A Road to Main Injector Operation

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March 2, 1999

- Introduction and History
- Pre-Beam Commissioning
- Beam Commissioning
- Status and Future plans

Introduction

The Fermilab Tevatron is the highest energy accelerator/collider operating in the world today.

Fermilab will retain this position until LHC comes online.

The purpose of the Main Injector Project and other accelerator upgrades at Fermilab is to maximize the discovery potential of the Tevatron before LHC.

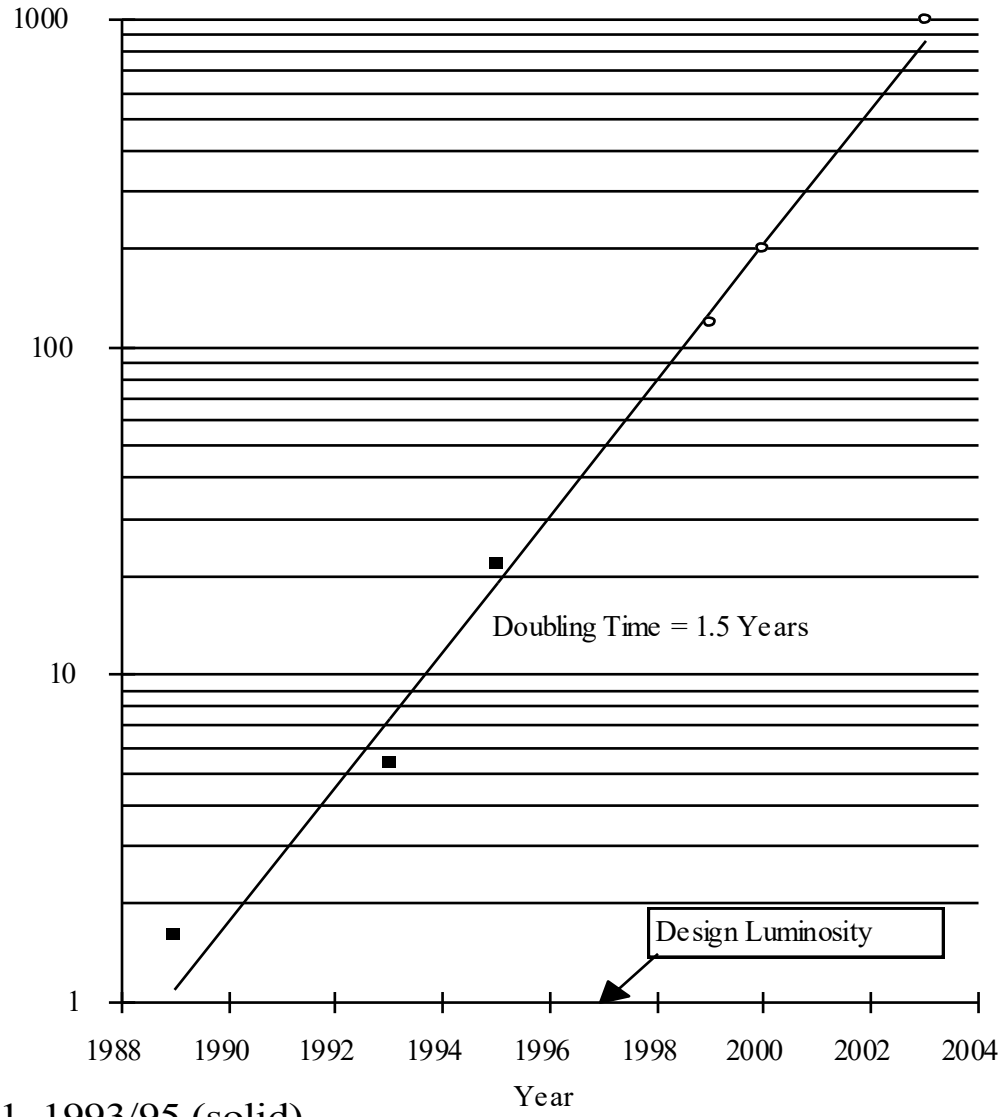
The next run of the Tevatron Collider(RUN-II) will start in 2000.

Run-II Performance Goals:

Tevatron Luminosity $5\text{-}20 \times 10^{31}$ $cm^{-2}sec^{-1}$

120 GeV Fixed Target $> 3 \times 10^{13}$ ppp

Fermilab Luminosity Performance: Past and Future



Actual 1988/89, 1990/91, 1993/95 (solid)

Predicted MI, Tevatron*, Tevatron33 (open)

Working Parameter Table

RUN	IB (1993-95)	II (MI)	II (MI+ Recycler)	
Protons/bunch	2.32×10^{11}	2.70×10^{11}	2.70×10^{11}	
Pbars/bunch	5.50×10^{10}	3.00×10^{10}	7.00×10^{10}	
Total Pbars	3.30×10^{11}	1.30×10^{12}	2.5×10^{12}	
Pbar Production Rate	6.00×10^{10}	1.70×10^{11}	2.00×10^{11}	pbar/hour
Proton emittance	23π	20π	20π	mm-mr
Pbar emittance	13π	15π	15π	mm-mr
β^*	0.35	0.35	0.35	m
Energy	900	1000	1000	GeV
Bunches	6	36	36	
Bunch length (rms)	0.60	0.43	0.38	m
Form Factor	0.59	0.70	0.70	
Typical Luminosity	1.6×10^{31}	8.1×10^{31}	2.0×10^{32}	$cm^{-2}sec^{-1}$
Integrated Luminosity	3.2	16.3	41.0	pb^{-1}/week
Bunch Spacing	~3500	396	396	nsec
Interactions/crossing	2.7	2.3	5.8	
(@ 50 mb)				
Pbar tune shift (HO)	0.015	0.020	0.022	
Pbar tune spread (LR)	0.001	0.008	0.005	
Proton tune shift (HO)	0.006	0.003	0.006	

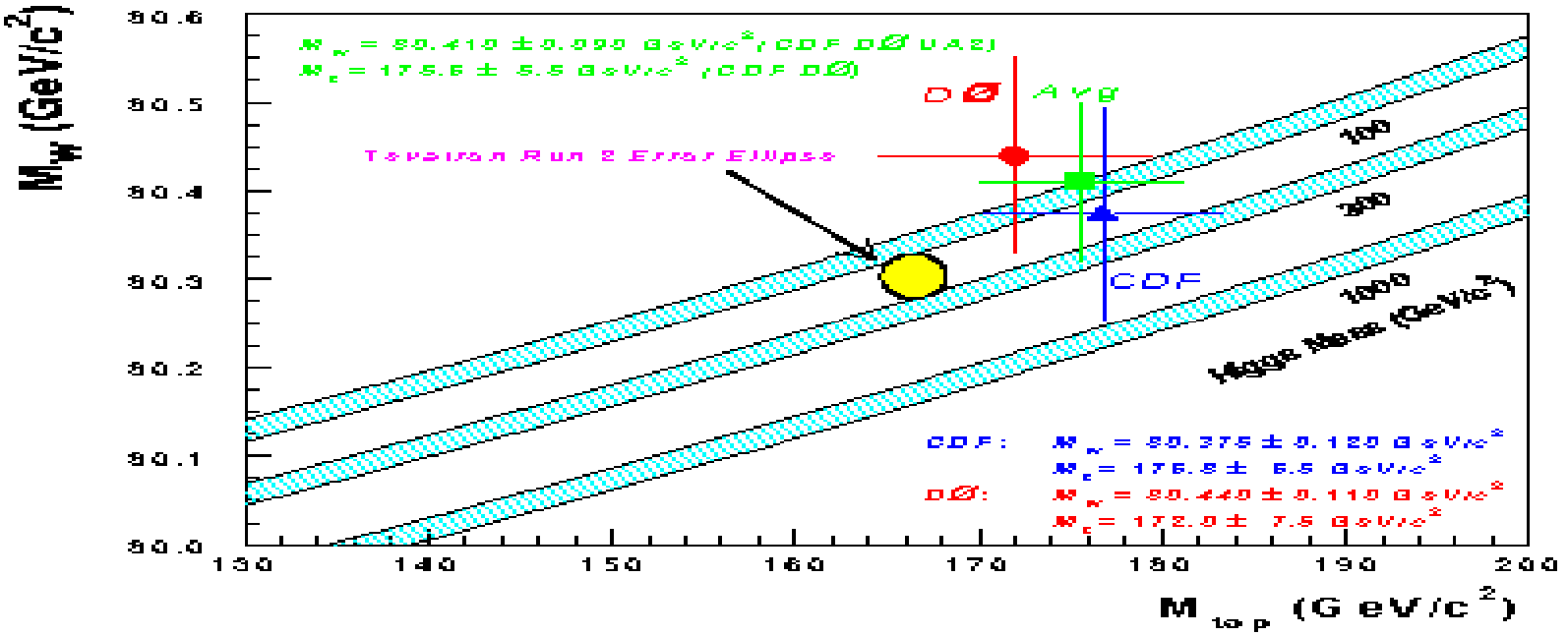
*Run IB column represents average of 32 stores over the period March 8-April 21, 1995.

Main Injector Performance Goals

- $5x10^{12}$, 120 GeV protons on antiproton target every 1.5 Sec.
- $3x10^{11}$ protons per bunch for the Collider program
- $3\text{-}7x10^{10}$ antiprotons per bunch for the Collider program
- Resonantly extract > $3x10^{13}$ protons per pulse, at 120 GeV, with 1.9-2.9 sec repetition rate.
- Resonantly extract > $2.5x10^{13}$ protons per pulse, at 120 GeV, simultaneous with delivery of $5x10^{12}$ protons onto the antiproton production target.
- Deliver $6x10^{13}$ protons to the Tevatron for acceleration and resonant extraction.
- Accept antiproton bunches from the Tevatron(decoalese, decelerate and transfer to the Recycler.

Higgs Mass Sensitivity

- In the Standard Model, M_W and M_{top} provide indirect measurement of M_{Higgs}
- Combining CDF and DØ results will yield $\delta M_{Higgs} \approx 40\% \, M_{Higgs}$ after Run II



Preparations for Beam Commissioning

- There were 16 DOE Review, 7 F3TAC Review and many other internal and external review of the project.
- Readiness & Safety review of the major subsystems (Dipole & Quadrupole Power Supply, Radiation etc..)
- Complete inspection of electrical system. Removed ground faults from all powered busses. Check out all the correction systems.
- Check out all the instrumentation without beam.
- Data and Document Availability on Web:
  - Magnet data
  - Detailed FMI Lattice and Lattice Functions
  - Calibration data

Preparations ...

- Low field check (~5 Amps) of corrector magnet polarity using gauss meter. Checked channel assignments.
- Verified Magnet Klixon functionality. Inspection of vacuum valve position and operation.
- Check the position and operation of multi-wires.
- Check physical locations of BLMs.
- Check BPM continuity
-

Application Programs

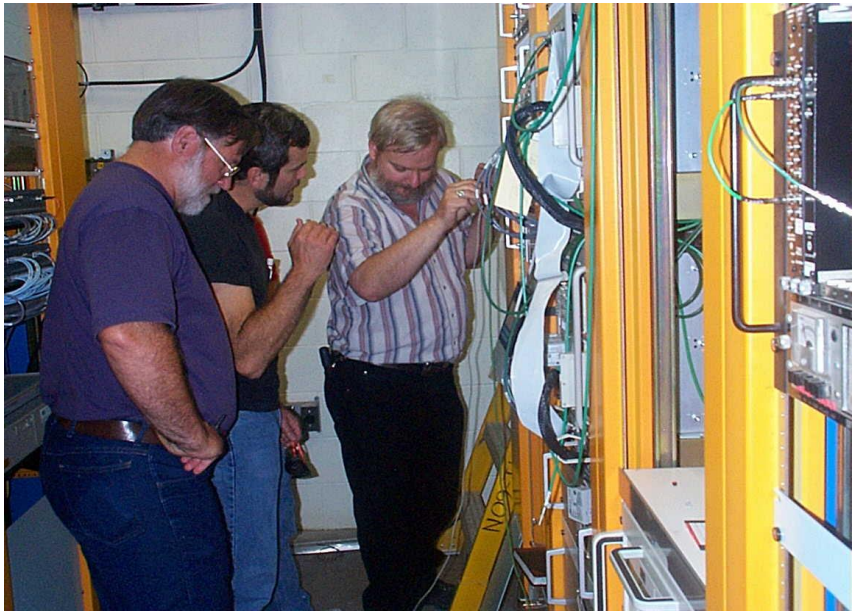
- 17 Application programs were written for the FMI operation.
- All the application programs needed for the initial commissioning of the FMI was ready by Aug 15th.
- LLRF and Harmonic corrector programs needed more work. But they were also ready on time when they were needed.
- There were three software reviews of all the application programs prior to beam commissioning. The author and overseers of the Application program participated in these reviews.
- These reviews and interactions between authors and uses insured that the programs will be ready for use when beam arrives.

Commissioning Goals of the FMI

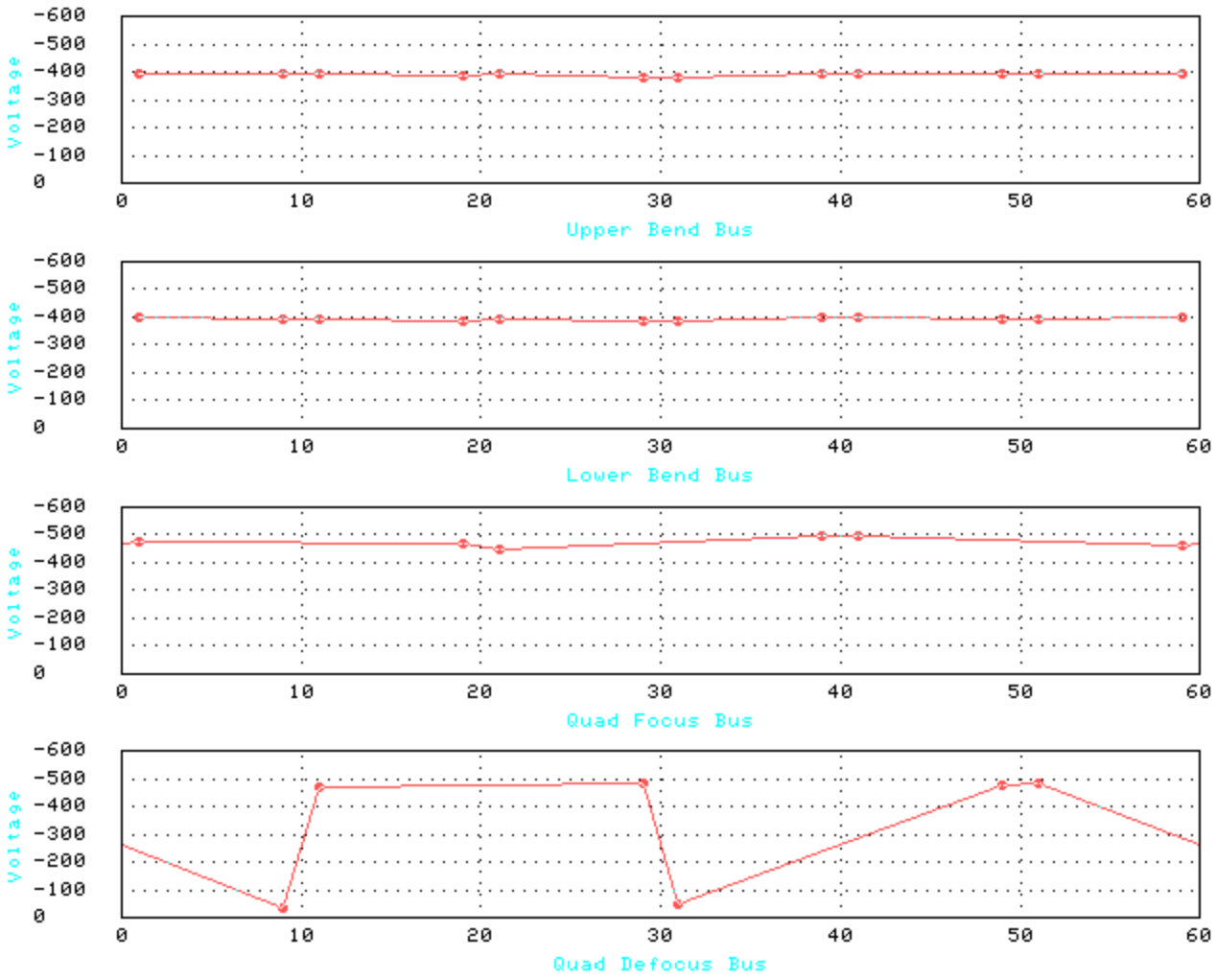
- Proton Energy for injection into the Tevatron — 150 GeV
- Number of Protons injected per Tevatron cycle — 2×10^{13}
- Proton and Antiproton Transmission Efficiencies — 75%
- Proton Energy for Antiproton Production and Test Beams — 120 GeV
- Cycle time to 120 GeV — 2.5 Sec
- Protons to Antiproton target per cycle — 2×10^{12}
- Protons slow spilled per cycle — 2×10^{13}

1st Pictures of MI Bend Bus Turn-on at KRS and MI60

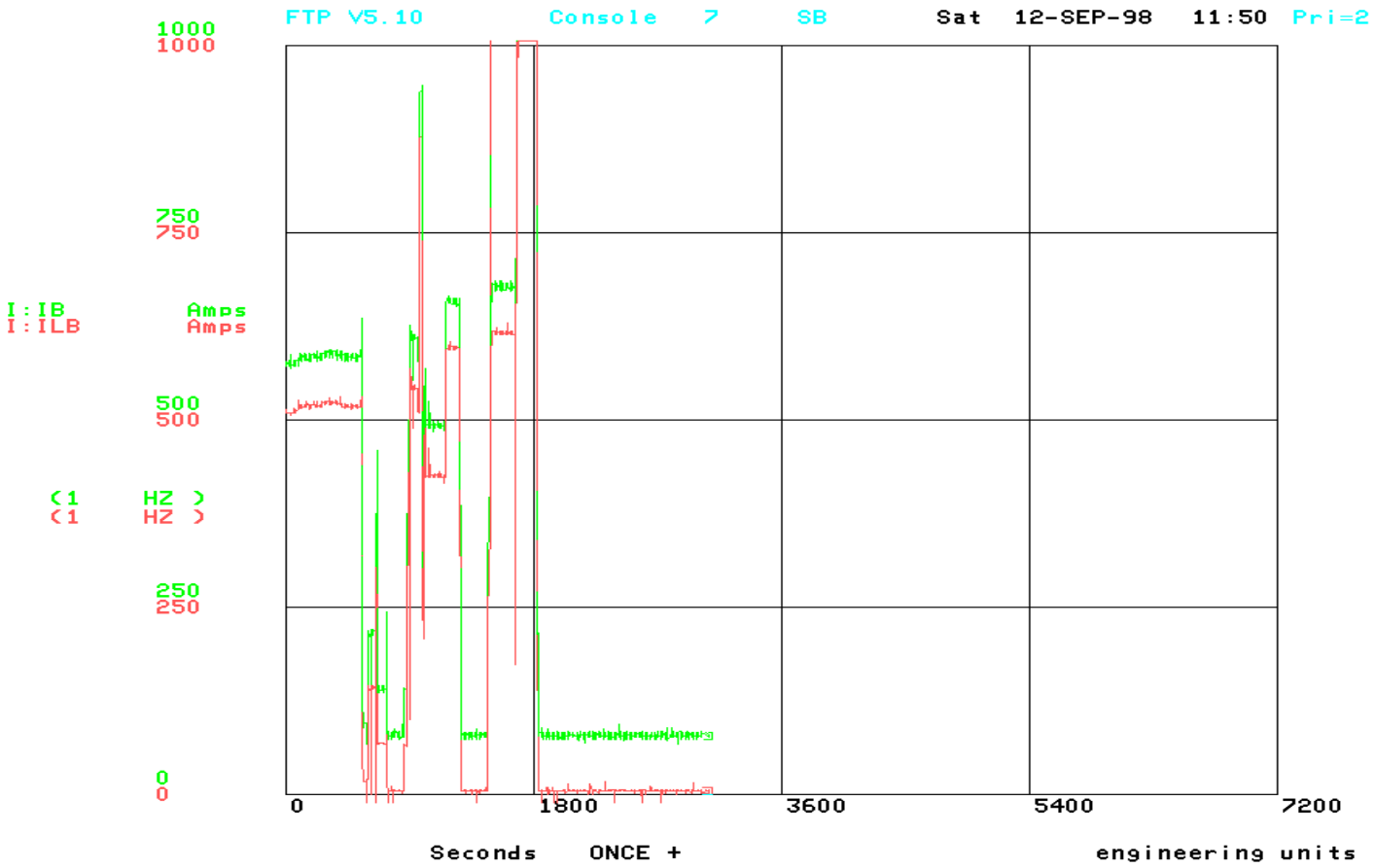
Sept 12th 1998.



1st Hi-Pot of the Main Injector Sept 12th 1998

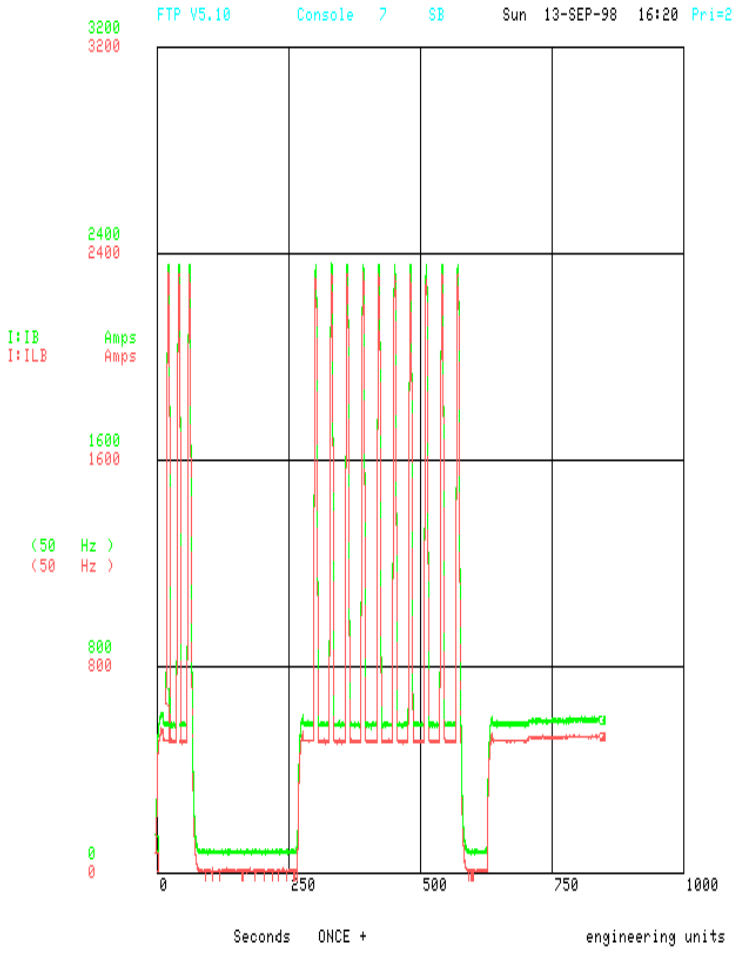


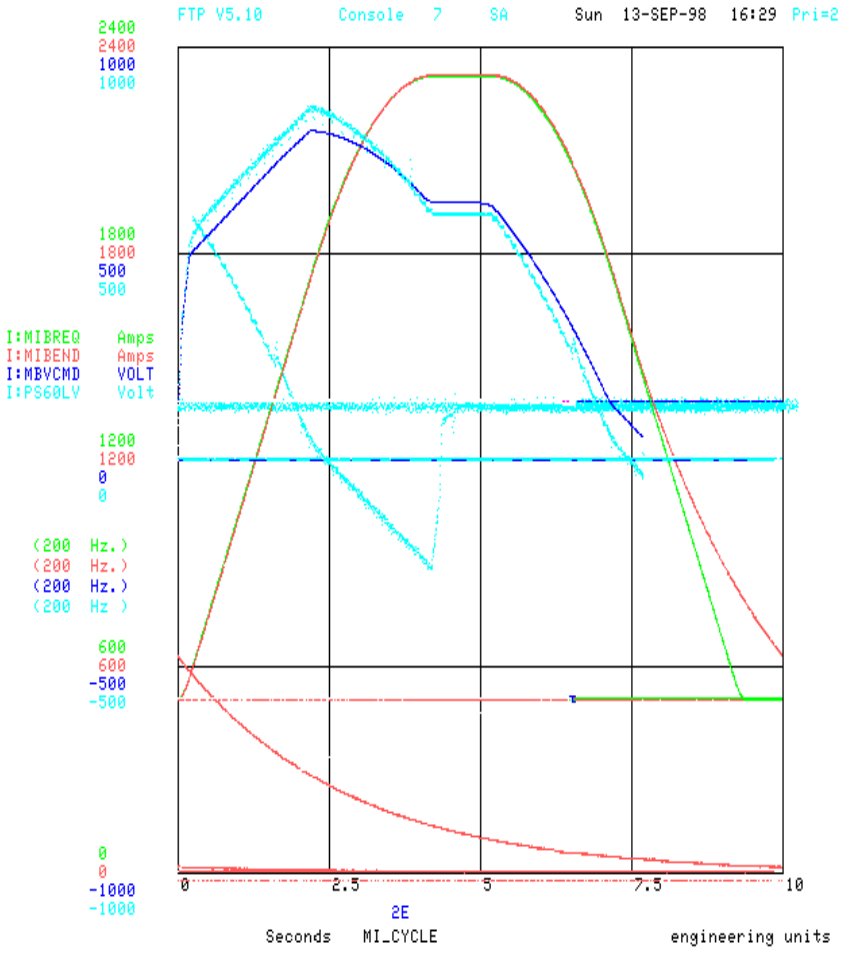
1st Turnon of the Dipole Bus, Sept 12th 1998



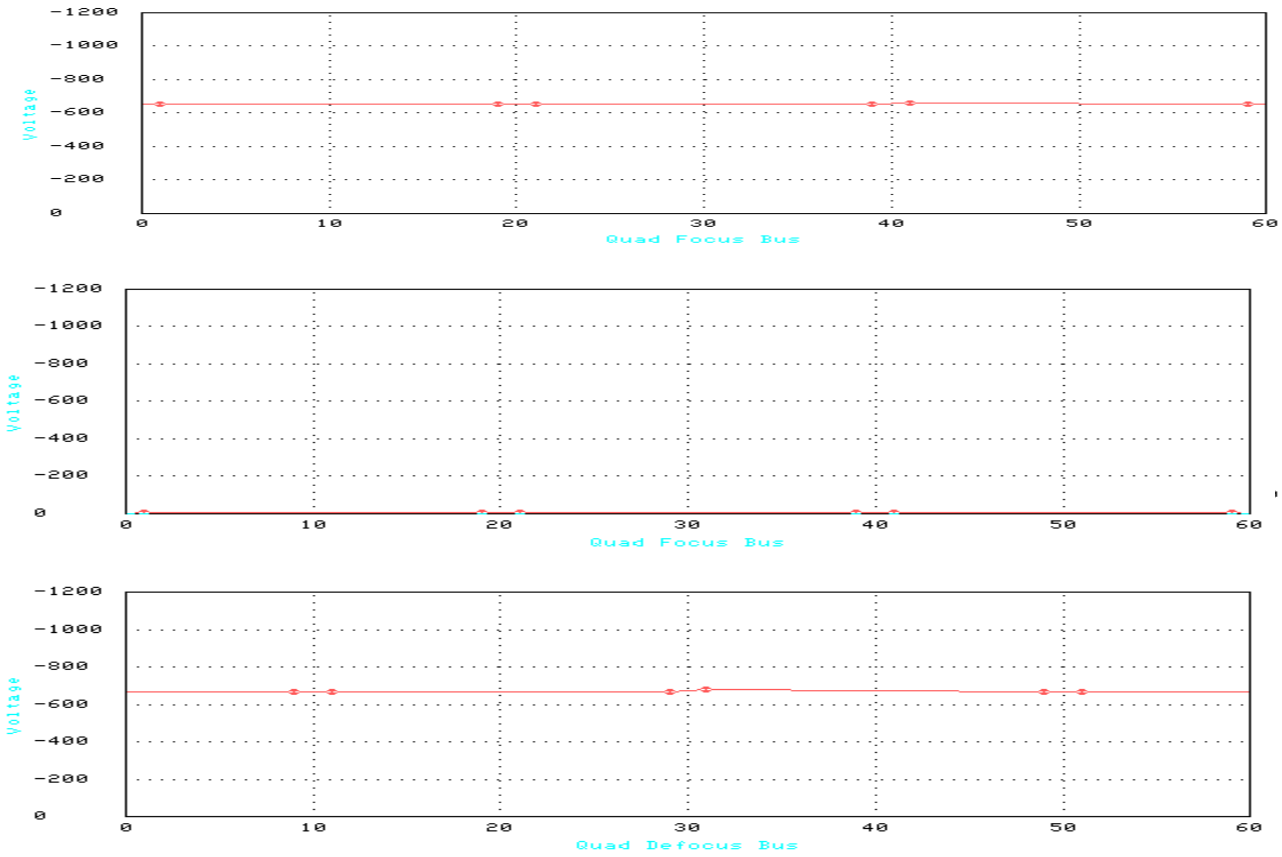
Power Supply Commissioning and Studies Continued.

1st MECAR Ramp of the Main Injector Dipole Bus 9/13/98

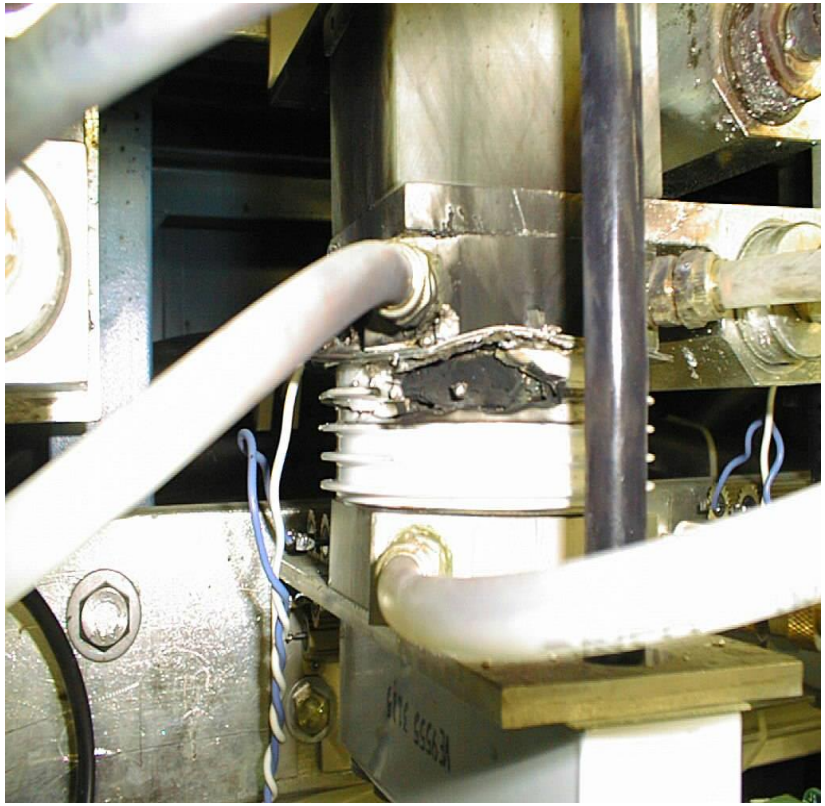


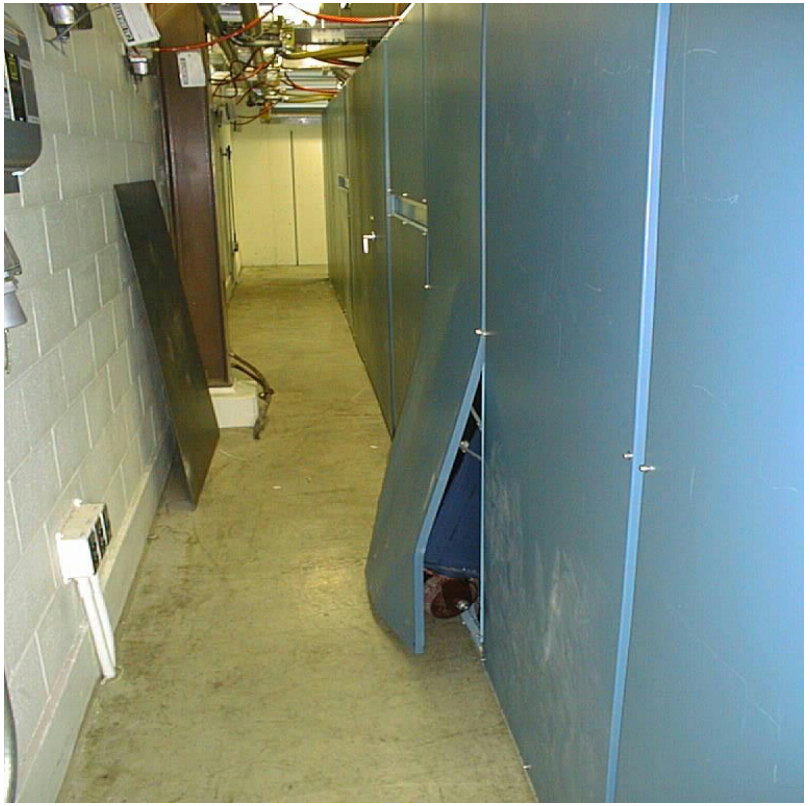


1st Quadrupole Bus Hi-Pot, Sept 19th 1998



Digital pictures of the failed MI30 upper bend power supply. The first pictures show the failed SCR. The second pictures shows the chokes that tipped over. (9/19/1998)

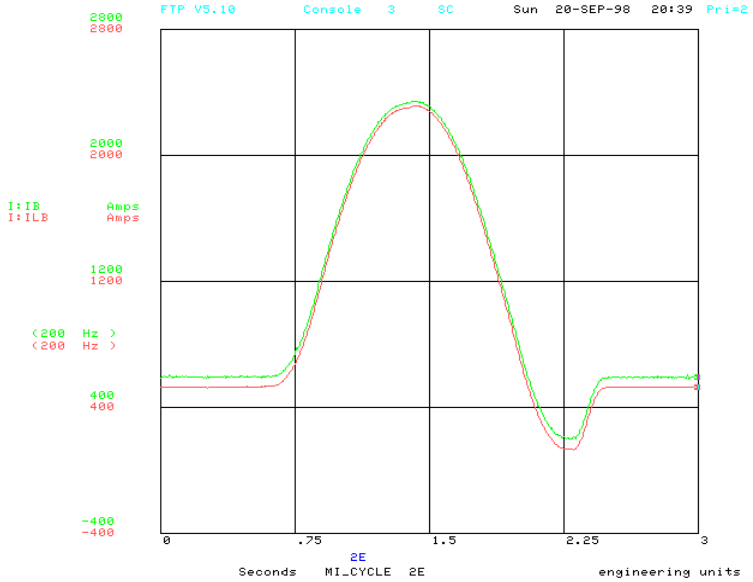


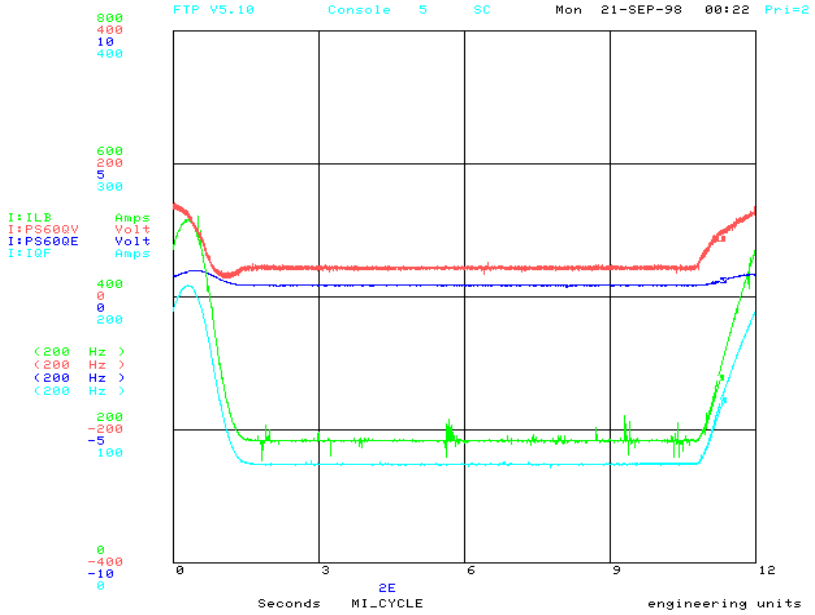


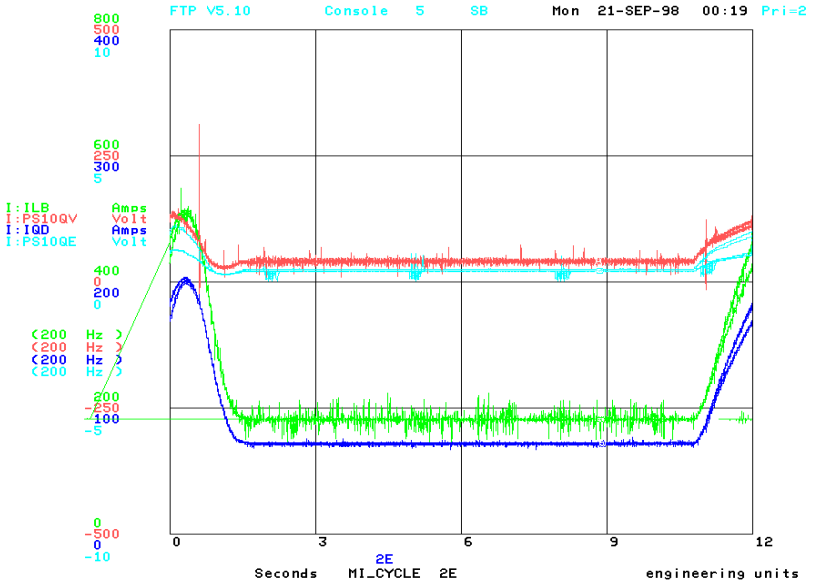
MECAR Study Continued

Dipole and Quadrupole Ramps using MECAR 9/20/98.

All three buses were successfully ramped, $2E 12 seconds apart.







Getting Ready For Beam

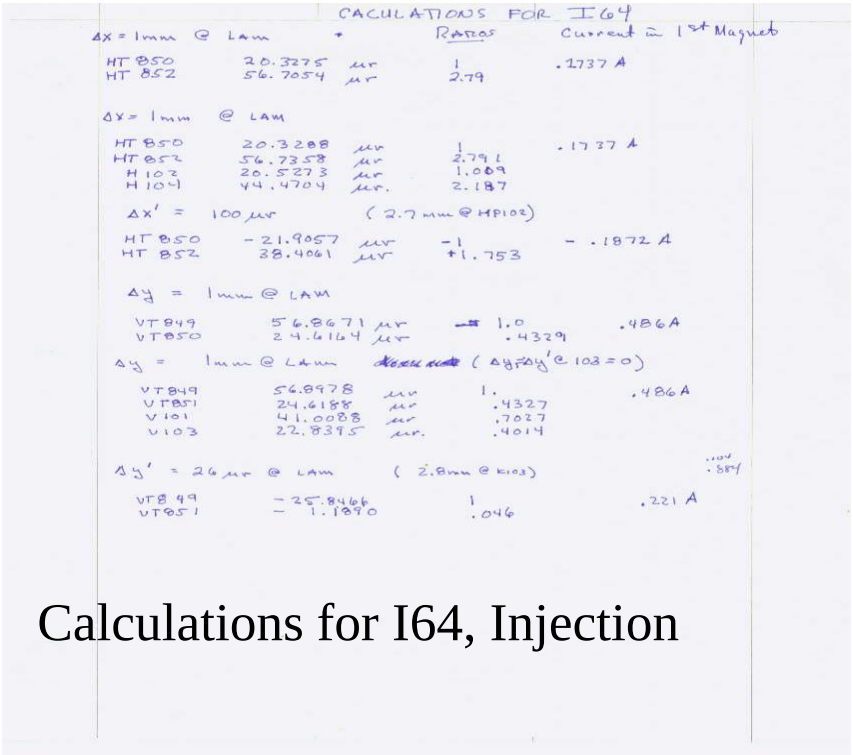
- The Plan for Sat 9/26/98 was to inject beam into MI8 Line from Booster, transport the beam to MI852, inject the beam into the Main Injector and stop it downstream of 103.

- Dave Johnson calculated initial injection settings.

MI Injection Orbit

- Lambertson entrance: x = - 47 mm, x' = 35 mr, y = 34 mm, y' = 0 mr
- Lambertson exit: x = 0 mm , x' = 0 mm, y = 35.7 mm, y' = 1.4 mr
- Q101: y = 37 mm
- VP101 (injection bpm) y = 35.5 mm
- Q102: y = 9.5 mm

Dave Johnson 07/27/98
revised 09/25/98



Calculations for I64, Injection

Getting Ready For Beam….

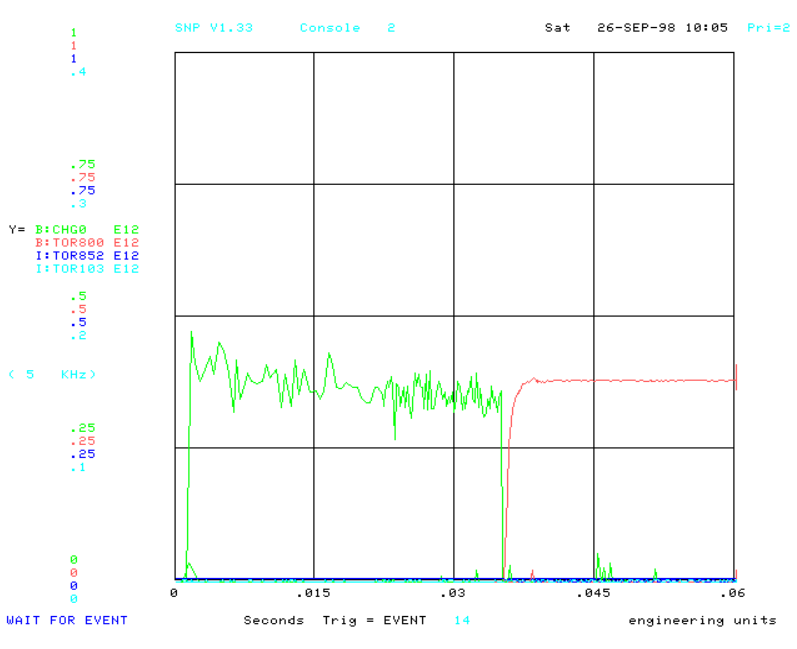
• Bruce Brown calculated the Bus current as a function of p, using Magnet data.

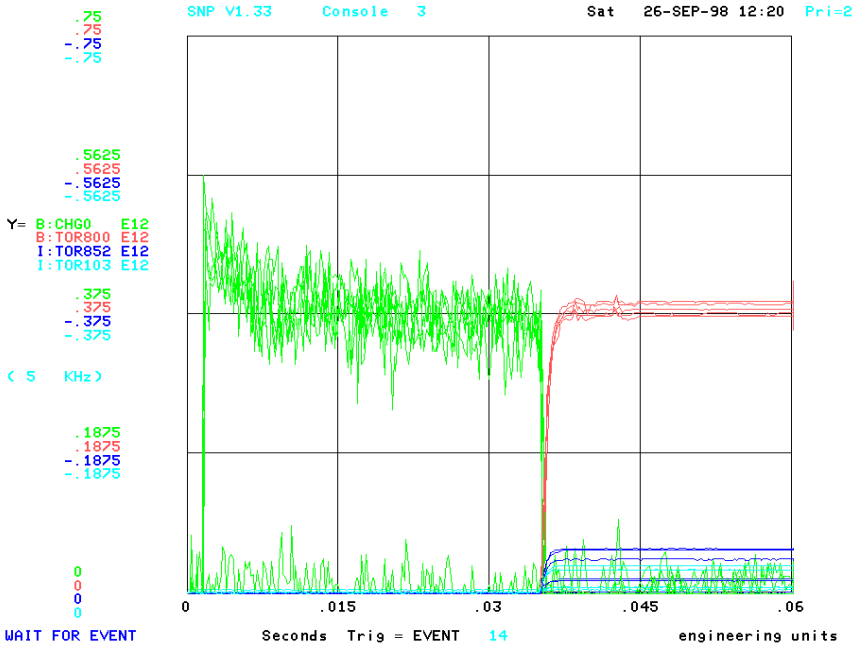
p	T	I_bend	I-Qf	I_Qd
GeV/c	GeV	A	A	A
8.8889	8	511.5675	207.6809	203.1785
20	19.0837	1156.12	468.9606	458.8737
26	25.0786	1503.347	609.8188	596.727
50	49.0705	2892.112	1172.93	1147.694
86	85.0668	4991.949	2019.713	1976.166
100	99.0661	5819.048	2350.429	2299.625
120	119.065	7035.995	2824.68	2763.494
150	149.065	9230.331	3544.046	3464.982

• During the Commissioning we have adjusted these numbers by less than a few Amps.

First Beam in the Main Injector

- The Main Injector Beam Commissioning Started at 08:00, Sat, Sept 26 1998.
- Beam was injected into MI8 at 10:05.

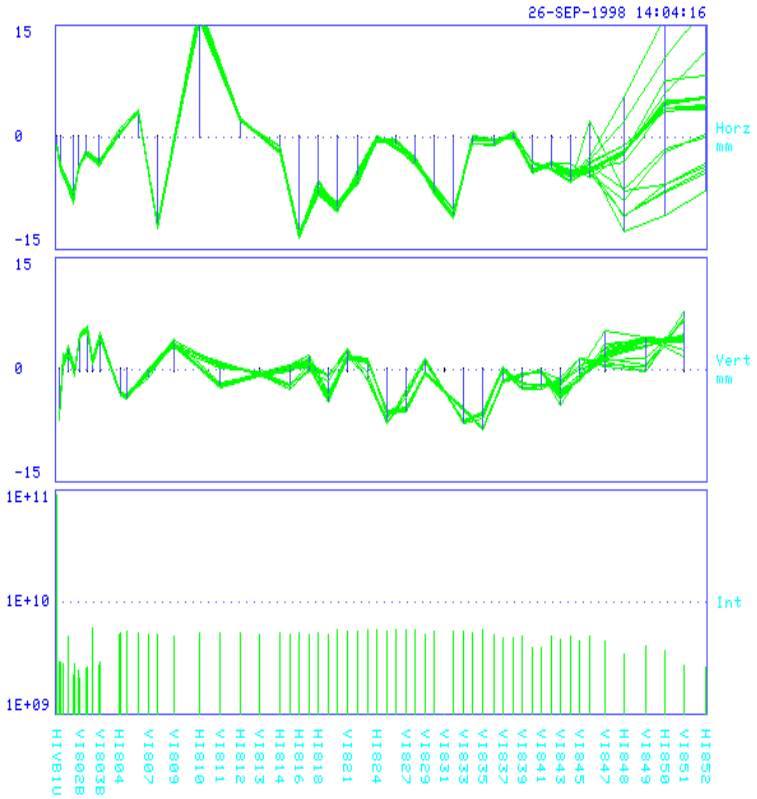


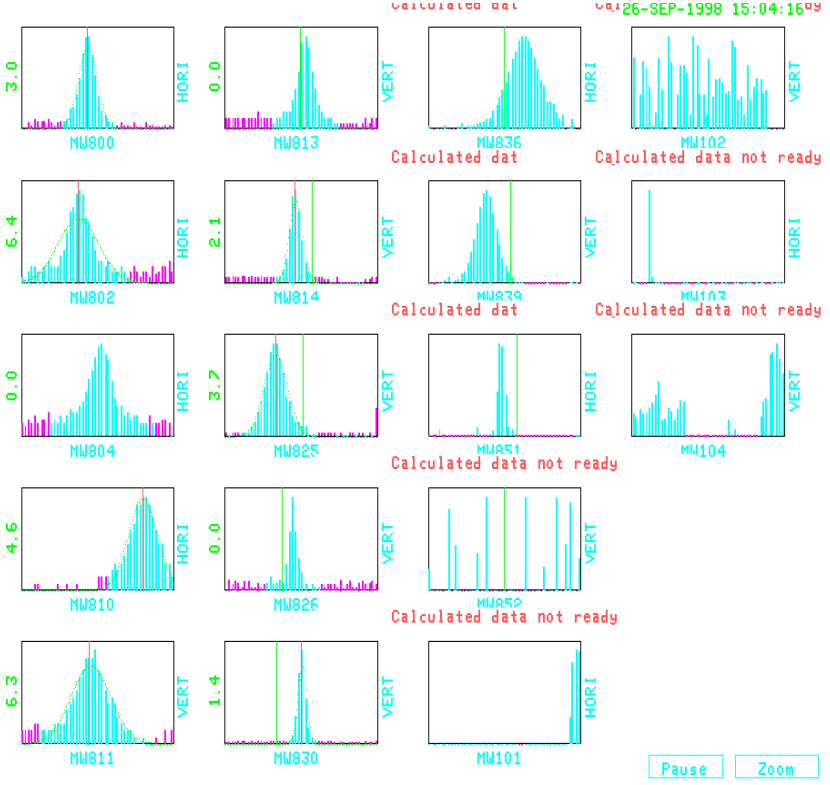


- Beam was visible at TOR103 by 12:20.

First Beam in the Main Injector….

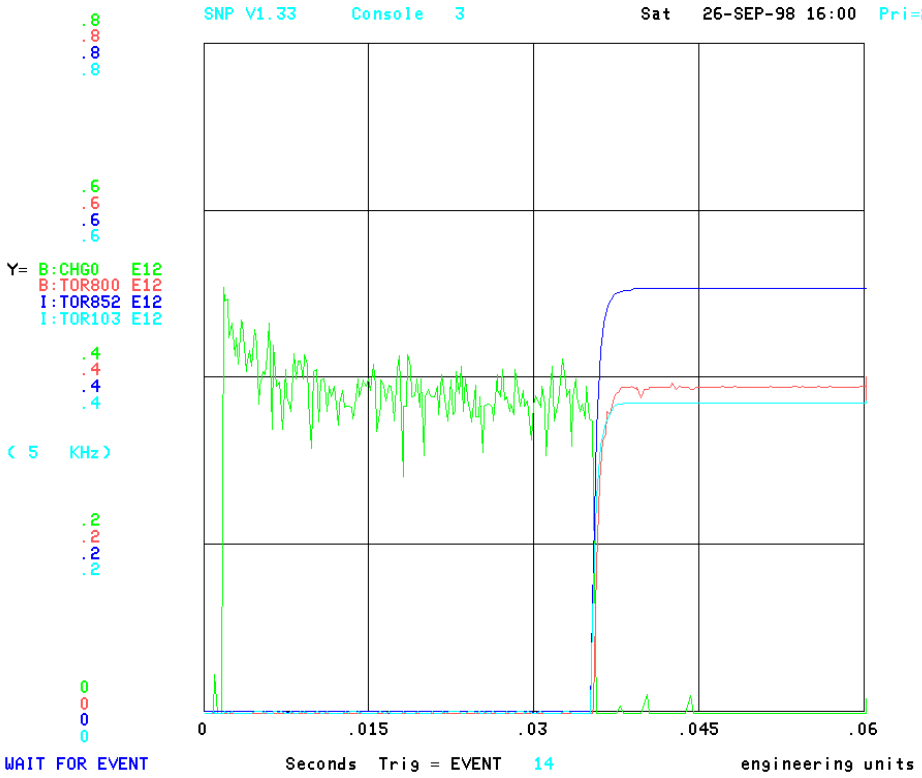
• BPM and Multi-wire timing continued by RFI Group. Beam was visible on both the BPMs and Multi-wires till 851 by 15:00.





First Beam in the Main Injector….

- After more work on instrumentation, beam was visible all the way to TOR103 by 16:00 with good efficiency.



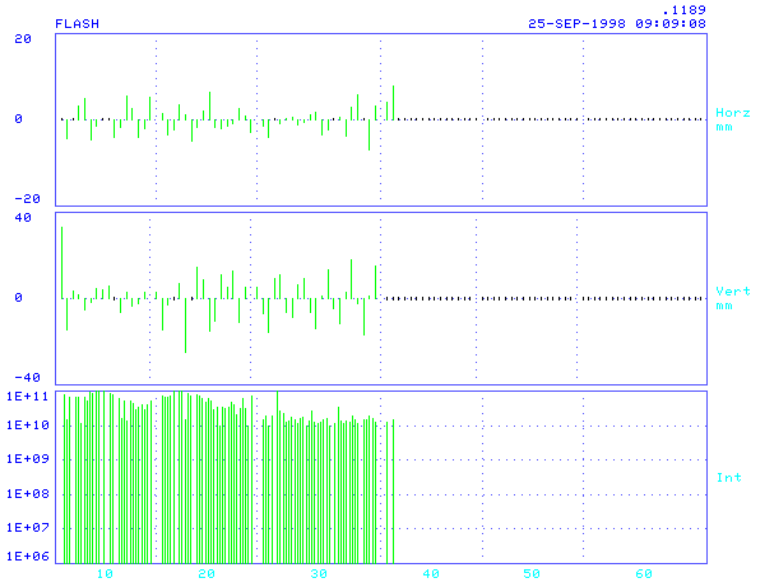
Pictures From the First beam in MI

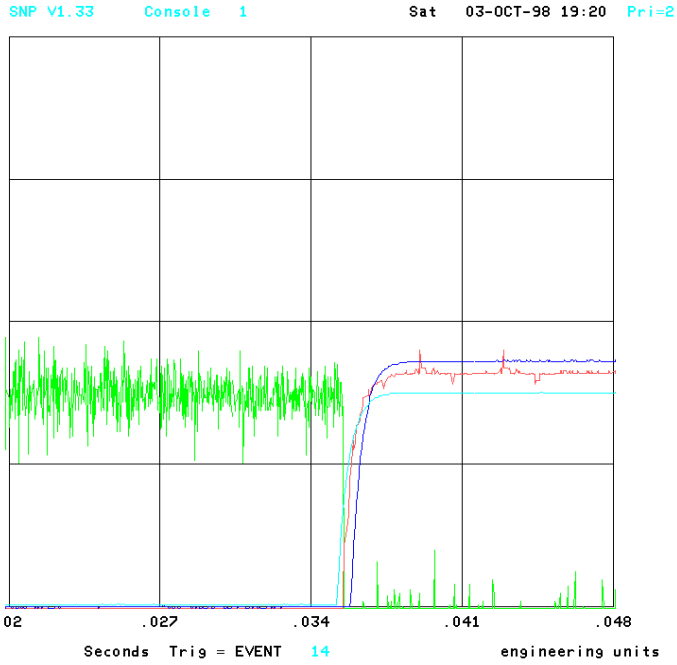
Dave Capista, Phil Martin, Shekhar Mishra, Saeed Assadi, Ioanis Kourbanis, Dave Johnson, Stan Pruss, Alan Hahn, Ming-Jen Yang, Jim Lackey, Milorad Popovic, Carol Johnstone, Jim Crisp, Greg Vogel, Ed Barssott, Gianni Tassotto, Pick Pierce, Steve Hays, Bob Flora, Kevin Martin, George Krafczyk, Dan Wolff, Ann Mason, Brian Hendricks, Bob Mau, Dean Still, Brian Drendel and Operations crew

Beam to MI40 Abort

- The Plan for Sat 10/3/98 was to inject beam into MI8 Line from Booster, transport the beam to MI852, inject the beam into the Main Injector and abort it into MI40 Abort.

- Beam was injected into MI8 at 15:30. After injection problems into MI, BPM reboots and other instrumentation were resolved the beam was clearly visible at MI40 by 19:30 without any orbit correction.

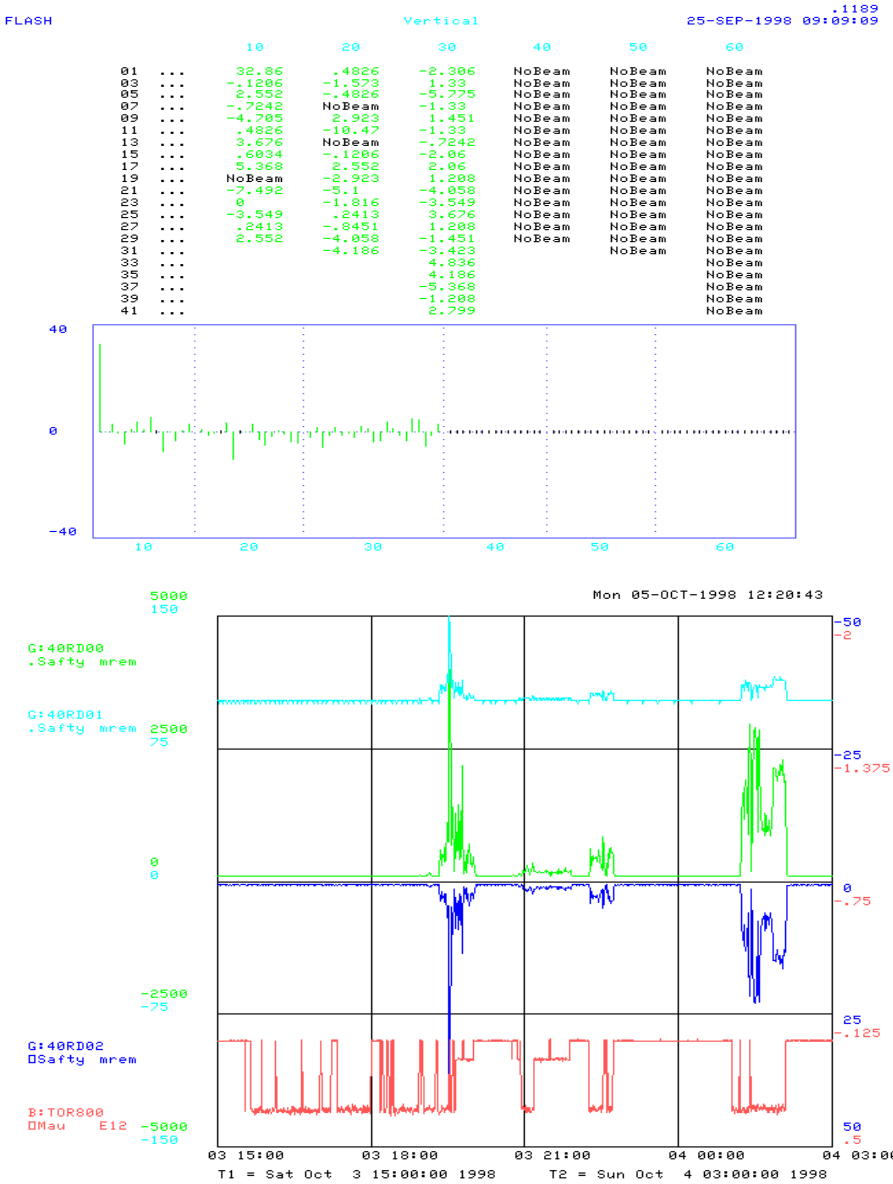




Beam to MI40 Abort….

- Injection Kicker at 103 and LAM10 was used to inject beam into the Main Injector.

- Radiation detectors in abort room for first beam.



Getting Ready To Circulate Beam in MI

Fermilab

October 9, 1998

To: Bob Mau

From: Steve Holmes S. D. Holmes

SUBJECT: PERMISSION TO CIRCULATE BEAM IN THE MAIN INJECTOR

Attached you will find the completed Beam Permit for 8 GeV line and Main Injector operations. This beam permit supercedes that issued on October 2. You are authorized to deliver beam from the Booster through the 8 GeV line and into the Main Injector subject to the attached operating limits. You will note that through this weekend I am requiring that no acceleration of beam beyond the 8 GeV injection energy is authorized and that the total beam intensity delivered to the Main Injector is limited to 6×10^{13} protons per hour.

cc:
M. Andrews
J. Marriner
P. Martin

Permission to Circulate Beam

Fermilab

BEAM PERMIT

MI Beam Envelope

The maximum hourly beam power transmitted through the MI-8 beamline and the MI accelerator is limited to 3.0×10^{14} protons.

No accelerator or beam line will transmit beam without an operational beam interlock safety system.

MI Beam Operating Limits

The maximum charge transmitted through the MI-8 beamline and the MI is limited to 2.7×10^{14} protons per hour.

Examples: Charge/hr = number of pulses/hr x number of protons/pulse

#1 600 pulses per hour at 4.5×10^{11} protons per pulse = 2.7×10^{14} protons per hour.

#2 60 pulses per hour at 4.5×10^{12} protons per pulse = 2.7×10^{14} protons per hour.

Special conditions and comments:
No acceleration of beam beyond the 8 GeV injection energy is permitted.

Prepared by [redacted] 10/9/98 Philip S. Martin 10/9/98
Operations Department Head/Date and Main Injector Department Head/Date

Reviewed by [redacted]
Associate Beams Division Head for Systems/Date

Reviewed by Mitchell A. Leonard 10/9/98
Beams Division Radiation Safety Officer/Date

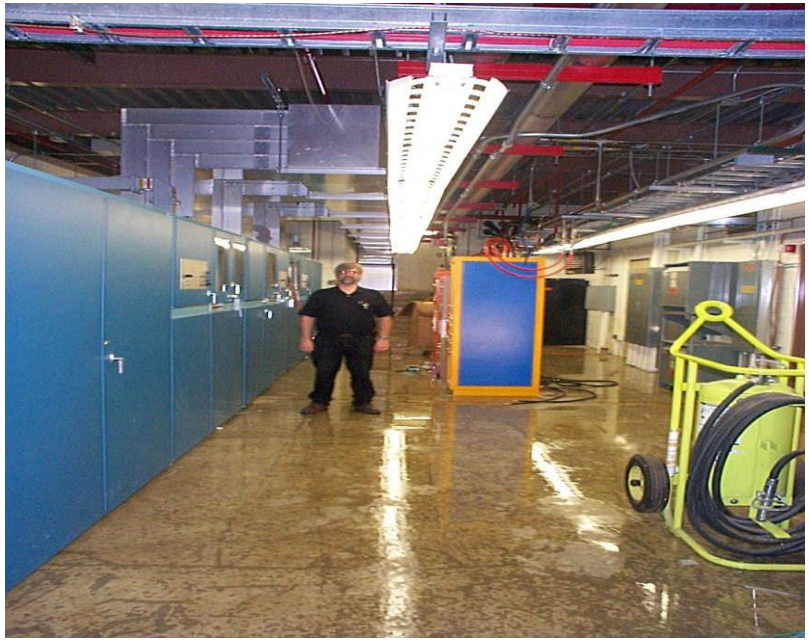
Approved by S. D. Holmes 10/9/98
Beams Division Head/Date

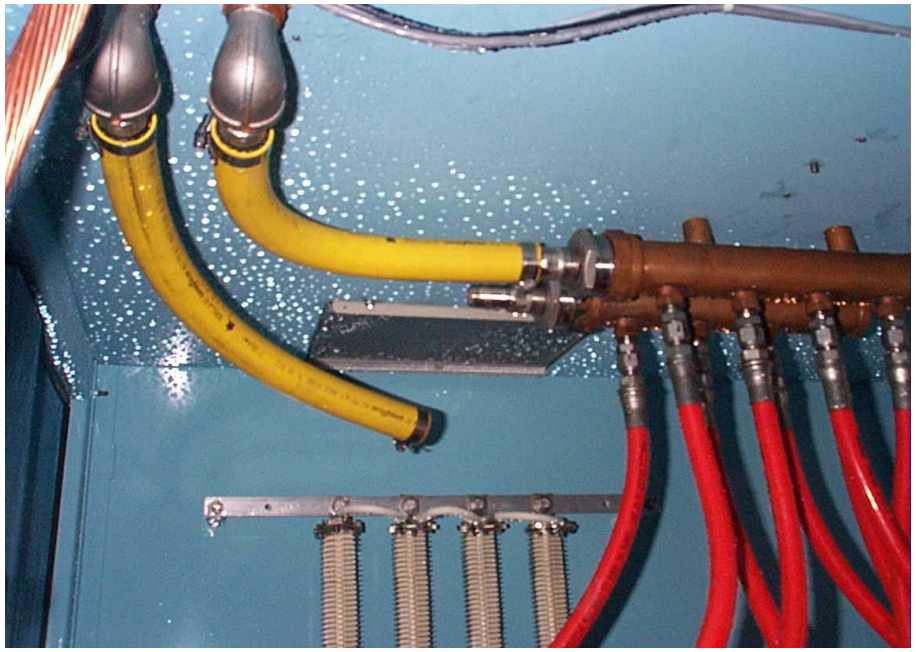
Page 1 of 1
Rev: 1.4
09/25/98

Beam Permit 3e14 p/h @ 8 GeV.

Getting Ready To Circulate Beam in MI...

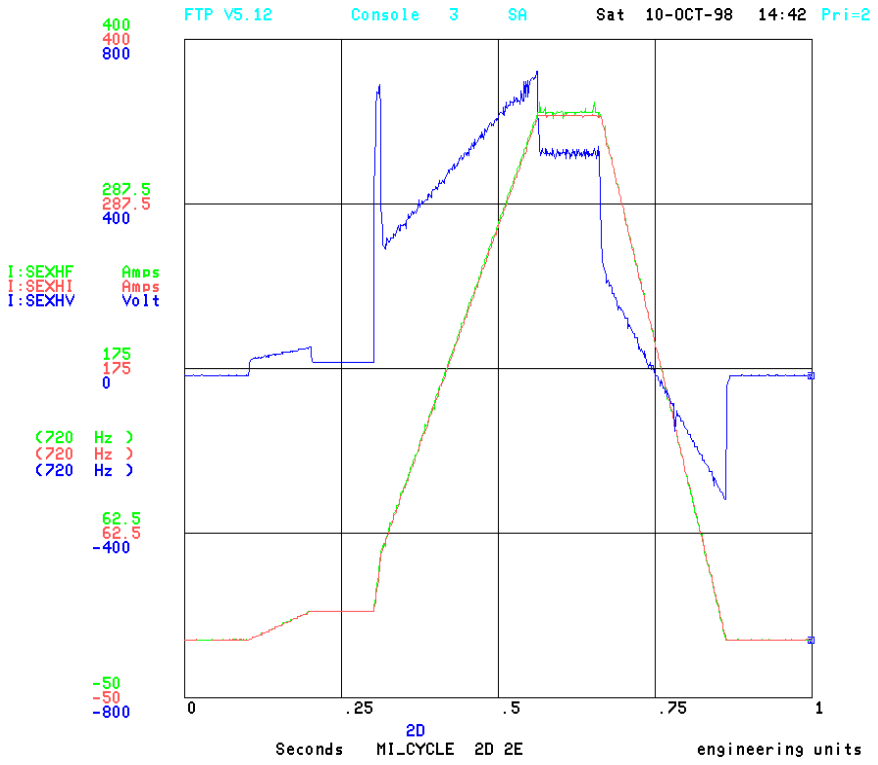
- Before beam every weekend Operations crew
  - S&S the tunnel
  - Hi-Poted all the bus and cleared any Ground Fault.
  - Put all the available power supply in circuit and Racked in at KRS.

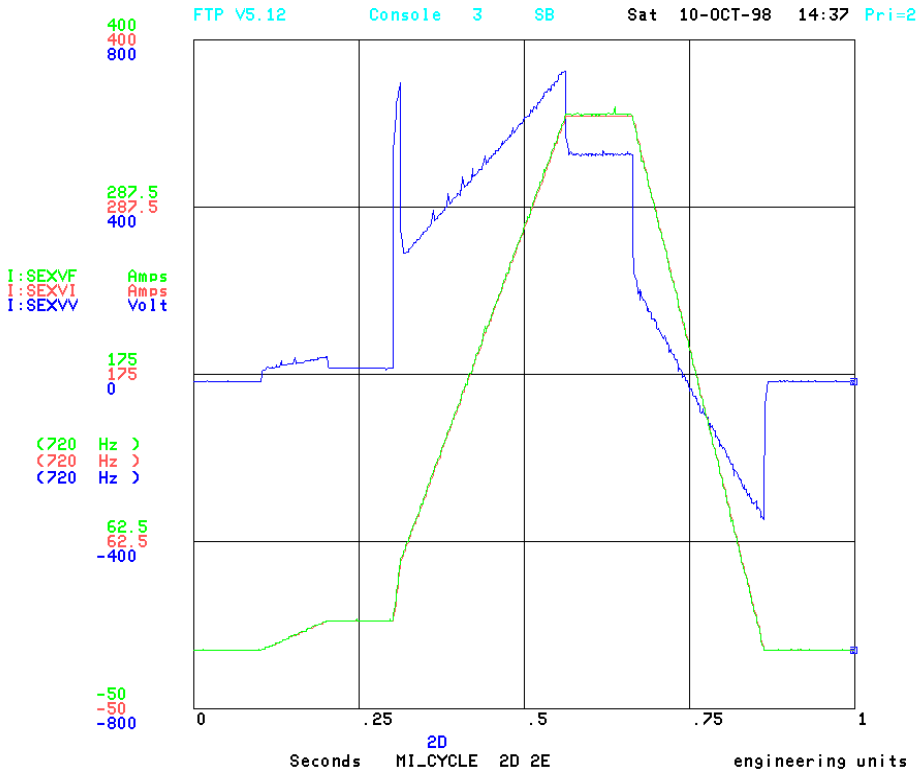




Getting Ready To Circulate Beam in MI...

- Power Supply tuning and commissioning during the morning shift of every weekend before beam commissioning.
- Sextupole power supply was commissioned on 10/10/98.



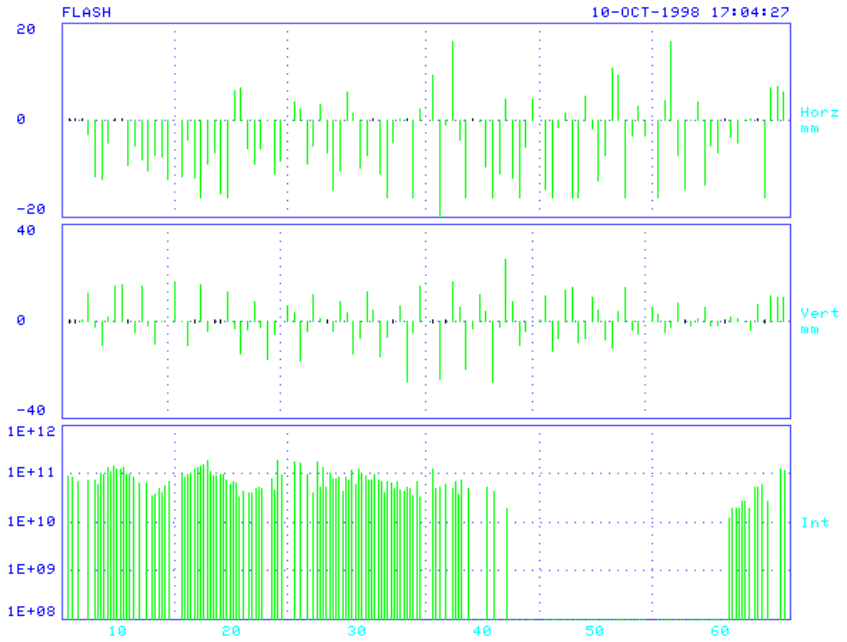


First Circulating Beam in MI (10/10/98)

Studiers: Saeed Assadi, Shekhar Mishra, Phil Martin, Dave Johnson, T. Sen, Dave Capista, Tom Meyer

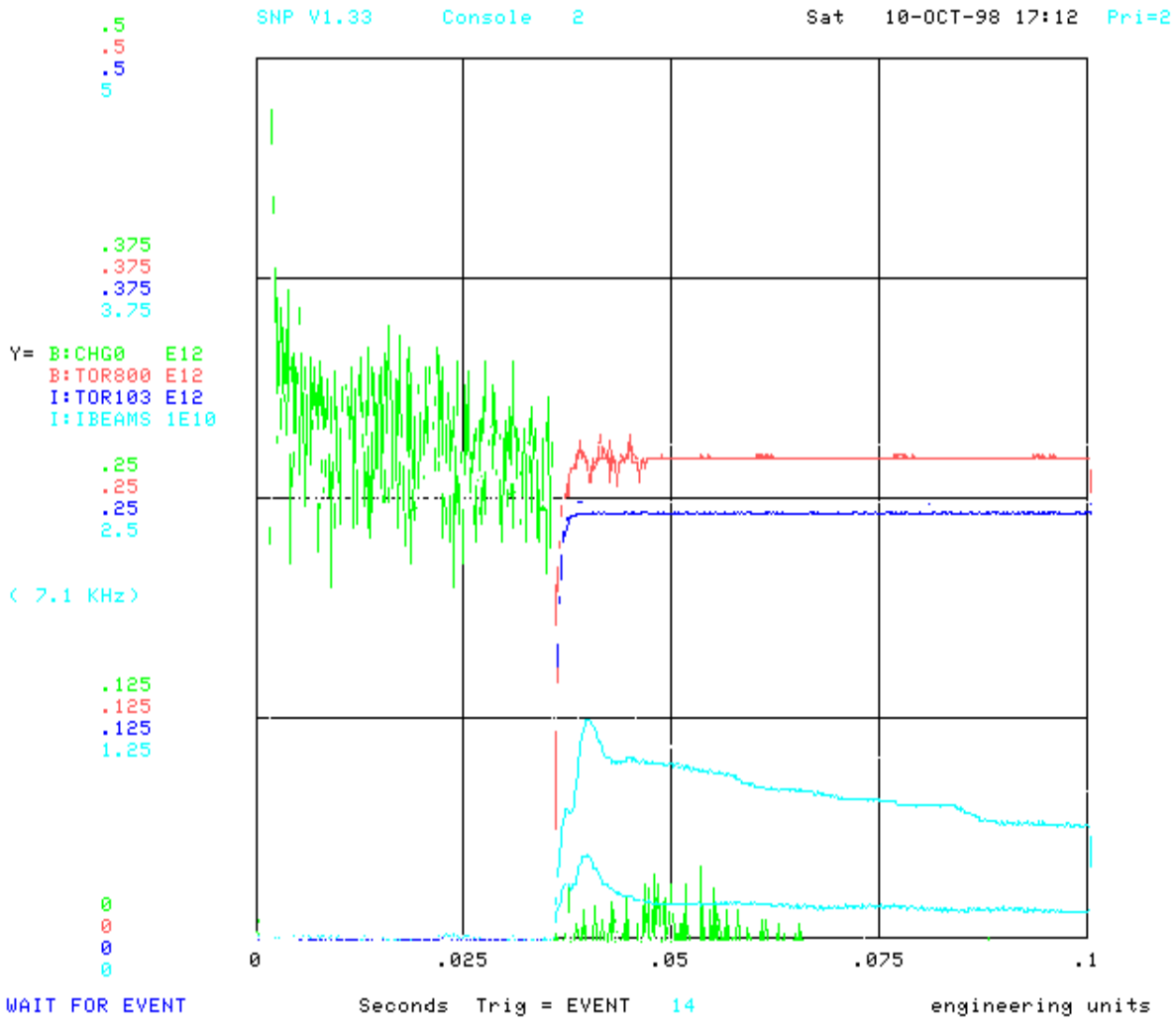
The GOAL for these studies were to CIRCULATE beam in the Main Injector for the first time.

- Beam was injected into MI8 at about 16:40.
- Beam had successfully made it around the ring without any orbit correction by 17:00.
- We did had to adjust the beam momentum to center the beam.



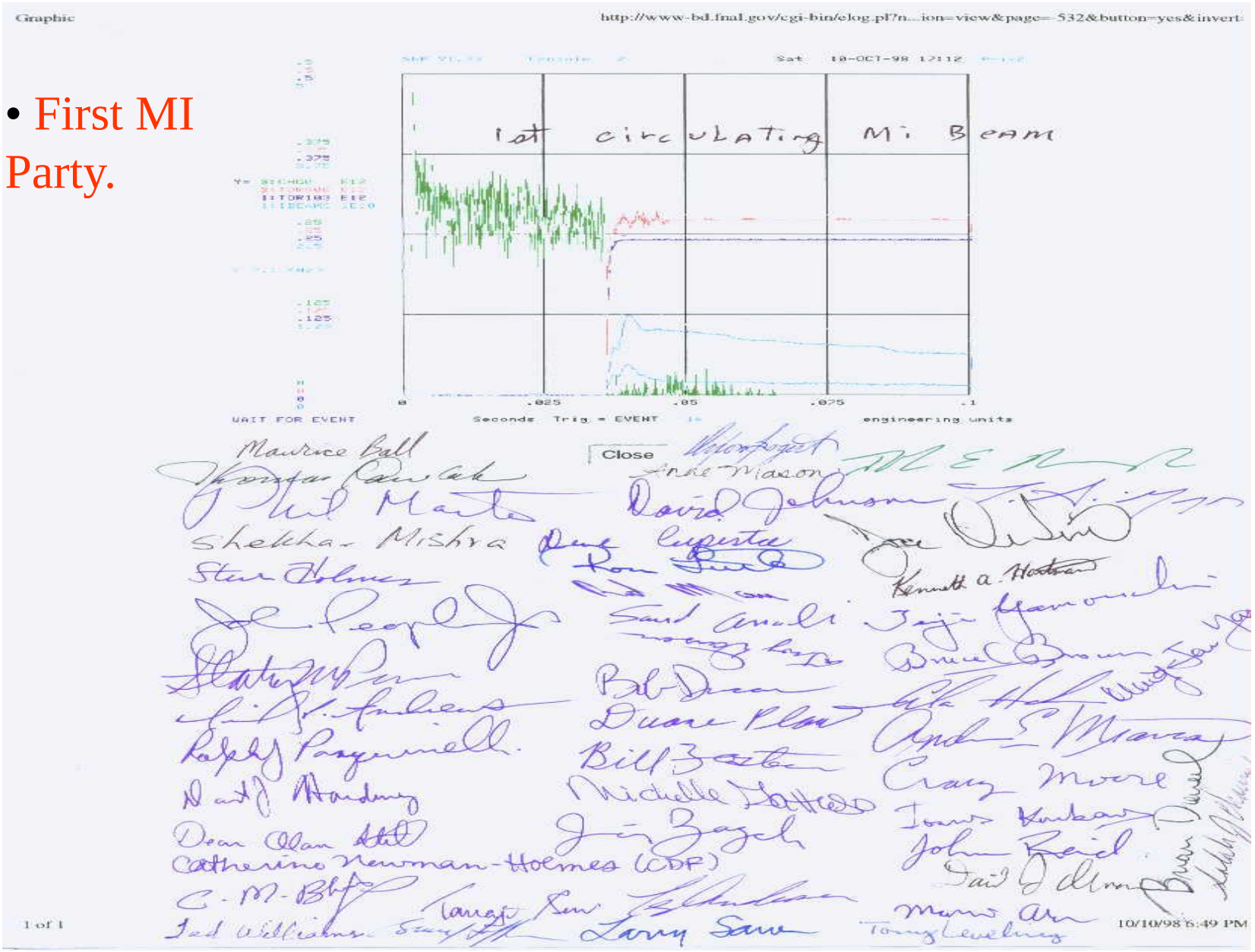
First Circulating Beam in MI….

- Excellent Injection Efficiency



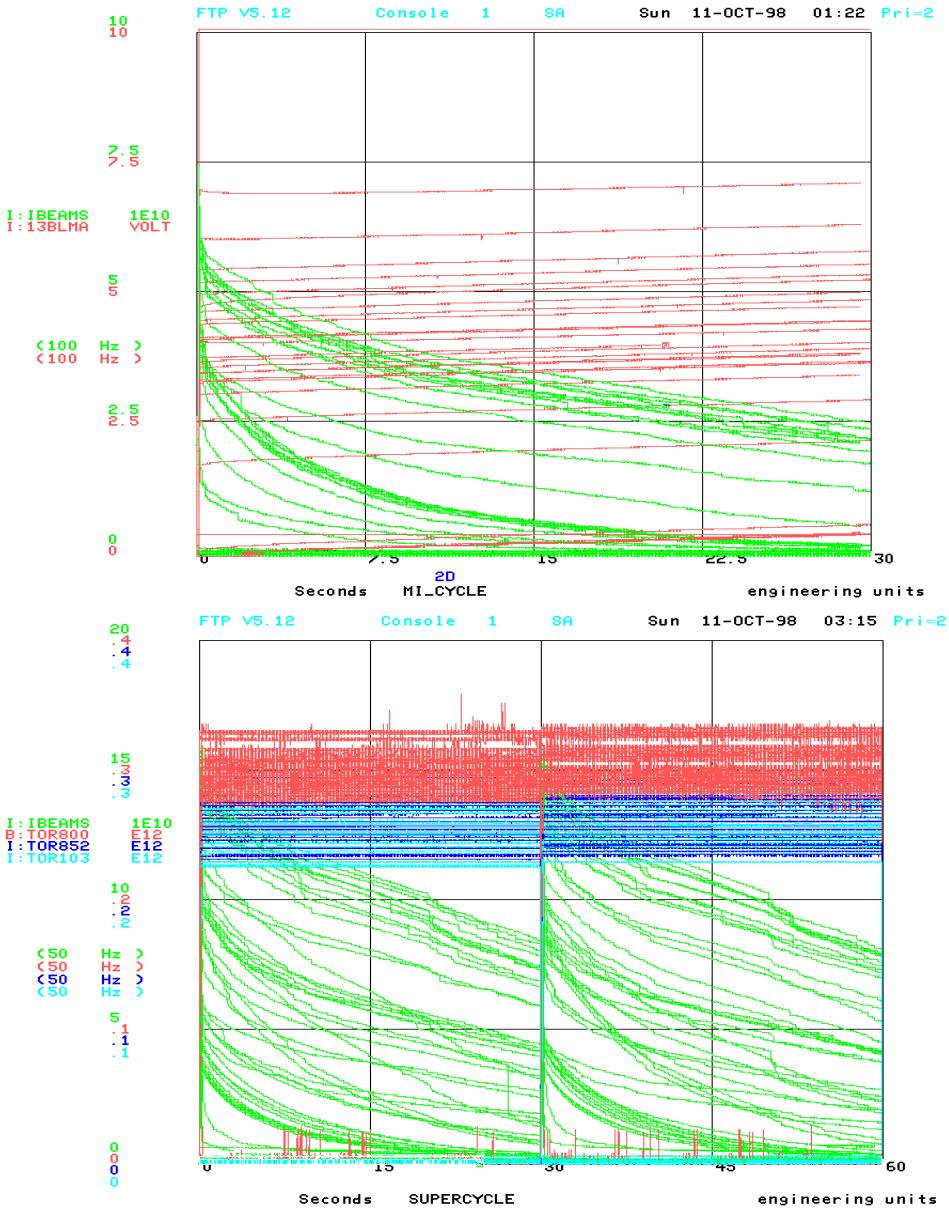
First Circulating Beam in MI...

- First MI Party.



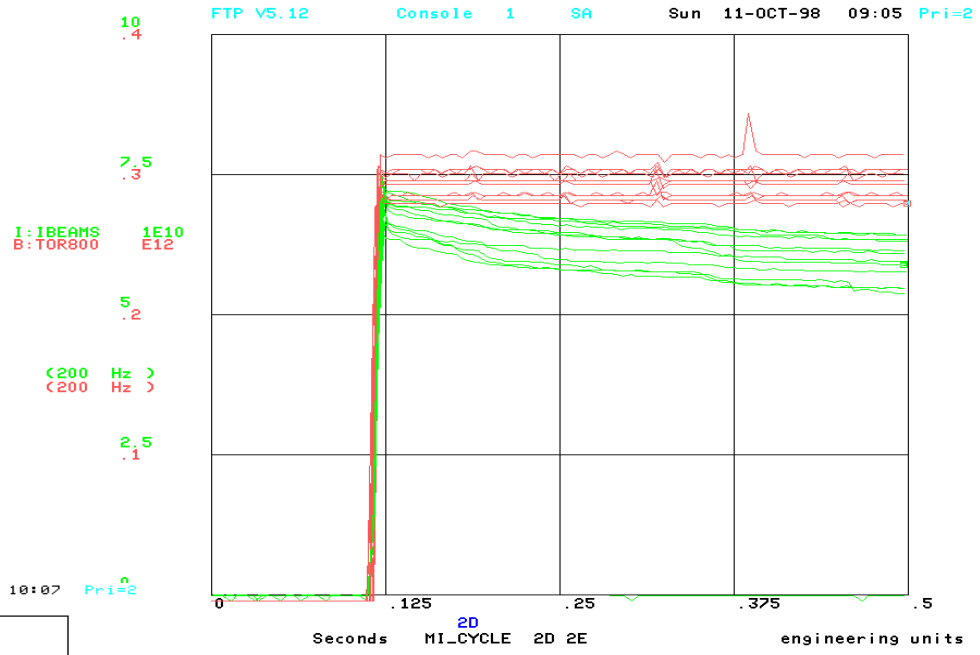
First Circulating Beam in MI...

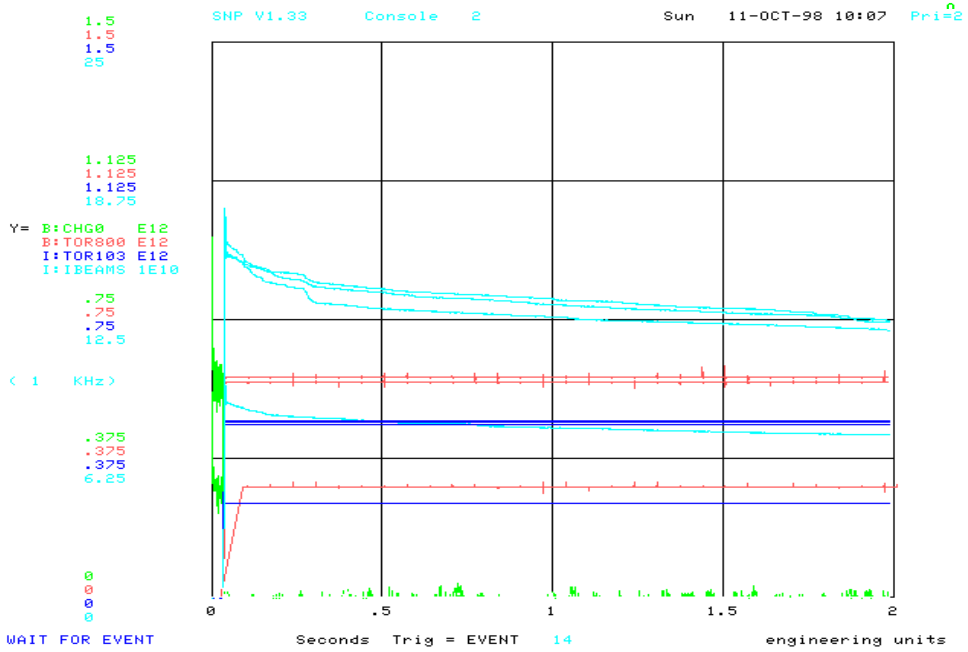
- Lifetime in 10's of Seconds.
- At this time we had not adjusted
  - orbit
  - tune
  - chromaticity
  - No RF was ready.
- Circulating beam efficiency was about 50% w.r.t. Tor800.
- We had problem smoothing the vertical orbit, which was later resolved by fixing the tune.



First Circulating Beam in MI...

- Beam lifetime improved after sextupole current adjustments.
- No RF Stations on yet.



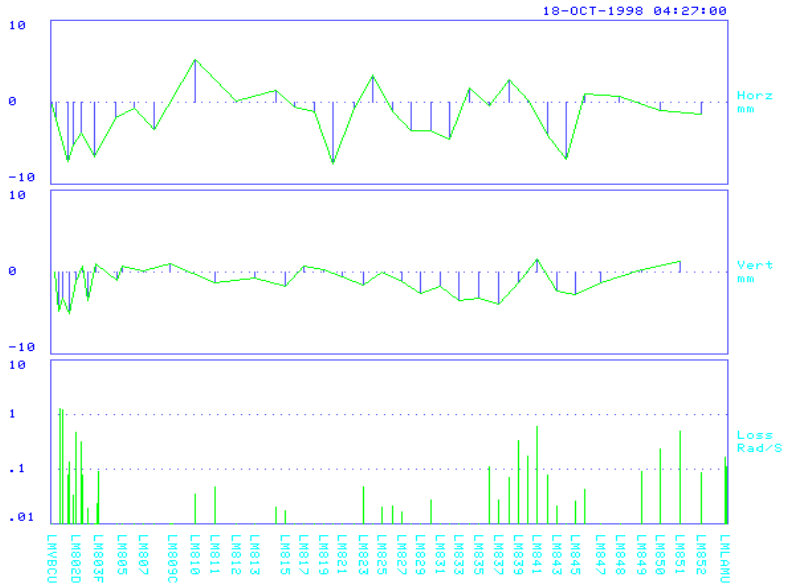


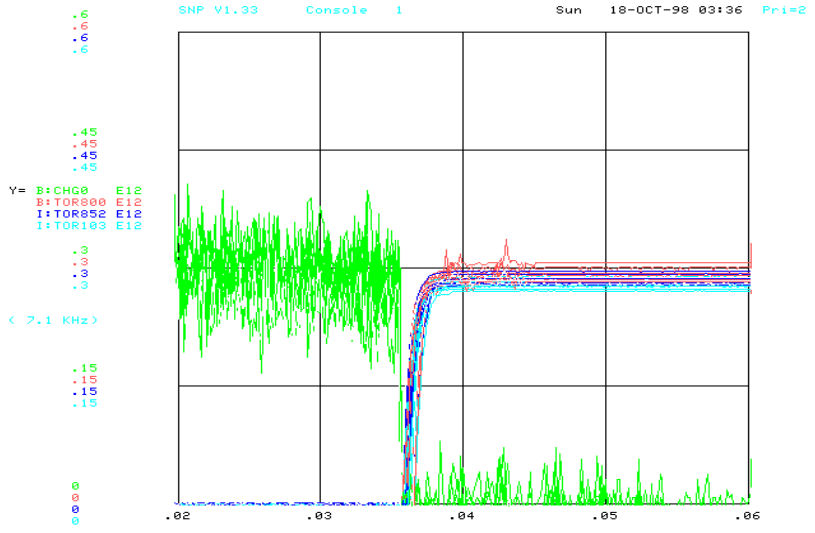
- Beam lifetime was not much effected by intensity.

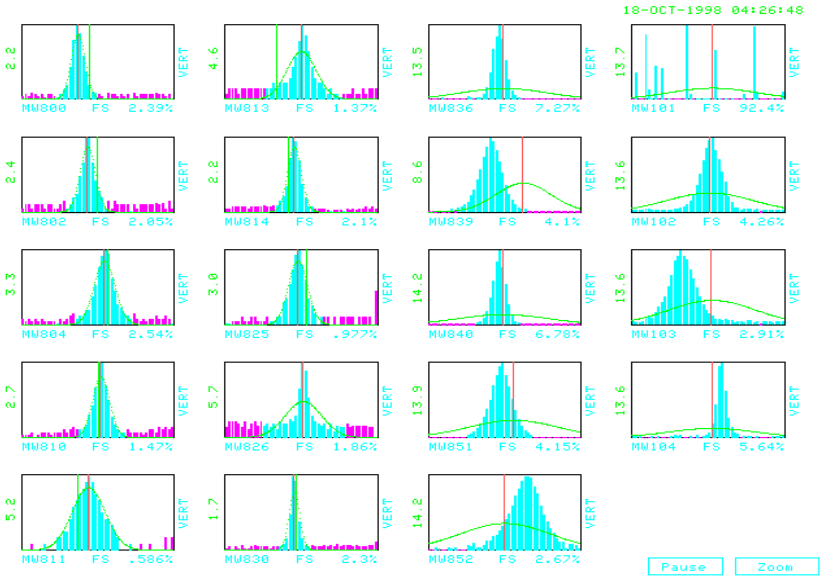
MI8 Efficiency and Studies

Systematic study and tuning of MI8 line.

- Beam Line Analysis Program
- MICADO

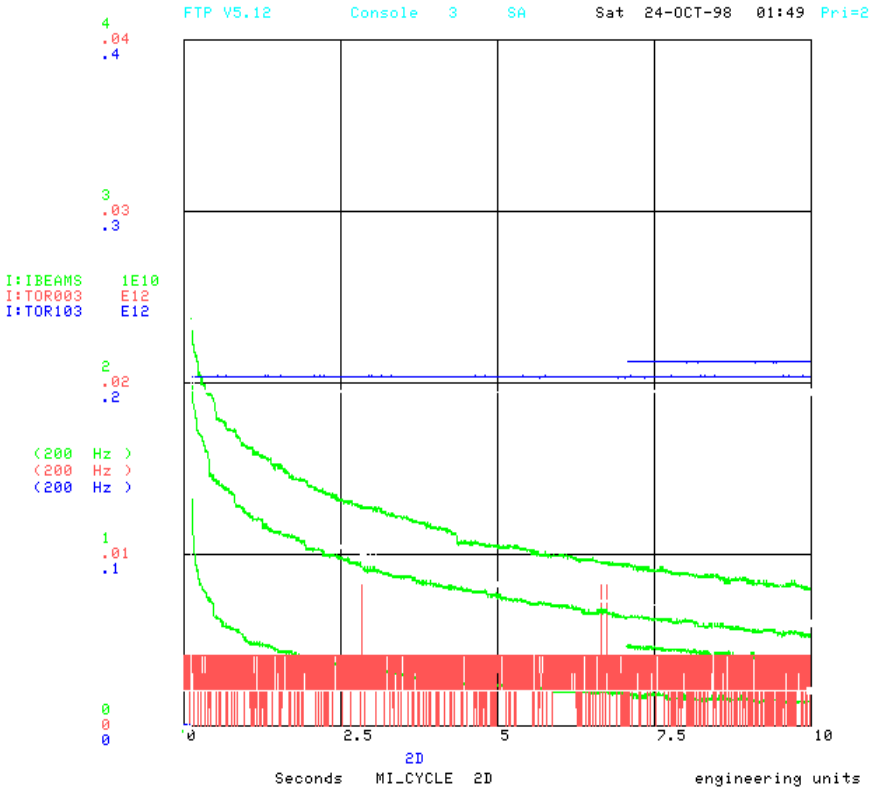


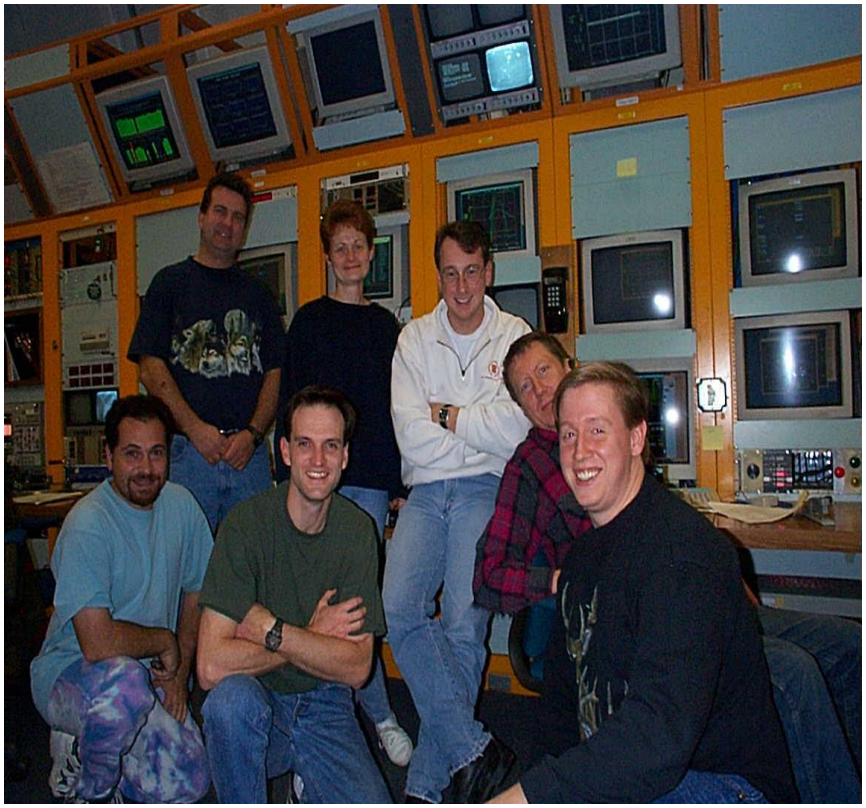




Operation Establishes Circulating Beam

On 10/23/98 Operation got their first chance. Job well done !

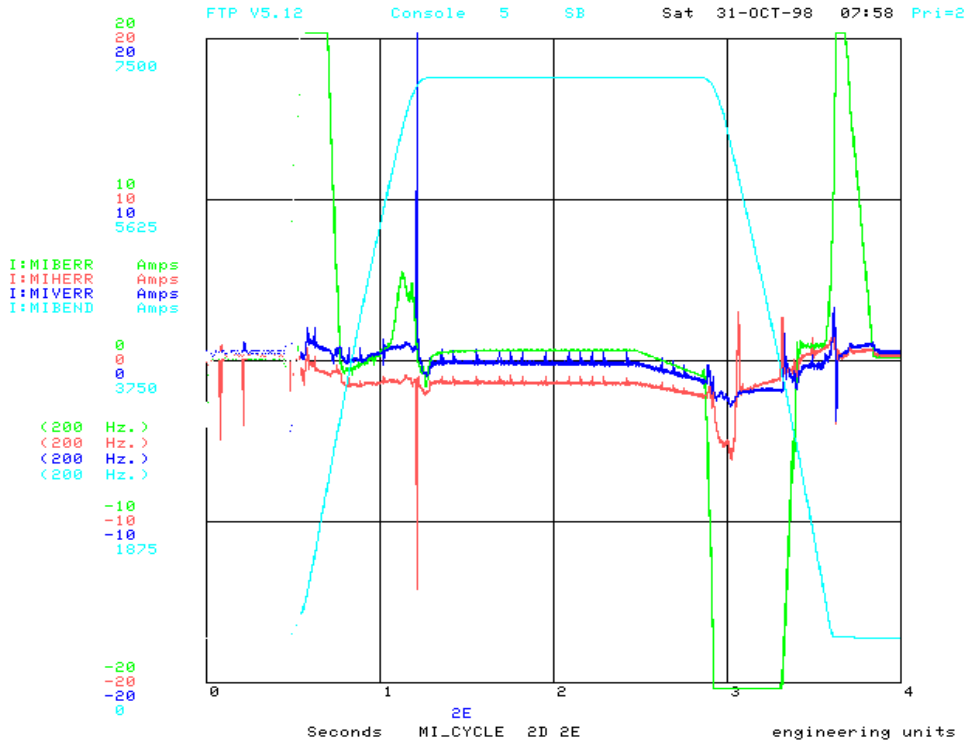




Beam Tuning and Power Supply Study

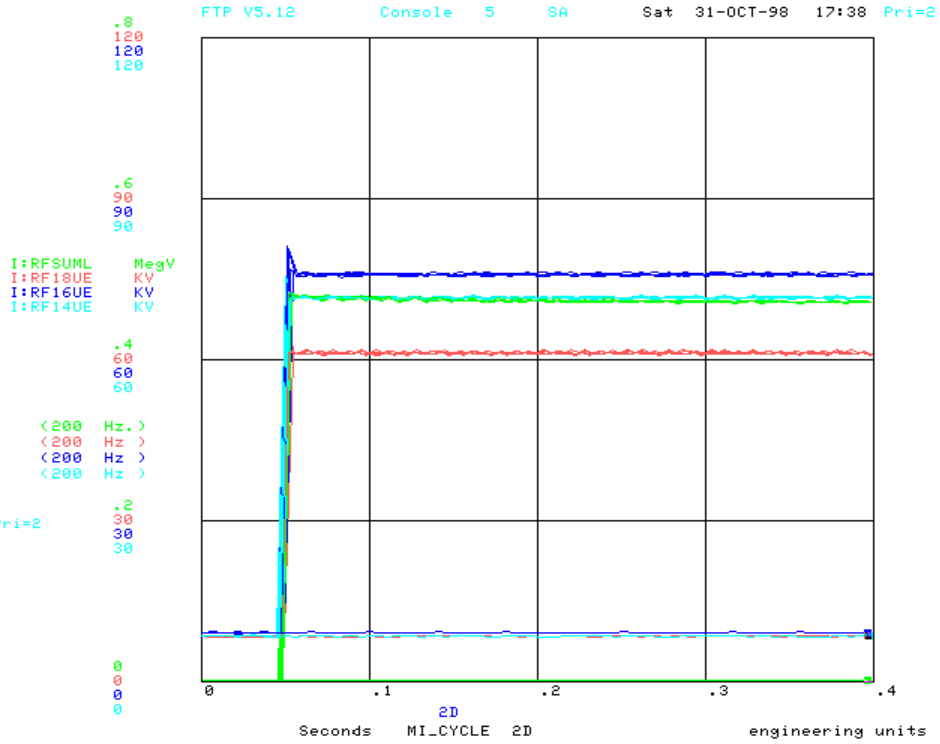
- Beam tuning of Full MI8 Line.
- Injection tuning
- Measurement of tune (Integer and fractional part)
- Orbit Smoothing
- Power Supply studies

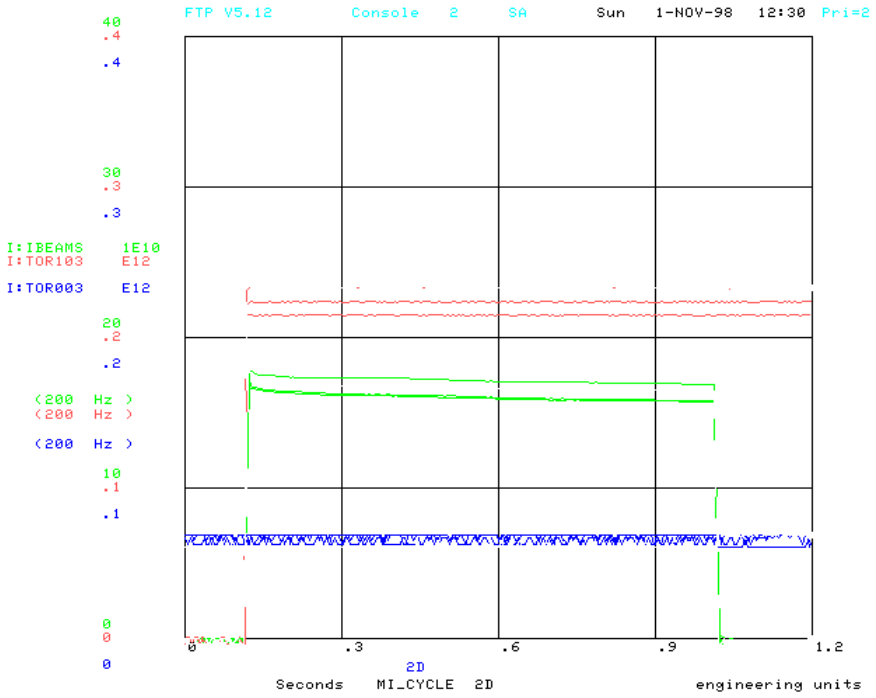
1st Ramp of the Main busses to 120 GeV on 10/31/98.



Tuning and Studies

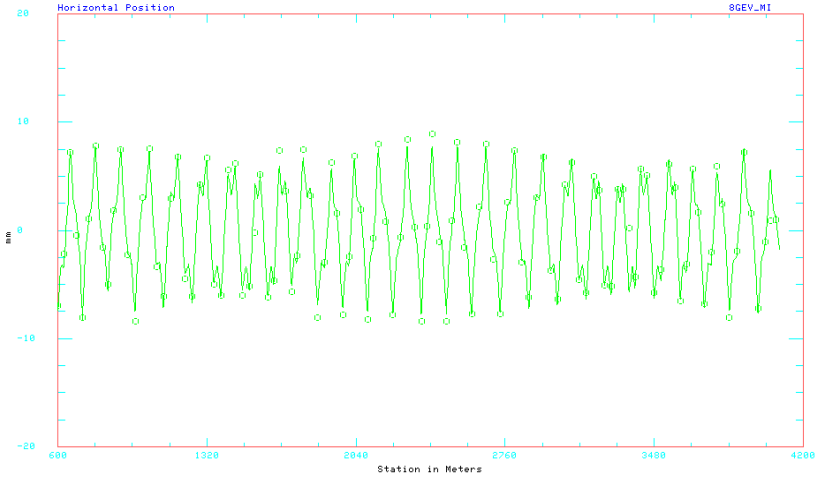
- 6/18 RF stations were turned on for the first time in MI on 10/31/98.

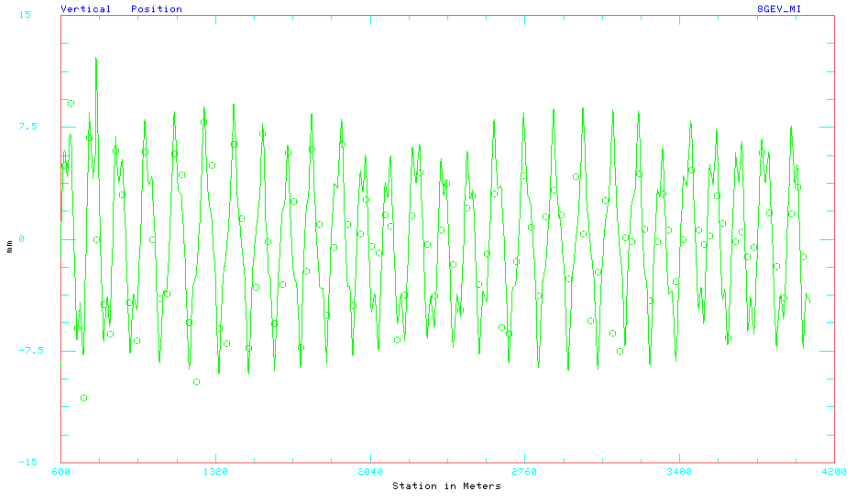


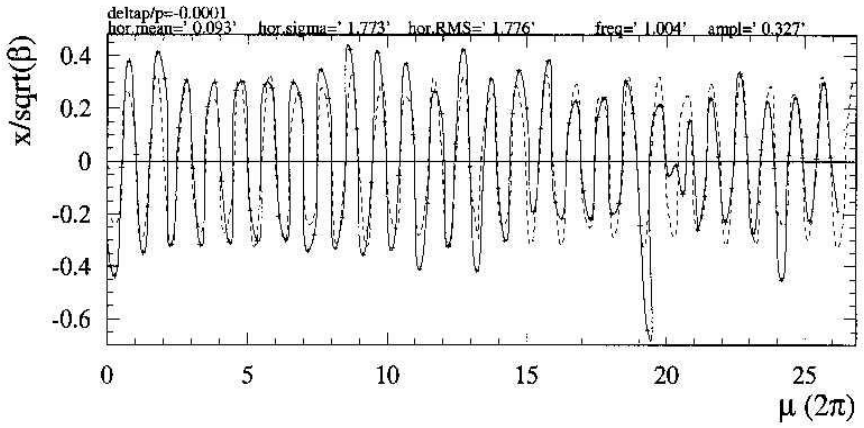


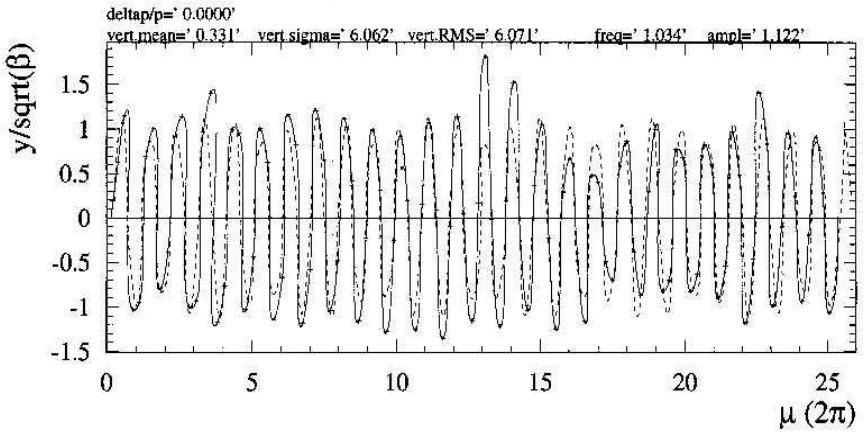
- After tune was adjusted to the design value (26.42,25.41) lifetime improved.

Early Lattice Function Measurements



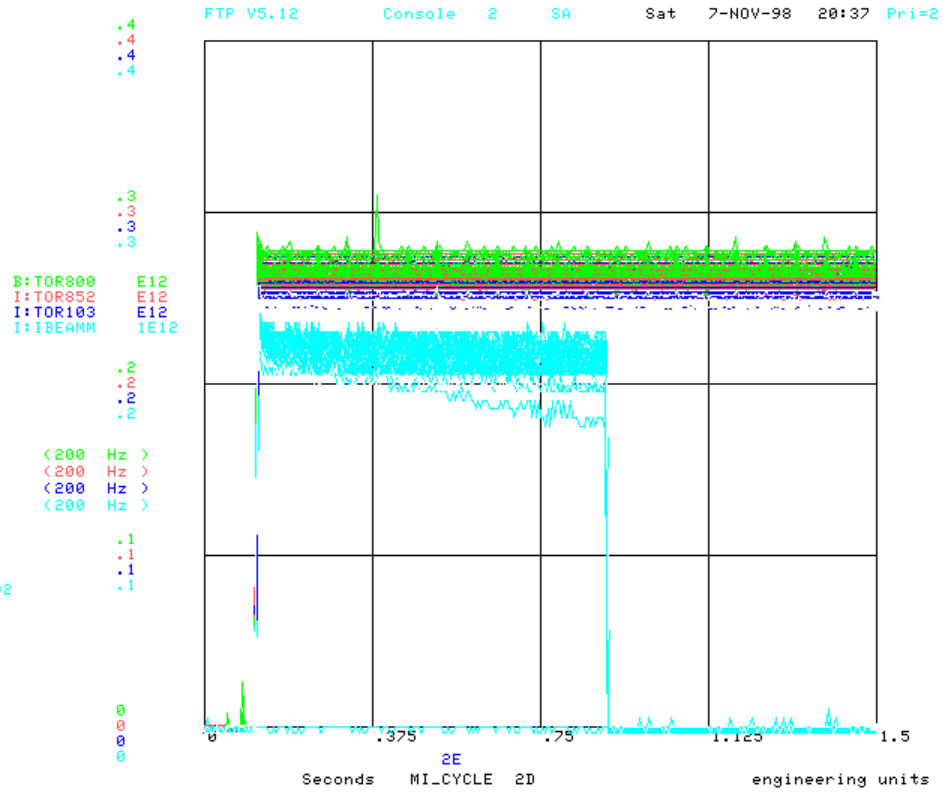


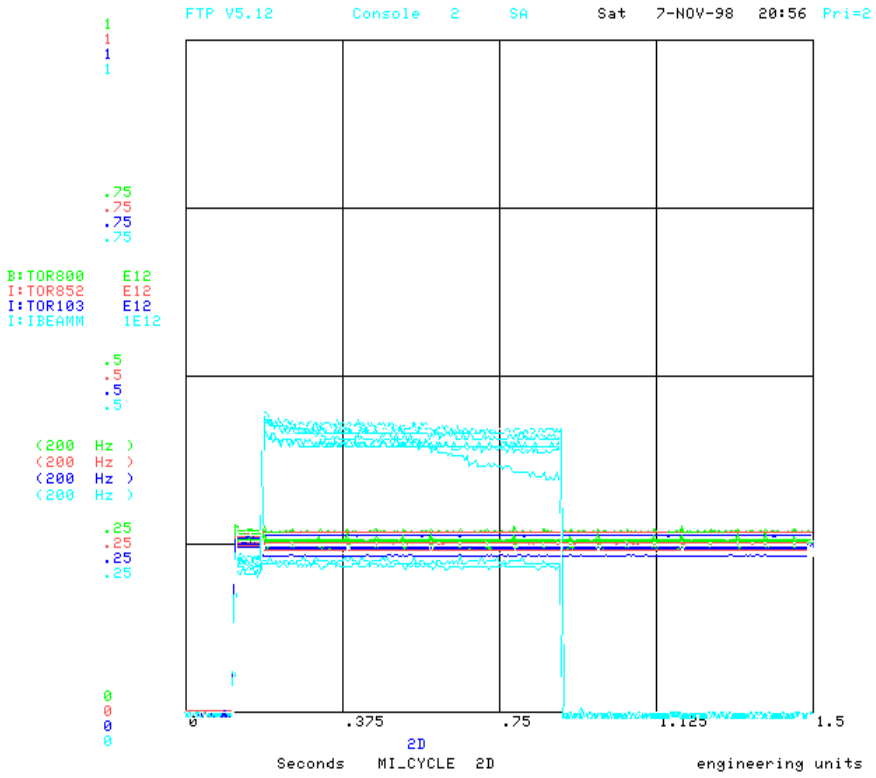




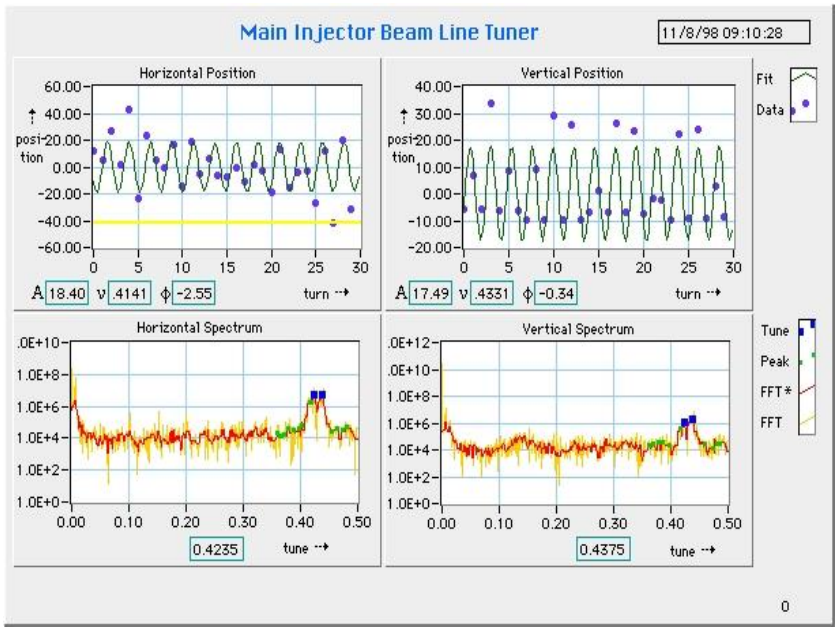
Vertical tune wrong by one unit.

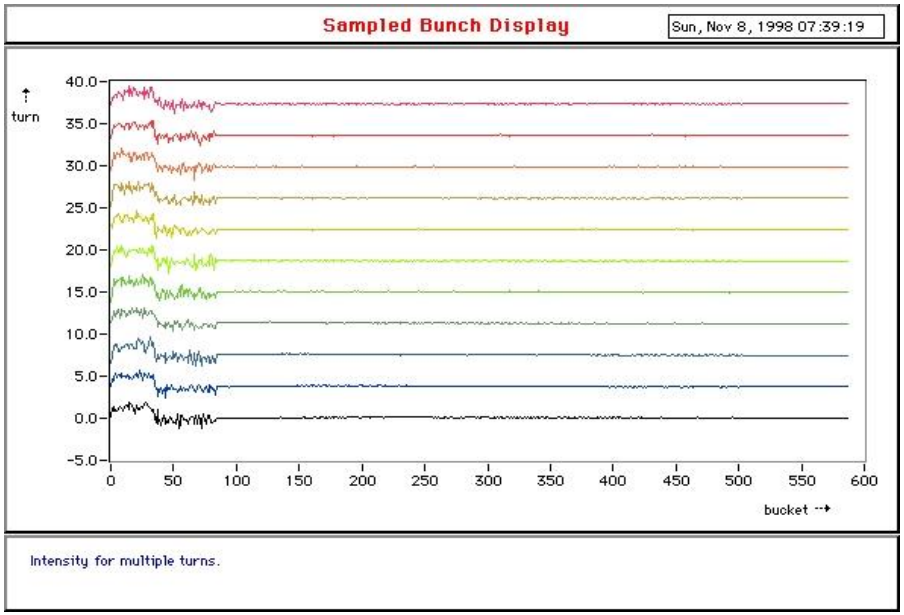
~90% efficiency at
8 GeV.

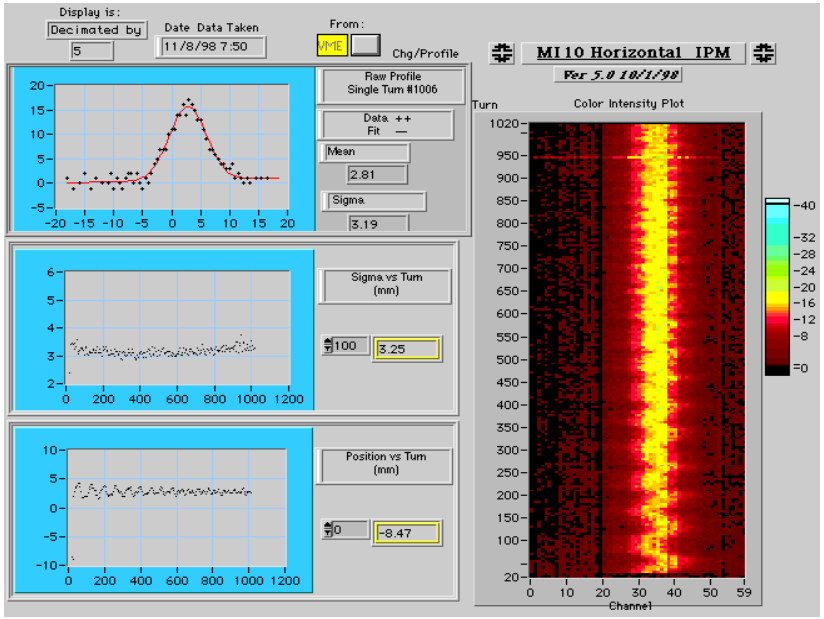


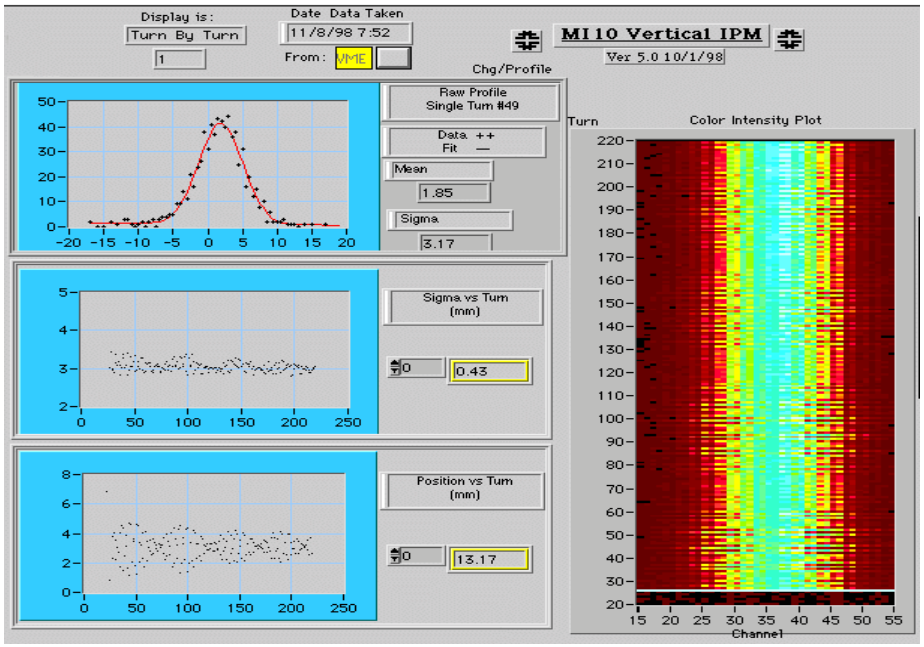


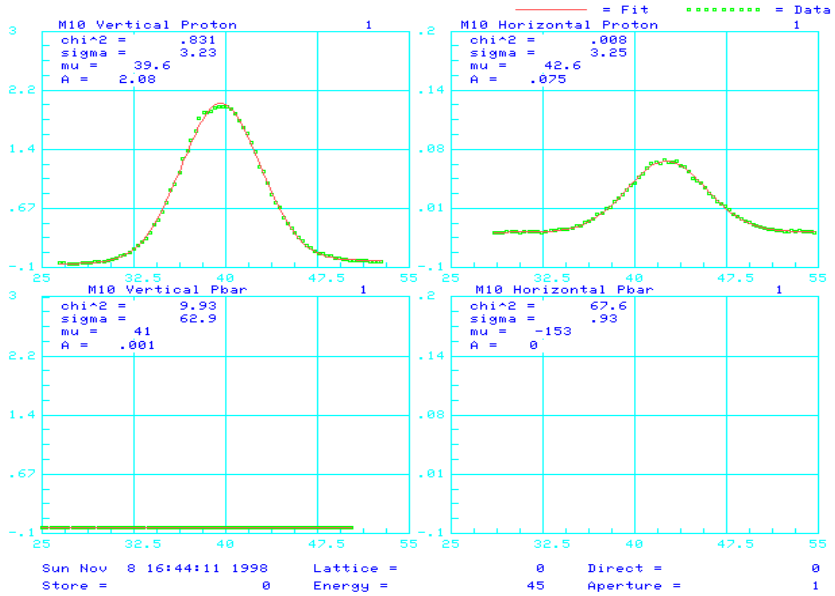
LLRF was working Well.
1st try of Multibatch injection.

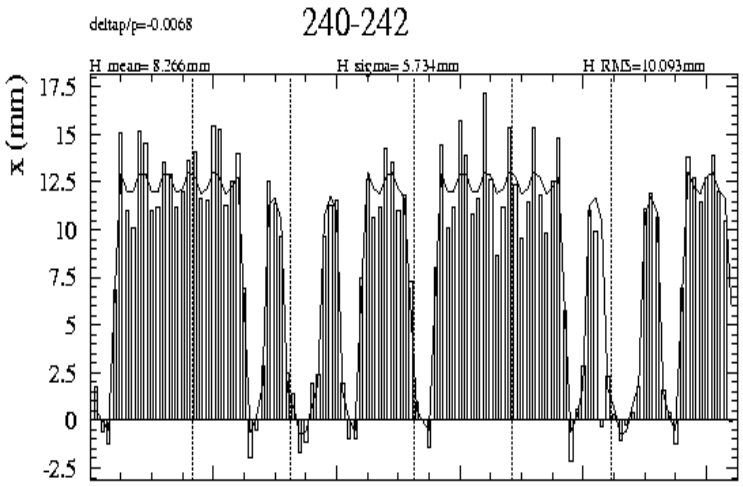

Main Injector Beam Line Tuner
11/8/98 09:10:28
Horizontal Position
Vertical Position
Fit
Data
A 18.40 ν .4141 ϕ -2.55
A 17.49 ν .4331 ϕ -0.34
turn
Horizontal Spectrum
Vertical Spectrum
Tune
Peak
FFT*
FFT
0.4235
0.4375
tune

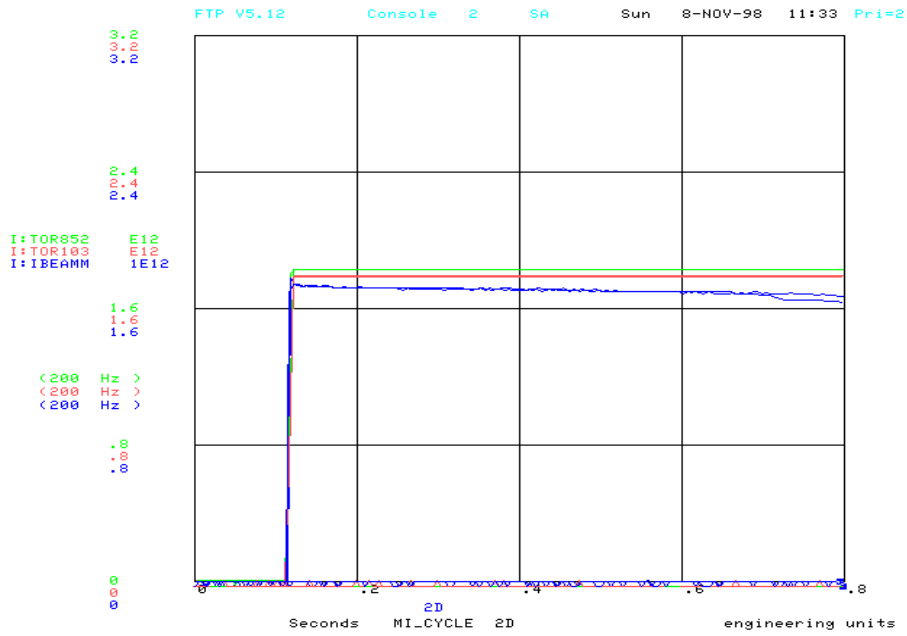

Sampled Bunch Display
Sun, Nov 8, 1998 07:39:19
turn
bucket
Intensity for multiple turns.

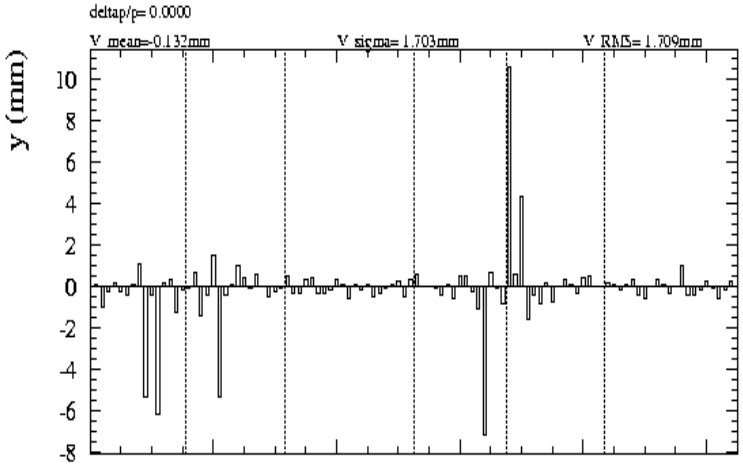

Display is:
Decimated by
5
Date Data Taken
11/8/98 7:50
From:
VME
Chg/Profile
MI10 Horizontal IPM
Ver 5.0 10/1/98
Raw Profile
Single Turn #1006
Data ++
Fit —
Mean
2.81
Sigma
3.19
Sigma vs Turn
(mm)
100
3.25
Position vs Turn
(mm)
0
-8.47
Turn
Color Intensity Plot
Channel


Display is:
Turn By Turn
1
Date Data Taken
11/8/98 7:52
From:
VME
Chg/Profile
MI10 Vertical IPM
Ver 5.0 10/1/98
Raw Profile
Single Turn #49
Data ++
Fit —
Mean
1.85
Sigma
3.17
Sigma vs Turn
(mm)
0
0.43
Position vs Turn
(mm)
0
13.17
Turn
Color Intensity Plot
Channel


= Fit
= Data
M10 Vertical Proton
chi^2 = .831
sigma = 3.23
mu = 39.6
A = 2.08
M10 Horizontal Proton
chi^2 = .008
sigma = 3.25
mu = 42.6
A = .075
M10 Vertical Pbar
chi^2 = 9.93
sigma = 62.9
mu = 41
A = .001
M10 Horizontal Pbar
chi^2 = 67.6
sigma = .93
mu = -153
A = 0
Sun Nov 8 16:44:11 1998
Lattice = 0
Direct = 0
Store = 0
Energy = 45
Aperture = 1


deltap/p=-0.0068
240-242
H mean=8.266mm
H sigma=5.734mm
H RMS=10.093mm
x (mm)


FTP V5.12
Console 2
SA
Sun 8-NOV-98 11:33 Pri=2
I:TOR852 E12
I:TOR103 E12
I:IBEAMM 1E12
(200 Hz)
(200 Hz)
(200 Hz)
2D
Seconds MI_CYCLE 2D
engineering units


deltap/p=0.0000
V mean=0.132mm
V sigma=1.703mm
V RMS=1.709mm
y (mm)

11/8/98

Fermilab

November 13, 1998

To: Bob Mau

From: Steve Holmes John Marriner

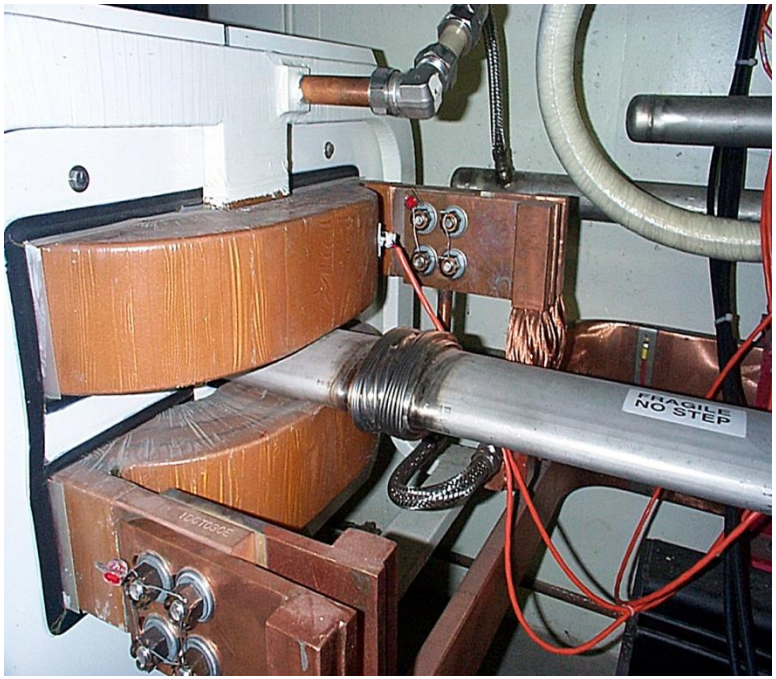
SUBJECT: PERMISSION TO ACCELERATE BEAM IN THE MAIN INJECTOR

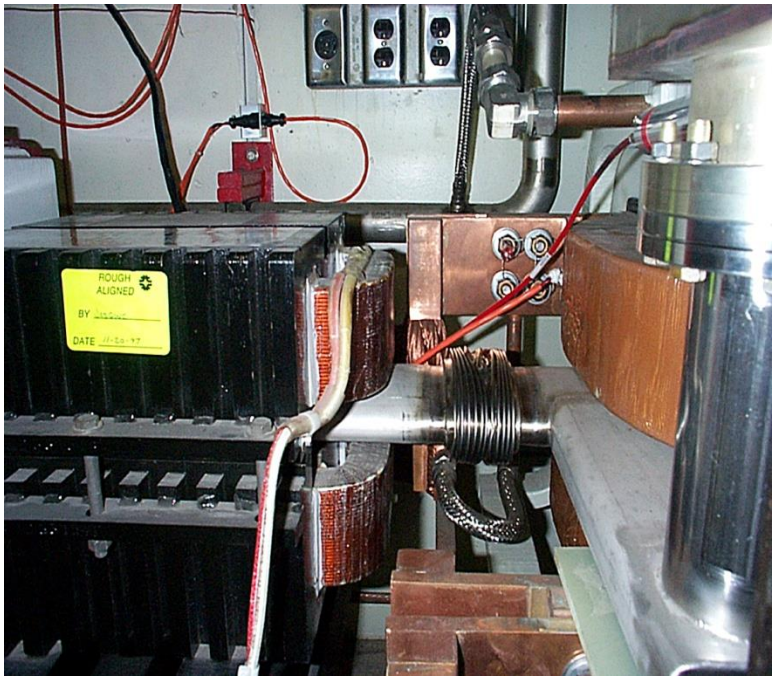
Attached you will find the newly completed Beam Permit for 8 GeV line and Main Injector operations. This beam permit supercedes that issued on October 9. You are now authorized to accelerate beam in the Main Injector subject to the attached operating limits.

cc:
M. Andrews
J. Marriner
P. Martin

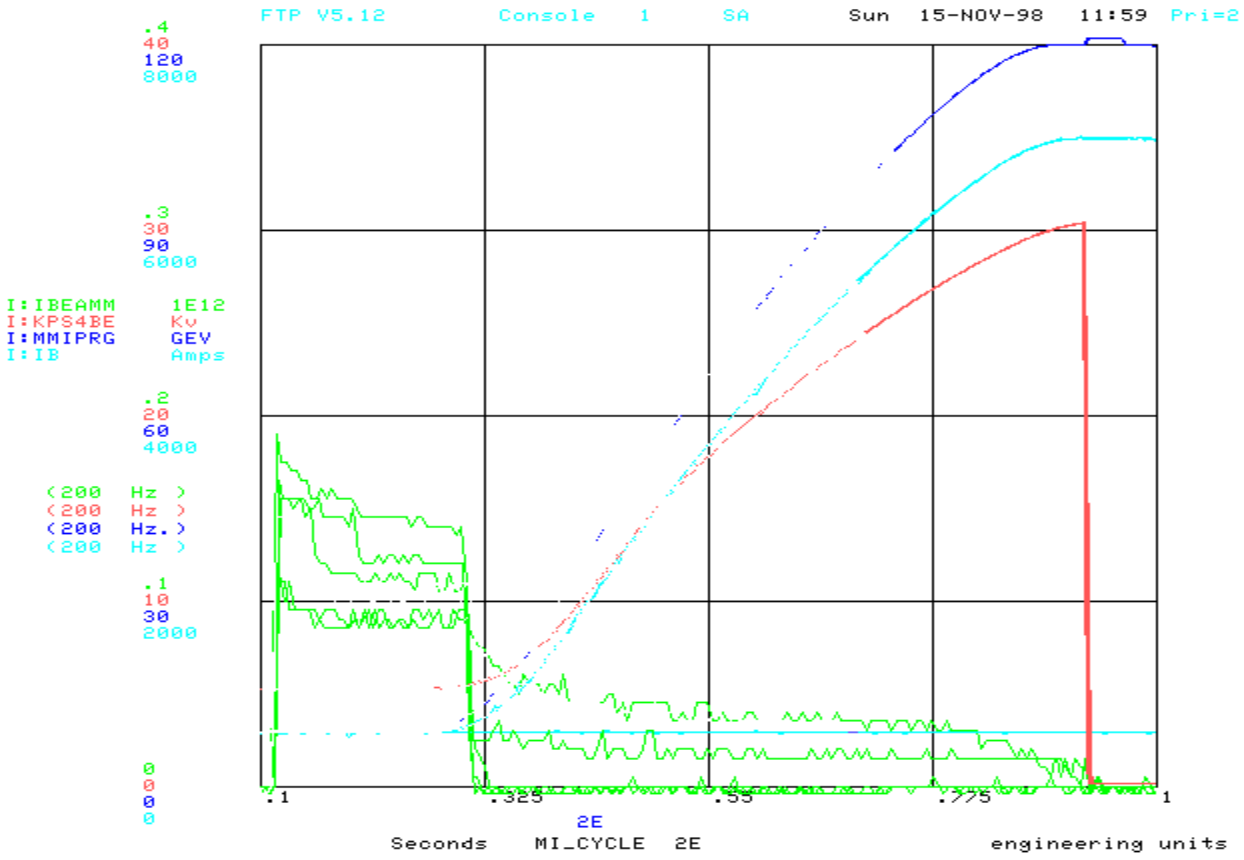
After a lot of paper ES&H work, MISRC meetings. The Main Injector Commissioning got the approval to accelerate beam in the Main Injector on Nov 13th 1998.

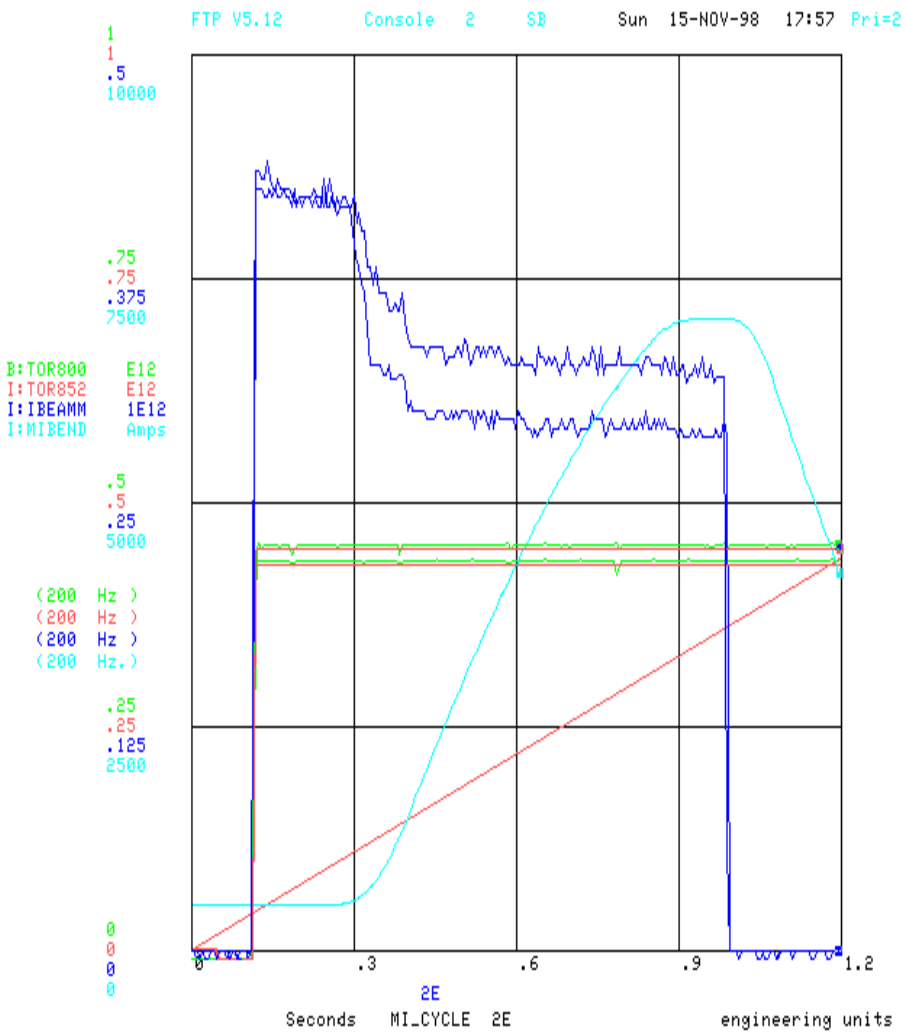
Another Accident Just before Acceleration





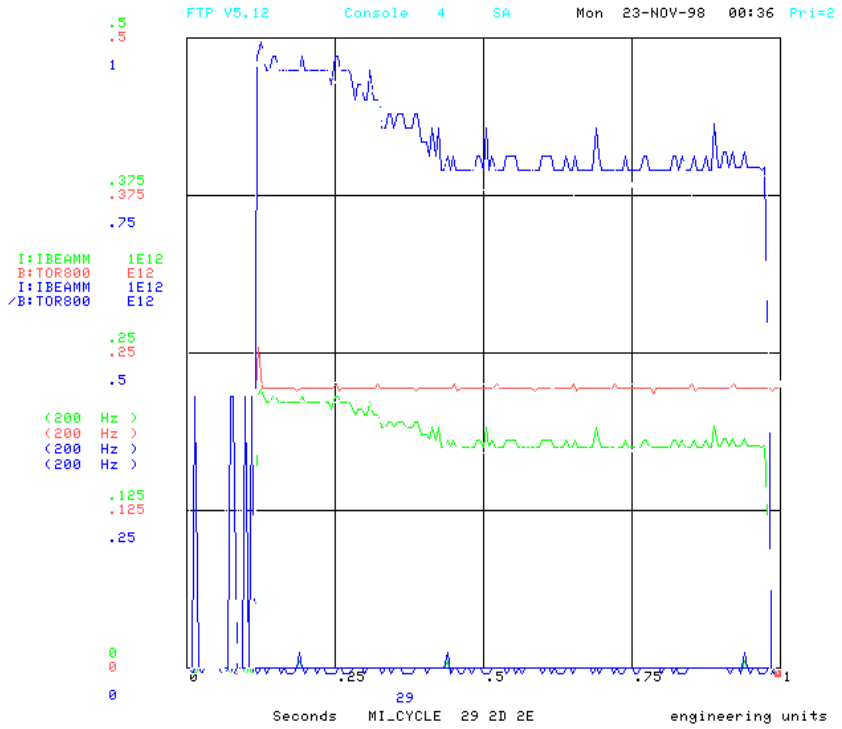
Beam Acceleration 120 GeV (11/15/98)




FTP V5.12 Console 2 SB Sun 15-NOV-98 17:57 Pri=2
1
1
.5
10000
.75
.75
.375
7500
B:TOR800 E12
I:TOR852 E12
I:IBEAMM 1E12
I:MIBEND Amps
.5
.5
.25
5000
(200 Hz)
(200 Hz)
(200 Hz)
(200 Hz.)
.25
.25
.125
2500
0
0
0
0
0
.3
.6
.9
1.2
2E
Seconds MI_CYCLE 2E
engineering units

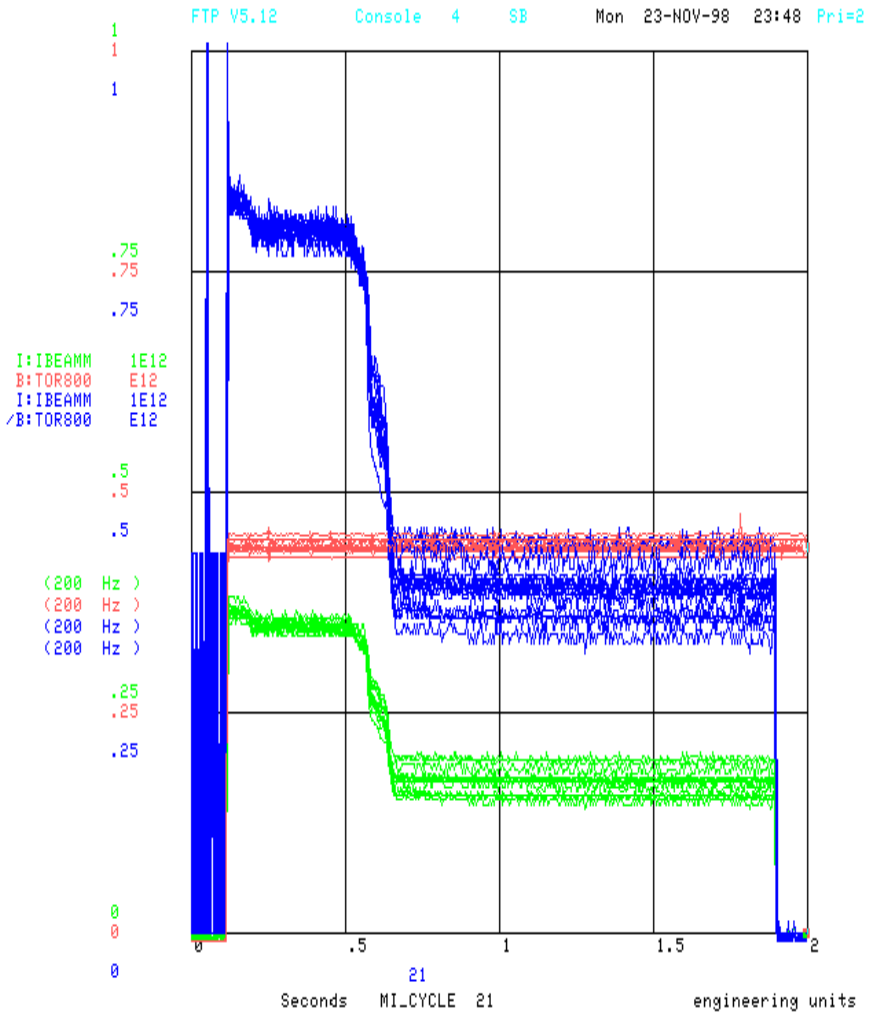
Working towards Commissioning Goals

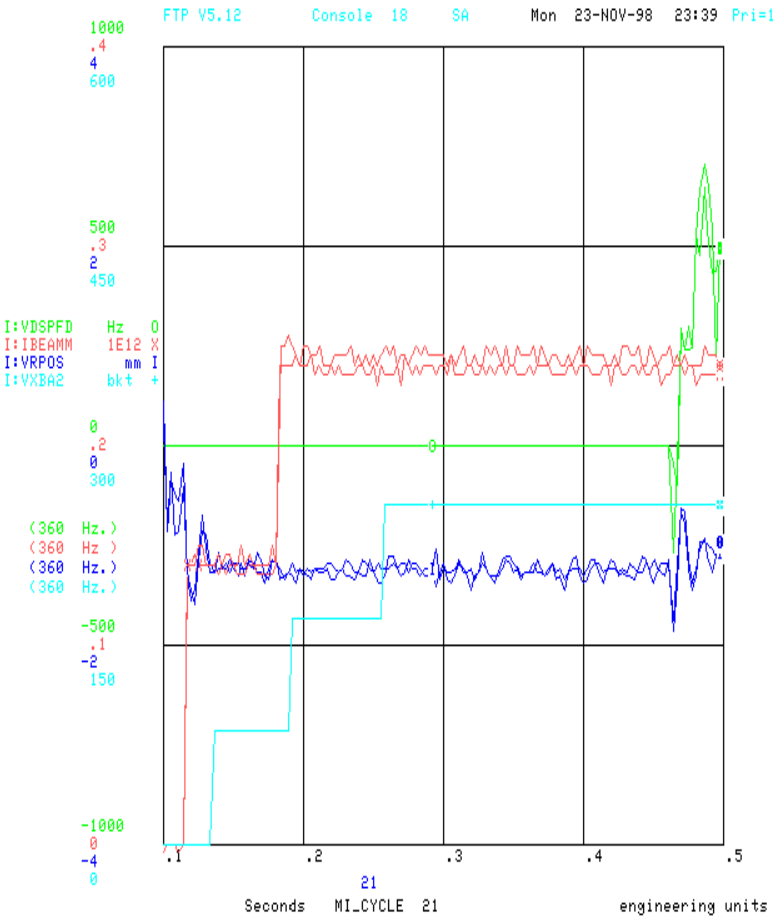
Now the party was over and long shifts towards commissioning goals started over the Thanks Giving holidays.



Adjustment of injection, orbit, tune, chromaticity up the ramp help improve the efficiency.

150 GeV Acceleration

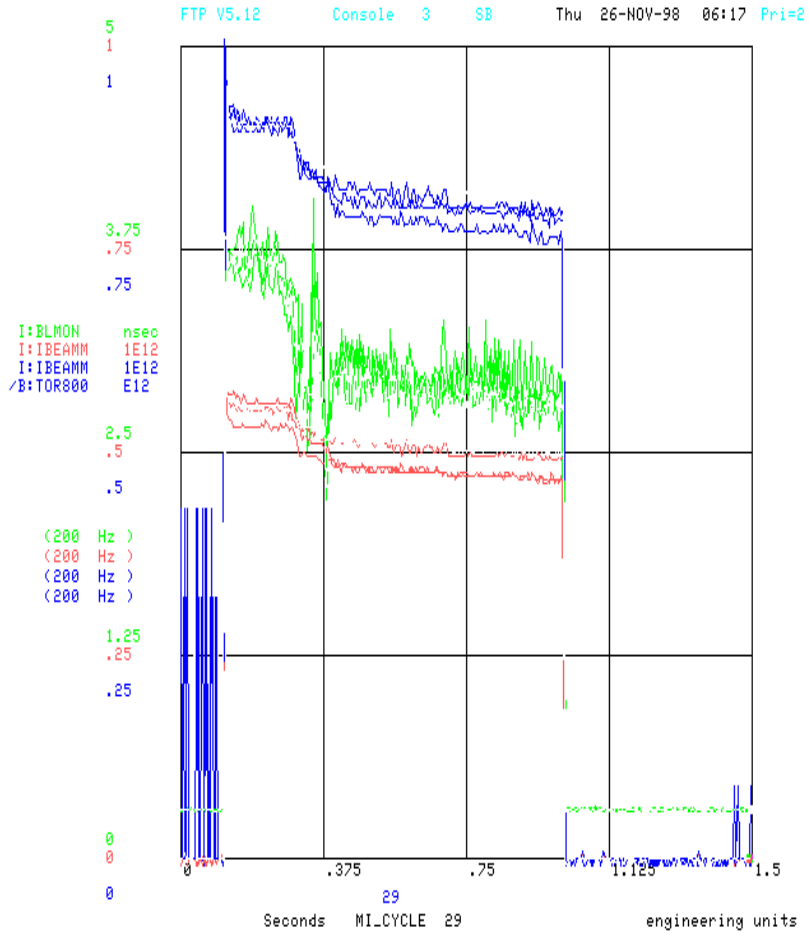




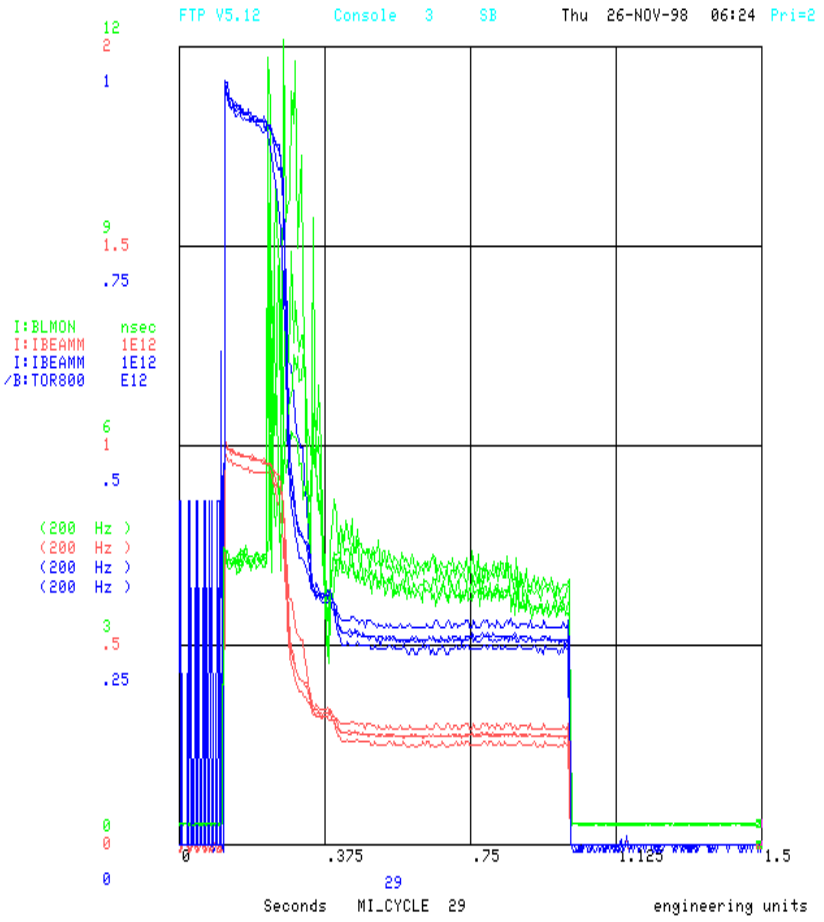
Multi-batch to 150 GeV

1st Main Injector Quadrupole Failed 11/24/98

Increasing Intensity in the Main Injector



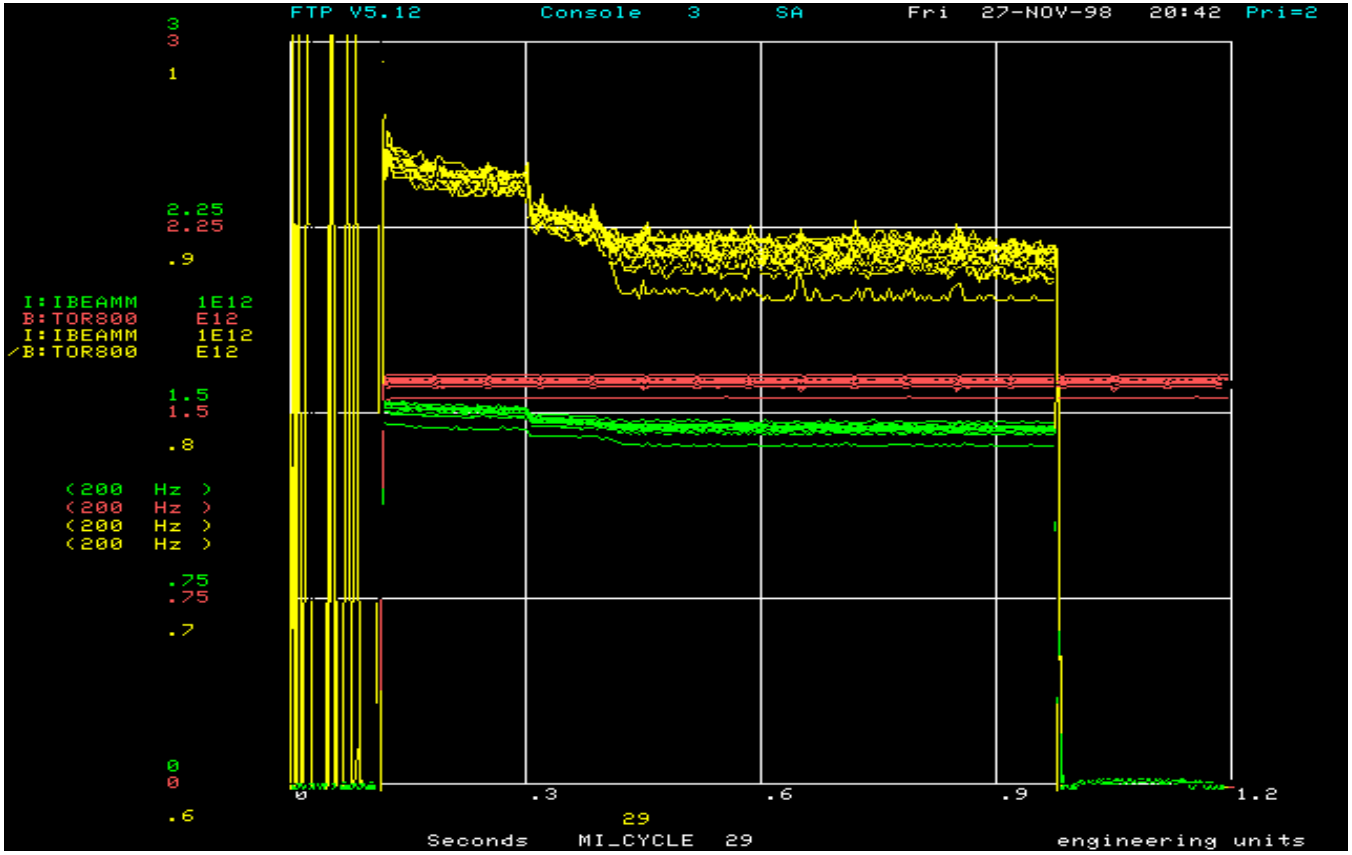
2 turns



3 turns

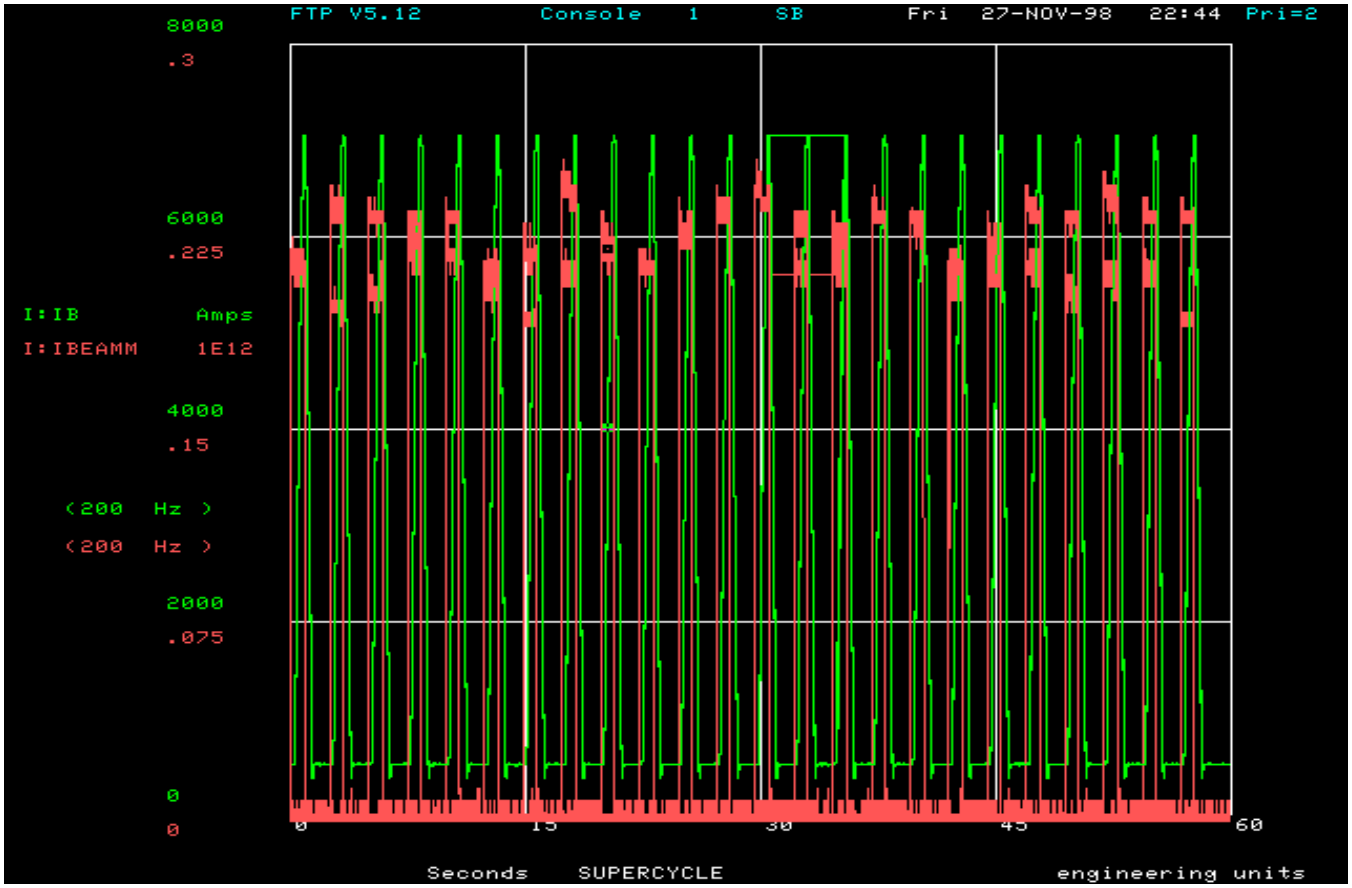
On Nov 27th 1998, Fermilab Main Injector accelerated high intensity proton per batch to 120 GeV. Protons were accelerated to 120 GeV with a transmission efficiency of ~85% to 120 GeV. This satisfied one of the Main Injector commissioning goal.

- 120 GeV Protons Energy for antiproton production.



On Nov 27th 1998, We successfully ramped the Main Injector with beam at a repetition rate of 2.5 Sec. This satisfied the commissioning goal

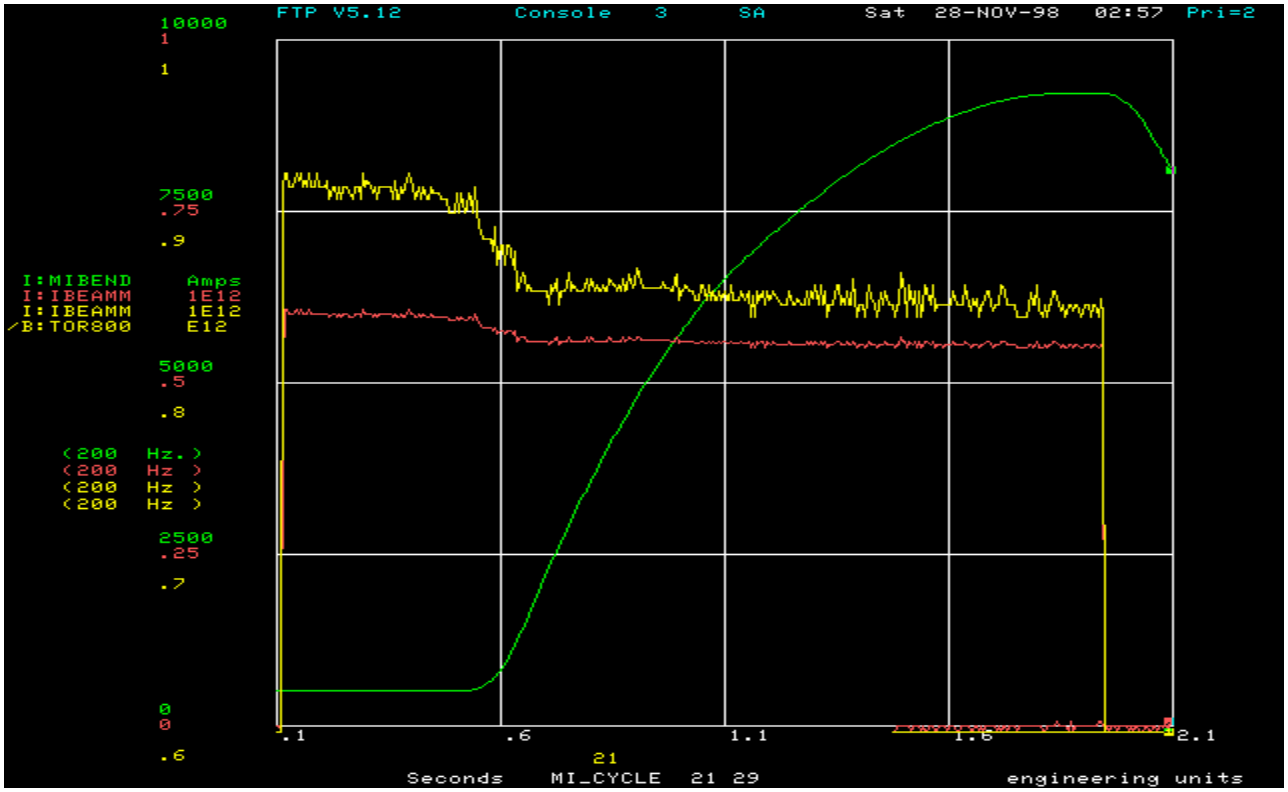
- 2.5 sec Cycle Time to 120 GeV.



On Nov 28th 1998, We successfully ramped the Main Injector to 150 GeV with beam. The overall efficiency was ~85% at 150 GeV.

This satisfied two Main Injector commissioning goals.

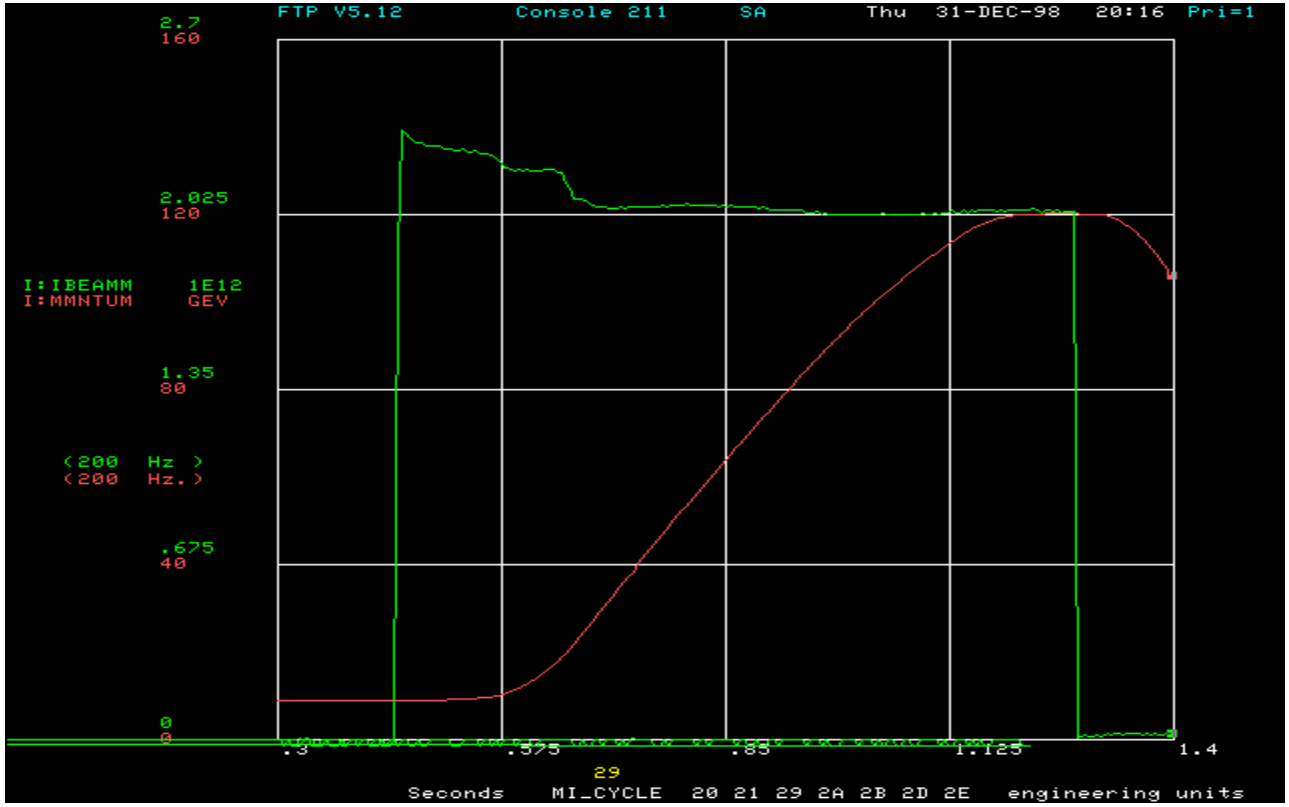
- 150 GeV Proton Energy for injection into Tevatron.
- 75% proton transmission efficiency at 150 GeV.



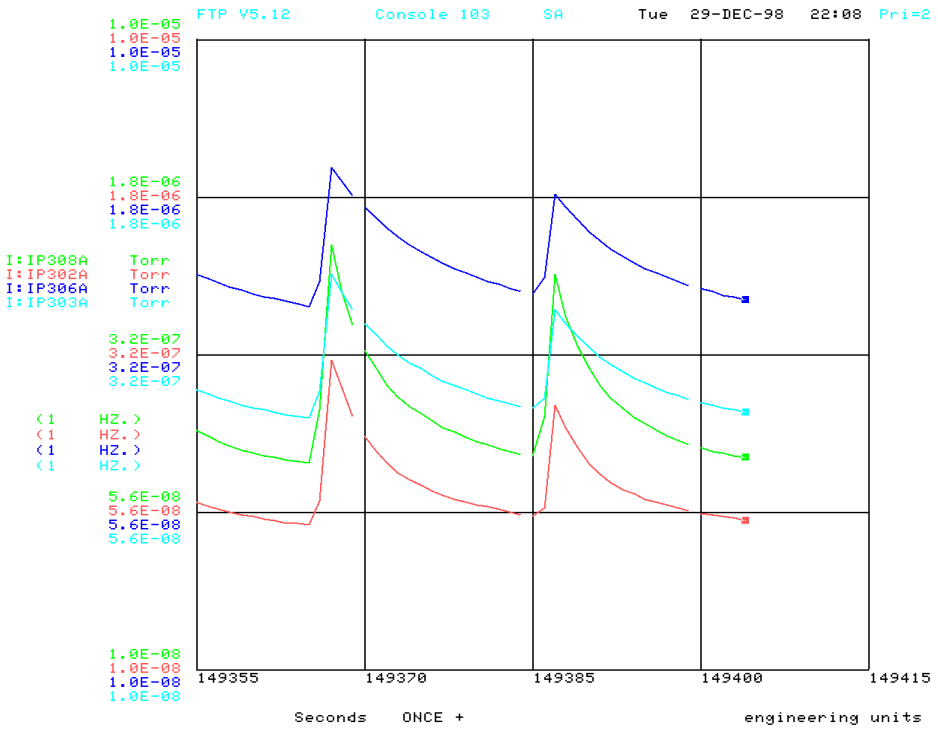
On Dec 24th 1998 Fermilab Main Injector achieved 2.2e12 protons/batch intensity @ 120 GeV. The overall efficiency achieved was ~75% at this intensity.

This satisfied one of the Main Injector commissioning goal:

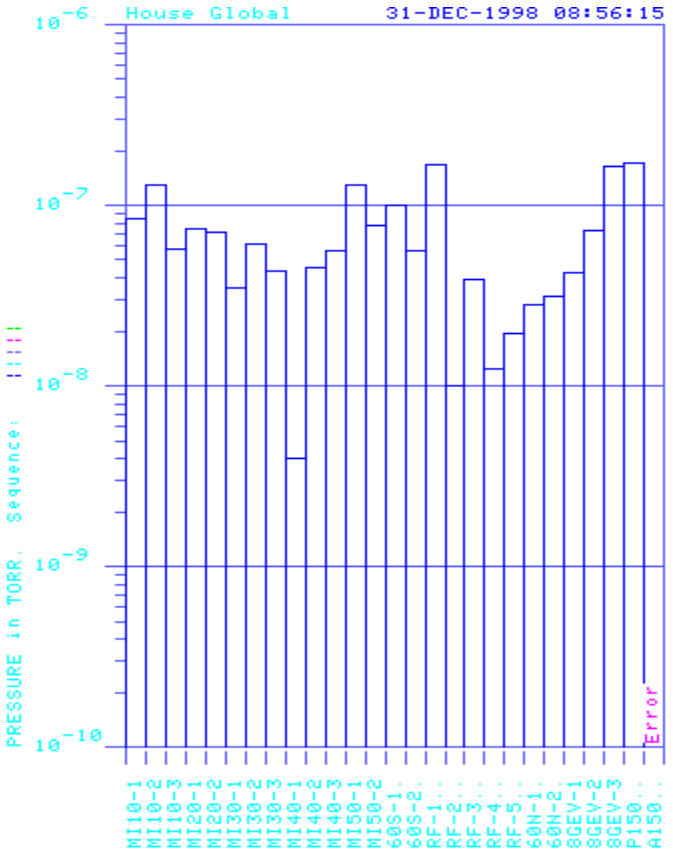
- 2e12 protons for antiproton production per cycle.



Vacuum Problem

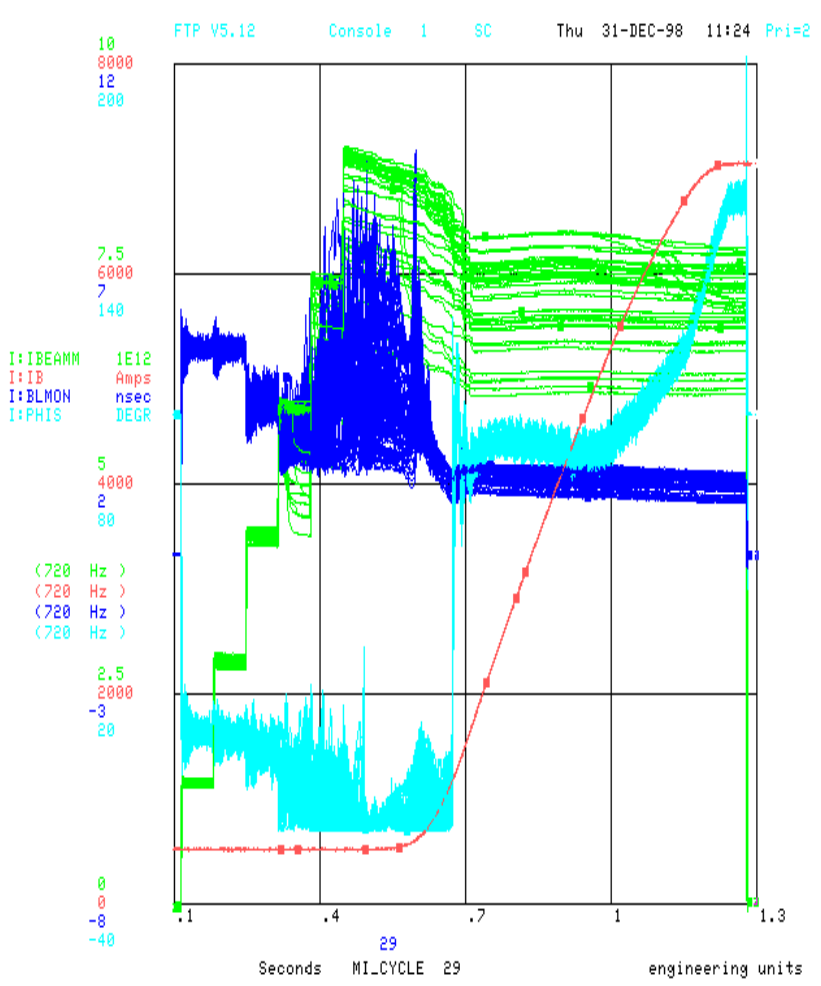


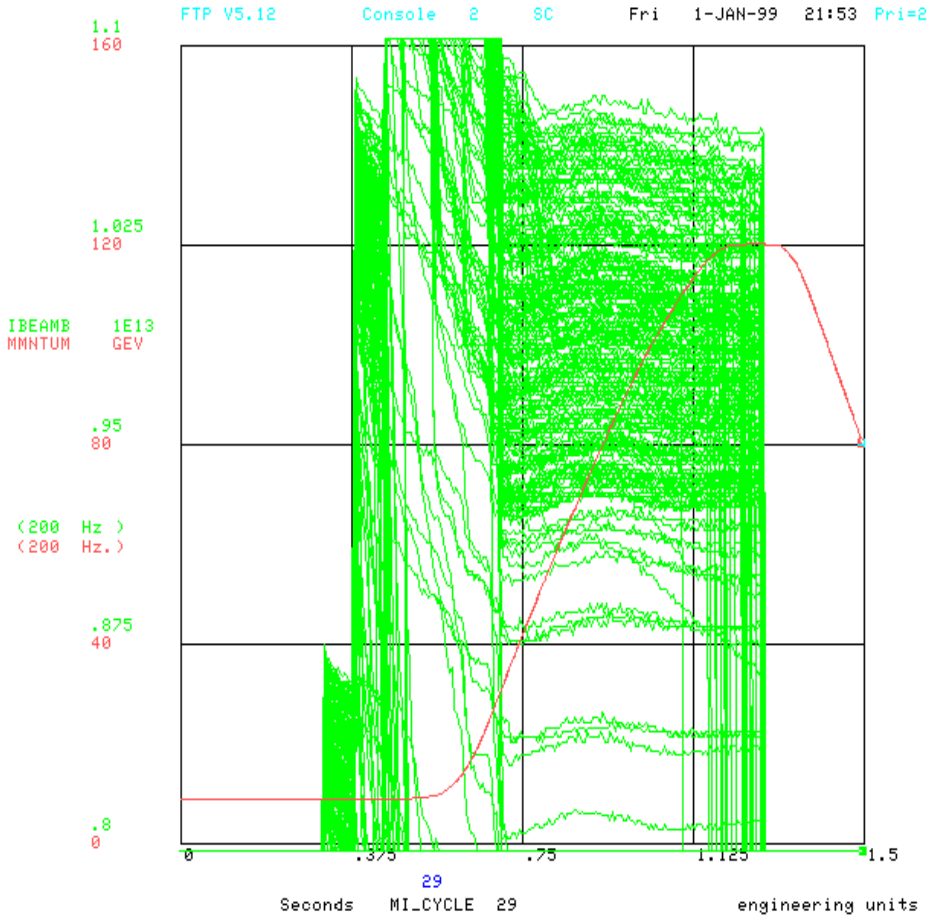
Vacuum induced beam valve closing.



Ring Wide Vacuum

Push for higher intensity





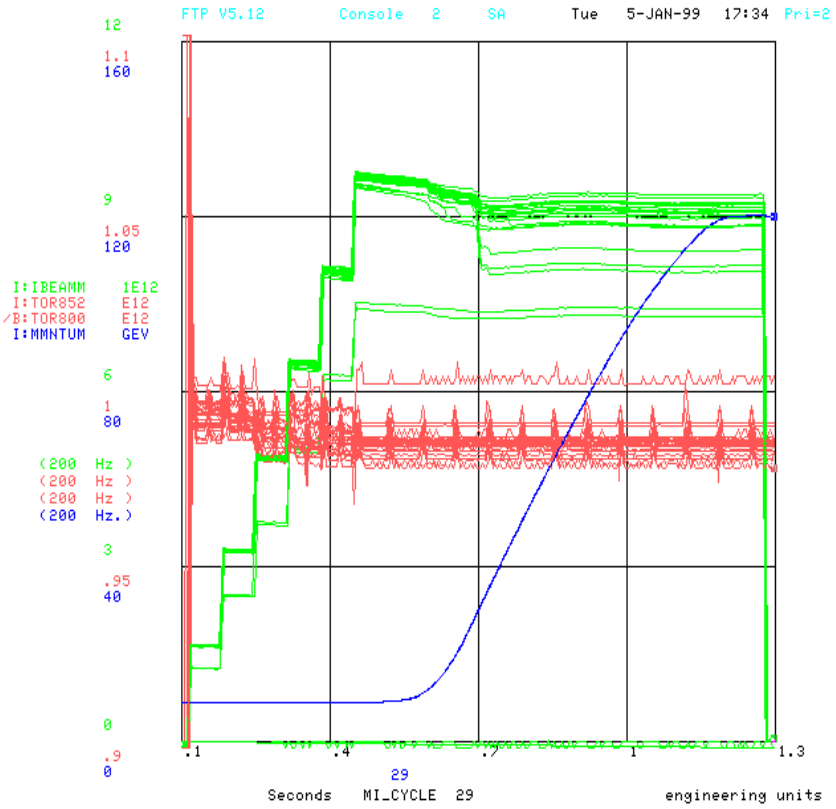
120 GeV > 1.0e13

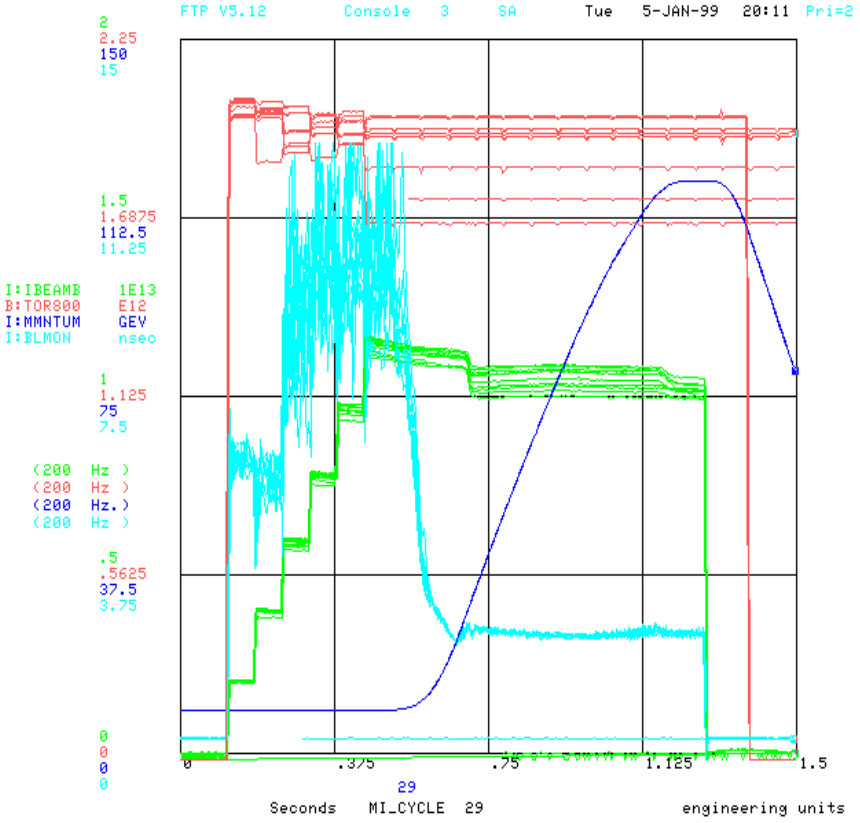
Push for higher intensity...

Tuning for higher intensity continued for days. Essentially tuning and optimizations were performed on all fronts.

- Orbit
- Tune and Chromaticity up the Ramp (Injection chromaticity was adjusted to about -30 to keep the beam stable in the MI.)
- HLRF voltage,
- LLRF
- Reducing loss at injection, start of acceleration and transition by changing all of the above.

LLRF work improved the efficiency. We could get about 9e12 with only 4 Booster turns.

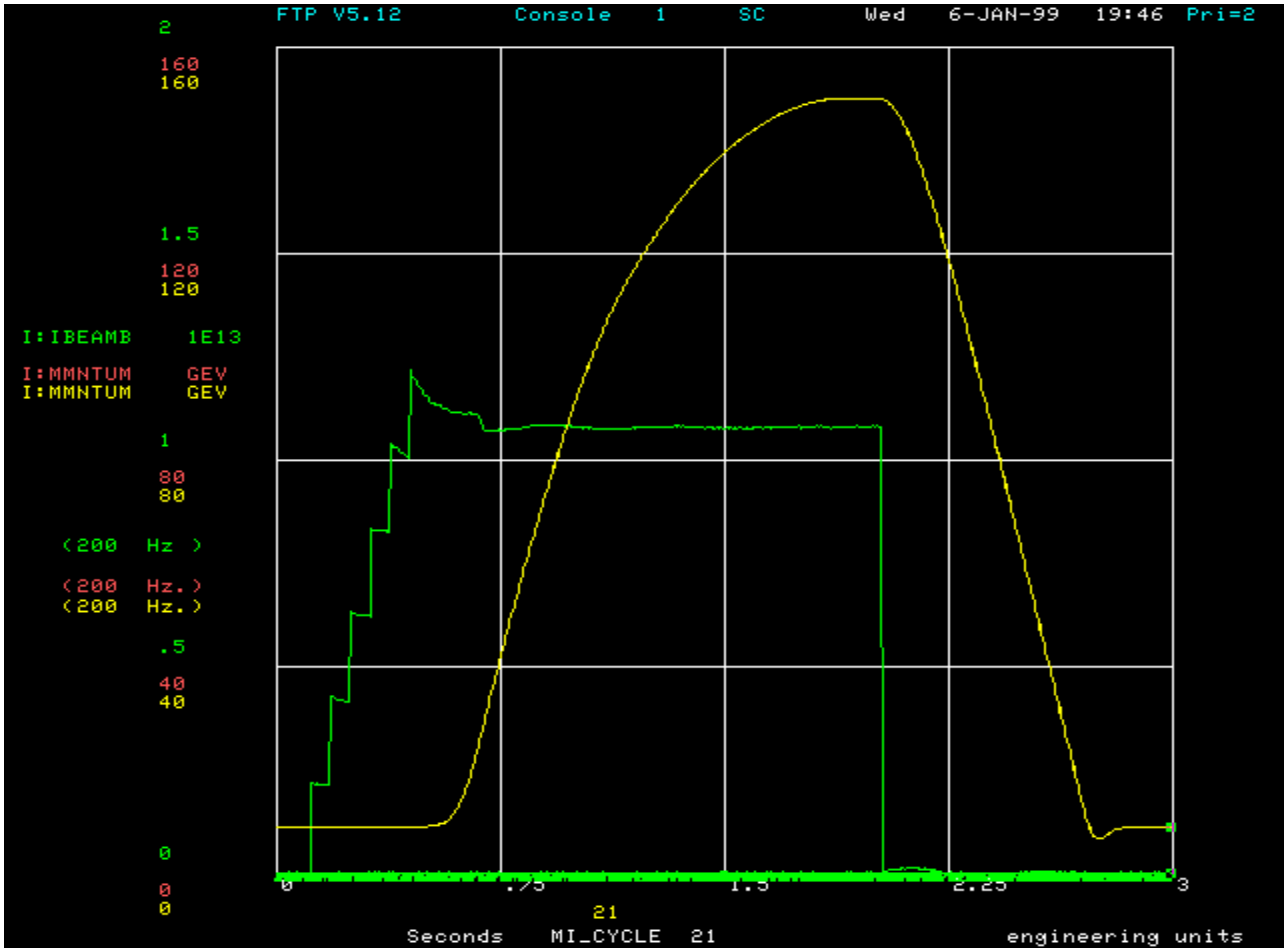




BLMON was increasing for 3-6 batch injection, with 5 turns from Booster.

On Jan 6th 1999 Fermilab Main Injector achieved >1e13 protons/6 batch intensity @150 GeV. The Main Injector Commissioning goal was to achieve

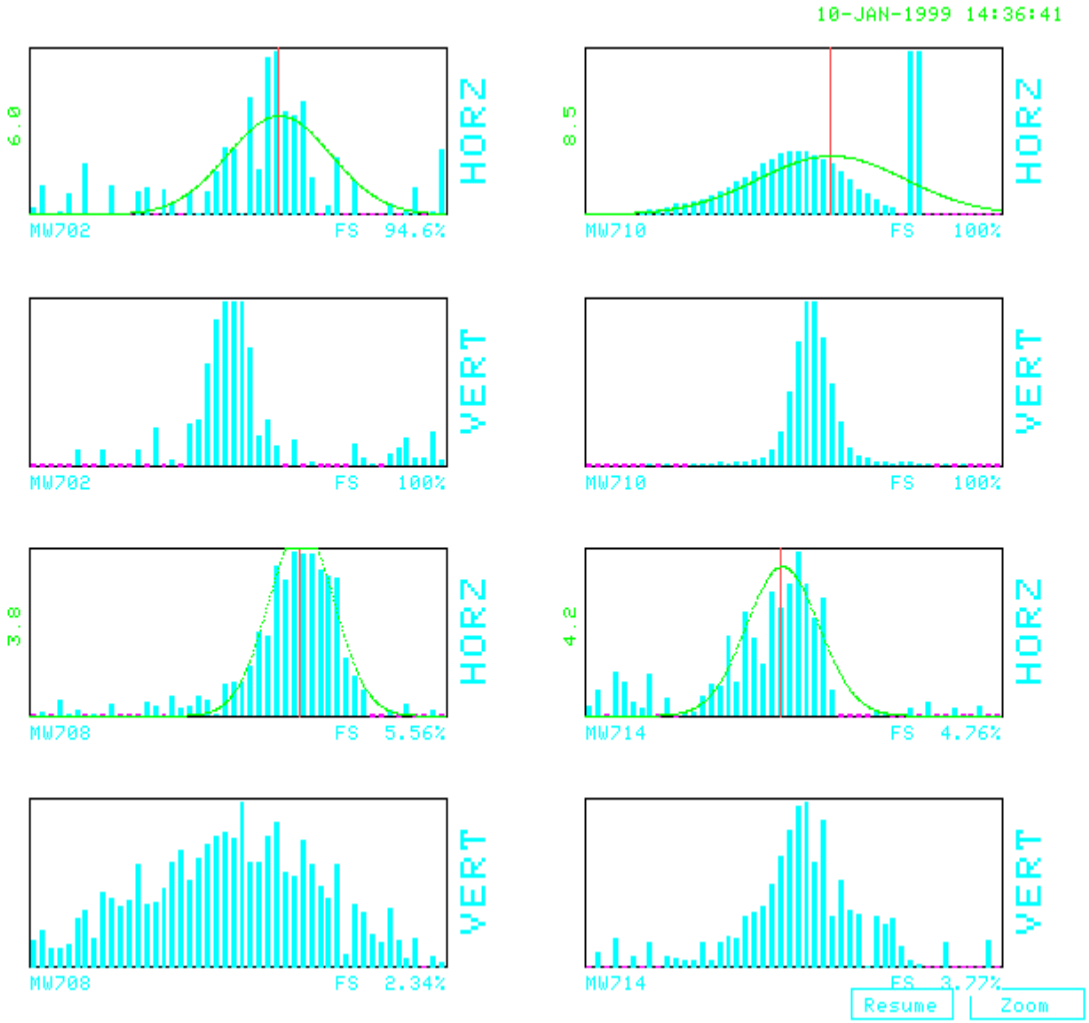
- 1e13 protons/6 batch intensity @150 GeV.



6th Goal of MI celebrated

Beam towards pbar

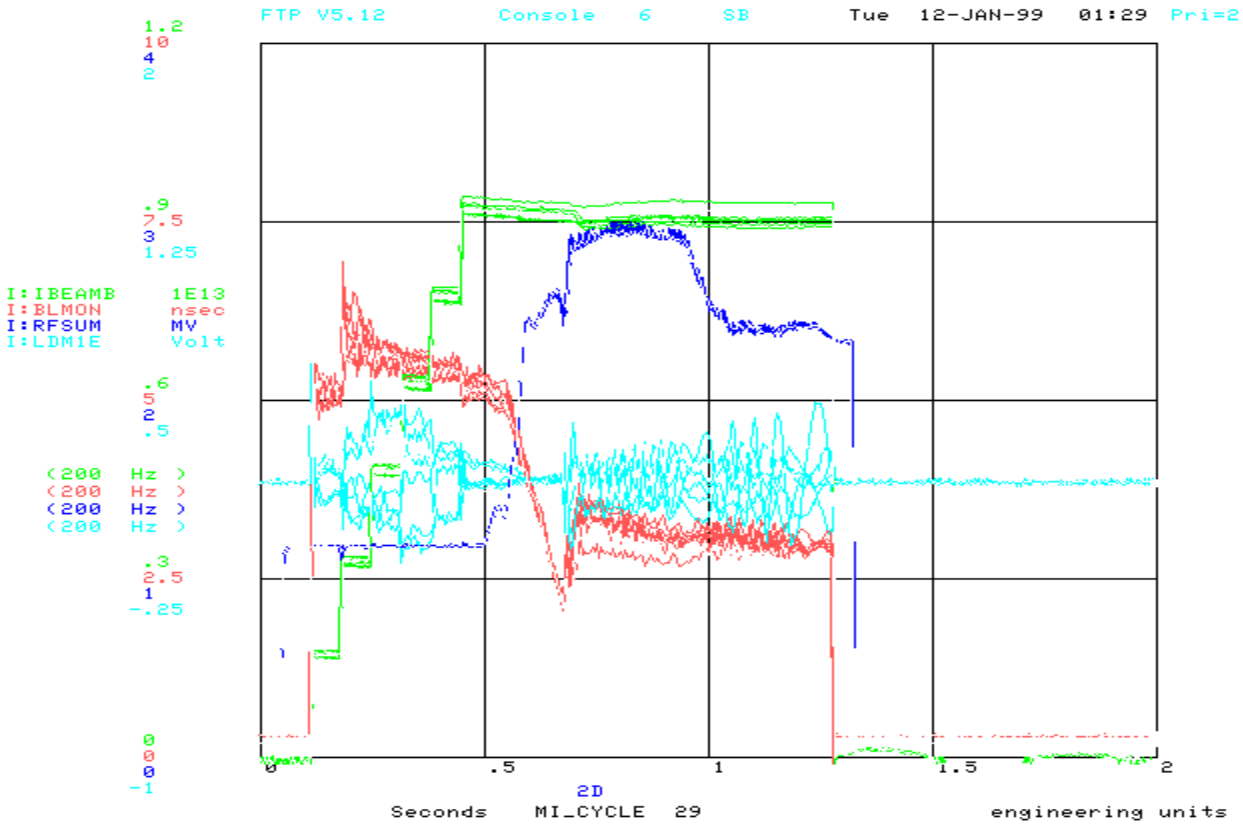
At the end of this running period we made a unsuccessful attempt to send beam to pbar



Problems

- Quads and Dipoles wired backwards.
- Quads misaligned
- Several other misalignments.

Longitudinal Dampers



Last Commissioning Goal

- 2e13 proton/pulse slow extracted at 120 GeV.

We had achieved >1e13 protons/pulse at 120 GeV by considerable tuning.

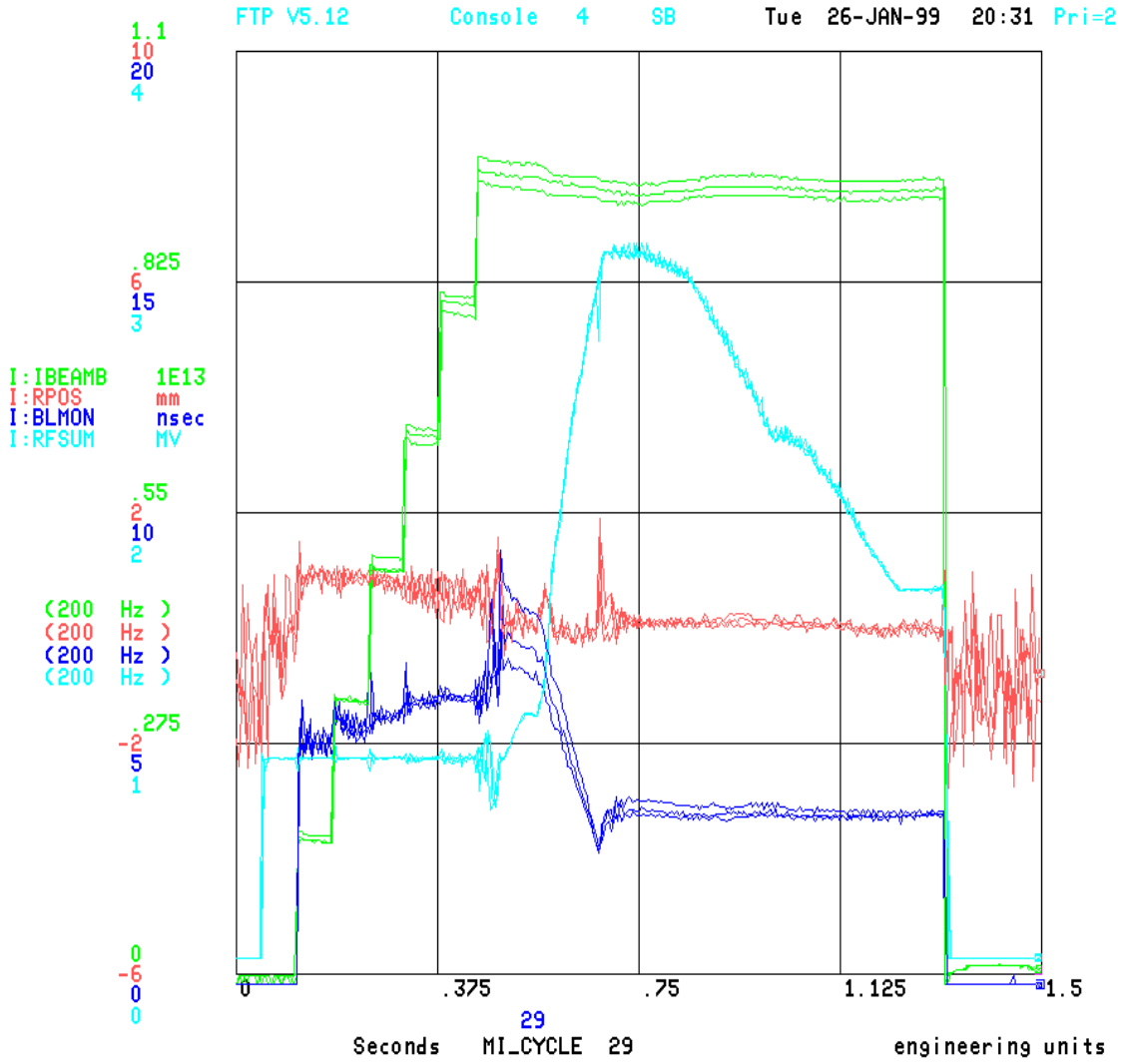
We worried that instability must be just around the corner which will prevent us from increasing intensity any further.

We spend sometime looking for signs of instability, in order to put together a plan for installing and commissioning damper systems after a short shut down.

During the shutdown

- Dampers
- Septa and QXR
- P1/P2 Line

After Shutdown goal 2e13 ppp

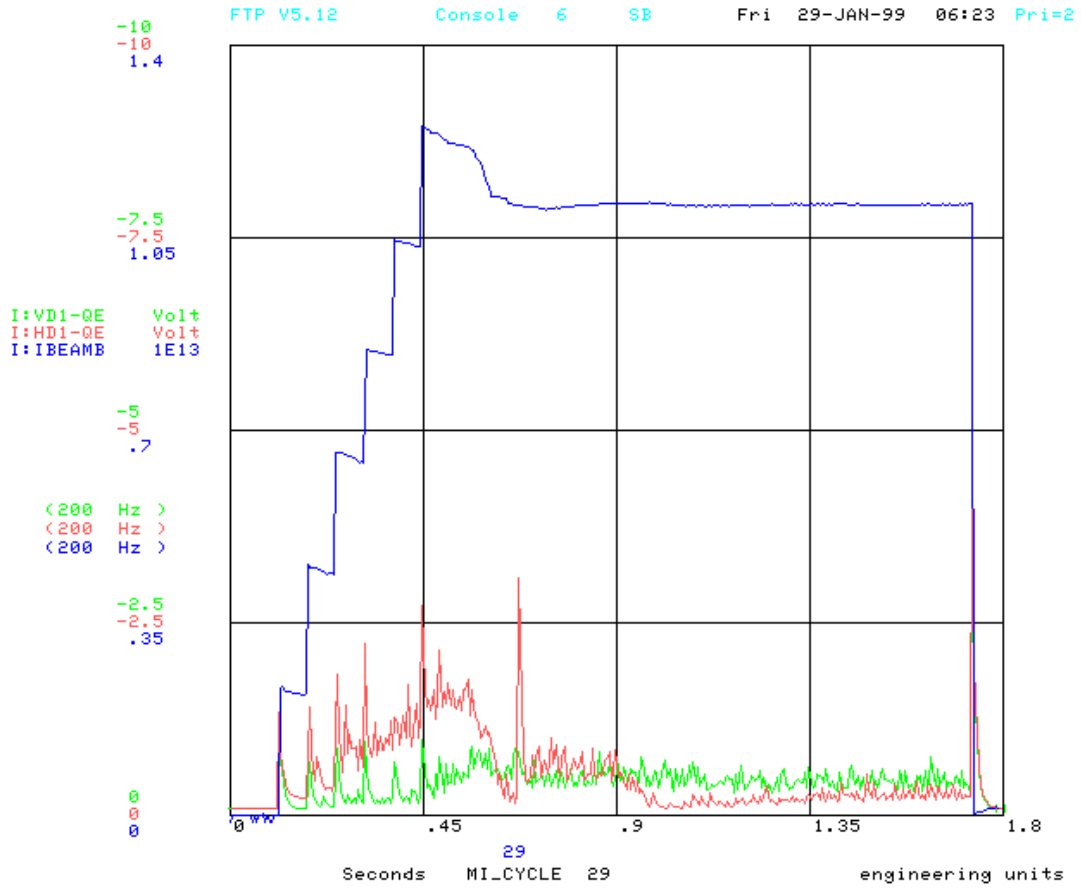


Booster became very unstable just after the shutdown was over.

Two Goals:

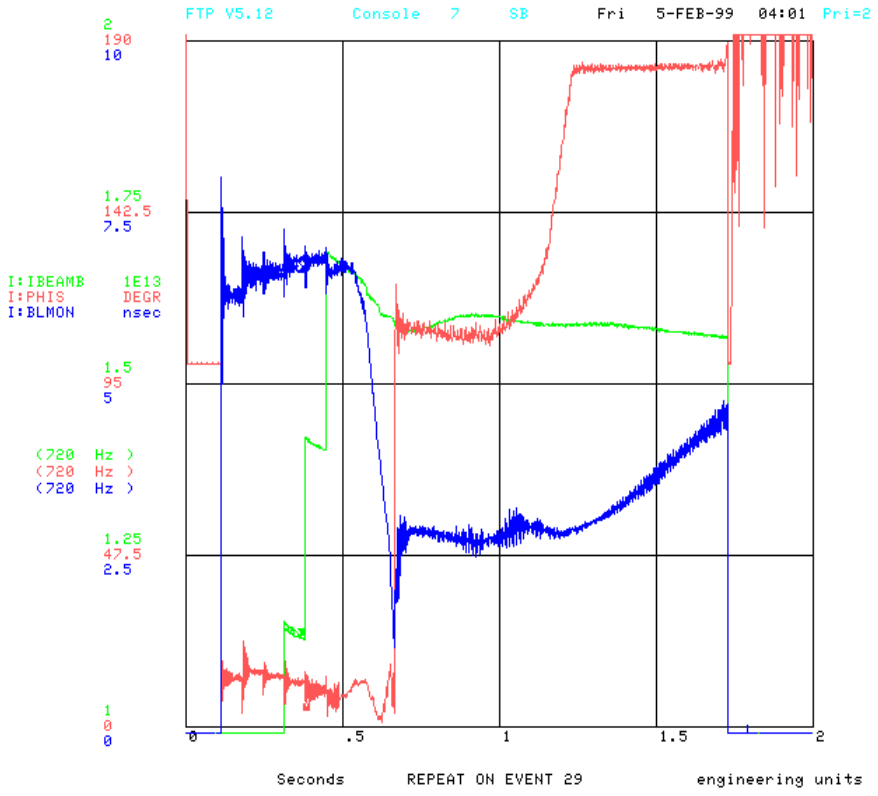
- MI High Intensity
- P1/P2 at 8 GeV

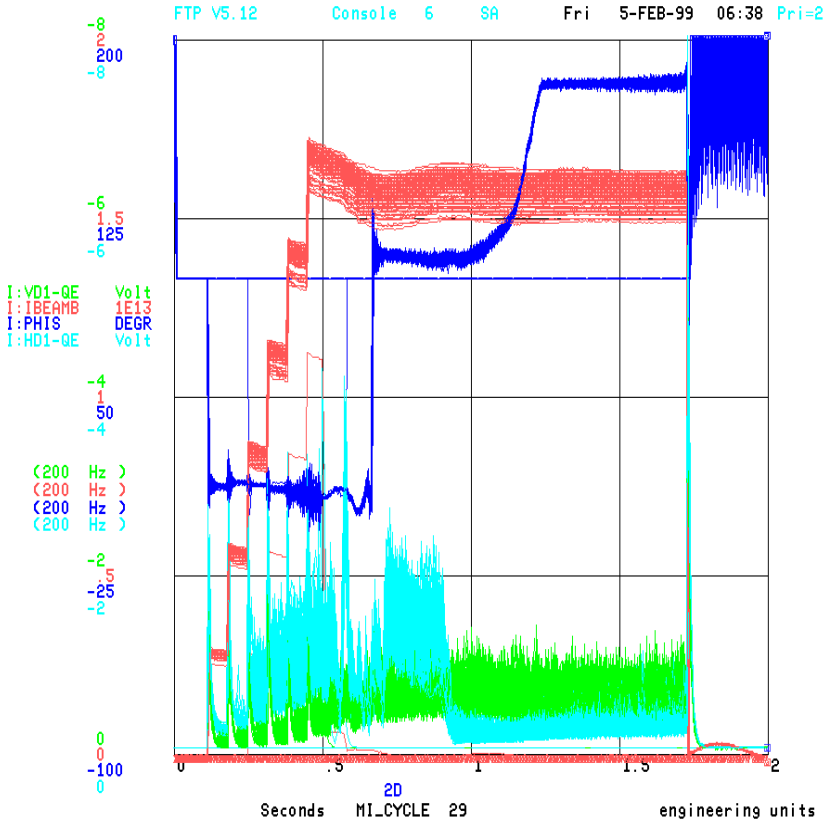
Transverse Damper



1-q error signals with the highest intensity observed so far. Even with the dampers off the error signals indicate no instability.

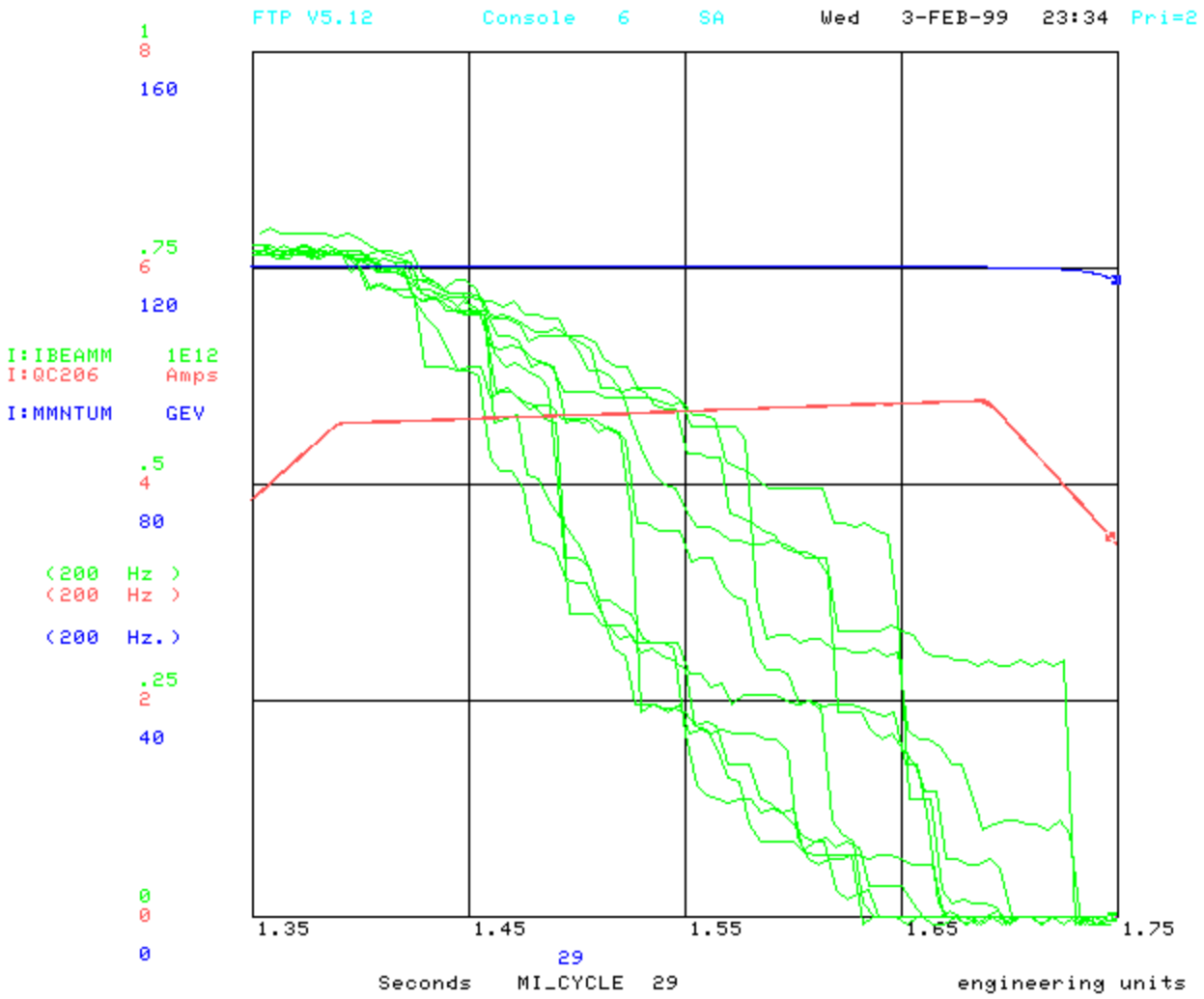
Max Intnesity



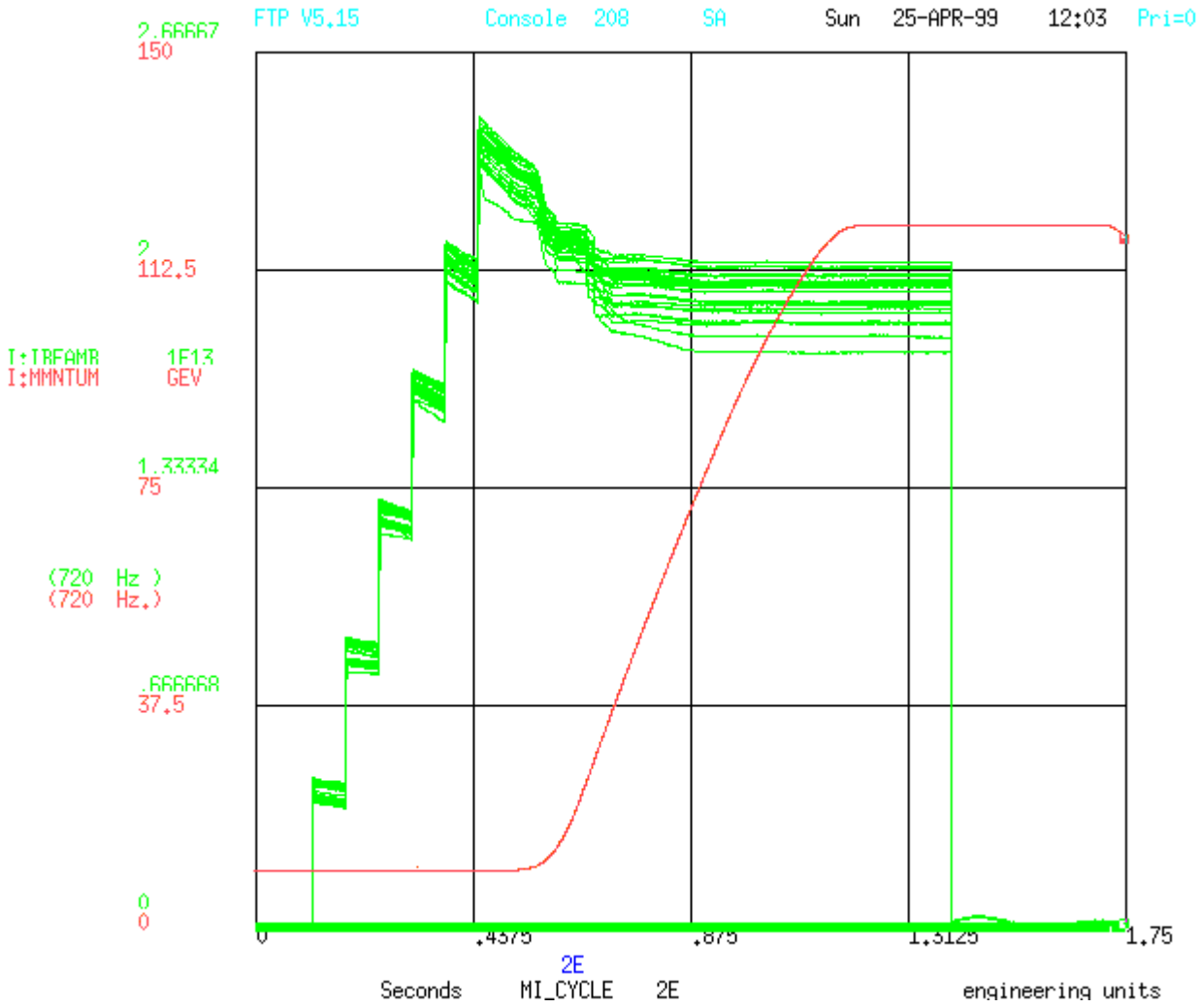


Max Intensity with no instability. ppp > 1.6e13 with >85% efficiency

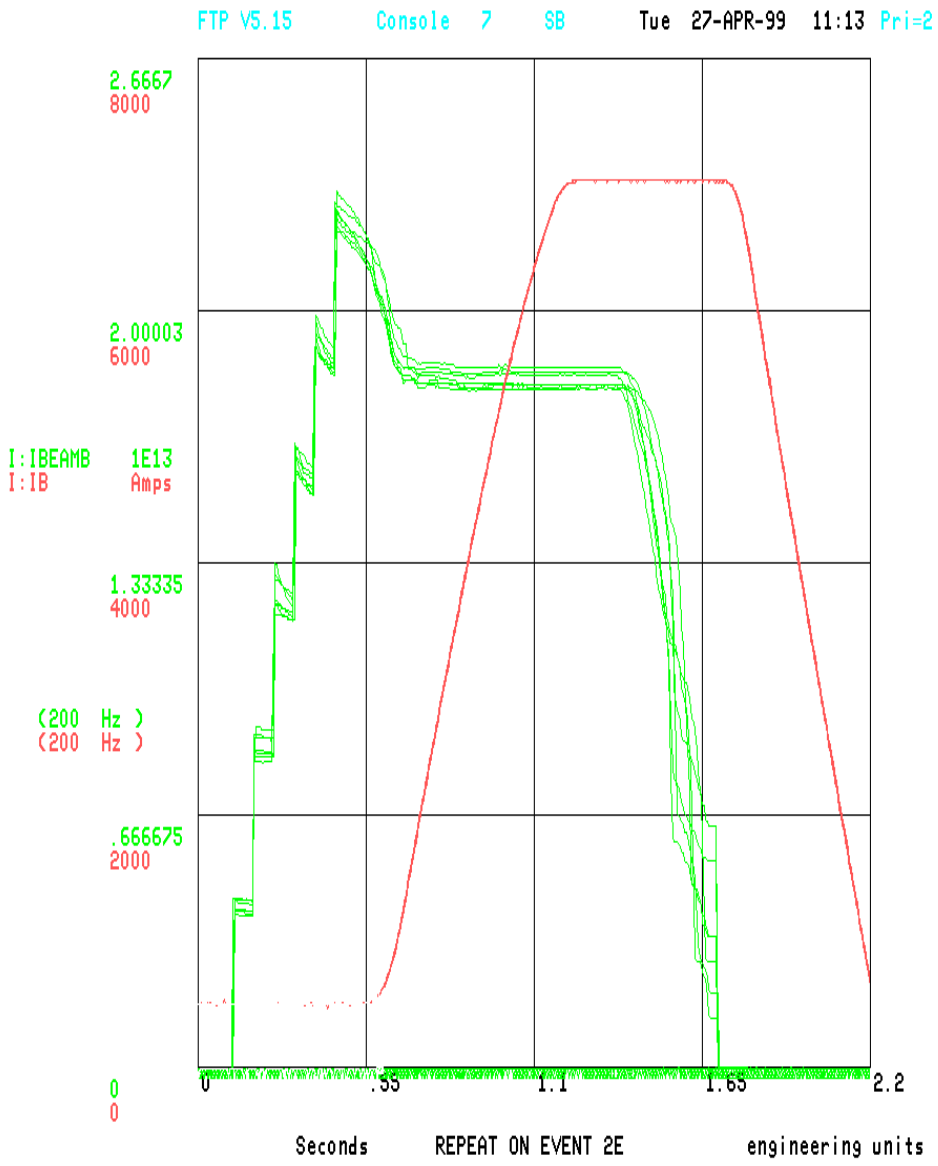
Slow Extraction

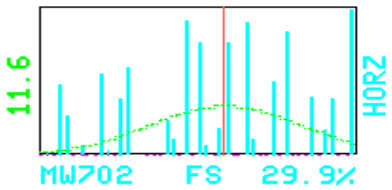


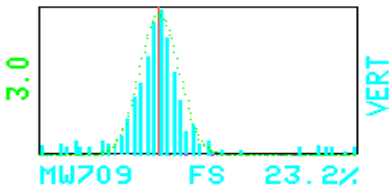
2e13 Protons at 120 GeV

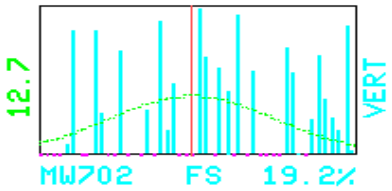


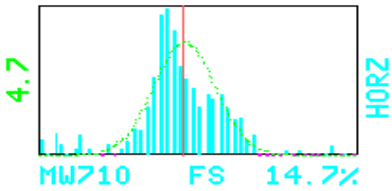
2e13 proton Slow Extracted to P1 Line at 120 GeV

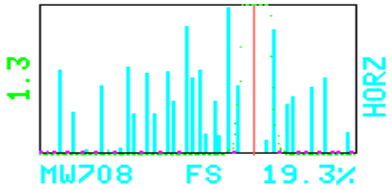


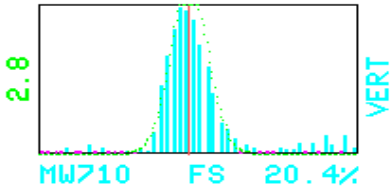


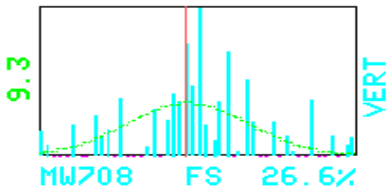


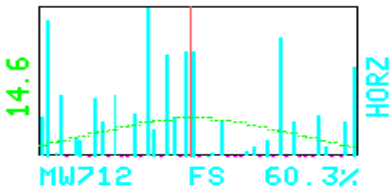


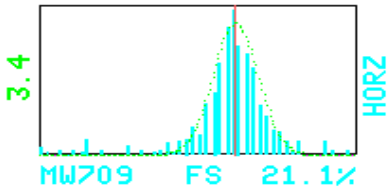


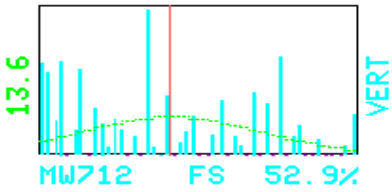








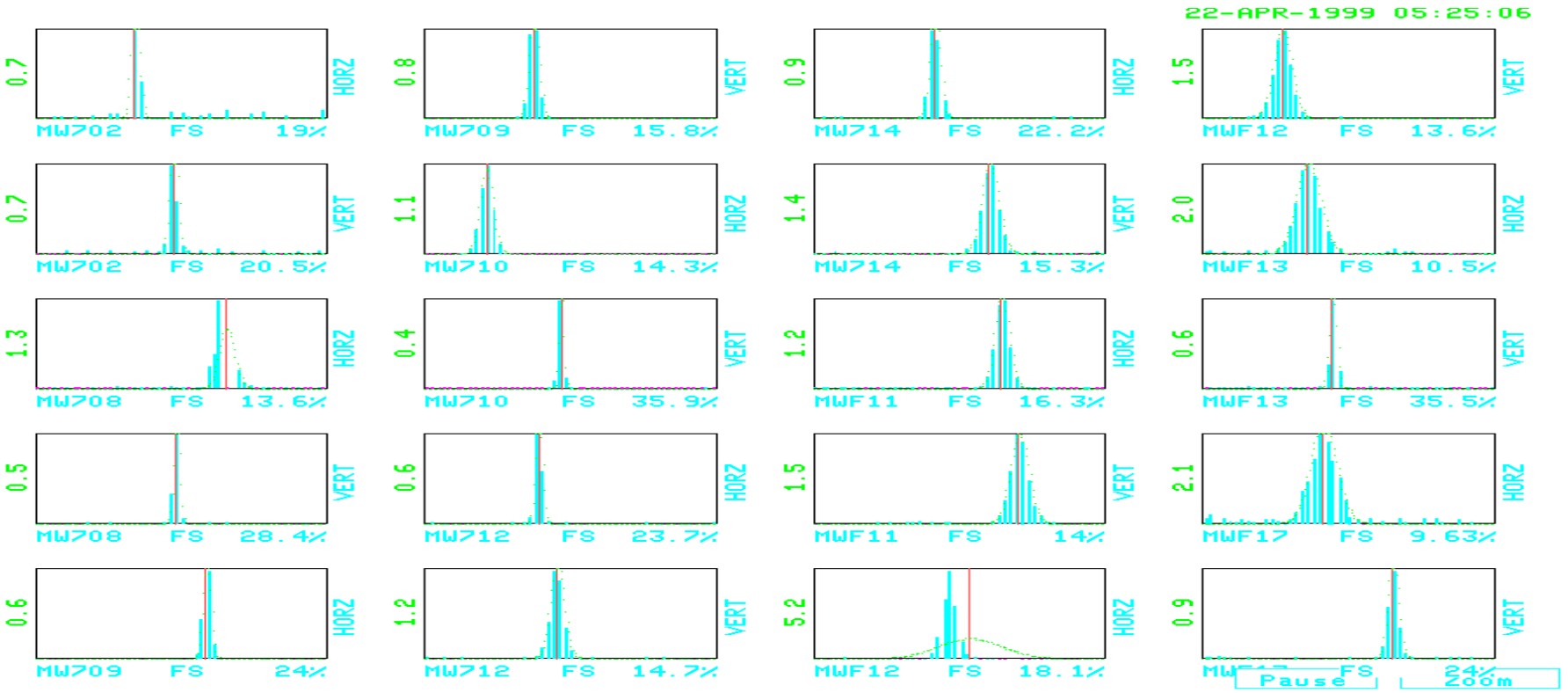




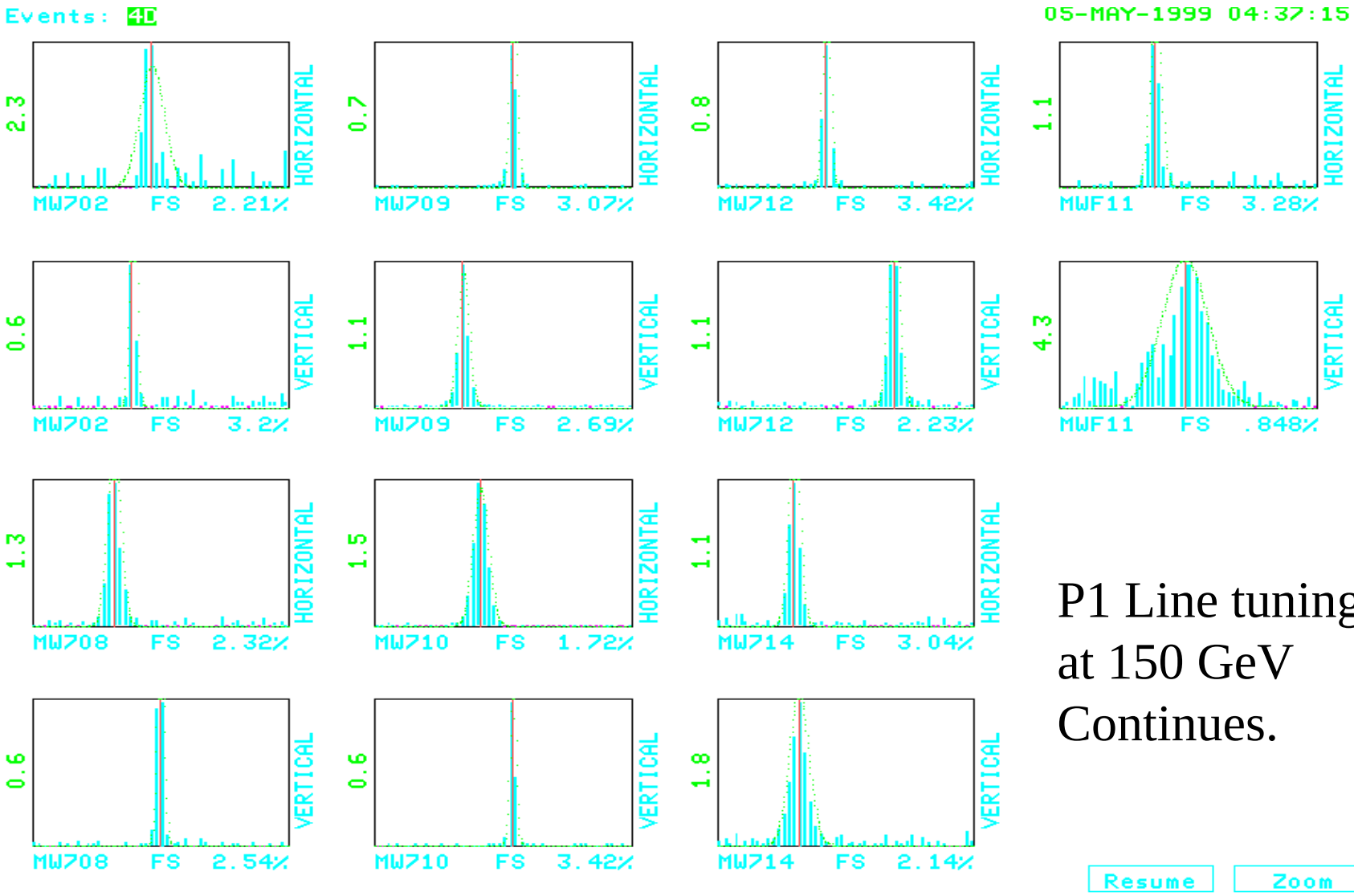
Beam from MI to Antiproton

- The commissioning and tune-up of P1, P2 and AP1 line for 8 GeV and 120 GeV operation started in late Jan 99.

- After the Recycler Installation shutdown we have been able to deliver 120 GeV beam to pbar dump with high efficiency > 90%.

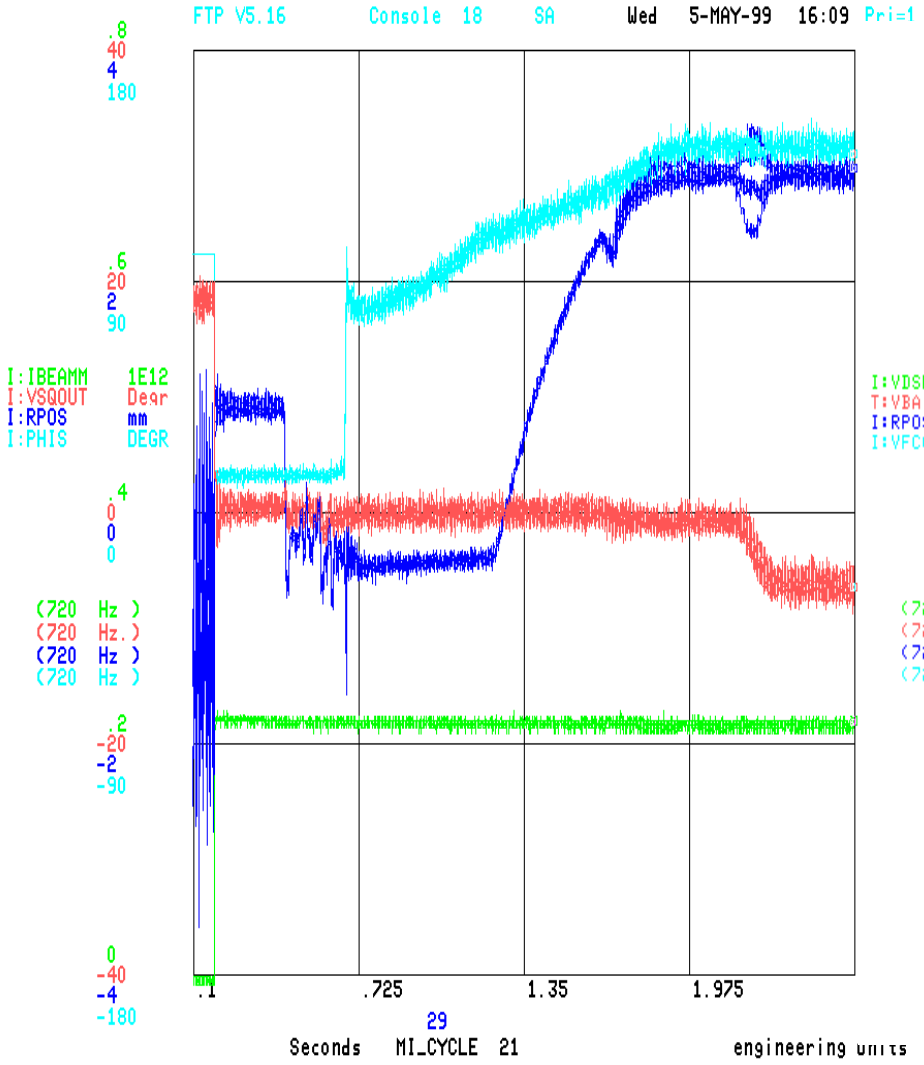


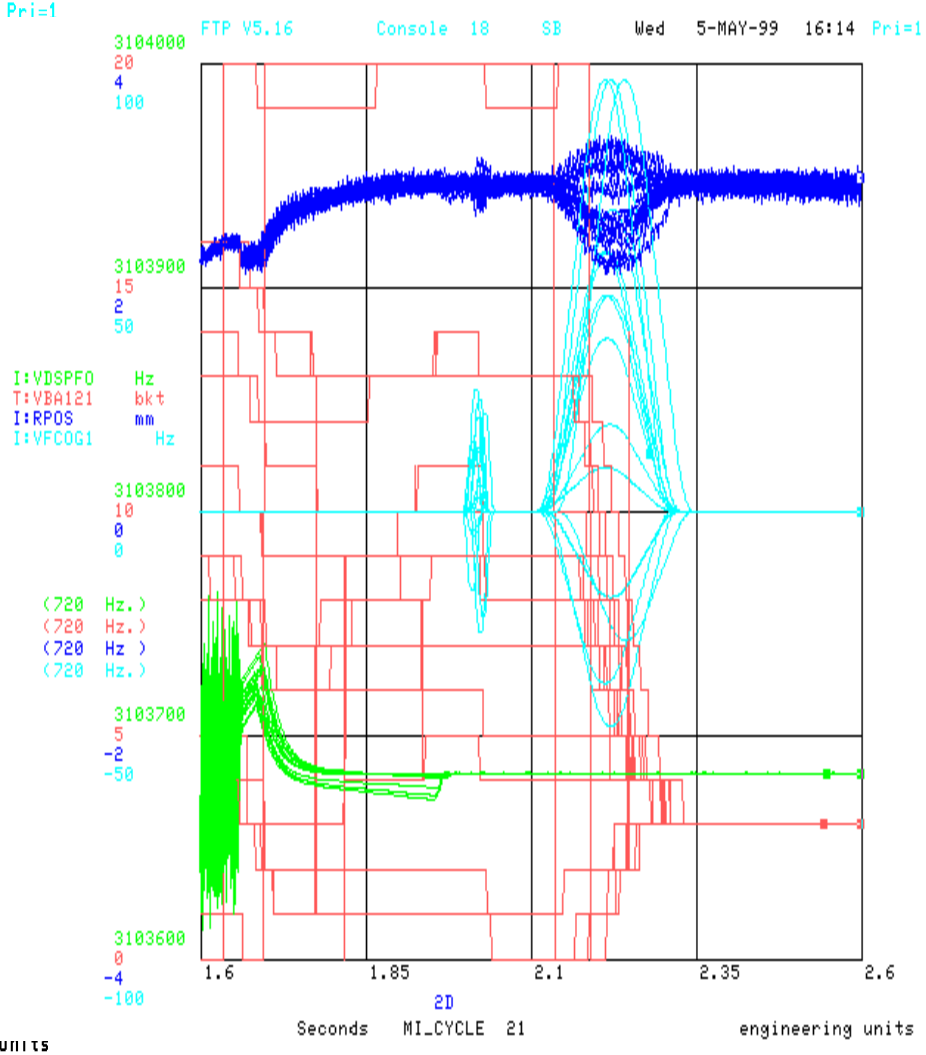
MI to P1 Line commissioning at 150 GeV



P1 Line tuning at 150 GeV Continues.

MI to TeV Transfer cogging commissioning





Summary

- Main Injector had a very successful commissioning. We have achieved all commissioning goals.
- The Main Injector is running very stable and has great potential to meet and/or exceed its design goals.
- Even at these high intensities the Main Injector shows no sign of transverse instability. We used longtudinal dampers for the ease of operation.
- Main Injector operates at the design tune and its lattice function is close to design.
- This is a great success because of hard work of several people from the very beginning of the project and through the commissioning phase.
- Main Injector will now aim towards operation.