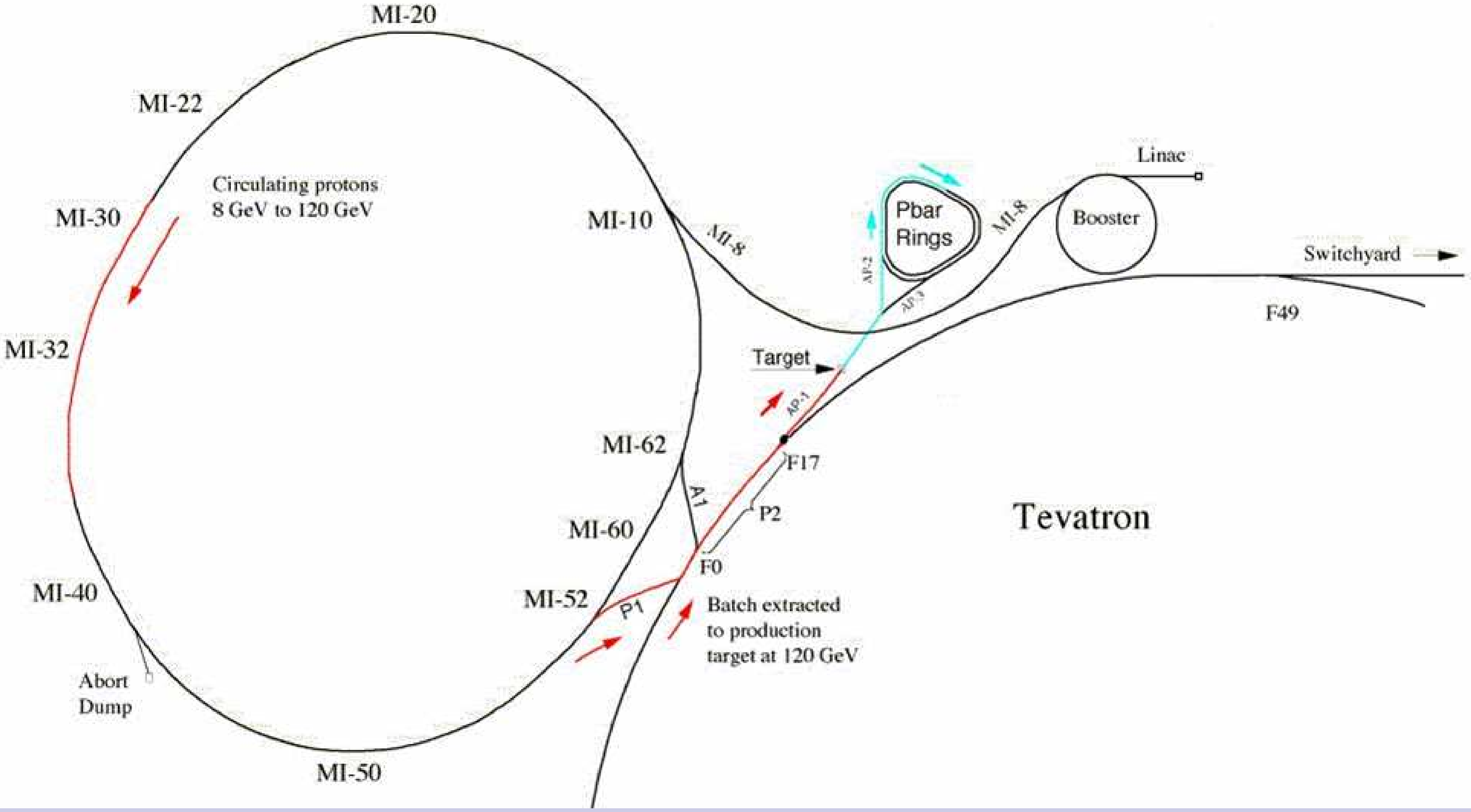
Phil Adamson
Fermilab Accelerator Division

Fermilab Main Injector status and plans

Main Injector • Performance & Improvements
Collider • NuMI • Future

Main Injector

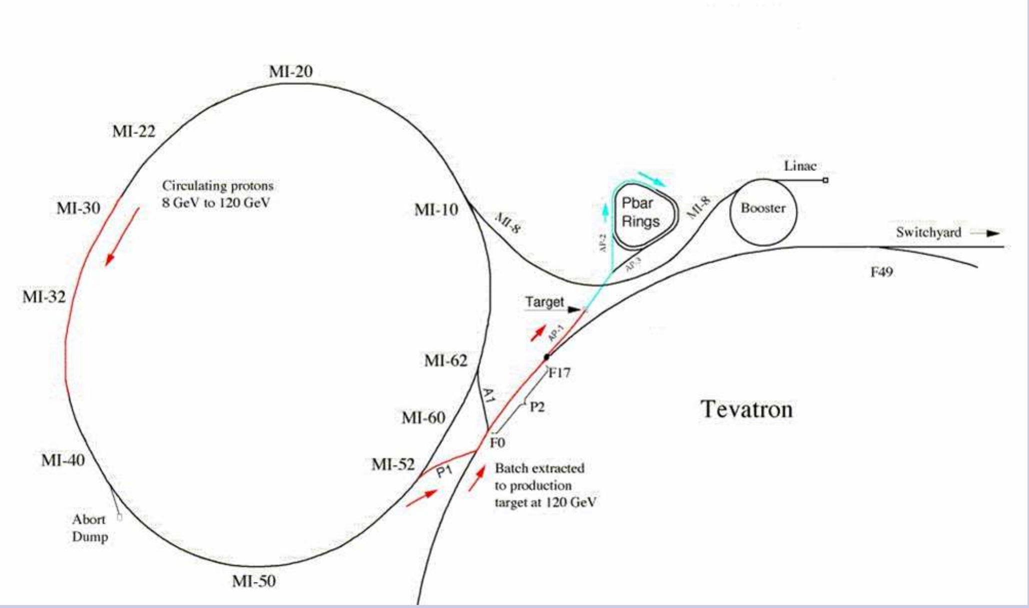
P. Adamson
Accelerator Division
Fermilab



Main Injector

P. Adamson
Accelerator Division
Fermilab

- Main Injector is a rapid cycling (up to 240 GeV/s) proton synchrotron
- h = 588
- 8.9 to 120 and 150 GeV/c
- Currently ramp to 120 Gev/c every 2.2 s
- Protons and antiprotons



- Protons from Booster to NuMI / antiproton source / Switchyard 120
- Protons from Booster to Tevatron
- Antiprotons from Accumulator to Recycler
- Antiprotons from Recycler to Tevatron
- Intensities from 10^{10} particles (antiprotons) up to 4×10^{13} (protons to NuMI)

P. Adamson
Accelerator Division
Fermilab

Tevatron collider

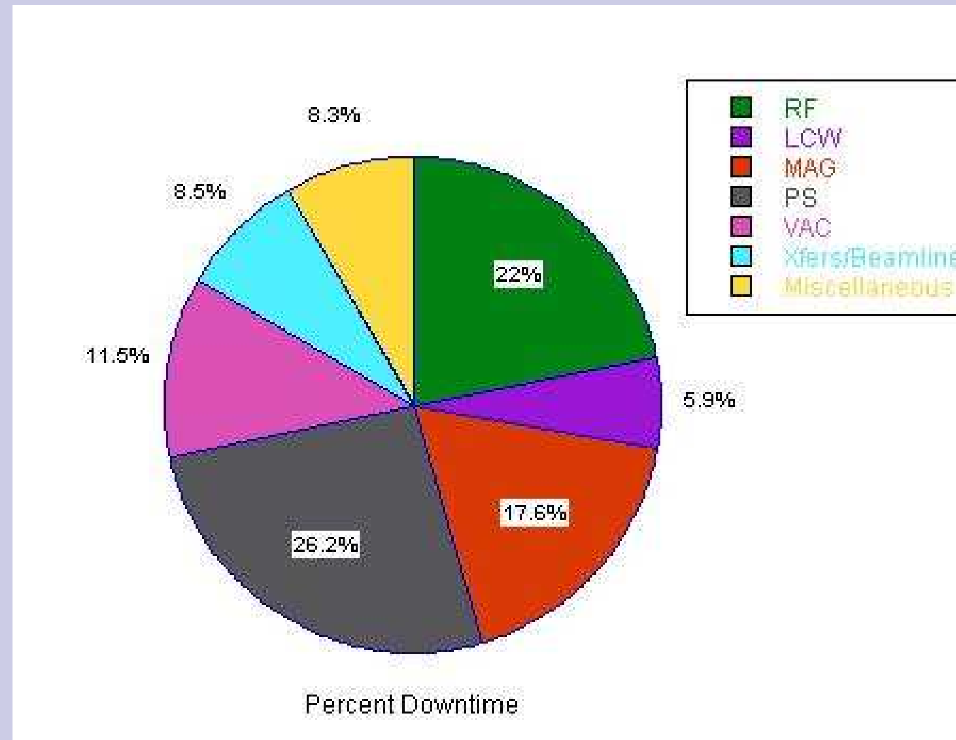
- Collider program will run through FY11
- Focus on reliability and efficiency rather than dramatic changes
- MI affects integrated luminosity in many ways:
  - ⇒ Protons for pbar stacking
  - ⇒ Pbar transfers to recycler
  - ⇒ Proton and pbar transfers to Tevatron
- Worry about:
  - ⇒ Downtime
  - ⇒ Time taken for transfer process
  - ⇒ Transfer efficiency
  - ⇒ Emittance

Tevatron collider

P. Adamson
Accelerator Division
Fermilab

- Collider program will run through FY11
- Focus on reliability and efficiency rather than dramatic changes
- MI affects integrated luminosity in many ways:
  - ⇒ Protons for pbar stacking
  - ⇒ Pbar transfers to recycler
  - ⇒ Proton and pbar transfers to Tevatron

- Worry about:
  - ⇒ Downtime



  - • MI Uptime since Jan 2008: 96.3%
  - ⇒ Time taken for transfer process
  - ⇒ Transfer efficiency
  - ⇒ Emittance

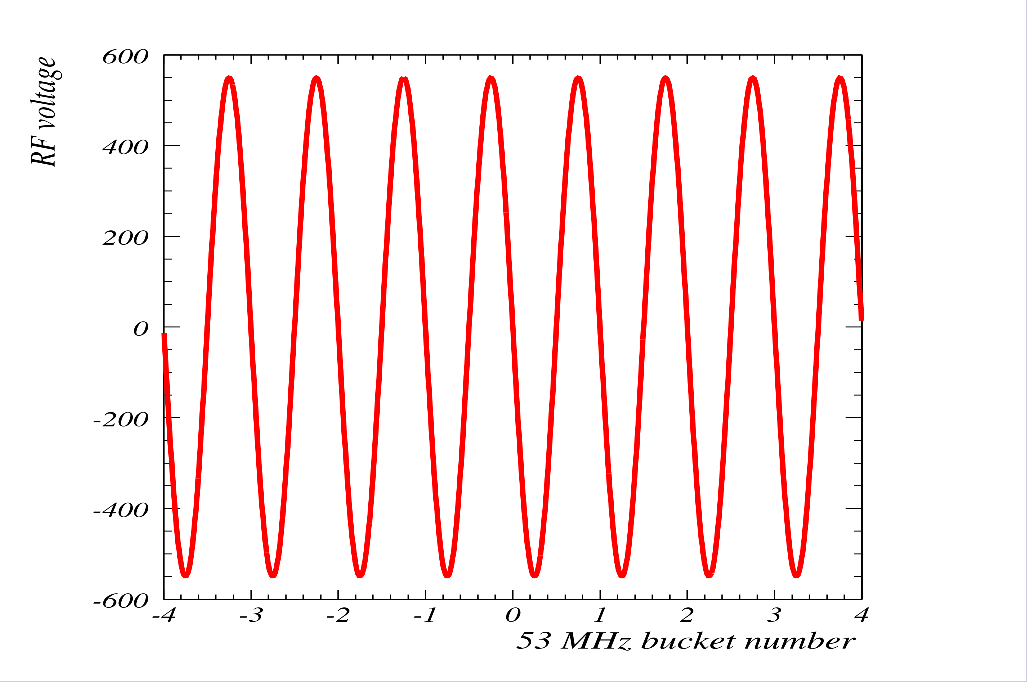
P. Adamson
Accelerator Division
Fermilab

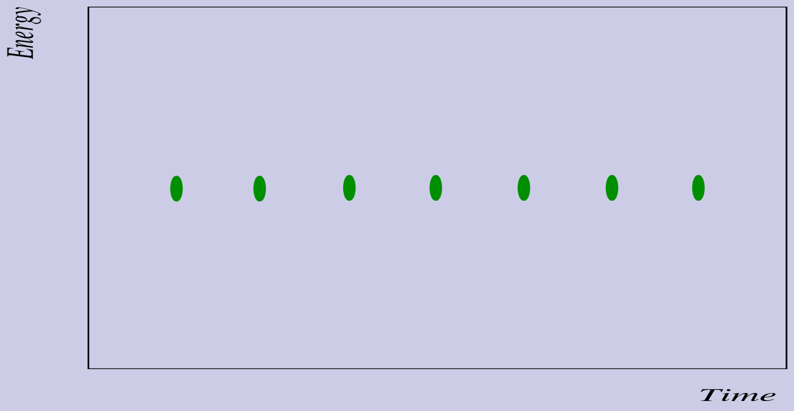
Tevatron collider

- Collider program will run through FY11
- Focus on reliability and efficiency rather than dramatic changes
- MI affects integrated luminosity in many ways:
  - ⇒ Protons for pbar stacking
  - ⇒ Pbar transfers to recycler
  - ⇒ Proton and pbar transfers to Tevatron
- Worry about:
  - ⇒ Downtime
  - ⇒ Time taken for transfer process
    - Lots of effort in whole complex to speed this up
    - Automation
    - For transfers to Recycler, implementing transverse injection damping for pbars reduces need for tuneups
    - For Tevatron shots, speedups elsewhere in complex → worth speeding up 36 bunch proton load (...)
  - ⇒ Transfer efficiency
  - ⇒ Emittance
    - Transverse scraping of protons to Tevatron with collimator (brightness, fewer quenches)

Coalescing

- Sequence of RF bunch rotations to produce intense bunch for collider operations
- Begin in stationary bucket at 150 GeV

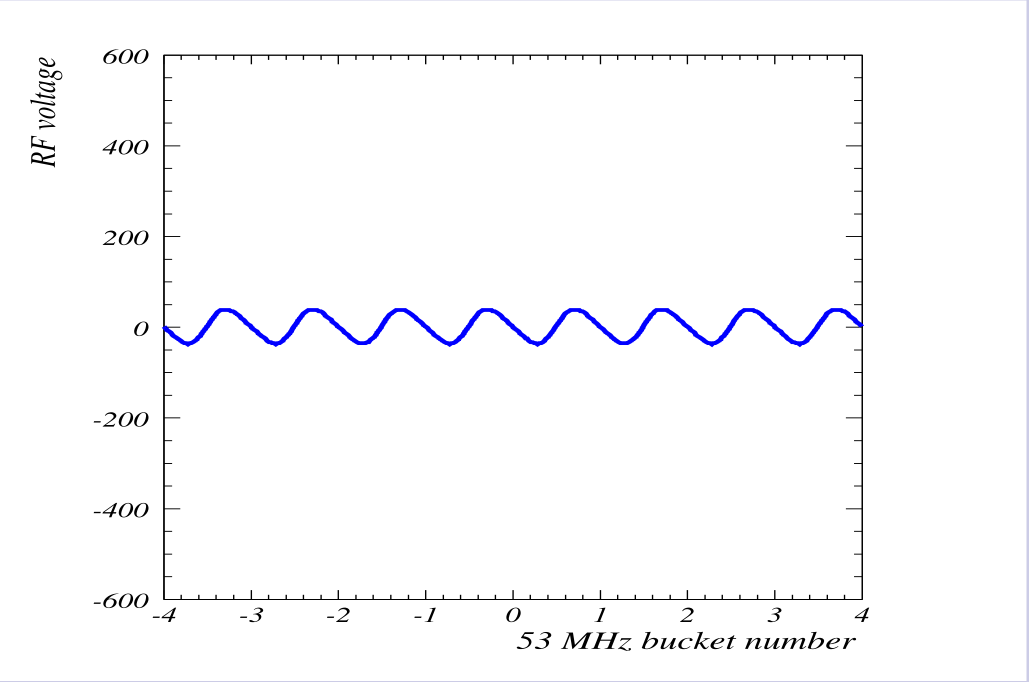


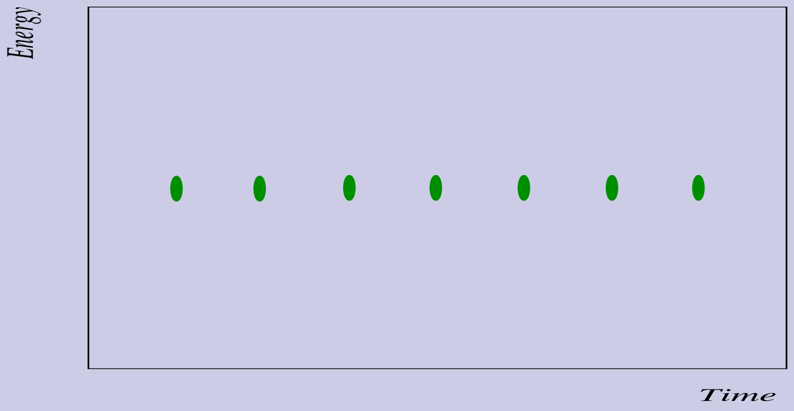


Coalescing

P. Adamson
Accelerator Division
Fermilab

- Sequence of RF bunch rotations to produce intense bunch for collider operations
- Begin in stationary bucket at 150 GeV
- Snap voltage down—bunch begins to rotate
  - ⇒ 2nd harmonic (106 MHz) cavity to linearize bucket

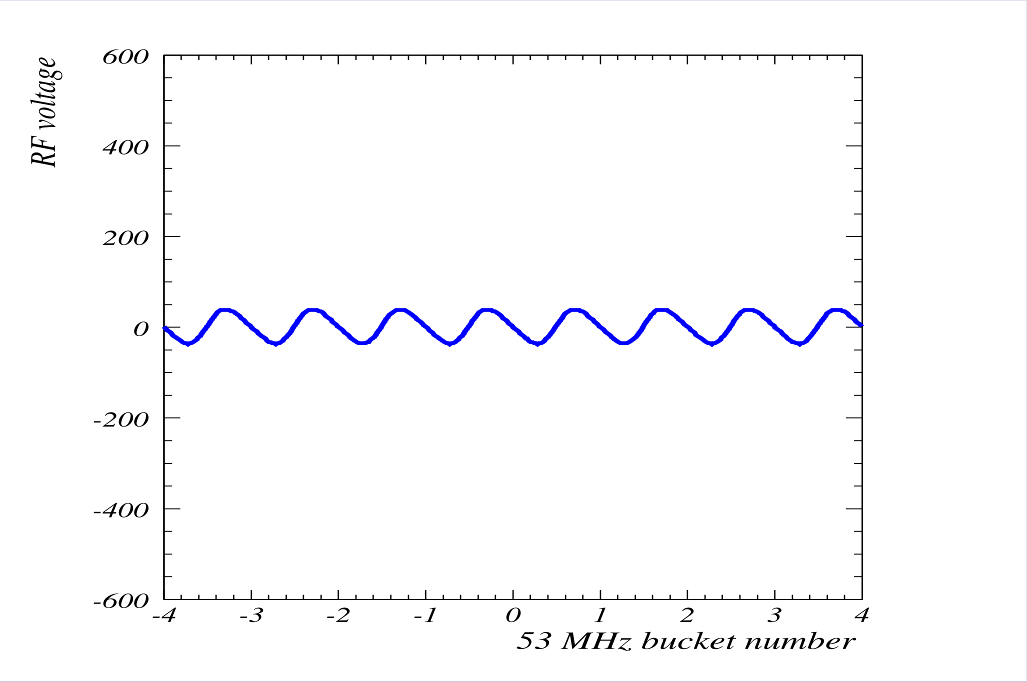


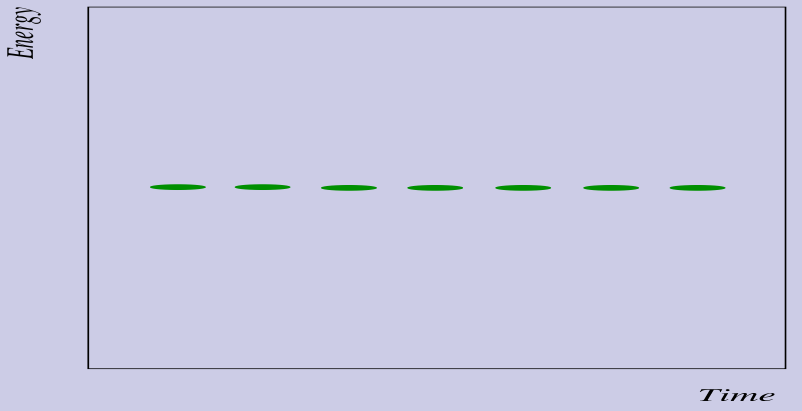


Coalescing

P. Adamson
Accelerator Division
Fermilab

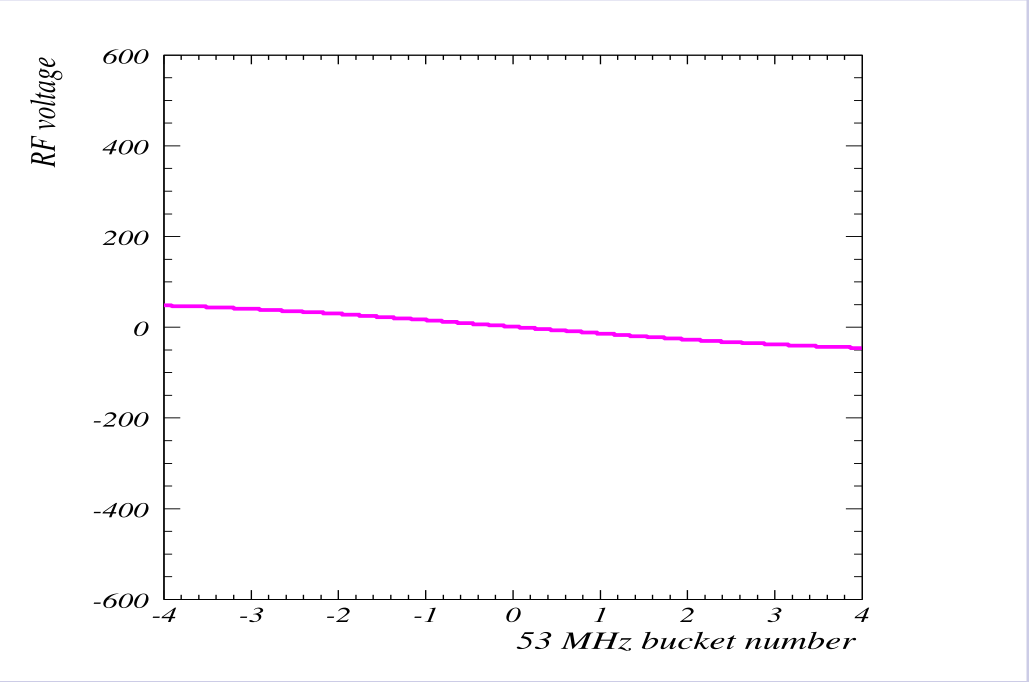
- Sequence of RF bunch rotations to produce intense bunch for collider operations
- Begin in stationary bucket at 150 GeV
- Snap voltage down—bunch begins to rotate
  - ⇒ 2nd harmonic (106 MHz) cavity to linearize bucket

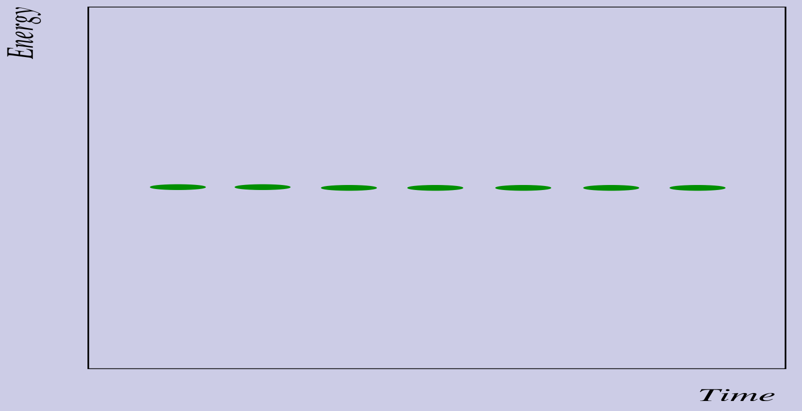




Coalescing

- Sequence of RF bunch rotations to produce intense bunch for collider operations
- Begin in stationary bucket at 150 GeV
- Snap voltage down—bunch begins to rotate
  - ⇒ 2nd harmonic (106 MHz) cavity to linearize bucket
- Snap 53 MHz off and 2.5 MHz on—whole bunch train rotates

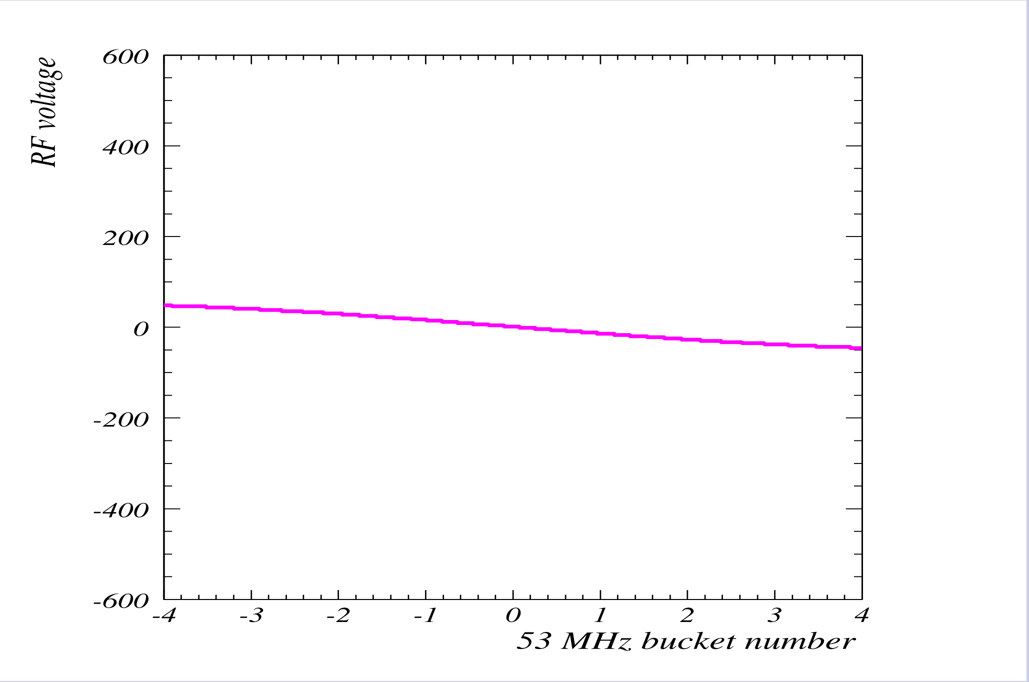


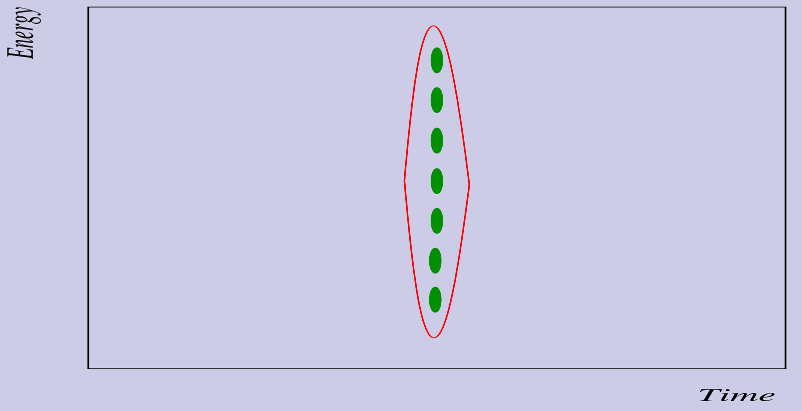


Coalescing

P. Adamson
Accelerator Division
Fermilab

- Sequence of RF bunch rotations to produce intense bunch for collider operations
- Begin in stationary bucket at 150 GeV
- Snap voltage down—bunch begins to rotate
  - ⇒ 2nd harmonic (106 MHz) cavity to linearize bucket
- Snap 53 MHz off and 2.5 MHz on—whole bunch train rotates
- Snap 53 MHz on at initial voltage—recapture beam in single bucket
- Need good beam loading compensation
  - ⇒ For a single batch, can compensate with 2.5 MHz alignment
  - ⇒ Not possible with multiple batches

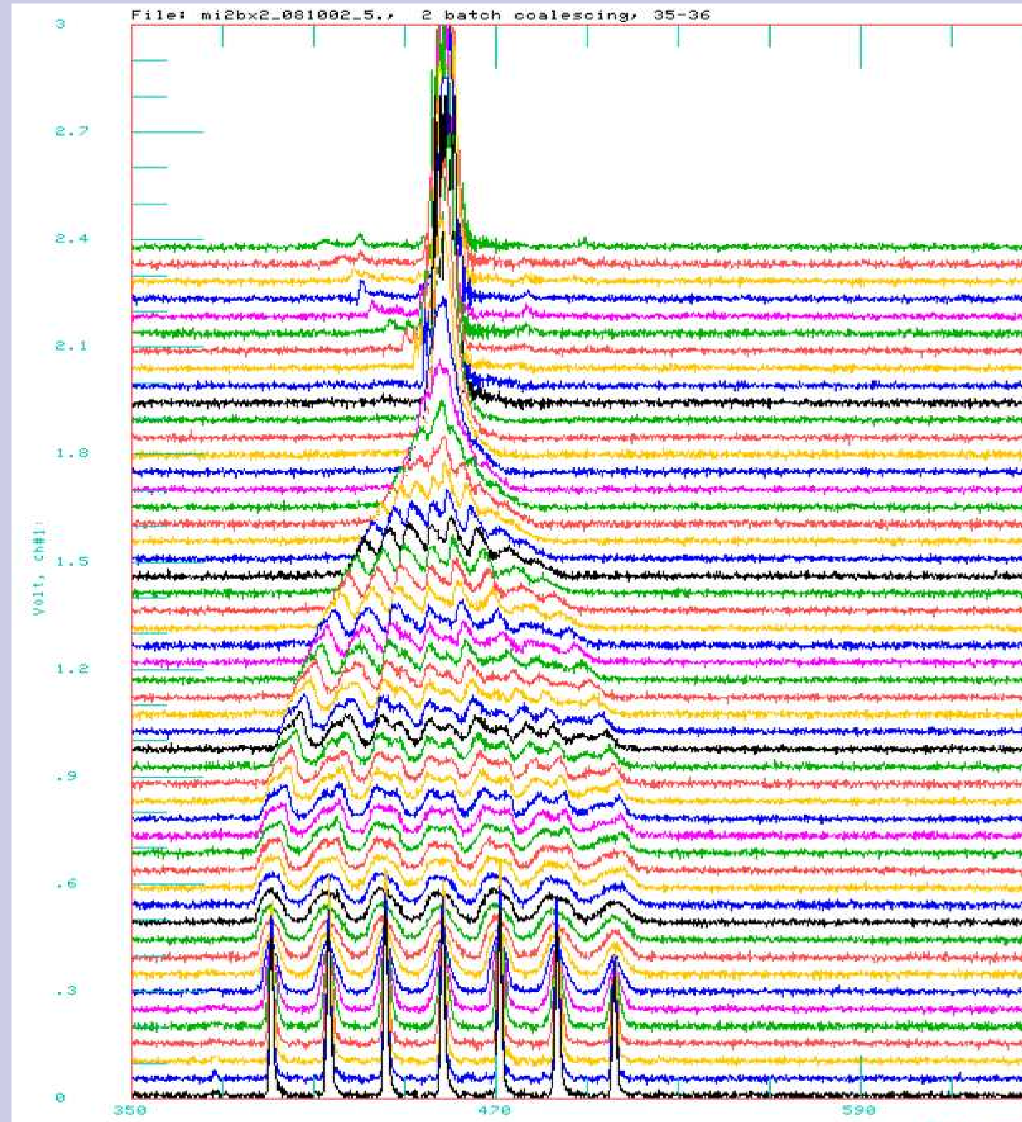




Coalescing

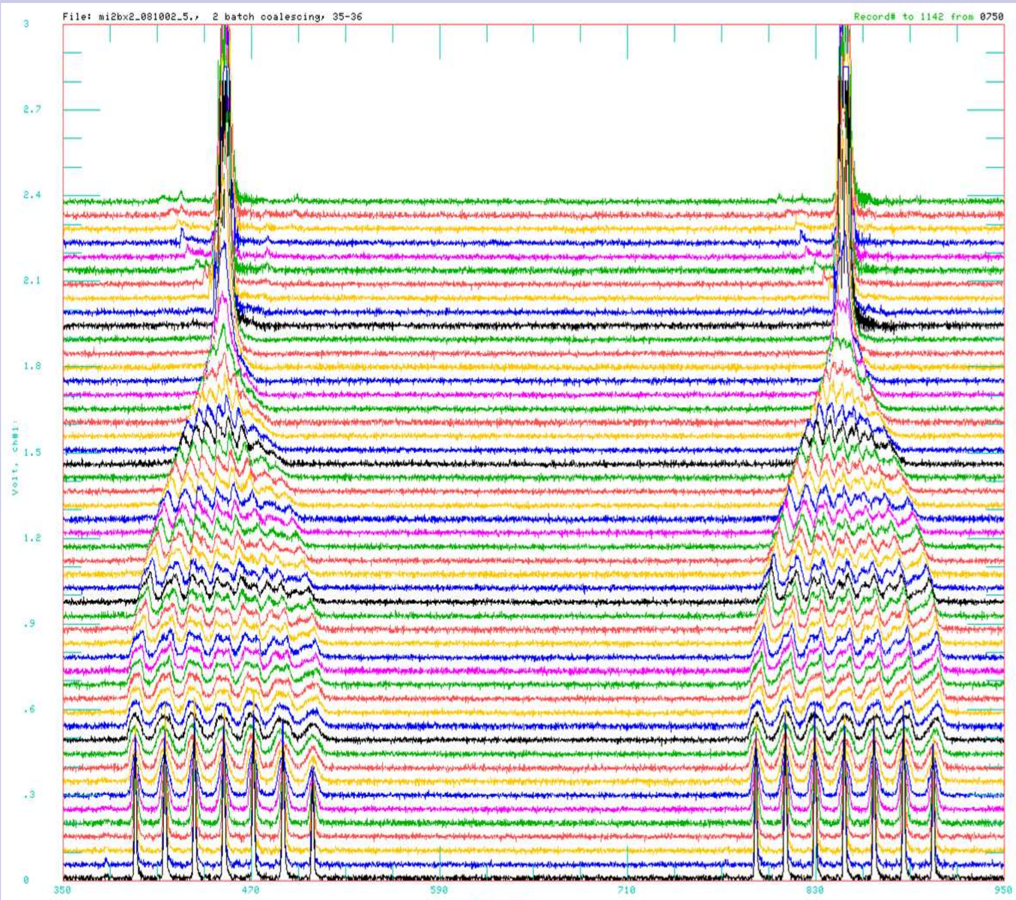
P. Adamson
Accelerator Division
Fermilab

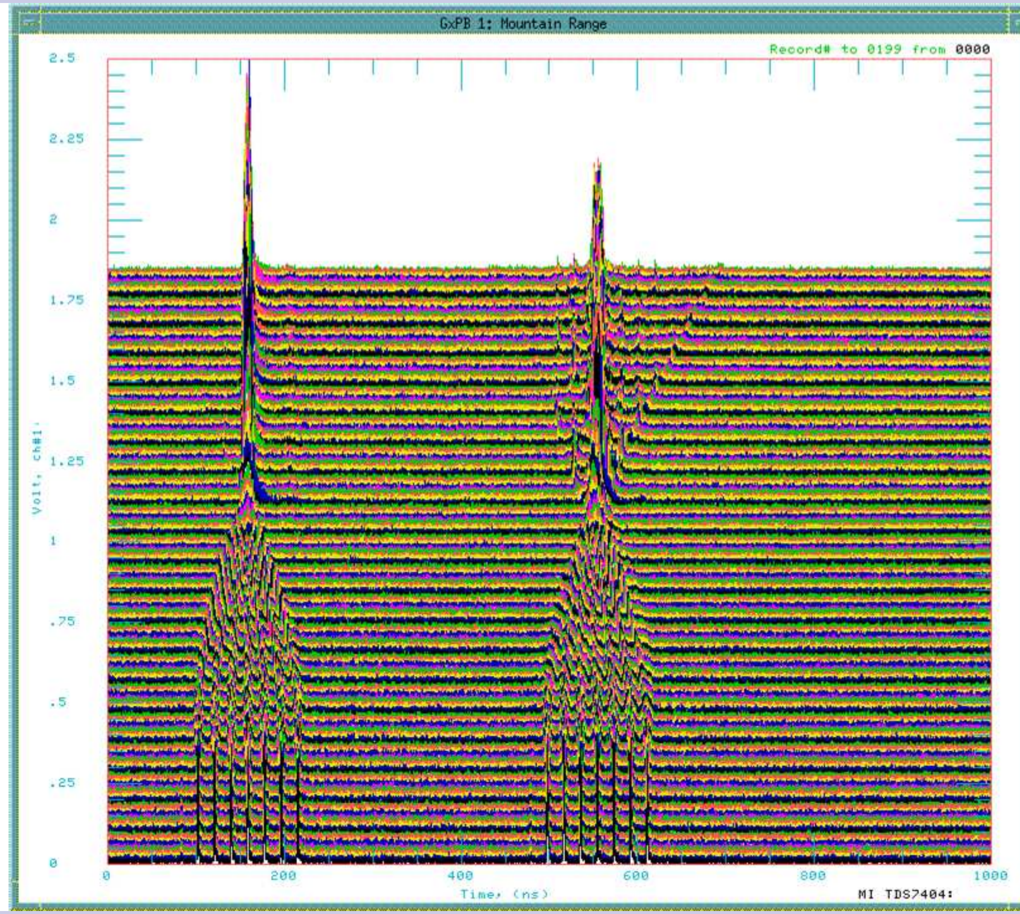
- ▷ Sequence of RF bunch rotations to produce intense bunch for collider operations
- ▷ Begin in stationary bucket at 150 GeV
- ▷ Snap voltage down—bunch begins to rotate
  - ⇒ 2nd harmonic (106 MHz) cavity to linearize bucket
- ▷ Snap 53 MHz off and 2.5 MHz on—whole bunch train rotates
- ▷ Snap 53 MHz on at initial voltage—recapture beam in single bucket
- ▷ Need good beam loading compensation
  - ⇒ For a single batch, can compensate with 2.5 MHz alignment
  - ⇒ Not possible with multiple batches



Beam loading compensation

P. Adamson
Accelerator Division
Fermilab



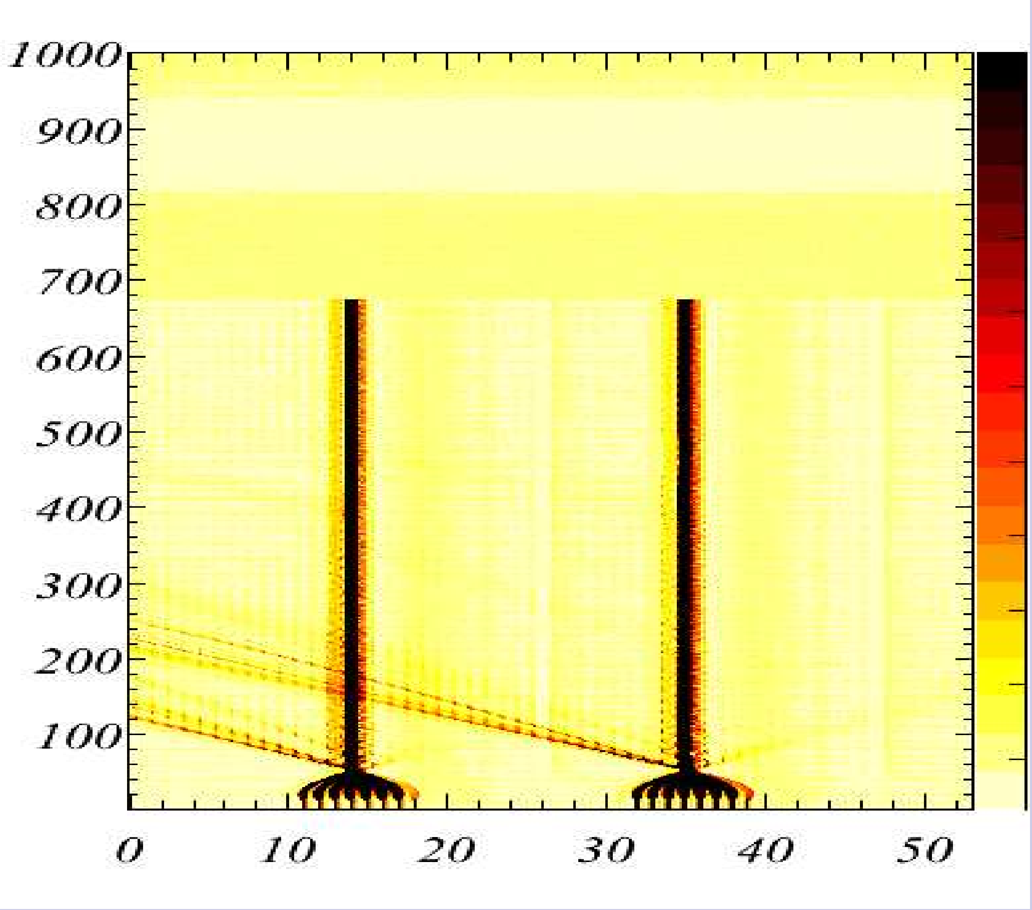


- ▷ Good coalescing
- ▷ Not enough beam loading compensation
- ▷ Improved BLC achieved with separate delay paths for 8 and 150 GeV, feedback for 106 MHz cavity and much attention to detail

DC beam

P. Adamson
Accelerator Division
Fermilab

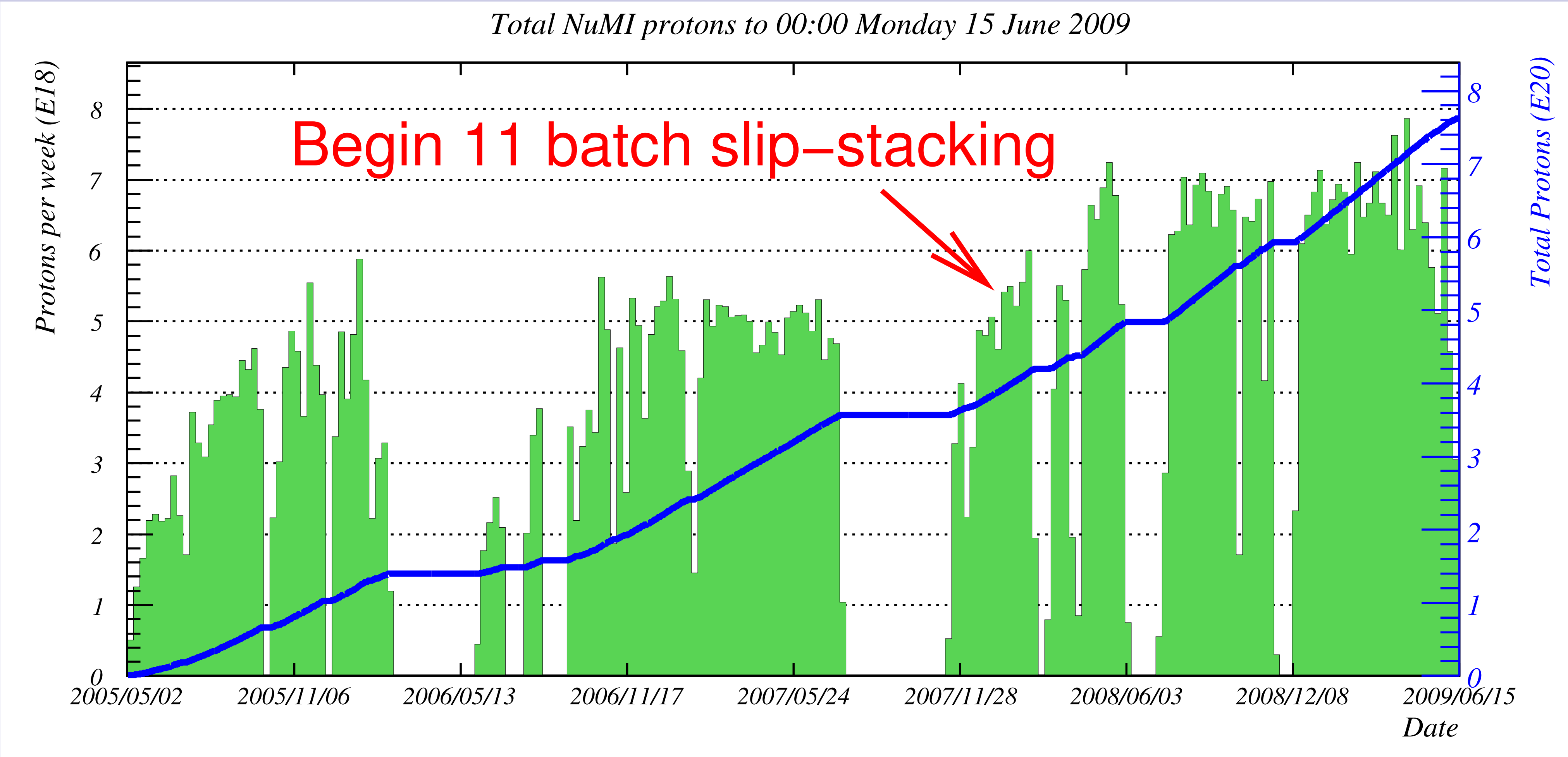
- For single batch injection, kickers only select one bunch
- Is there a problem with two batches?
  - ⇒ No—uncaptured beam moves far away from beam by extraction time
- We have always coalesced 4 antiproton batches at a time, but they aren't as intense
  - ⇒ 4 pbar batches are about the same total intensity as a single proton batch
- Two batch coalescing now $\sim$ 90% efficient—same as single batch
- Reduces shot setup time by $\sim$ 7 minutes



- Greatly expanded z scale

P. Adamson
Accelerator Division
Fermilab

Beam to NuMI

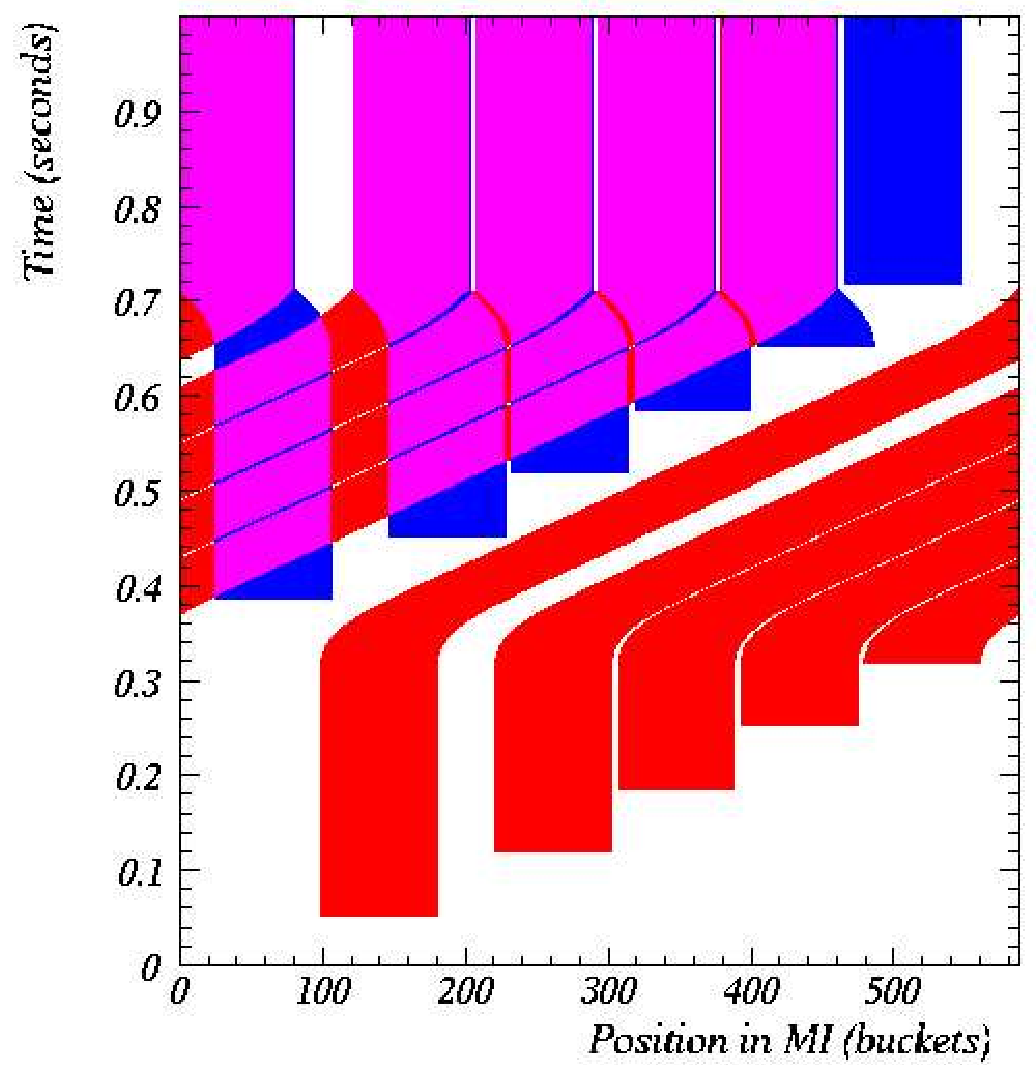


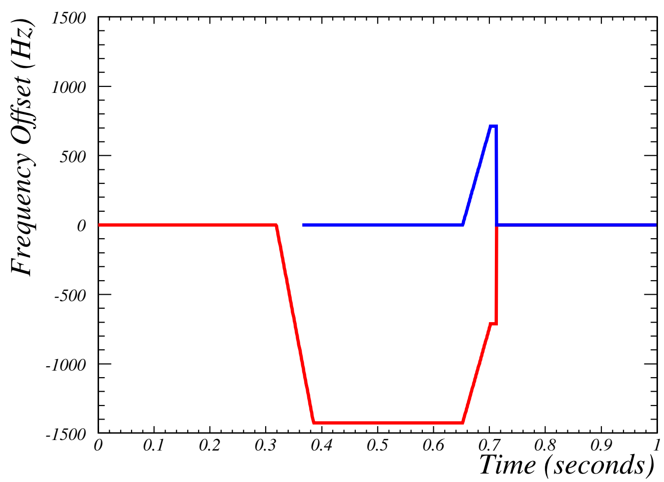
- Neutrino flux proportional to number of protons (no nonlinearities!)

P. Adamson
Accelerator Division
Fermilab

Slip-stacking

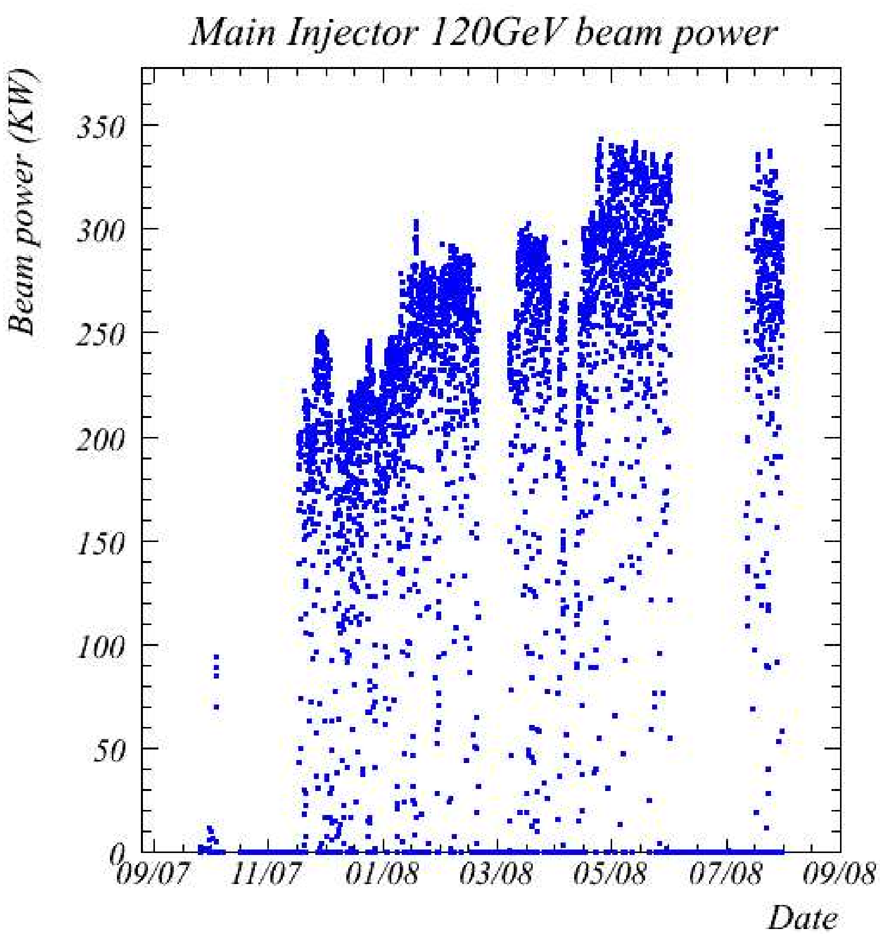
- Have been slip-stacking 11 batches for mixed-mode NuMI and pbar operation since January 2008
- Works well, but process is lossy due to small RF buckets
- Losses constrain operational beam power
- MI beam power 340 kW

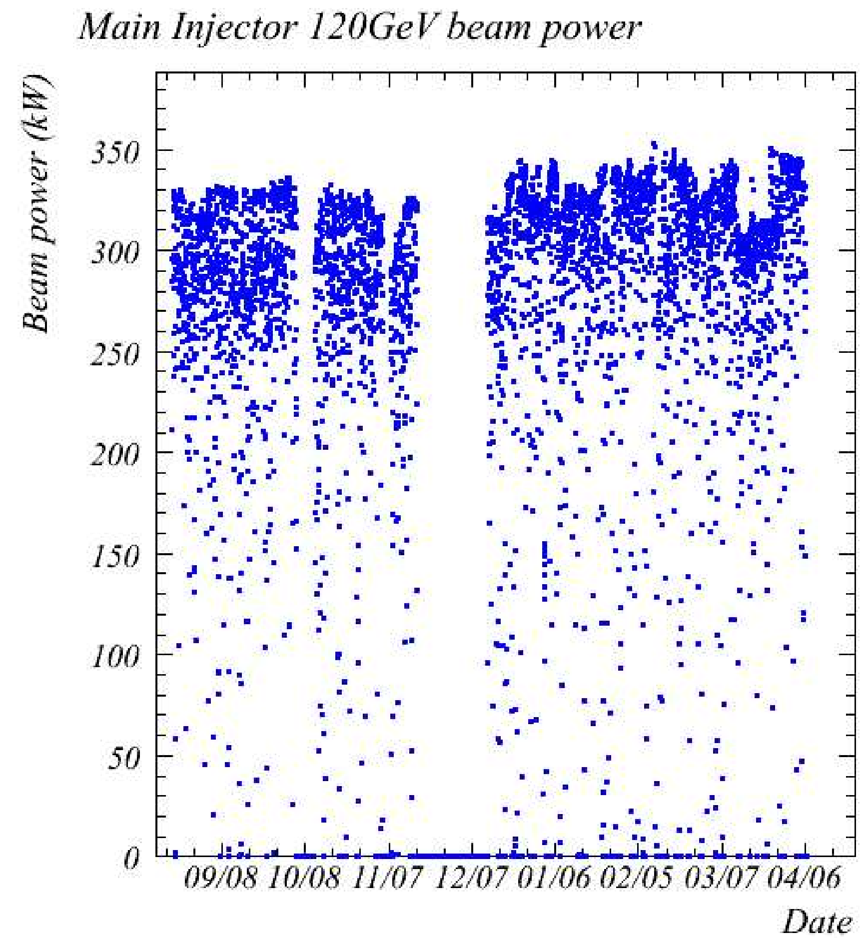




P. Adamson
Accelerator Division
Fermilab

MI beam power

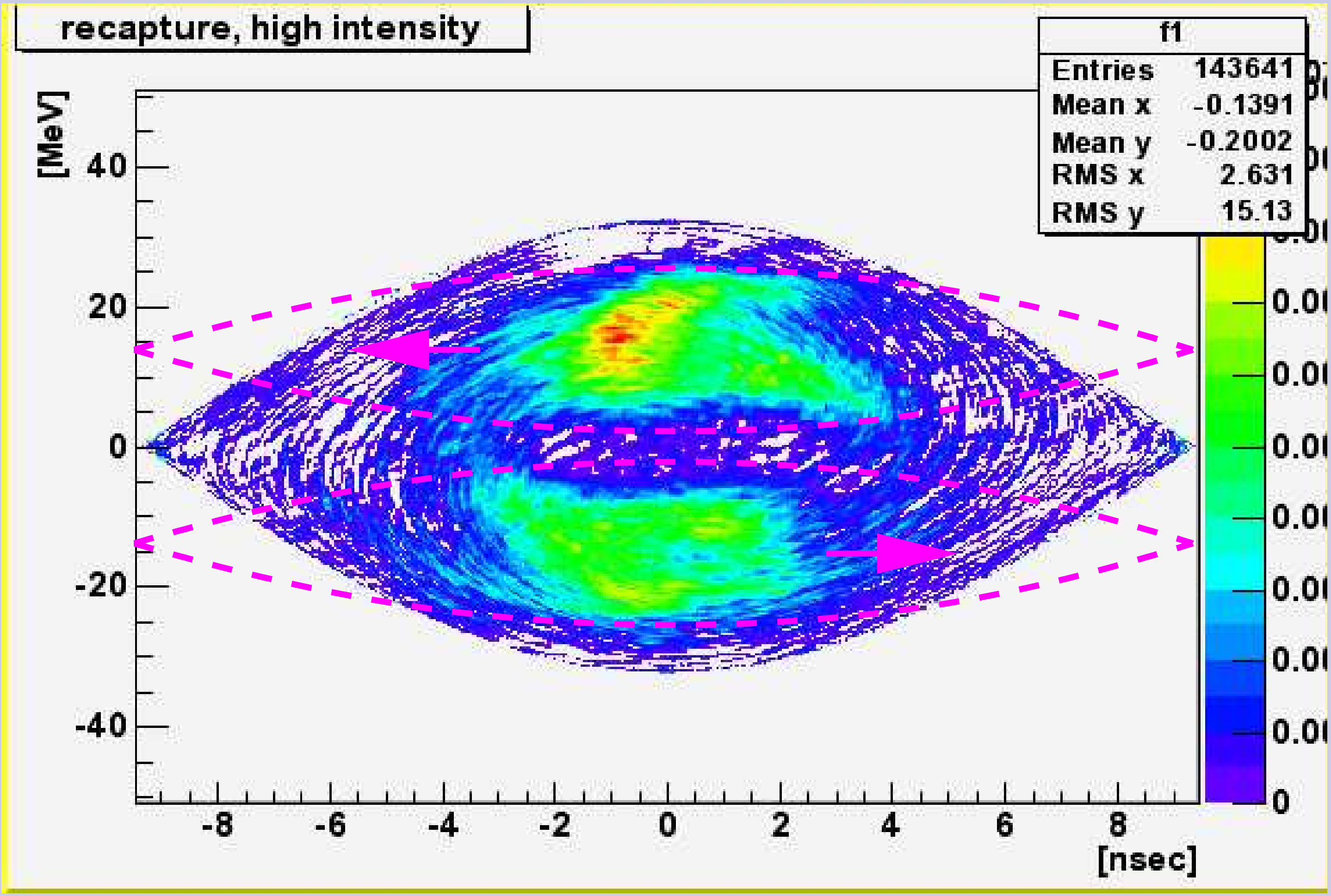




- MI beam power at 120 GeV, September 2007 to April 2009
- Scatter in power is due to timeline effects (Tev shots, SY120, ...)

P. Adamson
Accelerator Division
Fermilab

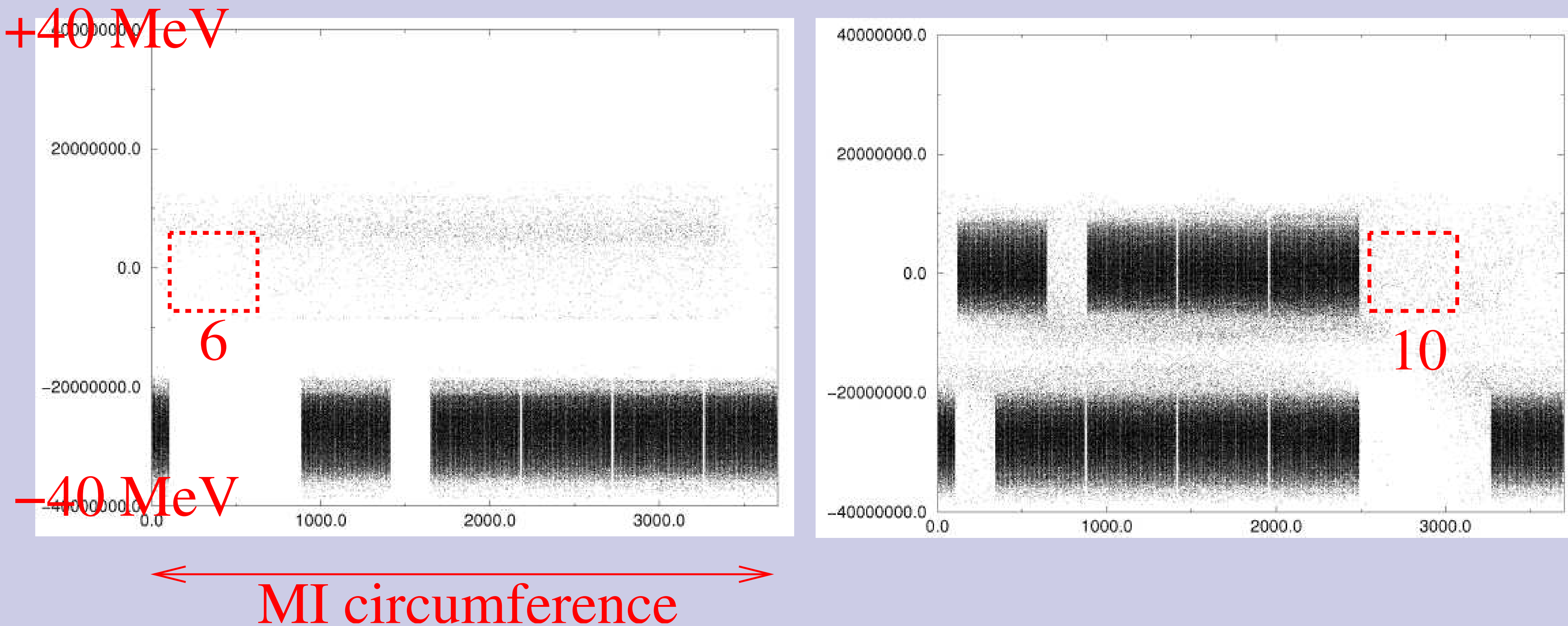
Small RF buckets



- ▷ Tomographic reconstruction of one bunch at slip-stack recapture
- ▷ Slipping buckets sketched in magenta
- ▷ Injection buckets must be small to allow two to fit in one full 8 GeV bucket
- ▷ Not all beam captured at injection → losses

Slip-stack injection

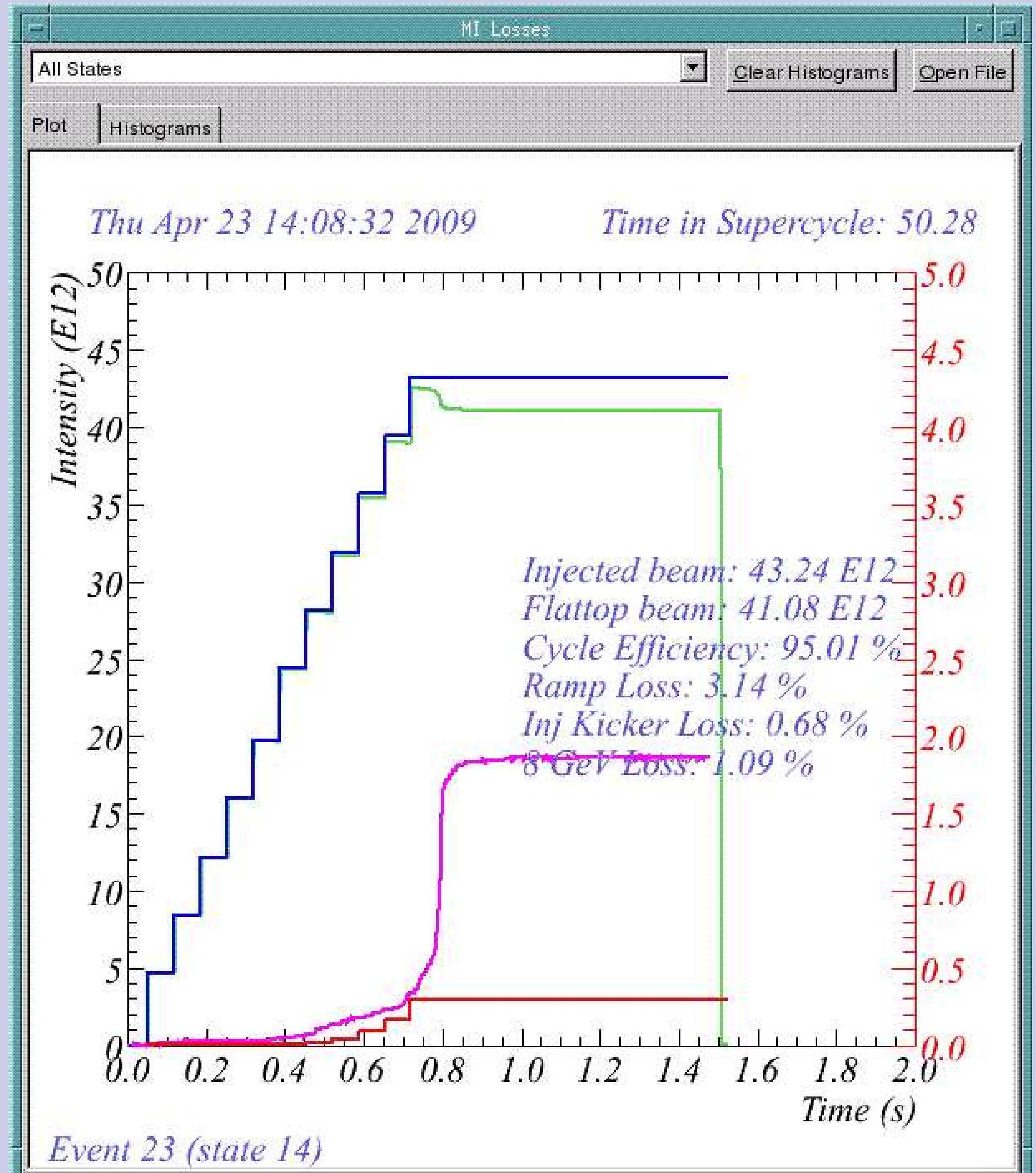
P. Adamson
Accelerator Division
Fermilab



- ▷ Some beam escapes from small slip-stack buckets
- ▷ Injection kickers fire—displaced beam hits 104-105 region
- ▷ At recapture, some beam is captured in the “wrong” place, and becomes extraction loss
- ▷ Some other beam isn’t captured and is lost at start of ramp

Slip-stacking losses

- Three major losses—three solutions
  - ⇒ Loss at start of ramp
    - Uncaptured beam is not accelerated
  - ⇒ Injection kicker loss
    - Beam strays into injection gap. When injection kicker fires, beam hits quads in injection region
  - ⇒ Extraction loss
    - Beam under extraction kicker rising/falling edge sprayed over extraction region



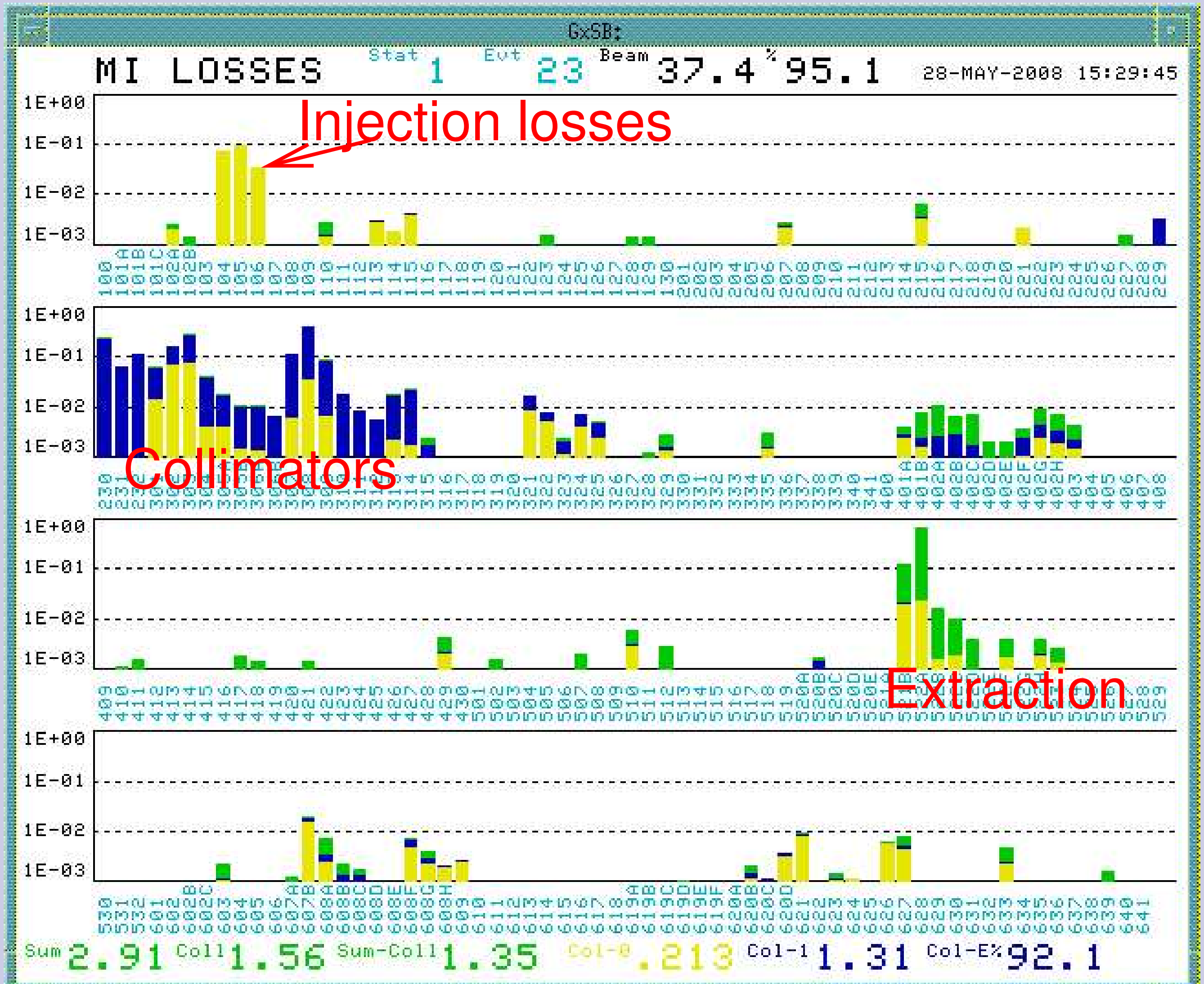
P. Adamson
Accelerator Division
Fermilab

Collimators

- Primary scraper (0.25 mm W) in dispersive region
- 4 marble-clad 20 ton steel secondary collimators
- steel/marble and steel/concrete masks to protect downstream elements from spray

Losses with collimation

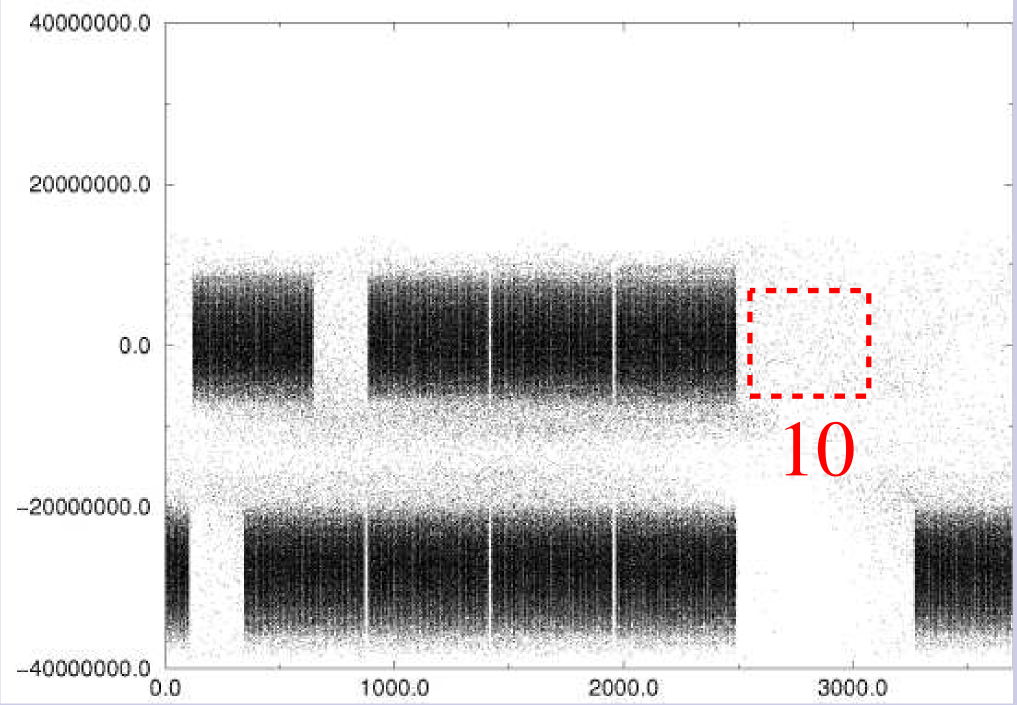
P. Adamson
Accelerator Division
Fermilab



- Losses around MI (log scale)
- 3 colours—8 GeV, start of ramp, high field
- Collimators 97-99% efficient for uncaptured beam
  - ⇒ B. C. Brown *et. al.*, PAC 2009
- Residual activation at lambertsons reduced 30-35% (so far!)

Injection loss

- How to stop injection kickers from hitting beam?
  - ⇒ Build some new kickers (84 buckets long, fast rise and fall time) and kick beam to MI abort instead
  - ⇒ Fire kickers half a turn before each injection
- MI gap clearing kicker project
  - ⇒ Magnets built—will be installed in current shutdown
  - ⇒ Penetrations (cables, load cooling) built
  - ⇒ New building will be constructed on top of penetrations for power supplies, PFN...
  - ⇒ Then tie everything together in a short shutdown to make system operational.



Injection loss

P. Adamson
Accelerator Division
Fermilab

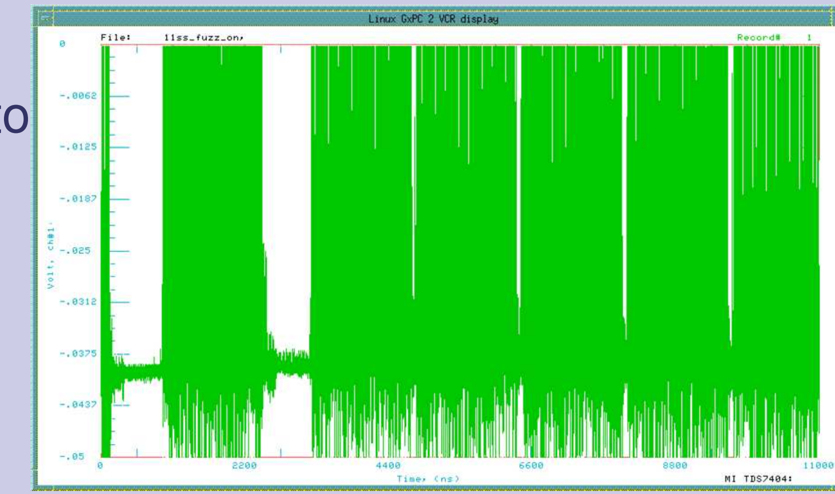
- How to stop injection kickers from hitting beam?
  - ⇒ Build some new kickers (84 buckets long, fast rise and fall time) and kick beam to MI abort instead
  - ⇒ Fire kickers half a turn before each injection
- MI gap clearing kicker project
  - ⇒ Magnets built—will be installed in current shutdown
  - ⇒ Penetrations (cables, load cooling) built
  - ⇒ New building will be constructed on top of penetrations for power supplies, PFN...
  - ⇒ Then tie everything together in a short shutdown to make system operational.

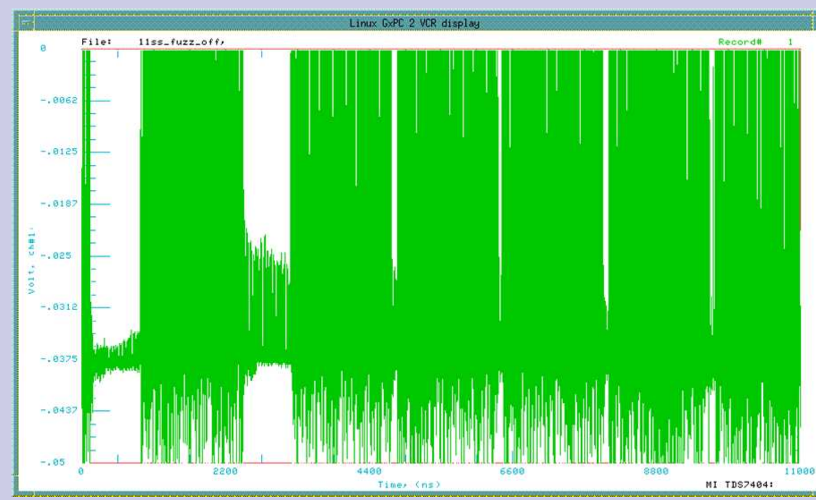
Extraction loss

P. Adamson
Accelerator Division
Fermilab

- Have been “fuzzing” the beam with the transverse damper system
  - ⇒ Drive transverse kicker at machine tune (beam signals too small for active feedback to work)
  - ⇒ Chromaticity makes this harder
  - ⇒ Power limited
- Build new system
  - ⇒ “spare” injection kicker in tunnel (no vacuum work)
  - ⇒ FET pulser, NIM module with FPGA and ethernet for control
  - ⇒ Production system installed just before shutdown
- Fuzz at 8 GeV → energy deposited in ring reduced by factor 15
- Fuzzed beam goes to collimators

MI wall current monitor at extraction:

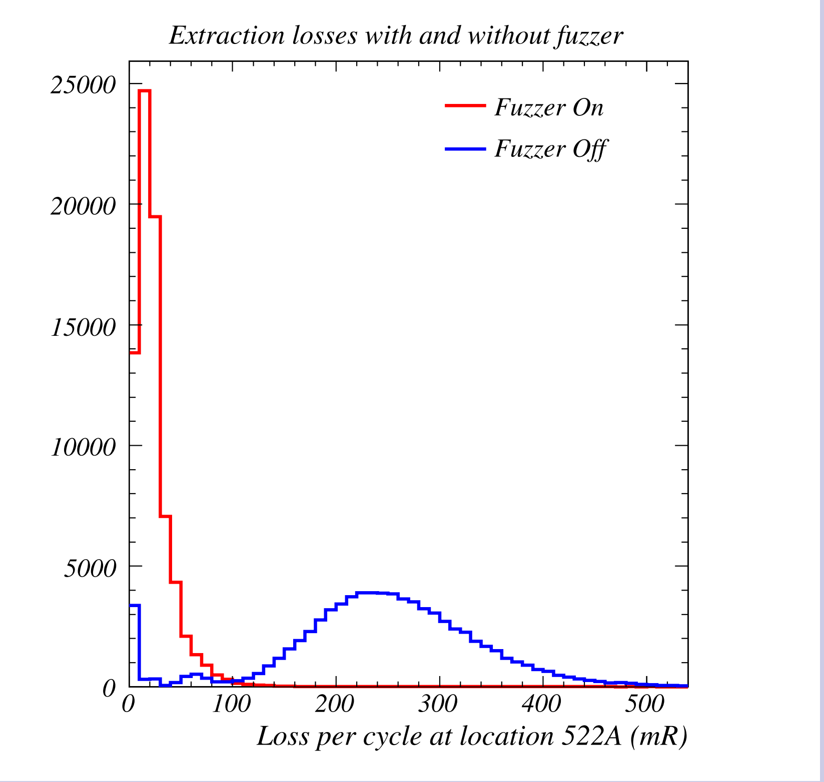




- Fuzzing on (top) and off with existing damper system

Extraction loss

- Have been "fuzzing" the beam with the transverse damper system
  - ⇒ Drive transverse kicker at machine tune (beam signals too small for active feedback to work)
  - ⇒ Chromaticity makes this harder
  - ⇒ Power limited
- Build new system
  - ⇒ "spare" injection kicker in tunnel (no vacuum work)
  - ⇒ FET pulser, NIM module with FPGA and ethernet for control
  - ⇒ Production system installed just before shutdown
- Fuzz at 8 GeV → energy deposited in ring reduced by factor 15
- Fuzzed beam goes to collimators

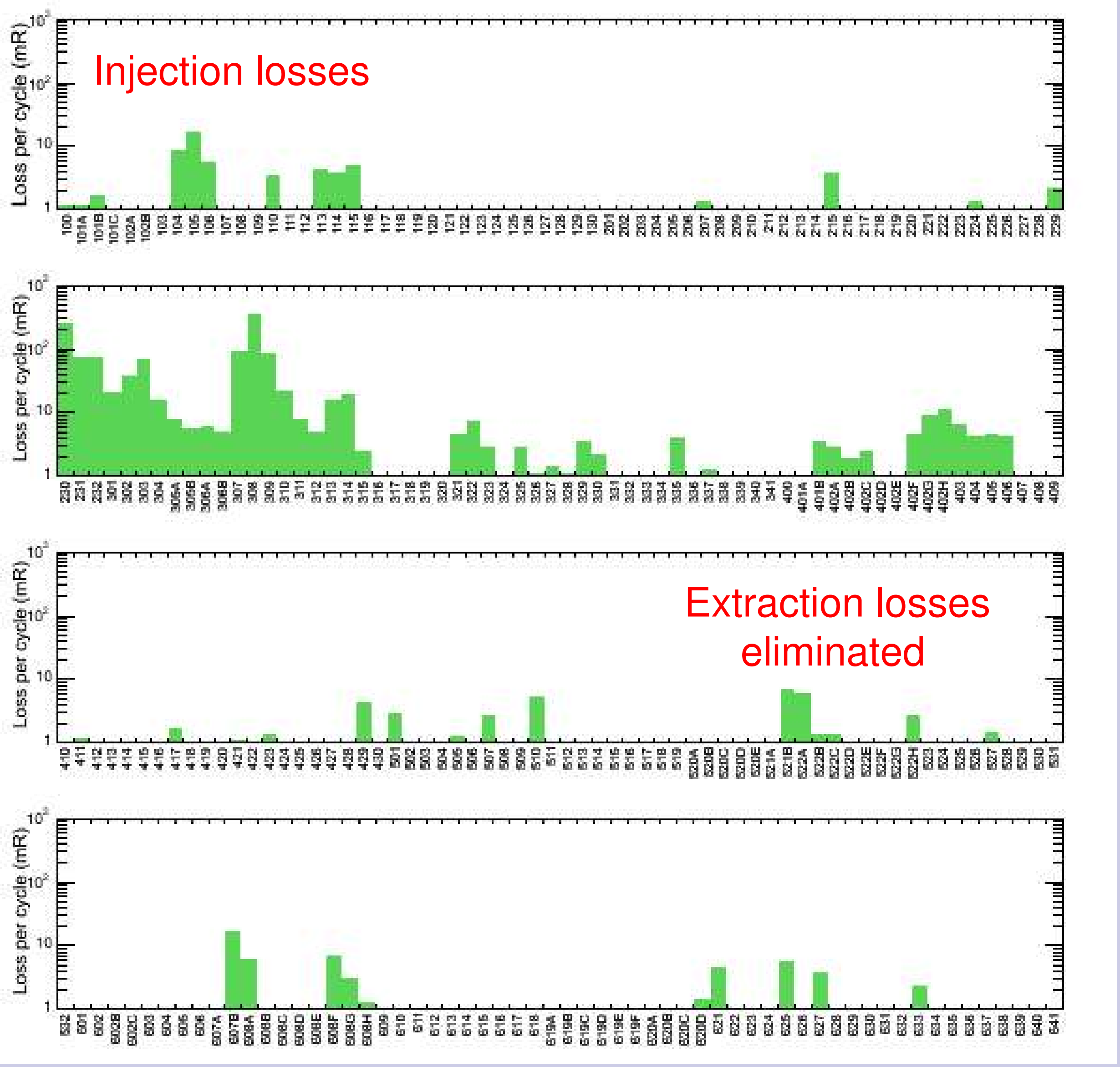


- Blue—loss with damper fuzzing
- Red—loss with new fuzzer

Losses summary

P. Adamson
Accelerator Division
Fermilab

Ring-wide losses with fuzzer operational



- ▷ Three major losses during slip-stacking
  - ⇒ Ramp loss mitigated with collimator system
  - ⇒ Extraction loss eliminated with Fuzzer
  - ⇒ Injection loss will be eliminated with gap clearing system
- ▷ Nothing else stands in the way of design 400 kW

The Intensity Frontier

P. Adamson
Accelerator Division
Fermilab

- Tevatron run ends 2011
  - $\Rightarrow$ Pass the high energy baton to CERN
- NOνA is the first step in a program of proton beam intensity upgrades
- Repurpose recycler as proton stacker—cycle time 2.2s $\rightarrow$ 1.33s
- Small increase in per-pulse intensity (11 batches $\rightarrow$ 12) 4.9×10^{13} protons
- Design: 700 kW
- Year-long shutdown after Tevatron finishes

NOνA upgrades:

- Remove unnecessary bits (MI 2.5 MHz, 5MHz cavities, pbar extraction, recyler electron & stochastic cooling, ...)
- Add 2 RF stations (18 $\rightarrow$ 20)
  - $\Rightarrow$ 204 $\rightarrow$ 240 GeV/s at same bucket size
- New vertical quad bus supply
- New transfer lines (MI8 $\rightarrow$ recycler, recycler $\rightarrow$ MI)
- Recycler 53 MHz RF system
- New kickers
- New recycler BPM cables/electronics

- Project X (8 GeV SC linac) increases per-pulse intensity by factor of $\sim$3—need new RF system. Electron cloud?

Phil Adamson

Fermilab Accelerator Division

Fermilab Main Injector status and plans

Main Injector • Performance & Improvements

Collider • NuMI • Future