Lattice Design and Performance for PEP-X Light Source

Yuri Nosochkov

SLAC National Accelerator Laboratory

With contributions by M-H. Wang, Y. Cai, X. Huang, K. Bane

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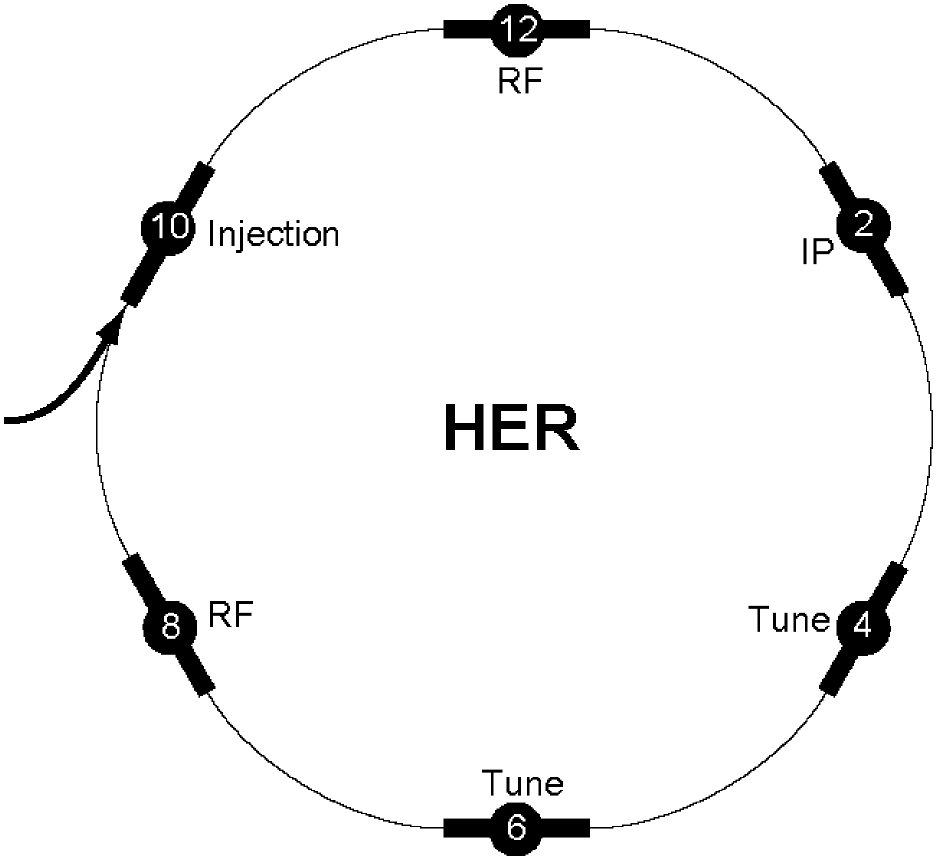
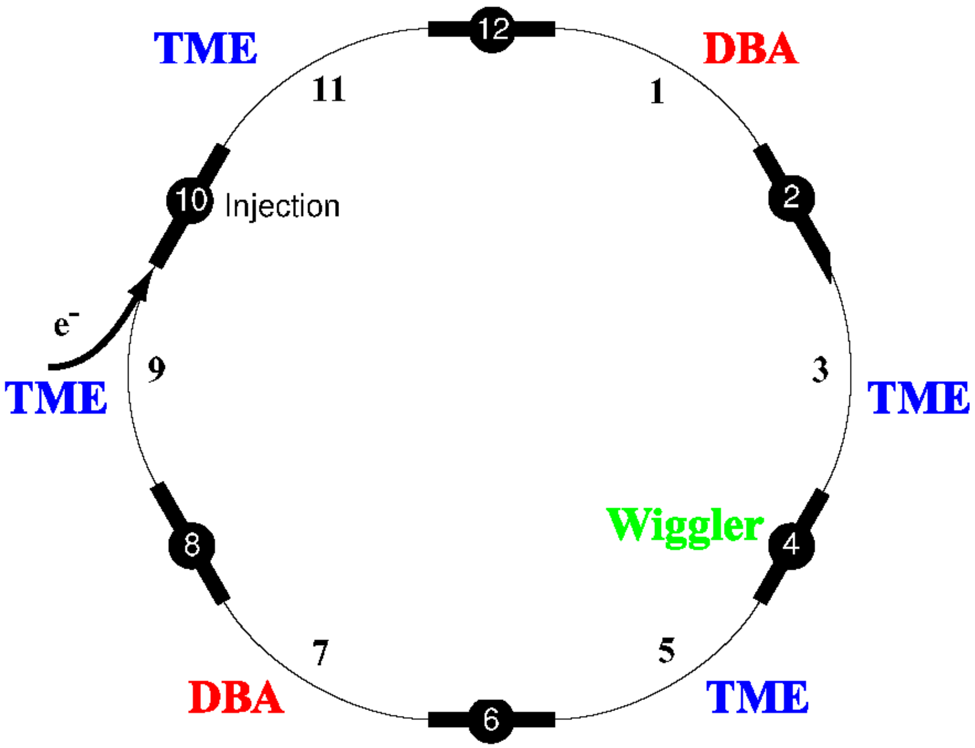
Existing PEP-II rings



- **2.2 km existing rings in PEP tunnel**
- **Six 243 m arcs and six 123 m long straights**
- **60 or 90 deg FODO lattice**
- **Can reach ~5 nm-rad emittance at 4.5 GeV (w/o wiggler) – too high for a modern light source**

PEP-X low emittance ring



Design a new low emittance ring in the PEP-II tunnel.

Goals:

- **~0.1 nm-rad emittance at 4.5 GeV for high brightness**
- **>24 dispersion free straights for insertion devices**
- **Use existing PEP-II tunnel and utilities**

New optics with:

- **Two DBA arcs yielding 30 ID straights**
- **Four TME arcs for low emittance**
- **~90 m wiggler to reach ~0.1 nm-rad emittance at 4.5 GeV**
- **FODO optics in long straights**
- **PEP-II based injection system**

Layout of PEP-X with photon beamlines at SLAC

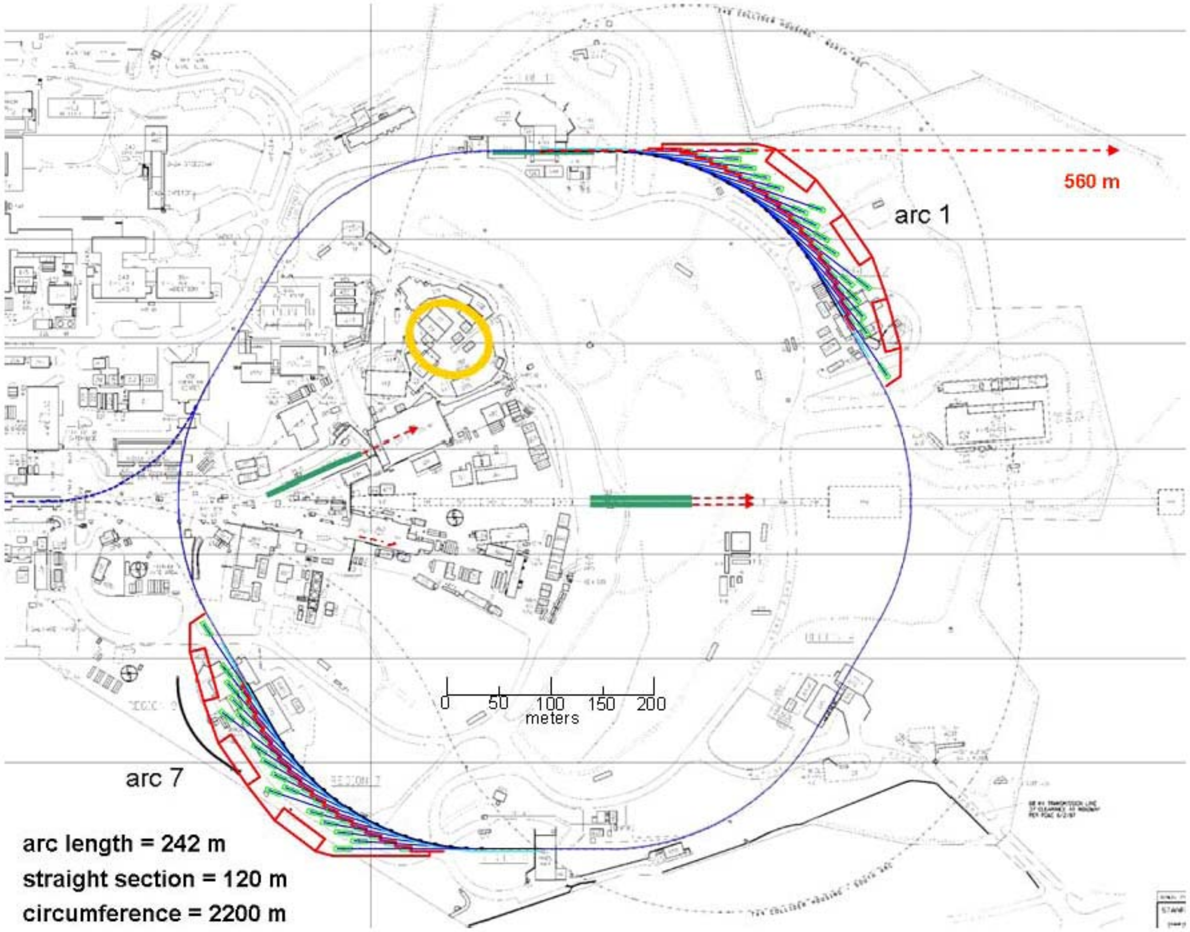
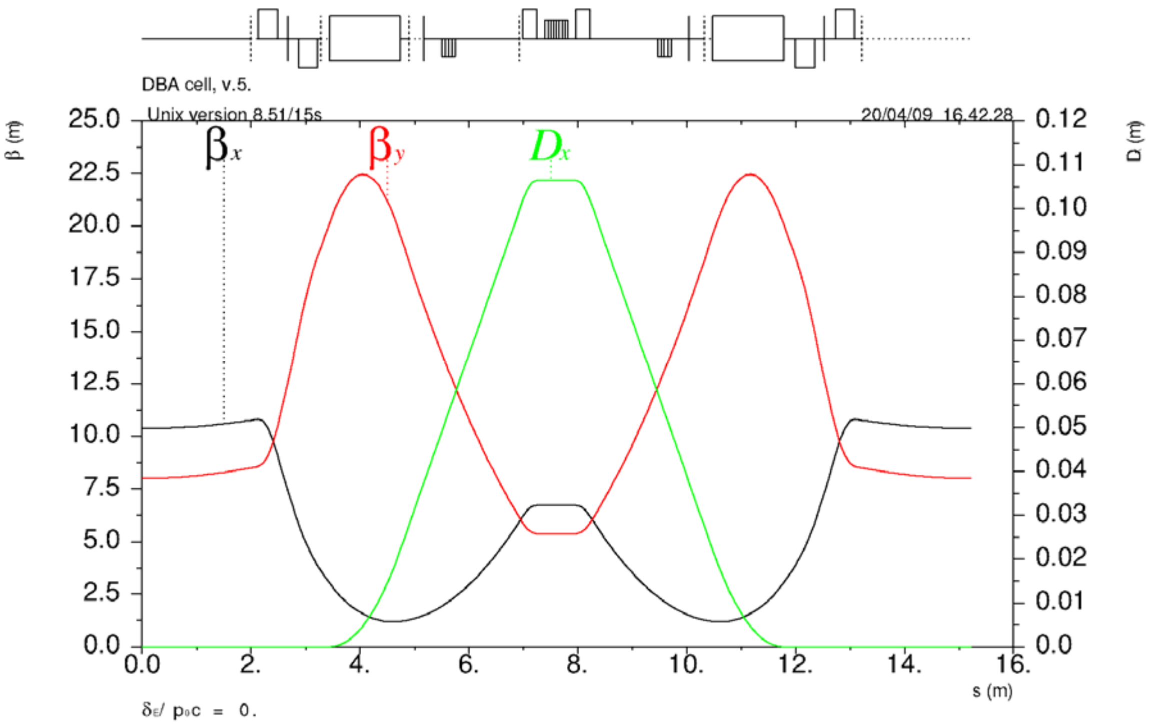


Figure 1.1: A conceptual layout of PEP-X light source with two experimental halls containing 30 X-ray beamlines reaching a brightness of 10^{22} (ph/s/mm^2/mrad^2/0.1% BW) at 10 keV.

Initial DBA design: Standard cell



- Initial design: 15.2 m DBA cell with gradient bend and 4.3 m ID straight
- 16 DBA cells per arc for 30 ID straights
- X and Y phase advance near $3\pi/2$ and $\pi/2$ for compensation of sextupole geometric and chromatic aberrations and maximum dynamic aperture
- Optimized for low emittance, maximum momentum compaction and aperture
- ID β_x and β_y = 10.4 m and 8.0 m – lower β is desired for higher brightness

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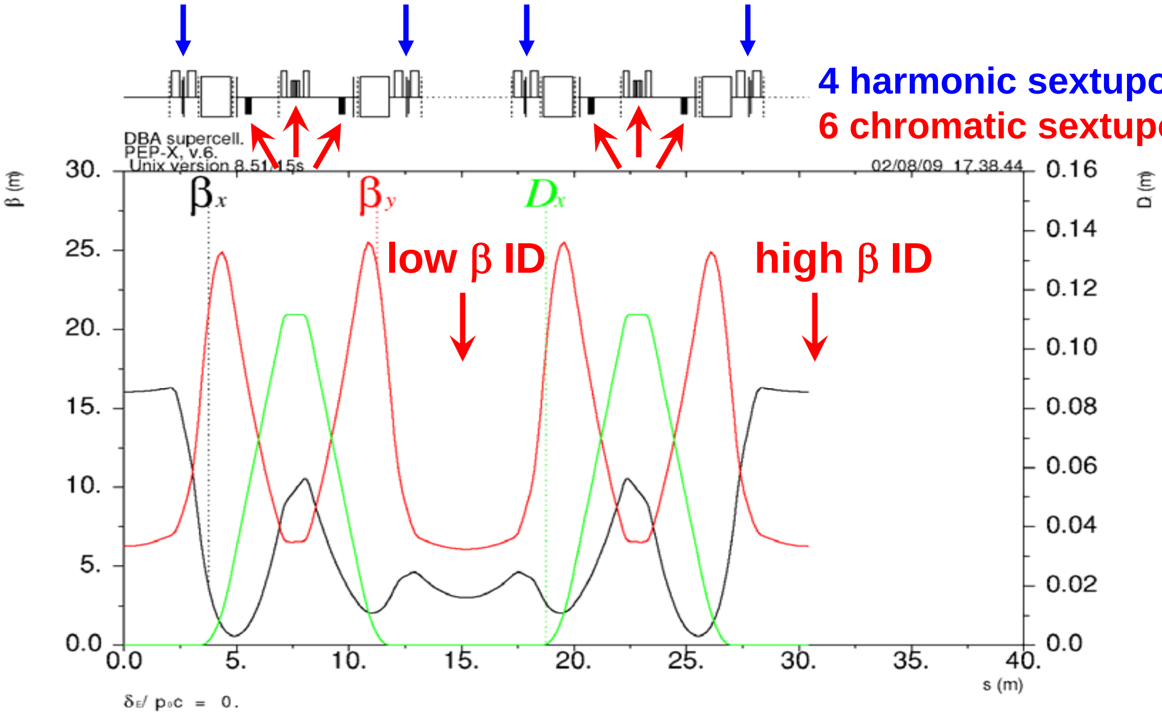
Present DBA design: Supercell



4 harmonic sextupoles, 2 families

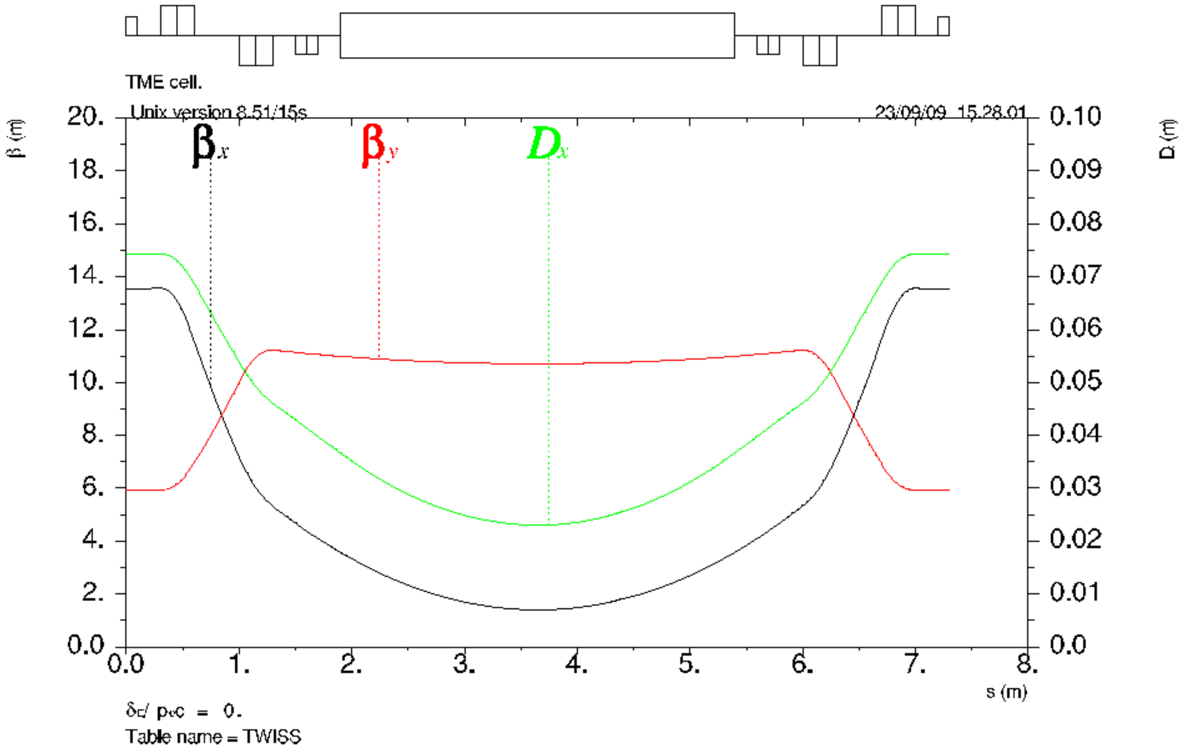
6 chromatic sextupoles, 4 families

low β ID

high β ID

- Two standard cells are combined into one supercell with a low and high ID beta: $\beta_{x,y}$ = 3.00, 6.07 m and $\beta_{x,y}$ = 16.04, 6.27 m.
- Phase advance is optimized for compensation of both sextupole and octupole driving terms and maximum dynamic aperture: $\mu_x/2\pi = 1.5+3/128$, $\mu_y = \mu_x/3$.
- Harmonic sextupoles are added for further reduction of the resonance effects and amplitude dependent tune spread.

TME cell

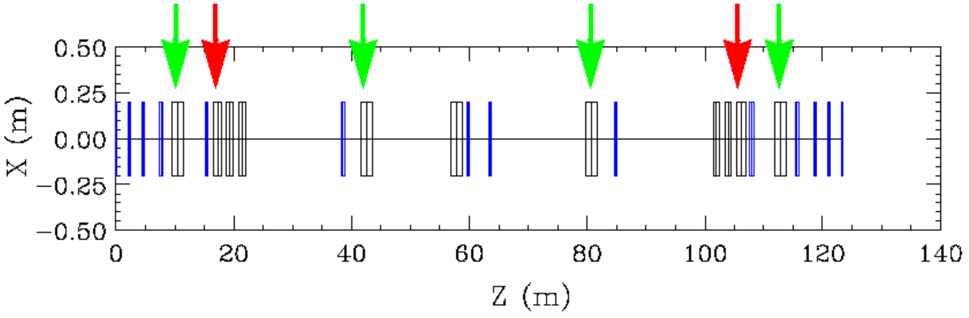


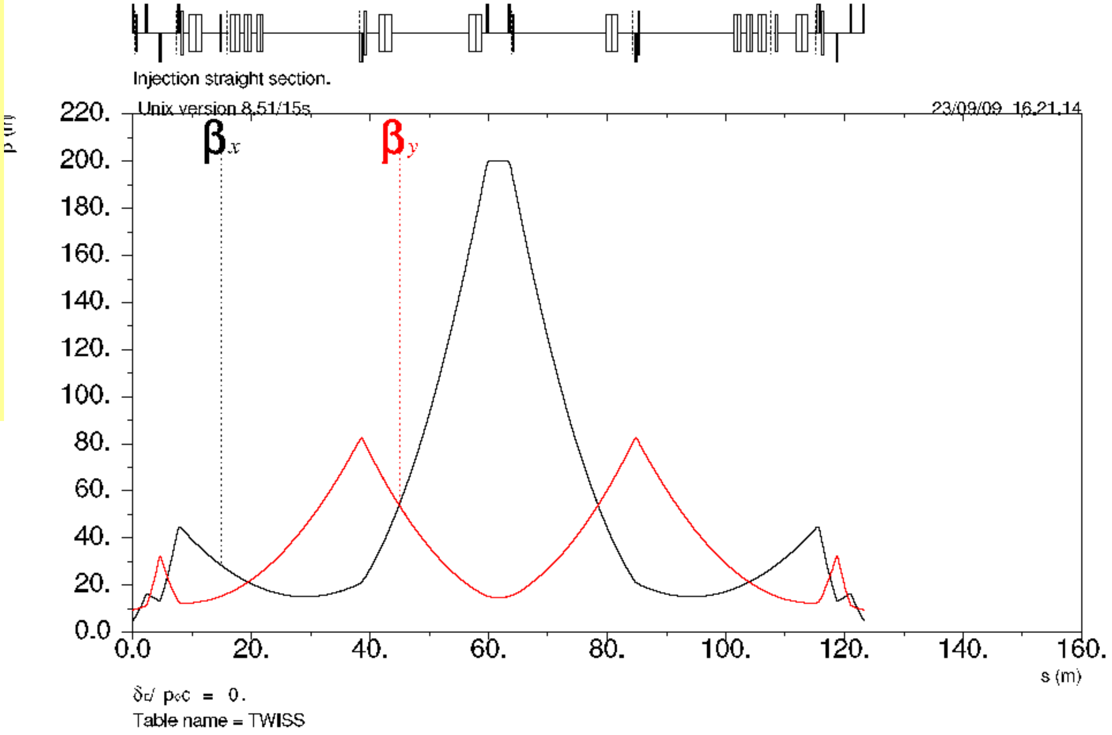
- 7.6 m cell with ~0.1 nm-rad intrinsic emittance.
- 32 standard and 2 matching cells per arc.
- X and Y phase advance is set near 3π/4 and π/4 for compensation of sextupole and octupole effects and maximum dynamic aperture.
- Optimized for maximum momentum compaction.

Injection straight

- Existing PEP-II injection straight with 4 additional quads.
- PEP-II vertical injection optics is changed to horizontal to avoid vertical injection oscillations in the IDs.
- Large horizontal β_x = 200 m at septum for larger injection acceptance.
- Existing 4 DC bump magnets and 2 fast kickers.

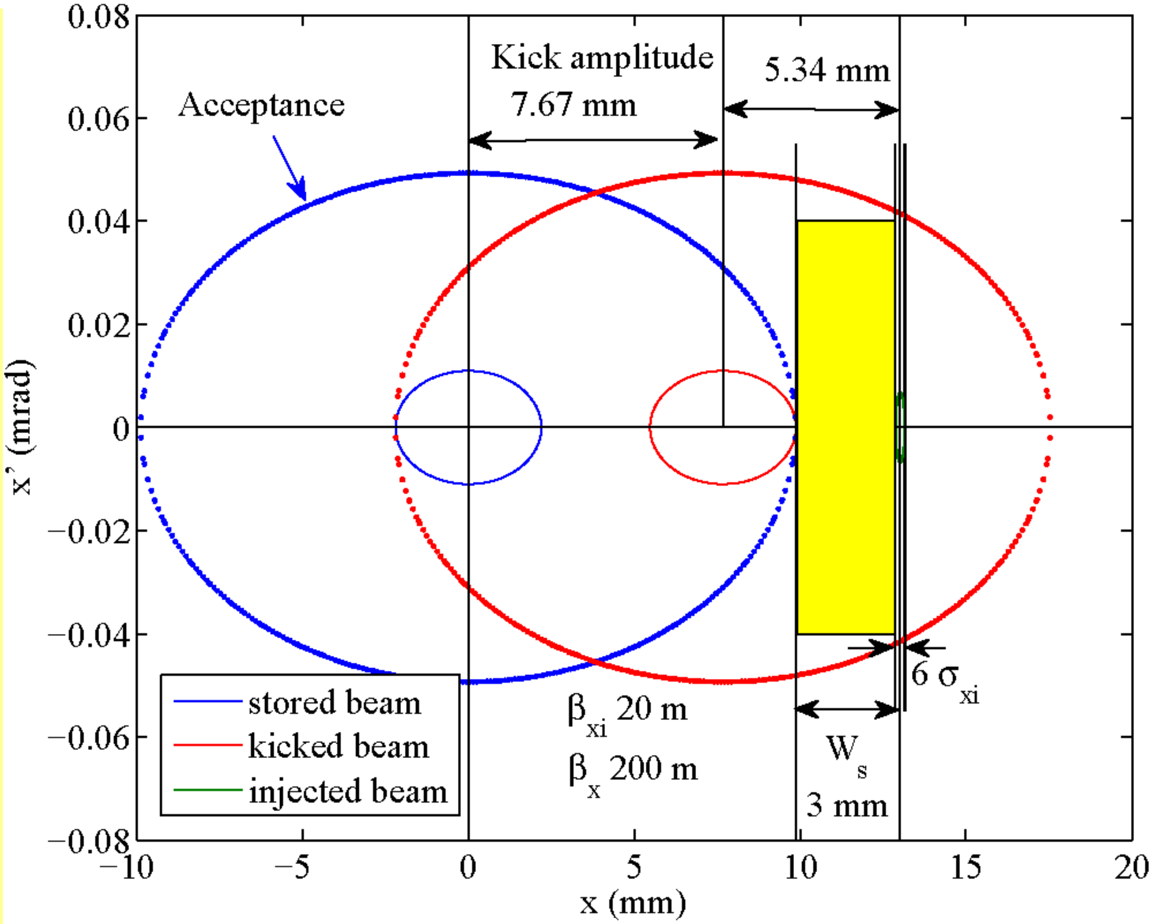
4 DC bump magnets (green) and 2 kickers (red)



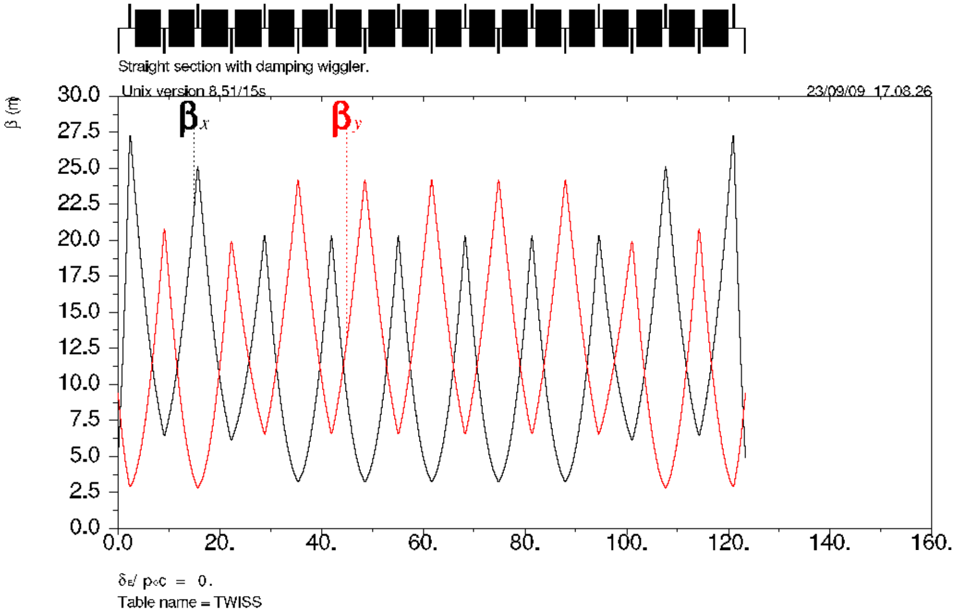


Phase space diagram at injection point

- **Conventional off-axis injection using SLAC linac.**
- **3 mm septum placed at edge of stored beam dynamic aperture (~10 mm).**
- **Stored beam placed at 8σ_x from the septum (2.2 mm w/o wiggler).**
- **Minimal size for injected beam: 6σ_{xi} .**
- **Assume low emittance injector ($\gamma\varepsilon$ ~ 1 μm-rad).**
- **Injection beta optimized for a best match to stored beam acceptance phase space.**
- **Kick amplitude: 7.67 mm.**
- **Minimal required dynamic aperture: 5.5 mm.**

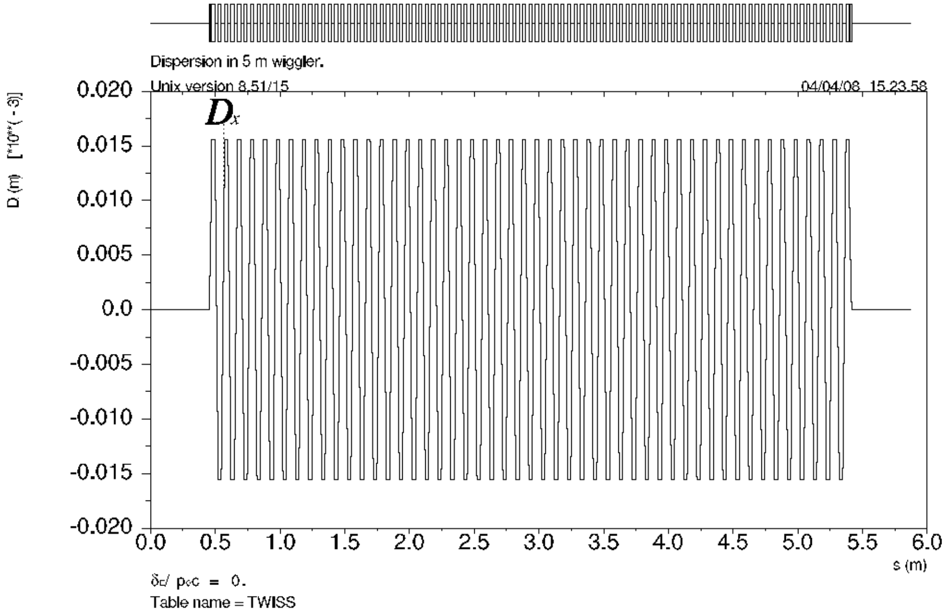


Wiggler straight



- DBA and TME arcs without wiggler yield ε = 0.38 nm-rad
- 89.3 m wiggler is inserted in one long straight section yielding ε = 0.086 nm-rad.
- Wiggler is split in 18 identical sections to fit FODO cells.

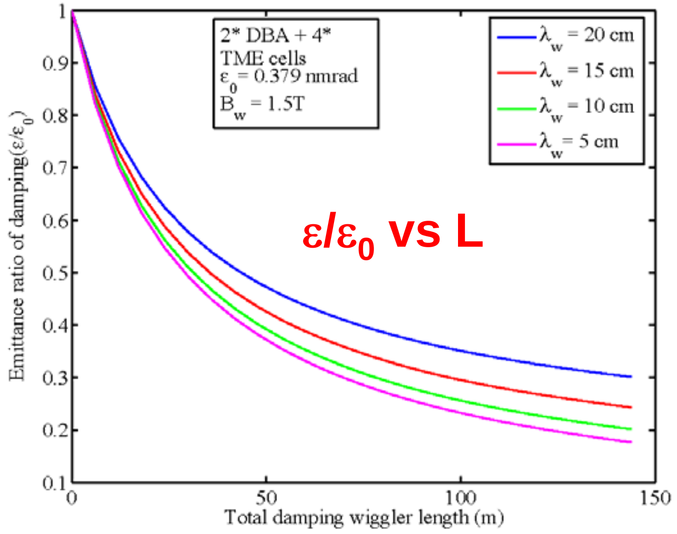
Dispersion in ~5 m wiggler section



- Wiggler parameters optimized for strong damping effect: 10 cm period, 1.5 T field.
- The long wiggler can be split in half and placed in two separate straights for better handling of radiated power (4.7 MW at 1.5 A).

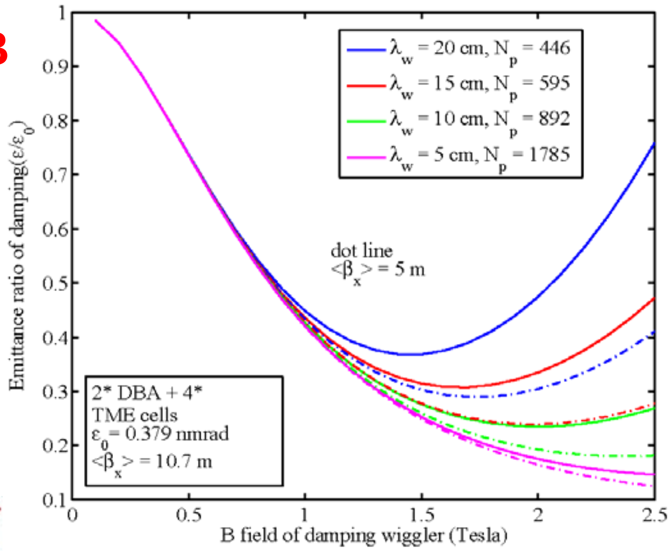
Optimization of wiggler parameters

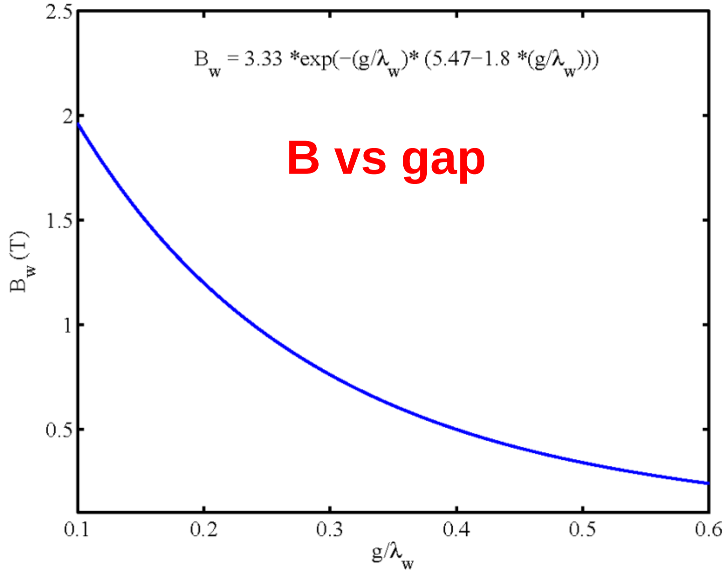
Based on analytic formulas:
- **Most efficient damping for L < 100 m.**
- **More damping with a shorter period, higher field and lower β_x, but the rate of reduction gradually decreases.**
- **High peak field requires a smaller gap which reduces vertical acceptance and increases resistive wall impedance.**
- **Selected parameters: 10 cm period, 1.5 T peak field, 89.3 m total length.**



$\varepsilon/\varepsilon_0$ vs L

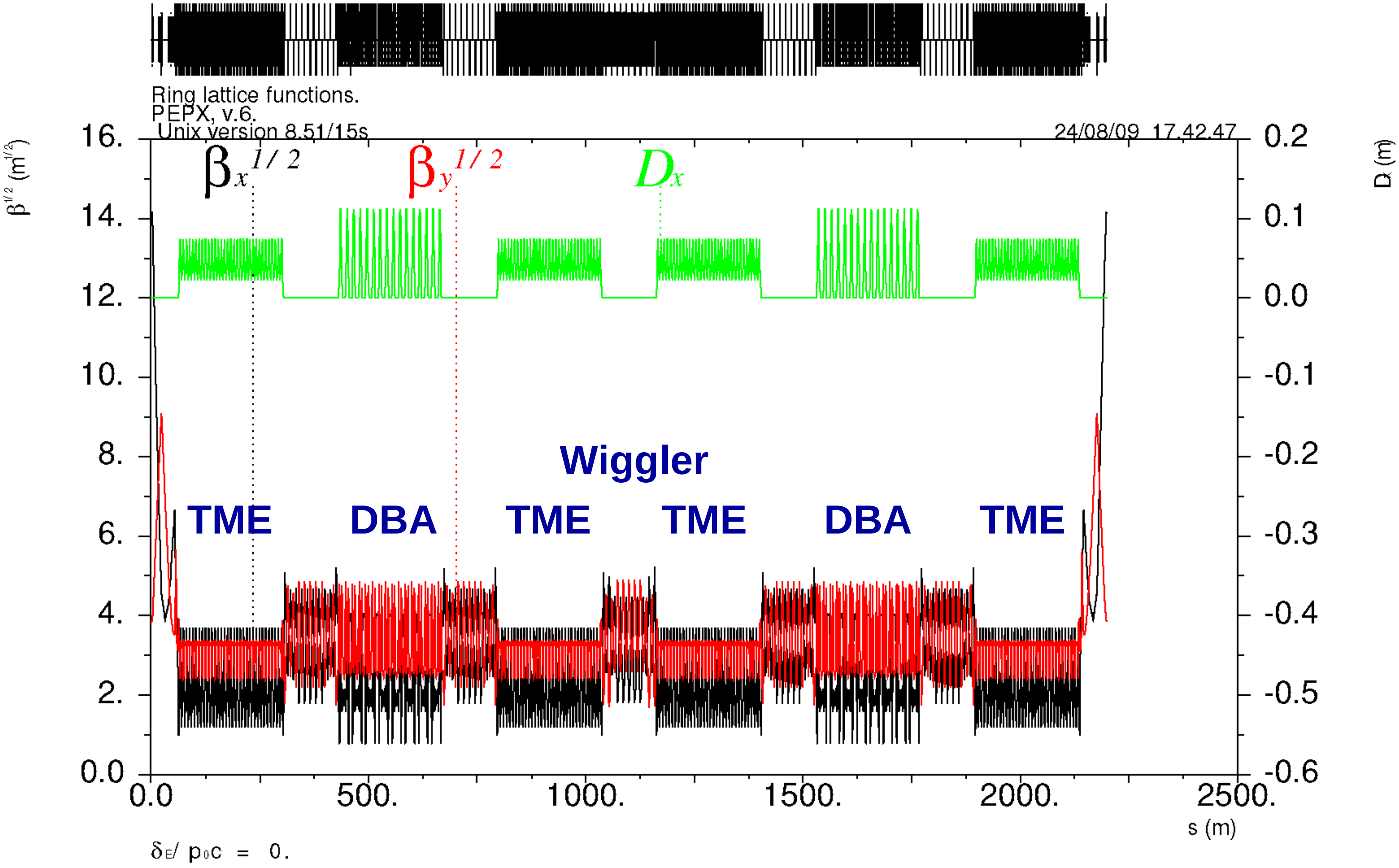
$\varepsilon/\varepsilon_0$ vs B





B vs gap

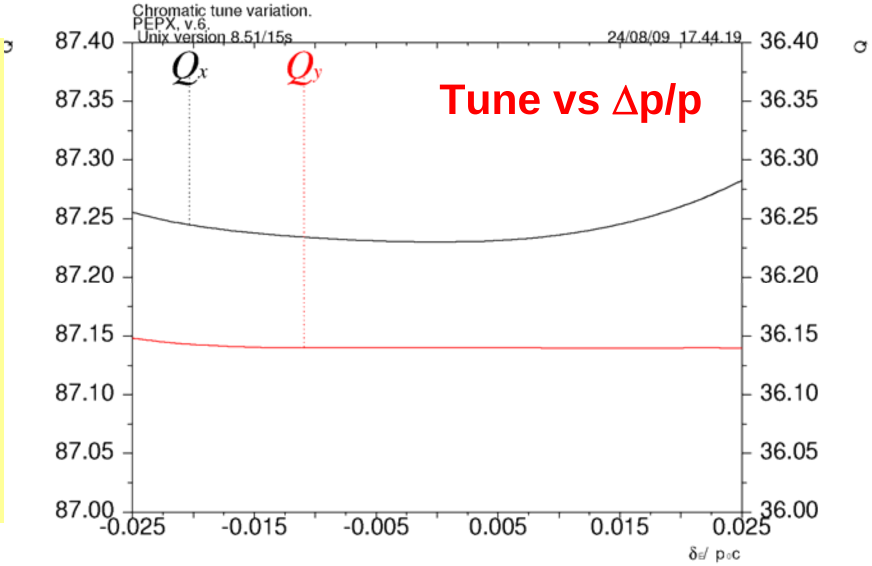
Complete ring lattice



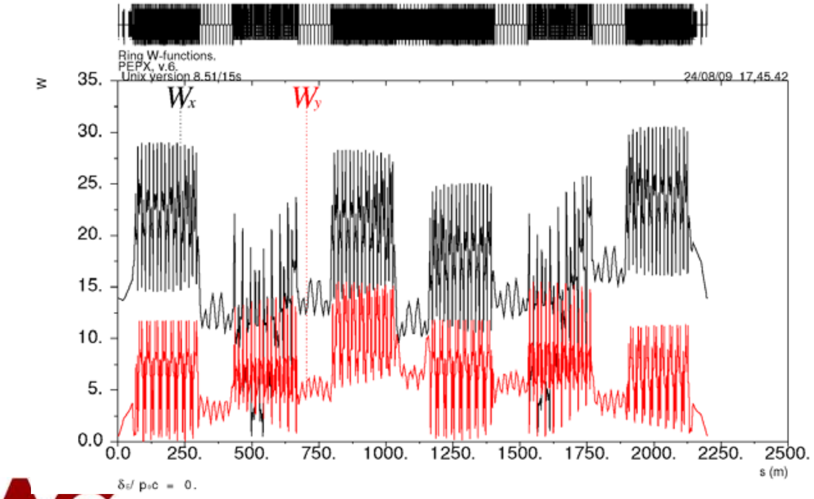
Symmetric locations of DBA and TME arcs and mirror symmetry with respect to injection point.

Chromatic correction

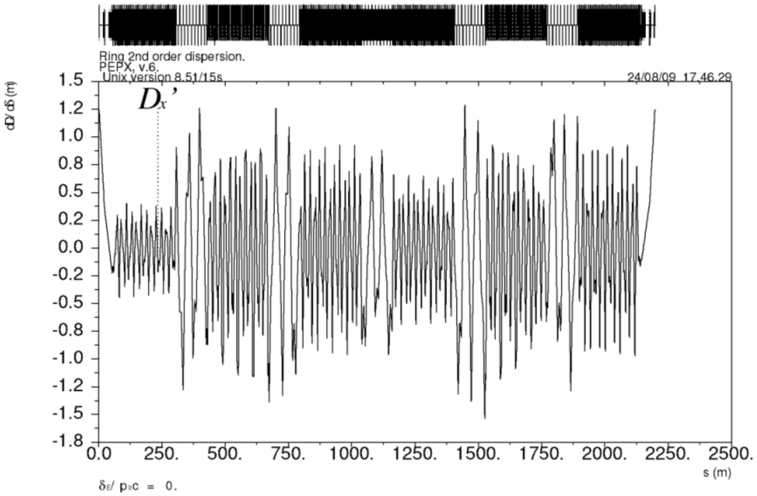
- **DBA and TME sextupole positions and strengths as well as cell and long straight phase advance are optimized for maximum energy dependent aperture.**
- **Optimization of non-linear chromatic terms using MAD HARMON and empiric optimization of momentum dynamic aperture in LEGO tracking simulations.**


Tune vs Δp/p

W-functions

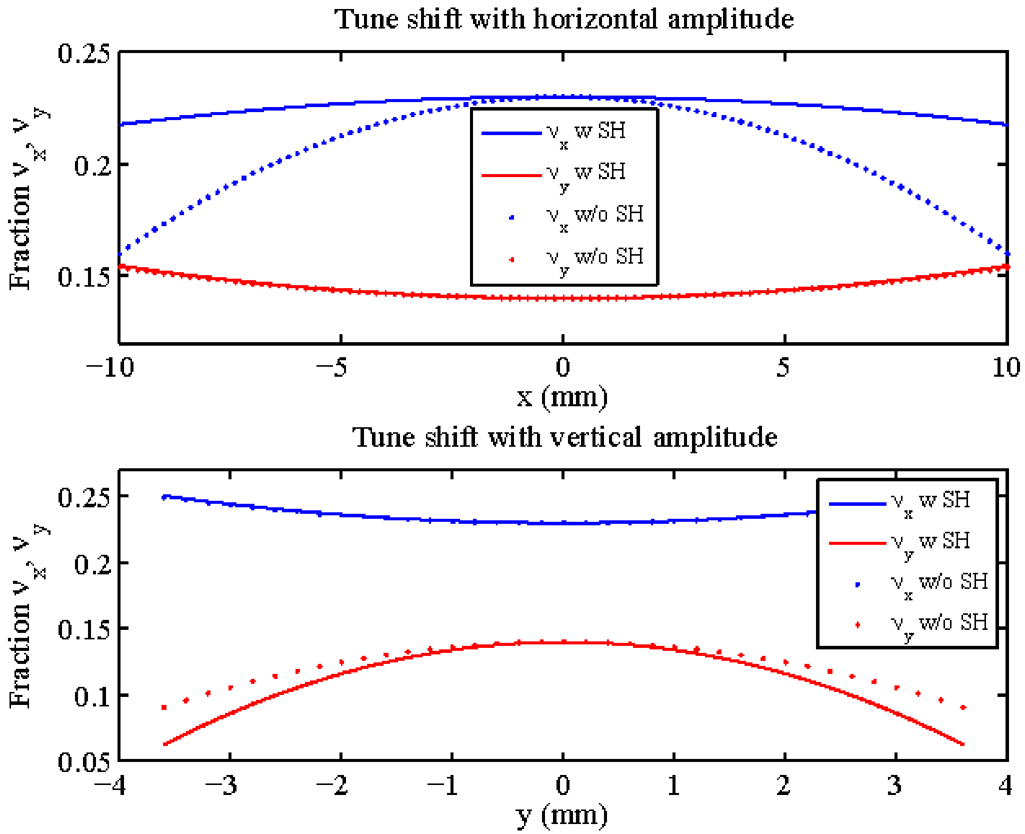


2nd order dispersion



Tune shift with amplitude

- 2 weak harmonic sextupoles near each ID straight reduce the amplitude dependent tune shift and resonance driving terms generated by chromatic sextupoles and increase dynamic aperture for horizontal injection.
- Minor adjustment will be needed to accommodate realistic length harmonic sextupoles.



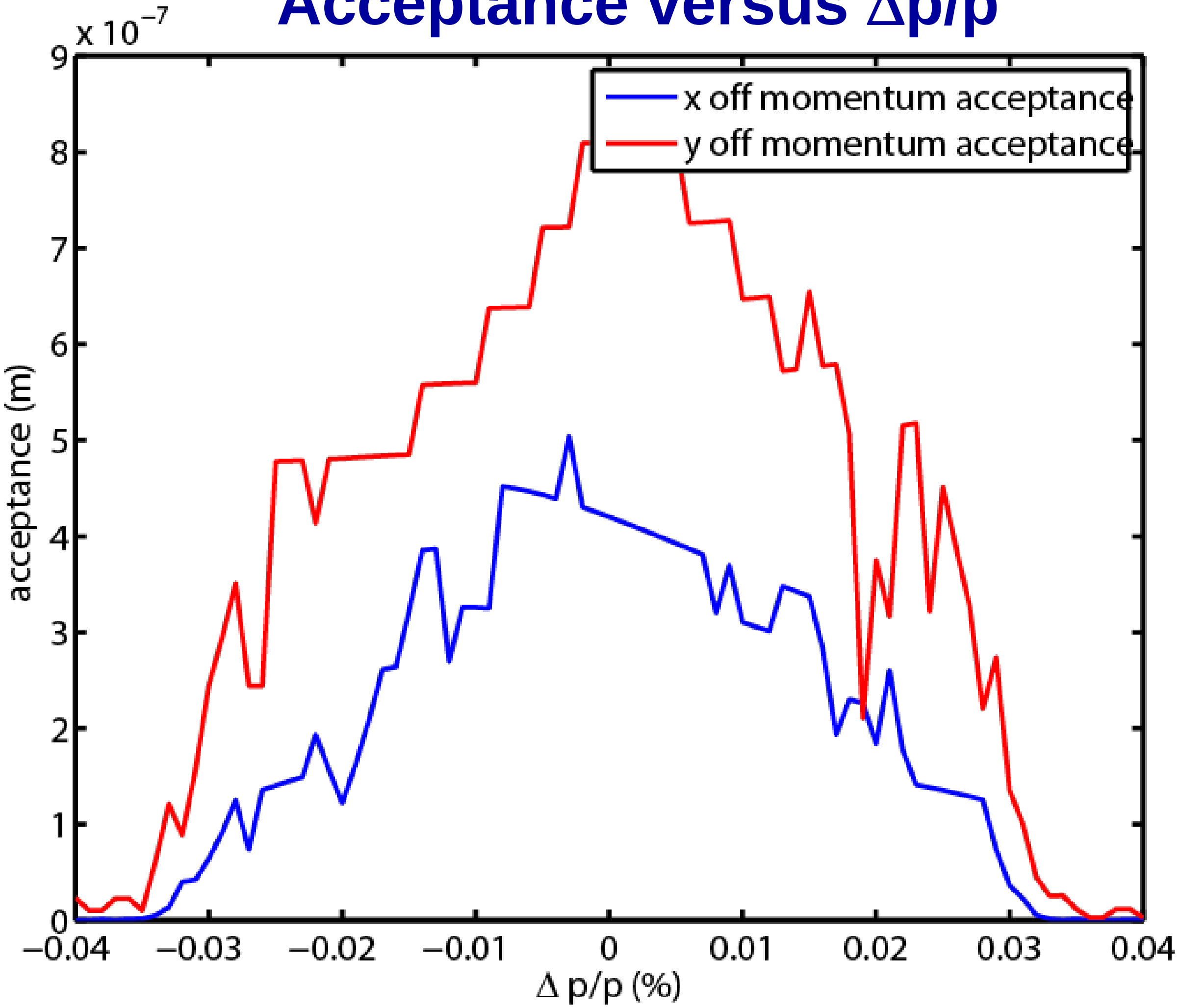
	$d\nu_x/d\epsilon_x$	$d\nu_y/d\epsilon_y$	$d\nu_y/d\epsilon_x$
with SH1, SH2	-2.41×10^4	-1.10×10^5	3.02×10^4
without SH1, SH2	-1.39×10^5	-6.94×10^4	2.86×10^4

Parameters with wiggler on and off

Parameter	**Wiggler on**	Wiggler off
Energy, E_0 [GeV]	**4.5**	
Circumference, C [m]	**2199.32**	
Emittance, ε_x [pm-rad, 0 current]	**85.7**	379
Beam current, I [A]	**1.5**	
Harmonic number, h	**3492**	
Number of bunches, n_b	**3154**	
Bunch length, σ_z [mm]	**3.0**	
Energy spread, σ_δ	**1.14×10^{-3}**	0.55×10^{-3}
Momentum compaction, α_p	**5.81×10^{-5}**	5.81×10^{-5}
Tunes, $\nu_x/\nu_y/\nu_s$	**87.23 / 36.14 / 0.0077**	87.23 / 36.14 / 0.0037
Damping times, $\tau_x/\tau_y/\tau_s$ [ms]	**20.3 / 21.2 / 10.8**	101 / 127 / 73
Energy loss, U_0 [MeV/turn]	**3.12**	0.52
RF voltage, V_{RF} [MV]	**8.9**	2.0
β_x/β_y at ID center, [m] (low/high β)	**[3.00 / 6.07], [16.04 / 6.27]**	

Momentum aperture

Acceptance versus Δp/p



Obtained in LEGO dynamic aperture tracking w/o errors

IBS emittance and Touschek lifetime

κ	ϵ_{x0} [pm]	ϵ_x [pm]	ϵ_y [pm]	σ_p [10^{-3}]	σ_z [mm]	$\mathcal{T}$ [min]
.049	82.	164.	8.0	1.20	3.16	29.
1.	43.	69.	69.	1.17	3.08	92.

1% current stability will require top-up injection every few seconds

PEP-X parameters used for IBS calculations

Parameter	Value	Units
Energy, E	4.5	GeV
Circumference, C	2199.	m
Average current, I	1.5	A
Bunch population, N_b	2.18	10^{10}
Number of bunches, M	3154	
Relative rms energy spread, σ_{p0}	1.14	10^{-3}
Rms bunch length, σ_{z0}	3.0	mm
Horiz. emittance parameter, ϵ_{x00}	85.7	pm
Horiz. radiation damping time, τ_x	13.5	ms
Long. radiation damping time, τ_p	7.2	ms

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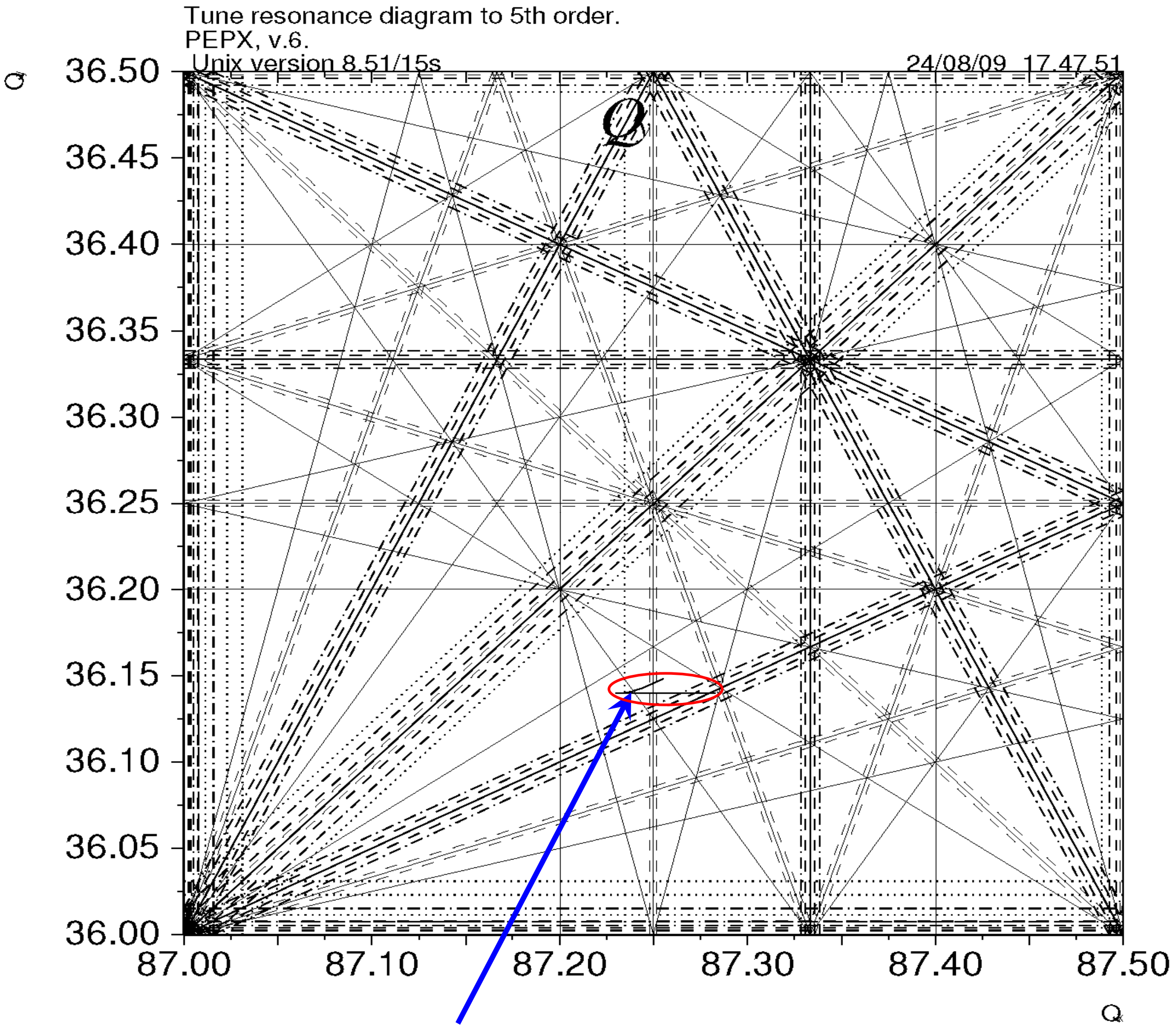
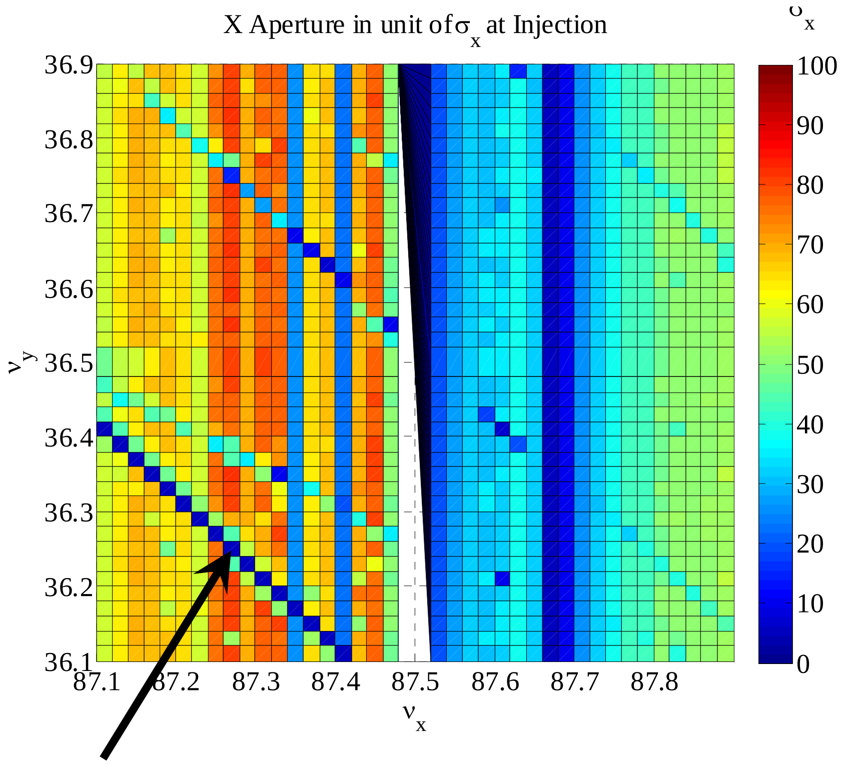
PEP-X working point on tune diagram



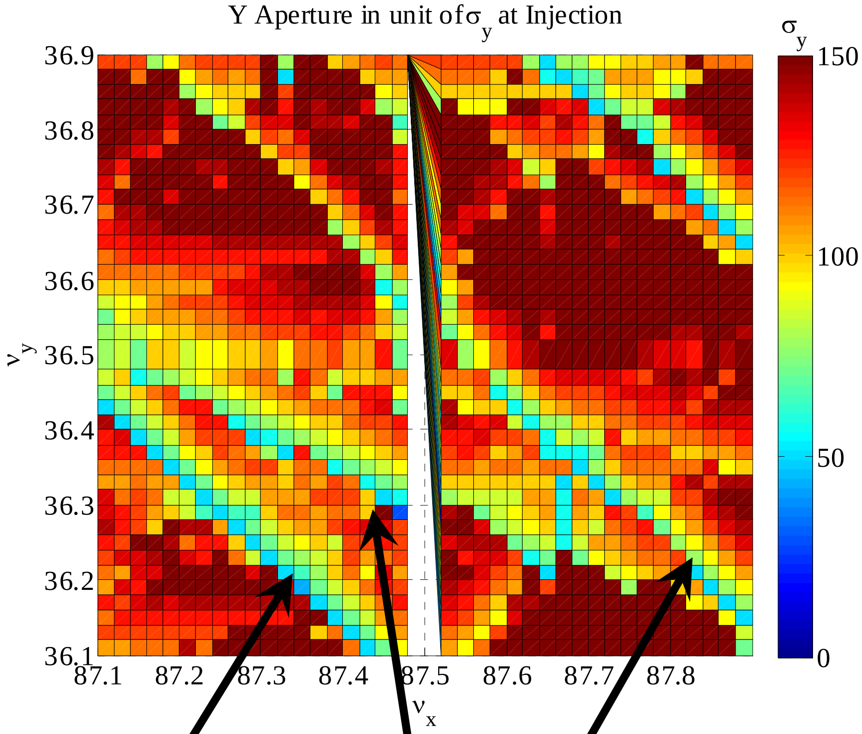
$Q_{x,y}$ = 87.23, 36.14 (Red: chromatic tune spread for δ=±2.5%)

Dynamic aperture tune scan

Horizontal



Vertical



$2\nu_x+2\nu_y=247$

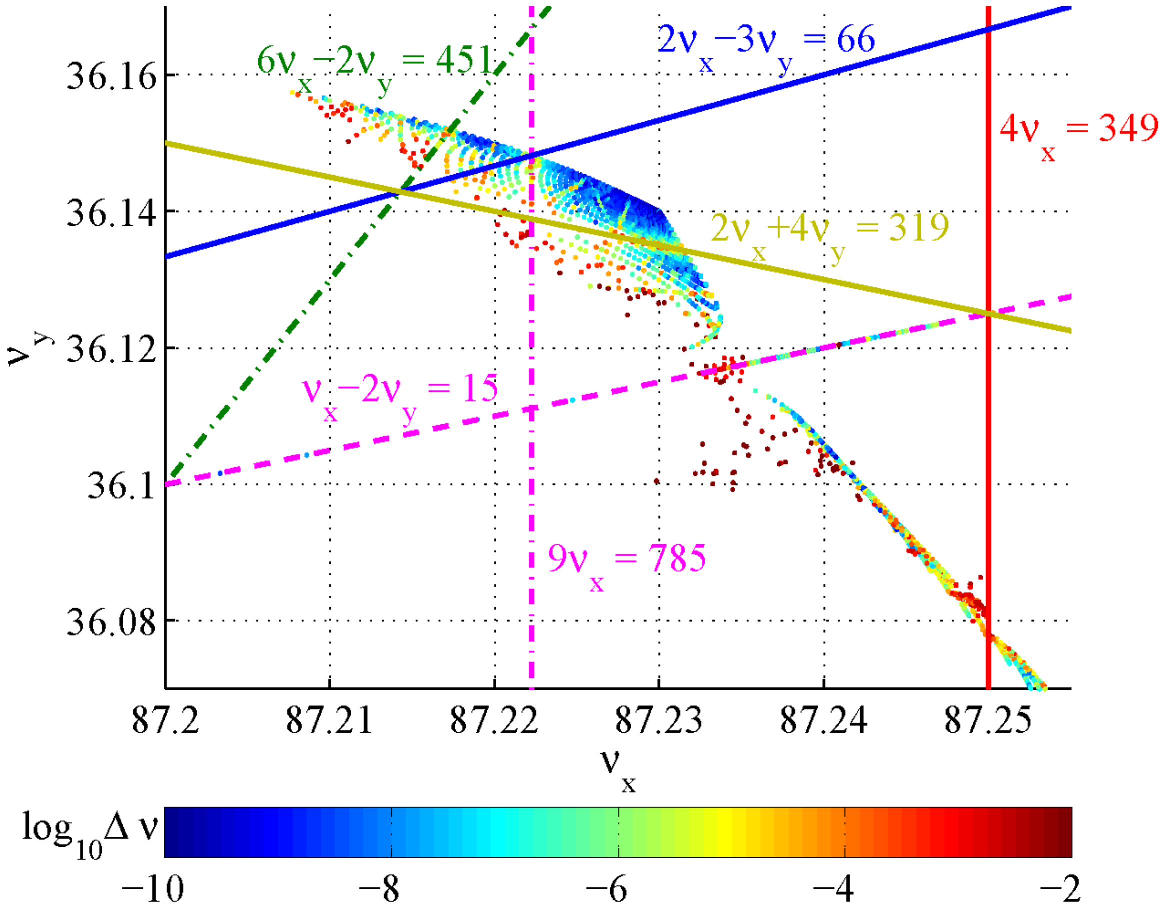
$2\nu_x+2\nu_y=247$

$2\nu_x+2\nu_y=248$

Nominal tune:
ν_x=86.23 and ν_y=36.14

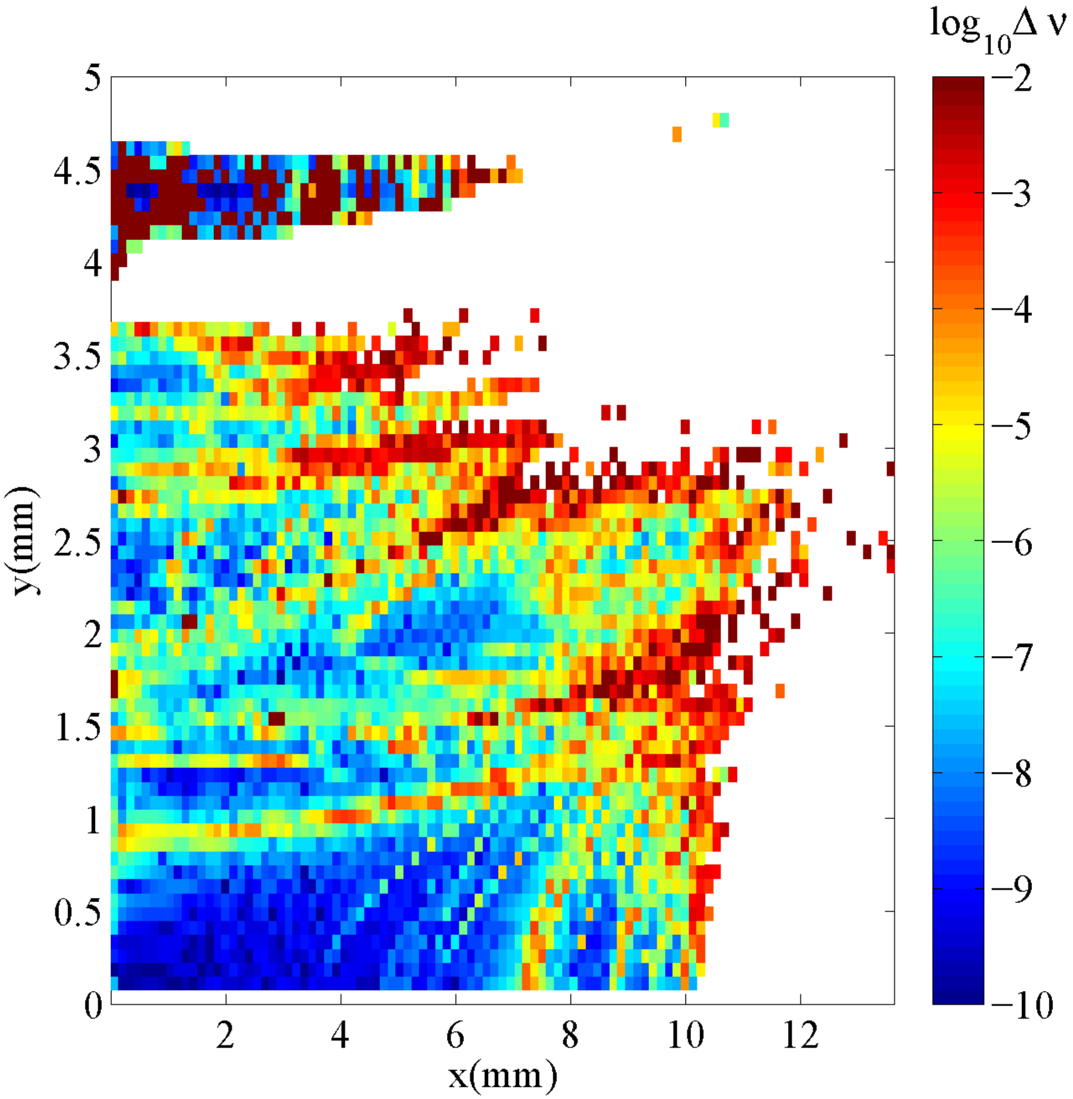
$\nu_x+2\nu_y=160$

Frequency map analysis: tune spread



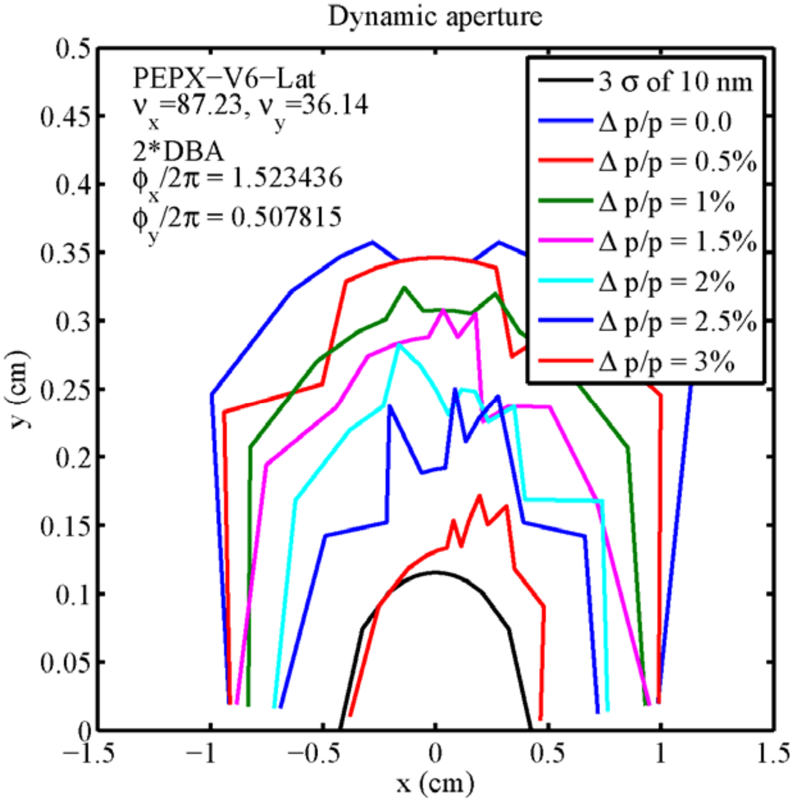
Strong chromatic sextupoles generate high order resonance driving terms

Frequency map analysis: dynamic aperture

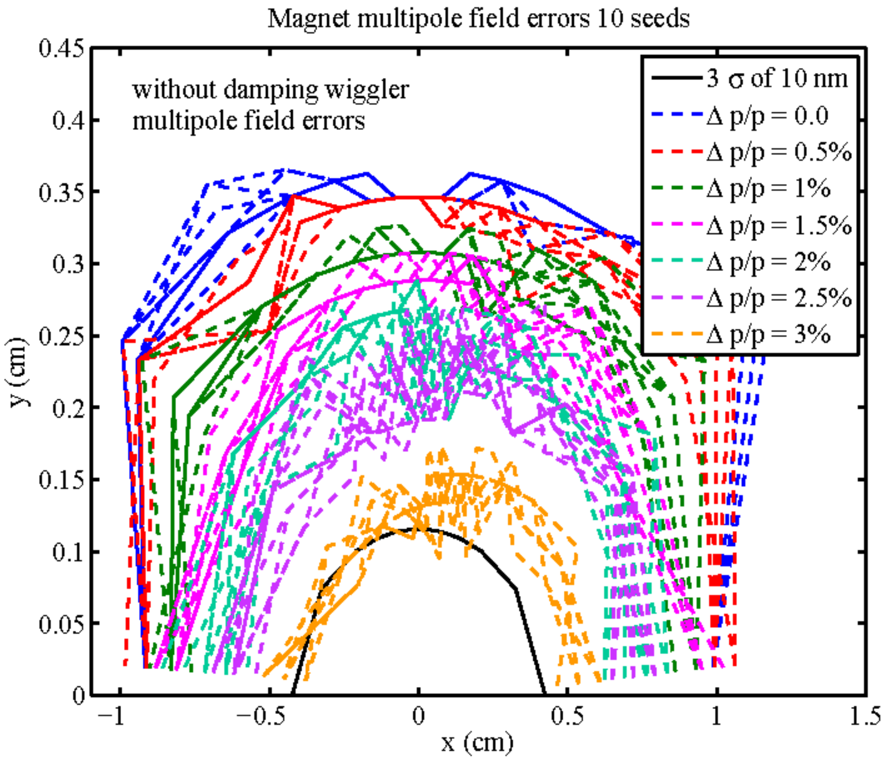


Dynamic aperture (1)

Without errors



PEP-II multipole field errors only (10 seeds)



- Δp/p up to 3%
- Effect of multipole errors is small

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Dynamic aperture (2)

Multipole + field + quad misalignment

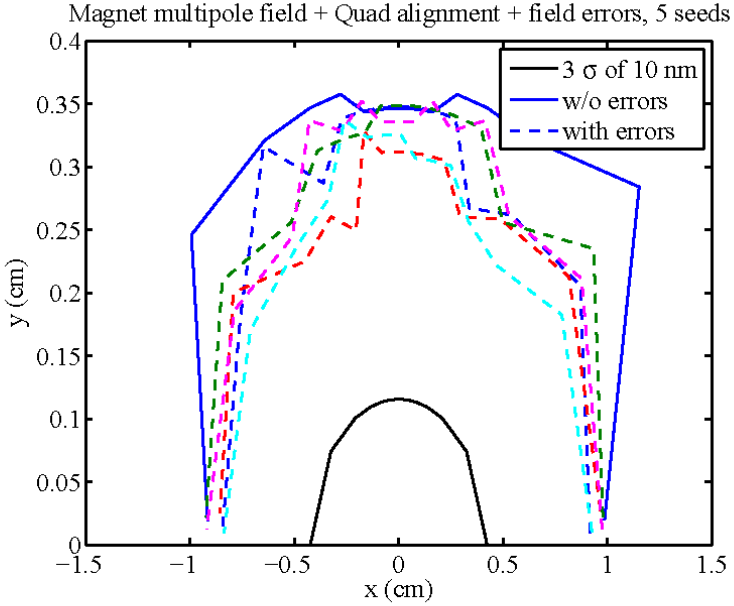
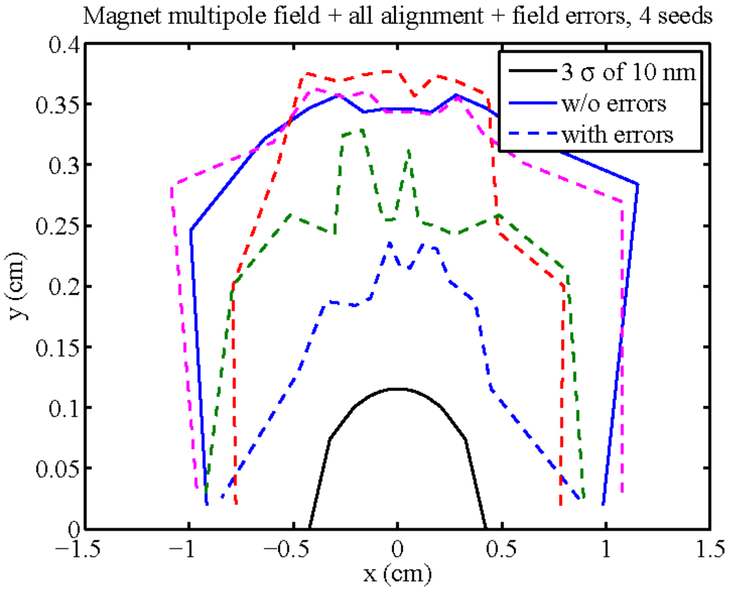


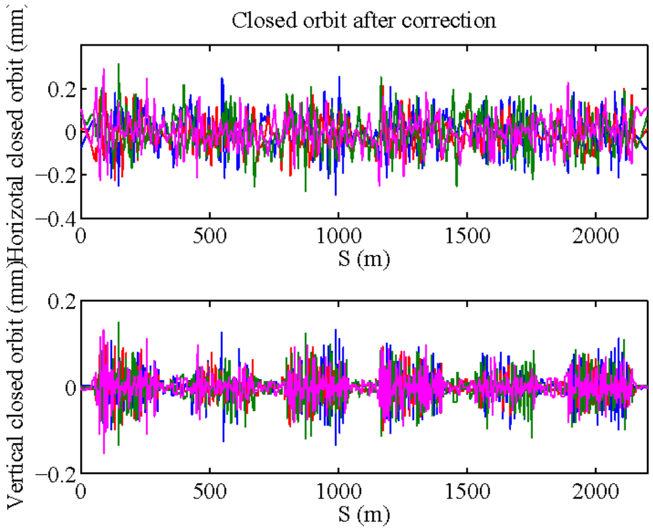
Table 3.3: RMS values of transverse alignment tolerances and field errors.

	$\Delta x (\mu\text{m})$	$\Delta y\ (\mu\text{m})$	Roll (m-rad)	$\frac{\Delta B_N}{B_N}$
Dipole	100	100	0.5	1×10^{-4}
Quadrupole	30	30	0.2	5×10^{-4}
Sextupole	30	30	0.2	5×10^{-4}

- **Quad misalignment is ok.**
- **Sextupole misalignment needs better orbit correction at sextupoles.**
- **Horizontal injection aperture is ok.**

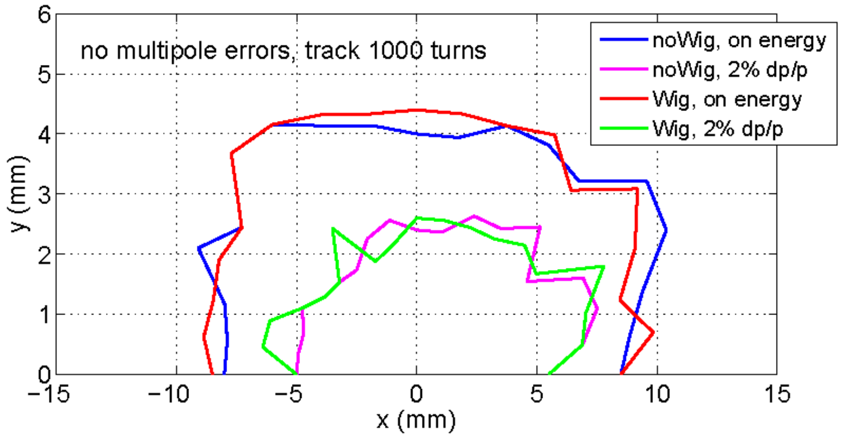
Multipole + field + all misalignment



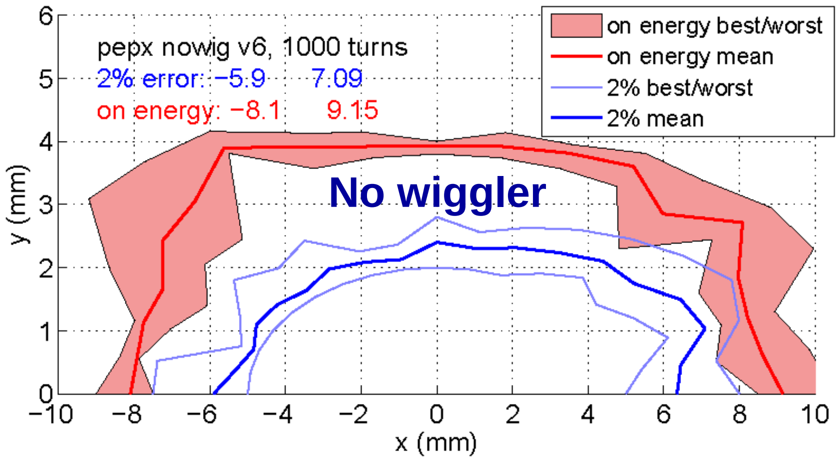


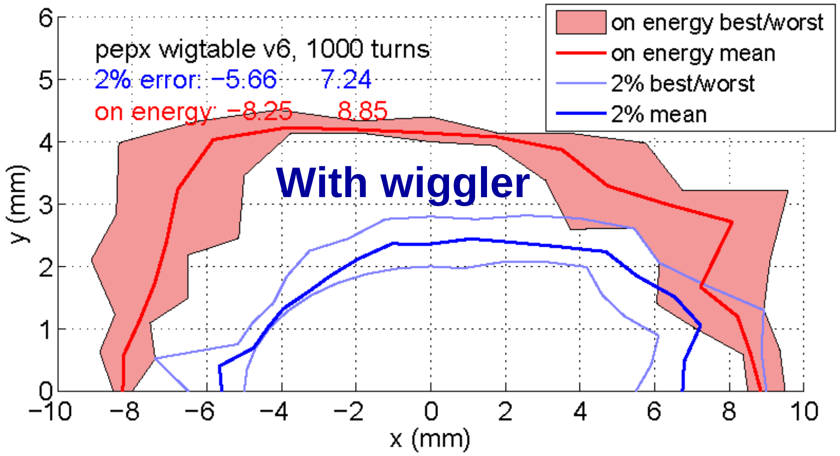
Wiggler effect on dynamic aperture

No magnet errors, with and w/o wiggler



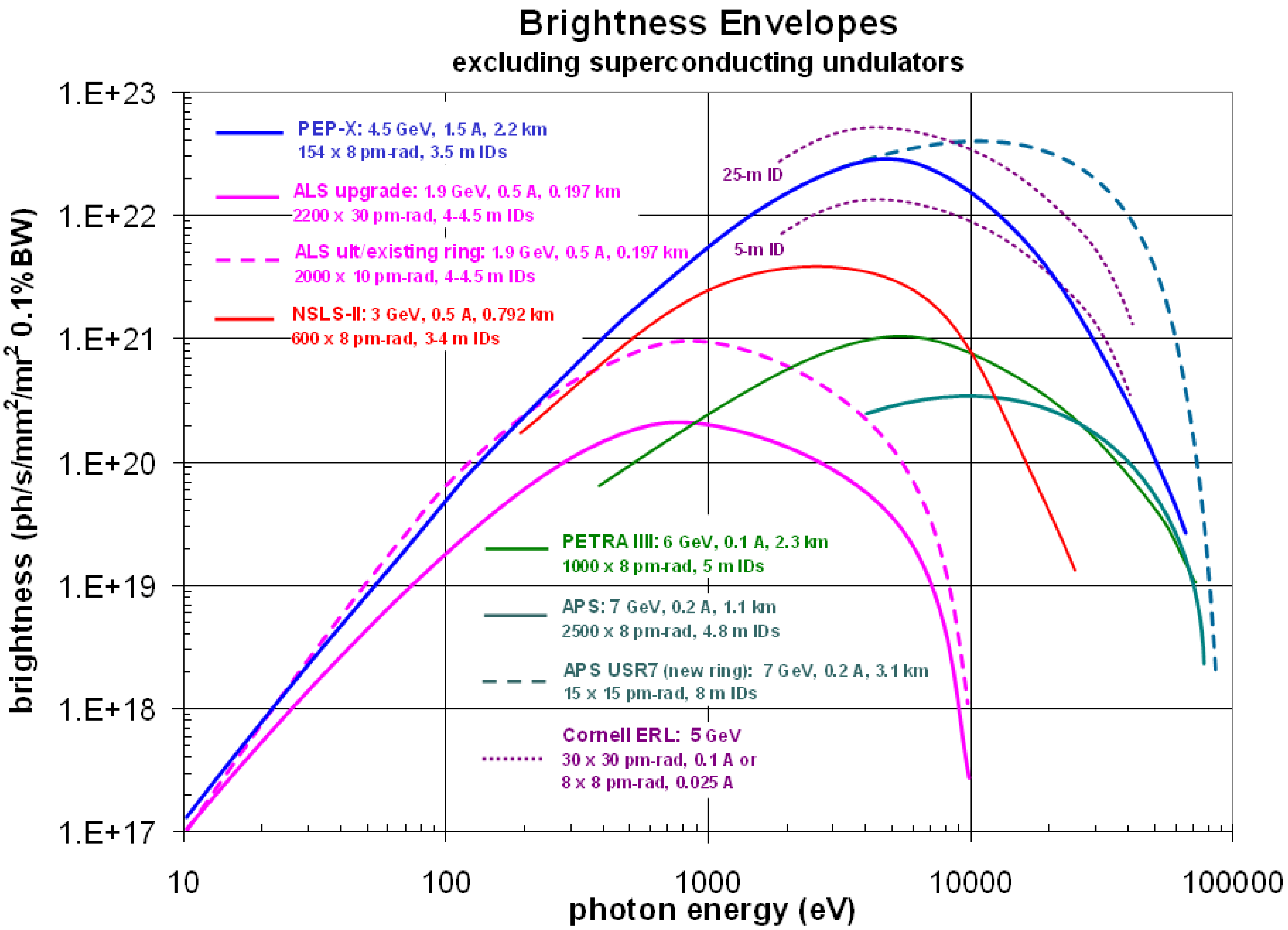
With magnet errors





- **Wiggler intrinsic non-linear field is studied using tracking table method (insert kick maps in the wiggler) and tracking simulation with AT code.**
- **The resultant effect on dynamic aperture is sufficiently small, both without and with magnet errors.**

PEP-X brightness



Brightness Envelopes
excluding superconducting undulators

Summary

- The baseline lattice for PEP-X is designed.
- It uses DBA and TME cell optics and ~90 m damping wiggler yielding 30 ID straights and an ultra-low emittance.
- Photon brightness of ~10^{22} (ph/s/mm^2/mrad^2/0.1 % BW) can be reached at 1.5 A for 3.5 m IDs at 10 keV.
- Dynamic aperture is adequate to accommodate a conventional off-axis injection system.
- Work is in progress to define specification for alignment tolerances, to improve the correction schemes, and to further increase momentum aperture.