Lecture 4 (Part-1)

Practical Issues:
Beam Injection and Extraction

Chandra Bhat

Beam Injection and Extraction

Goal: Achieve transfer of beam from one machine to another with

a. No beam loss

b. No emittance growth

There are several beam injection and extraction schemes in use . Each scheme is specific to the requirement.

1. Fast injection and extraction
2. Multi-turn injection and Phase-space painting
3. Charge-exchange injection
4. Resonant extraction
5. Combined stacking and cooling
6. Longitudinal Phase-space coating

Fast (single-turn) Injection and Extraction:

The most straight forward way of beam injection and extraction is by using ,

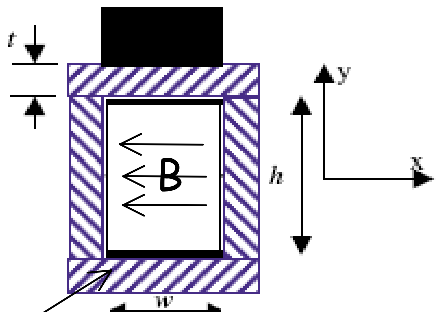
a. Fast kicker — This is an electrostatic or magnetic device that provides an angular deflection to the beam. The rise and fall time of the kicker is generally in the range of a few nsec to 100 nsec.

b. Septum — This is a device with an aperture divided into

1. Field-free region
2. Uniform field region

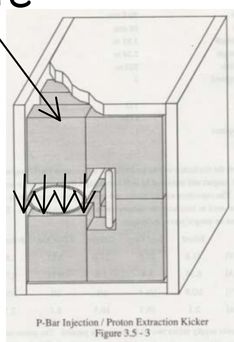
Kickers and Septum Magnets

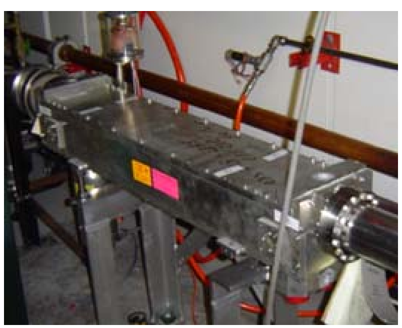
Kicker magnets



Ferrite

B





Main Injector

Lambertson Magnets

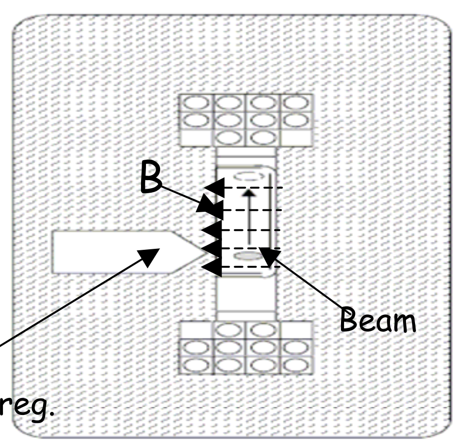
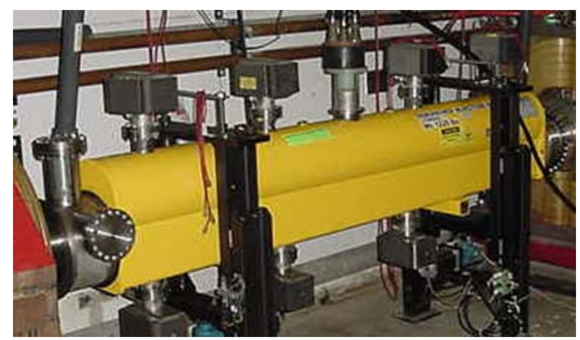


Figure 6.4 F17 Lambertson cross section

Field free reg.

MI NiMI Lam.

Fermilab Debuncher Septum

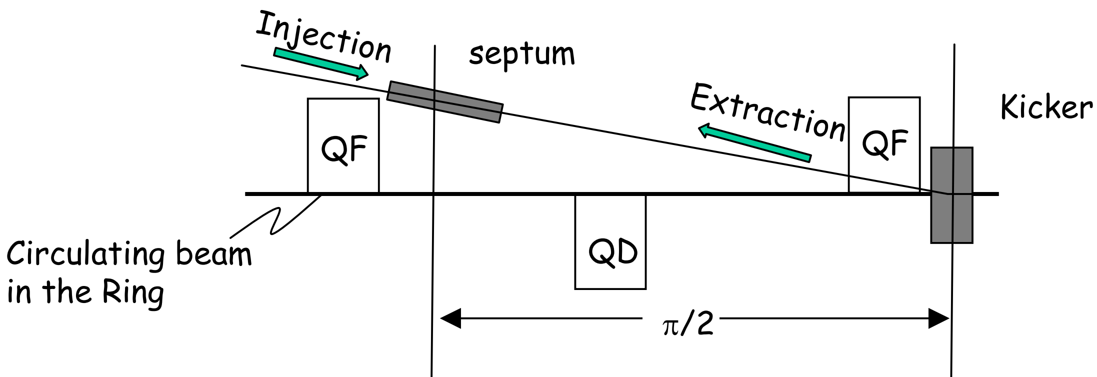


Injection and Extraction (cont.)

Injection: The beam is injected onto the central orbit of a synchrotron via a septum unit and a fast kicker with appropriate matching in both transverse and longitudinal planes.

Extraction: Kicker is used to deflect the beam from the central orbit onto an extraction orbit and onto the field region aperture of the septum.

For both injection and extraction a FODO cell is used with a phase advance of $\pi/2$.



In the case of injection, the first requirement is that the lattice functions have to be matched at the entry point of the ring.

➔ β_x, α_x, β_y, α_y, D_x, D_x', D_y and D_y', at the exit from the septum unit must be identical to the ring lattice parameters at that point.

The reverse is for beam extraction.

Injection and Extraction (cont.)

Calculation of the Kick Angle:

The kick on the closed orbit to bump the beam into an extraction channel is similar to introducing a transient dipole error at the transfer point in a perfect lattice.

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{\beta}{\beta_0}}[\cos(\Delta\psi) + \alpha\sin(\Delta\psi)] & \sqrt{\beta\beta_0}\sin(\Delta\psi) \\ \sqrt{\frac{1}{\beta\beta_0}}[(\alpha_0 - \alpha)\cos(\Delta\psi) - (1+\alpha\alpha_0)\sin(\Delta\psi)] & \sqrt{\frac{\beta_0}{\beta}}[\cos(\Delta\psi) - \alpha\sin(\Delta\psi)] \end{bmatrix} \begin{bmatrix} 0 \\ \theta \end{bmatrix}_k$$

$$\therefore \quad \theta_k = x_{close}(s) \Big/ \sqrt{\beta_x(s_k)\beta_x(s)}\sin(\Delta\psi) \quad \text{with } \beta = \beta_x(s) \;\&\; \beta_0 = \beta_x(s_k) \qquad (1)$$

where $\theta_k = \frac{\int B_k ds}{B\rho}$

is the kicker strength. B_k is kicker dipole field. $\Delta\psi$ is the phase advance between kicker location to that of the septum.

From Eq. 1 it may be seen that a high value of $\beta_x(s_k)$ is advantageous to reduce the kick angle. Also a high value of $\beta_x(s)$ helps in reducing the relative contribution to the kick angle due to septum thickness.

Thus, with $\Delta\psi = \pi/2$, we get ,

$$\theta_k = x_{close}(s) / \sqrt{\beta_x(s_k)\beta_x(s)}$$

$$\text{and} \quad x' = -\alpha_x x_{close}(s) / \beta_x$$

Injection and Extraction (cont.)
(a variation)

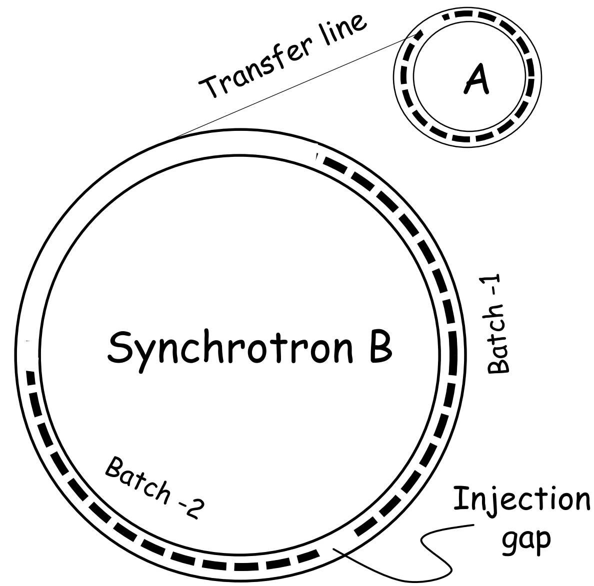
Box-Car stacking:

This is a variation on the fast injection or extraction scheme. This method is adopted quite often to fill a larger synchrotron (B) using a smaller synchrotron(A).

In this case the beam from the smaller synchrotron is transferred to the larger synchrotron in the form of batches (box-car) until the latter is filled.

The following conditions need to be met for an efficient Box-car stacking:

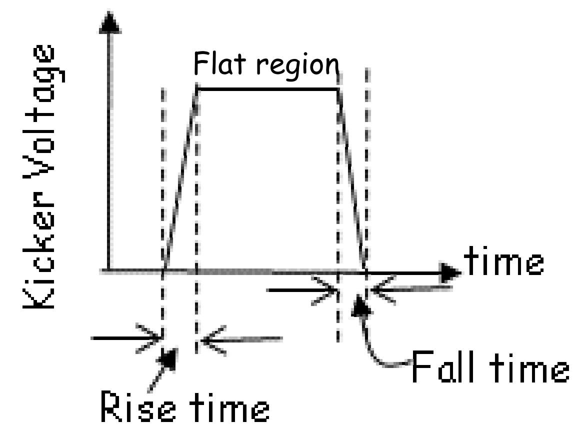
1. The beam is bunched in both machines and rf buckets are matched between the synchrotrons.
2. The kicker rise and fall time must be smaller than the bunch spacing or spacing between the "box-cars" in both machines.



Depending upon the length of kicker flat region, one can extract part or entire beam from the accelerator.

At Fermilab we adopt this method to

1. Fill MI using Booster (up to six batches)
2. Fill Tevatron using Main Injector (36 times for p and 9 times for antiprotons)
3. Fill Recycler using Accumulator
4. To extract protons for pbar production and for NuMI experiment (use two different extraction systems)



Efficiency of this technique is ~100%

Injection and Extraction (cont.)

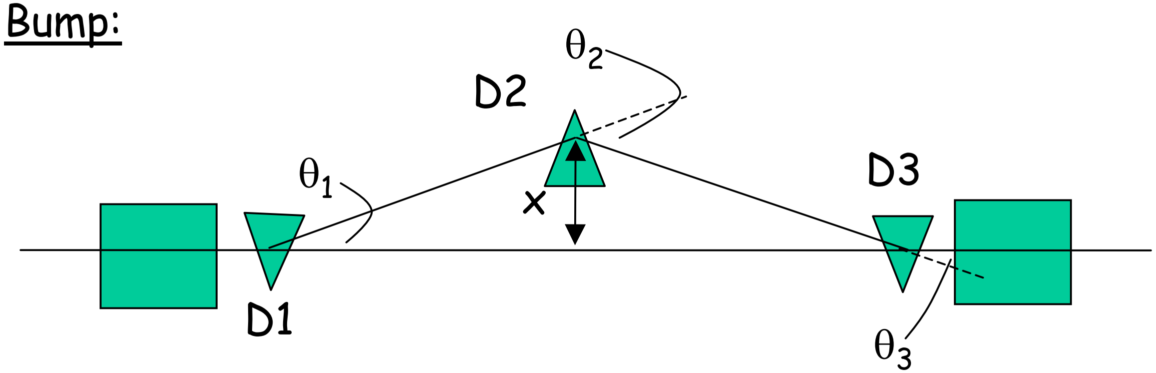
<u>Orbit Bump (an application of dipole error):</u>

To get better matching during extraction or injection the orbit of the beam can be bumped by using a set of trim dipole dipoles. For example,

a. Three dipoles for “3-bump”
b. Four dipoles for “4-bump”

These bumps are designed such that the closed orbit outside the bump remains unchanged.

<u>Bump:</u>

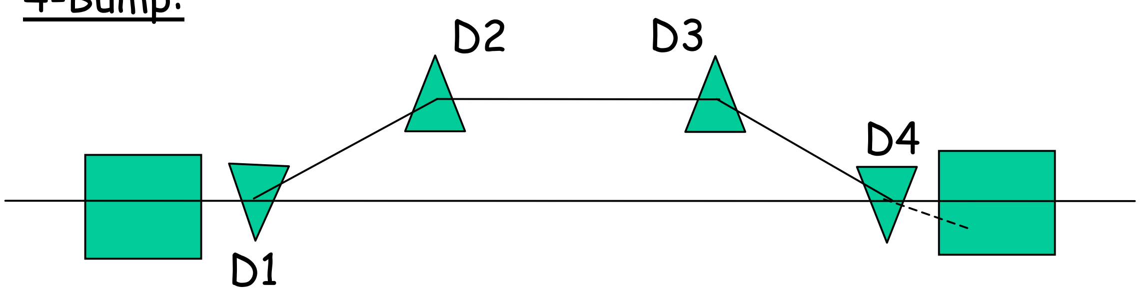


$$\theta_1 = \frac{x}{\sqrt{\beta_1\beta_2}\,\sin(\psi_{21})},$$

$$\theta_2 = -\frac{x\sin(\psi_{31})}{\beta_2\sin(\psi_{21})\sin(\psi_{32})} \quad \text{and}$$

$$\theta_3 = \frac{x}{\sqrt{\beta_3\beta_2}\,\sin(\psi_{23})} \tag{2}$$

<u>4-Bump:</u>

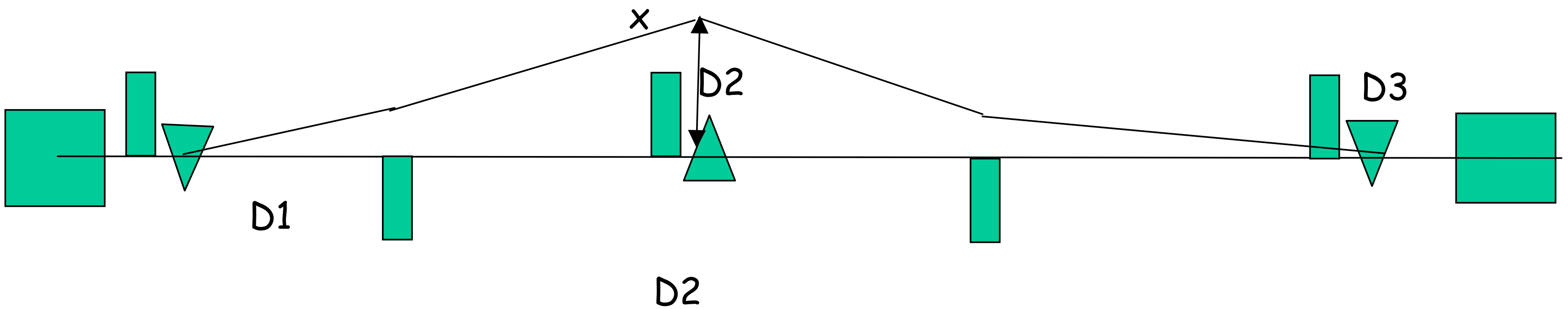


These bumps are extremely useful while steering the beam in aperture restricted areas like septum magnets. These can be some time local bumps or time bumps (??)

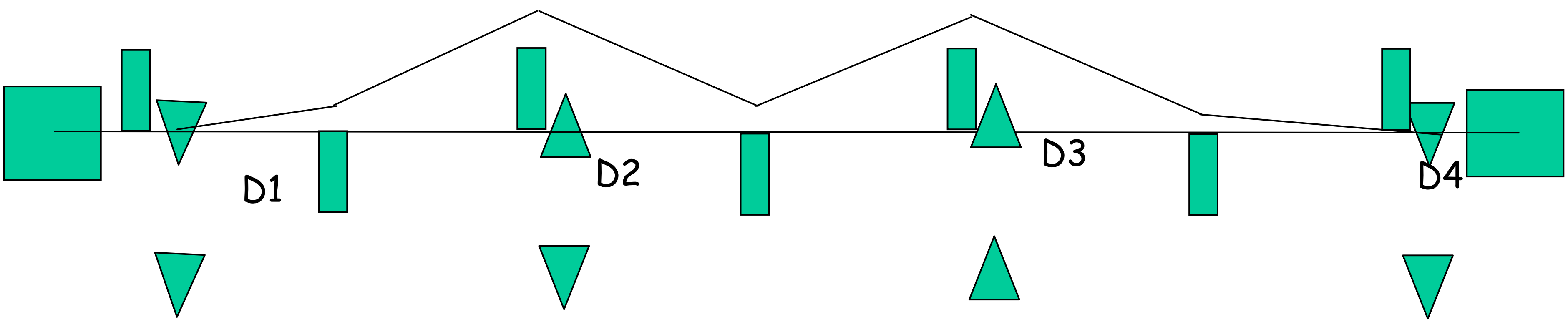
Injection and Extraction (cont.)

<u>Orbit in Reality</u>
In reality we will have focusing and defocusing quads in between dipole trims which form orbit bumps.

<u>3-Bump:</u>



<u>4-Bump:</u>



Multi-turn Injection

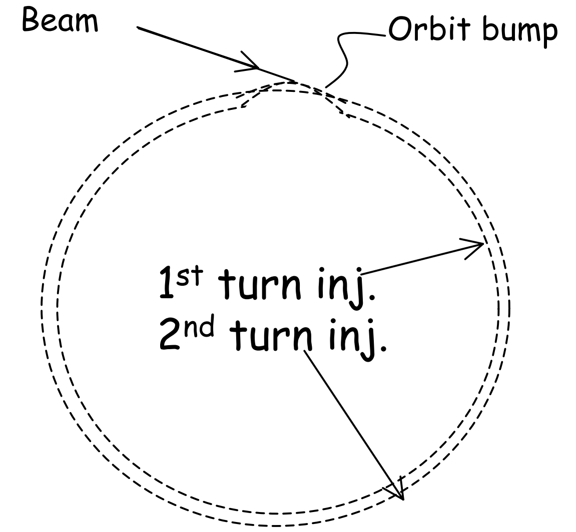
This involves use of,

a. Septum
b. A programmed orbit bump in the vicinity of the septum

In case of protons, the orbit bump is reduced with time so that the early beam occupies the central region of the horizontal acceptance and the later beam occupies periphery of the acceptance. By the end of the injection the bump is reduced to zero.

This scheme evidently gives rise to emittance dilution. Generally, the resulting emittance is

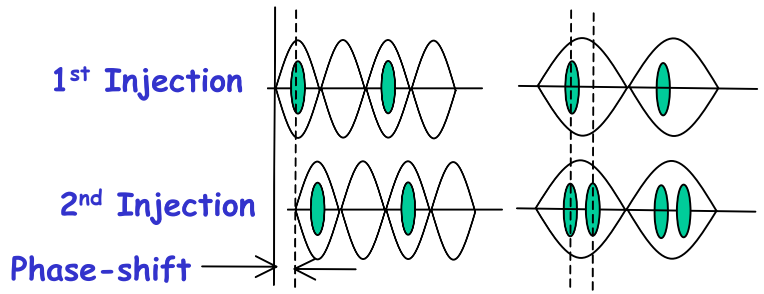
$$\varepsilon_{result} > 1.5 n \varepsilon_i \quad n = \text{number of turns}$$



Here the issues are
1.Space charge in-coherent tune shift
2.Non-linear forces

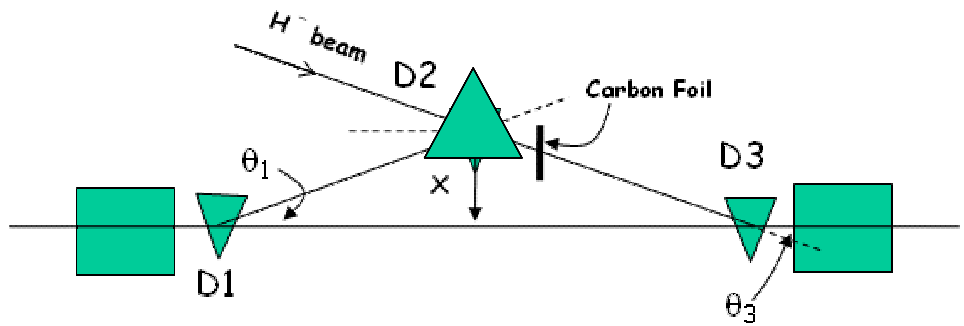
<u>Betatron Phase-space-painting:</u>
During the multi-turn injection, if the betatron tunes (ν_x and ν_y) and orbit bump are properly adjusted then the particle distribution in the transverse phase-space can be optimized. This is called transverse phase-space painting.

<u>Longitudinal Phase-space-painting:</u>
If the injection is done by slowly varying the injection RF phase during bucket to bucket transfer then the beam will be painted longitudinally.



Charge Exchange Injection

Concept of H-charge exchange is invented at the Budker institute, Russia, (Budker and Dinov, Novosibirsk). Principle of charge exchange is adopted in this technique. This needs a 3-bumps or 4-bumps at the time of injection.



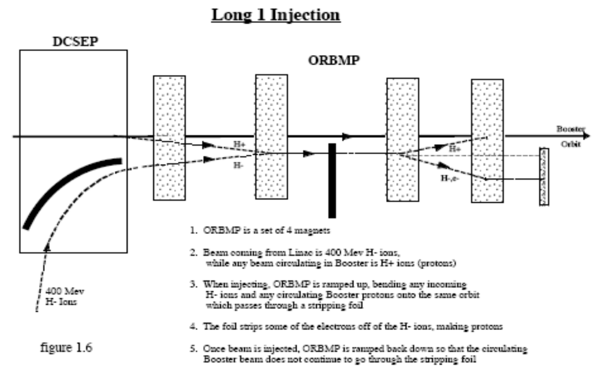


figure 1.6

The steps involved in this scheme are

1. The closed orbit of the circulating beam is bumped onto the injection orbit of H^- beam.
2. The injected H^- beam and the circulating proton beam is made to go through a thin carbon foil (thickness of about 10-400 ug/cm**2). In this process the electrons will be stripped off the H^- ions.
3. Since the constraints imposed by Liouville's theorem on conventional multi-turn injection does not apply here (because the charge states of the injected beam and circulating beam are different), one can inject several turns (2-40 turns).
4. Orbit bump is removed after the injection.

The injected beam can also be painted in transverse phase space by changing the closed-orbit bump.

Additional Injection/Extraction Schemes

Resonant Extraction:

Beam particles can be peeled off by using

1. 3rd-order or
2. half-integer resonances

in a controlled fashion. The large amplitude particles moving along the separatirx are intercepted by **a thin septum wire** and are kicked off to another septum and transported to experimental area.

Combined Cooling and stacking: (S. van der Meer, CERN)

In this case each antiproton pulse (containing about ~1E7 particles) is

1. First subjected to fast longitudinal cooling
2. Next these antiprotons are deposited by an **rf system** at the high momentum edge of a stacked beam
3. This beam undergoes stochastic cooling and makes room for next similar transfer

In this manner about 40,000 beam pulses are injected in about 24 hrs.

Longitudinal Phase-space Coating: (C. Bhat, Fermilab)

In this case each antiproton pulse (containing about 3E11 particles) is

1. injected using a fast injection scheme into a barrier bucket in a synchrotron.
2. Then these antiprotons are coated in longitudinal phase space in the form of ribbon over already existing beam captured in another barrier bucket.
3. This can be repeated as many times as the momentum acceptance of the machine allows. (At Fermilab we demonstrated up to 5-coats for antiproton transfer from Accumulator Ring to the Recycler).

Lecture 4 (part-2)

Practical Issues: Accelerator Commissioning

Chandra Bhat

Commissioning of an Accelerator

Now let us address issues involved in commissioning of beamlines and accelerators.

In an ideal world, if every thing is set according to theoretical calculations the machine just works as we have designed. In reality, there can be a number of issues like,

1. Magnets not built exactly to our specifications
2. Misalignment errors in the installation of magnets or issues with diagnostics.

Commissioning of any accelerator has never been an easy job.

<u>Assumptions:</u>

1. Good diagnostics. This is an essential constituent of any accelerator or beamline.

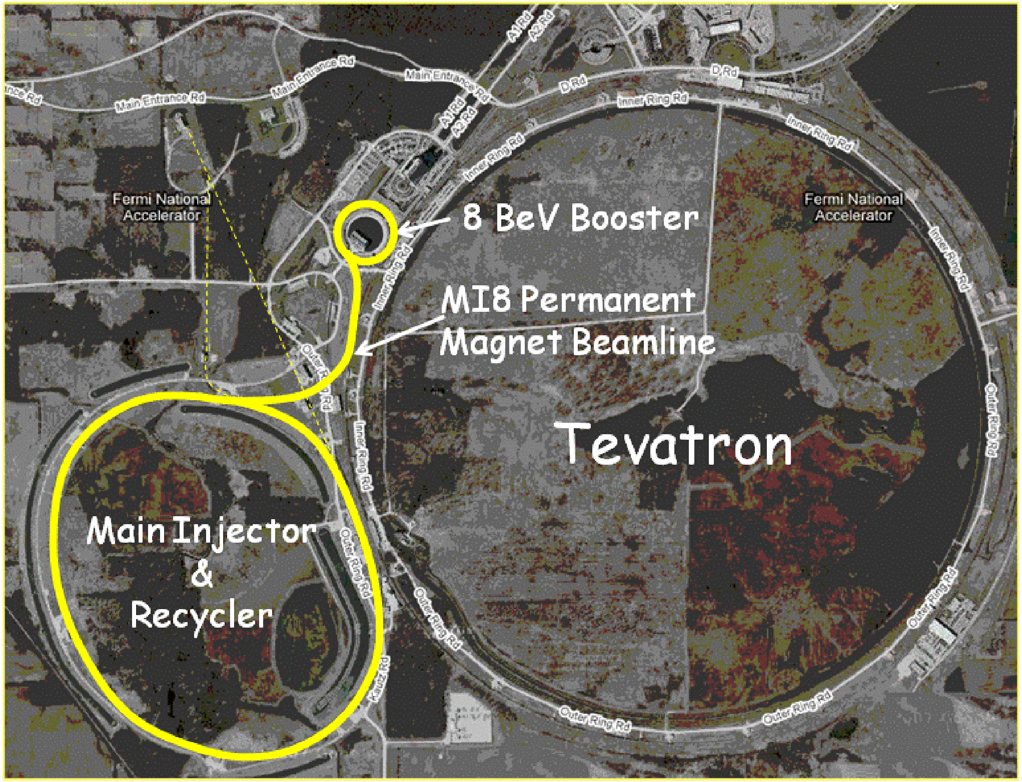
2. The beamline/accelerator vacuum is good enough for the type of operation. For example,
   a. For transfer lines vacuum ~ 10^{-7} torr
   b. For a low intensity rapid cycling accelerators a vacuum of 10^{-7} to 10^{-8} torr may be good.
   c. For higher intensity we need better vacuum
   d. For beam storage rings or collider vacuum > 10^{-9} torr

3. Beam can be steerable remotely
4. The accelerator is set to theoretically best tunes and chromaticities.

Illustrations with Examples

The examples that I am going to give are specific to that at Fermilab.
Commissioning of
1.MI8 Beamline ← Beamline between the Booster and the Main Injector
2.Main Injector ← Accelerator
3.Recycler ← Storage Ring

But, the general philosophy behind the commissioning other facilities, hadron or lepton system, is the same. The specific details will change.



Accelerator Commissioning

Establish the Beam

1. Set the momentum by proper bend field in transfer-line and in the machine
2. Set the theoretical lattice
3. Set the synchronous RF buckets if needed
4. Inject the beam

Smoothing the Orbit

1. Transport the beam from element to element. Steer systematically. Get first turn beam in the machine
2. Smoothing the orbit ← identify which set of desired positions to use for smoothing a specific point
3. Understand how many correction elements should track their reference during smoothing
4. Scan tune, chromaticity with attention to lifetime

Beam Acceleration

1. Setup acceleration Ramp: Magnet, RF and Radial feed-back
2. Have optimum number of "break-points" on the ramp
3. Smoothing (steps from stage 2)

Transition Crossing

1. Set the proper time for transition phase jump
2. Adjust the RF voltage through transition.
3. Fine tune the phase jump and frequency at transition

Beam Extraction

1. Beam extraction to the down-stream machine (if needed)
2. Beam dump (if beam is not of required quality)

Prepare to Establish Beam: Initial Settings

Setting the Momentum:

MI8 beamline is a permanent magnet beamline with its lattice designed to accept 8 GeV protons . The admittance of the beamline is 40 π-mm-mr and momentum acceptance of about 0.4% . These are fixed by design.

→ (See Figure on next page)

To set the initial momentum, one adjusts the bend field of the machine, so that

$$p[GeV] = 0.2997 \times B\rho\,[\mathrm{Tm}] = 8.889\ \mathrm{GeV/c}$$

→ (Table on page 18)

in the case of the Main Injector.

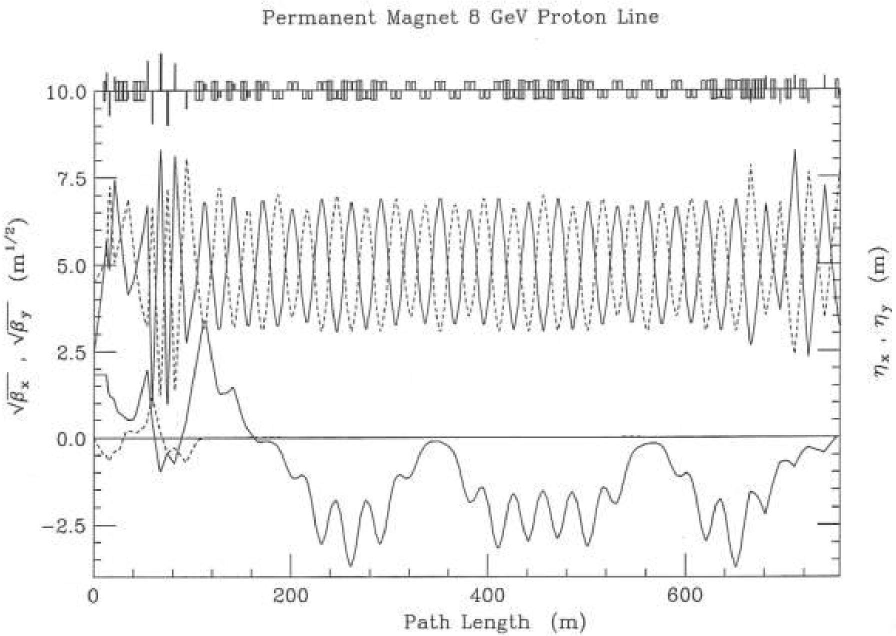
We assume that the RF frequency,

$$f_{rf} = h \times f_{rev} = h \times \frac{2\pi\,\mathrm{R}}{\beta c} \qquad \mathrm{R\ is\ the\ Radius\ and\ } \beta\mathrm{c} = \mathrm{beam\ velocity}$$

$$= 52811400\ \mathrm{Hz} \qquad \mathrm{and} \quad \mathrm{R} = 528.670\ \mathrm{meter}$$

is stable and the radius of the machine is fixed. If there are any drifts in voltage, it may be mostly due to power supplies. Sometimes the sources of the problems may be somewhere else. For example, in the case of new constructions the orbit drift can arise due to settling of the ground or ground motion. These issues need additional understanding/investigation.

Theoretical Lattice from MAD calculations

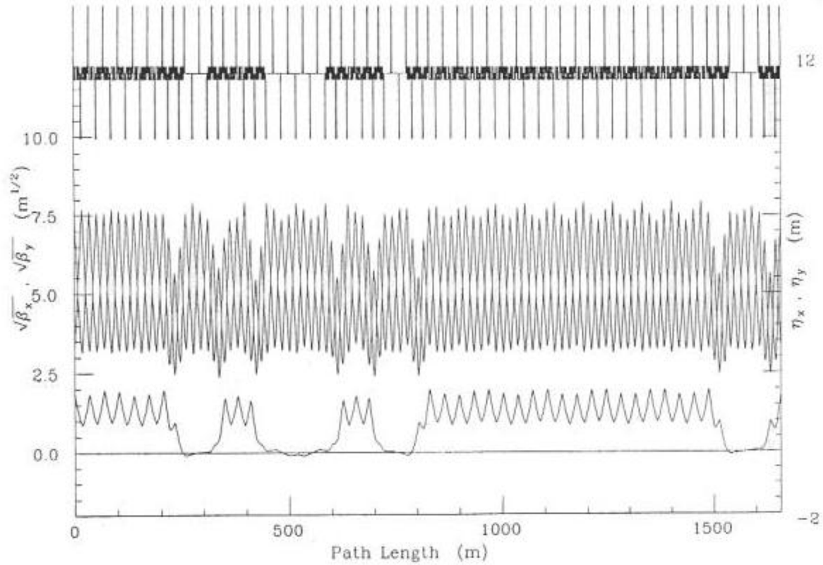


MI8 Beamline Lattice

Design Parameters for Main Injector

Tunes ν_x=26.425, ν_y=25.415

Natural Chromaticities ξ_x=-33.6, ξ_y=-33.9



Main Injector Lattice

Main Injector and 8 GeV beamline Magnet counts

WBS LEVEL 4	=	Ring	8GeV	Spare
IDA dipole 240"	N	108	-	5
IDB dipole 240"	N	108	-	5
IDC dipole 160"	N	64	-	4
IDD dipole 160"	N	64	-	4
PDD (perm dipl)	N	-	45	
PVD (vert dip)	N	-	4	
EPB 5-1.5-120	R	-	4	1
IQC (100.13" MI)	R	32	-	3
IQD (116.26" MI)	R	48	-	4
IQB (84" MR) ring	R	122	-	6
IQE (84" MR) ring	R	4	-	2
IQF (84" MR) ring	R	1	-	1
SQA (17" P-Bar)	R	-	9	2
SQC (26" P-Bar)	R	-	5	2
SQF (48" P-Bar)	R	-	2	1
PGD (gradient)	N	-	65	
IQG, rolled	R	1	-	1
PQP (Perm quad)	N	-	9	

ISA (sextupoles)	N	108	-	6
MR trim quads	R	16	-	3
MR skew quads	R	16	-	3
MR skew sext	R	0	-	0
MR trim sext	R	0	-	3
MR octupoles	R	66	-	5
CR quad - skew	R	4	-	1
HDC MR horiz trim	R	-	26	5
HDD MR horiz trim	R	-	-	3
IDH MI horiz trim	N	104	-	15
VDC MR vert trim	R	-	18	9
HDR MR vert trim	R	-	7	2
IDV MI vert trim	N	104	-	6
Lambertson, 8 GeV	R	-	1	1
Lambertson, FMI	N	-	-	4
C-Magnet, FMI	N	-	-	4
Lambertson, RR	N	-	-	2
	Totals	970	195	183

Initial settings (cont.)

Relevant 8 GeV Booster Parameters:

1. Beam KE= 8 GeV
2. Transverse Emittance 10-20 π-mm-mr
3. Harmonic number= 84
4. RF frequency= 52811400 Hz
5. Vrf(extraction) = 375kV
6. RF bucket half height = 33.4 MeV
7. Beam Intensity ~ 0.5E10- 6E10 p/bunch

Relevant MI RF Parameters to be set to:

1. Beam KE= 8 GeV
2. Transverse Emittance 10-20 π-mm-mr
3. Harmonic number= 588
4. RF frequency= 52811400 Hz ⟵
5. Vrf(Injection) = 1.05MV ⟵
6. RF bucket half height = 33.4 MeV
7. Beam Intensity ~ 0.5E10- 6E10 p/bunch

Beam diagnostics in the Beamline:

Multi-wires:

15 Multi-wire scanner systems are in the beamline.

1. 8 in Vertical planes
2. 7 in Horizontal planes

4 Multi-wire scanner systems in the MI+ one in the Abortline.

1. 2 in Vertical planes
2. 2 in Horizontal planes

Insert all of these before injecting the beam

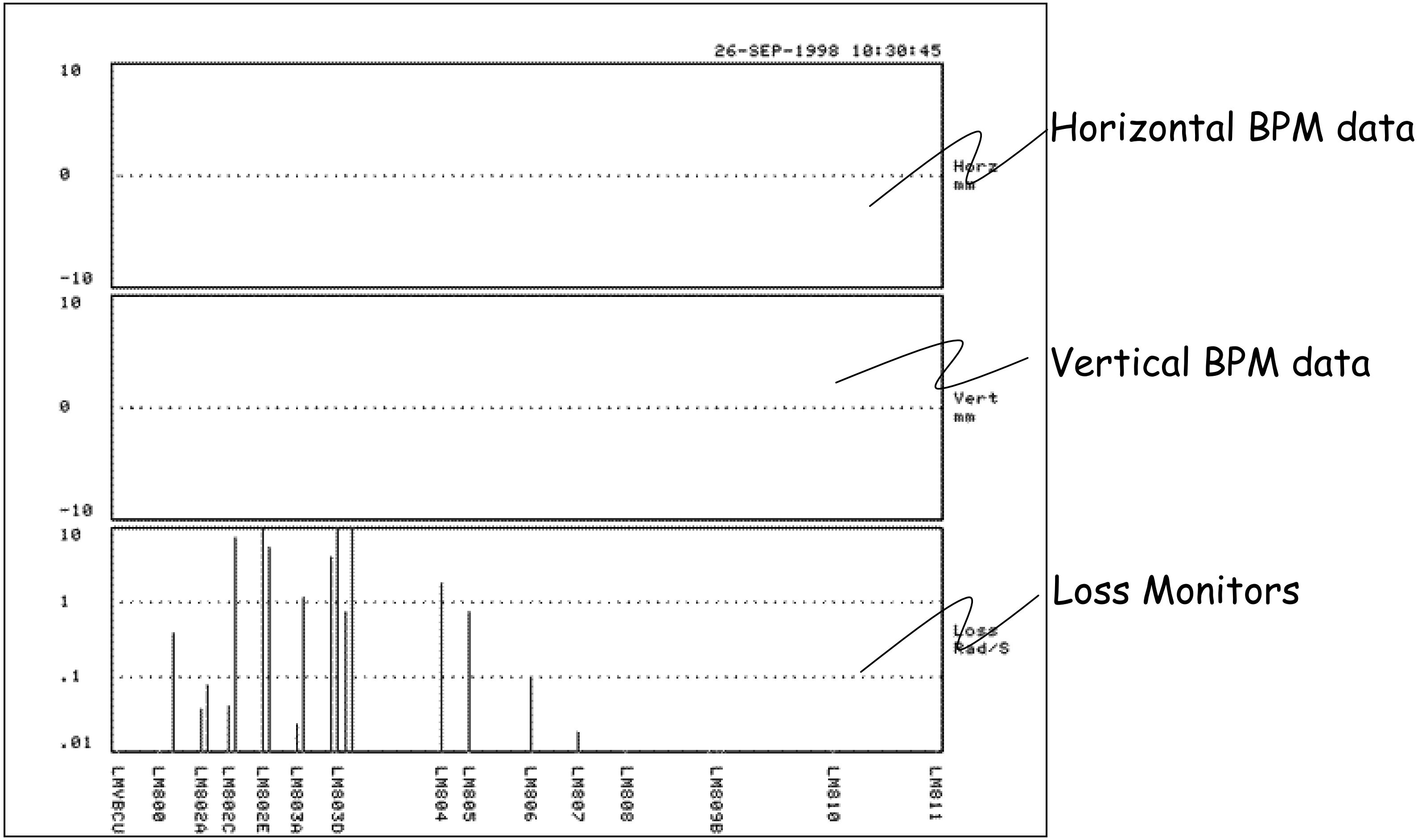
BPM:	Beam Current Transformers:	Beam Loss Monitors
Several	Several toroids	>60 loss monitors

All of them to be enabled.

Inject the beam. From the safety point of view start with **minimum beam as needed**.

MI8 Loss Monitor Data

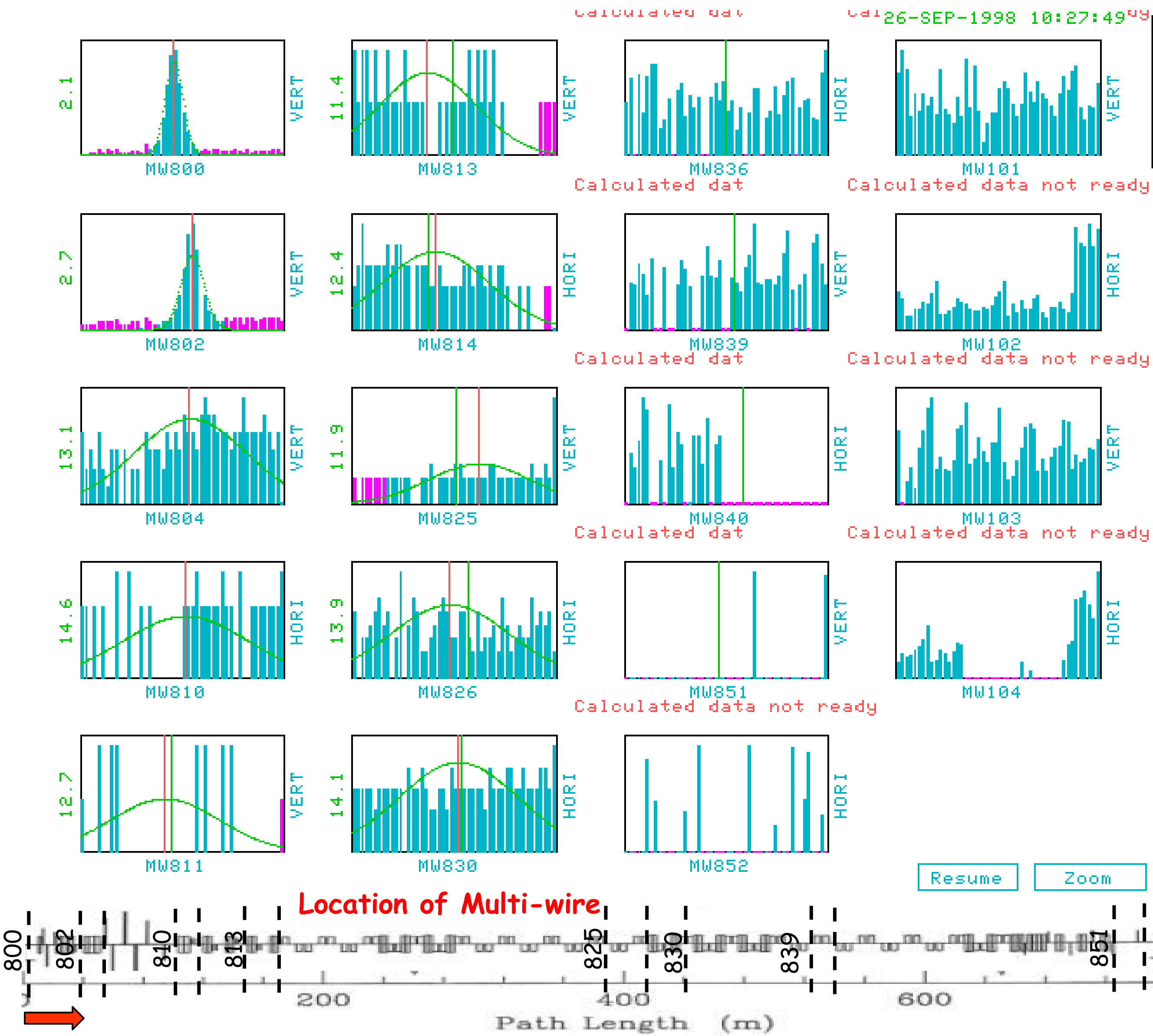
(September 29, 1998)



Yes! There is some beam got transported through the tunnel but, no BPMs lit.
Beam energy may be wrong?, Some upstream magnetic field settings may be wrong?
Many questions?

MI8 Beamline Multi-wire data (Earliest attempt)

(September 26, 1998)



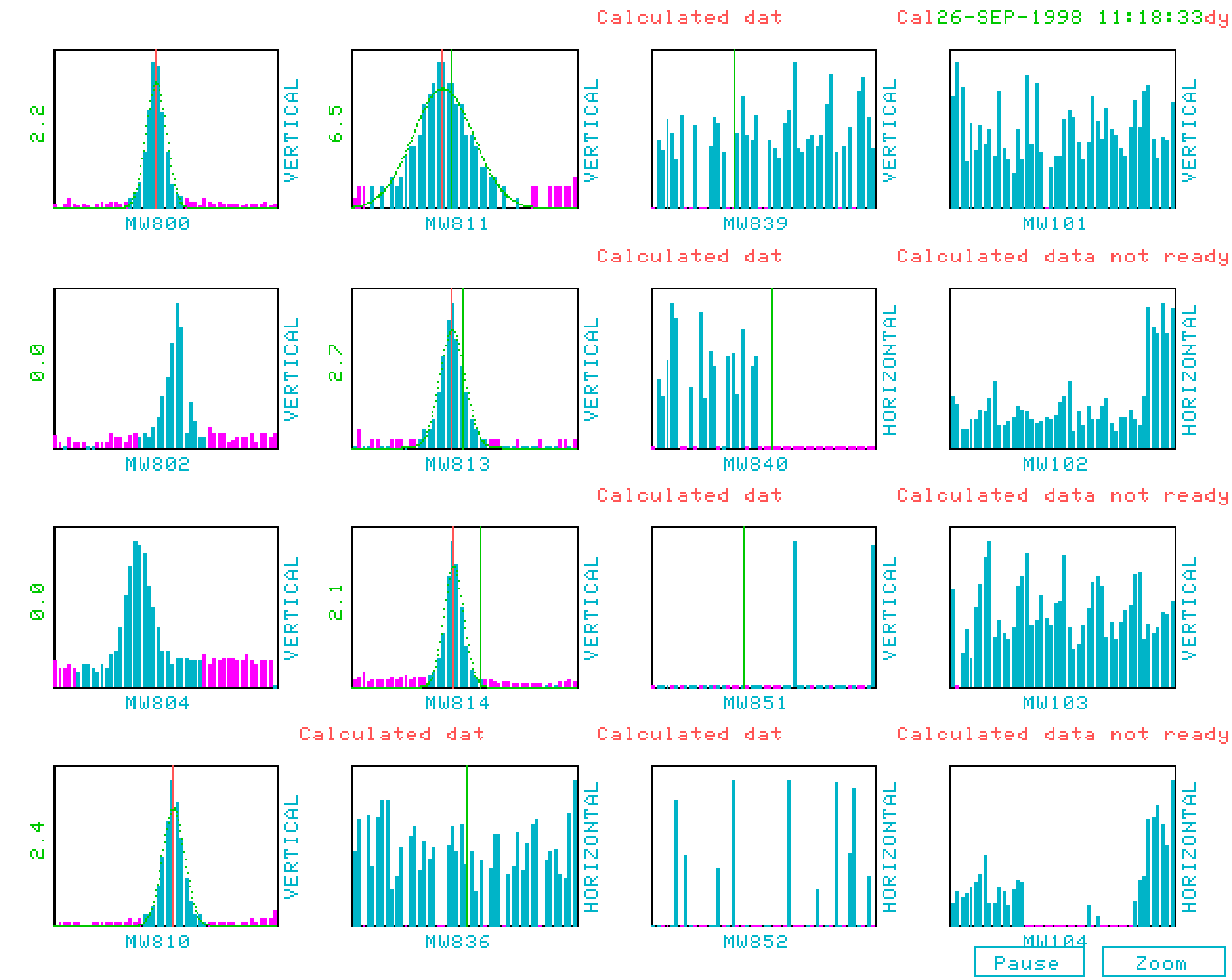
After adjusting kick angle and 3-bump at the extraction region

Some beam got transported up to about **30 m** from the injection point into the beamline!!

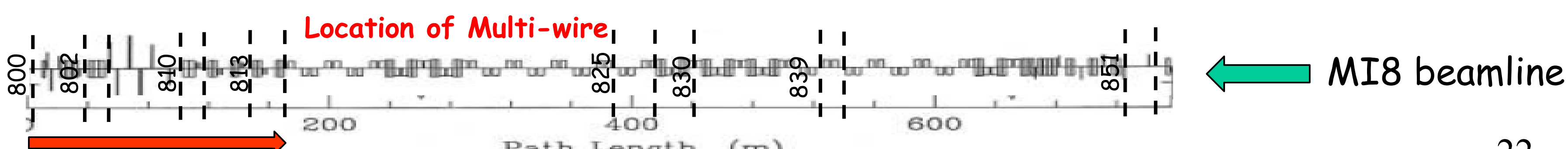
MI8 beamline

MI8 Beamline Multi-wire data (cont.)

(September 26, 1998)

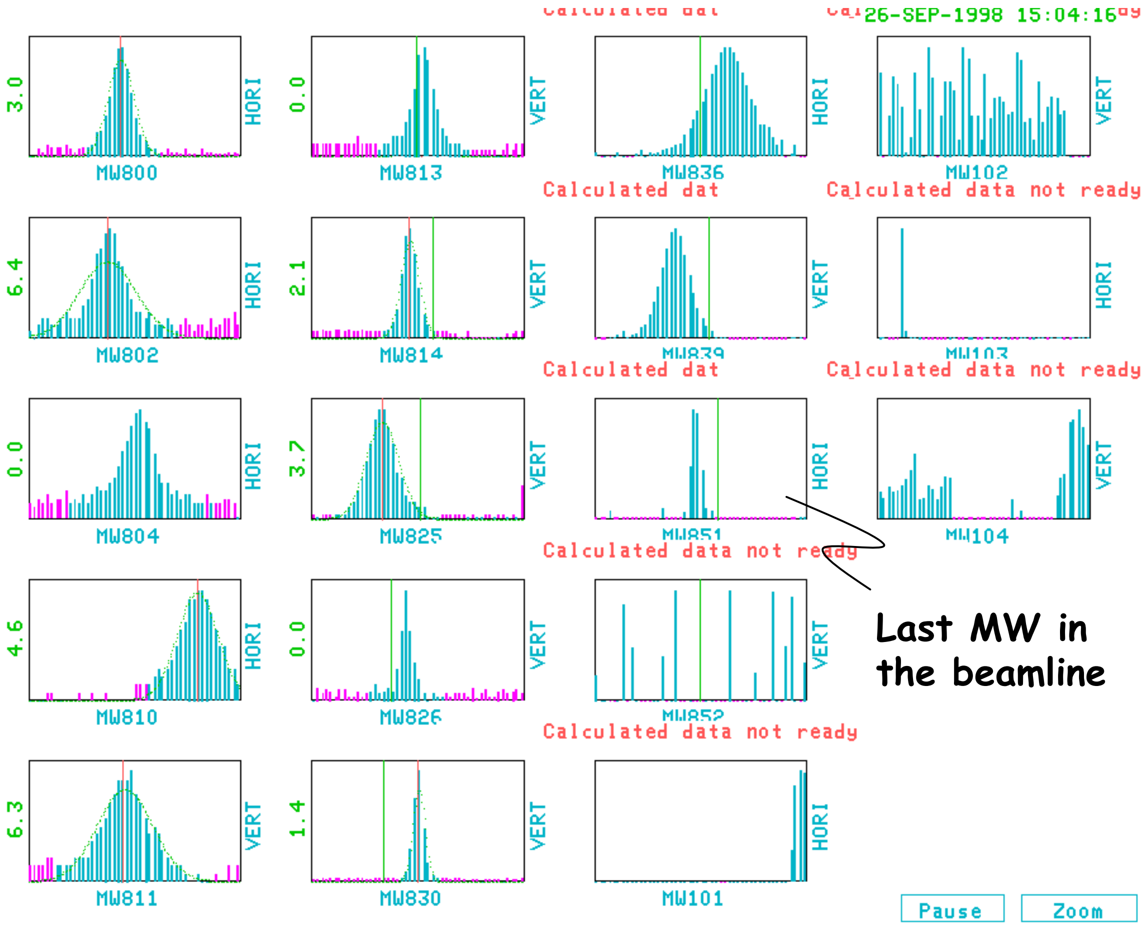


After tweaking the MP02, Booster extraction septum. Beam got transported by about **150 m**.



MI8 Beamline Multi-wire data (cont.)

(September 26, 1998)



Last MW in the beamline

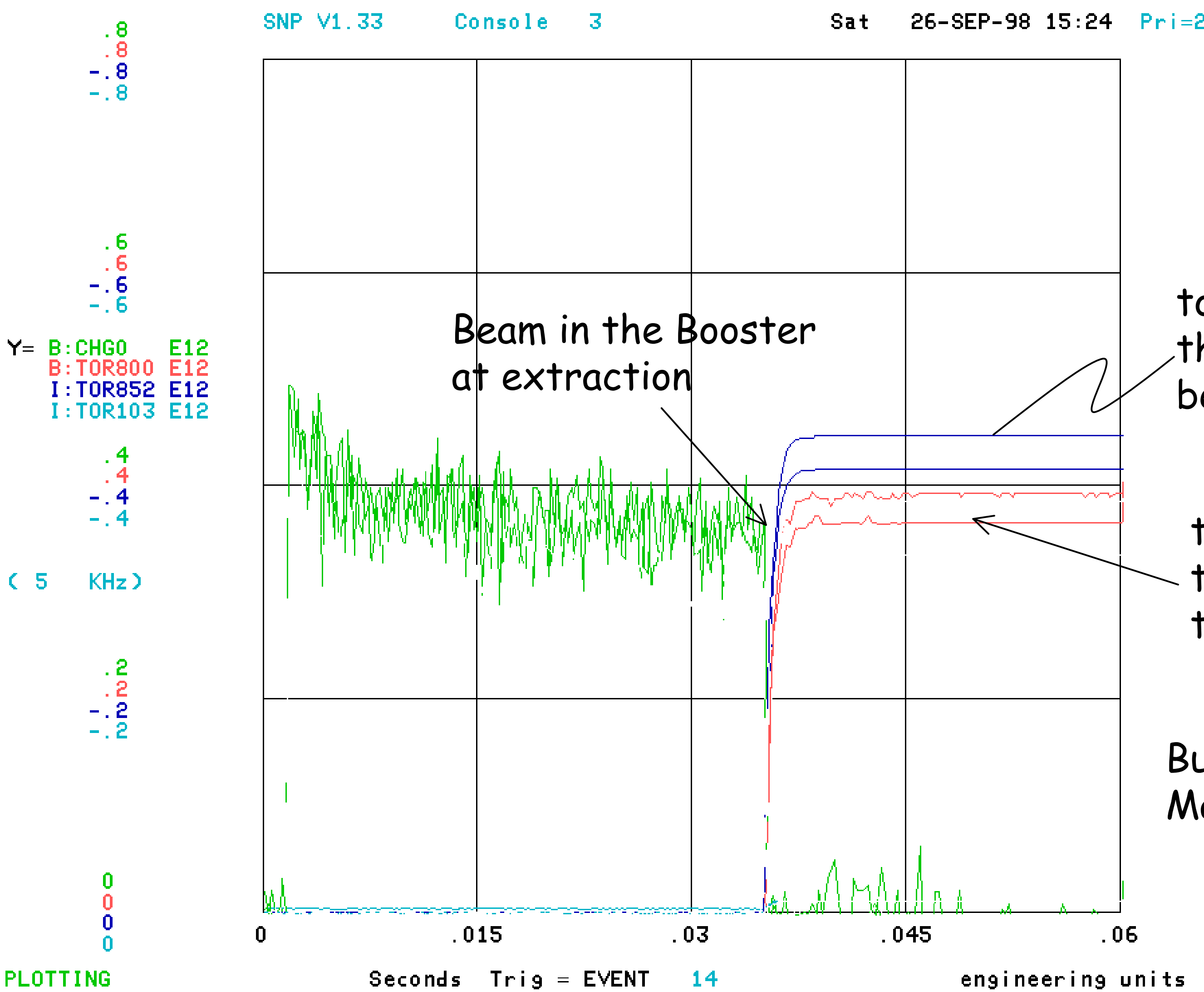
Booster to MI injection region has a "dogleg" in its lattice – beam is kicked vertically and bent down by about 8 feet before the permanent magnet region starts. There are only a few electromagnet devices which can be adjusted.

After tweaking some injection devices, the beam reached the end of the beamline. (about **760m** long)

For a group of experts this took about 8 hours to reach this stage. These people were responsible for designing this beamline

Current Transformers Data

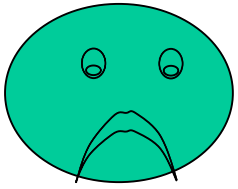
(September 26, 1998)



toroid data at the exit of the beamline

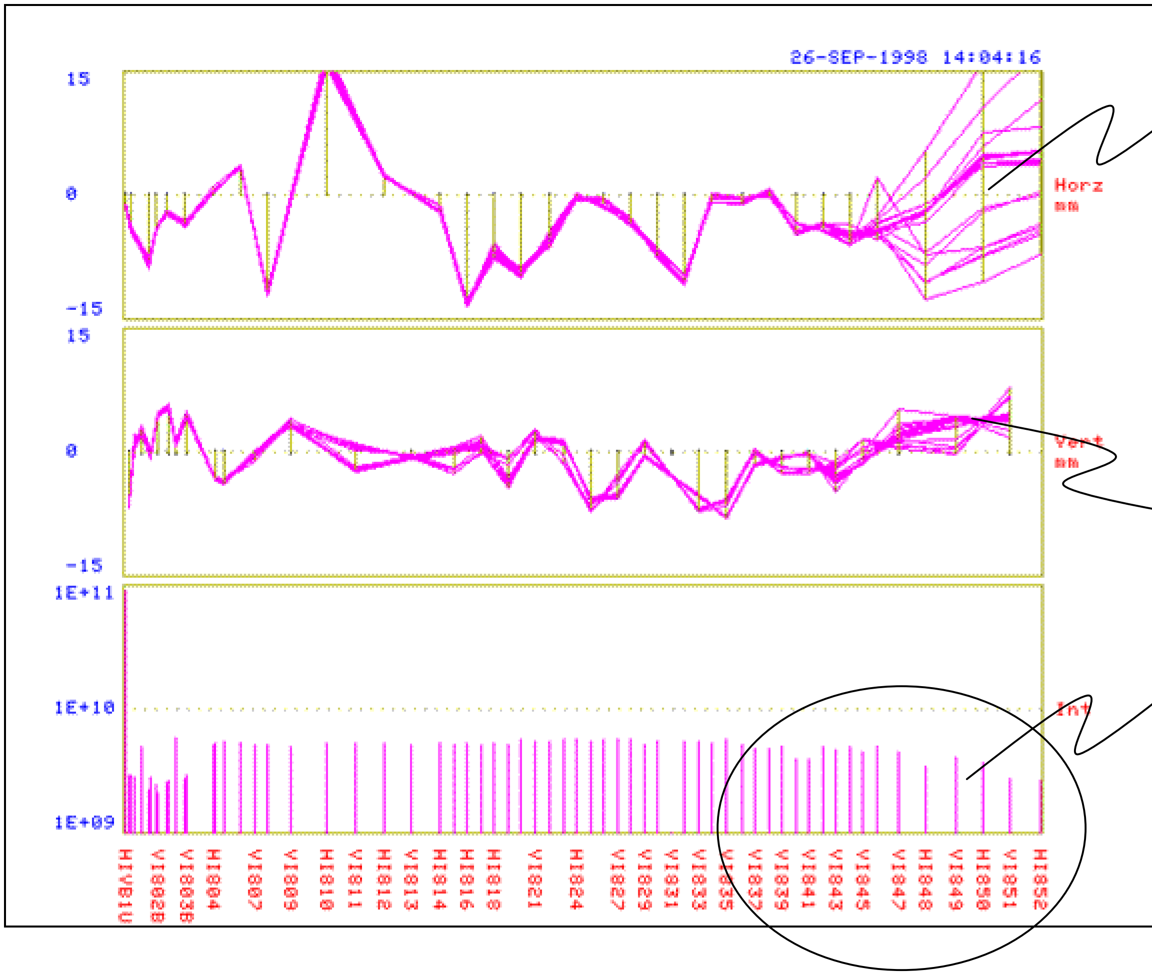
toroid data at the entrance of the beamline

But no beam in the Main Injector!!??



MI8 beamline BPM Data

(September 26, 1998)



Horizontal BPM data

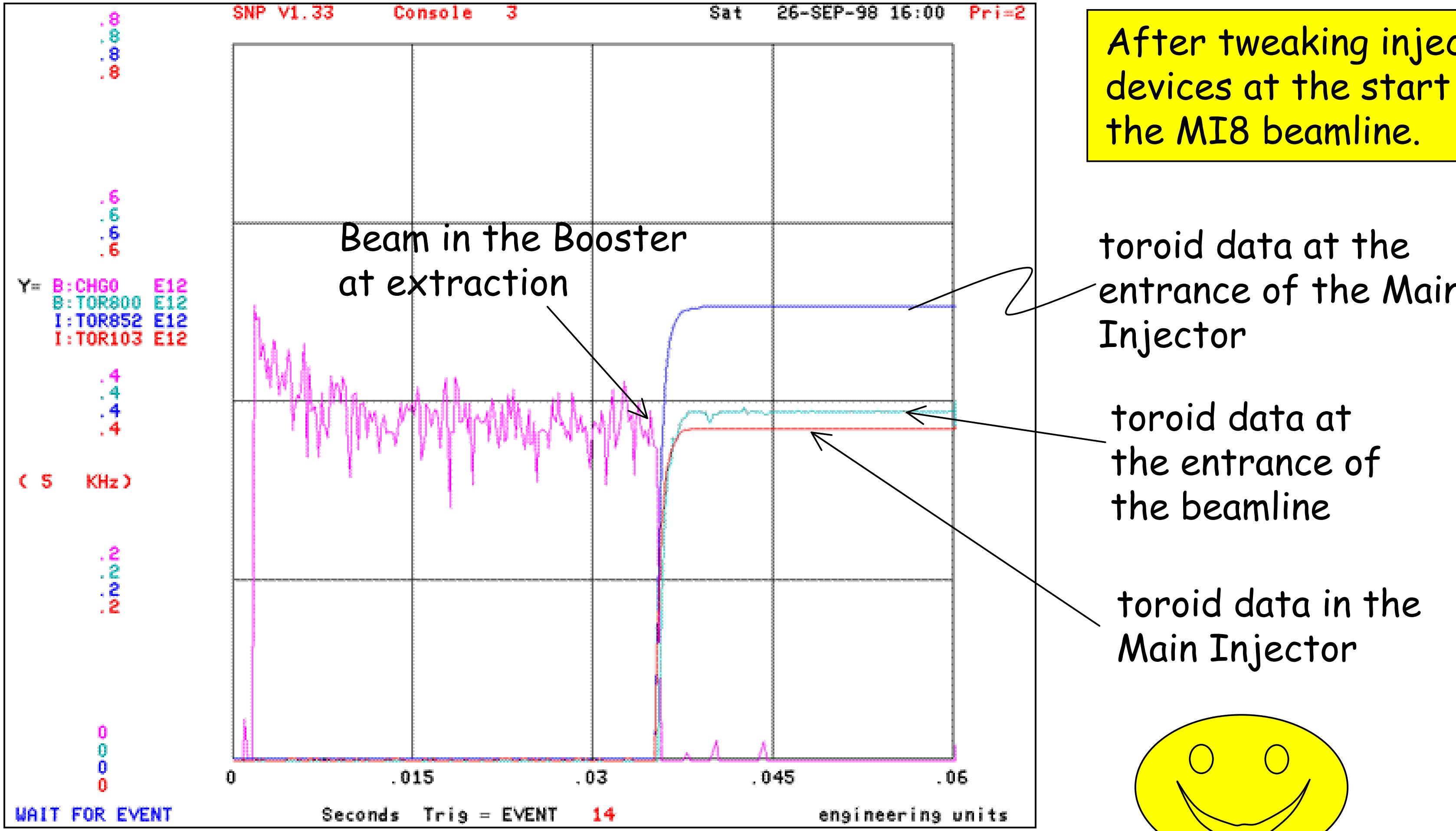
Vertical BPM data

Relative beam intensities measured using the BPM.

What we need is 100% transmission.

1st Beam in the MI, Current Transformers Data

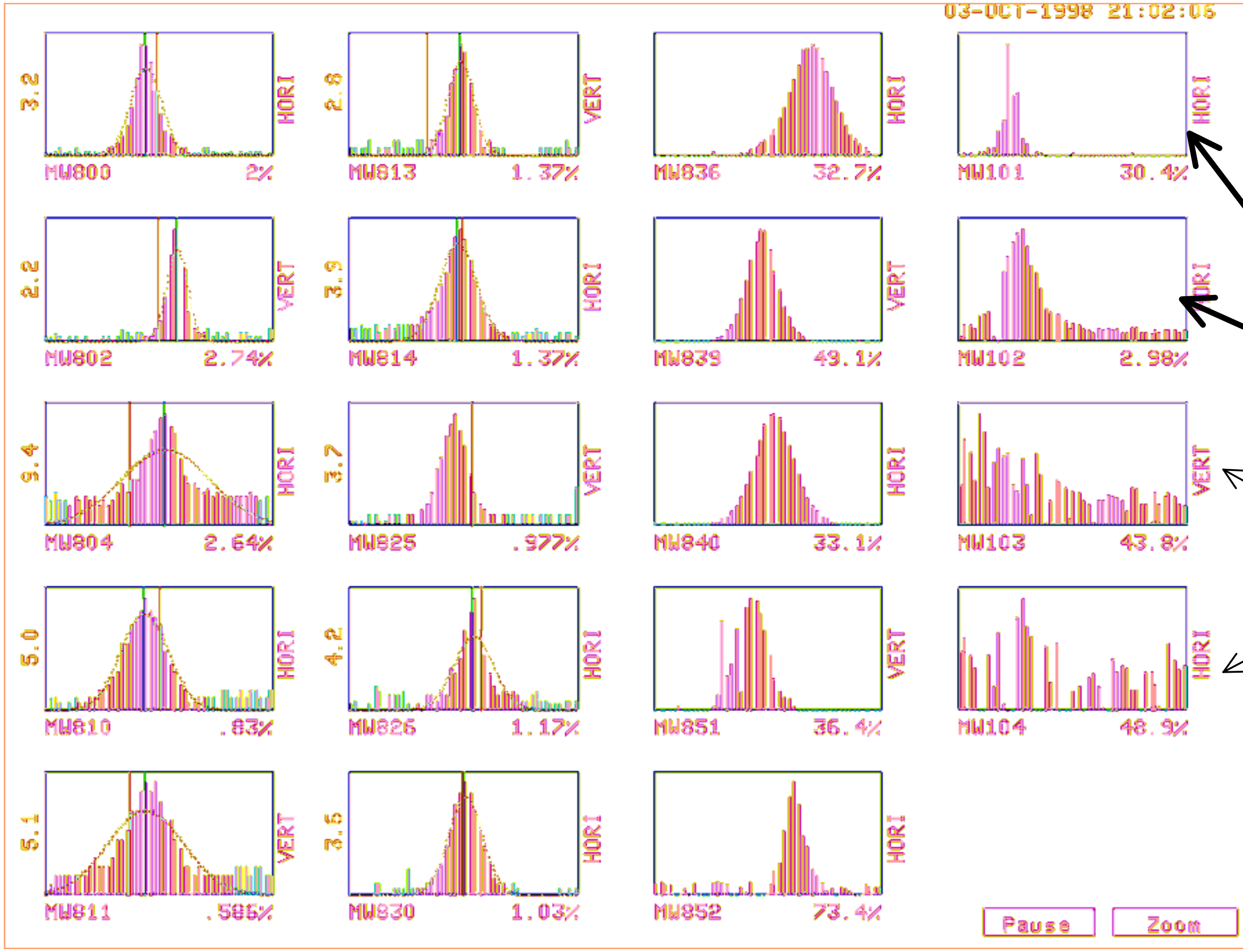
(September 26, 1998)



After tweaking injection devices at the start of the MI8 beamline.

MI8 Beamline & MI Multi-wire data (cont.)

(October 3, 1998)

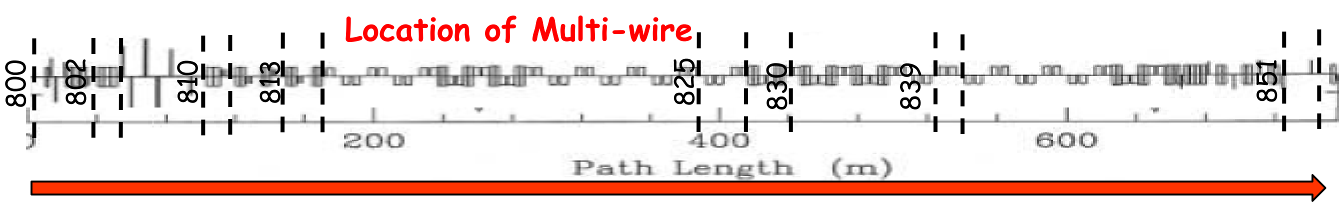


After tweaking the kicker timing of the beam into the Main Injector.

Beam profiles in the Main Injector

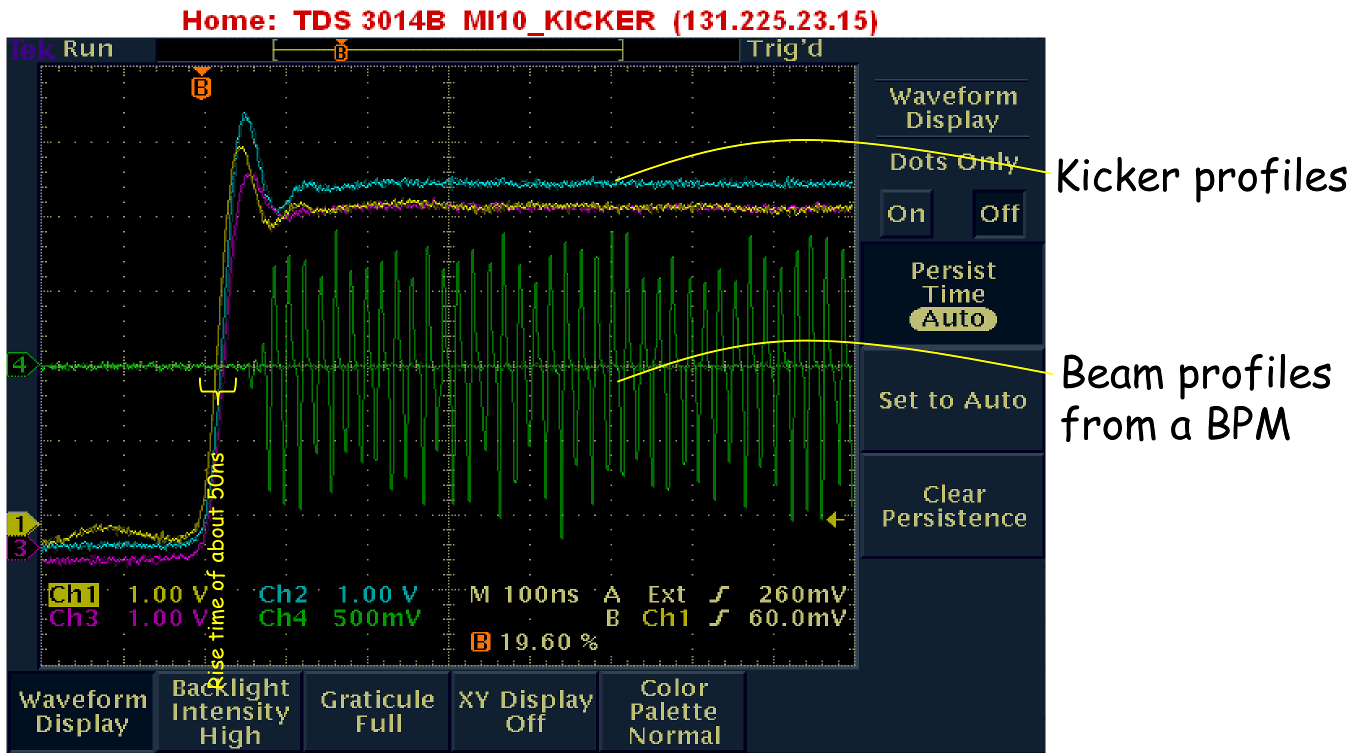
Broken MWs

Beam went beyond the MW104 location because →



MI8 beamline

Kicker profiles



MI BPM Data

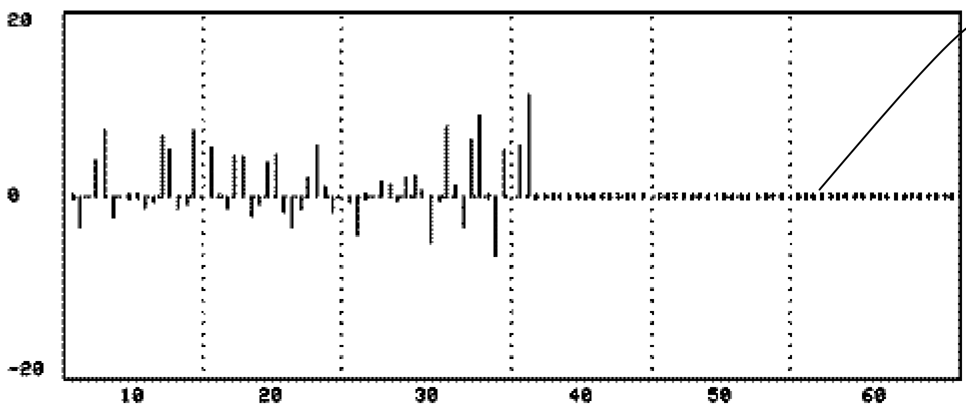
(October 3, 1998)

FLASH

Horizontal

.1189
25-SEP-1998 09:09:09

		10	20	30	40	50	60
00	...	NoBeam			5.49		
02	...	-3.409	5.196	-.6661	10.95	NoBeam	NoBeam
04	...	-.0832	.0832	-4.26	NoBeam	NoBeam	NoBeam
06	...	3.9	-1.417	NoBeam	NoBeam	NoBeam	NoBeam
08	...	7.214	4.535	0	NoBeam	NoBeam	NoBeam
10	...	-2.250	4.169	1.585	NoBeam	NoBeam	NoBeam
12	...	0	-2.174	1.167	NoBeam	NoBeam	NoBeam
14	...	NoBeam	-.8328	-.5828	NoBeam	NoBeam	NoBeam
16	...	NoBeam	3.723	2.085	NoBeam	NoBeam	NoBeam
18	...	-1.334	4.535	2.089	NoBeam	NoBeam	NoBeam
20	...	-.6661	-1.753	.5828	NoBeam	NoBeam	NoBeam
22	...	6.532	-3.372	-5.004	NoBeam	NoBeam	NoBeam
24	...	5.1	-1.585	-.4162	NoBeam	NoBeam	NoBeam
26	...	-1.334	2.085	7.454	NoBeam	NoBeam	NoBeam
28	...	-.9162	5.49	1.083	NoBeam	NoBeam	NoBeam
30	...	7.214	.9162	-3.285	NoBeam	NoBeam	NoBeam
32	...		-1.837	6.102		NoBeam	NoBeam
34	...			8.761			NoBeam
36	...			NoBeam			NoBeam
38	...			-6.423			NoBeam
40	...			5.1			NoBeam



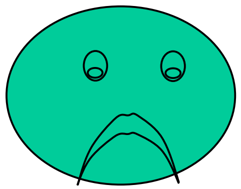
BPM data showed that beam halfway through the machine !!!

Horizontal BPM data

BPM did not respond

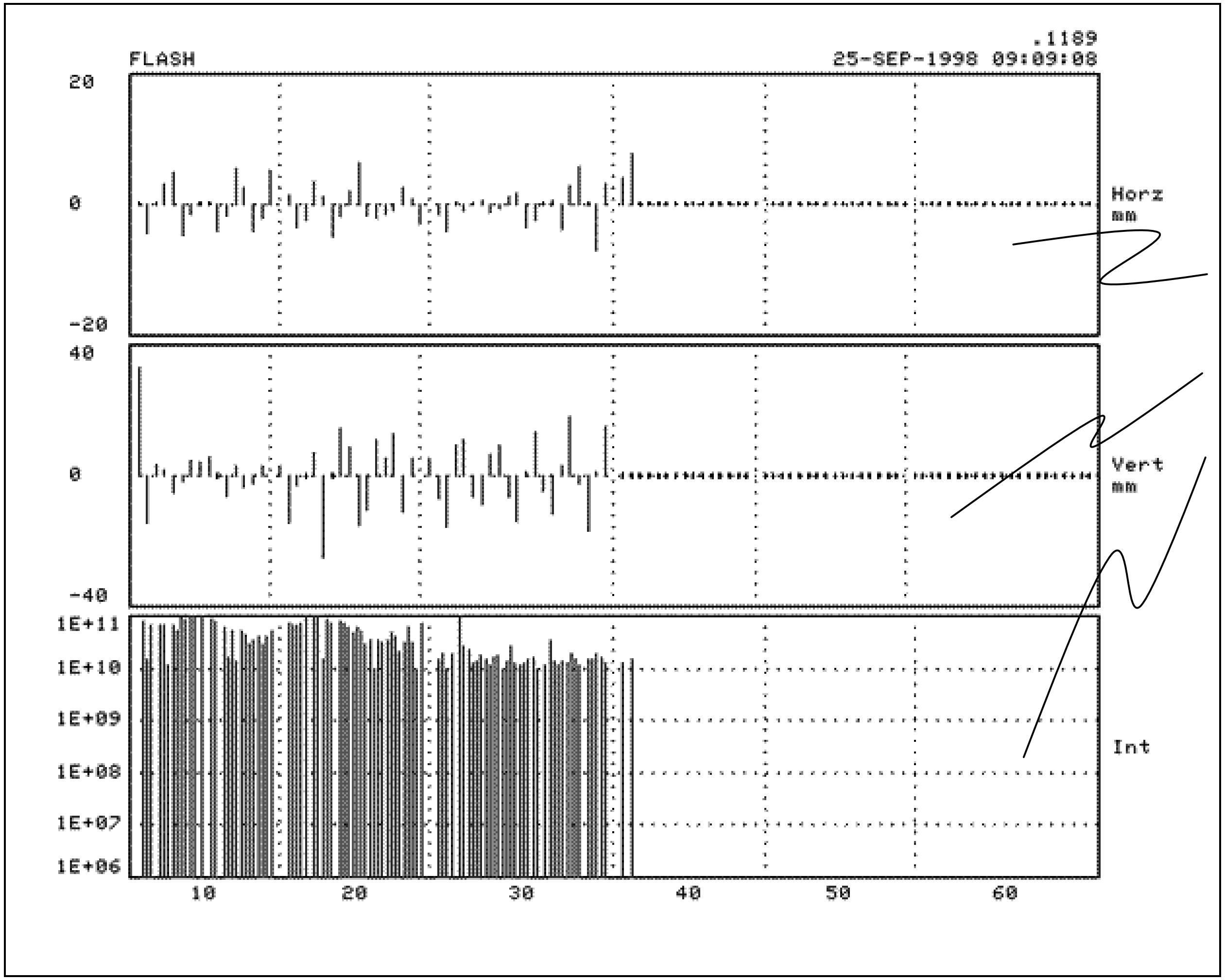
BPM plot

What we need is 100% transmission???



MI BPM Data

(October 3, 1998)



BPM data showed that beam halfway through the machine !!!

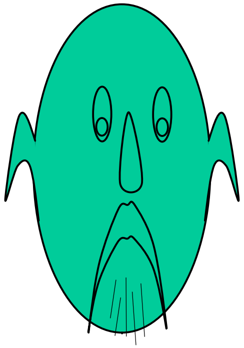
Horizontal BPM data

Vertical BPM data

Beam intensity from BPM

Beam got lost between MI30 and MI40

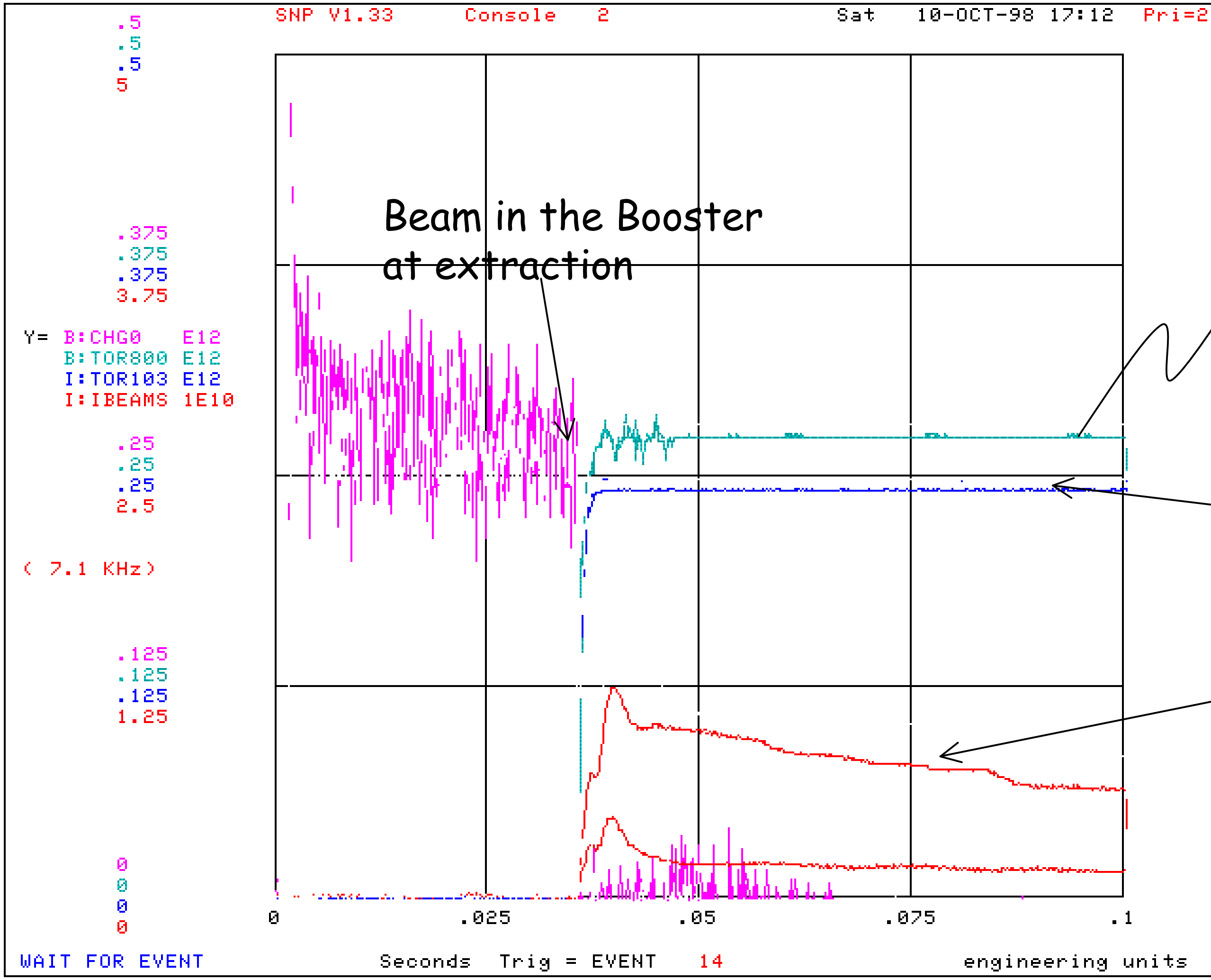
What we need is 100% transmission???



Experts figured out that there is about **1.9 deg roll angle** in the injection **Lambertson** magnet and Booster **injection energy was off by about 25 MeV.** We can proceed only after fixing these problems.

1st Beam in the MI, Current Transformers Data

(October 10, 1998)

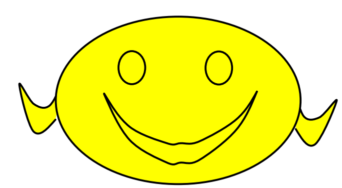


After fixing the identified problems in the Main Injector

toroid data at the entrance of the MI8 beamline

toroid data in the Main Injector

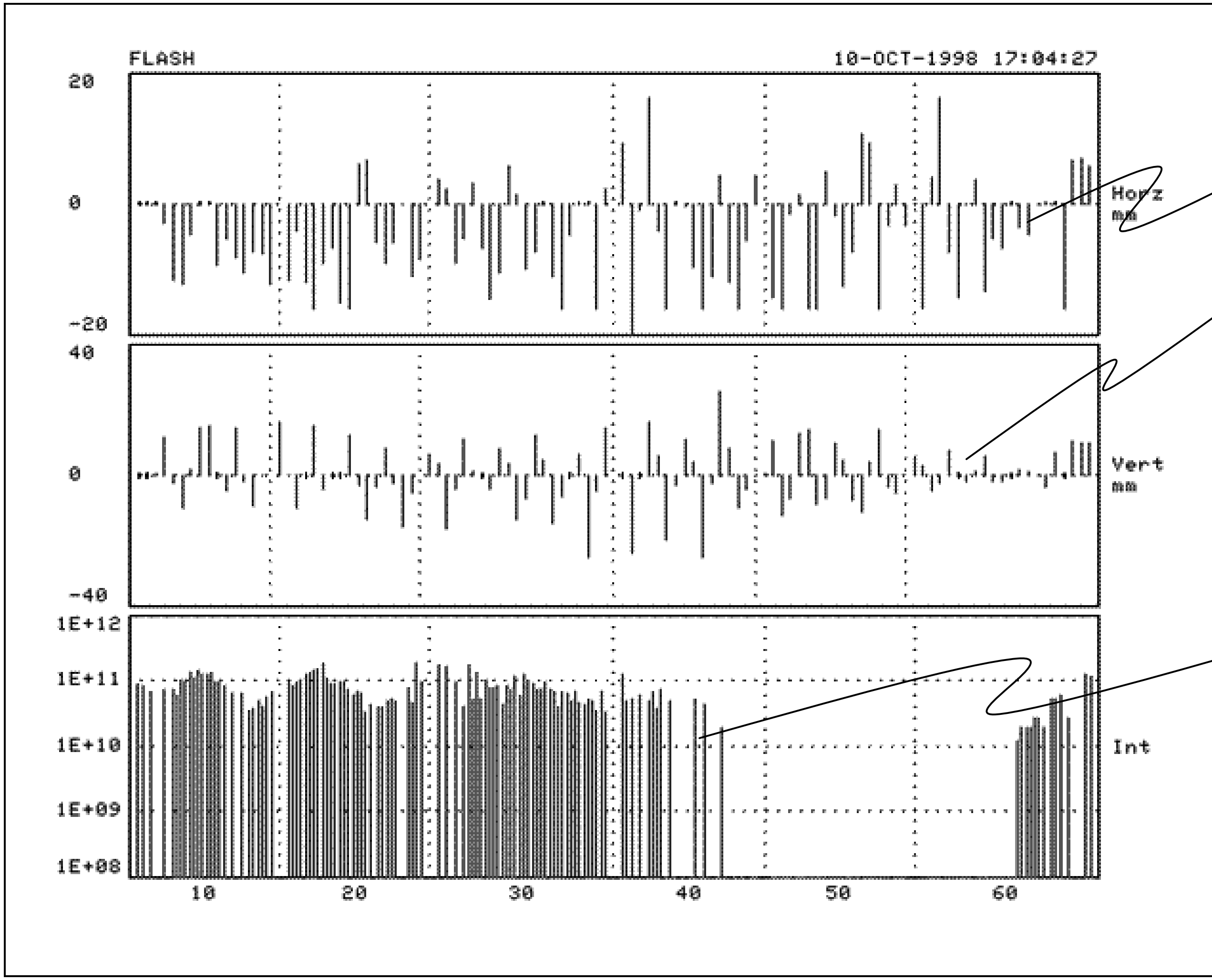
Current transformer in the Main Injector



1st Circulating Beam in the Main Injector BPM Data

(October 3, 1998)

After fixing identified problems



Horizontal BPM data

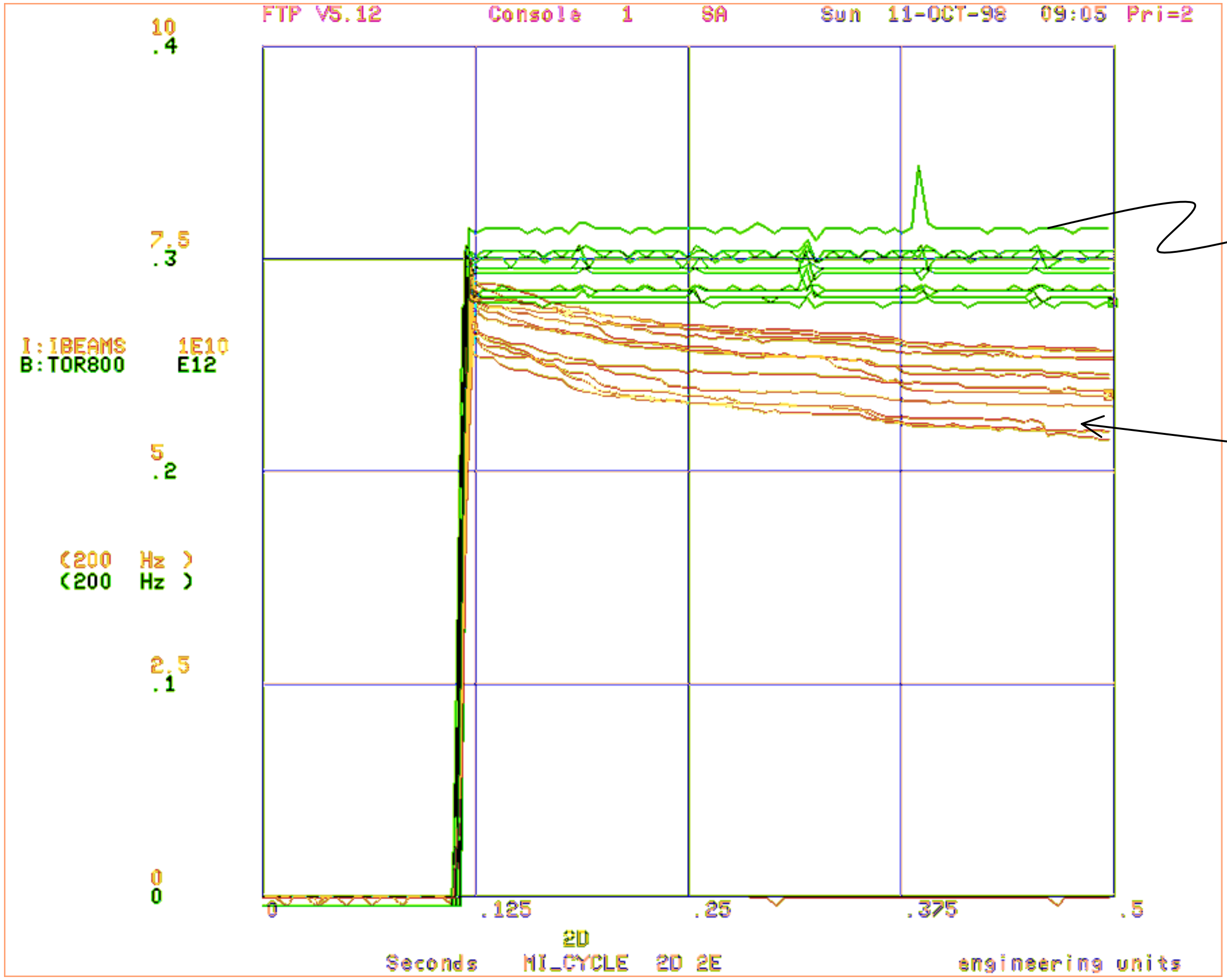
But the Beam was inside relative to BPM centers

Vertical BPM data

Beam intensity using BPM sum signal

More stable in the MI, Current Transformers Data

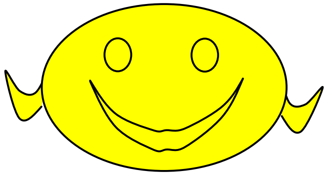
(October 11, 1998)



After tweaking H and V chromaticity corrections at the 8 GeV slot

toroid data at the entrance of the Main Injector

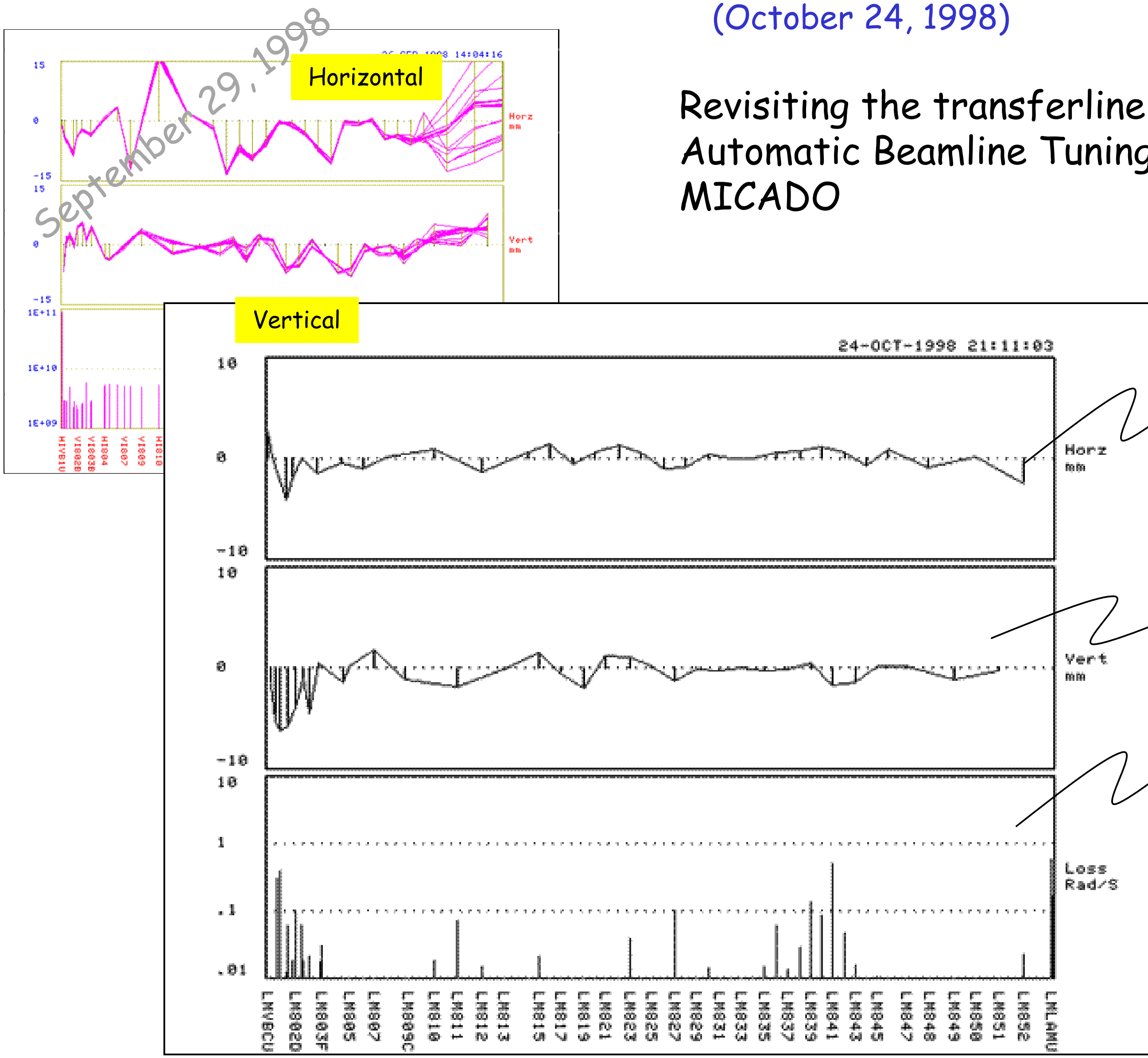
MI DCCT data



MI8 BPM Data

(October 24, 1998)

Revisiting the transferline using
Automatic Beamline Tuning Program
MICADO



Horizontal BPM data

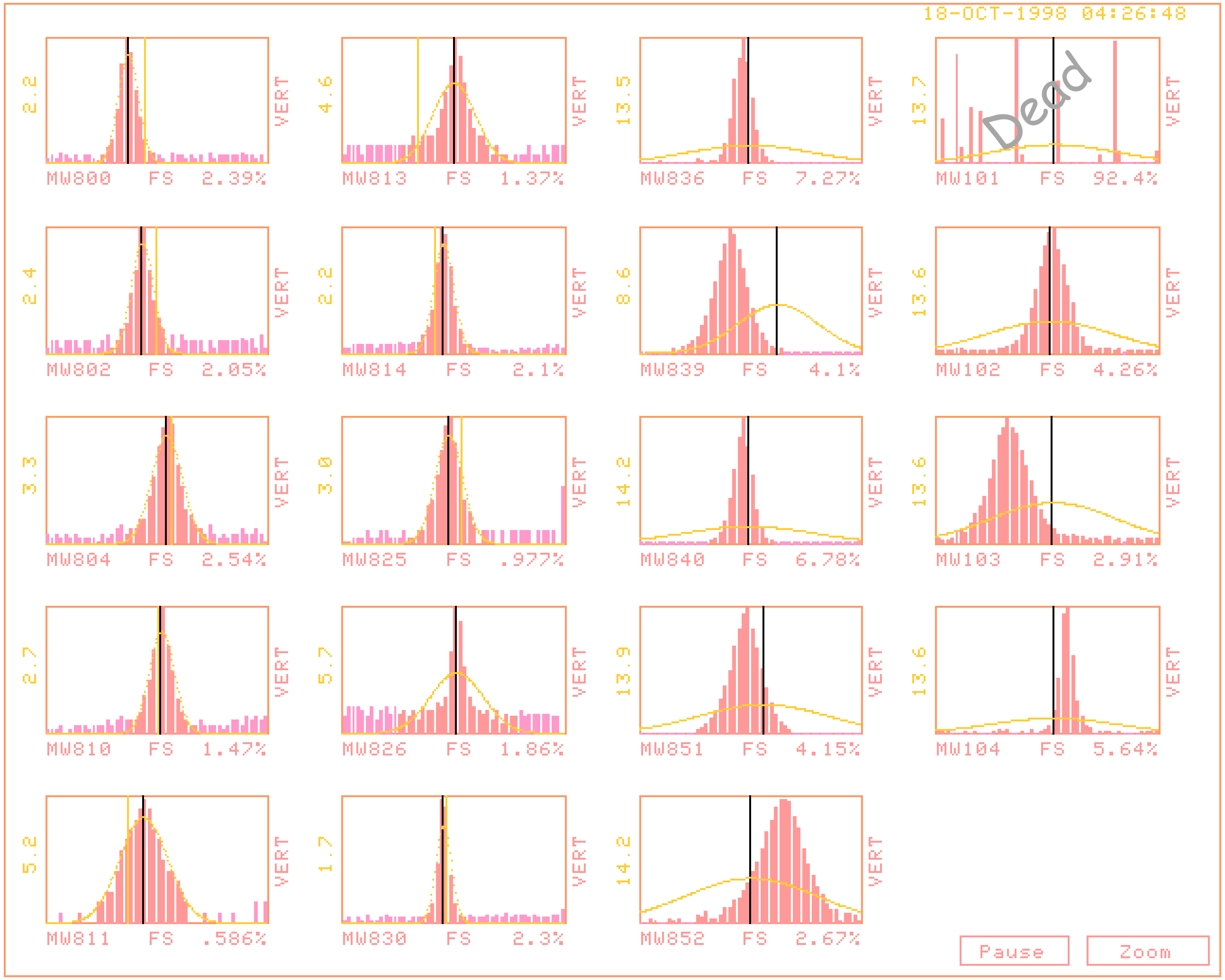
Vertical BPM data

Loss Monitors

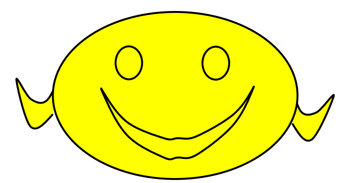
All of these loss
monitors lit→ beam loss
at a few points

MI8 Beamline & MI Multi-wire data (cont.)

(October 18, 1998)

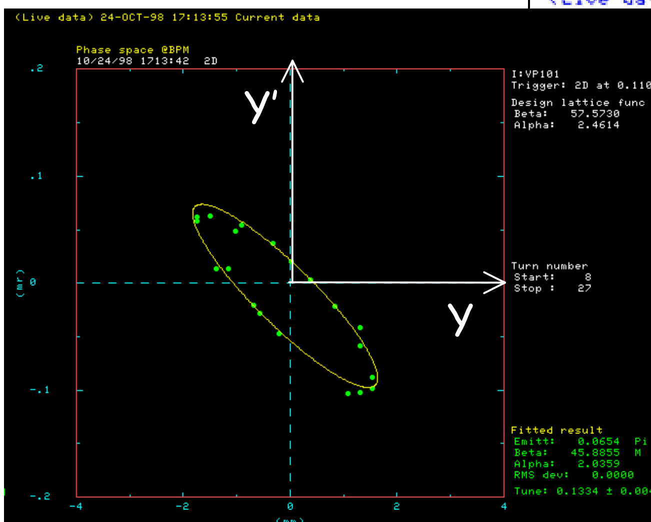


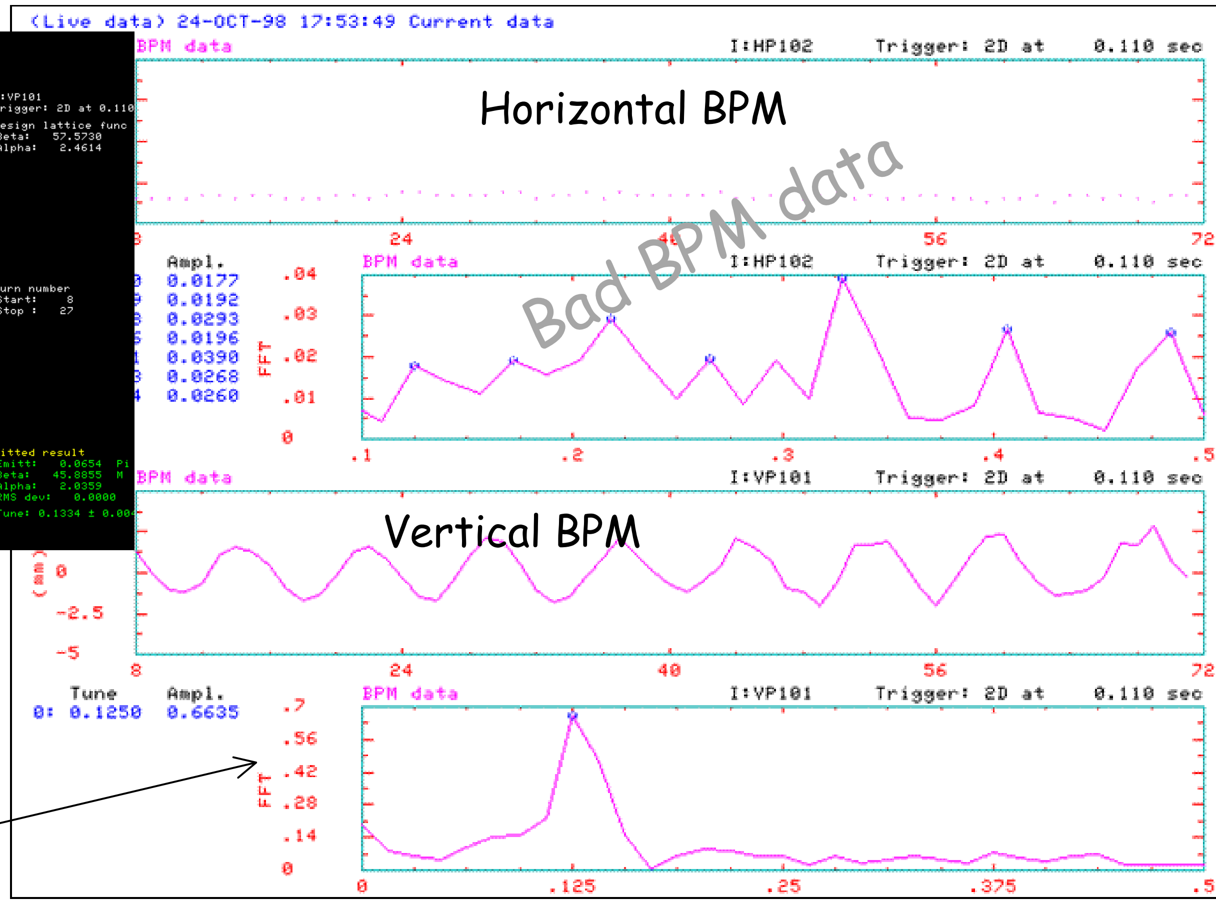
Good transmission and beam profiles in all of these MWs!



1^{st} Tune Measurement and Transverse Phase-space plot using TBT

<u>Tune measurements using Turn-by-turn (TBT):</u> An FFT of BPM data taken after exciting oscillations shows a peak at the machine's tune value.



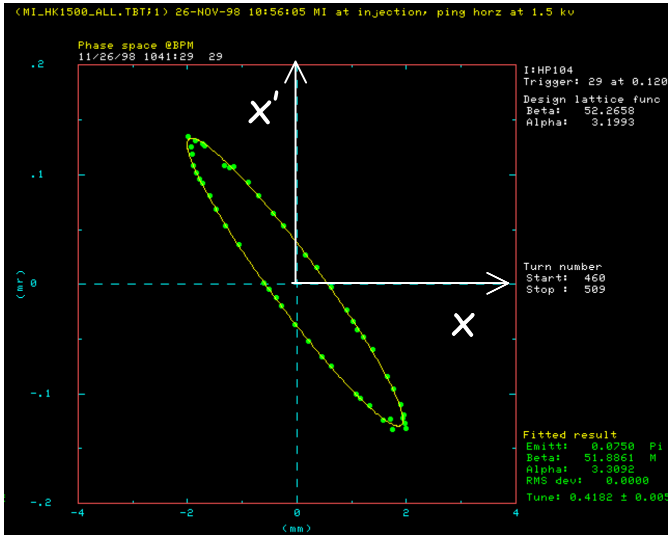


Design ν_x=0.425 ν_y=0.415

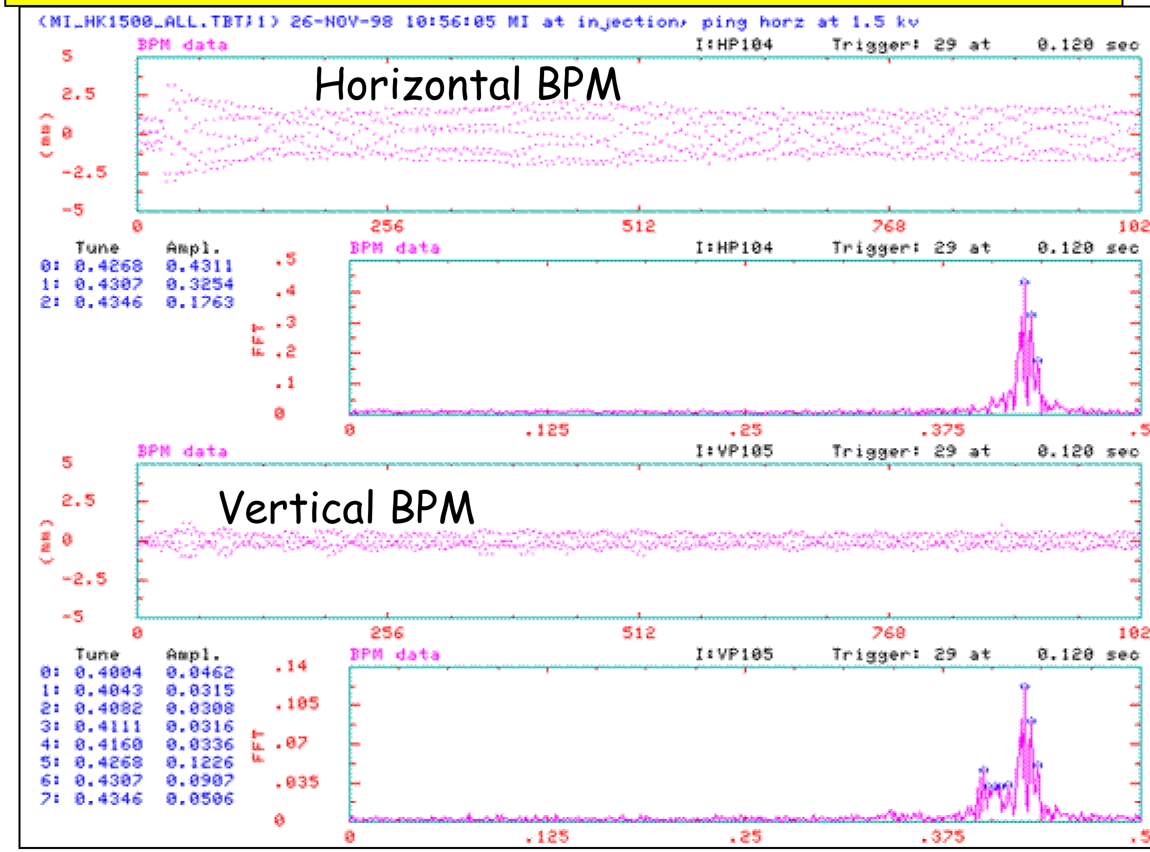
Measured ν_x=?? ν_y=0.125

Close to 8^{th} order resonance. Beam survives but not good!!

H and V-Tune Measurement and Transverse Phase-space plot using TBT (cont)



After calibration of the tune from magnet data and re-adjusting the tune at 8 GeV



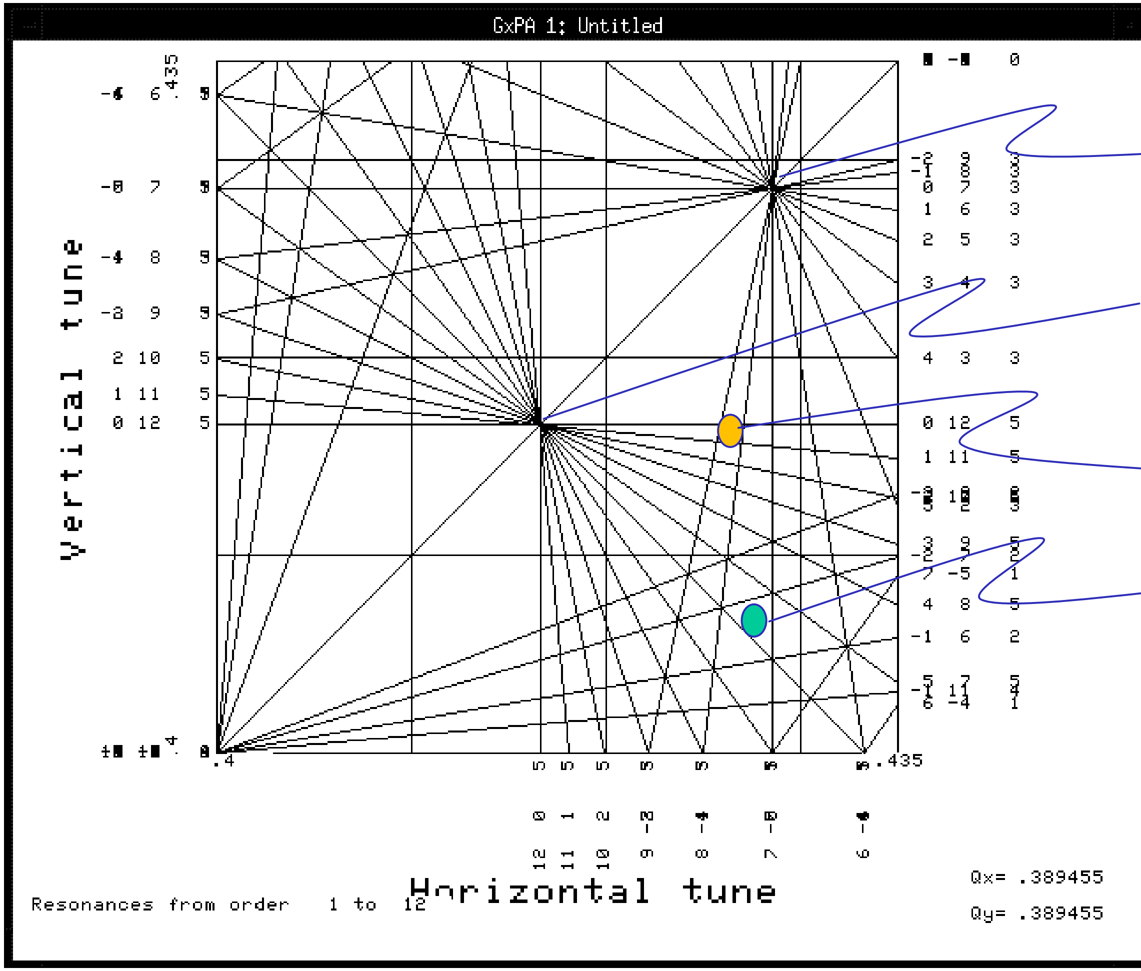
We ping the beam in the horizontal plane using a kicker soon after beam injection

Design $\nu_x=0.425$
$\nu_y=0.415$

Measured $\nu_x=0.426$
$\nu_y=0.405$ — This is a separate measurement after pinging the beam vertical plane

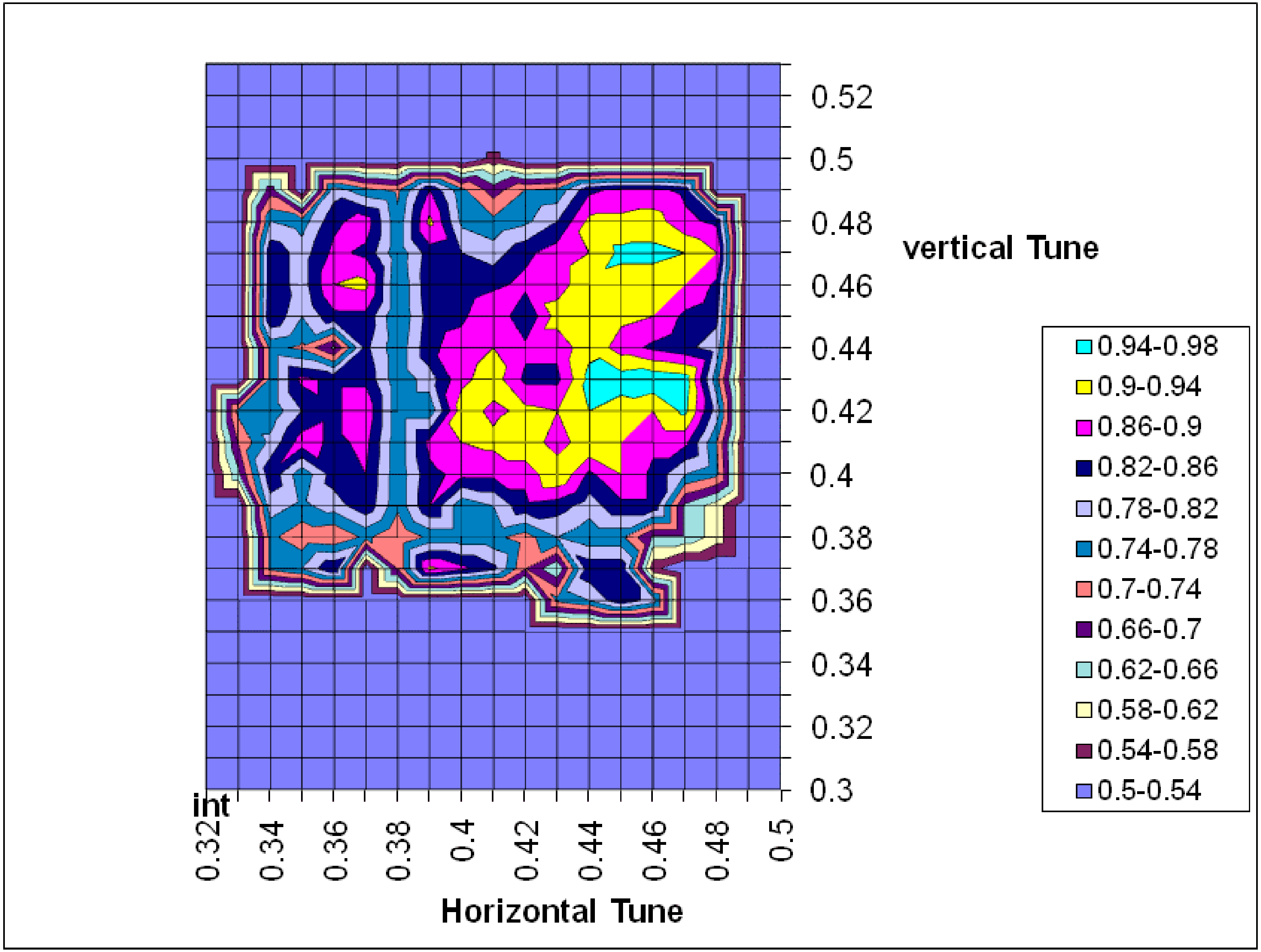
This is away from any resonances. Still not a good region!

Tune point on the Tune Diagram



We can set the machine to theoretical tunes by simply changing quad settings. But, still we have not closed the orbit yet. This is critical to minimize the beam loss and for better beam transmission

Tune Scan for Recycler

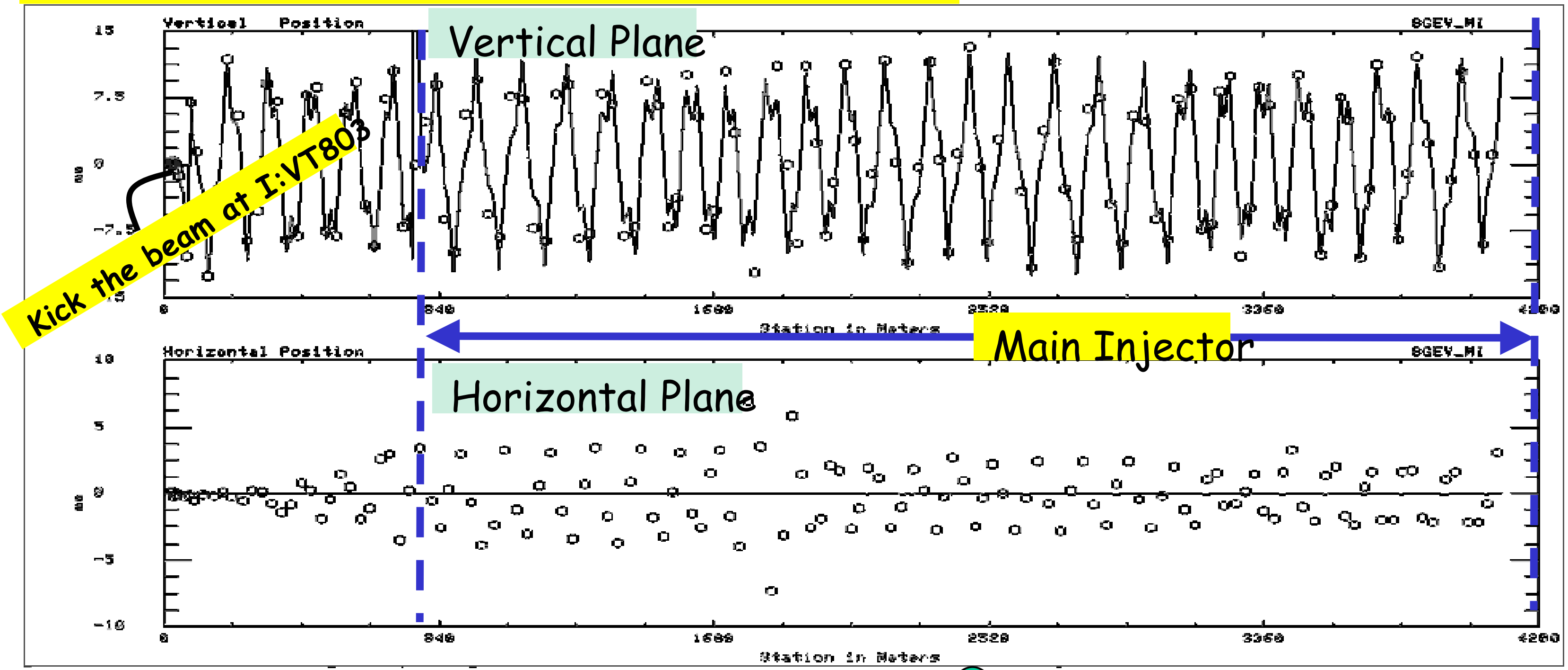


From Cons Gattuso

Measuring the Integer part of the Tune

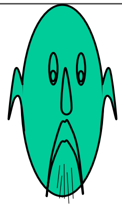
Measuring the integer part of the tune involves
a.Measuring the difference orbit with and without a dipole kick on the orbit
b.Count the number of betatron oscillations

Example of Tune Measurement in Vertical Plane



Measurements: **26 (V)** & 26(H)

Design: 25 (V) & 26(H)



Correcting the integer tune was a major job.

Smoothing the Orbit

Goal: In a high energy synchrotron, one generally will have several 2- and 3-bumps for

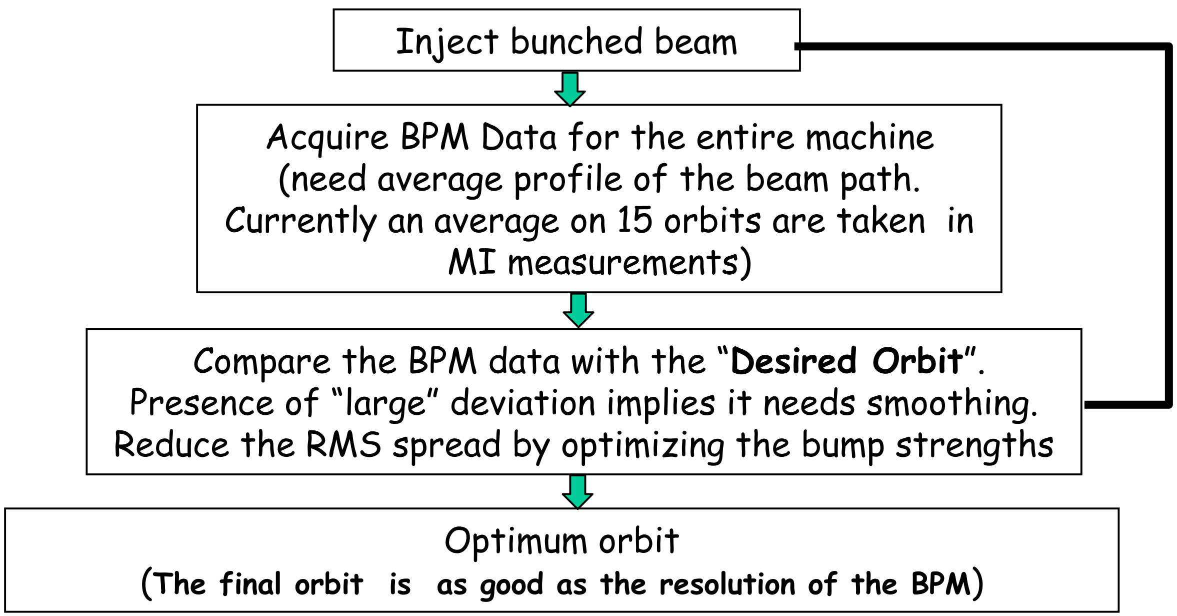
1. beam injection
2. extraction and
3. for special beam gymnastics

Nonetheless, the machine orbit should be "undisturbed" outside these bumps. If not, these locations become the main sources of transverse emittance dilution and beam losses.

→ Need to establish new closed orbit and open the dynamic aperture.

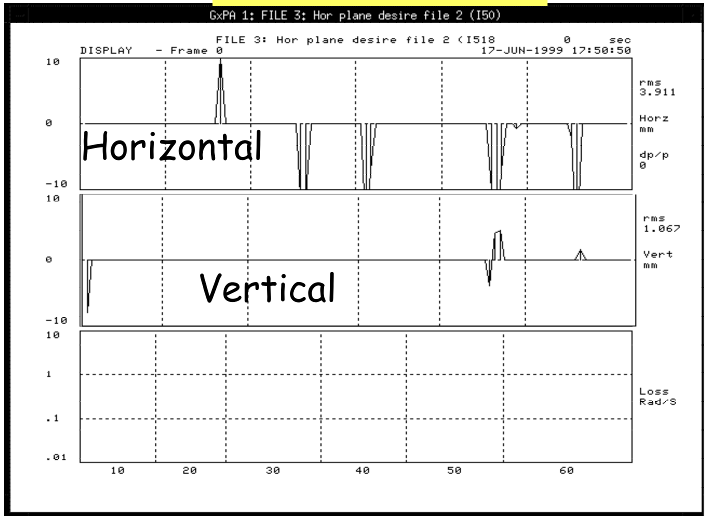
This step is an iterative procedure and needs

1. Reliable BPM system to measure the orbit accurately
2. A number of dipole correctors

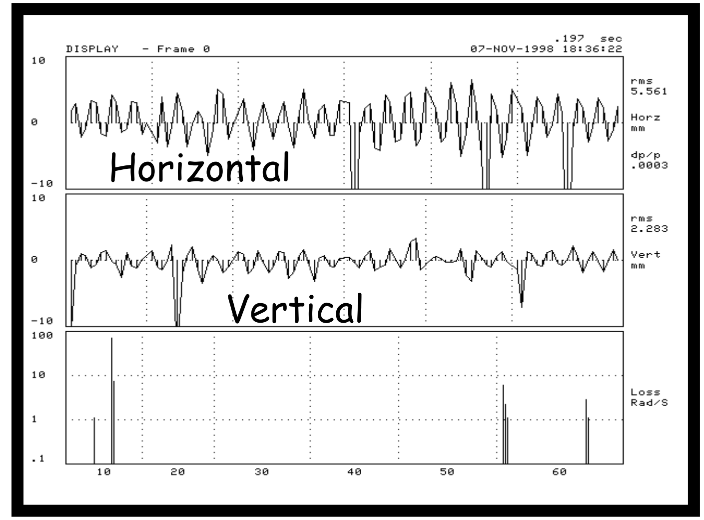


Smoothing the Orbit (cont.)

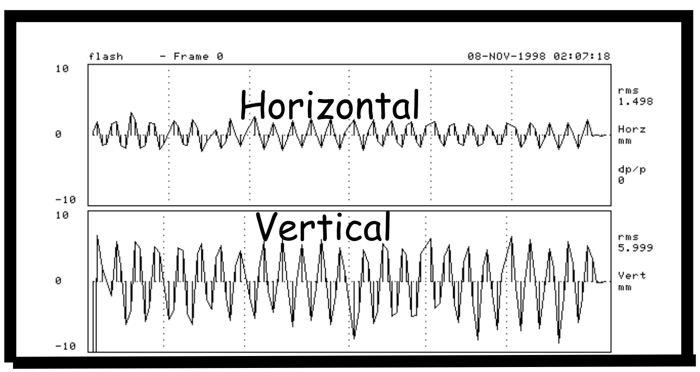
Desired Orbit



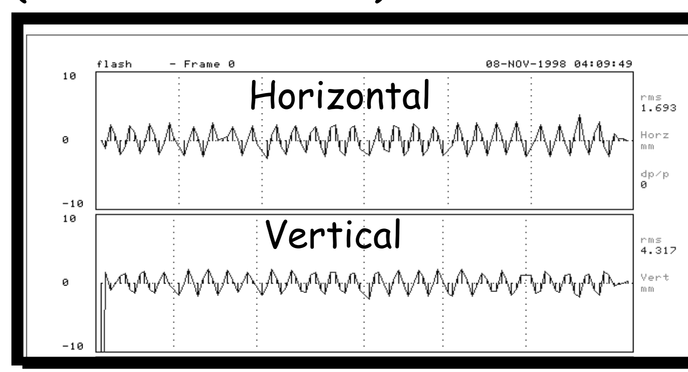
Data Before smoothing



(1st turn - 2nd turn) before smoothing



(1st turn - 2nd turn) after smoothing



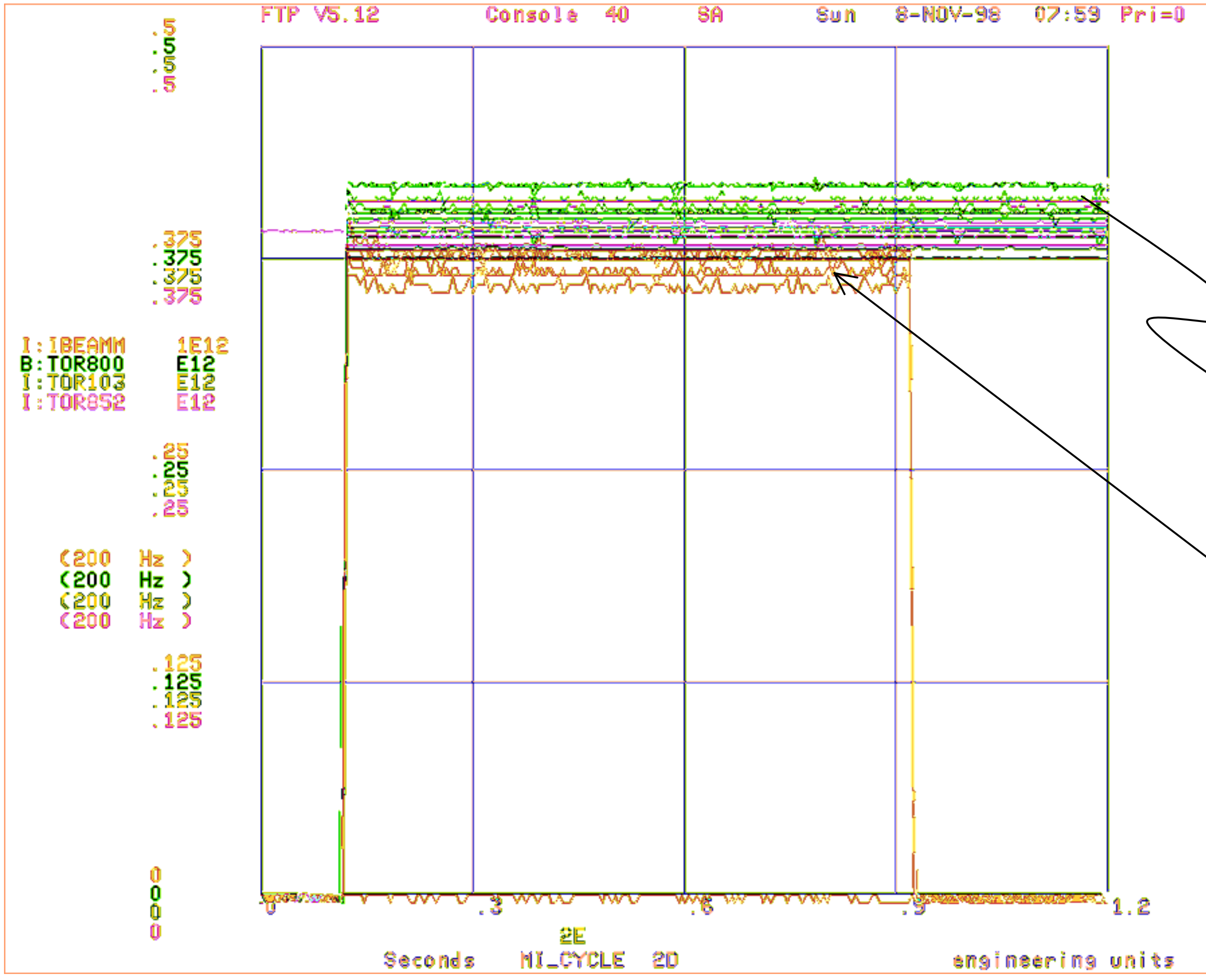
Vertically it improved significantly during this smoothing.

Stable Beam in the MI with good beamlife time,

(November 8, 1998)

$$I = I_0 \, e^{-\frac{t}{\tau}}$$

$$\tau = \text{Beam Lifetime}$$



After smoothing the orbit

toroid data at the entrance of the Main Injector

DCCT data

Injection Closure or beamline Tuner (BLT)

Goal: Match the injection orbit to that of the closed orbit

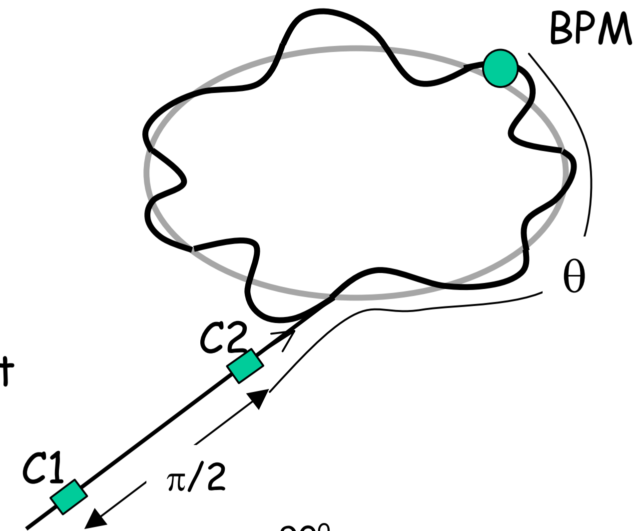
Advantages: Eliminate transverse emittance growths associated with the injection

This technique has two steps:

1. Calibrate the BLT
2. Implementation of BLT

Requirements:

1. Two correctors C1 & C2, in the injection beamline which are separated by a phase advance of $\pi/2$
2. A BPM in the ring sensitive to beam intensity of interest



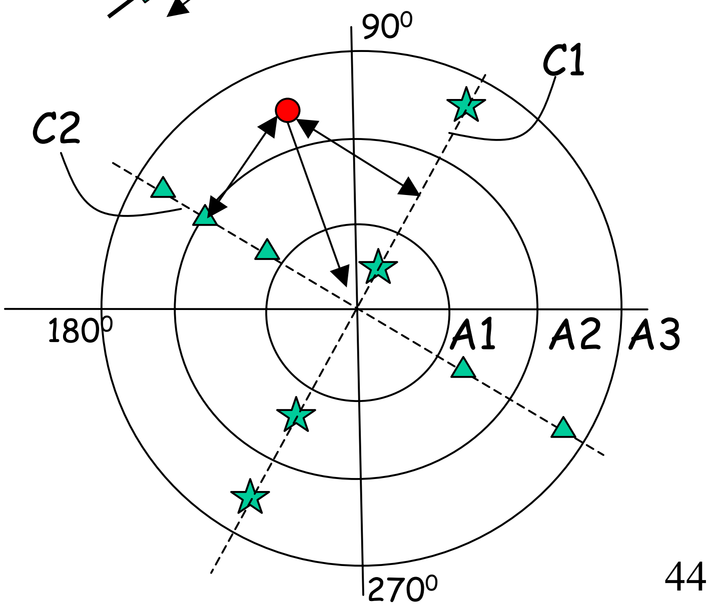
Calibration: Measure

$$S1 = \frac{\text{Beam oscillation Amplitude from TBT}}{\text{Corrector Strength (Amp)}}$$

for C1 keeping C2 constant. Similarly $S2$ for C2.

Implementation: Inject the beam and measure the amplitude & the phase of the beam at BPM by fitting TBT data. Using $S1$ and $S2$ one can determine exact amount of corrector strengths needed to achieve

ΔAmplitude = 0
ΔPhase = 0 at the injection point

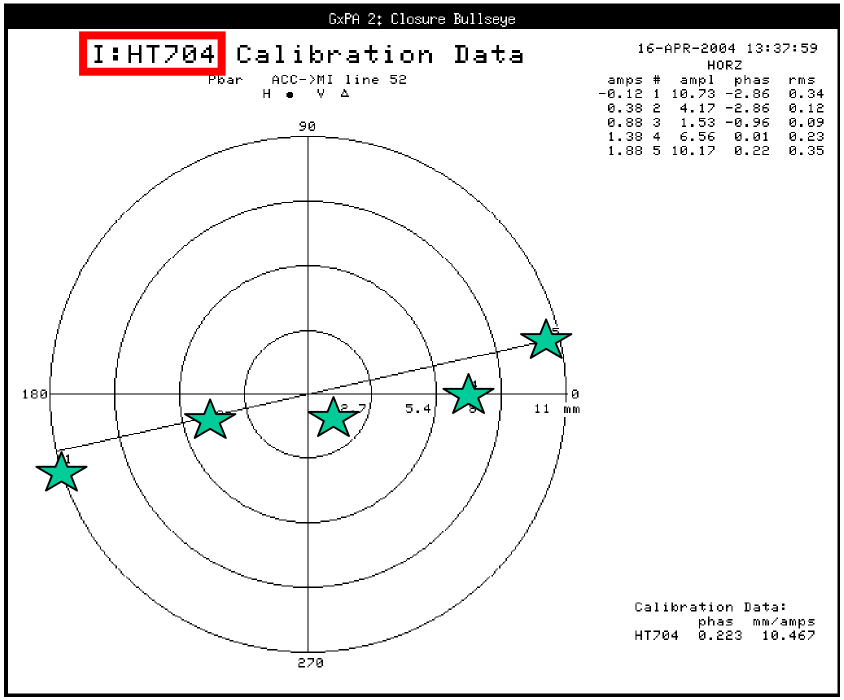


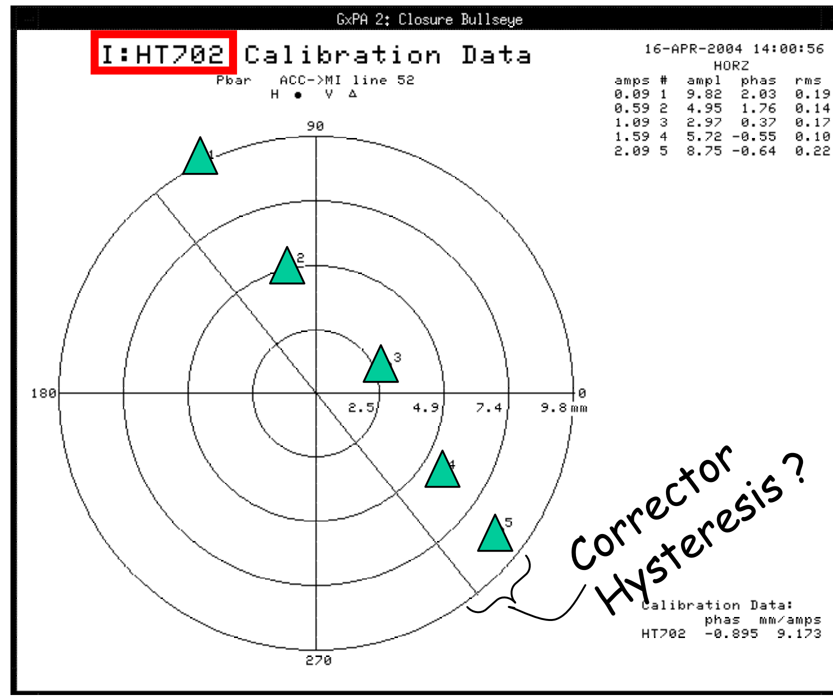
Injection Closure

Accumulator pbars → Main Injector

(Calibration of BLT)

<u>Calibration for Horizontal Injection Closure:</u>



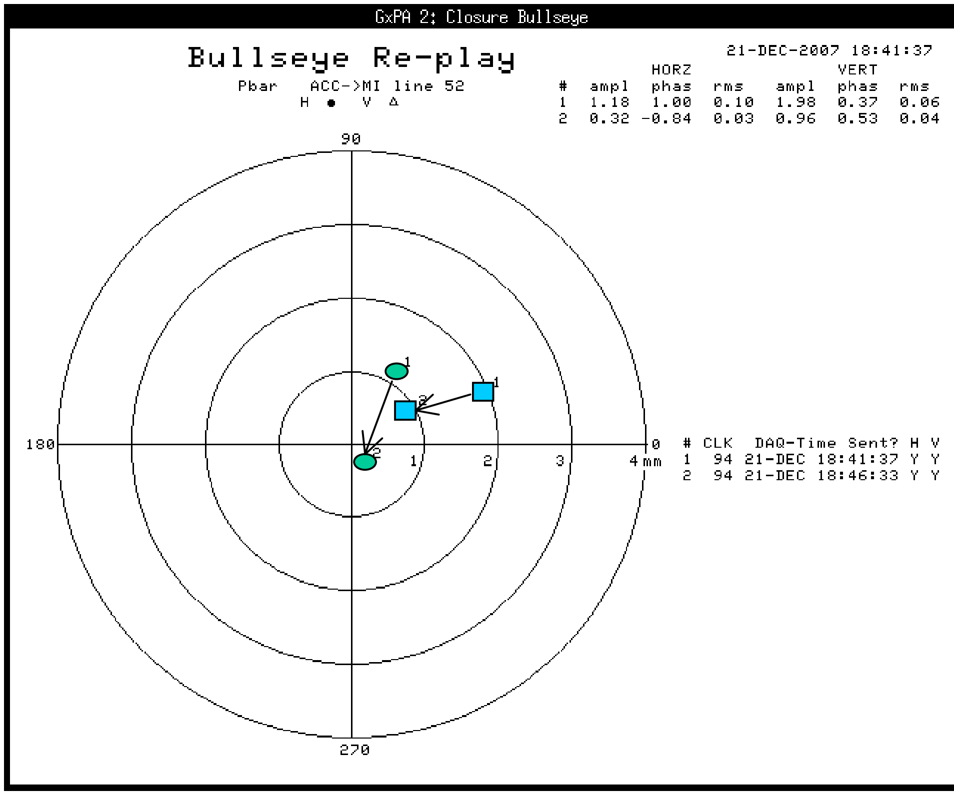


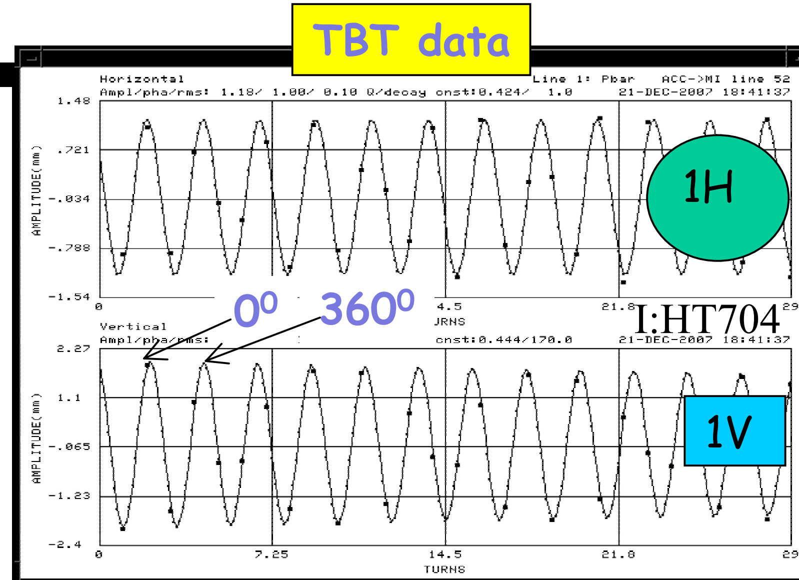
Issues in these calibrations: These two dipole correctors were not exactly 90deg apart?
There are some hysteresis effects.

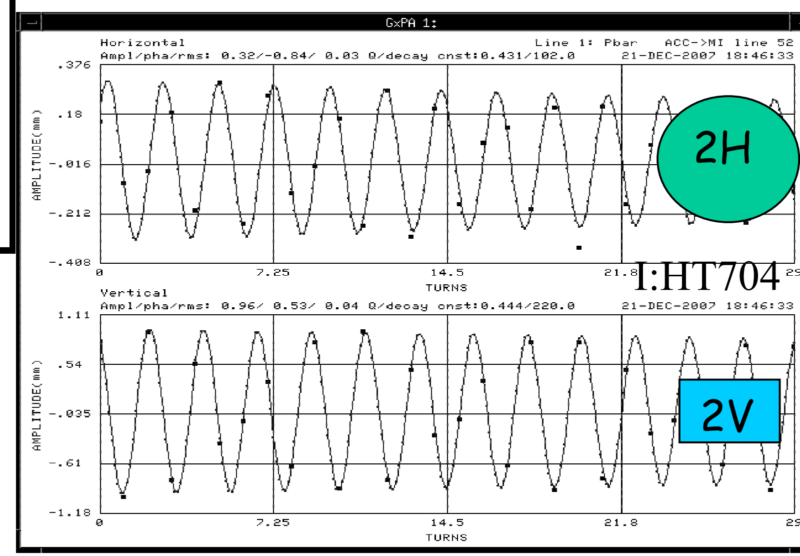
Similar calibration is carried out for the Vertical plane

Example on Injection Closure (cont.)

Accumulator pbars → Main Injector

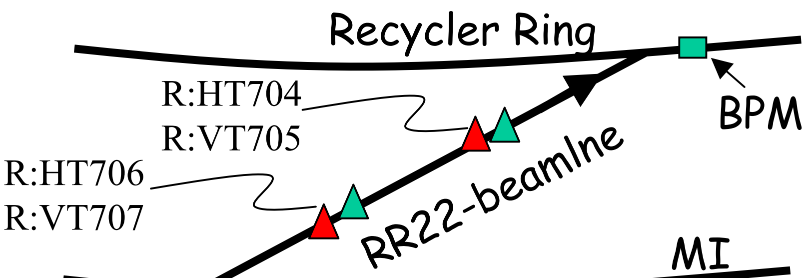




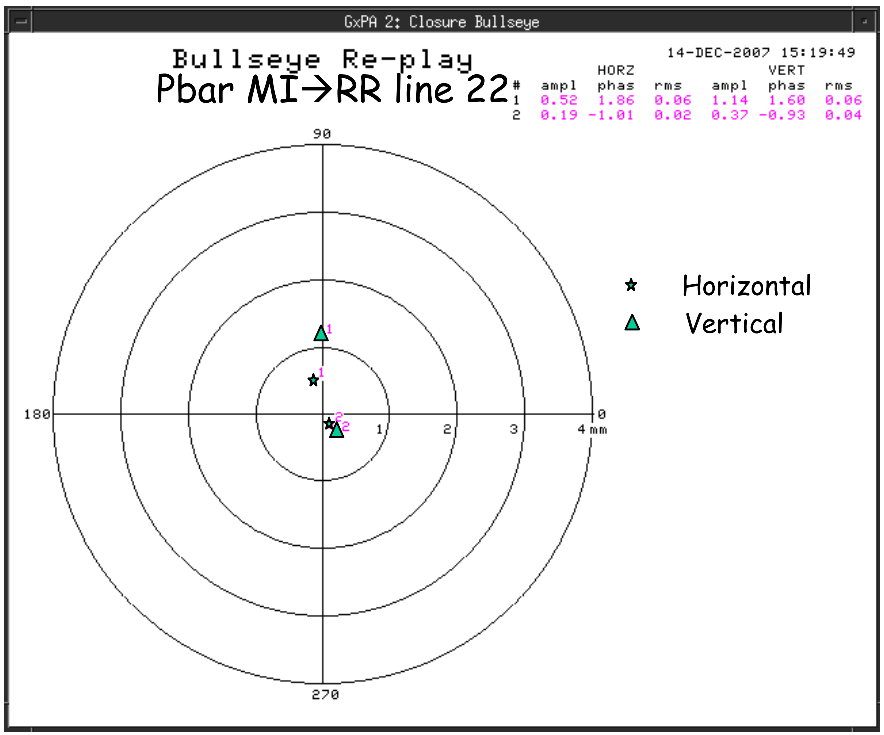


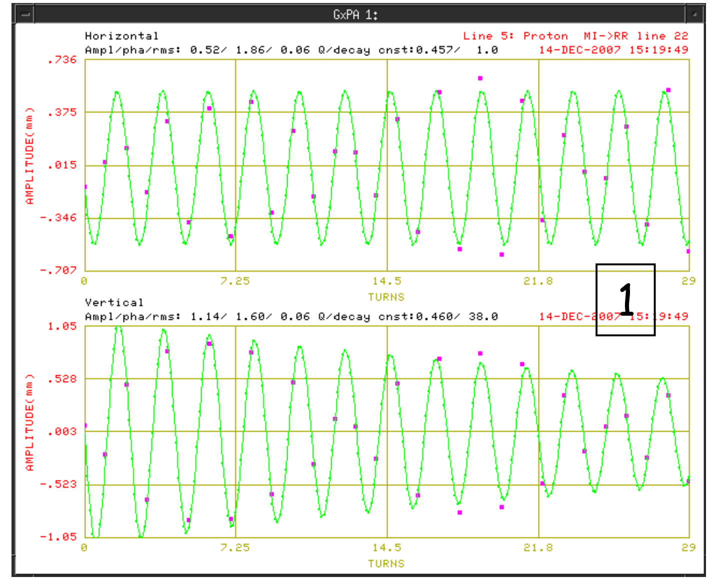
Reduced the transverse emittance growth by ~3 π-mm-mr from 1st to the 2nd transfer

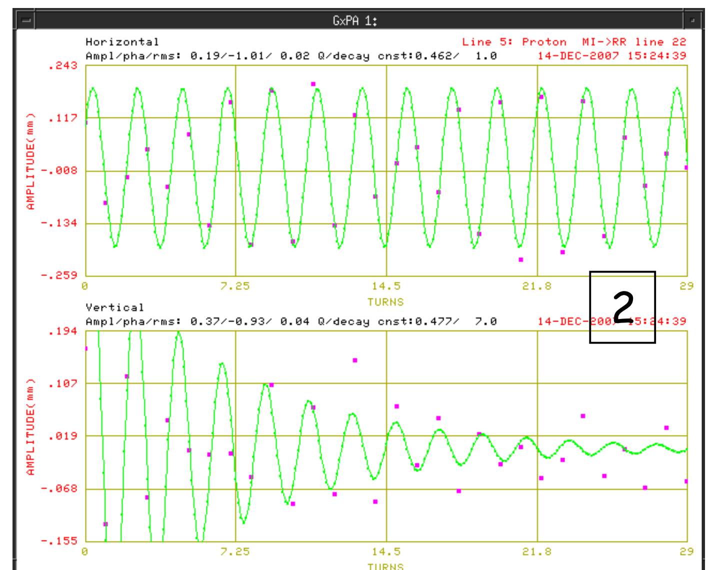
Recycler Beamline Tuner



Beam position versus Beam Phase







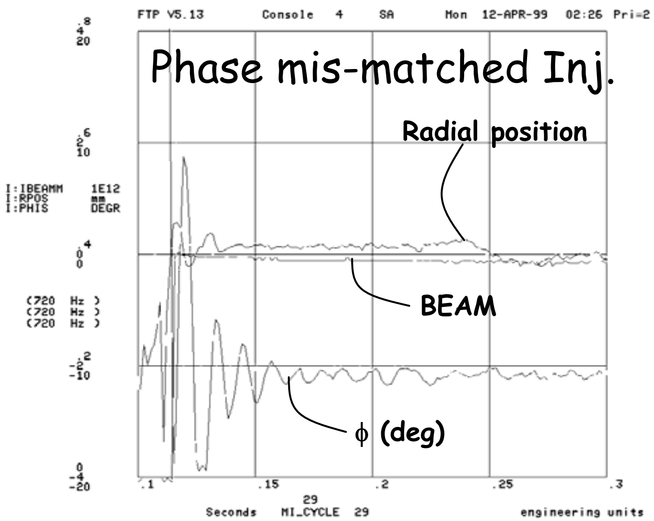
An Example on Injection phase and Energy Tuning

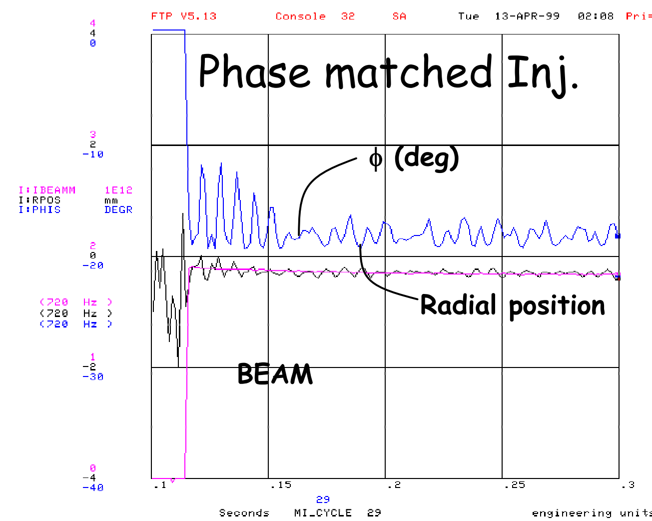
(Longitudinal)

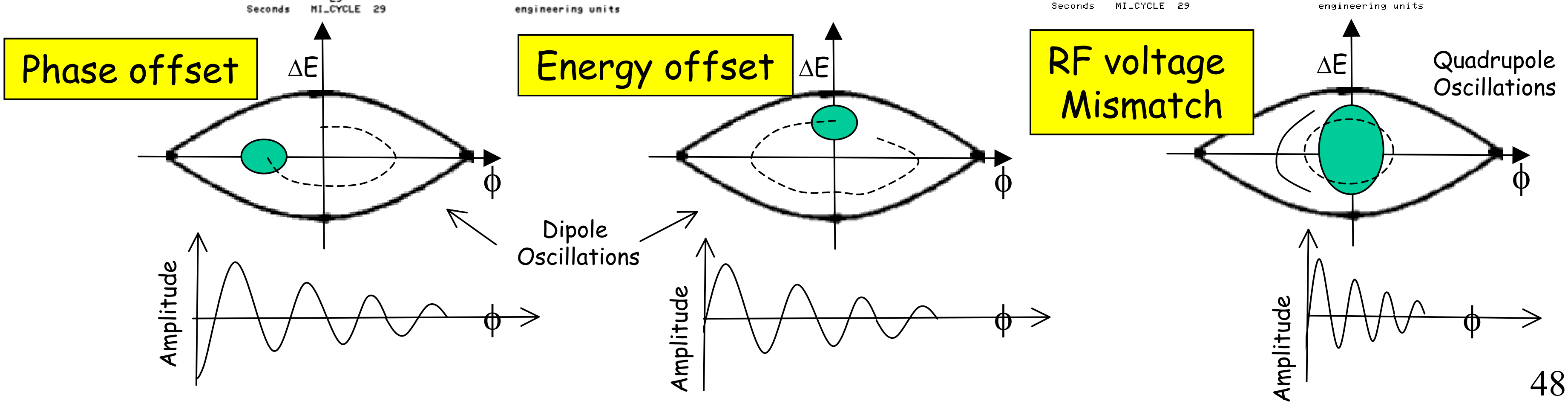
Booster protons→ Main Injector

Matching RF Voltage at 8 GeV : $\left|\frac{V\cos(\phi_s)}{h\eta}\right|_{Booster} = \left|\frac{V\cos(\phi_s)}{h\eta}\right|_{MI}$

	ϕ (deg)	h	η	V MV
Booster	180	84	0.0223	0.375
MI	0	588	-0.0089	1.035







Measurements of Admittances

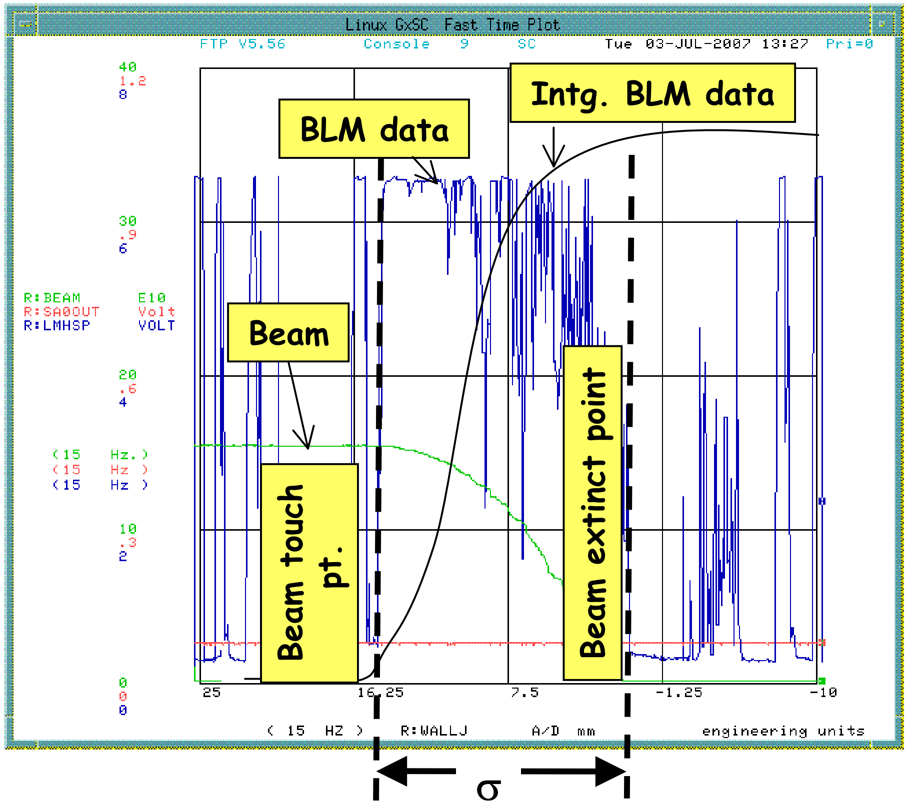
There are two types of admittances to be measured and optimized:

1. Transverse admittance
2. Longitudinal admittance ← $\left[\frac{\Delta p}{p}\right]_{Max}$

<u>Transverse admittance</u>

Different methods are used for accelerators and beam storage rings. An example of admittance measurement in the Recycler is shown here.

1. Inject the beam,
2. Heat the beam by pinging till it fills up the entire aperture
3. Move a scraper till it touches the beam as observed by a loss monitor
4. Move the scraper till all the beam disappears.



Then admittance is given by

$$A = \frac{6\pi\beta\gamma\sigma^2}{\beta_{lattice}} \quad \text{For the non-dispersion region}$$

Similarly for the other plane

<u>Long. Admittance :</u>

Inject the beam into an RF bucket and change the rf freq. up and down till beam touches the aperture point.

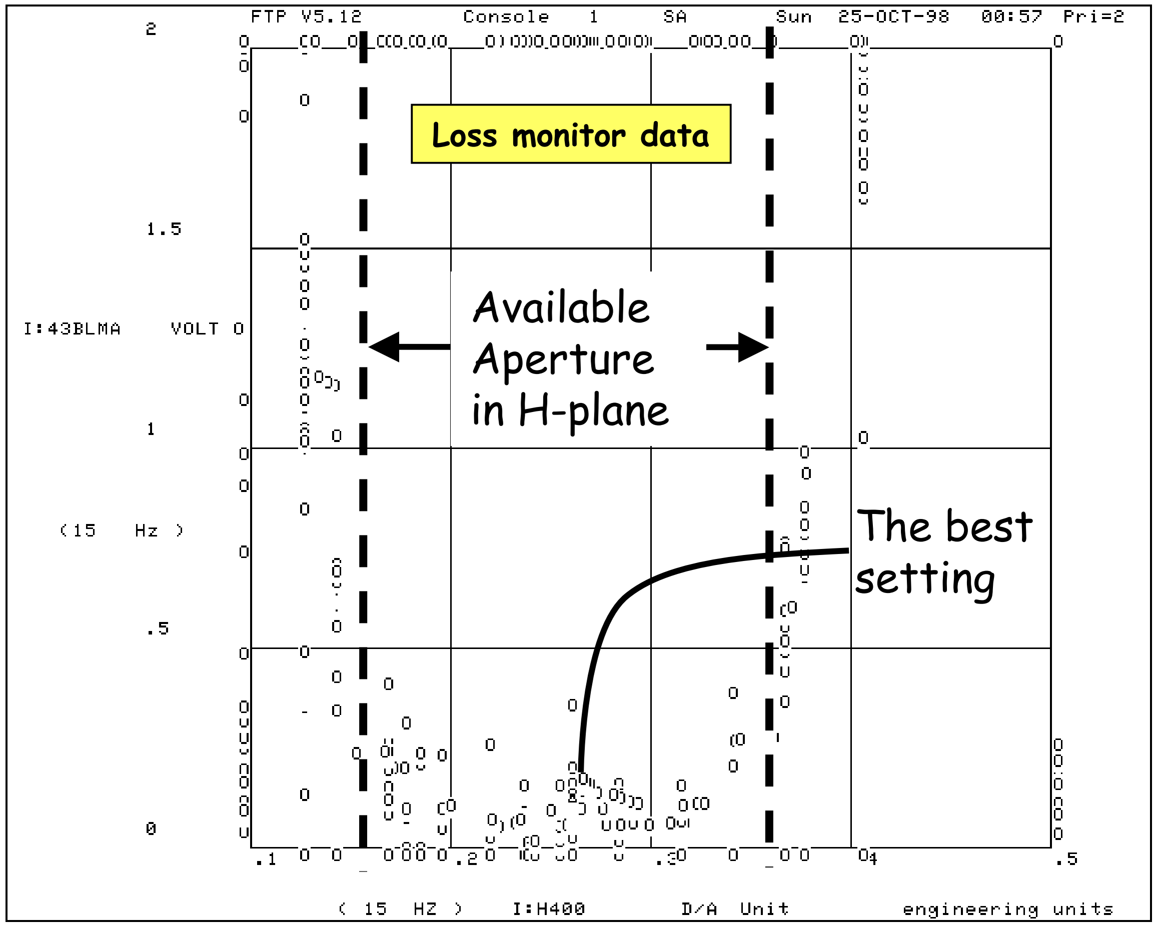
$$\frac{\Delta p}{p} = -\frac{1}{\eta}\frac{\Delta f}{f}$$

Opening the Aperture

(Aperture Scan)

It is highly essential to optimize the aperture for the best beam transmission.

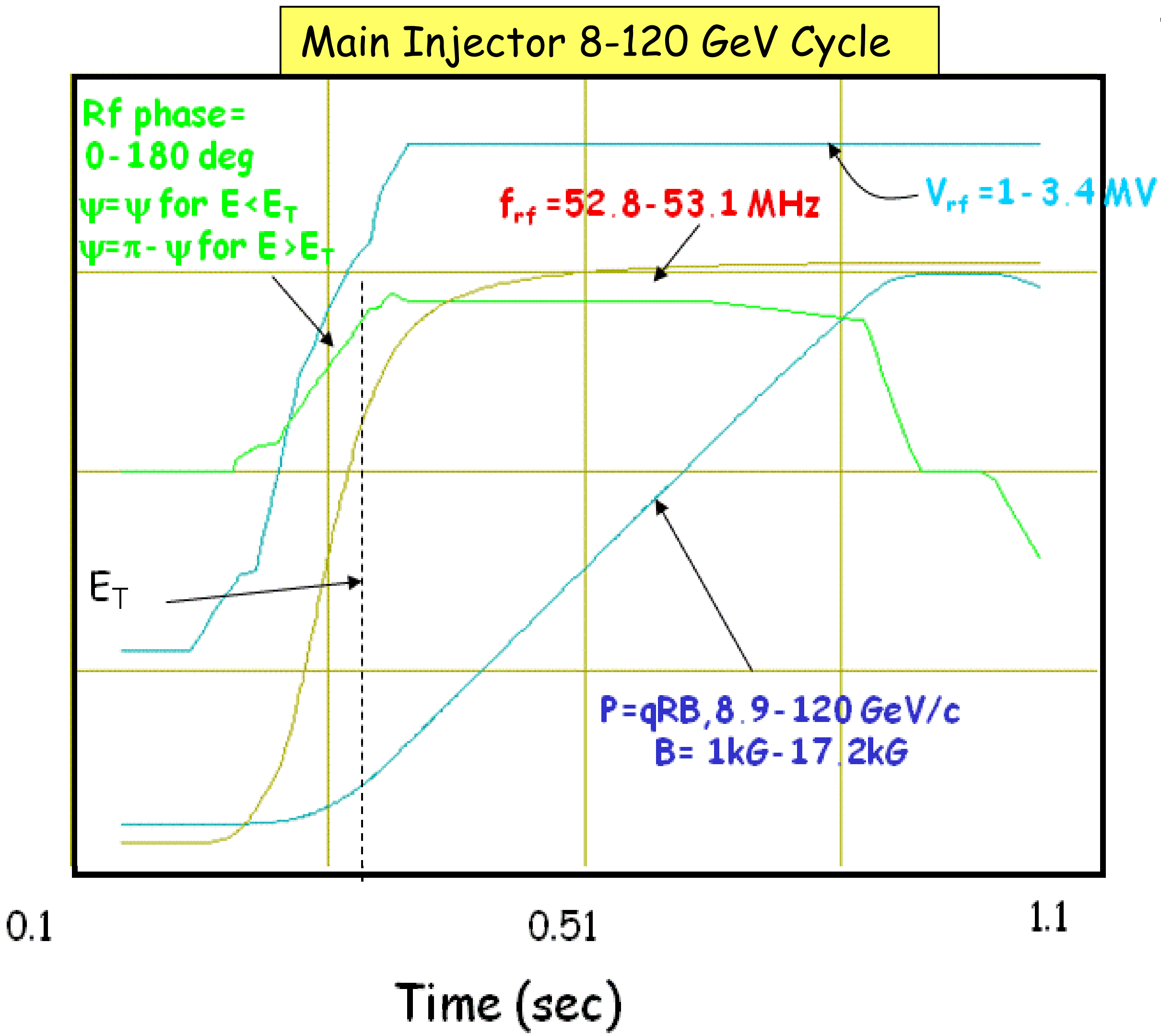
This is done by monitoring the beam loss as the beam is moved by varying the magnet dipole corrector strength at that location.



This procedure should be repeated at every point in the Ring/transfer lines.

Similarly for the vertical plane

Beam Acceleration



Setup acceleration Ramps:

a. Magnet ramp for dipoles, quads, sextupoles, all correctors

b. Set RF voltage curve

c. Set proper accel. phase

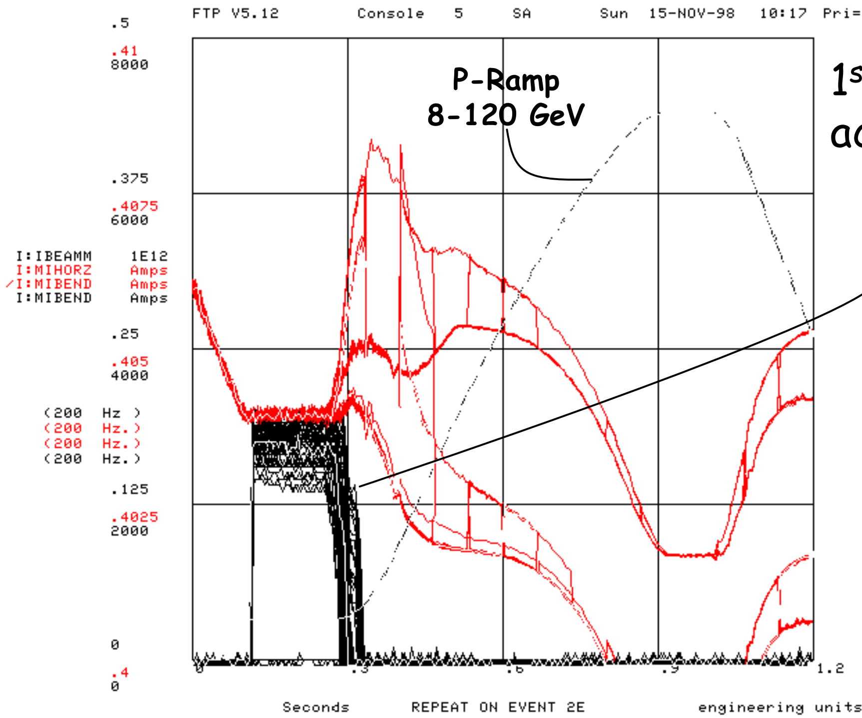
d. Radial feed-back (this is to keep the rf frequency synchronous with the dipole magnet)

e. Transition phase jump

f. Proper orbit, tunes, chromaticities.

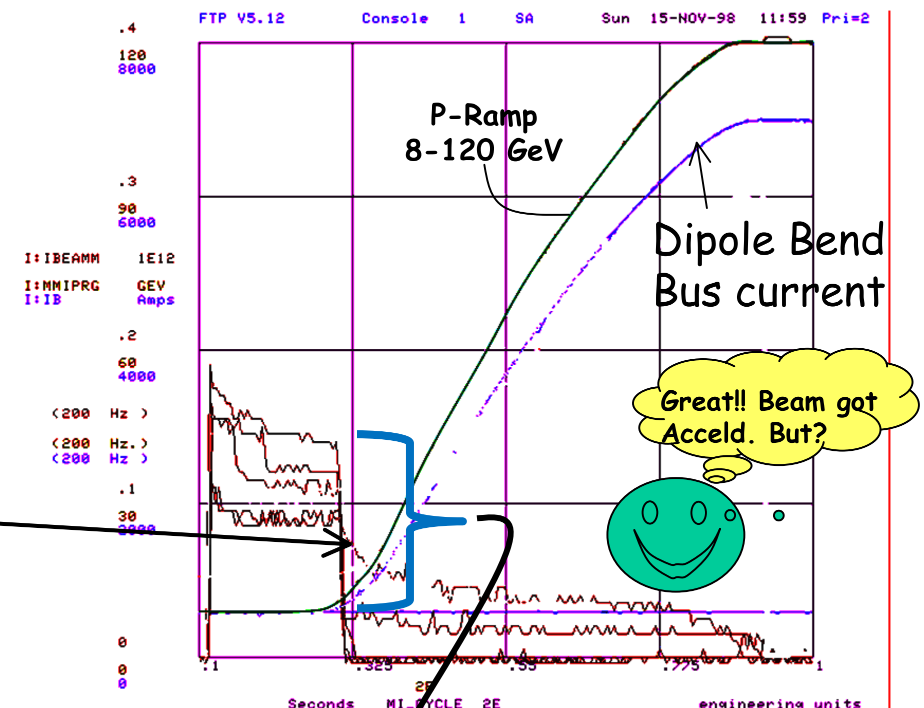
In an ideal case, beam will be accelerated as desired with above settings. But, ??

Beam Acceleration (cont.)



1st attempt to accelerate the beam

1st Beam Acceleration

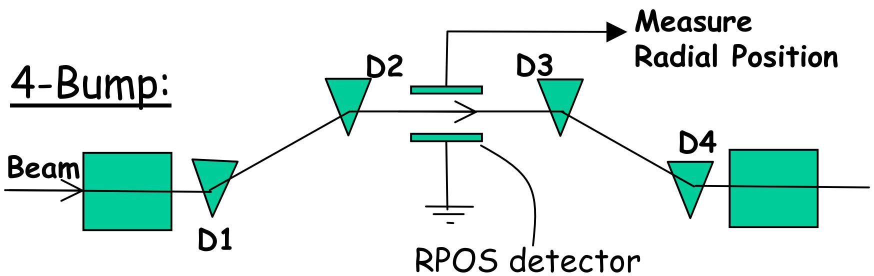


Beam After tweaking the transverse tunes up the ramp

But, Large beamloss

Tweaking the Radial Feed-back & Accel. Phase Angle

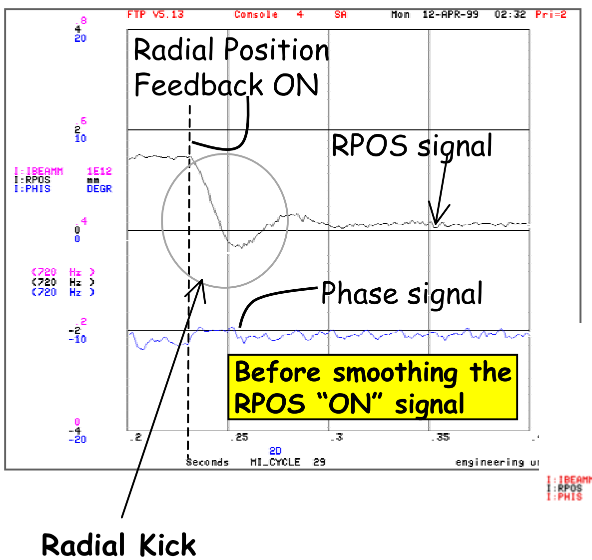
Whenever there is a large frequency swing from injection energy to the top energy, one uses a radial feedback to keep the beam in the center of the machine during acceleration.

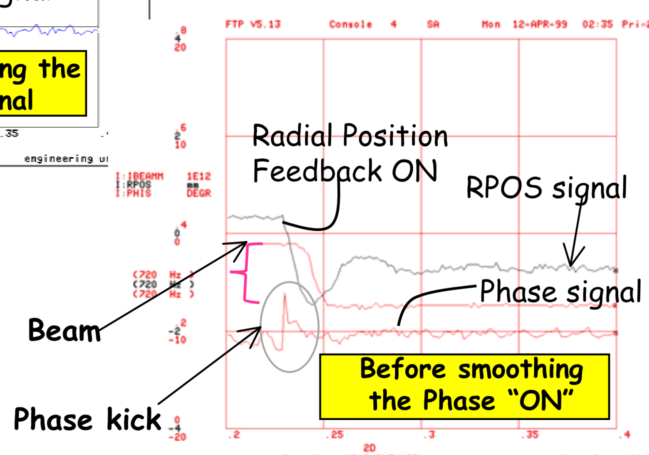


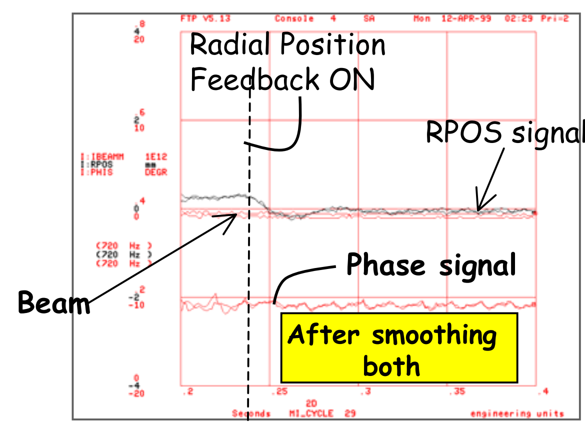
As the beam is accelerated, the beam moves away from the center of the RPOS detector . Then, the RF freq. should be increased in sync with momentum. The RPOS feed back system ensures to keep the desired beam position (i.e., $\Delta r = 0$). That is, at

1. the instant of Radial feedback "ON" time
2. Throughout the acceleration→ generally a $(\Delta r, t)$ -curve is set.
3. This also has to follow a phase curve.

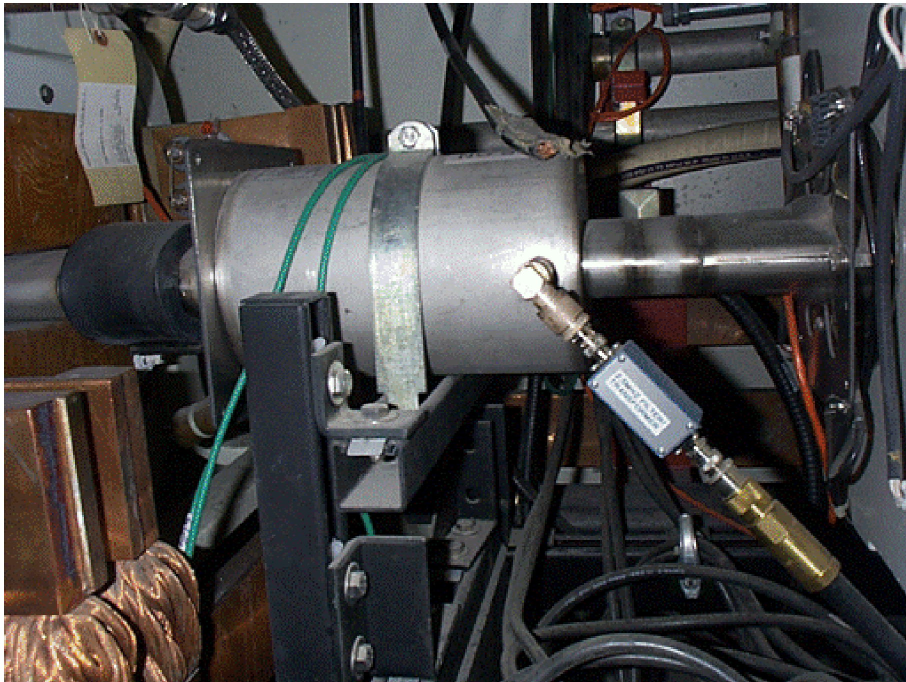
Otherwise beam can fall out of the beam pipe.



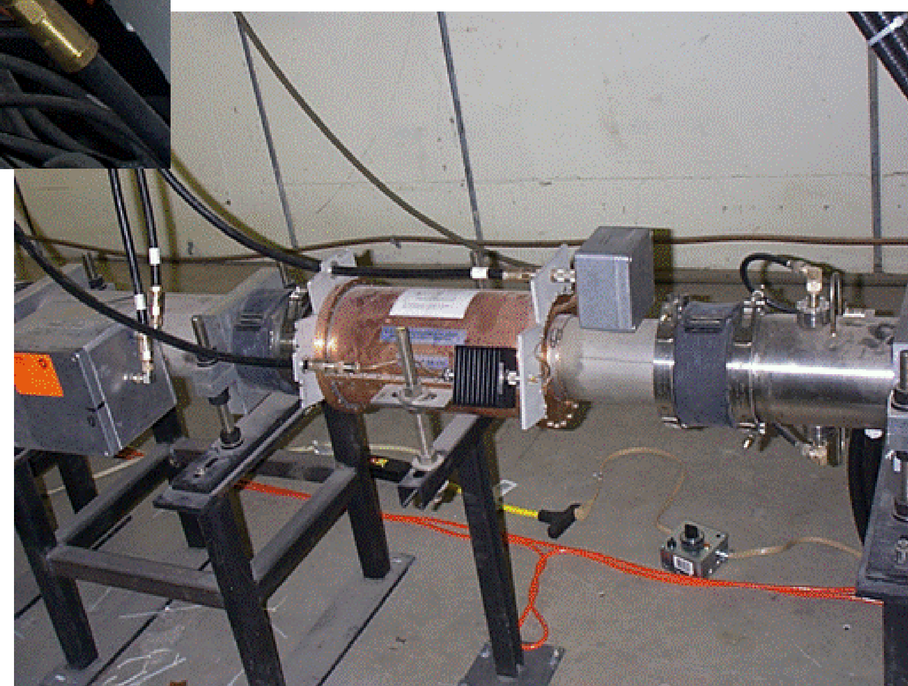




Example of Radial and Phase detectors in the MI Ring



MI612
2.5MHz Rpos Det.



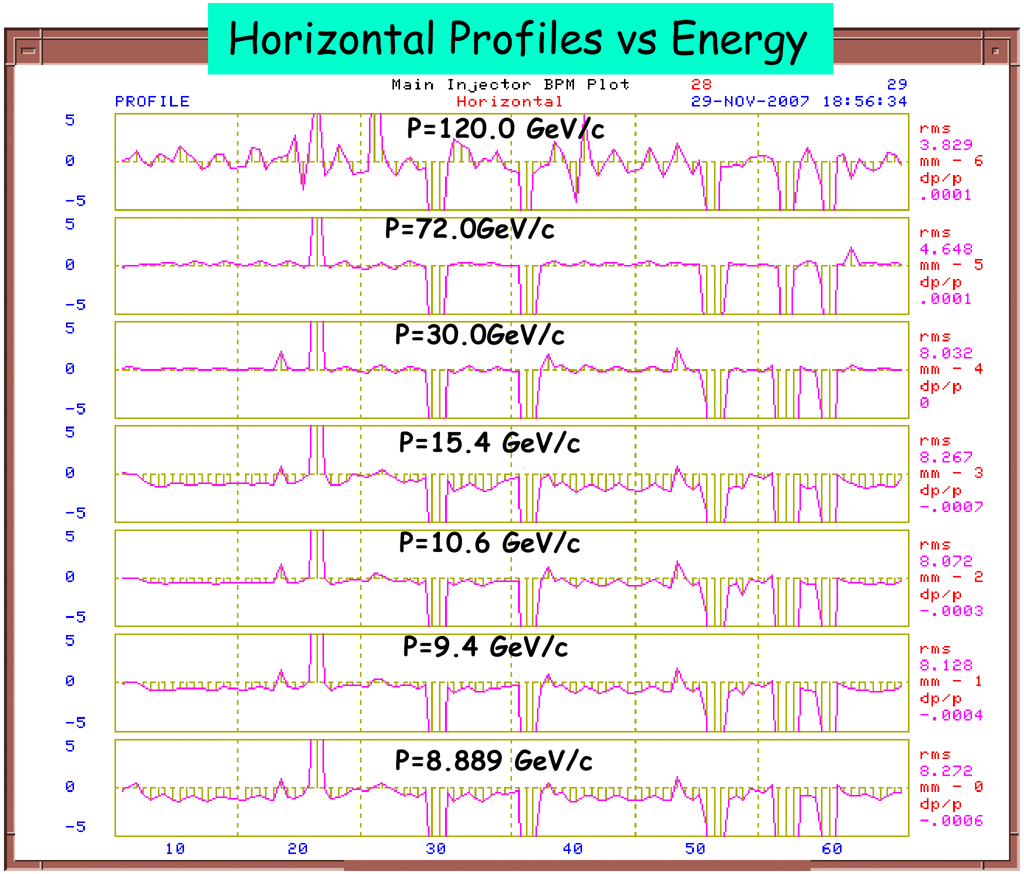
MI603
Longitudinal Kicker
2.5MHz Phase Det.

Beam Acceleration (cont.)

It is highly essential to keep

1. Beam in proper tune space
2. Chromaticity space and chromaticity jump across the transition

throughout the beam acceleration so that machine will not cross any dangerous resonances.



Similarly for the vertical plane

Transition Crossing

Transition crossing is one of the major issues for hadron synchrotrons. For example, the synchrotron frequency at transition is

$$[f_s]_{Transition} = \sqrt{\frac{eV_0 h\,\eta\omega_s \cos\phi_s}{2\pi\ p_s R_s}} \rightarrow 0 \quad \& \quad \frac{\Delta p}{p} \rightarrow \infty$$

This implies the phase focusing disappears and particles get **FROZEN**. Further, the particles change their direction of motion in $(\Delta E,\phi)$-phase space as it crosses the transition.

$\therefore$ It is highly essential to

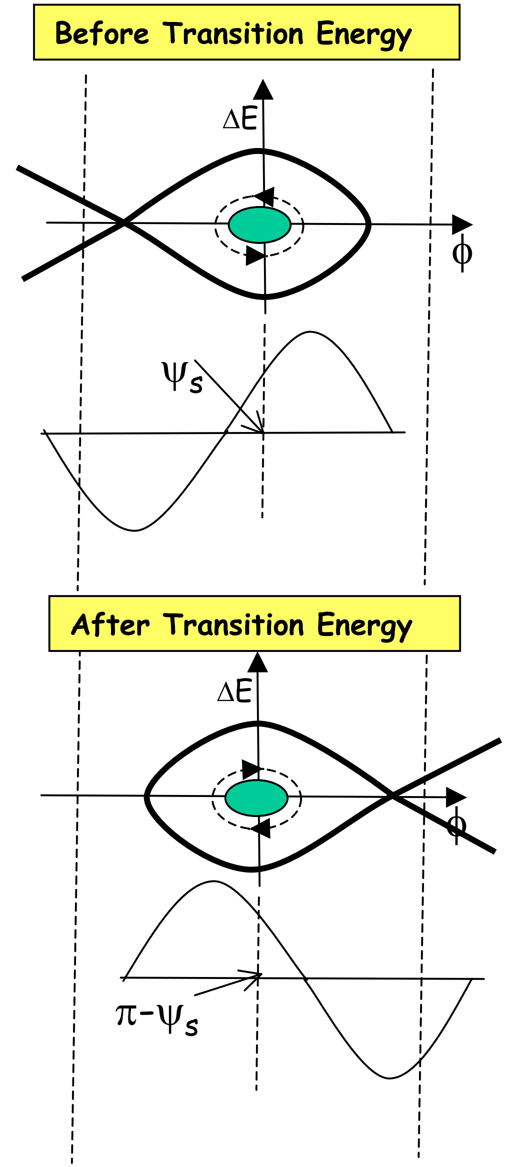
1. Change the rf phase from rising side of the rf wave to falling side of the wave, (phase jump)
2. Set proper time for transition phase jump.
3. Match the rf voltage before & after transition crossing
4. Keep the radial position of the beam un-disturbed,

Consequence of not doing these are

a) longitudinal emittance growth

b) may be beam loss.

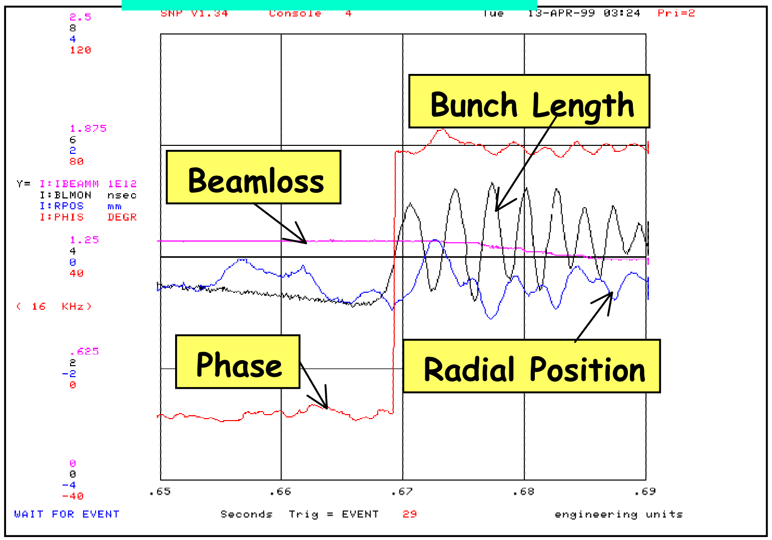
In some hadron accelerators special transition crossing schemes are used.



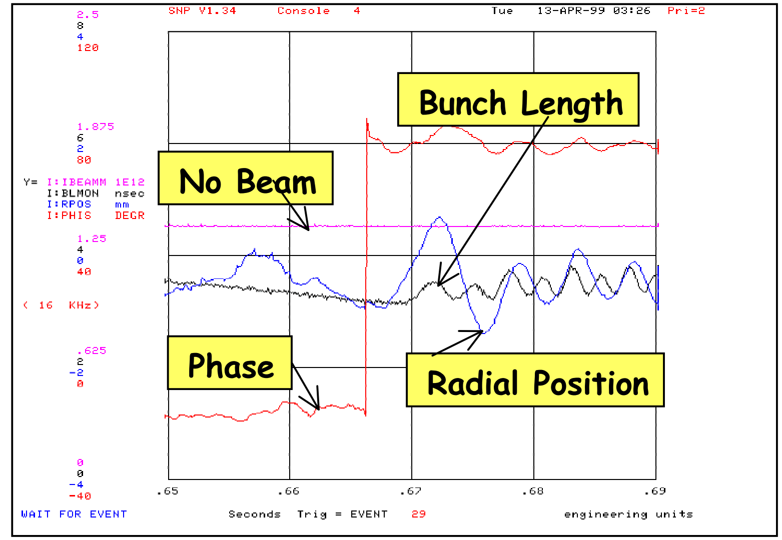
Experiments on Transition Crossing (cont.)

(Adjusting the crossing time)

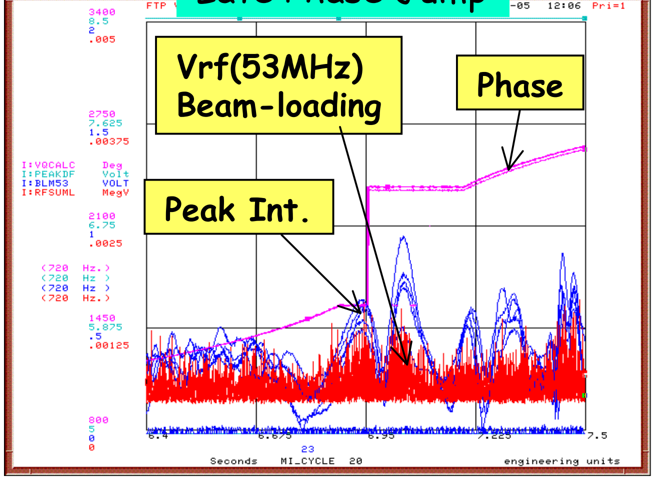
Transition time set late



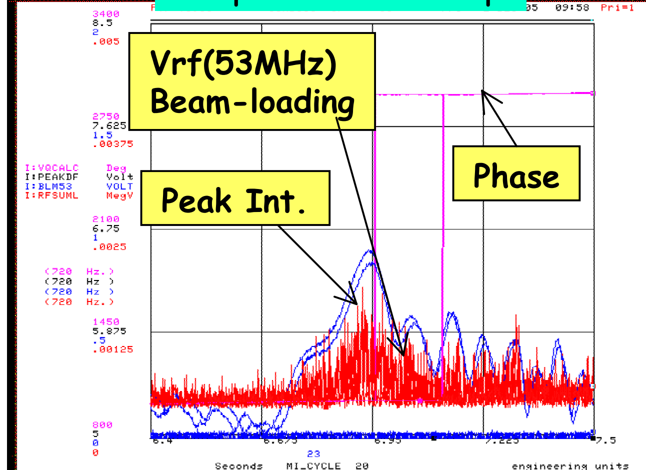
Properly set transition time



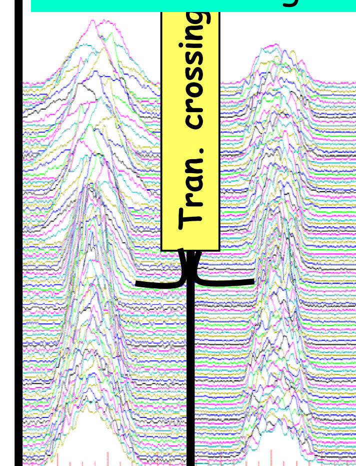
Late Phase Jump



Proper Phase Jump



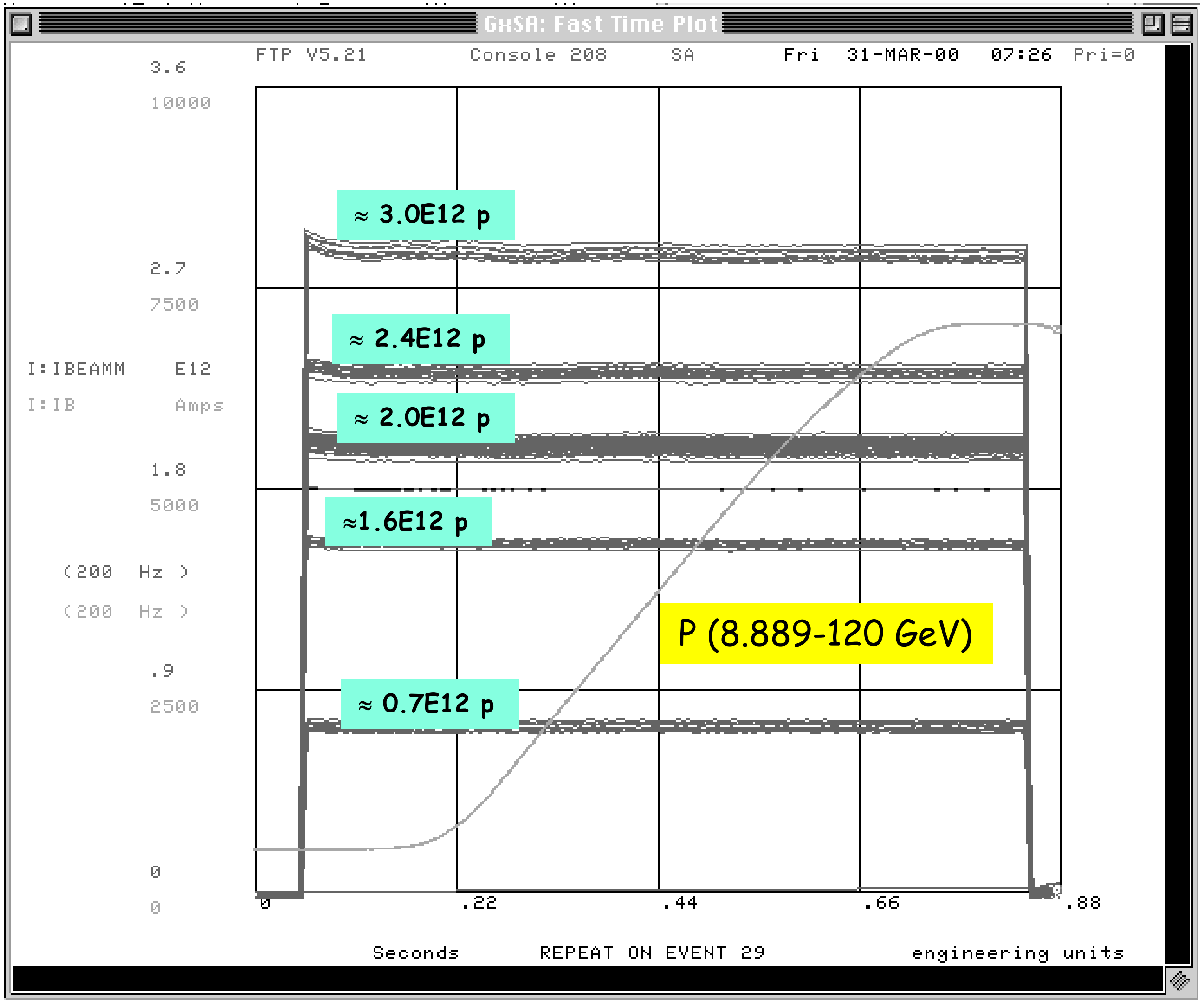
Mountain Range



Bad

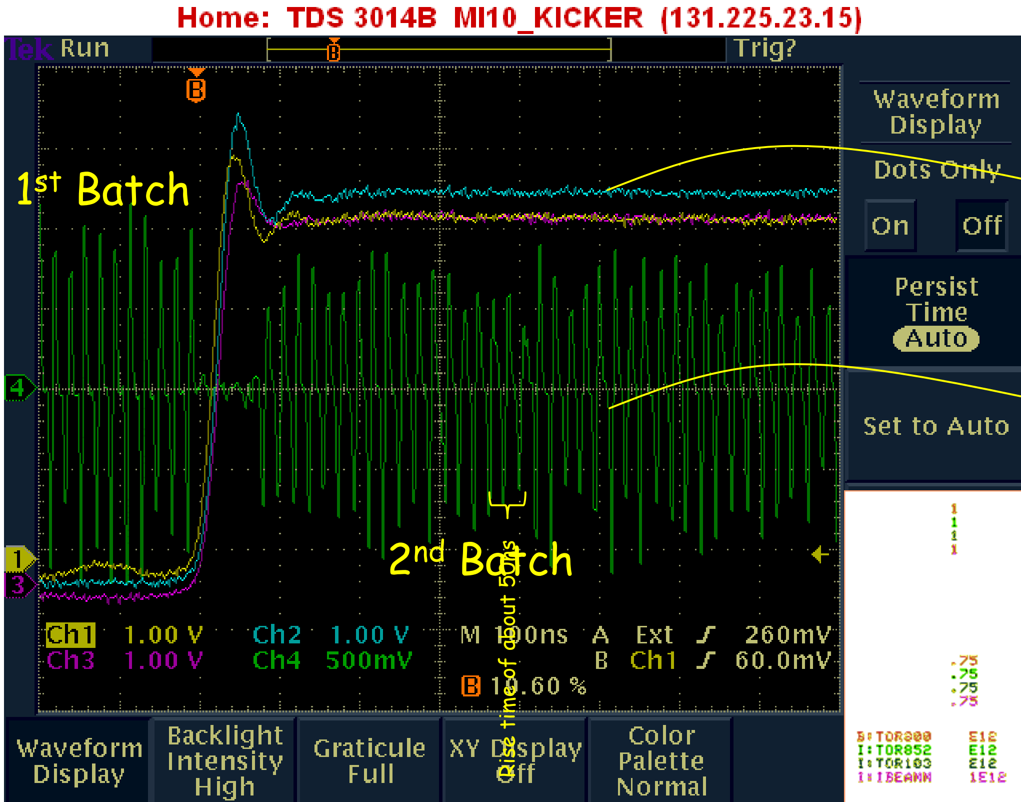
Good

Beam in MI on 8-120 GeV cycle



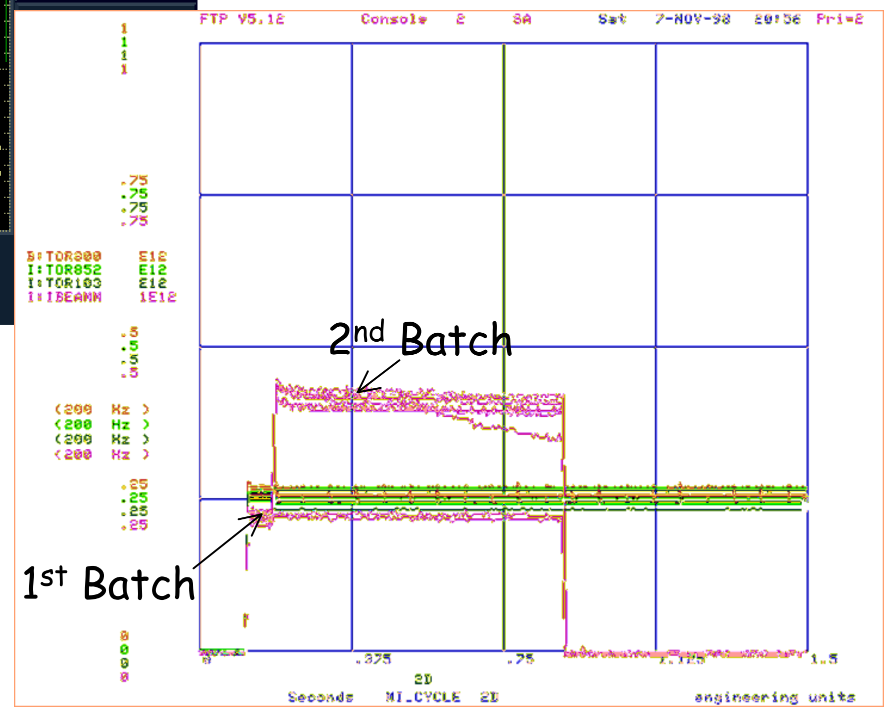
Have accelerated >5E12p

Kicker Profiles for Multi-batch Injection



Kicker profiles

Beam profiles from a BPM



Beam Measurements

Beam Properties of Interest:

1. Beam Intensity √

2. Global Quantities
a) Tunes √
b) Chromaticity

3. Lattice Measurements
a) Orbits: Flash, Display, Profile √
b) Dispersion measurements

4. Emittances:
a) Transverse Emittance: H and V
b) Longitudinal Emittance

And so on

Chromaticity Measurements

To the 1st order, the chromaticity ξ is given by, $\Delta\nu = \xi \dfrac{\Delta p}{p}$

Further, we have the following relation, $\dfrac{\Delta p}{p} = -\dfrac{1}{\eta}\dfrac{\Delta f}{f}$

Thus, by measuring tune as a function of $\Delta p/p$, one can measure the chromaticity.

In the case of Main Injector,

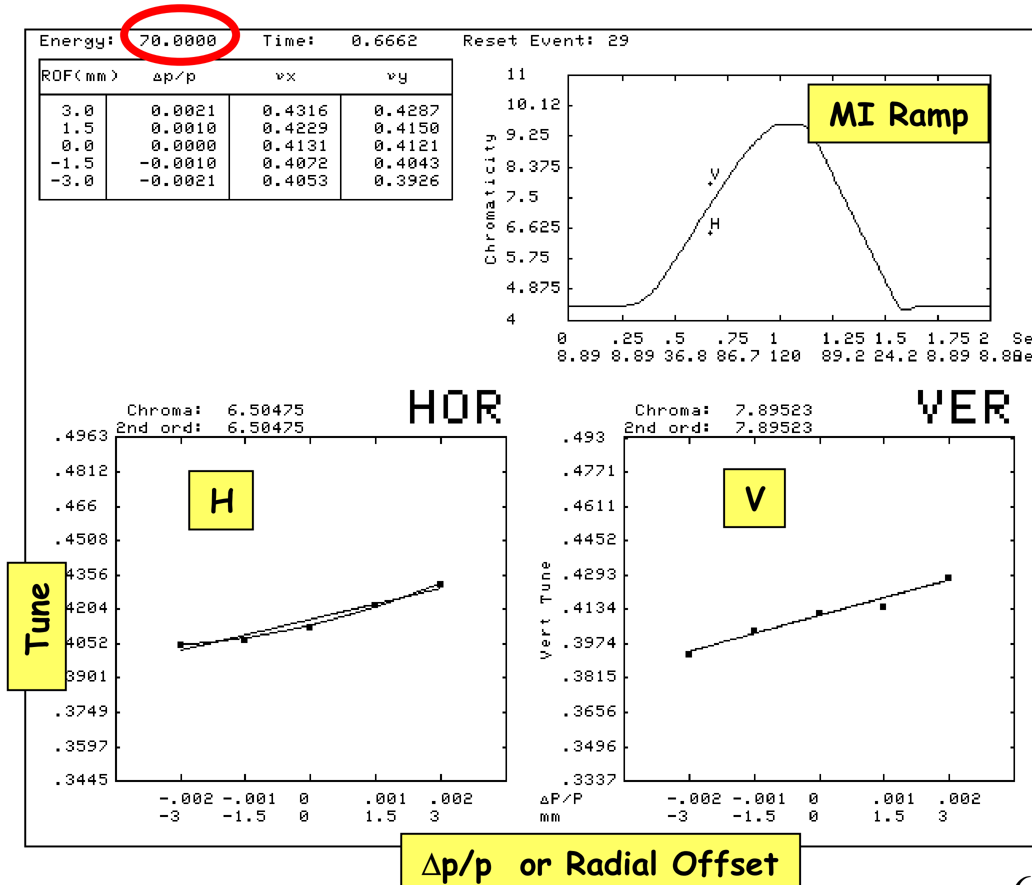
1. the reference value for the radial-feed- back loop is nominally "0"
2. changing it by a few mm leads to change in rf frequency
3. Since,

$$x = x_{co} + \mathrm{D(s)}\frac{\Delta p}{p} \quad \text{or} \quad \frac{\Delta p}{p} = \frac{x - x_{co}}{\mathrm{D(s)}}$$

Comparison between new orbit and the closed orbit and knowing D(s), one can measure $\Delta p/p$

By changing the radial position offsets, one can set different values for $\Delta p/p$. Thus, chromaticity can be measured.

The tune is measured by TBT data for each set of ΔR.

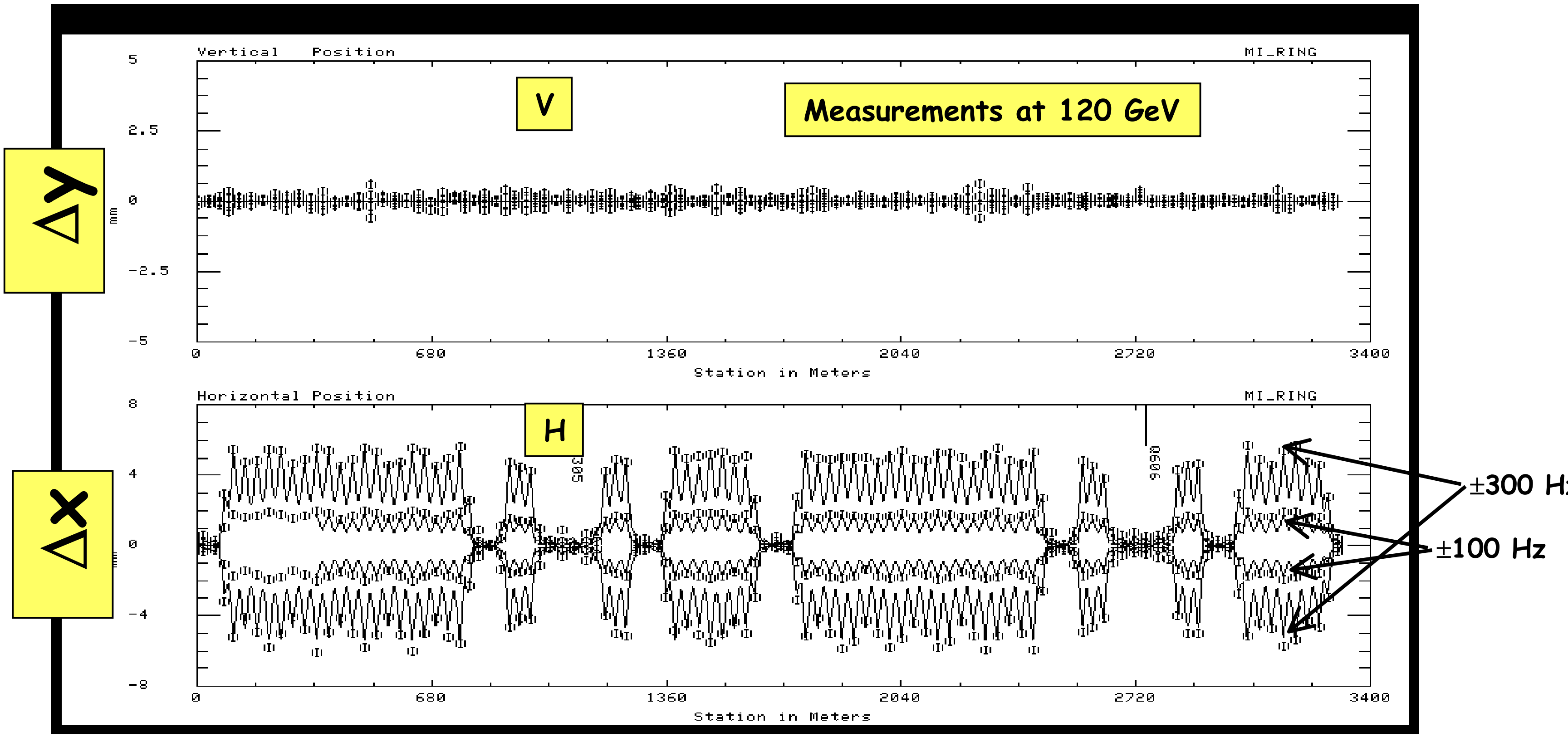


ROF(mm)	Δp/p	νx	νy
3.0	0.0021	0.4316	0.4287
1.5	0.0010	0.4229	0.4150
0.0	0.0000	0.4131	0.4121
-1.5	-0.0010	0.4072	0.4043
-3.0	-0.0021	0.4053	0.3926

Dispersion Measurements

To the 1st order the dispersion function D(s) is given by,

$$\Delta x = D_x(s)\frac{\Delta p}{p} = -D_x(s)\left[\eta\frac{\Delta f}{f}\right]$$



Beam Emittance Measurements

Transverse Emittance:

Transverse beam profile monitors are used to measure the beam size . For example, if σ_x is the measured beam size in non-dispersive region, then,

$$\sigma = \sqrt{\frac{\varepsilon_x \beta_x}{6\pi\beta\gamma}}$$

is used to measure the transverse emittance ε_x (normalized)

Longitudinal Emittance

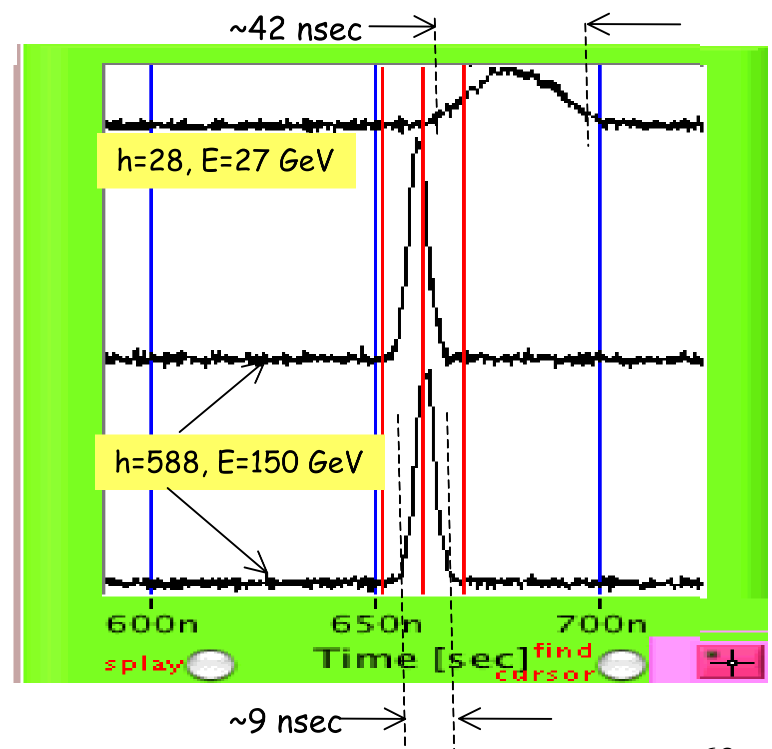
This is the beam area in (ΔE,ϕ) phase space. For the beam in sinusoidal stationary bucket, if Δ is the bunch length measured using "wall current monitor", then the longituidnal emittance is obtained by,

$$LE = \sqrt{32}\,\frac{V_0 R_s^{\,2} E_s}{2\pi h^3 c^2 |\eta|} \int_0^{\frac{\Delta}{2}} \sqrt{\cos(x) - \cos\left[\frac{\Delta}{2}\right]}\,dx \quad \text{and}$$

$$\text{"Half Beam Height, } \hat{\Delta E}\text{"} = \text{Bucket height} \times \sin\left[\frac{\Delta}{4}\right]$$

Vo=0.05MV, Rs= 528m, Es= 27 GeV, h=28, η=0.001, Δ=46 nsec give LE= 1.95 eVs and Δp/p=0.1%

Vo=0.55MV, Rs= 528m, Es= 150 GeV, h=588, η=0.0021, Δ=9 nsec give LE= 1.95 eVs and Δp/p=0.1%



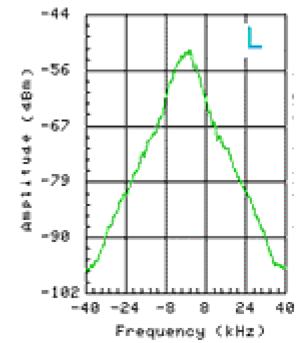
Beam Emittance and Tune Measurements

(using Schottky Signals)

Use of Schottky signals in measurements of beam properties is one of the most wonderful technique for storage rings. These signals can be used to measure

1. Longitudinal emittance
2. Beam intensity
3. Transverse emittances
4. Tune of the machine,
5. Chromaticity

Longitudinal Schottky data



Longitudinal Emittance, Energy spread & Beam Intensity:

Measure the longitudinal Schottky spectrum using a longitudinal Schottky detector. Then,

Total Schottky Power $\propto$ Beam intensity

RMS width $\propto$ RMS Momentum spread

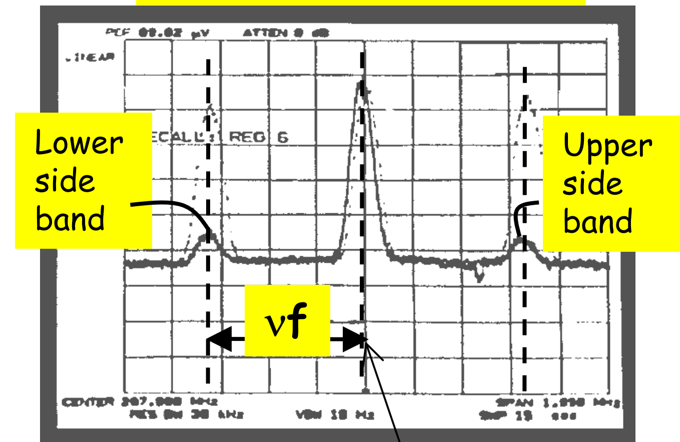
RMS LE = $\pi(\sigma \times$ RMS Bunch Length from wall current monitor)

Transverse Emittance:

Measure the transverse Schottky spectrum using a transverse Schottky detector. Then,

Total Schottky Power of the side band $\propto$ Transverse emittance

Transverse Schottky data



Harmonic number = n
f= revolution frequency

Transverse Tune:

The distance of the sideband from the center peak is a measure of fractional tune of the machine.

Chromaticity:

The width of the sideband is measure of the tune spread.

$$Chromaticity = \xi = \Delta\nu \Big/ \frac{\Delta p}{p}$$

Accumulator Horizontal Schottky Spectrum