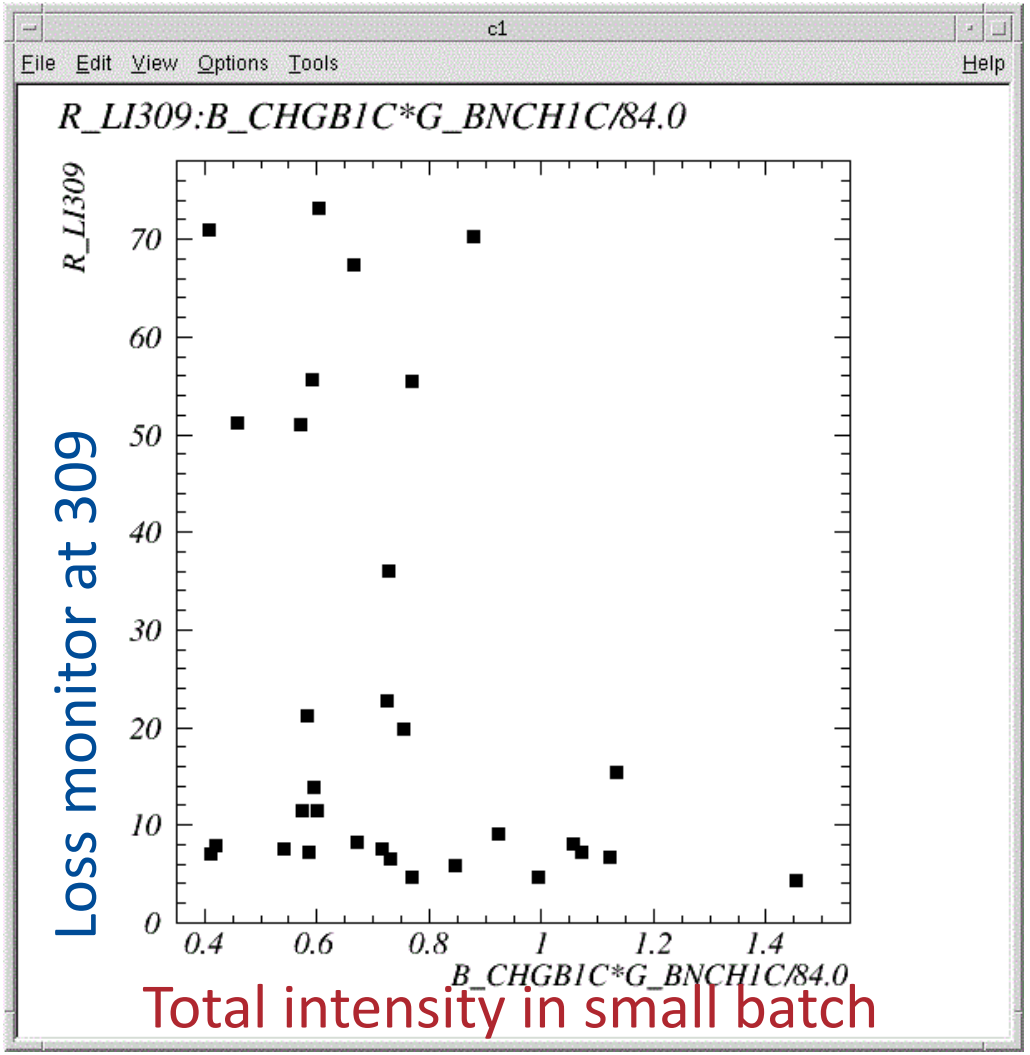


MI SEY (TiN coating) for different intensities

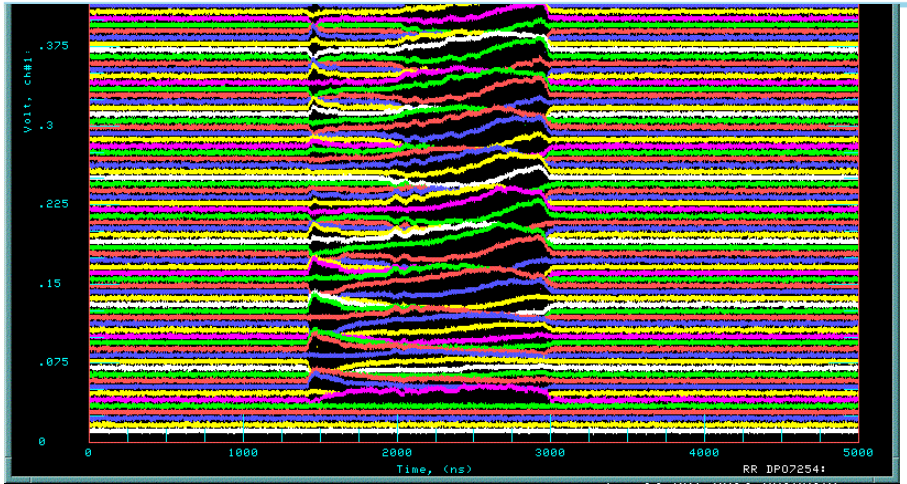


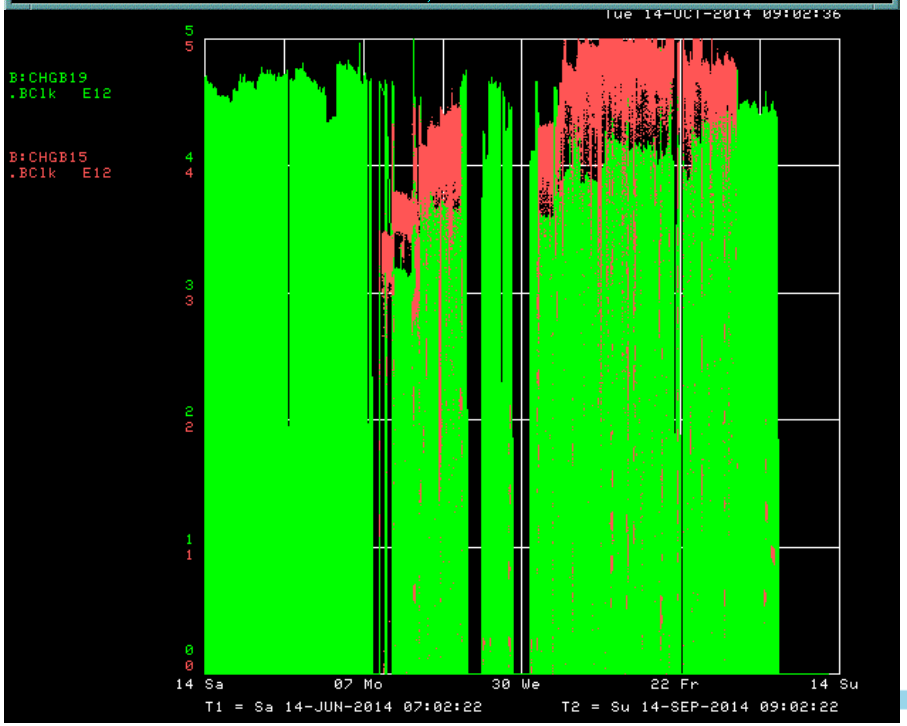
Leading small batch stabilizes large batch

- A batch that would go unstable is stable if there's already a small batch in the machine
  - Depends on total beam in the small batch
  - Not on bunch intensity or number of bunches
- But has to remain in the ring. Replacing the small batch with the large one doesn't have stabilizing effect



A surprise: Recycler fast horizontal instability

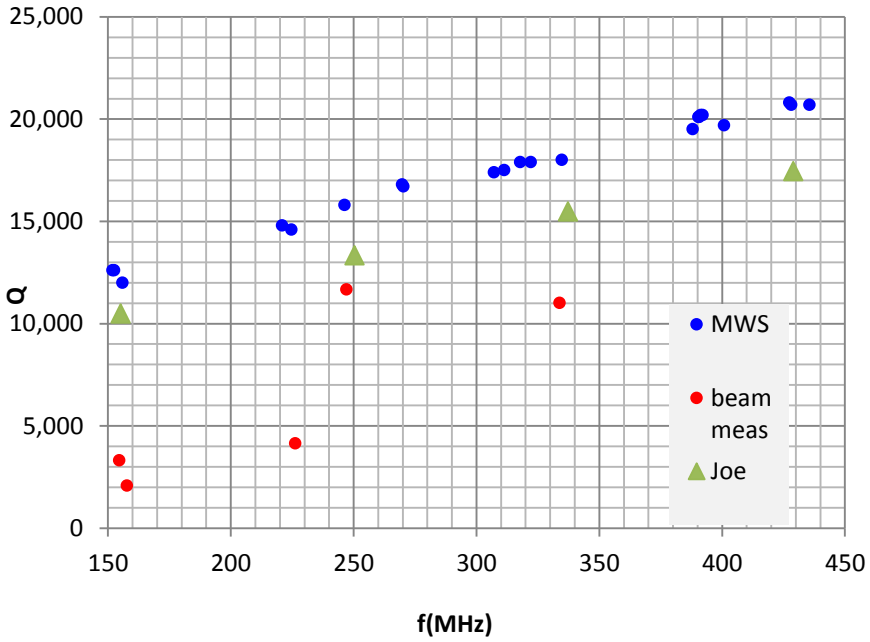


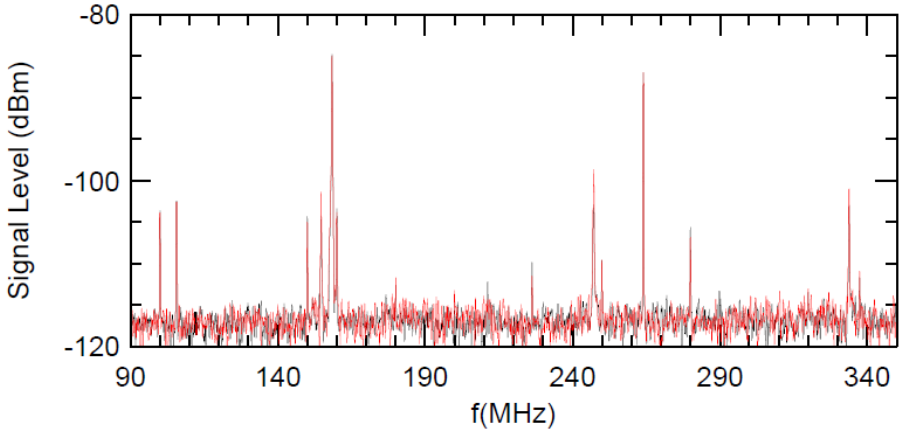


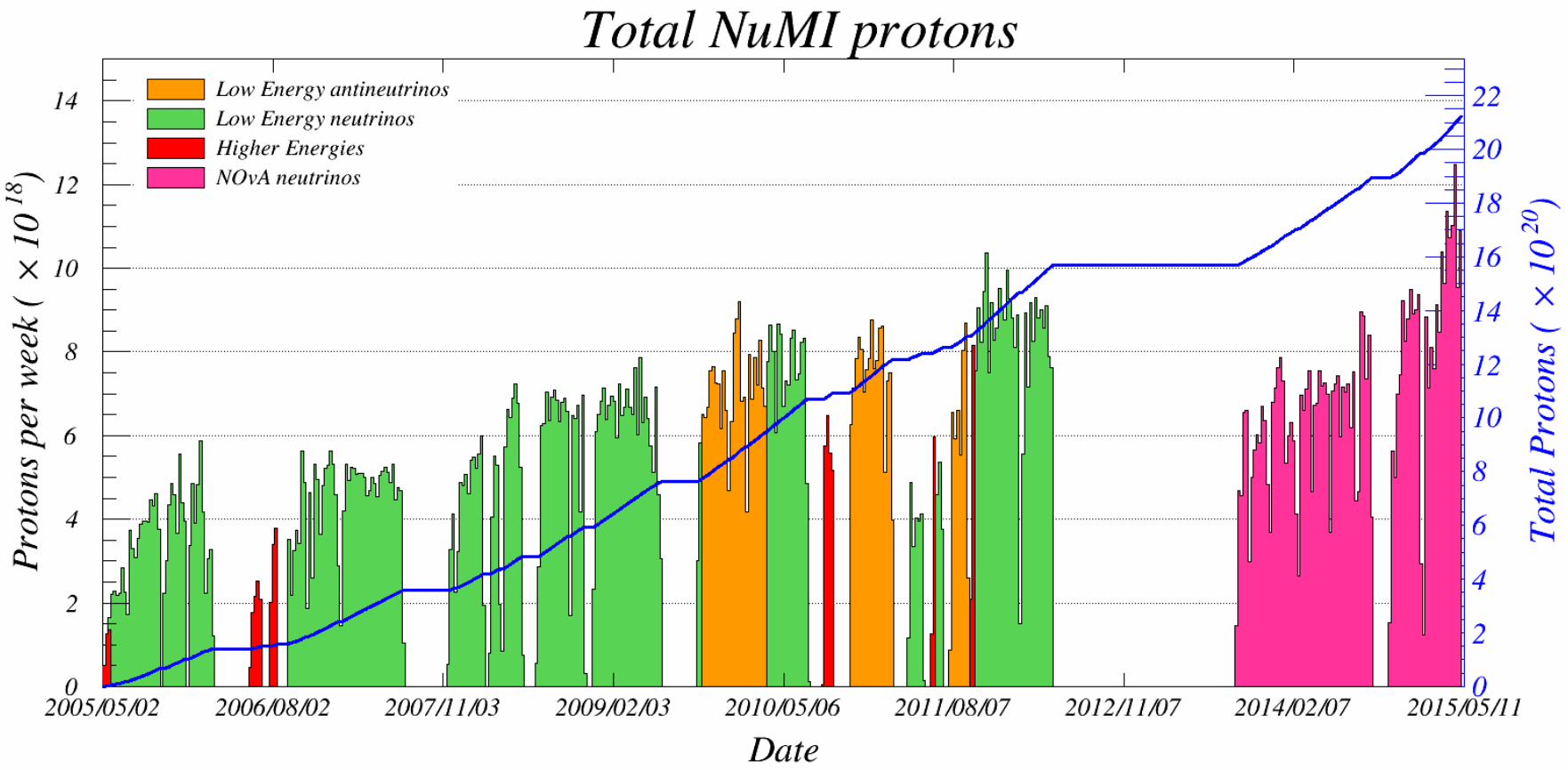
- Coherent horizontal motion grows in second half of batch
  - Coupling between bunches
- Before fall shutdown
  - Instability present for second and subsequent injections on multi-batch cycle, but threshold is higher
    - Green: first injection
    - Red: Other injections
- Since shutdown, instability does not impede normal operation
  - Don’t need smaller first batch

Some causes of Recycler Instability ruled out

- Happens with and without transverse dampers
- RF cavity modes match simulation – no surprises
- Changing cavity tuning has no effect
- Other impedance in machine a few orders of magnitude too small to make 10-15 turn growth rate






Total NuMI protons
Low Energy antineutrinos
Low Energy neutrinos
Higher Energies
NOvA neutrinos
Protons per week (× 10 18)
Total Protons (× 10 20)
Date
0
2
4
6
8
10
12
14
16
18
20
22
2005/05/02
2006/08/02
2007/11/03
2009/02/03
2010/05/06
2011/08/07
2012/11/07
2014/02/07
2015/05/11