Touschek Lifetime Considerations for NSLS-II

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Cockcroft Institute Seminar

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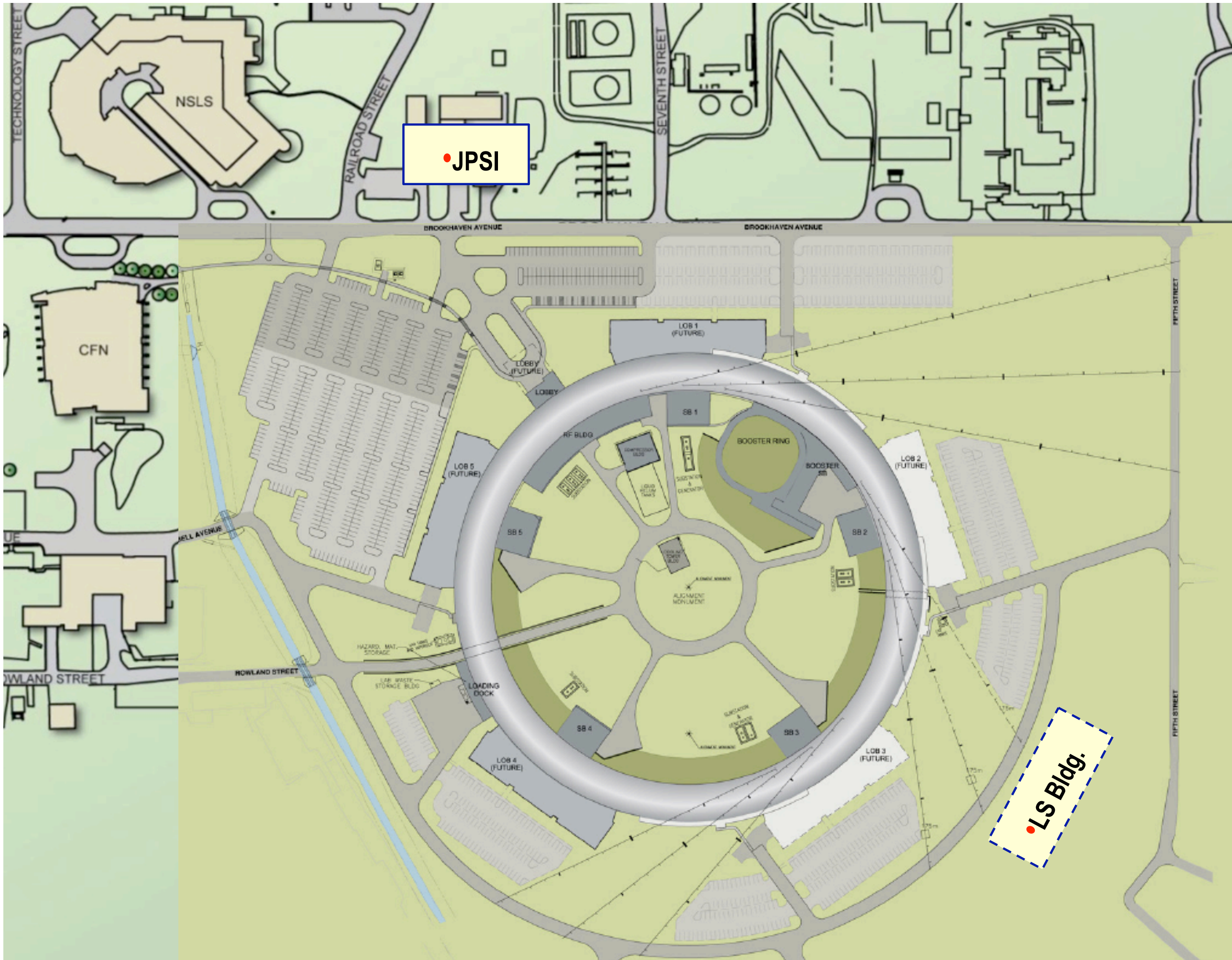
Outline

- NSLS-II overview
- Touschek lifetime overview
- Off-momentum dynamics
- Higher order multipole errors
- Dynamic aperture impact from multipole errors
- Touschek lifetime results
- Conclusions

NSLS-II: New 3rd Generation Sychrotron Light Source at BNL



rendering of future location

NSLS-II Key Milestones

- Aug 2005 **CD-0**, Approve Mission Need______________________________ (Complete)
- Jul 2007 **CD-1**, Approve Alternative Selection and Cost Range_______________ (Complete)
- Jan 2008 **CD-2**, Approve Performance Baseline (Complete)
- Dec 2008 **CD-3**, Approve Start of Construction_________________________ (Complete)
- Feb 2009 Contract Award for Ring Building______________________________ (Complete)

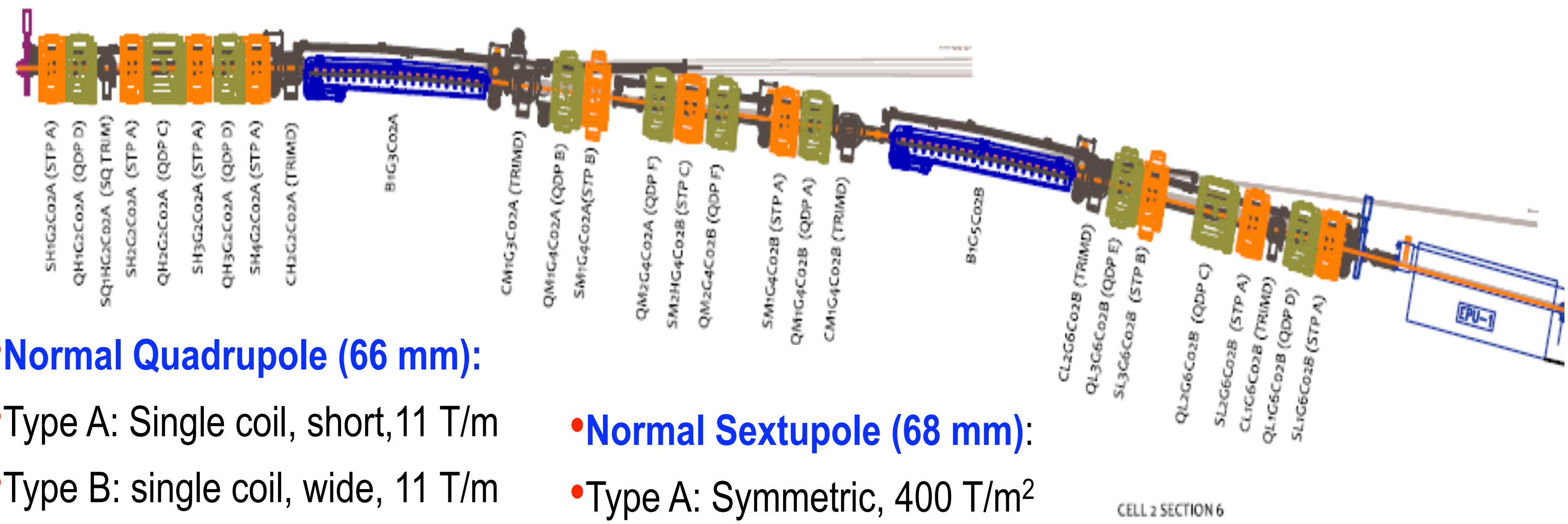
Aug 2009 Contract Award for Storage Ring Magnets

- Mar 2010 Contract Award for Booster System
- Feb 2011 1st Pentant of Ring Building Ready for Accelerator Installation
- Feb 2012 Beneficial Occupancy of Experimental Floor
- Oct 2013 Start Accelerator Commissioning
- Jun 2014 Early Project Completion; 1st Beam to Beamlines soon afterwards
- Jun 2015 **CD-4**, Approve Start of Operations

NSLS-II Parameters

•Beam Energy	3 GeV
•Emittance	$eps_x < 1nm$, $eps_y \sim 10pm$
•Circumference	792 m
•Circulating average current	500 mA
•Bunch current/charge	0.5mA/1.3 nC
•Total number of buckets	1320
•Lifetime	>3 hours
•Electron beam stability	10% beam size
•Top-off injection current stability	<1%
•ID straights for undulators	>21
•Straight length	9.3/6.6 m

Lattice and Magnet Types

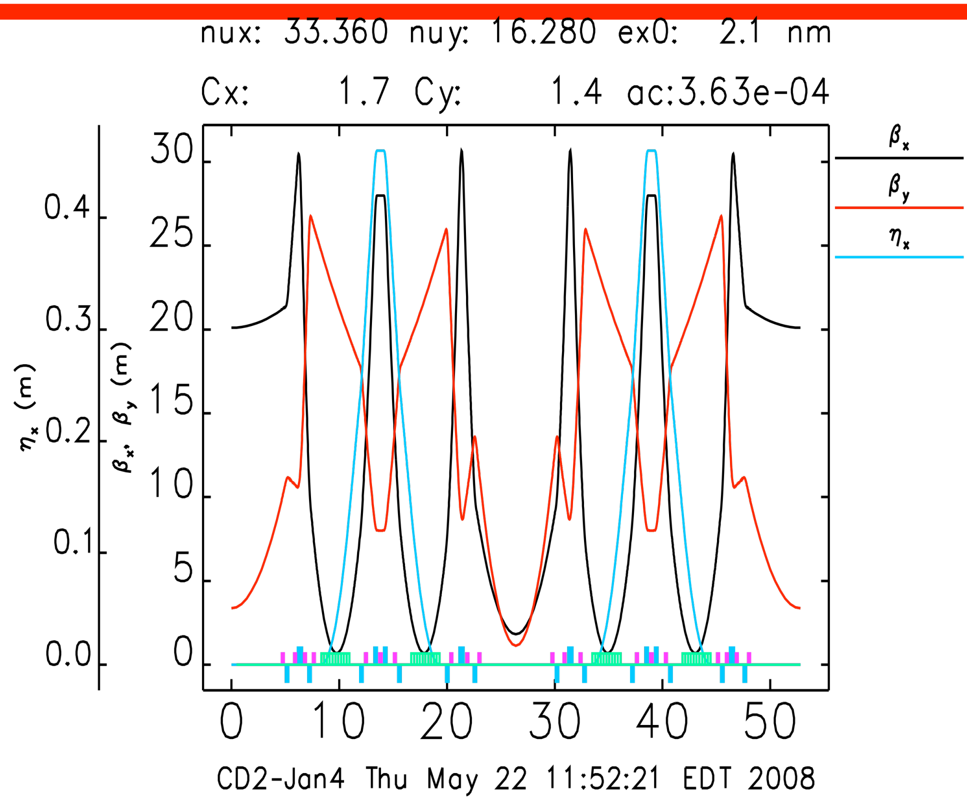


- **Normal Quadrupole (66 mm):**
- Type A: Single coil, short,11 T/m
- Type B: single coil, wide, 11 T/m
- Type C: Double Coil, long, 22 T/m
- Type D: Double Coil, short, 22 T/m
- Type E: Double Coil, Wide, 22 T/m
- **High precision: 90 mm, 15 T/m**

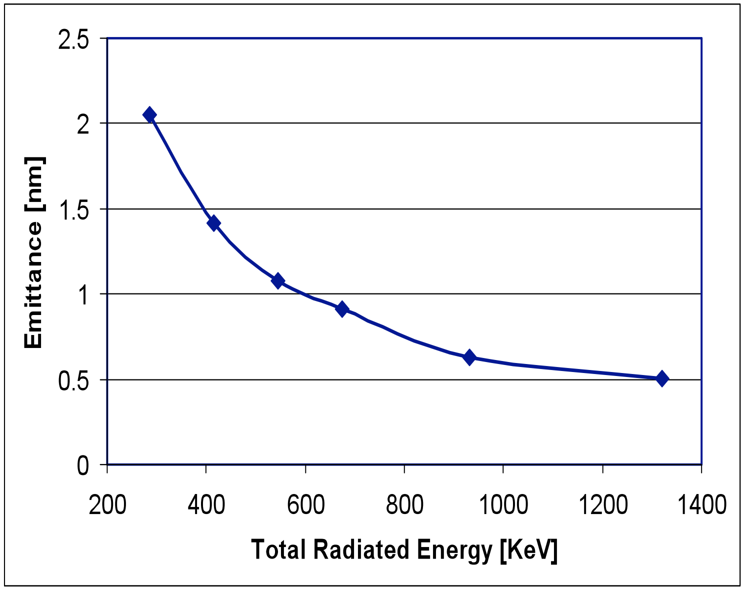
- **Normal Sextupole (68 mm)**:
- Type A: Symmetric, 400 T/m^2
- Type B: Wide, 400 T/m^2
- **High precision: 76 mm**

High precision magnets at max dispersion

Low Emittance Lattice Approach



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



- Quad. Family: 8, 10 magnets per cell
- Sext. Family: 9, 10 magnets per cell
- Chromaticity per cell: -3.4/-1.4

- < 1 nm goal for emit. w/ DW

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Touschek Lifetime Overview

- Particles scattering off each other in beam. Main effect is energy gain of one particle and energy loss of the other. This is a single scattering effect, in contrast to IBS-> multiple scattering.
- If particle’s energy is outside energy aperture, then particle is lost.
- Thus, adequate energy aperture is important in order to have reasonable Touschek Lifetime.

Bruck formula for Touschek Lifetime

$$\frac{1}{\tau} = \left\langle \frac{r_0^{\ 2} cN}{8\pi\gamma^3 \sigma_x \sigma_y \sigma_s \sigma_{x'} \delta_{acc}^{\ \ 2}} C(\varepsilon_m) \right\rangle$$

$$\tau = \tau_{1/2}$$

- (time for loss of ½ particles assuming
- rate stayed the same)

$$\varepsilon_m = \frac{\delta_{acc}^{\ \ 2}}{\gamma^2 \sigma_{x'}^{\ \ 2}}$$

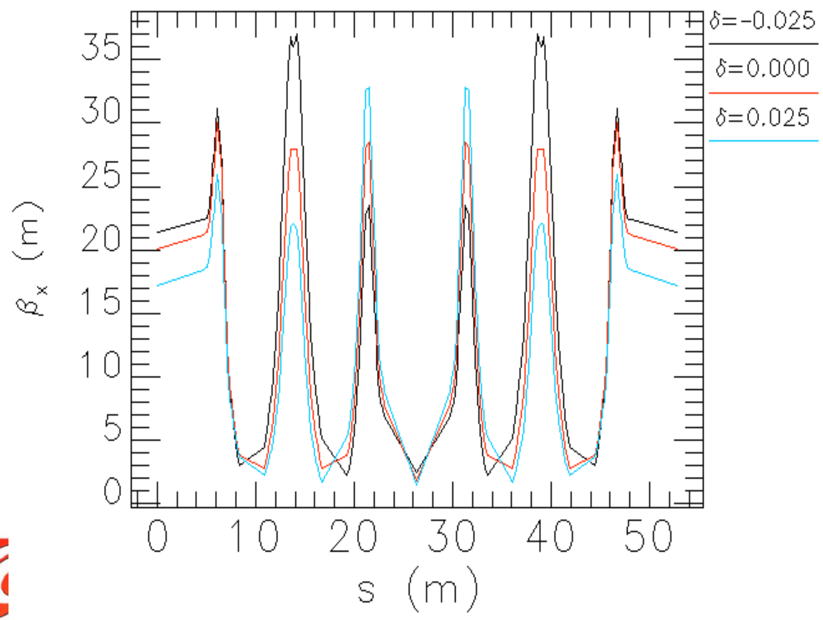
$$\tau \propto \delta_{acc}^{3.5}$$

$$C(\varepsilon_m) = \int_0^1 \left(\frac{1}{u} - \frac{1}{2} \ln \frac{1}{u} - 1 \right) e^{-\frac{\varepsilon_m}{u}} du$$

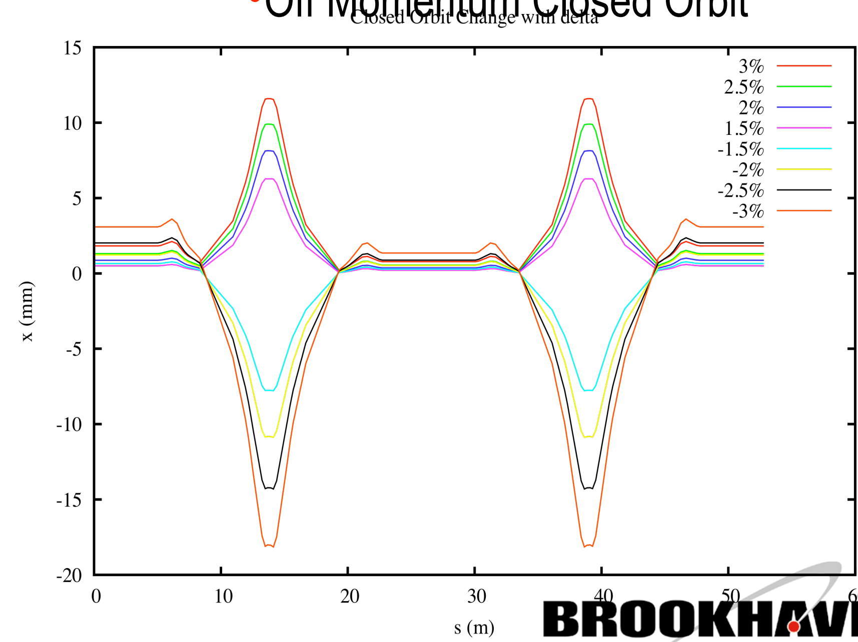
Off Momentum Dynamics

- particle scatters in dispersion region
- induces betatron oscillation about new orbit
- linear optics depends on energy

- Off Momentum Beta Function



- Off Momentum Closed Orbit

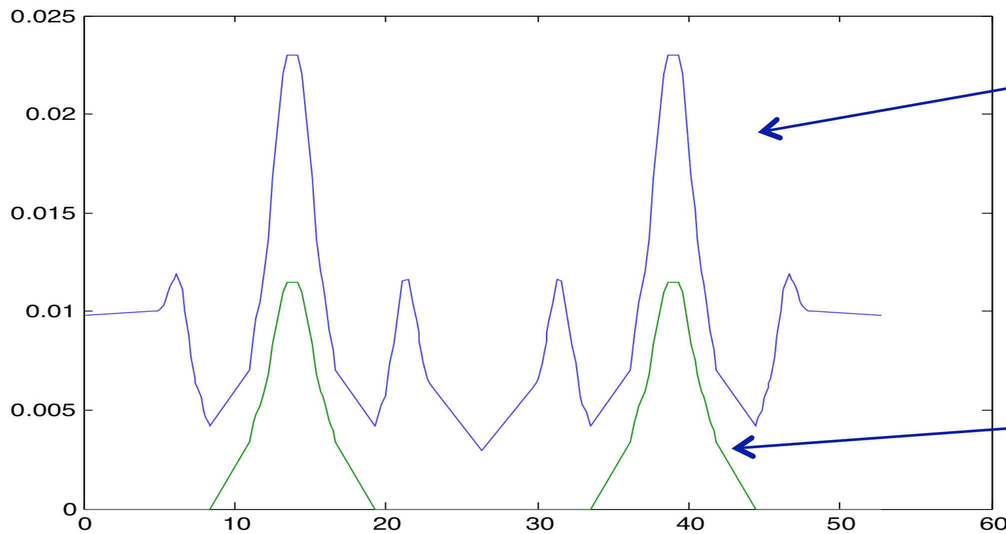


Why Different Tolerances for magnets at high dispersion?

- Amplitude of Oscillation for Scattering at different positions

$$x(s_2) = \left(\eta^{(1)}(s_2) + \sqrt{\mathcal{H}_1 \beta_x(s_2)}\right) \delta + \eta^{(2)}(s_2)\delta^2$$

- with 2.5% :



- scatter in disp region
- scatter in straight

Magnetic Field Multipole Expansion

$$(B_y + iB_x)(r,\phi) = B\rho \sum_n (b_n + ia_n) r^{n-1} e^{i(n-1)\phi}$$

- b_1 = dipole, b_2 = quadrupole, b_3 = sextupole
- a_n = skew components

$$(B_n + iA_n)(R) = \frac{1}{2\pi}\int_0^{2\pi} (B_y + iB_x)(\phi;R) e^{-i(n-1)\phi} d\phi$$

- Measured by
- Rotating coil

$$B_N{}^n = \frac{\int_0^L B_n(s;R)ds}{\int_0^L B_N(s;R)ds} \propto R^{n-N}$$

- Field ratio of given harmonic to design field
- at a given radius. Here we use R = 25 mm.

Multipole Errors (cont.)

for y=0, $$B_y + iB_x = B\rho \sum_n (b_n + ia_n) x^{n-1}$$

- Off momentum particles will start to see higher order multipole errors.

Sources of Systematic and Random Multipole Errors

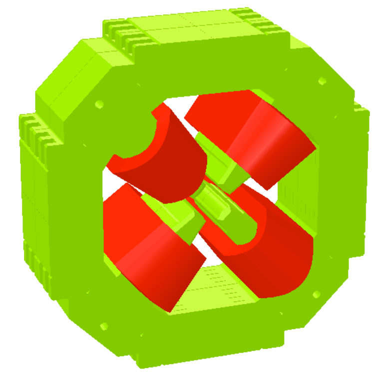
- For ideal, symmetric 2N-pole magnets, higher order multipoles consistent with symmetry ("allowed multipoles"): N(2m+1), m=0,1,2,…

  dipole (N=1): 1,3,5,7, …

  quadrupole (N=2): 2, 6, 10, 14, …

  sextupole (N=3): 3, 9, 15, 21, …

  - 1st 3 allowed multipoles are sufficient to characterize field



- Random Errors from manufacturing tolerances

Multipole Tolerances for NSLS-II Quadrupoles

Allowed harmonics	Normal [x 10^{-4}] @ 25 mm	High precision[x10^{-4}] @ 25 mm
b6	1	1.0
b10	4.5	0.5
b14	4.0	0.1
non-allowed harmonics		
B1	1.0	1.0
B3	3.0	3.0
B4	1.0	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

Multipole Tolerances for NSLS-II Sextupoles

Allowed harmonics	Normal [x 10^{-4}] @ 25 mm	High precision[x10^{-4}] @ 25 mm
b9	1	0.5
b15	1	0.5
b21	4	0.5
Non-allowed harmonics		
b1	10	10
b2	1	1
b4	1	1
b5-b7	0.5	0.5
b8	0.1	0.1
b10-b14	0.2	0.2
b16-b20	0.1	0.2
Skew terms		
a1	5.0	5.0
a4	1.0	1.0
a5 and above	0.1	0.1

Tracking Calculations Approach

- Use Tracy Library interface
- Lattice files, optics design, sextupole settings… S. Krinsky, S. Kramer, W. Guo, J. Bengtsson
- Tracking uses 4th order symplectic integrator.
- Insertion devices may be modeled with Halbach basis Y. Wu integrator, or using kick maps
- Multipole errors, misalignment errors, orbit correction and correction for damping wiggler optics distortions.

How to Set Sextupoles?

- sextupole families:
- SL1, SL2, SL3, SH1, SH2, SH3, SH4, SM1, SM2

- Fix the problems that the chrom. corr. causes!

- Chromaticity correction

- OPA minimizes:

- C_x
- C_y
- h21000
- h30000
- h10110
- h10020
- h10200
- h20001
- h00201
- dv_x/dJ_x
- dv_x/dJ_y
- dv_y/dJ_y

- h31000
- h40000
- h20110
- h11200
- h20020
- h00310
- h00400

- C2x
- C2y

- Lie Generators of one turn map Calculated using analytical formulas

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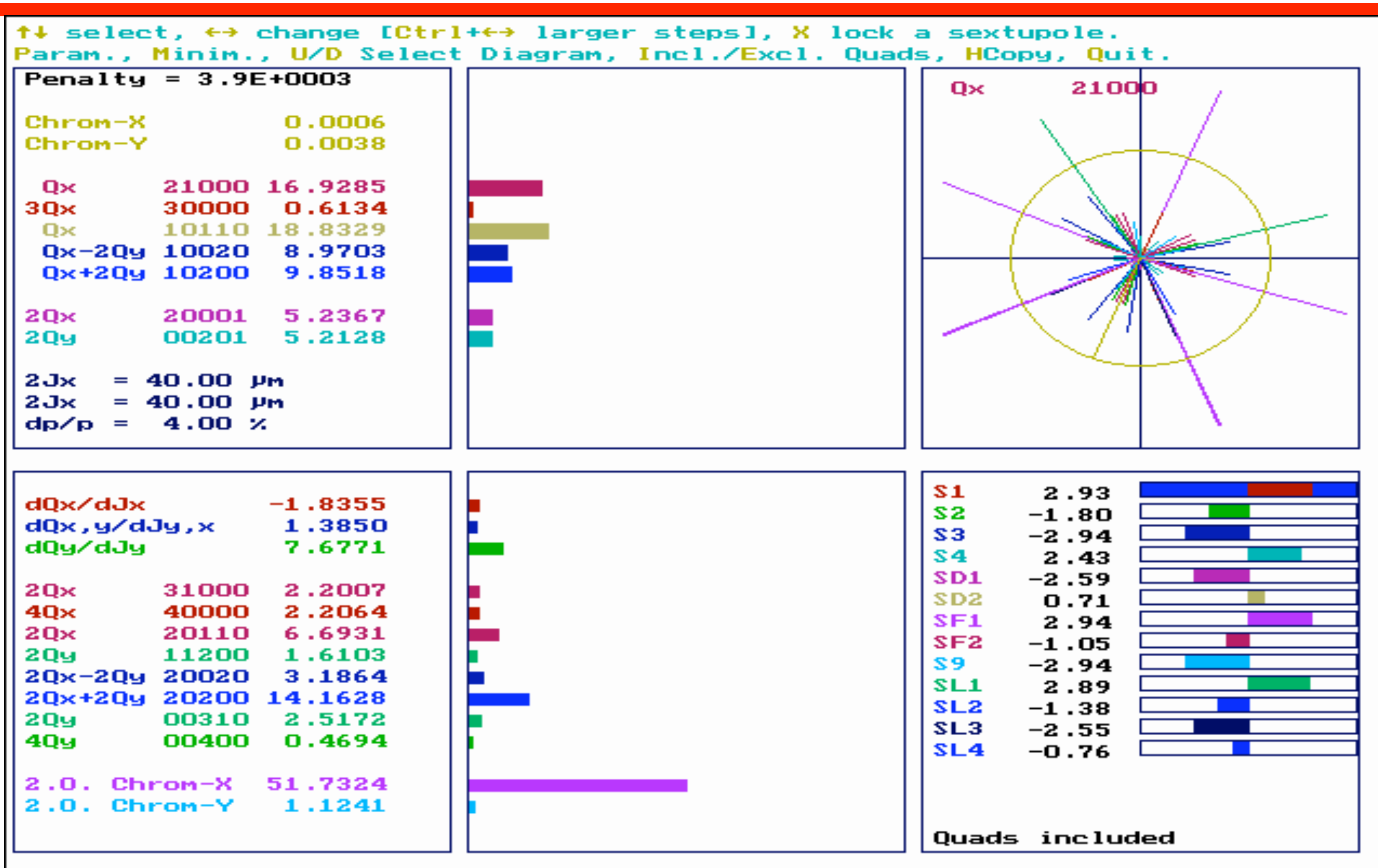
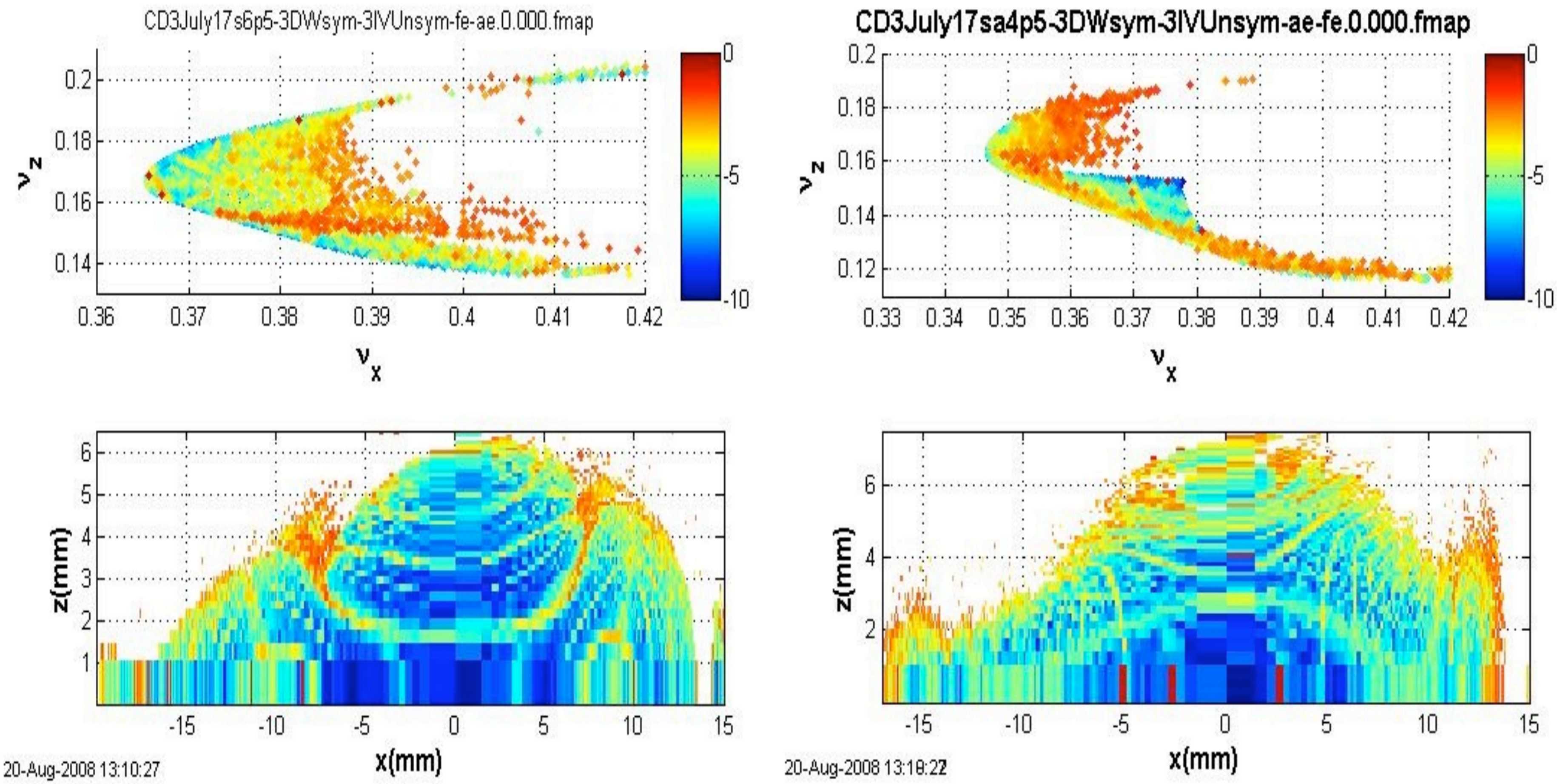
OPA Optimization



Frequency Maps on Momentum - two different sextupole tunes



• Frequency map calculates tunes and tune diffusion for different initial conditions

J. Laskar, Physica D, 67, 257-281 (1993)

S. Kramer, B. Nash

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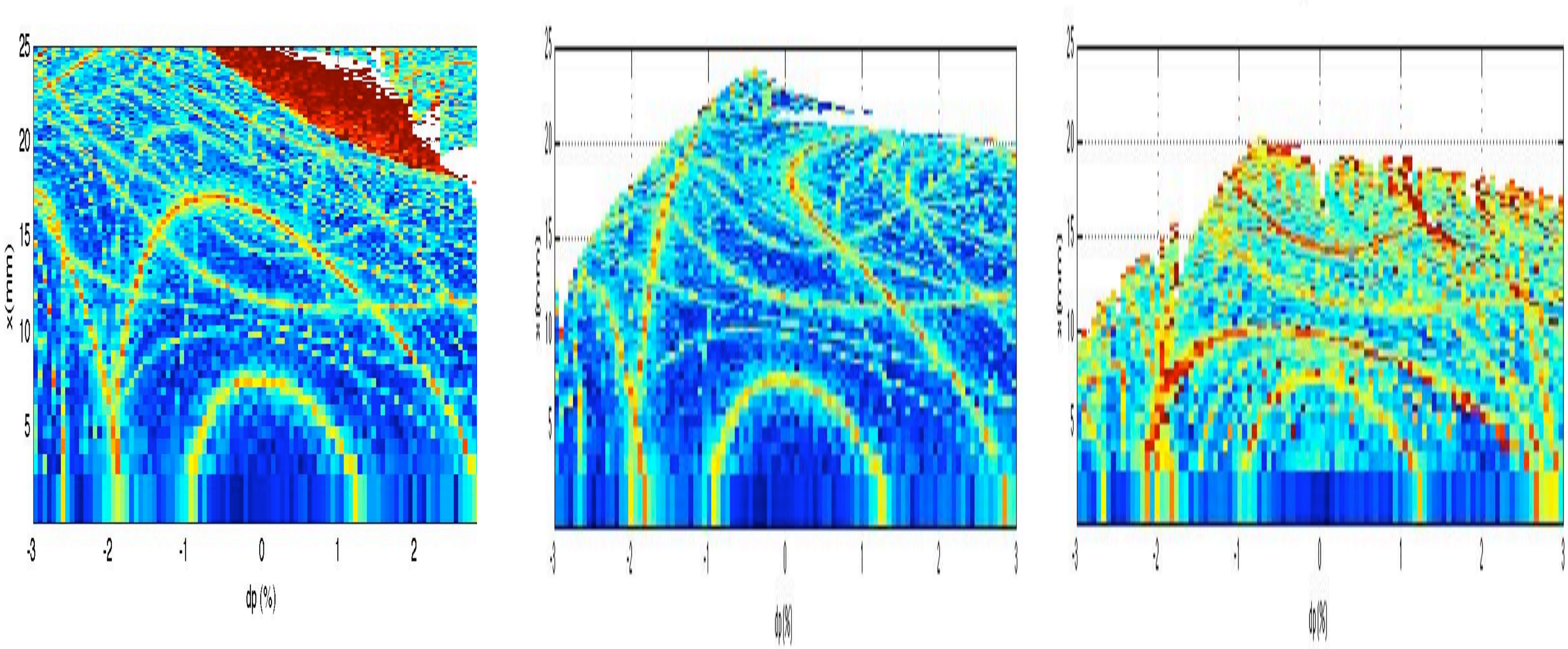
X-δ Frequency Map- Effect of Multipole Errors

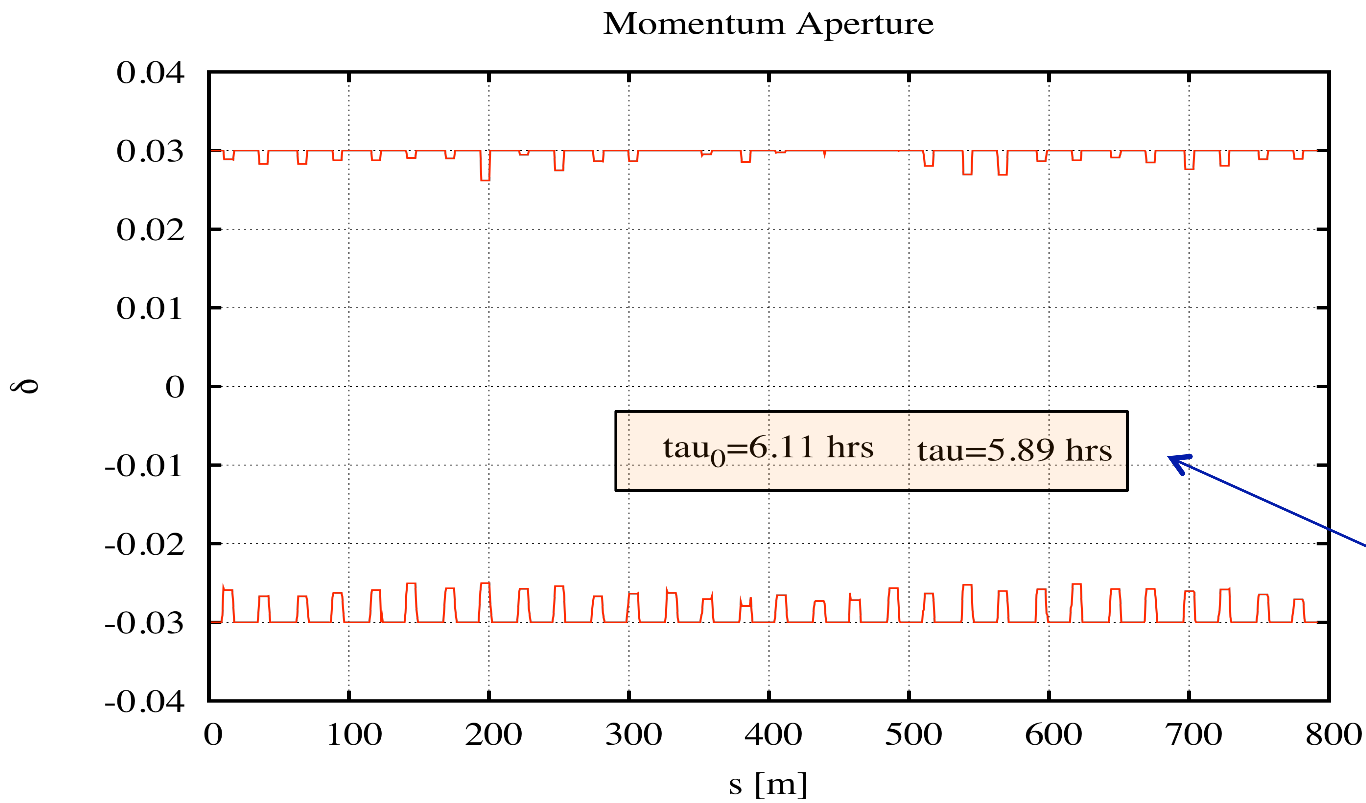
- Unstable region increases particularly at negative momentum



- No errors
- Systematic multipole errors
- Sys + Rand errors

CD2 lattice

But what really matters for Touschek lifetime is the momentum aperture.



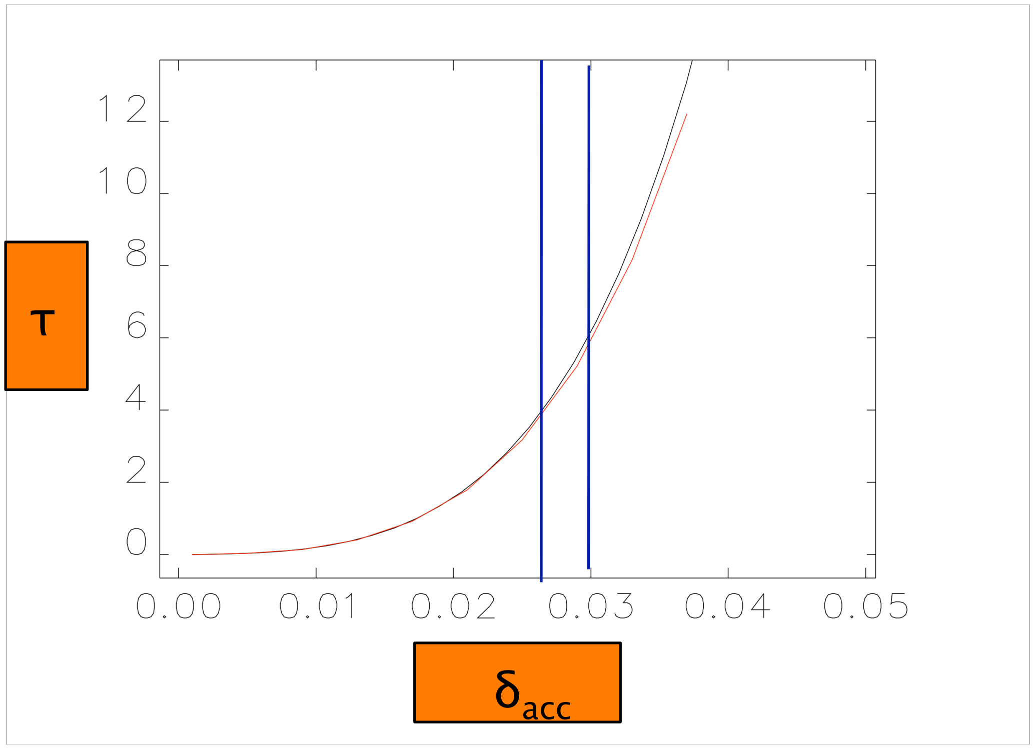
4% decrease in lifetime

ε_x = 1nm σ_s =4.5 mm (no Landau cav)

ε_y = 10pm Q=1.3nC

$\delta_{RF} = 3\%$.

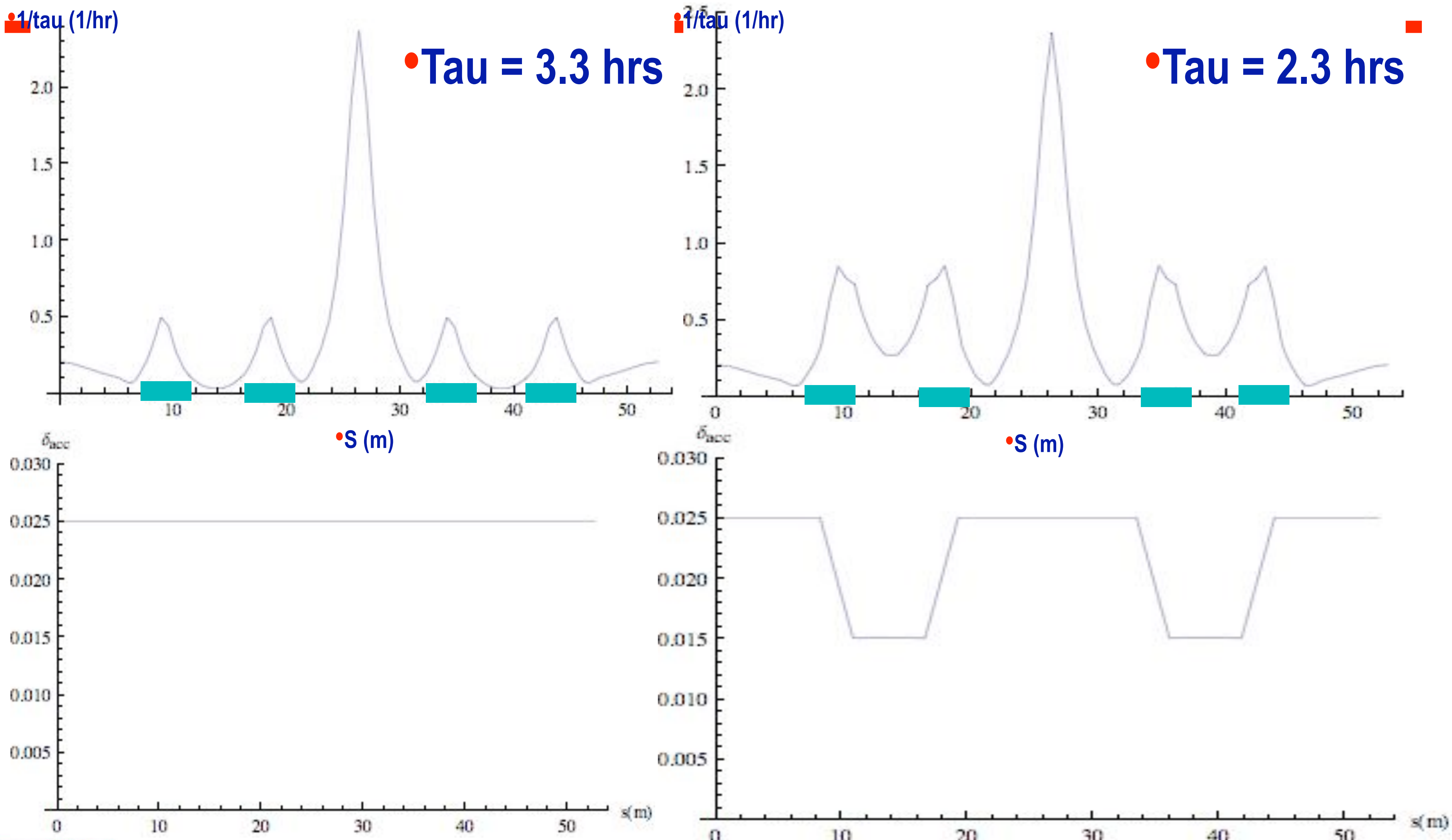
Why such small change in Touschek lifetime?



- Looks like it should be more…

Answer: Touschek Lifetime is less sensitive to momentum aperture in dispersion region.

Local Touschek Scattering Rate

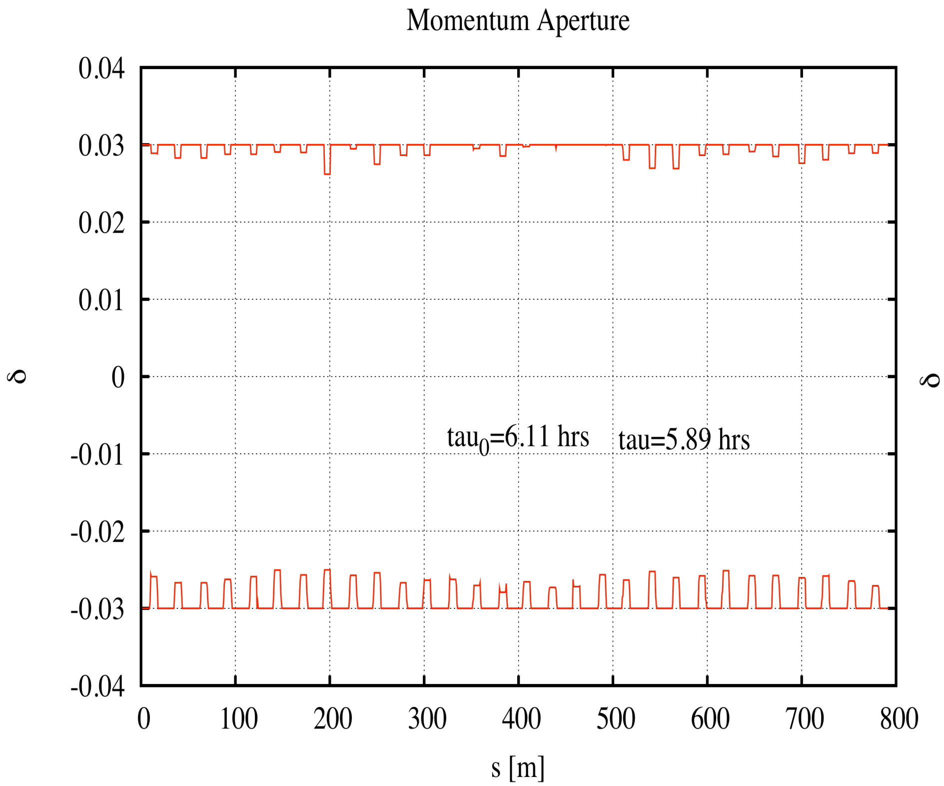


Touschek Lifetime for varying momentum aperture in straight and disp. region

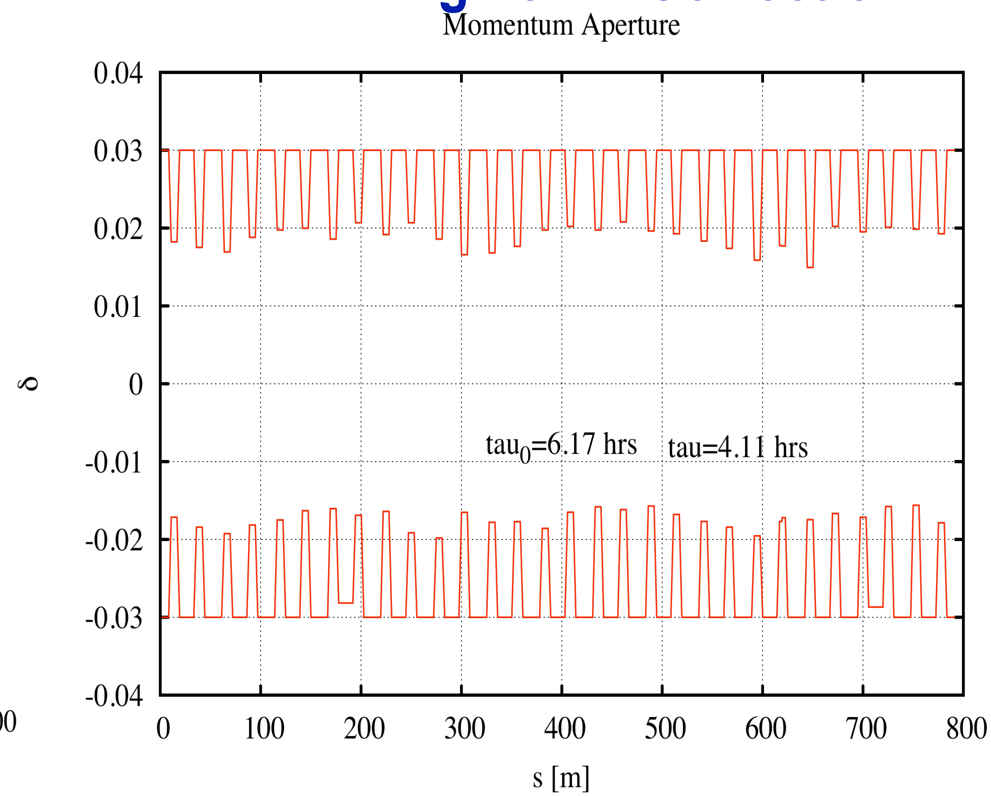
δ_{acc} (str)	δ_{acc} (disp)	τ (hr)
3%	3%	6.2
3%	2.5%	5.5
3%	2.0%	4.6
3%	1.5%	3.3
2.5%	2.5%	3.3
2.5%	2.0%	2.9
2.5%	1.5%	2.3

Momentum Aperture With Further Engineering Tolerances and Insertion Devices

- Field errors



- Also add: 3 DW, 3 IVU
  +/- 2.5 mm IVU gap
  - Align err + Correction



- (DW: λ=90mm, B=1.8T,n=78)
- (IVU: λ=20mm, B=1.2T,n=160)

Conclusions

- Touschek Lifetime of 3 hours design for NSLS-II
- Multipole errors in the dispersive magnets reduce off-momentum dynamic aperture
- Larger magnets with tighter multipole specifications for these magnets reduce this problem.
- Due to less scattering in dispersion regions, Touschek lifetime is less sensitive to dispersion region momentum aperture.
- Momentum Aperture of 2.5% in straights, 1.5% in dispersion region gives >3 hour lifetime (with Landau cavity). So far, adding all non-linearities and errors, NSLS-II appears to have a reasonable margin for this.