Progress on Beam-Beam Simulations and New Working Points at the Tevatron

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DOE Tevatron Operations Review

SC-1 Breakout

March 21, 2006

Contents

- Optics measurements and design of the new (28cm beta*) lattice.
  - Orbit response method
  - Machine model
  - Implementation of the new optics
- Weak-Strong Beam-Beam simulations
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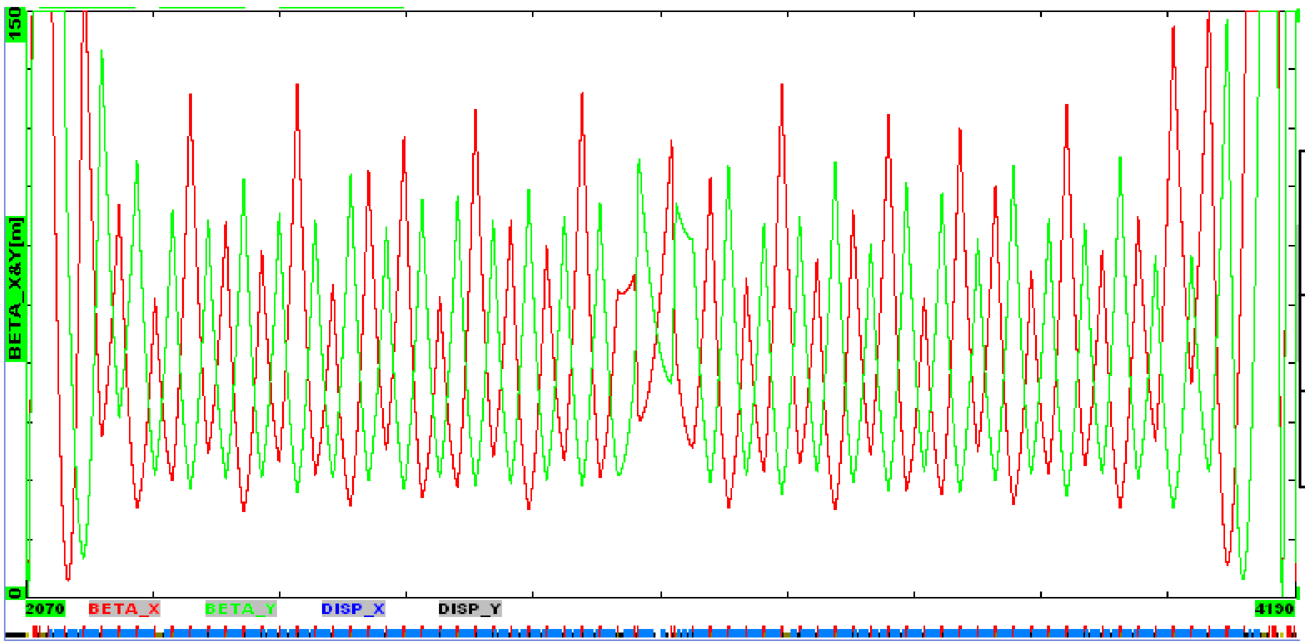
  - Justification of the code results
  - Predictions for 35cm vs. 28cm
  - Effect of Chromaticity
  - Increasing the proton intensity and New betatron tune working points
- Lattice Chromaticity Correction
  - Chromaticity Measurements
  - Design of Correction Circuits
- Development of Strong-Strong Simulation
  - BB3D and BBSS codes – capabilities, development
  - Progress, testing

Optics Measurements

- Orbit Response Method developed and tested during year of 2004 in collaboration with ANL*.
- New BPM system allows beta function measurement with accuracy of 5%
- Typical beam study time is 2 hours, data processing 6 hours -> Machine model

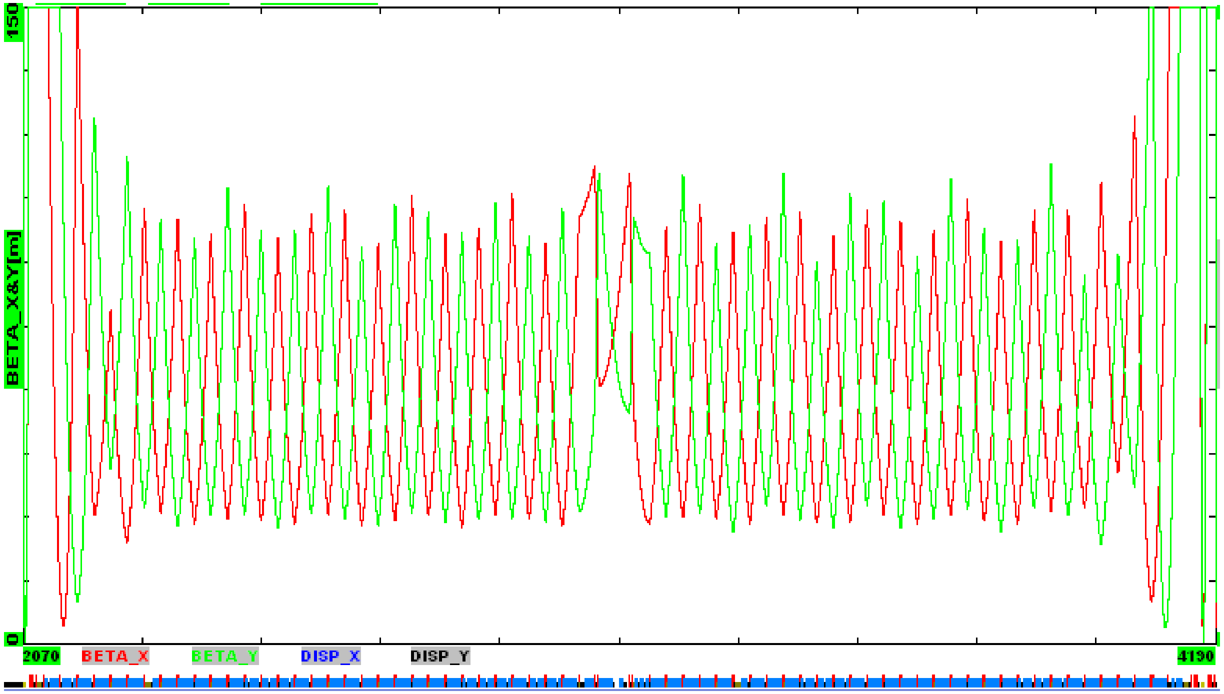


	β_x^* (cm)	β_y^* (cm)
CDF	32.0	37.1
D0	35.8	40.0

* V.Sajaev et al., PAC2005

New Tevatron Optics

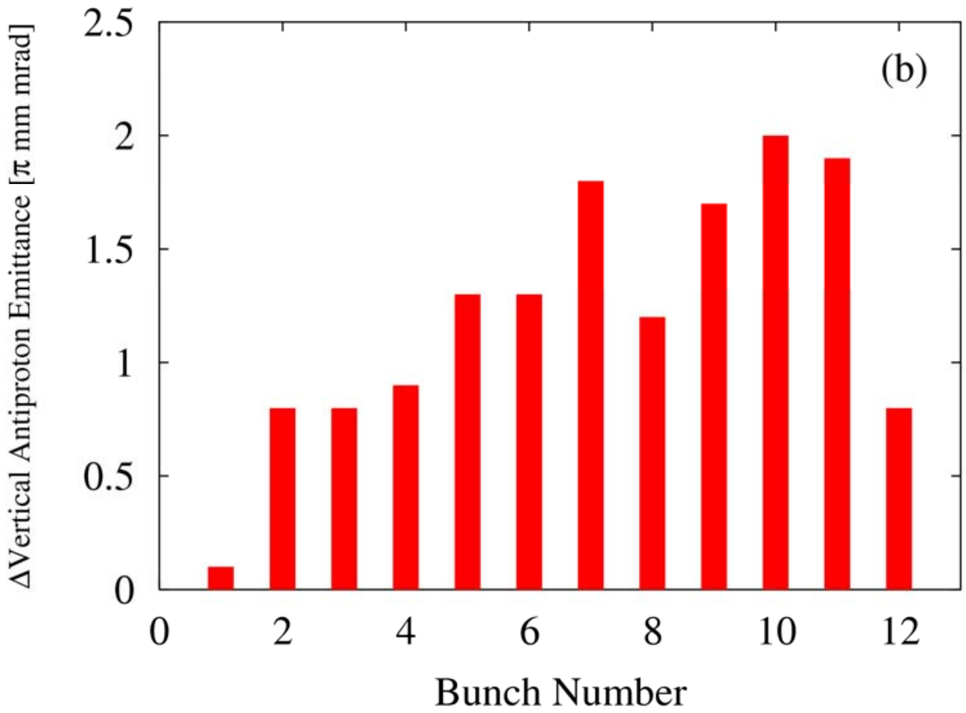
- Decrease beta* from 35cm to 28cm (expected gain in initial luminosity is 11%
- Eliminate beta-beating in the arcs

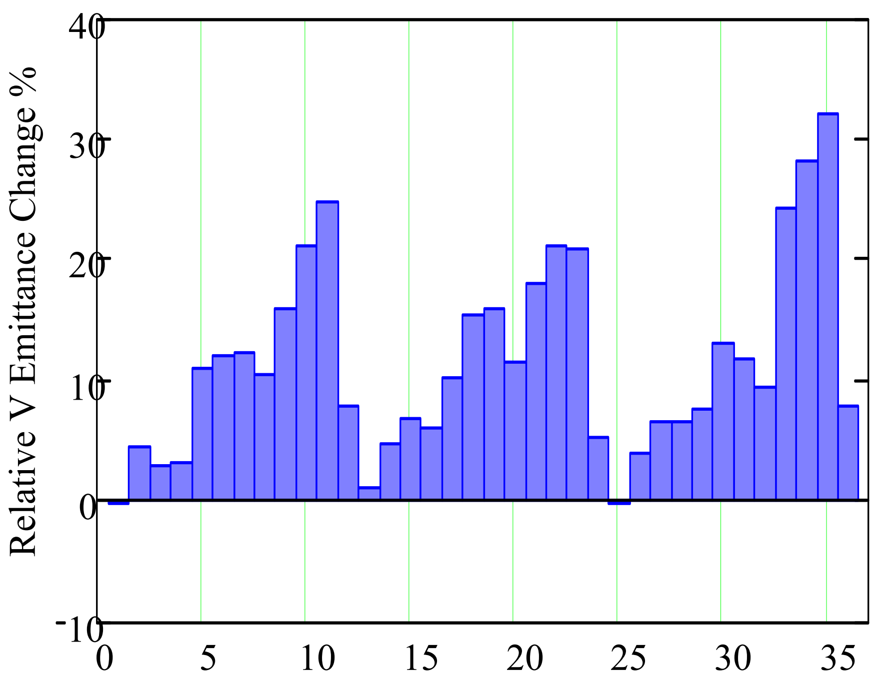


	β_x^* (cm)	β_y^* (cm)
CDF	30.3	29.1
D0	29.2	28.2

Weak-Strong Beam-Beam Simulation

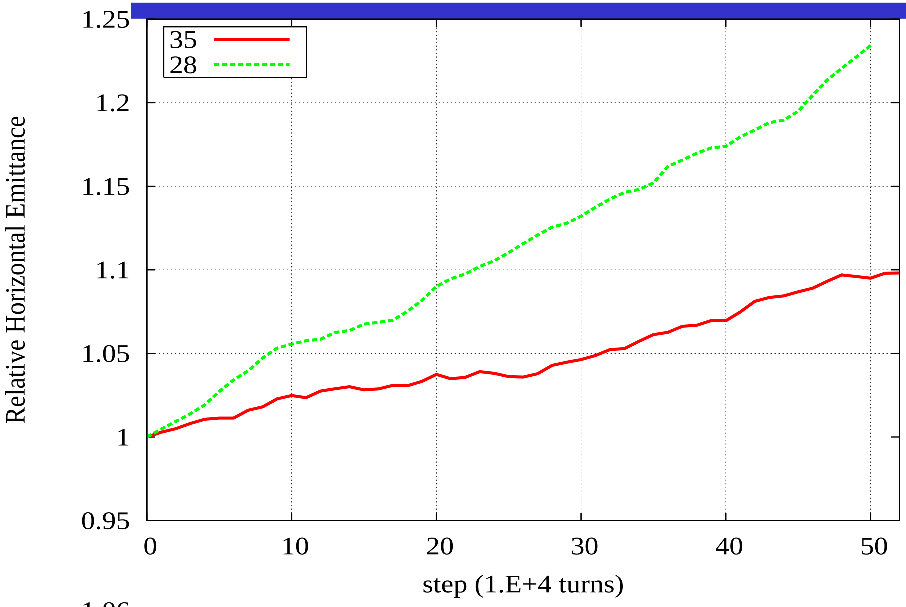
- Simulation code LIFETRAC* initially developed for e+e- colliders, modified for the Tevatron: 2 main IP's, 70 LR collision points; added diffusion.
- Optics parameters (beta functions, phase advances, etc.) are taken from measurements

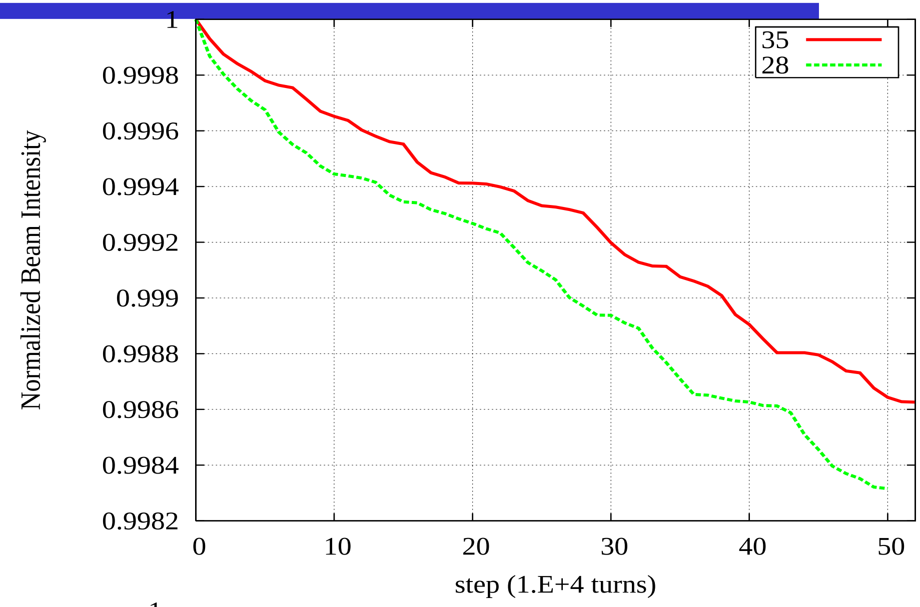


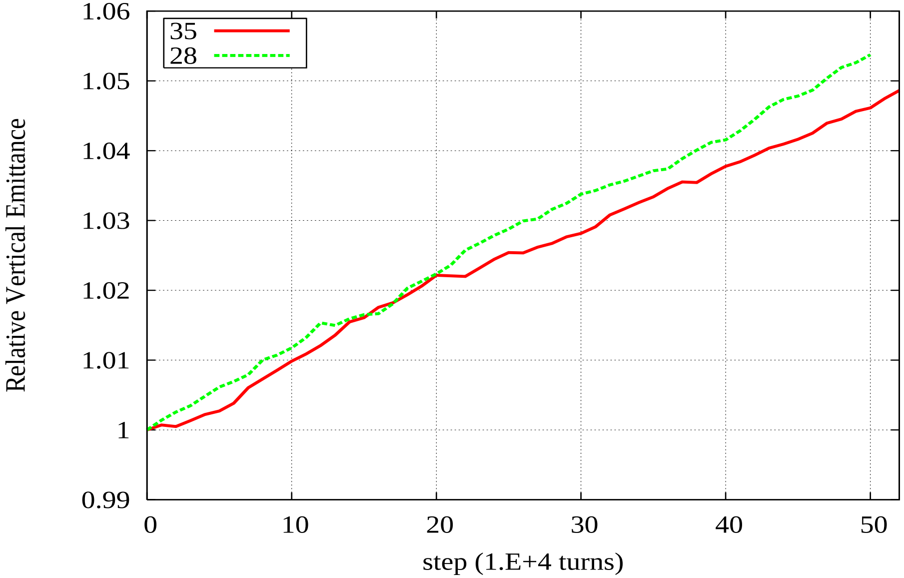


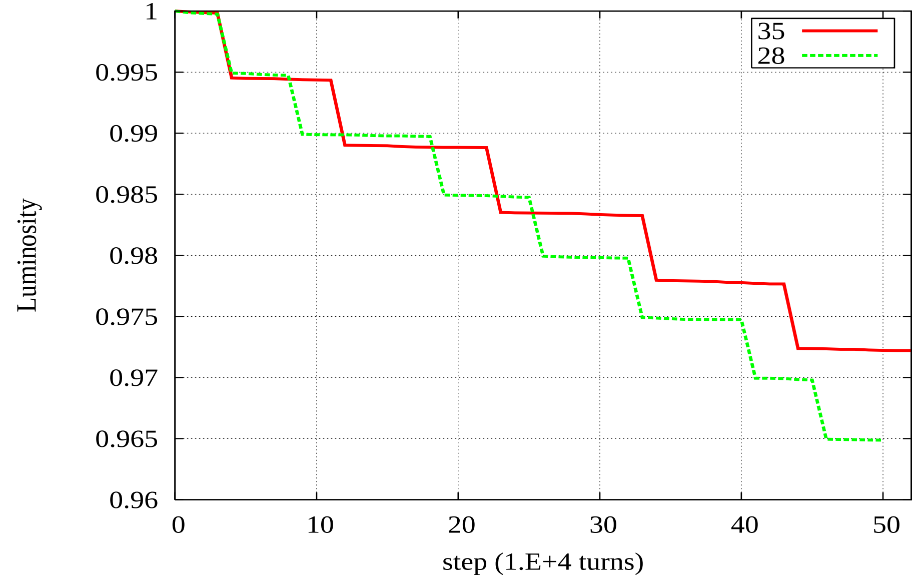
* D. Shatilov, Part. Accel. 52, 65 (1996); A.Valishev et al., PAC2005

Simulation for 35cm vs. 28cm beta* Optics

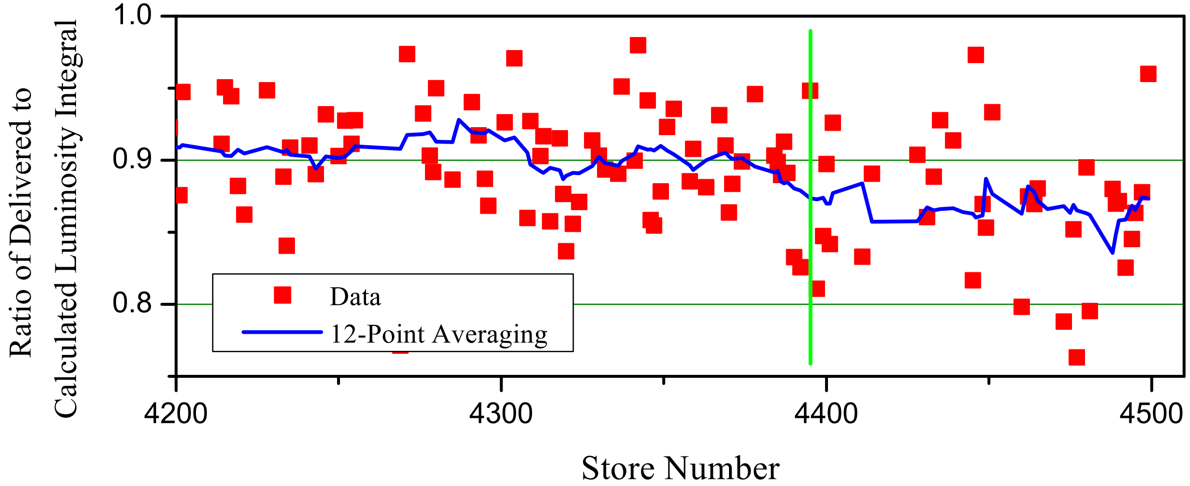






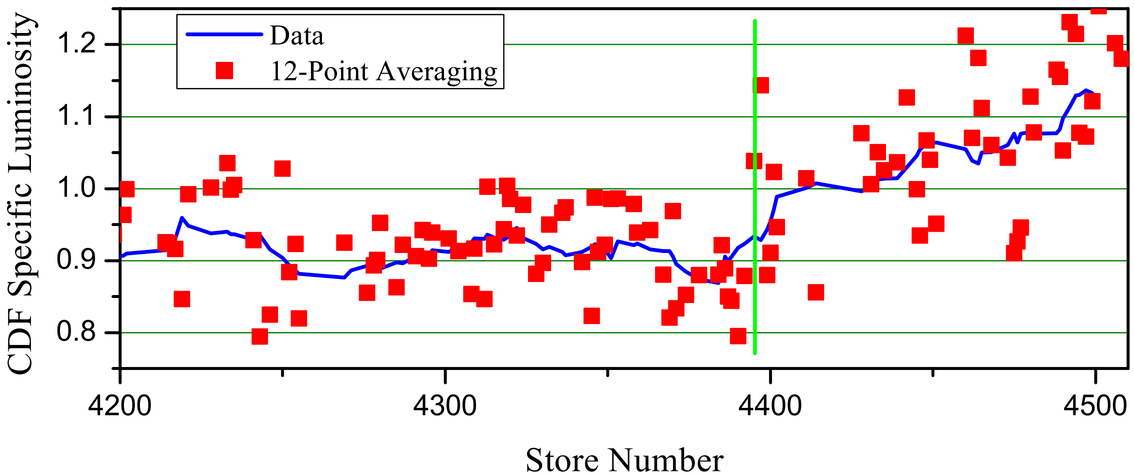


Effect of the New Optics on Luminosity



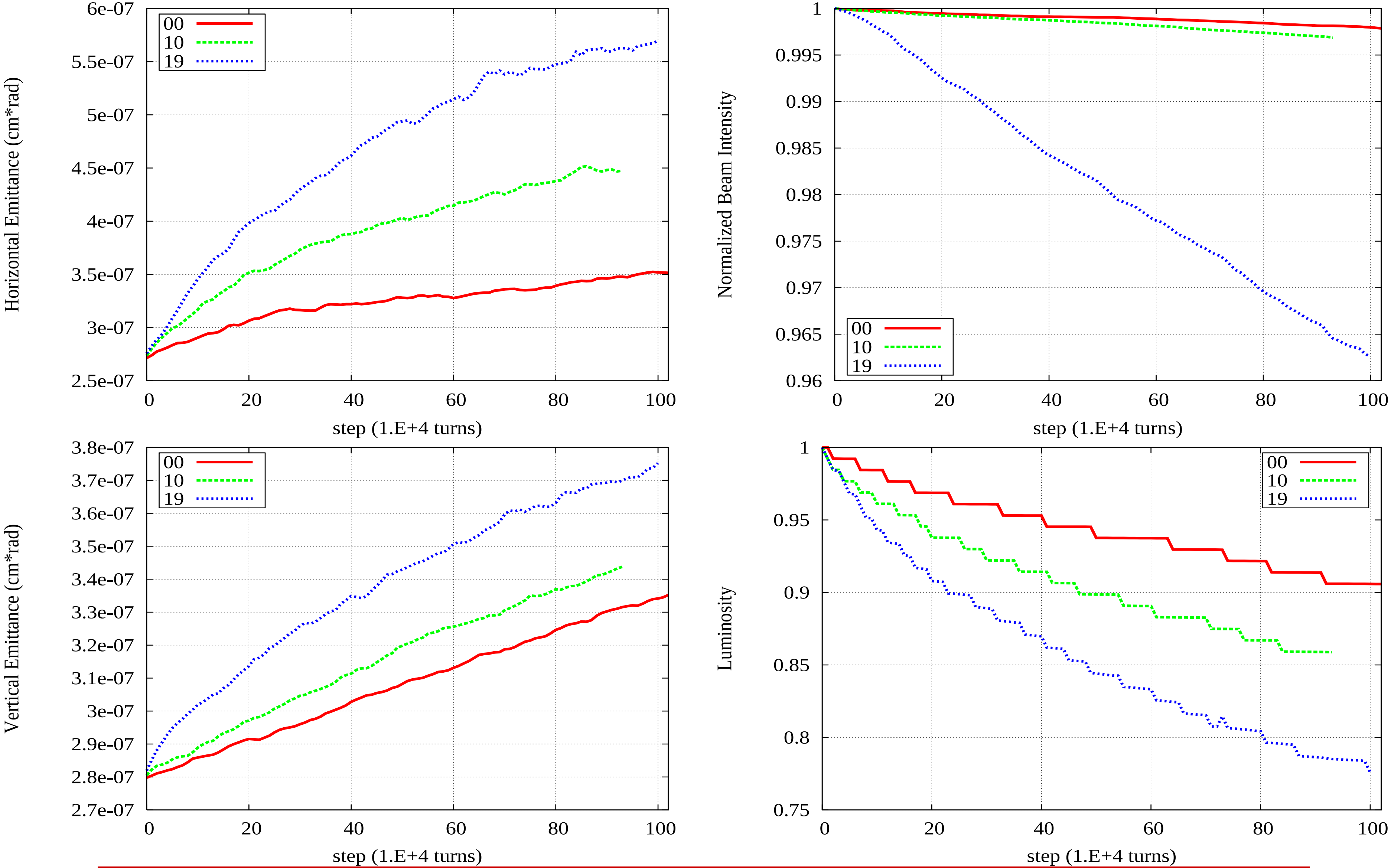
$$L = \frac{L_0}{1 + t/\tau}\ ^{*}$$

$$IntL = L_0 \tau \ln\left(1 + \frac{T}{\tau}\right)$$



* E.McCrory, V.Shiltsev, Beams Document 1777

Effect of Betatron Tune Chromaticity



Differential Chromaticity Studies

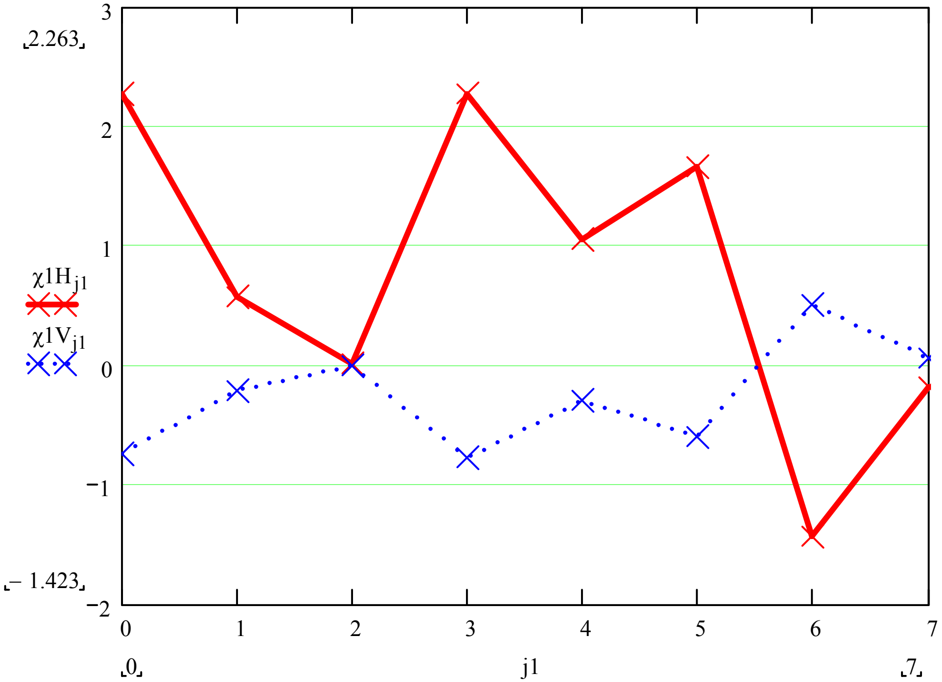
- High (~ +10) betatron tune chromaticity is required to maintain stability of the proton beam
- So far, antiprotons do not suffer from collective effects
- Use octupoles to decrease pbar chromaticity while keeping proton constant
- Calibrate O1 and O2

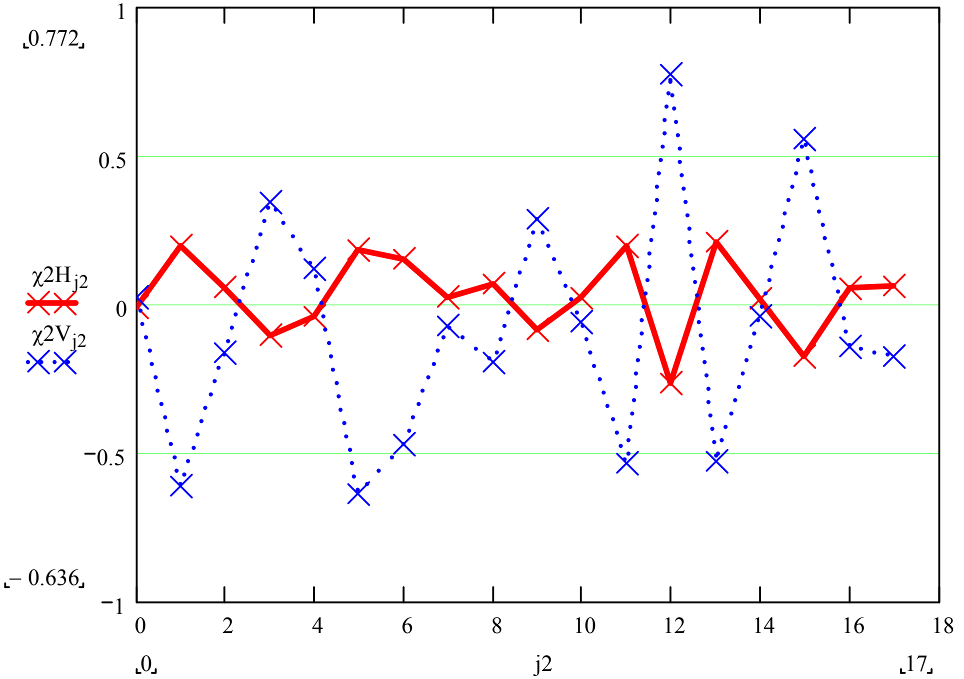
	dCh	dCv
O1 (+40A)	5	-4
O2 (+50A)	1.5	-2.5

dC = dCp - dCa

Differential Chromaticity Model

$$\Delta Ch = \frac{Bo}{4\pi \cdot BR}\beta_x\left(D_x x - D_y y\right) \qquad \Delta Cv = \frac{-Bo}{4\pi \cdot BR}\beta_y\left(D_x x - D_y y\right)$$





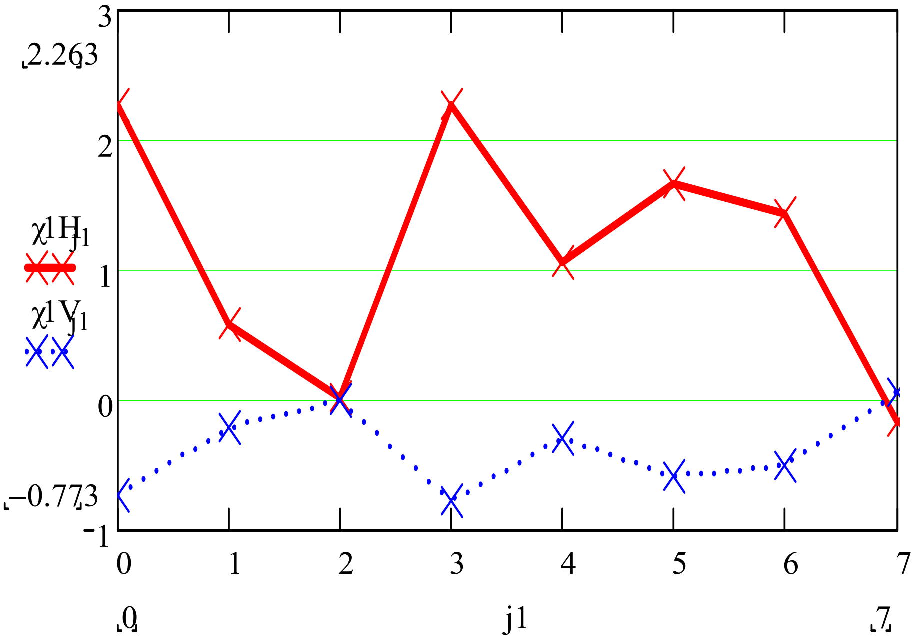
dCh = 6.2 (5)

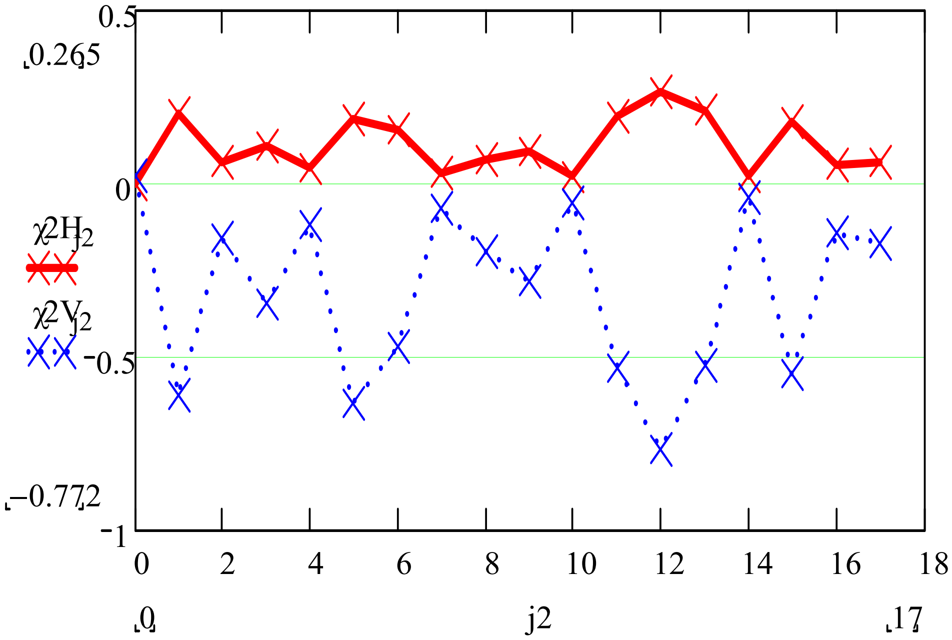
dCv = -2.0 (-4)

dCh = 0.5 (1.5)

dCv = -1.5 (-2.5)

Possible Change of the Octupole Families





O1- 6

O2 – 3,4,9,12,15

dCh = 6.2 -> 9

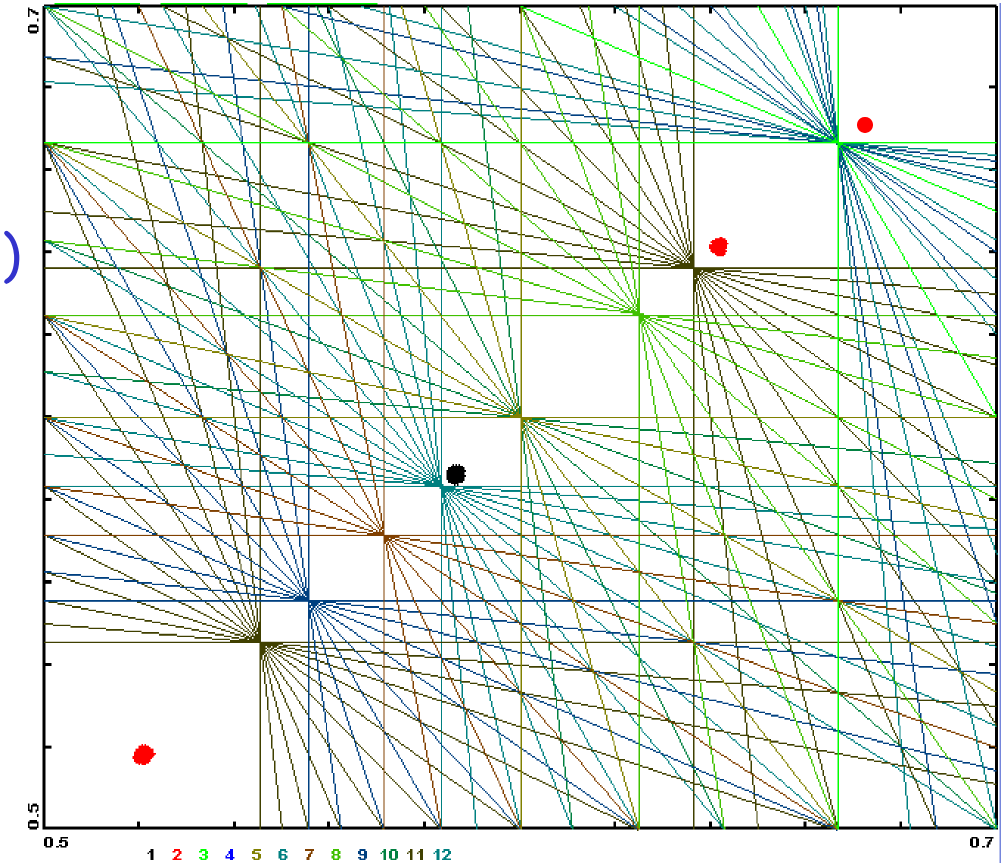
dCv = -2.0 -> -3

dCh = 0.5 -> 1.9

dCv = -1.5 -> -5.7

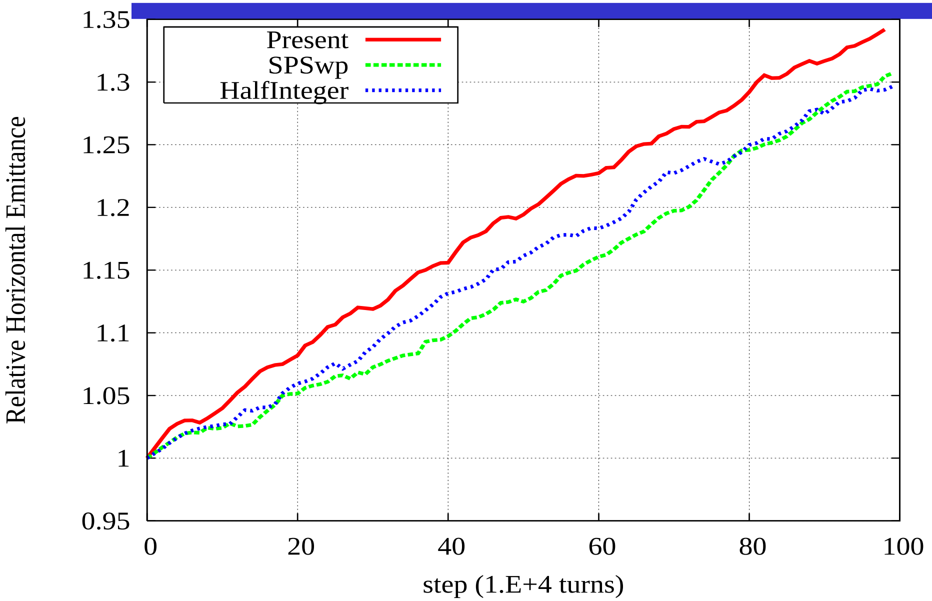
Towards Higher Proton Intensity – New Working Points

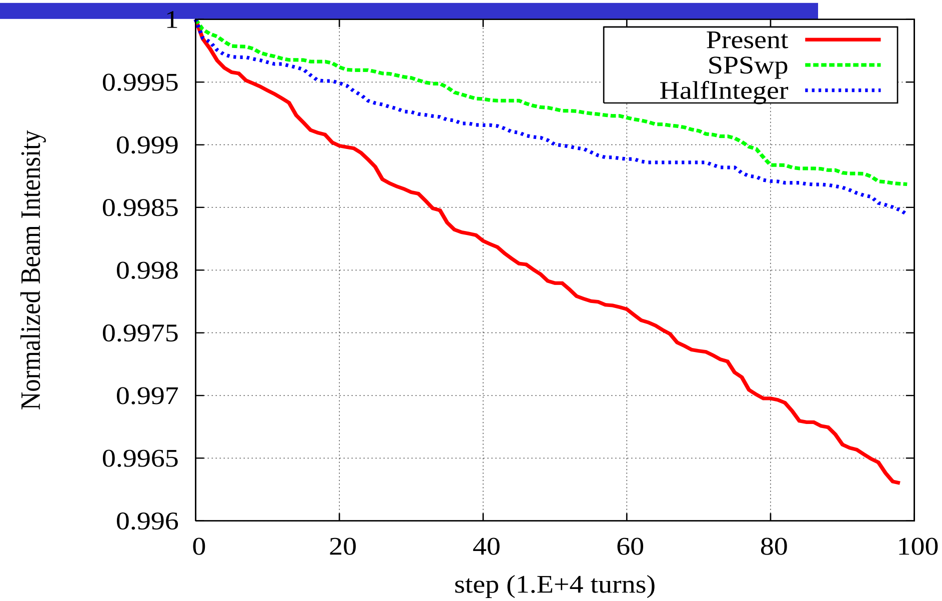
- With present proton intensity the beam-beam tuneshift for antiprotons is 0.02-0.025
- Present operating point between 7th and 5th order resonances (0.028)
- Possible candidates
  - 0.52-0.53 (1/2)
  - .676 .672 (2/3, or SPS)

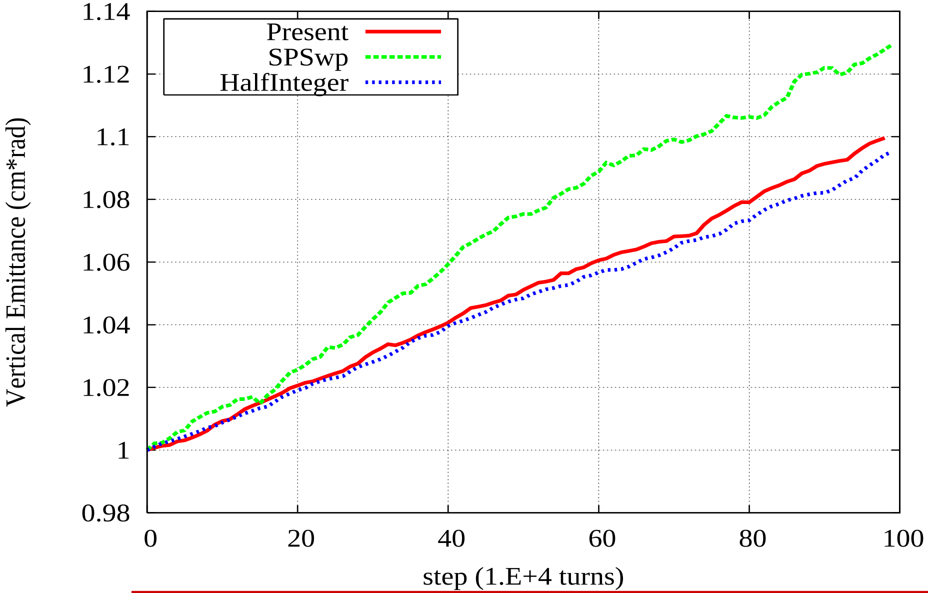


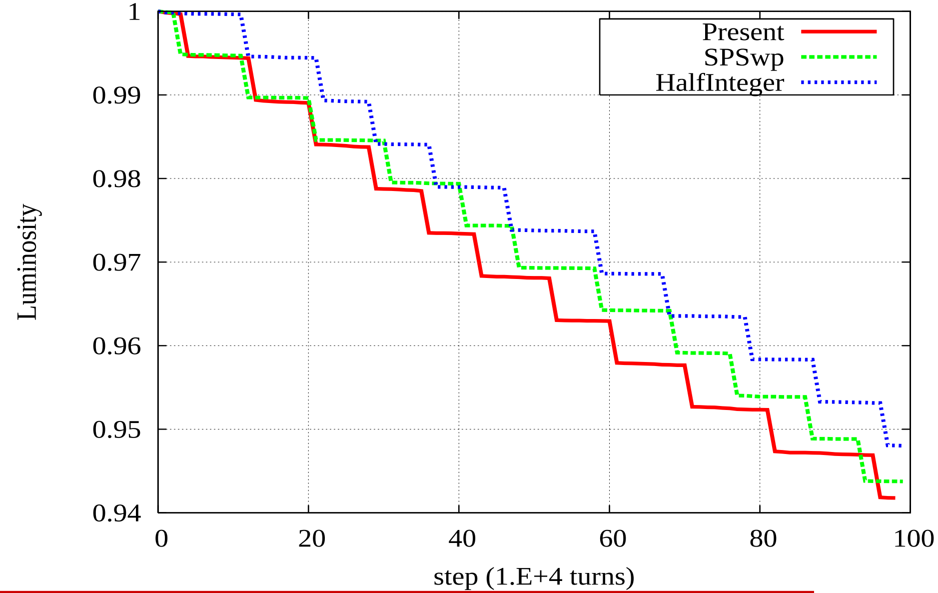
V.Shiltsev, Beams Document 1876

Weak-Strong Simulation: Present Proton Intensity

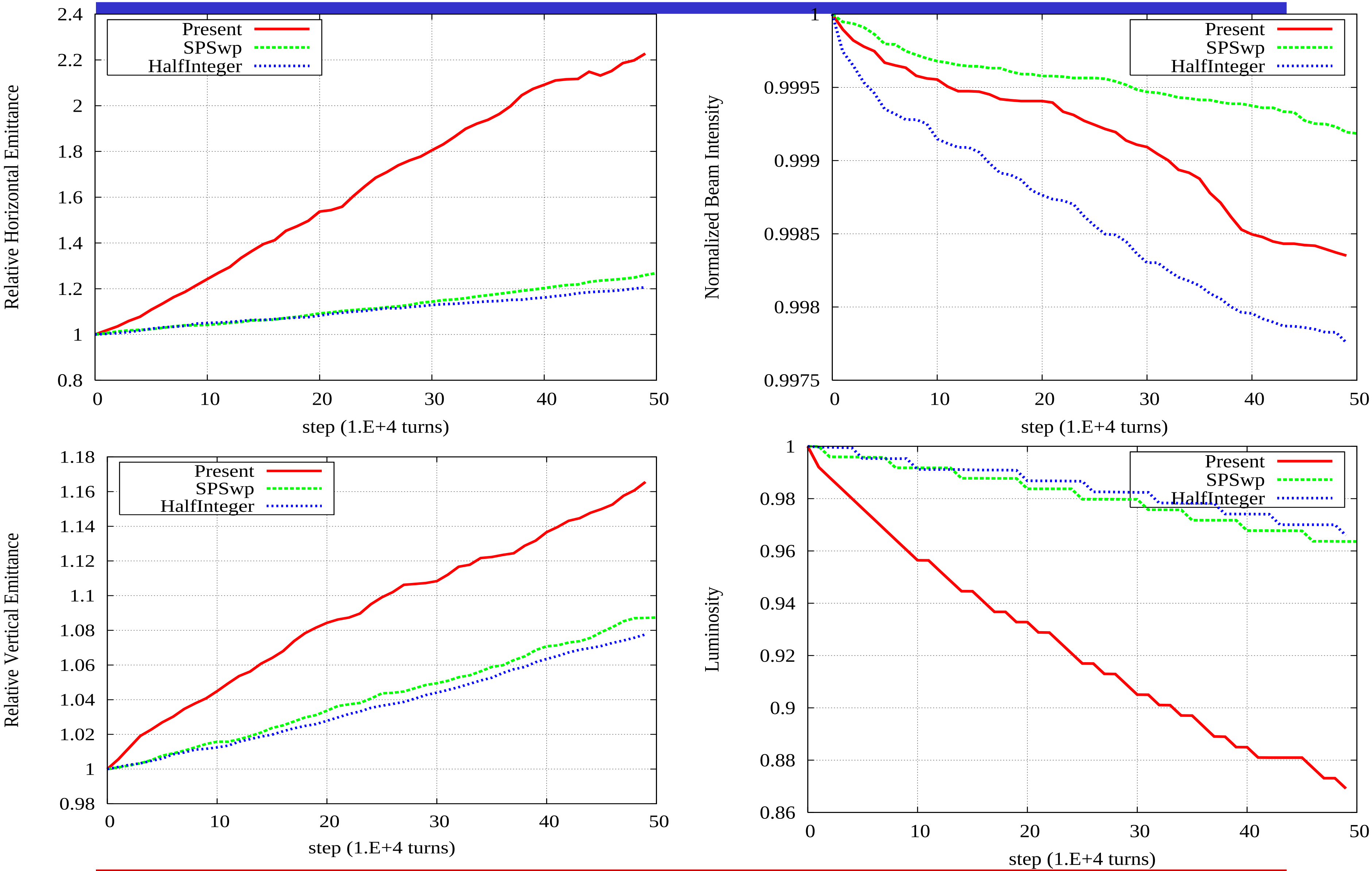








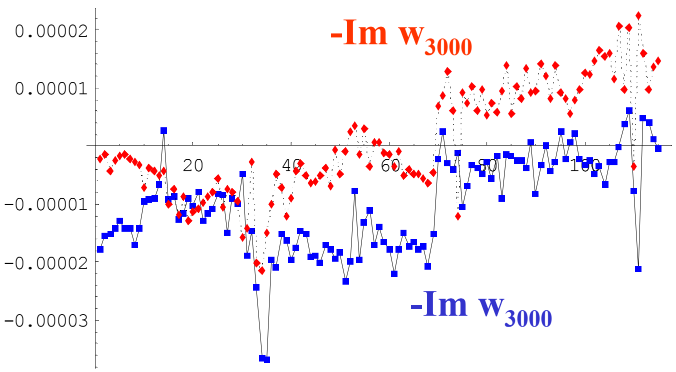
Weak-Strong Simulation: Proton Intensity Increased by 30%

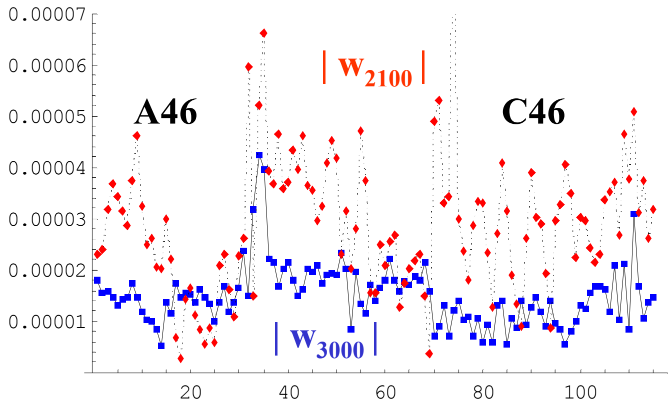


Limiting Factors for the Proposed WPs

- 2/3 – Dominated by distribution of sextupole errors and lattice sextupoles. Measured width is ~0.015
- 1/2 – Driven by quadrupole errors which cause distortions of beta-function. Primary source – chromatic errors. Measured width ~0.02
  - Need ability to control beta-beating
  - Correct chromatic beta-beating

Y.Alexahin





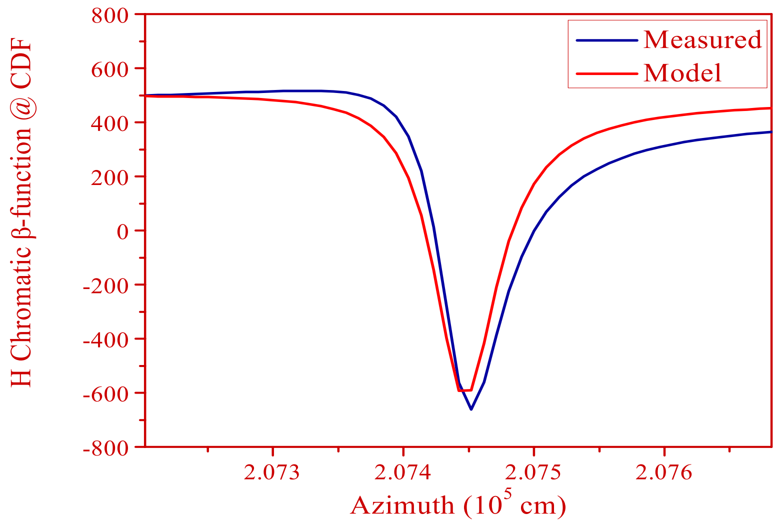
Generating functions of Qx±2Qx resonances vs HBPM number starting from HF19

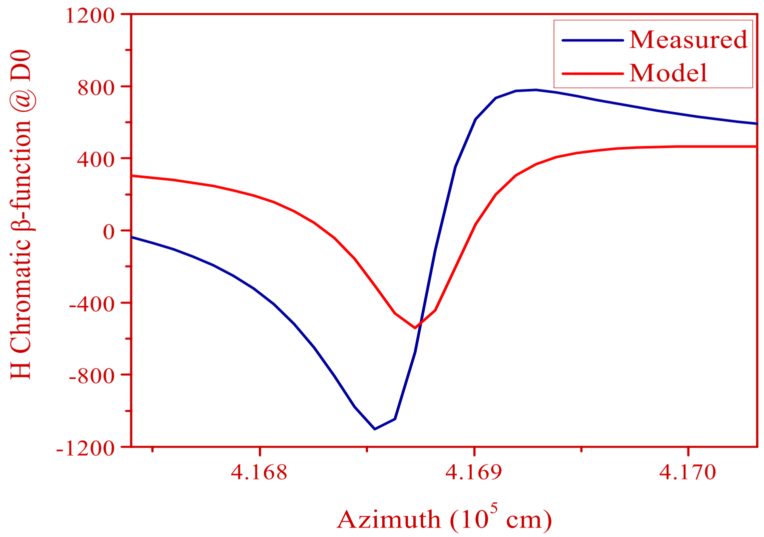
Measured and computed resonances driving terms at 150:

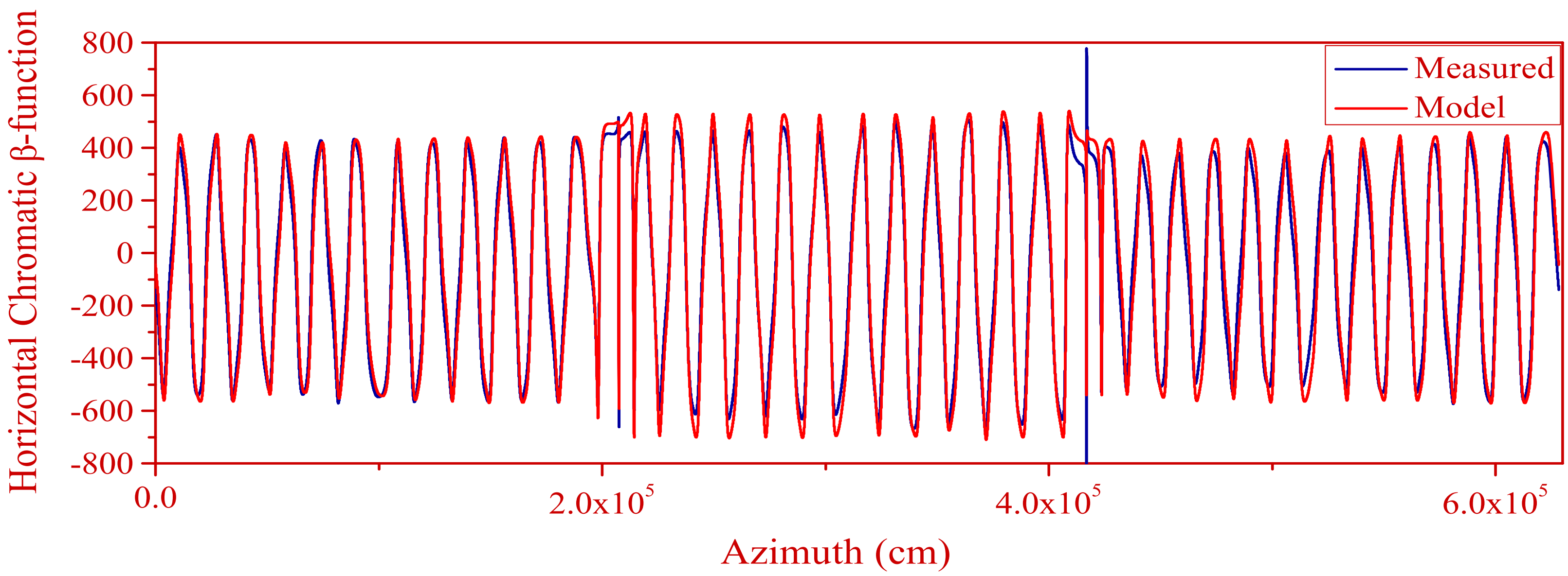
case	Res.	Re R	Im R	| R |
nominal	$3Q_x$	5.1	3.4	6.1
MAD, S6 only	$3Q_x$	4.1	4.0	5.7
S6=0, S6A0=200A	$3Q_x$	-1.7	-1.1	2.0
nominal	$3Q_y$	- 0.9	- 0.2	0.9

- 3Qx RDT is almost entirely produced by S6 feeddown sextupoles
- their replacement with S6A0 will solve the problem (if it arises)

Horizontal Chromatic Beta Function

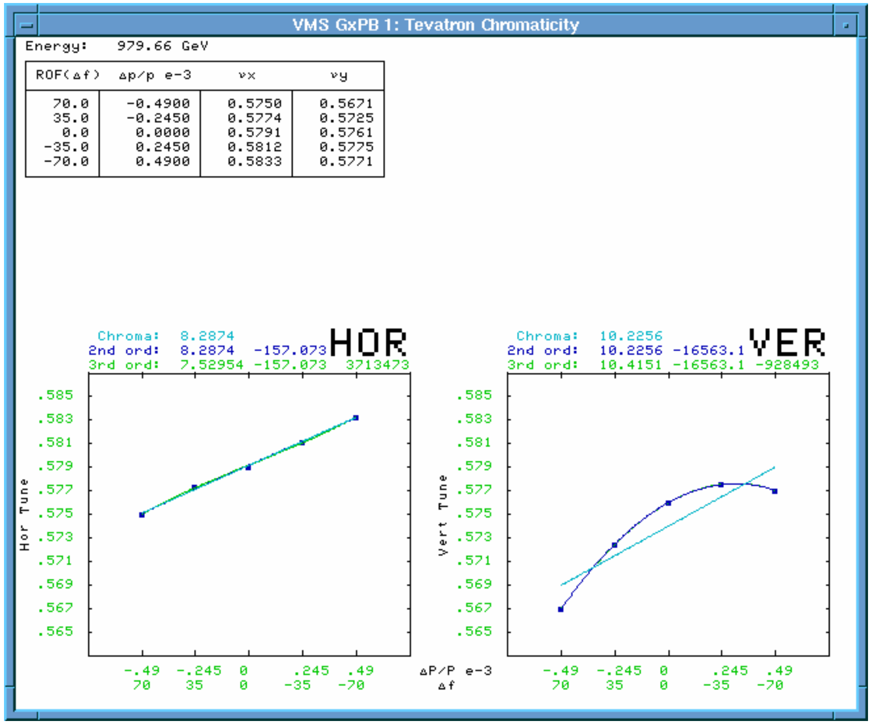


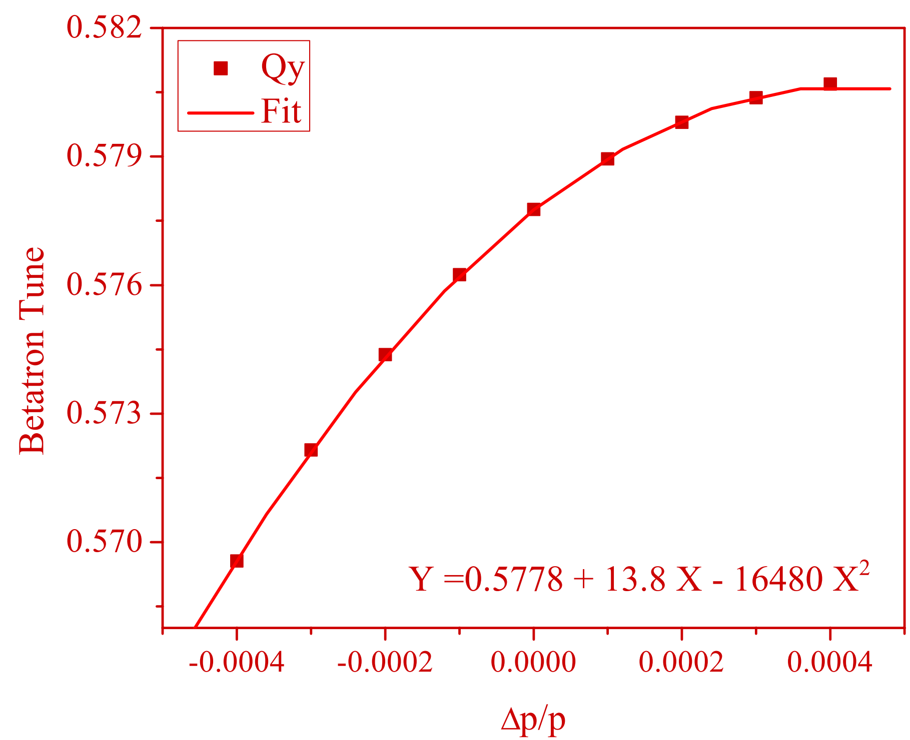




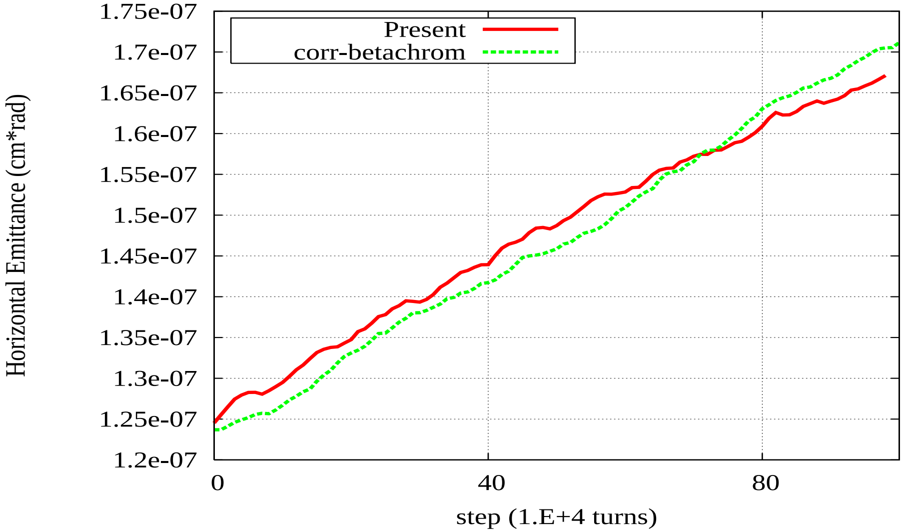
Second Order Tune Chromaticity

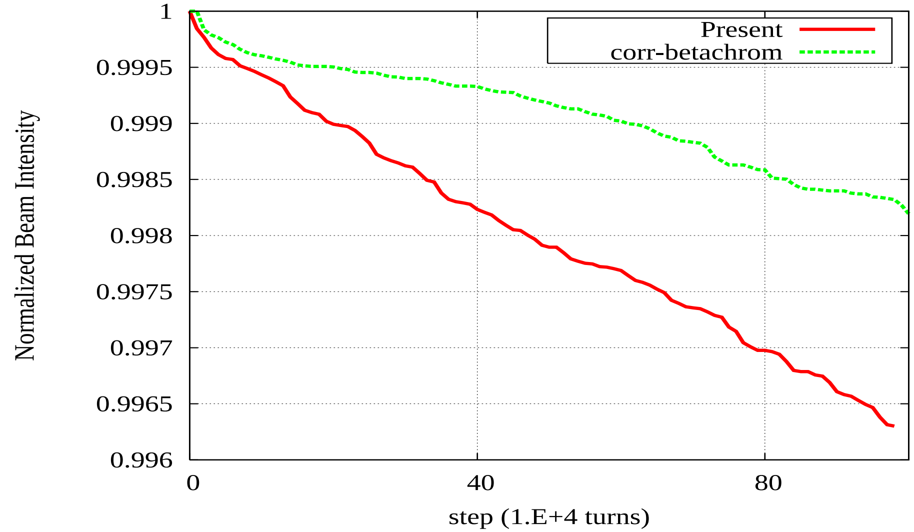
Measured C2 = -16560 Model C2 = -16480

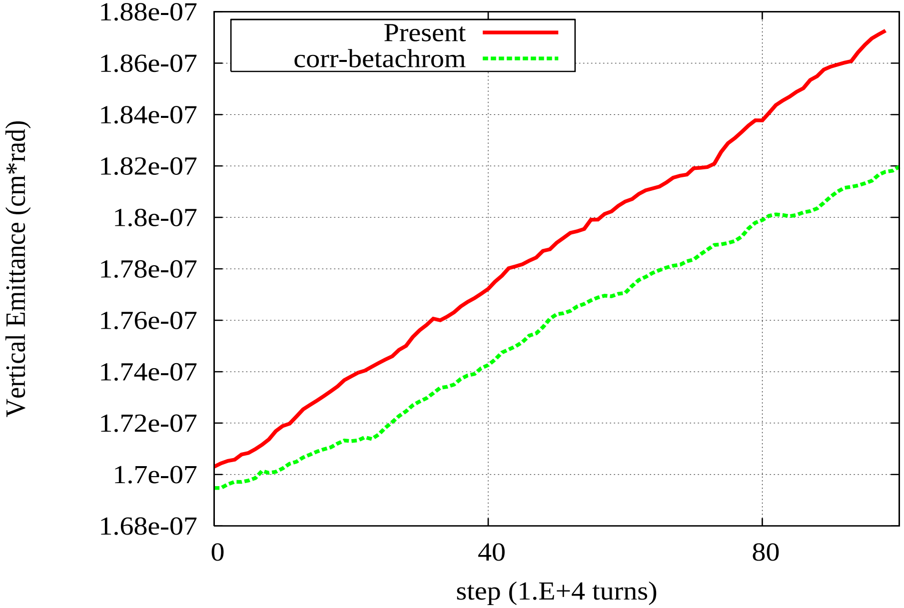


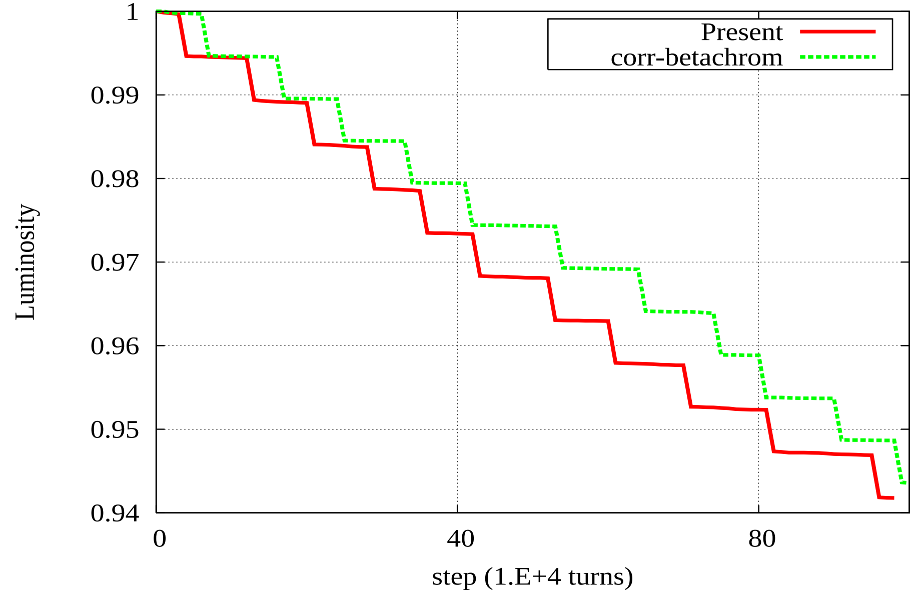


Corrected Second-Order Chromaticity – Present Optics

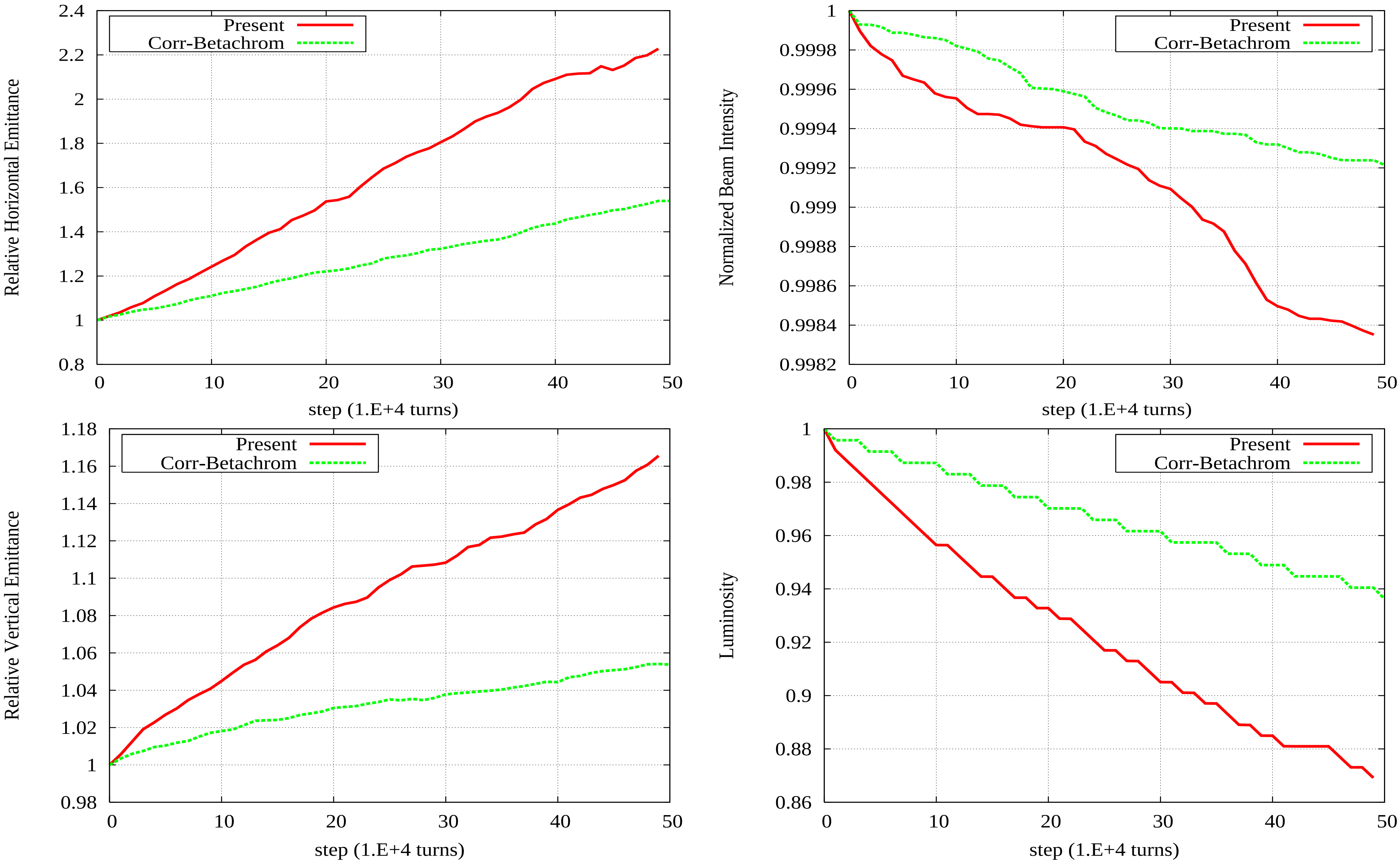






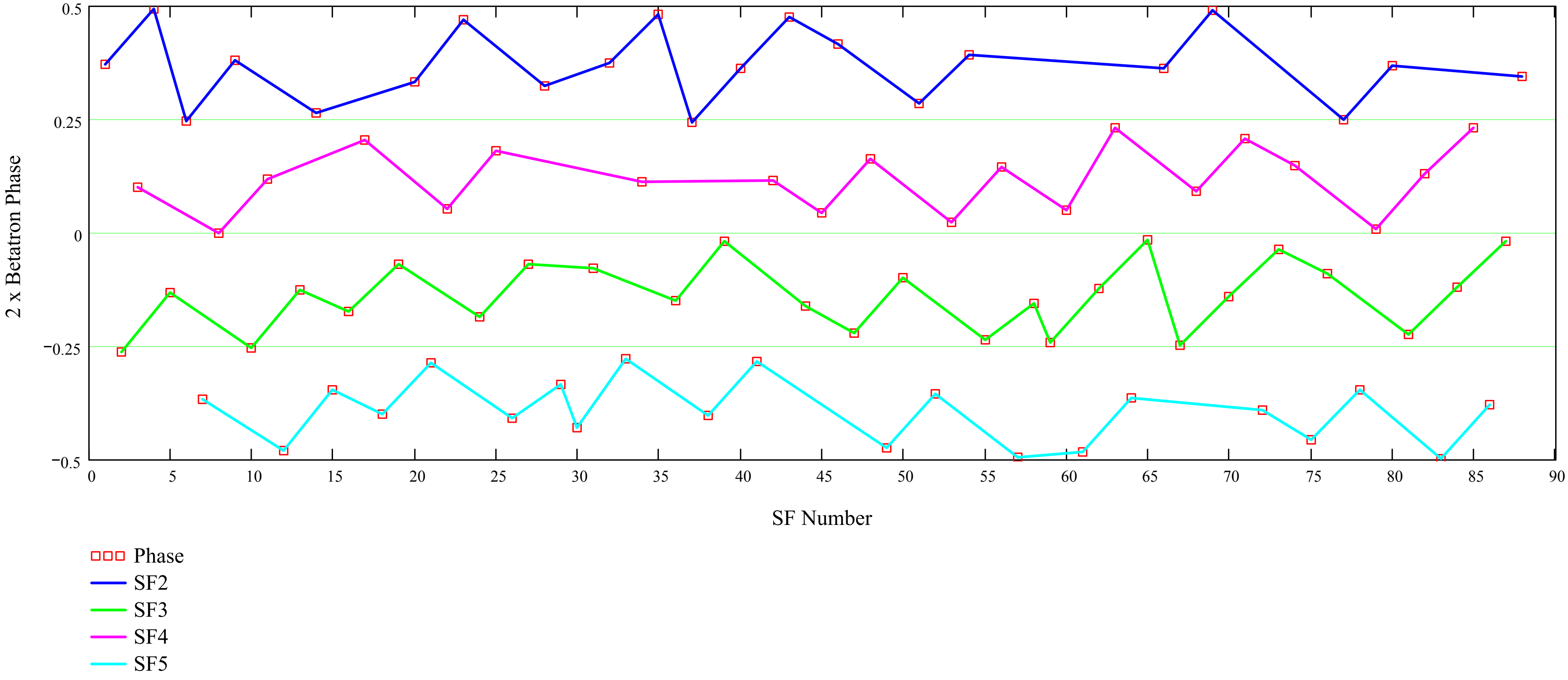


Corrected Second-Order Chromaticity – Present Optics +30% Protons



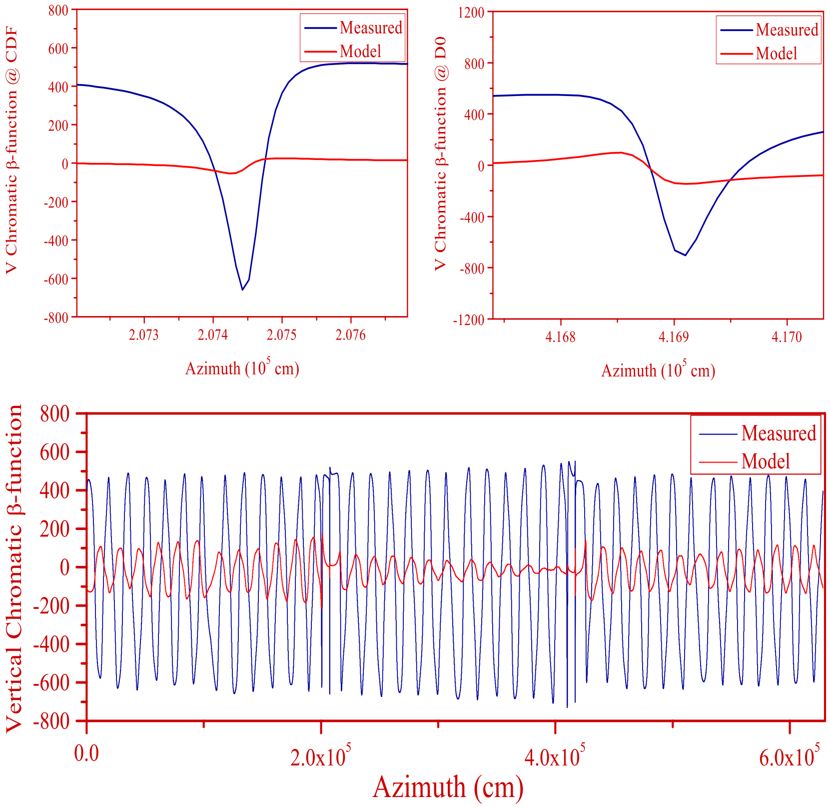
Correction of Beta Chromaticity

$$\frac{\Delta\beta_{x,y}}{\beta} = \frac{\Delta\beta_{Nat}}{\beta} + \frac{\pm 1}{2\sin(2\pi Q_{x,y})}\sum_i S_i D_{xi}\left(\beta_{x,y}\right)_i \cos\left(2\left|\varphi(s) - \varphi_{x,y_i}\right| - 2\pi Q_{x,y}\right)$$

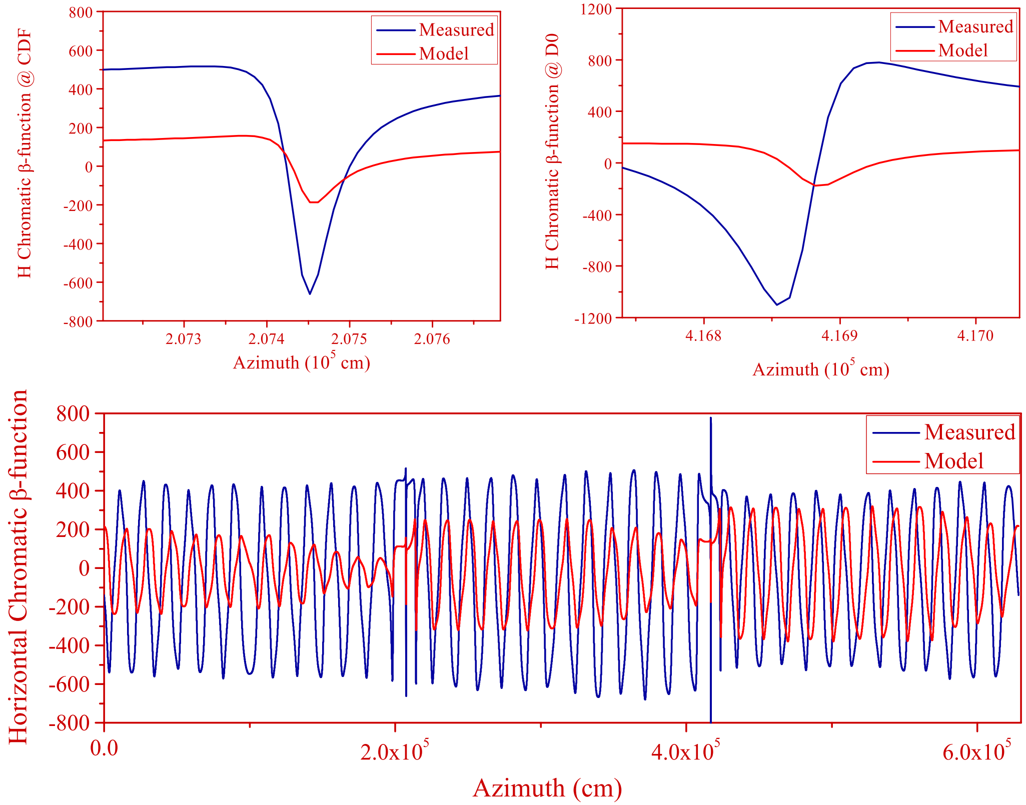


Correction of Beta Chromaticity

Version 1



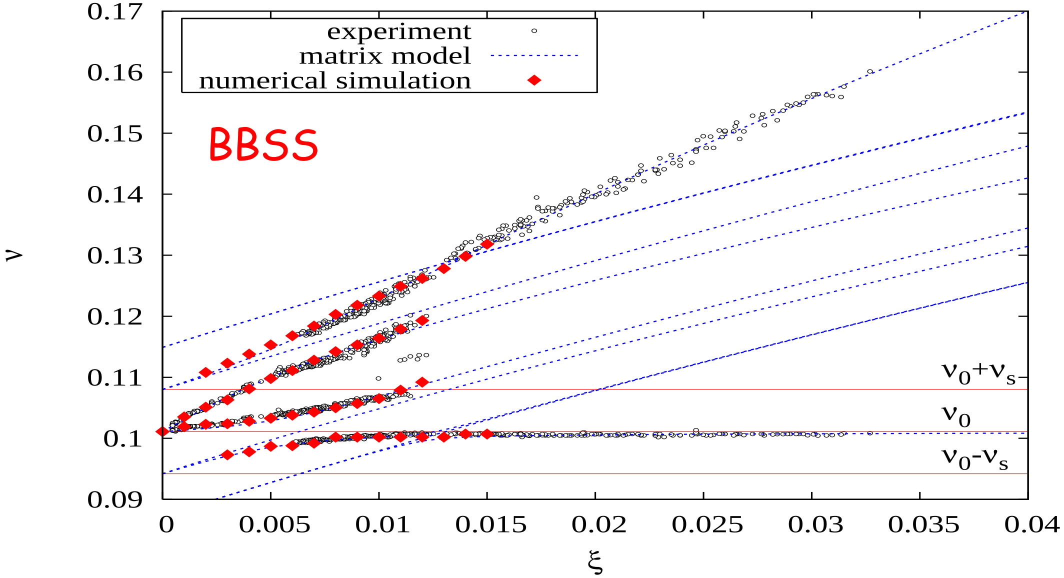
Version 3

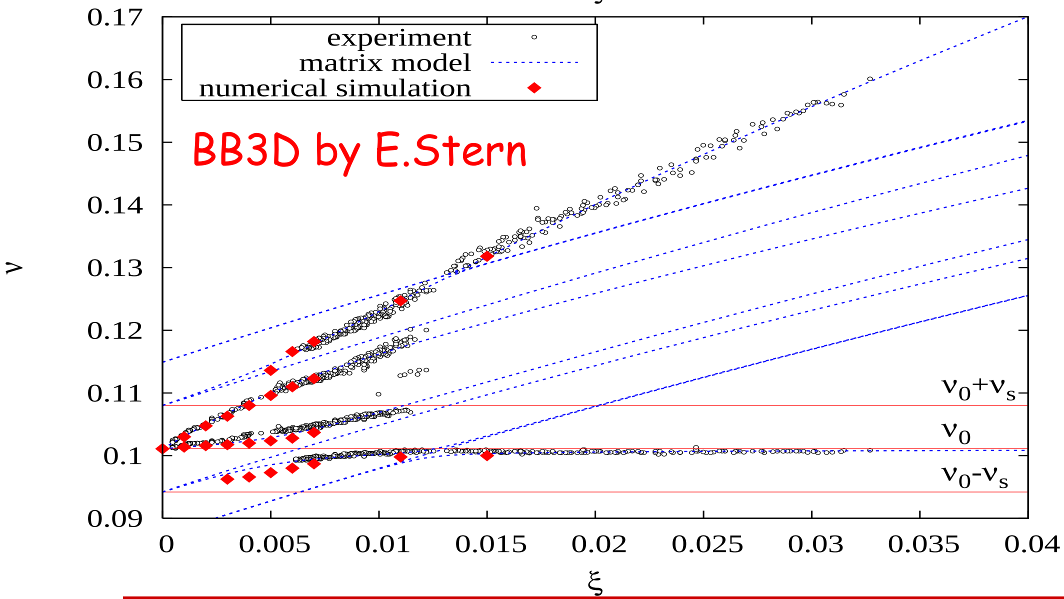


Strong-Strong Simulation

- Weak-Strong simulation addresses beam life time and emittance growth
- With increased antiproton beam intensity coherent beam-beam effects may appear
- Requirements for Strong-Strong Beam-Beam simulation
  - Multibunch, each bunch has full pattern of collisions (72 IP's)
  - Machine impedance included
- Work is underway to modify existing programs
  - BeamBeam3D (LBL) – 3D PIC (Ji Qiang et al., J. Comp. Phys. 163, 434-451 (2000)) – CD/ Part of Fermilab SciDAC
  - BBSS (KEK) – 3D PIC (K. Ohmi, Phys. Rev. E 62, 7287 (2000)) – KEK/BINP/Fermilab
- Benchmarking the codes

Strong-Strong Code Comparison





Not the Tevatron case!

Synchrobetatron beam-beam modes can be excited in a model experiment*

Data taken at VEPP-2M e+e- collider

Good test for a 3D code

* E.Perevedentsev, A.Valishev, Phys. Rev. ST Accel. Beams 4 (2001) 024403

Summary

- Well-developed method of optics measurement allows vast improvements in the machine.
- Results of Weak-Strong simulations are in qualitative agreement with observations.
- Based on the modeling results the following changes are being studied and implemented as a way to allow higher beam intensities
  - Introduction of chromaticity difference for protons and antiprotons
  - Correction of beta function chromaticity
  - New betatron tune working point (either 1/2 or 2/3)
- Strong-Strong simulation is under development to study possible coherent beam-beam instabilities.

Backup Slides

Backup: RM (Differential Orbit) Measurements

- The aim is to find gradient errors utilizing the fact that quadrupoles act as dipole correctors with off-center orbit

$$\theta = Kl \cdot x$$

- Initially, closed orbit is excited using a single dipole corrector

$$x_i(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi\nu)}\theta\sqrt{\beta(s_0)}\cos\left(\left|\varphi(s)-\varphi(s_0)\right|-\pi\nu\right)$$

- The orbit distortion due to quadrupoles is given by

$$x_q(s) = \frac{\sqrt{\beta_x(s)}}{2\sin(\pi\nu_x)}\sum_j Kl_j x_{ij}\sqrt{\beta_{xj}}\cos\left(\left|\varphi_x(s)-\varphi_{xj}\right|-\pi\nu_x\right)$$

$$y_q(s) = \frac{\sqrt{\beta_y(s)}}{2\sin(\pi\nu_y)}\sum_j SQ_j x_{ij}\sqrt{\beta_{yj}}\cos\left(\left|\varphi_y(s)-\varphi_{yj}\right|-\pi\nu_y\right)$$

- Dispersion measurement $x_d(s) = -\frac{D(s)}{\eta}\frac{\Delta f_{RF}}{f_{RF}}$

- Use BPM system to measure and record orbit differences

Backup: Parameters of the Orbit Response Matrix

- Quadrupole gradient errors
- Steering magnet calibrations
- BPM gains

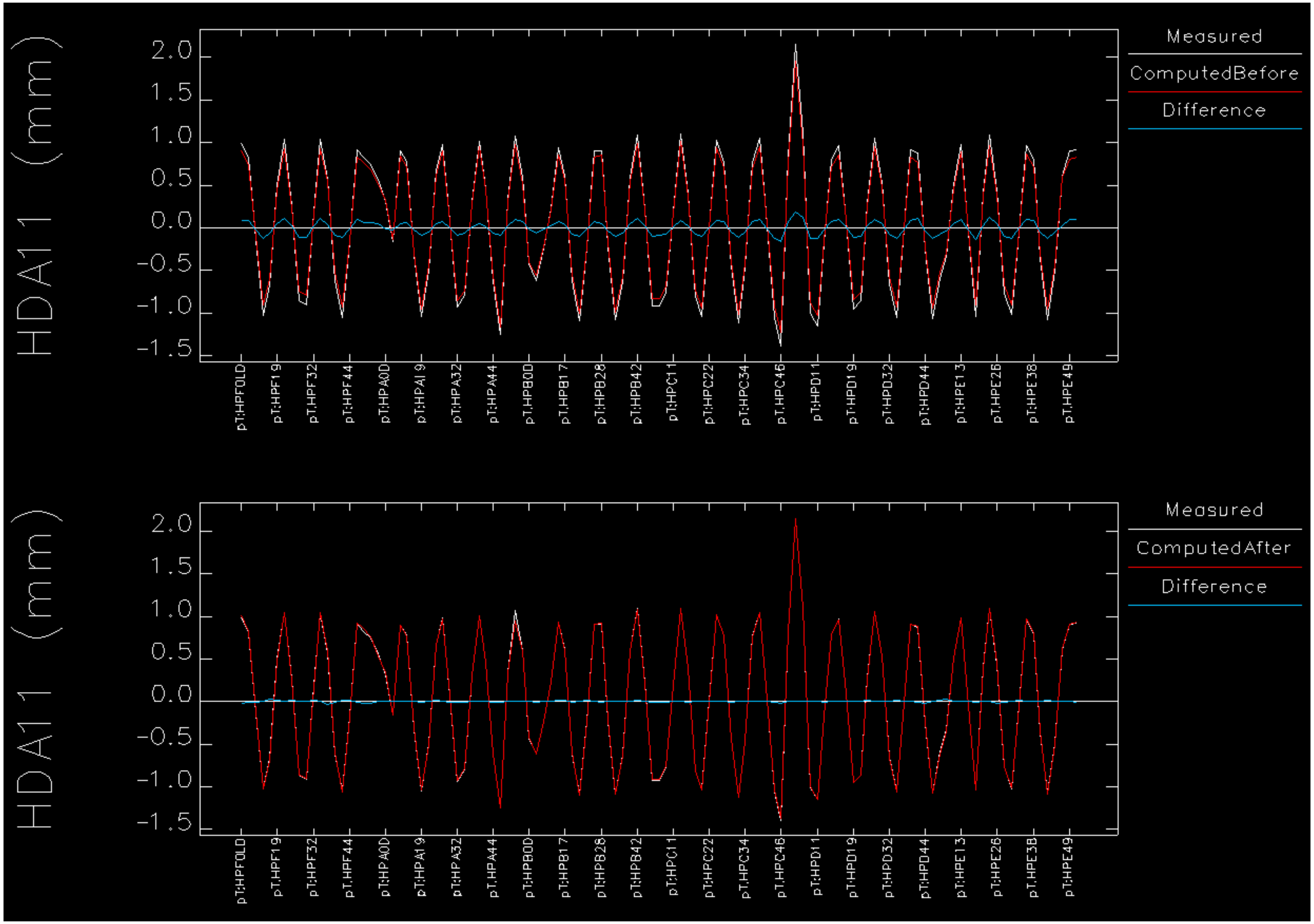
- Quadrupole tilts
- Steering magnet tilts
- BPM tilts

- Energy shift associated with steering magnet changes

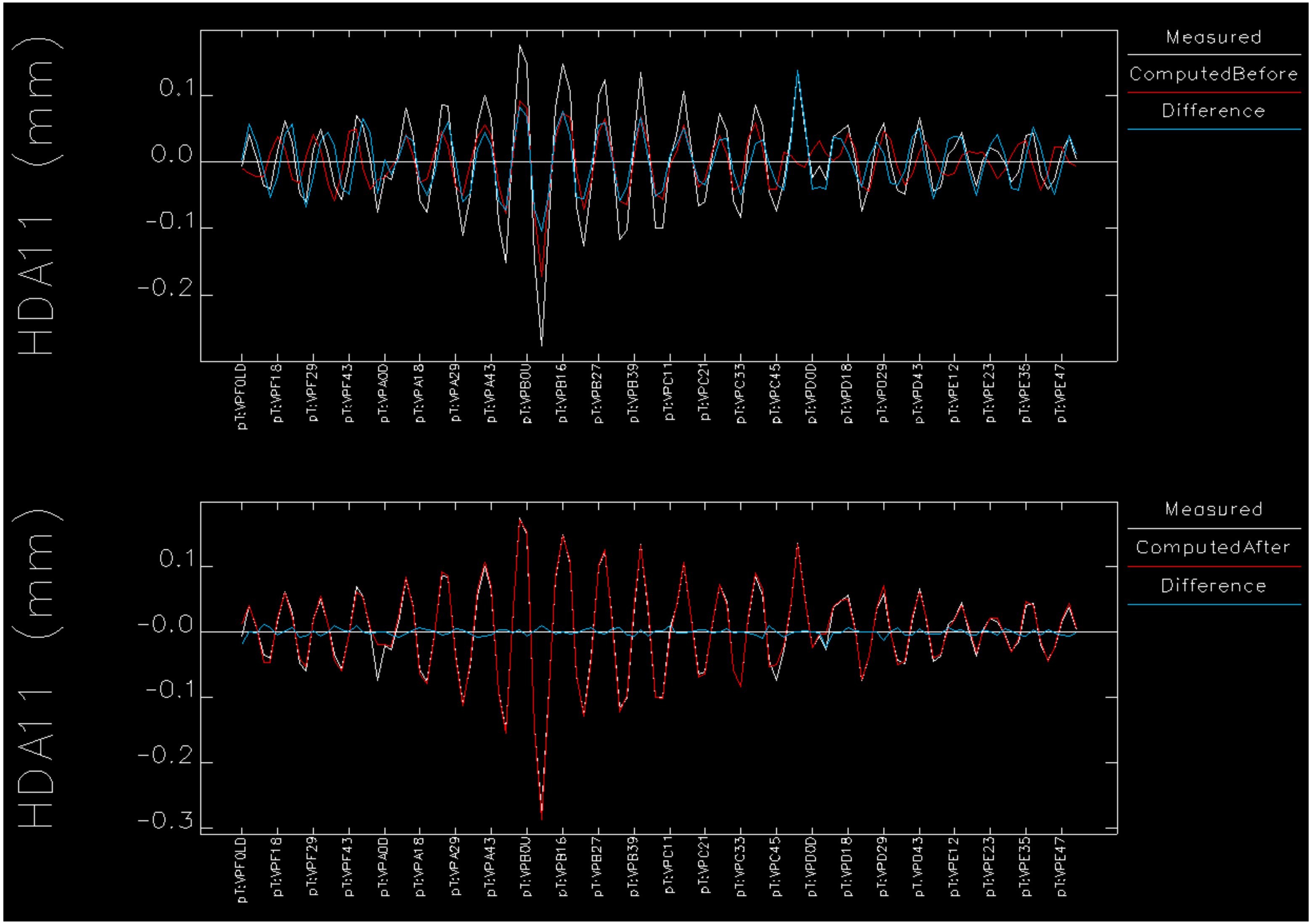
Main parameters (Quadrupole gradient errors, Steering magnet calibrations, BPM gains)

Main coupling parameters (Quadrupole tilts, Steering magnet tilts, BPM tilts)

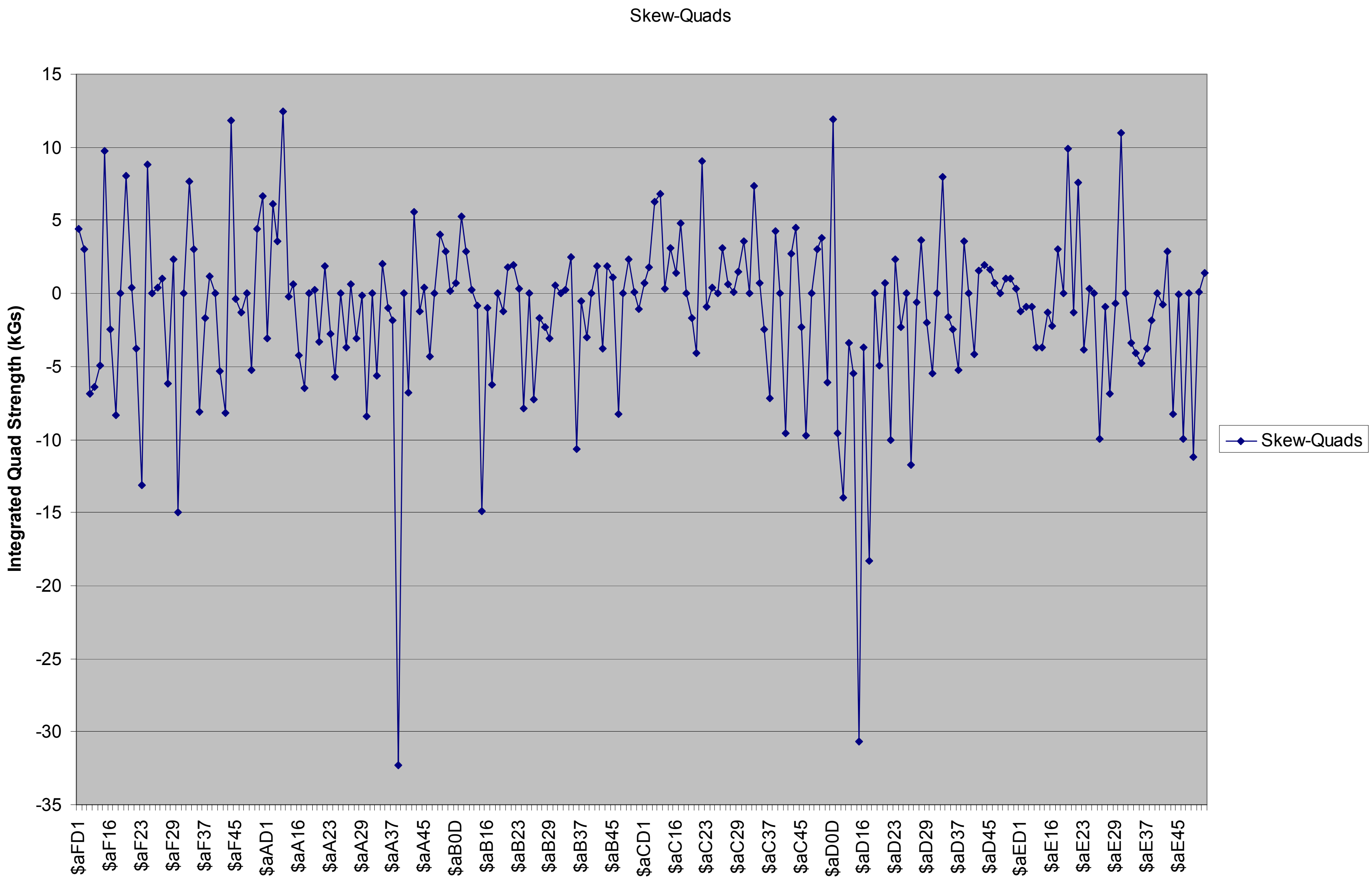
Backup: Differential Orbit. X Corr. - X plane



Backup: Differential Orbit. X Corr. – Y plane

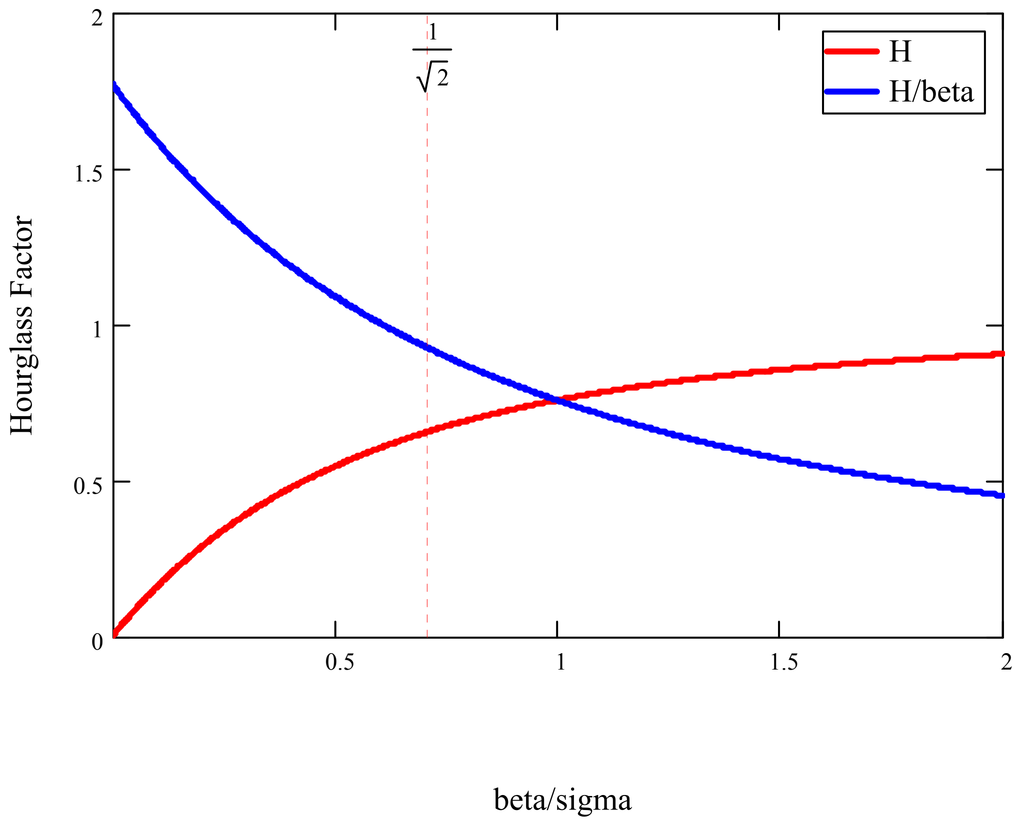


Backup: Fitted Skew-Quadrupole Errors



Backup: Lattice and Luminosity

$$L = \frac{N_p N_a f \cdot H(\beta^* / \sigma)}{2\pi \sqrt{\sigma_{p,x}^2 + \sigma_{a,x}^2} \sqrt{\sigma_{p,y}^2 + \sigma_{a,y}^2}} = \frac{N_p N_a f \cdot H(\beta^* / \sigma)}{2\pi \sqrt{\varepsilon_{p,x}\beta_{p,x} + \varepsilon_{a,x}\beta_{a,x}} \sqrt{\varepsilon_{p,y}\beta_{p,y} + \varepsilon_{a,y}\beta_{a,y}}}$$



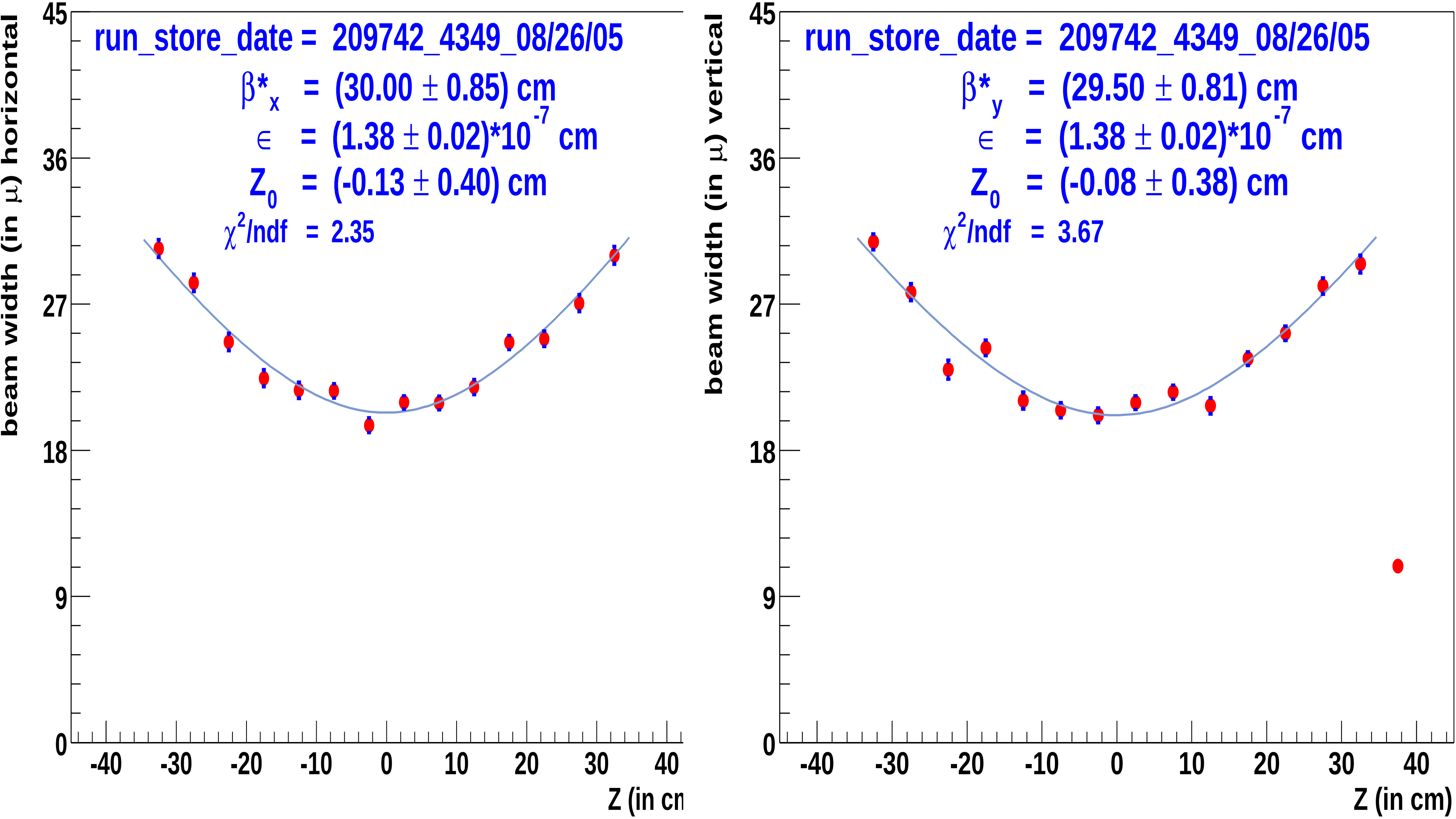
$$\rightarrow \frac{N_p N_a f \cdot H(\beta^* / \sigma)}{2\pi(\varepsilon_p \beta_p + \varepsilon_a \beta_a)}$$

$$\rightarrow \frac{N_p N_a f}{4\pi\varepsilon} \frac{H(\beta^* / \sigma)}{\beta^*}$$

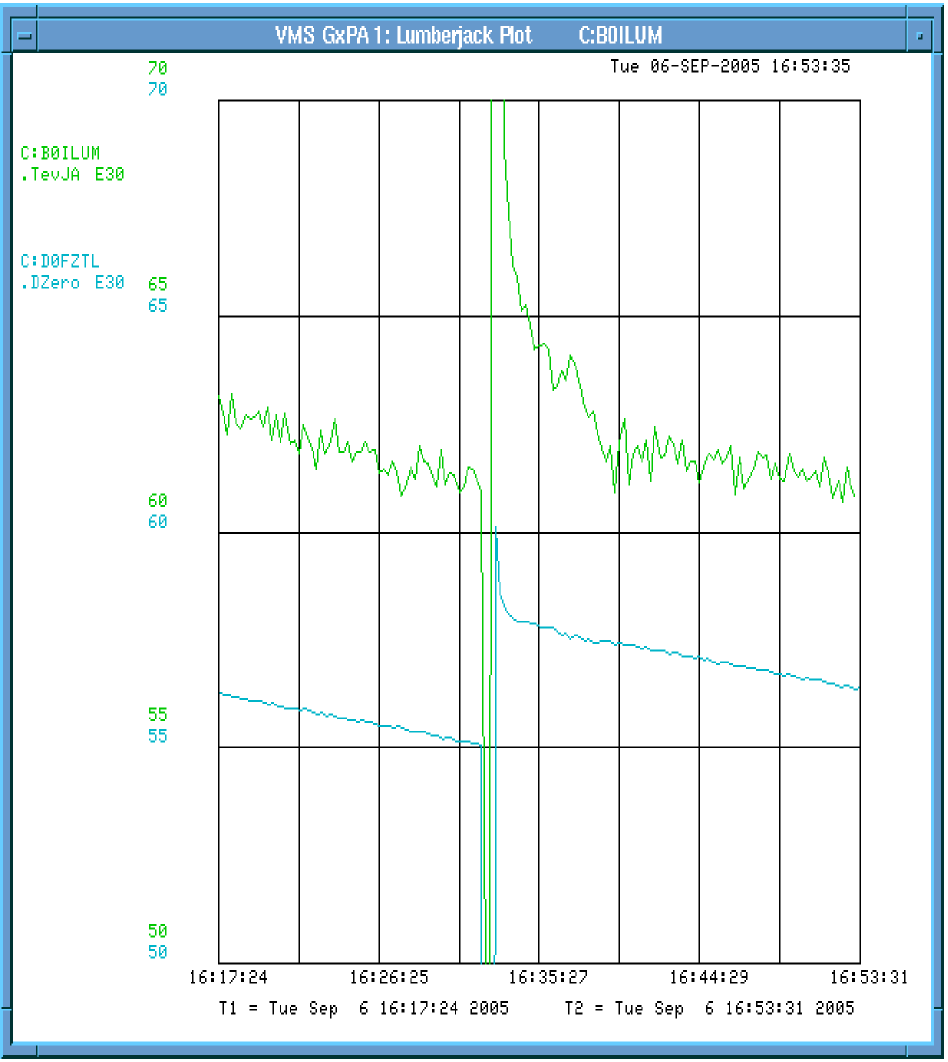
$$\beta(z) = \beta^* + z^2 / \beta^*$$

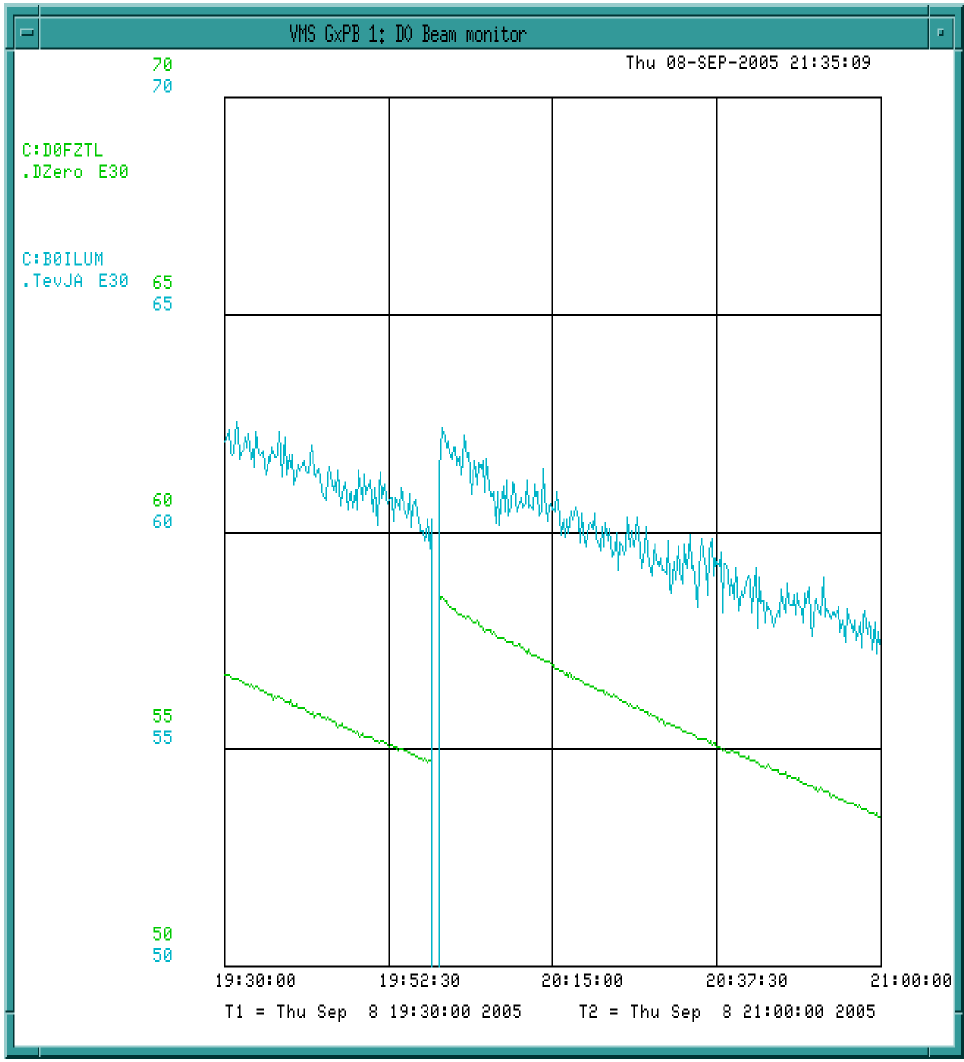
Beta* 35cm -> 28cm
gain is 11% not 25%!

D0 Measurement of beta* in 8/26 EOS (Michele Weber) 28cm beta* optics

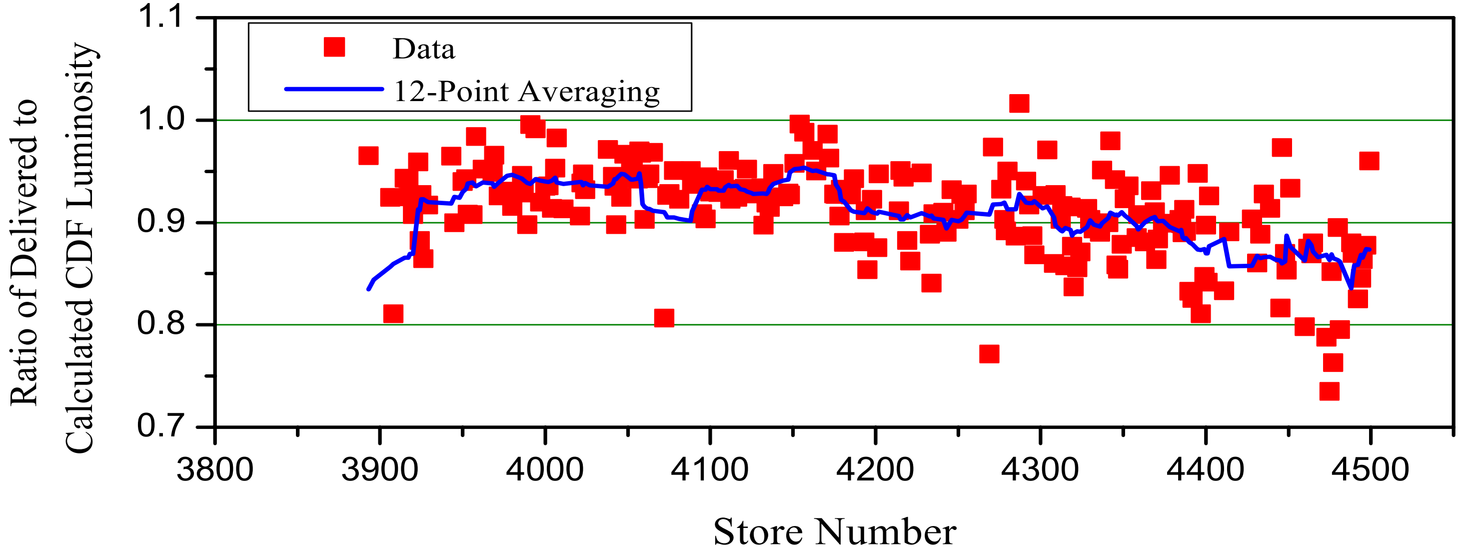


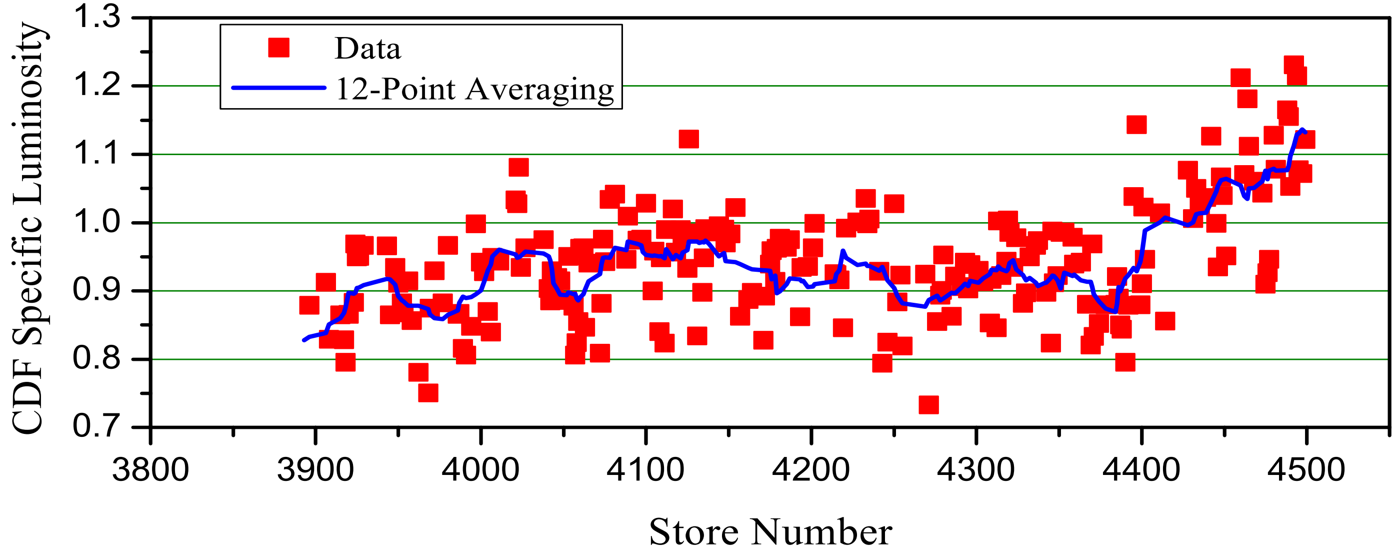
Backup: 28cm beta* End of Store Studies 9/6 and 9/8



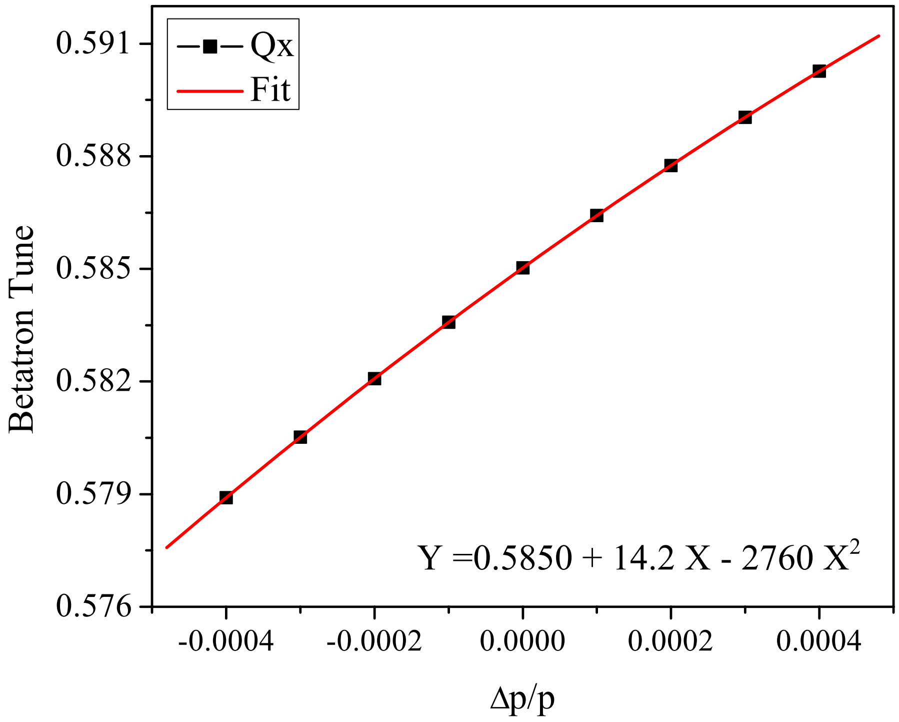


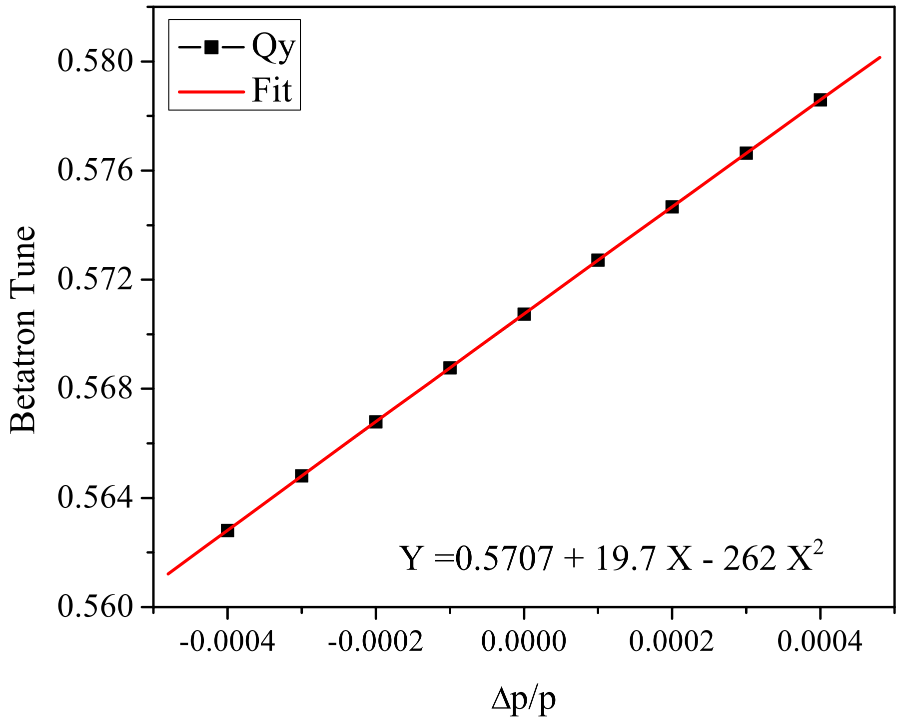
Effect of the New Optics on Luminosity





Backup: Tune Chromaticity – Corrected





Backup: Sextupole Resonance Driving Term V3

$$A3F2C := \sum_{k=0}^{NF2-1} \left[\frac{SF\cdot F2}{BR} \cdot \left(\beta xf_{nsf2_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf2_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{\left(nsf2_k-1\right)}}{C0} \right]\right] \qquad A3F2C = -20.673$$

$$A3F3C := \sum_{k=0}^{NF3-1} \left[\frac{SF\cdot F2}{BR} \cdot \left(\beta xf_{nsf3_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf3_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf3_k-1}}{C0} \right]\right] \qquad A3F3C = 17.005$$

$$A3F2S := \sum_{k=0}^{NF2-1} \left[\frac{SF\cdot F2}{BR} \cdot \left(\beta xf_{nsf2_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf2_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf2_k-1}}{C0} \right]\right] \qquad A3F2S = -5.475$$

$$A3F3S := \sum_{k=0}^{NF3-1} \left[\frac{SF\cdot F2}{BR} \cdot \left(\beta xf_{nsf3_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf3_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf3_k-1}}{C0} \right]\right] \qquad A3F3S = 3.931$$

$$A3F4C := \sum_{k=0}^{NF4-1} \left[\frac{SF\cdot F4}{BR} \cdot \left(\beta xf_{nsf4_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf4_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf4_k-1}}{C0} \right]\right] \qquad A3F4C = -3.834$$

$$A3F5C := \sum_{k=0}^{NF5-1} \left[\frac{-SF\cdot F4}{BR} \cdot \left(\beta xf_{nsf5_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf5_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf5_k-1}}{C0} \right]\right] \qquad A3F5C = 1.753$$

$$A3F4S := \sum_{k=0}^{NF4-1} \left[\frac{SF\cdot F4}{BR} \cdot \left(\beta xf_{nsf4_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf4_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf4_k-1}}{C0} \right]\right] \qquad A3F4S = 0.531$$

$$A3F5S := \sum_{k=0}^{NF5-1} \left[\frac{-SF\cdot F4}{BR} \cdot \left(\beta xf_{nsf5_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf5_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf5_k-1}}{C0} \right]\right] \qquad A3F5S = -5.532$$

$$A3F6C := \sum_{k=0}^{NF6-1} \left[\frac{SF\cdot F6}{BR} \cdot \left(\beta xf_{nsf6_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf6_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf6_k-1}}{C0} \right]\right] \qquad A3F6C = -0.867$$

$$A3F7C := \sum_{k=0}^{NF7-1} \left[\frac{-SF\cdot F6}{BR} \cdot \left(\beta xf_{nsf7_k-1}\right)^{\frac{3}{2}} \cdot \cos\left[6\cdot\pi\cdot\phi xf_{nsf7_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf7_k-1}}{C0} \right]\right] \qquad A3F7C = 2.205$$

$$A3F6S := \sum_{k=0}^{NF6-1} \left[\frac{SF\cdot F6}{BR} \cdot \left(\beta xf_{nsf6_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf6_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf6_k-1}}{C0} \right]\right] \qquad A3F6S = 2.739$$

$$A3F7S := \sum_{k=0}^{NF7-1} \left[\frac{-SF\cdot F6}{BR} \cdot \left(\beta xf_{nsf7_k-1}\right)^{\frac{3}{2}} \cdot \sin\left[6\cdot\pi\cdot\phi xf_{nsf7_k-1} - 2\cdot\pi\cdot(3Qx - m)\cdot\frac{sf_{nsf7_k-1}}{C0} \right]\right] \qquad A3F7S = 5.628$$

Backup: Beam-Beam Tune Shift vs. Q