Main Injector Operation Status

David Johnson

Main Injector/Recycler Department

- Recent Developments in MI
- Main Injector Current Performance
  - Pbar production, Proton for Collider, Pbar for Collider
- Run II Plan Project Update
- Other Efforts

Main Injector Recent Developments

- Lattice Match between Injection lines(MI8) and Main Injector
- Beam Loading compensation and tune up of the proton coalescing for Collider program
- Multi batch Beam Loading compensation and tune up of the pbar coalescing for the Collider program
- Studies to understand the longitudinal emittance growth in the Main Injector and R&D its solution
- Bunch-by Bunch Damper studies
- Studies to understand an apparent vertical emittance growth between 8 and 150 Gev
- Slip stacking studies
- 2.5 Mhz Acceleration studies
- Development of Recycler pbar extraction and acceleration/coalescing in MI

Main Injector Current Performance

- Pbar Production
- Proton Performance
- Pbars from Accumulator
- Pbars from Recycler

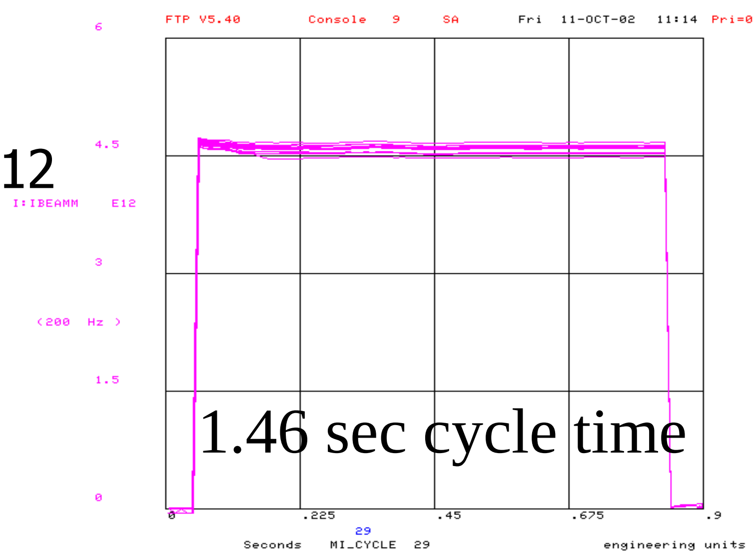
Pbar Production Cycles

Run II Goal: 5E12/pulse @ 1.5 sec. cycle time

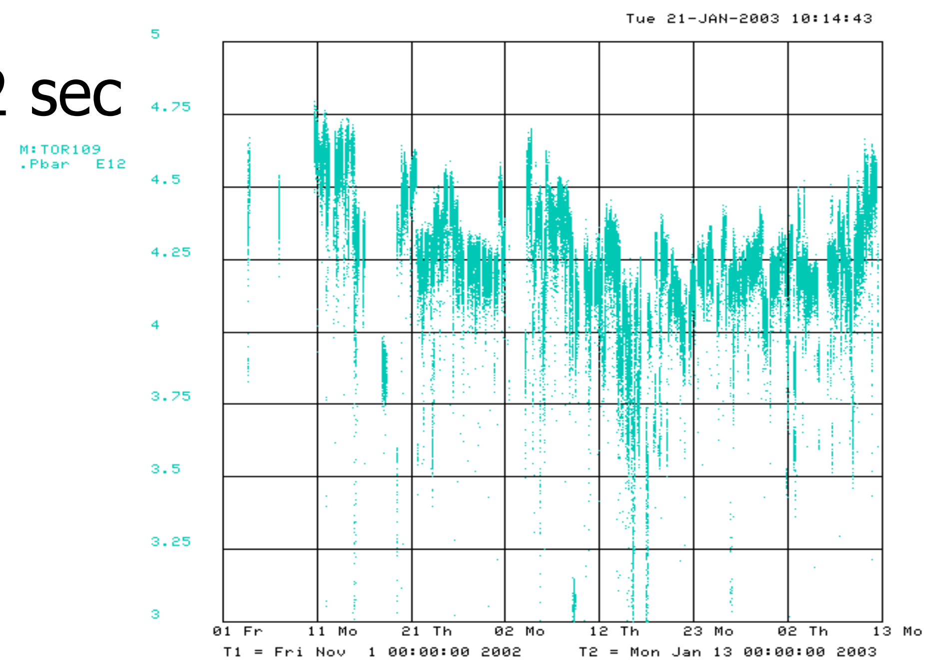
Current status:

>4.25E12 @ cycle time > 2 sec depending on stack size

4.5E12



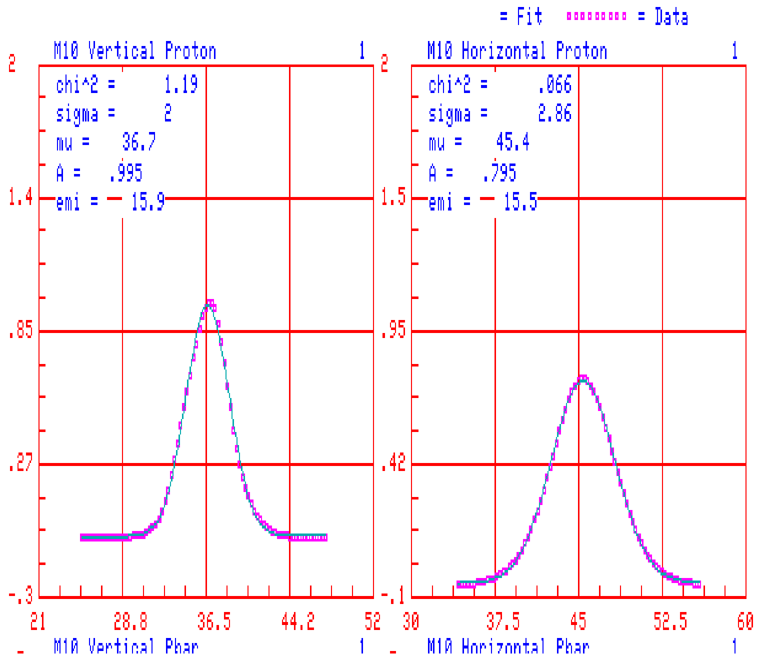
1.46 sec cycle time



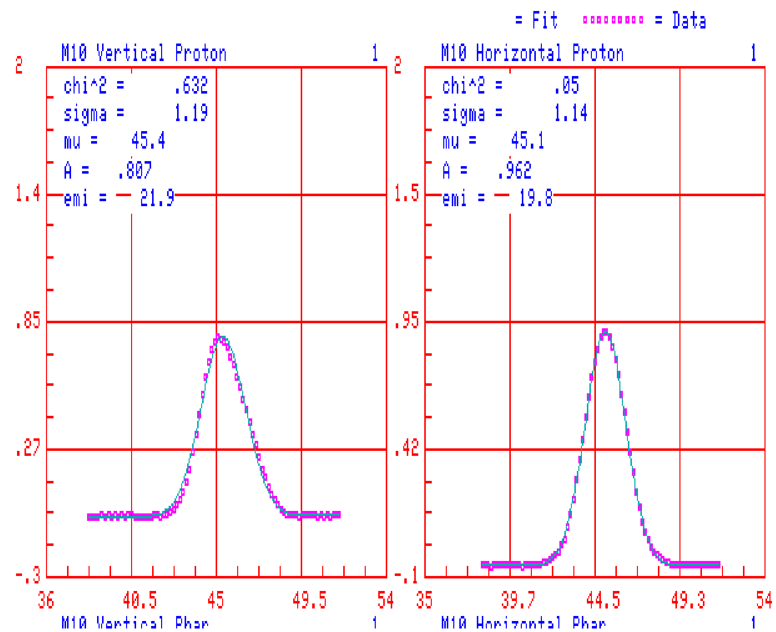
Intensity on target (E12)
(Nov 1 – Jan 13)

Pbar Production Cycles: Transverse

Transverse emittance growth between 8 and 120 GeV:
Horizontal: 16 π -> 20 π   Vertical: 16 π -> 22 π *



8.9 GeV



120 GeV

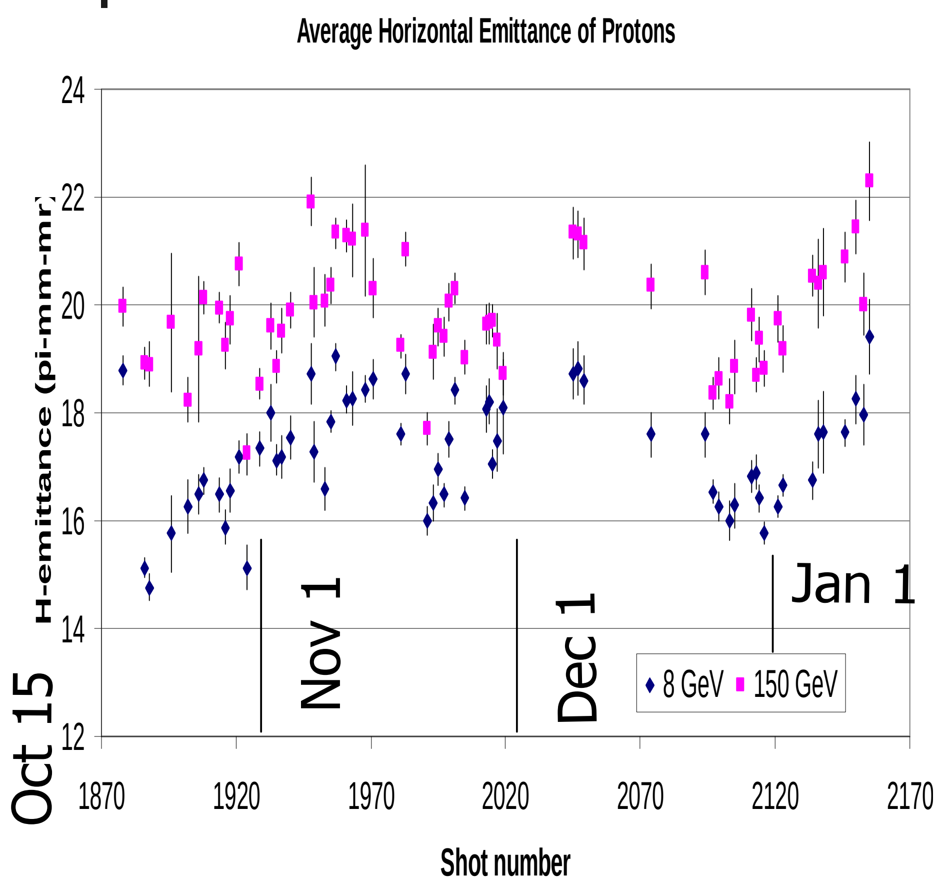
*Instrumental issues (suspect FW PMT)

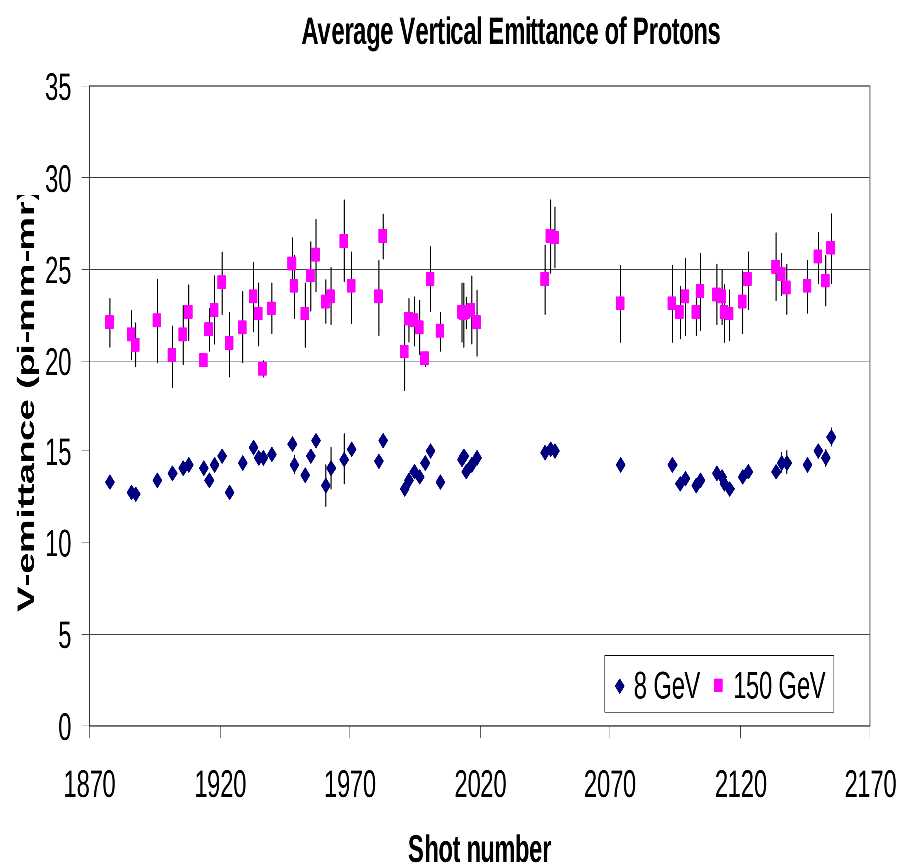
MI Proton Performance: Goals

Parameter	Goals (Run II)	Current Performance
Protons/bunch	270E9 at Collision ~300E9 at 150 MI *	>300E9 (7 bunch) 250E9 (5 bunch)
Coalescing eff.	90%	85% (7 bunch) 92% (5 bunch)
Transverse emittance (95% normalized)	20 π-mm-mr at collision 18 π-mm-mr at 150 MI	19 π-mm-mr Horizontal 22 π-mm-mr Vertical
Longitudinal emittance (95% normalized)	2.0 eV-sec at collision	2.8-3.2 eV-sec (7 bunch) 2.2-2.6 eV-sec (5 bunch)

*Assume 90% eff. to collision

Proton Performance: Transverse



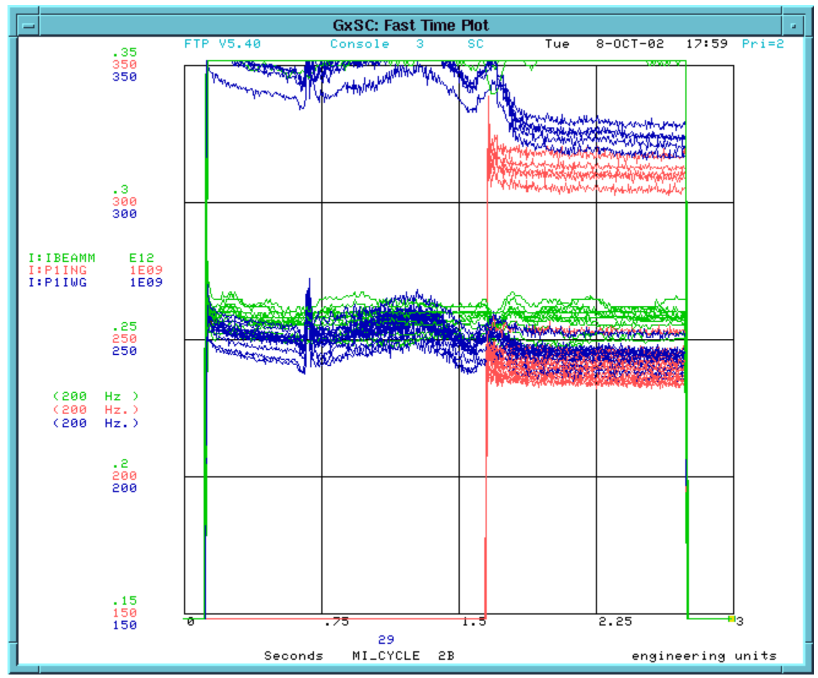


- Horizontal data not corrected for non-zero dispersion
- We need to understand apparent vertical plane emittance growth and minimize it.

Proton Performance: Coalescing

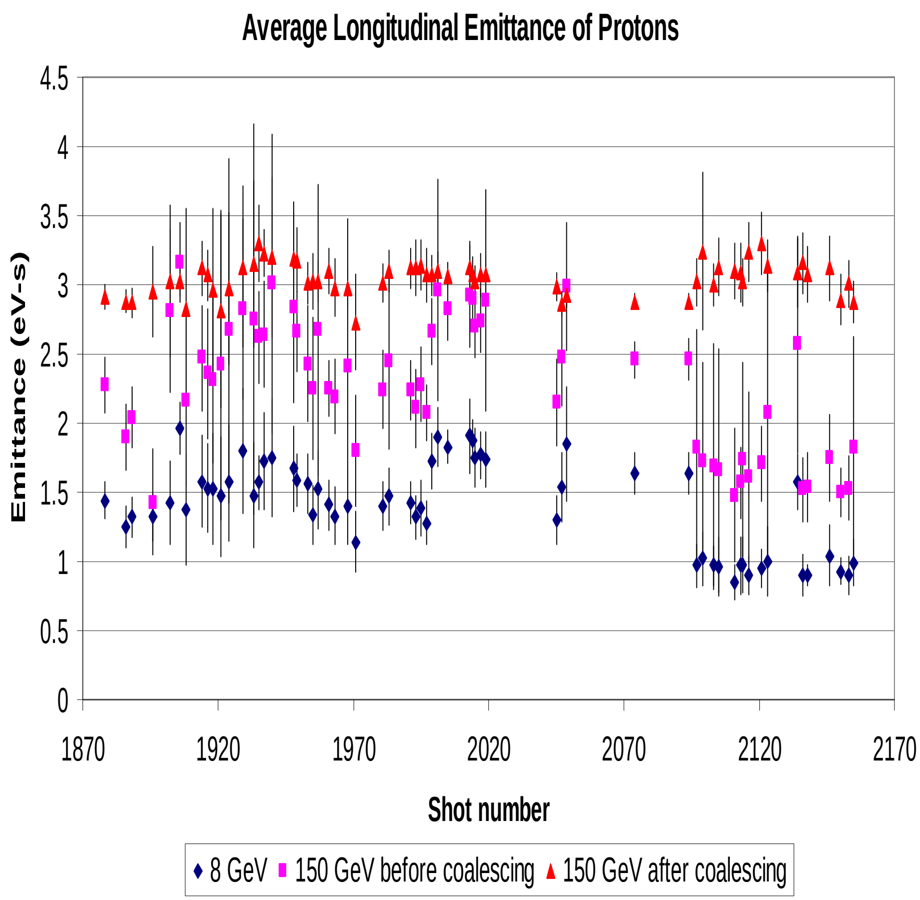
- Gain of Booster Quad damper reduced to allow longitudinal emittance of Booster bunches to grow from .15 eV-sec to about .3 eV-sec to reduce long emit blow up in Main Injector (see longitudinal damper)

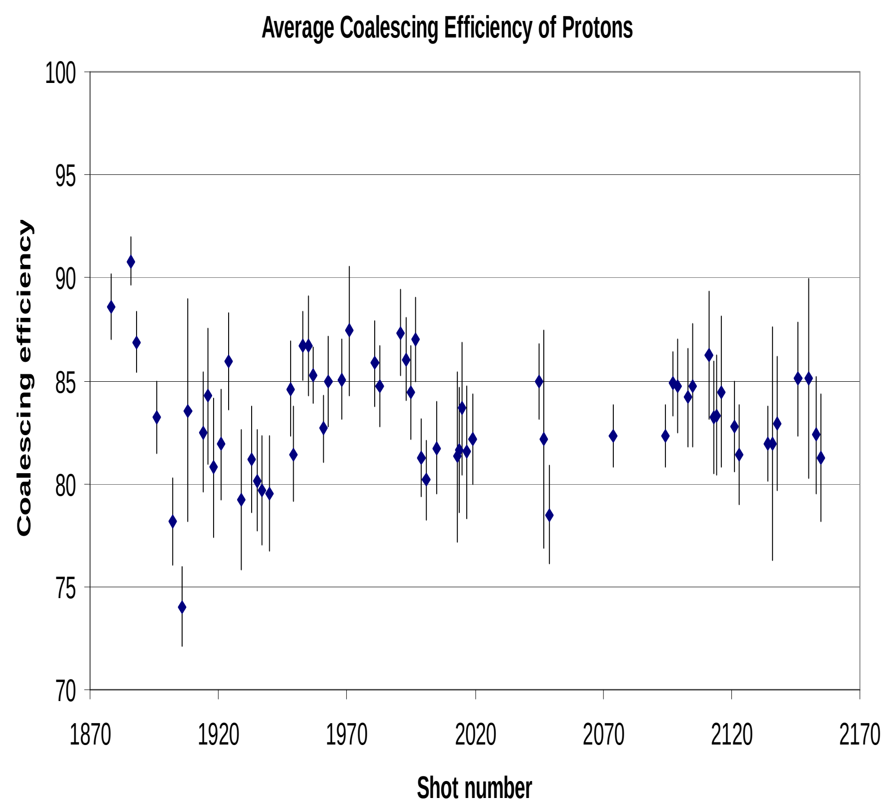
- Coalesced bunch long emit. Vary from
  ~3.2 eV-sec (SBD,rms)   7 bunch
  ~2.2 eV-sec (SBD, rms) 5 bunch
  {2.9-4.0 eV-sec (gaussian fit to compare with Tev}



7 bunch ~ 85% efficiency (3% satellite , 12% DC beam), 310E9
5 bunch ~ 92% efficiency (1% satellite, 8% DC beam),   245E9

Proton Performance: Longitudinal





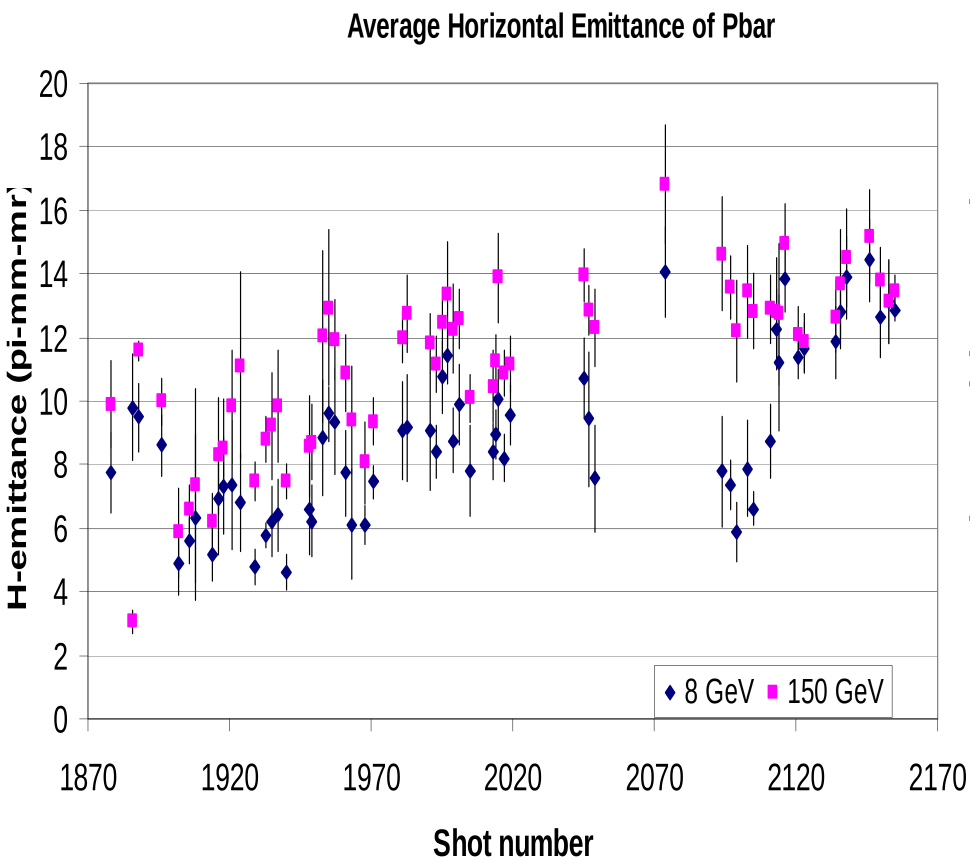
MI Pbar Performance: Goals

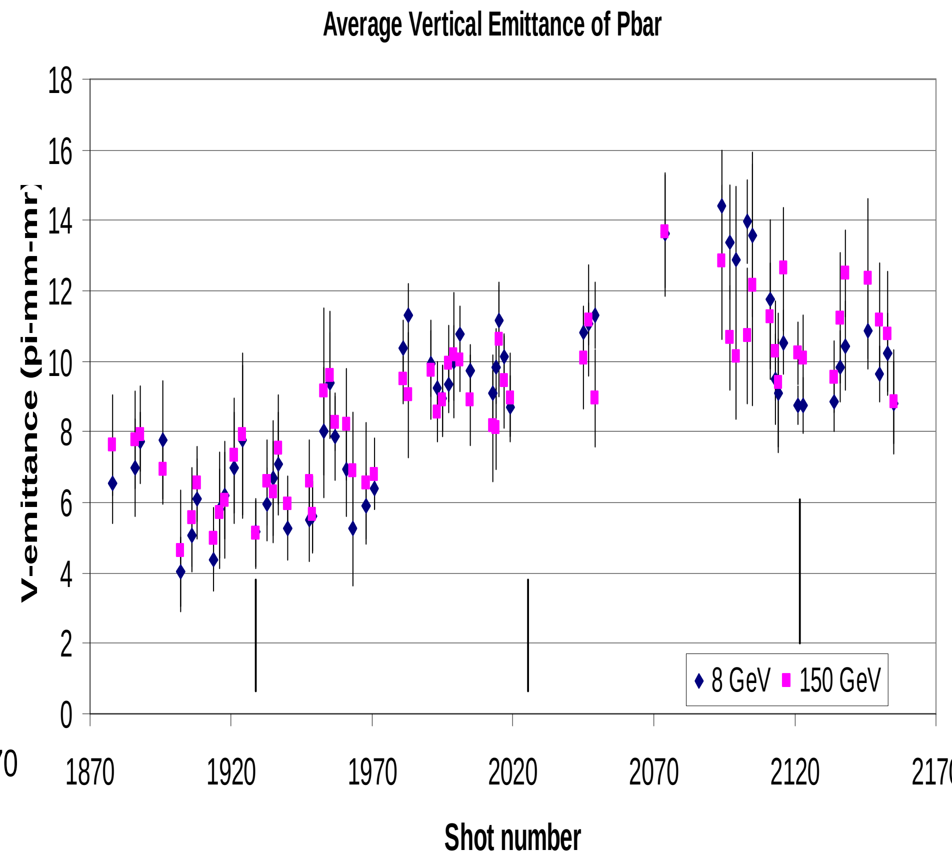
Parameter	Goals (Run II)	MI Current Performance
Pbars/bunch	31 E9 at Collision ** ~33 E9 at 150 MI *	22 – 35 E9 (depending on stack size)
Coalescing eff. Acc -> 150 GeV	90% transmission	85 - 90% coalescing eff 80 - 90% transmission
Transverse emittance (95% normalized)	15 π-mm-mr at collision 14 π-mm-mr at 150 MI	<14 π-mm-mr Horizontal <12π-mm-mr Vertical
Longitudinal emittance (95% normalized)	2 eV-sec collision	2.8-3.2 eV-sec

*Assume 90% eff. to collision

**FY03

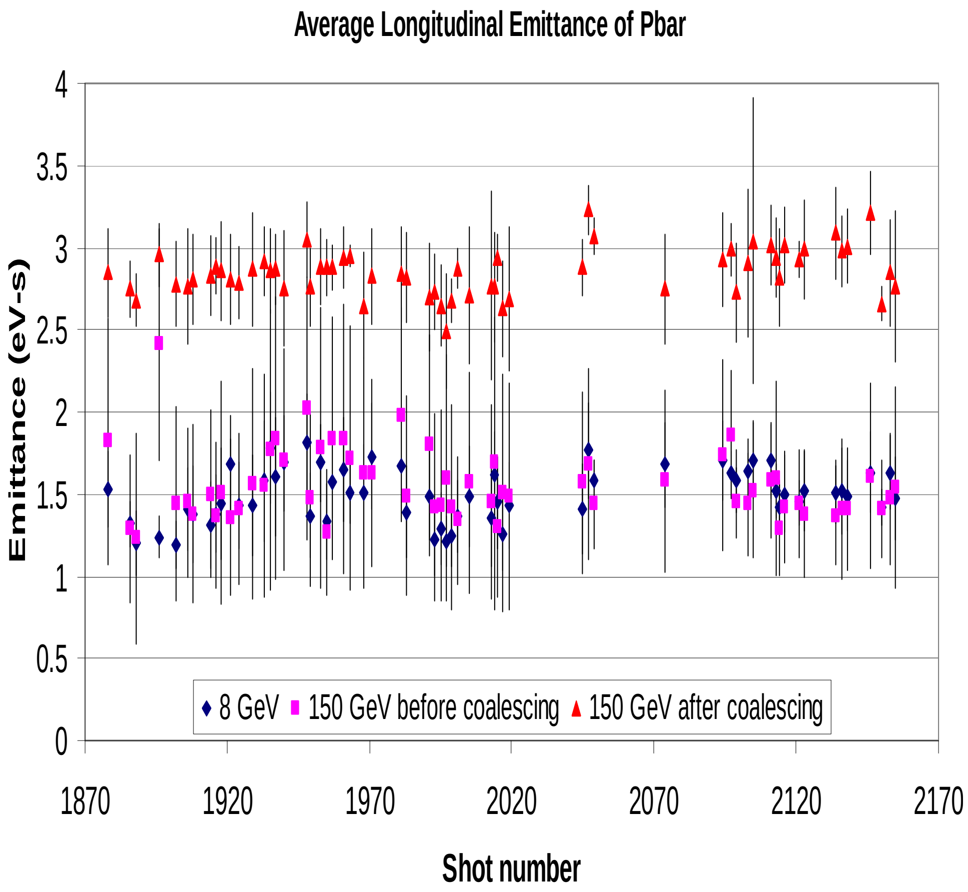
Pbar Performance: Transverse emittance

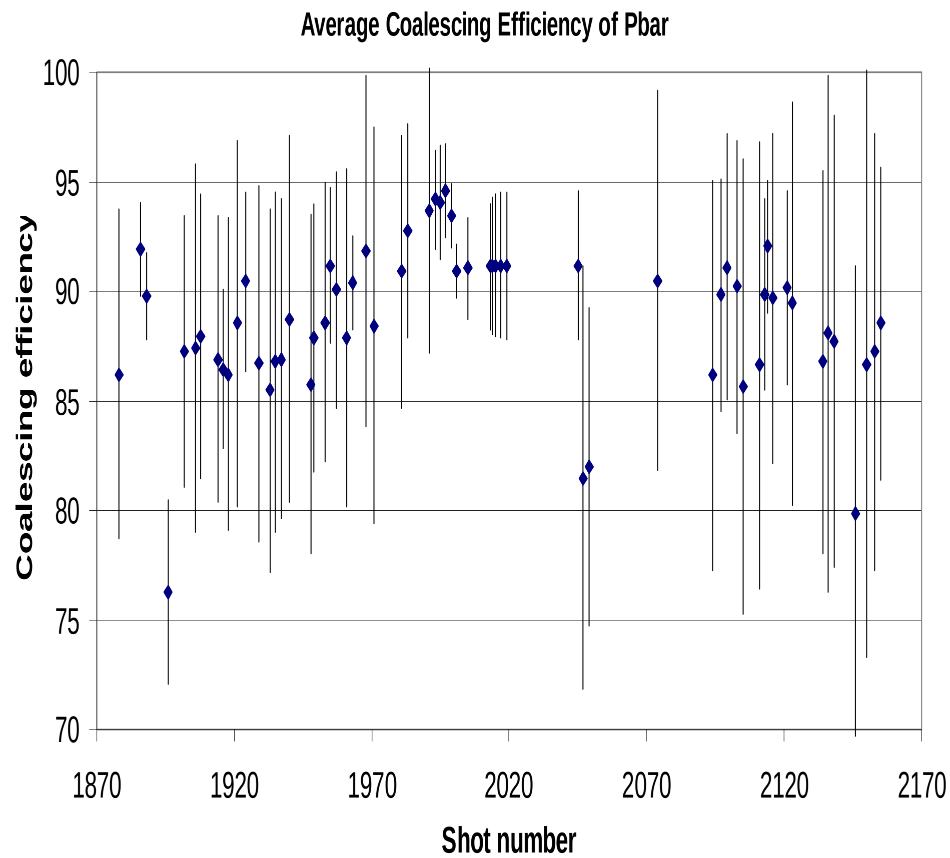




11/1 12/1 1/1

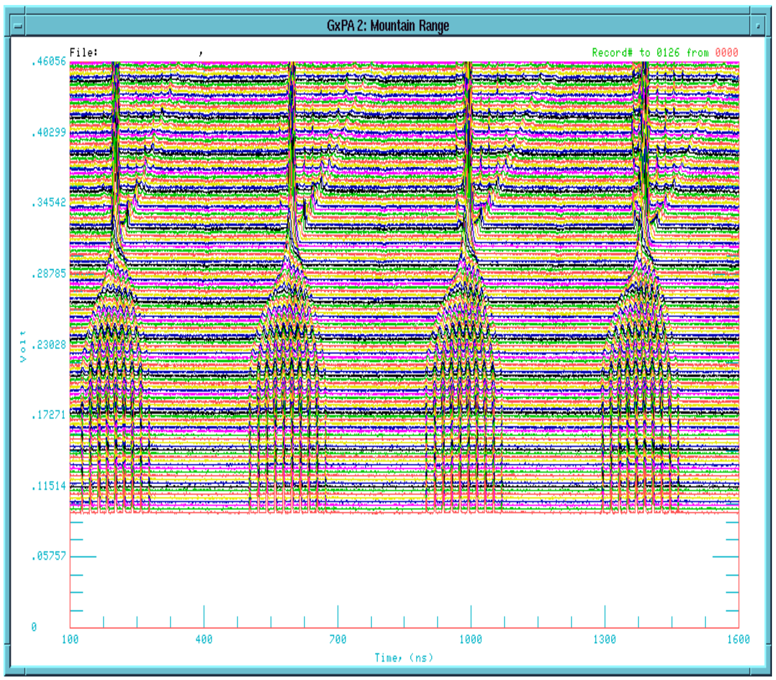
Pbar Performance: Coalescing



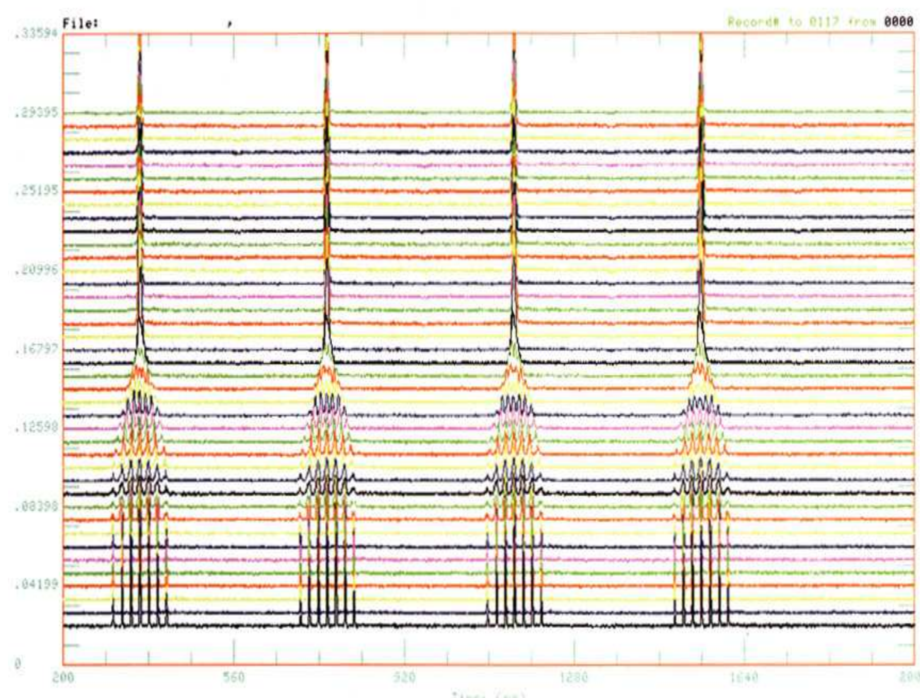


Pbars from Accumulator: Beam Loading Compensation

Mountain Range plot of 4 pbar 2.5 Mhz batches each with 7-9 53 Mhz bunches through the coalescing process



BLC off



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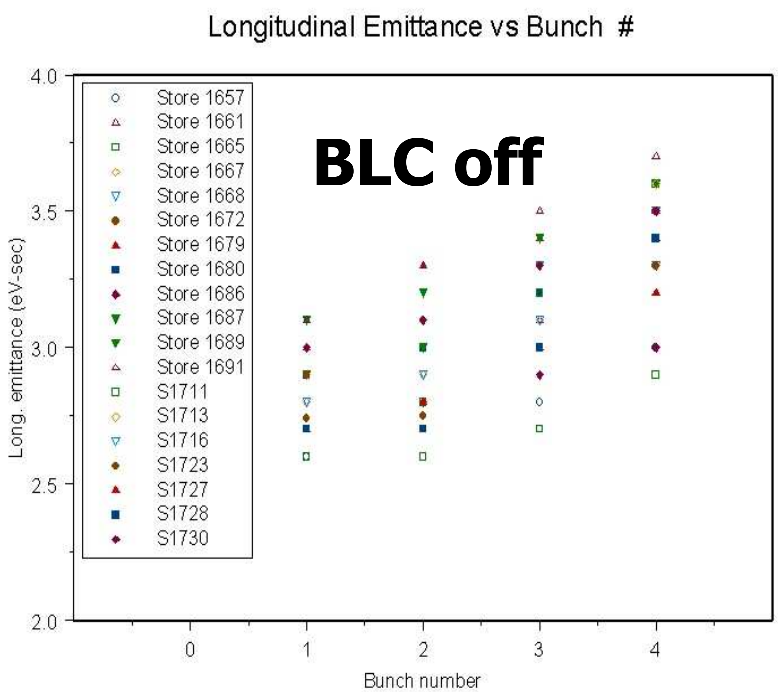
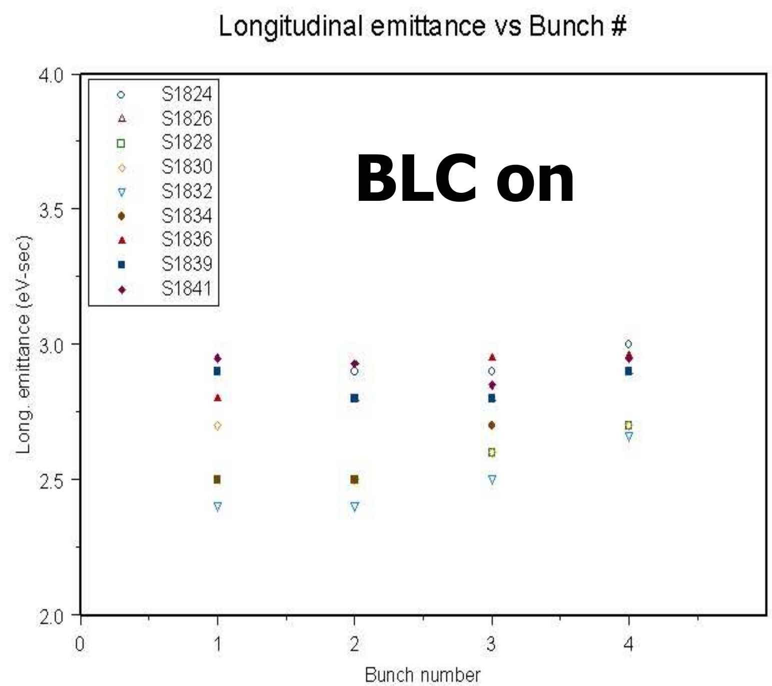
Pbars from Accumulator: Beam Loading Compensation

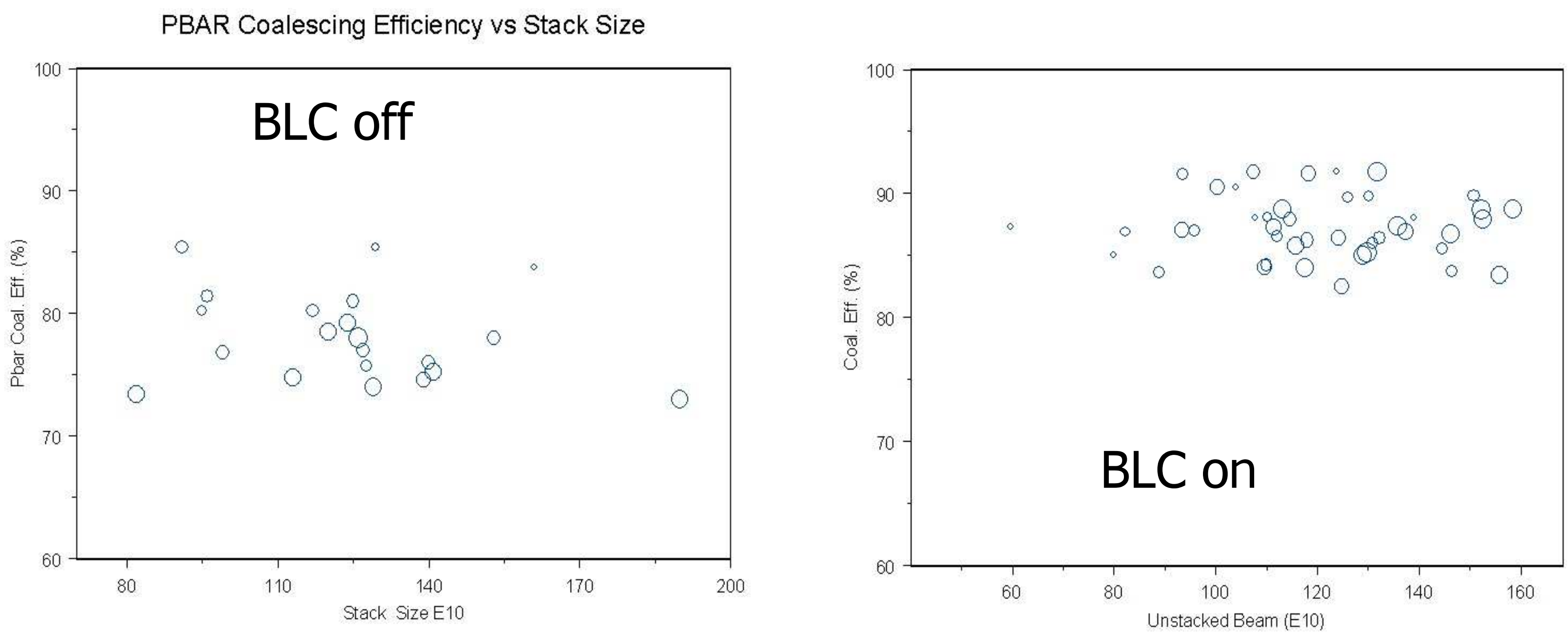




- Average Longitudinal emittance coalesced pbar bunches ~ 2.7 eV-sec
- No dependence on position of bunch in train observed

Pbars from Accumulator: Coalescing Efficiencies

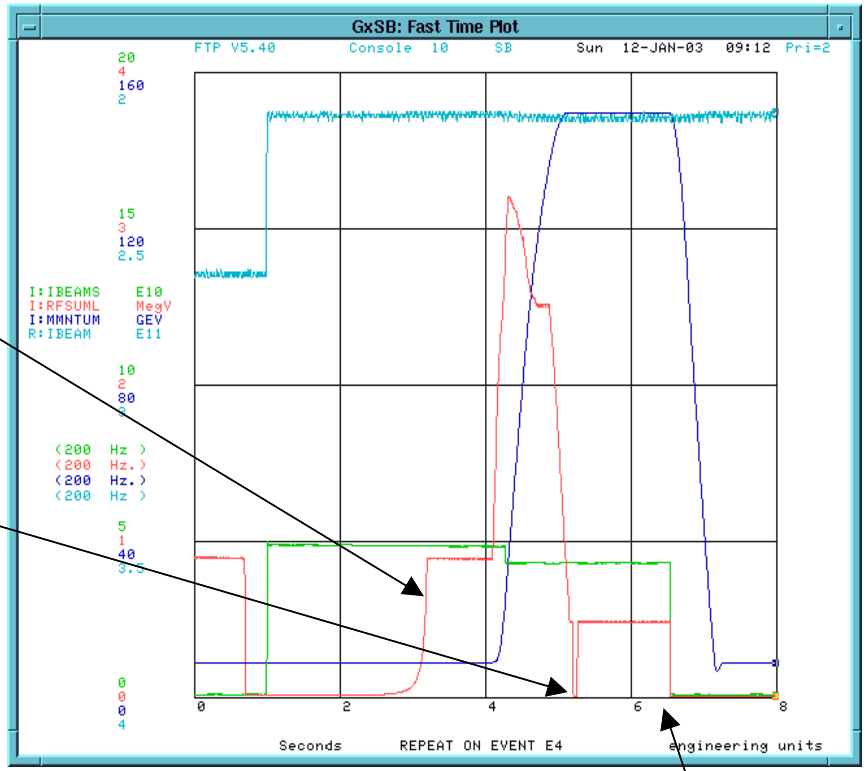
Pbar coalescing efficiency with Feed Forward Beam Loading Compensation is ~ 85% independent of stack size (efficiency At large stacks increased by 10-12% with implementation



Efficiency vs Pbars Unstacked

Pbars from Recycler

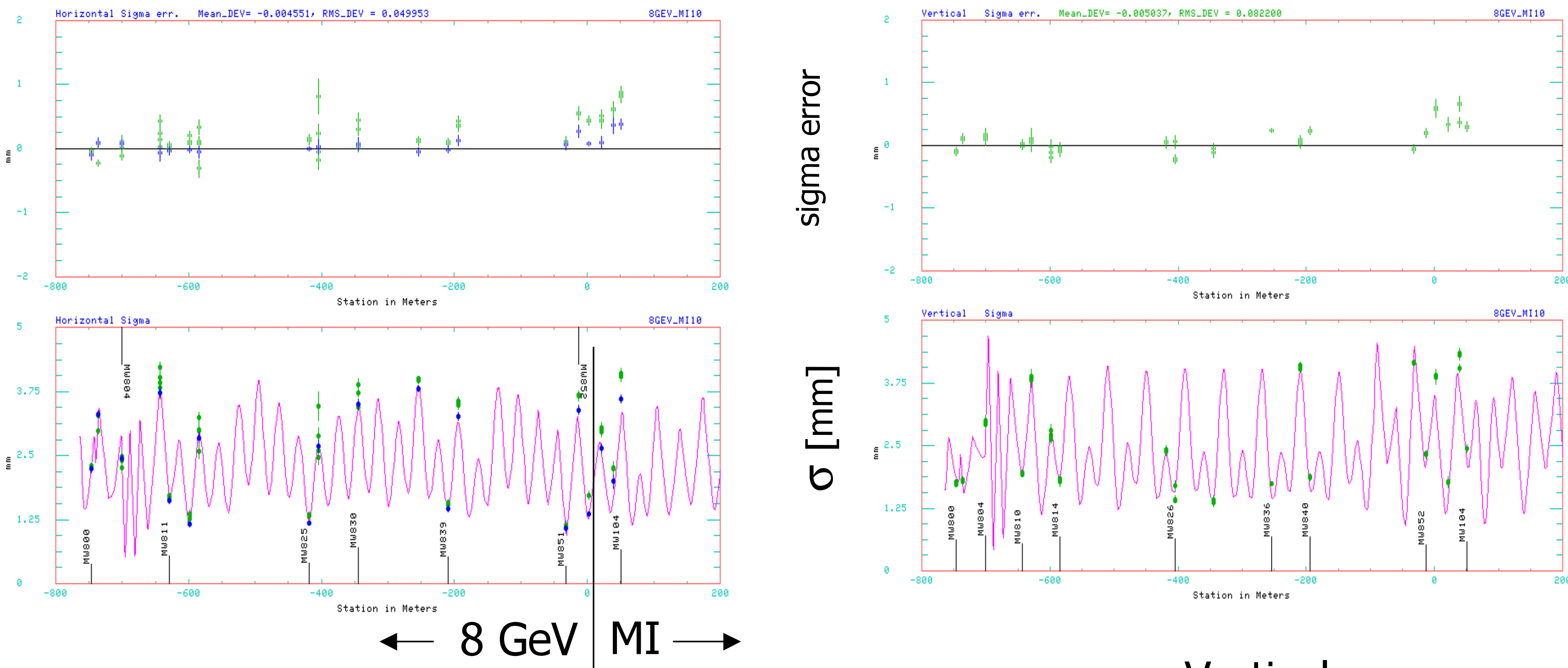
- **Early stages of development**
  - Synchronous transfer in 2.5 Mhz bucket
  - De-bunch and adiabatically capture in 53 Mhz
  - Accelerate in 53 Mhz buckets
  - Coalesce in 2.5 Mhz bucket for transfer to Tevatron
- **Last three steps will be eliminated with 2.5 Mhz acceleration to 27 GeV and rotated into 53 Mhz bunches**



Tev inj.

MI Lattice: Match 8.9 Gev line to Ring

Proton beam sigma in 8 Gev Line and MI before matching

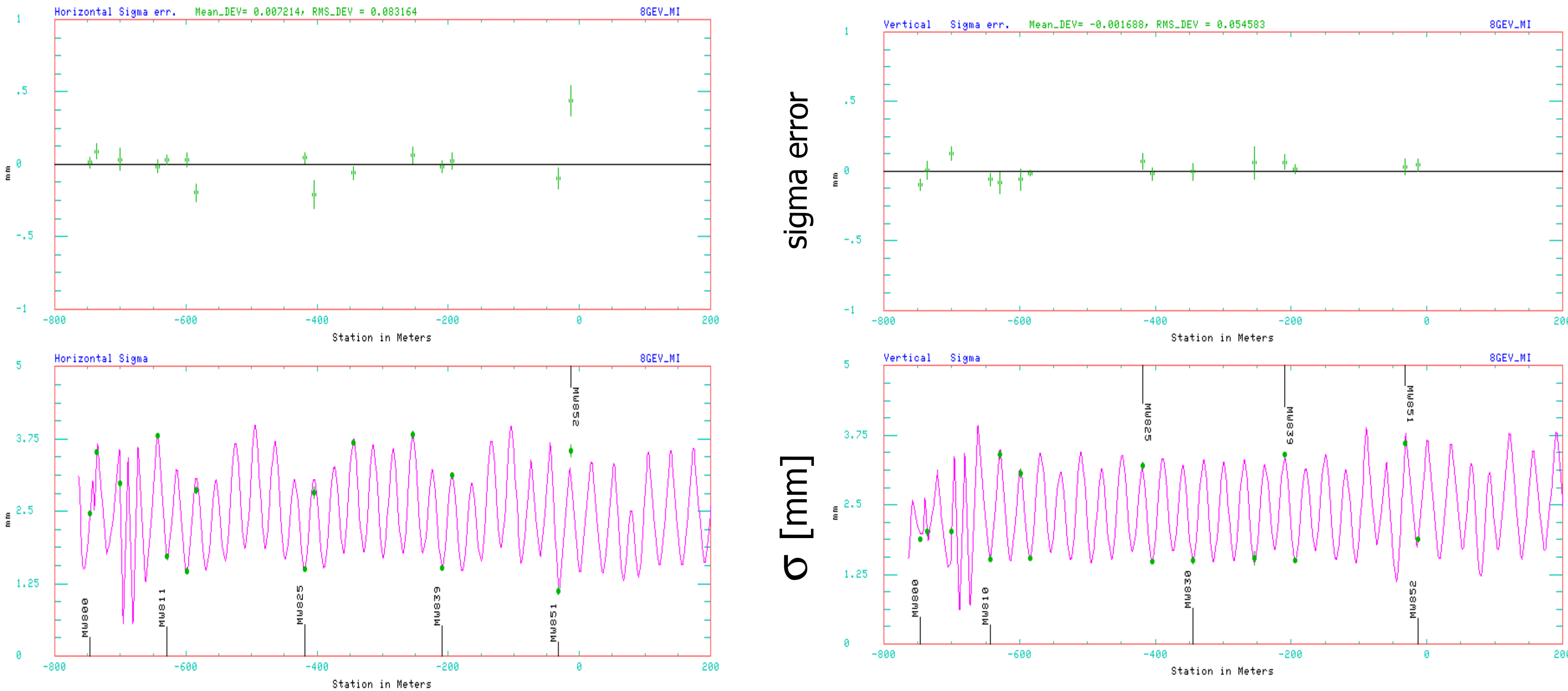


Horizontal

Vertical

MI Lattice: Match 8.9 Gev line to Ring

Proton beam sigma in 8 Gev Line and MI after matching

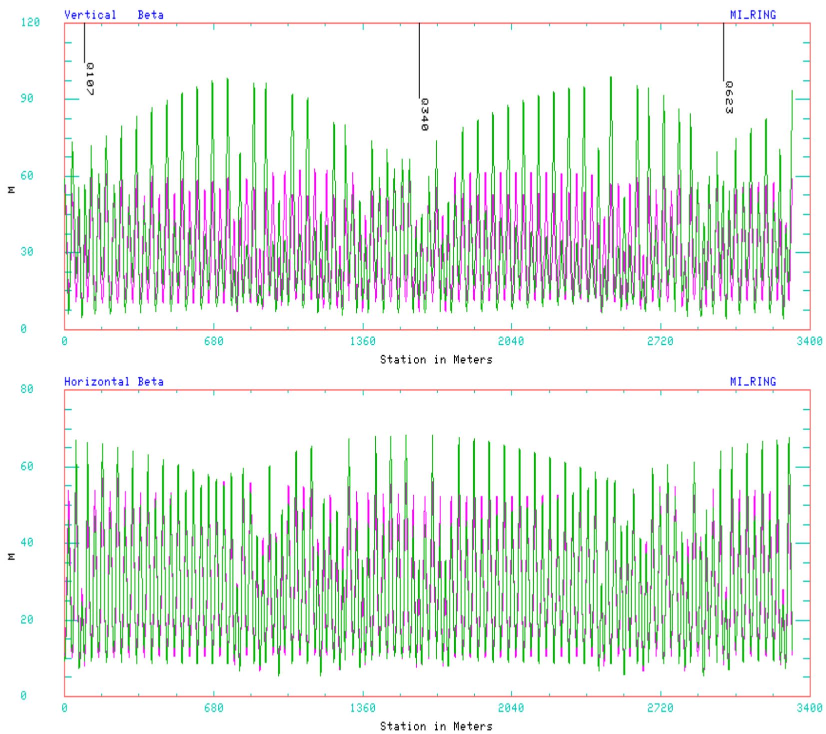


Horizontal

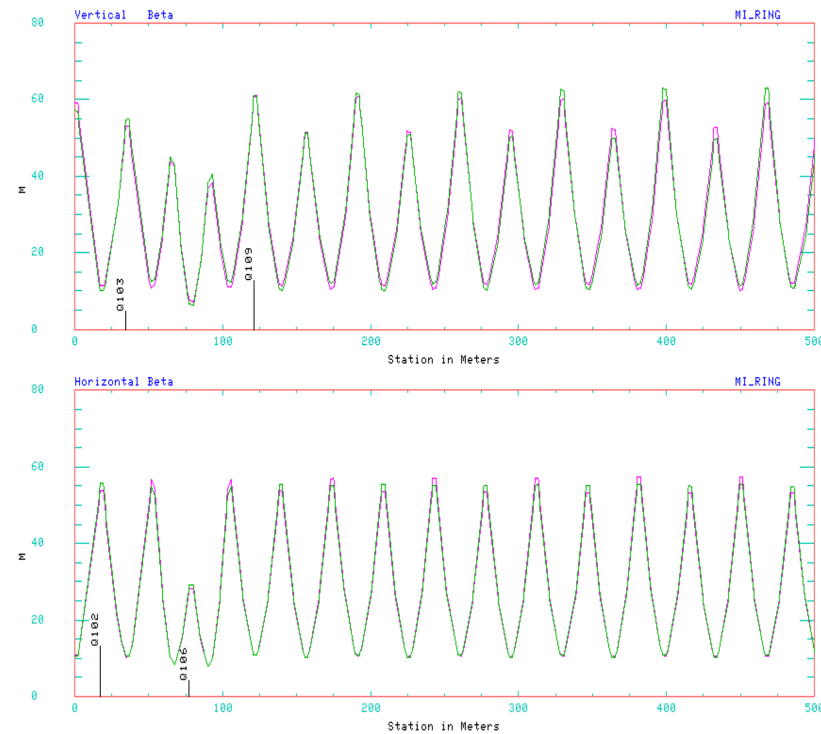
Vertical

MI Lattice: Match 8.9 Gev line to Ring

Comparison of first turn MI lattice functions for measured and design

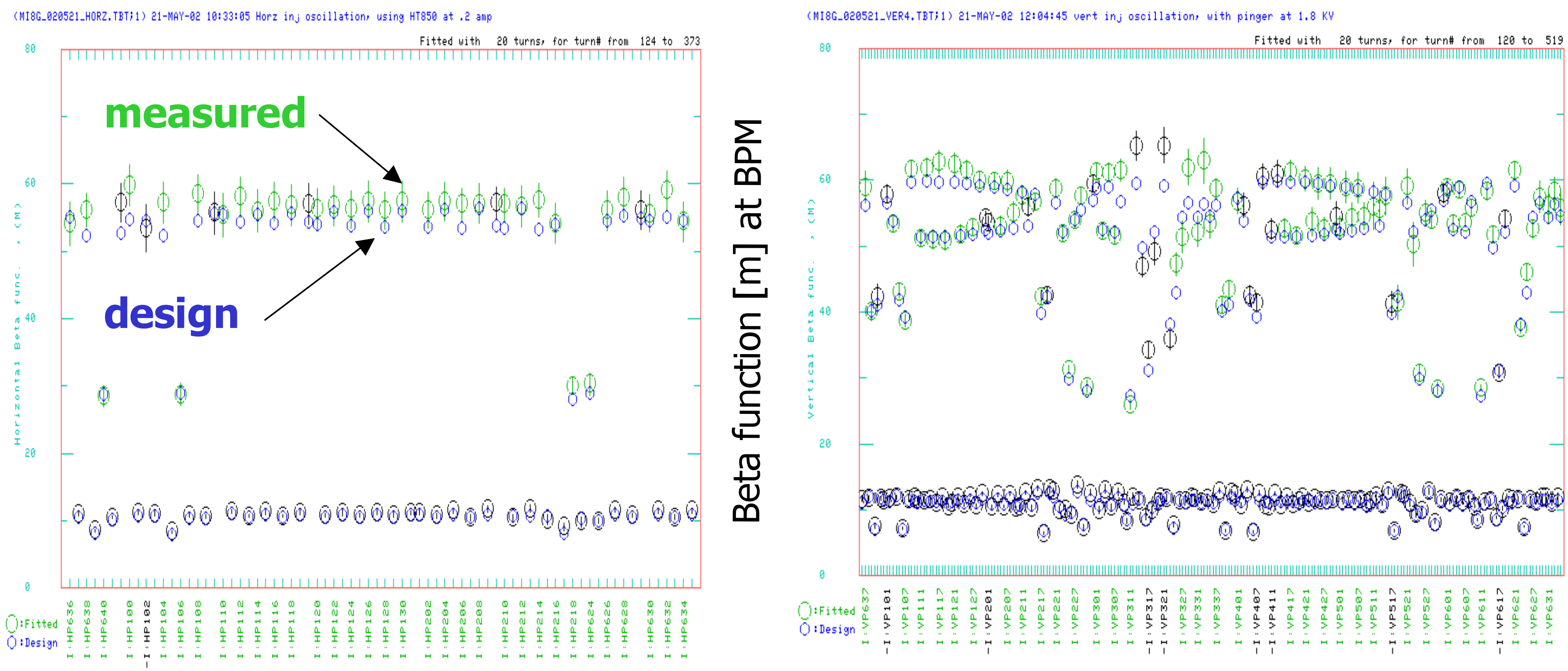


Before Injection match



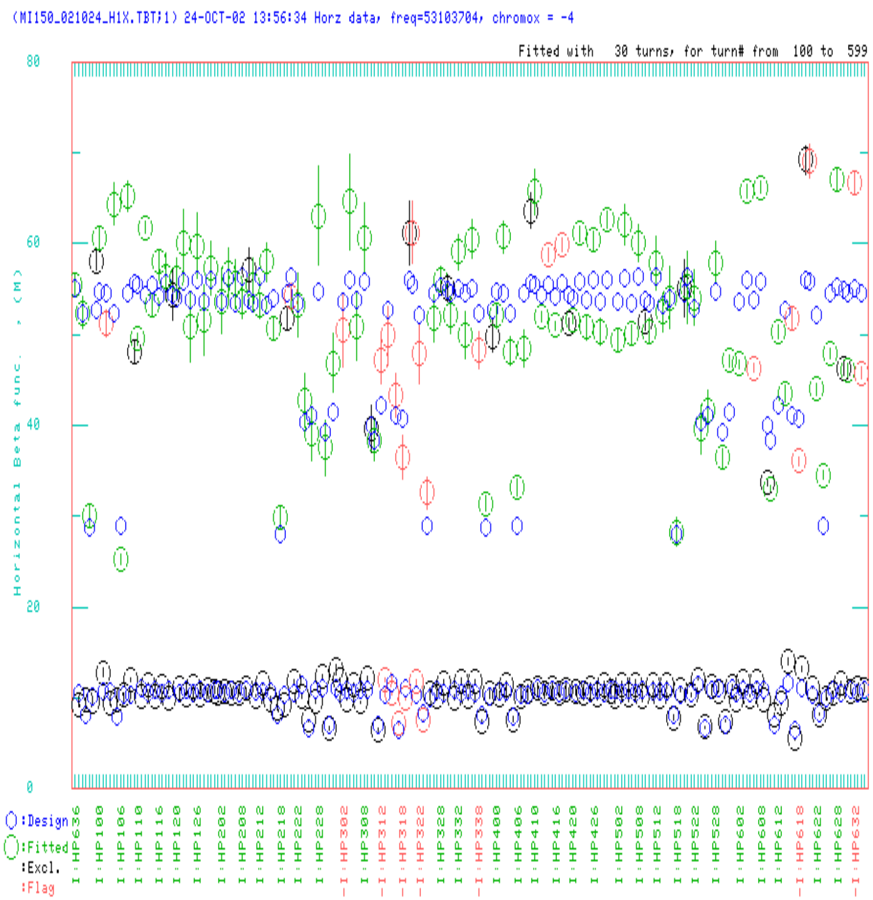
After Injection match

MI Lattice: 8 GeV Circulating Lattice



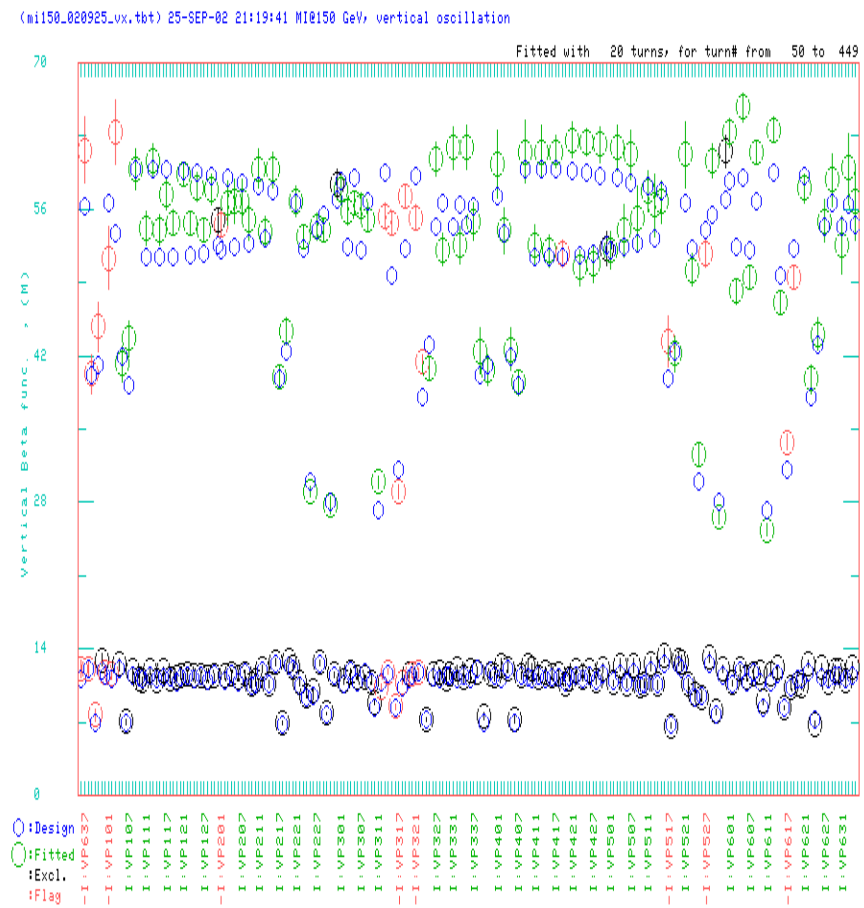
Horizontal Plane Vertical Plane

MI Lattice: 150 GeV Lattice



Horizontal Plane

Beta function [m] at BPM

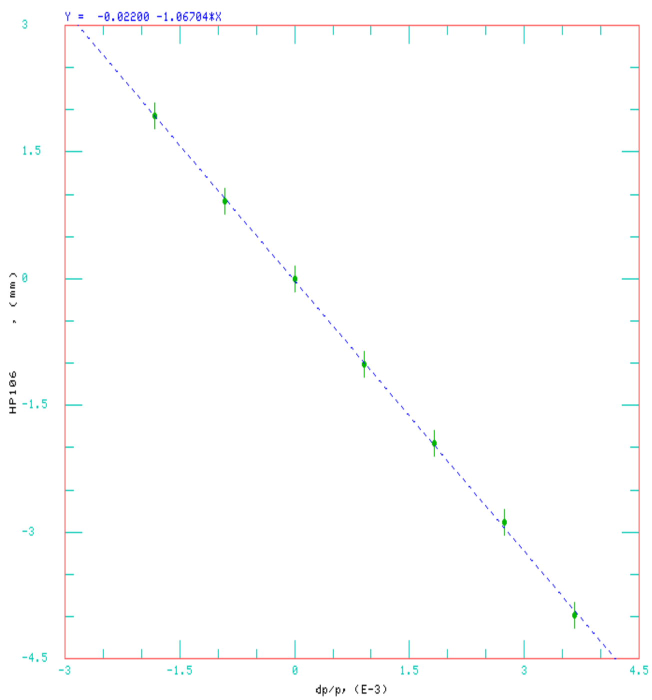


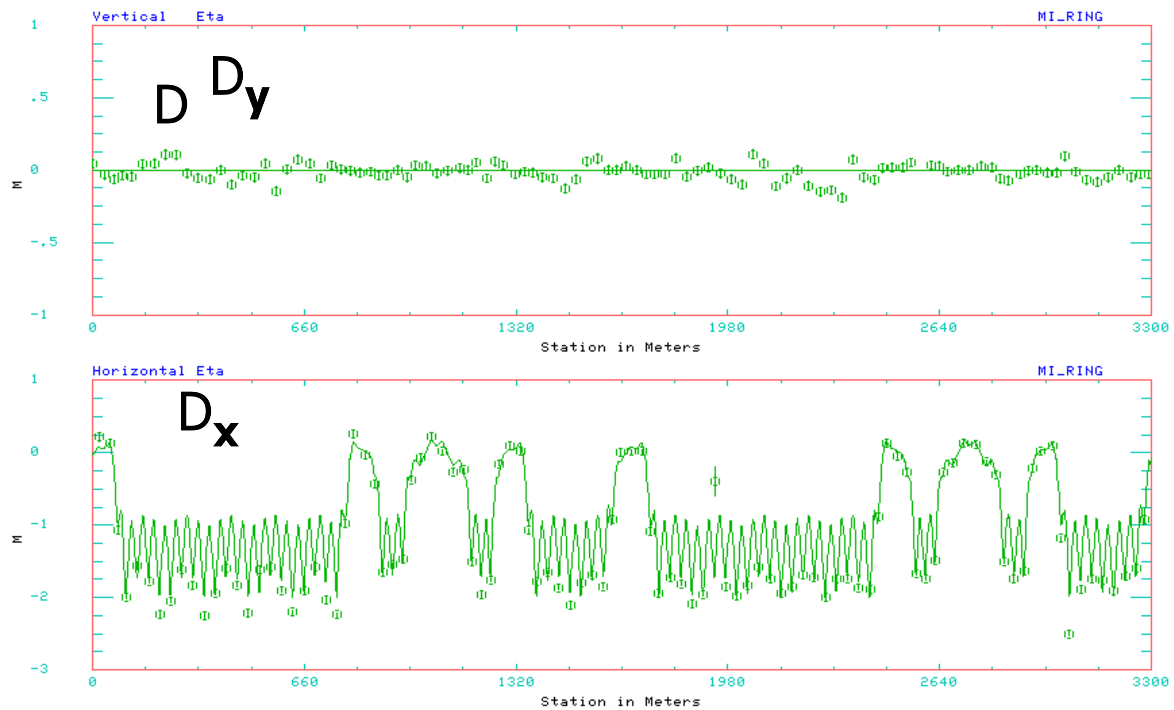
Vertical Plane

Data taken on Tevatron injection orbit (Δp/p ~.0036)

Ming-Jen Yang

MI Lattice: 150 GeV Dispersion





HP106 vs dp/p

Measured and calculated Horizontal And Vertical Dispersion

Run II Plan Projects

- Longitudinal Emittance Growth (Dave Wildman)
- Commissioning of 53 Mhz beam loading compensation for pbar coalescing (Joe Dey)
- 53 Mhz beam loading compensation on ramp (Joe Dey)
- Dampers in the MI (Bill Foster)
- BPM Upgrade in MI (Brajesh Choudhary)
- 2.5 Mhz Acceleration (Chandra Bhat)
- General Diagnostics Improvement (Dave Capista)
- Tune Meter for pbar operation (Denton Morris)
- Improvements in MI ramp and closure programs (Bruce Brown)
- Tune and chromaticity calculator program (Guan Wu)

WBS1.2.1 Longitudinal emittance growth

Injection

- Coupled-bunch motion (modes 16 & 36) observed on first turn in MI
  - Solution: 1 Check all existing passive dampers in Booster
    2 Increase gain on mode 36 active damper
    3 Build active damper for mode 16
  - Status: This is on going Booster effort. There are currently no plans for a more 16 active damper.

- Residual coupled bunch motion from the Booster drives to the MIRF cavity modes at 128 Mhz and 224 MHz
  - Solution: Build a bunch by bunch longitudinal damper in MI
  - Status: Parts on order see WBS 1.2.4

WBS 1.2.1 Longitudinal emittance growth

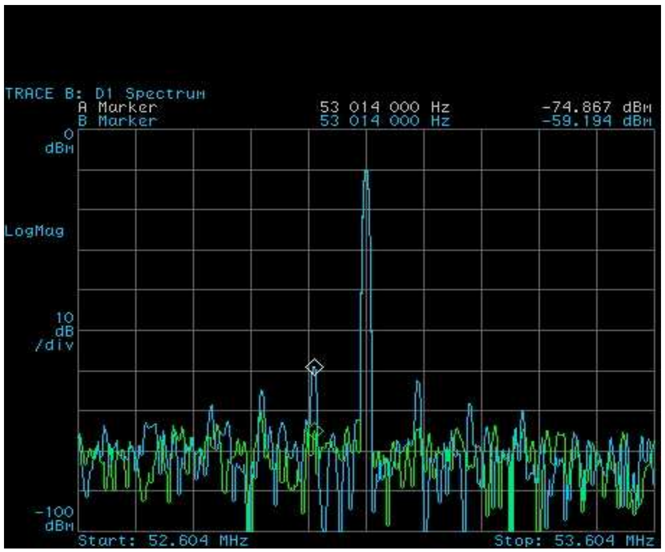
Transition

- There is a 10 degree phase error on the $29 cycles crossing transition with heavy transient beam loading which results in dipole oscillations that persist throughout cycle
  - Solution: The present high level transient feed-forward BLC system can reduce this phase error by X3. The system needs to be modified to operate throughout the cycle.
  - Status: to be commissioned March '03 See WBS.1.2.3

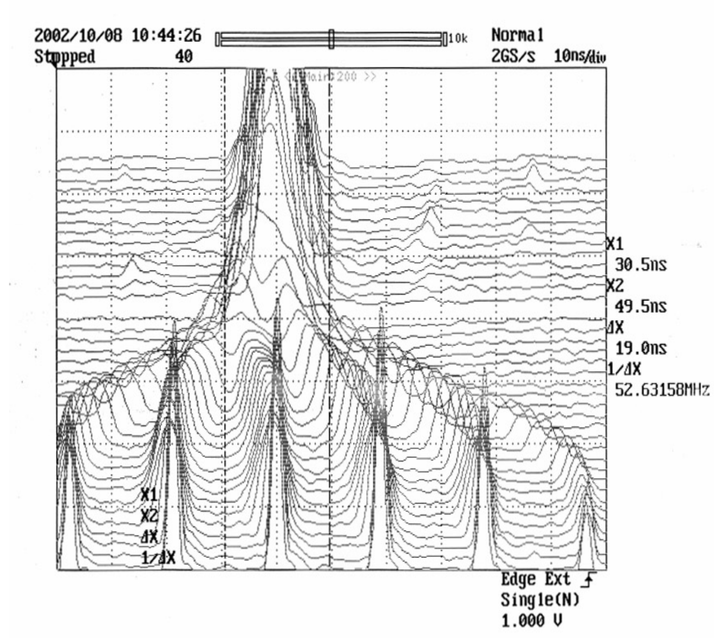
Flattop

- The excitation of the MIRF cavity mode at 224 Mhz is observed to grow throughout the cycle
  - Solution: The new bunch by bunch damper should effectively damp these coupled bunch oscillations
  - Status: Parts on order see WBS 1.2.4

WBS 1.2.2 Beam loading compensation



Green trace ON
Blue trace OFF



- Current system provides compensation during pbar coalescing at 150 GeV.

✓ System now fully commissioned

➢ System has been stable for at least the last two months

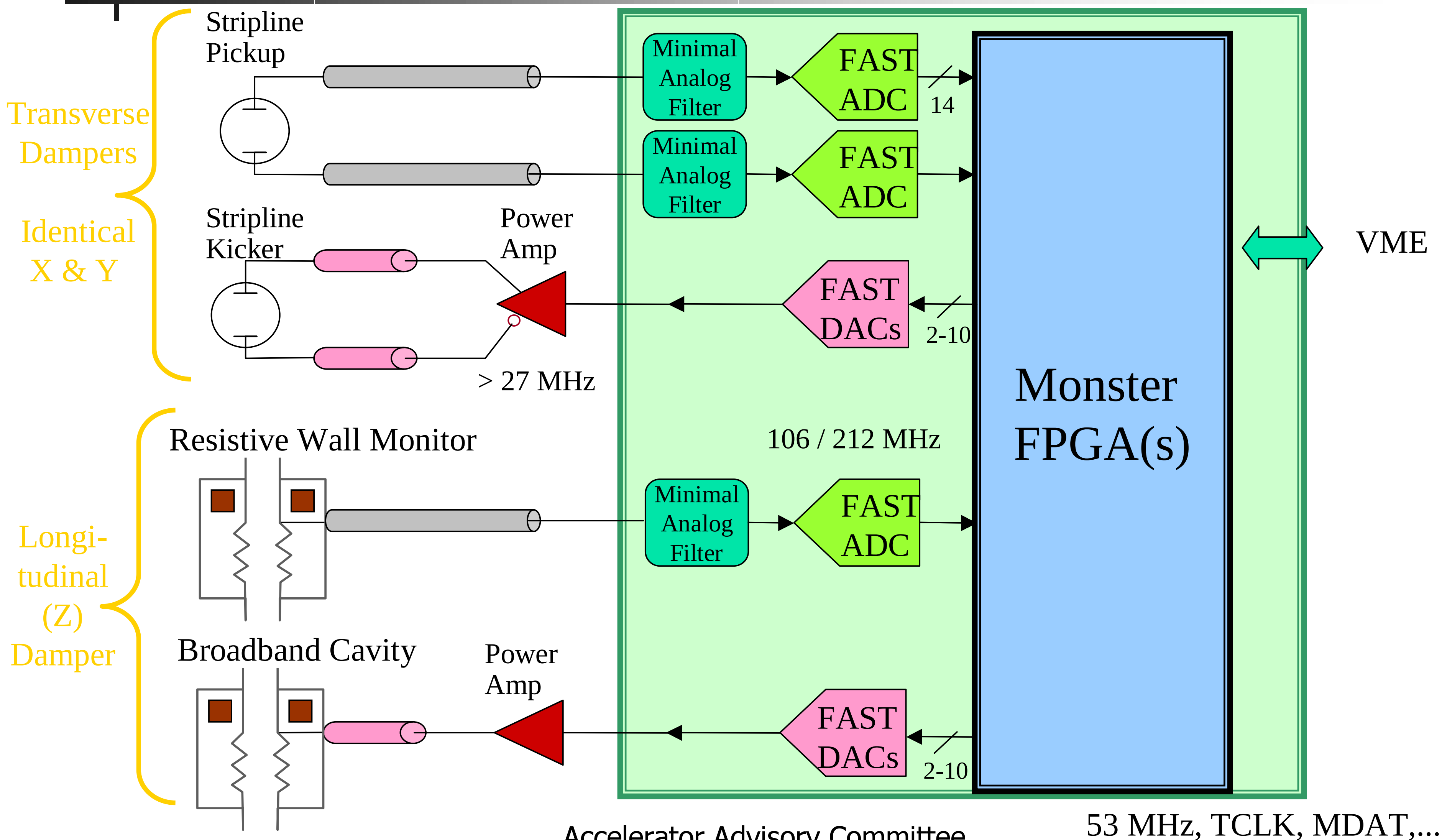
WBS 1.2.3 Beam loading compensation on Ramp

- Provide feed forward beam loading compensation on all cycles from injection through flattop.
- Will utilize 465 ramp which will track the MI energy
- Status:
  - Hardware installed over Jan '03 shutdown
  - Need commissioning and study time
  - Implemented March '03

WBS 1.2.4 Dampers in the MI

- All MI dampers controlled by a single commercial digital filter card with a large FPGA.
- Longitudinal
  - Remove coupled-bunch oscillations in beam delivered from Booster
  - Prevent growth of coupled-bunch instabilities
  - Allow bunch rotation to be effective on stacking cycles
  - Increase coalescing efficiency and reduce momentum spread after coalescing
- Transverse
  - Reduce emittance growth from injection steering errors (p and pbar)
  - Reduce any residual emittance growth during ramp
  - Permit MI operation at increased intensity in NuMI era

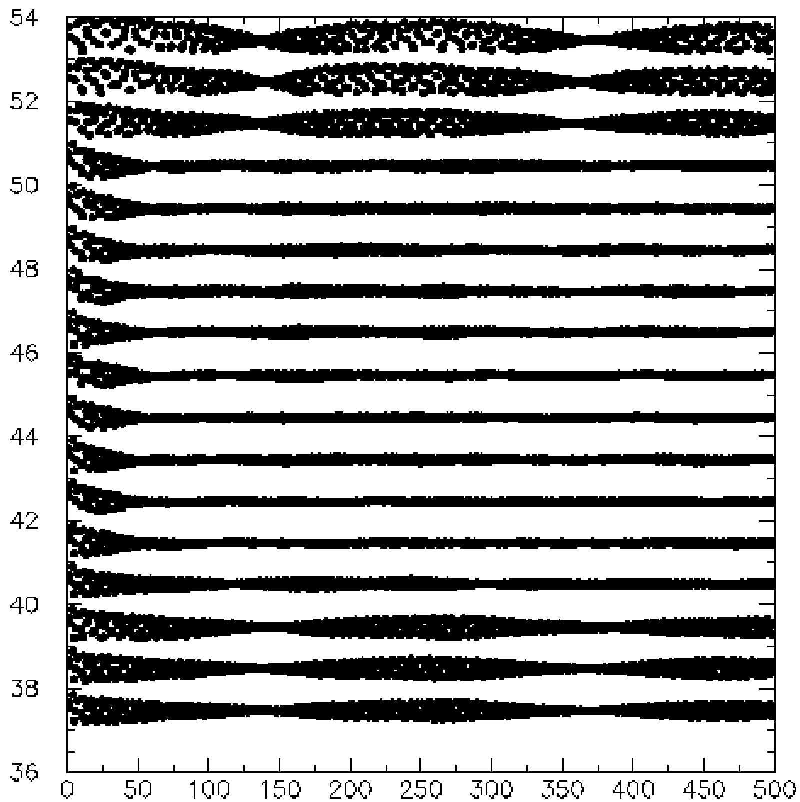
All-Coordinate Damper w/ Echotek Card



WBS 1.2.4 Dampers in the MI: Status

- Transverse
  - Demonstrated bunch by bunch damping in MI (next slide)
  - No new high level (used existing damper pickup and kicker)
  - Proof of principal demonstrated using three turn filter
  - A lot of software and cycle control is needed to become operational
  - Operational May ‘03
- Longitudinal
  - Parts for 3 wide band cavities ordered (June delivery for ferrite)
  - Power amplifiers have been ordered (May delivery)
  - A 1/3 power test (using spare Recycler PA and existing wide band cavity is planned for Feb – March ’03
  - Cavities (and PA’s) to be installed summer ’03

WBS 1.2.4 Dampers in the MI:



Damping kick shared for Bunches #41 - #51

← Pickup Signal from Bunch #43

...CAN ALSO ANTI-DAMP TO BLOW ANY SELECTED BUNCHES OUT OF THE MACHINE
➔ Anti-Satellite Device

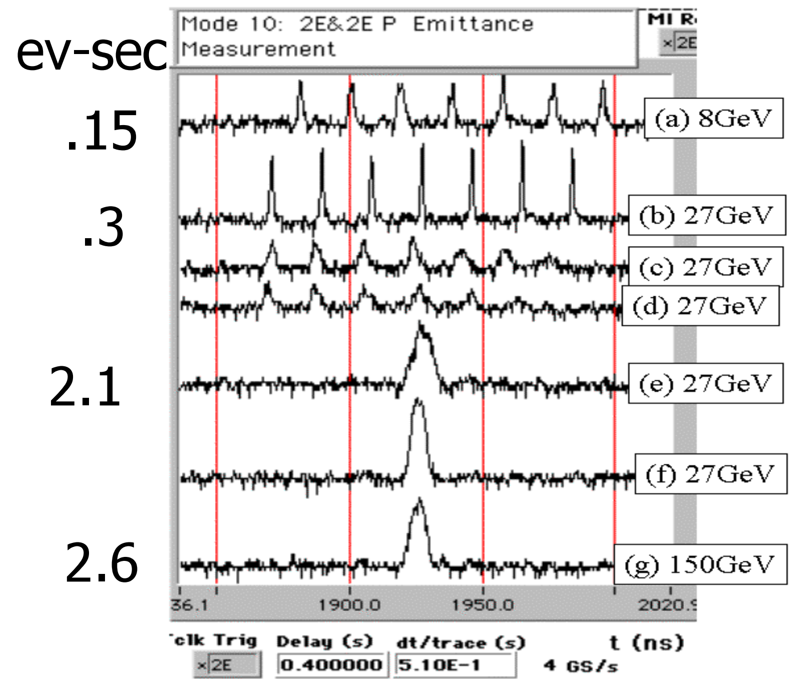
Ashmanskas, Foster, Wildman, Schappert, Crisp, Nicklaus

WBS 1.2.6 2.5 Mhz Acceleration

Goal: To provide low longitudinal emittance (2 eV-sec or less) pbars for Collider

The Scheme:

- Four pbar bunches ($\varepsilon_L \sim$ 0.5 to 1.5 eV-s) transferred in 2.5 Mhz bunches
- Accelerate slowly to 27 GeV
- Bunch rotated in 2.5 Mhz bucket
- Captured in 53 Mhz bucket
- Accelerated to 150 GeV



Initial Tests:

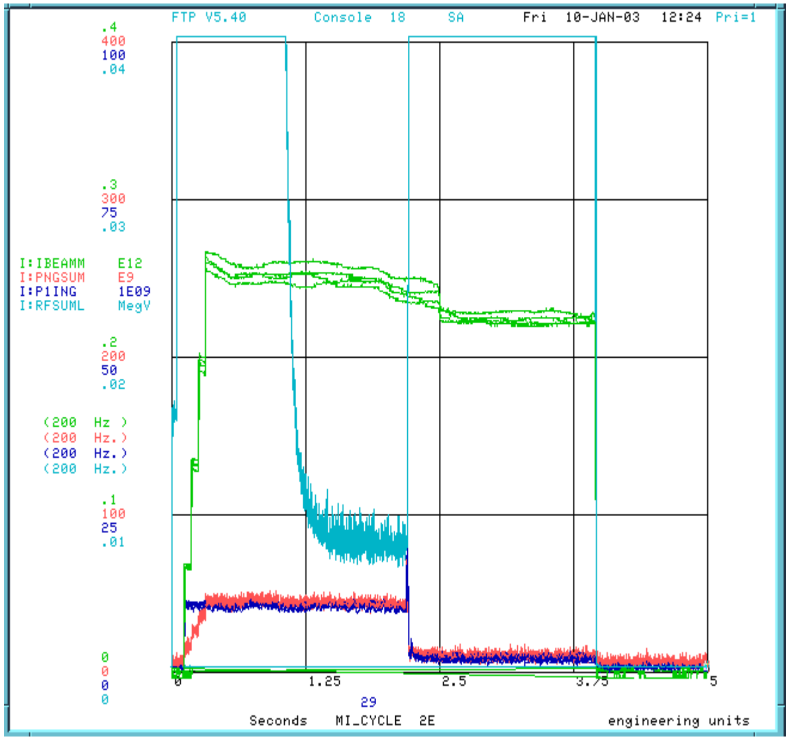
- Inject 7 bunches 53 Mhz from Booster
- Accelerate to 27 GeV and de-bunch
- Capture in 2.5 Mhz bucket and rotate
- Capture in 53 Mhz bucket, accelerate to 150 Gev

Bhat, Wu

WBS 1.2.6   2.5 Mhz Acceleration

<u>Current Issues</u> (requires tuning and optimization)

- Observe significant long emittance growth during 8 to 27 GeV acceleration in 53 Mhz
- 2.5 Mhz phase stability
- Beam loading compensation tuning



<u>Work in Progress</u>

- A 2.5 Mhz RF phase and radial feedback system is being constructed
- A 2.5 Mhz RF transition phase jump system is being constructed

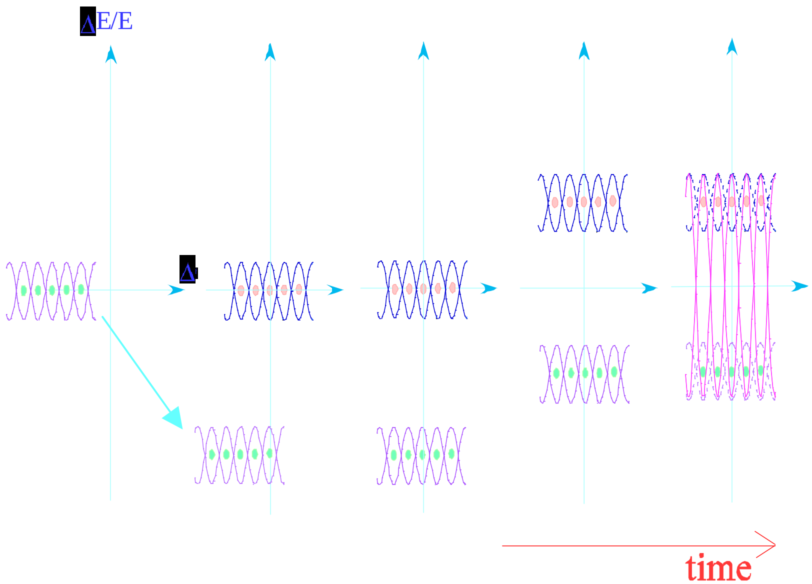
<u>Schedule</u>: March 2003 initial tests with pbars
Summer 2003 commissioned for pbars

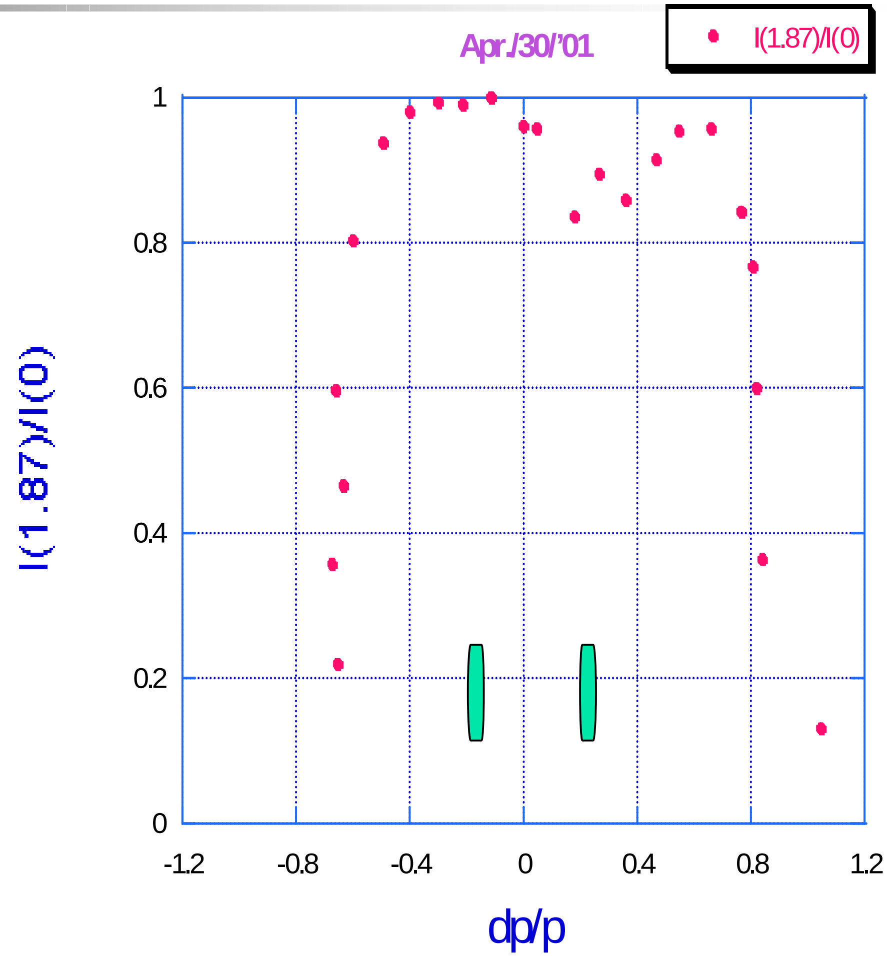
Bhat, Wu, Chase

Other Efforts/Projects

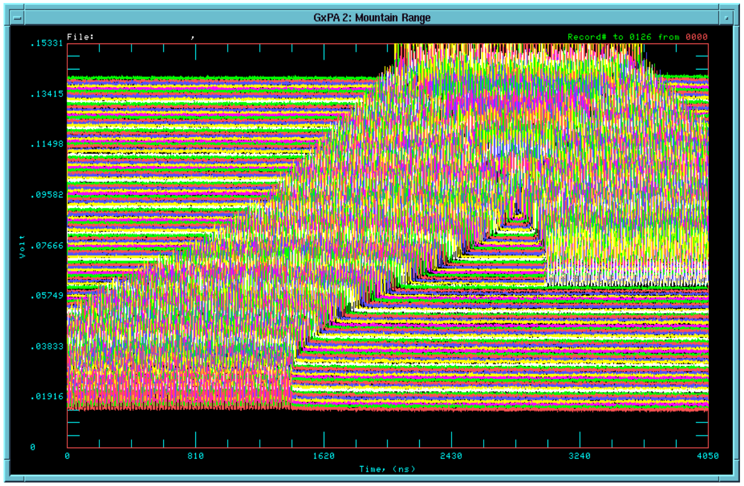
- Slip Stacking
  - Procedure is working at low intensities
  - Feed back and feed forward BLC development is underway
- Bunch compression
  - Demonstrated in Recycler with wide band cavities
  - Attempted in MI, but need new cavities
- Lattice characterization
  - Continued refinement of MI lattice at 8.9,120, and 150 GeV
- Operational Improvements (shot set up, etc)
- Instrumentation Improvements
- NuMI support
- SY120 Support

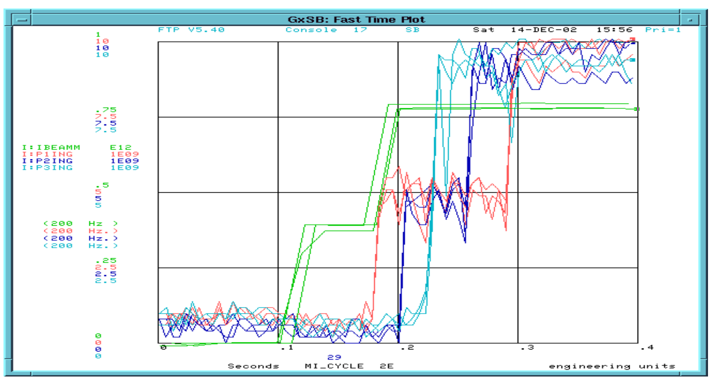
Slip stacking

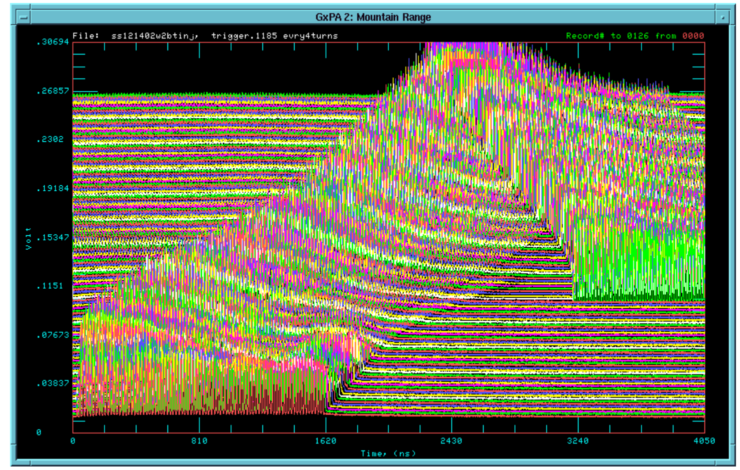




Slip stacking







1 Booster turn (.4E12/batch)

4 Booster turn (1.8E12/batch)

K. Koba

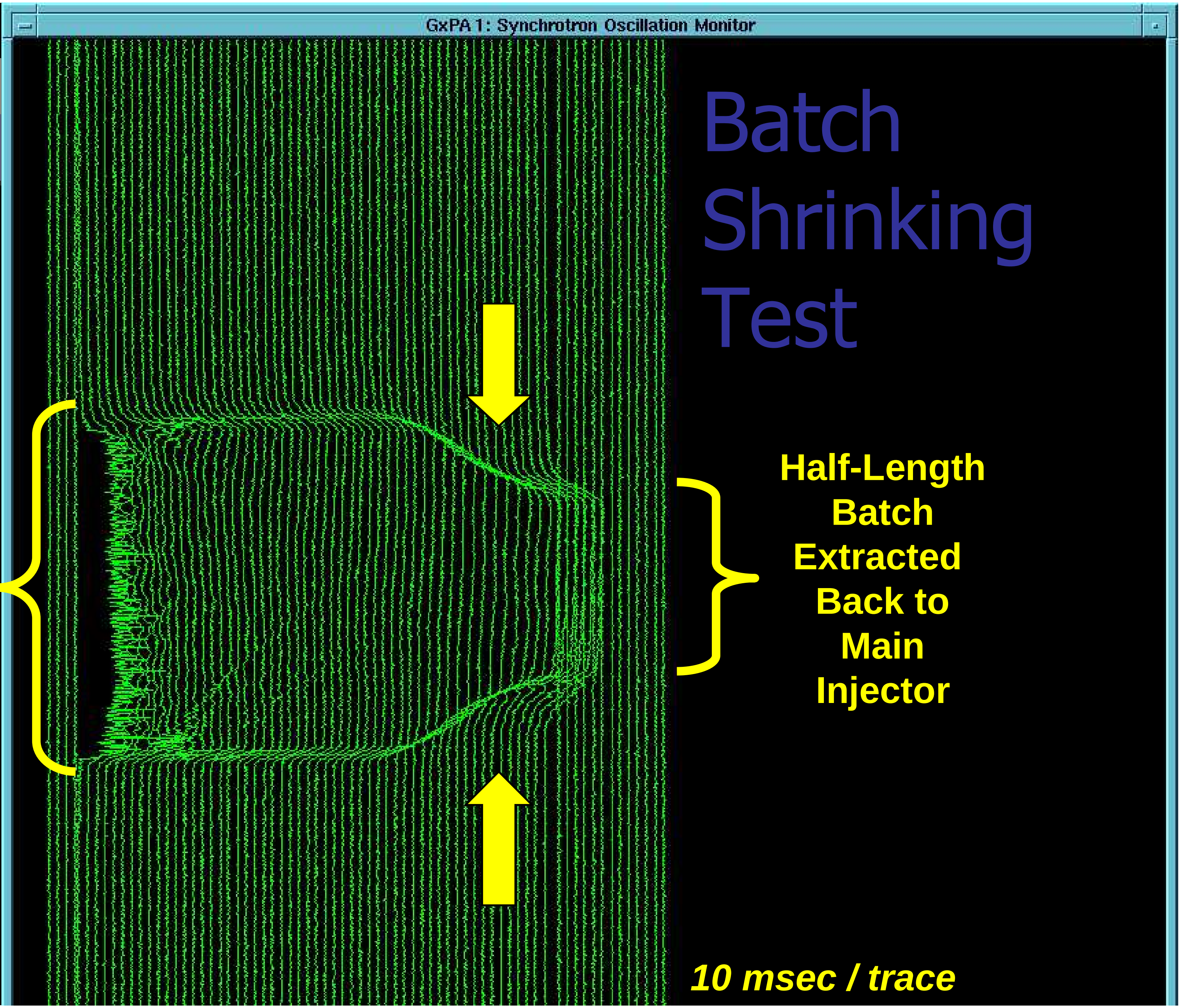
Slip stacking

- Status
  - Working with low intensity (.75E12 ppp)
  - No beam loss during process
  - Long. Emittance growth ~100% and due to LLRF timing jitter (should be 60% by ESME simulation)
    - LLRF problem fixed during this shutdown
  - Beam loading effects at high intensity
  - Working on BLC with feedback and feedforward

Bunch compression

- Alternate scheme for generating high intensity batches for stacking
- Initial test performed in Recycler using wide band cavities and modulating RF voltage between barrier buckets (see next slide)
- Test performed in MI using a spare Recycler PA and a ferrite loaded broad band cavity in MI
- Need higher voltages -> use new wide band cavities to be installed summer ‘03

Batch Shrinking Test



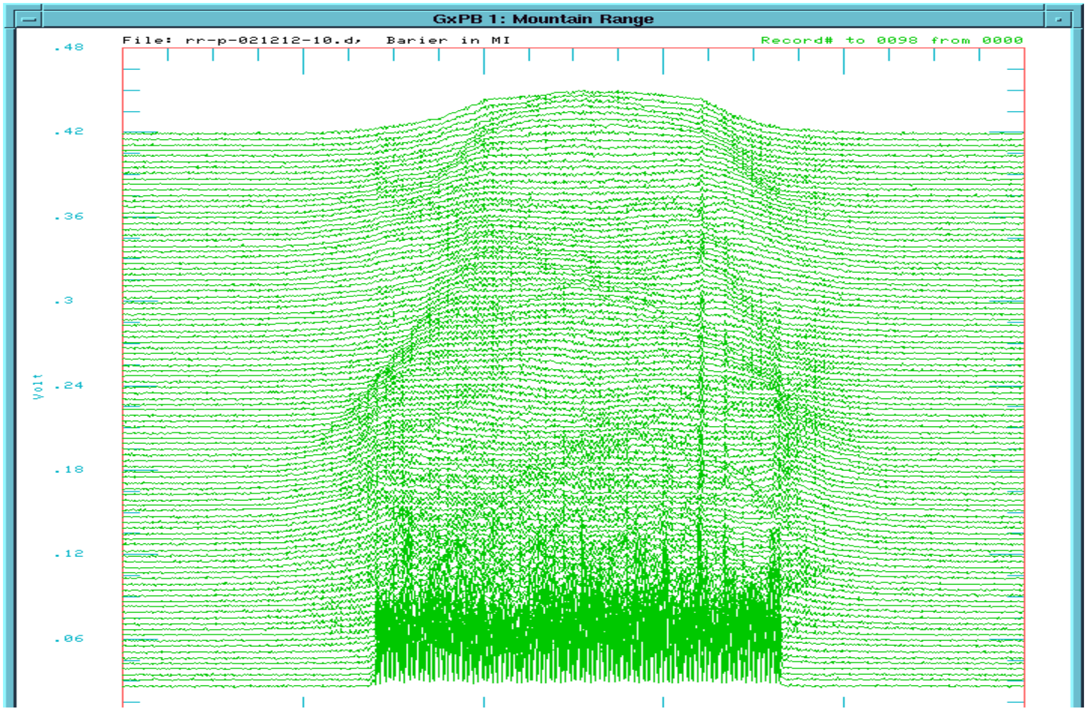
Injected Batch From Main Injector

Half-Length Batch Extracted Back to Main Injector

10 msec / trace

Bunch Compression

Inject 84 bunches into MI barrier bucket to test fast bunch compression in MI



Barrier bucket height ~500V

Summary

- MI8 line and Main Injector lattice has been matched. Beta and dispersion is matched to better than a few %. Lattice measurements at 150 GeV show 10-20% discrepancy… need further investigation.
- There are some lattice issue at 150 GeV between MI transfer lines and the Tevatron.
- Proton emittance growth during acceleration is an issue we are investigating. The coalescing efficiency is about 85%.
- Antiproton beam from Accumulator→MI→TeV also has less than 2 pi mm-mr emittance growth. The longitudinal emittance growth is as expected.
- The antiproton coalescing efficiency is co-related with the pbar longitudinal emittance. For small emittances MI has achieved 95% coalescing efficiency. On average the coalescing efficiency is about 85%.
- Beam loading compensation has been implemented for protons and pbars. This has improved coalescing performance 10-15 %.
- An R&D effort with beam studies for slip stacking process is underway.
- An R&D effort and beam studies for 2.5 MHz acceleration of pbar is also in progress.
- MI Transverse Damper proof of principal -> operational May '03 time frame
- MI Longitudinal damper 1/3 power test this spring with full capability after summer shutdown
- Pbars from Recycler have been accelerated and injected into Tevatron

Summary (The bottom line)

- Preservation of Longitudinal and Transverse emittance of both Protons and Pbars

  -> Dampers
- Feedforward Beam Loading on ramp

  -> in progress
- Increase proton intensity

  -> slip stacking, bunch compression, dampers
- Reduce longitudinal emittance of pbars (and protons?)

  -> 2.5 Mhz acceleration
- Improve Lattice & Machine Operation

  -> improvements in instrumentation (on going)
- Continued Machine studies