NSLS-II Lattice Design and Optimization

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Acknowledgement:

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Outline

1. Constraints for the linear lattice and flexibility
2. Effects of magnetic multipole field errors
3. Requirements for the nonlinear lattice
4. Introduction of a third chromatic knob
5. Integration of the damping wigglers
6. Dynamic aperture optimization with errors

Tools:

Elegant + SDDS + tcl/tk

Main Design Parameters

Beam Energy	3 GeV	Circumference	792 m
Circulating current	500 mA	RF buckets	1320 (500 MHz)
Lifetime	3 hours	Beam stability	10% beam size
Top-off stability	<1%	Cells:	30 DBA
Straight length	9.3/6.6 m		

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http://www.bnl.gov/nsls2/webcam/, Sep 06, 2009, 17.00.00

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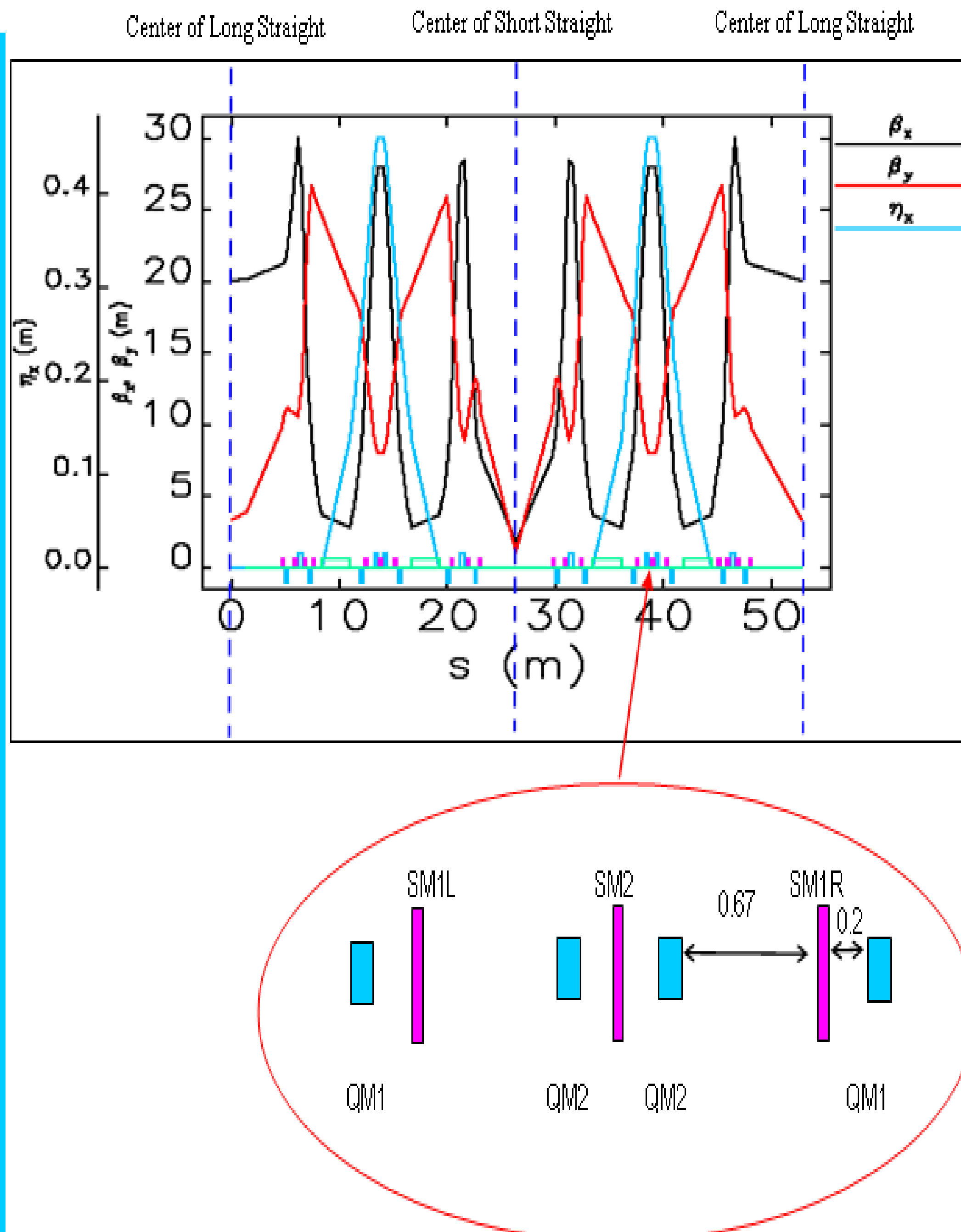
Linear Lattice and constraints

Linear Lattice properties:

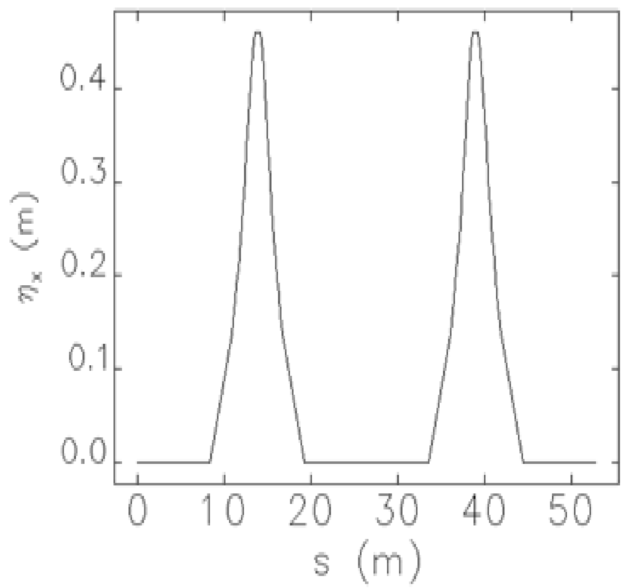
- 30 Strict double bend achromat
- Alternating long and short straight
- 8 quadrupole families:
  Triplet + two doublets + triplet
- 10 sextupole families
  3 chromatic, 7 geometric
- Chromaticity per cell: -3.4/-1.4
- ν_x / ν_y: 33.?? / 16.??
- β_x / β_y: 20/4.5, 1.2/1
- Three pole wiggler
- Magnet spacing: 17.5 cm
- Space for IDs: 31%



Linear Lattice design approaches

1. Large bending radius enhances the effect of the damping wigglers

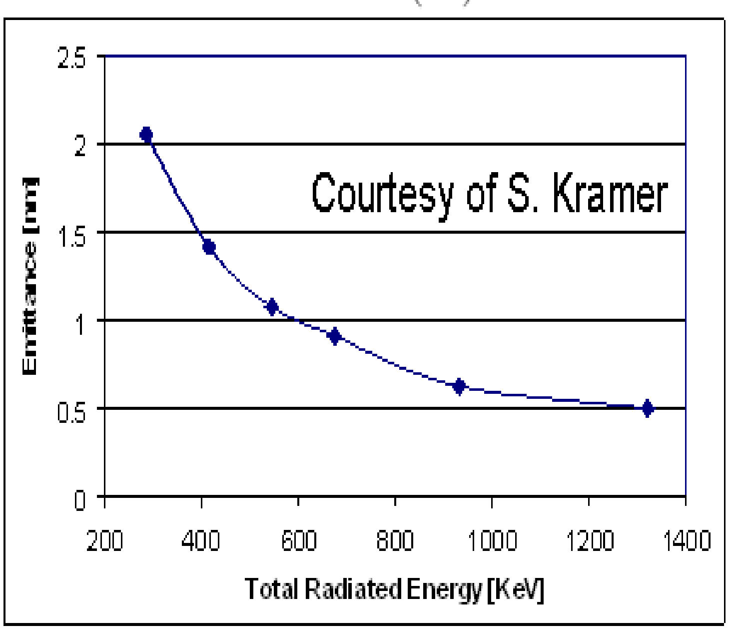
$$B = 0.4T, \rho = 25m, \begin{cases} D_x = \rho(1-\cos\theta) \\ D_x' = \sin\theta \end{cases}$$



2. Strict double-bend-acromat

Two reasons NSLS-II is sensitive to the residual dispersion:

- 1nm emittance. For β_x =2 m, η_x=4.5 cm, $\beta_x\varepsilon_x \sim (\eta_x\sigma_\delta)^2$
- Damping wiggler has quantumn excitation effect



Natural emittance with 0, 1, 2, 3, 5 and 8 DWs added

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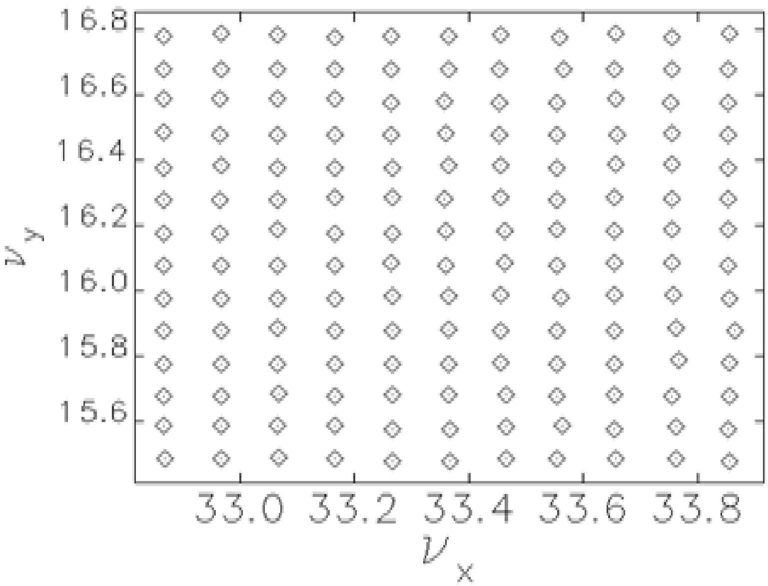
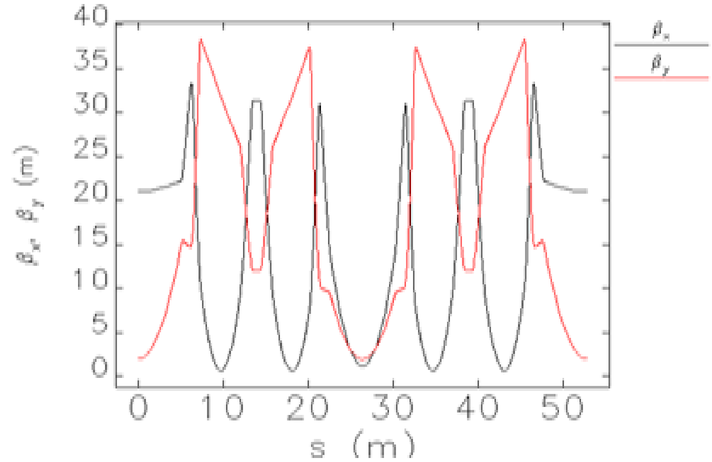
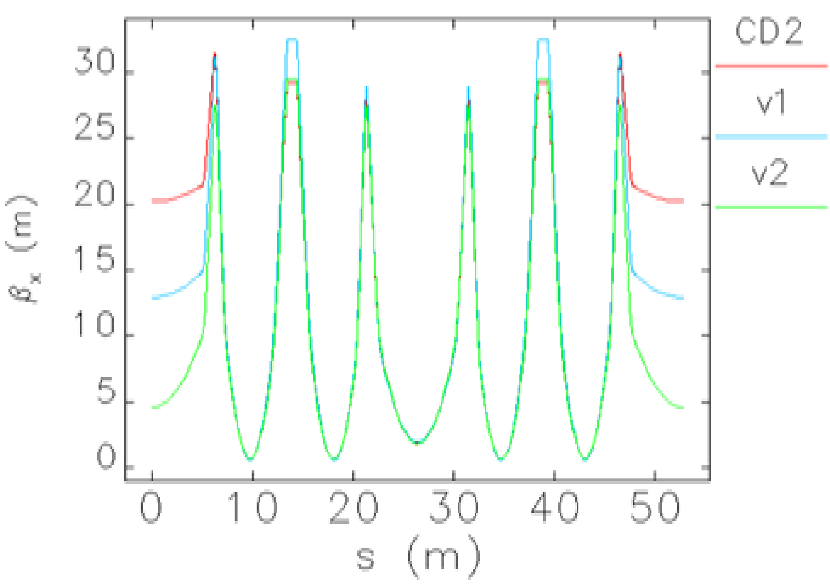
Flexibility: Quadrupole Tuning Range



Vary the tunes by ±0.5 units



Lower the betax in the short straights

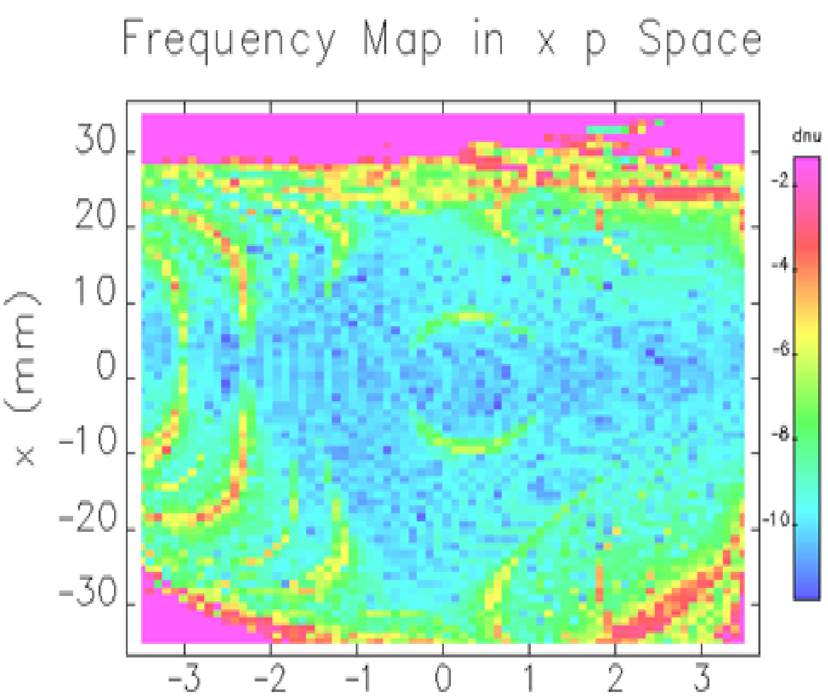


Lower the betax in the long straights

Statistics of quad strength (T/m)

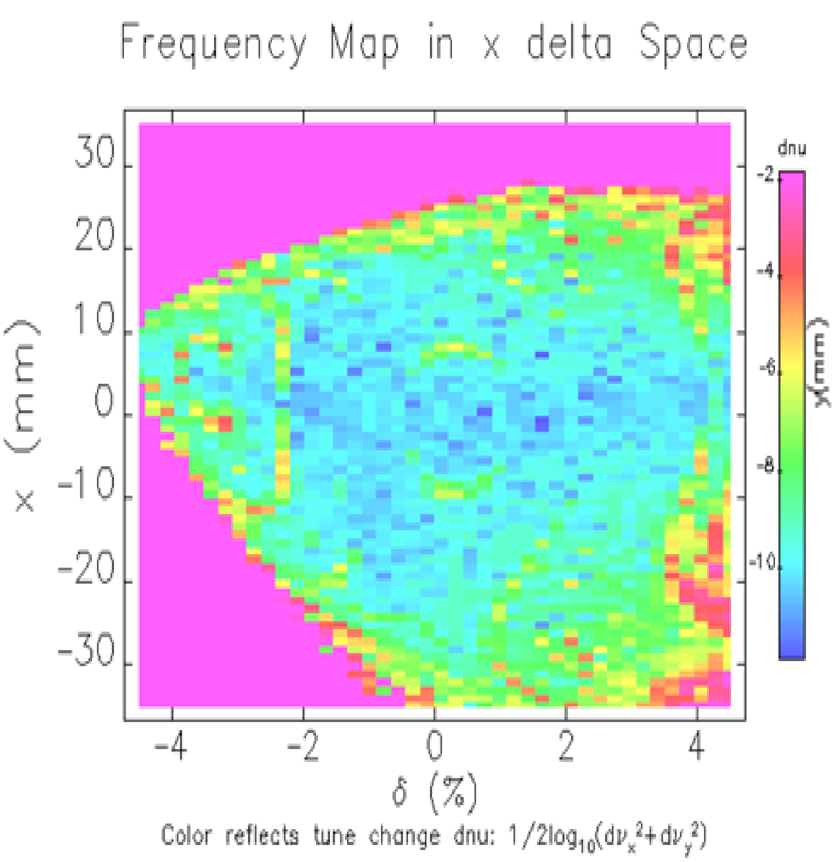
Quad	Len.	min	max	ave	Nominal
QH1	0.25	5.229	17.802	-6.996	-6.887
QH2	0.4	15.651	20.059	16.55	16.562
QH3	0.25	14.077	19.106	-18.486	-18.75
QL1	0.25	15.336	20.981	-18.123	-17.841
QL2	0.4	19.736	20.379	20.126	20.13
QL3	0.25	12.251	16.504	-15.282	-15.586
QM1	0.25	7.787	10.849	-8.497	-8.251
QM2	0.25	13.737	14.67	13.961	13.885

Effects of the Multipole Error

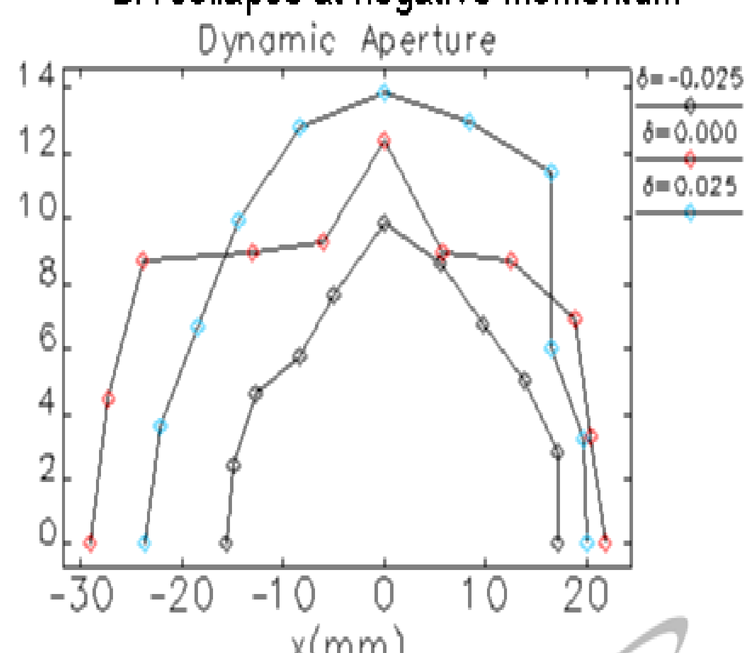


The Feb.-08 multipole components at 25 mm

Magnet Type	Magnet Aperture (mm)	Multipole Order	Relative Strength ($x10^{-4}$)
Quad	66	6	1
Quad	66	10	3
Sext	68	9	1
Sext	68	15	2



DA collapse at negative momentum



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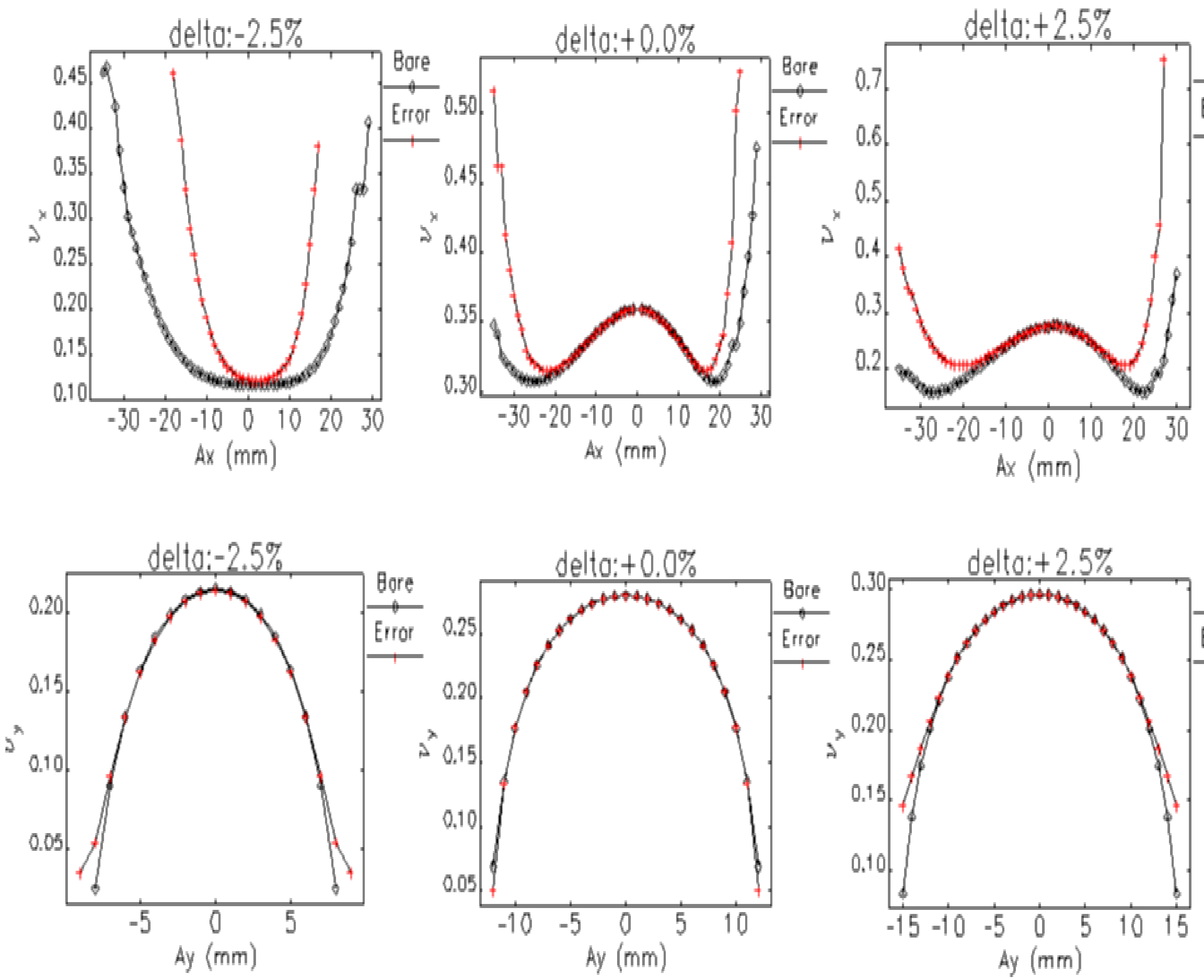
Amplitude Tune Dependence



Conclusion: Multipole terms changes the tunes at large amplitude dramatically, and makes the stable area smaller.

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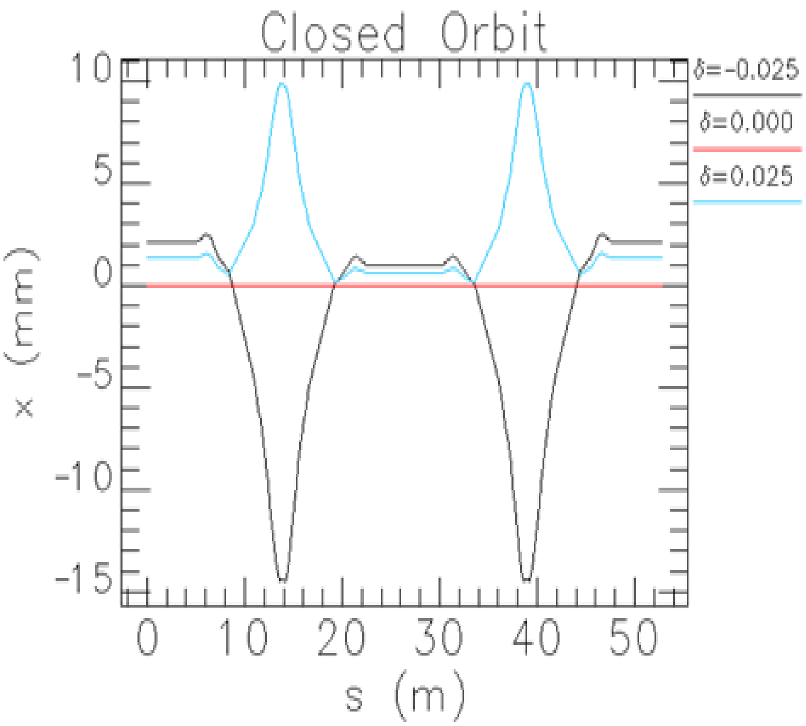
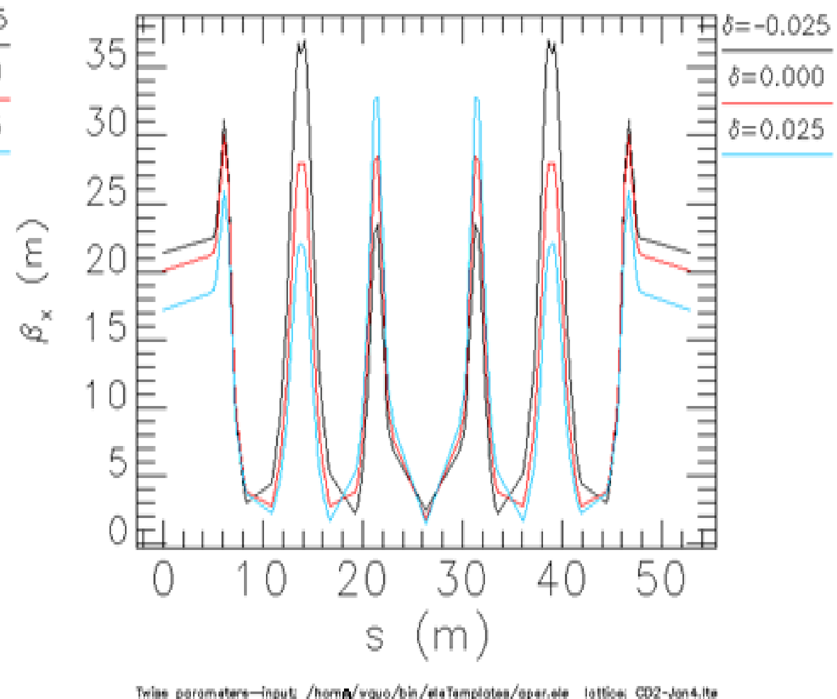
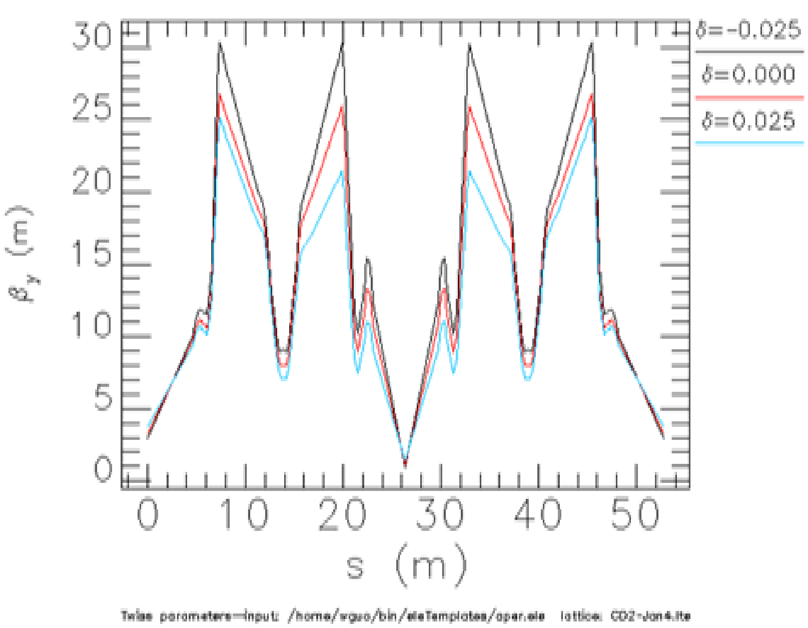
Why Negative Momentum?







$$H_{10} = -\frac{1}{B\rho}\frac{1}{10!}\frac{\partial^9 B_y}{\partial x^9}\left(x^{10} - 45x^8y^2 + \ldots\right),$$

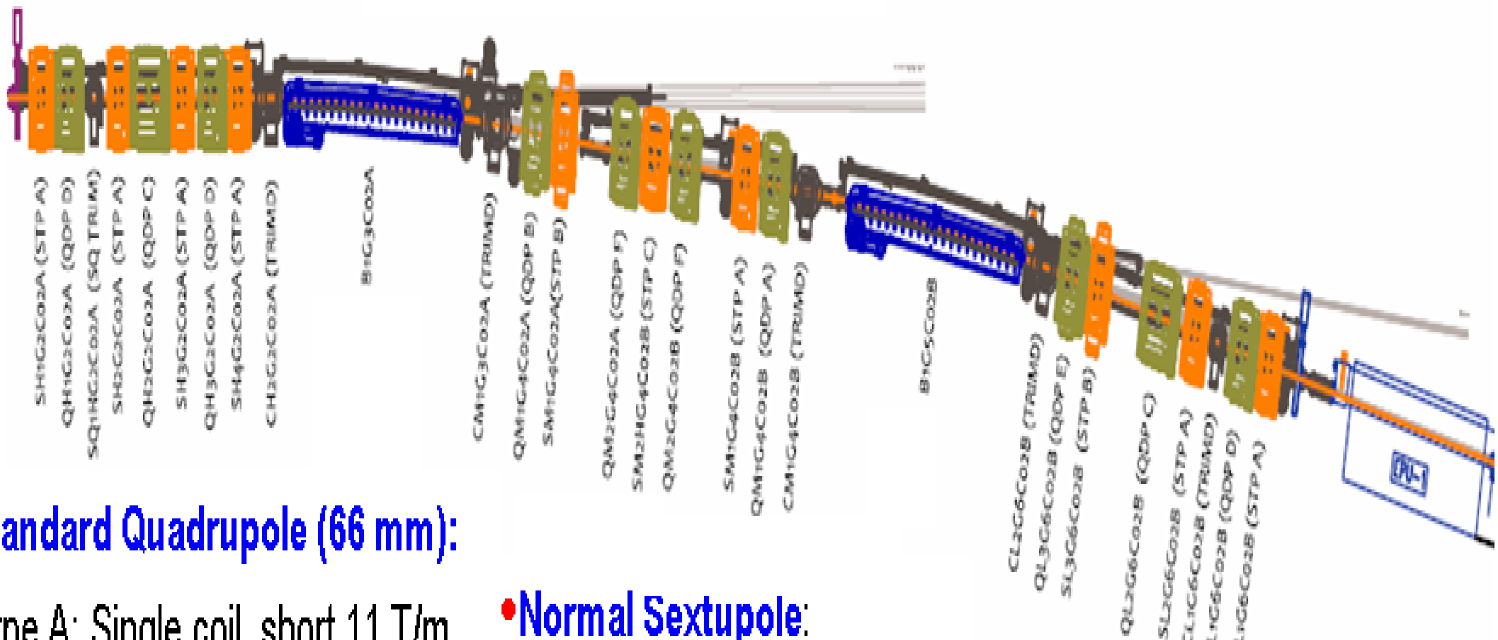
$$x = x_{c.o.} + x_\beta$$

$$\nu_{10} = \frac{1}{2\pi}\frac{\partial}{\partial J_x}\langle H_{10}\rangle$$

$$= -\frac{1}{2\pi}\frac{1}{B\rho}\frac{1}{10!}\frac{\partial^9 B_y}{\partial x^9}\times$$

$$\sum_{k=1}^{5} kC_{10}^{2k}\, x_{c.o.}^{10-2k}\,(2\beta)^k \langle \cos^{2k}\varphi\rangle J_x^{k-1},$$

Magnet Type and Strength



- **Standard Quadrupole (66 mm):**
- Type A: Single coil, short,11 T/m
- Type B: single coil, wide, 11 T/m
- Type C: Double Coil, long, 22 T/m
- Type D: Doulbe Coil, short, 22 T/m
- Type E: Double Coil, Wide, 22 T/m
- **High precision: 90 mm, 15 T/m**

- **Normal Sextupole**:
- Type A: Symmetric, 68mm
- Type B: Wide, 68 mm
- **High precision: 76 mm**
- All sextupoles have maximum strength of 400 T/m^2

Stability requirements:

Dipole: 25 ppm→ rms $\Delta p/p<5x10^{-5}$

Quadrupole: 50 ppm →

Peak to peak beta beat <0.5%

and peak to peak tune jitter $<1x10^{-3}$

Sextupole: 100ppm

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Nonlinear Constraints → 3rd Chrom. Knob

Sextupole optimization approach

Frist order chromatic terms (5)

$h_{11001} \rightarrow \xi_x^{(1)}$

$h_{00111} \rightarrow \xi_y^{(1)}$

$h_{10002} \rightarrow D^{(2)}$

$h_{20001} \rightarrow \frac{d\beta_x}{d\delta}$

$h_{00201} \rightarrow \frac{d\beta_y}{d\delta}$

Frist order geometric terms (5)

$h_{21000} \rightarrow \nu_x$

$h_{30000} \rightarrow 3\nu_x$

$h_{10110} \rightarrow \nu_x$

$h_{10020} \rightarrow \nu_x - 2\nu_y$

$h_{10200} \rightarrow \nu_x + 2\nu_y$

Amplitude tune dependence $\frac{\partial \nu_{x,y}}{\partial J_{x,y}}$

Second and third order chromaticity

$$\xi_x^{(2)} = -\frac{1}{2}\xi_x^{(1)} + \frac{1}{8\pi}\int ds\{K_2 D^{(2)}\beta_x - [K_1 - K_2 D^{(1)}]\frac{d\beta_x}{d\delta}\}$$

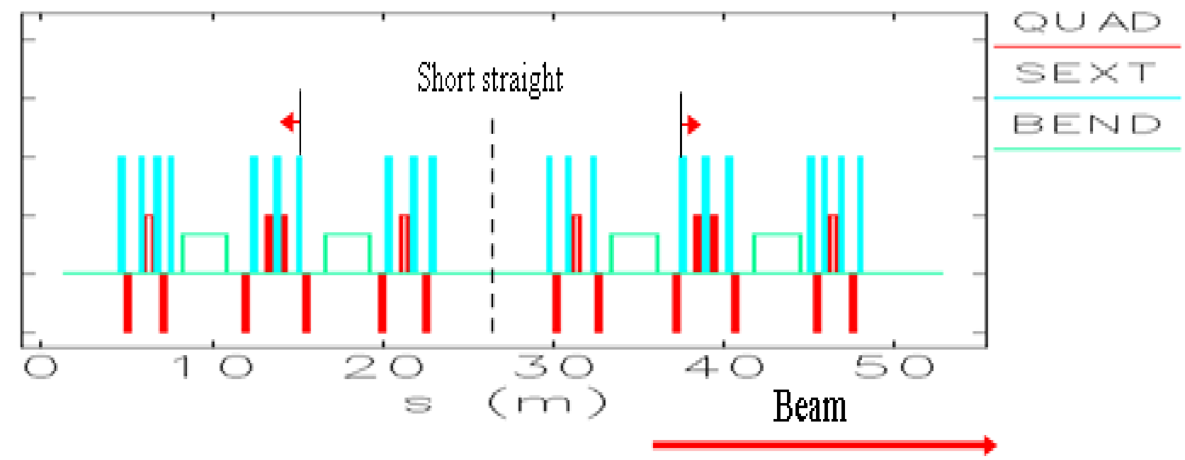
$$\xi_y^{(2)} = -\frac{1}{2}\xi_y^{(1)} - \frac{1}{8\pi}\int ds\{K_2 D^{(2)}\beta_y + [K_1 - K_2 D^{(1)}]\frac{d\beta_y}{d\delta}\}$$

Sin term and cos term:

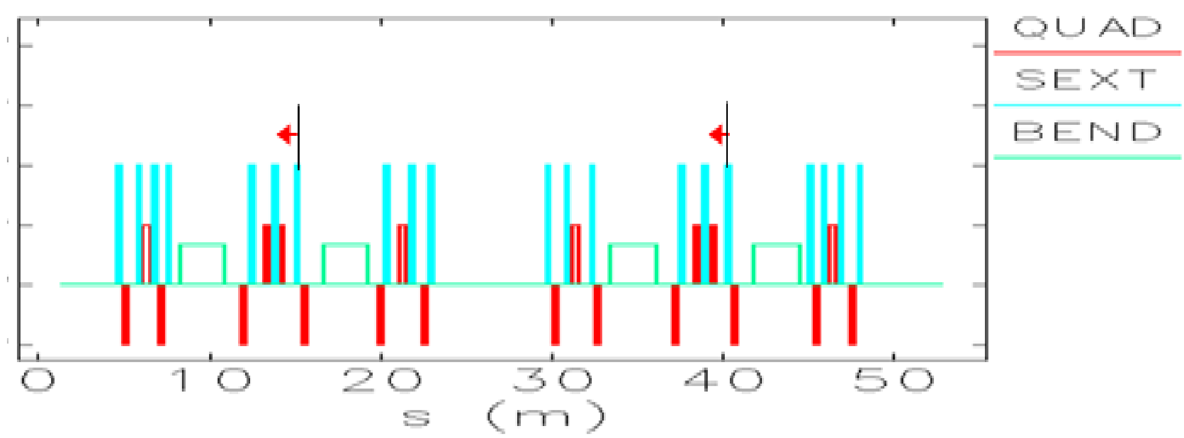
$$h_{21000} = -\frac{1}{8}\sum_{i=1}^{N}(K_2 L)\beta_{xi}^{3/2} e^{i\mu_x}$$

Reflection and Translation Symmetry

Reflection Symmetry



Translation Symmetry



Due to mechanical constraints, the upstream sextupole (SM1L) can be moved by a maximum of 10 cm. The downstream sextupole can be moved by 15 cm or 30 cm.

Effects of Adding or Moving Sextupoles

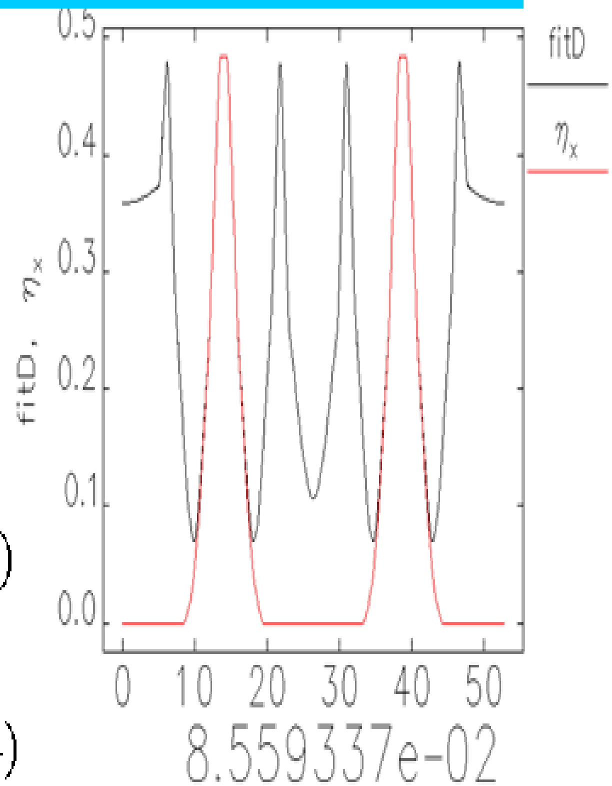
Effects: linear and nonlinear chromaticity, off-momentum beta function and closed orbit

$$\Delta \xi^{(1)}_{x,y} = \pm \int ds K_2 D^{(1)} \beta_{x,y} \qquad (1)$$

$$D^{(2)} = -D^{(1)} + \frac{\sqrt{\beta}}{2\sin(\pi\nu)} \int ds \left(K_1 - \frac{K_2}{2} D^{(1)}\right) D^{(1)} \times \sqrt{\beta}\cos(|\Delta\Psi| - \pi\nu) \sim K_2 D^{(1)} \beta_x \qquad (2)$$

$$\frac{d\beta_x}{d\delta} = \frac{\beta_x}{2\sin(2\pi\nu)} \int ds (K_1 - K_2 D^{(1)}) \beta_x \cos(2|\Delta\Psi| - 2\pi\nu) \qquad (3)$$

$$\frac{d\beta_y}{d\delta} = \frac{-\beta_y}{2\sin(2\pi\nu)} \int ds (K_1 - K_2 D^{(1)}) \beta_y \cos(2|\Delta\Psi| - 2\pi\nu) \qquad (4)$$



Dispersion fitting using $f(s) = C \bullet \sqrt{\beta_x(s)}$

Conclusion:

- The betatron phase advances in the dispersive region is small (x: ~ 10^0, y~ 20^0)
- The sextupole strength is constrained by the linear chromaticity correction
- The effects on the off-momentum closed orbit and beta functions are small

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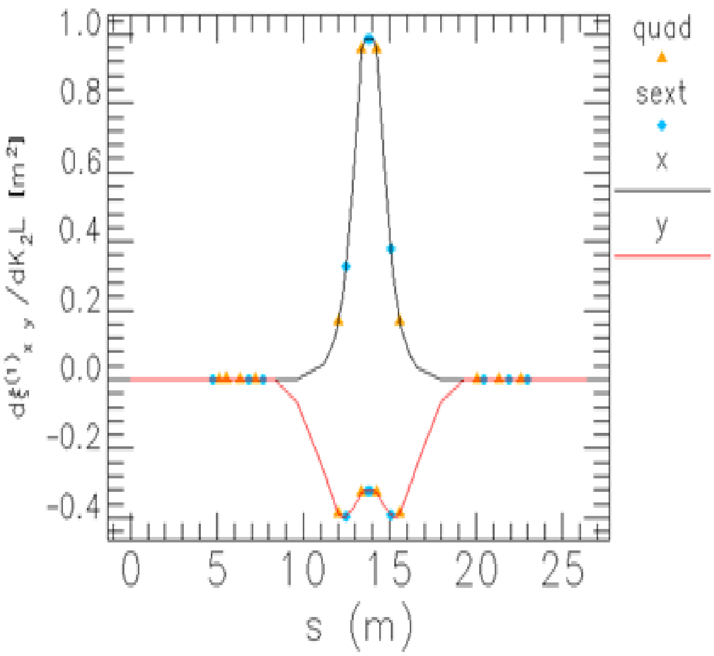
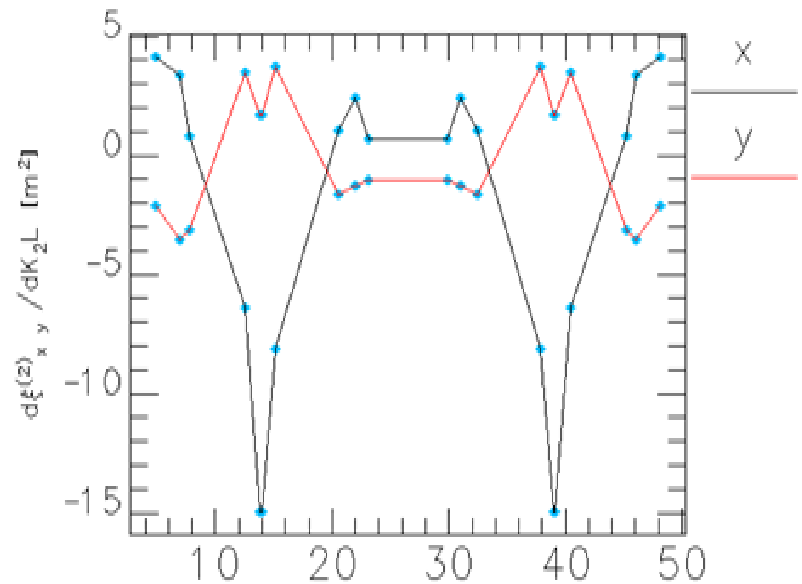
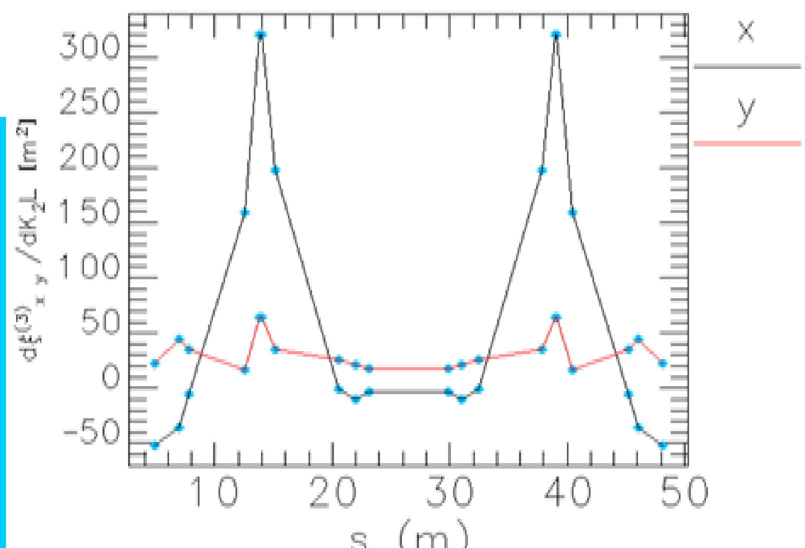
Sensitivity of Chromaticity





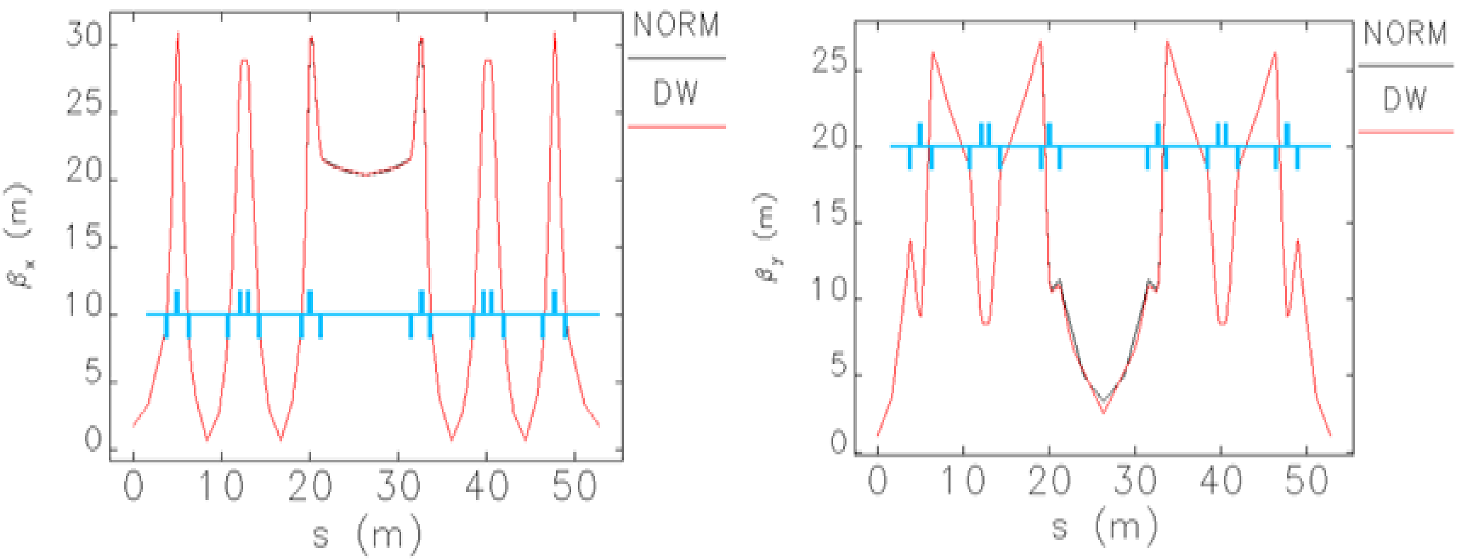


Sensitivity of the 1st (up), 2nd (upper left) and 3rd (lower left) order chromaticity per unit of sextupole strength change (ΔK2L).

The SM1 is moved 10 cm in reflection symmetry.

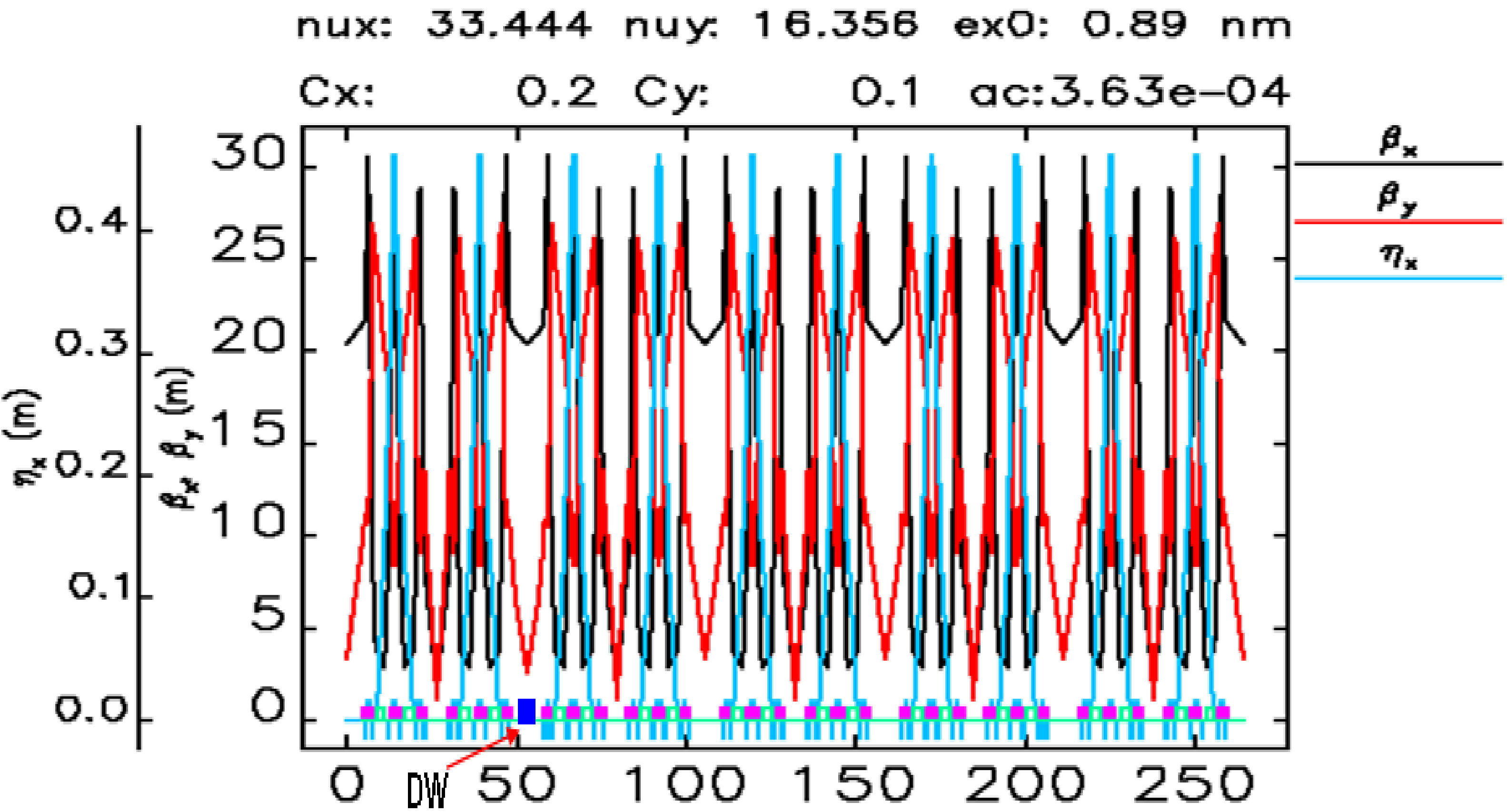
Solution: Move the downstream sextupole by 15 cm.

Integration of the Damping Wigglers



- Damping wigglers are modeled using kickmaps. Radiation integrals are derived from the simplified sinusoidal field model.
- The linear lattice is corrected using the three quadrupole families in the long straight. Symmetry in x (α_x=0), symmetry in y (α_y =0) and phase advance in x (μ_x) are restored.
- Phase advance in y is not restored due to lack of knobs but resulting deviation is tolerable.
- Quadrupole strength changes by ~ 1%, and linear chromaticity also changes slightly.
- The geometric sextupoles are powered independently in the DW straight. One-third of the ring is used for nonlinear optimization.

Dynamic Aperture Optimization with DWs



- Each Chromatic sextupole family has the same strength in 5 super-periods: 3 knobs
- Geometric sextupoles are powered independently in the DW matching section: 6+3 knobs

- Beta function

	Long St.	Short St.	DW LS
βx	20.4	1.8	20.3
βy	3.3	1.1	2.5

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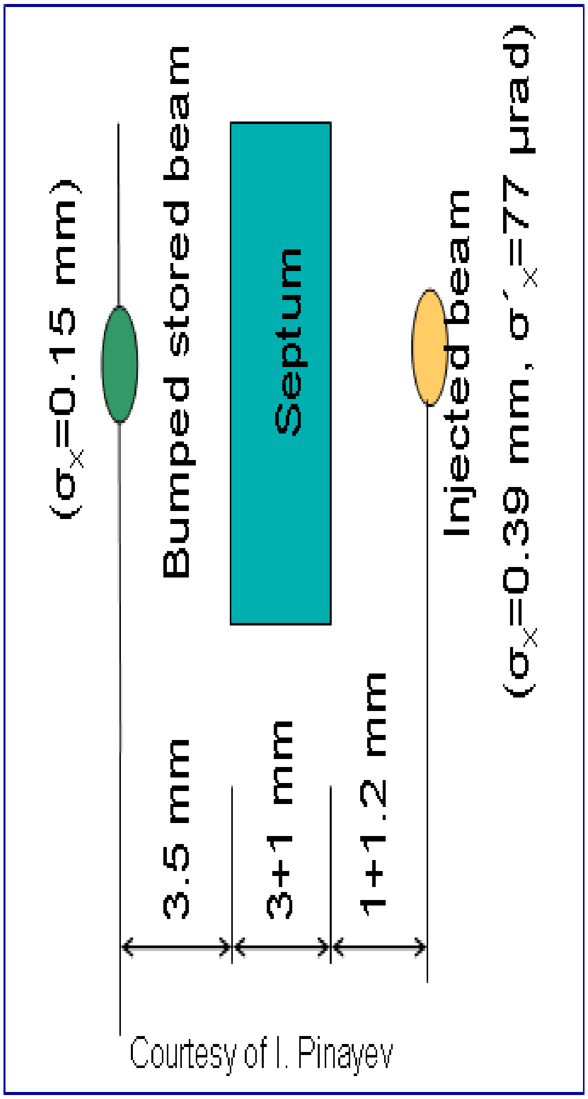
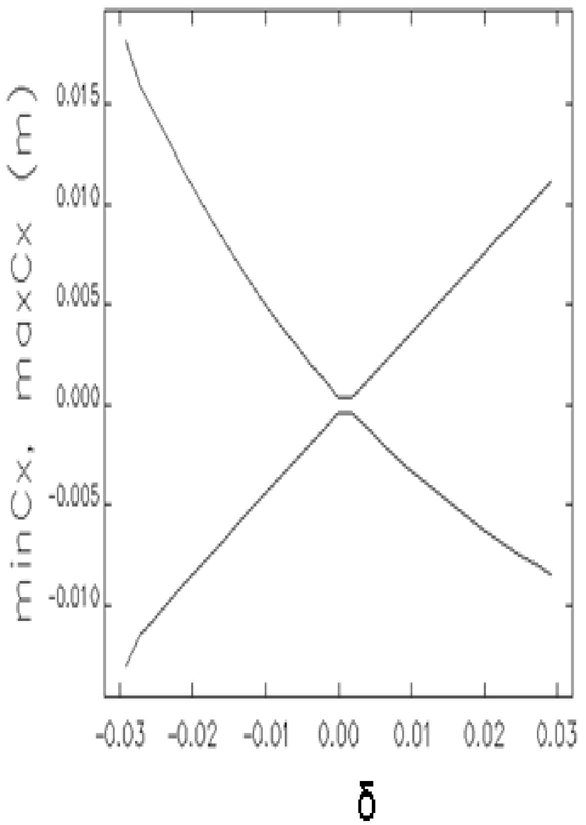
Nonlinear Design Goal





Minimum required dynamic aperture

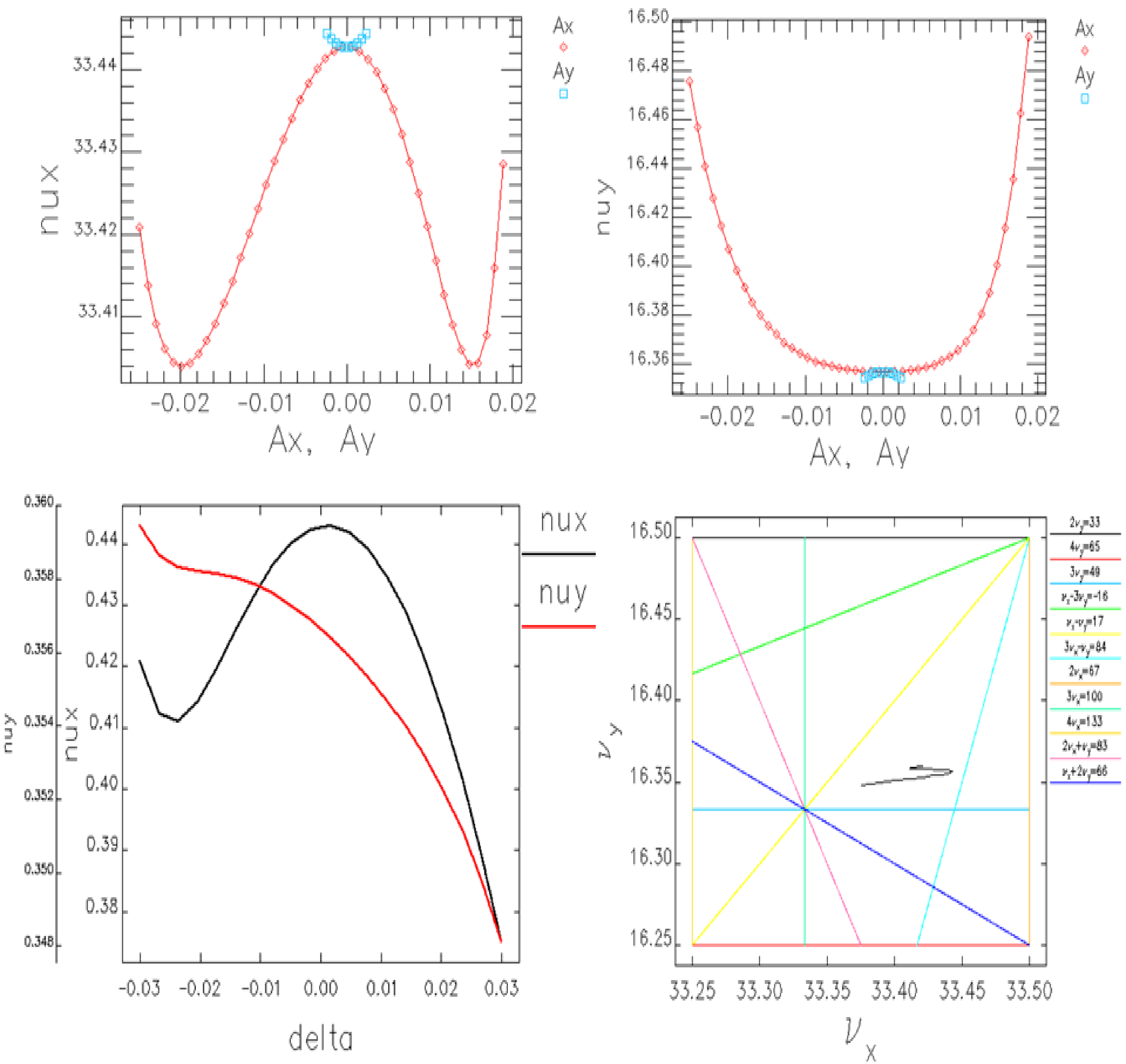
1. Sufficient dynamic aperture (>11mm) for injection

On momentum particle

2. Sufficient dynamic aperture to keep Touschek scattered particles with δ= ±2.5%

Off momentum particle

Tune variation with offsets



Misalignment Error and Closed Orbit Correction

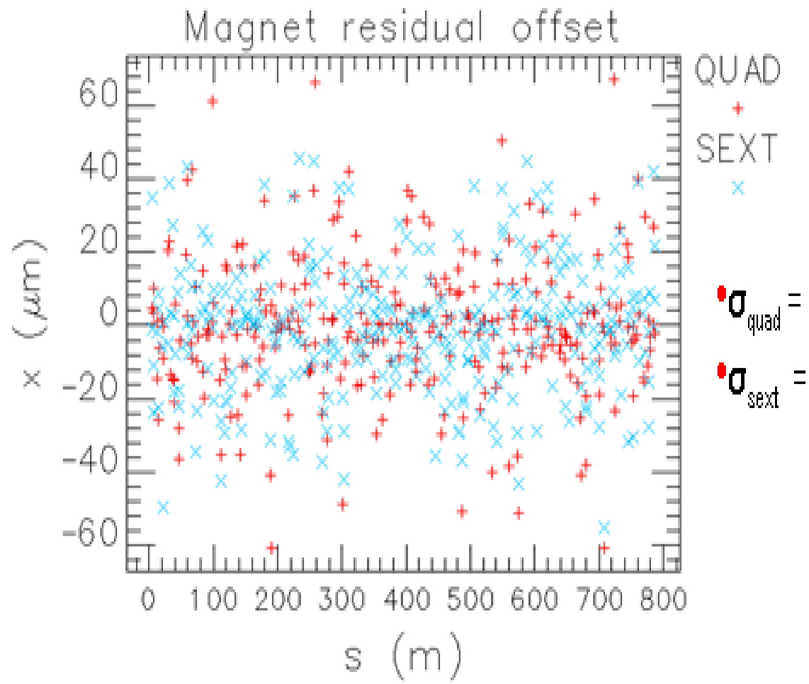
Misalignment Specification:

- Girder to girder : 100 μm
- Magnet on girder: 30 μm
- Girder roll: 0.5 mr
- Magnet roll: 0.2 mr
- Move along the beam direction: 0.5 mm

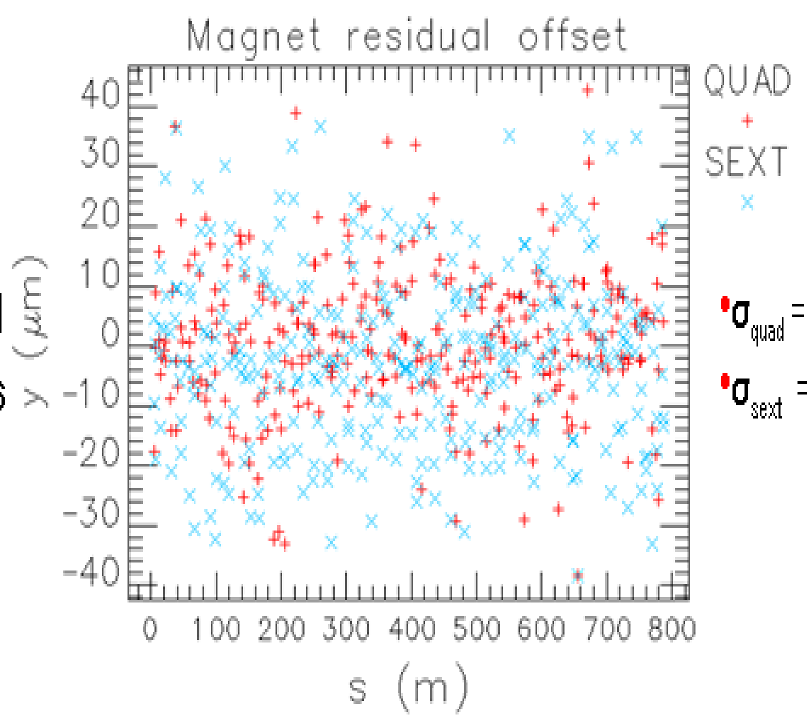
Simulation Method and Correction:

- Each Girder is modeled by two independent ends with offsets and roll errors;
- Each Magnet has its own offsets and roll;
- The total error is the summation.
- The closed orbit is corrected using a Beam-based Alignment like algorithm. Each cell has 6 correctors and 6 BPMs. Beam is centered at the BPMs.

Corrector strength: 40-50 μr (rms)



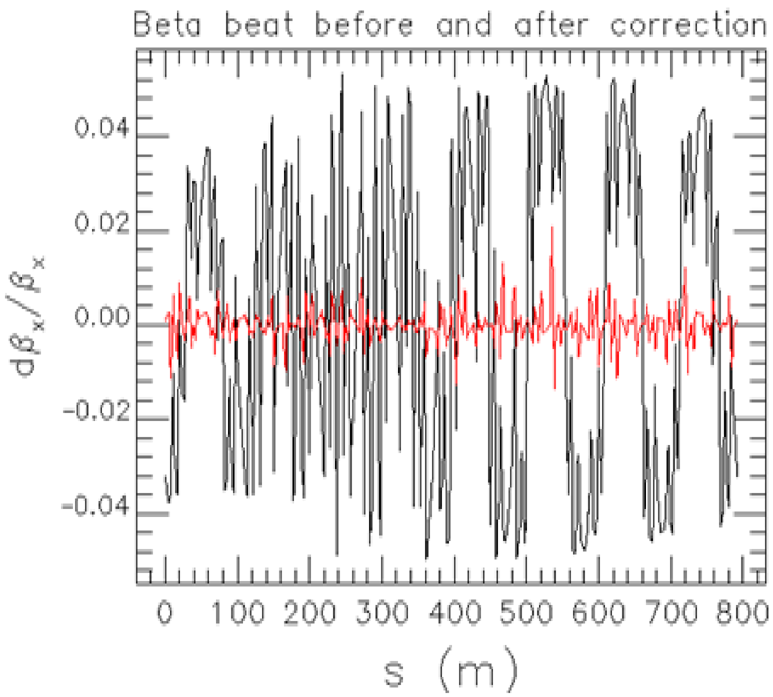
- σ_{quad} = 19 μm
- σ_{sext} = 17 μm

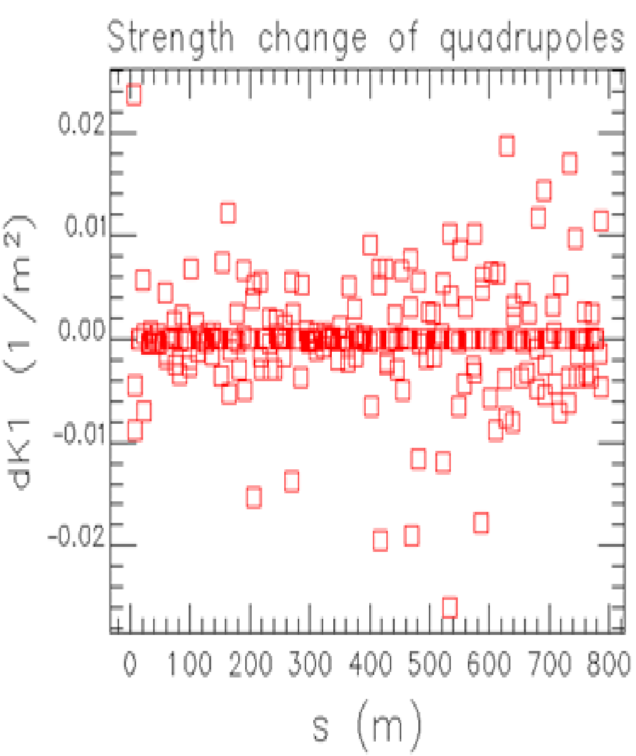


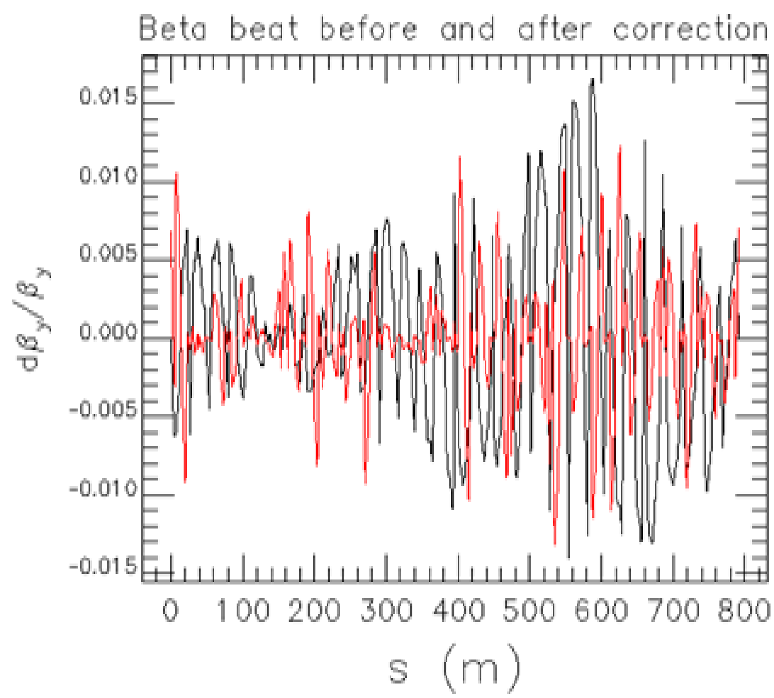
- σ_{quad} = 12 μm
- σ_{sext} = 14 μm

Beta Beat Correction

- All quadrupoles are powered independently.
- Beta functions are measured and corrected at the BPMs.
- The residual beta beat is 0.4% rms in both planes.







Higher Order Multipole Specification

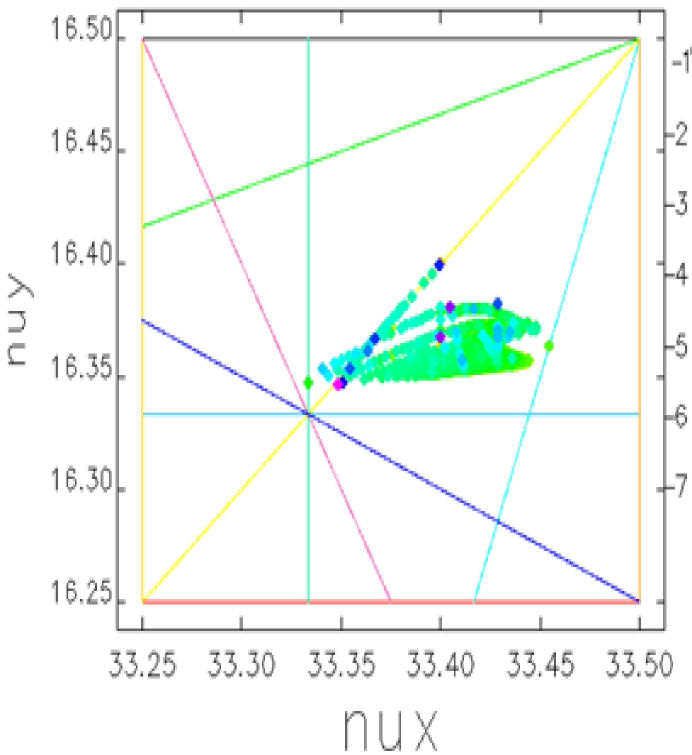
systematic	Normal Aperture [x 10^{-4}] @ 25 mm	Large Aperture [x10^{-4}] @ 25 mm
B6	1	1.0
B10	4.5	0.5
B14	4.0	0.1
non-systematic		
B1	1.0	1.0
B3	3.0	3.0
B4	1.0	
B5	0.1	0.1
B7-B9	0.1	0.1
B11-B13, B15-B20	0.1	0.1
Skew terms		
A1,A3	1	1
A4 and above	0.1	0.1

- Quadrupole Multipole Specification

systematic	Normal Aperture [x 10^{-4}] @ 25 mm	Larger Aperture [x10^{-4}] @ 25 mm
B9	1	0.5
B15	1	0.5
B21	4	0.5
non-systematic		
B1	10	2
B2	1	2
B4	1	0.5
B5-B7	0.5	
B8	0.1	
B10-b14	0.2	
B16-b20	0.1	0.2
Skew terms		
A1	5.0	
A4	1.0	1
A5 and above	0.1	0.1

- Sextupole multipole specification

Frequency Map in (x,δ) Space



Tune footprint in the required dynamic aperture

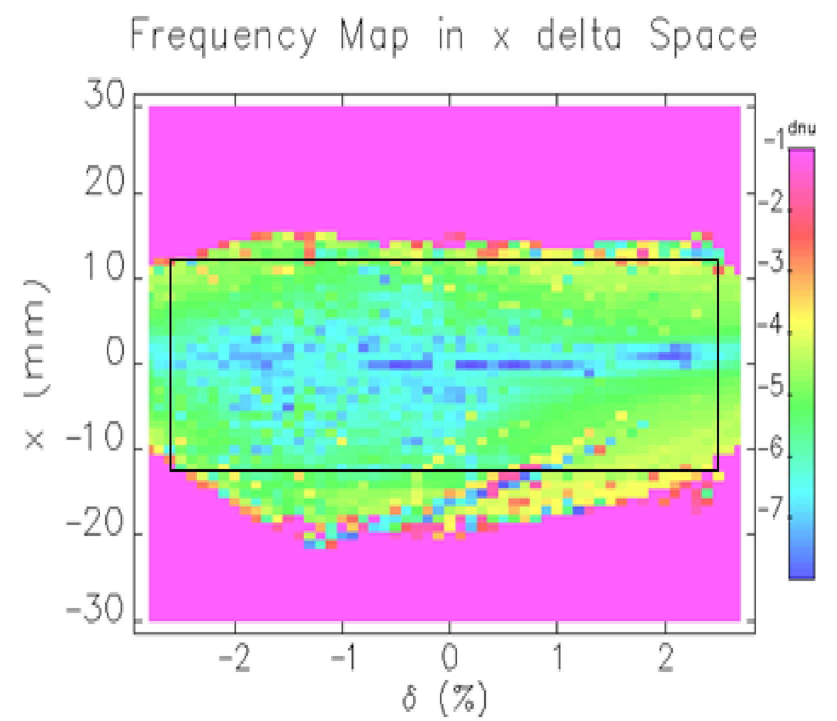
- 3 DWs
- Misalignment and magnet Error:

60 μm magnet to girder, 100 μm girder to girder

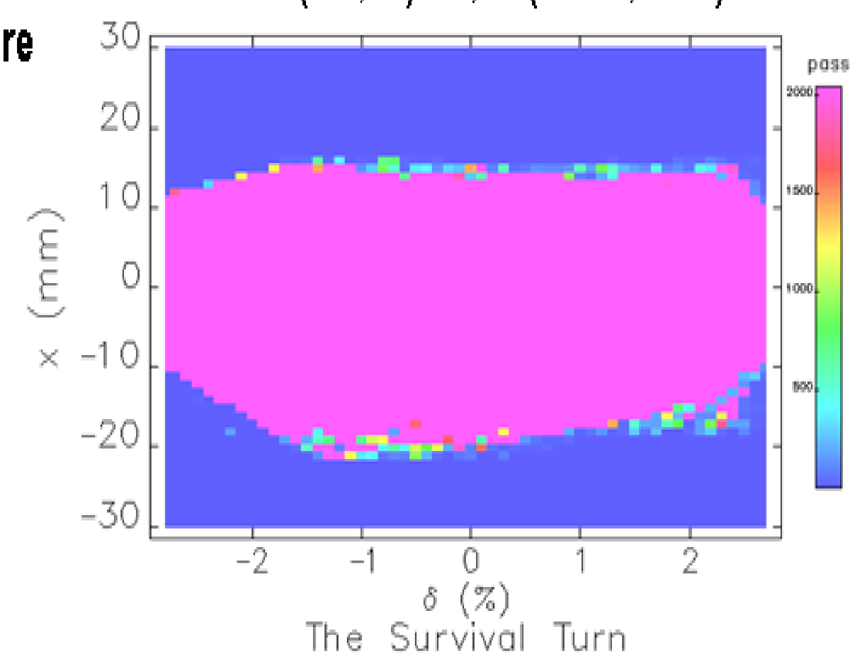
0.5 mr girder rotation, 0.2 mr magnet rotation

Systematic and random multipole errors

- Closed Orbit and beta beat corrected.



Frame: x: (-12,12)mm, δ: (-2.5%,2.5%)



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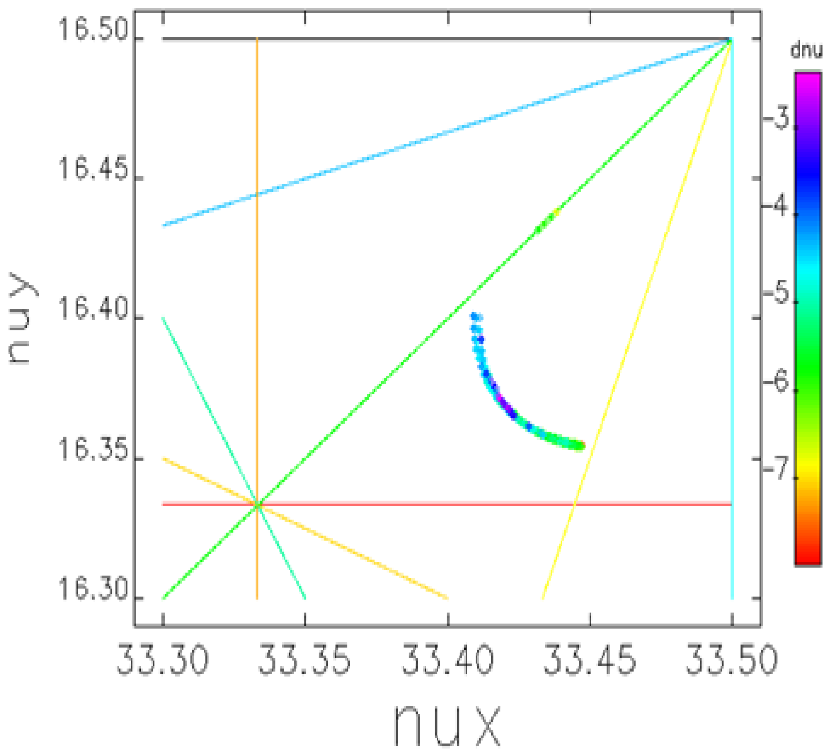
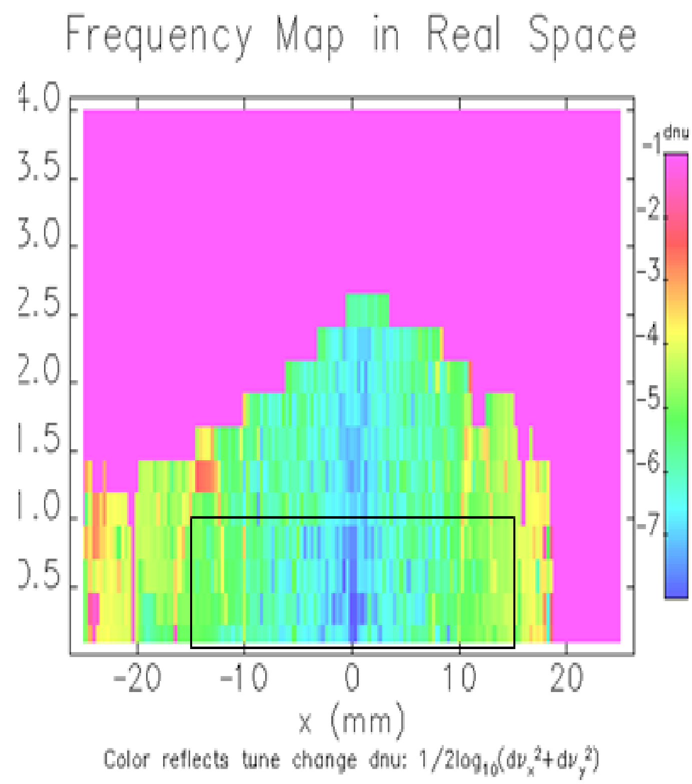
Frequency Map in (x,y) Space



Tune footprint in the required dynamic aperture



- 3 DWs
- Misalignment and magnet Error:

60 μm magnet to girder, 100 μm girder to girder

0.5 mr girder rotation, 0.2 mr magnet rotation

Systematic and random multipole errors

- Closed Orbit and beta beat corrected.

Frame:

x: (-15mm,15mm)

Y: (0, 1 mm)

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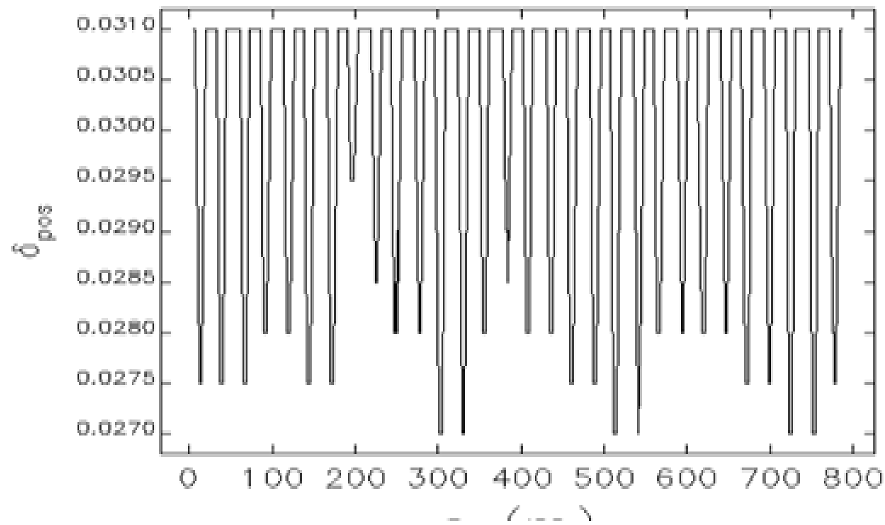
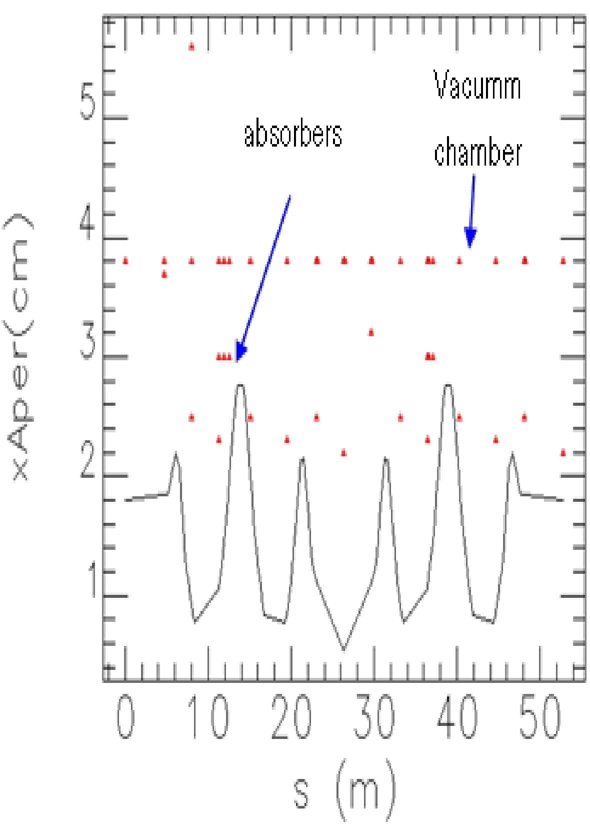
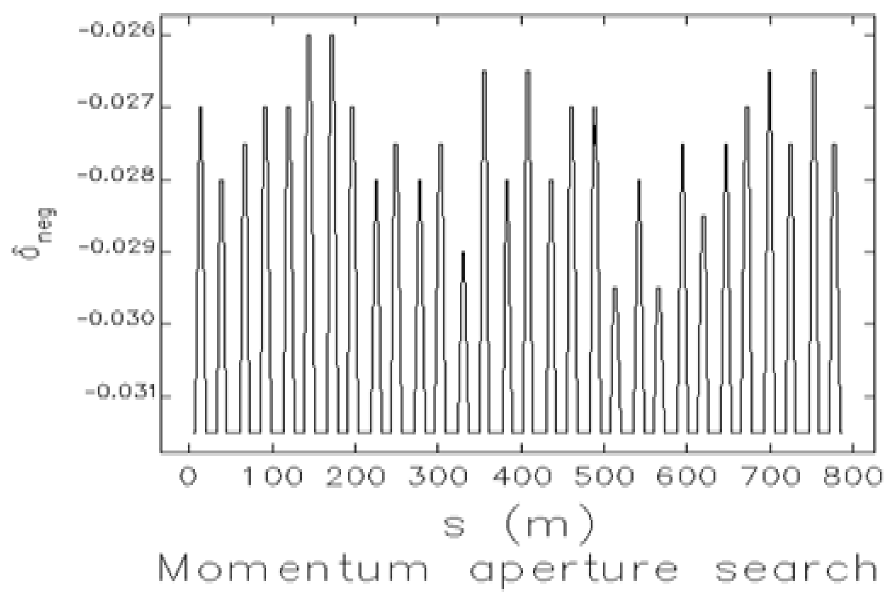
Momentum Aperture

- The horizontal physical aperture is limited by the photon absorbers.
- Vertical aperture is given by the kick-maps
- The photon absorbers are placed such that particles with **δ=±**3% are not blocked.







- Radiation damping and RF cavity are turned on.
- Vrf = 3.2 MV, rf bucket height is 3.1%.
- Touschek lifetime is 5.7 hours w/o Landau cavity.

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Summary

- NSLS-II will be one of the brightest light sources in the world due to the below 1 nm emittance. The emittance is achieved with weak dipole and damping wigglers.
- Magnets and power supplies are designed to have sufficient flexibility for lattice tuning.
- Magnets at the maximum dispersion have larger apertures to provide better field quality with small multipole errors.
- A third chromatic knob was introduced by moving one of the existing sextupoles. It is effective in controlling the 2nd order horizontal chromaticity. Nonlinear knobs are shown to be adequate for tuning.
- Damping wigglers were integrated as lattice elements.
- Dynamic aperture is optimized by minimizing the tune excursion with transverse and longitudinal offsets.
- Misalignment and magnetic errors are used to test the robustness of the solutions.
- A working point with satisfactory nonlinear behavior was presented. It satisfies the requirement on the dynamic aperture for injection and provides satisfactory Touschek lifetime.