Booster Cogging: Synchronization with the Main Injector for NuMI & Slip-Stacking

Robert Zwaska

University of Texas at Austin

Budker Seminar

July 27, 2004

Introduction

Myself

- Graduate Student at the University of Texas
  - Sine 1999
- NuMI/MINOS
  - Since 2000
- Booster Group
  - Since 2003
- Fermi Ph.D. program
  - Since 2003 or 2004

People Involved

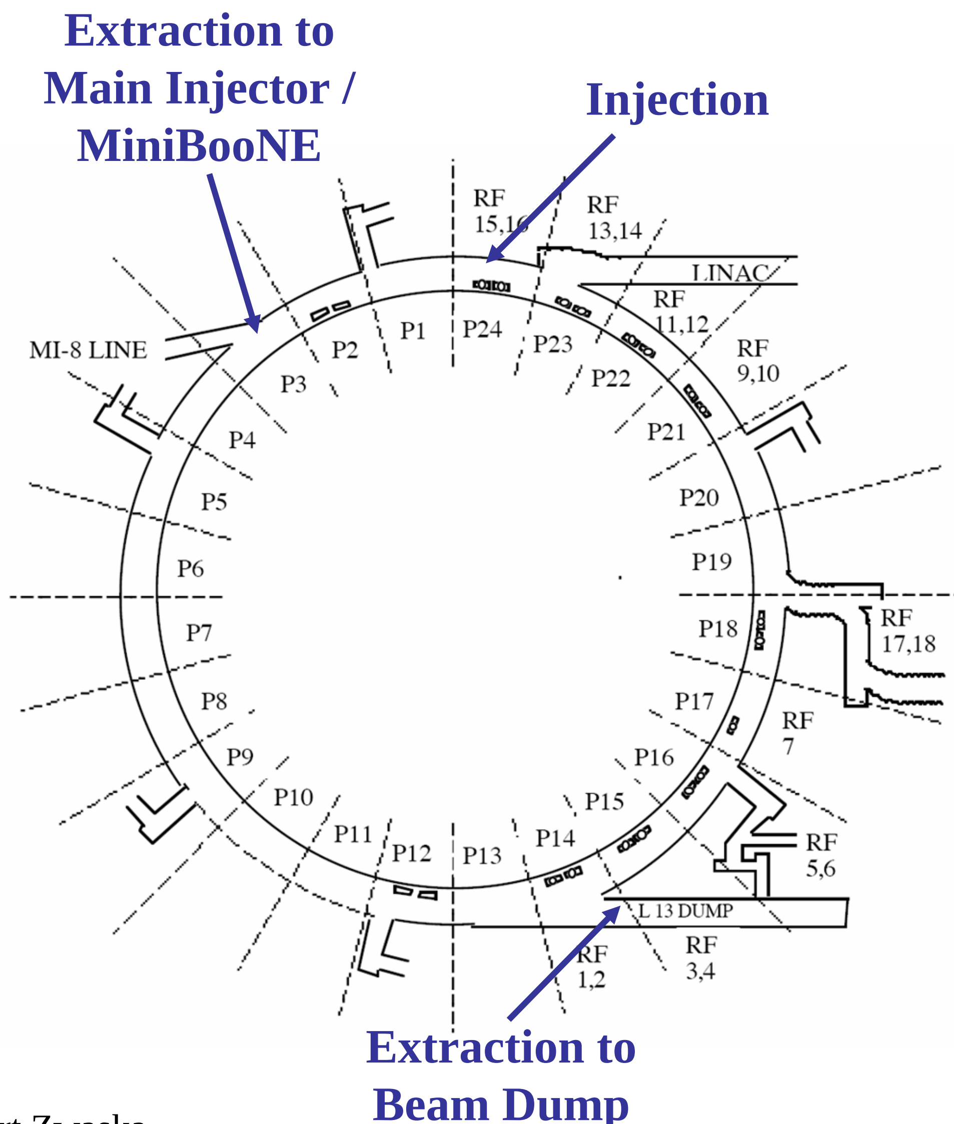
- Sacha Kopp
  - Advisor in Texas
- Eric Prebys
  - Supervisor at FNAL
- Bill Pellico
  - Cogger at FNAL
- Bob Webber
  - Earlier Cogger
- Rich Meadowcraft, Todd Sullivan, Andrew Feld, Jim Lackey, Alberto Marchionni, Alex Waller, Craig Drennan
  - Have helped out

Outline

I. Motivation
   i. Multi-Batch Operation
   ii. Booster Losses
II. Notching the Booster Beam
   I. Extracting with the Notch
III. Sources of Slippage
IV. Cogging Method
V. Examples of Issues Encountered

The Fermilab Booster

- Multiple-turn injection of H- ions
  - Carbon stripping foil
  - Typically 12-14 turns
- Accelerates 400 MeV → 8 GeV
- Fast cycling synchrotron
  - Resonant magnet ramp
  - Frequency of 15 Hz locked with wall-socket
- Circumference of 474 m
- Beam bunched at 37 MHz
  - Harmonic number = 84
  - 53 MHz at extraction
- 18 RF Stations → 0.9 MV
- Accelerates in 33 ms
  - $\gamma_T = 5.45$
- 5-6 x 10^{12} protons/pulse
  - 80 – 90 % efficient
- Single turn extraction
  - Two extraction regions



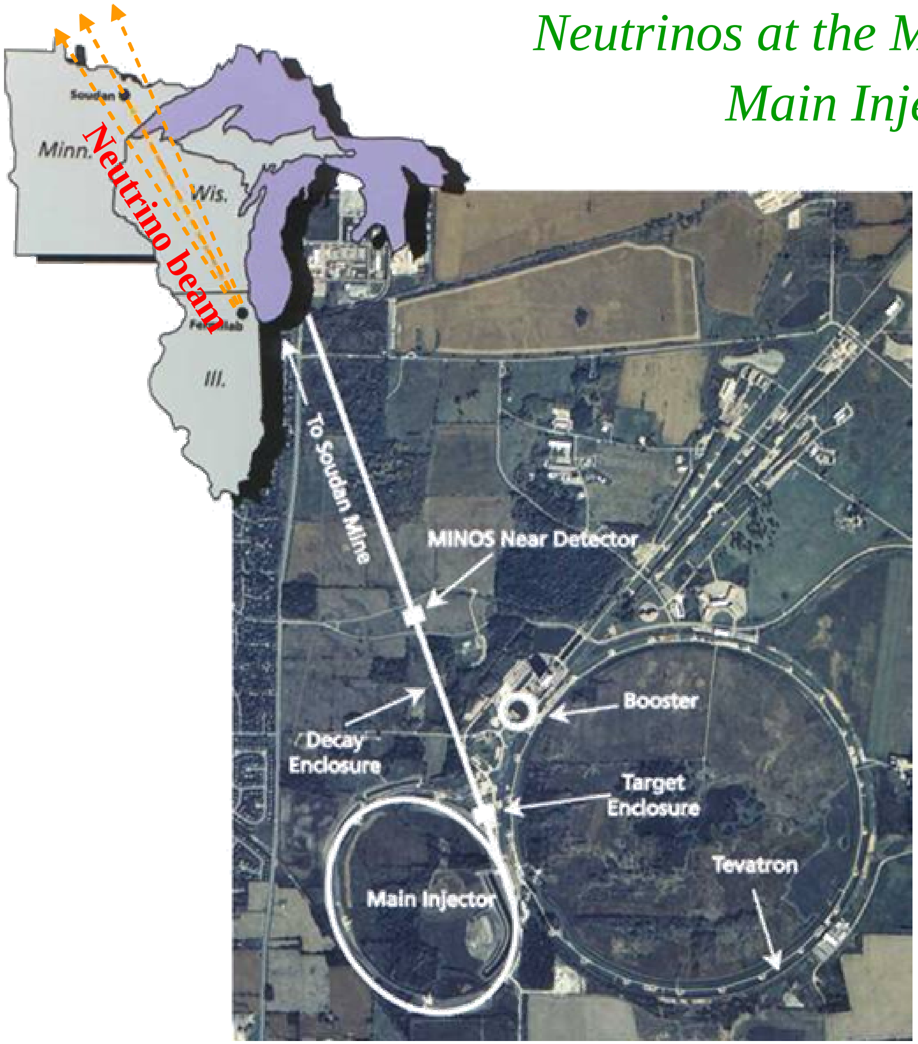
The Main Injector

- Accepts 8 GeV protons from the Booster
- Accelerates to 120 GeV
  - Uses 53 MHz from the Booster
  - 4 MV of RF power
- Circumference of 3319 M
  - 7 x the length of the Booster

NuMI/MINOS

Neutrinos at the Main Injector

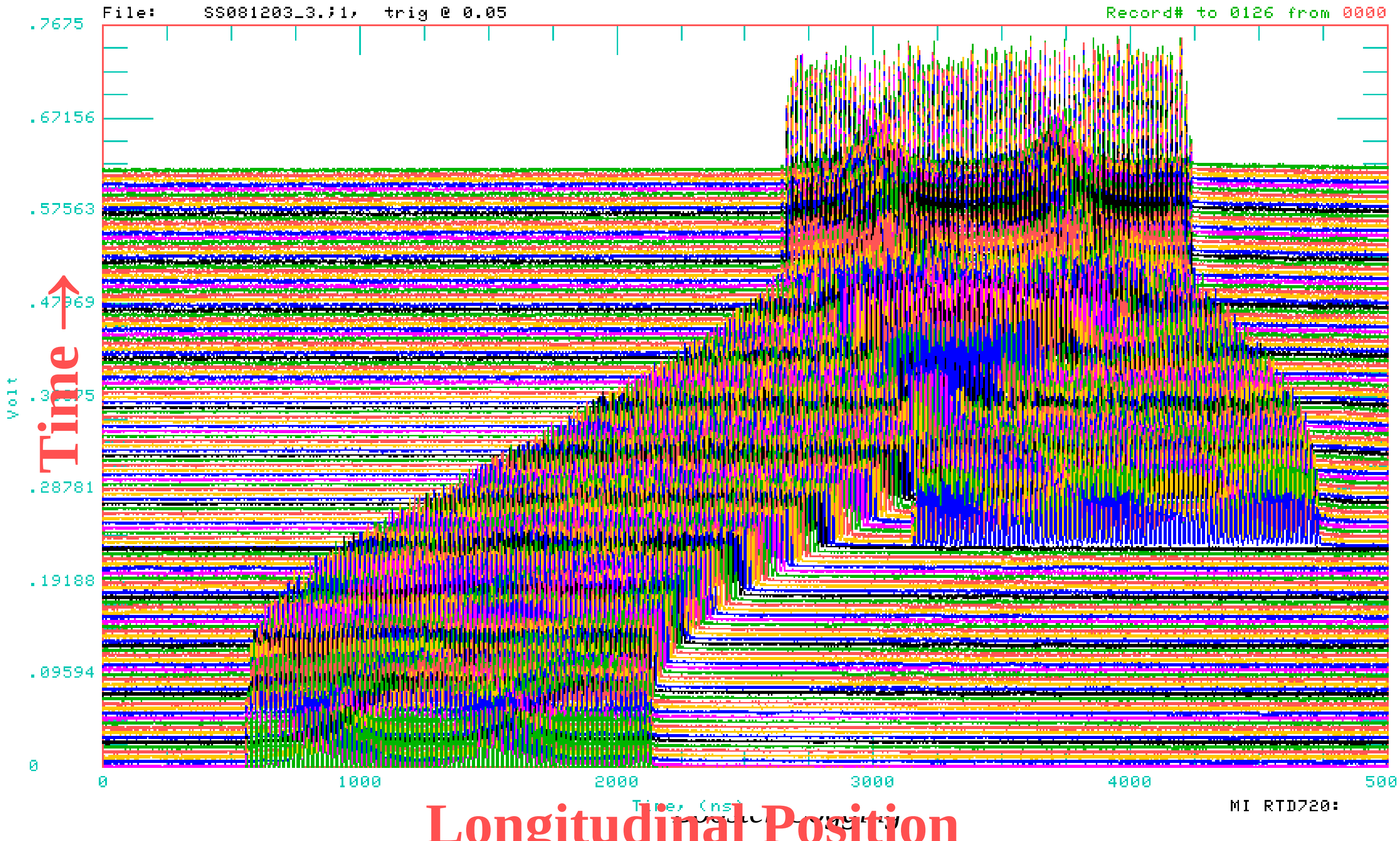
Main Injector Neutrino Oscillation Search



- Long-Baseline experiment
  - Neutrino oscillations measurements
  - 735 km
- Uses 120 GeV protons from the Main Injector
- Designed for 400 kW ave. power
  - Will be closer to 250 kW as start
- Seriously statistics limited
  - Initially needs 8 x 10^{20} protons
- Will start December 2004

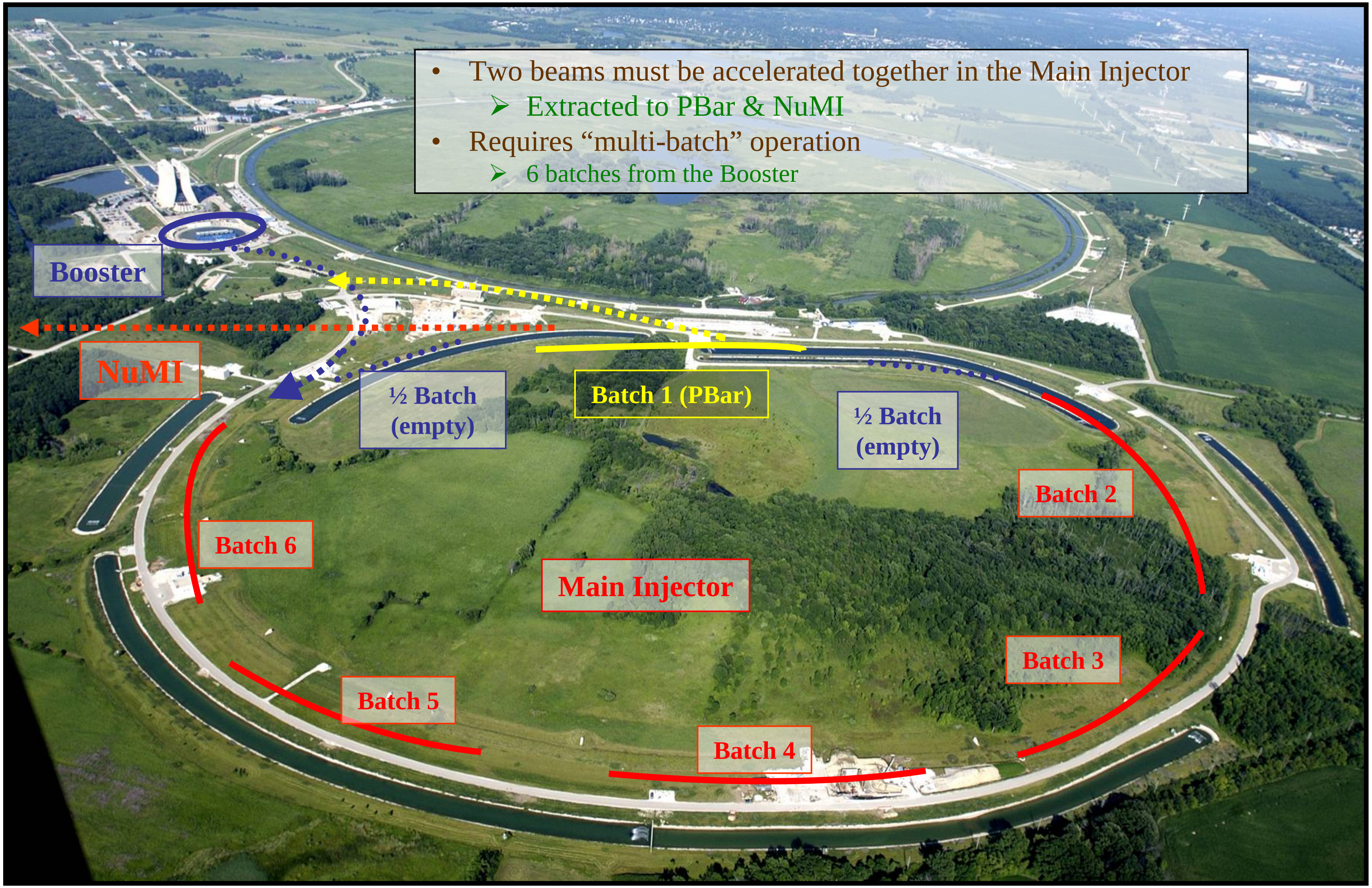
Slip-Stacking

- Combines two Booster batches longitudinally
  - In the Main Injector
- To be used, initially, for antiproton production
  - Part of Run II Upgrades



Multi-Batch Operation

- Two beams must be accelerated together in the Main Injector
  - Extracted to PBar & NuMI
- Requires "multi-batch" operation
  - 6 batches from the Booster

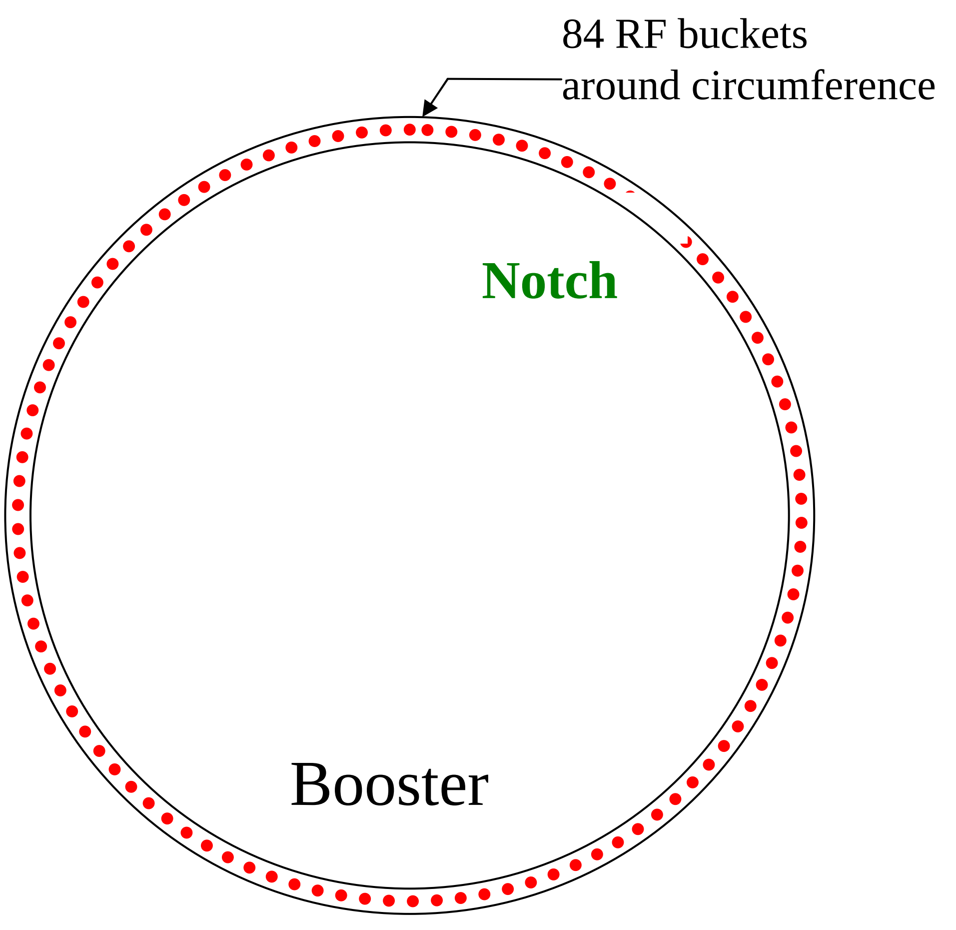


Radiation Issues

- Radiation is the operational limit on Booster operation
  - Limits integrated number of protons
- Residual activation in the tunnel
  - Radioisotopes created by showers
  - Long lived isotopes limit how much maintenance can be done in the tunnel
- Damage of beam components
- Prompt radiation from the showering of lost protons
  - Radiation scales with energy and number of protons lost
  - Very small amount penetrates the shielding

Extraction → Need for a Notch

- Extraction kicker magnet has a risetime of ~ 40 ns
  - Only ~ 10 ns between bunches
- Beam lost at 8 GeV
  - Lost on septum magnet at extraction
  - Intolerable for extended operation
- Instead, beam is removed at 400 MeV
  - Create a "notch" in the beam
  - Activation scales, roughly, with beam energy lost
    - Loss reduced by 95% (from this source)
  - Position of losses can be chosen as a non-critical area
- Extraction kicker firing must be synchronized with the notch
  - Easy with one batch…

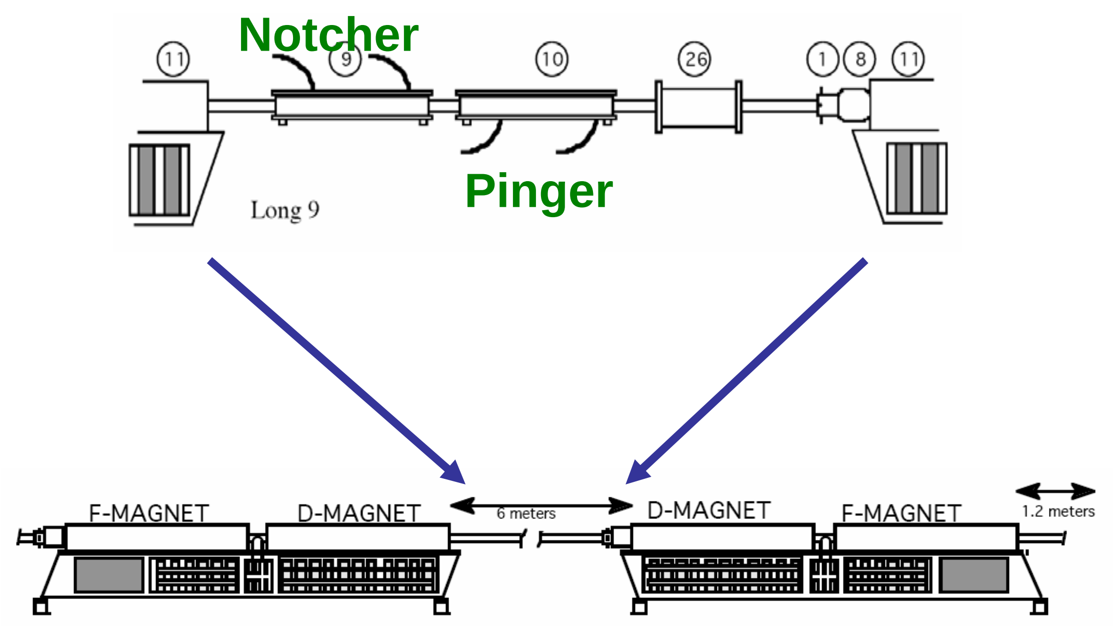


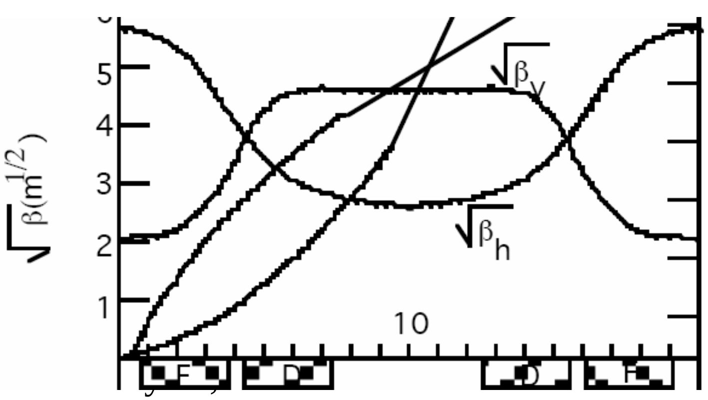
Notching

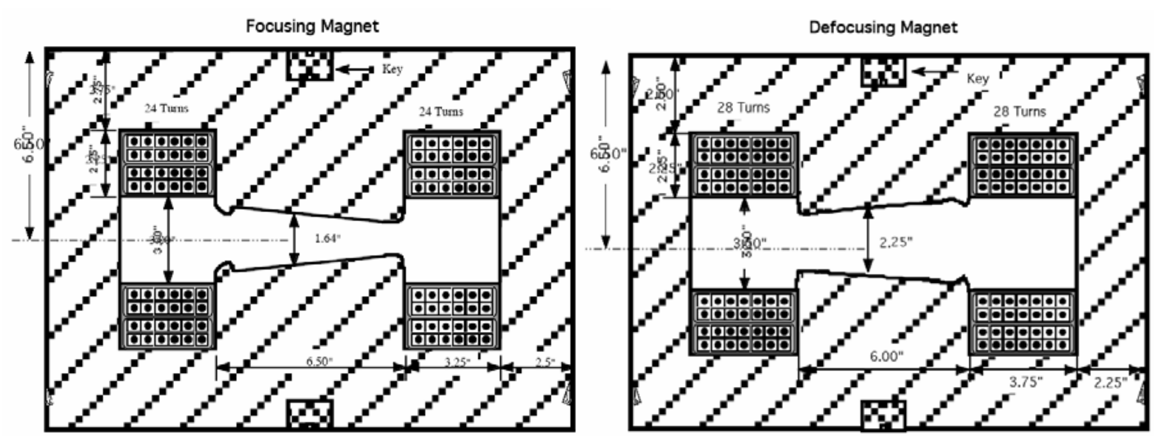
- Induce a large vertical betatron oscillation
- Uses a kicker magnet
- Displacement goes as:

$$\Delta y \propto \frac{\beta_y}{p} \sin(\phi_V)$$

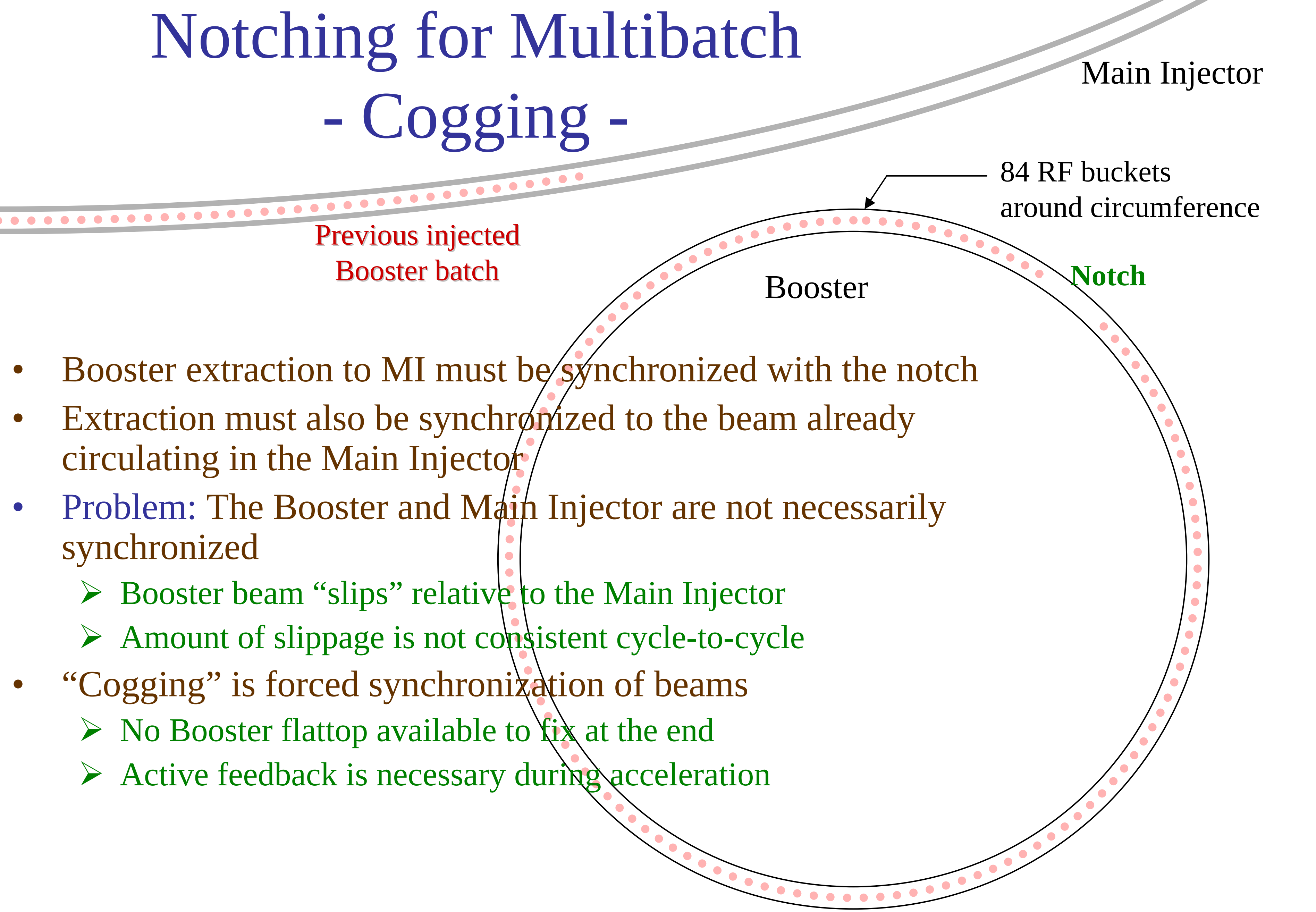
  - $\phi_y \sim 90^o$ / period
- Most of the beam is deposited in the third magnet
- Kick must be large enough to scrape off beam
  - Beam is stiffer at higher energy







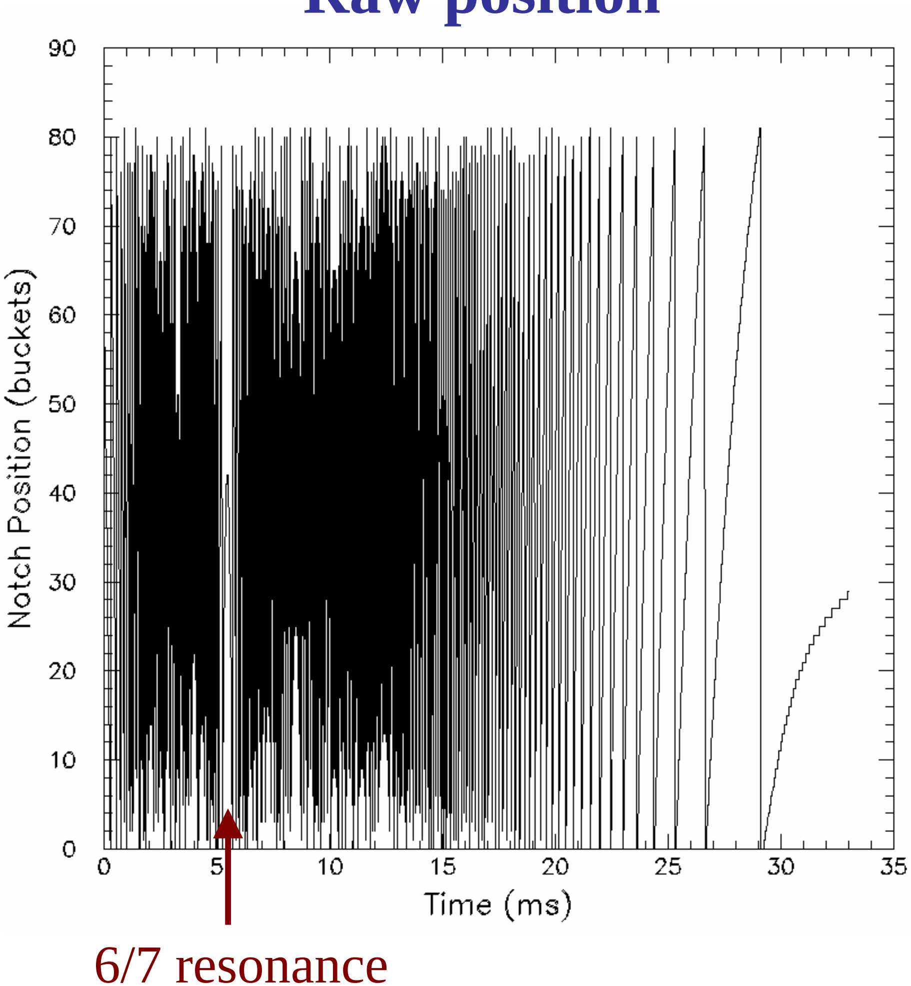
Notching for Multibatch
- Cogging -



- Booster extraction to MI must be synchronized with the notch
- Extraction must also be synchronized to the beam already circulating in the Main Injector
- Problem: The Booster and Main Injector are not necessarily synchronized
  - Booster beam "slips" relative to the Main Injector
  - Amount of slippage is not consistent cycle-to-cycle
- "Cogging" is forced synchronization of beams
  - No Booster flattop available to fix at the end
  - Active feedback is necessary during acceleration

Following the Notch

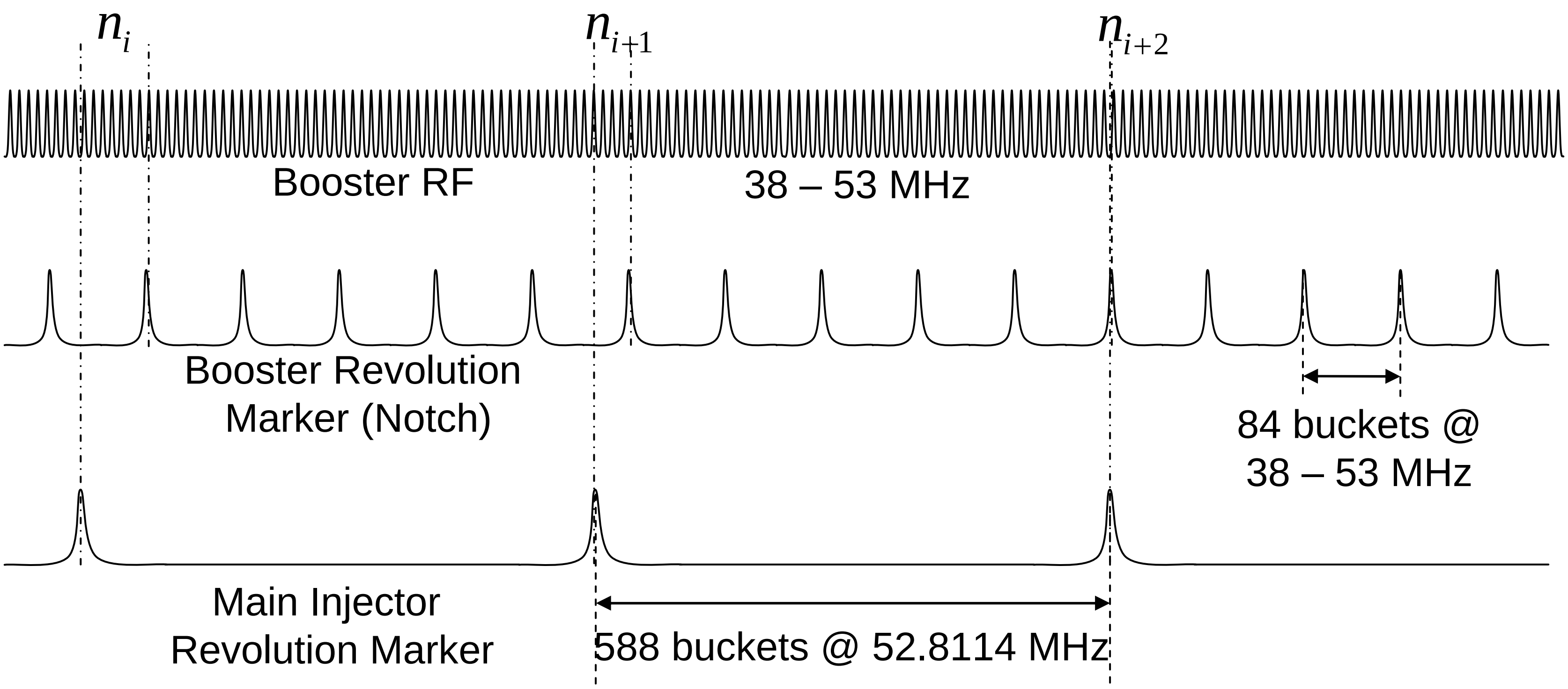
Raw position



- RF buckets slip at a rate $f_{MI} - f_B$
  - Initially 15 MHz
  - Notch wraps around the Booster many times
- Extraction with one batch
  - Count RF buckets to make a marker
  - Extract on marker
    - Tunable delay
  - Reset Main Injector
- With several batches
  - Possible if total slippage is exactly the same
  - Requires 1 in 100,000 consistency

Measuring Slippage

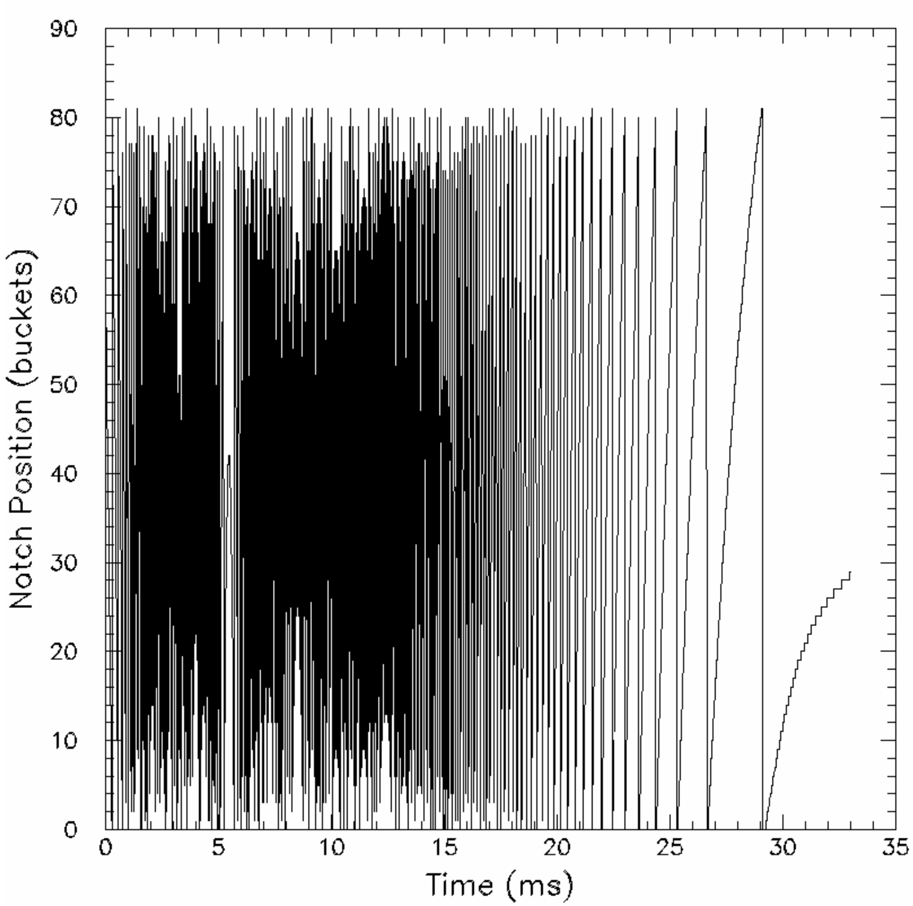
- Monitor Notch position throughout the cycle
- Use Main Injector RF as a standard clock
- Booster RF frequency varies with energy
    - 38 → 53 MHz
- Start counting on Main Injector revolution marker
- Stop Counting on Booster revolution marker
- Makes a table of positions (tripplan)

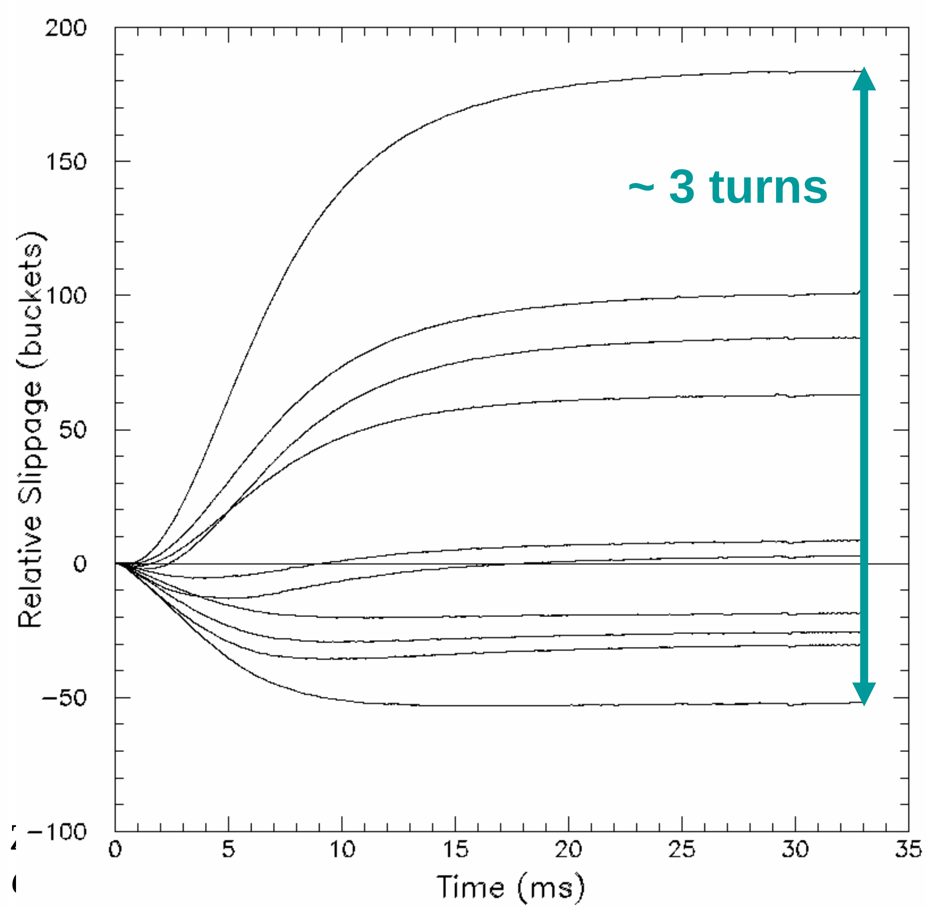


Relative Slippage

- Slippage in a cycle varies by > 200 buckets
  - About 3 circumferences
- Notch is essentially at a random position w.r.t the beam circulating in the Main Injector

Raw position ⇔ **Relative to baseline**





Sources of Slippage

- Any change in the difference of frequencies (f_{MI}, f_B) will cause slippage
- Some errors in the Booster can be parameterized as a change in p(t)
- Slip rate: η (buckets/ time)
  - ➢ 15 MHZ → 0
    - (inj. → ext.)
- Variations in wall socket frequency has long been suspected as a source of error
  - ➢ Booster 15 Hz is line f ÷ 4

$$\eta = f_{MI} - f_B = f_{MI}\left[\frac{1}{\beta_{MI}} - \frac{1}{\left(1+\frac{(mc)^2}{2p^2}\right)}\right]$$

$$S(t) = \int_0^t dt' \eta(t')$$

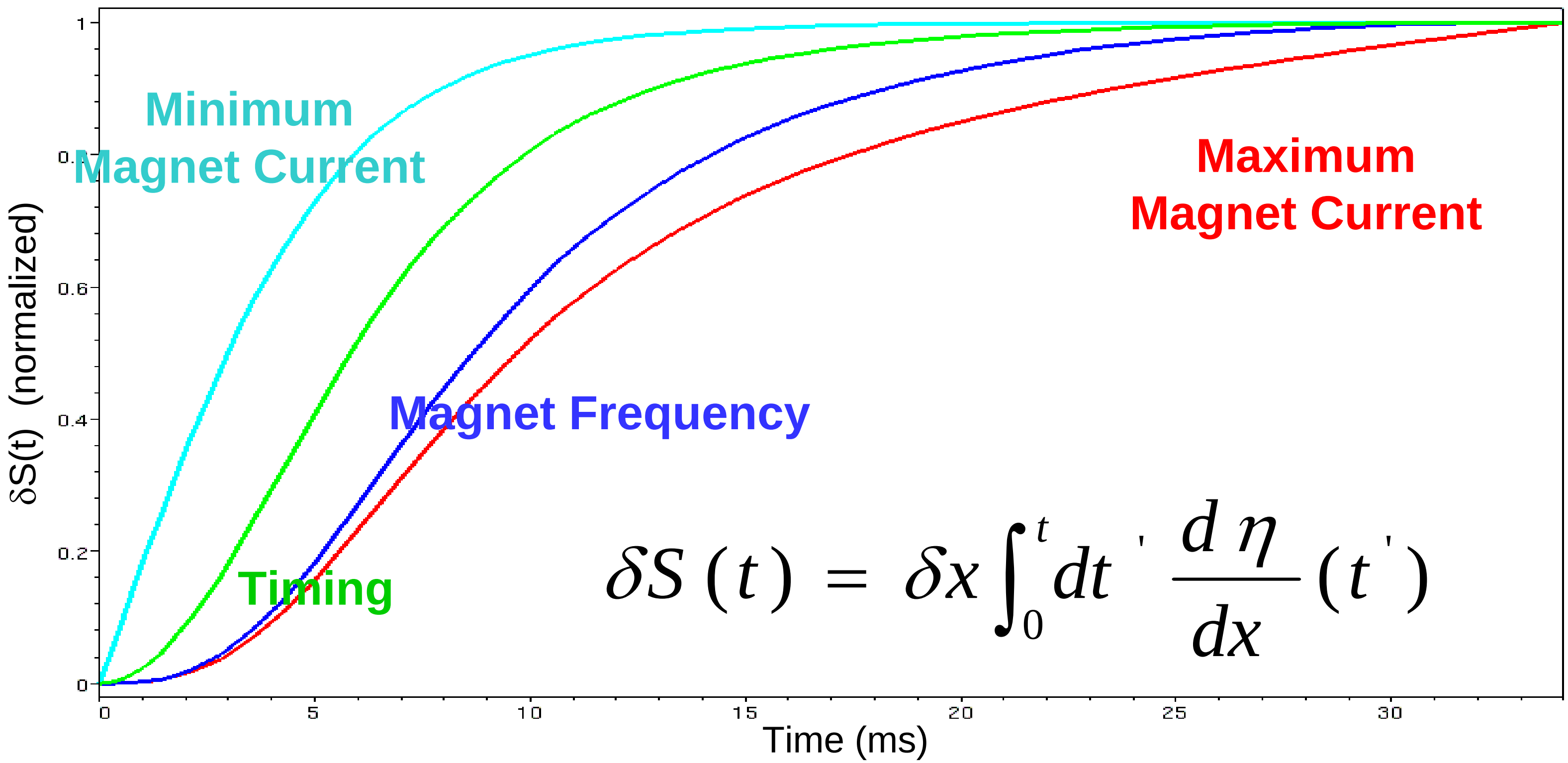
$$p(t) = p_0 - p_1 \cos(2\pi f t)$$

$$p_1 = \tfrac{1}{2}(p_e - p_i) = 3.9666 \text{ GeV/c}$$

$$p_0 = \tfrac{1}{2}(p_e + p_i) = 4.9223 \text{ GeV/c}$$

Error Characterization

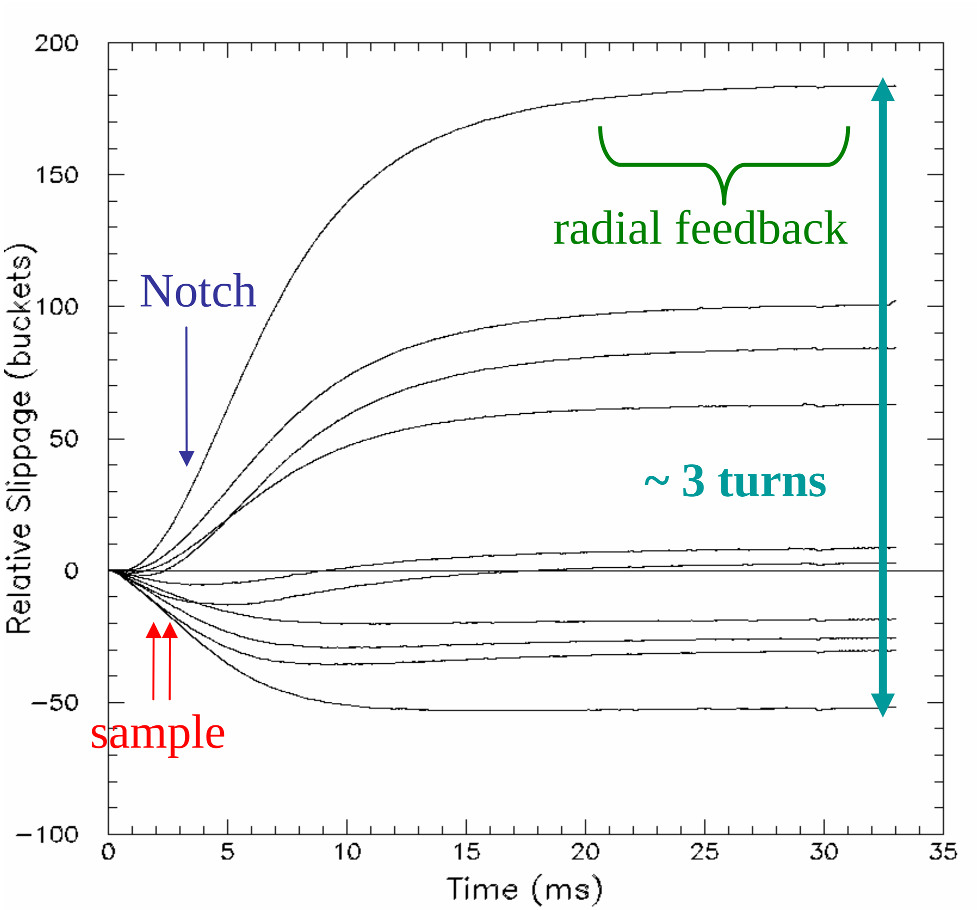
- Any perturbation to η(t) will resulting slippage
- Some errors can be parameterized as a change in p(t)
  - Each has a particularly shaped S(t) curve
- Several possible errors shown below:
  - Timing: 1 μs ⇒ 15 bucket slip
  - Magnet Frequency: 1 mHz ⇒ 6 bucket slip
  - Minimum Magnet current (δp_i): 1/10,000 ⇒ 10 bucket slip
  - Maximum Magnet current (δp_e): 1/10,000 ⇒ 7 bucket slip



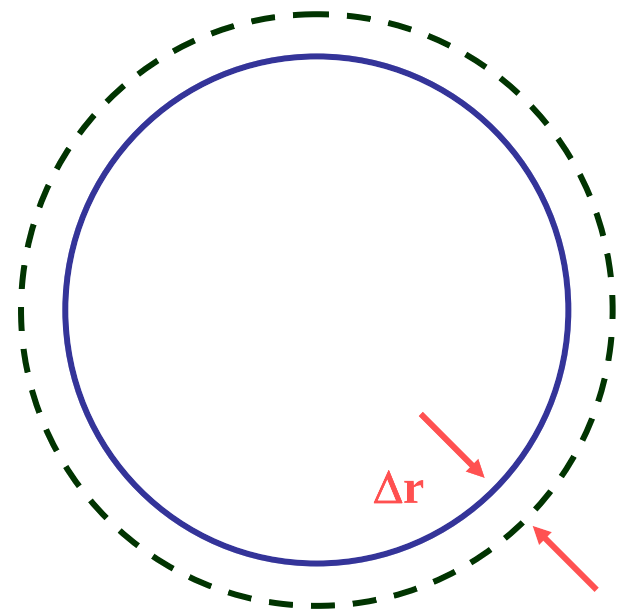
$$\delta S(t) = \delta x \int_0^t dt' \frac{d\eta}{dx}(t')$$

Cogging Method

- Use the early part of the cycle to predict net slippage before extraction
  - ➢ Place the notch anticipating further slippage (few ms into cycle)



- After transition slippage can be induced by changing the radial position of the beam
  - ➢ Changes the feedback of the Low Level RF systems
  - ➢ Changes the circumference, and thus period, of a revolution
  - ➢ Active feedback can correct to zero error

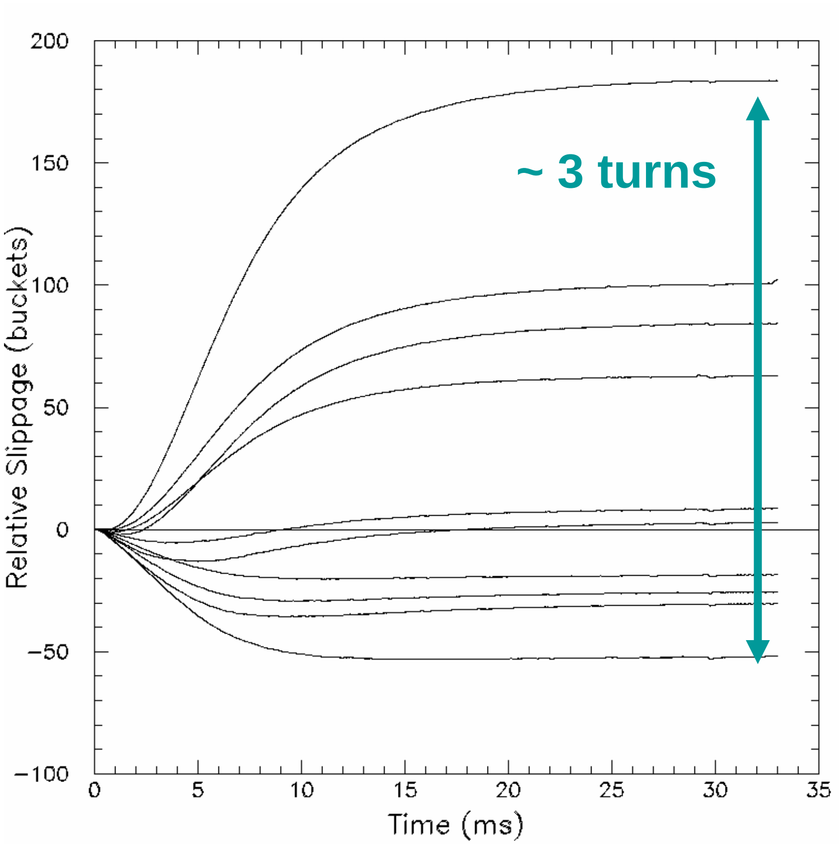


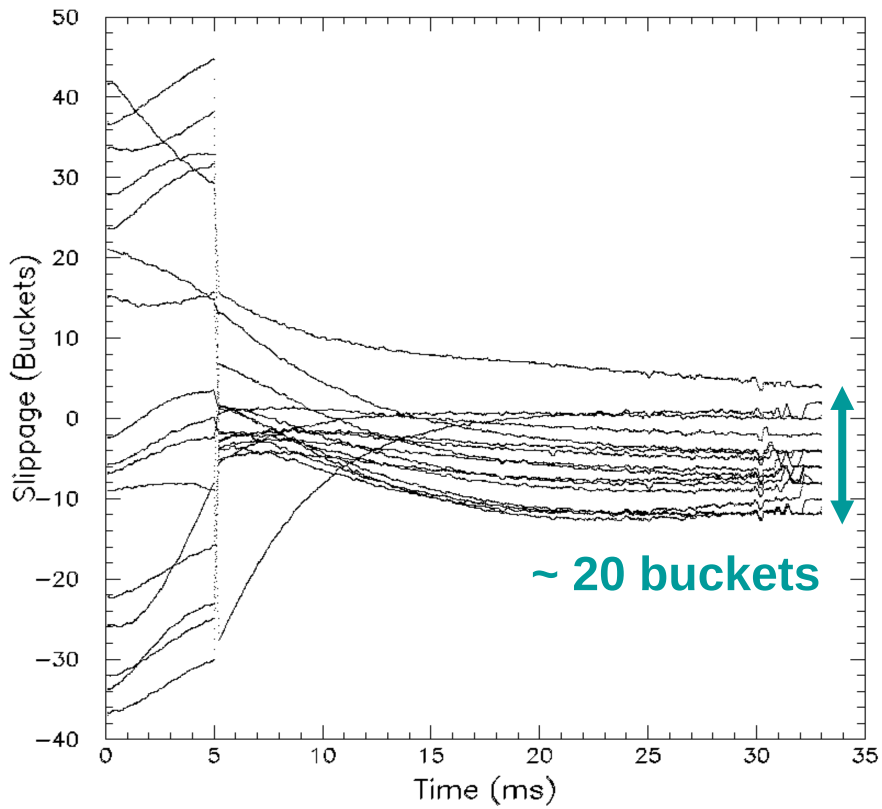
ska

ging

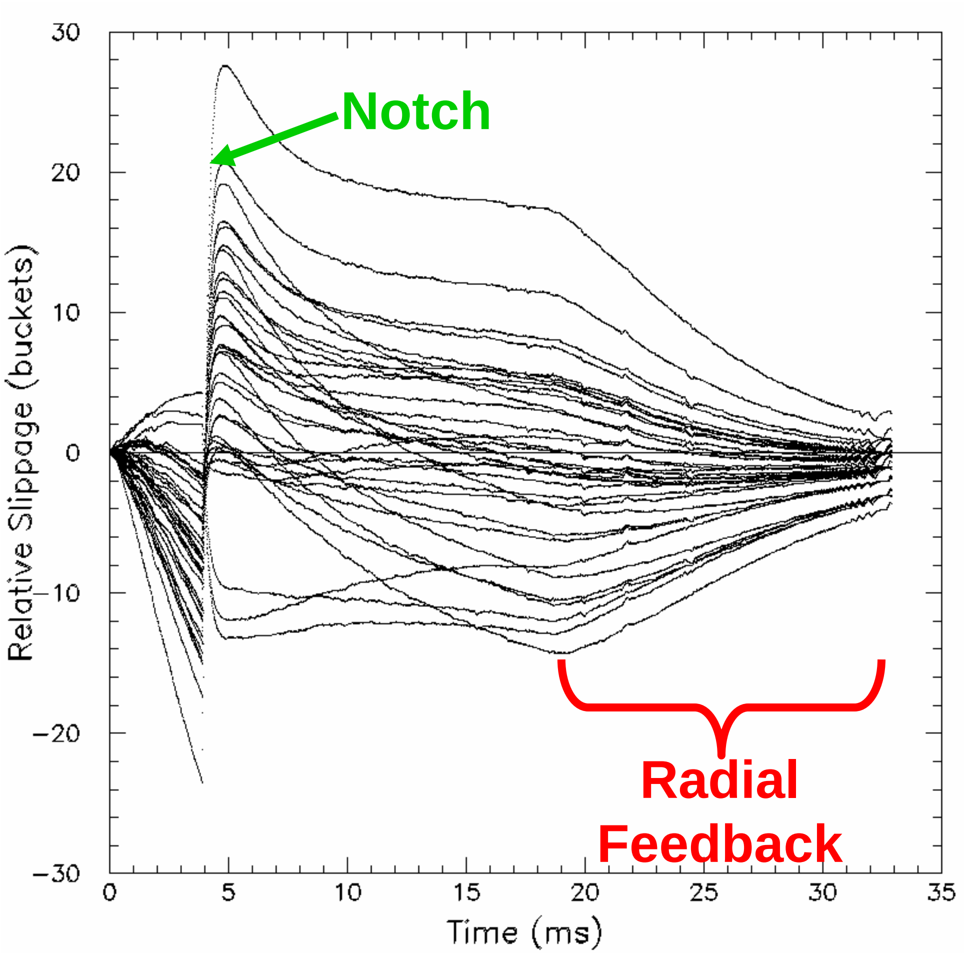
Intelligent Notching

- Depends on consistent slippages signature
  - i.e. source of slippage
- Application of the notch 5 ms later can reduce range



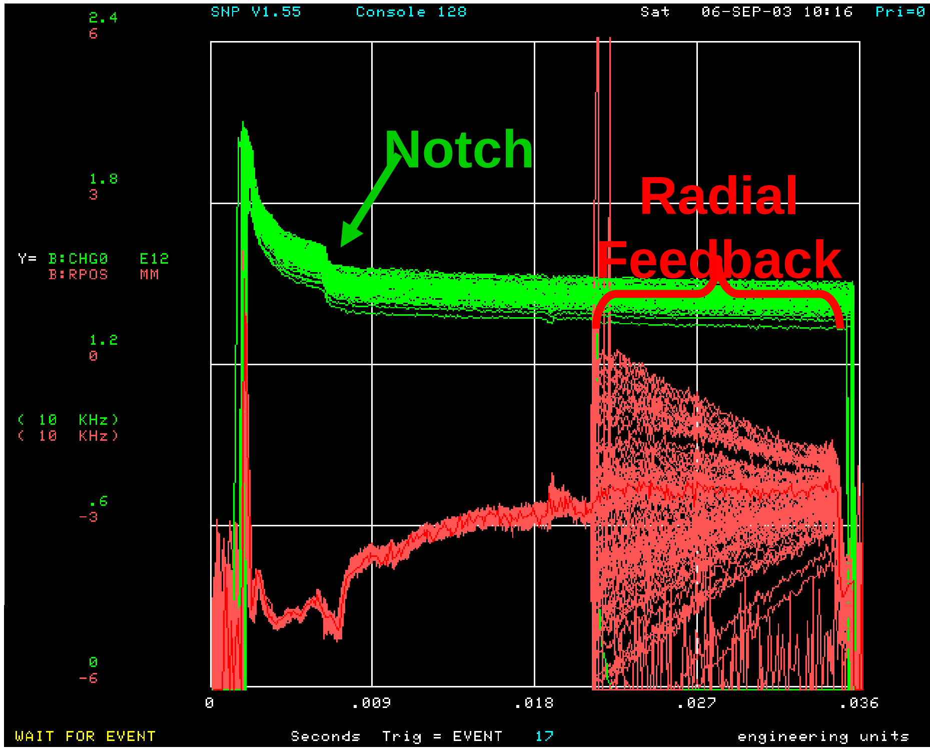


First Tests of Cogging



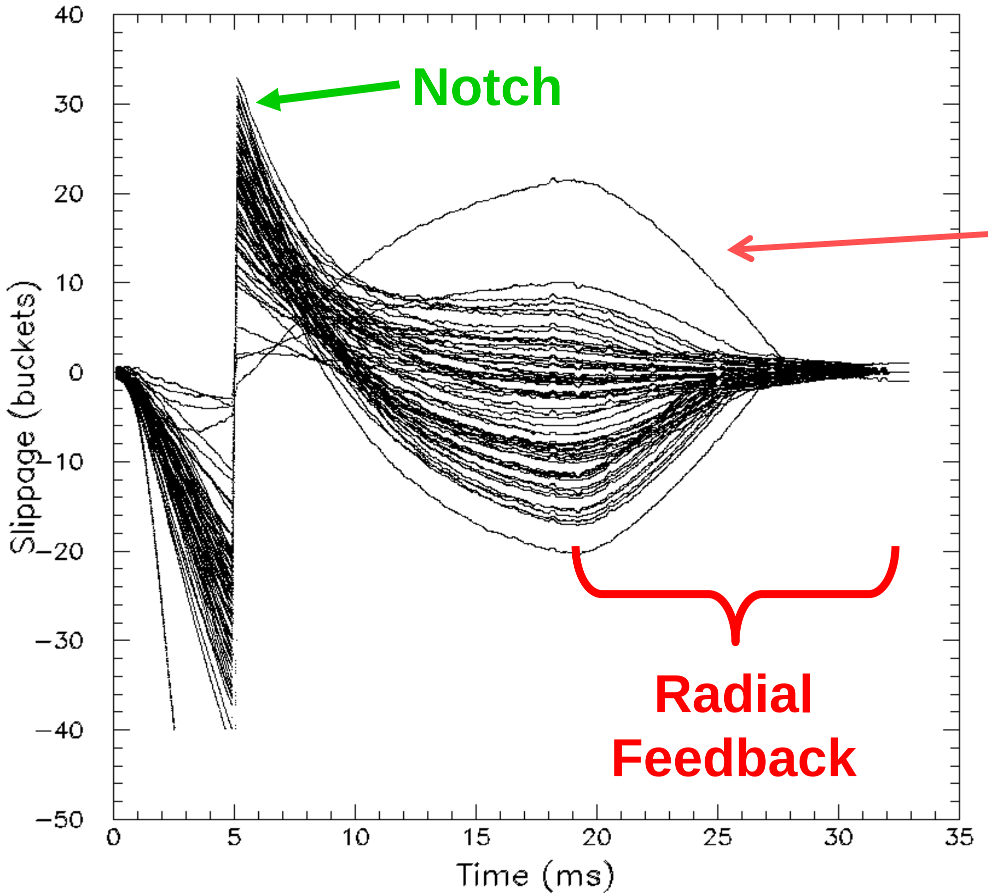
➢ Doesn't get to zero

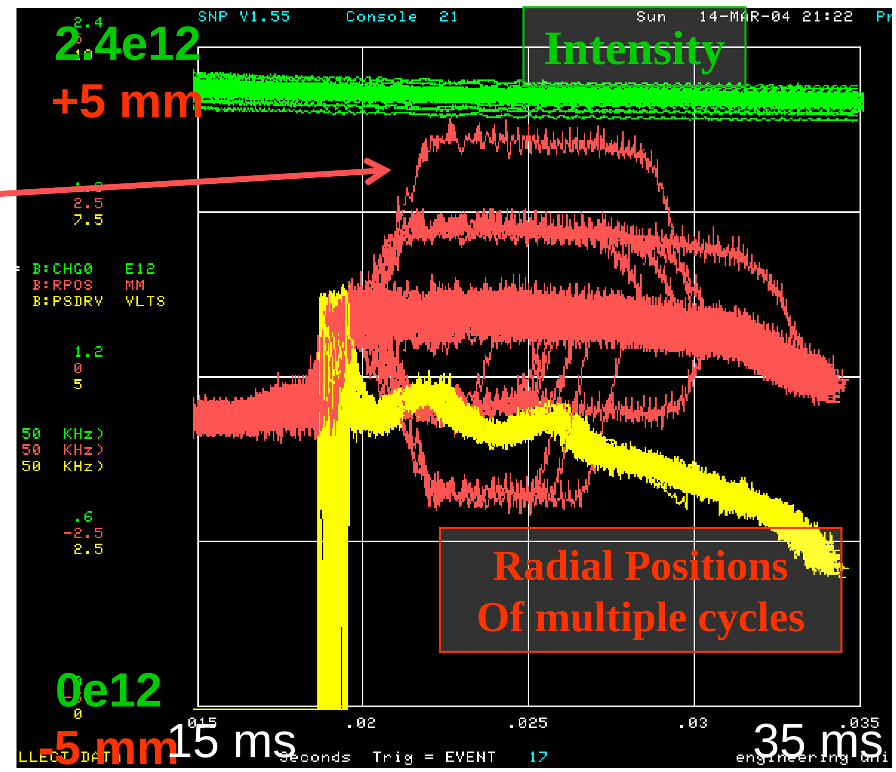
- Notch using prediction
- Radial Feedback late in the cycle
- $\Delta r = k \cdot \Delta S$
  - ➢ Exponential damping
  - ➢ $k \approx 0.2$ mm / bucket
  - ➢ e-folding time ≈ 10 ms



Recent Cogging in the Booster

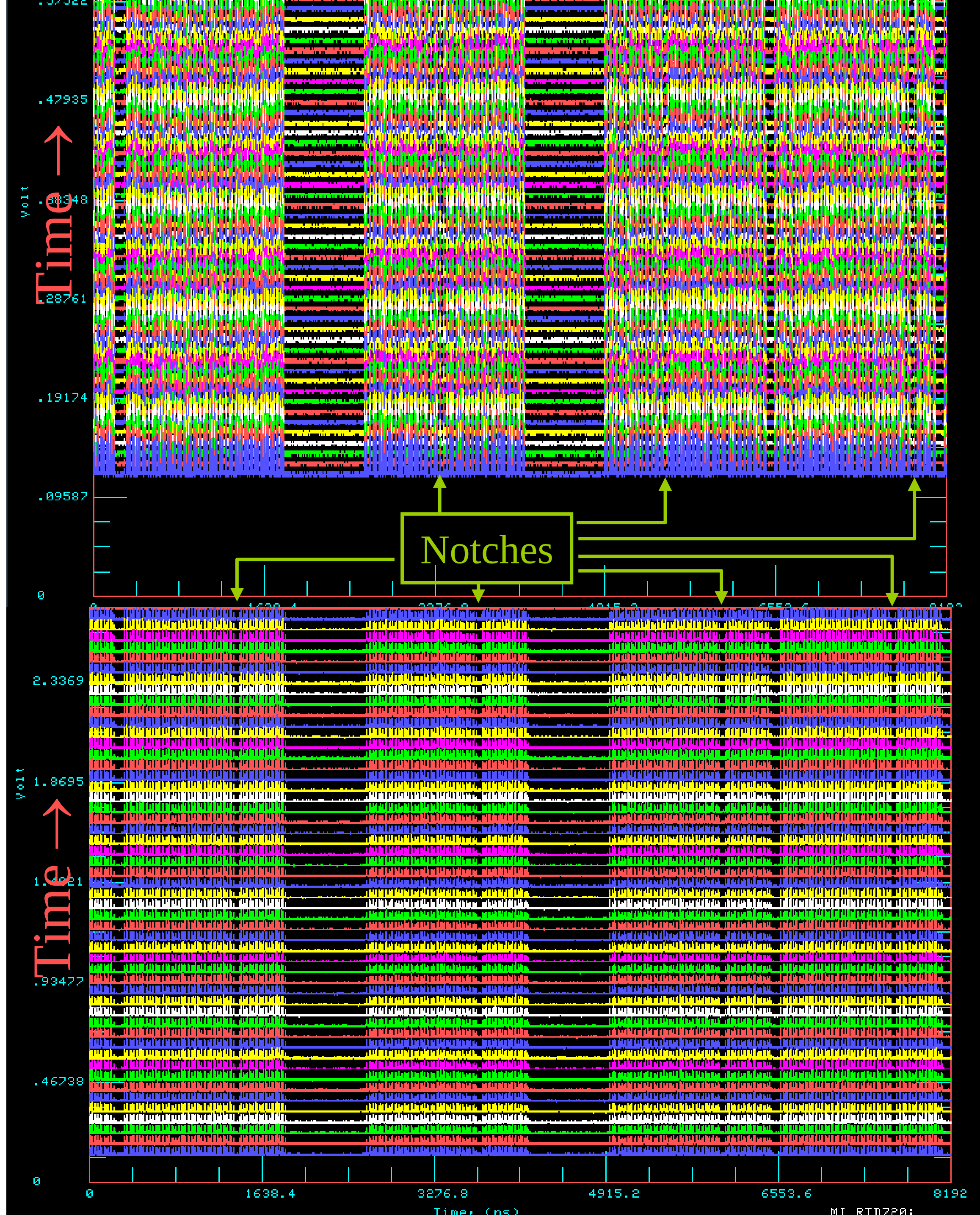
- Shown are the second batches of a slip-stacking cycle
  - All slippage is to one side
  - Radial feedback is significant
- Radial offset goes to a constant value to get closer to zero
  - 90% with 0 error
  - Other 10% with ± 1 (out of ~ 70)





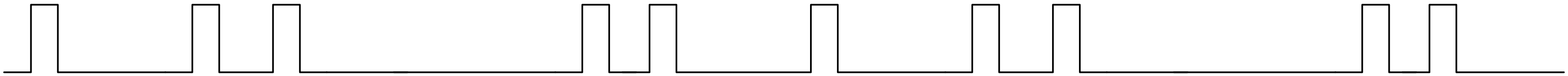
Beam in the Main Injector

- These are Booster Batches lined up in the Main Injector
  - ➢ Two different beam tests
- Kicker extraction is synchronized with beam in Main Injector
  - ➢ Not to the notch in Booster
- Upper set is uncogged
  - ➢ Notch appears randomly within the batches
- Second batch is cogged
  - ➢ Notch appears at a consistent position with each batch
  - ➢ Only the timing of the notcher need be adjusted
    - Wouldn't be visible otherwise

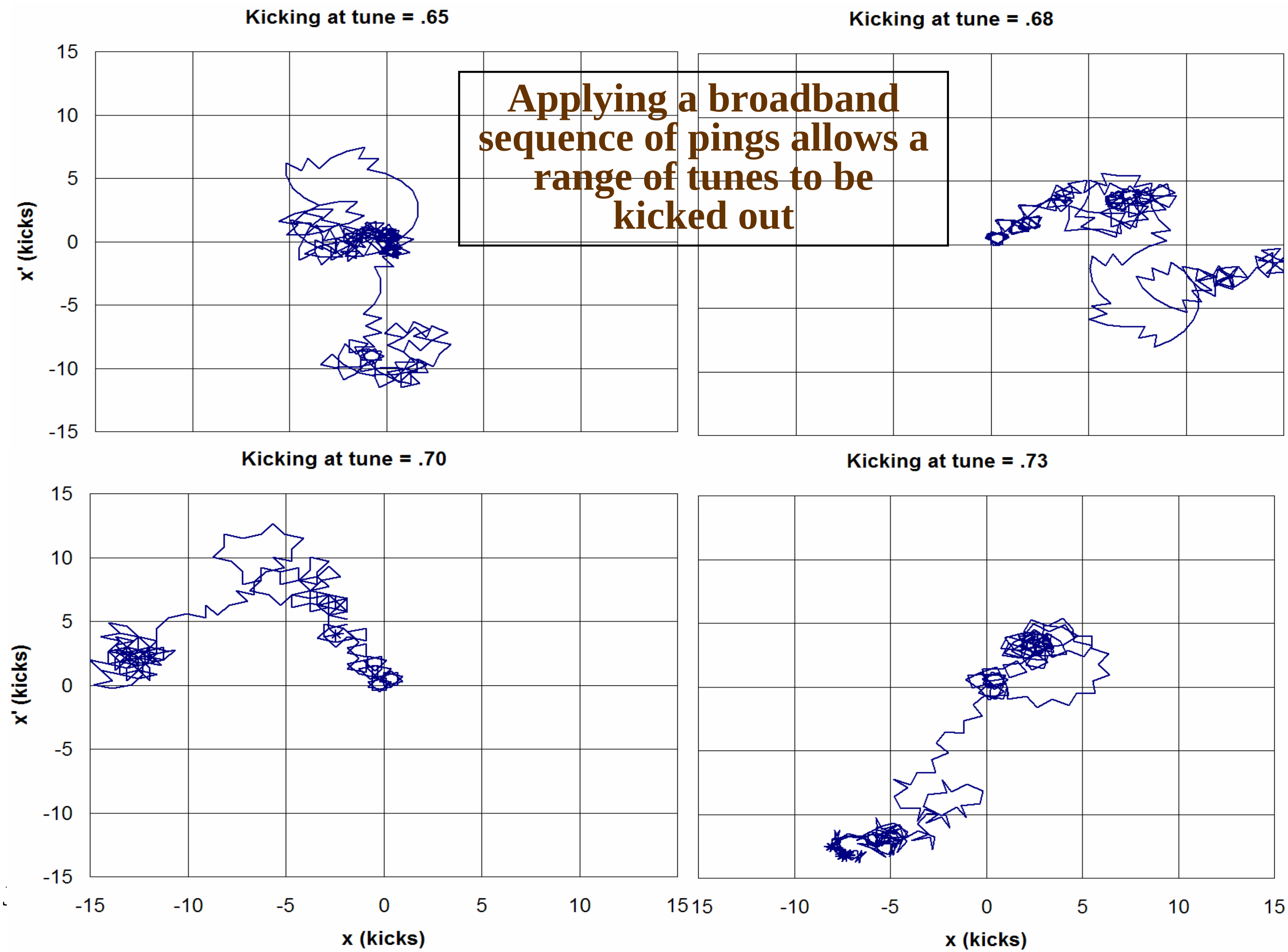


Ping Notching

- Current notch knocks out the beam with one kick
  - ➢ Works less well at slightly higher momenta
  - ➢ Activates one region with the loss
    - This loss is irreducible and scales with the number of protons
- Alternative: Apply a series of smaller kicks (pings)
  - ➢ Similar, in concept, to anti-damping
    - But, no feedback
  - ➢ Takes a few hundred turns
  - ➢ Uses a solid-state driver
  - ➢ Losses go into collimators
- Need to account for tune spreads and shifts



Broadband Pinging Simulation

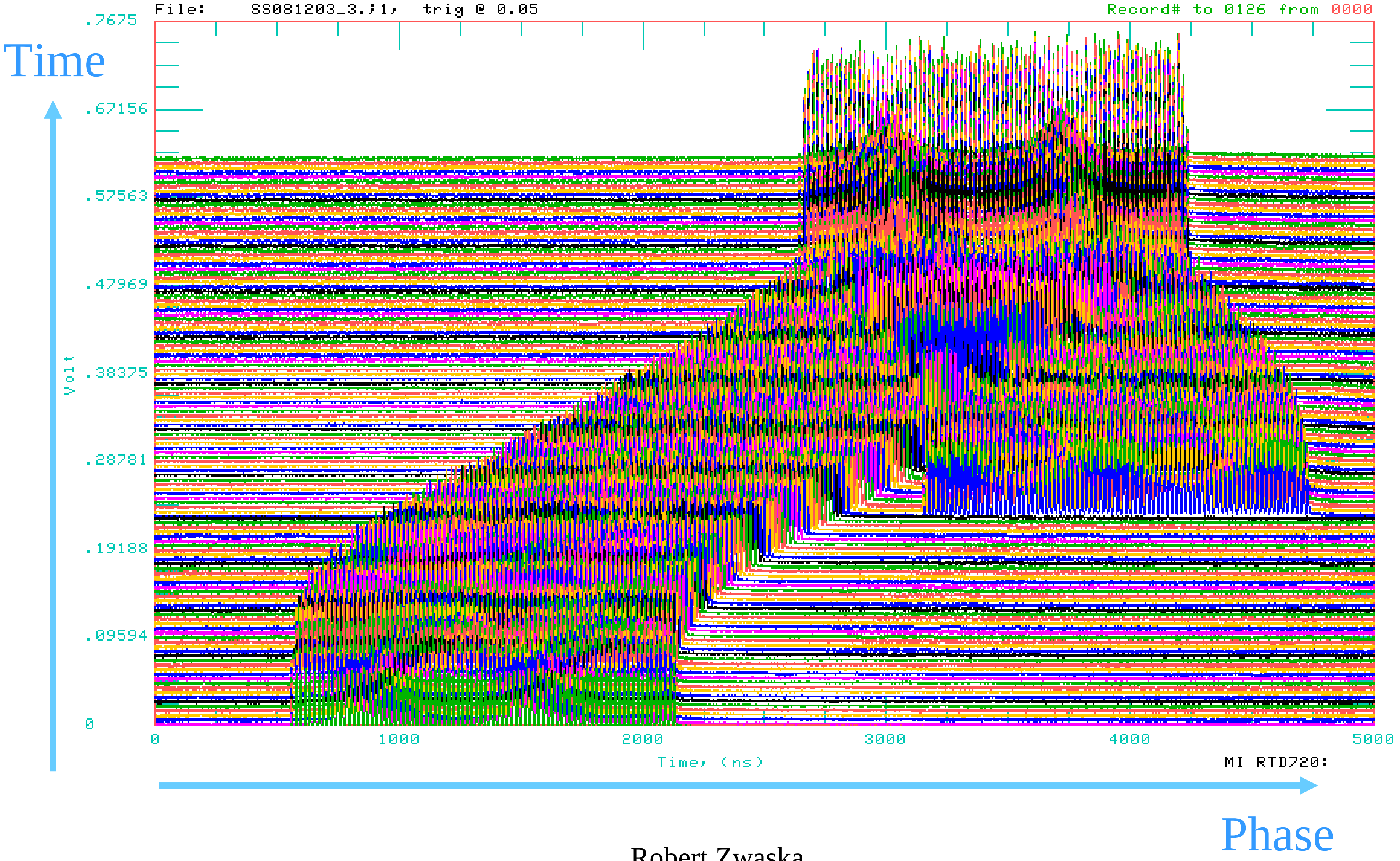


Applying a broadband sequence of pings allows a range of tunes to be kicked out

Intensity in the Main Injector

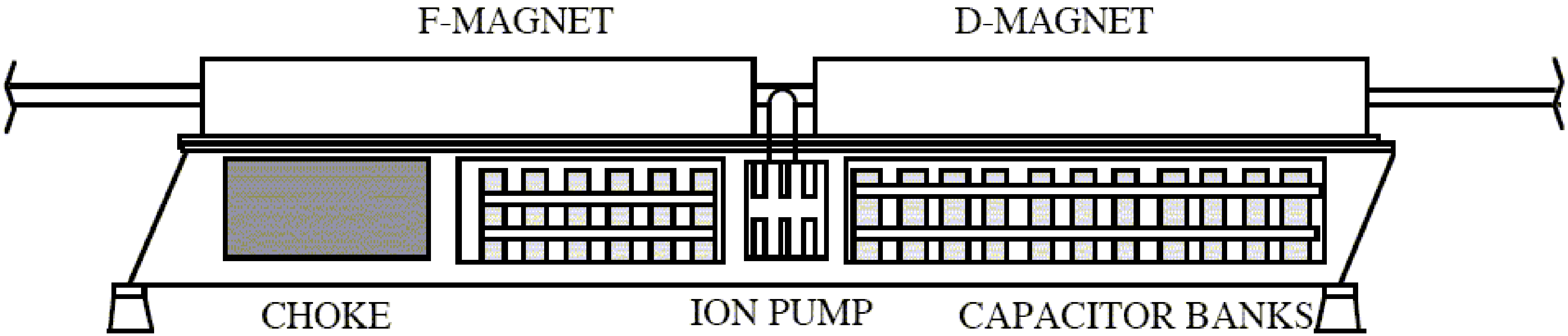
- Since commissioning, MI has run with only 5×10^{12} protons in it
  - 1/7 of the ring
- With NuMI, there will be at least 3×10^{13}
  - $5+1 \times 10^{12}$
  - Booster per-batch intensity may be higher
  - Stacking schemes might allow another 50%
- Numerous problems need to be addressed
  - Foremost are instabilities due to beam-loading and other collective effects
- This is just to get to our planned intensities, higher will require significant upgrades

A View of Slip-Stacking

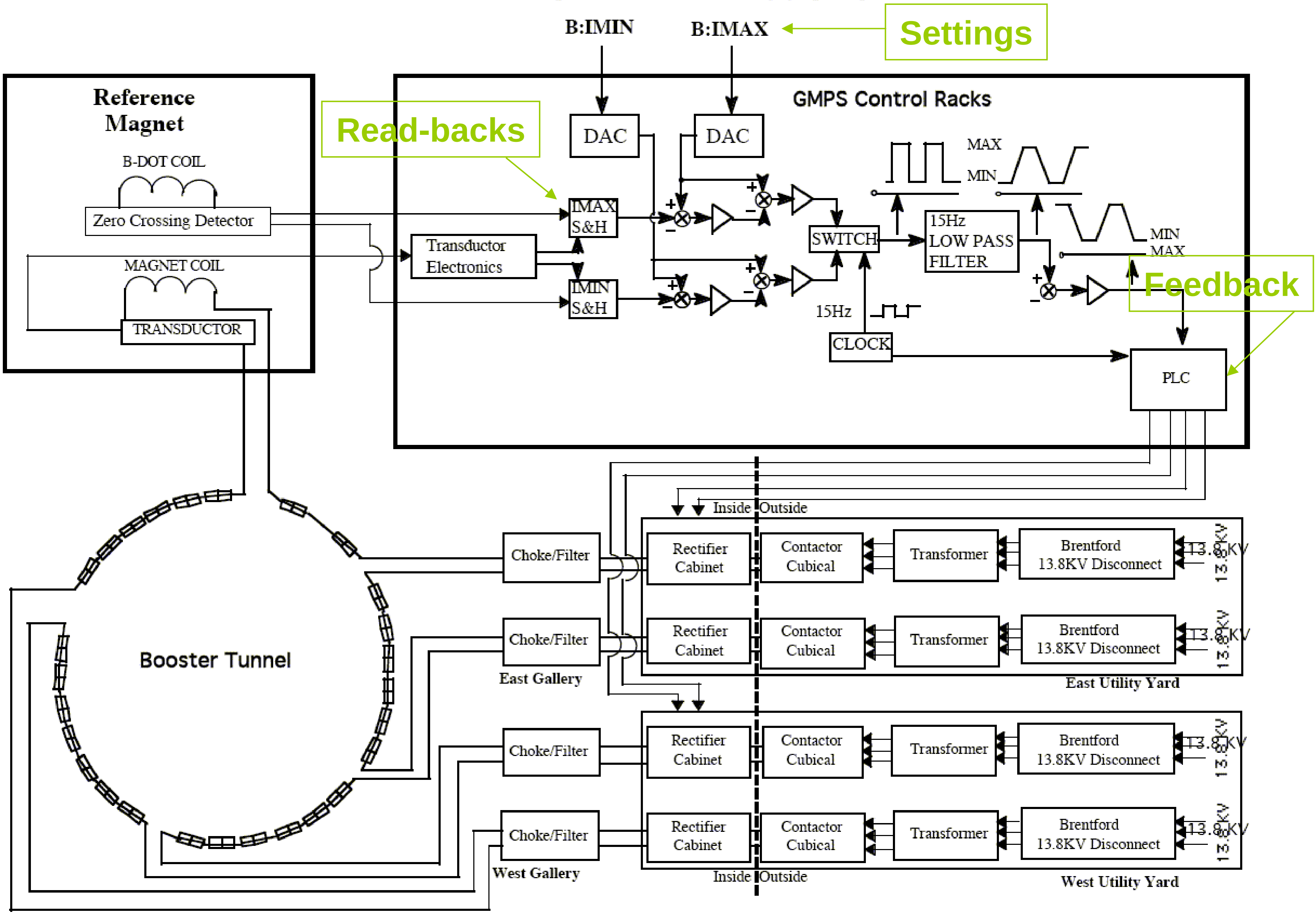


GMPS

- Booster magnets are part of a resonant circuit
  - ➢DC & AC components
  - ➢AC is part of a LRC circuit with choke & caps in tunnel
- Circuit controlled by "GMPS" (Gim-pis)
  - ➢Gradient Magnet Power Supply

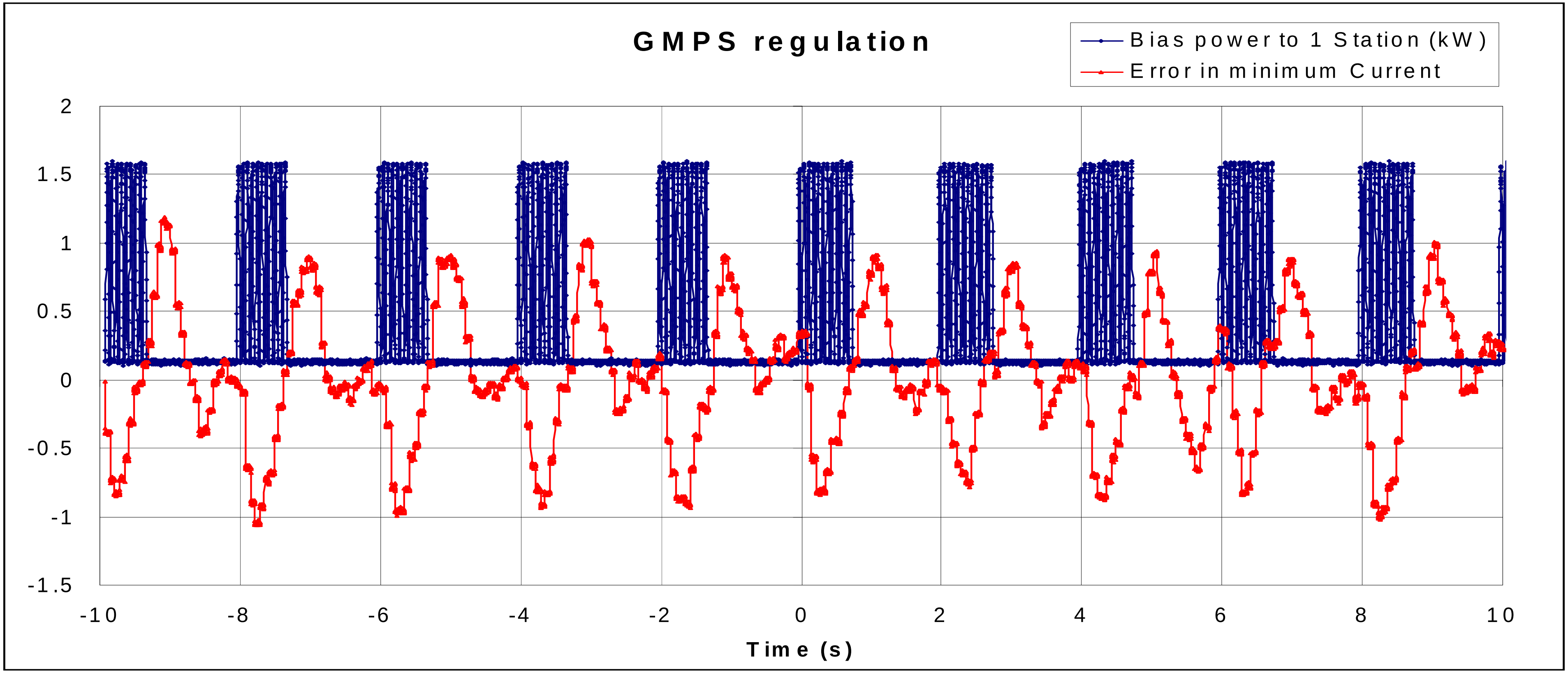


Gradient Magnet Power Supply System

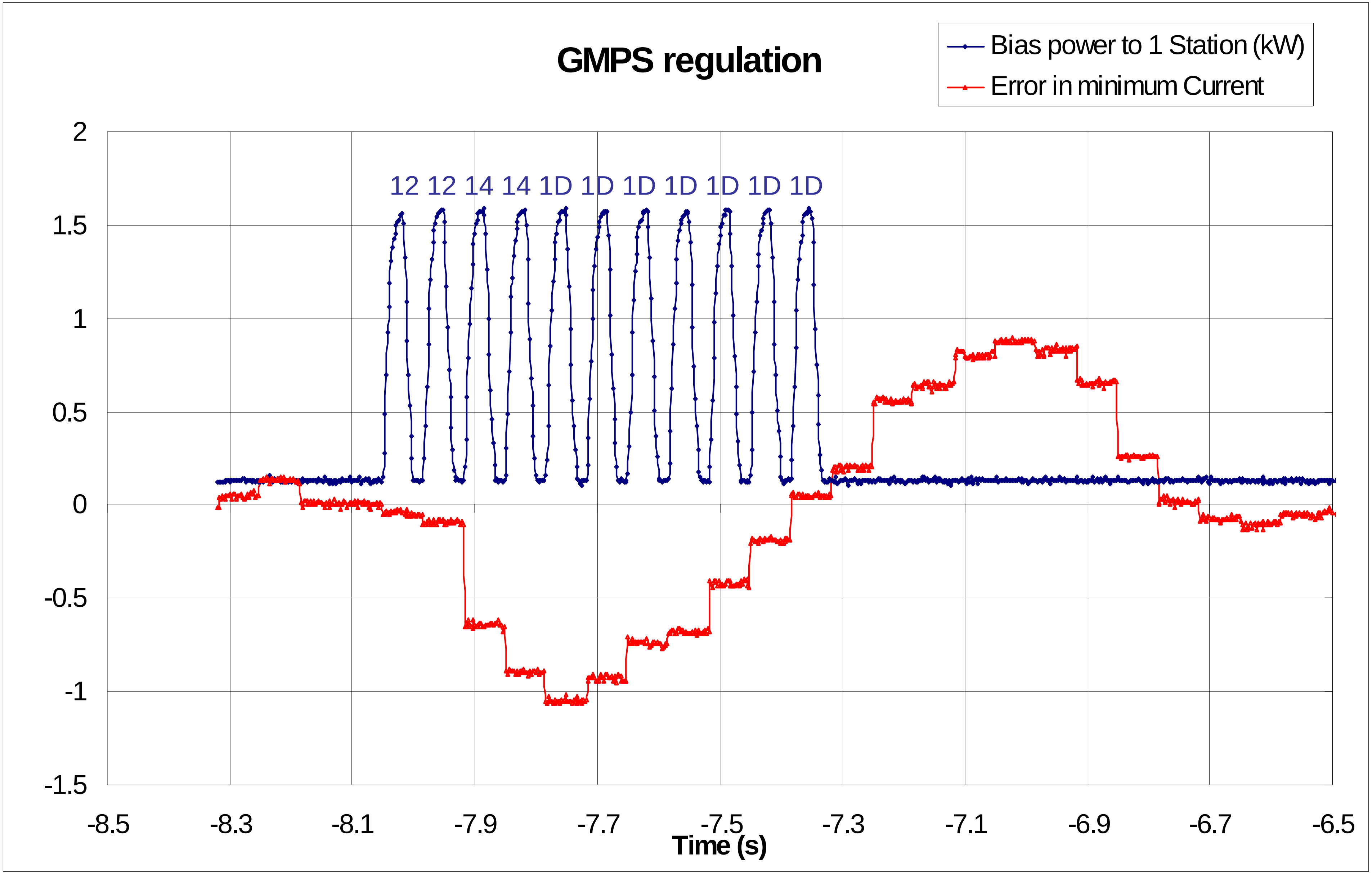


GMPS Regulation

- Observed Oscillation of minimum current
  - Occurs over a train of cycles
- Suggestive of line draw, and compensation
  - Feedback with t ≈ 400 ms
- Hypthesized cause:
  - Pulsed devices drag line current down
  - Lower line current reduces power input to GMPS
  - Particularly, RF & bias supplies

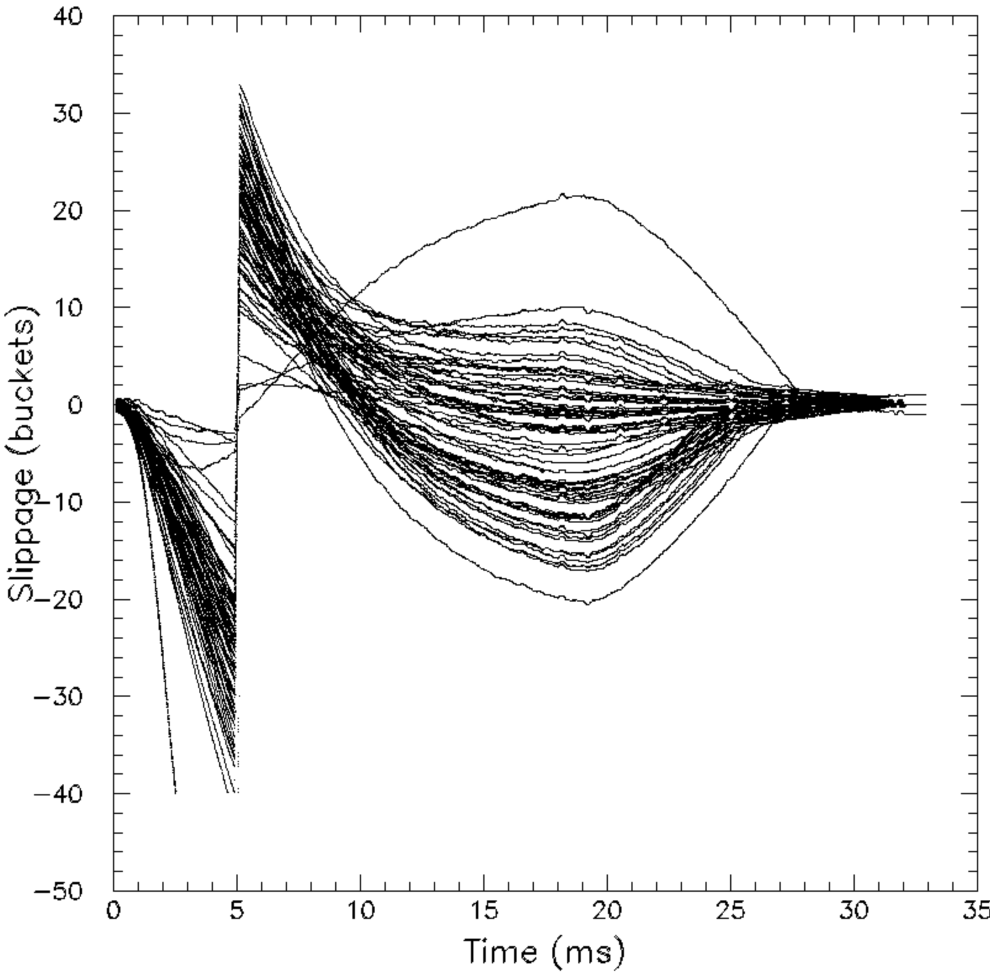


GMPS Over a Cycle Train



GMPS Effects

- These are all the second $14
  - w.r.t. a first $14
- All display an initial slippage
  - Starts after ~1 ms
  - Rate of ~ 7 buckets/ms
  - Turns around after notch
- Difference depends on position on train
  - Worse for NuMI cycles
  - Depends on the rest of the timeline
  - Different signature than other slips
    - *Hurts Prediction*
  - Can't be fixed by frequent tripplans
- What's Happening:
  - Beam is bunched into 38 MHZ buckets
    - Set externally
    - No initial Slippage
  - Phase feedback turns on quickly
    - Lower magnet current
    - Beam is pushed toward outside
    - Slippage begins
  - Radial feedback turns on after few ms
    - Gain ramps up
    - Beam moved to correct position
    - Slippage lessons quickly

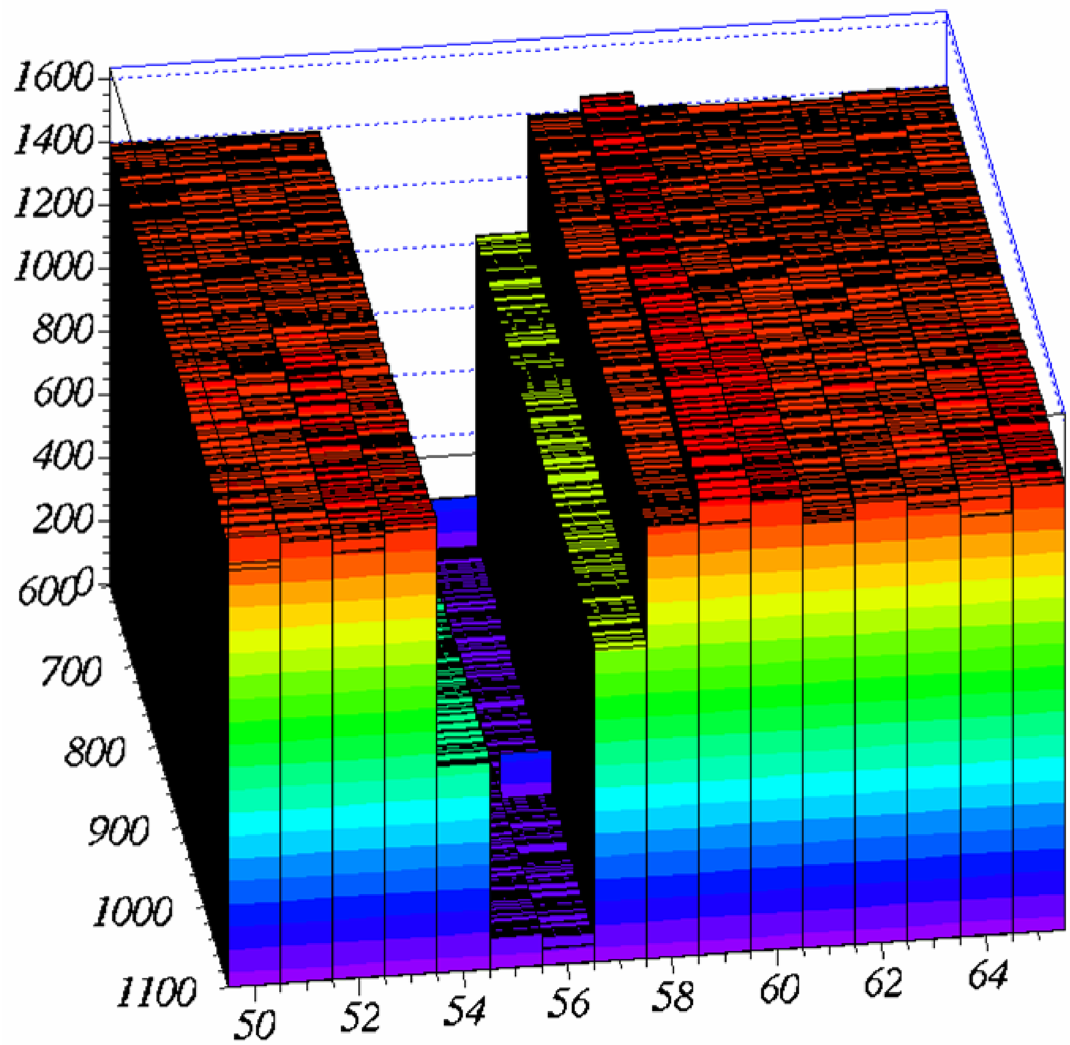


What to do with GMPS?

- Compensate with cogging:
  - Cogging “works” with this variation
    - However, beam is pushed more than we would like
  - Adequate for moderate intensities
- Fix GMPS:
  - EE Support is looking into feedback
    - Feedback should be able to be faster
  - More stable GMPS might be good all around
- Isolate GMPS
  - Move GMPS to a different feeder than pulsed devices
  - Under investigation

Half a Notch

- Notcher power supply is old and decrepit
- Notch is marginal on batch trains
- Notch is partial with cogging
  - ➢ 5-10% remains in two buckets
  - ➢ Only two buckets wide
- Makes cogging hard
  - ➢ We could always go with a wider notch, but we don't want to



Summary

- Proton demand at FNAL has been growing, and will continue to
  - Current experiments need more protons
  - NuMI is about to start using protons
  - Potential experiments need even more protons
- FNAL has an ongoing process of upgrade and improvement to its proton source
  - Focuses on the Booster and Main Injector accelerators
    - Improvement is expected in the Booster
    - Main Injector will start high-intensity operations
  - Improvements have been made with outside collaboration:
    - Universities, involved in experiments and otherwise
    - Other labs (KEK, BNL, LANL, RAL, etc.)
- Until a Proton Driver materializes, improvements in proton intensity will require investments throughout the accelerator complex