EIC Dynamic Aperture Optimization & Implications for FCC

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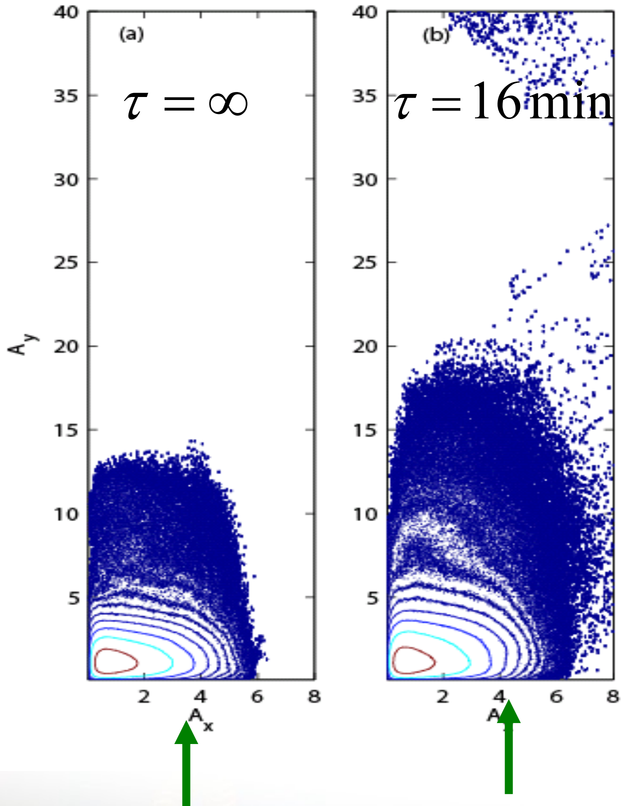
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY   Jefferson Lab   U.S. DEPARTMENT OF ENERGY | Office of Science

Motivation

Beam Distributions with Beam-Beam Interaction (PEP-II)



The distributions are averaged after 40,000 turns to improve the statistics.

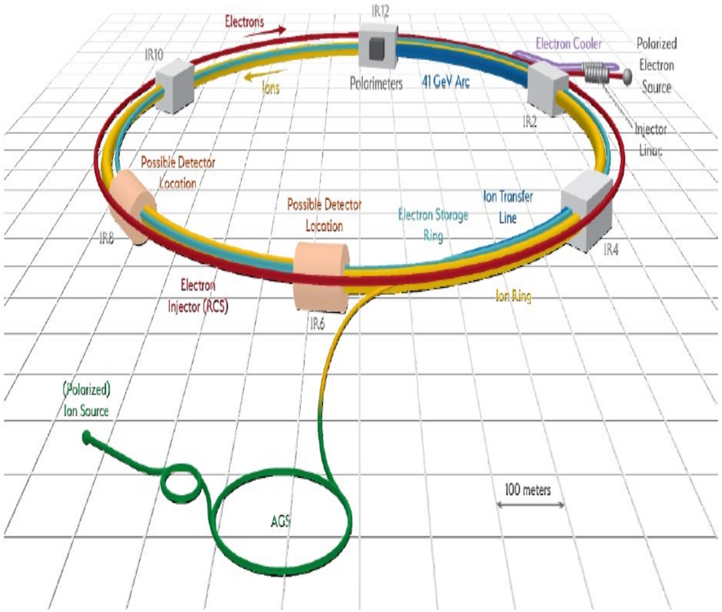
Contours started at value of peak/sqrt(e) and spaced in e. Labels are in σ of the initial distribution.

The core distribution is not disturbed much by the nonlinearity in the ring while the tail is strongly affected.

With a linear matrix or 8th order Taylor map (ν_x^+=0.5125). Nonlinear map is important because it defines the dynamic aperture.

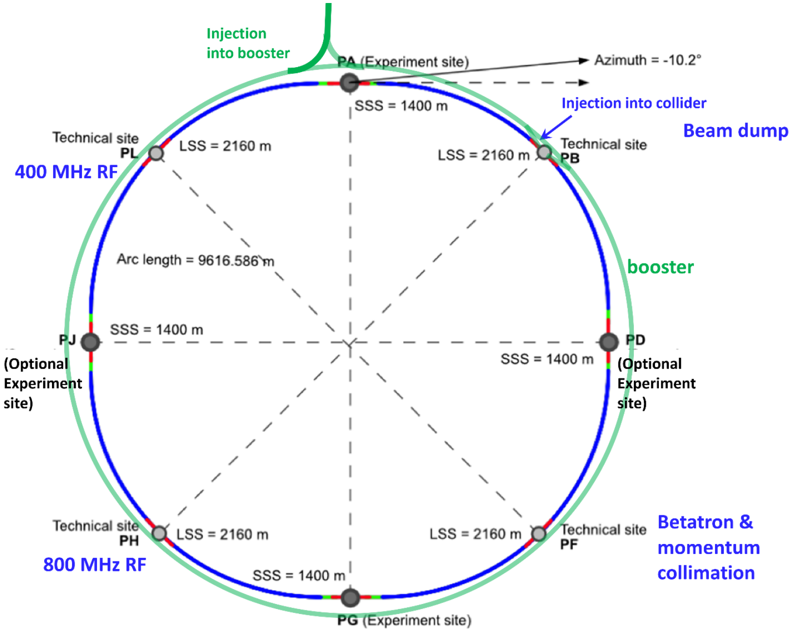
Collider Layouts

EIC



2 Interaction Points

FCC-ee



4 Interaction Points

Factory-level colliders: 10^{34} cm^{-2}s^{-1} luminosity

Main Parameters

Parameters	Units	EIC	FCC-ee
Energy	GeV	18	182.5
Circumference	m	3834	91174
Emittance	nm	28	1.5
Energy spread	10^{-4}	10	16/22
Betatron Tunes		52.12/45.10	402.22/394.36
Chromaticity		-106/-110	-552/-2083
IP betas	m	0.59/0.057	1.0/0.0016
L*	m	5.3	2.2

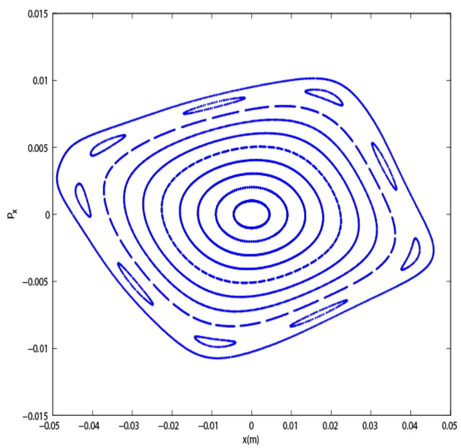
- Fractional tunes, may be selected by the beam-beam collisions, not changed
- Their closeness to integer makes chromatic compensation harder

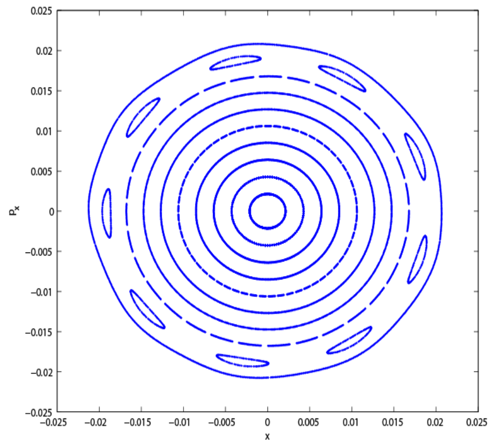
Nonlinear Normal Form

``Symplectic maps and chromatic optics in particle accelerators", Nucl. Instr. Meth. **A797**, p172 (2015).

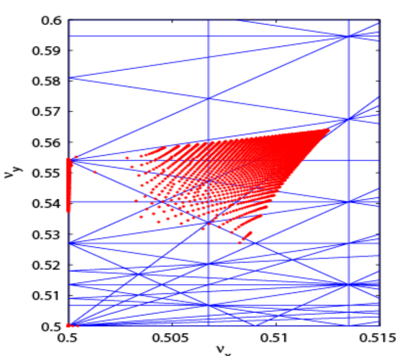
Physical coordinates — Normalized coordinates

Transformation approximated by a 10th order Taylor map

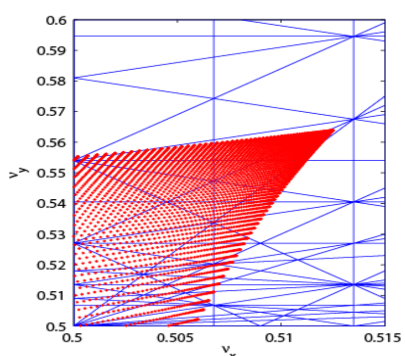




Frequency map

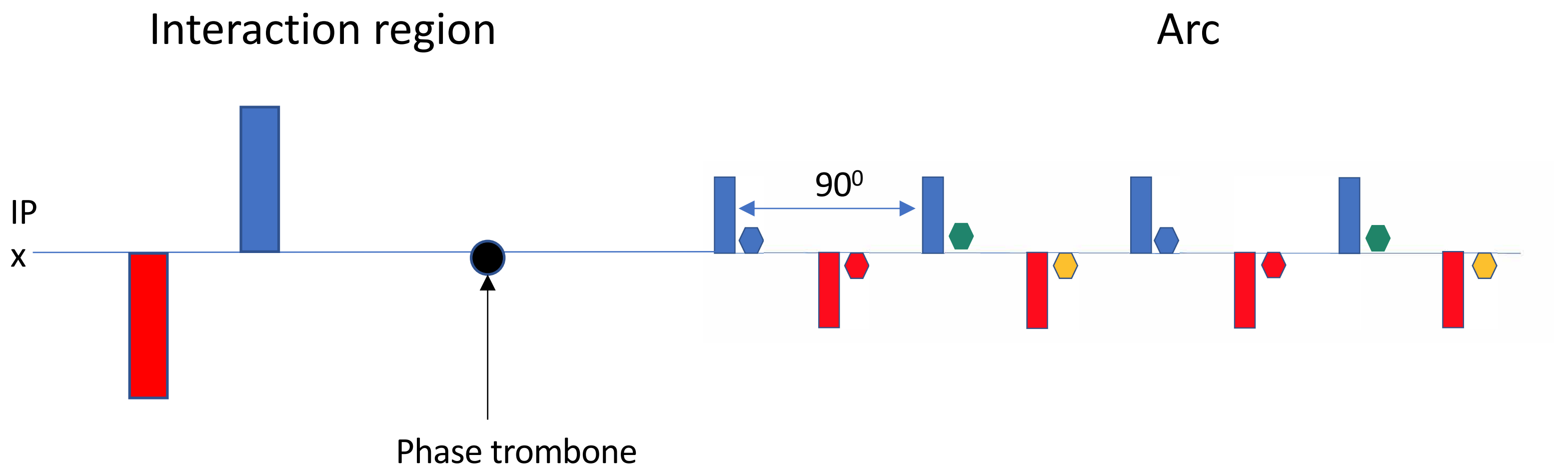


Normal form



- Introduce a Jacobian, with setting of $x=p_x=y=p_y=0$, that provides an intrinsic linkage between the map and the matrix with parameter $\delta=(p-p_0)/p_0$ dependence
- The link allows us to directly apply the formulation of the linear optics to compute the chromatic lattice with the parameter: δ

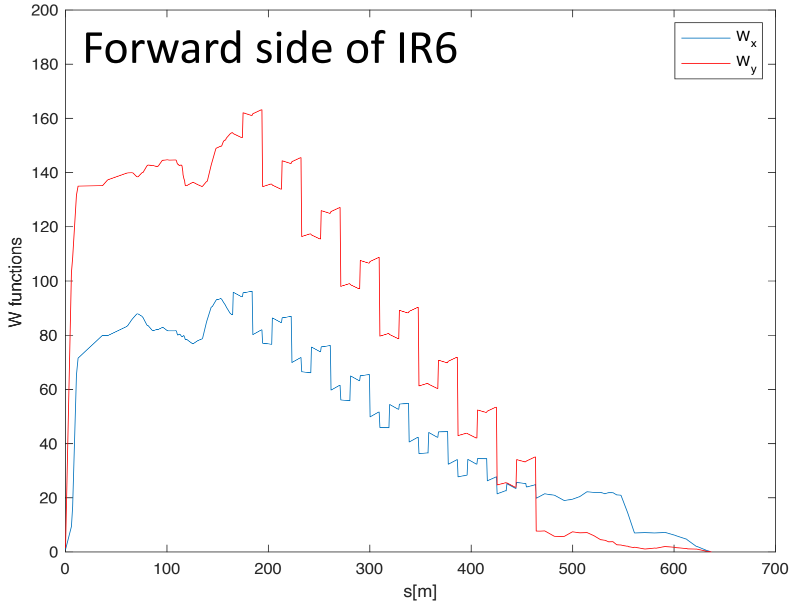
Semi-Local Chromatic Compensation Scheme

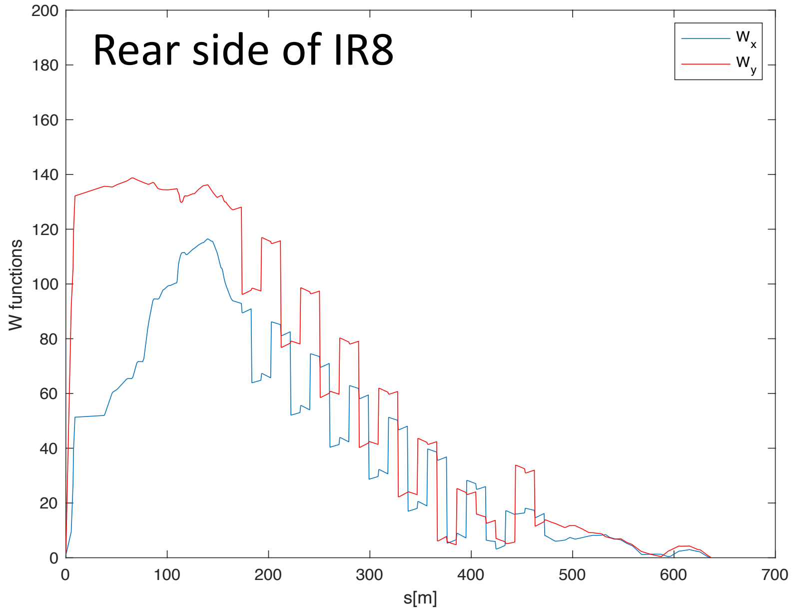


In each plane:

1) Members in the family add to the beta beating
2) The other family (same sign) cancel the beta beating but add chromaticity
3) Since all beating is in the same phase, a trombone is necessary to align the IR beating to the arc

First-Order Chromatic Matching

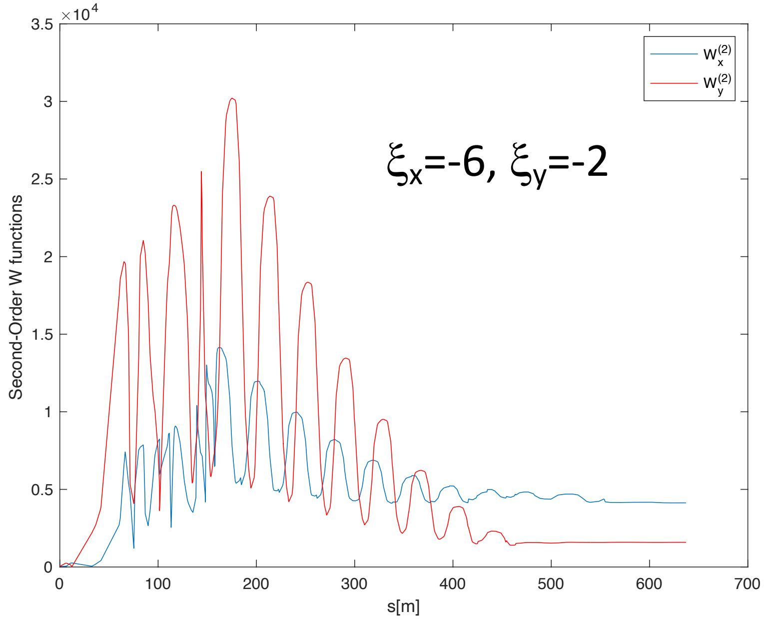




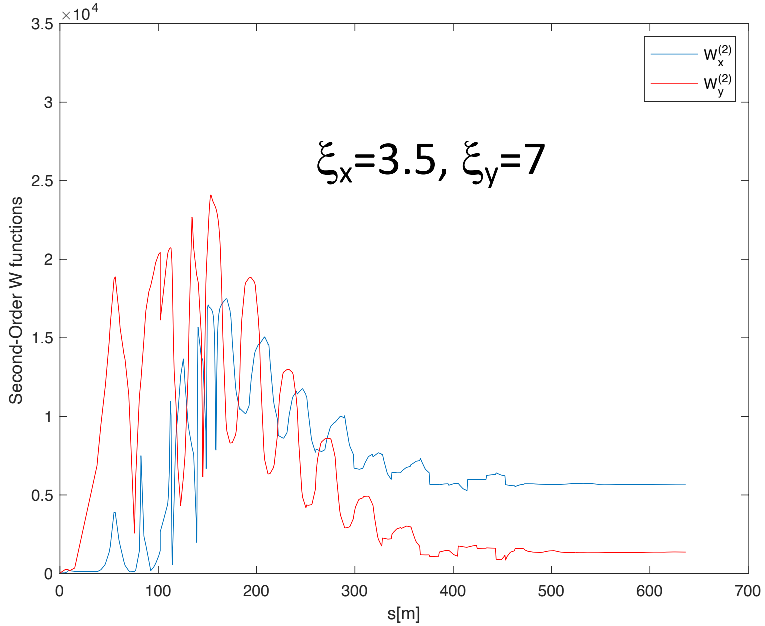
1) Four variables: strengths of two sextupole families, ν_x and ν_y
2) Four goals: β_x', α_x', β_y', α_y' setting by the periodic solution between 2IPs
3) Two local chromaticities ξ_x and ξ_y
4) Solutions are found with a downhill simplex optimizer

Second-Order Chromatic Optics

Forward side of IR6

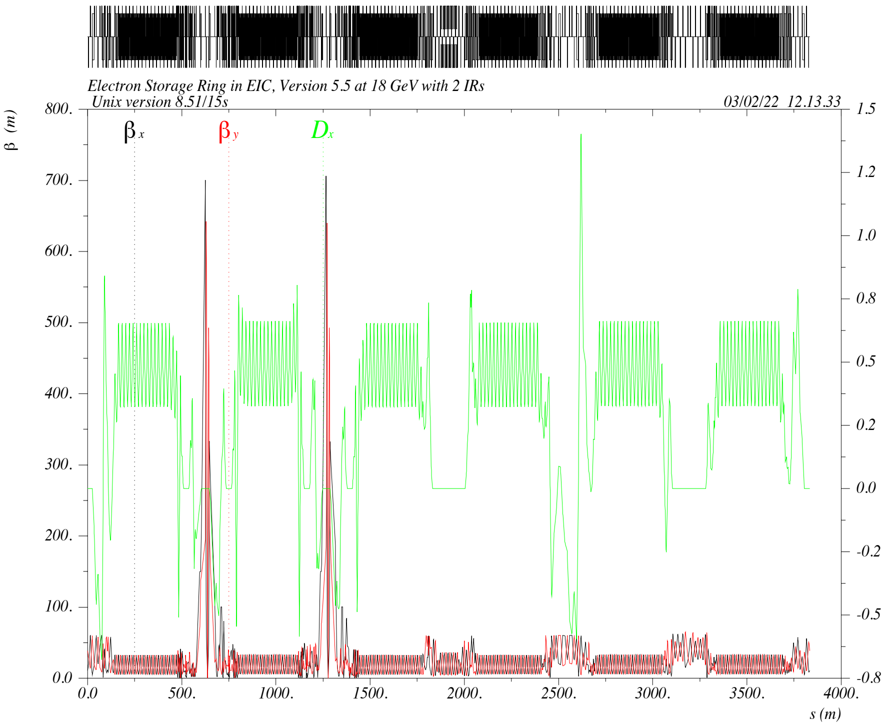


Rear side of IR8



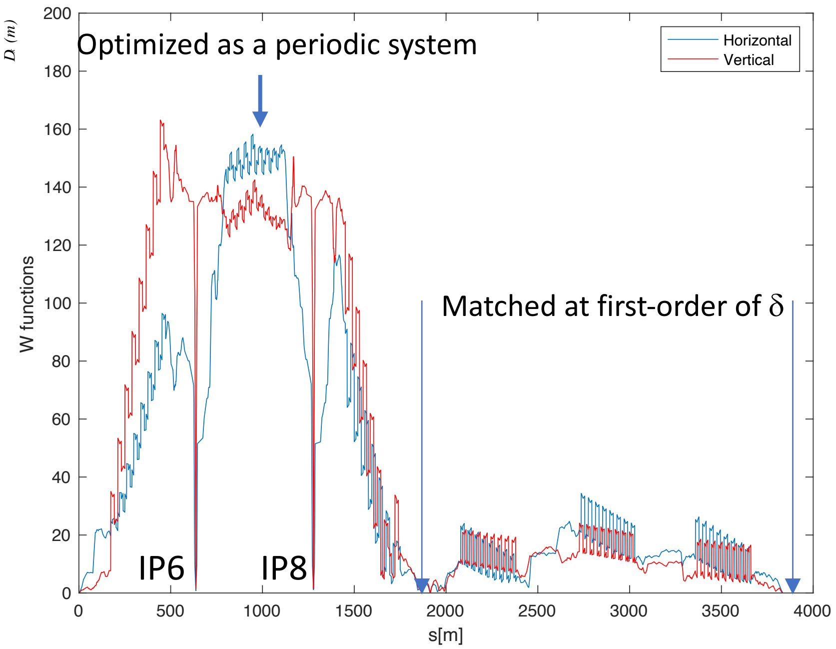
1) Local chromaticities are knobs to control higher order chromatic beatings
2) The optimal values of the local chromaticities are obtained by tracking

EIC Lattice Design at 18 GeV



Optics

Chromatic Beating

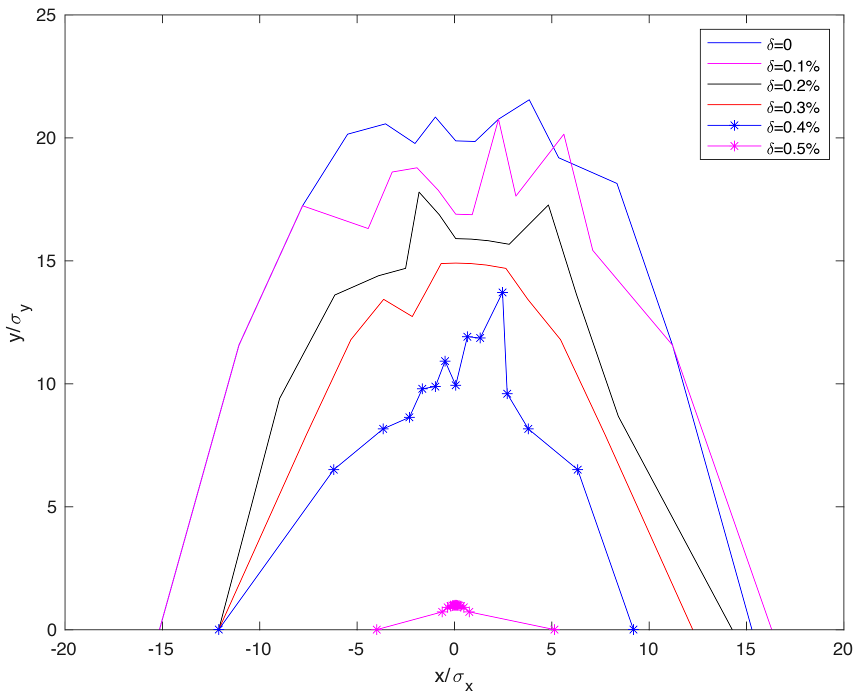


Chromatic Compensation

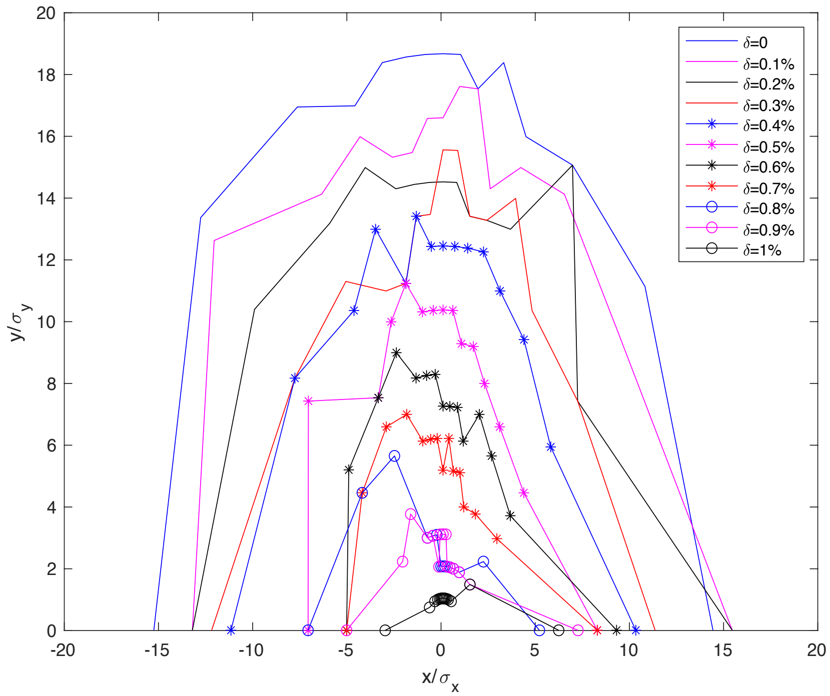
``Optimization of chromatic optics in the electron storage ring of the Electron-Ion Collider," Phys. Rev. ST Accel. and Beams **25**, 071001 (2022)

Dynamic Apertures in EIC

Two Families of Sextupoles

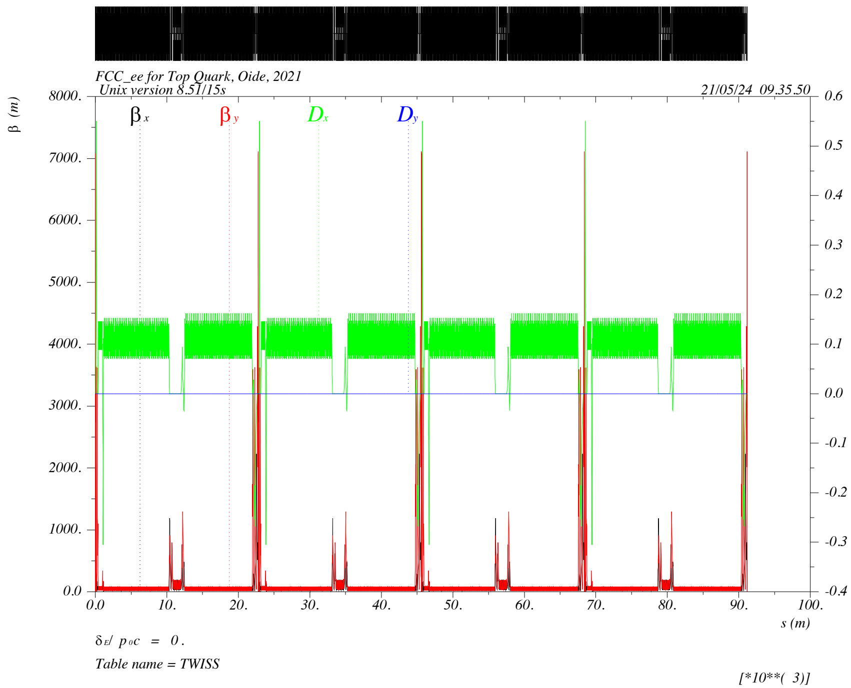


Semi-Local Chromatic Compensation



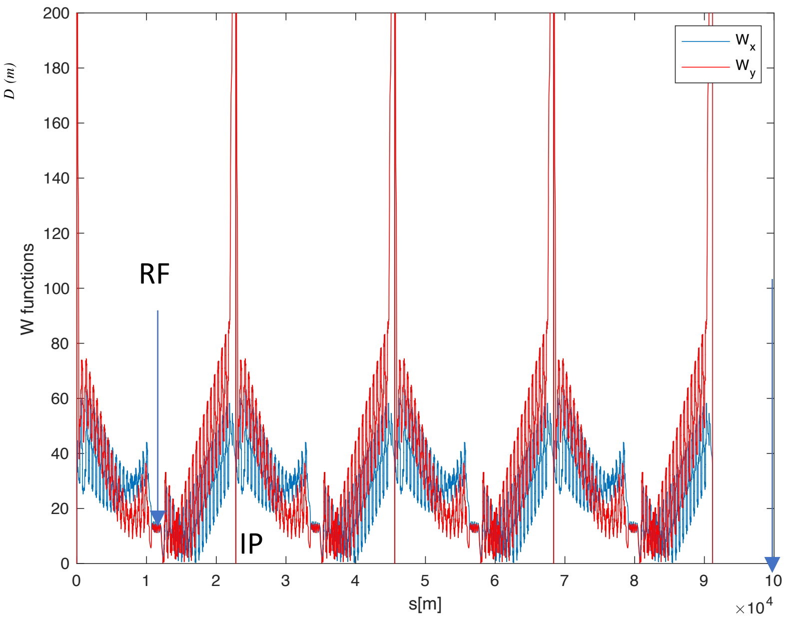
- Use two families of sextupoles in the arcs to correct linear chromaticity to one unit
- Momentum aperture is 0.4% consistent with momentum bandwidth
- Synchrotron radiation included in tracking

FCC-ee Design Lattice at 182.5 GeV



Optics

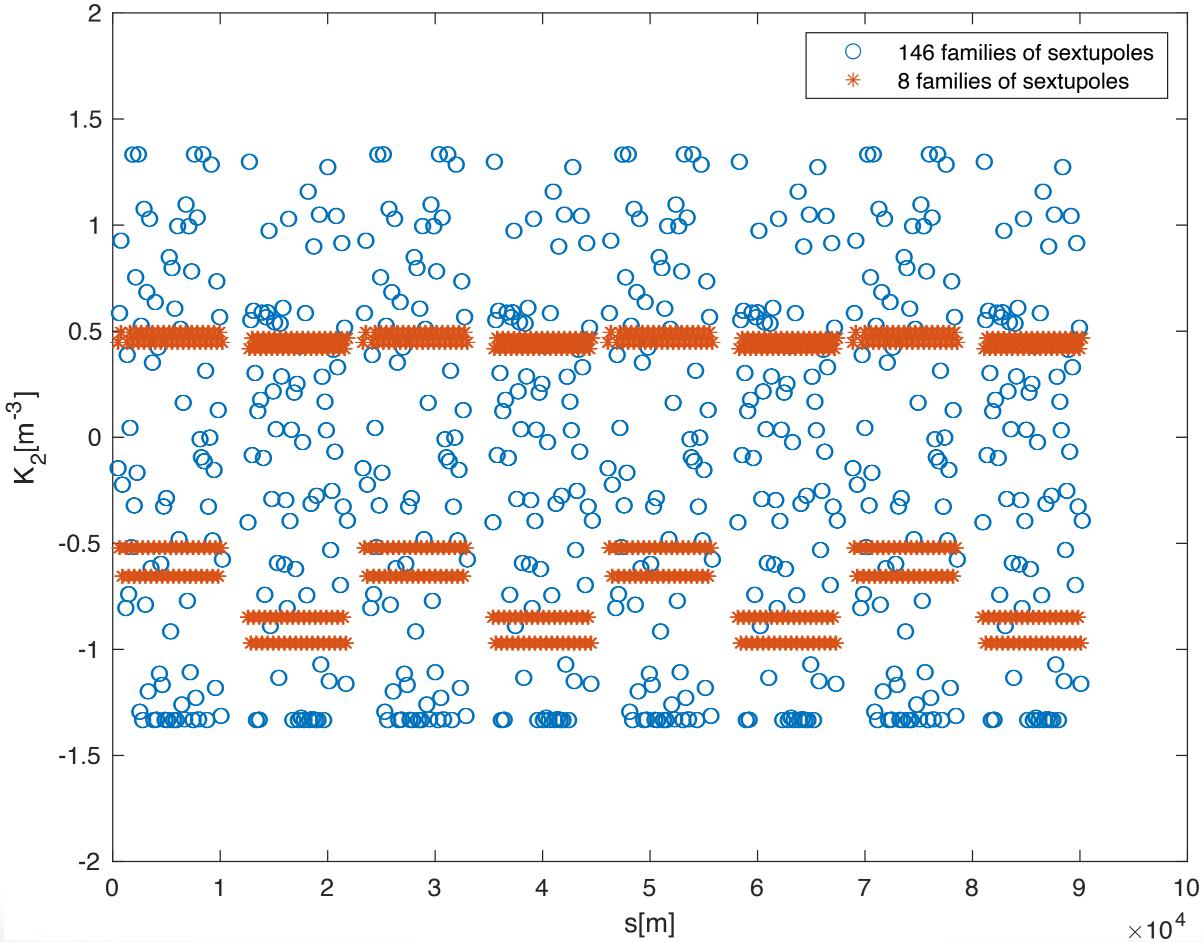
Chromatic Beating



Chromatic Compensation

146 families of sextupoles in the arcs are reduced to 8 families of sextupoles

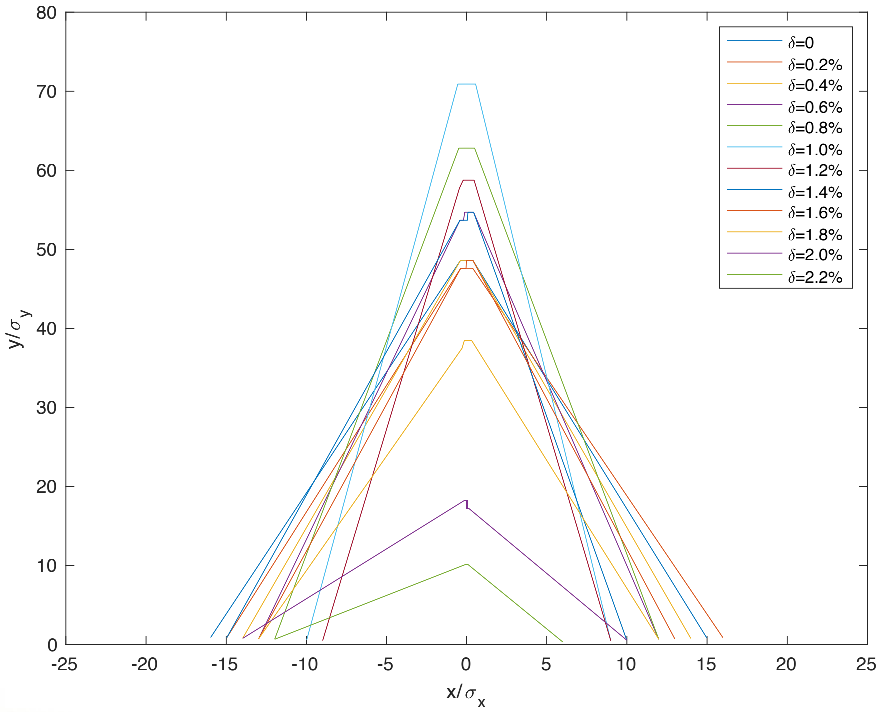
Sextupoles in the ARCs of FCC-ee



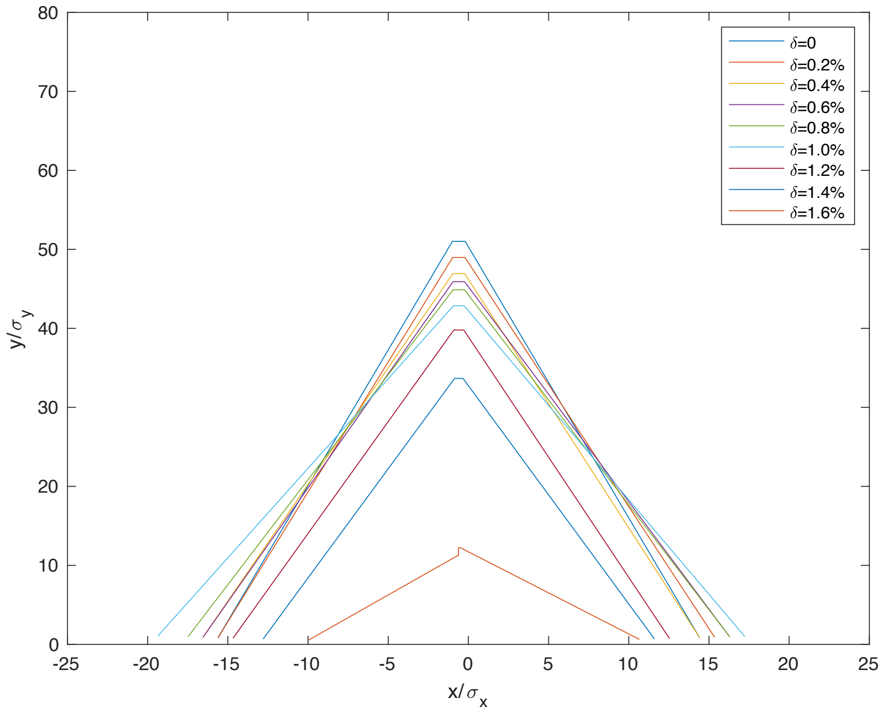
There are no changes in the positions or numbers of the sextupoles

Dynamic Apertures in FCC-ee

146 Families of Sextupoles in the Arcs



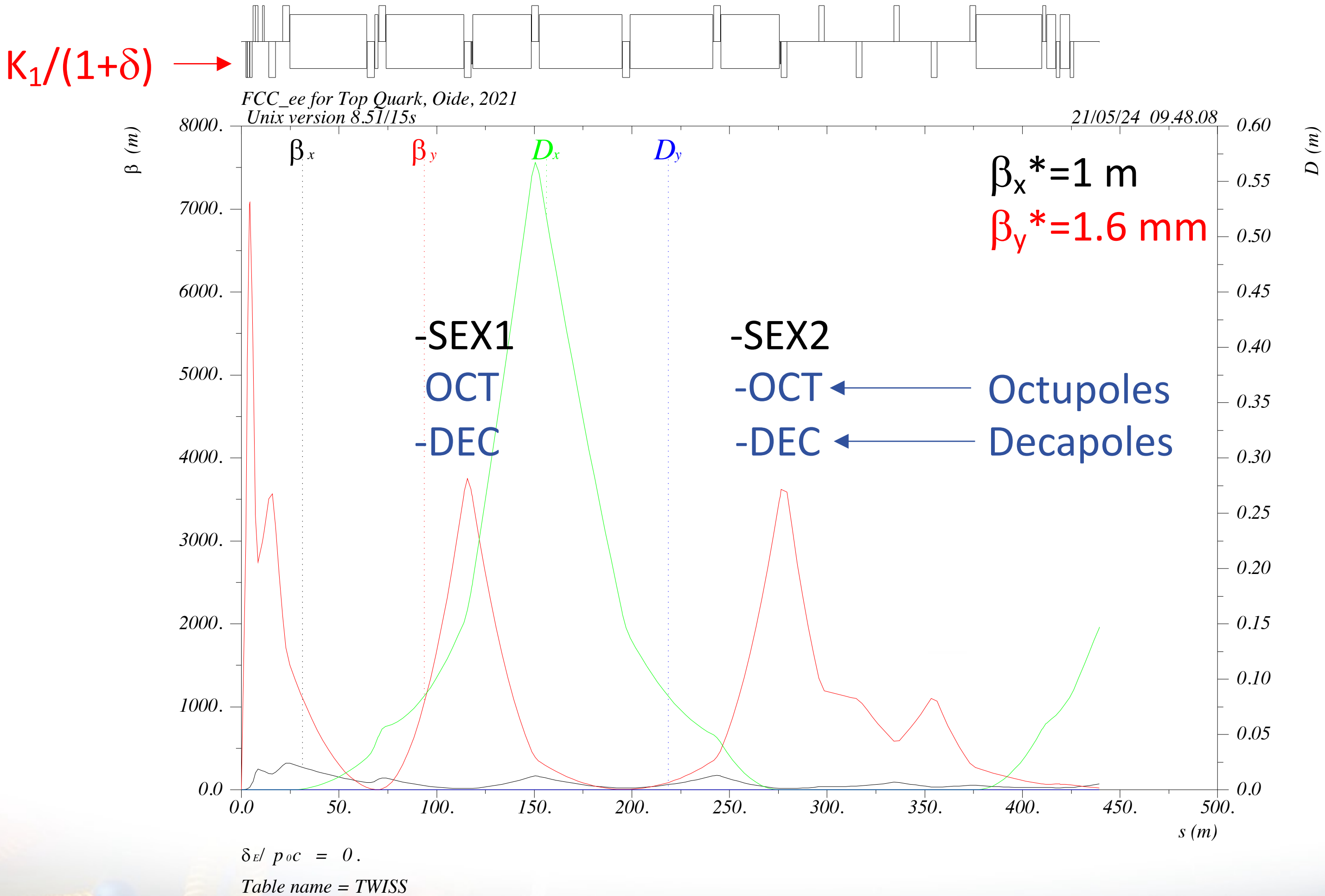
8 Families of Sextupoles in the Arcs



Synchrotron radiation is included in tracking with tapering

Momentum aperture is 1.6%, which is 10 σ for synchrotron radiation

Local Chromatic Compensation in FCC-ee



Residual is a first-order chromatic octupole

Tuning Knobs in FCC-ee

Parameters	Up Stream	Down Stream
Horizontal trombone Δ_x	0.01256654	0.25525786
Vertical trombone Δ_y	-0.06656187	0.15273498
Horizontal chromaticity ξ_x	-2.5	2.5
Vertical chromaticity ξ_y	23.3	-23.3
Magnet SY1: $K_2[\mathrm{m}^{-3}]$	12.54259199	-13.16370987
Magnet SY1: $K_3[\mathrm{m}^{-4}]$	50	50
Magnet SY1: $K_4[\mathrm{m}^{-5}]$	260000	-260000
Magnet SY2: $K_2[\mathrm{m}^{-3}]$	10.64833906	-11.26945694
Magnet SY2: $K_3[\mathrm{m}^{-4}]$	-50	-50
Magent SY2: $K_4[\mathrm{m}^{-5}]$	260000	-260000

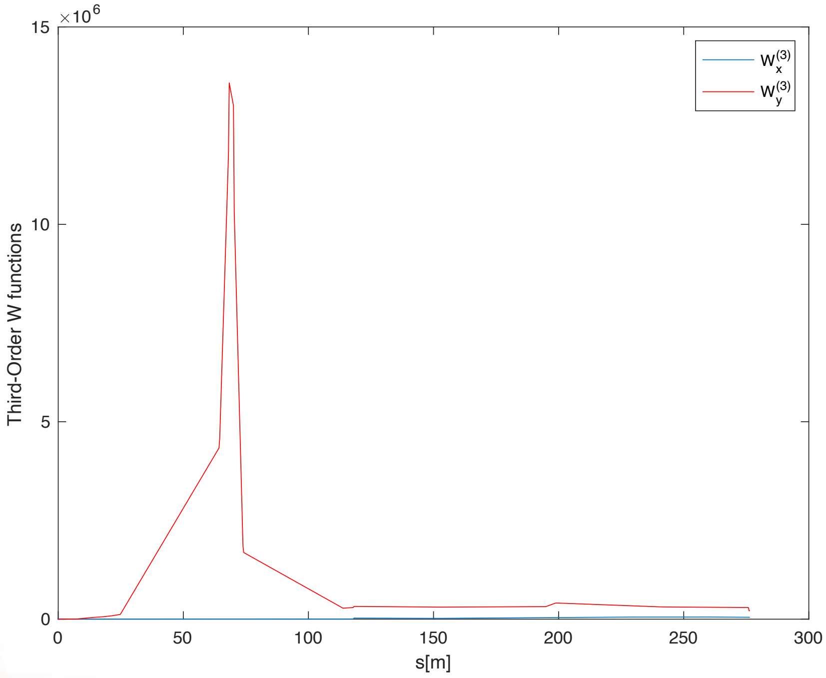
Nonlinear Chromaticity

Parameters	Without OCT, DEC	With OCT, DEC
$\partial \nu_y / \partial \delta$	0.00	0.00
$\frac{1}{2!} \partial^2 \nu_y / \partial \delta^2$	5.34×10^3	4.77×10^3
$\frac{1}{3!} \partial^3 \nu_y / \partial \delta^3$	-3.67×10^5	-1.83×10^5
$\frac{1}{4!} \partial^4 \nu_y / \partial \delta^4$	-3.00×10^7	-2.62×10^7

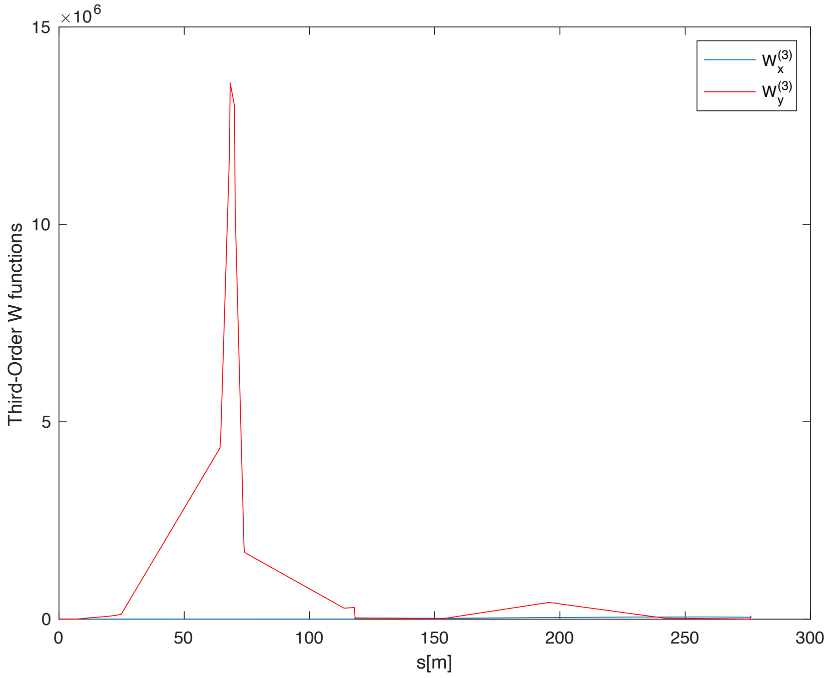
Momentum aperture is 1.6% without octupoles and decapoles

Third-Order Chromatic Beatings

Without Decapoles

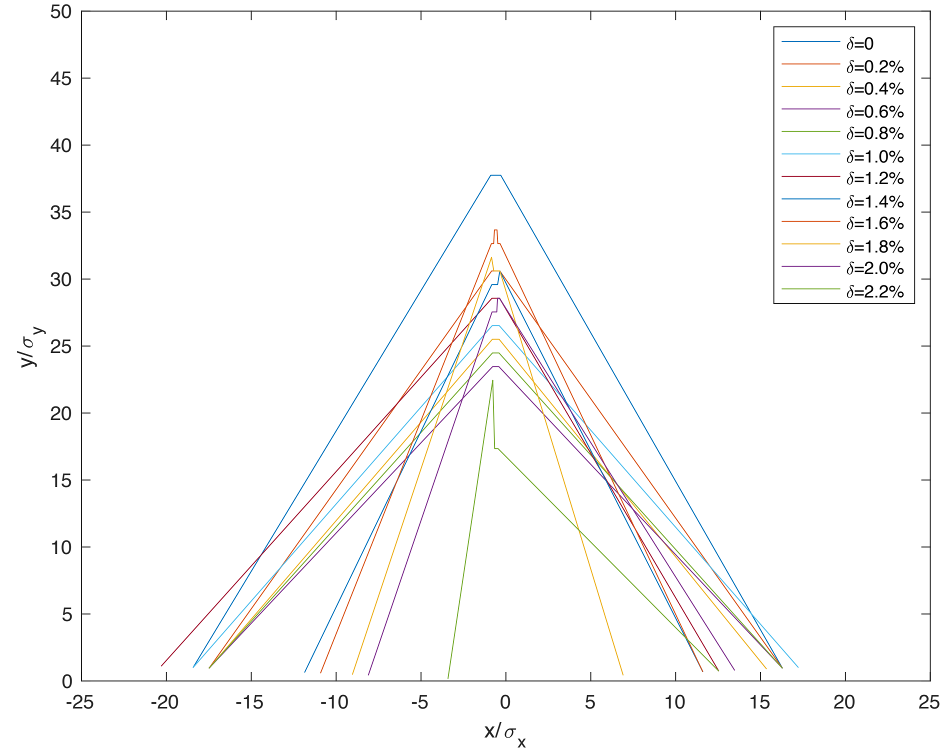


With Decapoles



Dynamic Apertures in FCC-ee

8 Families of Sextupoles in the Arcs and SOD in IRs



Synchrotron radiation is included in tracking with tapering
Momentum aperture is 2.2%, which is 10 σ for SR and BS

Conclusion

- Chromatic matching becomes an essential and powerful tool to systematically enlarge the momentum aperture in the colliders
- The combined crab waist and local chromatic compensation scheme can be improved by adding octupole and decapole pairs
- Our preliminary study shows that the semi-local chromatic compensation scheme may simply the FCC-ee design, reduce the cost, and make the tuning easier

Acknowledgements

- CERN: Katsunobu Oide for providing the FCC-ee lattices and Michael Benedikt and Frank Zimmermann for the invitation of this talk
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