Nonlinear Perturbations for High Luminosity e+e- Collider Interaction Region

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Outline

- Introduction (DA limiting factors and requirements)
- DA in the arcs
- Comparison of nonlinear sources of FF
- Simulation results, radiation influence
- Conclusion

High luminosity e+e- colliders

- Head-on collider with low IP beta (~1 mm)

  (preCDR CEPC)
- Nanobeam collider

  (Super KEKB)
- CW collider

  (CW CEPC, FCC-ee, SuperB/Italy, SuperCT/BINP)

DA limiting factors

Source	Factors	Scheme
Low vertical beta at IP	- High FF chromaticity (Q and β) requires strong local correction sextupoles. - Kinematic effects - Large beta in FF quads emphasizes fringe field effects and field quality tolerance.	H-on *) NB CW
Large collision angle (>20 mr) **)	- Detector solenoid brings large betatron coupling. - Solenoid fringes generate nonlinear field components. - Low emittance needed for large luminosity limits the arc DA (similar to synchrotron light source)	NB CW
Full CW scheme	- Strong CW sextupoles.	CW
High energy	Radiation effects: - Strong damping improve DA. - Saw-tooth effect distorts COD like pretzel and can reduce DA.	Any

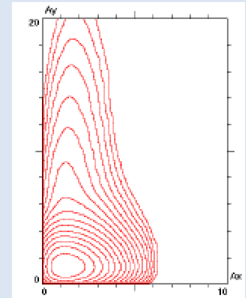
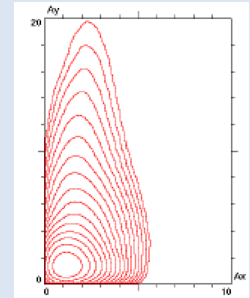
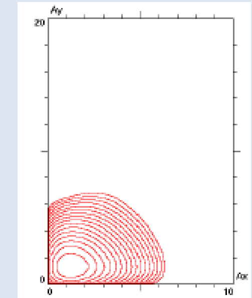
*) Large dispersion is required for local chromaticity correction in the low-beta head-on collision as well as in the CW scheme. For this reason the IR design for both schemes is almost same. But the beam separation in the arcs (pretzel) for the head-on scheme can destroy the symmetry and reduce the DA.
**) Single aperture first quad is undesirable for large collision angle due to the strong fringe sextupole.

DA requirements

Beam lifetime due to bb effects.
Recommendation from simulations by D.Shatilov:

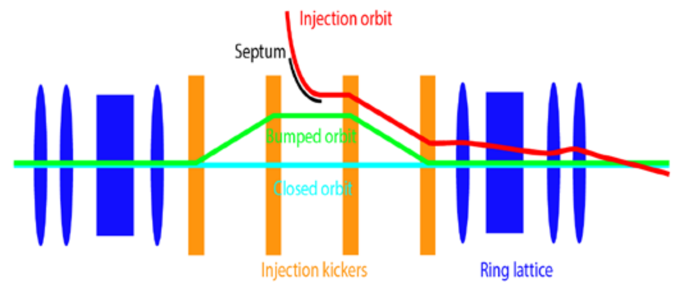
$DA \approx 10\sigma_x \times 50\sigma_y$

(incl.errors, misalignments,etc.)

Collision scheme	Head-on, $\beta_x = 0.5$m	30 mrad	Crab Waist
Density contour plots $10\sigma_x \times 20\sigma_y$			

Vertical beam tail growth example due to bb effects in FCC-ee at 120 GeV (D. Shatilov)

Effective injection (conventional type, on-energy, off-axis)



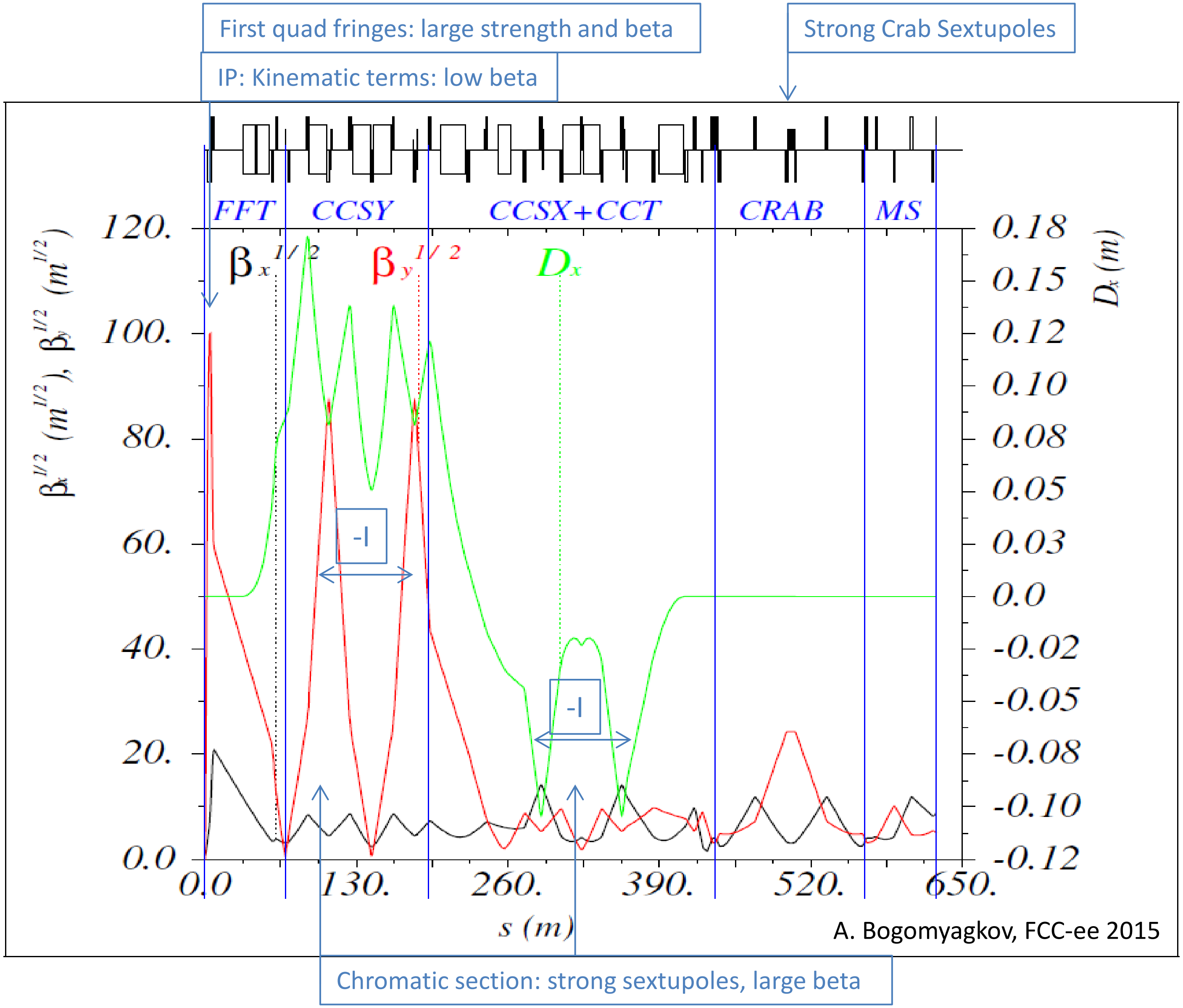
M. Aiba et al. FCCee review at CERN, 14.10.2015
$Ax \approx 13$ mm $\quad N \approx 16\sigma_x$
J. Seeman. FCC week, Washington DC, March 25, 2015
$Ax \approx 16$ mm $\quad N \approx 15\sigma_x$
K. Oide. FCC-ee Optics Meeting, CERN, 11 Sep. 2015
$N \approx 14.6\sigma_x$ @175 GeV $\quad N \approx 30\sigma_x$ @45.6 GeV (@$2.5\sigma_e$)

Required $DA \approx 20\sigma_x \times 50\sigma_y$ ←

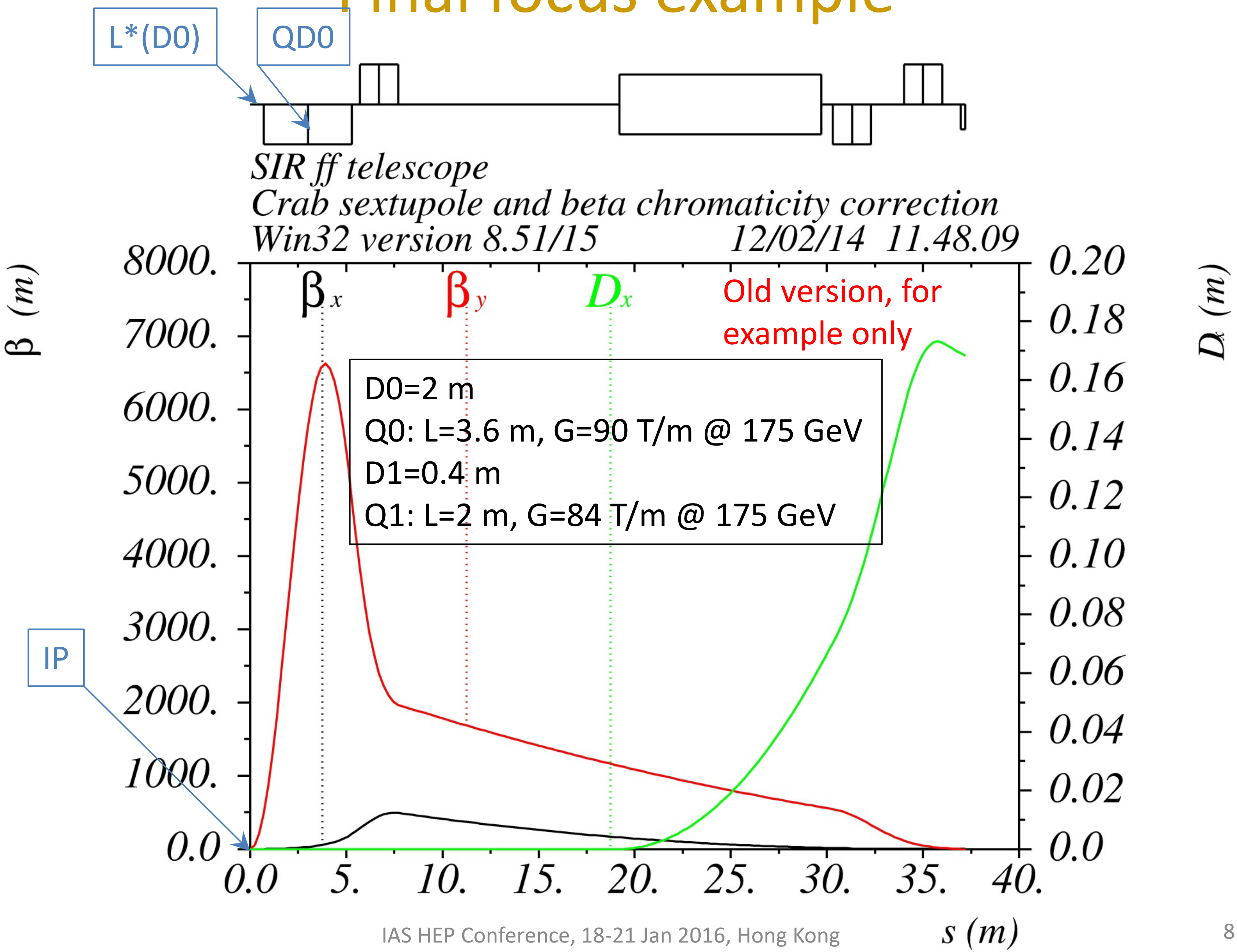
Interaction region DA

- Due to the low vertical beta ($\leq$ 1 mm) at the IP a paraxial approximation is not longer valid and the next (octupole-like) terms should be included.
- Due to the low vertical beta at the IP chromatic effects are severe and require strong sextupoles for compensation. In spite the sextupoles are usually arranged in the " – I pairs", the high order effects reduce the DA.
- Due to the high (~few km) betas in the first FF quadrupoles, the fringe field nonlinearities as well as the field errors are emphasized.

Optics blocks example

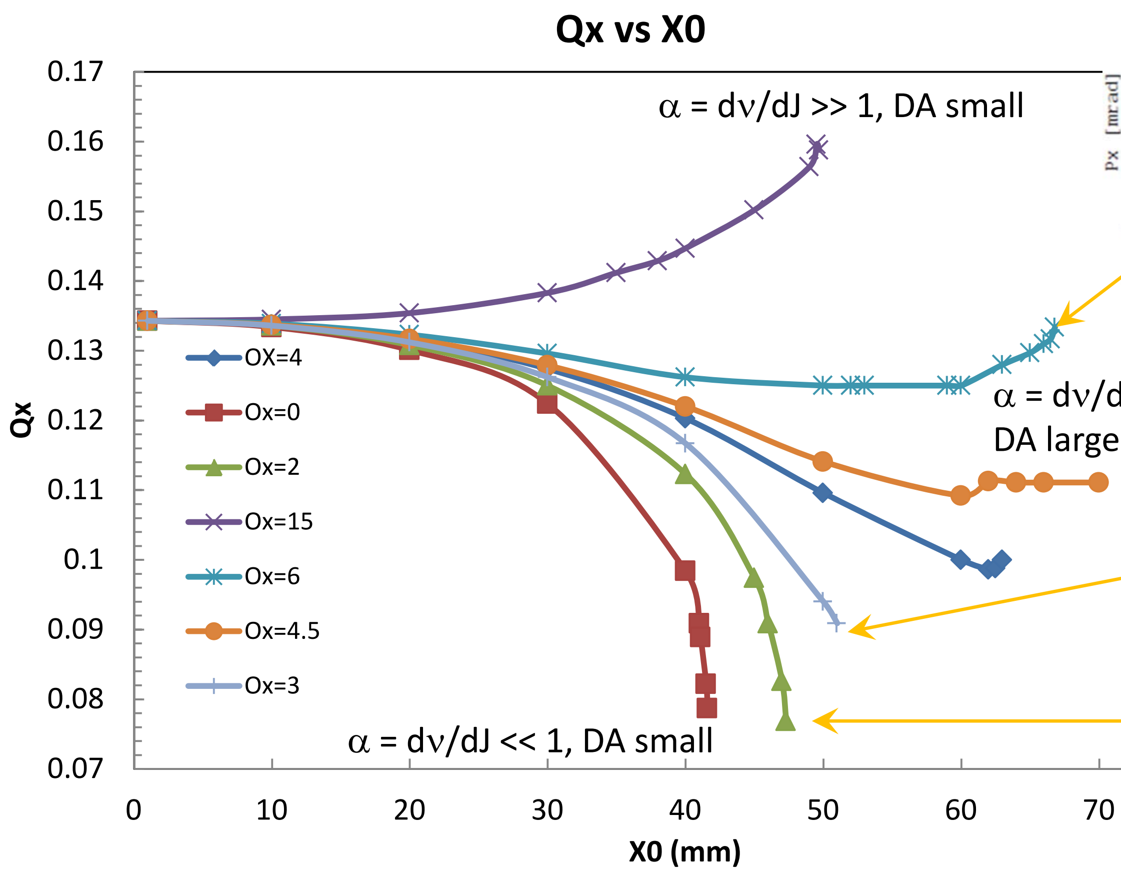


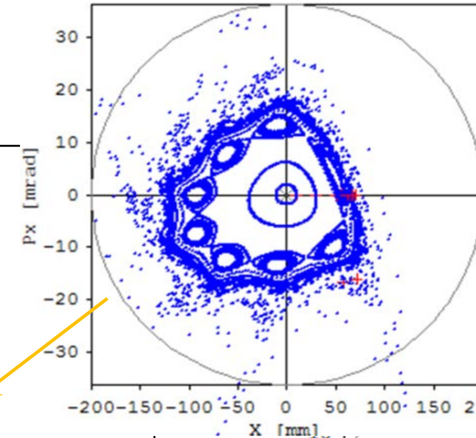
Final focus example

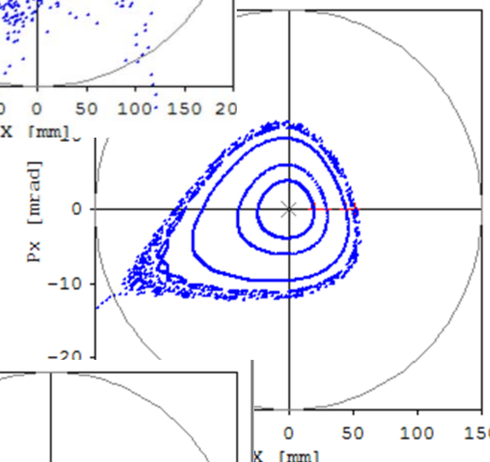


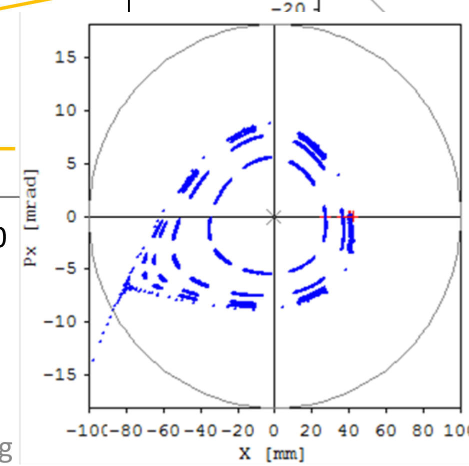
DA size simple

Strong low order resonance limits DA directly. Weak high order resonances overlap and form stochastic layer that also limits DA. Nonlinearity $\alpha = d\nu/dJ$ brings particle to resonance.









FODO lattice with fixed sextupoles but $\alpha = d\nu/dJ$ varied by octupoles.

IR nonlinearities figure of merit

How to compare power of different IR nonlinearities for different machines? Fortunately all three main ones (kinematics, fringes and –I sextupole pairs) are 3rd order (octupole-like) in leading term and we propose to use the first order nonlinear detuning

$$\Delta\nu = \alpha J, \qquad J_{max} = \frac{A^2}{2\beta_{obs}}$$

Advantages

- The detuning α is calculated by 1st order of perturbation theory.
- α is additive for different sources

$$\Delta\nu = J(\alpha_1 + \alpha_2 + \alpha_3 + \cdots) = J\left(\oint [F_1 + F_2 + F_3 + \cdots] ds\right)$$

For estimation and comparison!

Final quad QD0 and chromaticity

Defining the QD0 (thin lense) focusing requirements as $\alpha_o = -\alpha_I$ one can find

$$(-K_1 L)_{QD0} = \frac{2}{(L^* + 0.5 L_{QD0})}$$

The beta and its derivative in the end of L* are given by

$$\beta_e \approx \frac{L^{*2}}{\beta^*} \qquad \alpha_e \approx -\frac{L^*}{\beta^*}$$

FF vertical chromaticity(half of FF): $\mu_y' \approx -\frac{L^*}{\beta^*} + K_2 L_s \beta_s \eta_s$

QD0 natural chromaticity

Correction by sextupoles

Note: For FF μ' corresponds to the chromatic function excitation introduced by B.Montague (LEP Note 165, 1979)

$$\mu_y' = \frac{\Delta A}{2} \qquad \Delta W = \sqrt{\Delta A^2 + \Delta B^2} = \Delta A$$

Kinematics

For the extremely low β* and large transverse momentum the first order correction of non-paraxiality is given by

$$H_2 = \frac{1}{8}\left(p_x^2 + p_y^2\right)^2 \qquad \Delta\nu_x = \alpha_{xx} J_x + \alpha_{xy} J_y \qquad \Delta\nu_y = \alpha_{xy} J_x + \alpha_{yy} J_y$$

$$\alpha_{yy}^k = \frac{3}{16\pi}\oint \gamma_y^2(s)ds \qquad \alpha_{xy}^k = \frac{1}{8\pi}\oint \gamma_x(s)\gamma_y(s)ds \qquad \alpha_{yy}^k = \frac{3}{16\pi}\oint \gamma_y^2(s)ds$$

The main contribution comes from the IP and the first drift:

$$\alpha_{yy}^k = \frac{3}{16\pi}\frac{2L^*}{\beta_y^{*2}} = -\frac{3}{8\pi}\frac{\xi^*}{\beta_y^*}$$

where 2L is the distance between 2 QD0 quads around the IP.

QD0 Fringe Fields

Quadrupole fringe field nonlinearity is defined by

$$H = -k_1'(s)x^2 y p_y / 2 + k_1''\left(y^4 - 6x^2 y^2\right)/24$$

and the vertical detuning coefficient is given by

$$\alpha_{yy}^{f} = \frac{1}{16\pi} k_{10}\left(\beta_{y1}\beta_{y1}' - \beta_{y2}\beta_{y2}'\right)$$

Or, with above assumptions (k_{10} is the central strength):

$$\alpha_{yy}^{f} \approx -\frac{1}{4\pi} k_{10} \frac{L^{*3}}{\beta_y^{*2}} = -\frac{1}{4\pi} k_{10} L^{*} \xi^{*2}$$

E.Levichev, P.Piminov, arXiv: 0903.3028
A.V.Bogomyagkov et al. IPAC13, WEPEA049, 2615

Chromatic sextupoles

Vertical chromatic sextupole pair separated by –I transformer gives the following coordinate transformation in the first order*)

<u>Pair of sextupoles</u>

$$y = y_0$$
$$p_y = -p_{y0} - \frac{(K_2 L_s)^2 L_s}{6}\left(y_0^3 + x_0^2 y_0\right)$$

<u>Octupole</u>

$$y = y_0$$
$$p_y = p_{y0} - \frac{K_3 L}{6}\left(y_0^3 - 3x_0^2 y_0\right)$$

By analogy to the octupole and using the expression for the FF chromaticity we found for the vertical detuning (2 pairs)

$$\alpha_{yy}^{sp} = -\frac{1}{16\pi}(K_2 L_s)^2 L_s \beta_y^2 \approx -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\left(\frac{L^*}{\beta^*}\right)^2 = -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\xi^{*2}$$

*) A.Bogomyagkov, S.Glykhov, E.Levichev, P.Piminov http://arxiv.org/abs/0909.4872

Discussion

$$\alpha_{yy}^{k} = \frac{3}{16\pi}\frac{2L^{*}}{\beta_y^{*2}} = -\frac{3}{8\pi}\frac{\xi^{*}}{\beta_y^{*}}$$

Kinematic effect increases with L^* increase and β^* decrease.

$$\alpha_{yy}^{f} \approx -\frac{1}{4\pi}k_{10}\frac{L^{*3}}{\beta_y^{*2}} = -\frac{1}{4\pi}k_{10}L^{*}\xi^{*2}$$

Fringe field effect increases fast with L^* increase and β^* decrease. It is sensitive to the QD0 central gradient k_{10}.

$$\alpha_{yy}^{sp} \approx -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\left(\frac{L^*}{\beta^*}\right)^2 = -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\xi^{*2}$$

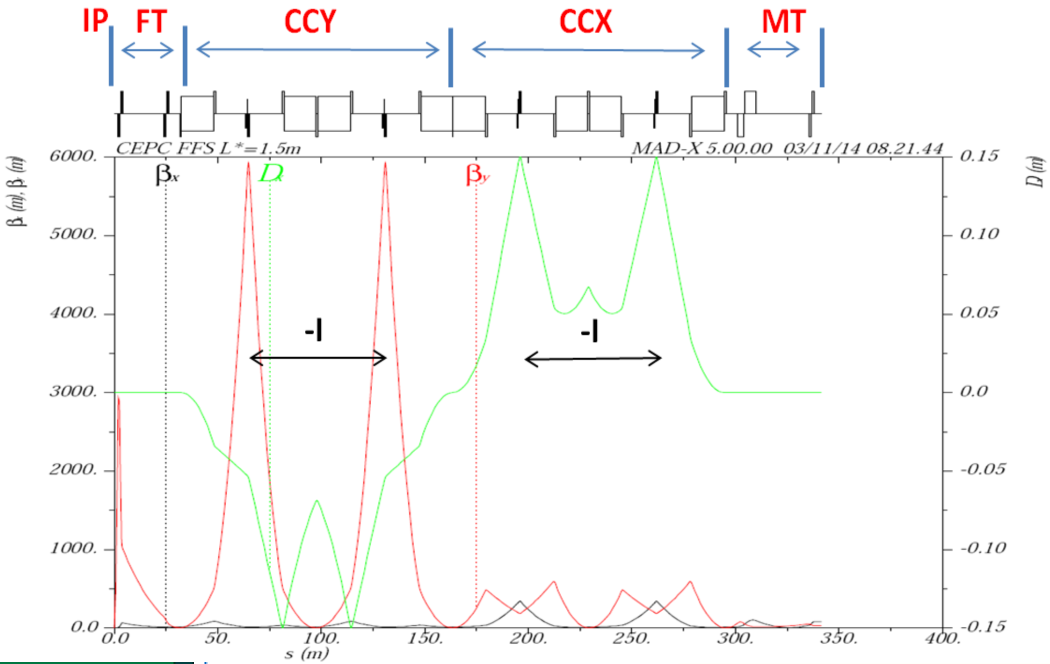
Sextupole pair effect increases with L^* increase and β^* decrease. Short sextupole and large dispersion are desirable.

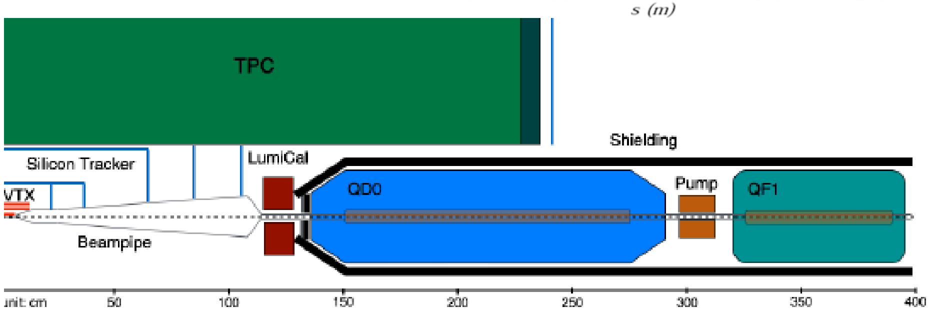
In spite the estimations are very rough, they seem reasonable and are confirmed by tracking simulation.

CEPC parameters

CEPC-SppC PreCDR, March 2015.

$L^* = 1.5$ m, $\beta_y^* = 1.2$ mm, $\beta_{yFFmax} \approx 3$ km, $\beta_{CCY} \approx 6$ km, $\eta_{CCY} \approx 5$ cm





Magnet	z [m]	Leff [m]	Field gradient [T/m]
QD0	1.5	1.25	-300
QF1	3.25	0.72	300

V.detuning for different lattices

	LEP[3] CERN	Super C-Tau[1] Novosibirsk	SuperKEKB[2] Japan	FCC-ee/AB 2015[4]	CEPC[*] IHEP
$10^3\ \beta^*$(m)	10	0.8	0.26	1	1.2
L^*(m)	3.5	0.6	0.76	2	1.5
$-\xi^*$	700	1500	5600	4000	2500
$-K_1$(m^{-2})	0.11	12.8	5.1	0.15	0.75
L_{QD0}(m)	2	0.2	0.32	3.6	1.25
β_{SY} (m)		180	2000	3700	≈6000
η_{SY} (cm)		13	46	15	≈5
$10^{-6}\ \alpha^f$ (m^{-1})	0.015	0.34	2.6	0.1	0.14
$10^{-6}\ \alpha^k$ (m^{-1})	0.008	0.11	1.3	0.24	0.12
$10^{-6}\ \alpha^{sp}$ (m^{-1})	NA	0.53	0.52	3.5	12

[1] SuperC-Tau CDR, Novosibirsk, 2009.
[2] K.Oide, FCC Kick-off Meeting, Geneva, 14 Feb 2014
[3] T.M.Taylor, PAC 1985
[4] A.Bogomyagkov, FCC-ee asymmetric design, BINP, Dec 2015.
[5] CEPC-SPPC PreCDR, v.II, March 2015.

[*] I have no precise data, many guesses.

Comparison with simulation

	Kin	Fringe	Sextupole pair
Simulation			
α_{xx} (cm^{-1})	0.6	11	-23
$\alpha_{xy} = \alpha_{yx}$ (cm^{-1})	3.8	153	-712
α_{yy} (cm^{-1})	755	1137	-1.8×10^5
Estimation			
α_{yy} (cm^{-1})	844	830	-0.2×10^5

Simulation considers all quads fringes (included those strong in the Y chromatic section) and realistic beta behavior

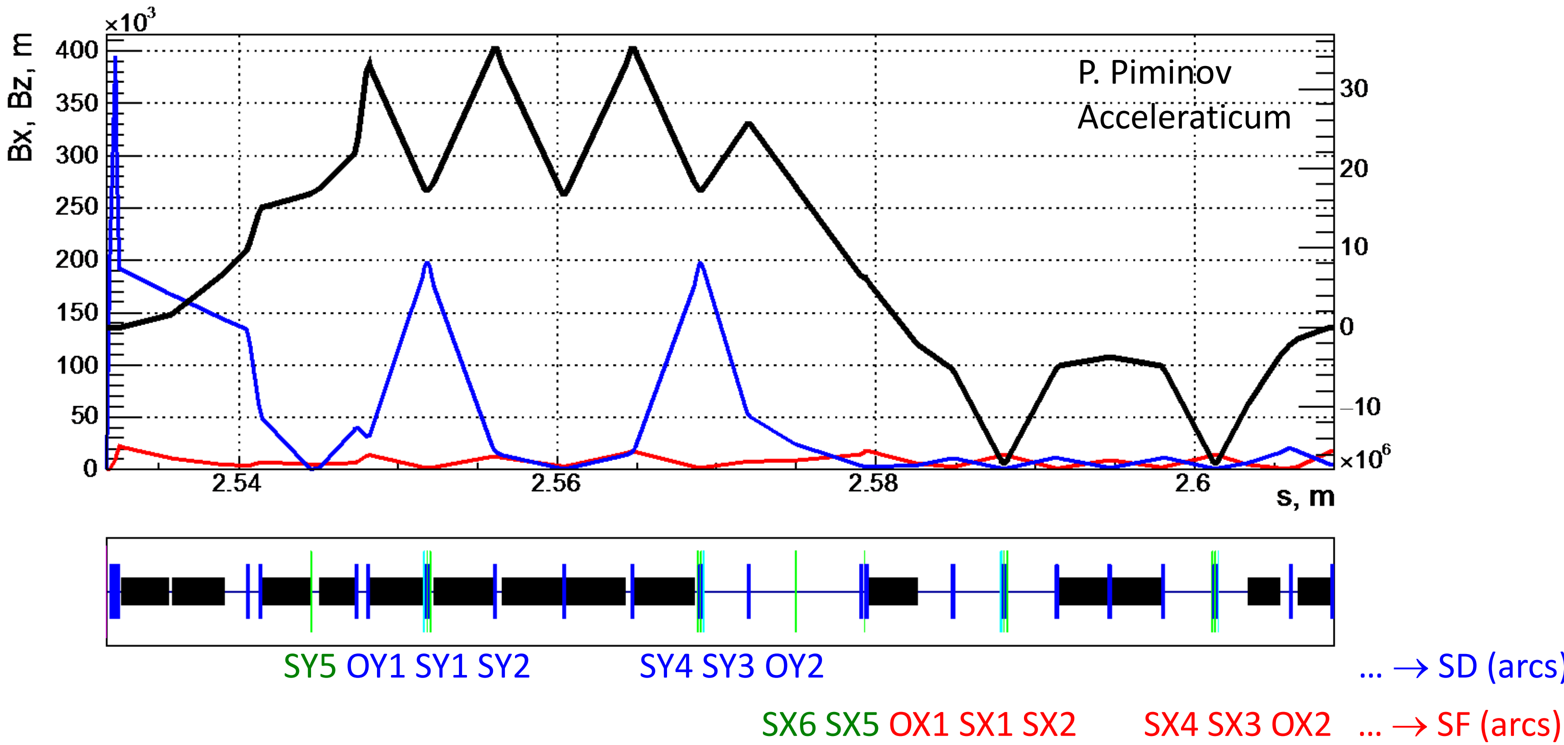
Simulation

- We use the following tracking codes: MAD8 and Acceleraticum[1)] (BINP home made).
- The tunes are fixed at (0.53, 0.57) to get large luminosity.
- Dynamic aperture and other nonlinear characteristics are defined from tracking for different sources to found their power ranking.
- We try to compensate (mitigate) every source locally by optimizing the phase advance, insertion of additional sextupoles and octupoles.
- We collect all the ring sections together and optimize 6D DA globally (damping, tapering, errors, BB effects, etc. can be included at this stage).

[1)] D.Einfeld, Comparison of lattice codes, 2nd NL Beam Dynamics Workshop, Diamond Light Source, 2009

Recent example

FCC-ee DA optimization (November 2015)



SY5, SX6, SX5 – increase of the noninear (dynamic) bandwidth

SY1, SY3 – main vertical section for the FF chromaticity compensation. Arranged in the – I pair.

SY2, SY4 – sextupole corrector to compensate the finit length effect of SY1 and SY3. Also arranged in the – I pair.

SX1, SX3 – main horizontal section for the FF chromaticity compensation. Arranged in the – I pair.

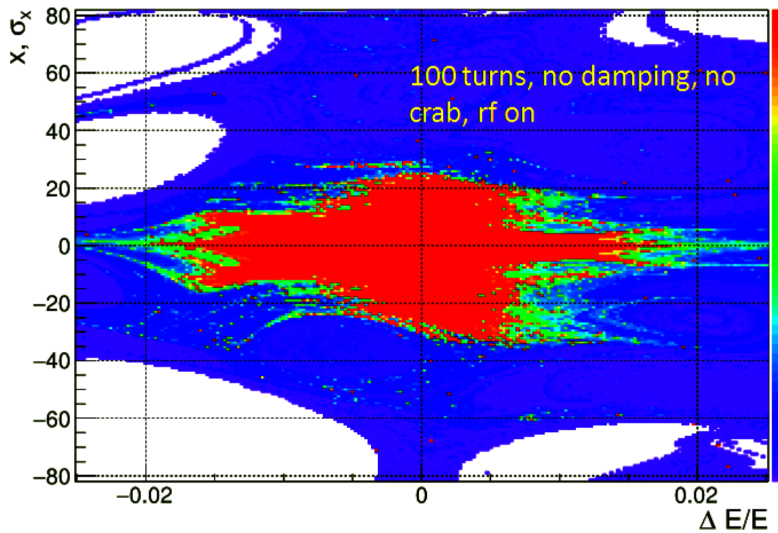
SX2, SX4 – sextupole corrector to compensate the finit length effect of SX1 and SX3. Also arranged in the – I pair.

OY1, OY2, OX1, OX2 – octupole correctors to mitigate the kinematic and FF fringes effects

SD, SF – vertical and horizontal sextupoles in the arcs.

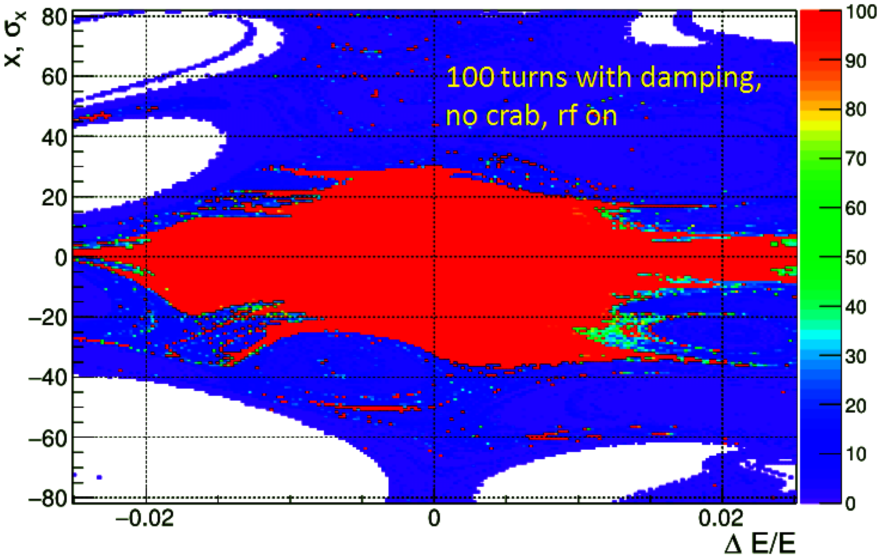
DA FCCee with/without damping

6D Dynamic Aperture @ b*=2 mm



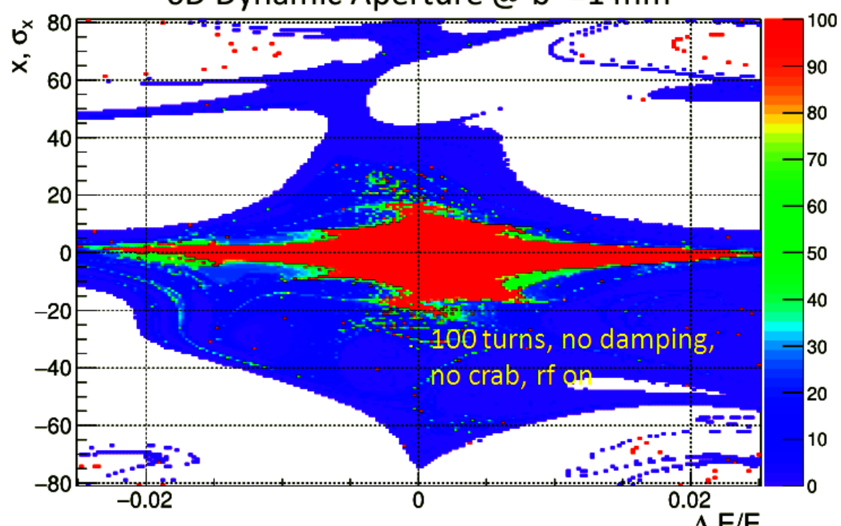
e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV

6D Dynamic Aperture @ b*=2 mm



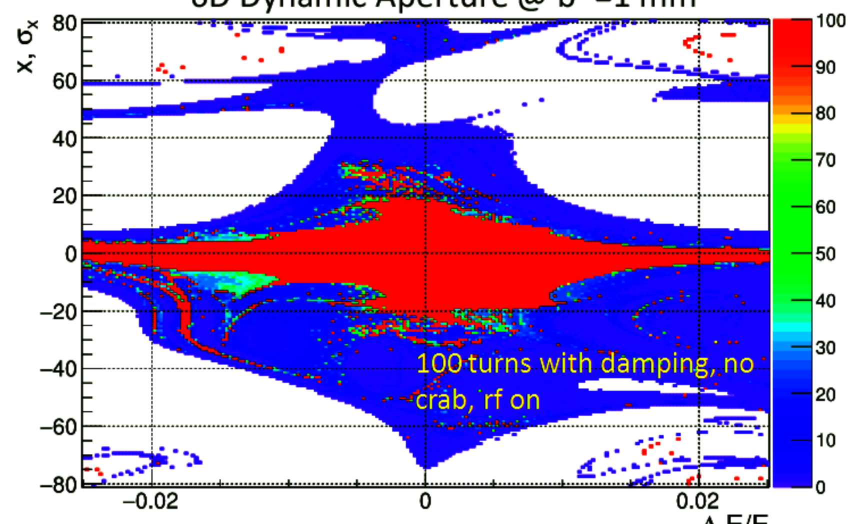
e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV, t_x=87.6

6D Dynamic Aperture @ b*=1 mm



e_x=1.33 nm·rad, 0.2% coupling, Qs=0.04, Urf=5.5 GV

6D Dynamic Aperture @ b*=1 mm



e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV, t_x=87.6

Conclusion

- For high performance e+e- factories DA limitation is a challenging problem.
- Main limiting factors are: vertical sextupole chromatic section in IR, FF quads fringes, arc sextupoles.
- Local + global compensation can schemes provide reasonable DA.
- Damping at high energy is an important factor increasing the DA.
- Remaining problems: interference of CW sextupoles with other IR nonlinearities reduces the DA; proper (distributed) radiation in the arcs; quads radiation contribution (“damping DA”); magnet tapering; detector solenoid (and other MDI elements) effects; machine errors and misalignments; BB effects.