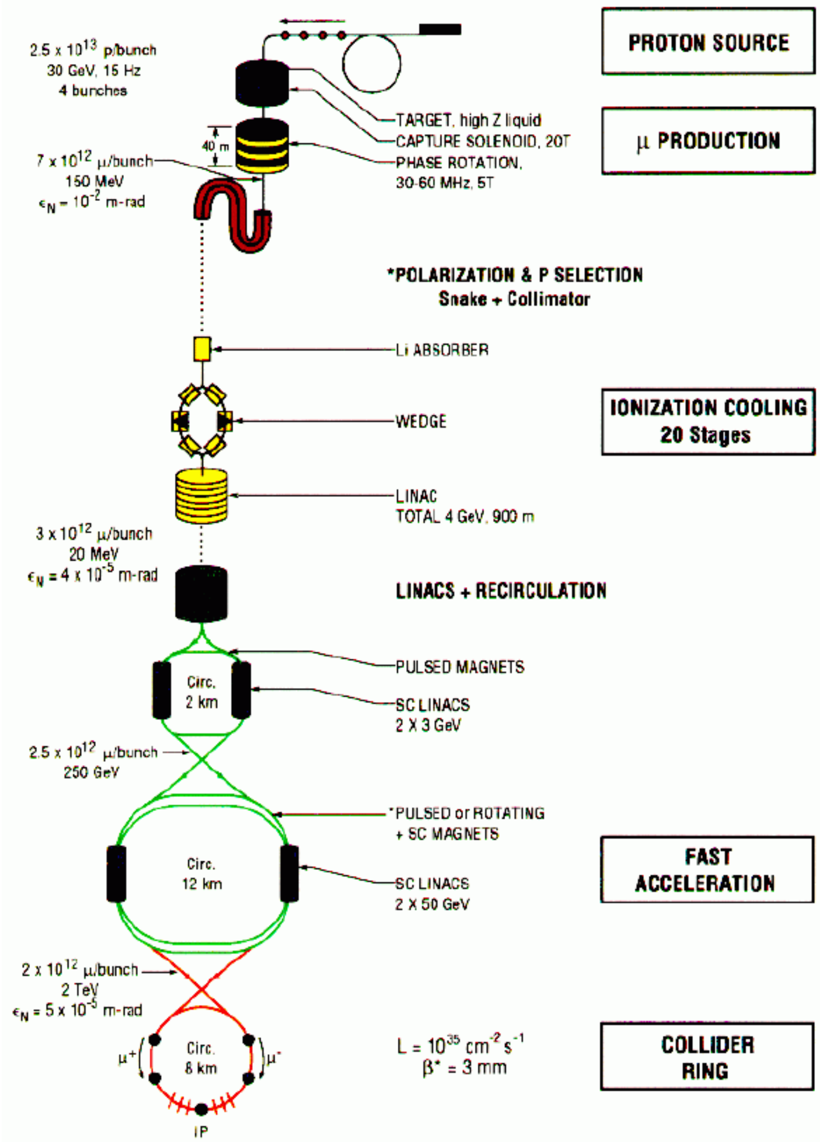
Muon Collider and Recycler Studies

Weishi Wan

Fermilab

- **Muon Collider 50 GeV Ring Dynamic Aperture Problem**
- **Recycler Commissioning**

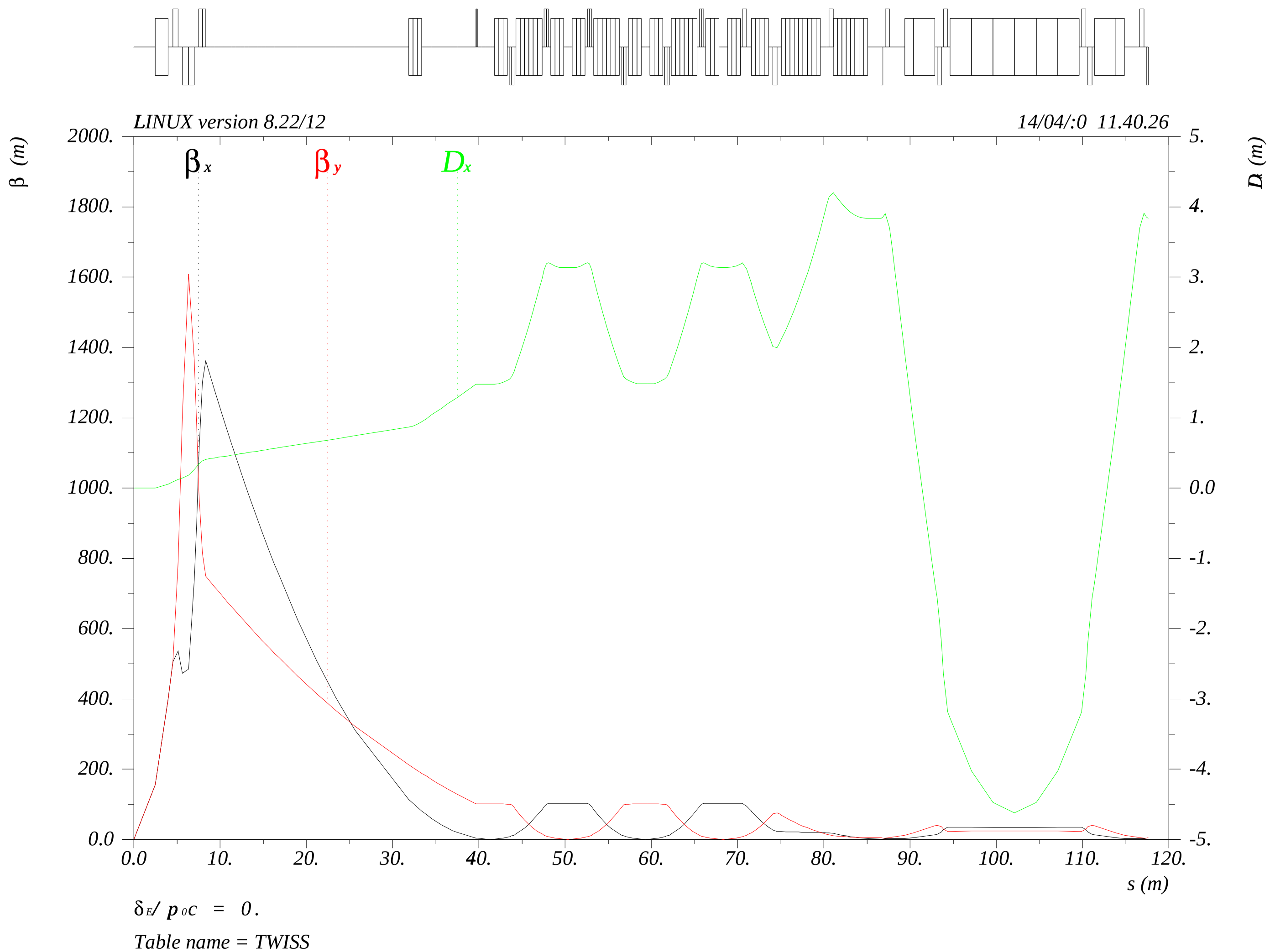
Schematic of a Muon Collider



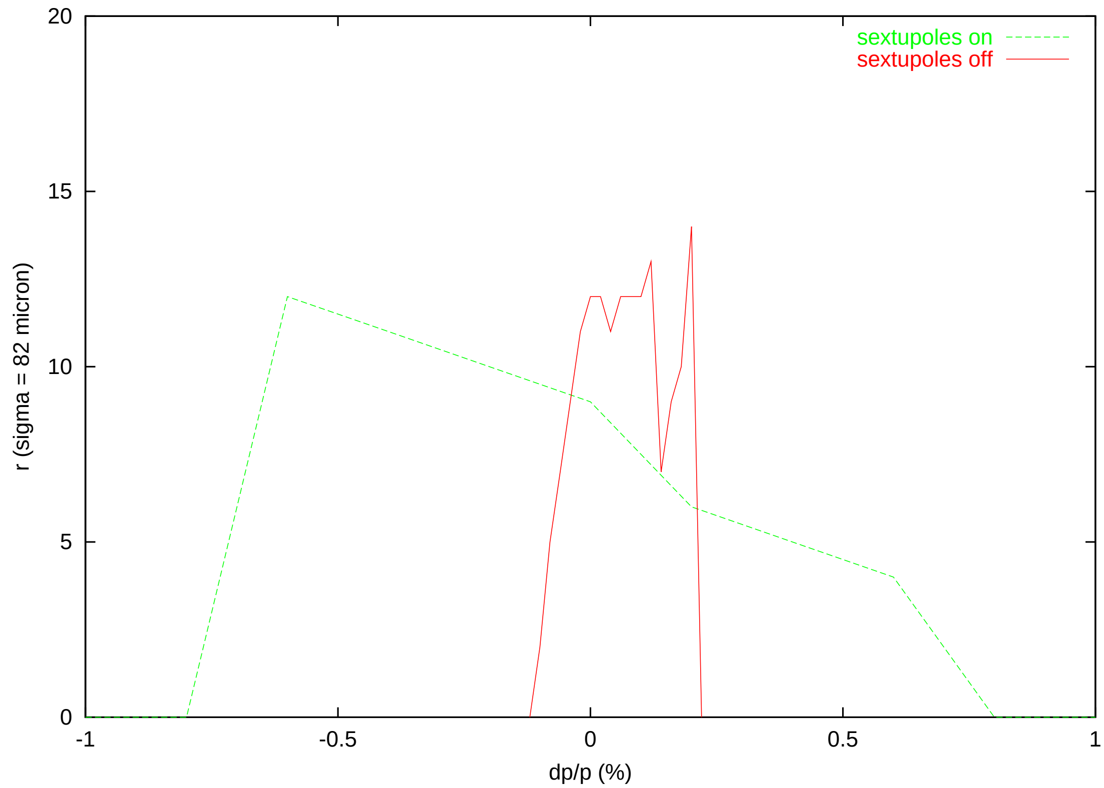
Baseline Parameters for a 50 GeV Muon Collider

COM energy (GeV)	100	
μ/bunch	4×10^{12}	
μ power (MW)	1	
Wall power (MW)	81	
Collider circum. (m)	350	
Ave bending field (T)	3	
rms $\Delta p/p$ (%)	0.12	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	85	290
β^* (cm)	4.1	14.1
σ_z (cm)	4.1	14.1
σ_r (μm)	86	294
σ_θ IP (mrad)	2.1	2.1
Tune shift	0.051	0.015
n_{turns} (effective)	450	450
Luminosity ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	1.2×10^{32}	10^{31}
Higgs/yr	1.9×10^3	3.9×10^3

50 GeV Collider Ring Optics



Dynamic Aperture Plot (β^* = 4 cm)



- **One beam only**
- **No errors of any kind**
- **1000 turns using 9th-order Taylor map**
- **Initial condition:**
  - r = 0 – 20 σ, θ = (0 – 15) × 360°/16
  - p_x = p_y = 0
  - $\delta p/p$ = (-10 – 10) × 0.1%

Chronicle of Numerical Studies

- First tracking of the “linear” lattice (Dec. 97)
- Controversy over the cause (Dec. 97 – Jul. 98)
- Study of completely different lattice (May 98 – June 98)
  - same IR, different arcs
  - no change in dynamic aperture
  - no change in detuneing
- Separate study done by S. Ohnuma (July 98 – Aug. 98)
  - RK integrator in IR, linear matrix in arcs
  - no change in dynamic aperture
  - independently verified previous results

Beyond Paraxial Approximation

- **Exact Hamiltonian: (no electric field, no fringe field)**

$$H = -p_s = -\frac{e}{c}A_s - \left(1 + \frac{x}{\rho}\right)\sqrt{(P^2 - P_x^2 - P_y^2)}$$

- **On-momentum particles only, IR only, to P_x^4**

$$H = \frac{1}{2}P_x^2 + \frac{1}{2}P_y^2 - \frac{1}{2}K_1(s)x^2 + \frac{1}{2}K_1(s)y^2 + \frac{1}{8}\left(P_x^2 + P_y^2\right)^2$$

- **Action-angle variables**

$$H_1 = \frac{J_x}{\beta_x} + \frac{J_y}{\beta_y} + \frac{1}{2}\left[\frac{J_x}{\beta_x}(\sin\theta_x + \alpha_x\cos\theta_x)^2 + \frac{J_y}{\beta_y}(\sin\theta_y + \alpha_y\cos\theta_y)^2\right]^2$$

Beyond Paraxial Approximation (continued)

- **Angle independent part**

$$H_{10} = \frac{J_x}{\beta_x} + \frac{J_y}{\beta_y} + \frac{1}{2}\left(\frac{3}{8}\gamma_x^2 J_x^2 + \frac{1}{2}\gamma_x\gamma_y J_x J_y + \frac{3}{8}\gamma_y^2 J_y^2\right)$$

- **Tune shift with amplitude**

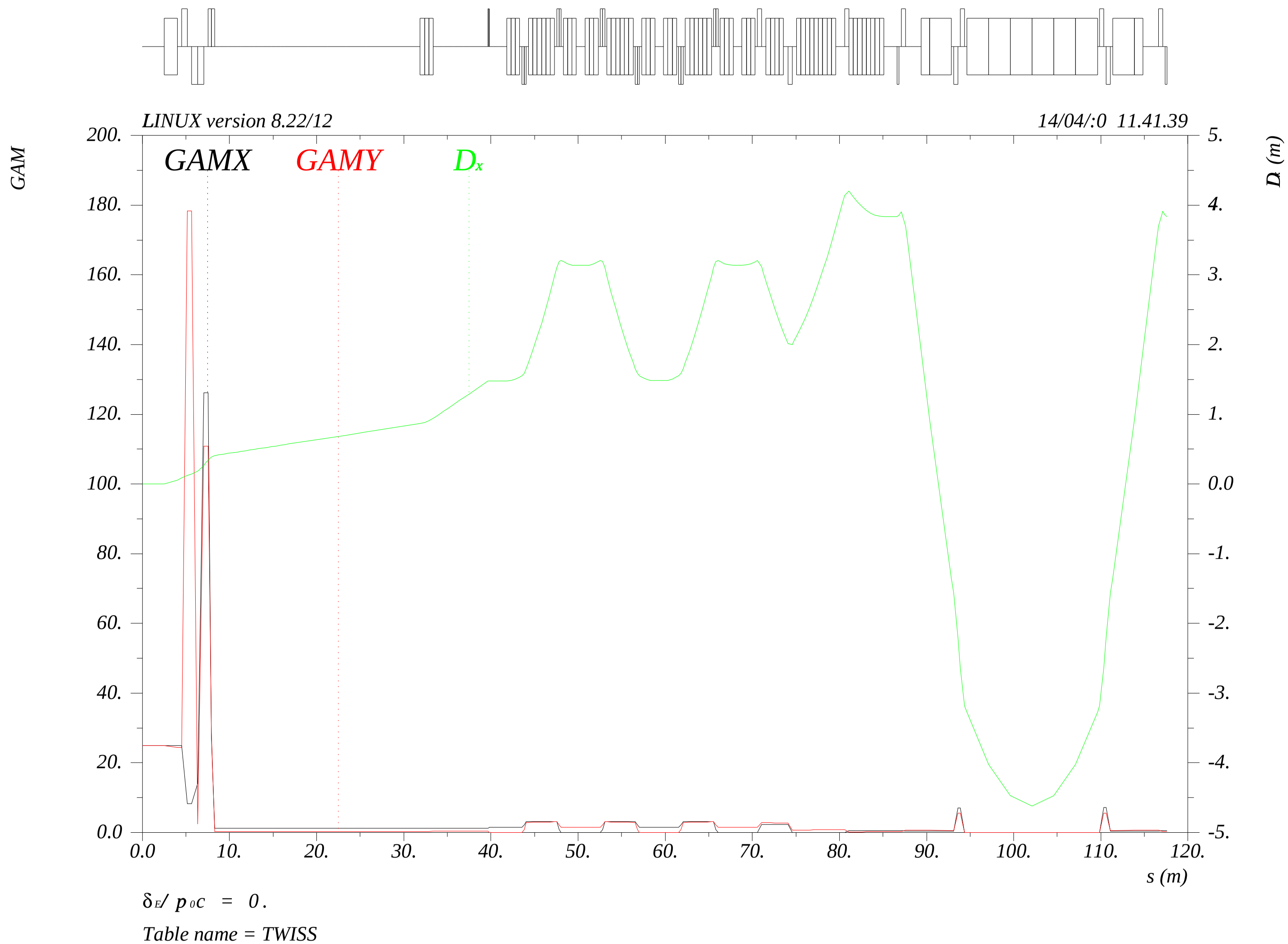
$$\nu_x(\vec{J}) = \nu_{x0} + \frac{1}{2\pi}\int_0^C \left(\frac{3}{8}\gamma_x^2 J_x + \frac{1}{4}\gamma_x\gamma_y J_y\right)$$

$$\nu_y(\vec{J}) = \nu_{y0} + \frac{1}{2\pi}\int_0^C \left(\frac{1}{4}\gamma_x\gamma_y J_x + \frac{3}{8}\gamma_y^2 J_y\right)$$

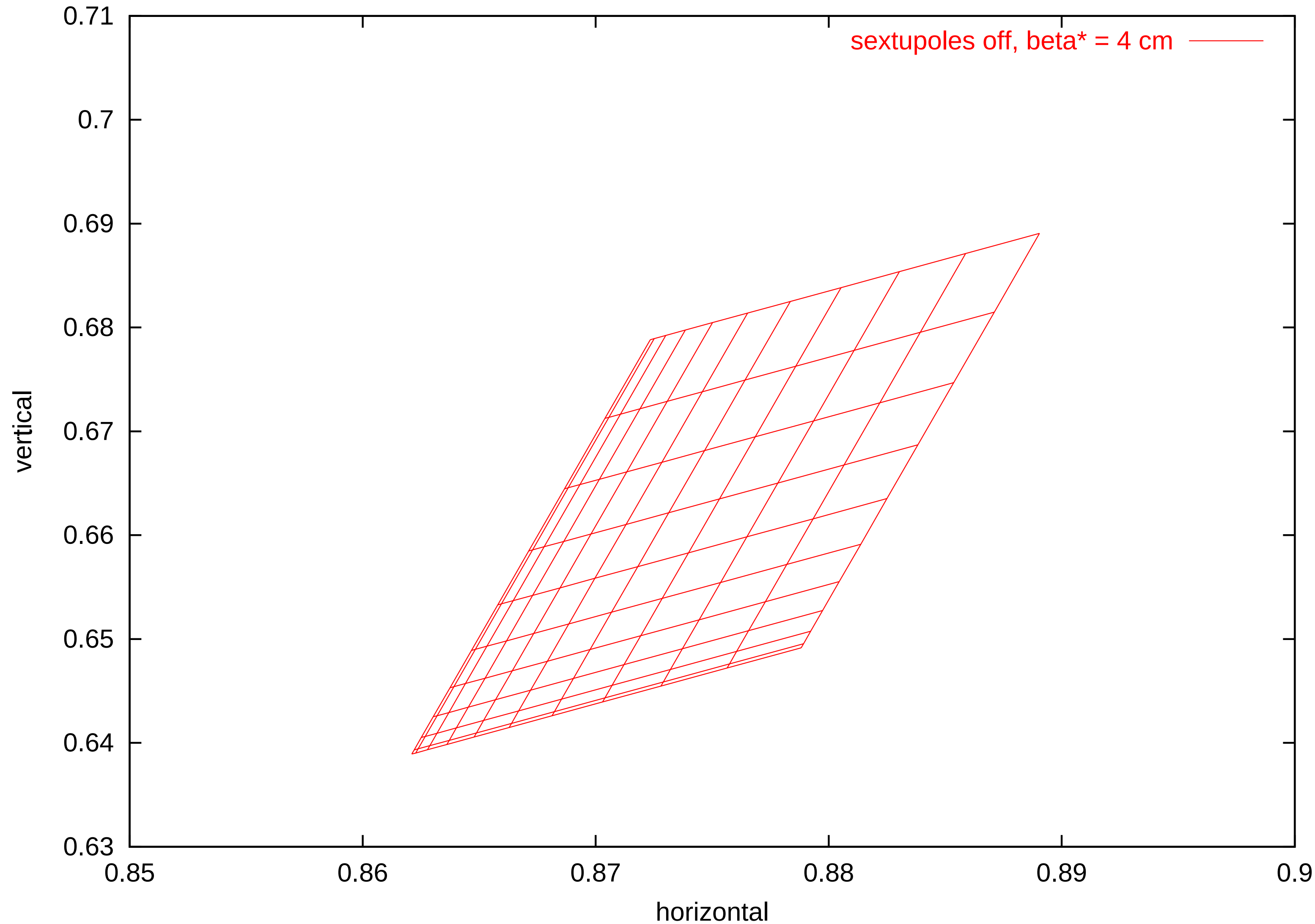
Comparison between LHC and MC

	LHC	MC
L (m)	46	9
β^* (m)	0.5	0.04
Lγ^{*2} (1/m)	184	5625
ϵ_{rms} (π mm mrad)	0.0005	0.168
$\Delta\nu_x$ (10σ)	2.7e-7	0.0028

50 GeV Collider Ring Optics



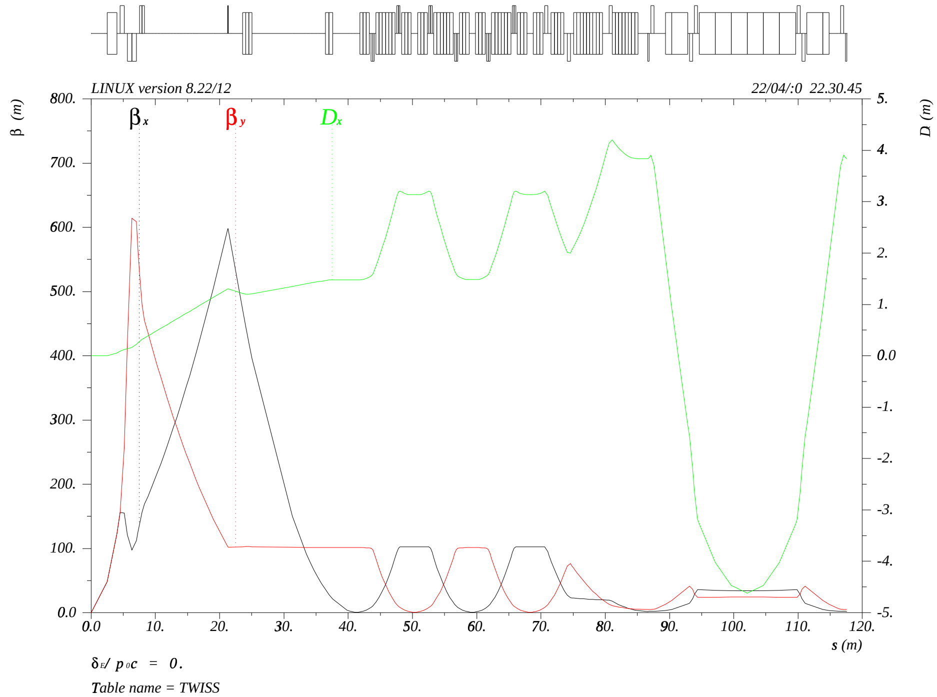
Tune Footprint Plot

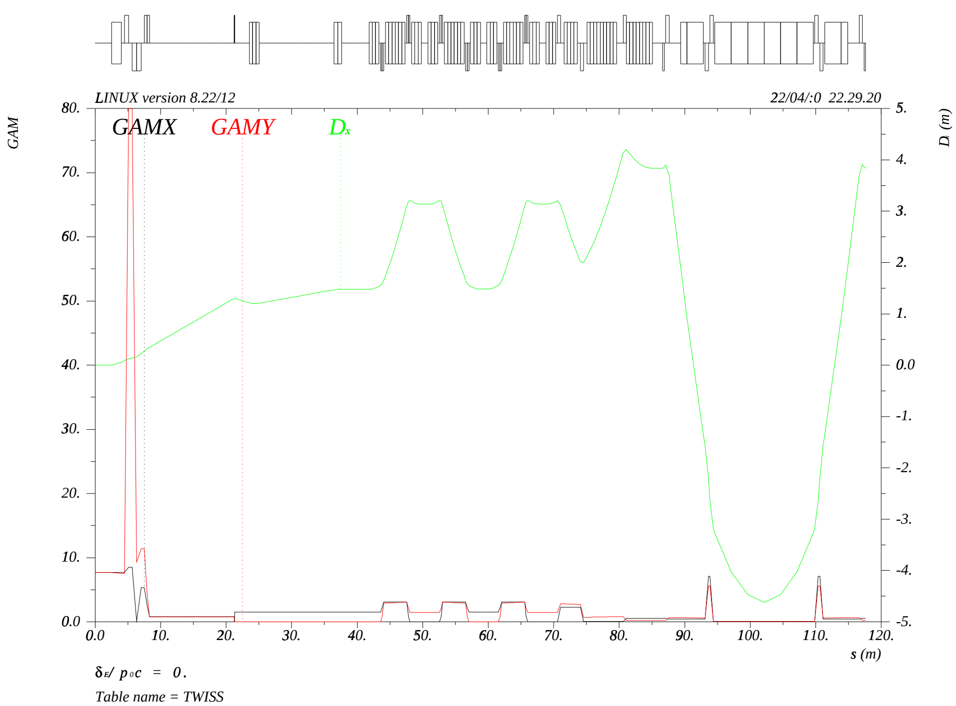


Possible Correction Scheme

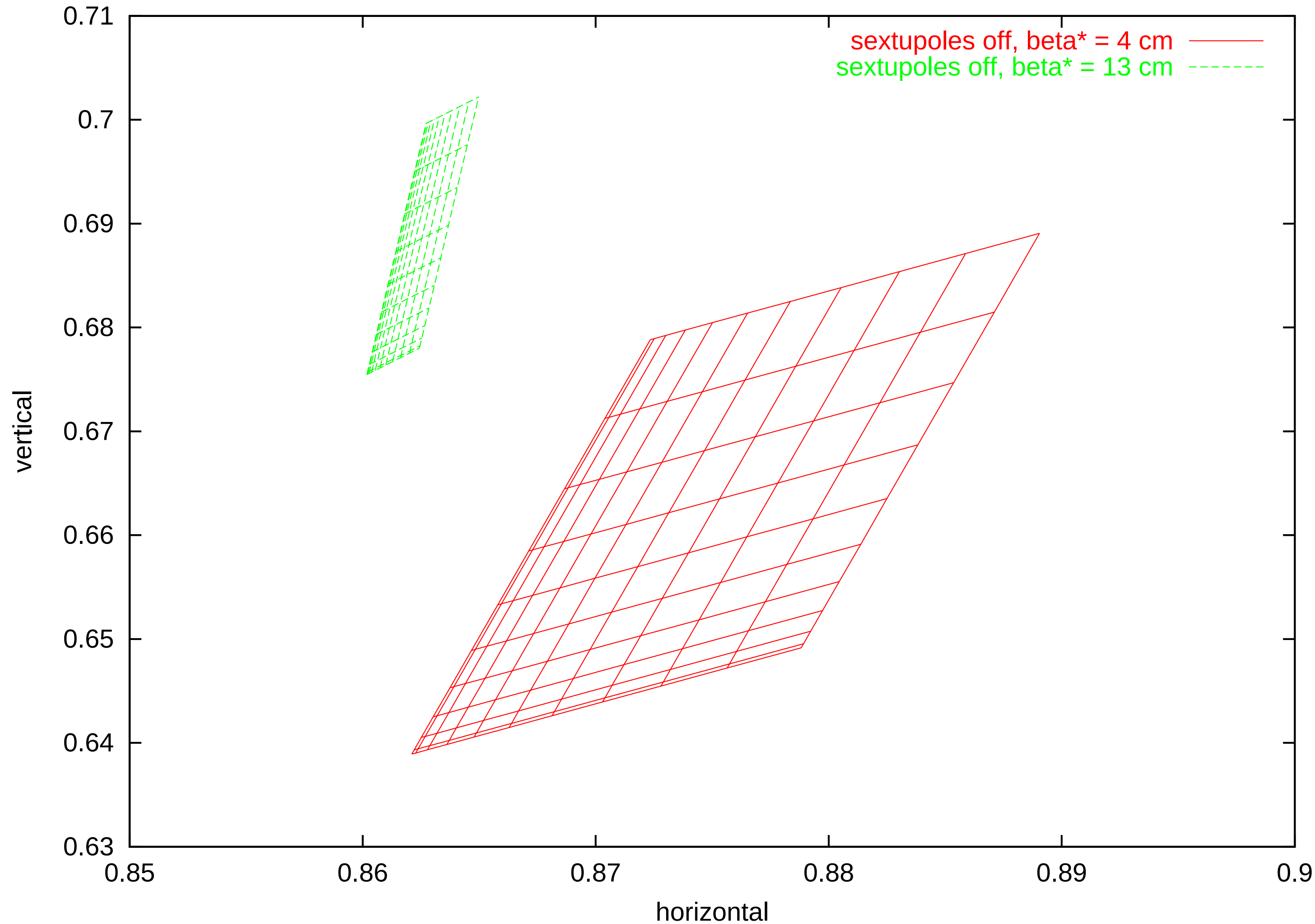
- Detuning is “octupole like”
- In principle octupoles can do the job
- Octupole pairs 45° apart don’t excite resonances
- Hard to find optimal locations in a small ring

50 GeV Collider Ring Optics (β^* = 13 cm)

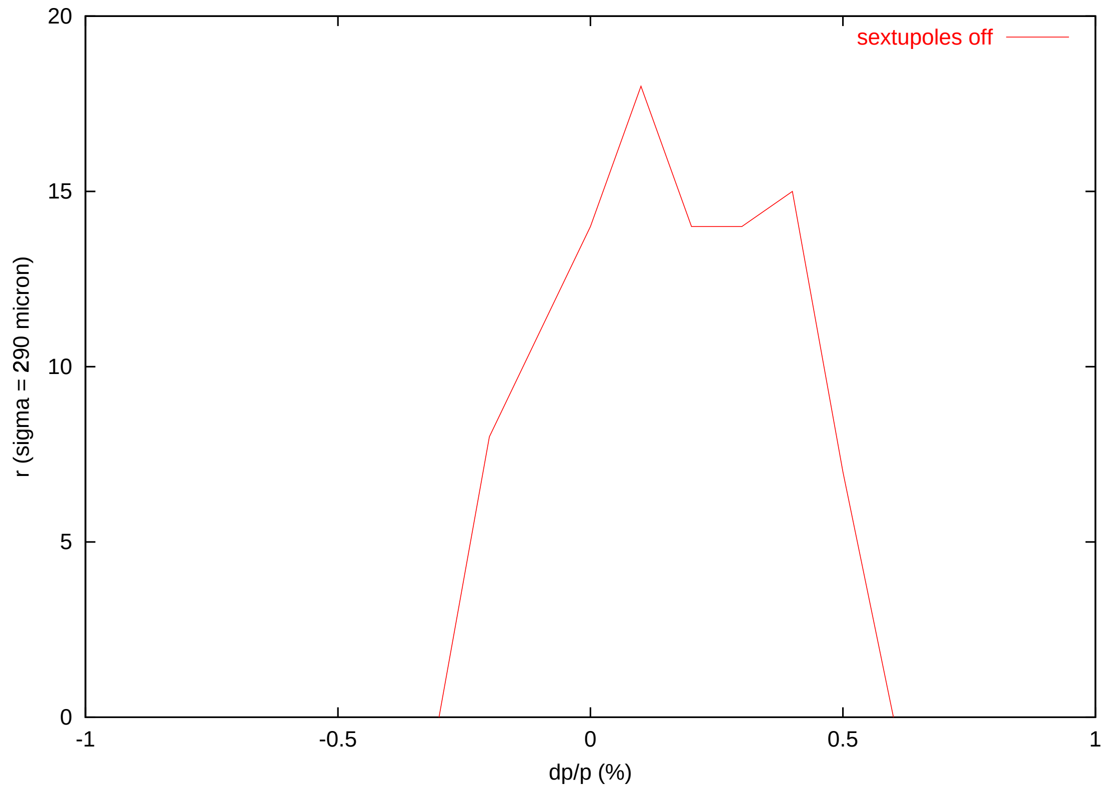




Tune Footprint Plot

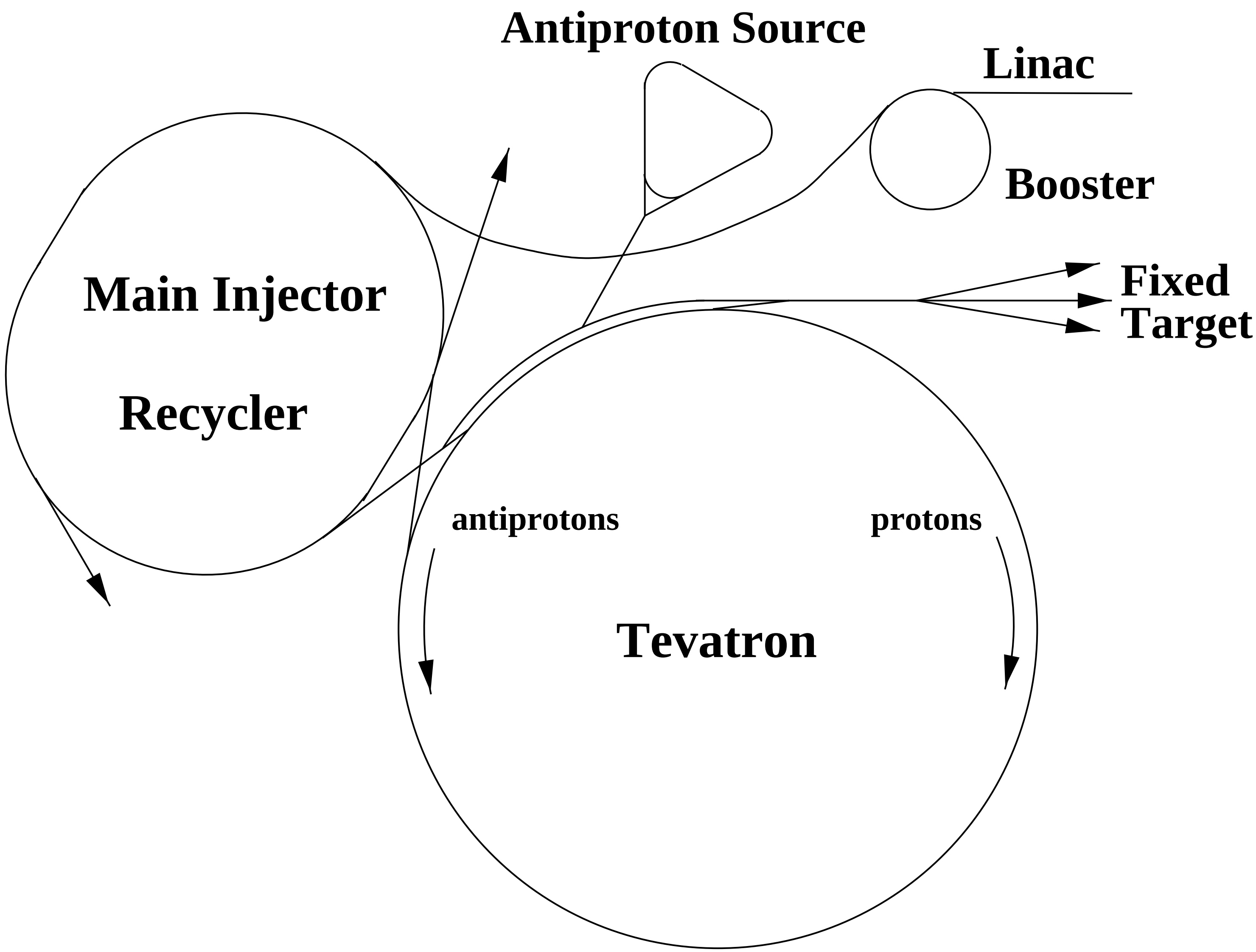


Dynamic Aperture Plot (β^* = 13 cm)



- One beam only
- No errors of any kind
- 1000 turns using 9th-order Taylor map
- Initial condition:
  - r = 0 – 20 σ, θ = (0 – 15) $\times$ 360°/16
  - p_x = p_y = 0
  - $\delta p/p$ = (-10 – 10)$\times$ 0.1%

Fermilab Accelerators



Tevatron

- **Tevatron highest energy accelerator/collider in the world**
- **proton – antiproton collisions**
- **$2 \cdot 900$ GeV $\rightarrow$ $2 \cdot 1$ TeV**
- **remain highest energy machine until LHC comes on-line**
- **maximize the discovery potential of the Tevatron before LHC**

$\Rightarrow$ Main Injector Project

Main Injector and Recycler Goals

- increase Tevatron luminosity from typical $\mathcal{L} = 1.6 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$\mathcal{L} = \frac{f N_p (B N_{\bar{p}})}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} H(\sigma_L/\beta^*)$$

- Main Injector:
  - larger proton flux for $\bar{\mathrm{p}}$ production
  - more intense proton bunches
  - shorter cycles
  - $\Rightarrow \mathcal{L} = 8.6 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Recycler Ring:
  - store and cool recycled $\bar{\mathrm{p}}$ from Tevatron
  - $\Rightarrow \mathcal{L} = 20 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - highly reliable storage ring for $\bar{\mathrm{p}}$
  - accumulate/cool up to $3 \cdot 10^{12}$ $\bar{\mathrm{p}}$

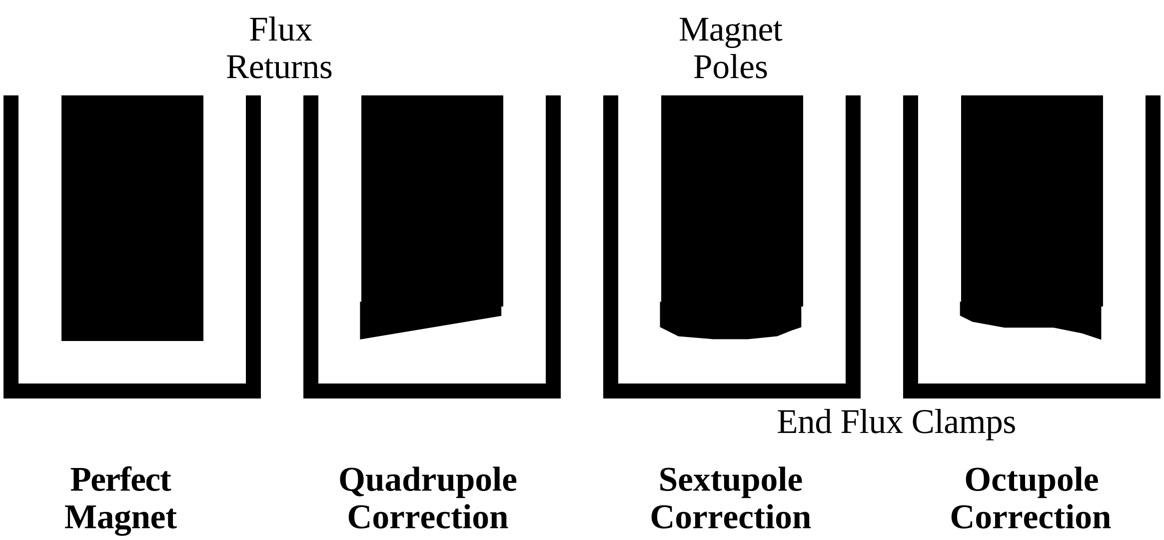
Main Injector Tunnel

Recycler Ring

- circumference: 3319.4 m
- storage ring: 8.0 GeV kinetic energy
- built from permanent magnets
  - 344 combined function magnets
  - 100 quadrupole magnets
  - strontium ferrite (excellent radiation and temporal stability)
  - no power supplies, cables, cooling water
  - $\Rightarrow$ low cost ($\sim$\$5000 a piece)
  - $\Rightarrow$ reliability
- initially stochastic cooling
- ultimately electron cooling
- accumulate/cool up to a total stack of $3 \cdot 10^{12}$ $\bar{\mathrm{p}}$

Recycler Combined Function Gradient Magnet

- 4 different types
  - regular arc cell / dispersion suppressor
  - focusing / defocusing
- dipole / quadrupole / sextupole field
- length 4.5 / 3.1 m
- central field 1.38/1.33 kG
- strontium-ferrite permanent magnets
- end-shims for field correction



- iron-nickel alloy for temperature compensation

Recycler Closed Orbit

- Design tolerances for magnetic fields
- Magnet alignment to 250μm
- $\Rightarrow$ closed orbit distortions
- powered correction dipoles
  - 27 horizontal
  - 28 vertical
  - located at septum and cooling locations
  - can be used for iniatial commissioning
- eventually all correction by magnet movements
  - increases reliability
  - effective correction needed

Tune / Chromaticity Adjustment

- **Tune: Phase Trombone**
  - **9 powered quadrupole magnets**
  - **located in one straight section**
  - **small tune adjustment $\sim$ 0.1**
  - **permanent magnet phase trombone planned**
  - **rotatable quadrupoles**

- **Chromaticity:**
  - **24 powered sextupole magnets**
  - **range $\sim$ 10 units**

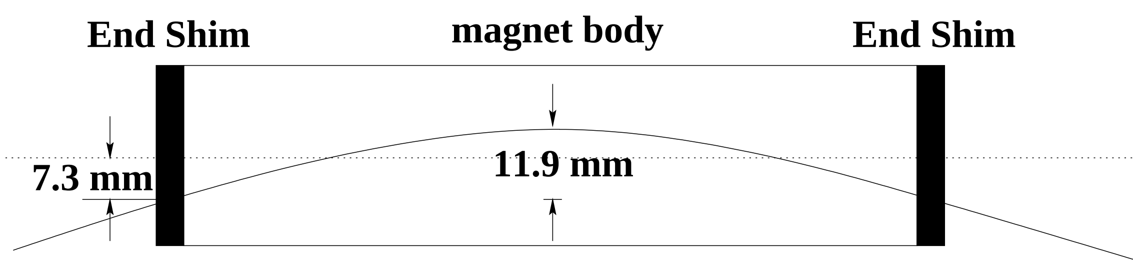
Recycler Commissioning 1999

- Jan 9: start partial turn commissioning
- Jan 12: beam to temporary dump
- mid April:
  - ring completed
  - 50% efficiency through transfer line from Main Injector
  - few turns
  - BPM commissioning
- May 4: 100% efficiency through transfer line
- May 18: circulating beam
- Problems:
  - BPMs
  - closed orbit
  - impact of the Main Injector ramp
  - tune / chromaticity

Tune Problem

- design tunes $Q_x = 24.425$ / $Q_y = 24.415$
- beam not circulating without trim quads
- vertical tune around half integer
- horizontal tune about .2 too low

- sextupole feed-down

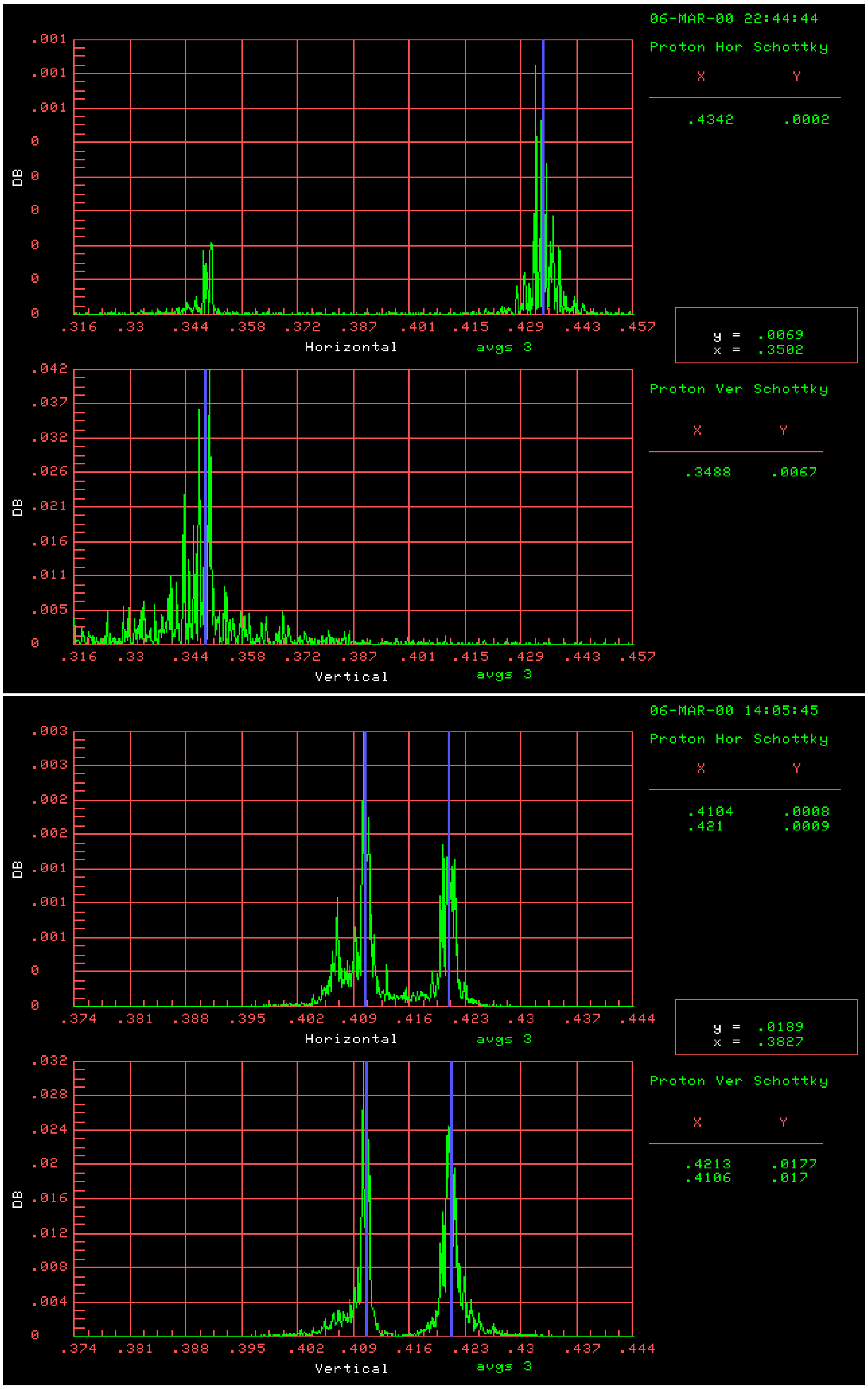


- sextupole not equally distributed
- RGF: 3 units in body + 3 in each shim
- RGD: -18 in body + 1.5 in each shim
- $\Rightarrow$ shim replacement on one side
- $\Rightarrow$ tunes $Q_x = 24.44$ / $Q_y = 24.36$

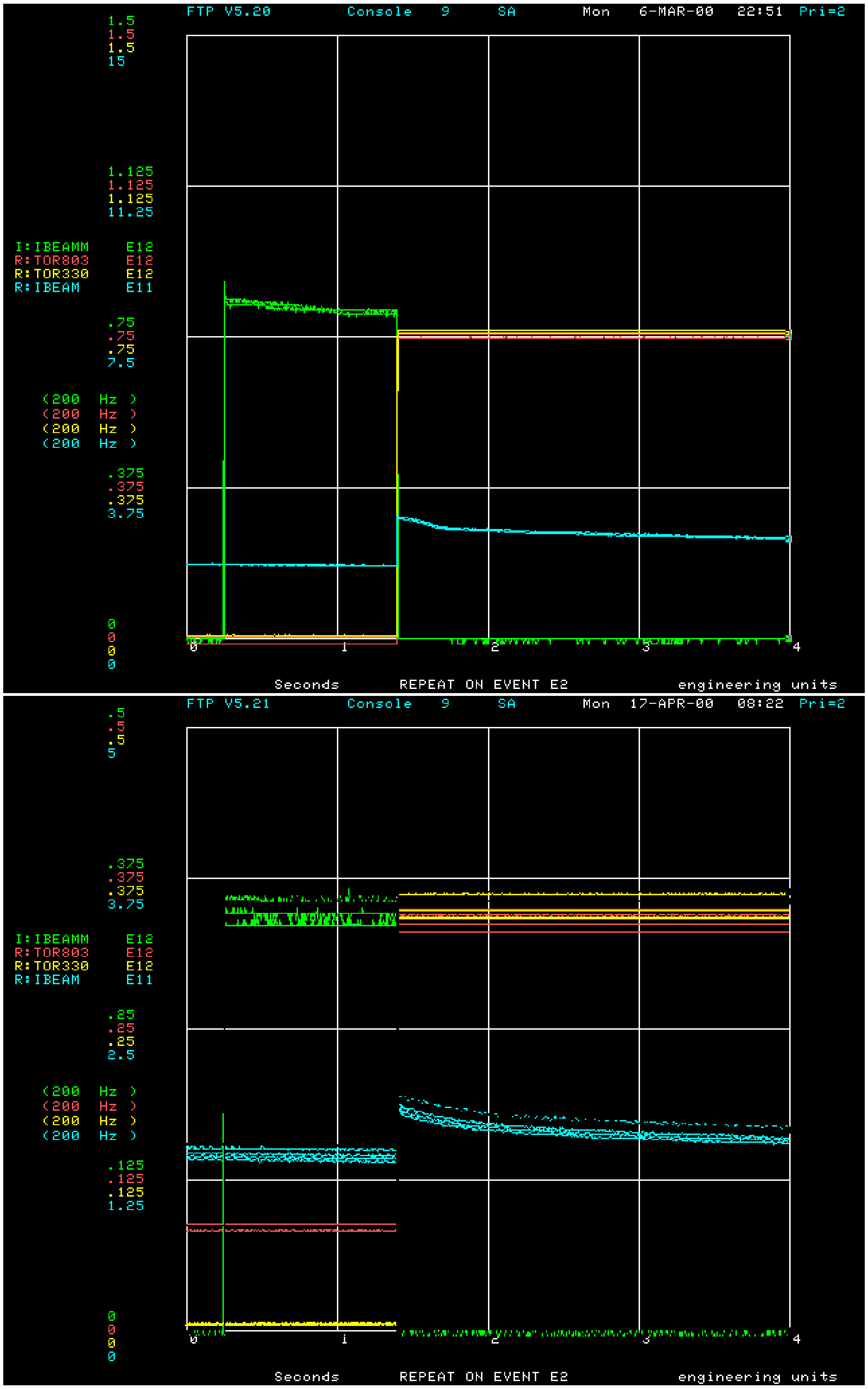
Comparison between Model and Measurement

	Tunes (MAD)		Tunes (data)	
	Horz	Vert	Horz	Vert
Quad trims off (old shims)	24.268	0.000	——	——
Quad trims off (new shims)	24.405	24.400	0.442	0.358
Quad trims on (new shims)	24.385	24.467	0.410	0.431
Difference between on and off	-0.020	0.067	-0.032	0.073

Recycler Tune Measurement



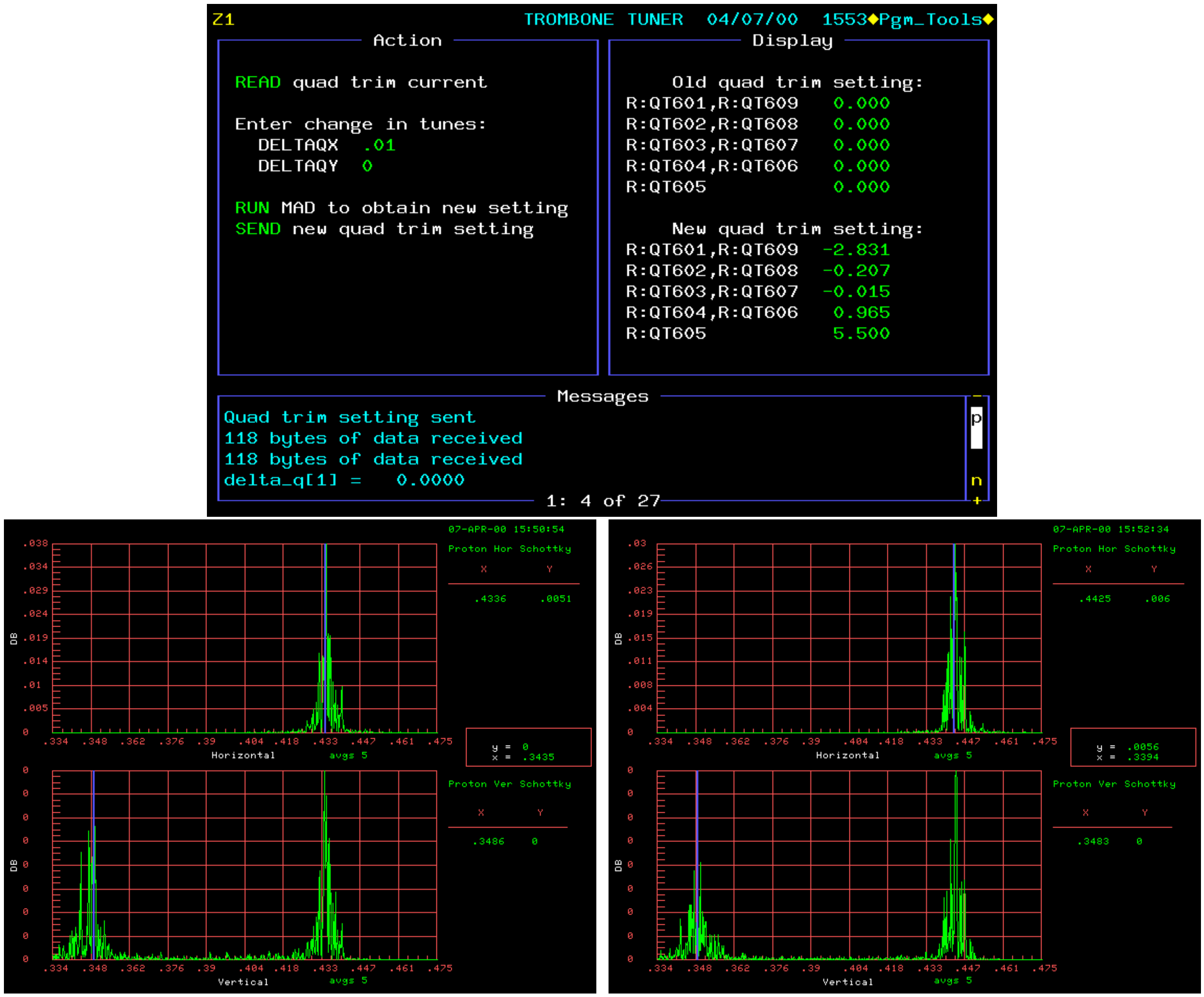
Recycler Beam Intensity Plot



Implementation of the Trombone Tuner

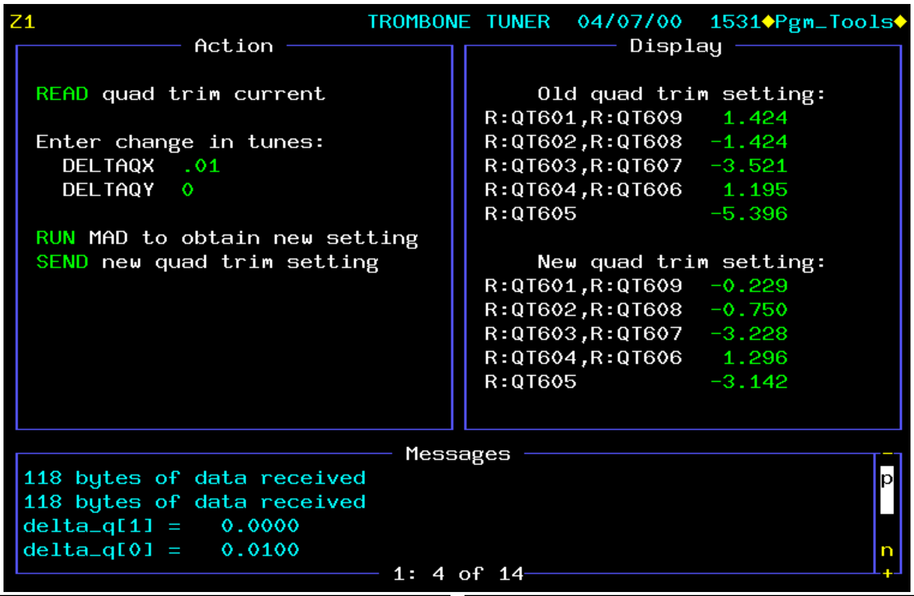
- Operations Console (VAX):
  - reads quad trim setting data from the front end
  - sends it along with tune change to a UNIX server via TCP/IP
  - receives new quad trim setting from the server
  - sneds the new setting to the front end
- UNIX Server:
  - receives quad trim setting from the operations console
  - runs MAD to find new quad trim setting for the new tune
  - sends the new setting back to the operations console

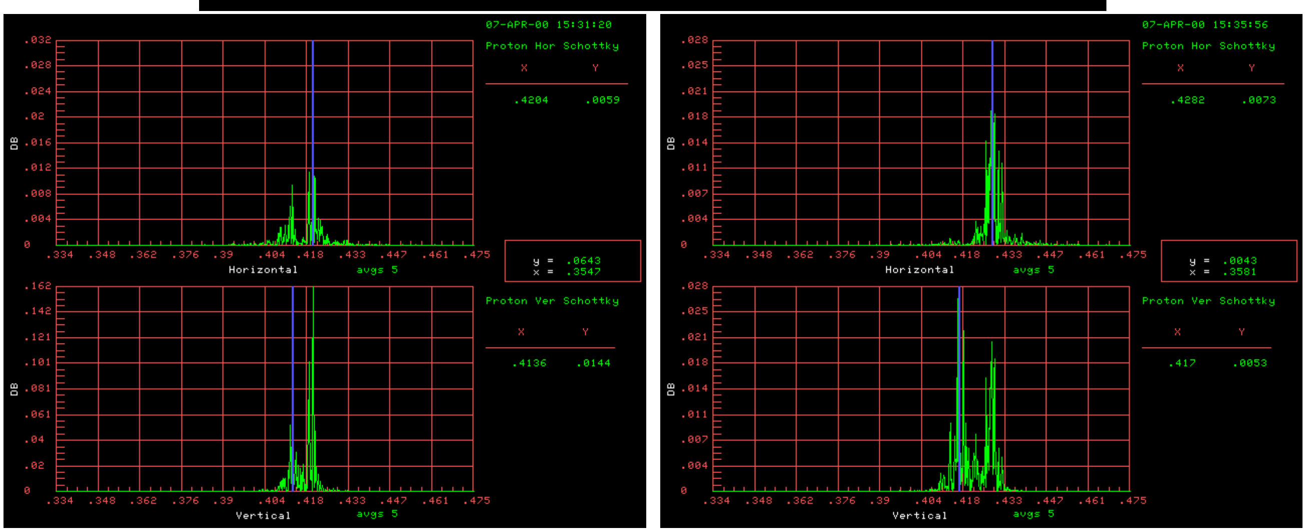
Trombone Tuner: Example #1



- $\Delta Q_x = 0.0089, \Delta Q_y = 0.0003$
- **Excellent agreement between model and measurement**

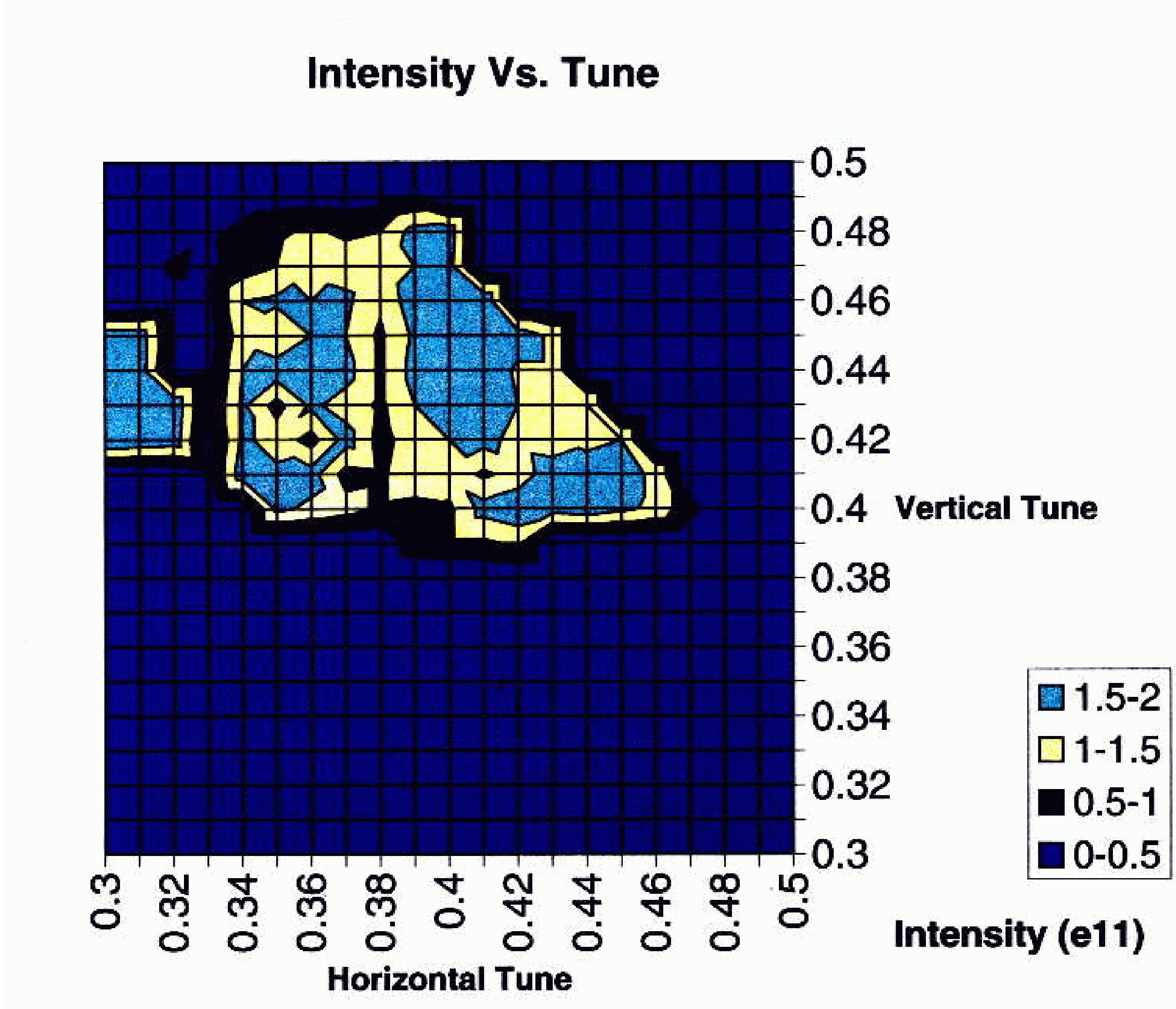
Trombone Tuner: Example #2





- $\Delta Q_x = 0.0078$, $\Delta Q_y = 0.0034$
- **Good agreement between model and measurement**
- **Coupling may play a role here**

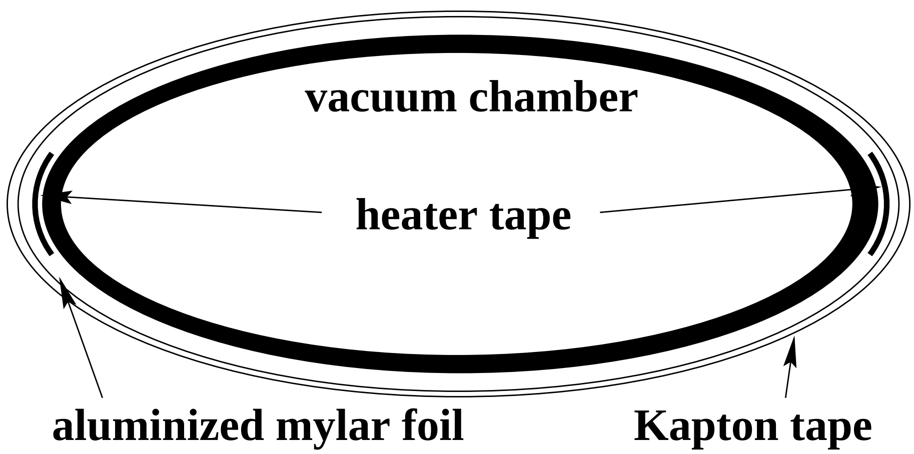
Recycler Trombone Tuning Range



Chromatiity Problem

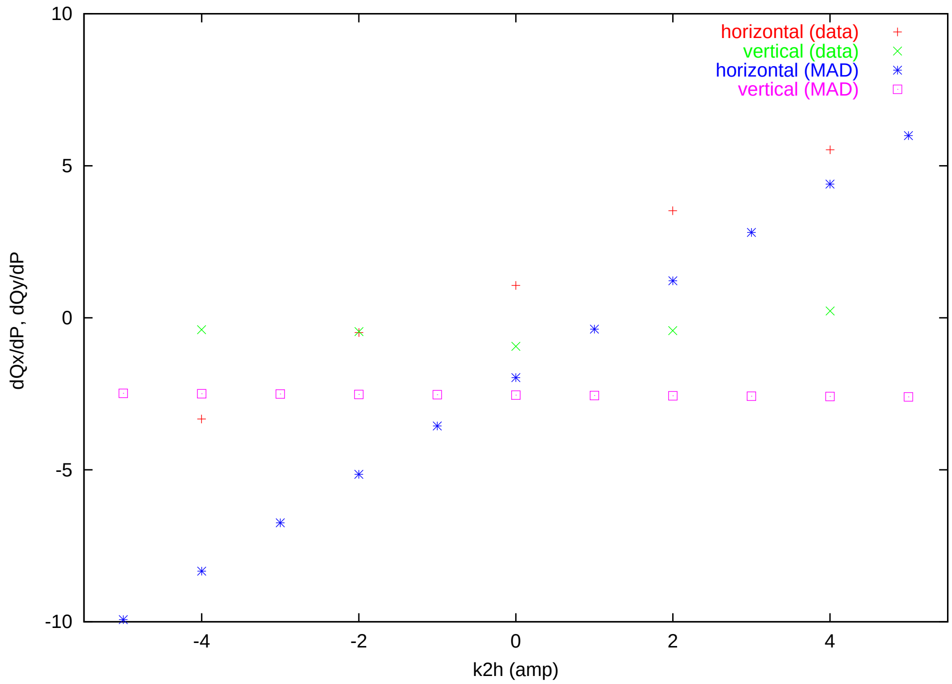
- design chromaticity slightly negative
- measured chromaticity $Q'_x = -20$ / $Q'_y = +6$

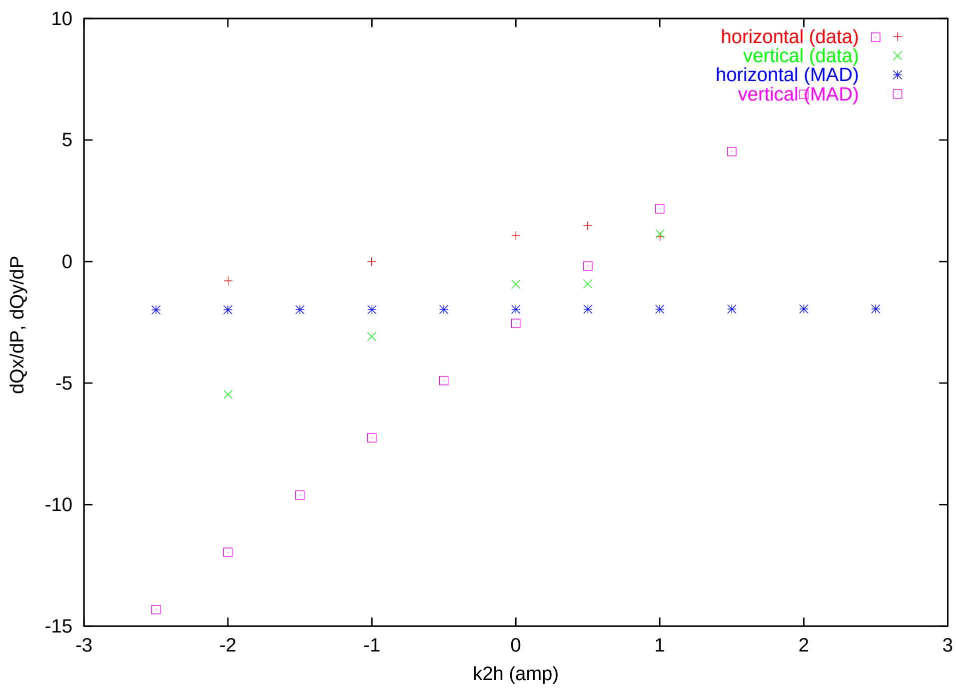
- heater tape problem



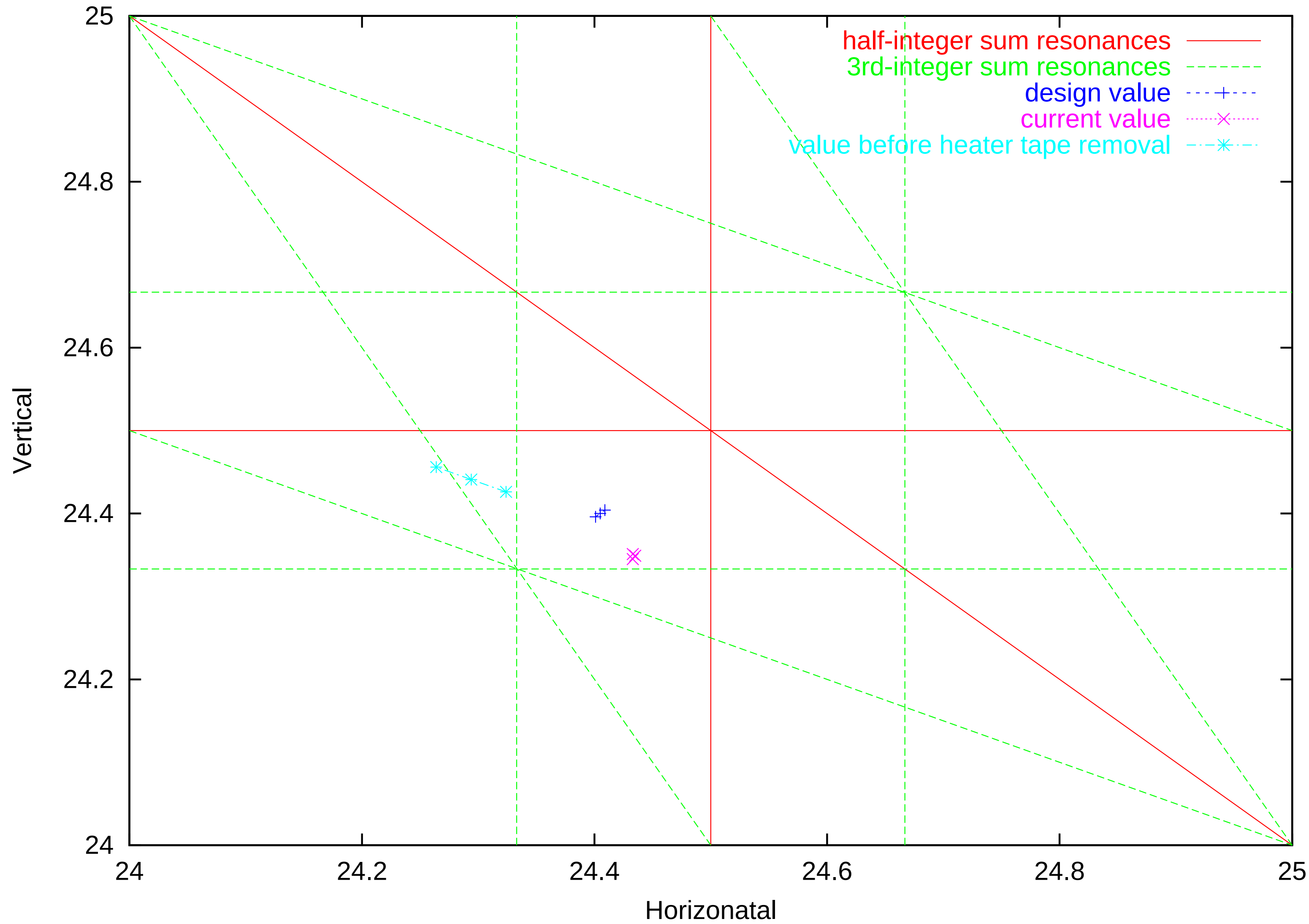
- heater tape magnetic
- all kinds of multipoles
- $\Rightarrow$ heater tape removed
- $\Rightarrow Q'_x = 1$ / $Q'_y = -1$

Recycler Chromaticity Measurement

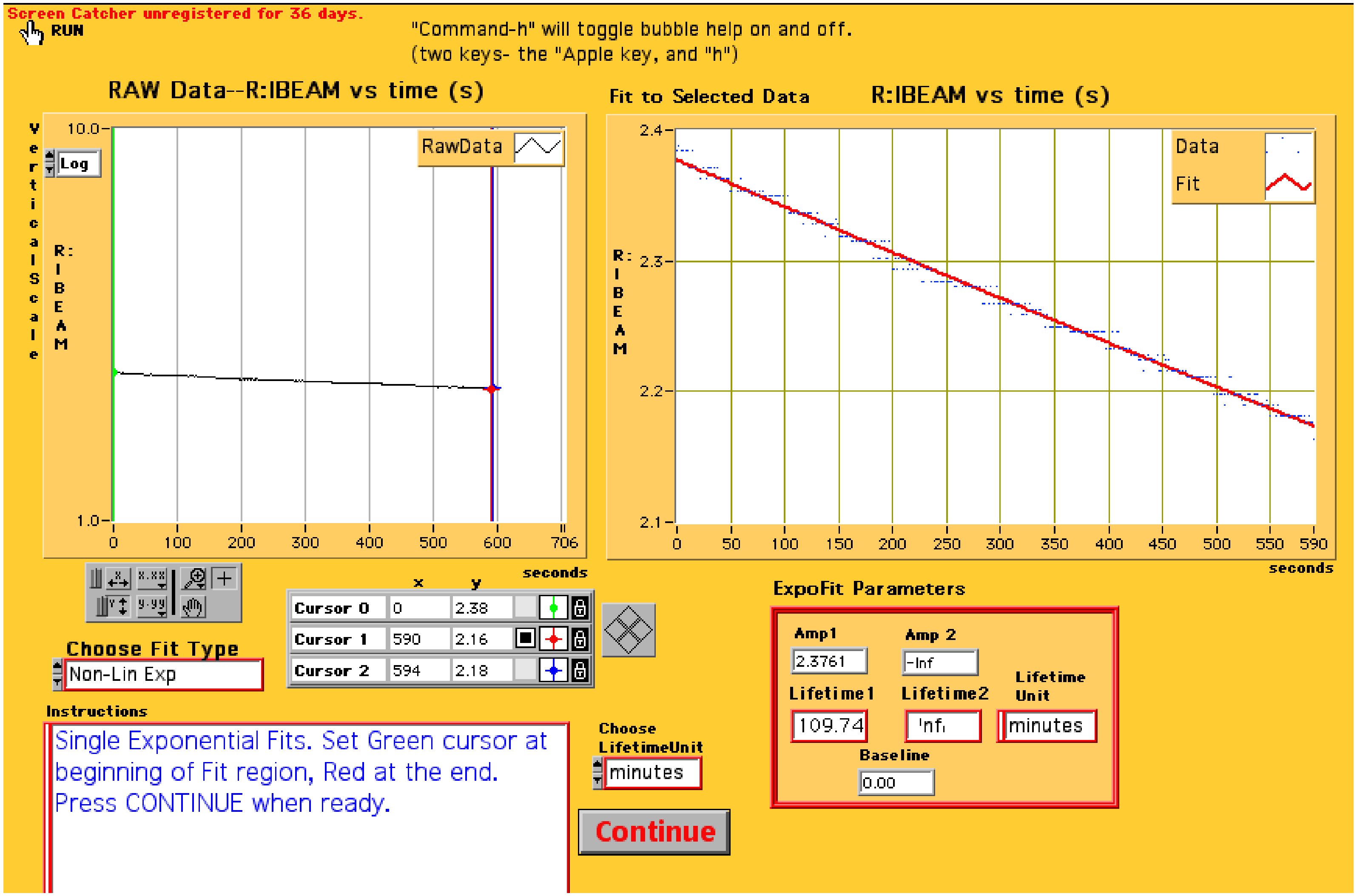




Recycler Operating Points



Proton Beam Lifetime of the Recycler



My Contribution

- simulation of the sextupole feed-down effect
  $\Rightarrow$ design of the new shims
  $\Rightarrow$ beam circulating without trim quads
- β-function measurement at trim quad locations
  $\Rightarrow$ showing agreement with model to $\sim$15%
- chromaticity mult design and calibration
  $\Rightarrow$ agreement with model
- momentum acceptance measurement
  $\Rightarrow$ agreement with model
- design, implementaion and testing of the trombone tuner program
- maitainance and development of orbit smoothing, injection closure and BPM utility programs originally written by a former team member

Work in Progress

- debugging the BPM system
- removing aperture restrictions
- quad cable compensation loop
- clearing electrodes
- RF manipulation of beam
- proton stochastic cooling
- pbar stochastic cooling