PEP-X Design and Implications with Damping Ring R&D

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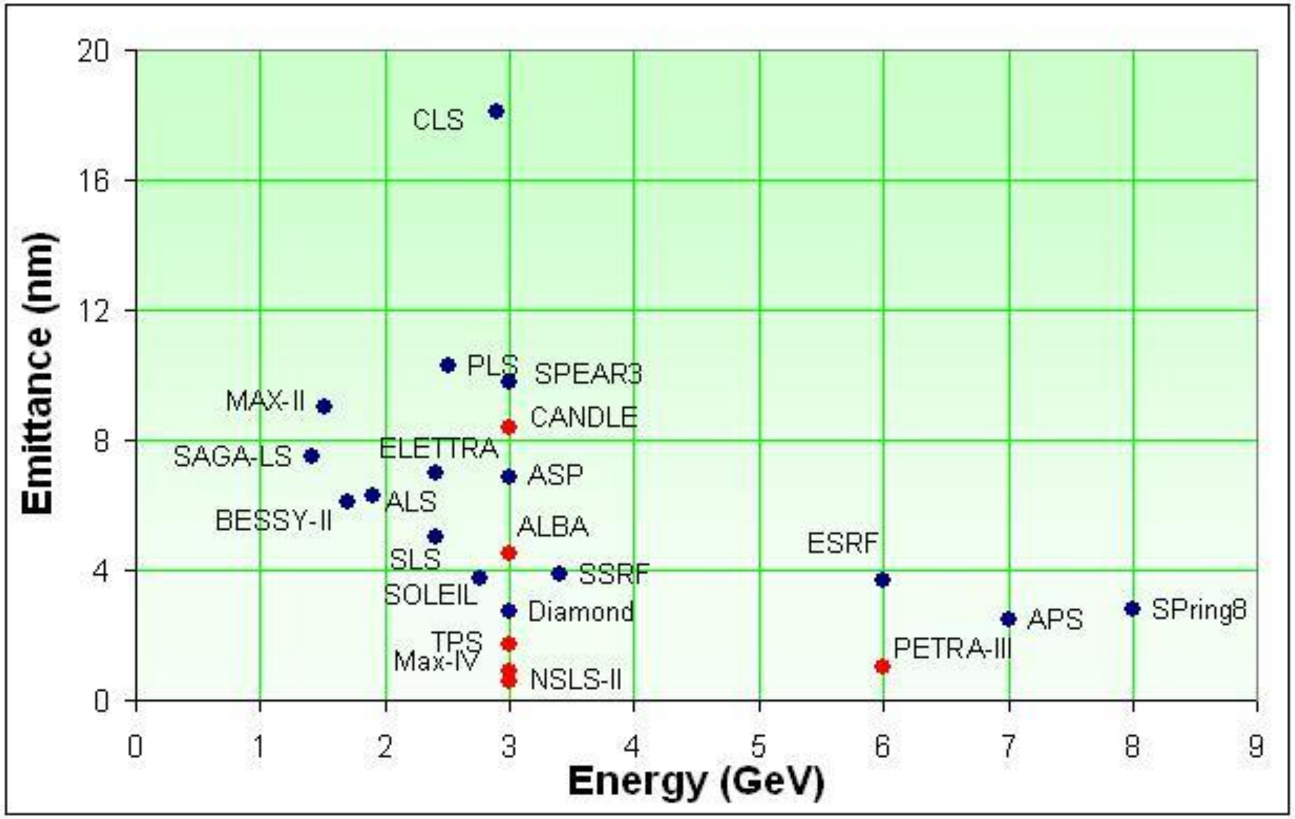
Arlington, TX, USA

3rd Generation Light Sources

Existing

Under construction

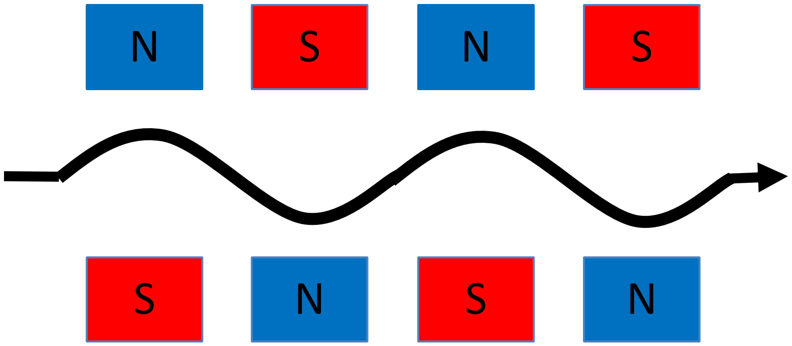
Storage Ring Light Sources



Courtesy of R. Bartolini, Low Emittance Rings Workshop, 2010, CERN

Synchrotron Radiation

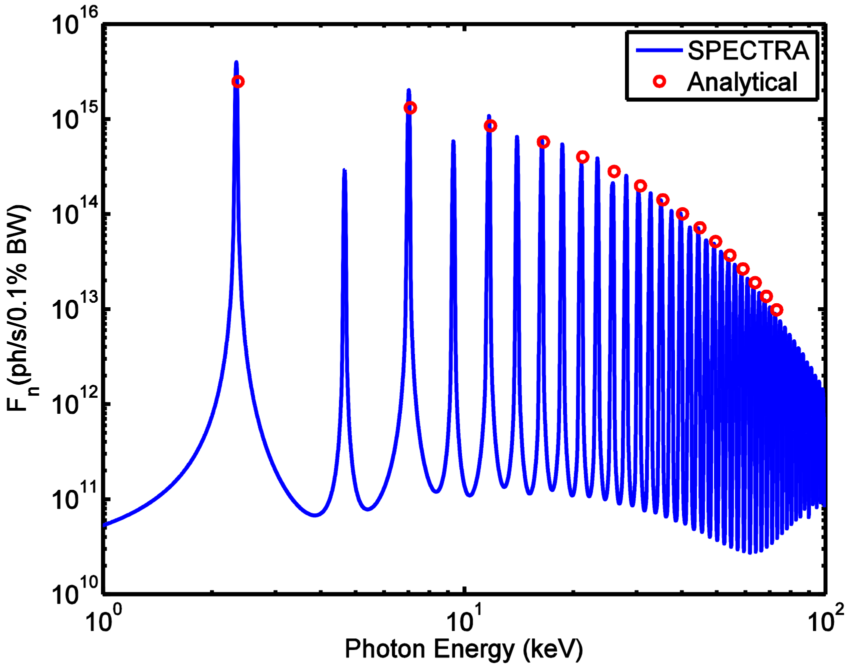
Electron beam in undulator



n^{th} harmonic wavelength:

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}(1+\frac{K^2}{2})$$

Photon spectral flux in 0.1% BW



$$F_n = \frac{\pi}{2}\alpha N_u Q_n(\frac{nK^2}{4+2K^2})\frac{\Delta\omega}{\omega}\frac{I}{e}$$

Spectral Brightness

Brightness of electron beam radiating at nth (odd) harmonics in a undulator is given by

$$B_n = F_n / (4\pi^2 \Sigma_x \Sigma'_x \Sigma_y \Sigma'_y)$$

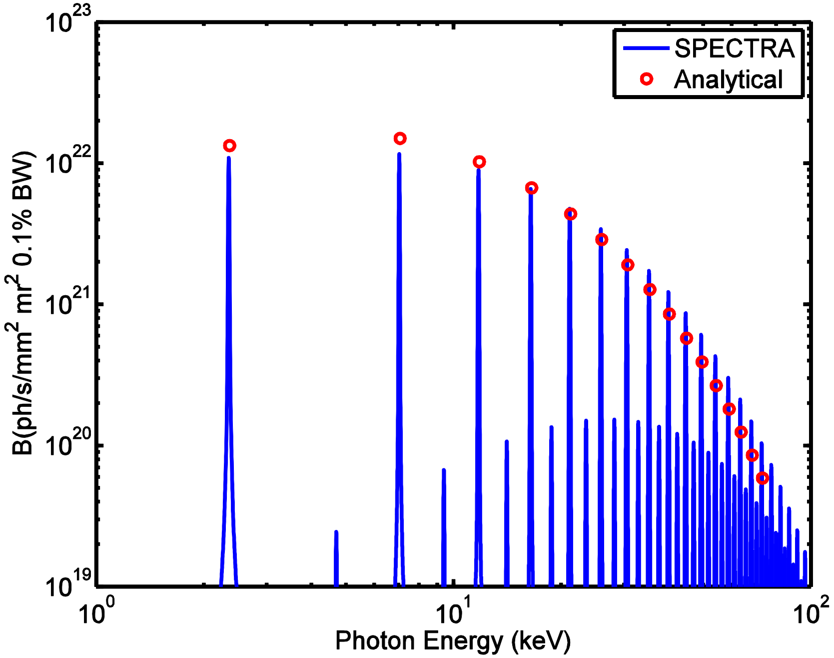
If the electron beam phase space is matched to those of photon's, the brightness becomes optimized

$$B_n = \frac{F_n}{4\pi^2(\varepsilon_x + \lambda_n / 4\pi)(\varepsilon_y + \lambda_n / 4\pi)}$$

Finally, even for zero emittances, there is an ultimate limit for the brightness

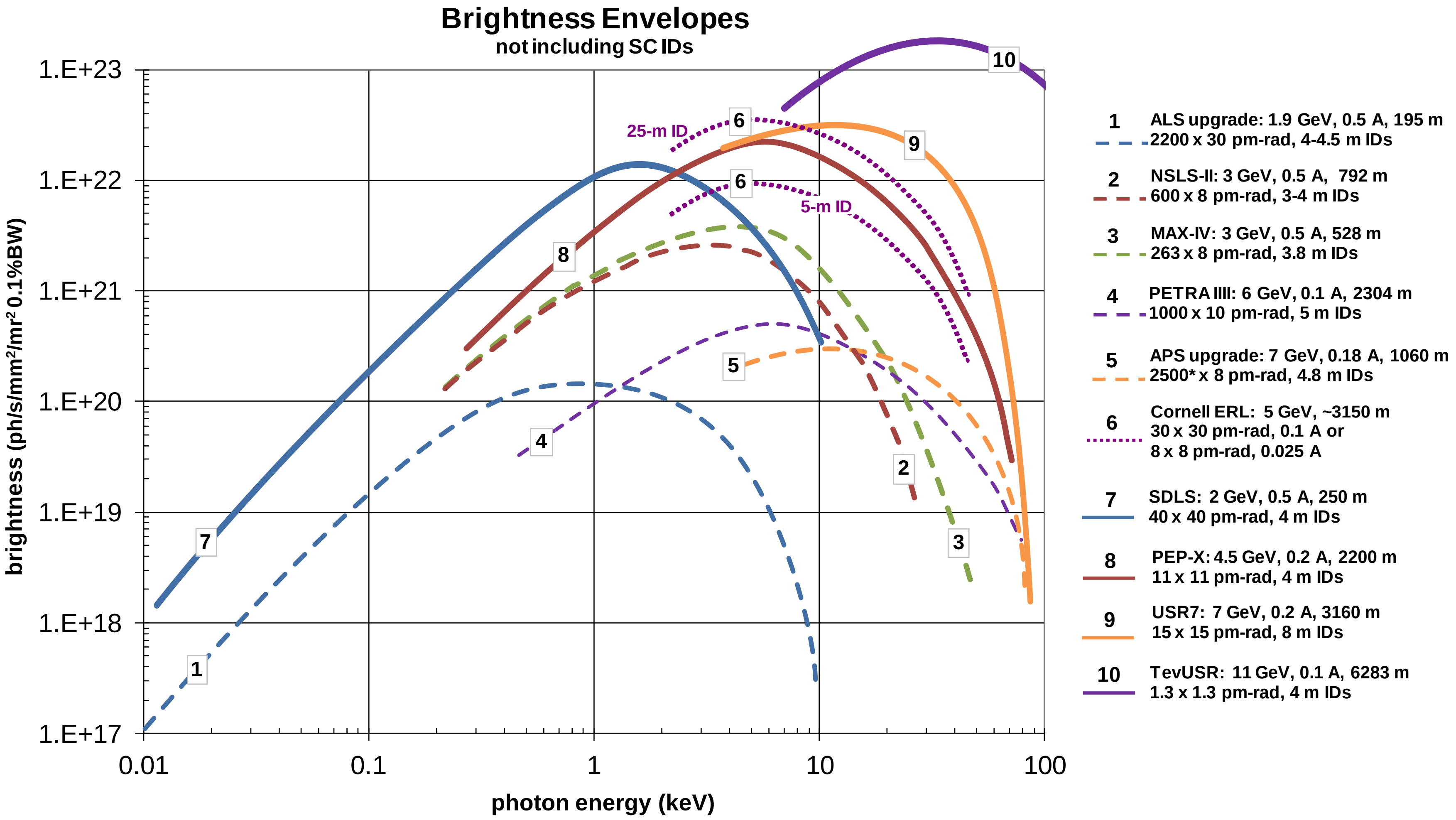
$$B_n = \frac{4F_n}{\lambda_n^2}$$

Spectral brightness of PEP-X



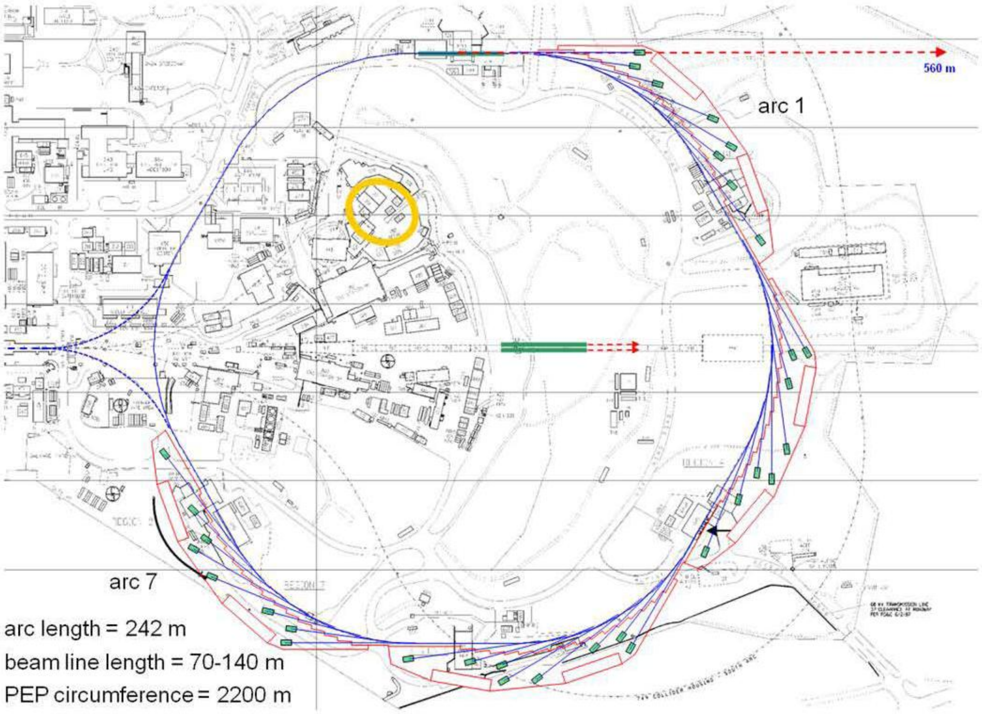
A diffraction limited ring at 1 angstrom or 8 pm-rad emittance

USRs - Spectral Brightness



Courtesy of R. Hettel

PEP-X Layout



To be Built in the PEP tunnel.

Y. Cai, K. Bane, R. Hettel, Y. Nosochkov, M-H. Wang, M. Borland,
Phys. Rev. ST Accel. Beams 15, 054002 (2012)

Parameter	**PEP-X**
Beam energy [GeV]	4.5
Circumference [m]	2200
Current [mA]	200
Betatron tune (H/V)	113.23/65.14
Natural chromaticity (H/V)	-162/-130
Momentum compaction	$4.96\text{x}10^{-5}$
Emittance [pm-rad]	12/12
Bunch length [mm]	3
Energy spread	$1.25\text{x}10^{-3}$
Energy loss per turn [MeV]	2.95
RF voltage [MV]	8.3
RF frequency [MHz]	476
Wiggler length [m]	90
Length of ID straight [m]	5
Beta at ID center (H/V) [m]	4.9/0.8

Energy Spread and Emittance

Balance between the quantum excitation and radiation damping results in an equilibrium Gaussian distribution with relative energy spread σ_δ and horizontal emittance ε_x:

$$\sigma_\delta^2 = \frac{\tau_s}{2E_0^2} < \dot{N}_{ph} < u^2 >>_s = C_q \frac{\gamma^2}{J_s} \frac{\langle 1/\rho^3 \rangle_s}{\langle 1/\rho^2 \rangle_s},$$

$$\varepsilon_x = \frac{\tau_x}{4E_0^2} < \dot{N}_{ph} < u^2 > \mathcal{H}_x >_s = C_q \frac{\gamma^2}{J_x} \frac{\langle \mathcal{H}_x/\rho^3 \rangle_s}{\langle 1/\rho^2 \rangle_s},$$

where and

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc},$$

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2$$

- The quantum constant C_q = 3.8319x10^{-13} m for electron
- γ is the Lorentz factor (energy)

Minimization of Emittance

For an electron ring without damping wigglers, the horizontal emittnace is given by

$$\varepsilon_0 = F_c \frac{C_q \gamma^2}{J_x} \theta^3$$

where F$_c$ is a form factor determined by choice of cell and q is bending angle of dipole magnet in cell. In general, stronger focusing makes F$_c$ smaller. Often there is a minimum achievable value of F$_c$ for any a given type of cell. For example, we have

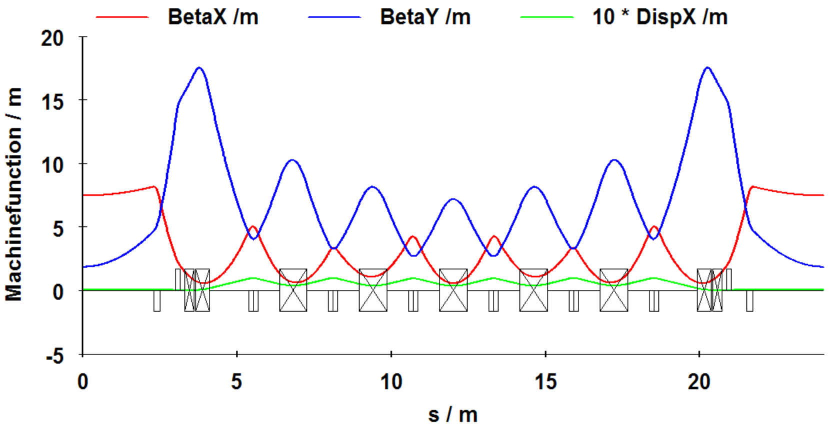
$$F_{min}^{DBA} = \frac{1}{4\sqrt{15}}$$

$$F_{min}^{TME} = \frac{1}{12\sqrt{15}}$$

There is a factor of three between the minimum values of DBA and TME cells. That's the price paid for an achromat, namely fixing the dispersion and its slop at one end of dipole.

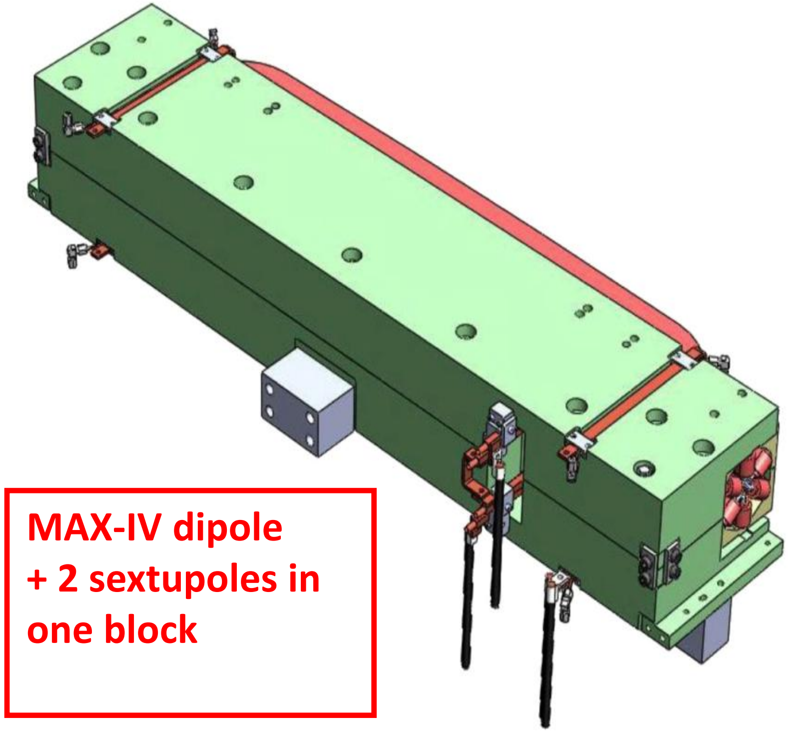
MAX-IV Light Source

7 Bend Achromat, at 3 GeV



Innovations:

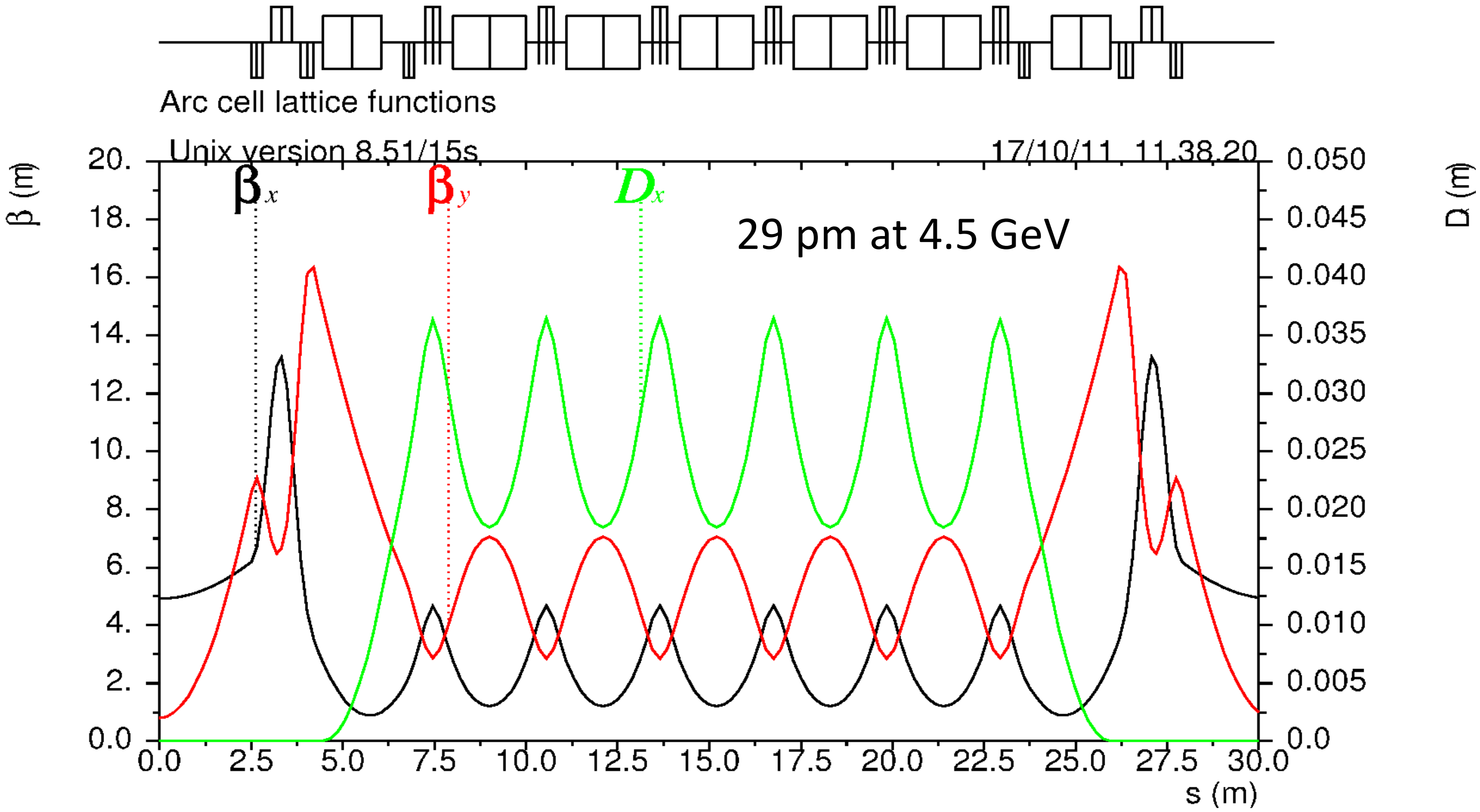
- Multi-bend achromat
- Compact and combined function magnets
- Octupoles



MAX-IV dipole + 2 sextupoles in one block

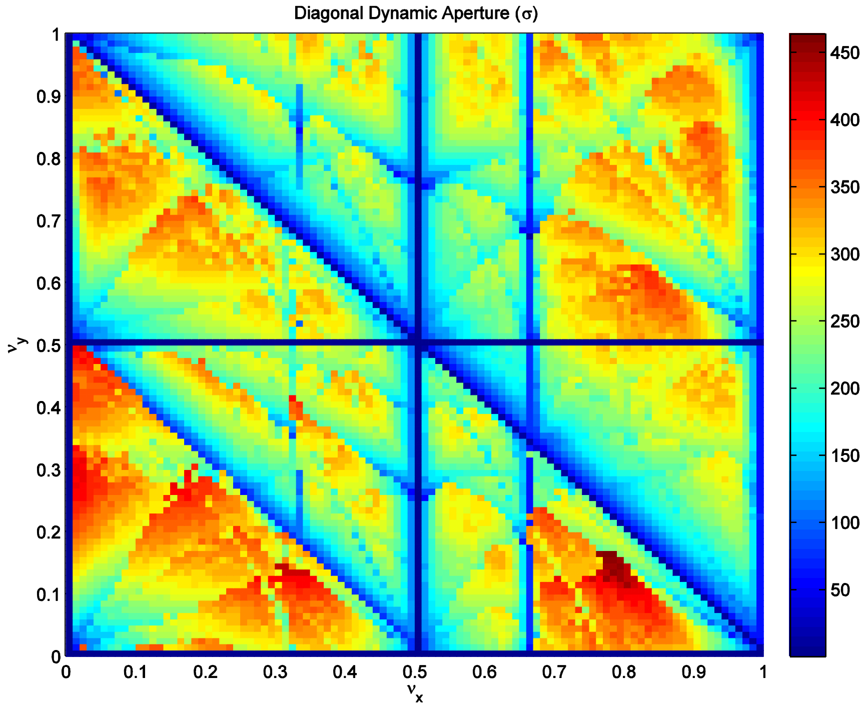
FIG. 6. (Color) Illustration of the unit cell dipole magnet block. The common iron block integrates the unit cell dipole and the two flanking defocusing sextupoles. Further integration of the unit cell focusing quadrupoles and focusing sextupole is presently under consideration.

PEP-X 7 Bend Achromat



Cell phase advances: μ_x=(2+1/8) x 360^0, μ_y=(1+1/8) x 360^0.

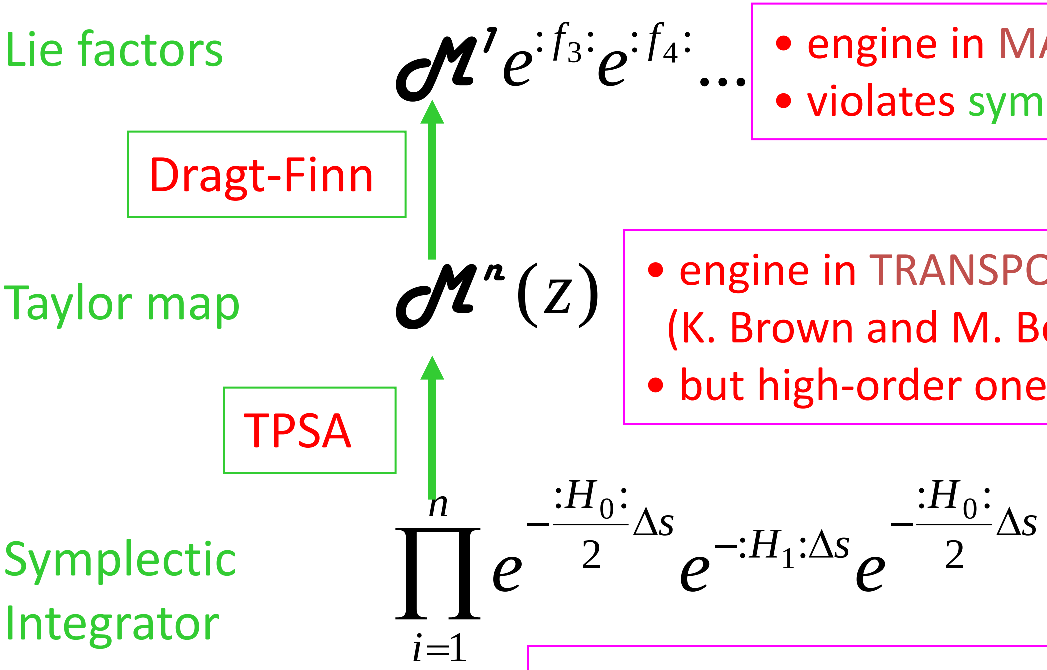
Resonance in Storage Rings



Dynamic aperture in a two-dimensional tune scan for the baseline design of PEP-X (2008).

Where these resonances come from?

Presentations for Magnetic Elements



Lie factors

$$\mathcal{M}' e^{:f_3:} e^{:f_4:} \ldots$$

- engine in MARYLIE (A. Dragt)
- violates symplecticity when evaluates

Dragt-Finn

Taylor map

$$\mathcal{M}^n(z)$$

- engine in TRANSPORT, MAD, COSY (K. Brown and M. Berz), simple R-matrix
- but high-order one violates

TPSA

Symplectic Integrator

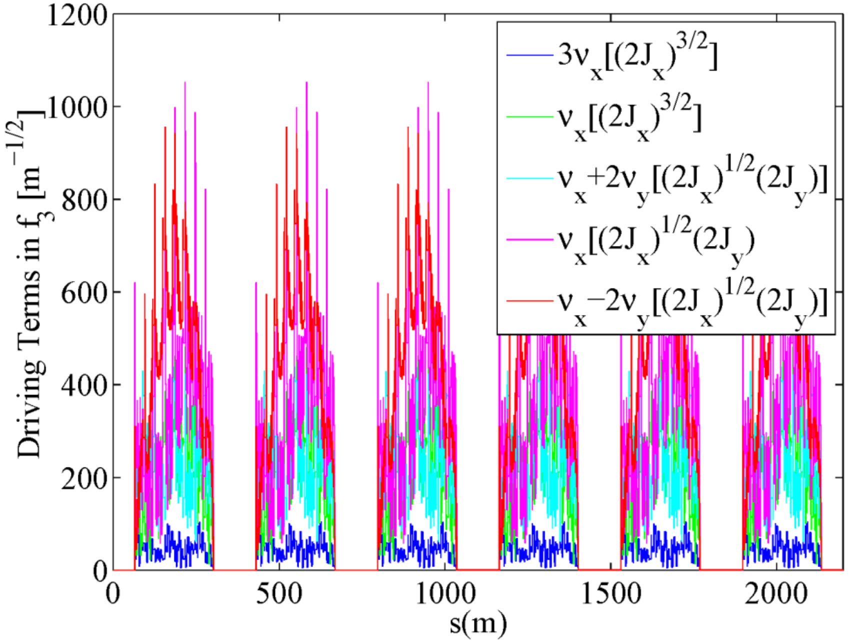
$$\prod_{i=1}^{n} e^{-\frac{:H_0:}{2}\Delta s} e^{-:H_1:\Delta s} e^{-\frac{:H_0:}{2}\Delta s}$$

- engine in TEAPOT, SAD, TRACY, **LEGO**, PTC (E. Forest, R. Ruth, and K. Hirata)
- preserves symplecticity
- simple and based on several known solutions
- emphasis on numerical process

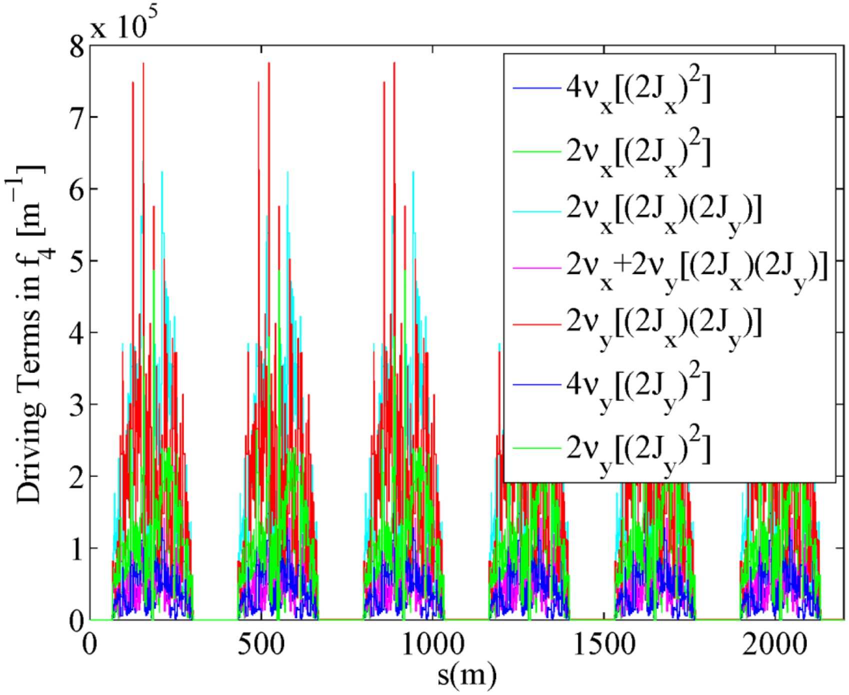
Cancellation of All Geometric 3rd and 4th Resonances Driven by Strong Sextupoles

except $2\nu_x$-$2\nu_y$

Third Order



Fourth Order



K.L. Brown & R.V. Servranckx

Nucl. Inst. Meth., A258:480–502, 1987

Yunhai Cai

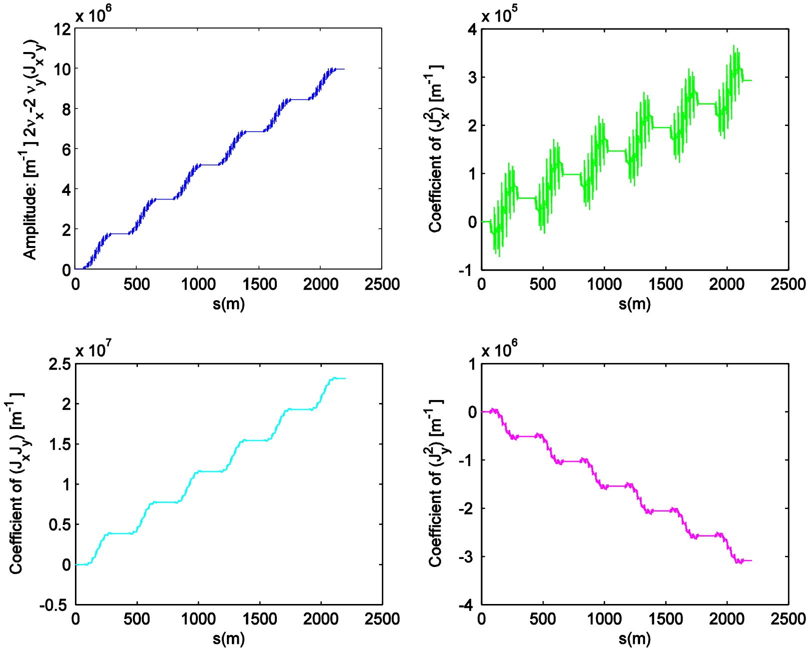
Nucl. Inst. Meth., A645:168–174, 2011.

There are still three tune shift terms.

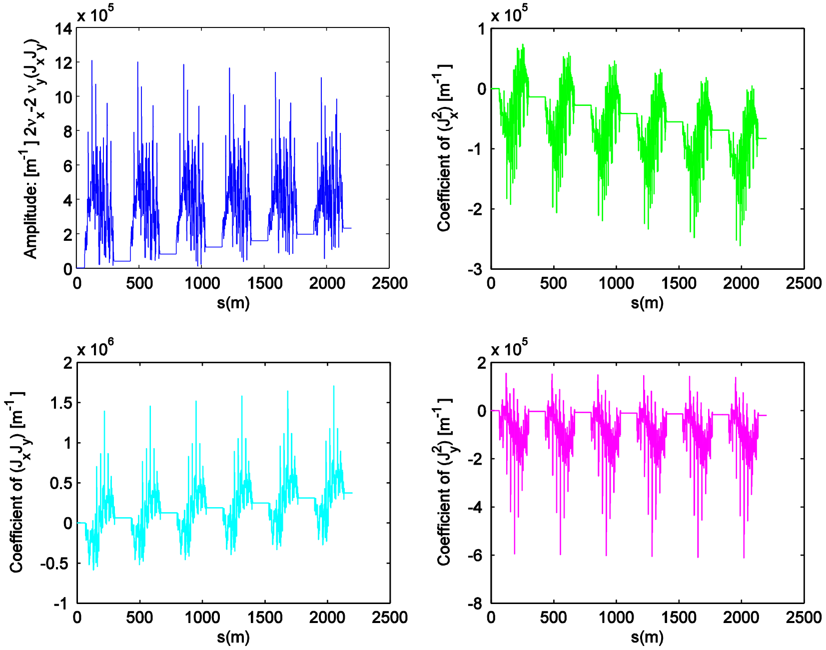
Harmonic Sextupoles

For Tune Shifts and $2\nu_x$-$2\nu_y$Resonance

Without harmonic sextupoles



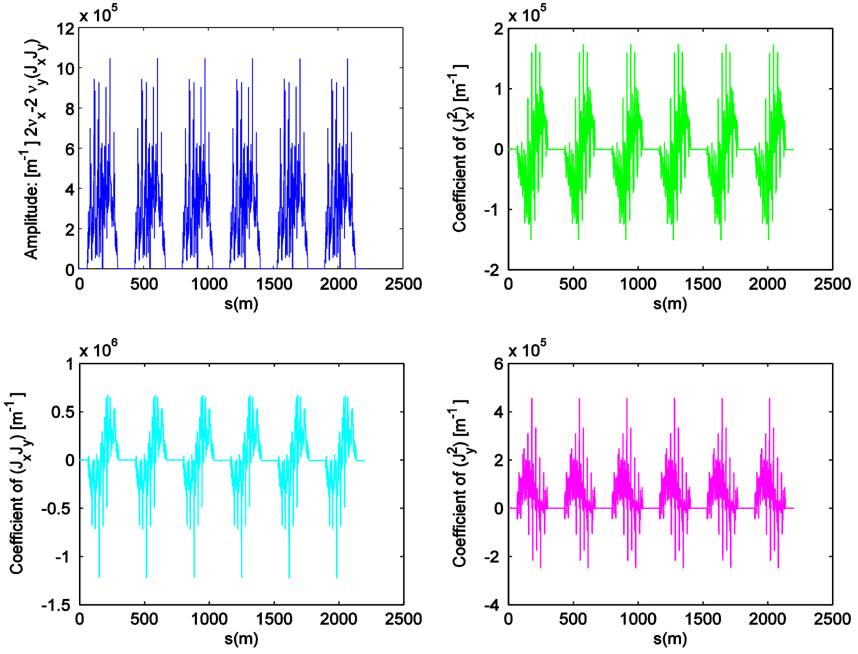
With harmonic sextupoles



OPA is used for optimizing the setting of 10 families of sextupoles. Due to the cancellation of many resonances, the optimization becomes much simpler and easier. OPA is an Accelerator Design Program from SLS PSI developed by A. Streun.

4th Order Geometric Achromat

4th order geometric achromat



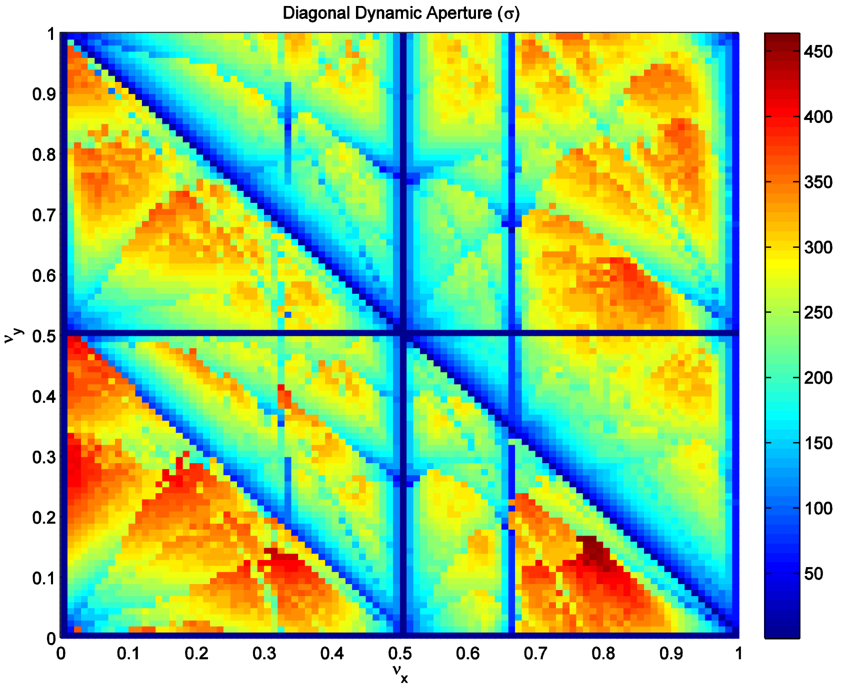
Chromatic effects

$\partial \nu_{x,y} / \partial \delta$	**0,0**
$\partial^2 \nu_{x,y} / \partial \delta^2$	-57,-89
$\partial^3 \nu_{x,y} / \partial \delta^3$	1332,-150
$\eta_{x,y}$	0,0
$\partial \eta_{x,y} / \partial \delta$	0,0

There are 4 families of chromatic sextupoles and 6 families of harmonic ones. The 4th order geometric achromat ($f_3=f_4=0$) was obtained with the analytical Lie method.

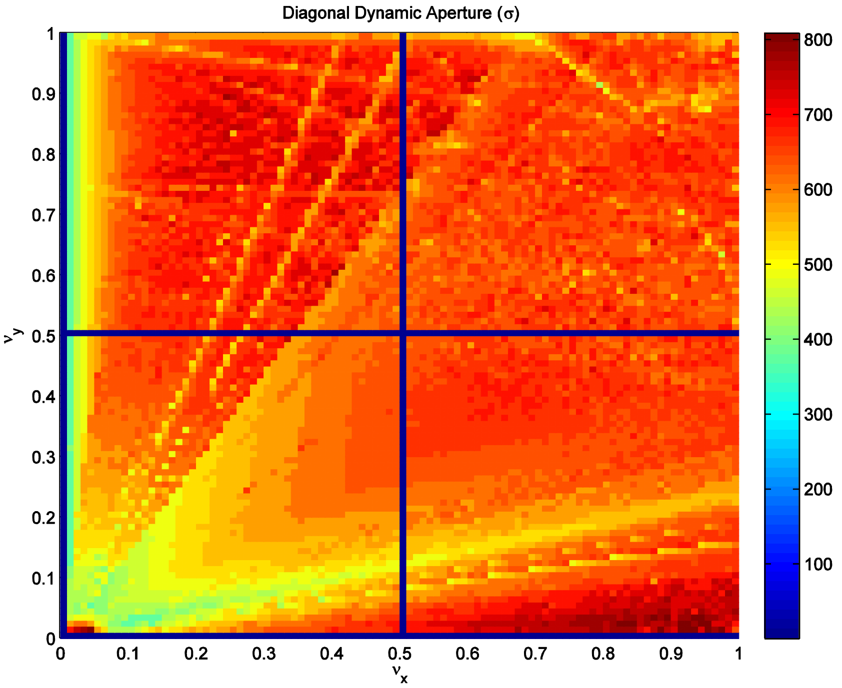
Tune Scan of Dynamic Aperture

PEP-X: Baseline (2008)



Diagonal Dynamic Aperture (σ)

PEP-X: USR (2011)



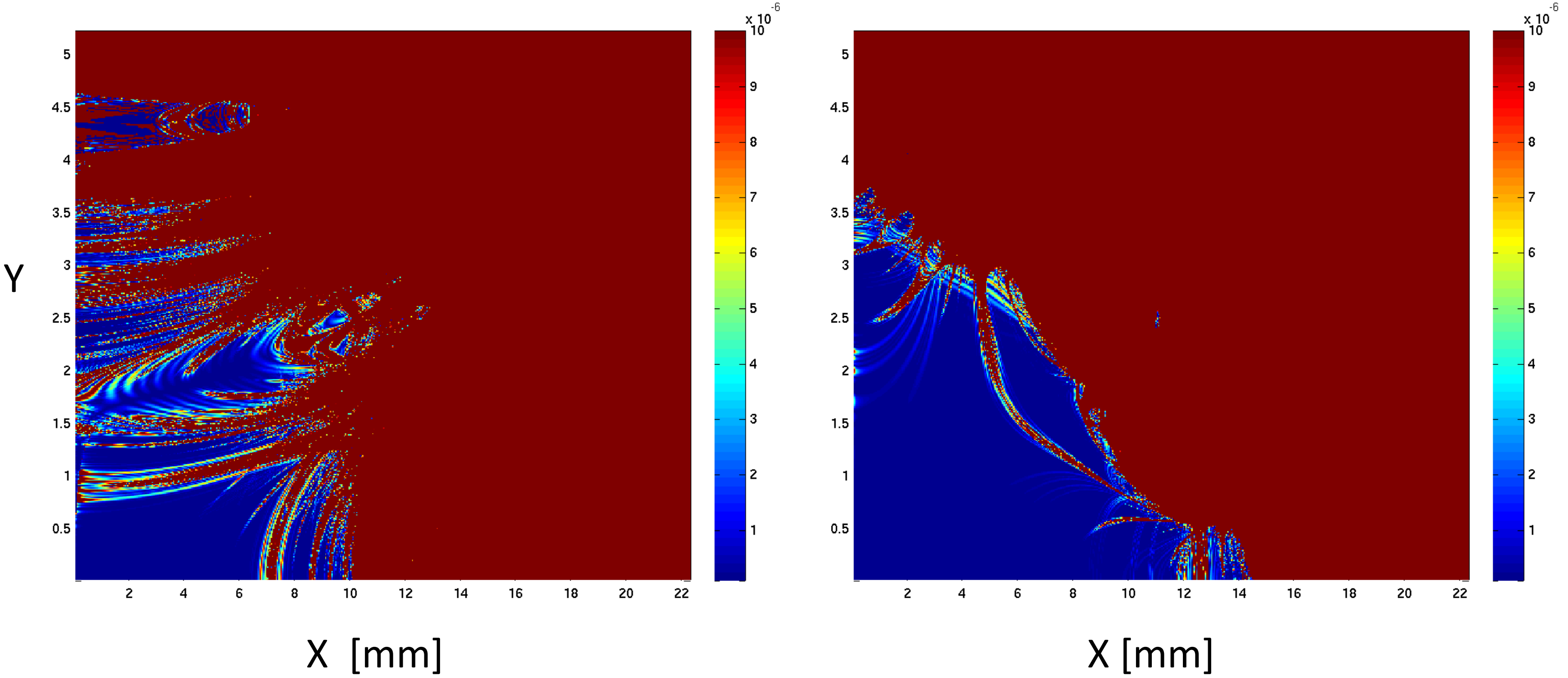
Diagonal Dynamic Aperture (σ)

The dynamic aperture is in unit of sigma of the equilibrium beam size. The USR design is built with 4th-order geometric achromats and therefore no 3rd and 4th order resonances driven by the sextupoles seen in the scan.

Frequency Map Analysis

PEP-X: Baseline (2008)

PEP-X: USR (2011)

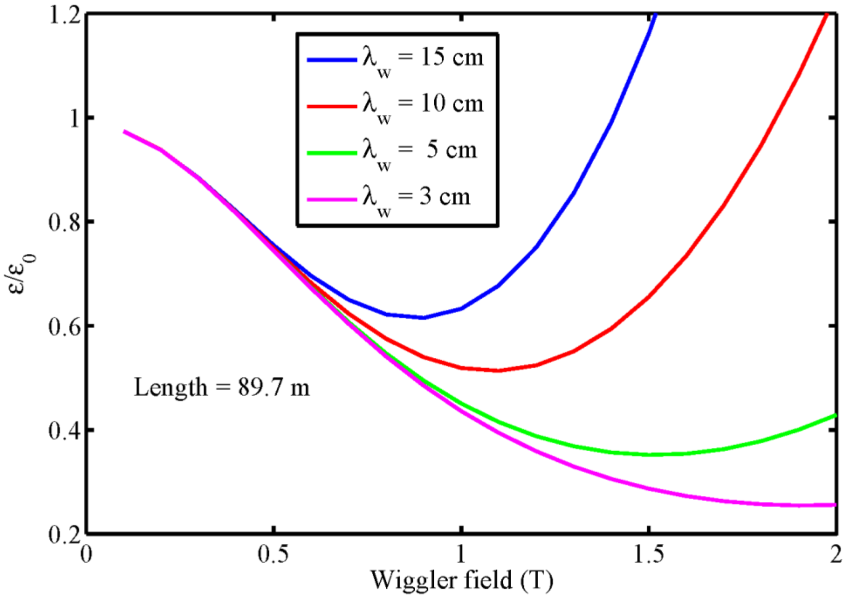


The dynamic aperture is in unit of mm at the injection. The baseline design has a factor of ten larger emittance than the one in the USR design.

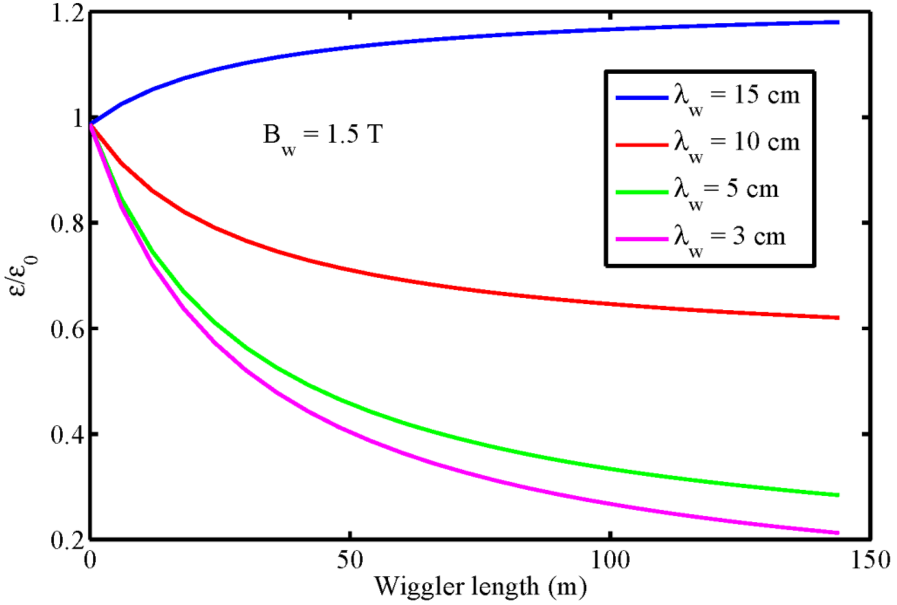
Reduce Emittance with Damping Wigglers

Emittance = 11 pm-rad at 4.5 GeV with
parameters λ_w=5 cm, B_w=1.5 T

Wiggler Field Optimization



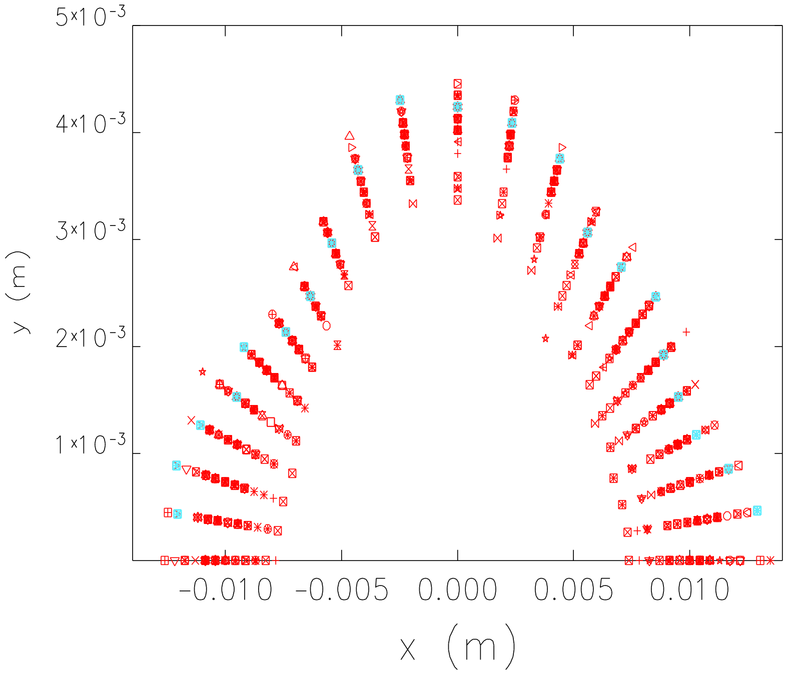
Wiggler Length Optimization



Average beta function at the wiggler section is 12.4 meter.

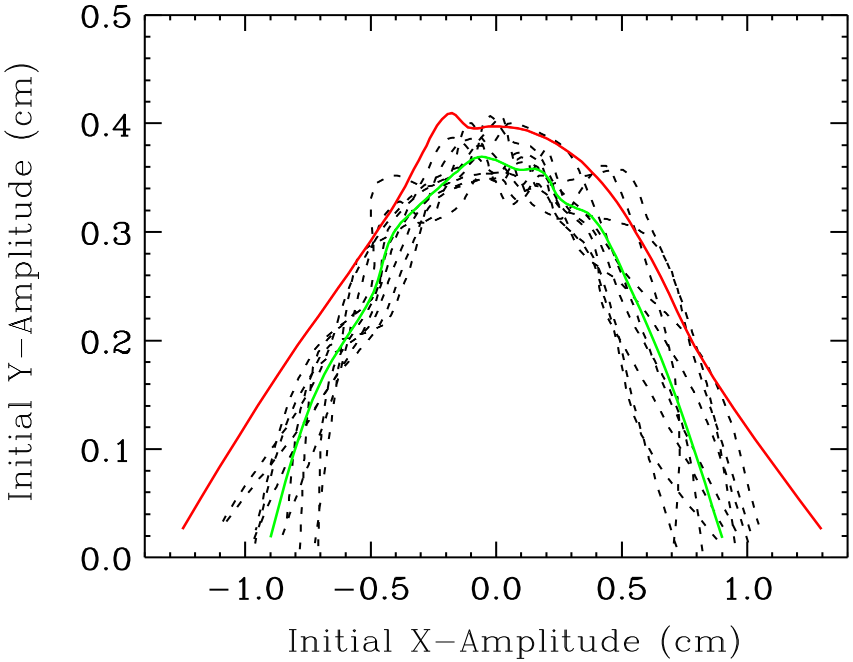
Dynamic Aperture with Machine Errors

ELEGANT Tracking



1% coupling & 1% beta beating

LEGO Tracking



Misalignments 20 microns in x.

Intra-Beam Scattering

The growth rate in the relative energy spread σ_δ is given by

$$\frac{1}{T_p} = \frac{r_e^2 c N_b (log)}{16\gamma^3 \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta^3} < \sigma_H g(\alpha)(\sigma_x \sigma_y)^{-1/2} >,$$

where N_b is the bunch population and (log) the Coulomb log factor and the other factors are defined by

$$\frac{1}{\sigma_H^2} = \frac{1}{\sigma_\delta^2} + \frac{\mathcal{H}_x}{\varepsilon_x}, \alpha = \sqrt{\frac{\varepsilon_y \beta_x}{\varepsilon_x \beta_y}},$$

$$g(\alpha) = \alpha^{(0.021 - .0044 \ln\alpha)}.$$

And the horizontal growth rate is given by

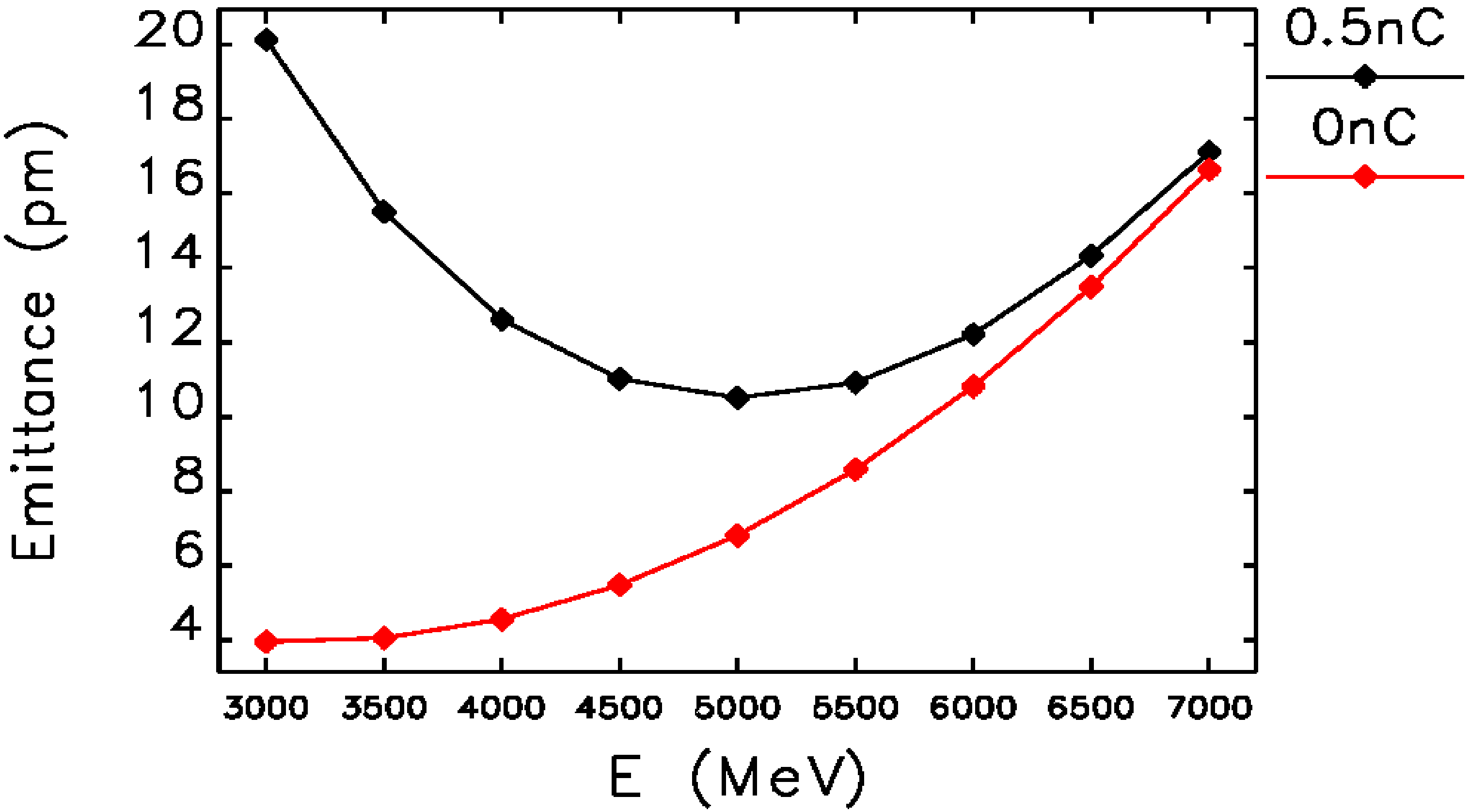
$$\frac{1}{T_x} = \frac{\sigma_\delta^2}{\varepsilon_x} < \mathcal{H}_x \Delta(\frac{1}{T_p}) > .$$

Combined with synchrotron radiation

$$\varepsilon_x = \frac{\varepsilon_{x0}}{1 - \tau_x / T_x}, \sigma_\delta^2 = \frac{\sigma_{\delta 0}^2}{1 - \tau_s / T_p},$$

$$\varepsilon_y = \kappa \varepsilon_x$$

Optimization of Energy



Touschek Lifetime

When a pair of electrons go through a hard scattering, their momentum changes are so large that they are outside the RF bucket or the momentum aperture. This process results in a finite lifetime of a bunched beam. The lifetime is given by

$$\frac{1}{\mathcal{T}} = \frac{r_e^2 c N_b}{8\sqrt{\pi}\gamma^4 \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta} < \sigma_H F(\delta_m) > ,$$

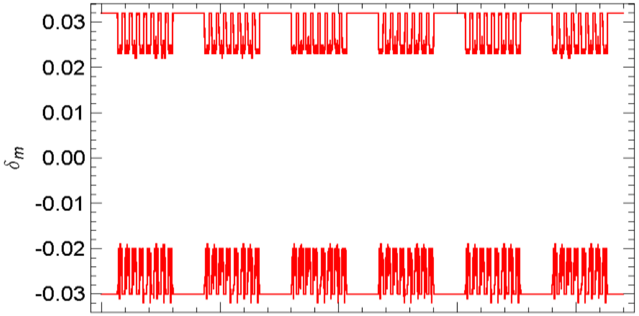
with

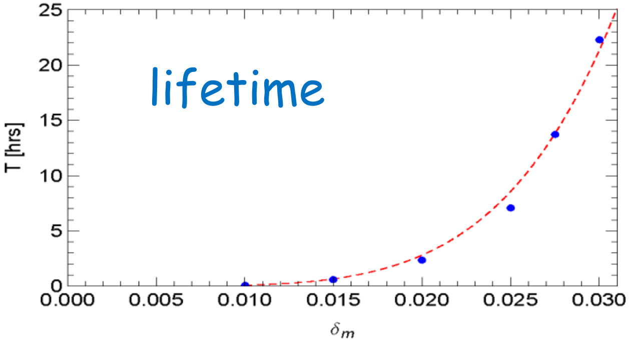
$$F(\delta_m) = \int_{\delta_m^2}^{\infty} \frac{d\tau}{\tau^{3/2}} e^{-\tau B_+} I_0(\tau B_-)[\frac{\tau}{\delta_m^2} - 1 - \frac{1}{2}\ln(\frac{\tau}{\delta_m^2})],$$

$$B_\pm = \frac{1}{2\gamma^2}\left|\frac{\beta_x(\beta_x\varepsilon_x + \eta_x^2\sigma_\delta^2)}{\varepsilon_x(\beta_x\varepsilon_x + \beta_x\mathcal{H}_x\sigma_\delta^2)} \pm \frac{\beta_y}{\varepsilon_y}\right|,$$

where δ_m is the momentum acceptance.

momentum aperture



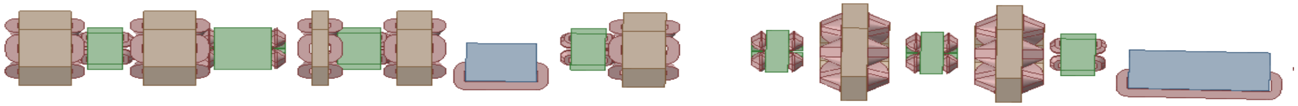


Achievements

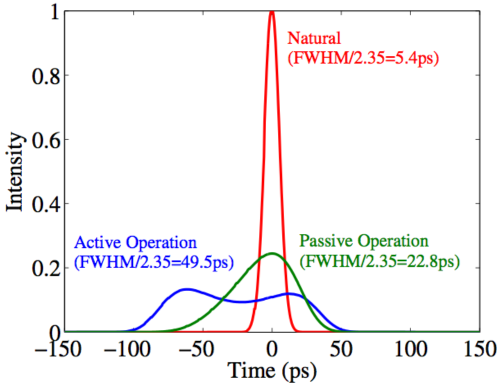
- We have developed an excellent design of an ultimate storage ring
  - Diffraction limit at 1.5 angstrom
  - Reasonable beam current 200 mA
  - Good beam lifetime 3 hours
  - Good injection with 10 mm acceptance
  - Achievable machine tolerances 20 microns

General R&D Items

1. Better understanding of beam dynamics
2. New injection scheme for smaller dynamic aperture
3. Compact and strong magnets (sextupoles)



4. Higher harmonic RF system
5. Precise magnet alignment
6. Accurate beam position monitors



Lengthen the beam

Beyond the Ultimate Brightness

Parameter	PEP-X	LCLS-(1.5nm)
Energy [GeV]	4.5	4.3
Normalized emittance [um-rad]	0.1	0.4
Peak current [A]	17	500-3000
Energy spread	1.25×10^{-3}	$(0.5\text{-}3.0)\times10^{-4}$

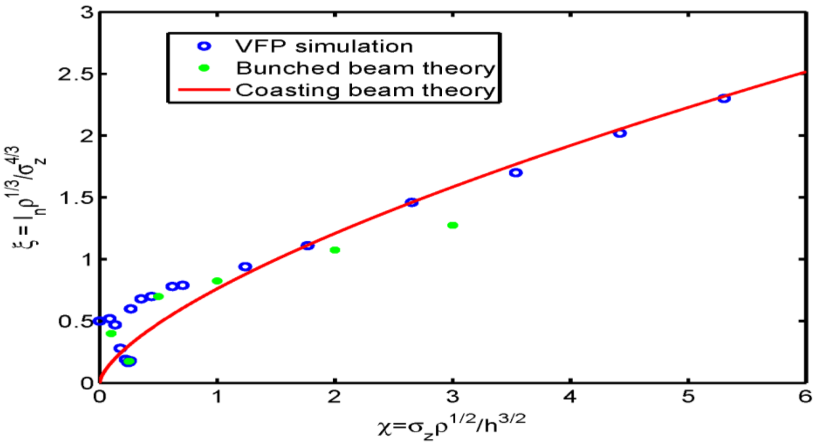
- Increase the peak current by much stronger longitudinal focusing
  - 1.5 GHz, 200 MV CW SCRF
- Any FEL schemes to accommodate larger energy spread?
- Can we achieve lasing or at least partial lasing?

Threshold of Instability
Driven by CSR

Based on the bunched beam theory, the threshold can be written as

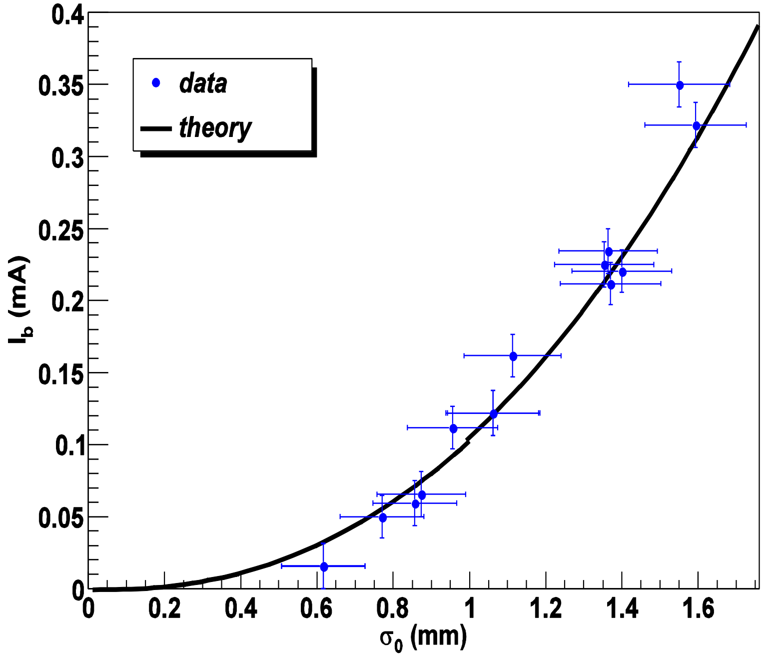
$$\sigma_z^{7/3} = \frac{c^2 Z_0}{8\pi^2 \xi^{th}(\chi)} I_b^{th} \rho^{1/3} /(V_{rf} \cos\varphi_s f_{rf} f_{rev})$$

where ξ^{th} is given by



My talk, IPAC 2011, San Sebastian, Spain

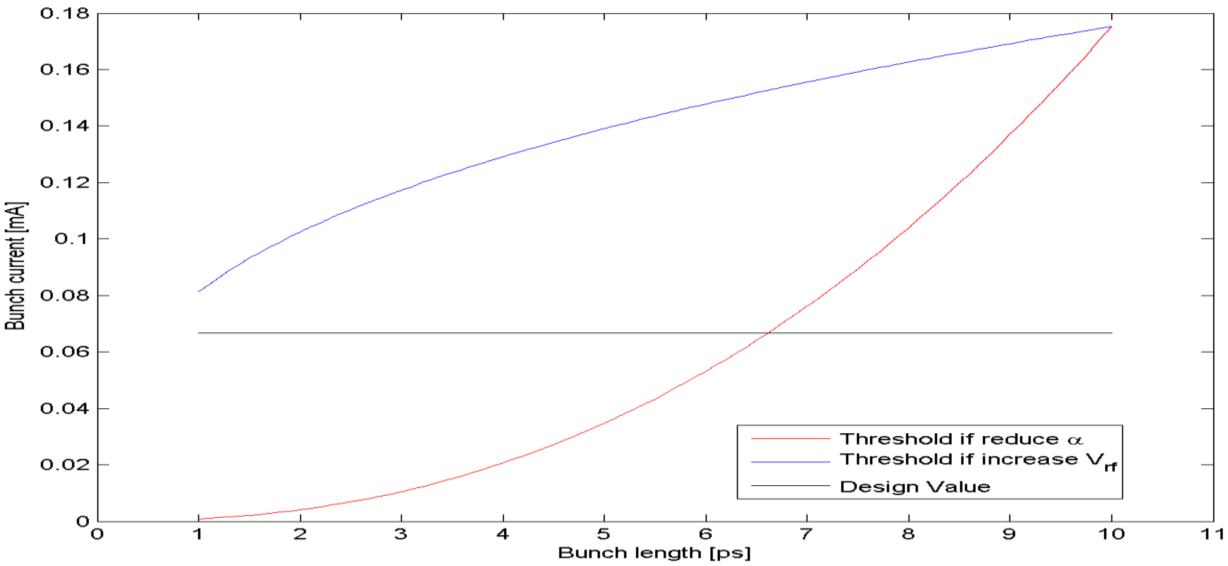
Measured bursting threshold at ANKA
See M.Klein et al. PAC09, 4761 (2009)



(courtesy of M. Klein, ξ^{th}=0.5 used.)

Reduce Bunch Length from 10 ps to 1 ps without reducing bunch current

Calculation of threshold



An illustration using PEP-X nominal parameters: f_{rf} = 476 MHz, V_{rf}=8.3 MV, f_{rev} = 136.312 kHz, σ_z=3 mm, I_b=0.067 mA.

Conclusion

- Ultra-low emittance at 10 pm is clearly feasible for the next generation of storage rings although some R&D are necessary to further advance the design for construction.
- High-order achromats can be used in realistic design of low-emittance storage rings. This approach significantly simplified the optimization process and improved the dynamic aperture.
- Analytical methods are important for design of modern accelerators. They are complementary to the numerical approach using computers.
- Longitudinal beam dynamics will well be the next frontier of these storage rings.