Chromaticity correction and dynamic aperture of electron ring EAR

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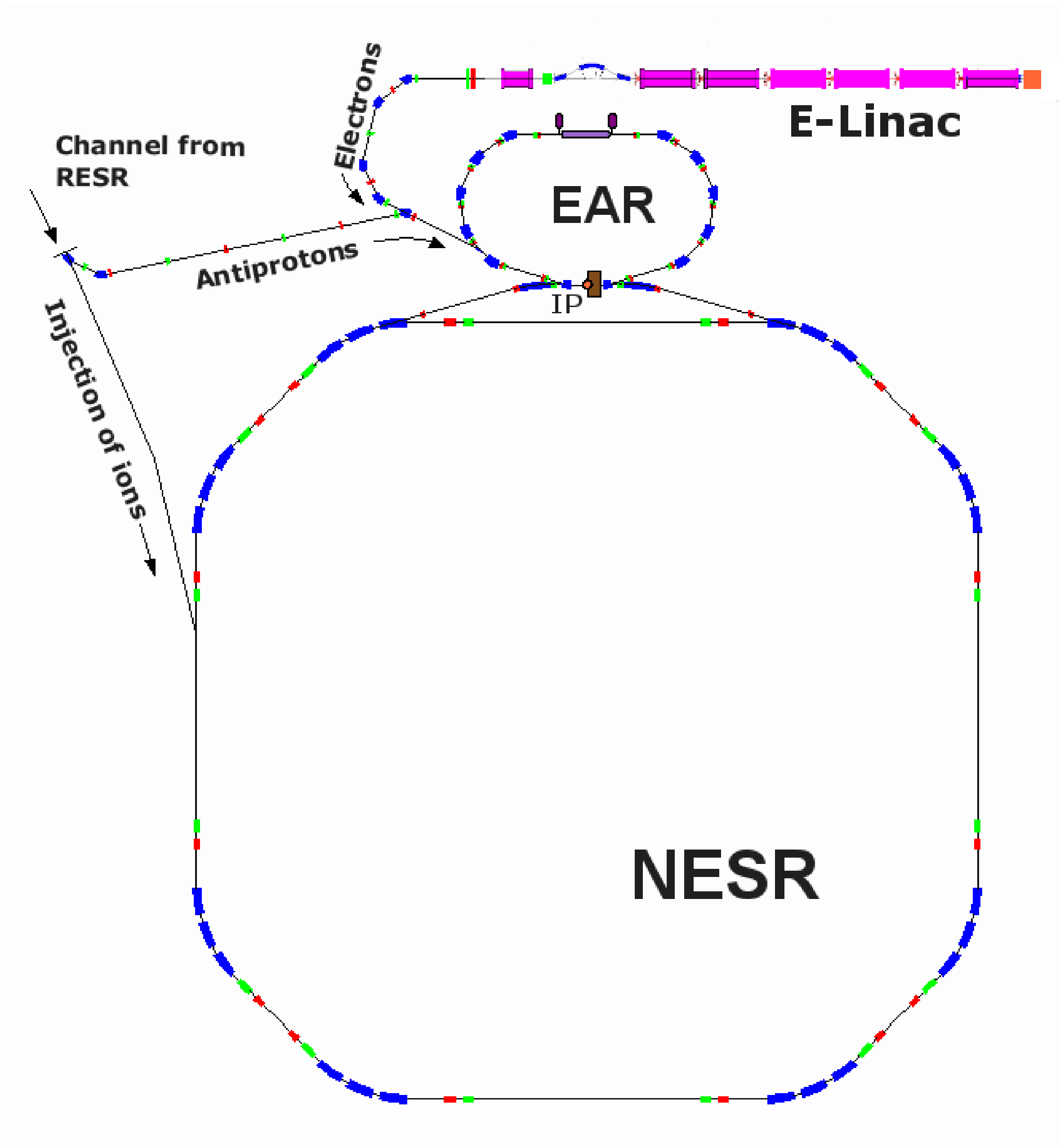
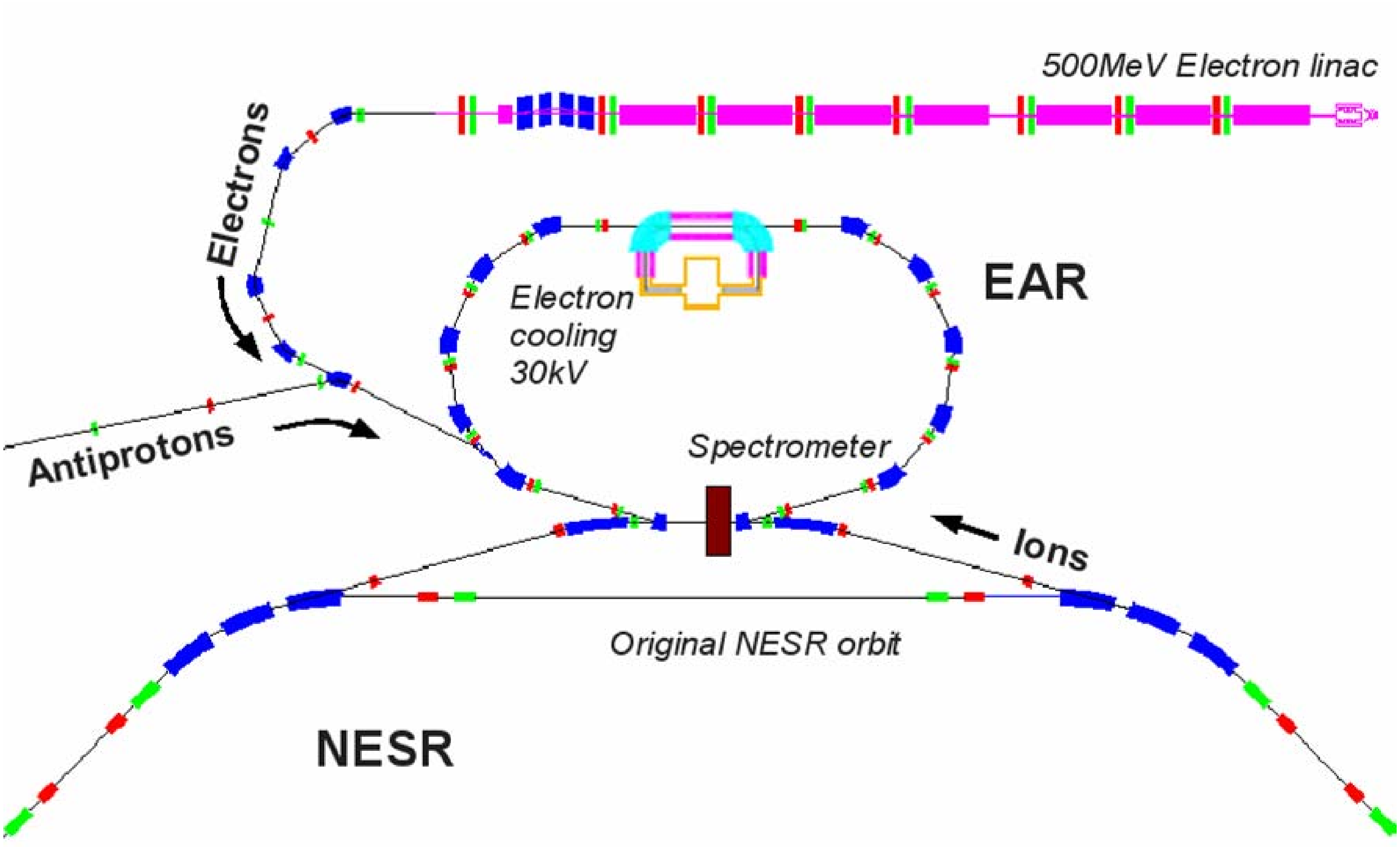
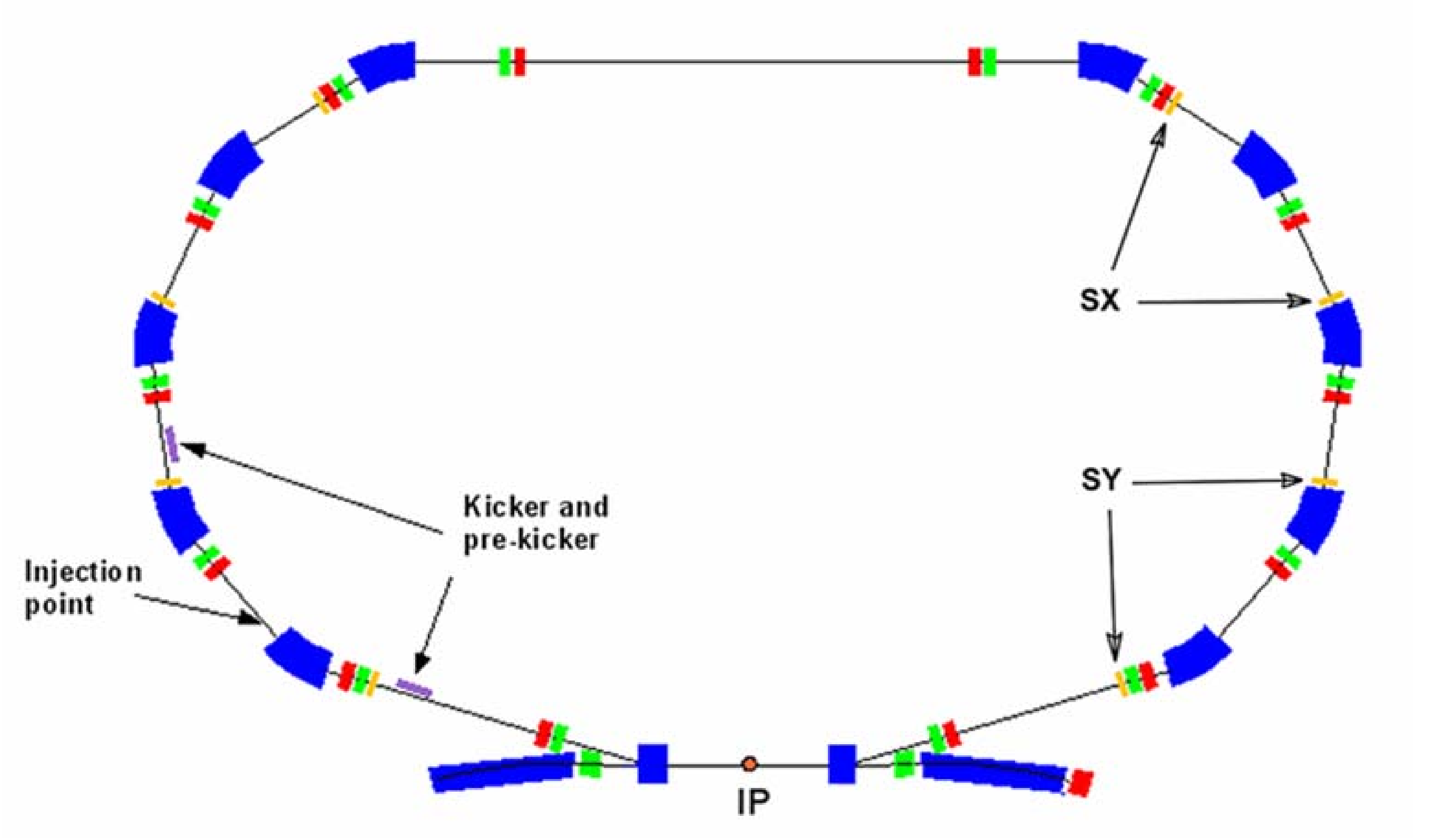
Electron-Ion Collider



e-A collider, zoom in (electron part)

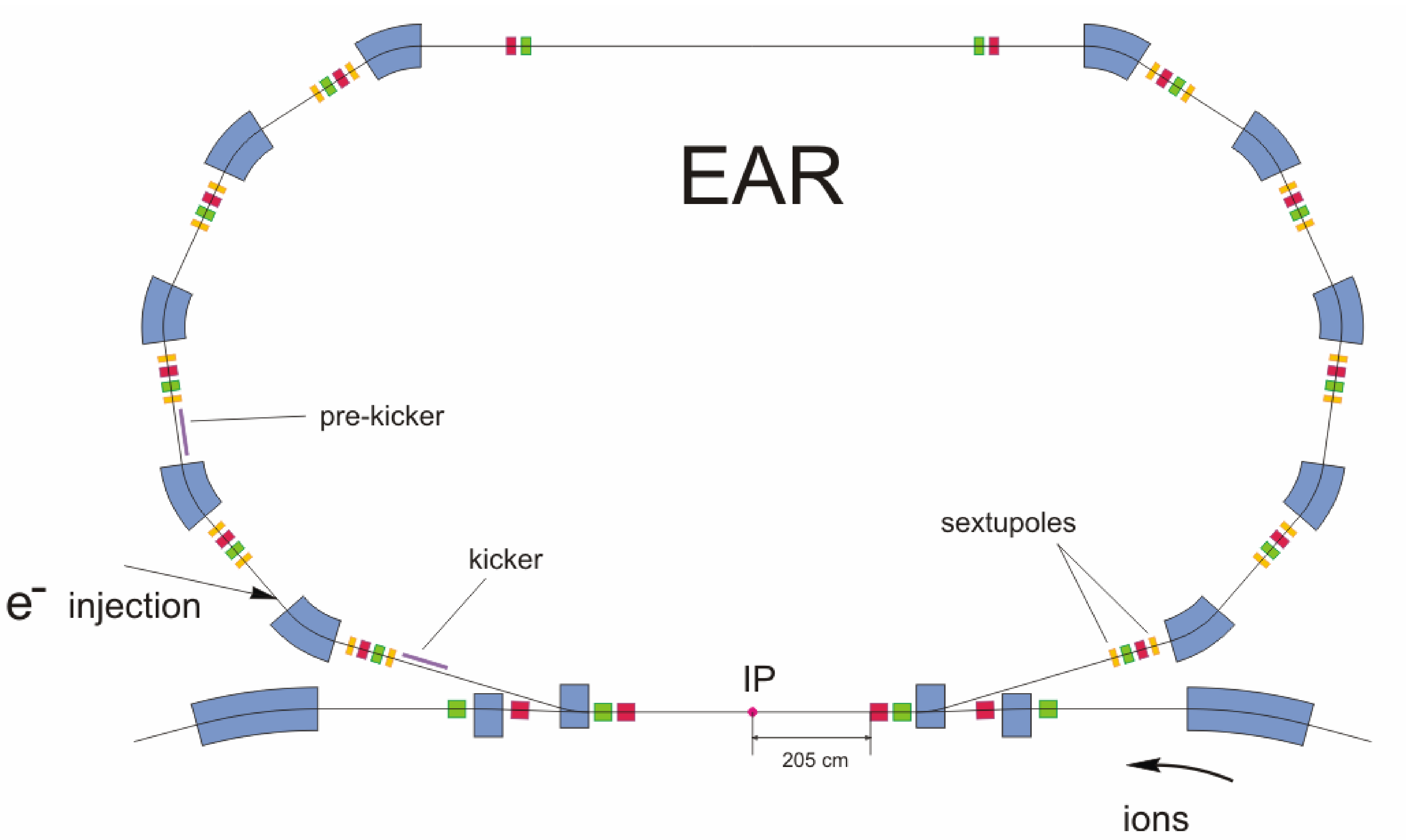


Electron Ring (2007)



Sextupole scheme: small number of sextupole lenses (8) placed with adjusted betatron phase advance.

Electron Ring, current status

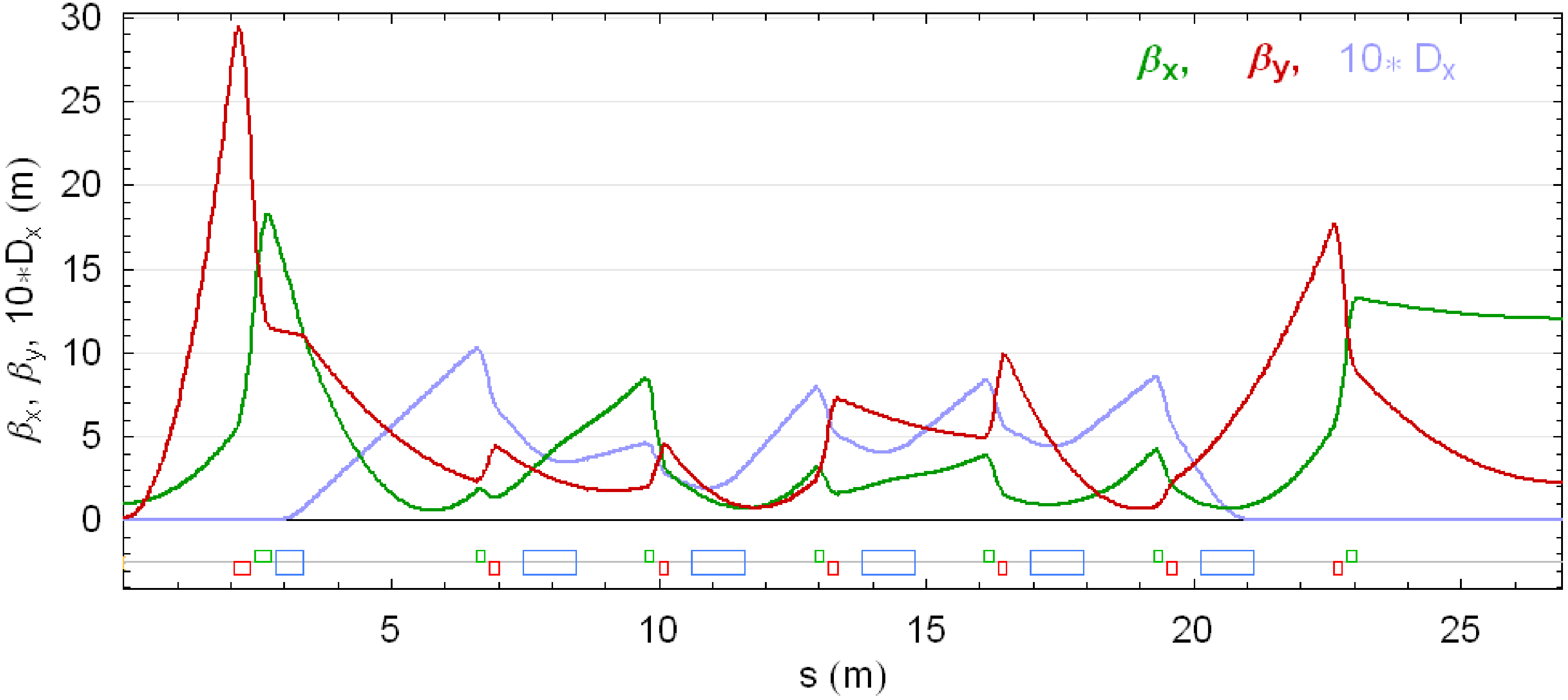


Many sextupoles (20) for flexible optics.

Table of parameters

Energy, E	500 MeV
Harmonic number	24
Betatron tunes, ν_x, ν_y	4.2, 3.2
Beta functions in IP, $\beta^*_{x,} \beta^*_y$	100 cm, 15 cm
Beam emittances, $\varepsilon_{x,y}$	$2.4 \cdot 10^{-6}$ cm·rad
Beam sizes in IP, σ_x, σ_y	0.15mm, 0.06mm
Momentum compaction, α_p	0.034
Momentum spread, $\sigma_{\Delta p/p}$	$3.1 \cdot 10^{-4}$
Damping time, τ_x	70 ms

Lattice functions of one half of the ring (basic option)



EAR requirements

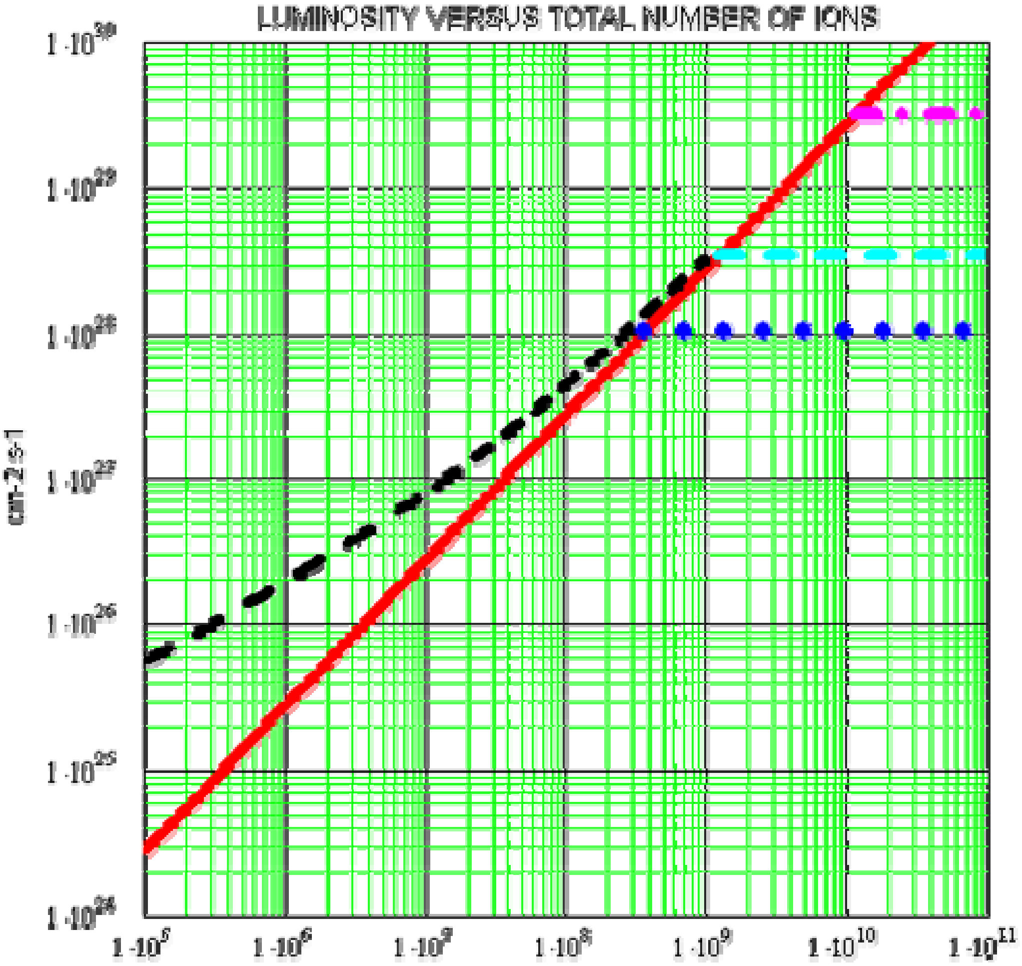
- Wide energy range, 200-500 MeV. (Higher resolution of detector for some experiments need low e^- energies).
- Integer ratio of ions and electrons revolution periods. ($T_i=5T_e$ for basic option).
- Variation of bunch number. (Collective effects, intrabeam scattering).
- Equal transverse emittances $\varepsilon_x = \varepsilon_z$. (Similarity of ion and electron beams profile in cross-section).
- Variable emittance (Luminosity considerations).

Luminosity estimations

$$L_\xi = f_i n_i \frac{A}{Z}\left(1+\frac{\sigma_z}{\sigma_x}\right)\frac{N_{ib}\xi_{ix}\gamma_i\beta_i}{2r_p\sqrt{\beta_x\beta_z}}$$

$L \propto f_i n_i N_{ib}$ – red line

Black dashed curve shows luminosity benefit for small ion beam current with significantly reduced ion beam emittance.



Electron beam sizes in the storage ring

Radiation damping forms Gaussian electron bunch distribution during several damping times, τ ~ 50ms (at 500 MeV).

Momentum spread:

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{55}{32\sqrt{3}}\frac{\lambda_e}{J_E}\frac{\left\langle 1/r_0{}^3\right\rangle}{\left\langle 1/r_0{}^2\right\rangle}\gamma^2$$

Bunch length:

$$\sigma_l = \frac{c\,\alpha_p}{\Omega_s}\frac{\sigma_E}{E}$$

Horizontal emittance:

$$\varepsilon_x = \frac{55}{32\sqrt{3}}\frac{\lambda_e}{J_X}\frac{\left\langle H/r_0{}^3\right\rangle}{\left\langle 1/r_0{}^2\right\rangle}\gamma^2$$

$$H = \gamma_x D^2 + 2\alpha_x DD' + \beta_x D'^2$$

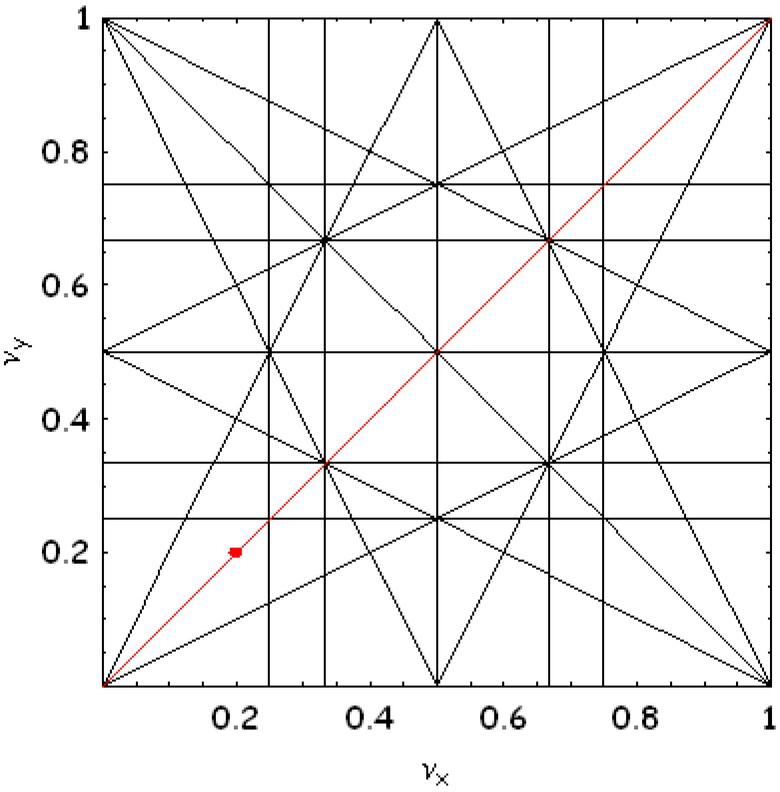
Vertical emittance:

$$\varepsilon_z = \kappa \cdot \varepsilon_x$$

$\kappa \ll 1$ – betatron coupling coefficient

Working point at the tune diagram

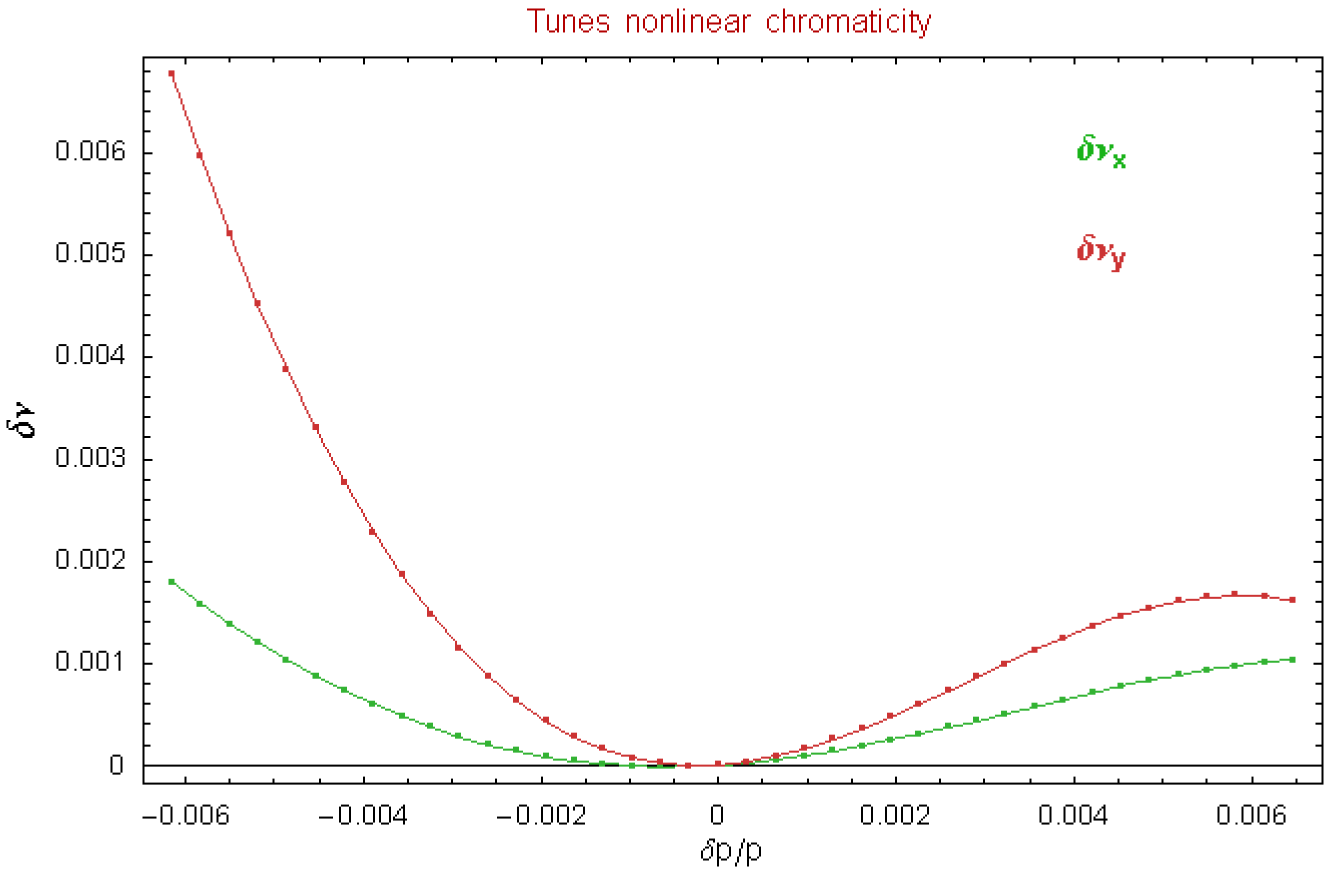
To provide equal transverse emittances working point should stay on the coupling resonance.



Basic option:

$$\nu_x = 4.2, \quad \nu_z = 3.2$$

Tune dependence on momentum deviation after chromaticity compensation (2007)



$\sigma_{\Delta p/p} = 3.2 \cdot 10^{-4}$

Natural chromaticity: $\partial\nu_x/\partial\delta = -7$, $\partial\nu_y/\partial\delta = -15$

Sextupoles strength: $\partial^2 H_y/\partial x^2 = 0.25$ kGs/cm², L=10cm

Chromatic variables

$$A(s) = \frac{\alpha(\delta)\beta(0) - \alpha(0)\beta(\delta)}{\sqrt{\beta(\delta)\beta(0)}} \cdot \frac{1}{\delta}$$

$$B(s) = \frac{\beta(\delta) - \beta(0)}{\sqrt{\beta(\delta)\beta(0)}} \cdot \frac{1}{\delta}$$

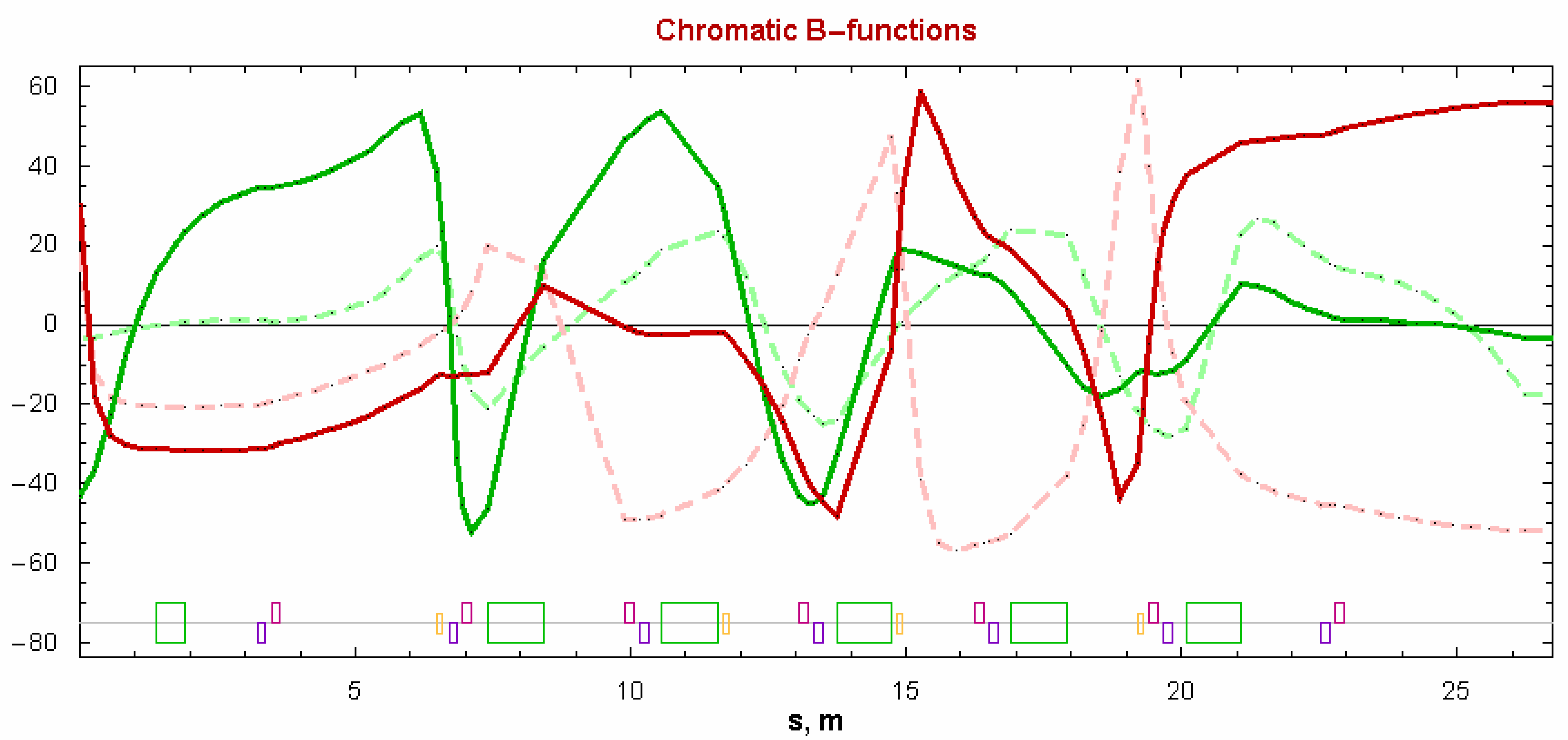
– normalized beta function chromaticity

$$W = \sqrt{B_x{}^2 + B_y{}^2 + A_x{}^2 + A_y{}^2}$$

– chromatic "invariant",

absolute measure of lattice chromaticity

Lattice chromaticity (2007)

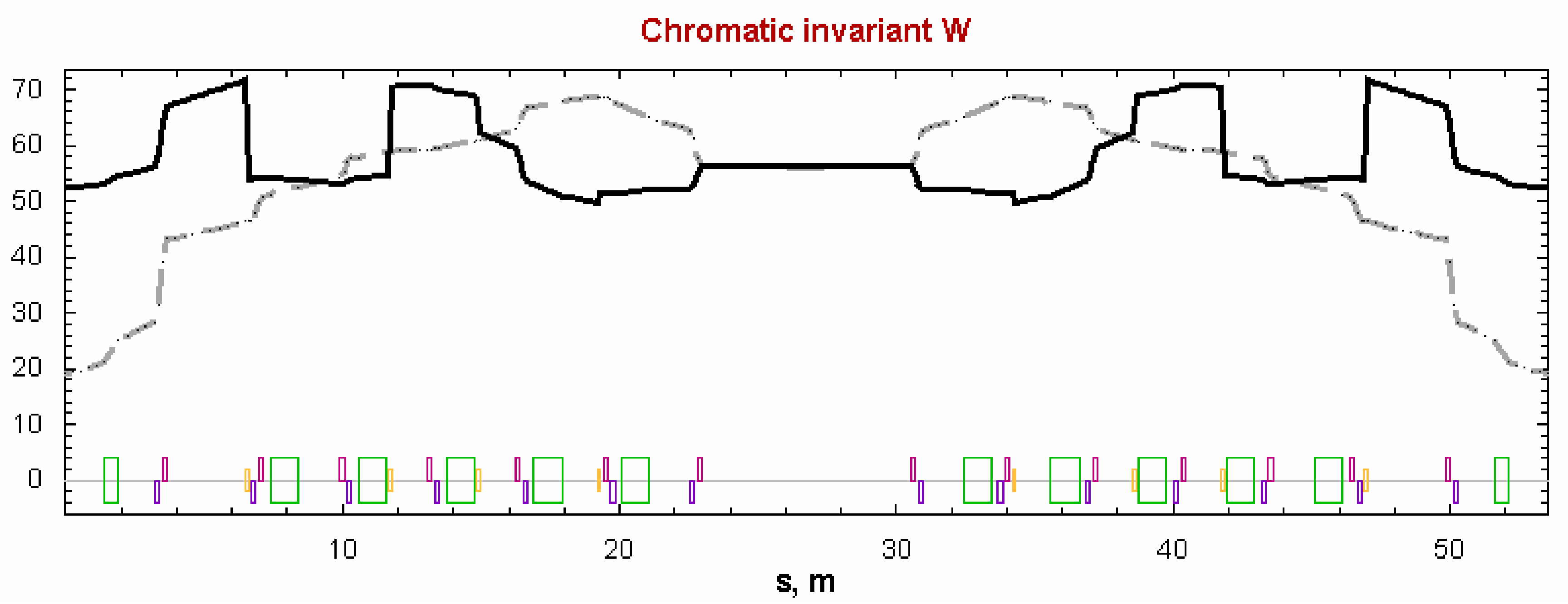


Dashed lines – sextupoles off, solid lines – sextupoles on.

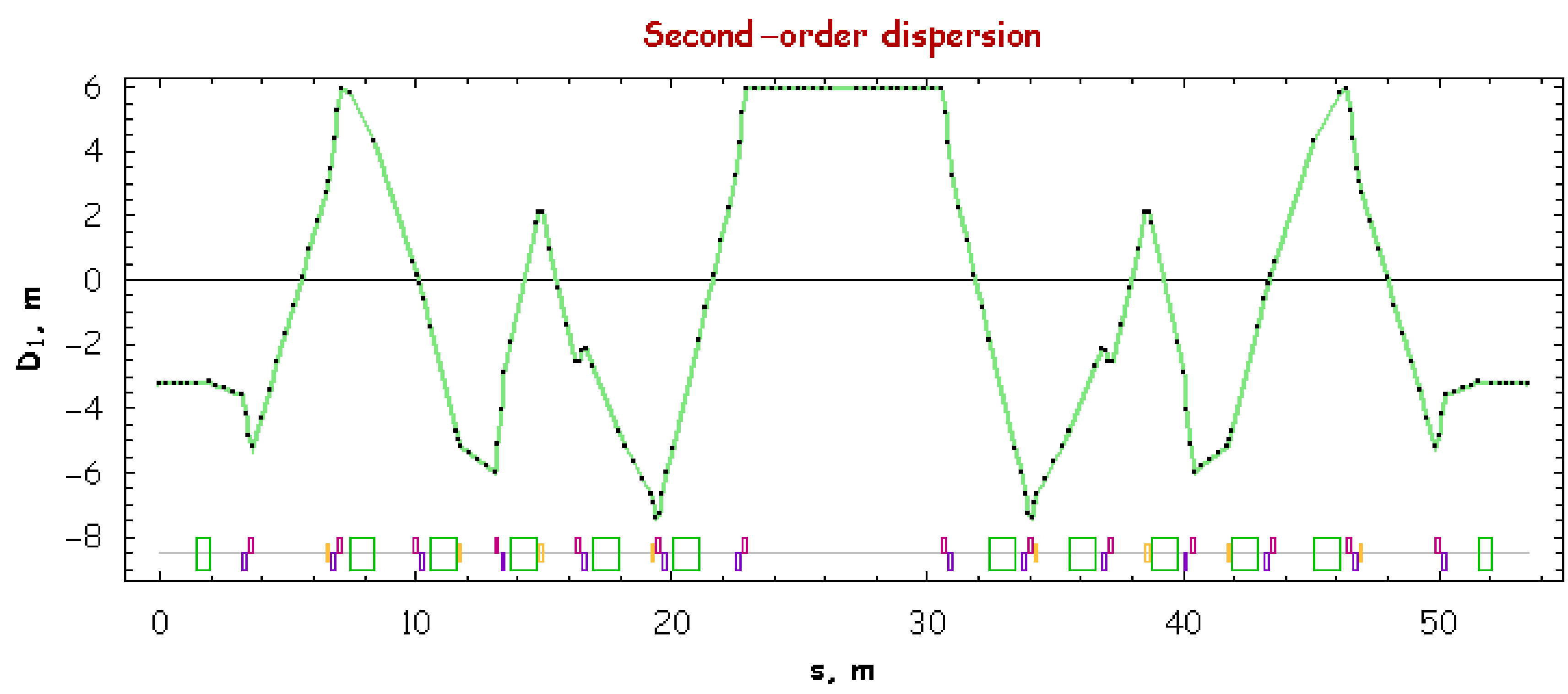
Vertical, horizontal.

$$\sigma_{\Delta p/p} = 3.2 \cdot 10^{-4},\ \ B \sim 40 \ \ \rightarrow \frac{\delta\beta}{\beta} = B \cdot \frac{\delta p}{p} \sim 1\%$$

Chromatic "invariant" (2007)



Second-order dispersion function (2007)

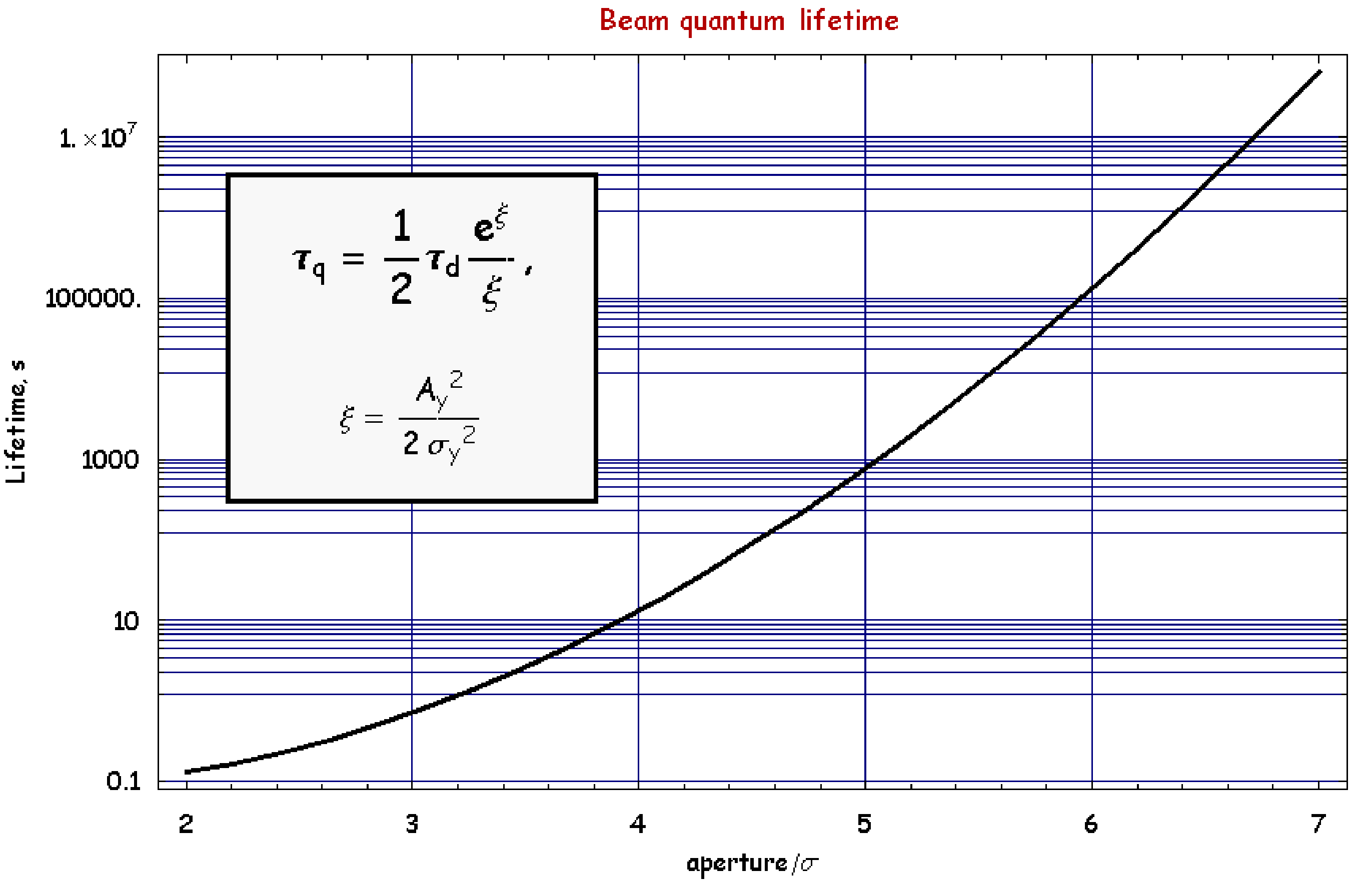


$$\delta x(s) = D \cdot \delta + D_1 \delta^2$$

D_1~ 10m, δ~ $3 \cdot 10^{-4}$ → δx ~ 1μm

Closed orbit distortions caused by second-order dispersion are negligible.

Quantum lifetime with finite aperture



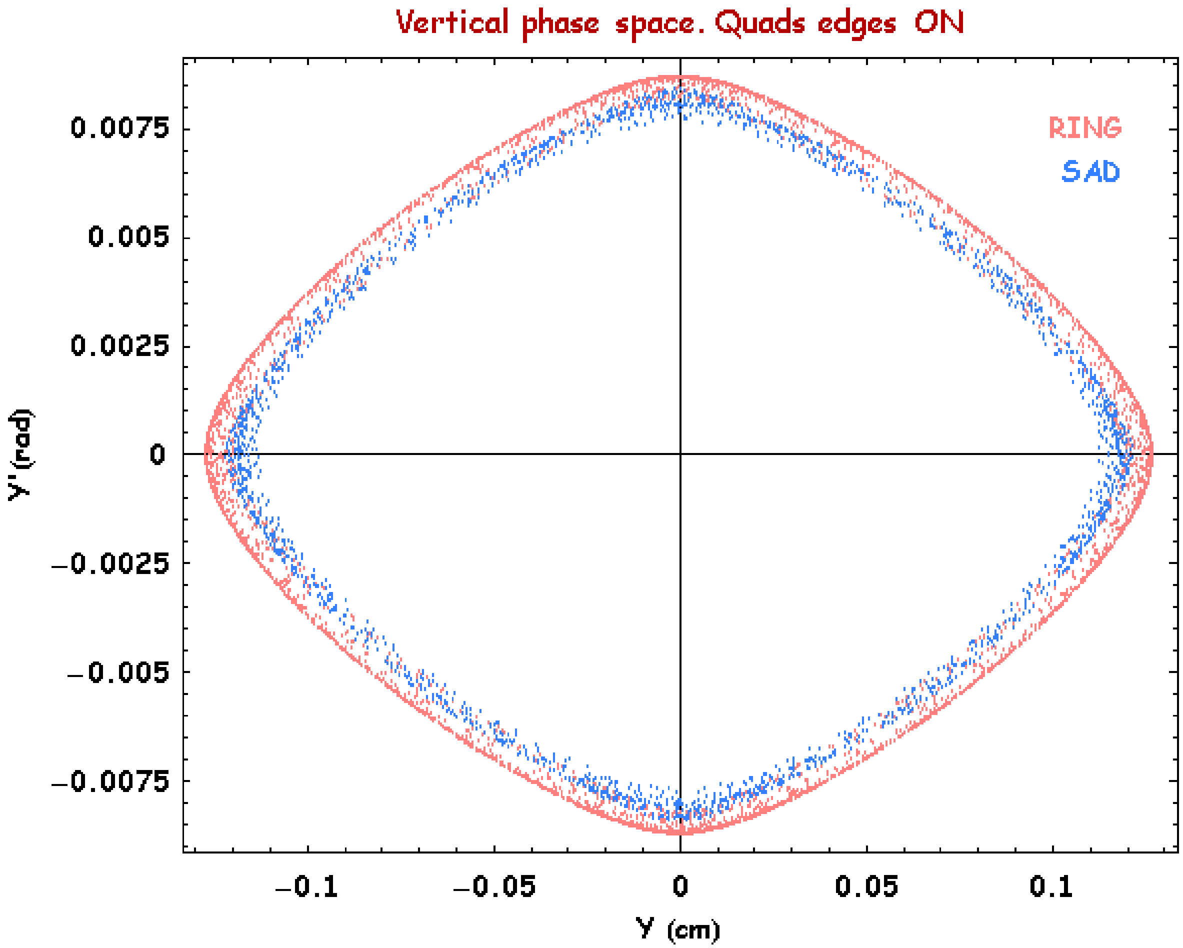
$$\tau_q = \frac{1}{2}\tau_d \frac{e^{\xi}}{\xi},$$

$$\xi = \frac{A_y{}^2}{2\,\sigma_y{}^2}$$

Electron beam always has Gaussian particles distribution that is a balance between radiation damping and quantum fluctuations of radiation.

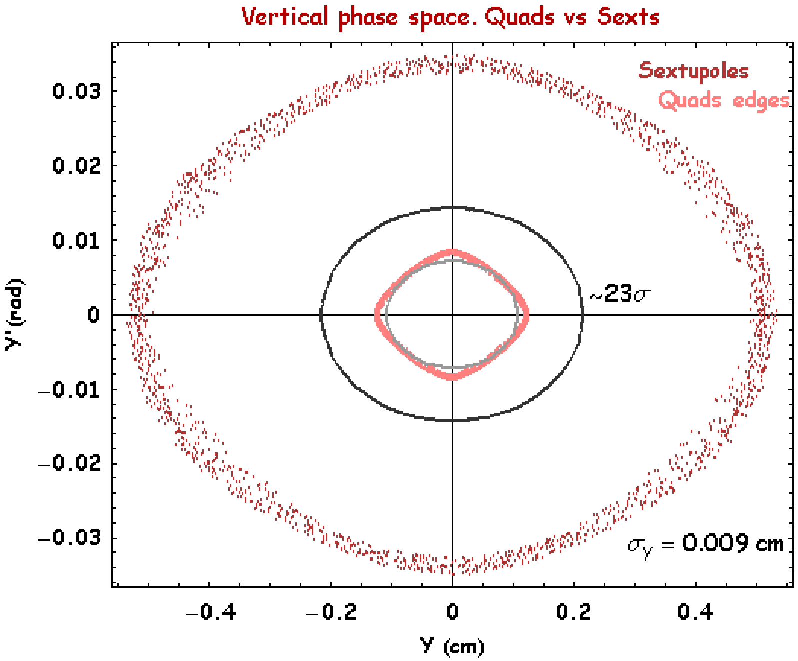
Cutting off the "tails" by finite aperture leads to permanent particles loss.

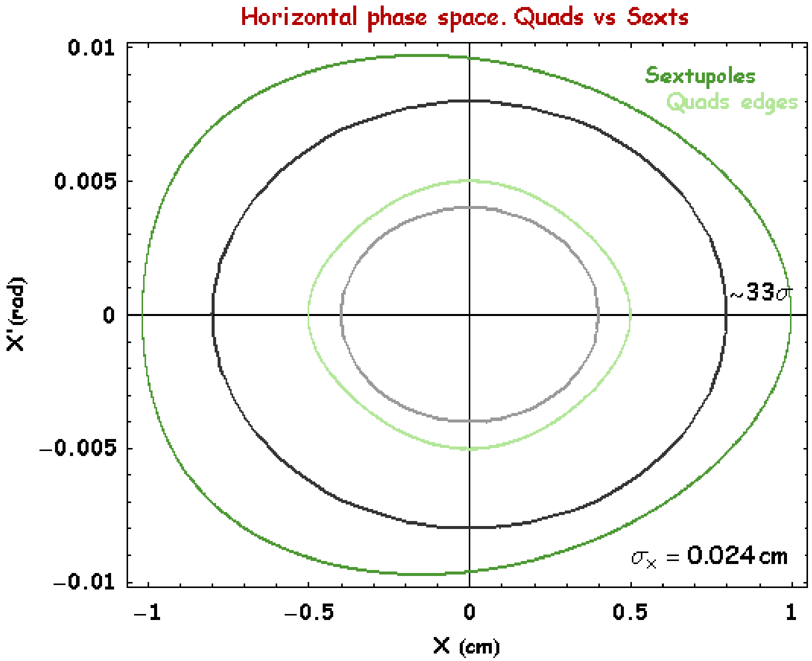
Nonlinear dynamics. Quads fringes. (2007)



RING code (BINP, Novosibirsk) and SAD code (KEK, Japan) give similar results. Nonlinear fringe fields effect seems to be a reality, not a bug.

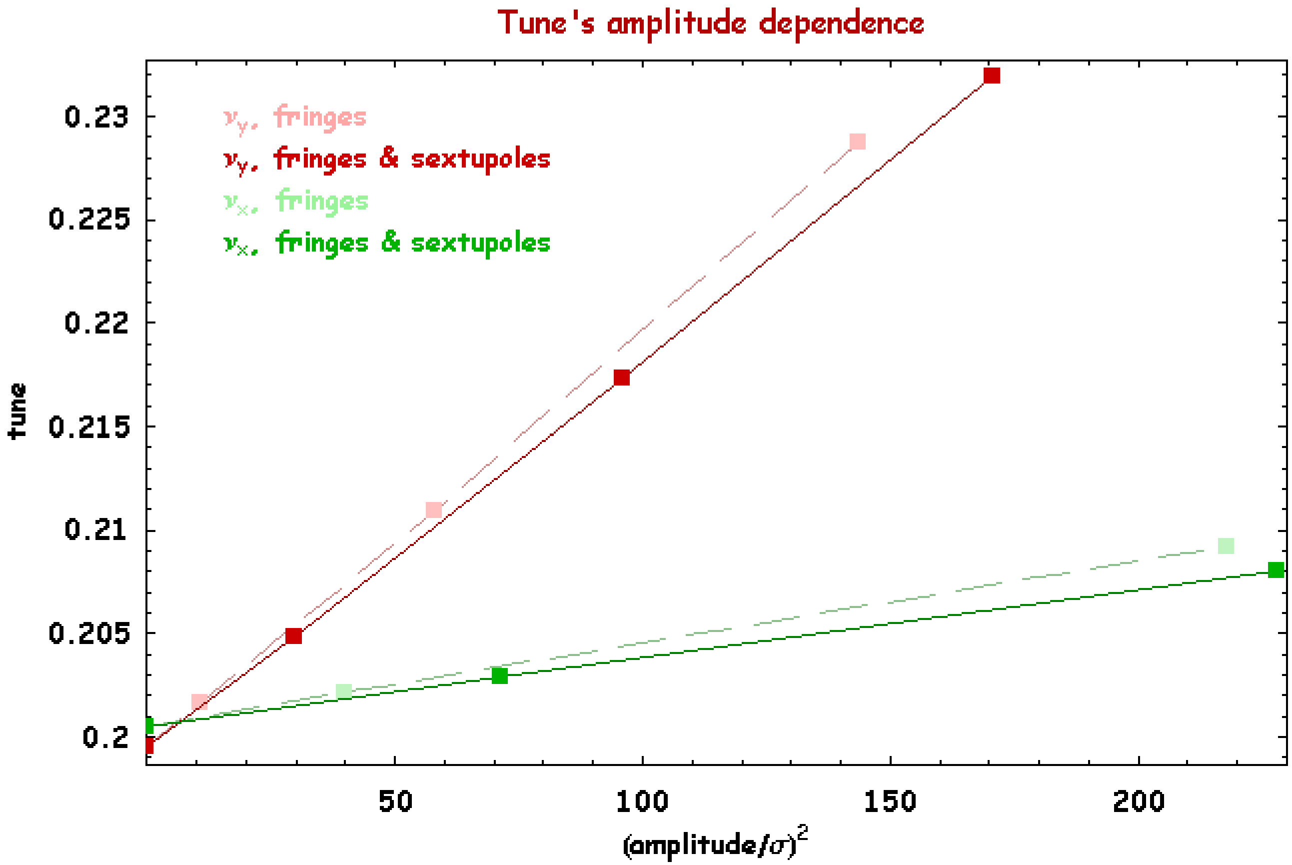
Nonlinear dynamics: sextupole fields vs. quads fringe fields (2007)





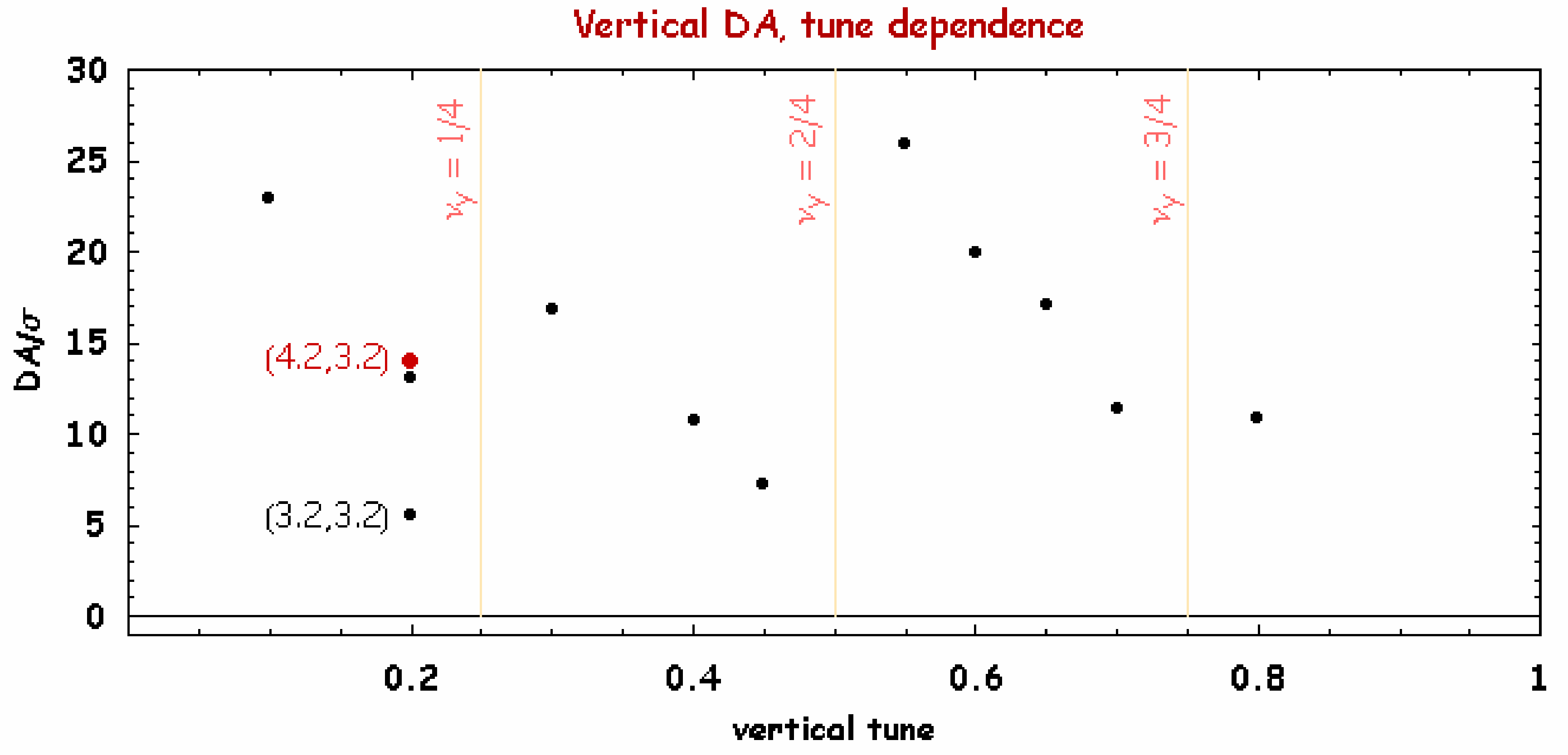
Nonlinear fringes give much stronger limitations on DA in both planes than sextupole fields do.

Tune dependence on amplitude (2007)



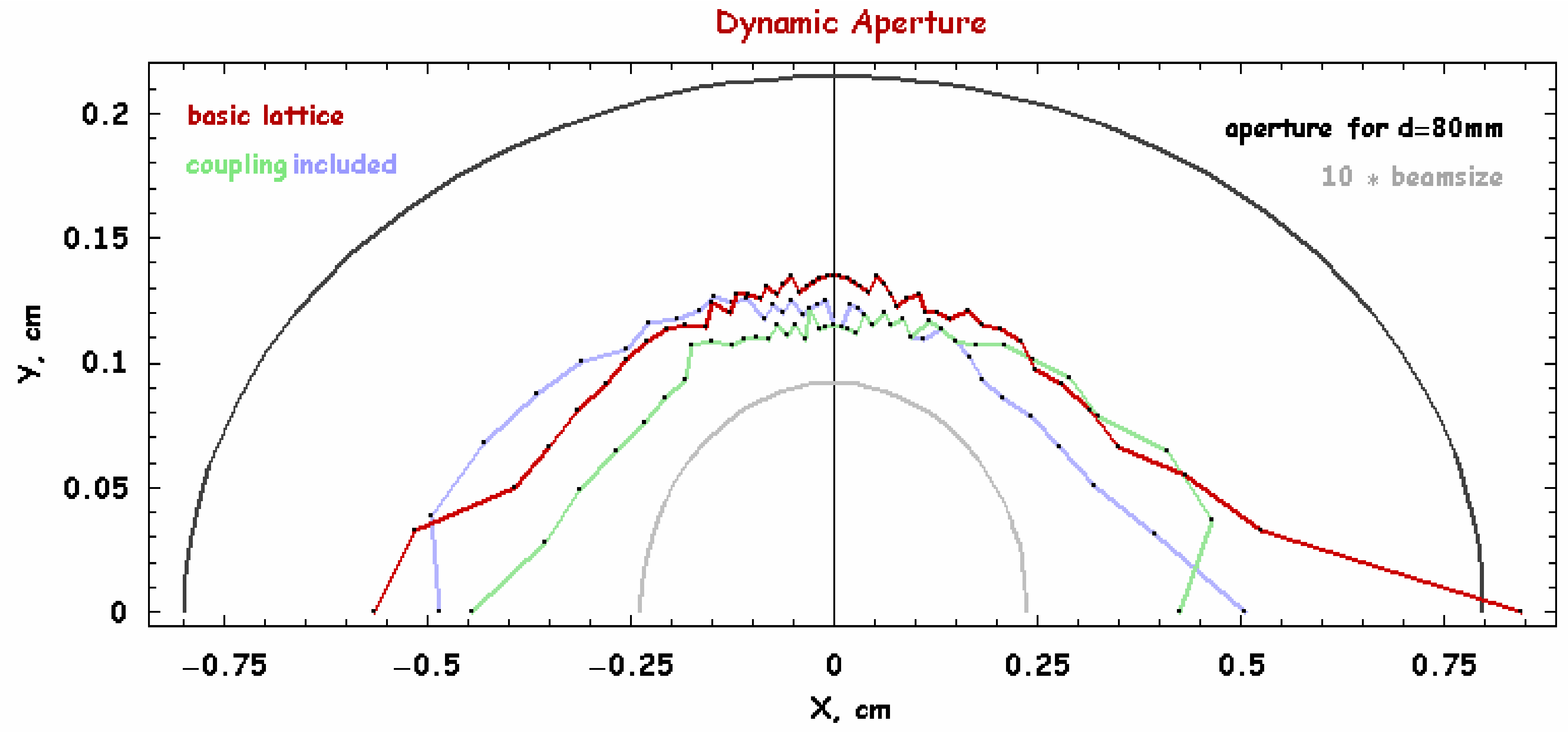
Particles oscillating with large amplitudes moves closer to “octupole” resonance of 1/4. Correction of amplitude dependence with real octupoles slightly increase the vertical DA, but reduce the horizontal one…

Tune scan,fringes only (2007)



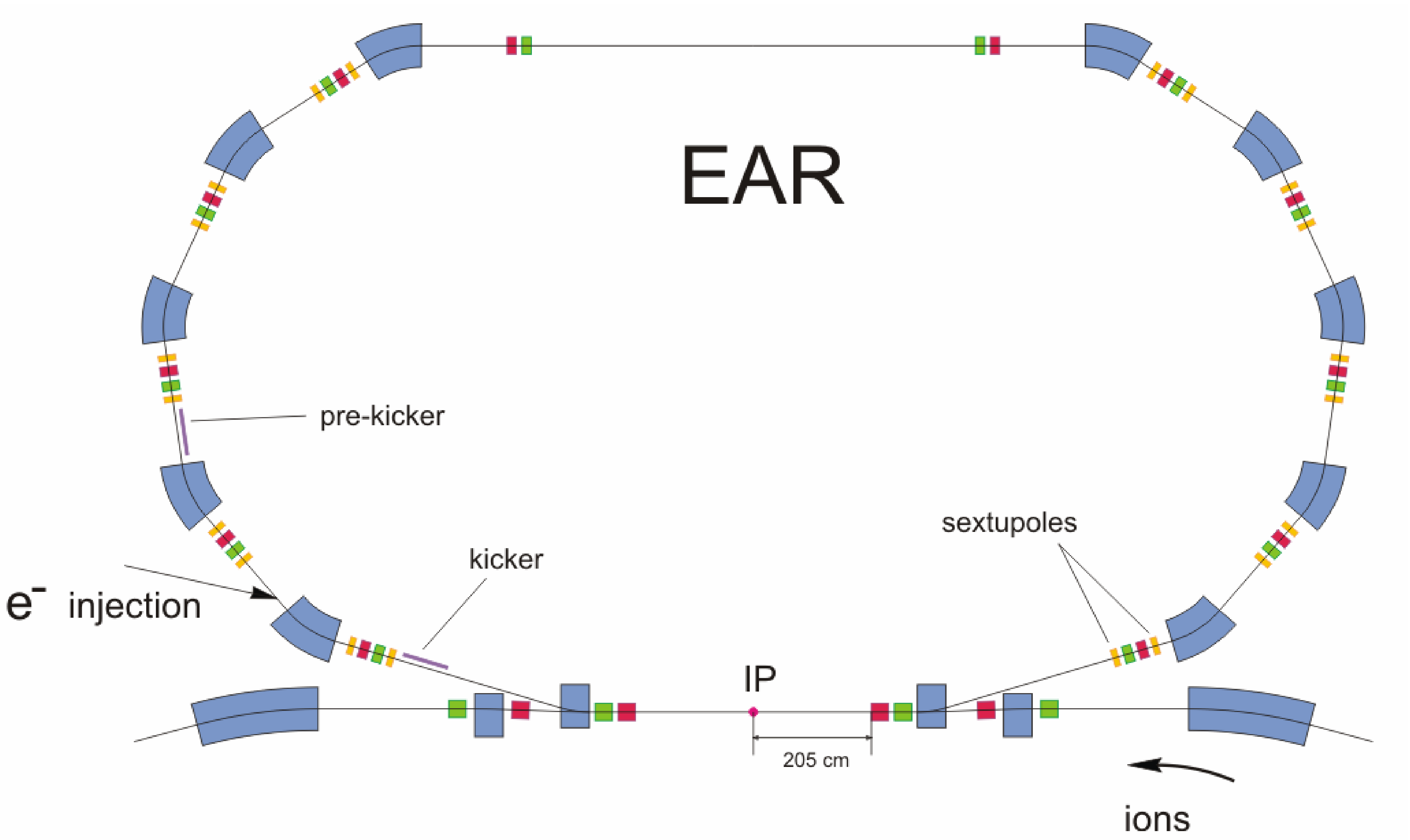
Working point being just below the 1/4 resonance correlates with small DA.

Dynamic aperture in presence of betatron coupling (2007)



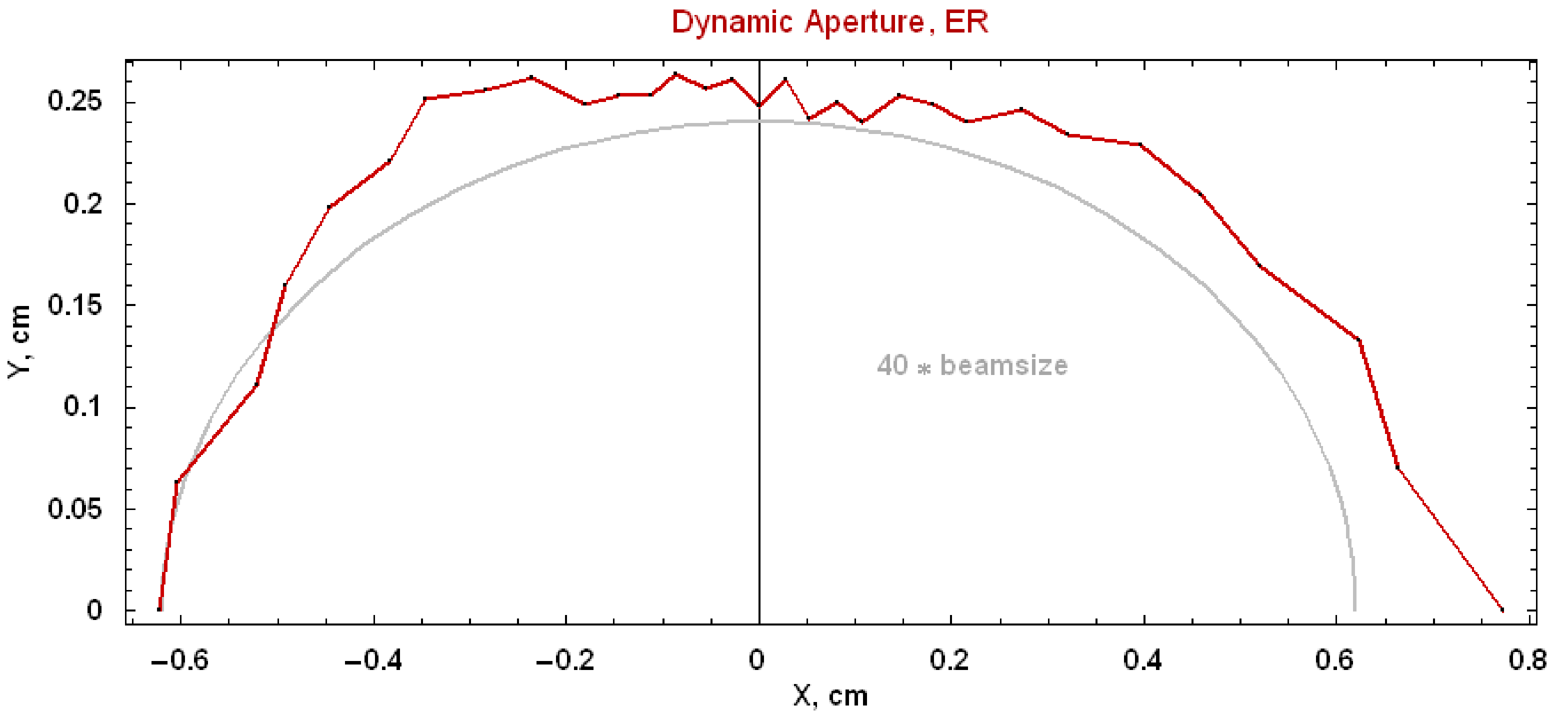
Two different handmade “random” sets of quads rotations were providing the betatron coupling, that makes equal emittances and tune split of ~0.01.

Electron Ring, current status



Final focus lenses are lengthened to avoid strong nonlinear fringe fields.

Preliminary dynamic aperture estimations



Plans for future

- Preparation of linear optics modes with different emittances
- Tunes chromaticity correction for different modes
- Lattice functions chromaticity control and improvement if necessary
- Dynamic aperture estimations, optimization of sextupole scheme
- Evaluation of tune-amplitude dependence, fringe fields effects etc.
- Rude estimations of beam-beam effects and luminosity limits.