Booster Cogging

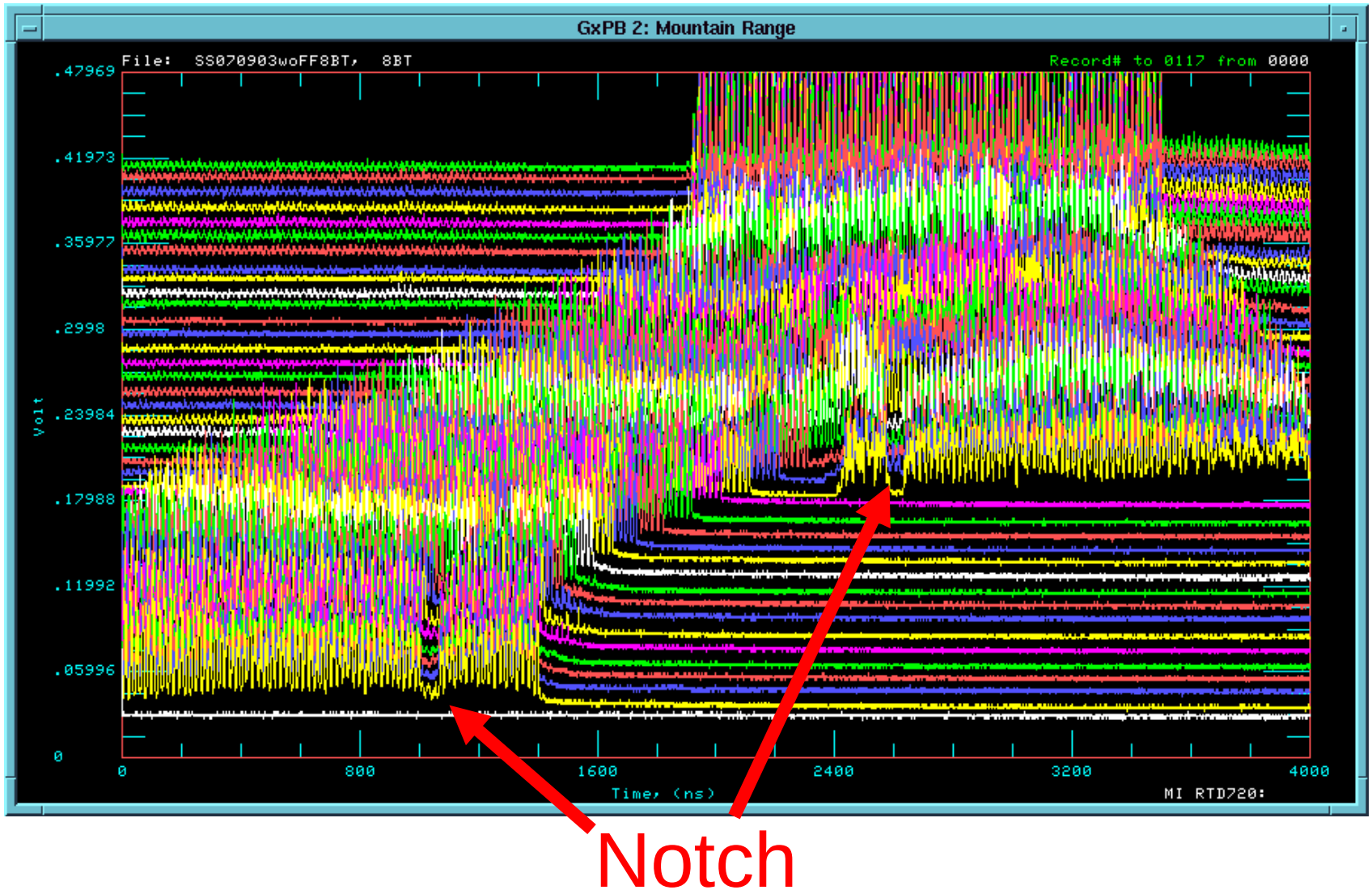
Bob Zwaska
University of Texas at Austin

Bill Pellico
FNAL

The Need for Cogging

- Booster beam has a notch in it
  - Extraction kicker risetime of ~ 40 ns
  - Bunch spacing of ~ 19 ns
  - 1-2 bunches of beam are lost on extracting
  - Notching the beam at 400 MeV involves less loss
- Requires extraction to be synchronized with the notch
- Extraction must also be synchronized to the beam already in the Main Injector
- Problem: The Booster and Main Injector are not synchronized.

Nominal Notching



The Role of Cogging

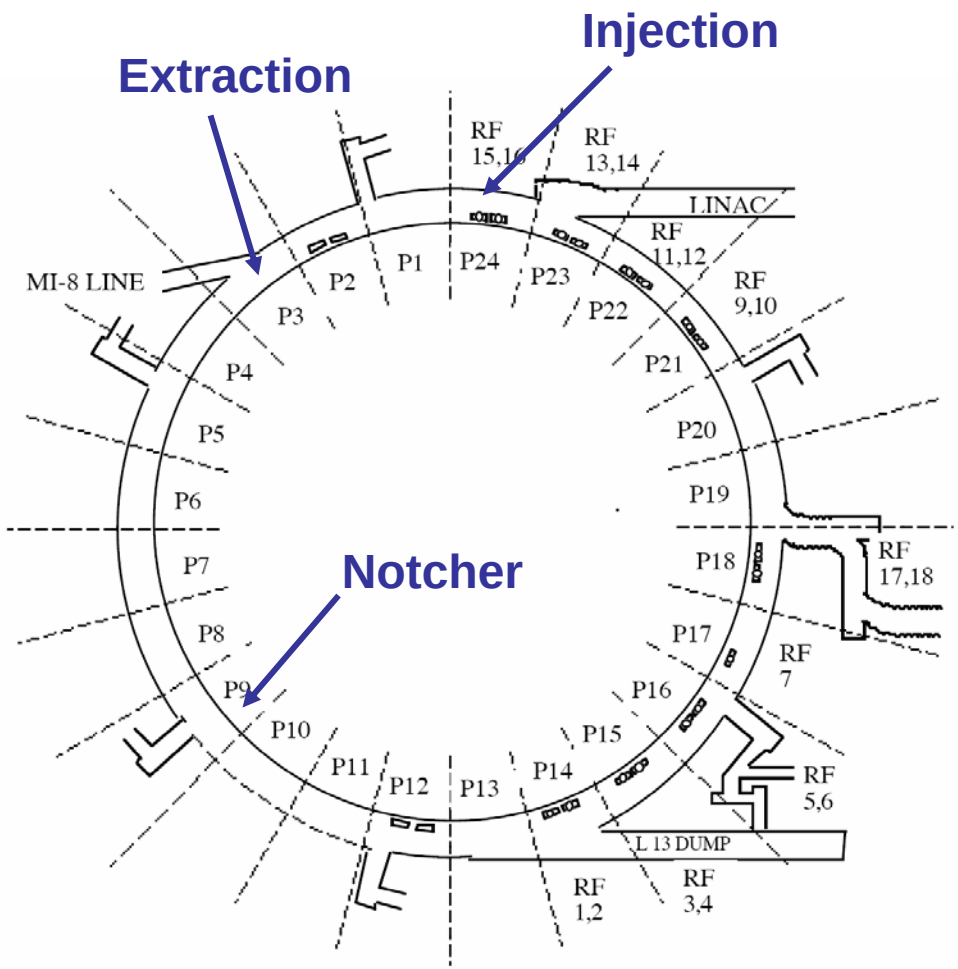
- Cogging will synchronize the Booster notch to beam in the Main Injector
- Necessary for any multibatch use of the Main Injector
  - NuMI
  - Slip-stacking
- Booster has no flattop during which beam can be manipulated
- Cogging must be done during acceleration
  - Notch created anticipating slippage
  - Radial feedback corrects unanticipated slippage

Outline

- Measuring slippage in the Booster
- Origins of slippage
  - Some can be eliminated
  - Others can only be reacted to
- Intelligent notching of the beam
  - Position notch anticipating slippage
  - Involves a later notch
- Radial manipulation of the beam
  - Moves beam within an envelope at high field
  - Concerns about beam quality
  - Effectiveness for cogging

The Booster

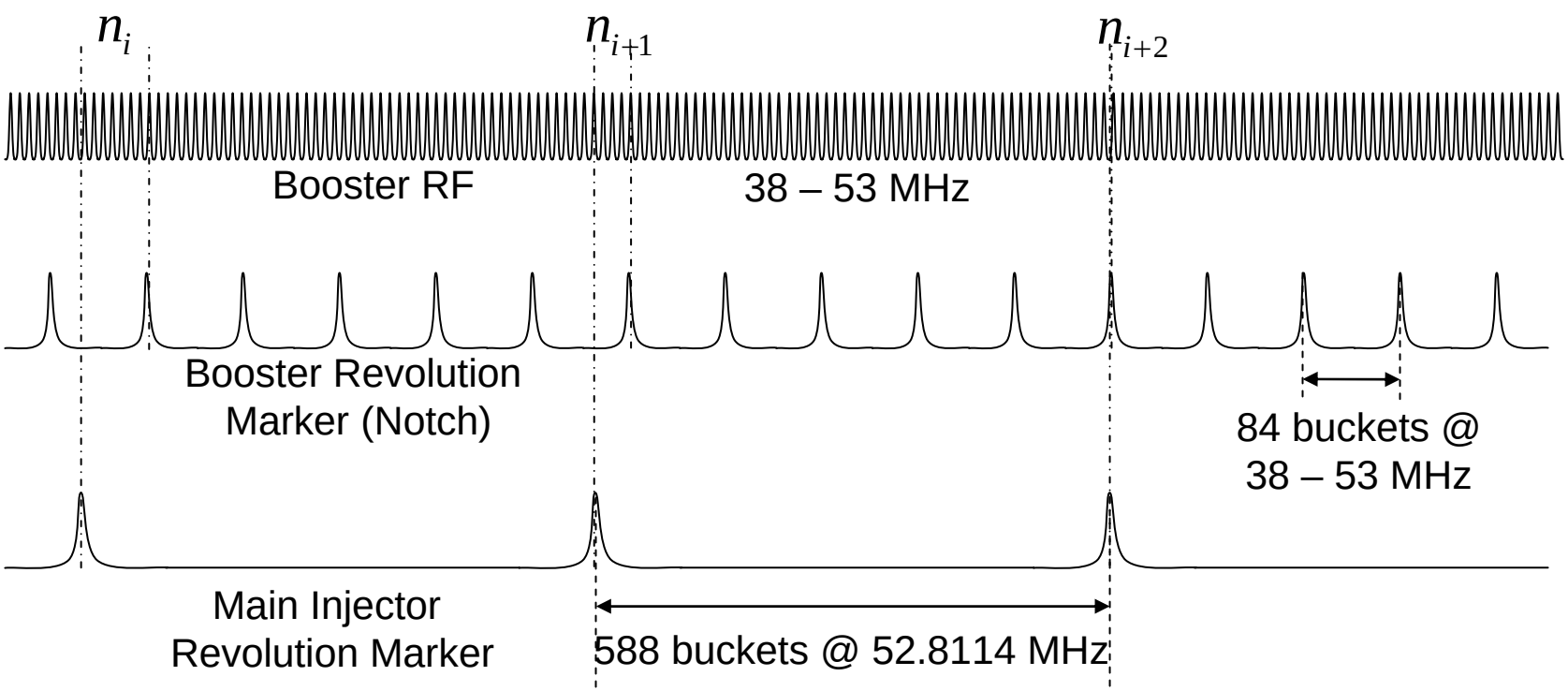
- Accelerates from 400 MeV to 8 GeV in 33 ms
  - Magnets are on a 15 Hz resonant circuit
- h = 84
- p: 0.95 → 8.89 GeV/c
- β: 0.71 → 0.99
- f: 37.9 → 52.8 MHz
  - MI stays at 52.8 MHZ (8 GeV)
  - Booster starts slipping at 14.9 MHZ w.r.t. MI



Measuring Slippage

- Monitor Notch position throughout the cycle
- Use Main Injector RF as a standard clock

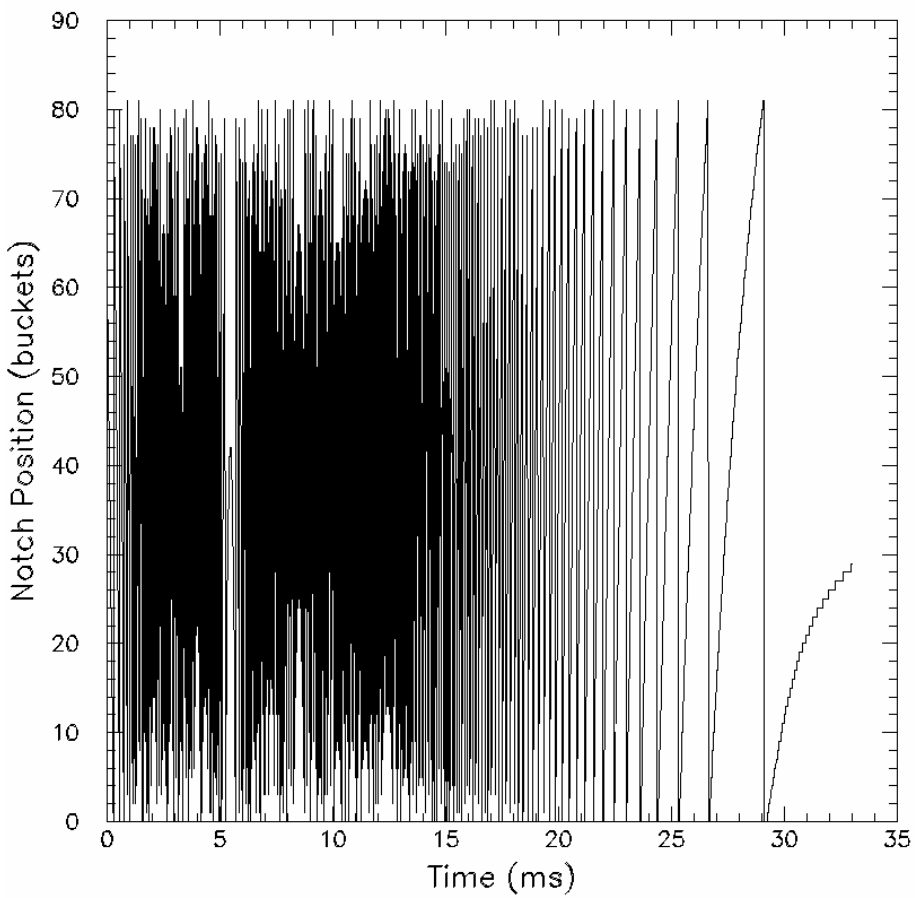
- Start counting on Main Injector revolution marker
- Stop Counting on Booster revolution marker
- Makes a table of positions (tripplan)

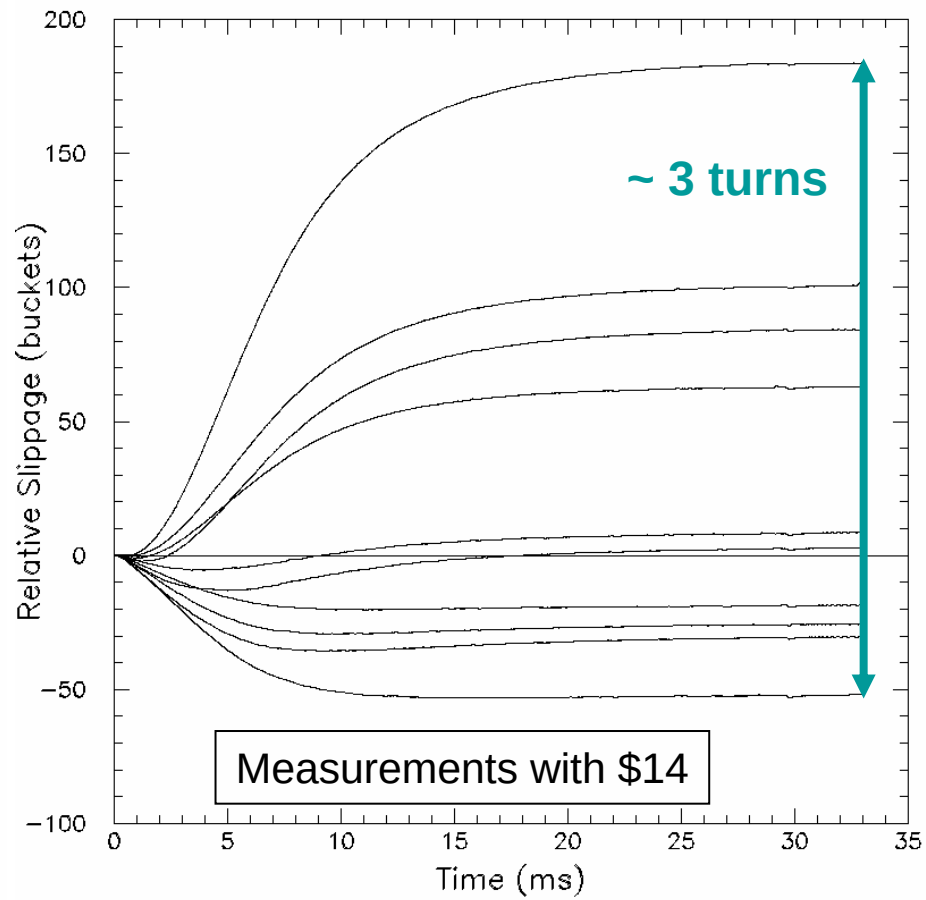


Relative Slippage

- RF buckets slip at a rate $f_{MI} - f_B$
  - Initially 15 MHz
- We consider only the relative, cycle-to-cycle slippage

Raw position ⇔ **Relative to baseline**





Sources of Slippage

- Slip rate: η (buckets/ time)
  - 15 MHZ $\rightarrow$ 0 (inj. $\rightarrow$ ext.)
- Total slippage: S (buckets)
  - $S_{tot} \approx$ 100,000 buckets
  - Only (S_{tot} mod 84) is relevant
  - 1 part in 1000 difference $\approx$ 1 turn!
- Variations in wall socket frequency has long been suspected as a source of error
  - Booster 15 Hz is line f ÷ 4

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

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

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

$$p_1 = \tfrac{1}{2}(p_{\mathrm{e}} - p_{\mathrm{i}}) = 3.9666 \text{ GeV/c}$$

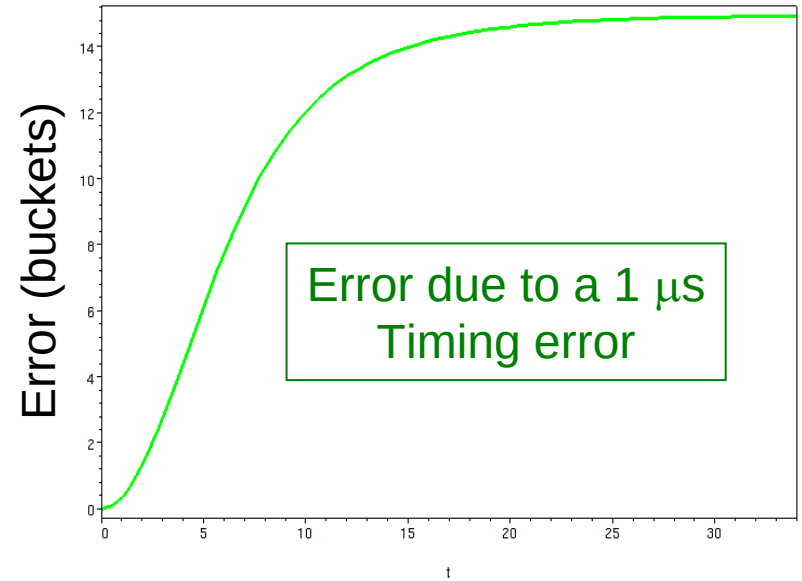
$$p_0 = \tfrac{1}{2}(p_{\mathrm{e}} + p_{\mathrm{i}}) = 4.9223 \text{ GeV/c}$$

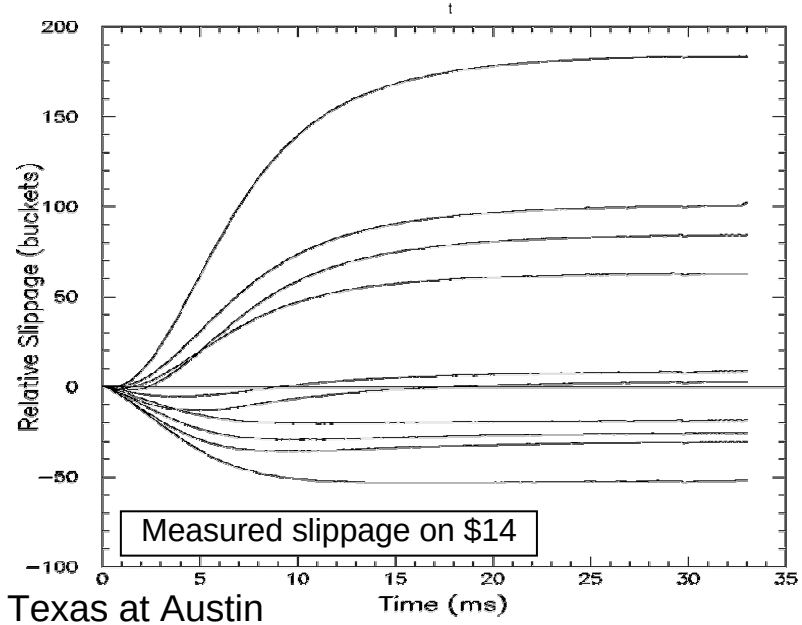
Timing Errors

- Change in slippage due to a timing error of δt:

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

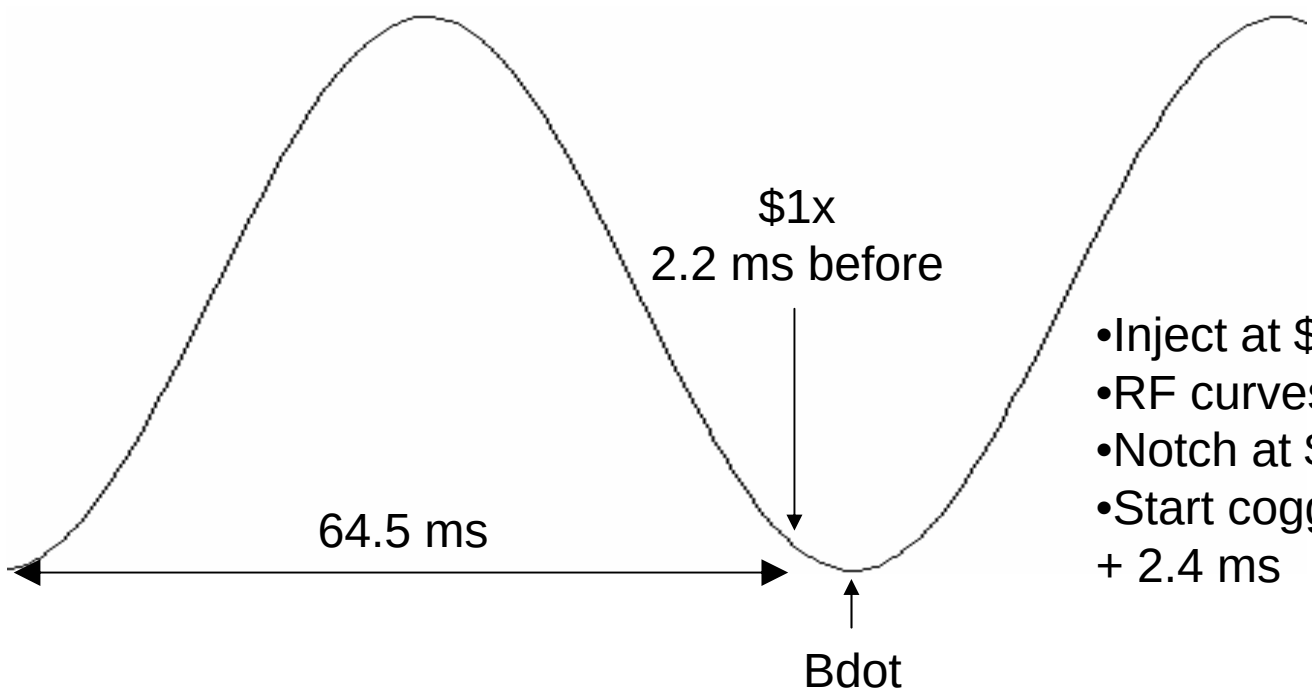
  - 1 μs error $\rightarrow$ 15 bucket slip
- Most Booster systems are insensitive to timing errors
  - Feedback picks up the slack
- Unsynchronized MI revolutions contribute an 11 μs error
- We found TCLK timing gives another ~ 10 μs error
- Timing looks like our dominant error





Source of TCLK Timing Errors

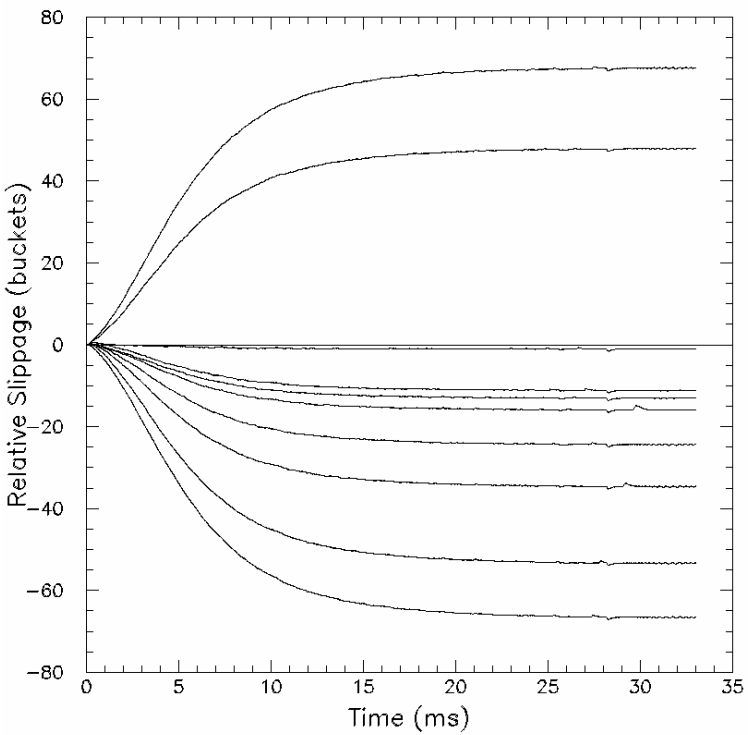
- Timing of $12, $14, $1D, etc. is predicted from the Bdot of the previous cycles
- Small variation in 15 Hz frequency can lead to ms errors

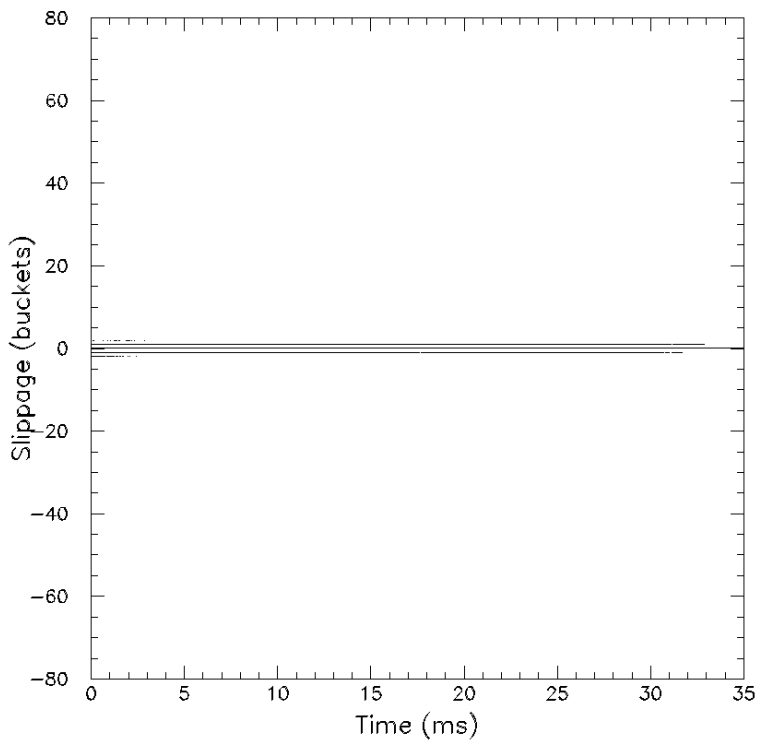


- Inject at $1x + 2 ms
- RF curves start at $1x + 2 ms
- Notch at $1x + 2.4 ms
- Start cogging software at $1x + 2.4 ms

Correcting Timing Errors

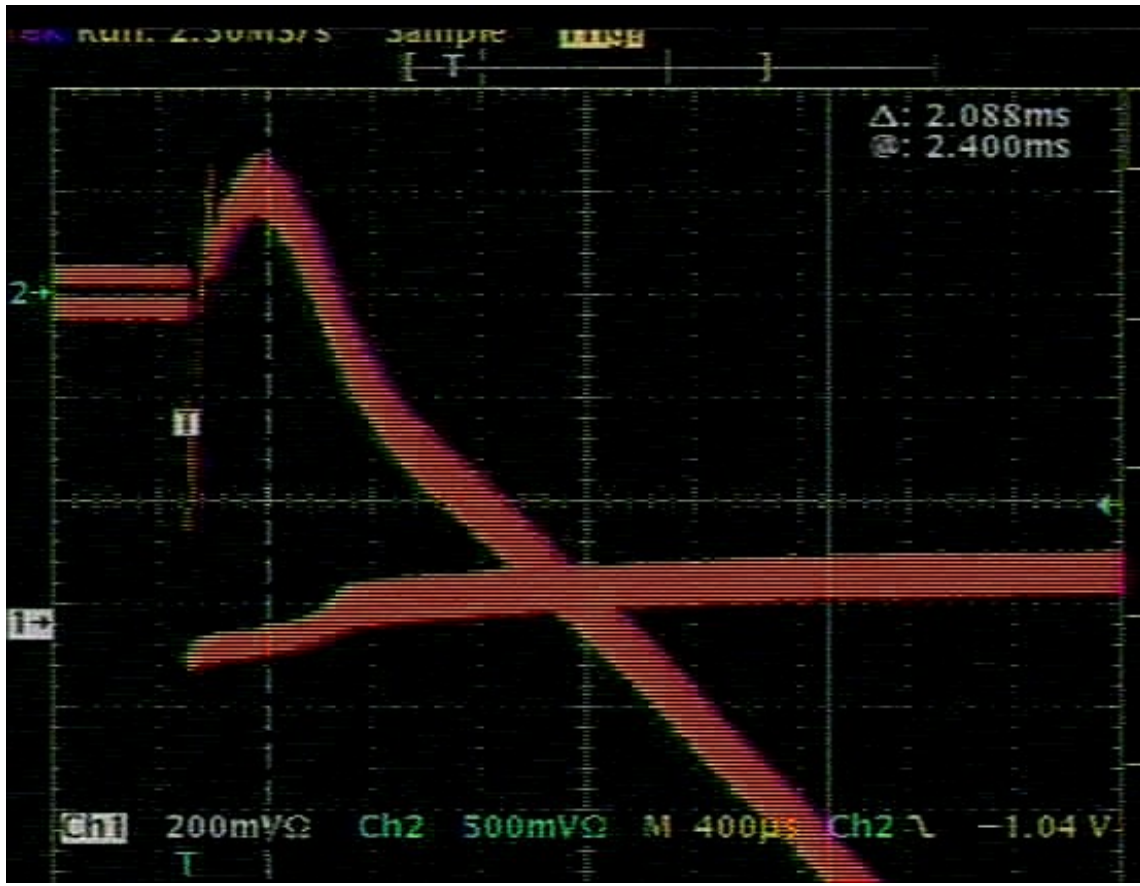
- Conducted a test to correct timing errors
- Created a fake MI revolution marker
- Used B-dot signal as trigger
  - For cogging software
  - For Booster frequency curves
  - Previous signal was a delayed TCLK
- Tested on Booster cycles w/o beam ($12)
- Eliminated slippage on no-beam cycles





LLRF Phase Error

- Triggering RF curves on Bdot
- Very consistent pulse-to-pulse phase error
  - Shown with beam
- Not yet tuned to be flat
- Previously, the curve has changed wildly pulse-to-pulse
  - Fine tuning was impossible

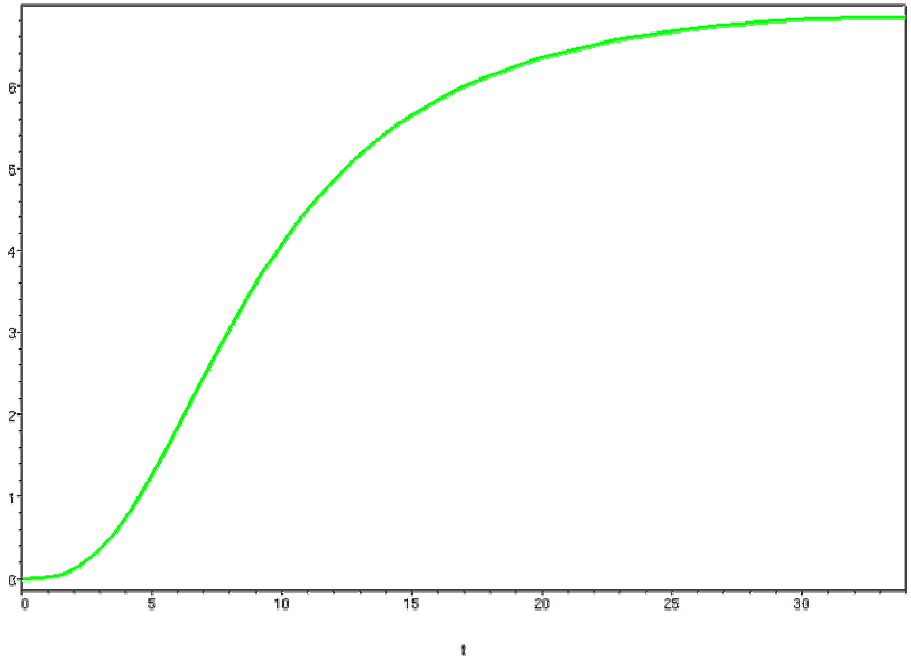


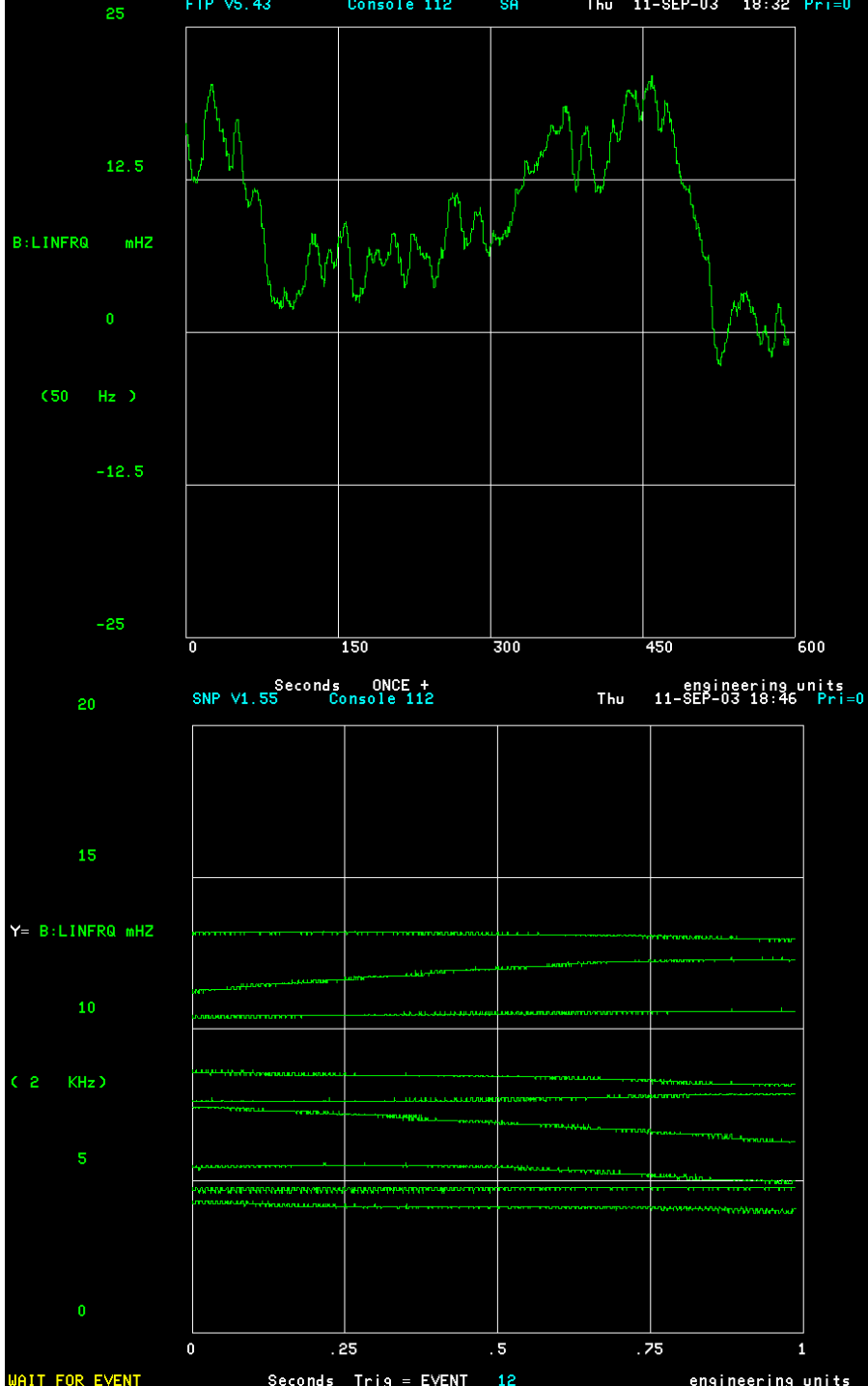
Frequency Variation

- Change in slippage due to a frequency error of δf:

$$S_f(t) = \delta f \int_0^t dt' \frac{d\eta}{df}(t')$$

- ~ 6.5 bucket slip / mHz error
- But, Booster is resonant circuit, so variations only occur on a scale of ~1 s
  - Problem might go away





Magnet Current Errors

Error in injection current of $\delta I_i/I_i$:

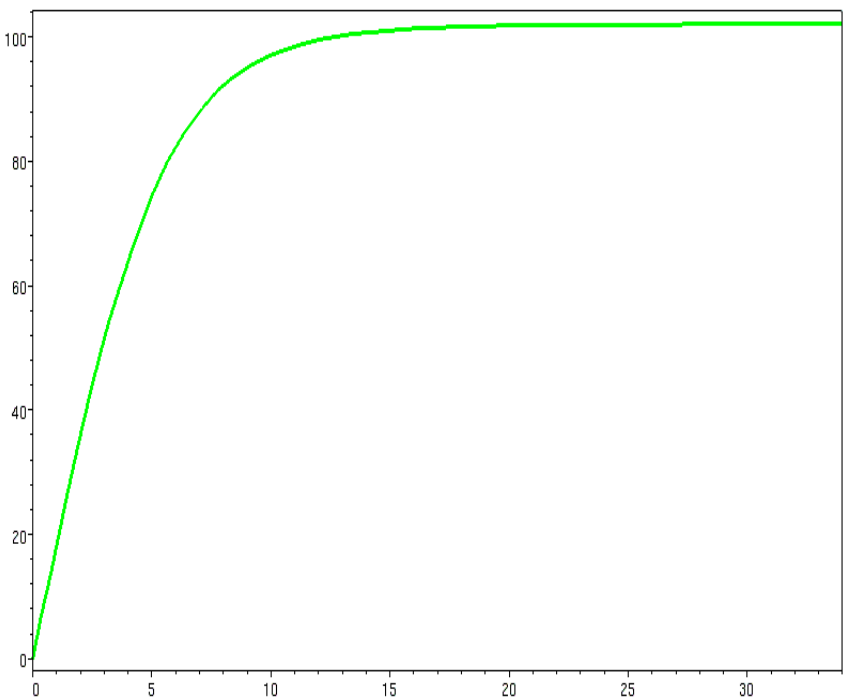
$$S_i(t) = \frac{\delta I_i}{I_i}\int_0^t dt' \frac{d\eta}{dp_i / p_i}(t')$$

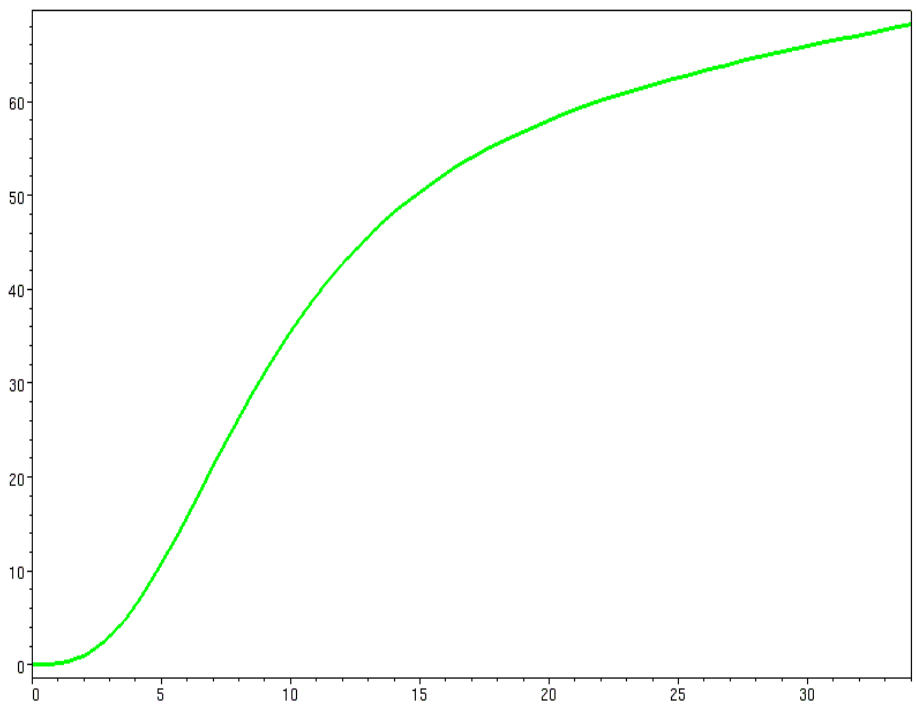
~ 10.2 bucket slip for 1E-4 error

Error in extraction current of $\delta I_e/I_e$:

$$S_e(t) = \frac{\delta I_e}{I_e}\int_0^t dt' \frac{d\eta}{dp_e / p_e}(t')$$

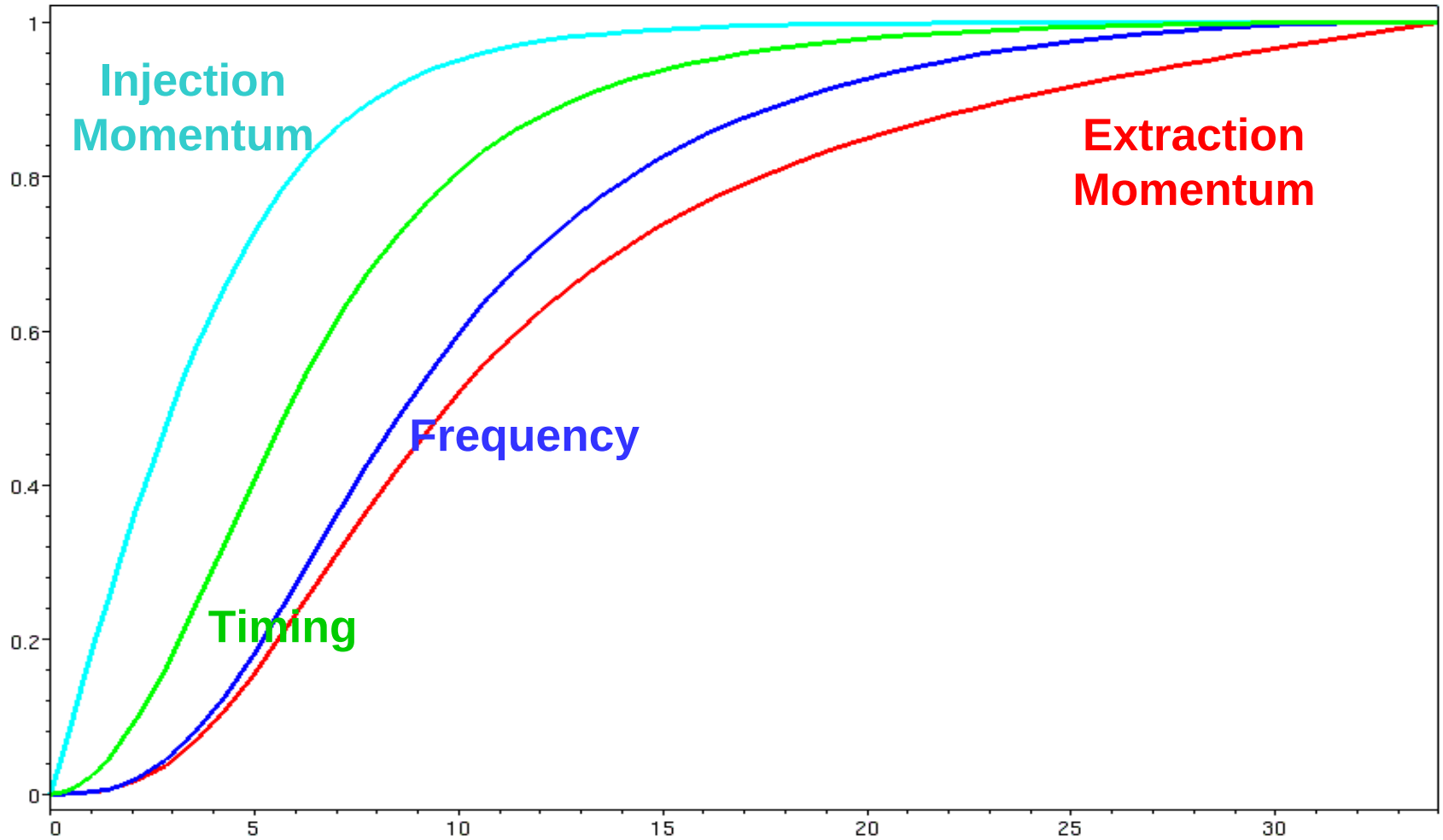
~ 6.8 bucket slip for 1E-4 error





Error Summary

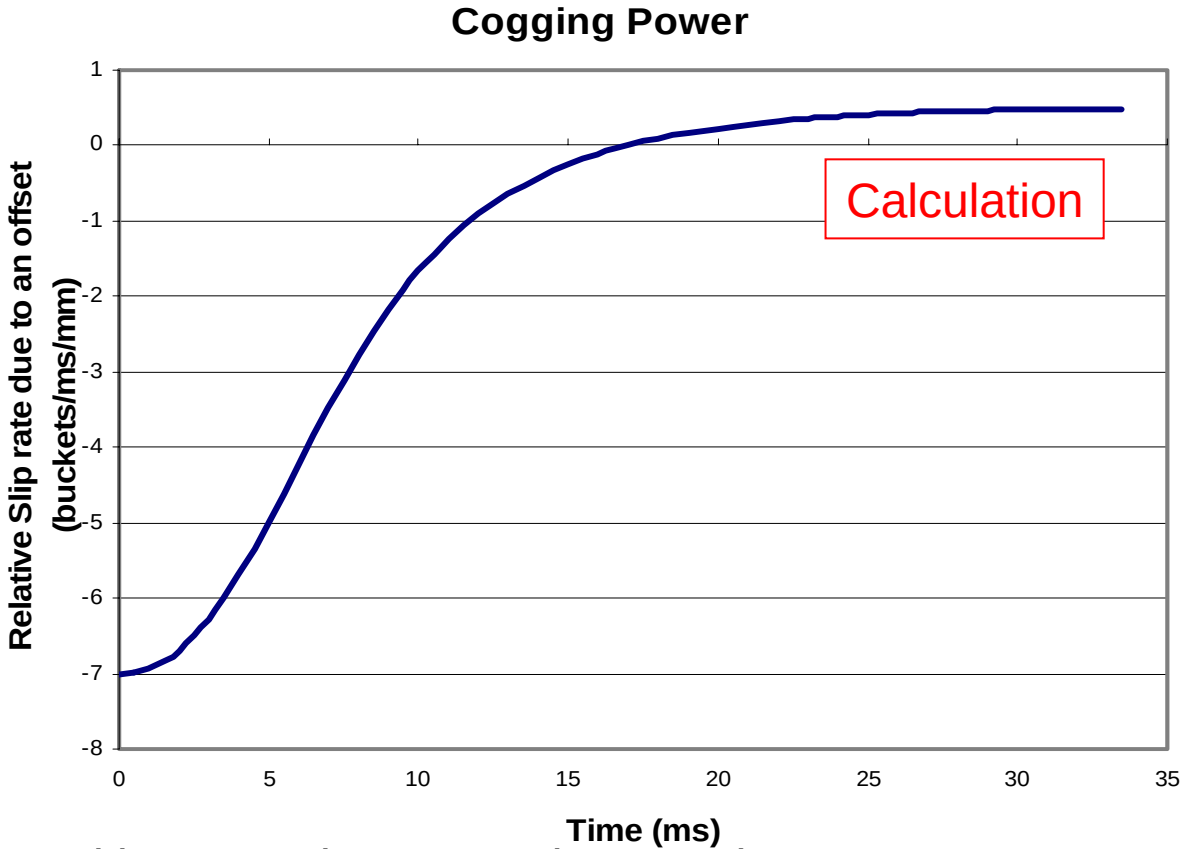
- Timing errors identified and will be eliminated
- Other errors are characterized, but no obvious fix



Cogging Method

- Use first batch of multibatch as a baseline
- Delay notch creation by 2-4 ms
  - Sample relative slippage to make a slippage prediction
  - Make notch so that it ends up in the right position
  - Takes care of errors present at the beginning of the cycle (e.g. timing)
- Change the beam's radial position (RPOS)
  - Changes relative rate of slippage
  - Takes care of residual errors from the notch, and those that occur after notch creation
  - Proof of Principle way back
    - *Pellico & Webber – IEEE PAC 1999*
    - Showed that slippage could be controlled by changing radial position

- This is radial derivative of slippage, $d\eta/dr$
- Sign changes through transition.
- Eg: to quicken beam,
  - --move outward in radius early (before trans)
  - -- move inward in radius late (after trans)



Note that

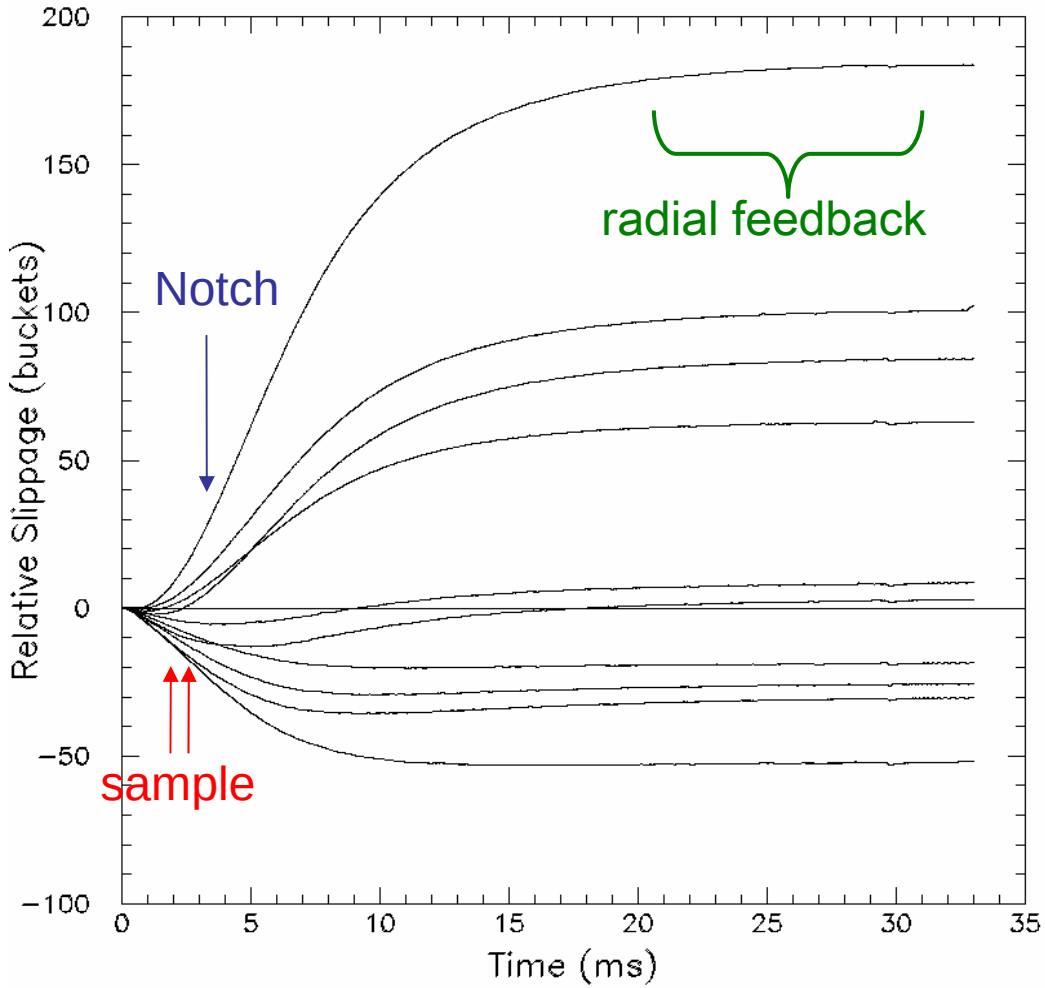
- Lots of ability to speed/retard beam early, not much power late
  - Beam is large early in the cycle
- Must perform opposite (signed) feedback later in cycle

Ramification:

- "Notch cogging" (intelligent notching) has the power to properly place the notch, but assumes no unanticipated slippage later in Booster cycle (>5ms)
- "Radial cogging" can be performed later in cycle to correct any imperfections in notch cogging.

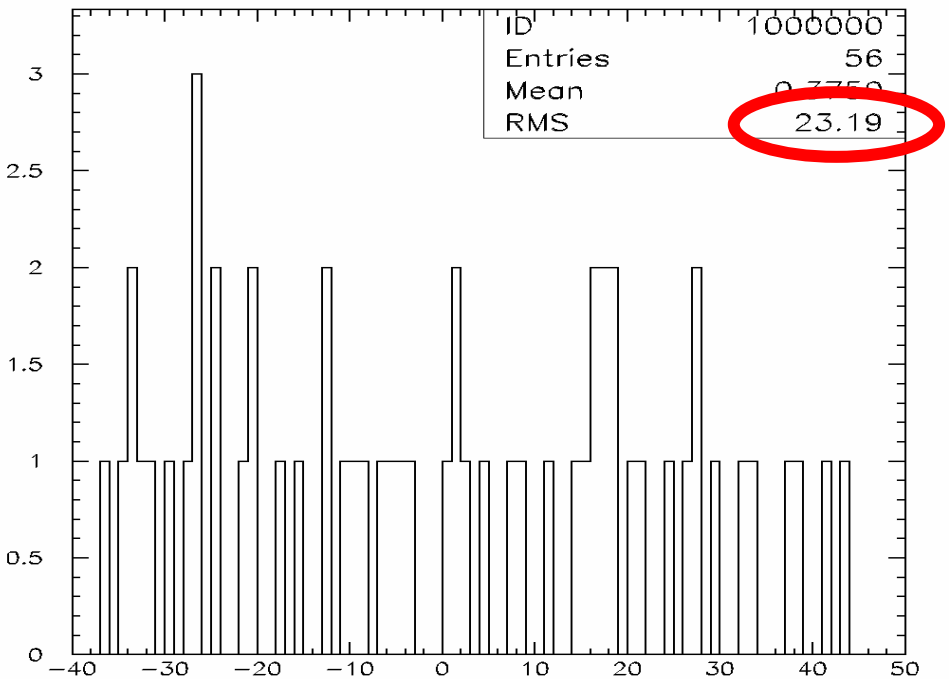
Slippage Relative to the Baseline

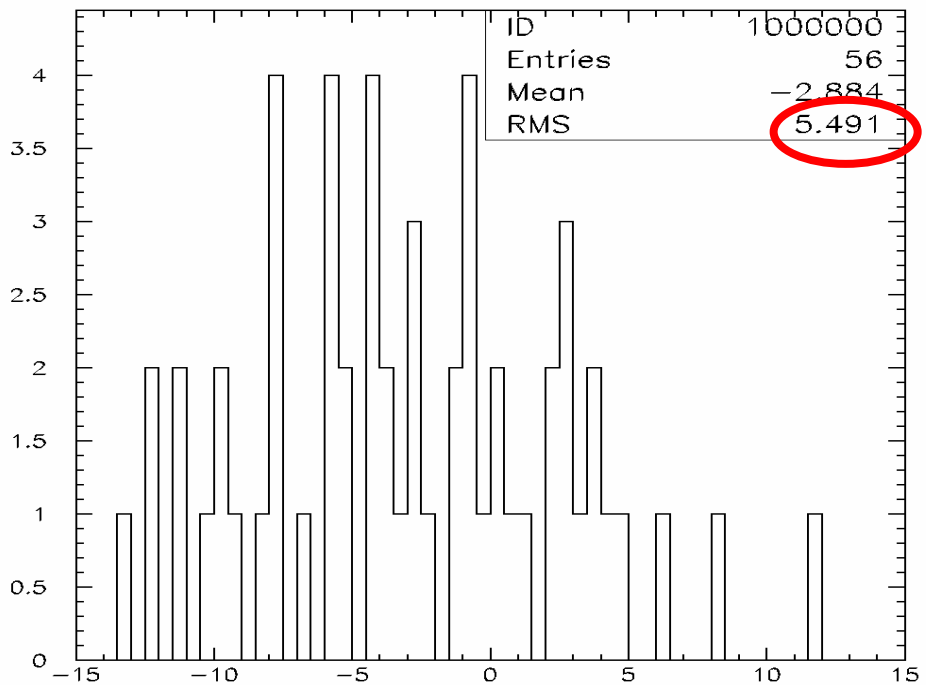
- Goal: use the early part of the cycle to predict net slippage by extraction
  - Place the notch at intelligent location
- Cycle variations require sampling again later and then doing radial cogging



Intelligent Notching

- Reduces spread of notch positions
  - Factor of 3-4
- The rest is left for radial feedback

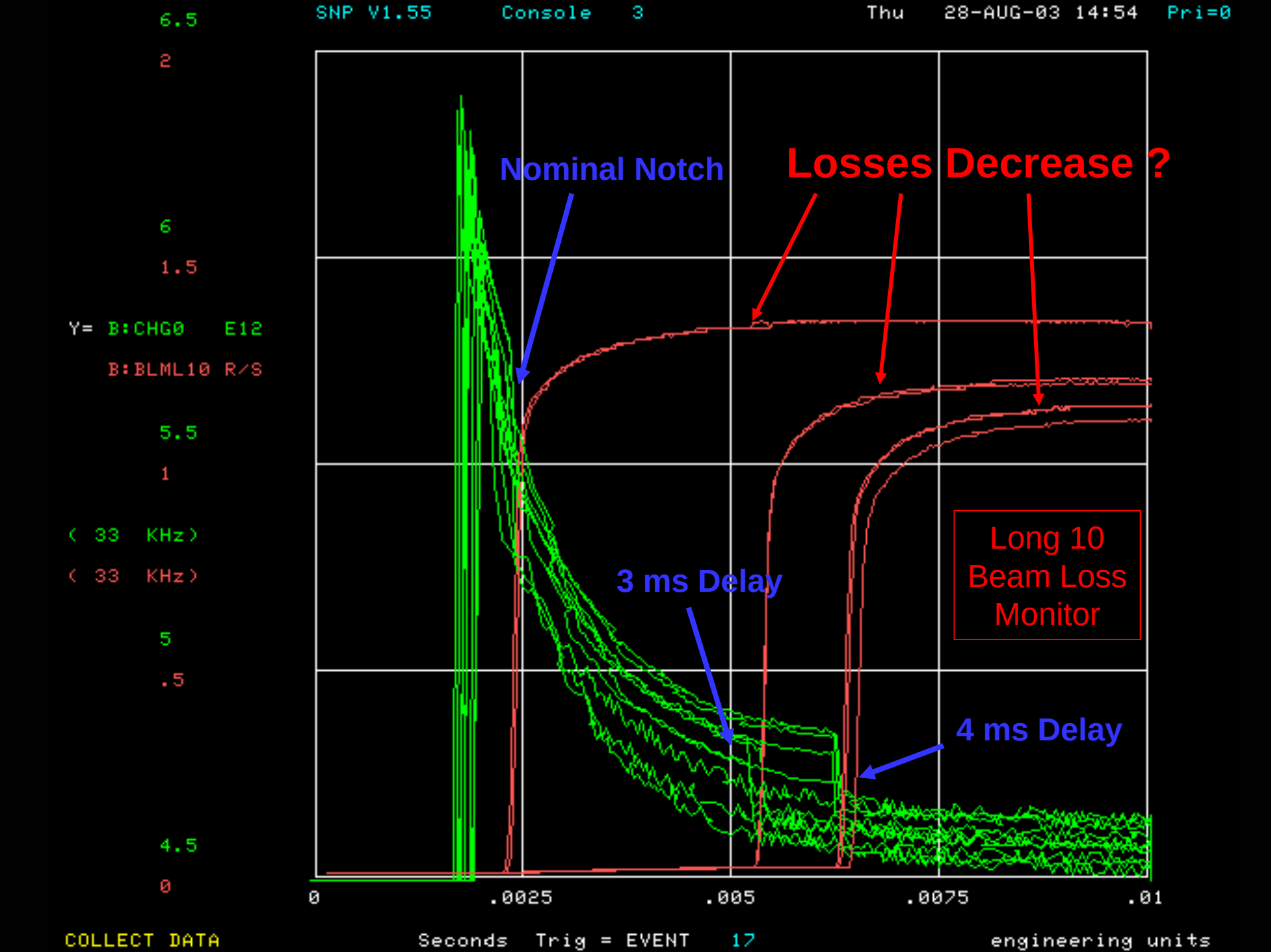


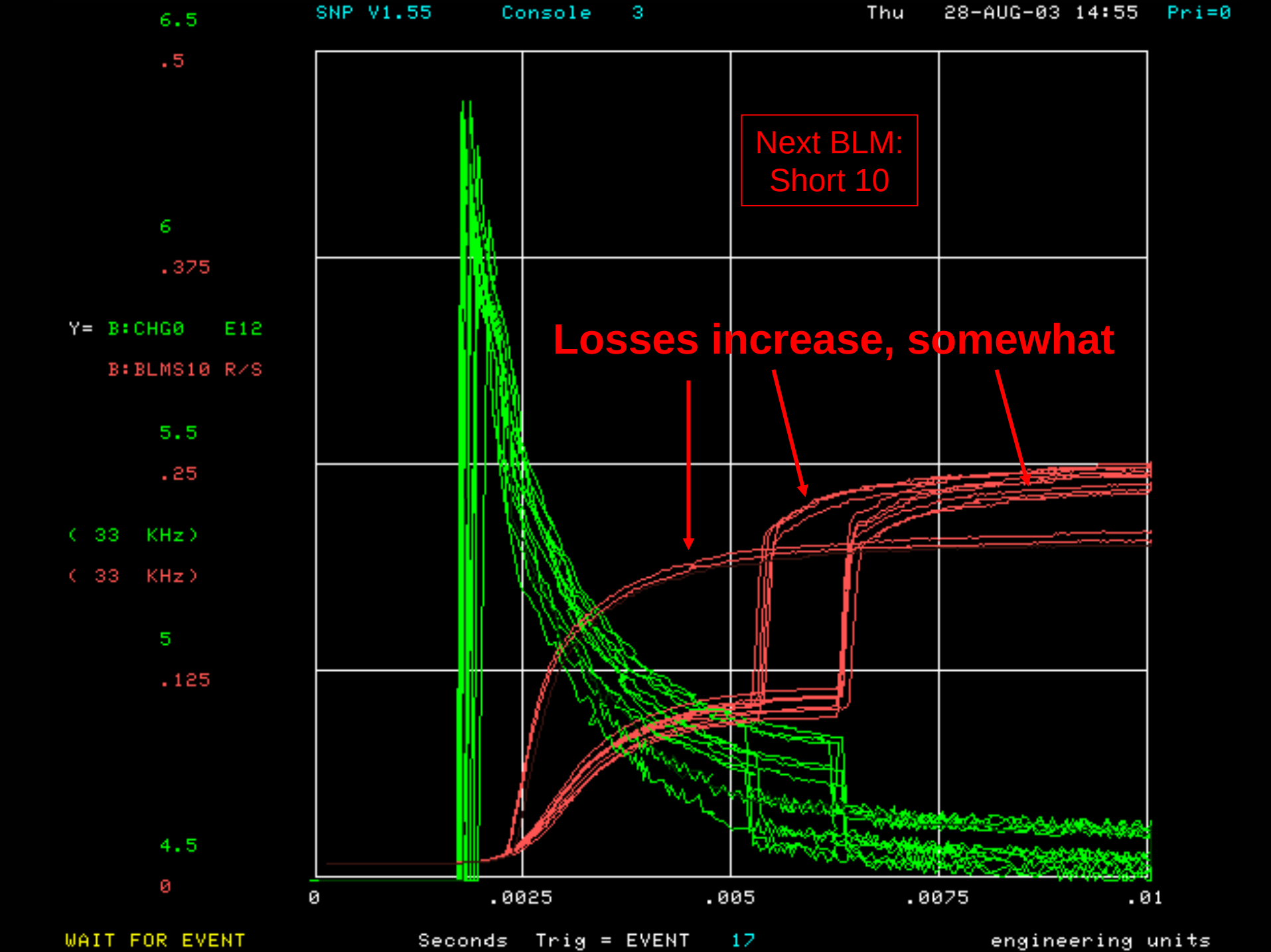


Notch position at extraction vs. MI marker

Delayed Notch

- Current notch at 0.4 ms; E ≈ 400 MeV
  - Delay 3-4 ms for cogging
- Need to know notch can be made
- Loss ramifications (from notching)
  - In principle, losses increase:
    - 35% with 3 ms (550 MeV)
    - 65% with 4 ms (660 MeV)
  - But, where do they go?


SNP V1.55 Console 3 Thu 28-AUG-03 14:54 Pri=0
6.5
2
6
1.5
Y= B:CHG0 E12
B:BLML10 R/S
5.5
1
(33 KHz)
(33 KHz)
5
.5
4.5
0
Nominal Notch
Losses Decrease ?
3 ms Delay
4 ms Delay
Long 10 Beam Loss Monitor
0
.0025
.005
.0075
.01
COLLECT DATA
Seconds Trig = EVENT 17
engineering units

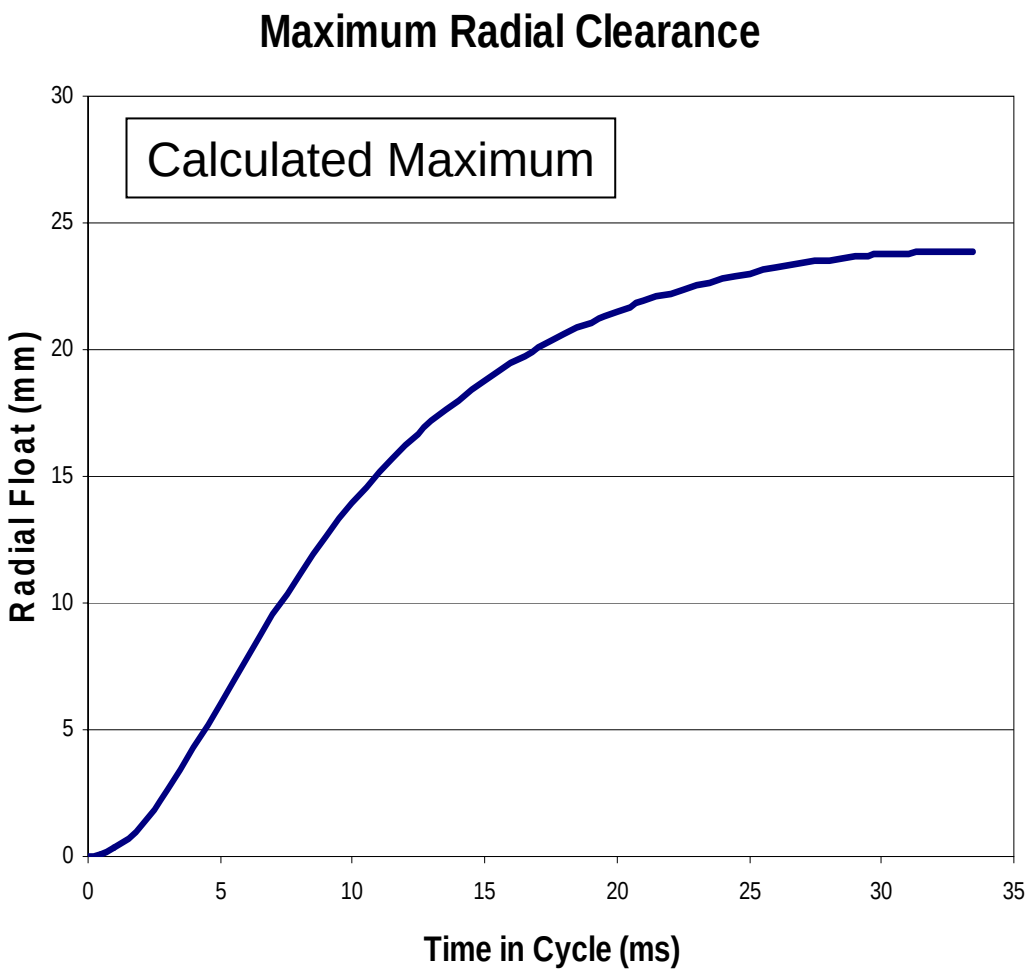

SNP V1.55 Console 3 Thu 28-AUG-03 14:55 Pri=0
6.5
.5
6
.375
Y= B:CHG0 E12
B:BLMS10 R/S
5.5
.25
(33 KHz)
(33 KHz)
5
.125
4.5
0
0
.0025
.005
.0075
.01
Next BLM:
Short 10
Losses increase, somewhat
WAIT FOR EVENT
Seconds Trig = EVENT 17
engineering units

Delayed Notch

- Kicker strength
  - Good at a delay of 3 ms
  - Voltage needed to be bumped up at 4 ms
- Losses spread downstream
  - Long 10 losses actually decreased
- New notching schemes
  - Take advantage of collimators
  - Might allow more flexibility

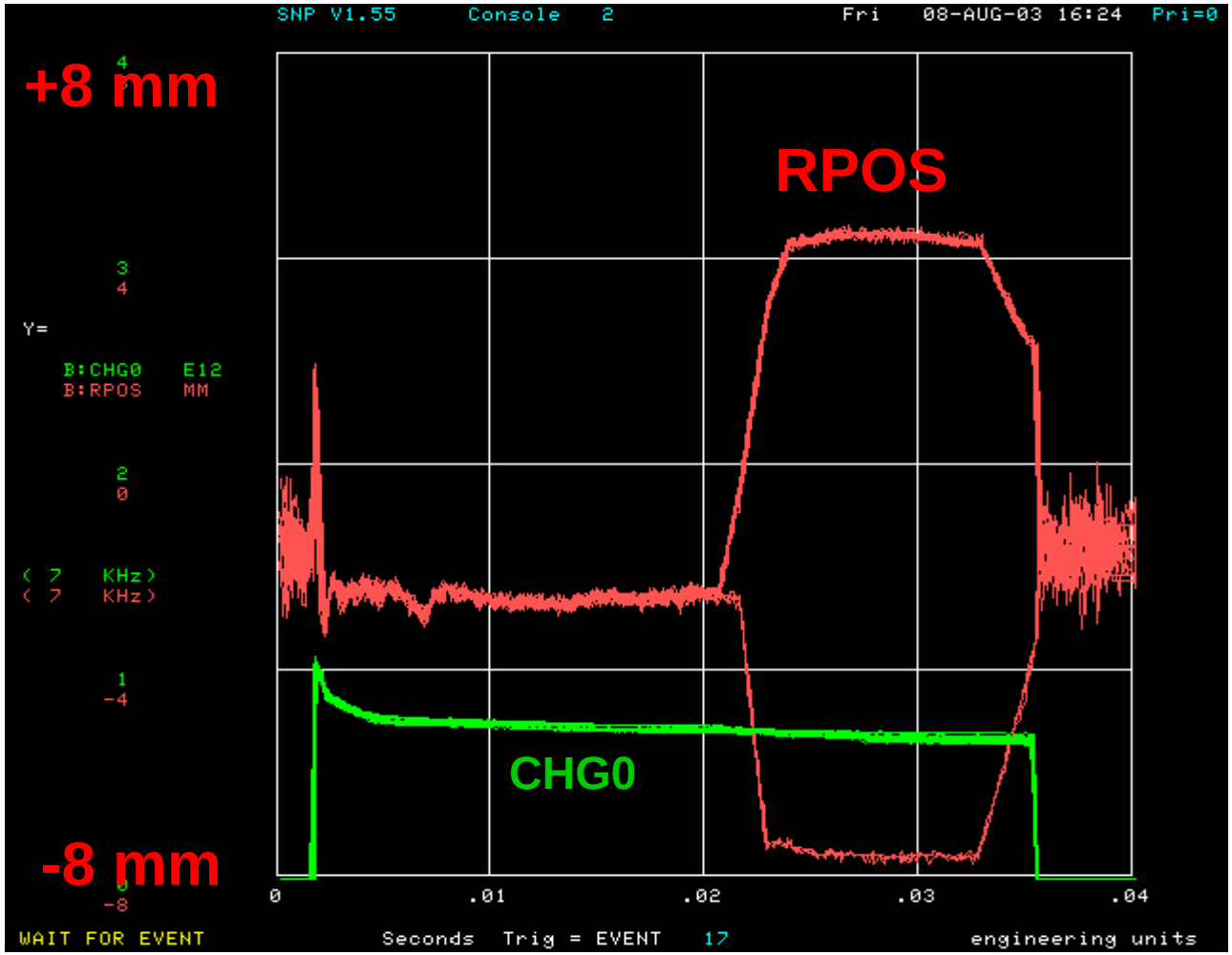
Radial Manipulation

- Plan to move the beam after transition
- In principle, there is ~ 20 mm of room
- Only a small portion is actually available for cogging
- e.g. magnet irregularities can cause emittance increases



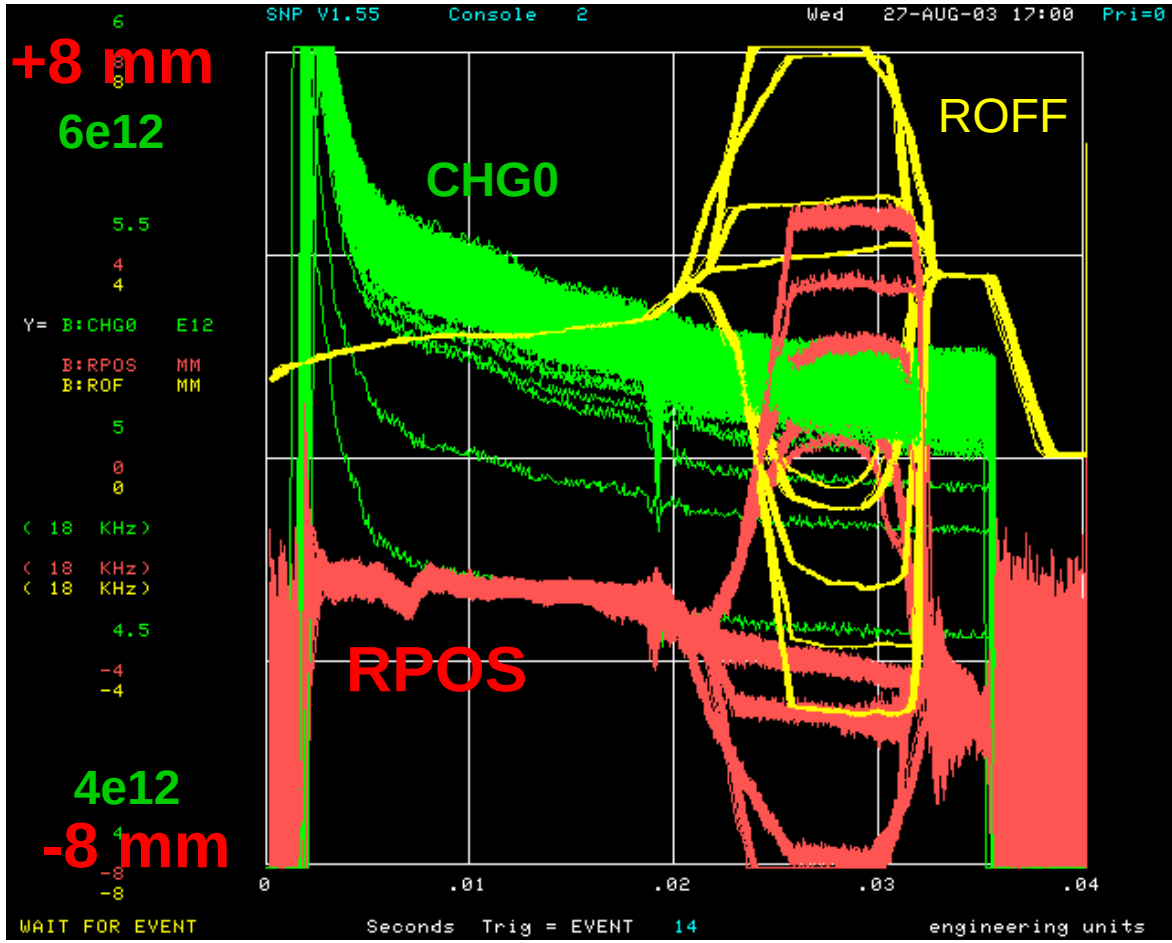
Low intensity

- Using $17
- Swung RPOS 12 mm without losses
  - After transition
  - Slow turn-on
- Intensity ~.7e12



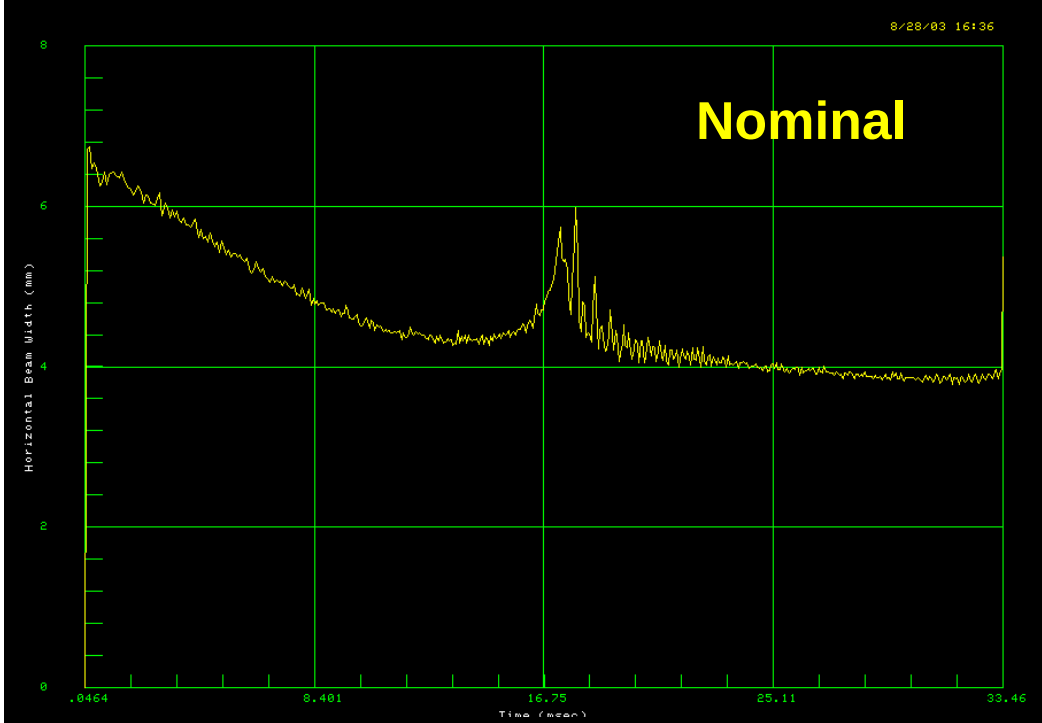
High Intensity

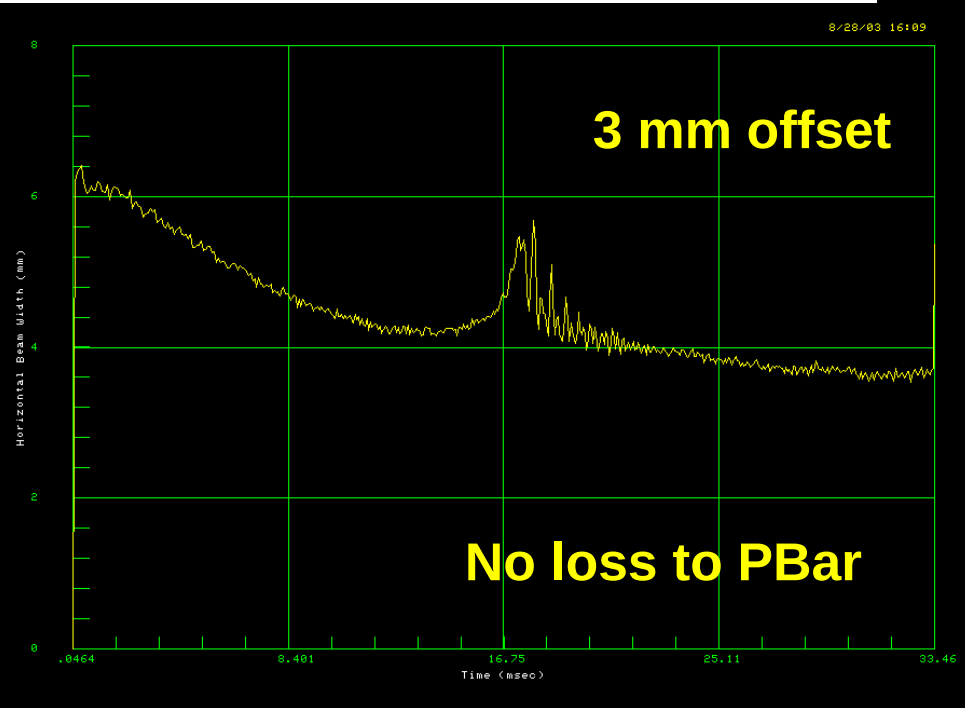
- Had to use $14s
- Swung RPOS ~ 15 mm with little loss
- However, fewer protons got to PBAR
- Flying wires in MI were inconclusive
- Beam was being collimated in the 8 GeV transfer line

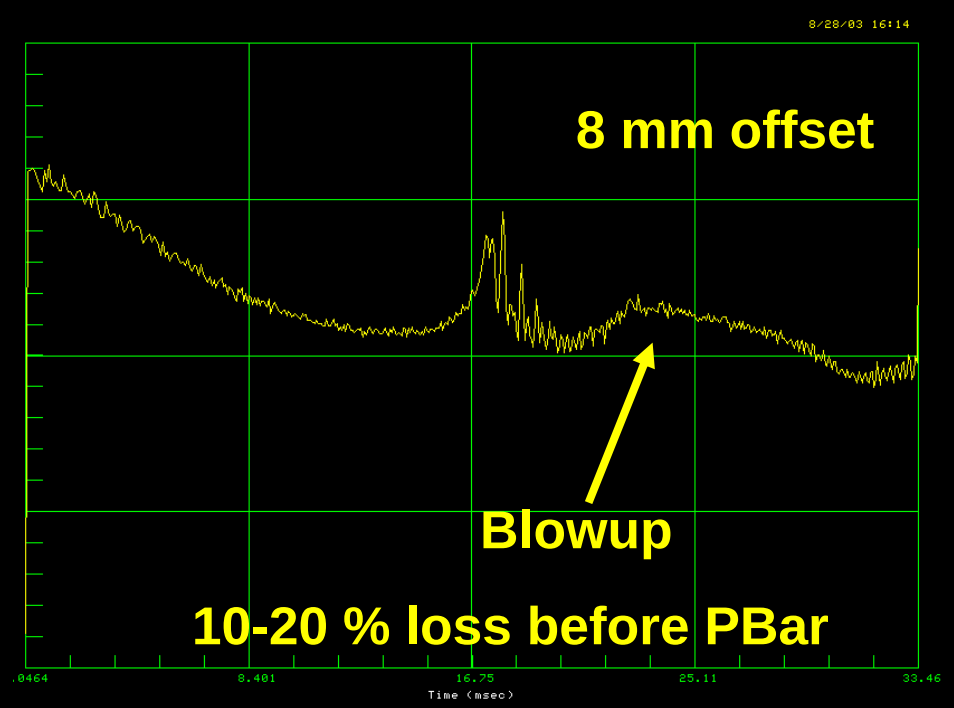


Booster IPMs

- Measure beam width in Booster
- Saw a definite blowup with large radial offsets





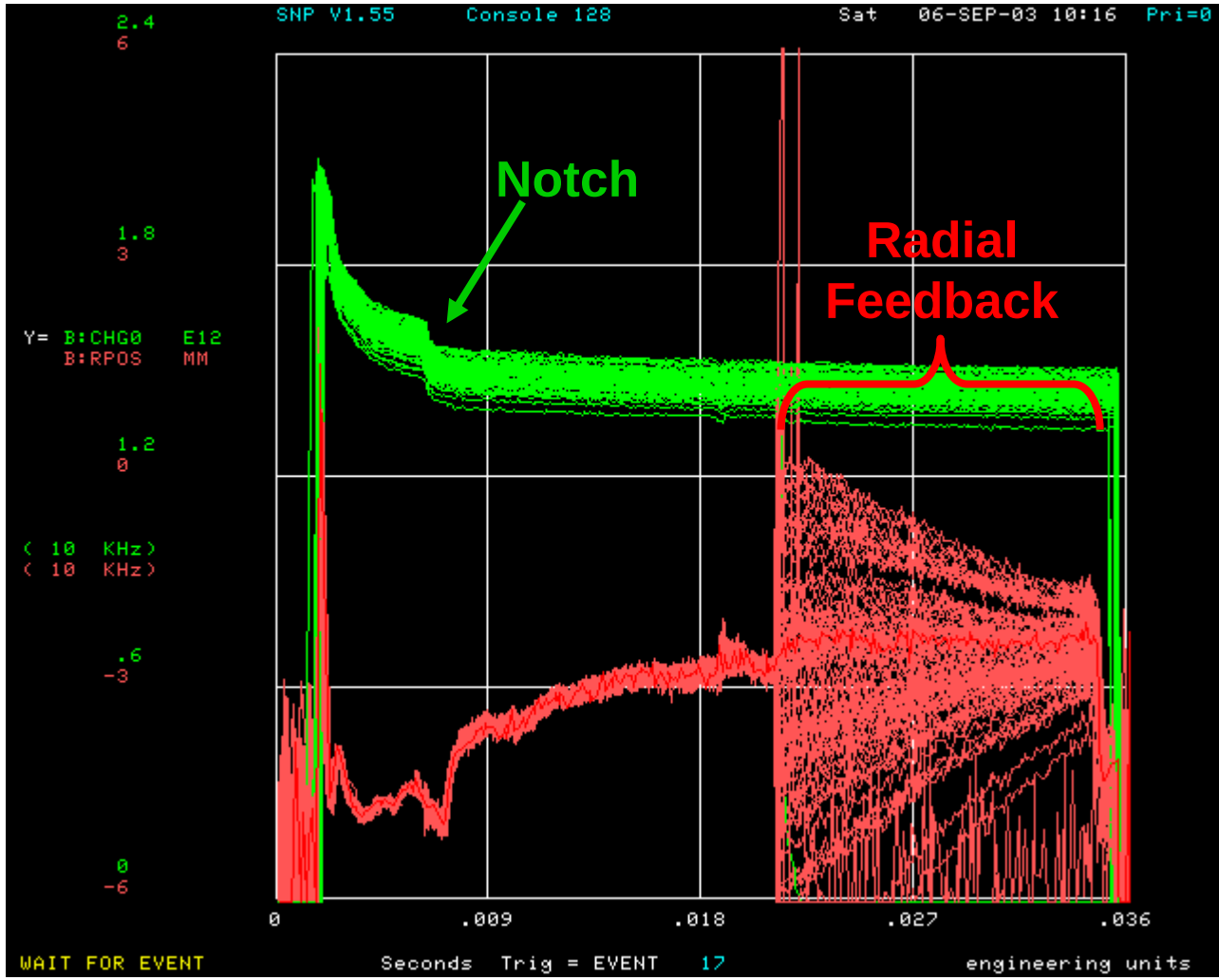


Radial Conclusion

- ±4 mm of radial motion causes little problem (after transition)
  - Allows correction of ~ 20 buckets worth of error
- Larger offsets do not cause losses in the Booster
  - But, beam is lost upstream of the Booster
- Tests will have to be redone after the shutdown
  - New lattice
  - Beam surviving injection will be different
  - Collimators

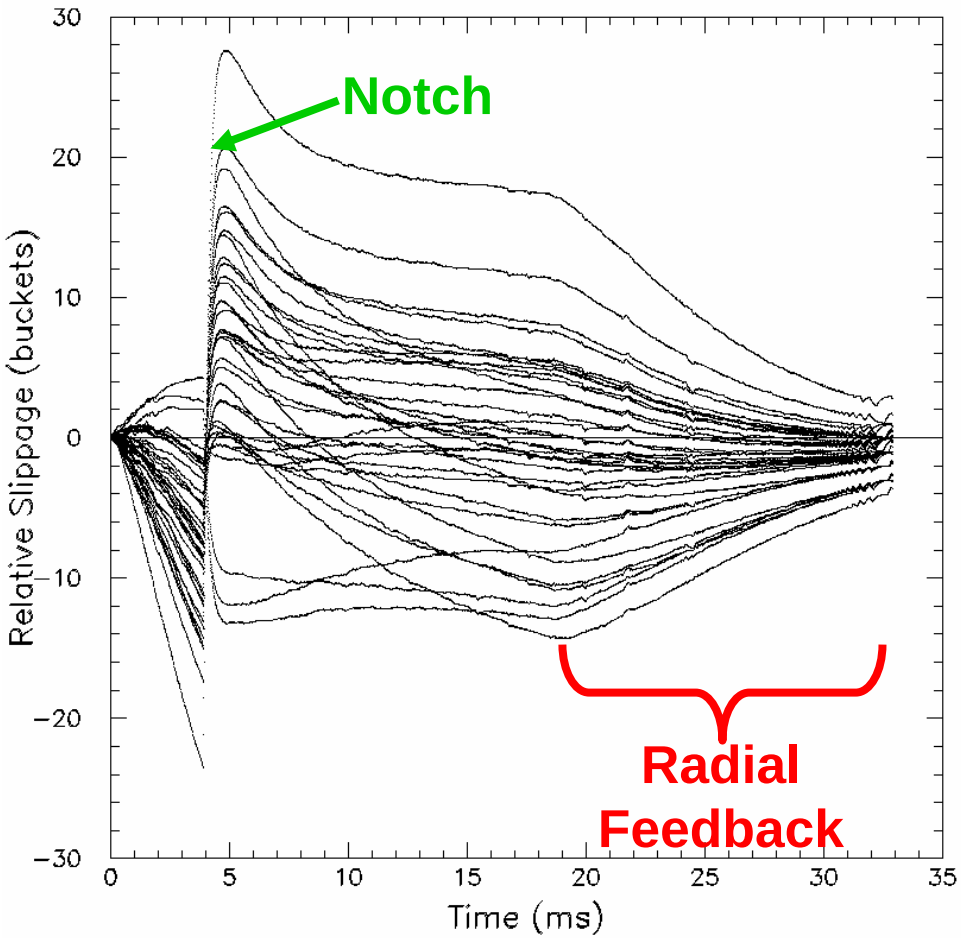
Tests of Cogging

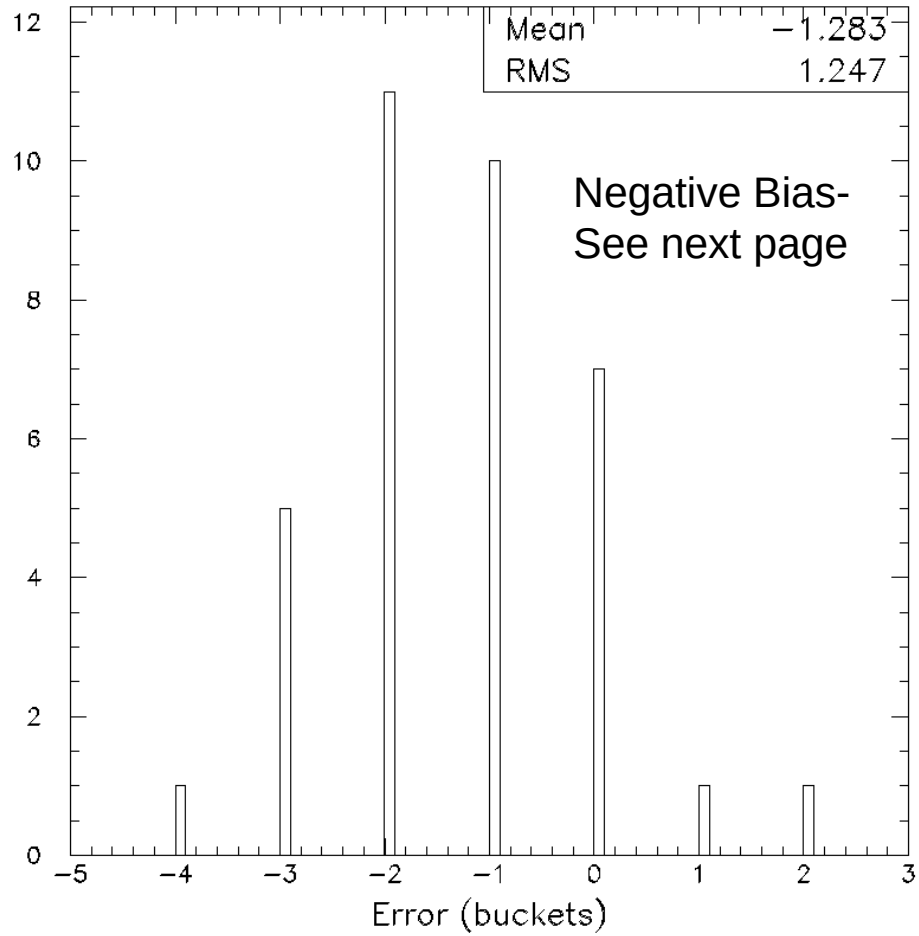
- Notch using prediction
  - Scale factor was off as timing errors were fixed
- Radial Feedback after transition
- $\Delta r = k \cdot \Delta S$
  - Exponential damping
  - $k \approx 0.2$ mm / bucket
  - e-folding time $\approx$ 10 ms



Cogging Data

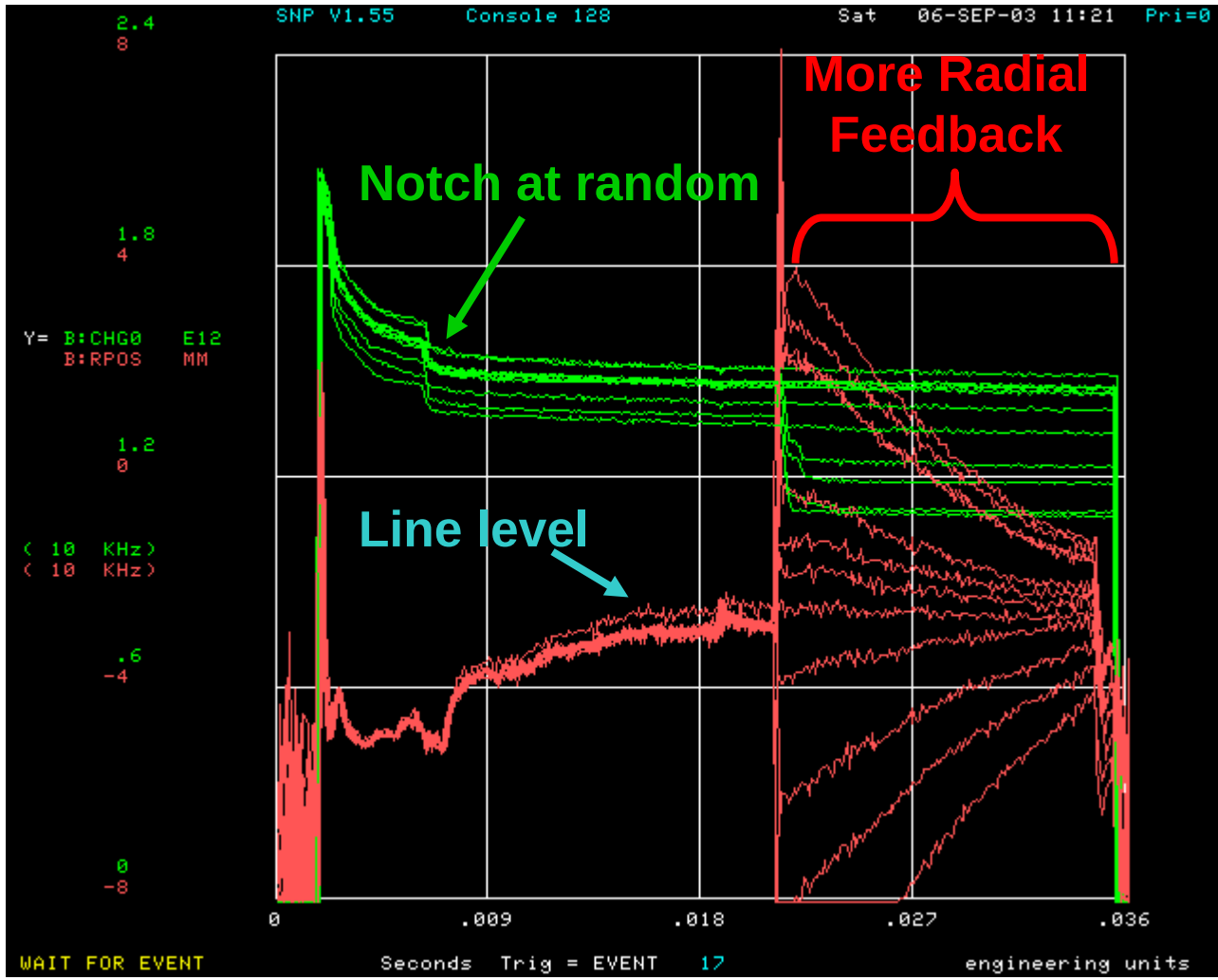
- Exponential damping slows the approach to zero
- Fixing the timing error reduced the overall slippage, but changed the scale factor





Without Intelligent Notching

- Consider the case without intelligent notching
- Same exponential damping, but offsets are much larger
- Losses occur
- Cogging without placing the notch is tougher



•Line level of electronics was not quite ground

- •RPOS changed when we plugged it in
- •Introduced negative bias in slippage
- •Won't be a problem

Cogging Summary

- Intelligent notching cuts down the needed correction
  - Scale factor needs to be reexamined
    - Timing losses eliminated
  - Notch time needs to be a bit earlier
- Feedback works as expected
  - Can start a few ms earlier
  - RPOS turn-on will need to be gradual
  - Damping needs to be faster than exponential

Summary

- Slippage is caused by subtle differences that do not affect other Booster systems
  - Timing problems are solvable
  - Other issues are less tractable
- Cogging shown to work in Booster to several buckets
  - Later intelligent notching is critical
  - Radial motion after transition is tolerable (keep an eye on emittances)
  - Needs to be tested with Main Injector
- Several improvements in the works
  - Better feedback & notching prediction
  - Get down to ~ 1 bucket resolution
- Lots of implementation left
  - See Bill's talk