



# Reuse Recycler: High Power Proton Stacking at Fermilab

Phil Adamson

HB2016

7<sup>th</sup> July 2016



# Reuse Recycler: High Power Proton Stacking at Fermilab

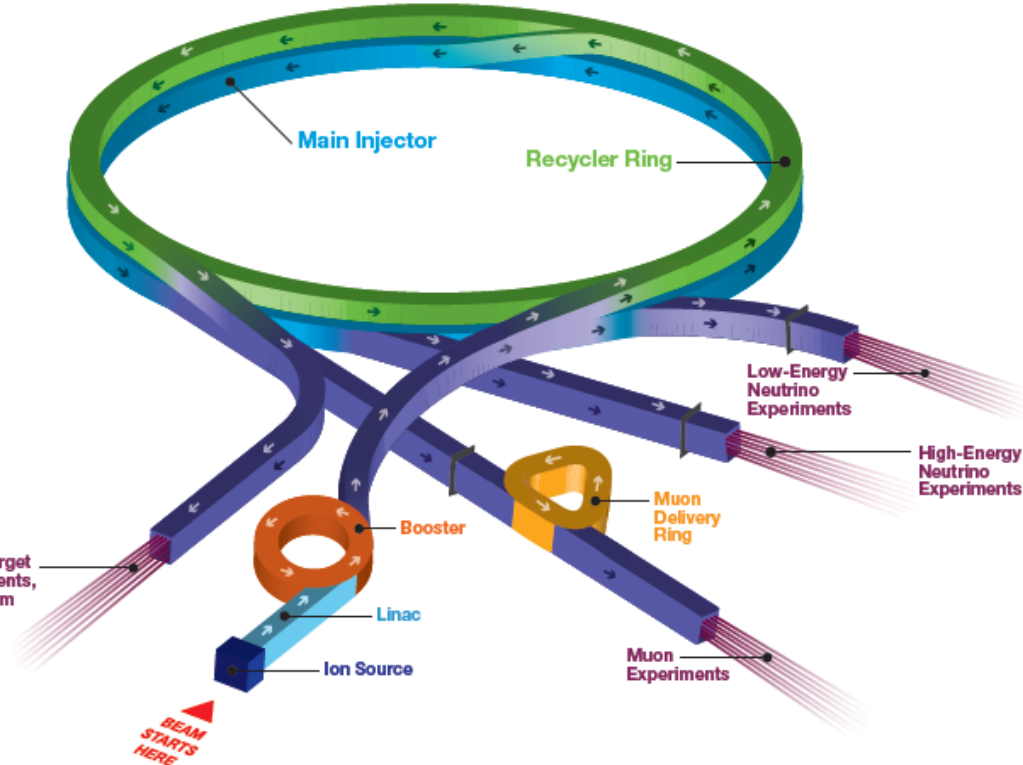
Phil Adamson  
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- Intro to Recycler
- Overview of progress
- Detailed issues

# About Recycler

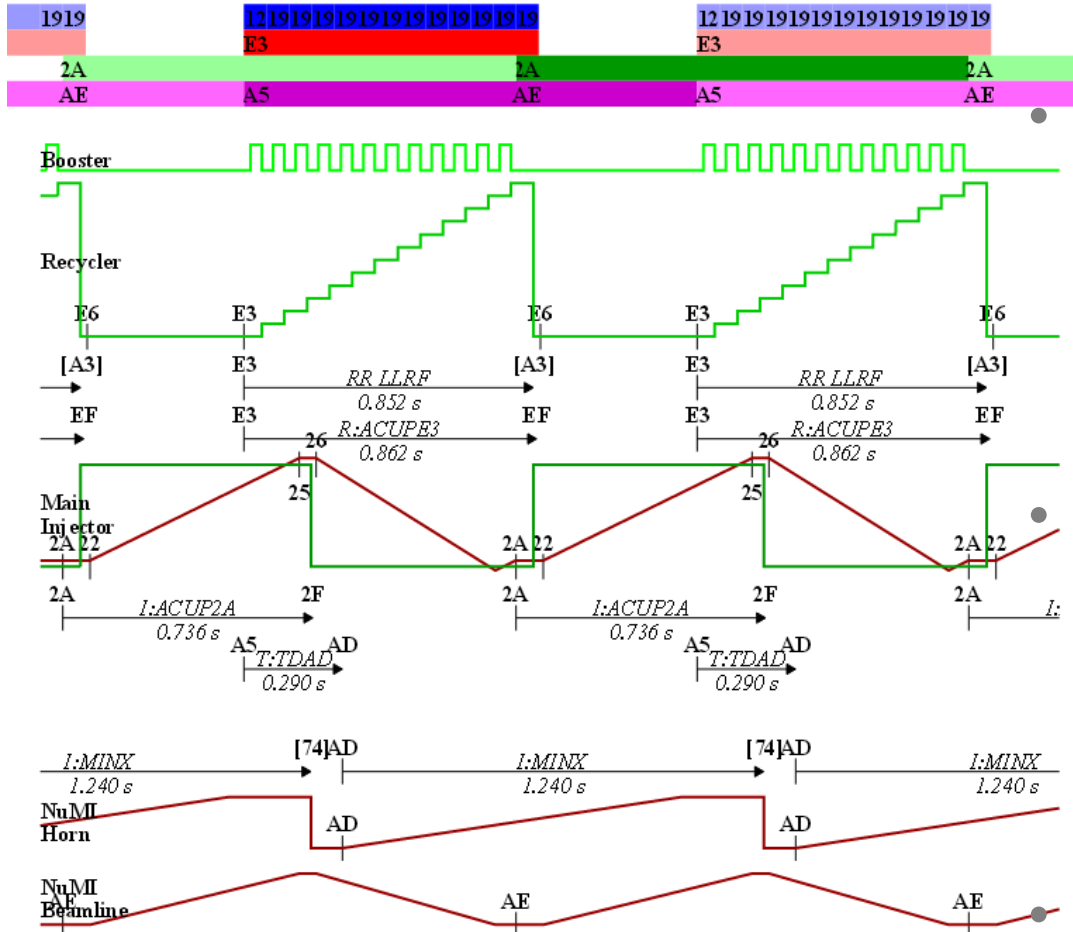
- Fixed 8 GeV KE ring
  - 3.3 km,  $h=588$  at 53 MHz
  - Combined function strontium ferrite magnets, FODO lattice
    - Strontium ferrite quads in straight sections
    - Powered trim dipoles / quads / sextupoles
  - Protons from Booster
    - (Slip-)Stack for MI
    - (From 2017) Rebunch in 2.5 MHz for Muon

## Fermilab Accelerator Complex



- NuMI is high-power user
  - Upgrade from 400kW to 700kW in NOvA project
  - NOvA, MINOS+, MINERvA

# NOvA upgrade scheme



- Recycle the Recycler as a proton stacker

- Hide 12-batch slip-stack process in recycler, allowing “overlap” of NuMI cycles and 1.33s rep rate

- Per-pulse intensity only increases 9% over 2012 – most gains from overlaps and increased ramp rate

In principle, Recycler looks like Main Injector...

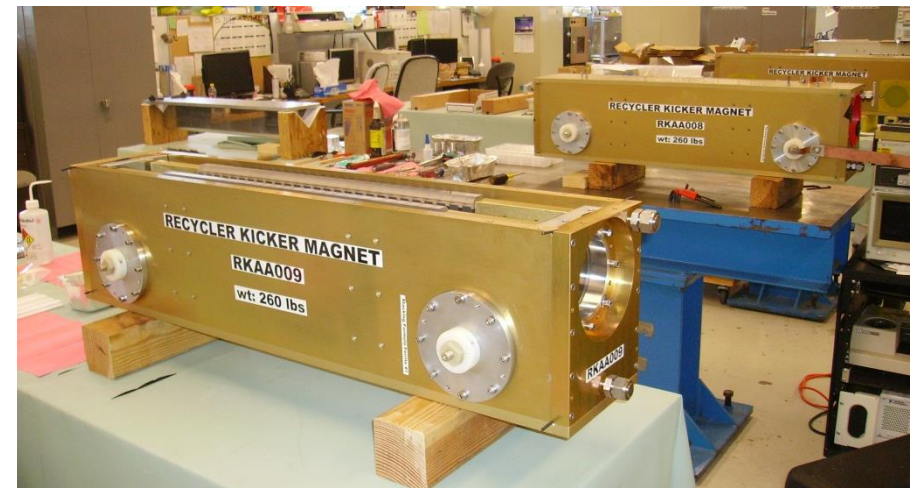
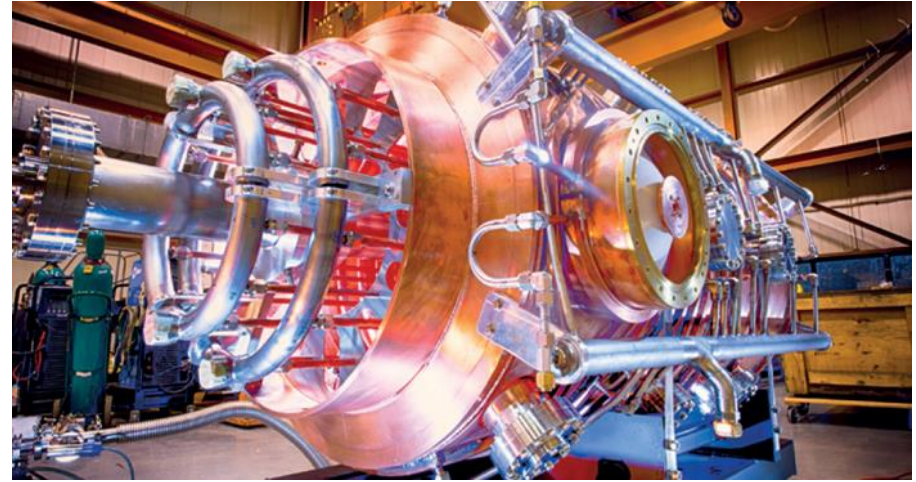
# Comparing old and new Recycler requirements

	Antiprotons (pre-2012)	Protons (2013-)
Beam structure	2.5 MHz and barrier buckets	53 MHz
Time beam in machine	Days	<1s
Normalized 95% emittance	2-10 $\pi$ mm mrad	15-20 $\pi$ mm mrad
Max beam intensity	$6 \times 10^{12}$ particles	$5 \times 10^{13}$ particles

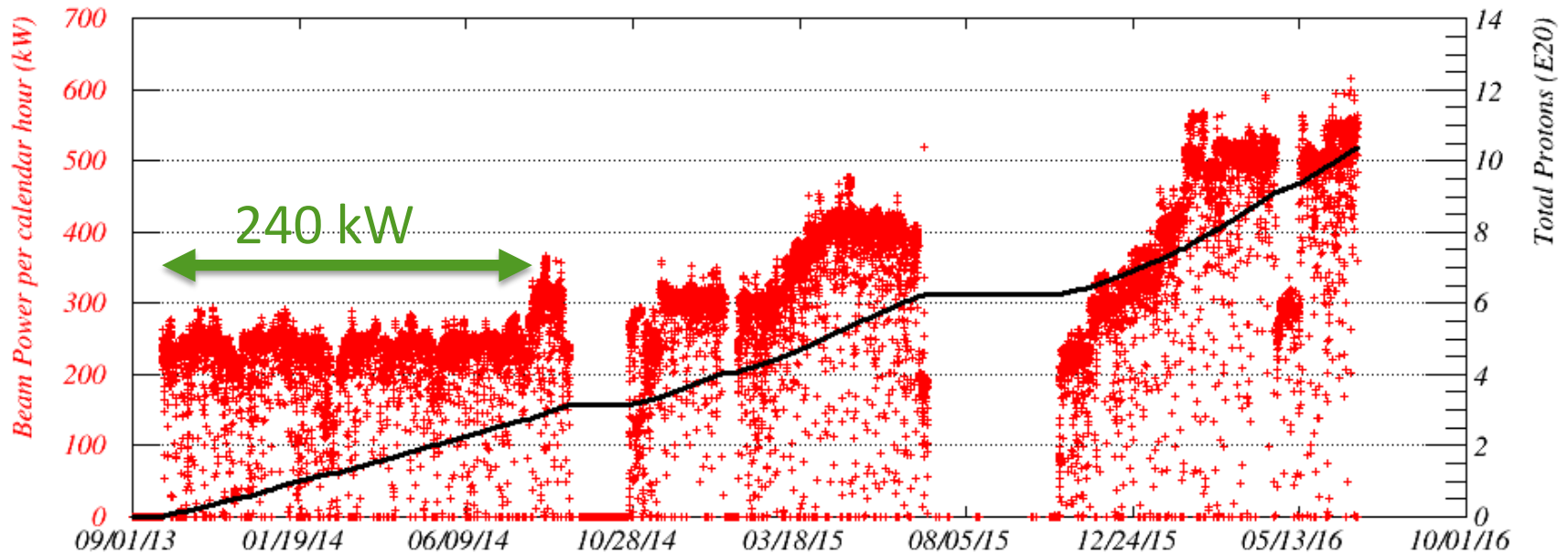
- These differences have consequences...

# Necessary Recycler Upgrades, 2012-2013 shutdown

- 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

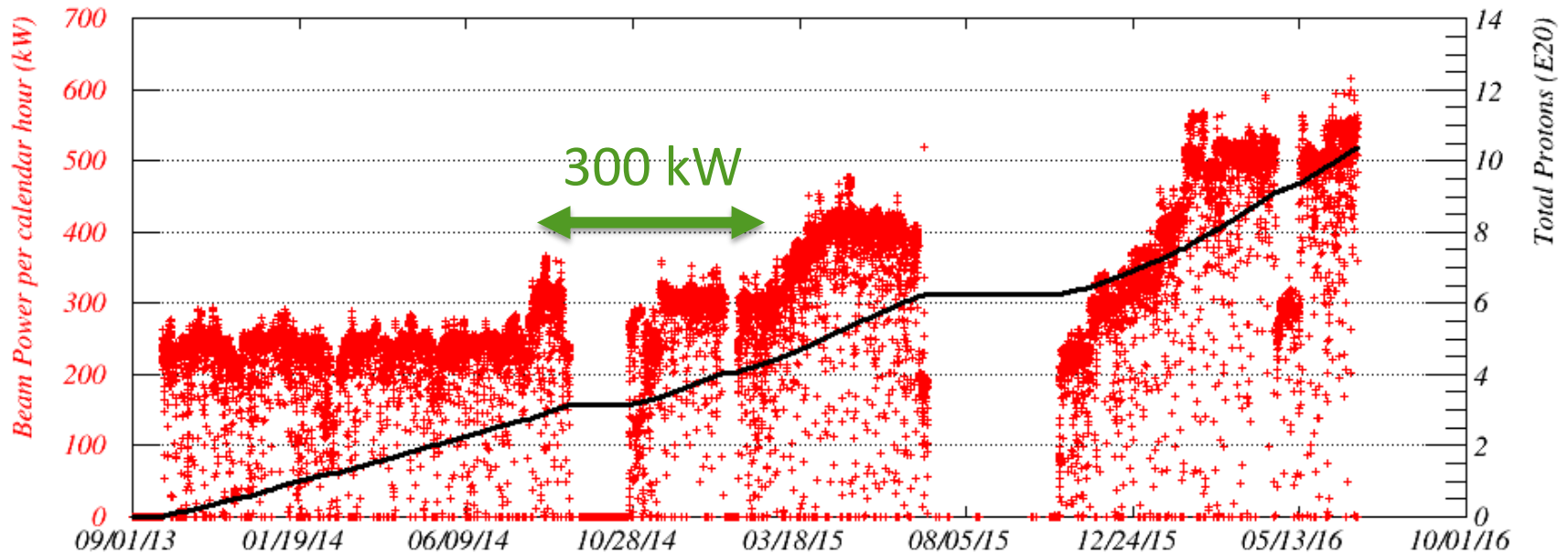


# Beam Power to NuMI since NOvA long shutdown



- Run NuMI with MI only
- Commission Recycler
  - Open up apertures (sequential!) (pbars smaller than protons)
  - rf, transverse dampers, BLMs and BPMs
  - Orbit & tune corrections while MI ramping
  - Condition beam pipe (scrubbing)

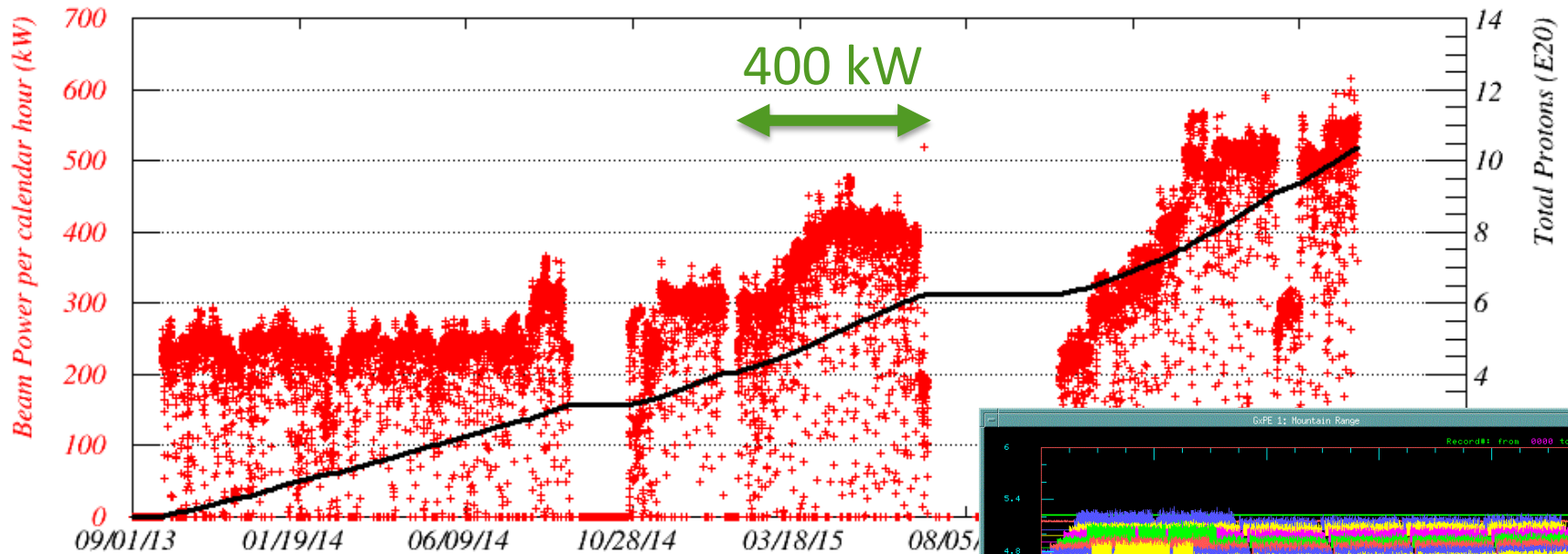
# Beam Power to NuMI since NOvA long shutdown



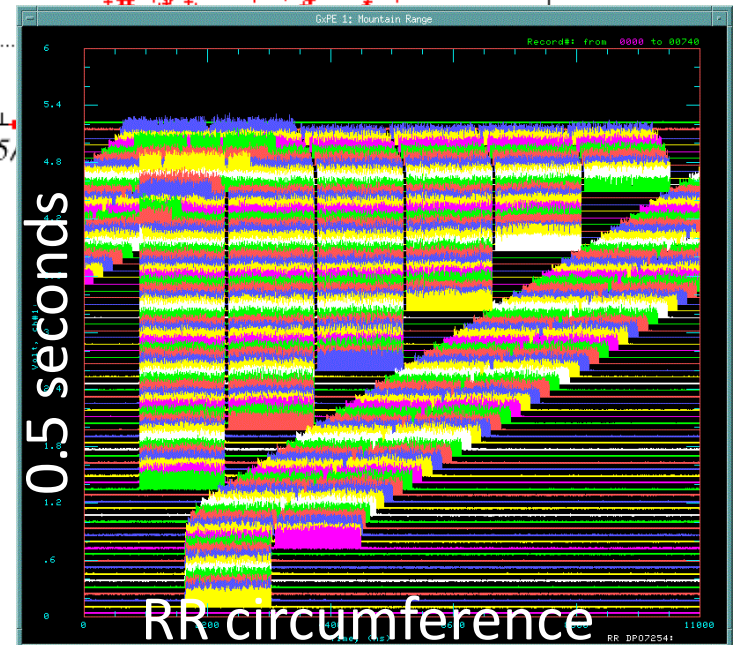
- Run 6-batch boxcar stacking in Recycler
  - When can break even in beam power
  - Cycle time reduced from 1.66s to 1.33s
  - Discovered fast instability (more later)



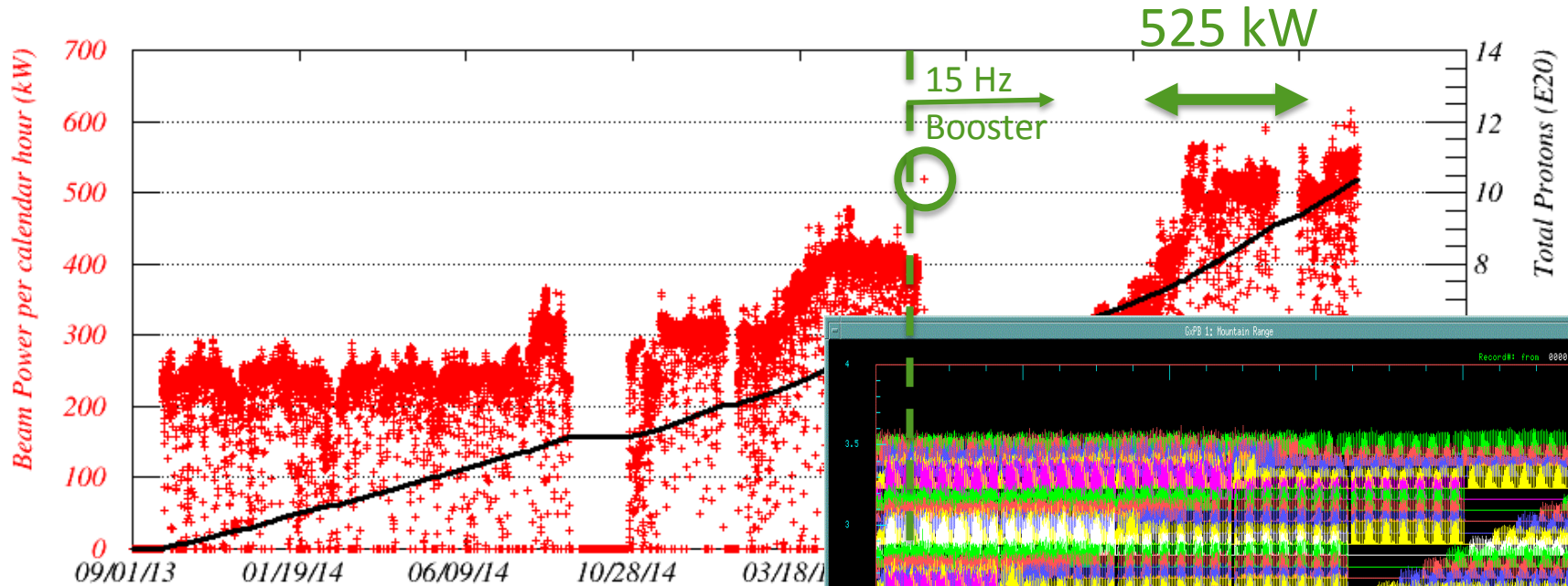
# Beam Power to NuMI since NOvA long shutdown



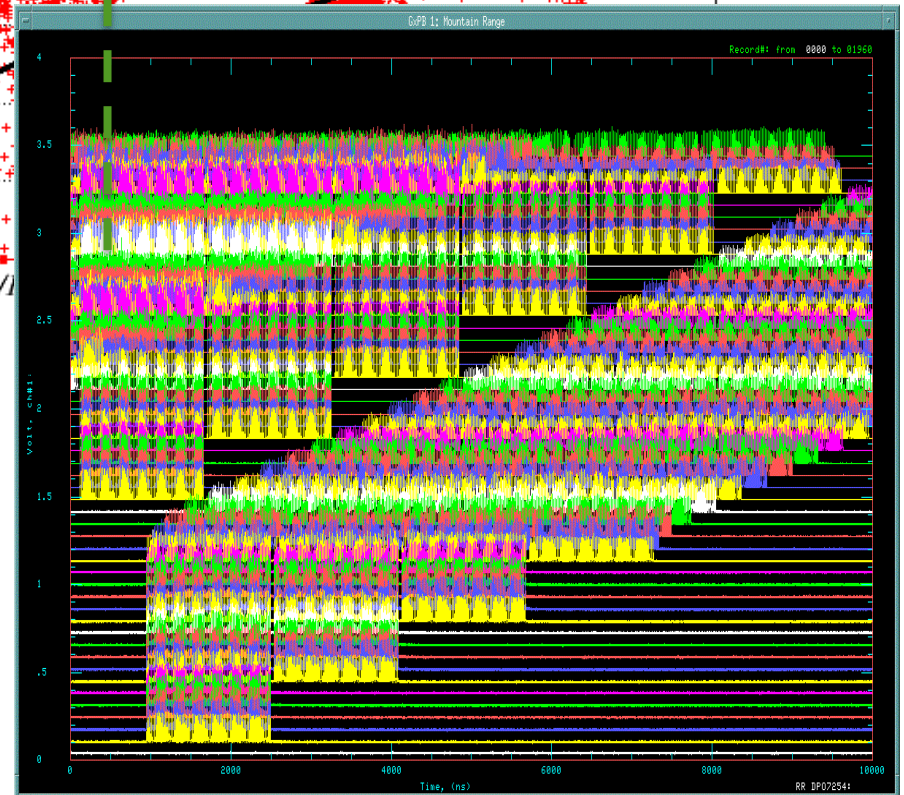
- 2+6 slip-stacking in Recycler
  - Doesn't need upgraded Booster rep rate (PIP)
  - Recapture by firing transfer kicker
    - 1MV bucket in MI



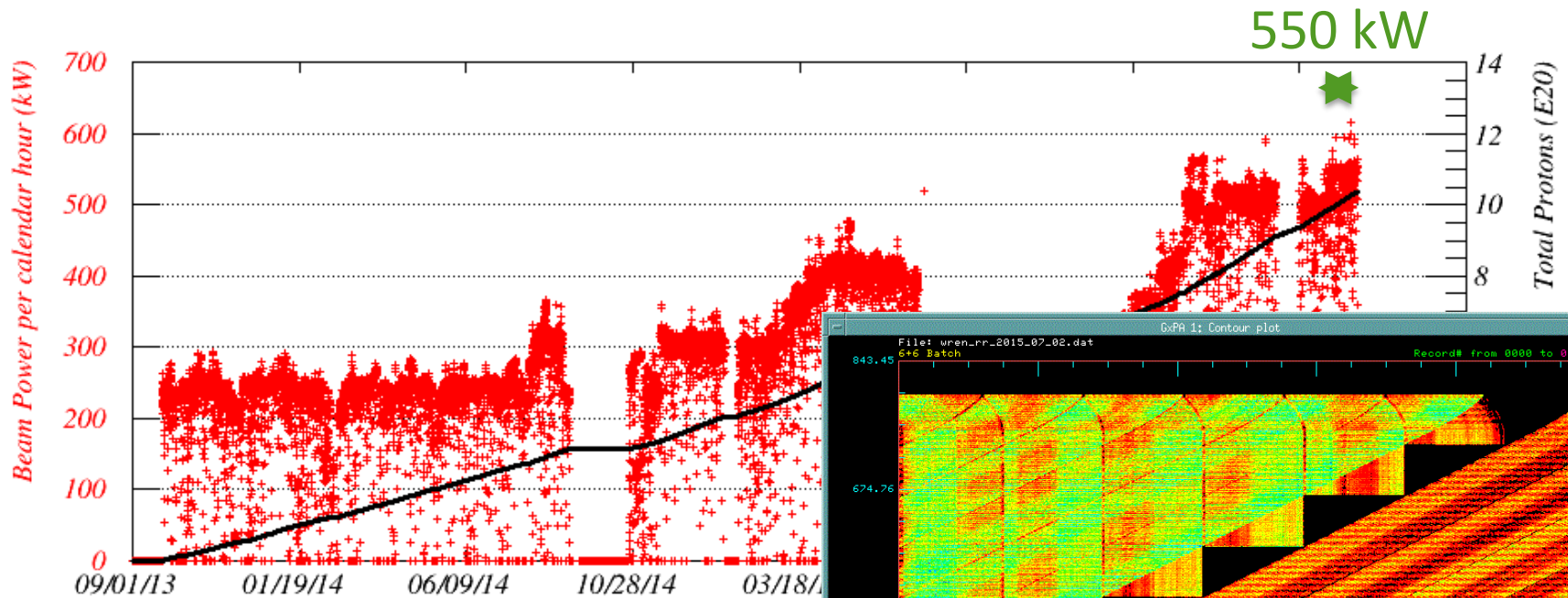
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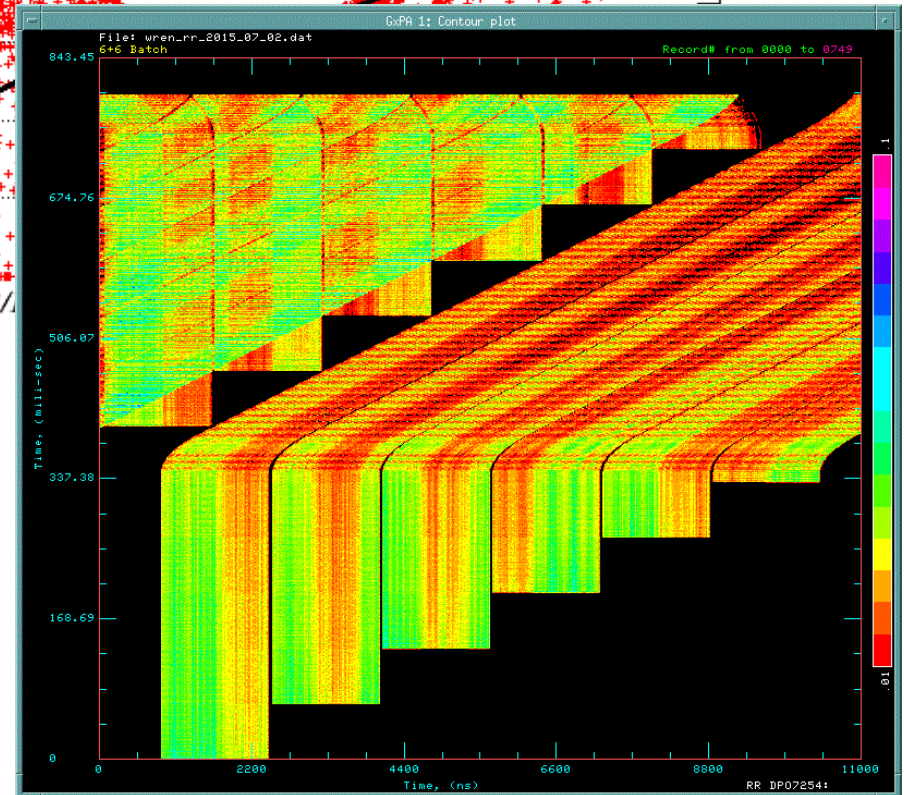
- 4+6 slip-stacking in Recycler
  - Needs 8.3 Hz from Booster
  - Typical 525 kW



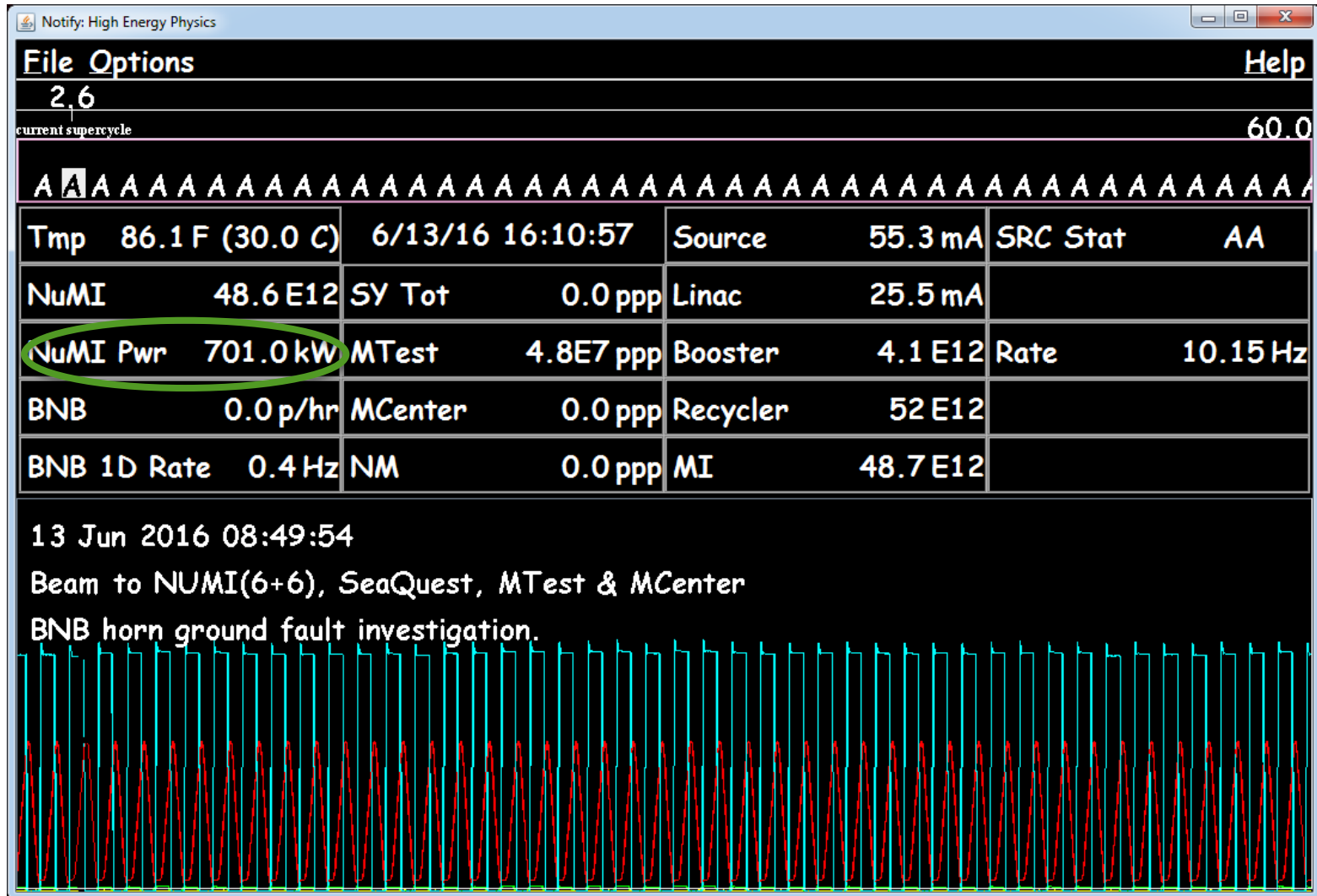
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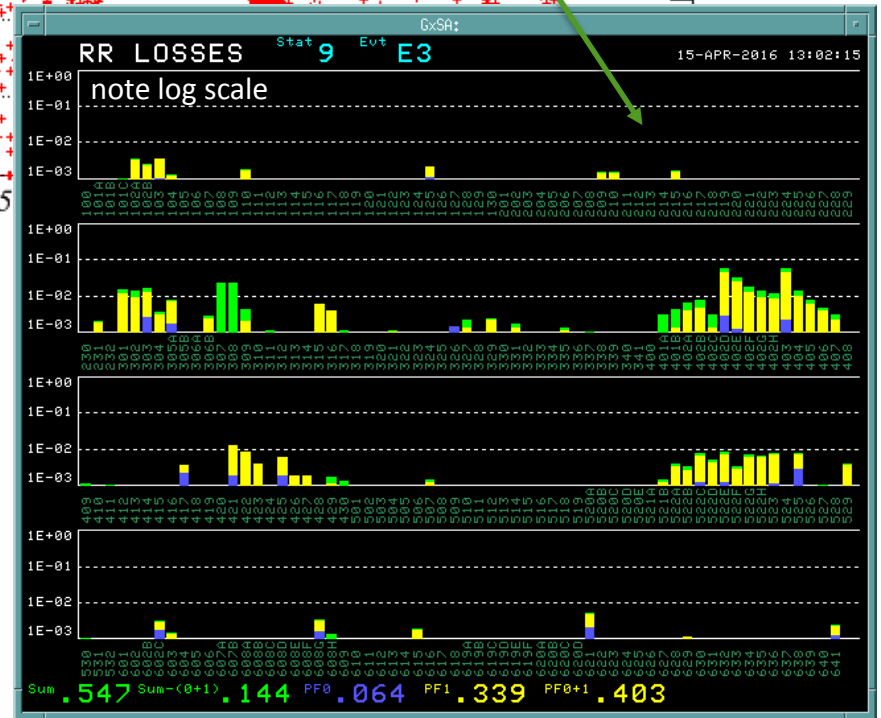
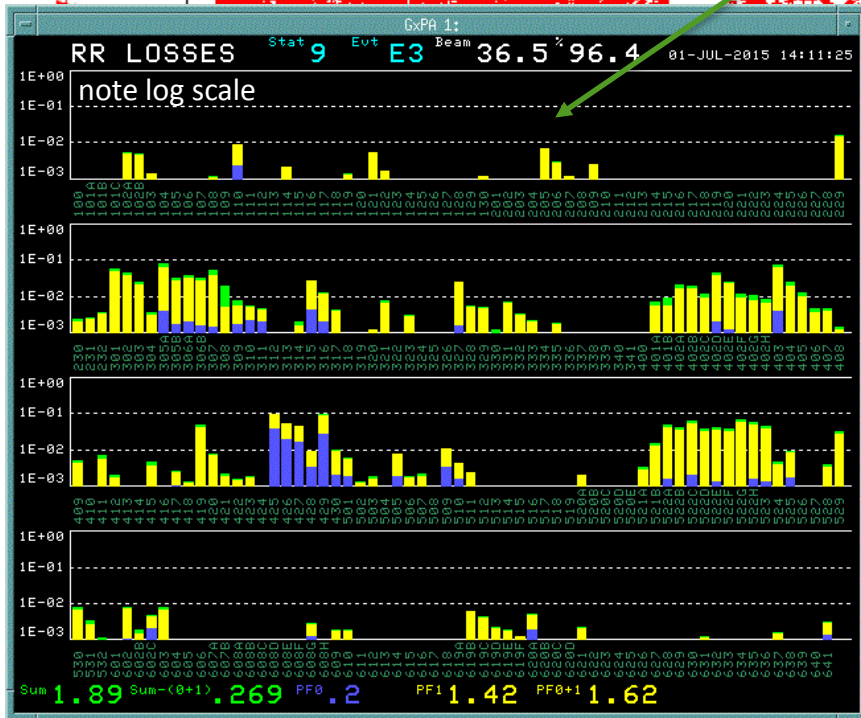
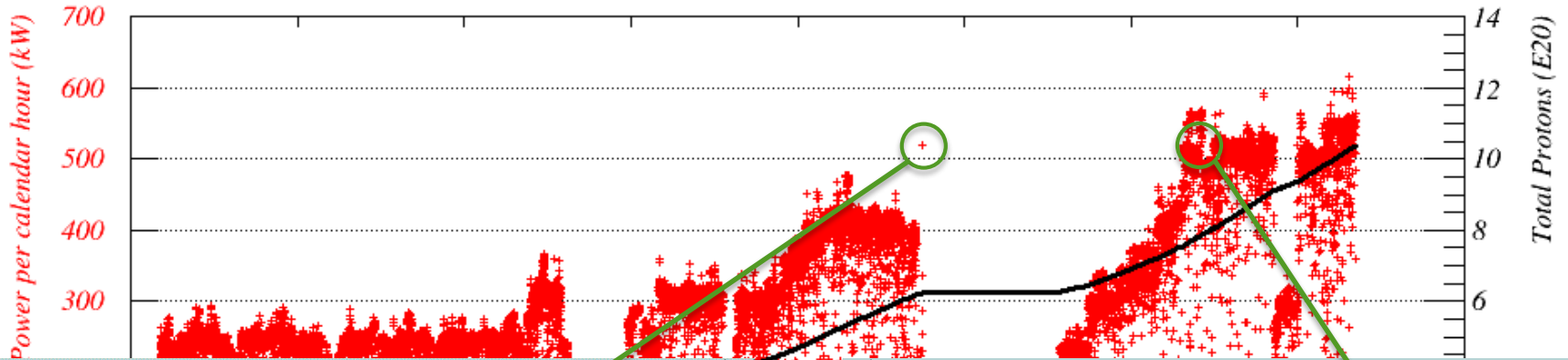
- 6+6 slip-stacking in Recycler
  - Needs 9.8 Hz from Booster
  - Best hour 615 kW (without SY120 running)



# Demonstrated >700kW (design power)



# Controlling beam loss



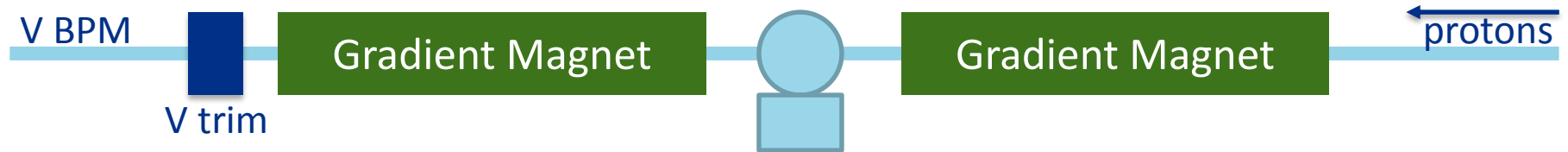
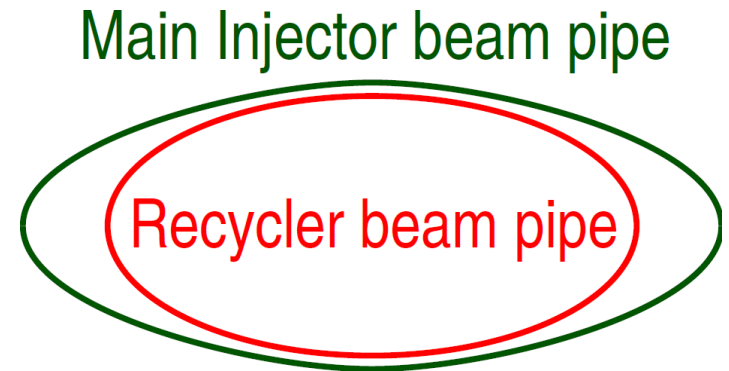
# Controlling beam loss

- Fix apertures in multiple locations
- Measure stopbands as function of chromaticity for high and low momentum beams
  - Find new working point (“low V tunes”)

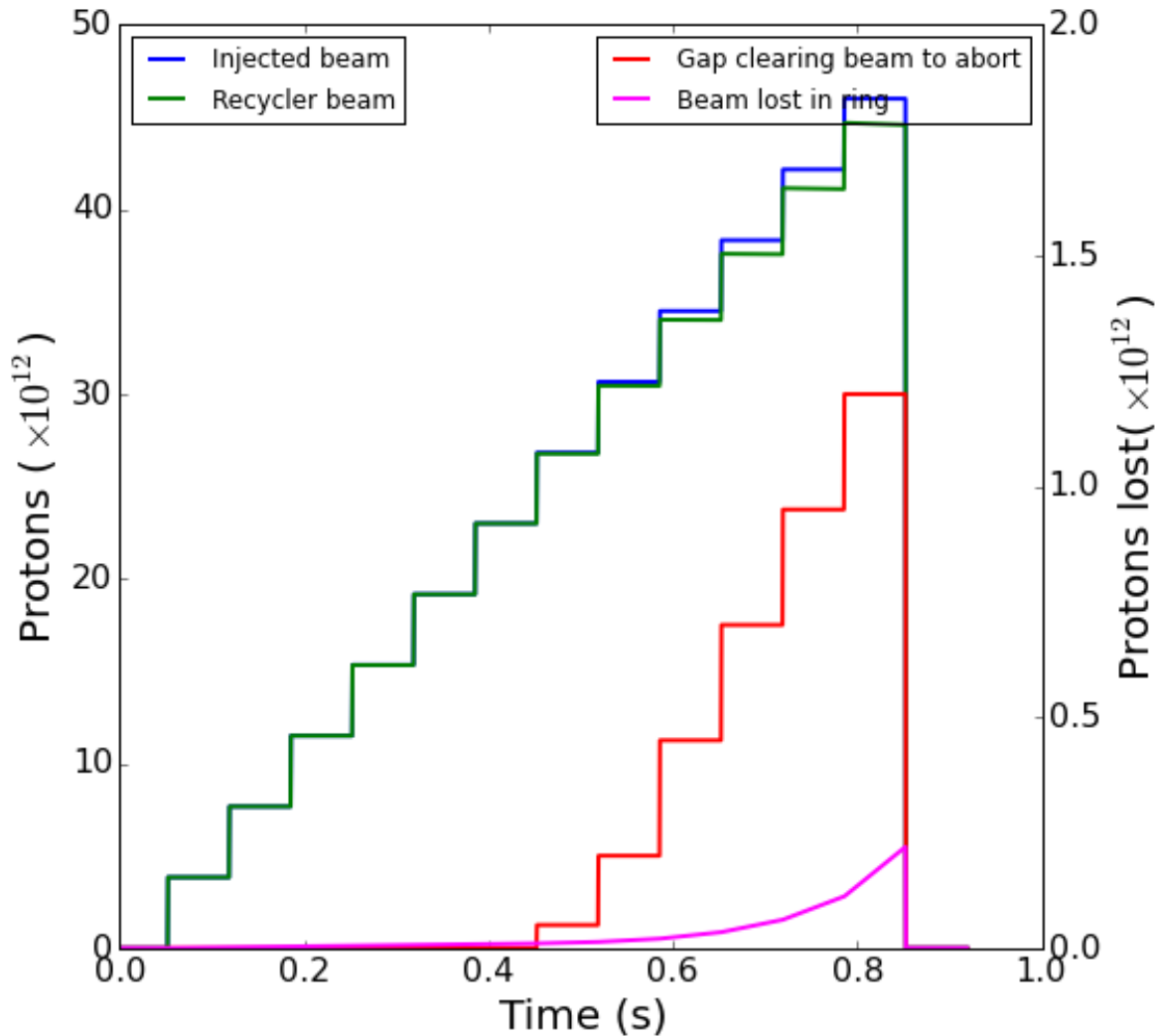


# Why are apertures & losses a challenge in Recycler?

- Recycler beam pipe is smaller
- Recycler has welds etc. at max beta (pipe joins, TSP, ...)
- Recycler magnets are smaller
  - less shielding -> greater residual activation for the same loss
- BPMs and correctors not (usually) at max beta



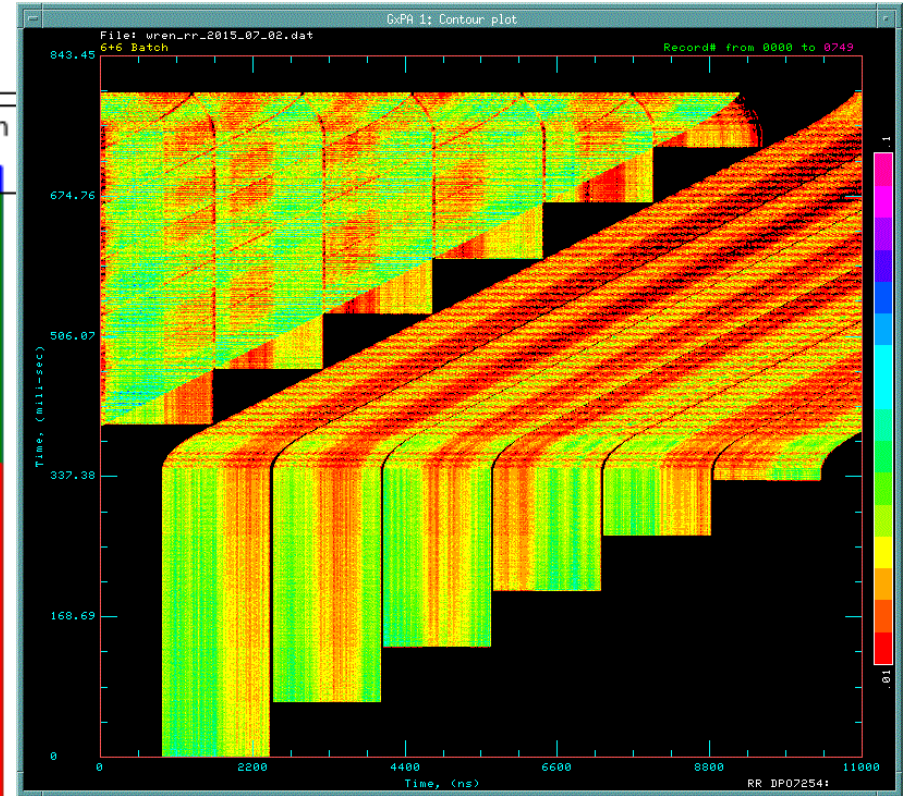
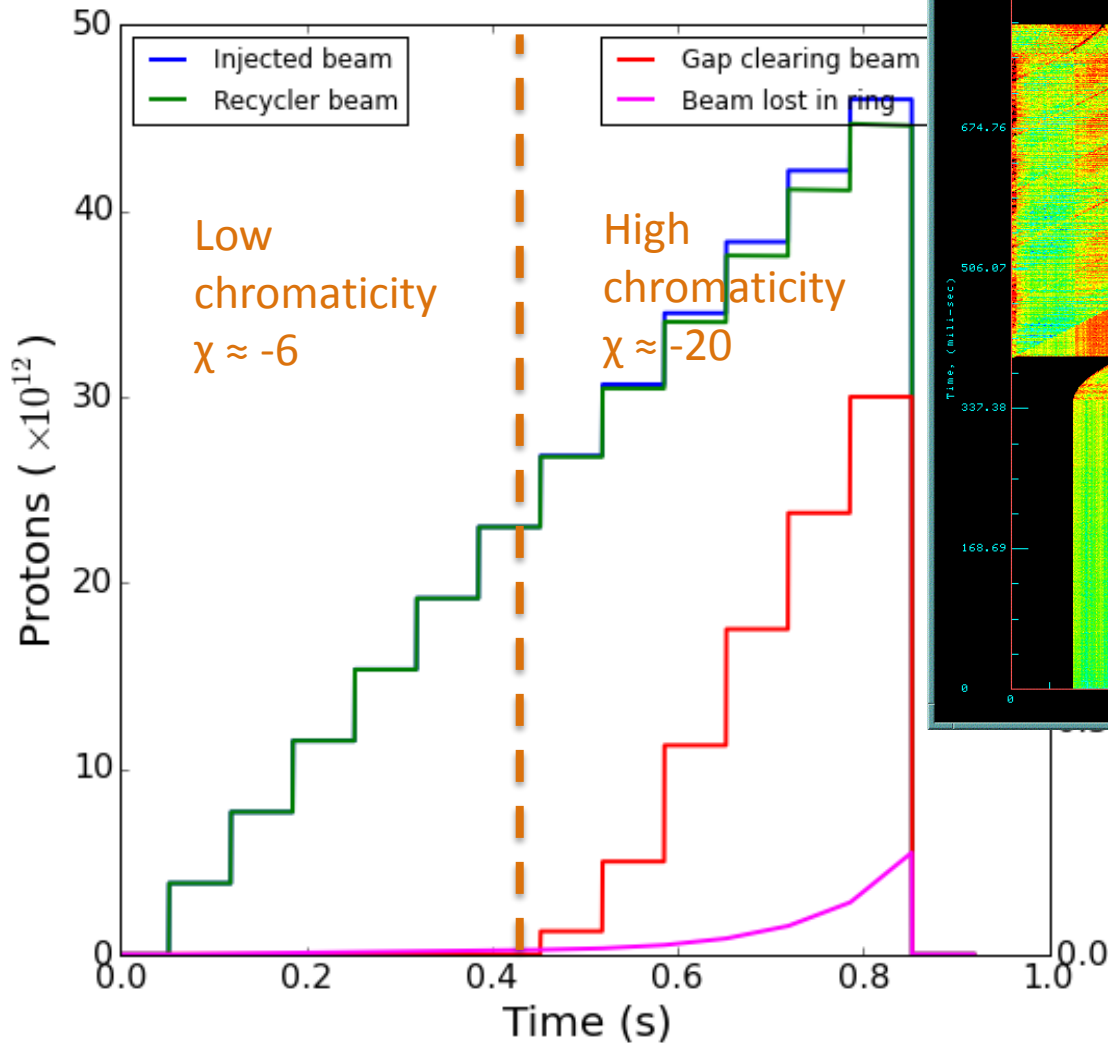
# Anatomy of a 6+6 cycle



- Efficiency 96.7%
- To abort 2.8%
- Uncontrolled loss 0.5% (25W)

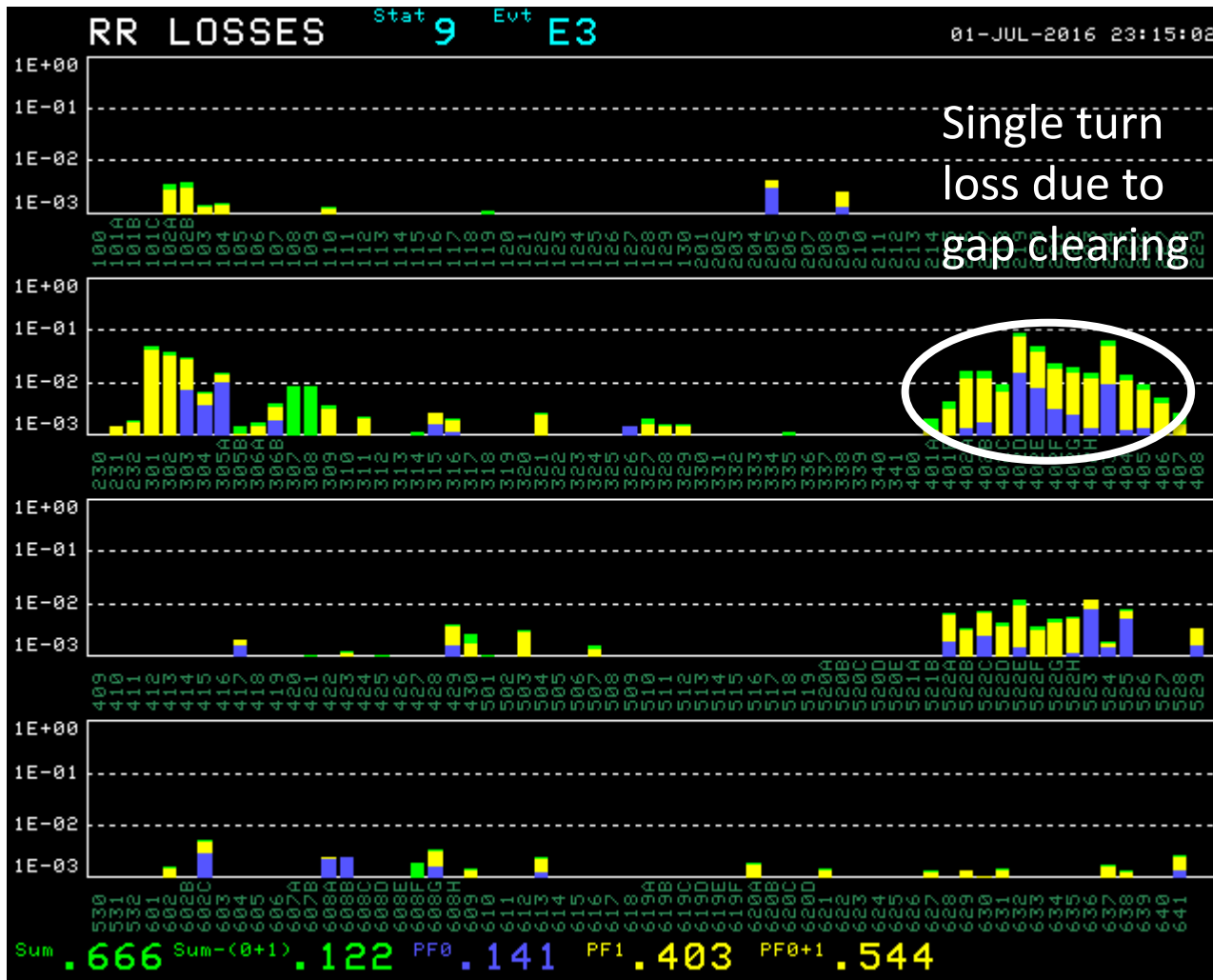


# Anatomy of a 6+6 cycle



- Transverse dampers don't work for overlapped beams

# Typical losses, 6+6 cycle at 615 kW

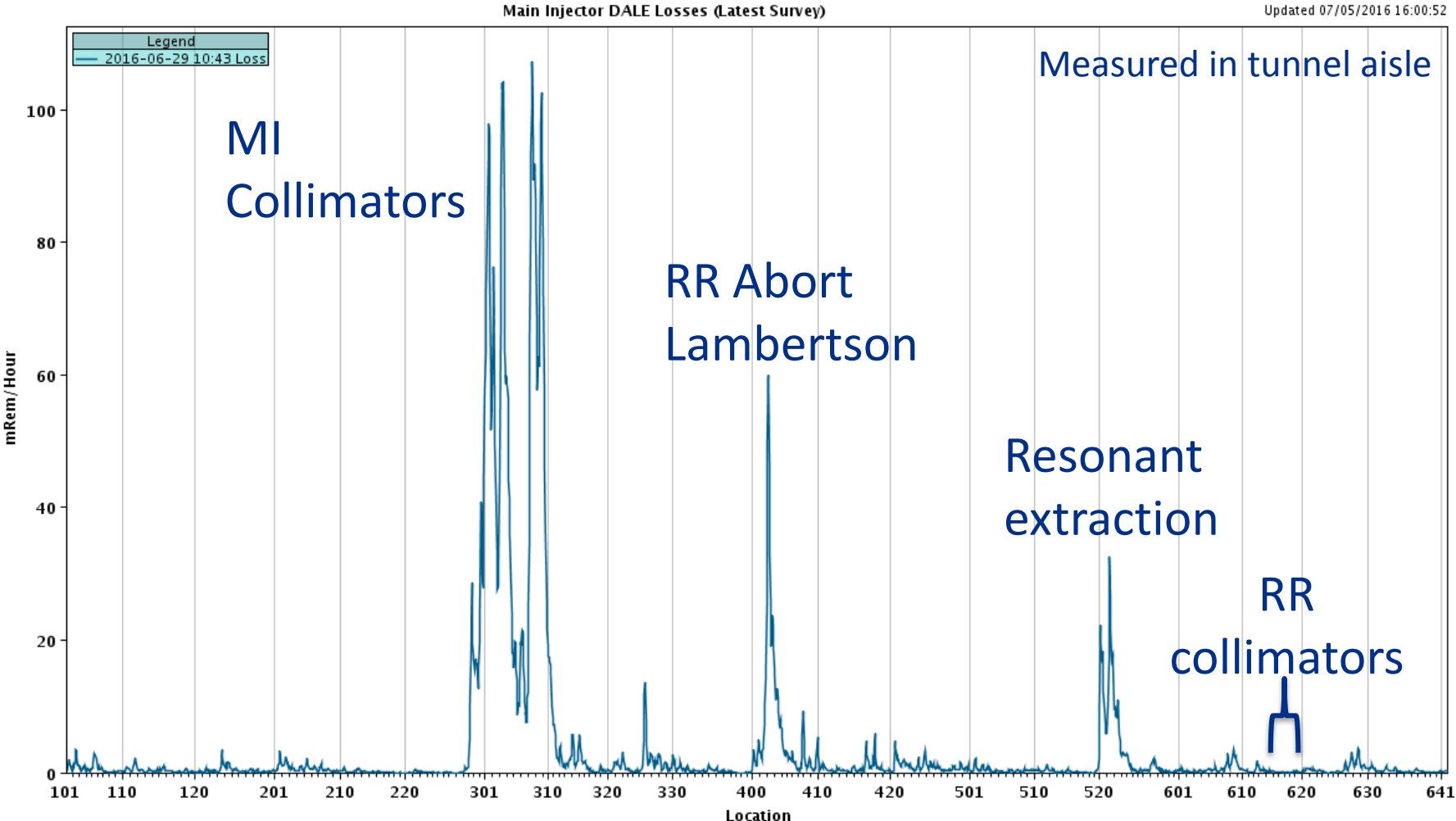


# Recycler Collimators: to be installed this summer

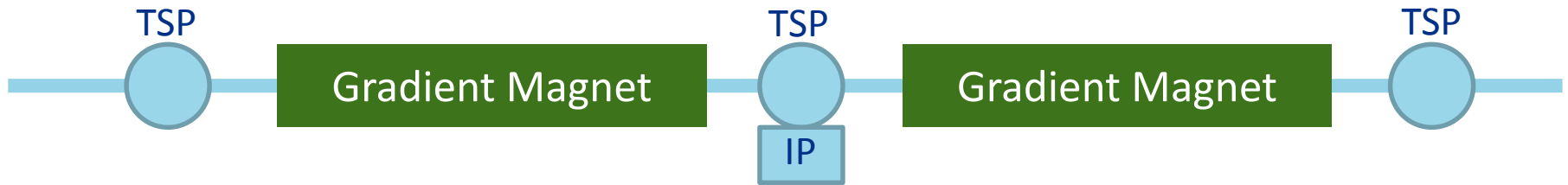
- Need collimators to contain losses in 700kW operation
  - Two-stage collimation scheme in vertical plane (scraper at max vertical beta)
    - Slip-stacking makes horizontal collimation challenging
      - Rely on coupling



# Current tunnel activation



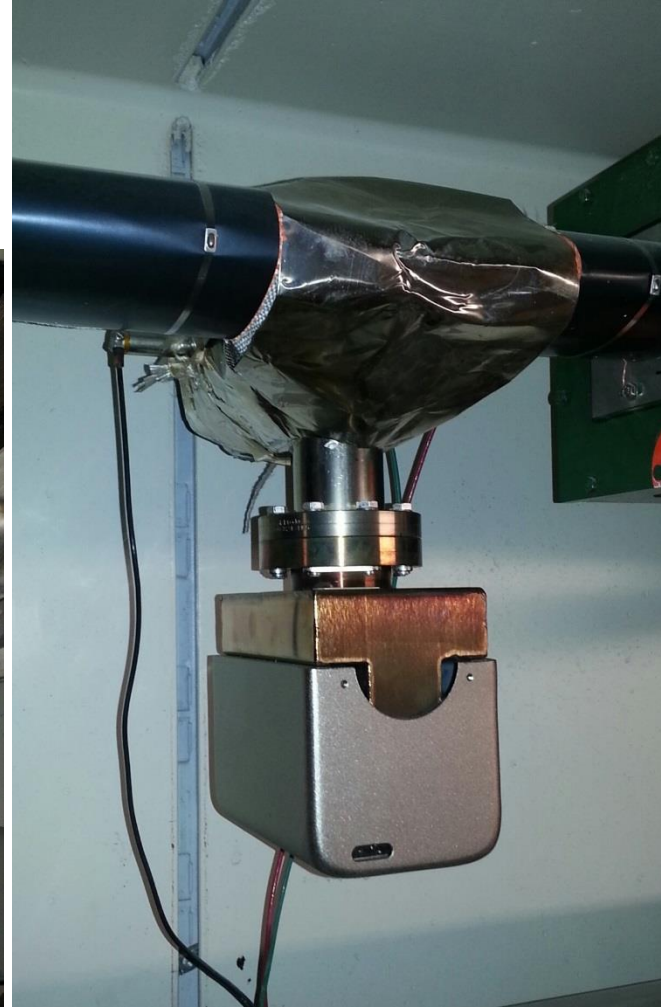
# RR vacuum TSP IP replacement



- Old recycler vacuum maintained  $\sim 1e-10$  torr with Titanium Sublimation Pumps
  - Ti layer quickly exhausted. Number of fires limited. Ti filaments close to end-of-life
    - Doing nothing not an option
  - TSPs were great for pbar storage ring
    - Not needed for beam times  $< 1s$
    - Have to bake beam tube (and heater tape is failing)
- Replace TSPs with new ion pumps to match MI vacuum design
  - $\sim 600$  new ion pumps (one third in each of FY15, FY16, FY17)

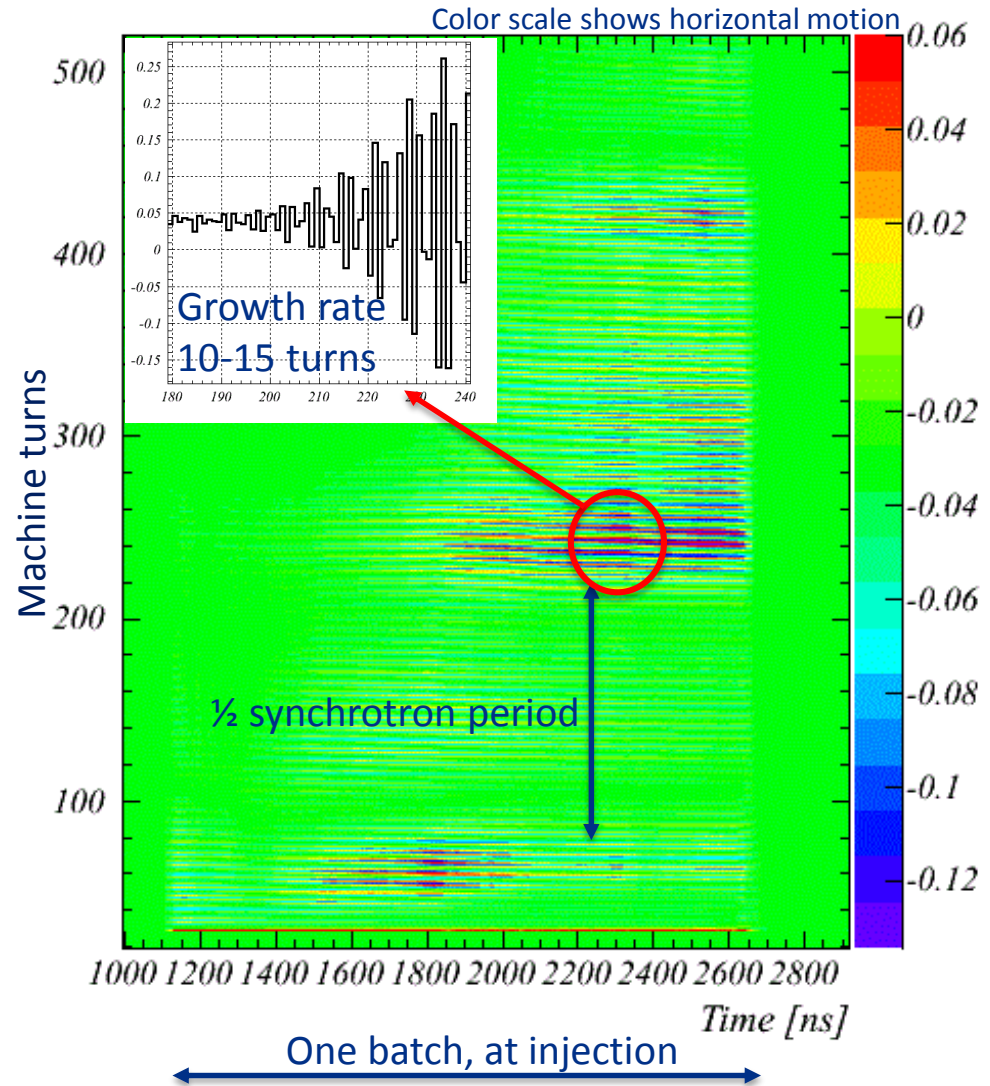
# TSP to Ion Pump Upgrade

- ~200 pumps on schedule in 2015
- Confidence for 2016/2017

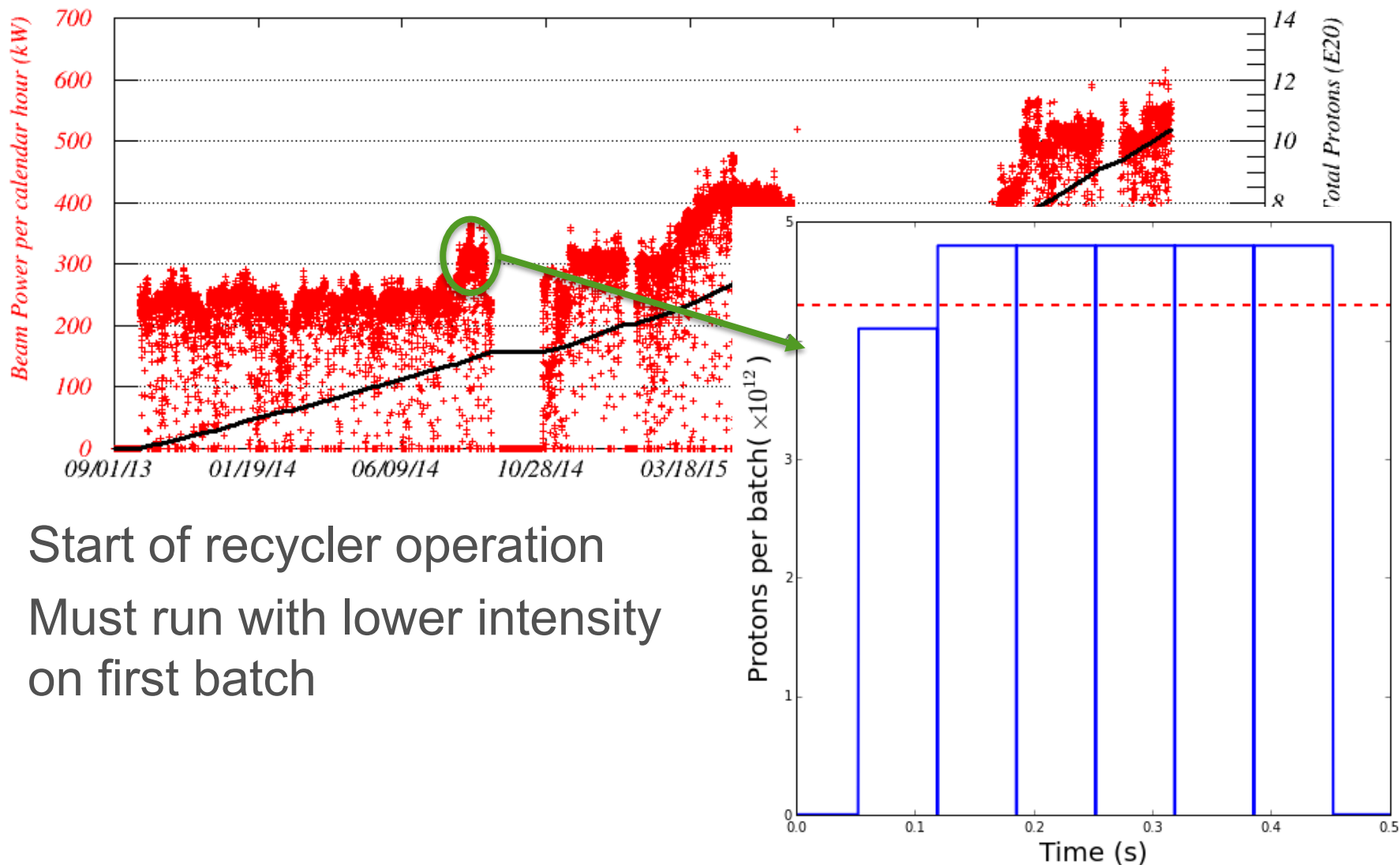


# Recycler Horizontal Fast Instability: a surprise

- 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



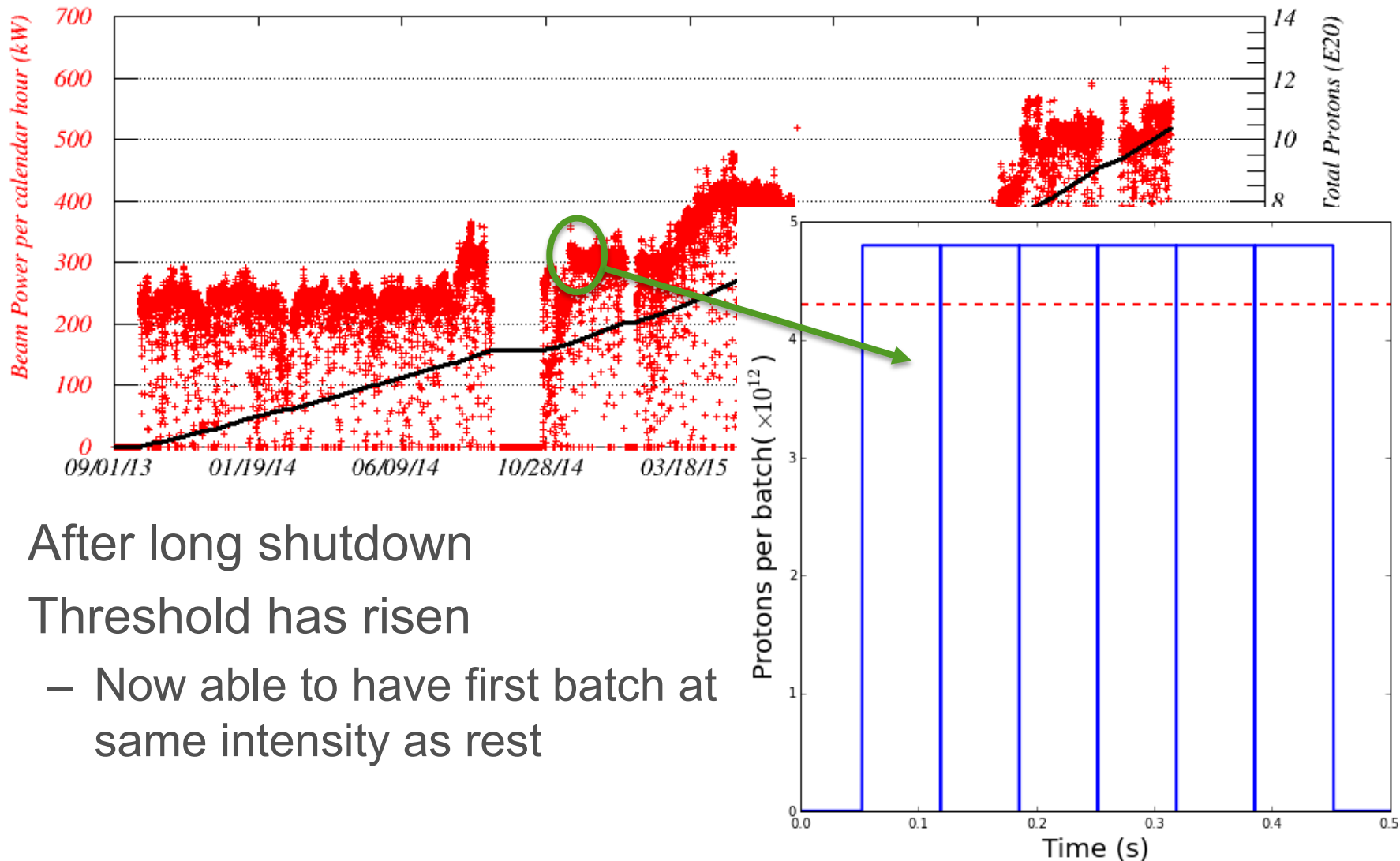
# Evolution of Recycler Instability



- Start of recycler operation
- Must run with lower intensity on first batch

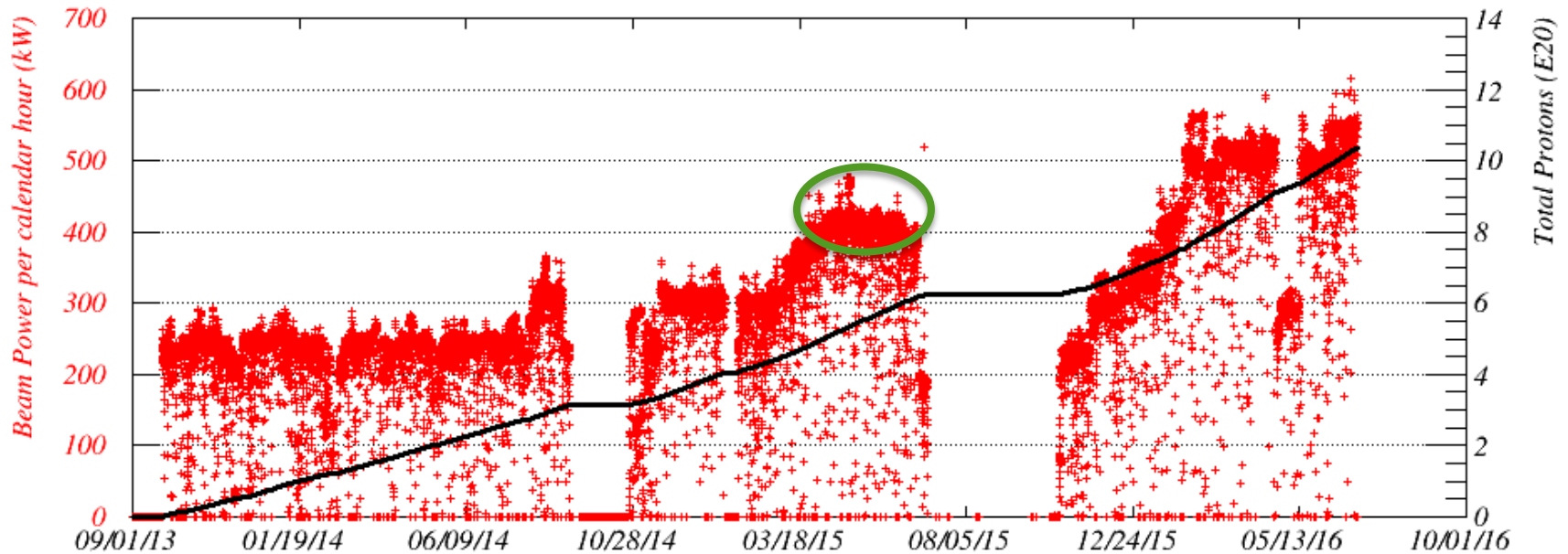


# Evolution of Recycler Instability



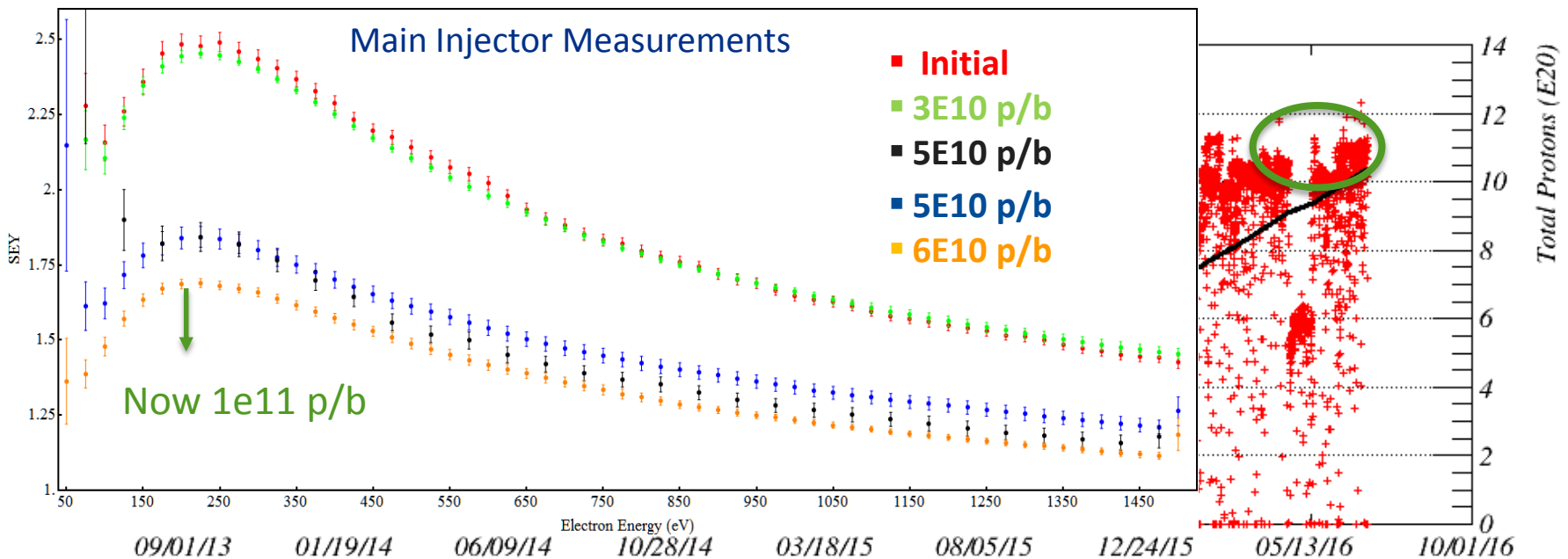
- After long shutdown
- Threshold has risen
  - Now able to have first batch at same intensity as rest

# Evolution of Recycler Instability



- Instability does not affect 2+6 slip-stacking operation
  - Able to generate instability by mistuning bunch rotation in Booster to generate high linear charge density

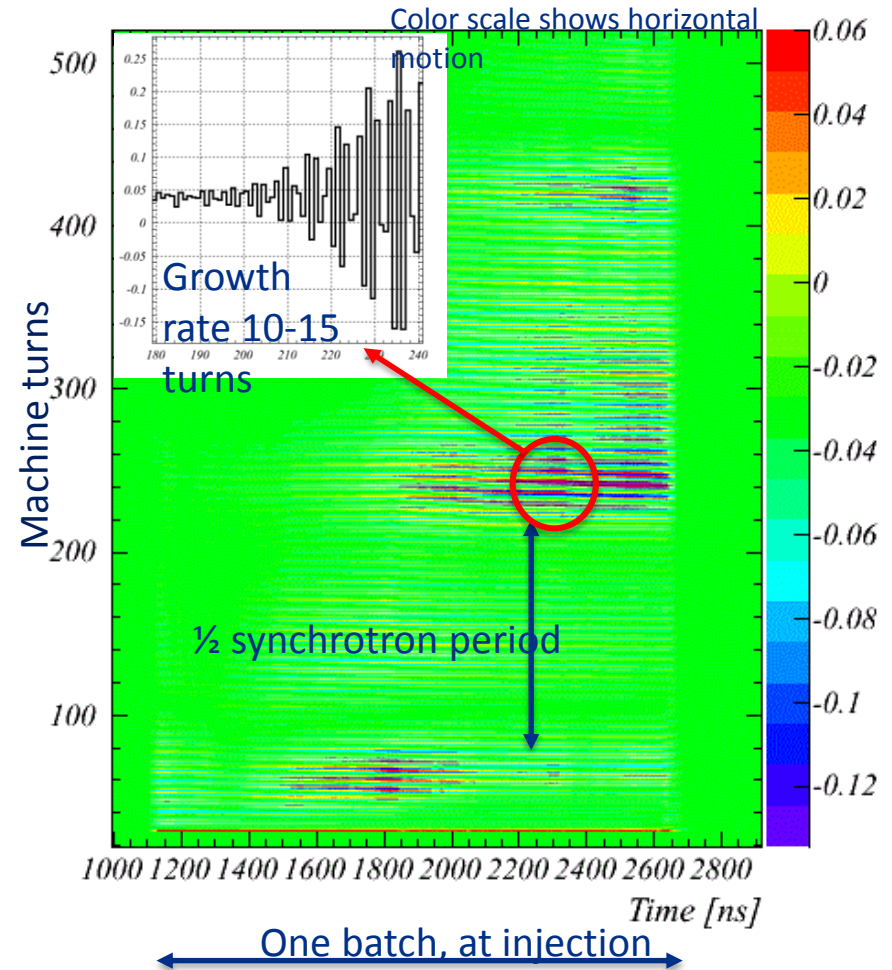
# Evolution of Recycler Instability



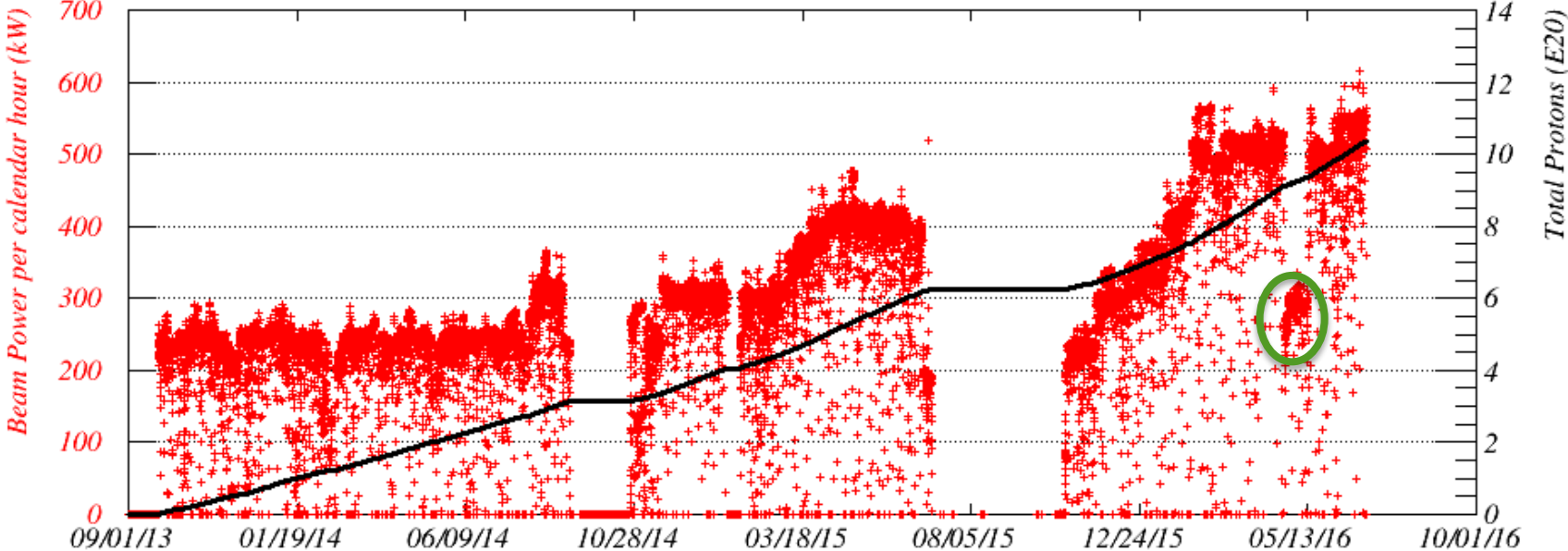
- Generating fast instability somewhere between very difficult and impossible
  - Beam scrubbing at higher intensity
    - Measure SEY of 316L steel in Main Injector – reducing still!
  - 1/3 ring ion pumps in 2015: aids scrubbing?

# Recycler Horizontal Fast Instability: a surprise

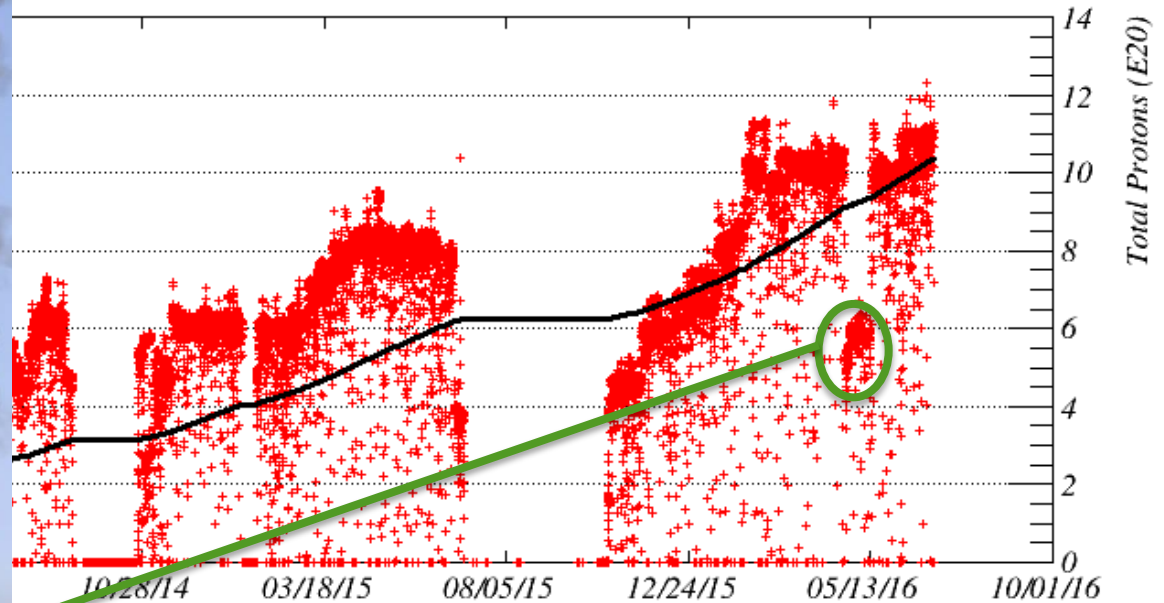
- Doesn't occur in Main Injector at same intensity
  - (even with shorter bunches)
- RR has combined function magnets
  - E-cloud is the only explanation for the growth rate
  - Assumption is that gradient magnet traps fraction of electrons in magnetic bottle
    - S. A. Antipov et al. "Study of Fast Instability in Fermilab Recycler", IPAC16
  - **Does not occur for 700kW operations**
    - Potential issue at PIP-II intensity



# A surprise!



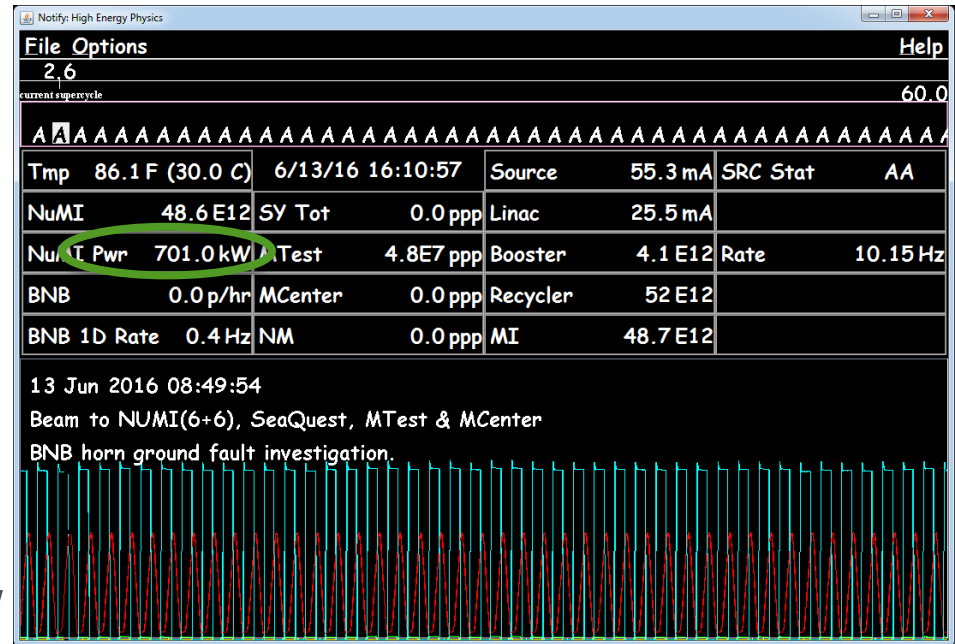
# A surprise!



- Transformer for the RRRF anode supply
- Beam running (MI only) 6 hours later
- Recabled RRRF to MI anode supply
  - Back to normal intensity 3 weeks later
  - (but no margin / flexibility)

# Summary

- We have commissioned the ultimate 6+6 slip-stacking mode in Recycler
- In this mode we have run consistently at greater than 550 kW whilst running SY120 (605 kW equivalent)
- Best sustained hour 615 kW
- Demonstrated 700 kW design power



- Install collimators this summer
- Continue to pursue increased beam power and lower losses