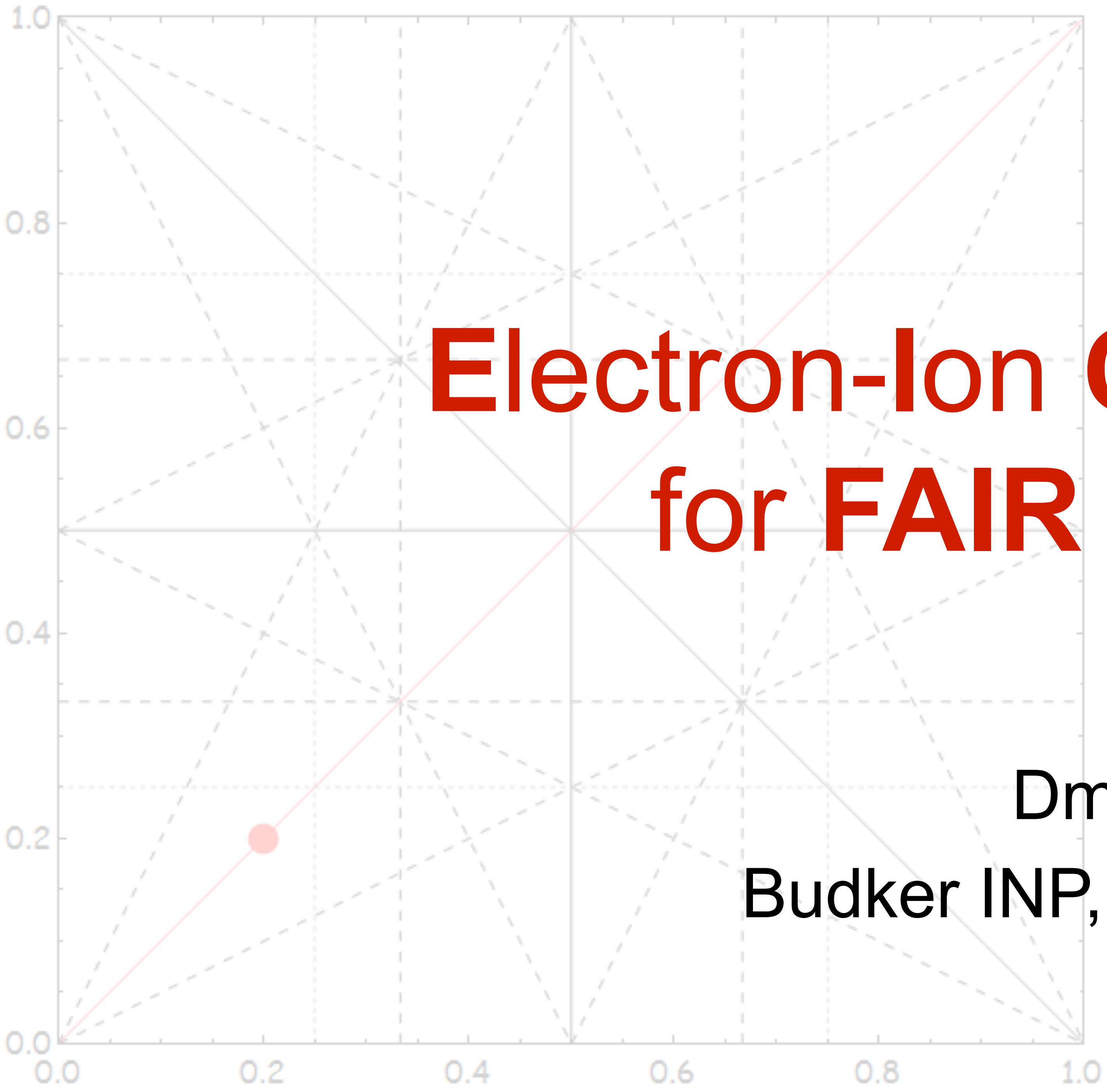


Electron-**I**on **C**ollider for **FAIR** Project

Dmitry Shwartz

Budker INP, Novosibirsk

Outline

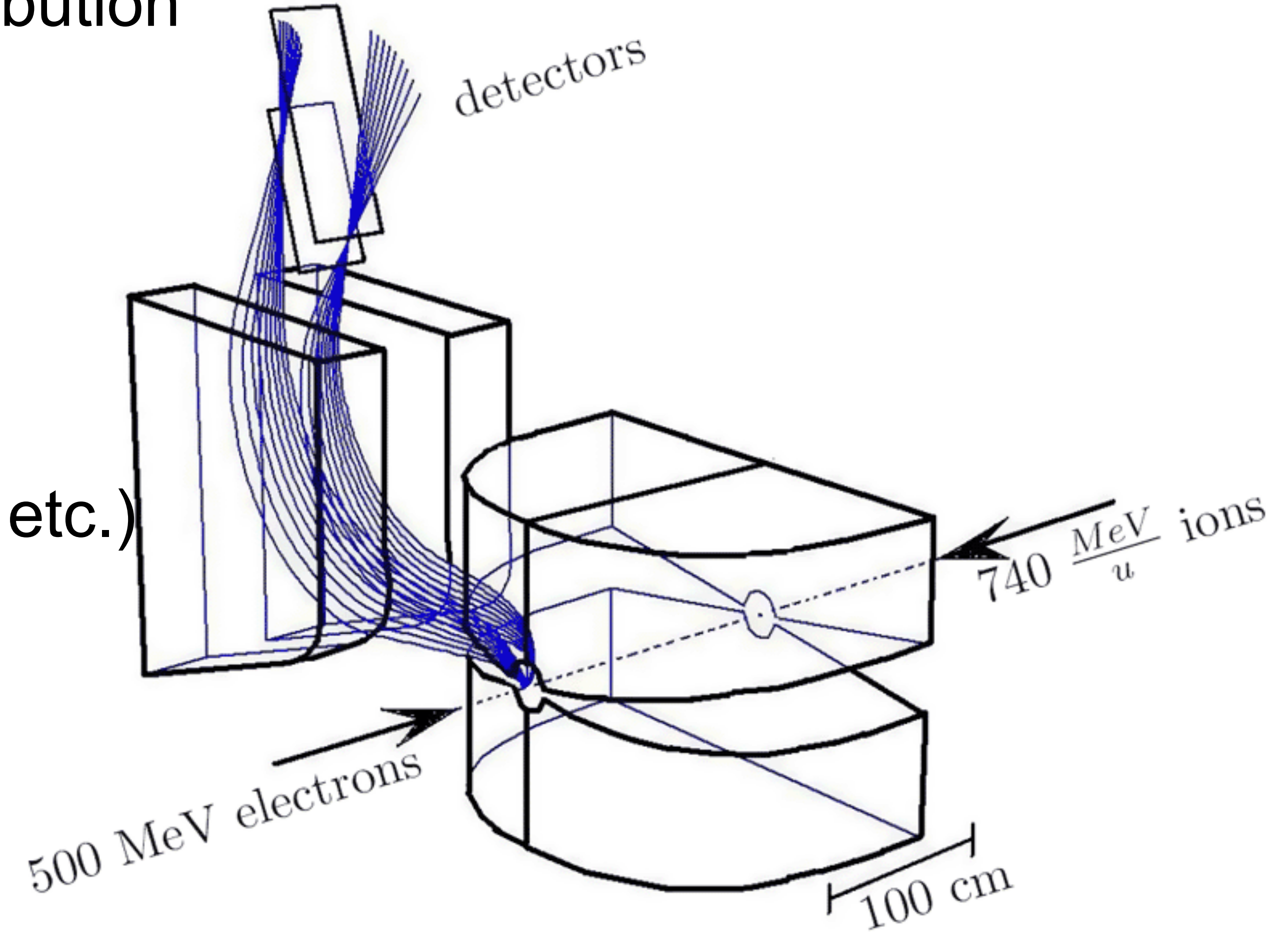
- ELISe experiment at Electron-Ion Collider
- EIC overview & parameters
- Interaction Region adopted for fission experiments
- Luminosity approach & limitations
- Emittance of electron beams, changeable emittance
- Chromaticity correction in EAR
- EAR Dynamic Aperture optimization: "best pairs" method.
- NESR (collider mode) DA estimations
- Conclusion

ELISe experiment @ EIC

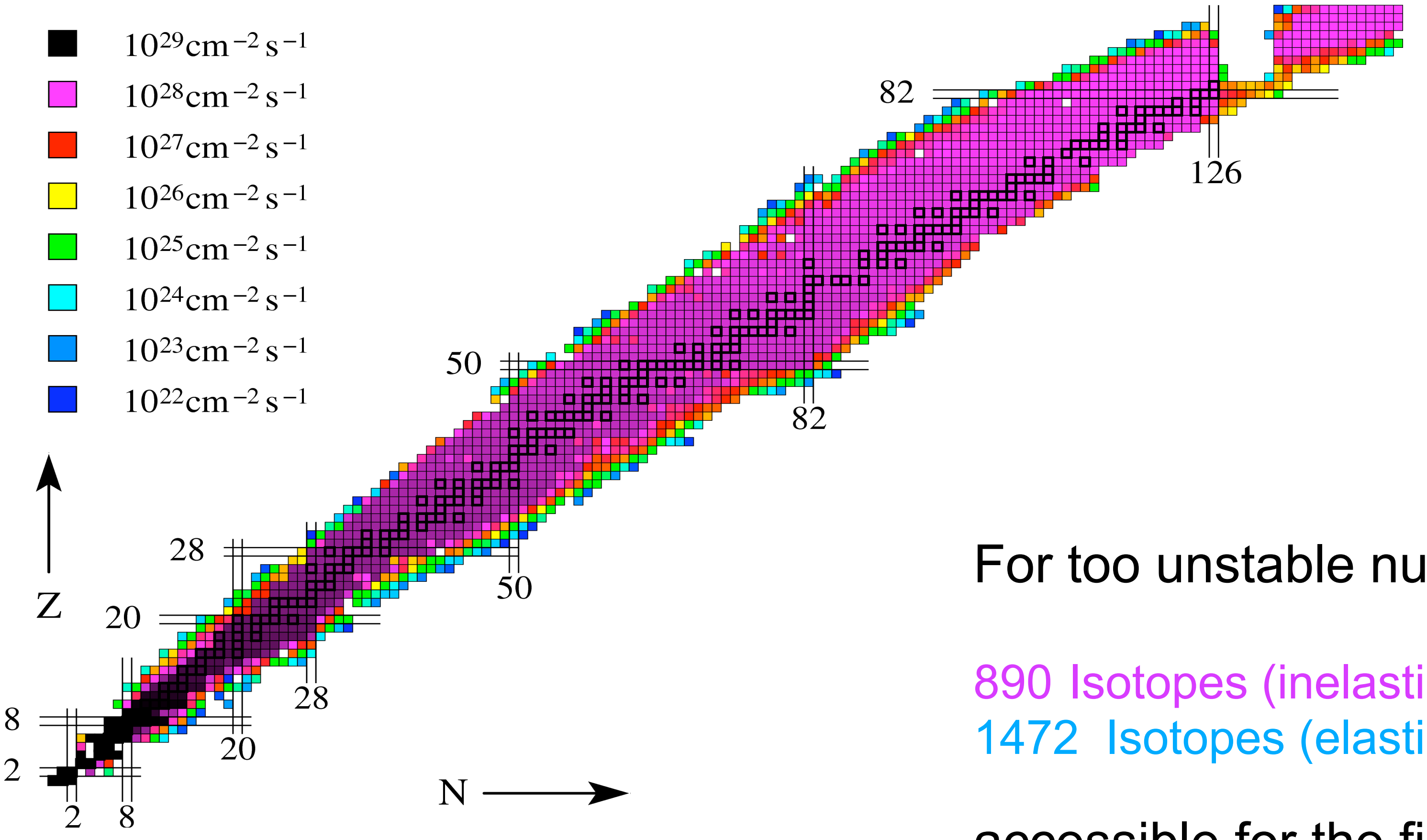
Electrons scattering on the nucleus:

1) elastic (charge distribution of exotic nuclei)
$L_{req} \sim 10^{24} cm^{-2} s^{-1}$;

2) inelastic (electro-magnetic excitations etc.)
$L_{req} \sim 10^{28} cm^{-2} s^{-1}$



ELISe mission



For too unstable nuclei ($T_{1/2}$< 1d)

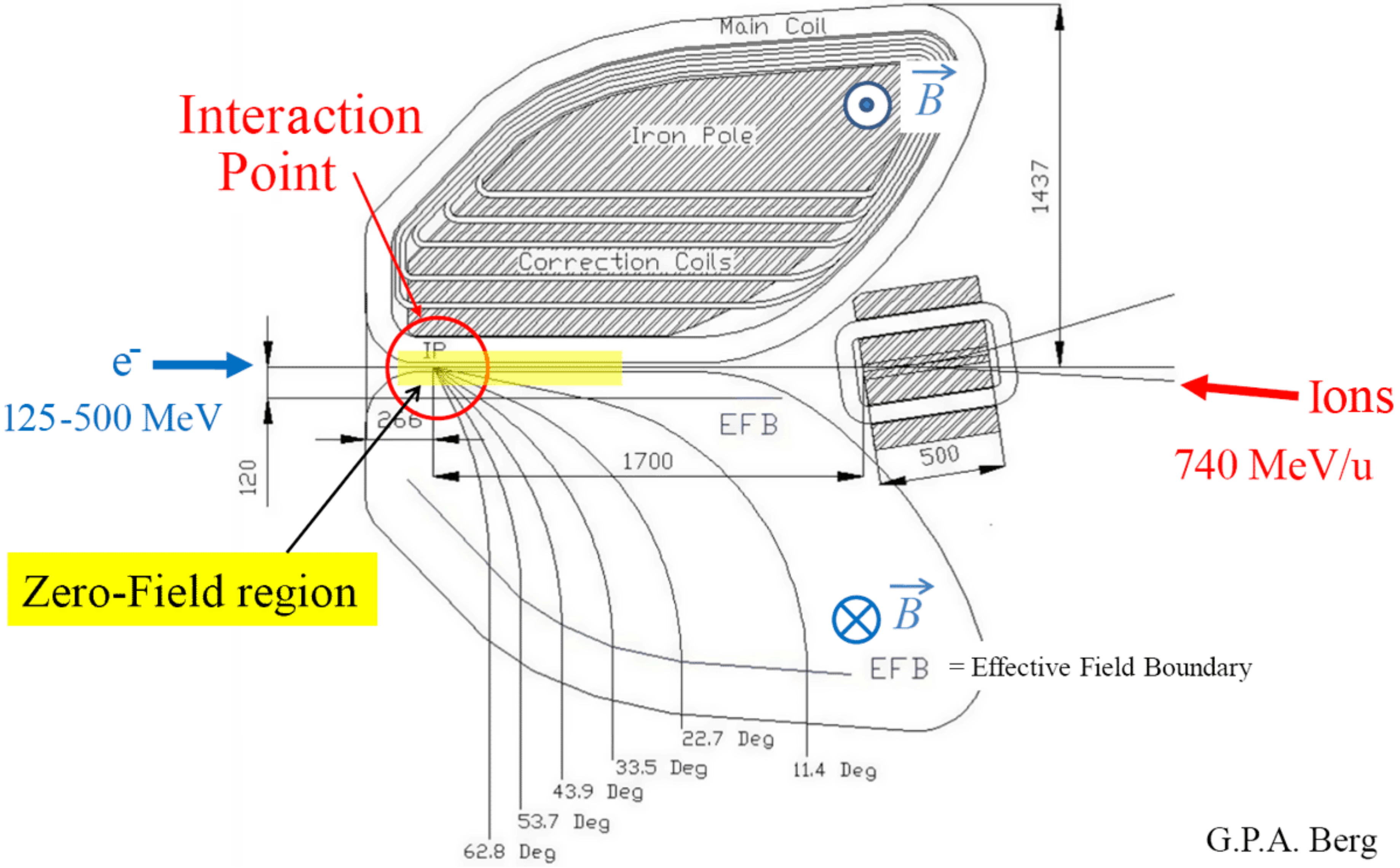
890 Isotopes (inelastic scattering)

1472 Isotopes (elastic scattering)

accessible for the first time!

by H.Simon

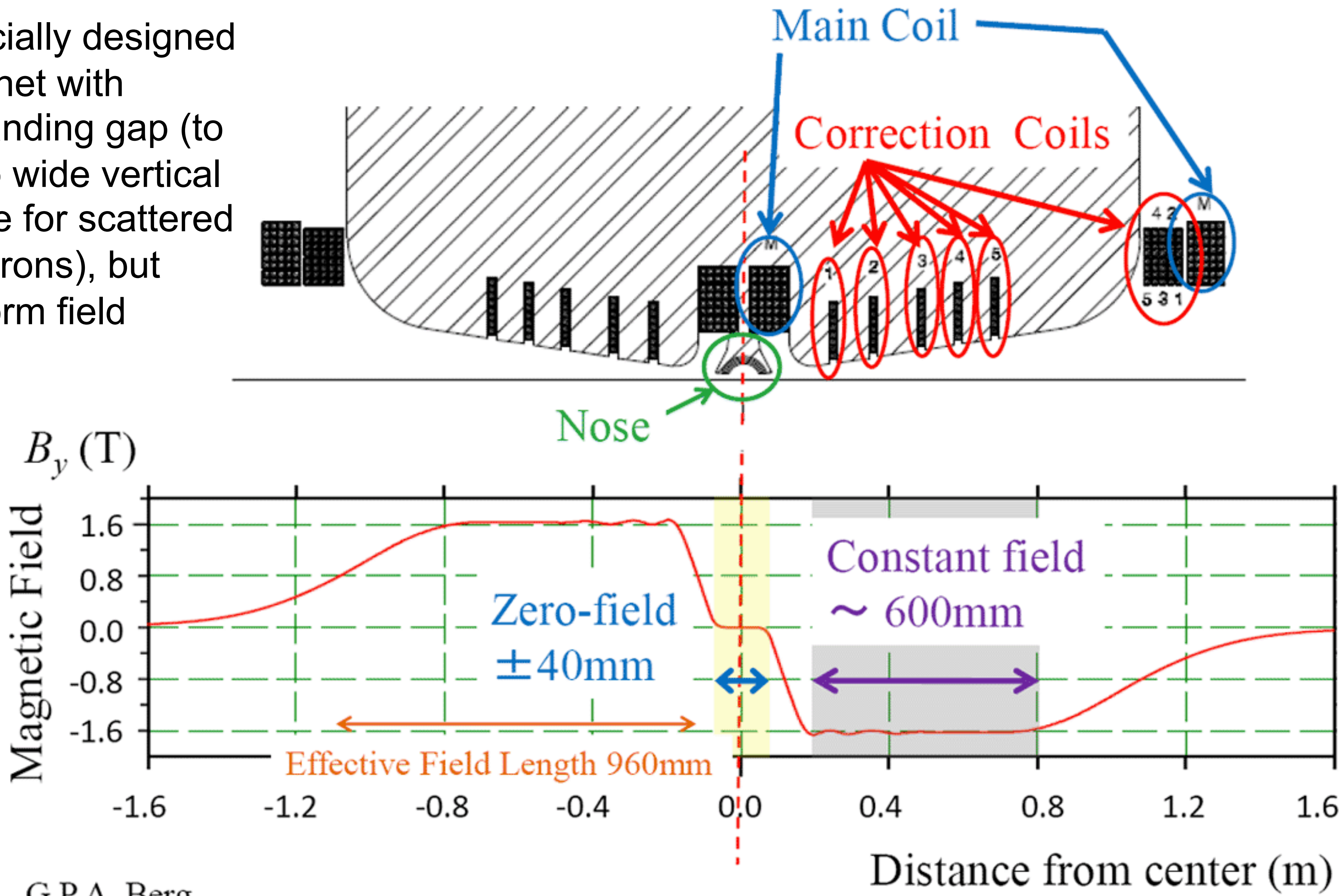
ELISe pre-deflector magnet ("Butterfly"), top view



G.P.A. Berg

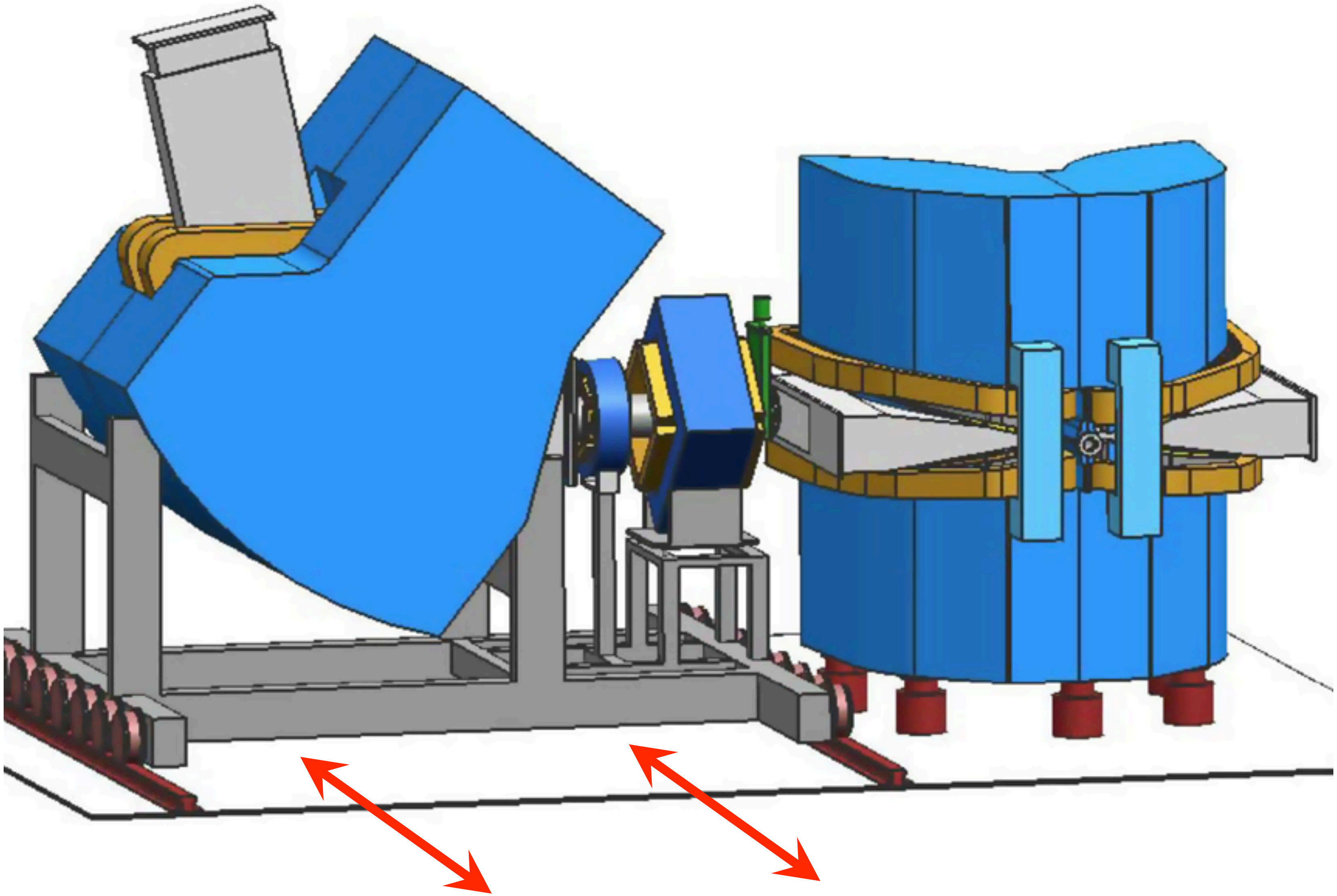
Butterfly magnet field transverse distribution

Specially designed magnet with expanding gap (to keep wide vertical angle for scattered electrons), but uniform field



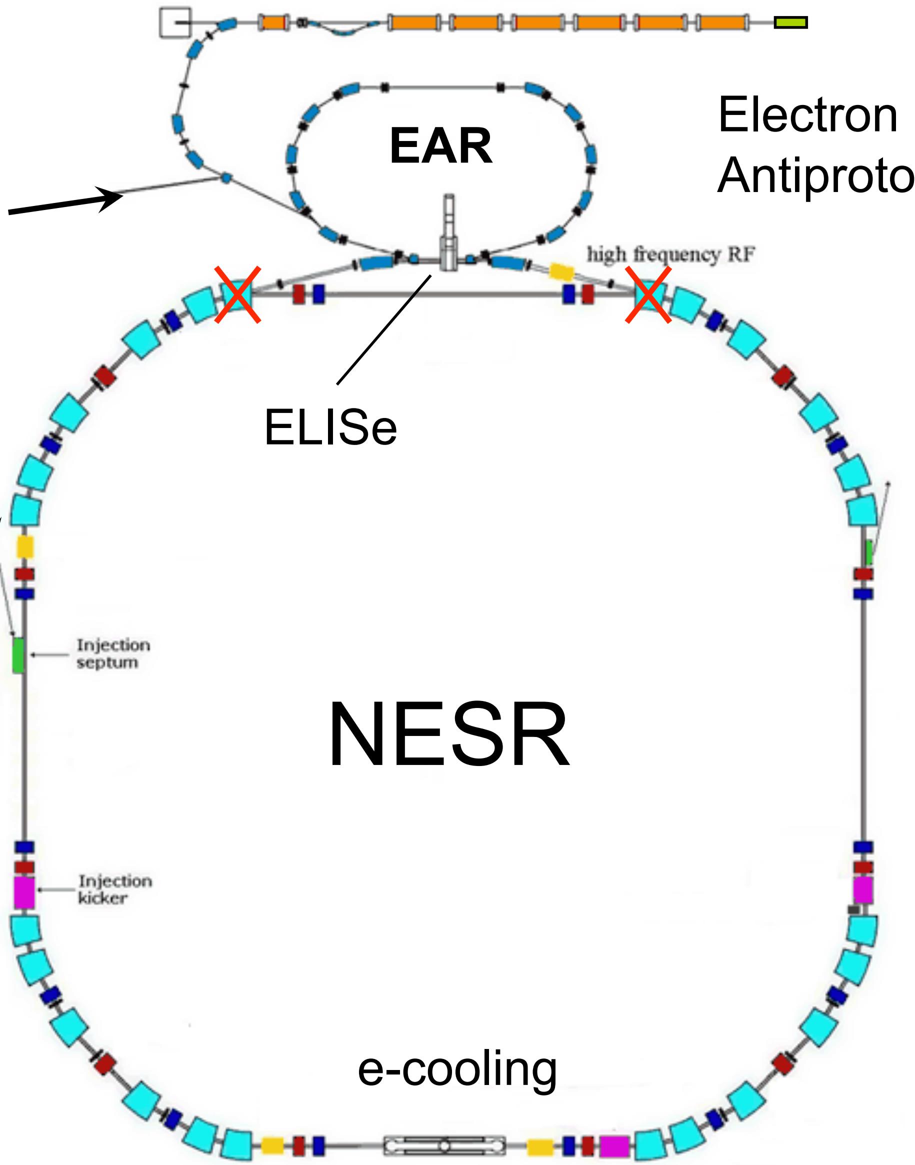
G.P.A. Berg

ELISe spectrometer 3D view



The assembly (except "butterfly") is movable on the rails to make scan along beam axis (i.e. electron scattering angle)

EIC General View



125-500 MeV Electron linac

EAR

Electron &
Antiproton Ring

20-125 MeV Antiprotons

high frequency RF

Precooled Ions
from CR

ELISe

Injection
septum

NESR

Injection
kicker

e-cooling

<u>BINP activity for EIC</u>

1) Linac – P.Logatchov, A.Levichev

2) e^- beamline – D.Berkaev (see poster)

3) NESR bypass & IR – P.Shatunov, I.Koop

4) EAR – D.Shwartz

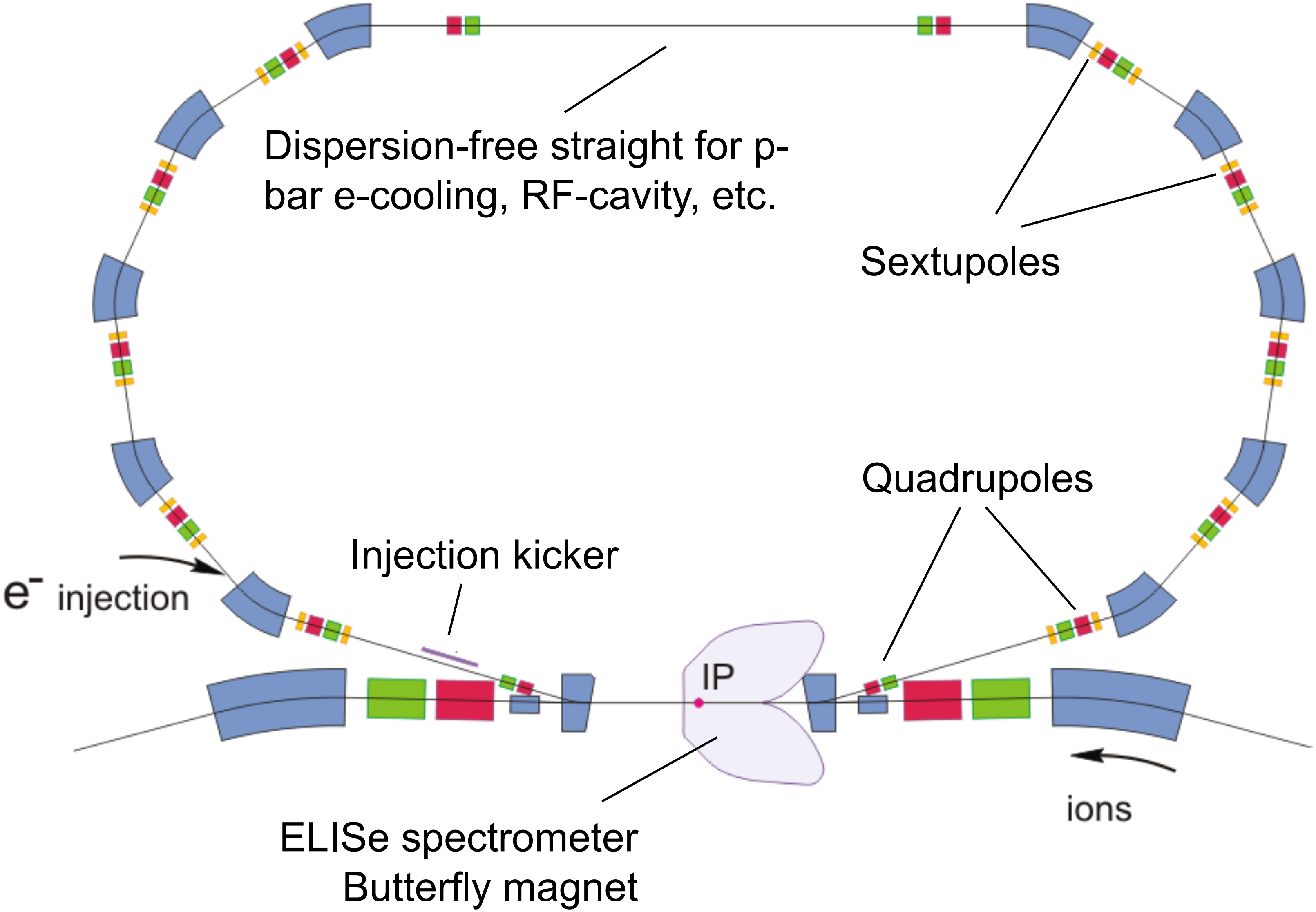
+

5) Electron cooling – V.Parkhomchuk et al.

Table of parameters

	EAR	NESR
Energy, E	125 ÷ 500 MeV	740 MeV/u
Revolution frequency, f_0	5.5717 MHz	1.1143 MHz
RF harmonic number, q	24	40?
Number of bunches	8	40
Bunch population	$5 \cdot 10^{10}$	$9 \cdot 10^{8}$
Betatron tunes, ν_x, ν_y	4.2, 3.2	4.55, 2.55
Beta functions in IP, $\beta^*_{x,} \beta^*_y$	100 cm, 15 cm	
Beam emittances, $\varepsilon_{x,y}$	$4 \cdot 10^{-6}$ cm·rad	
Beam sizes in IP, σ_x, σ_y	0.15mm, 0.06mm	
Bunch length, σ_s	4 cm	15 cm
Momentum compaction, α_p	0.034	0.036
Momentum spread, $\sigma_{\Delta p/p}$	$3.2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Damping time, τ_x	70 ms	20 ms
Luminosity, L	$1 \cdot 10^{28}$ cm^{-2} s^{-1}	

EAR layout



Dispersion-free straight for p-bar e-cooling, RF-cavity, etc.

Sextupoles

Quadrupoles

Injection kicker

ELISe spectrometer
Butterfly magnet

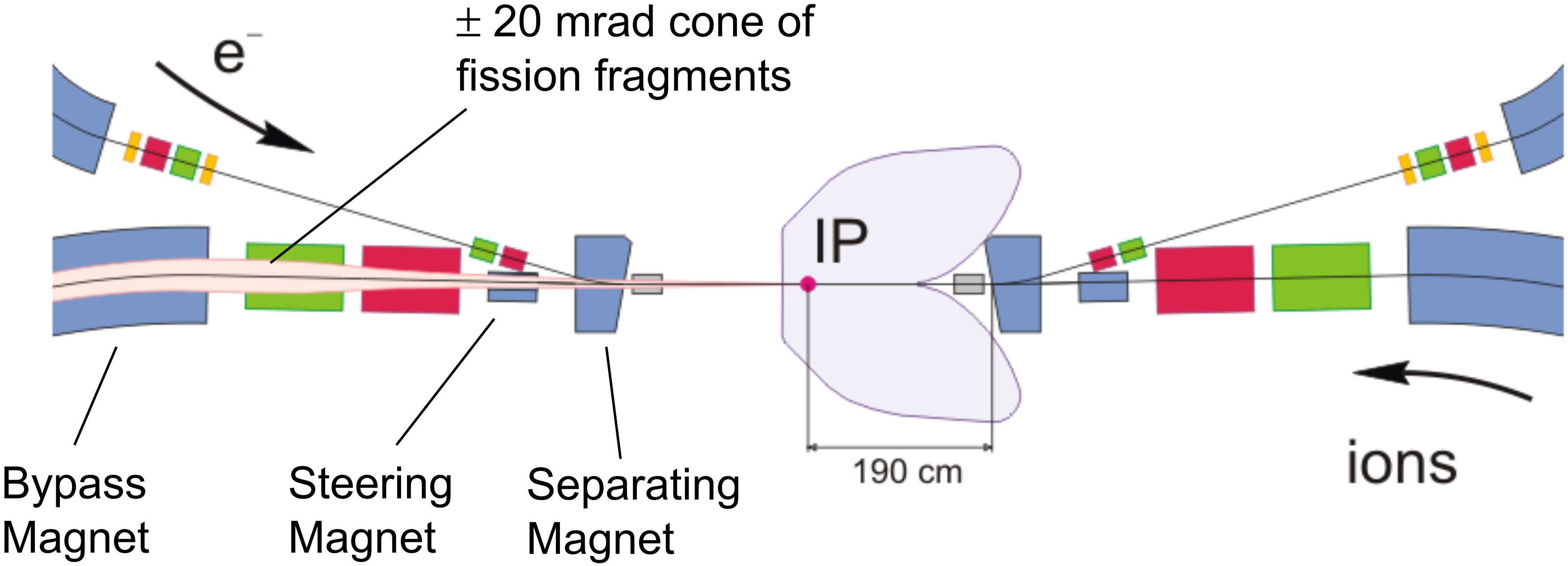
Interaction Region layout

1) Large space for ELISE spectrometer (deflection "butterfly-magnet")

2) 100 cm space in reverse direction needed for photon detection

3) "Local bump" to compensate different SM field (different electrons energy)

4) **Wide aperture bypass section in NESR for fission experiments**

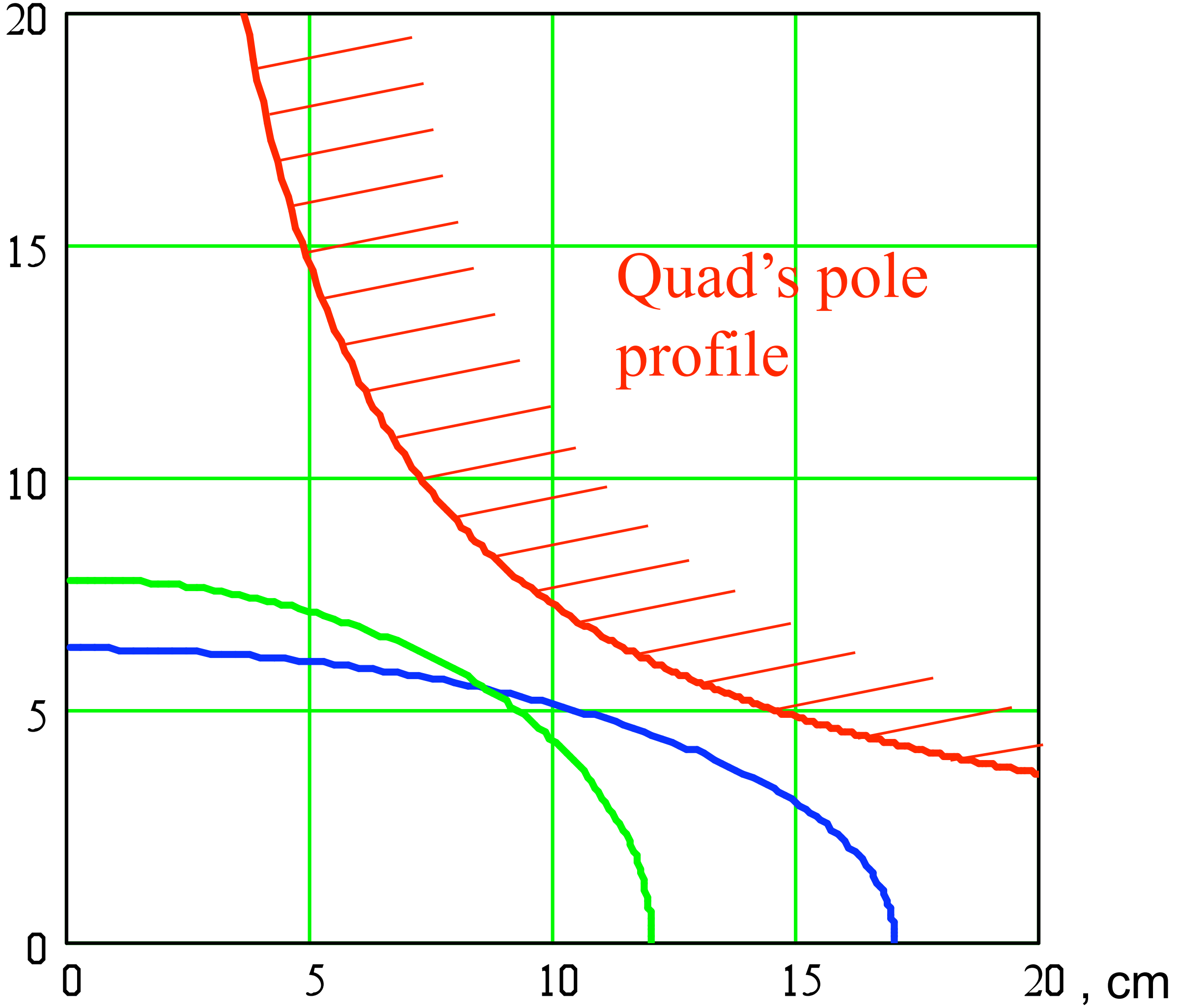


Bypass quads aperture requirements

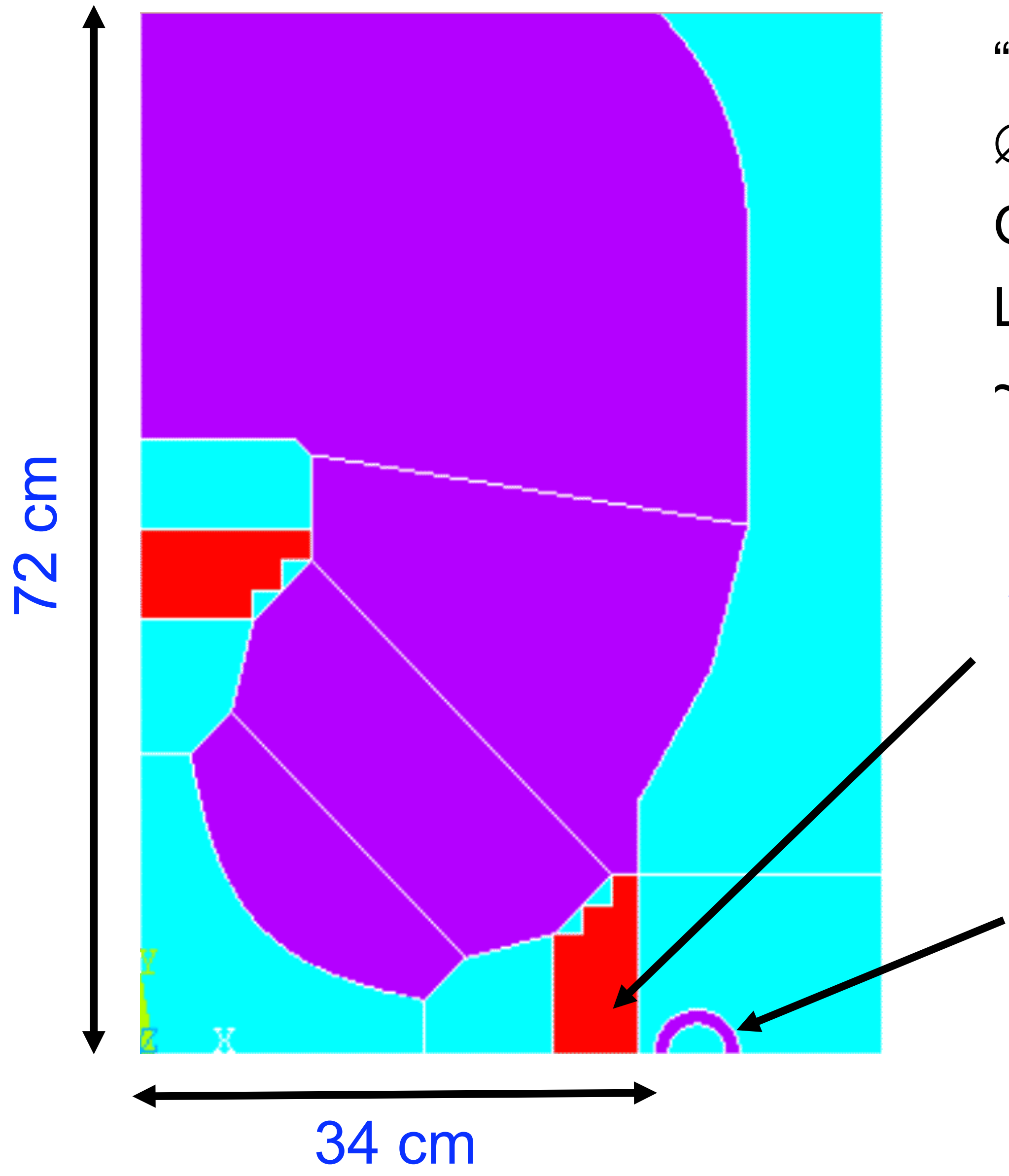
Zones in NESR D- and F-quads occupied by ± 20 mrad fission projectiles.

Some margins foreseen for case of BR > 13 T*m.

Bore radius 12 cm.



NESR bypass quads



“Figure eight” quadrupoles,
∅ 24 cm inscribed diameter,
G = 0.85 kGs/cm gradient,
L = 100 cm length,
~ 40 kW power consumption

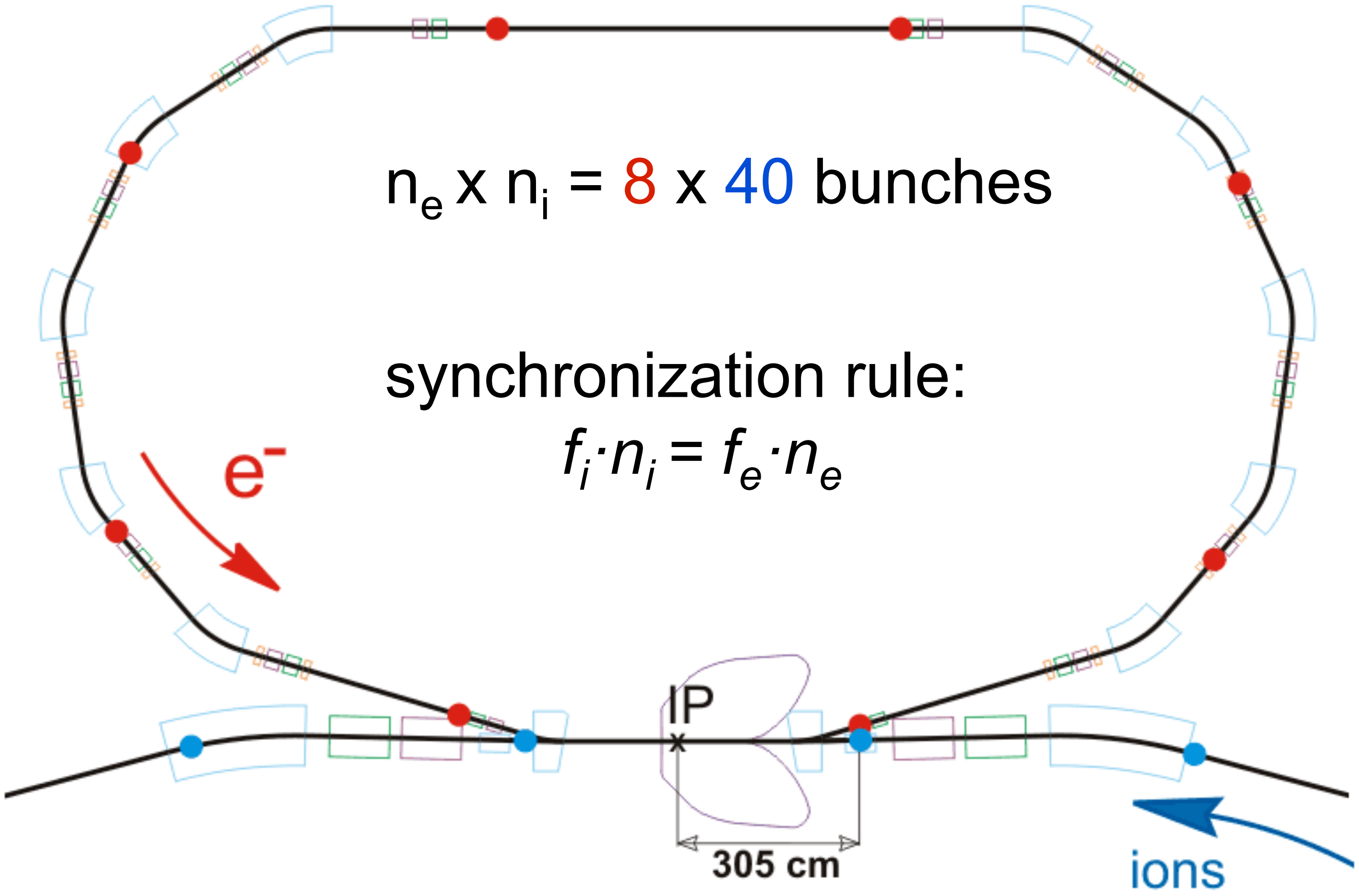
Warm coil
60 kA*turns

Zero field shield for
electron beam

EAR final
focus quads:

by P.Shatunov

Ion & electron bunches



n_e x n_i = 8 x 40 bunches

synchronization rule:

$$f_i \cdot n_i = f_e \cdot n_e$$

1) Each electron bunch meets with 5 ion bunches
2) Distance to 1-st parasitic crossing L_p = 305 cm, where bunches are separated into different vacuum chambers

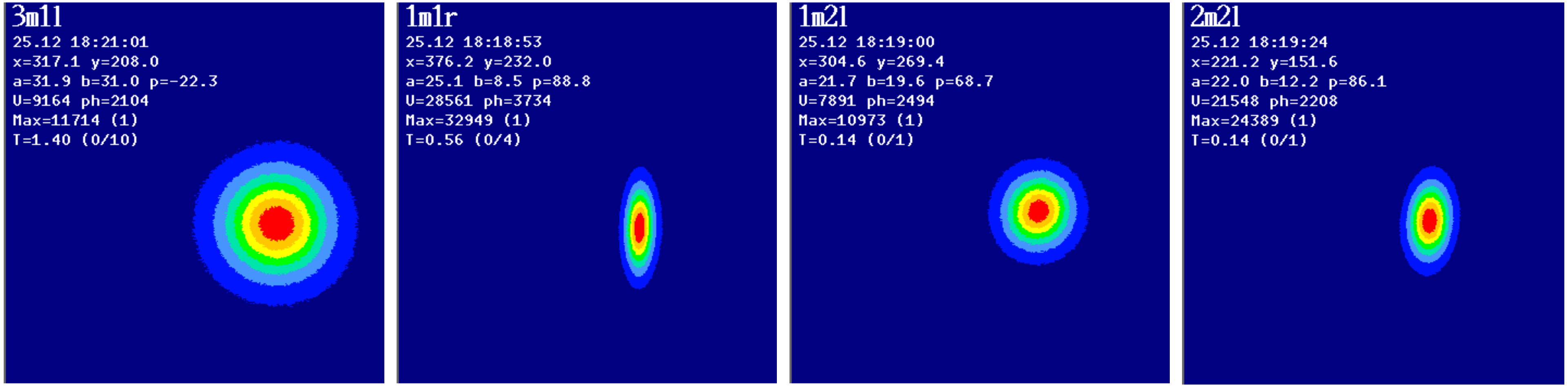
Lattice functions in synchrotron

$$\begin{cases} x'' + k_x(s)\,x = 0 \\ y'' + k_y(s)\,y = 0 \end{cases} \quad ® \quad x(s) = A\sqrt{\beta_x(s)}\cos(\psi_x(s)+\phi)$$

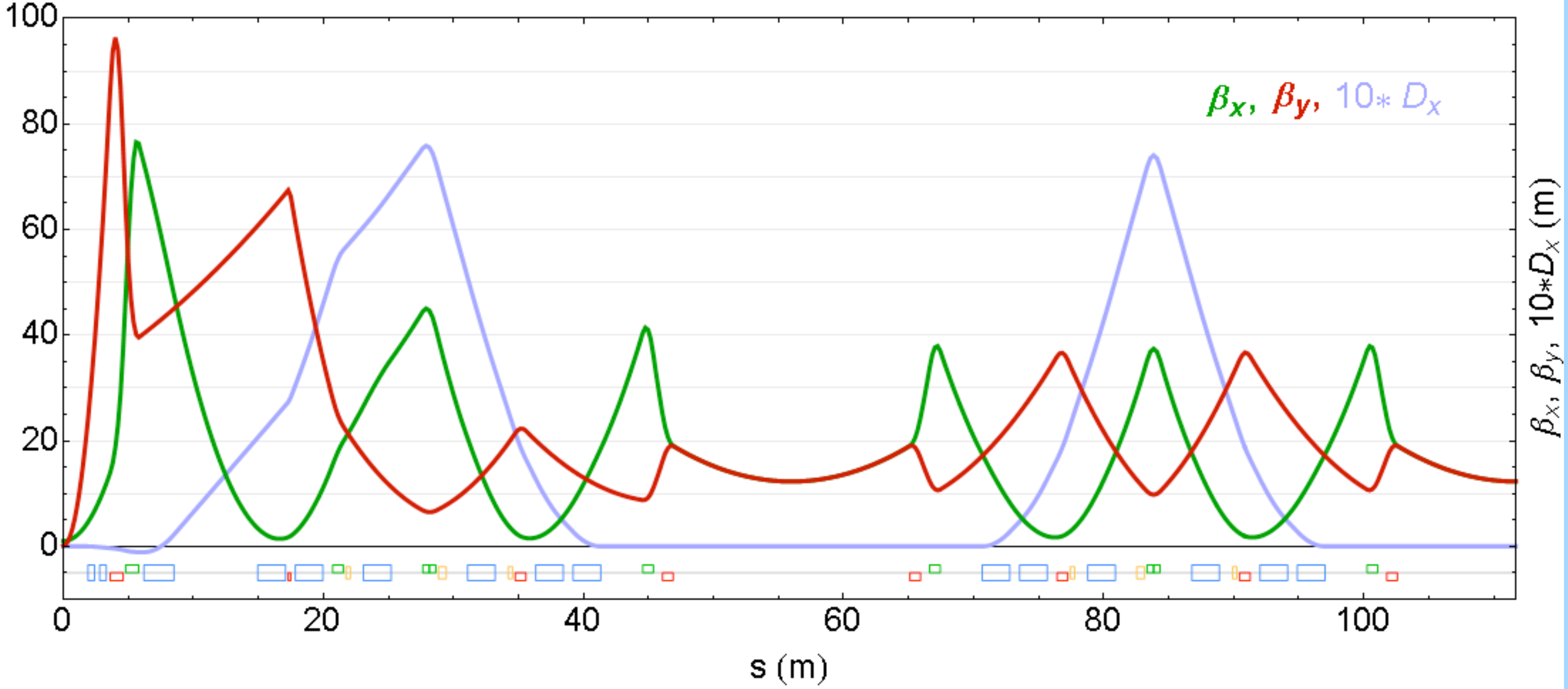
$$\sigma_x(s) = \sqrt{\varepsilon_x \times \beta_x(s)}$$

$$x_\beta(s) = D(s) \times \frac{\Delta p}{p} \qquad \sigma_{x,tot} = \sqrt{\sigma_x^2 + \sigma_E^2 D^2}$$

Round beam at VEPP-2000



NESR lattice



Collider mode breaks 4-fold regular NESR optics symmetry, but two arcs stay almost unperturbed

Luminosity limitations: beam-beam

Assuming $\beta_{i,x} = \beta_{e,x}$, $\beta_{i,y} = \beta_{e,y}$,
$\varepsilon_{i,x} = \varepsilon_{e,x} = \varepsilon = \varepsilon_{e,y} = \varepsilon$

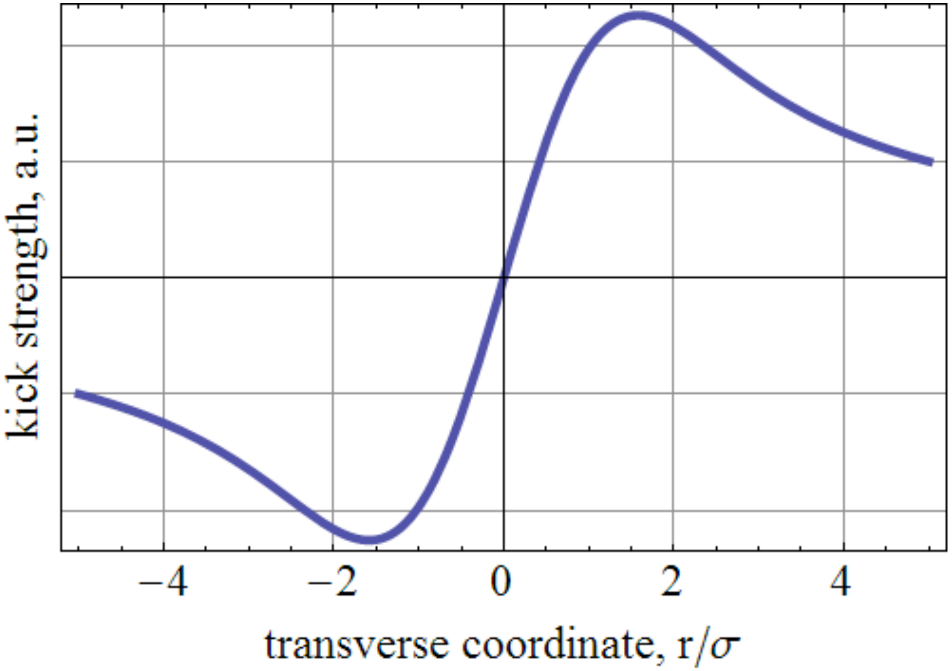
$$\xi_{ixz,} = \frac{Z}{A} \times \frac{N r_{ebpxz}}{2()\varepsilon_{iixzxz}\theta\theta\theta + } ,$$

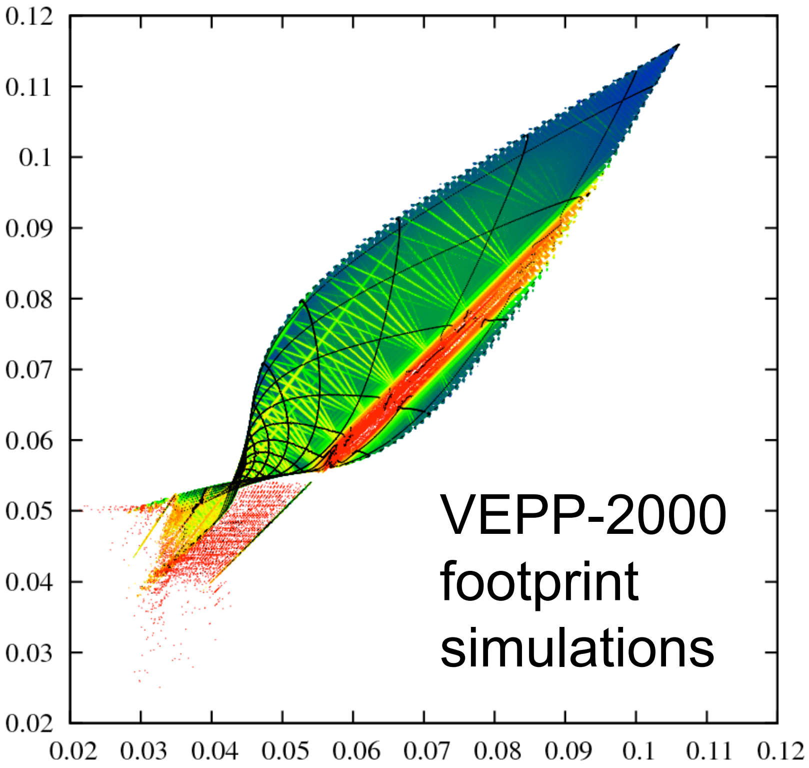
The problem with beam-beam interaction is a strong nonlinearity of beam-beam force

$$L = \frac{f n_{ee} N N_{ibeb}}{4\nu\theta\theta_{xz}}$$

Beam-beam parameter ξ - the tune shift in linear approximation

ξmax ~ 0.05




VEPP-2000 footprint simulations

Luminosity limited by beam-beam

Beam-beam effects are important only for ion beam and thus limit the opposite (electron) beam intensity:

$$N_{eb} = \frac{A}{Zr_{px}} \frac{2\nu\varepsilon_{iiix}\bar{\varpi}}{} \chi \left(1 + \sqrt{\frac{z}{}}\right)$$

Luminosity expressed via threshold beam-beam parameter:

$$L f n N n N N_{ilibibitot} = \frac{A}{Z} \frac{\bar{\varpi}\varepsilon_{ixii}}{2r_{pxz}\sqrt{}} \left(1 + \sqrt{\frac{z}{x}}\right)$$

Luminosity depends only on total ion beam current, not on the number of bunches. For weak ion beams (with no IBS problems) rationally to operate in 1x1-bunch regime to avoid potential difficulties with collective beam-beam effects.

Luminosity limitations: IBS

Tuneshift due to intrabeam scattering:

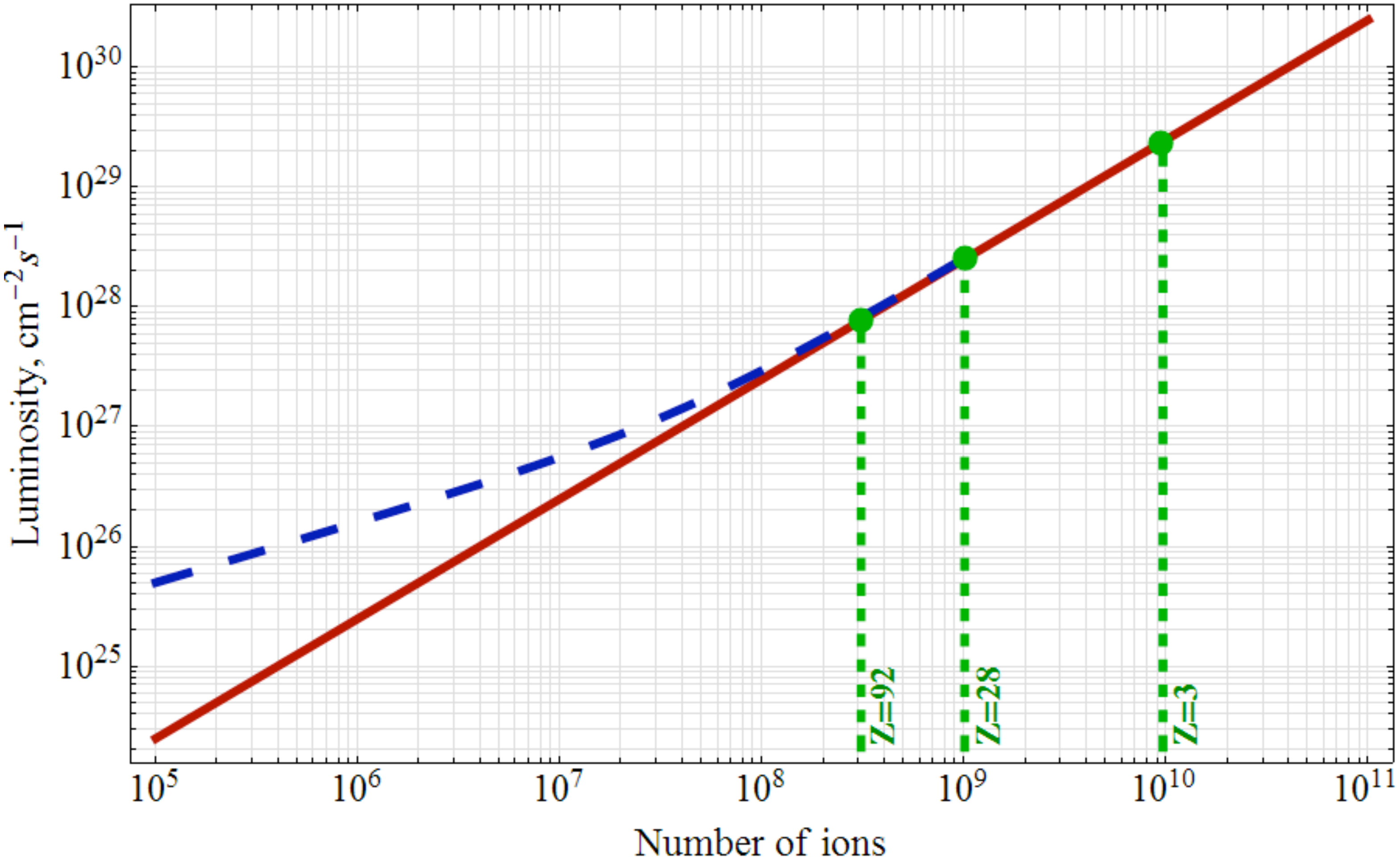
$$B\lambda = \times \times \frac{Z^2 R}{A} \frac{N r_{ibp}}{\varepsilon_{ii}^{32} \chi} \frac{}{2 2\sqrt{\ \nu \theta_s}} \qquad B\lambda_{\max} \sim 0.1$$

IBS tuneshift strongly depends on energy, and becomes negligible for ultra-relativistic electron beams (γ_i = 0.8303, γ_e = 1000). IBS thus limits ion beam intensity.

Limitations for the ion beam intensity (with given emittance):

$$\frac{N_{ibiis}}{\chi} = \times \times \frac{A}{Z^2 r R} \frac{\varepsilon^{32} \lambda \nu B \theta}{p} \frac{2 2\sqrt{\ }}{}$$

Luminosity Approach



Luminosity limited by beam-beam interaction.

Ion beam intensity limited by IBS.

Additional benefit for low-intensive ion beams

Luminosity benefit for exotic ion beams

Not mentioned ion beam intensity limitation – the production rate!

If available number of ions (exotic and radioactive)

$N_{ib} << N_{ib\ max}$ (for given $\varepsilon = 5 \cdot 10^{-6}\ cm$),

let us cool the beam down $\varepsilon \rightarrow 1 \cdot 10^{-7} cm$

Gain in luminosity:

1) Higher density in the core of electron beam (gain factor: x2)

2) Less nonlinearities in beam-beam force, larger ξ (gain factor: x10)

Nevertheless the electron beam emittance should be significantly reduced (while its intensity - increased to raise particles density and beam-beam parameter).

Beam emittance in electron storage rings

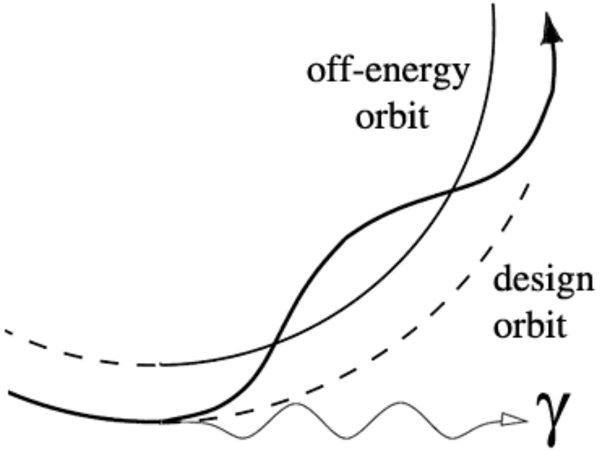
The balance between strong radiation damping and quantum fluctuations of synchrotron radiation forms Gaussian electron bunch distribution during several damping times, τ ~ 50 ms (@ 500 MeV).

Momentum spread: $$\left(\frac{\theta_E}{E J}\right)^2 = \frac{55}{32\sqrt{3}}\,\frac{\varphi_e}{{}_E}\,\frac{\langle 1/r_0^3\rangle}{\langle 1/r_0^2\rangle}\,\varepsilon^2$$

Bunch length: $$\theta_l = \frac{c\,{-}_{p}}{\mathrm{Y}_s}\,\frac{\theta_E}{E}$$

Horizontal emittance: $$\chi_x\varepsilon = \frac{55}{32\sqrt{3}}\,\frac{\varphi_e}{J_X}\,\frac{\langle H/r_0^3\rangle}{\langle 1/r_0^2\rangle}\;{}^2$$

where $HD = DDD^{22}_{xxx}\quad 2''$

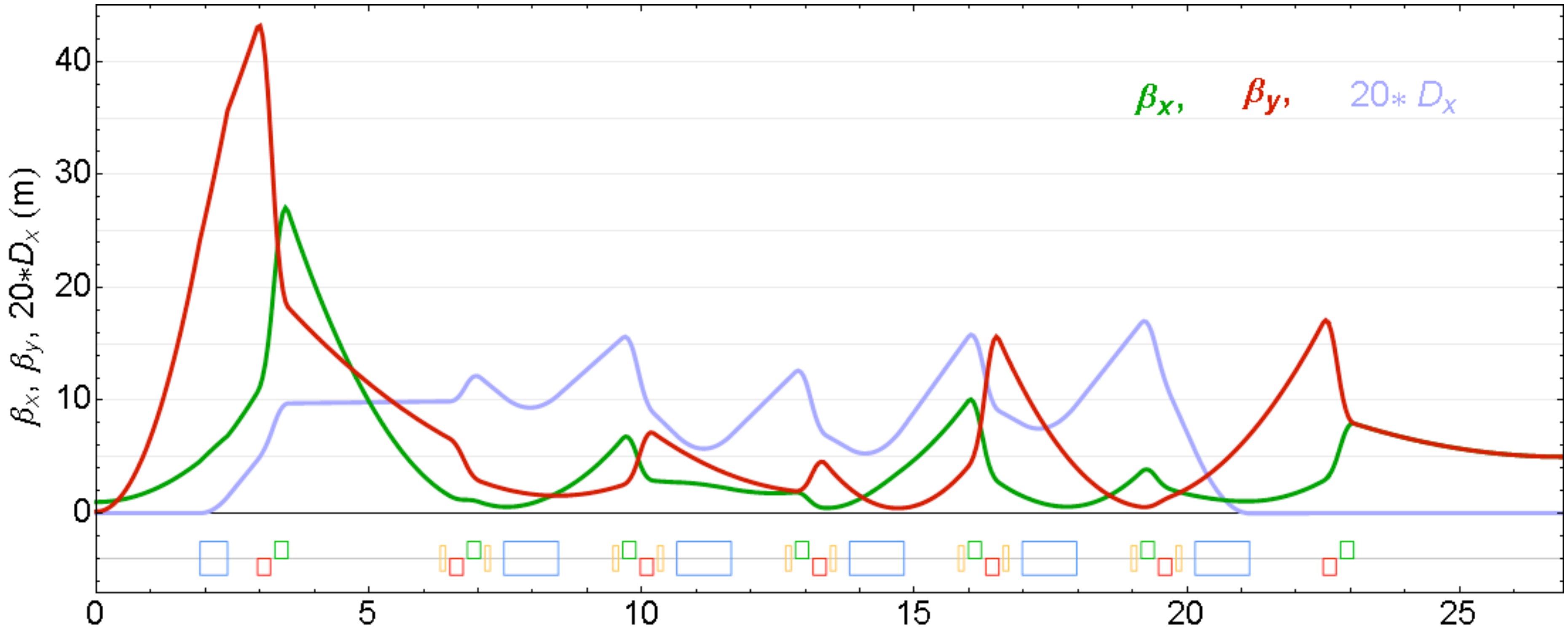


Vertical emittance: $\chi_{zx} 1 \neq \times$

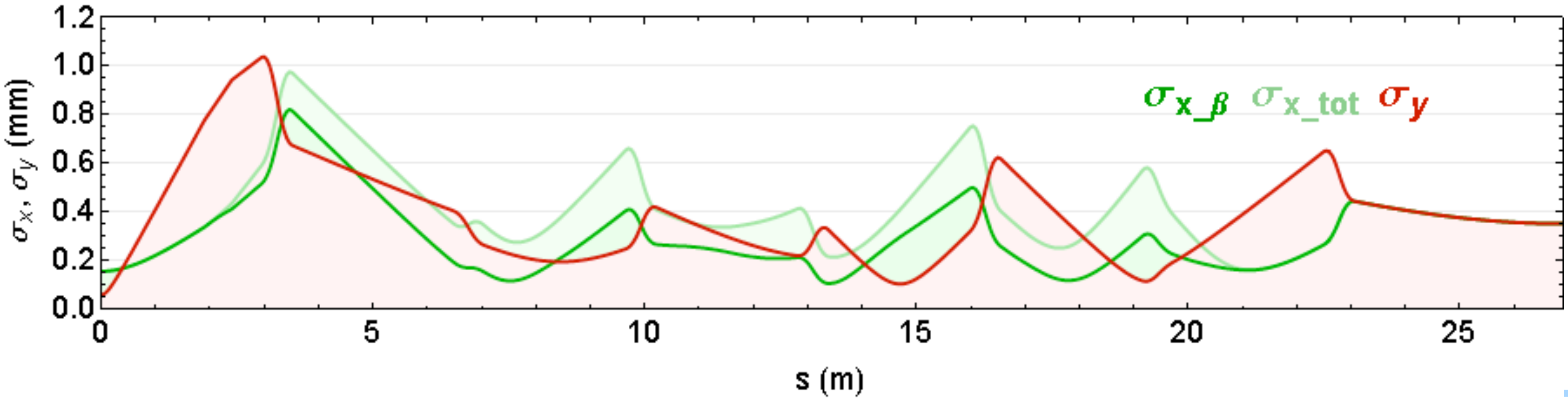
where κ << 1 – betatron coupling coefficient

Working point should be at the coupling resonance! $\{\lambda_z \lambda_z\} = \{\quad\}$

EAR lattice functions & beam size



Beam sizes



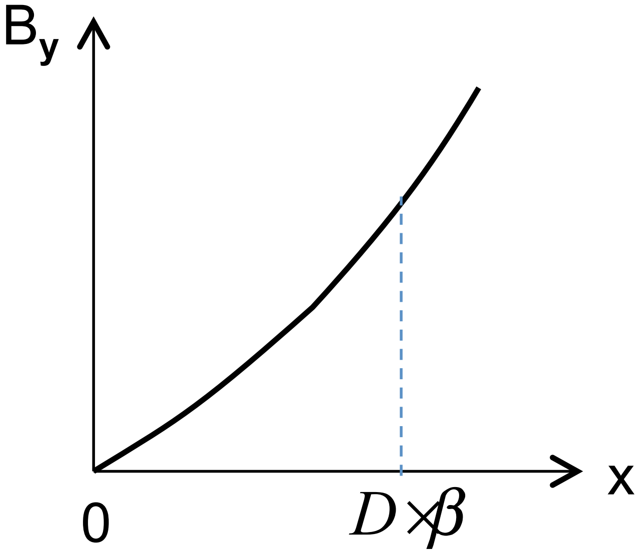
Chromaticity correction

Natural tune chromaticity in EAR ring: $\frac{\oplus\lambda_x}{\oplus\beta} =+ 7 \quad \frac{\oplus\lambda_y}{\oplus\beta} =+ 10$

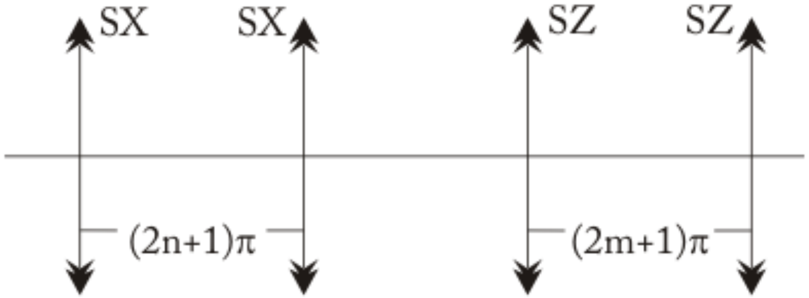
Uncompensated negative natural tune chromaticity:

- synchro-betatron coupling & resonanses
- footprint (due to beam momentum spread)
- **head-tail instability!** (with very low threshold)

Sextupoles needed to compensate tune dependence on momentum deviation.



Planning sextupole families



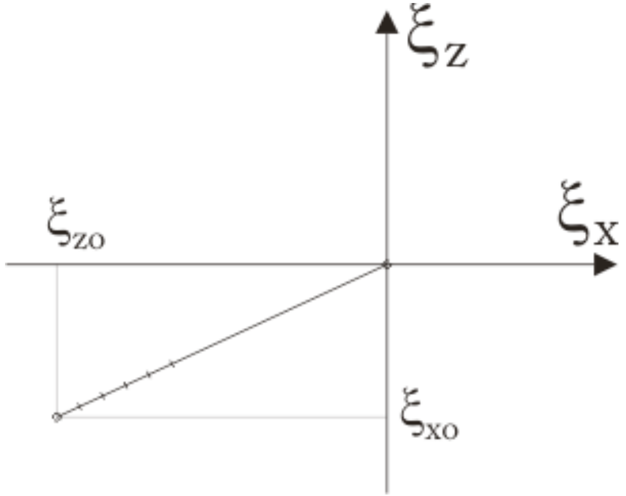
1. Self-compensated families of sextupoles arranged with proper betatron phase advance (works well for long multi-cell arcs).

2. Harmonic analysis of sextupole field distribution via resonant perturbation theory. Nearest resonance's strength suppression. (Only if the working point close to single nonlinear resonance).

$$\frac{\oplus^2 H_z}{\oplus x^2}()(s)()x\,A\,\sigma\cos(\overline{3/2})\Omega \quad \underset{n}{\leftrightarrow}{}_n$$

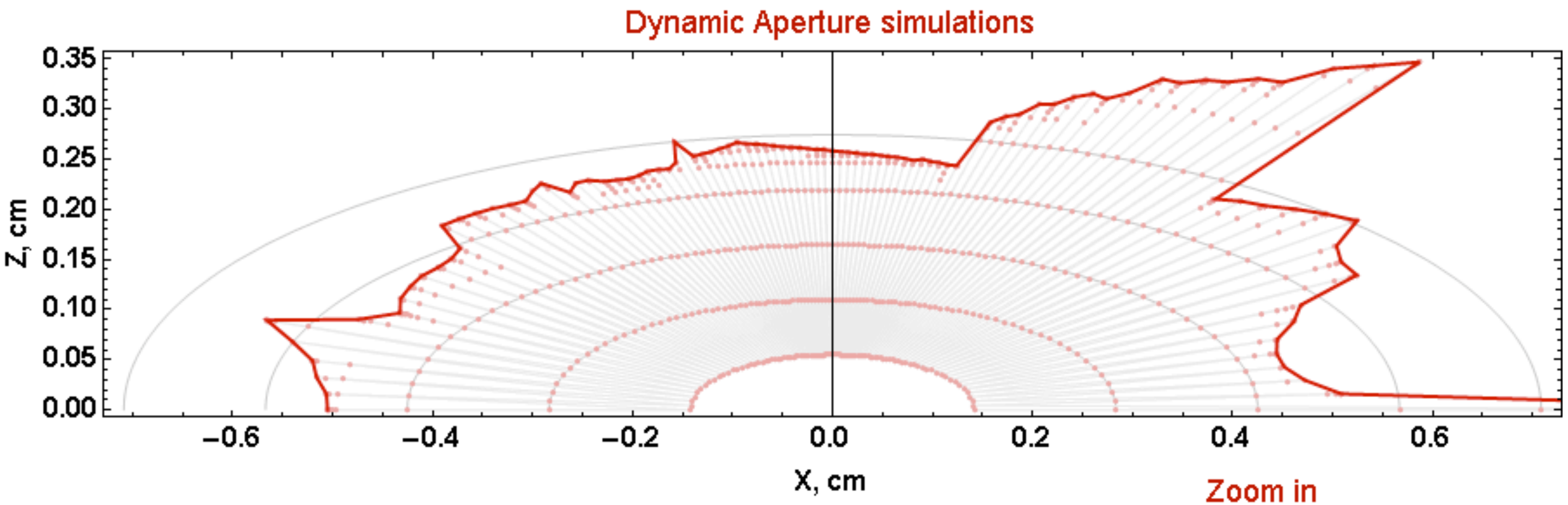
3. "Best pairs" optimization scheme (*E.Levichev, P.Piminov, EPAC'2006*).

Portion of chromaticity is compensated by one pair (SX_i, SZ_i), that gives the largest DA.



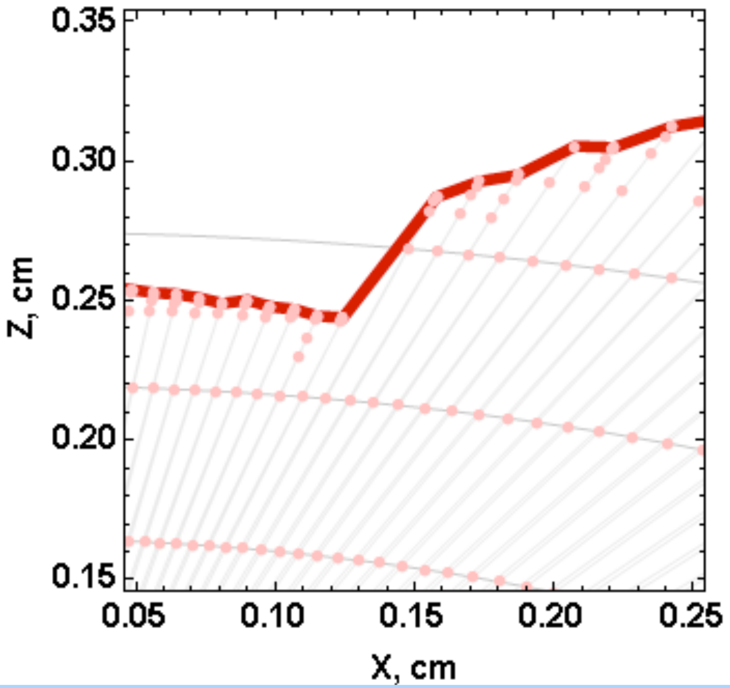
Dynamic Aperture (DA) - the region (in 4D phase space) of particle coordinates with stable betatron oscillations

Dynamic Aperture simulations

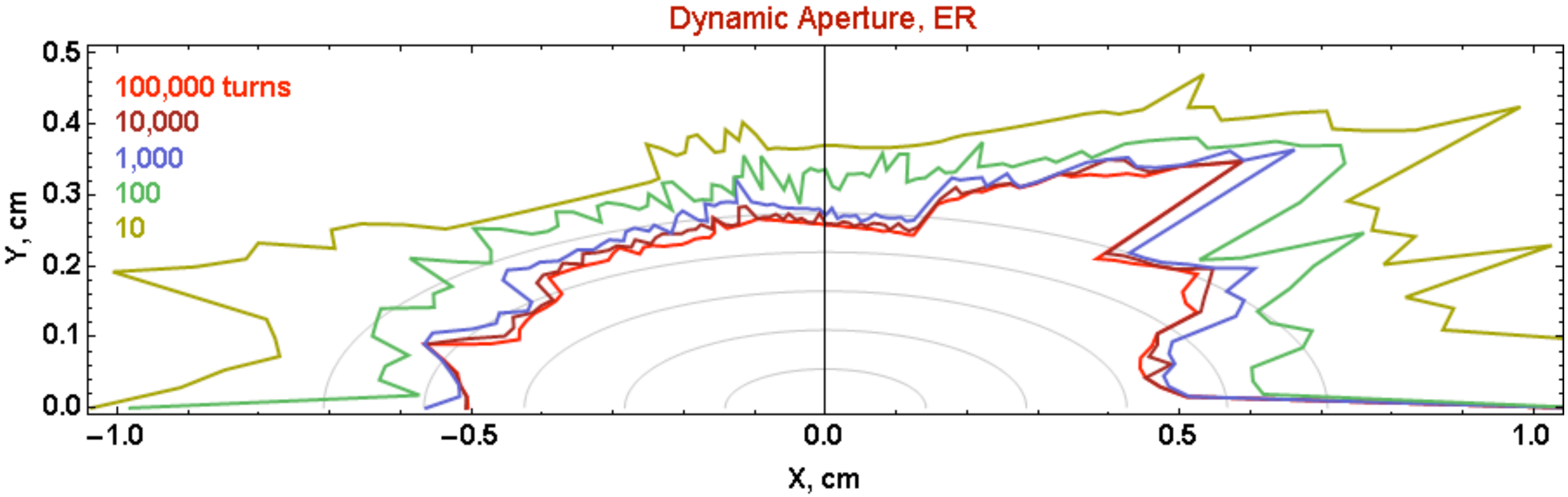


Each point of x-z plane of initial particle deviations tested to be stable by tracking with use of SAD code (KEK, Japan).

The steps decrease nearby DA border from 10σ to 0.01σ.


Zoom in

DA estimation accuracy vs. tracking parameters



Transverse damping time $\tau_{x,z} \sim 60$ msec,
revolution frequency $f_0 \sim 5.5$ MHz

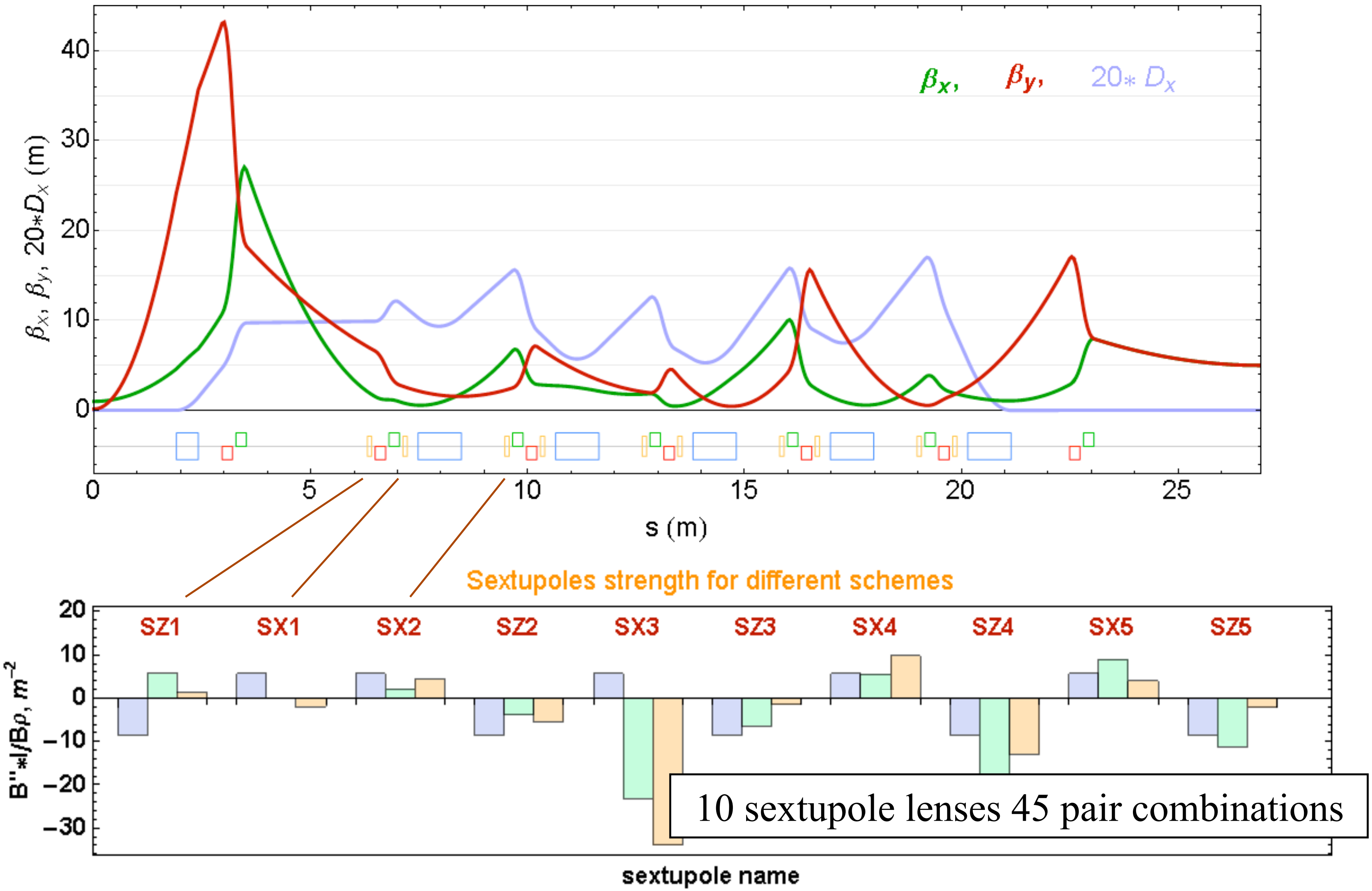
$\Rightarrow$ 300 000 turns tracking?

Too much!

2000-5000 turns used for standart DA estimations.
Only 300 turns for routine optimization procedures.

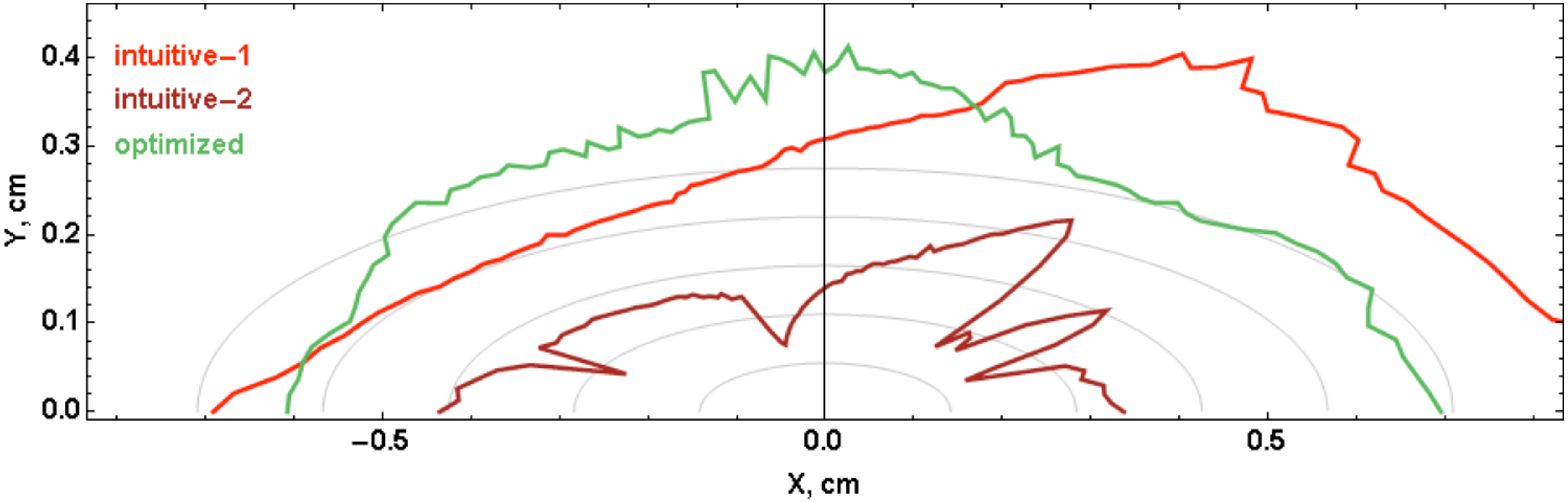
turns	DA/ σ
10	55.98
100	40.57
1000	34.63
10000	32.81
100000	32.81

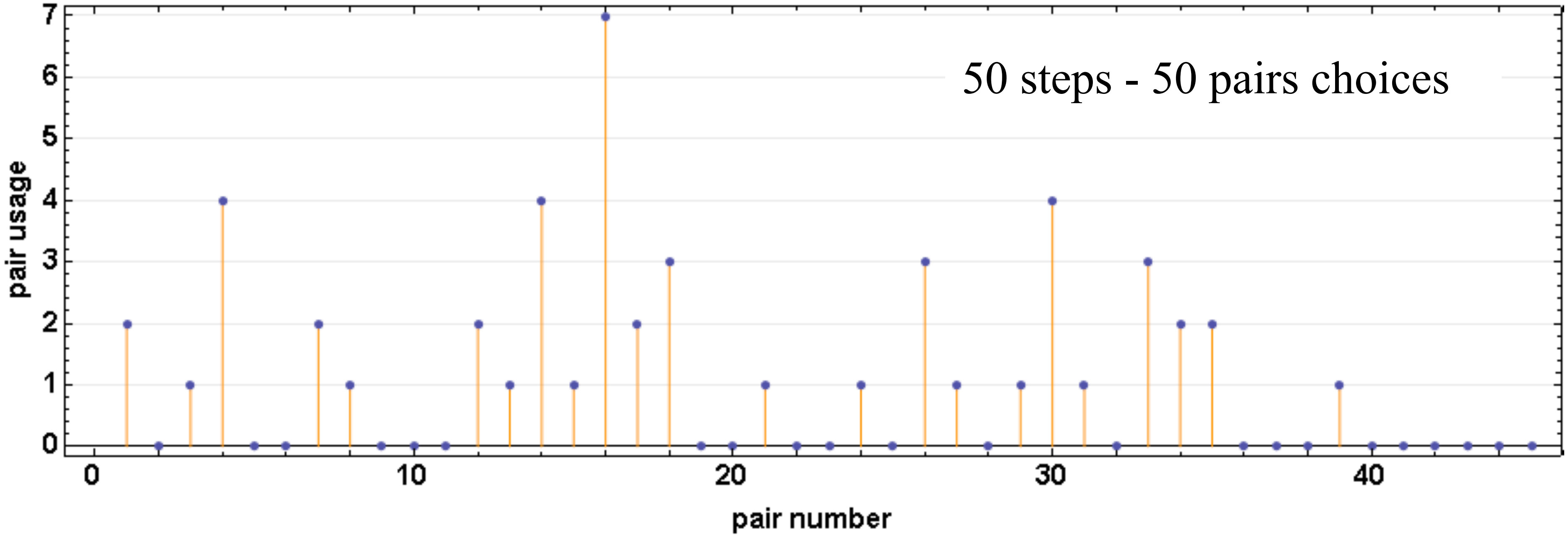
Solutions for sextupole scheme



10 sextupole lenses 45 pair combinations

Solutions for sextupole scheme



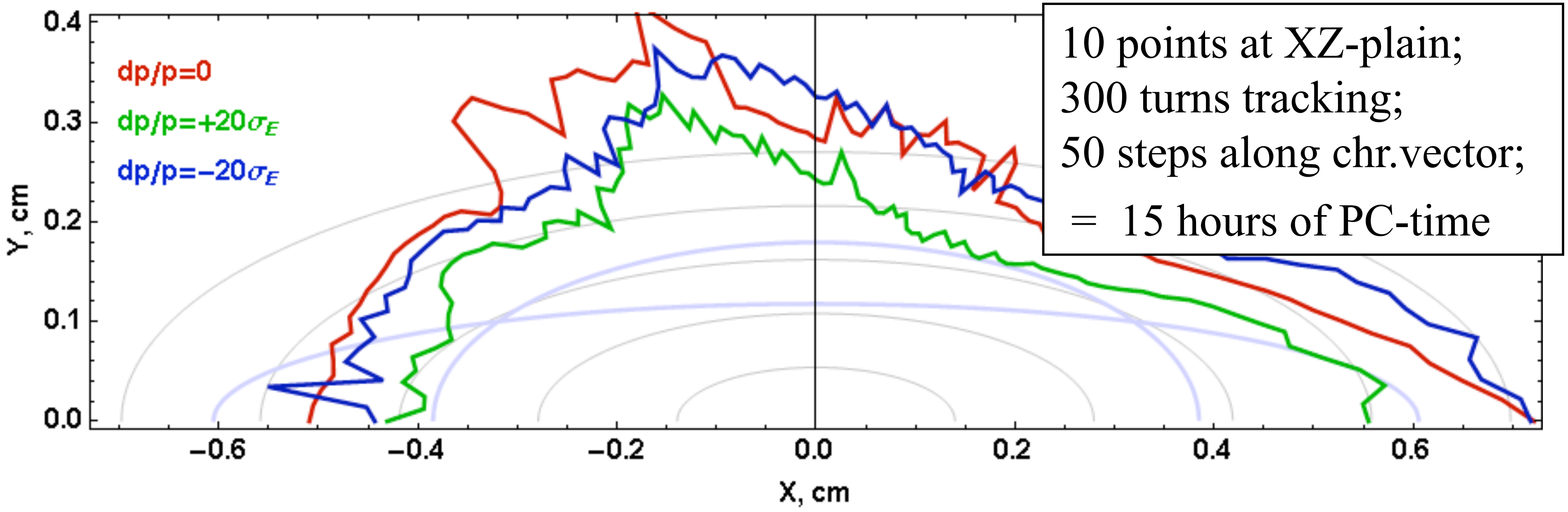


50 steps - 50 pairs choices

Dynamic Aperture optimized

Finally, optimization procedure also included:

1) switched on nonlinear quadrupole fringe fields;
2) DA estimations for on-energy and off-energy particles dp/p = {-10σ, 0, +10σ} simultaneously.

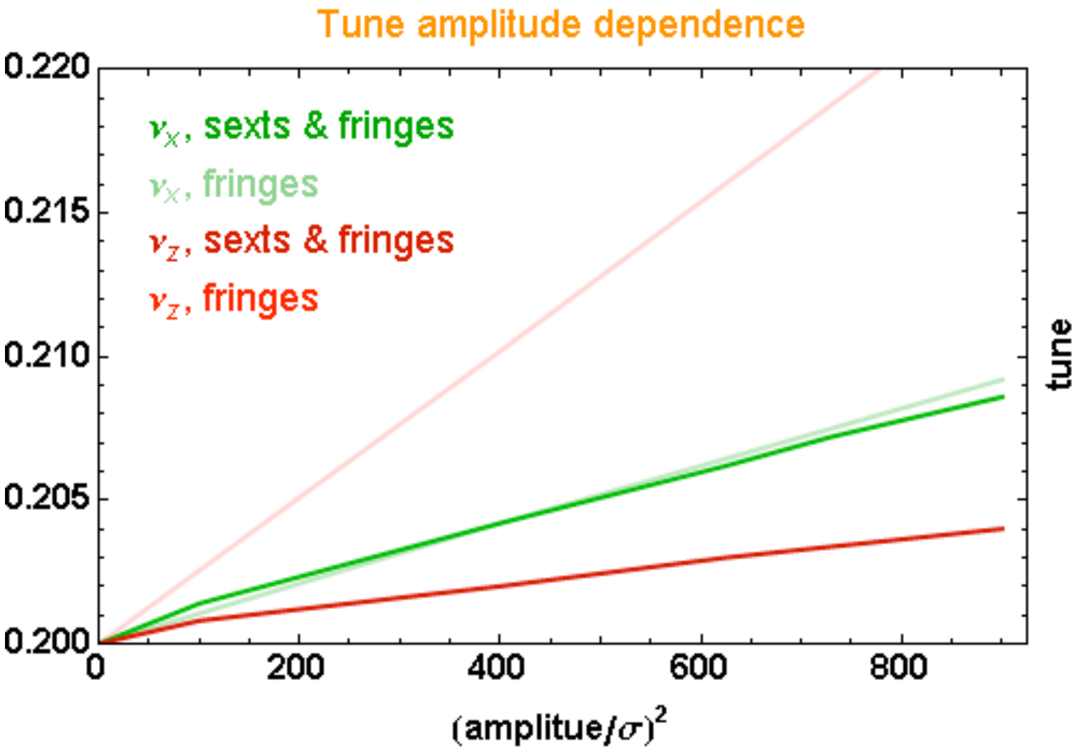


10 points at XZ-plain;
300 turns tracking;
50 steps along chr.vector;
= 15 hours of PC-time

Gray lines – n*10*beamsize

Light blue lines – physical aperture of ∅ 40mm vacuum chamber

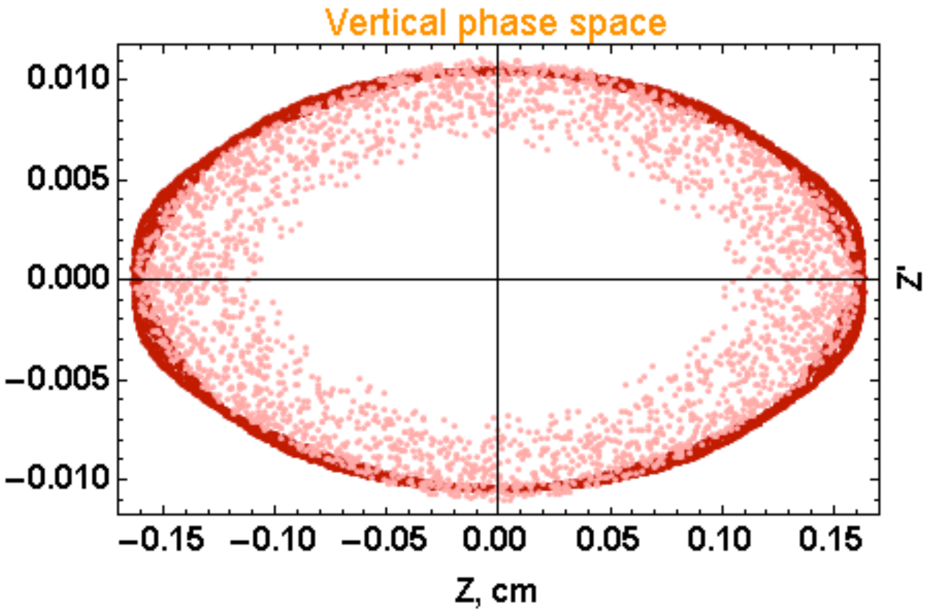
Nonlinear particle dynamics



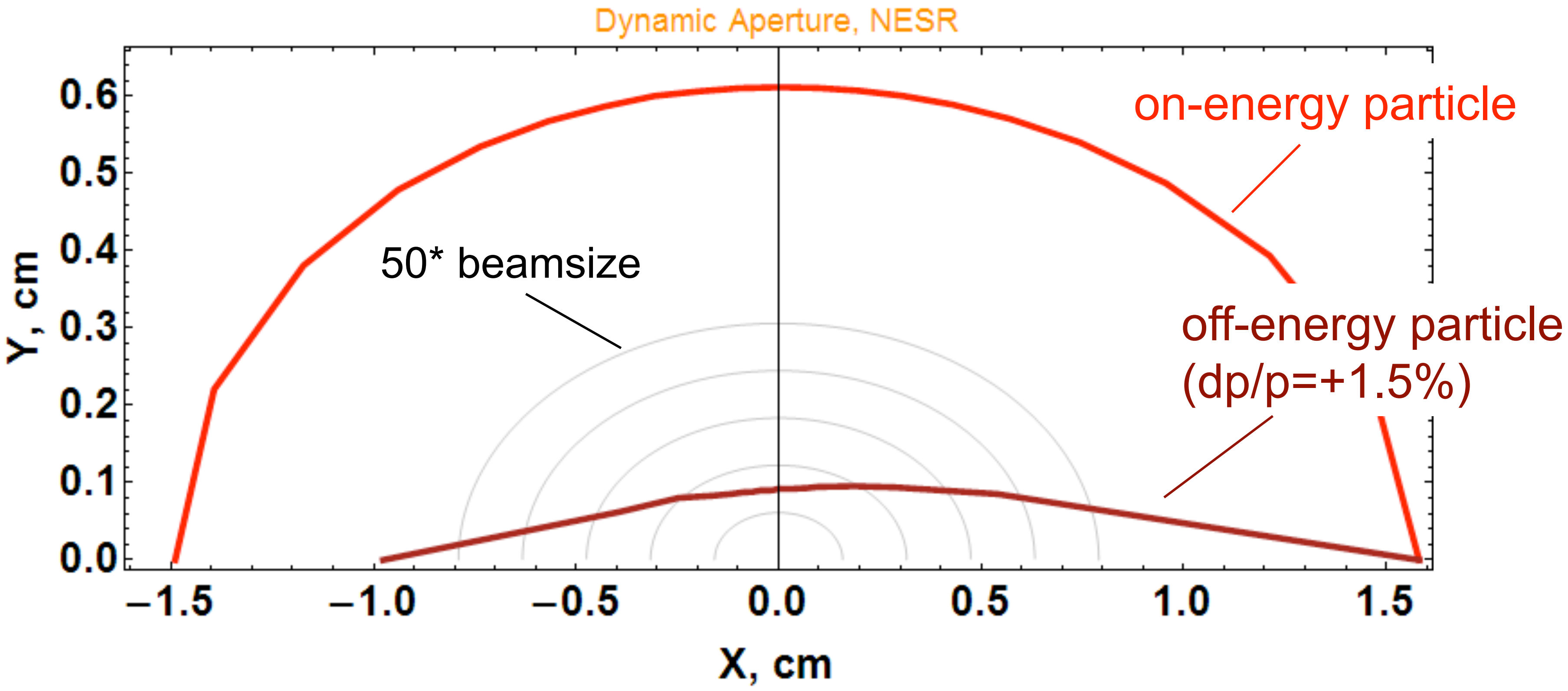
Octupole fields produce tune-amplitude shift in the first order of perturbation theory.

$$\mathrm{B}\lambda = -\frac{3}{8}\left\langle \quad {}^{2}b_{3}\right\rangle \frac{a^{2}}{{}_{0}}$$

Sextupoles also can shift betatron tunes, but only in second order (complicated formulas), and $\partial\nu/\partial a^2$ depends on working point.



NESR dynamic aperture



The NESR dynamic aperture in collider mode decrease drastically for large momentum deviation. To be fixed…

Thank you for attention!