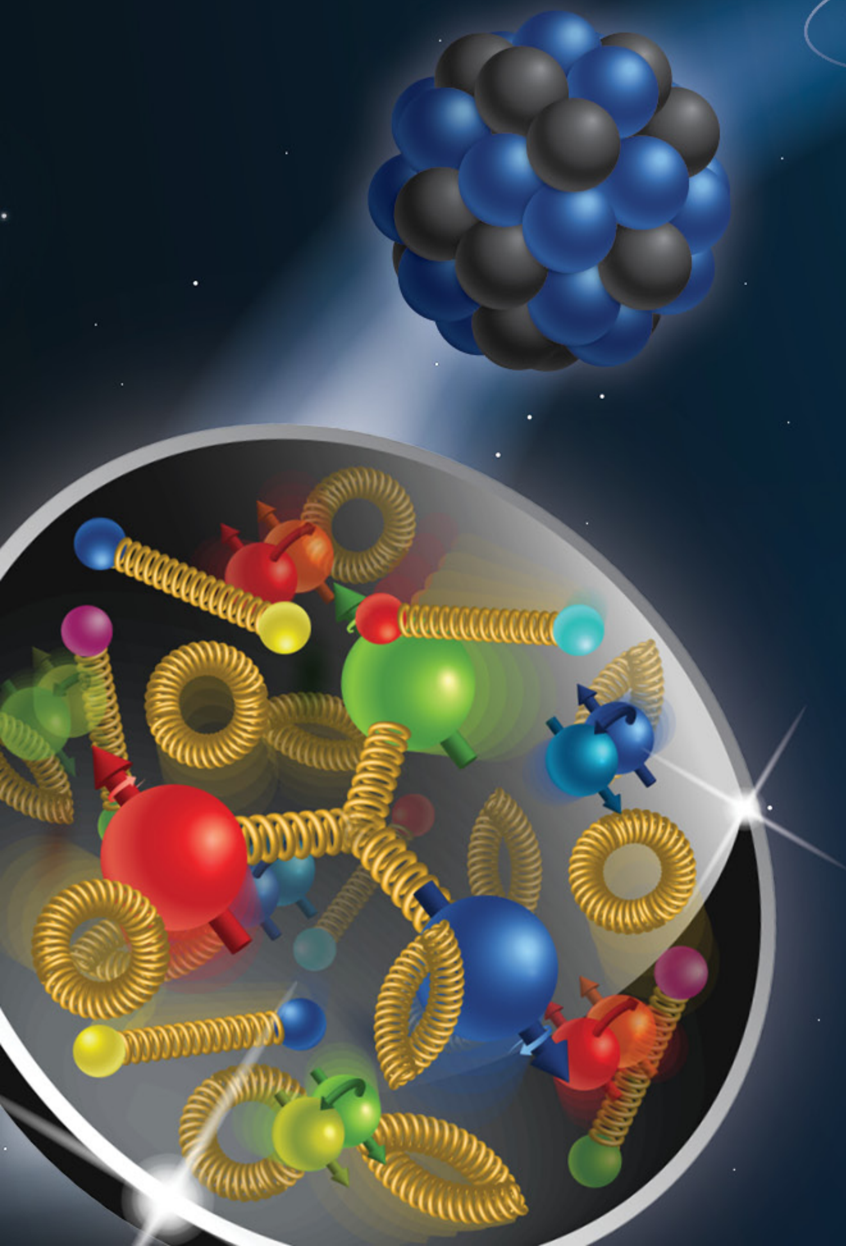


EIC Dynamic Aperture

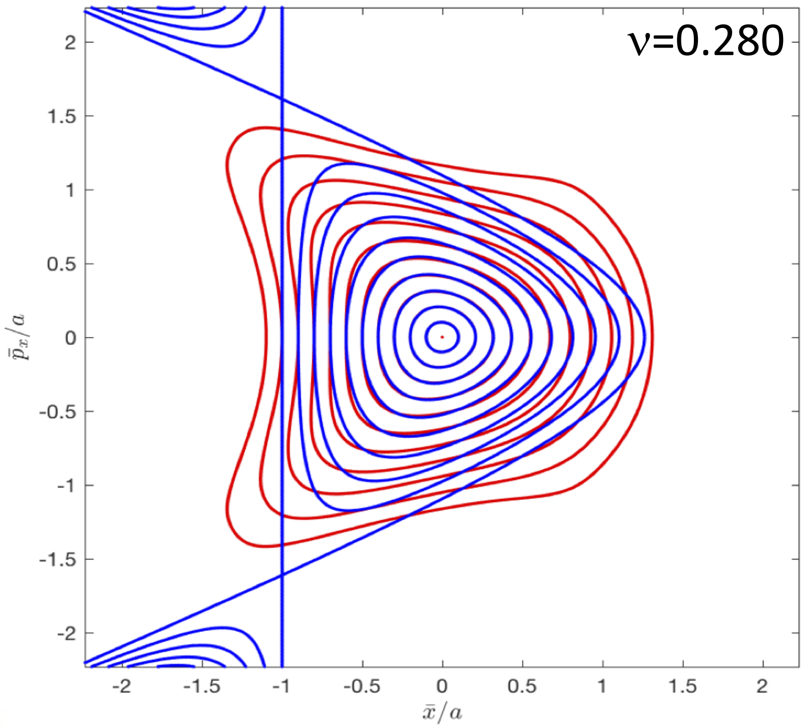
Yunhai Cai, SLAC

EIC Accelerator Collaboration Workshop
October 7-9, 2020

Electron-Ion Collider

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

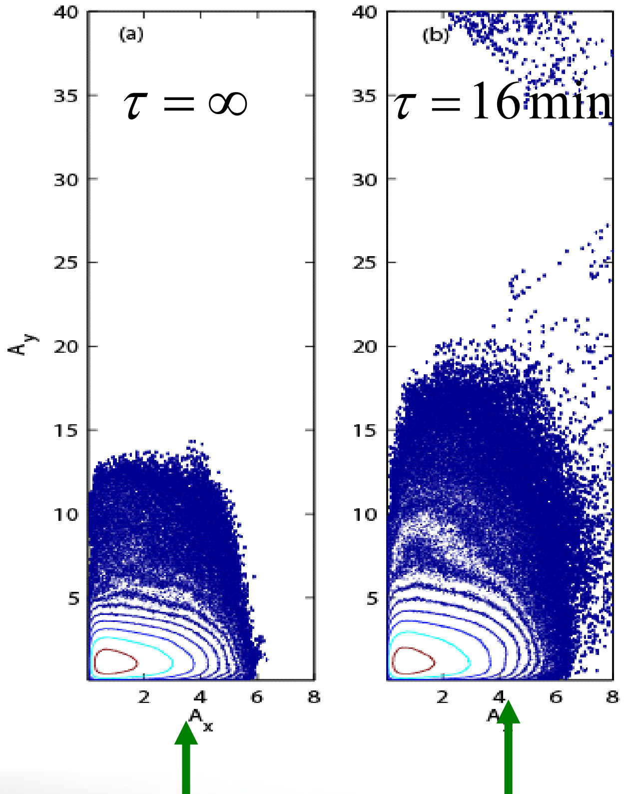
Dynamic Aperture



- Hadron Rings
  - Long-term stability
  - Mostly dominated by the magnetic errors of the dipoles
- Electron Rings
  - Short-term stability
  - Mostly dominated by the design sextupoles

Lower-order resonances play an important role in determining the dynamic aperture

Beam Distributions with Beam-Beam Interaction



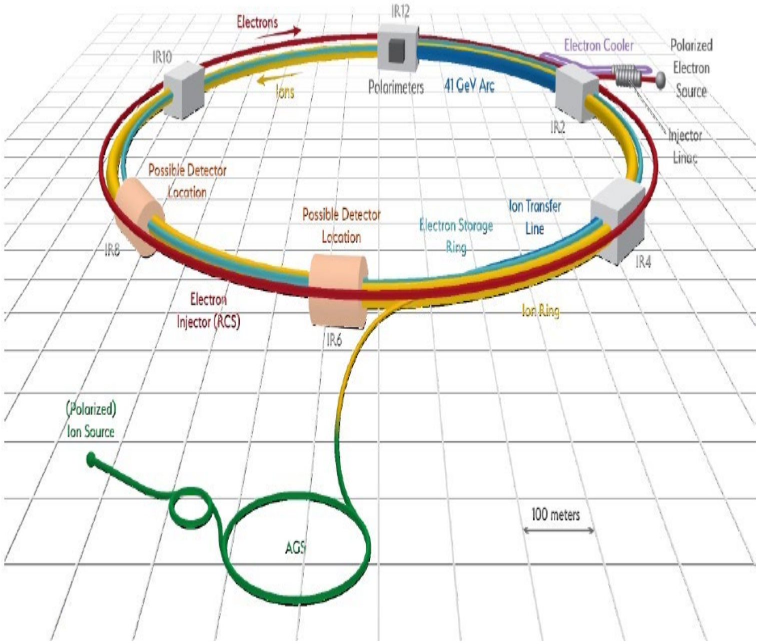
The distributions are averaged after 40,000 turns to improve the statistics.

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 effected.

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

Electron-Ion Collider



- Design luminosity: $10^{34} cm^{-2} s^{-1}$
- Highly polarized beams: 70%
- Hadron up to 275 GeV
- Electron up to 18 GeV
  - Electron collider ring
  - Rapid cycling synchrotron
  - Polarized electron source

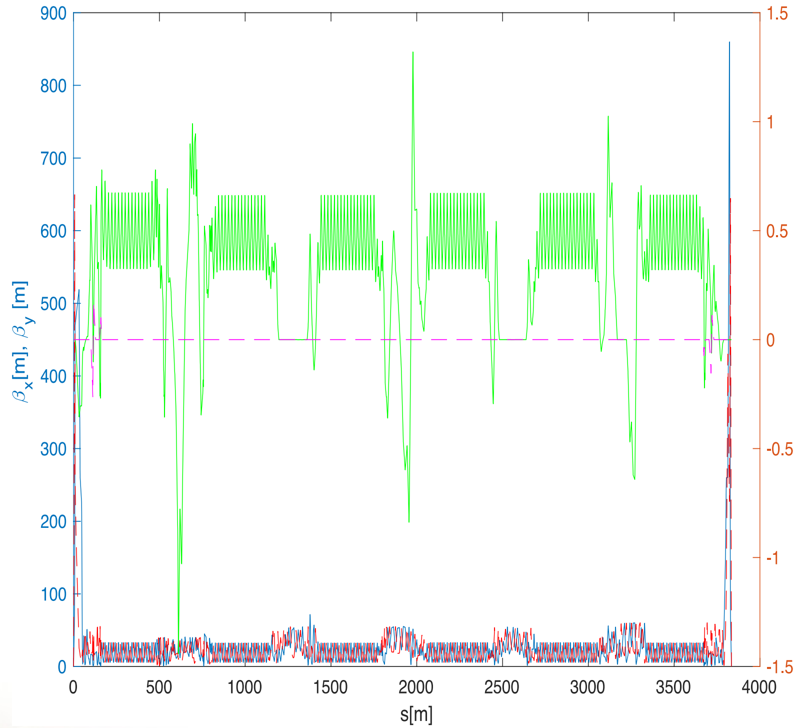
A factory that includes not only electrons but also hadrons

Relevant Parameters

Parameters	Units	60^0 Lattice	90^0 Lattice
Energy	GeV	10	18
Circumference	m	3834	
Emittance	nm	24	28
Energy spread	10^{-4}	5.5	9.8
Betatron Tunes		45.12/36.1	48.12/43.1
Chromaticity		-83/-91	-85/-94
IP betas	m	0.42/0.05	
L*	m	5.3	

- Fractional tunes are selected by the spin dynamics and beam-beam performance
- Their closeness to integer makes chromatic compensation harder

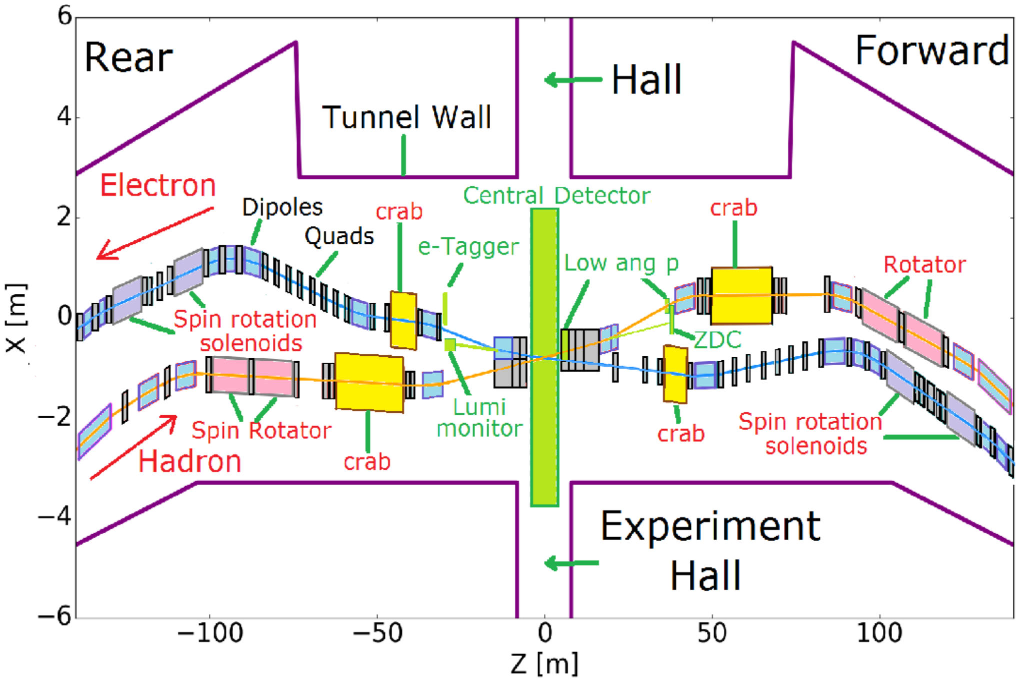
Design Optics at 18 GeV



- Fits in the RHIC tunnel along with the other rings
- 90^0 FODO cells in arcs
- On-axis injection
- One interaction region in the EIC scope
- Asymmetric interaction region

Lattice design is much more demanding because of the large energy range and the constraints

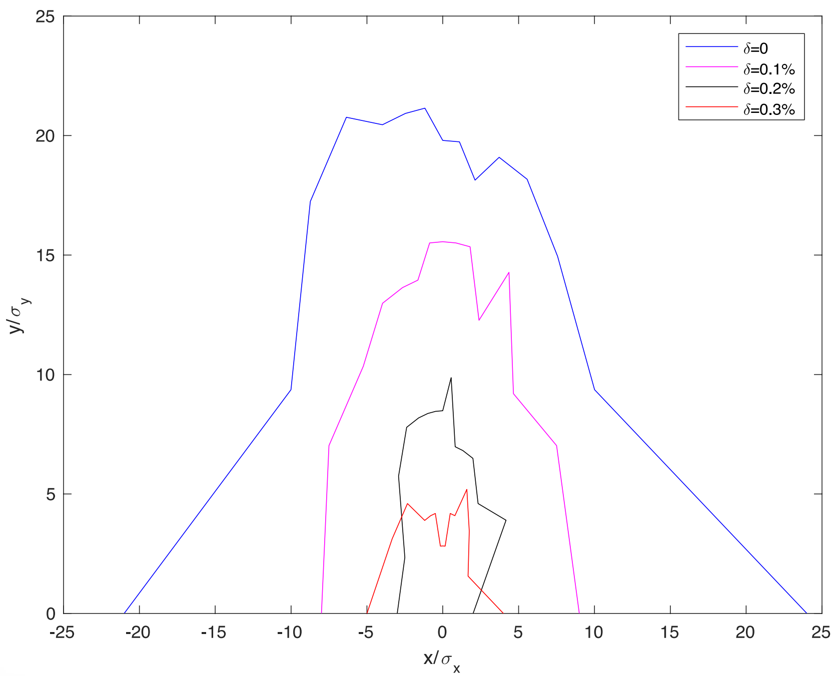
Interaction Region

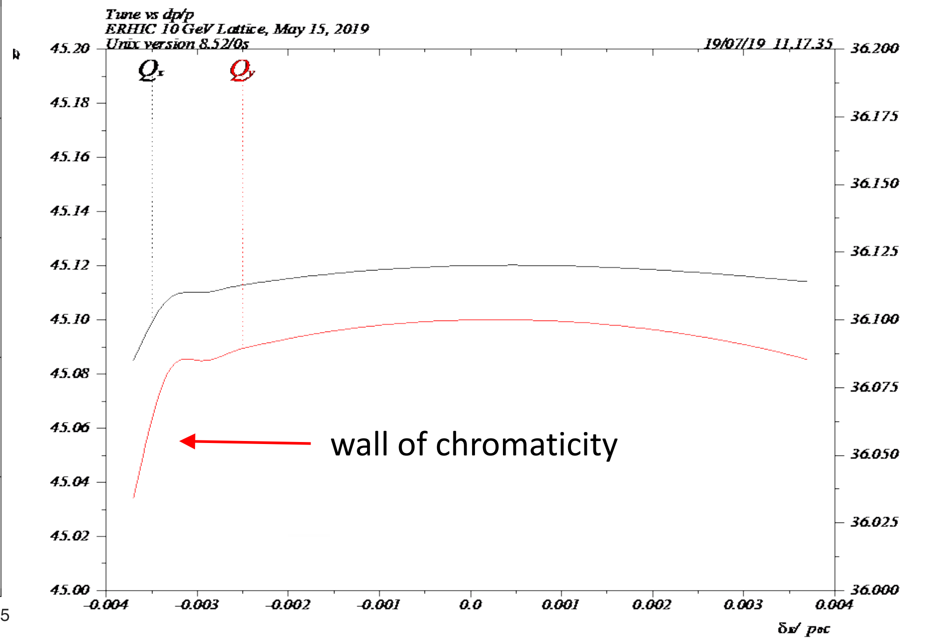


- Asymmetric
- Low-beta optics
- Crab cavity requires additional high-beta regions
- Coupled optics due to spin rotators

Interaction region is packed without leaving space for local chromatic compensation

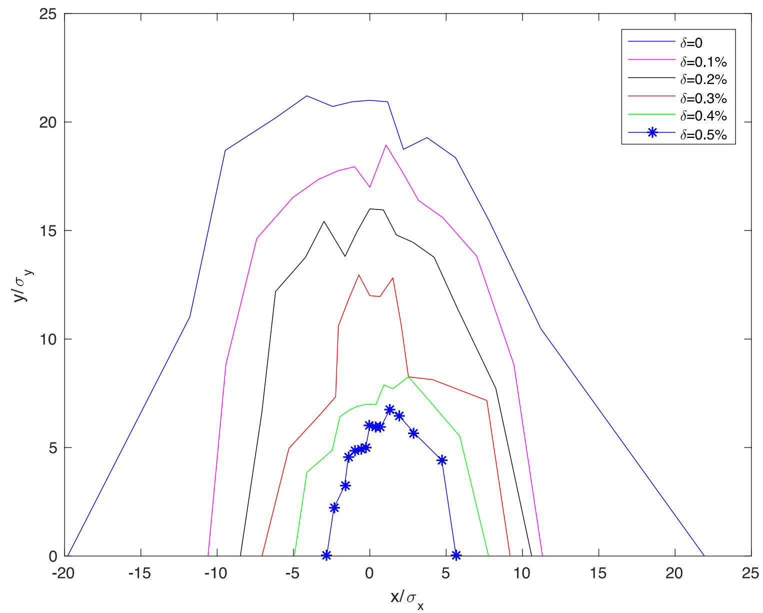
Dynamic Aperture of the 60^0 Lattice

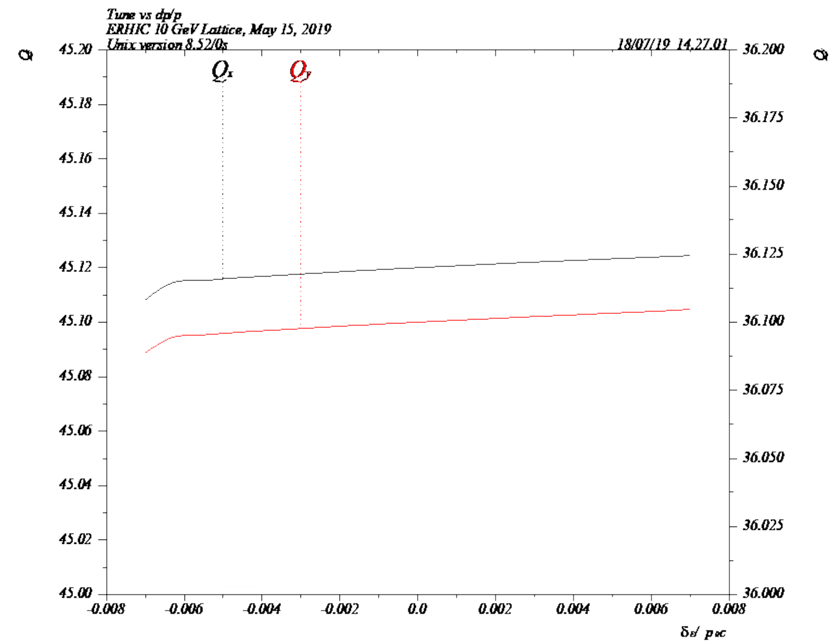




- Use two families of sextupoles in the arcs to correct linear chromaticity to one unit
- Momentum aperture is 0.3%, consistent with momentum bandwidth

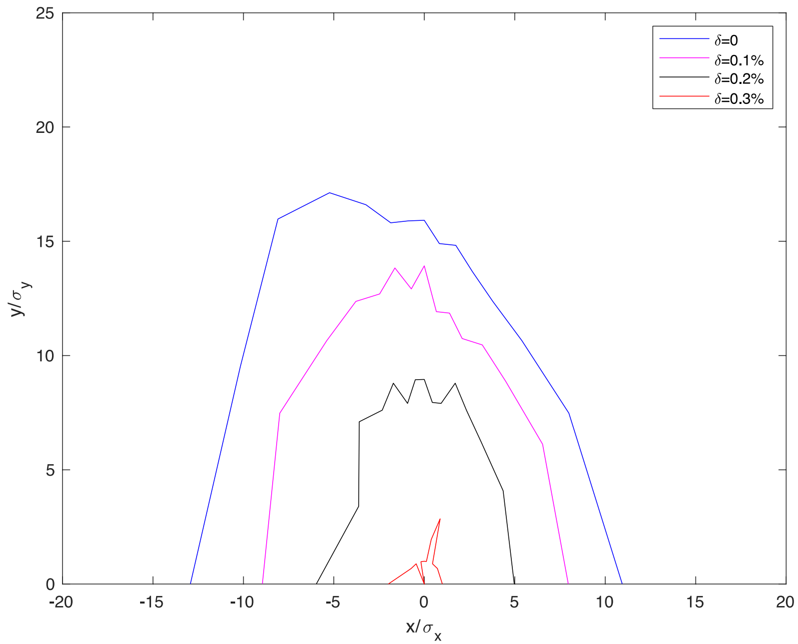
Global Chromatic Compensation of the 60^0 Lattice

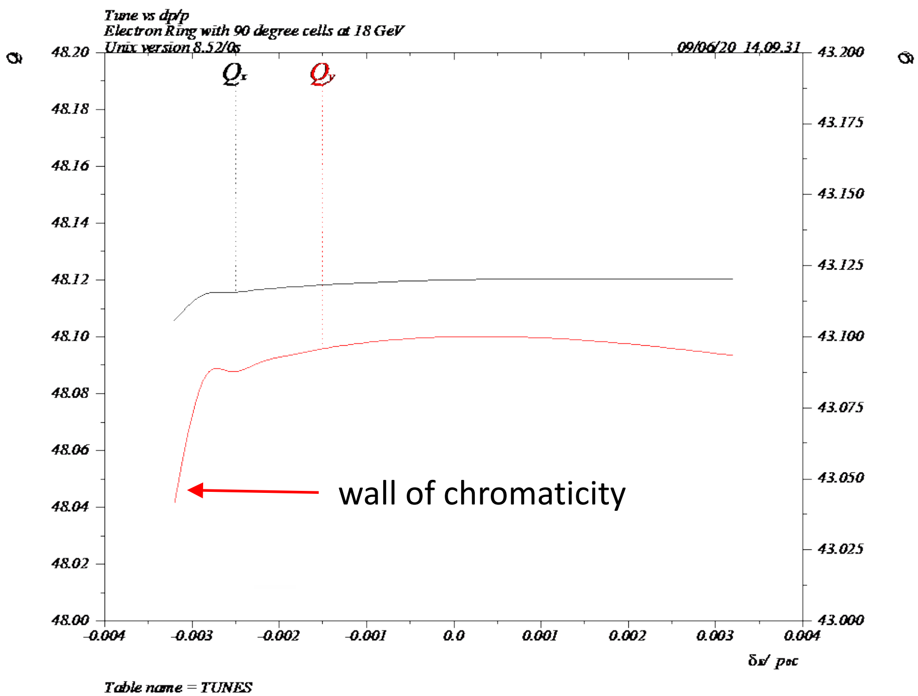




- Use 6 families of sextupoles in each arc, so total 36 families in the ring
- Correct nonlinear chromaticity up to 6^{th} order, so total 12 constraints
- Run a downhill simplex optimizer on iMac for a week
- Momentum aperture increases from 0.3% to 0.5% but smaller than bandwidth

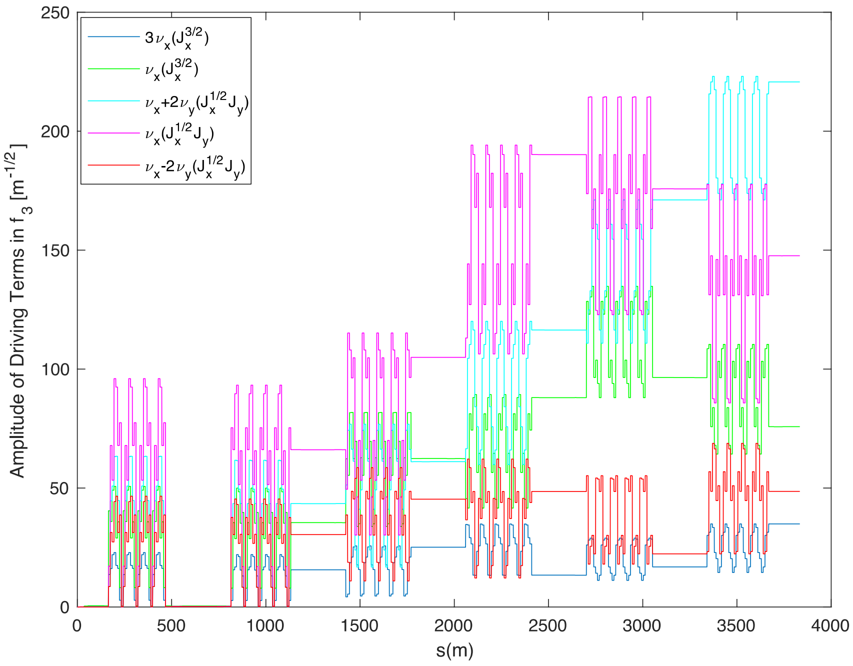
Dynamic Aperture of the 90^0 Lattice

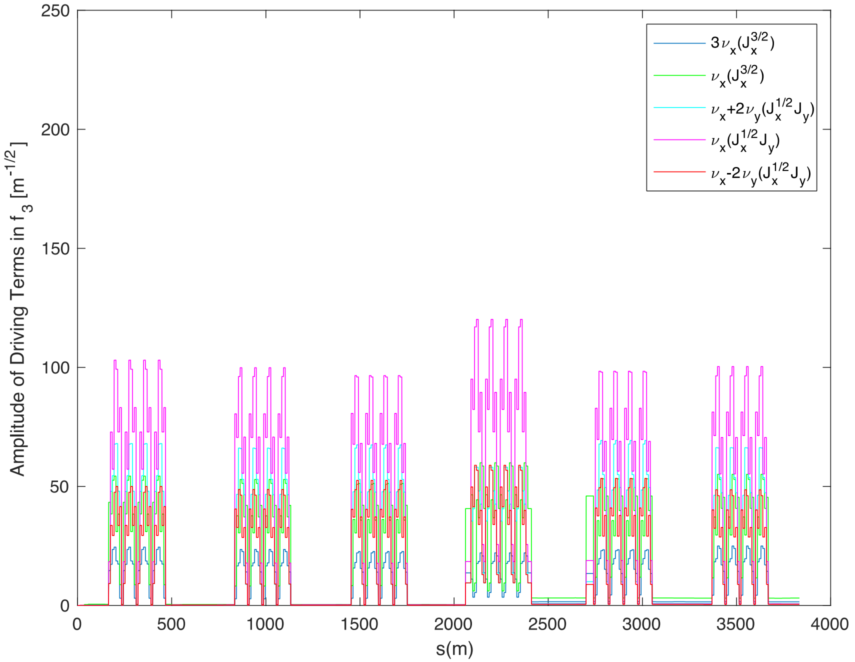




- Use two families of sextupoles in the arcs to correct linear chromaticity to one unit
- Momentum aperture is 0.3% consistent with momentum bandwidth
- On-momentum aperture is much smaller in comparison to the 60^0 lattice

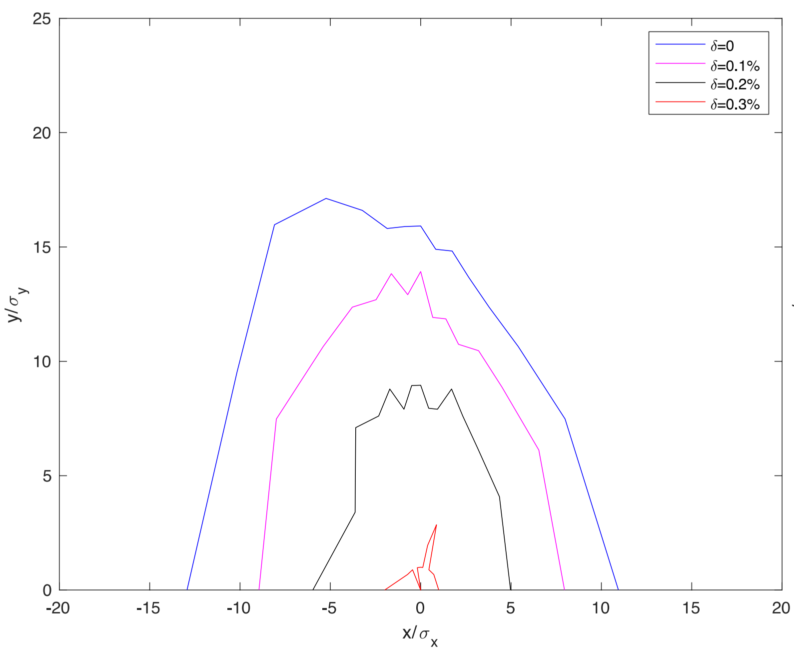
Mitigation of the Third-Order Resonances

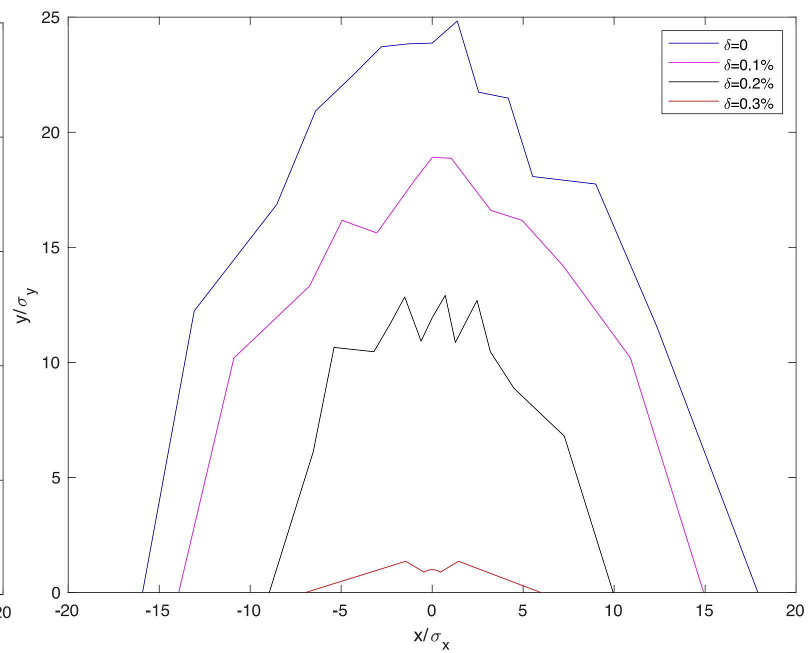




- Remove the sextupoles in the dispersion suppressors where the lattice functions are irregular and pair all sextupoles in 180^0

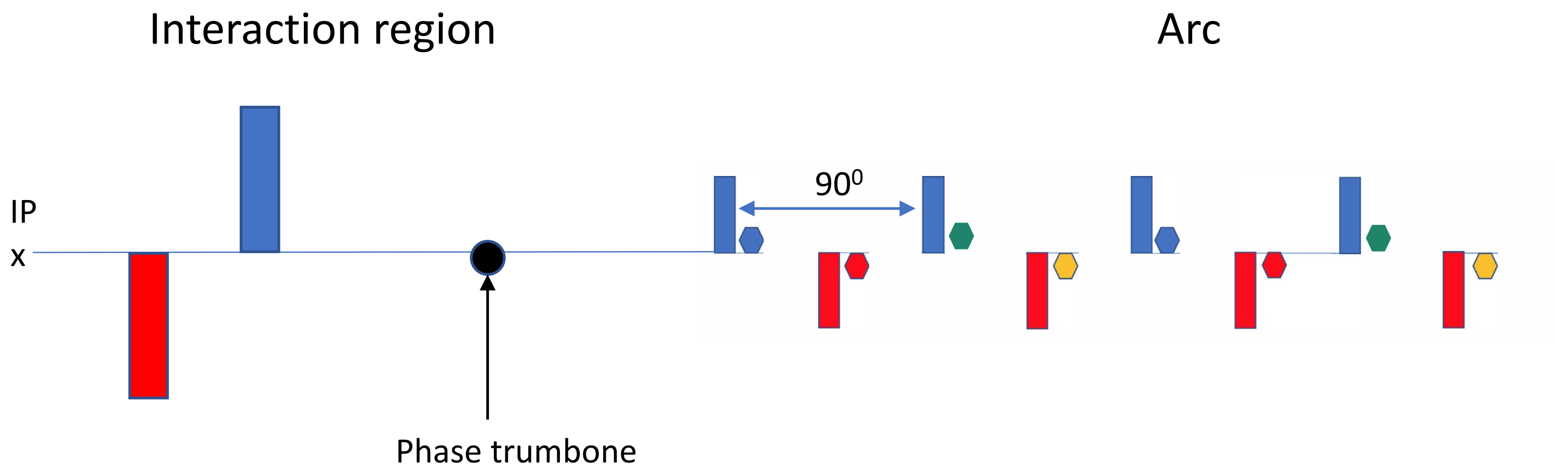
Improvement of Dynamic Aperture of the 90^0 Lattice





Eliminating all third-order driving terms by the sextupoles significantly increases the on-momentum aperture

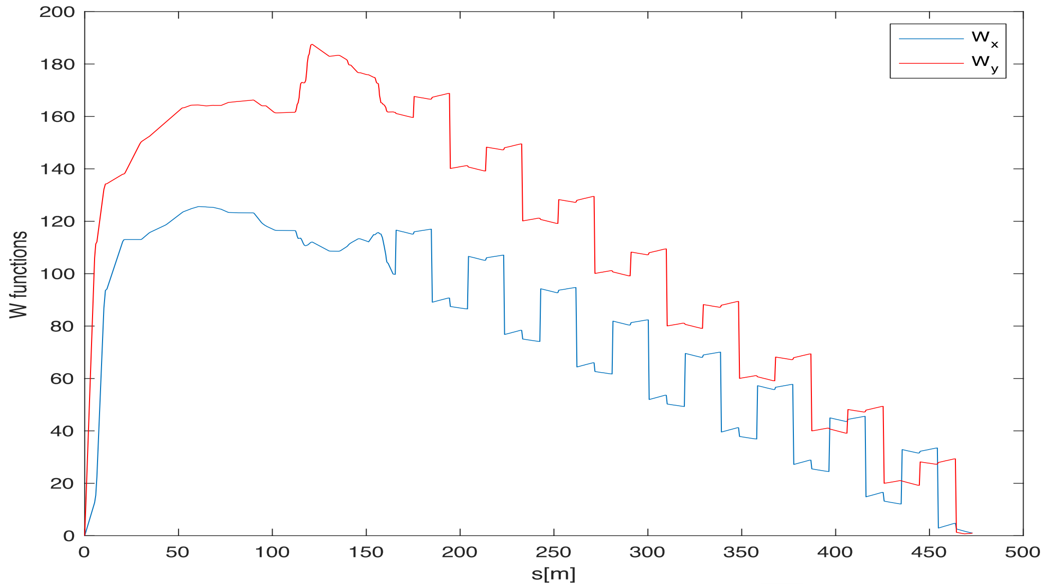
Semi-Local Chromatic Compensation Scheme



In each plane:

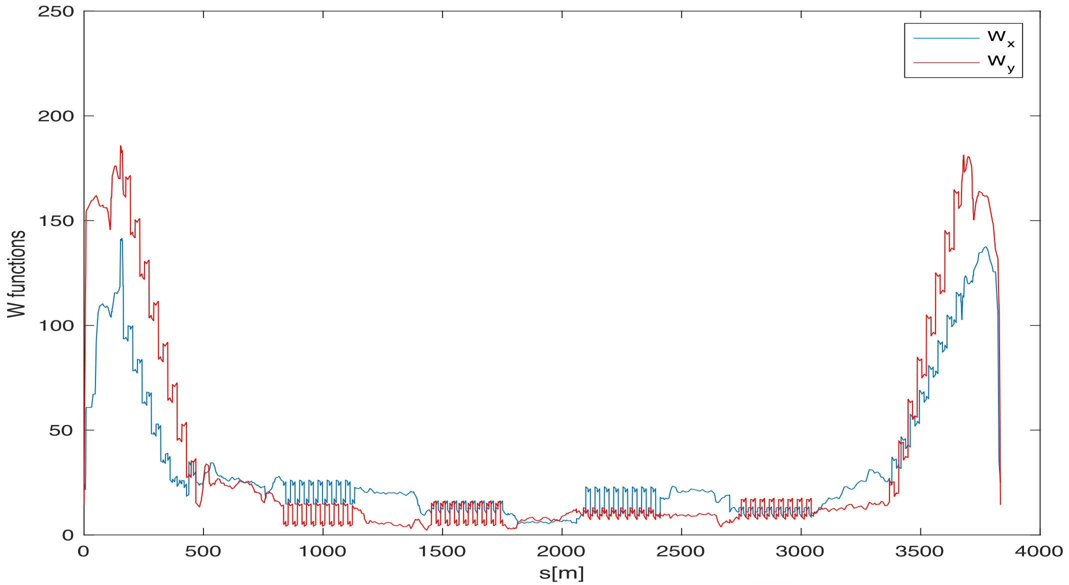
1) Members in the family add to the beta beating
2) The other family (same sign) cancel the beta beating but add chromaticity
3) Since all beating is in the same phase, a trombone is necessary to align the IR beating to the arc

From Chromatic Correction to Chromatic Matching



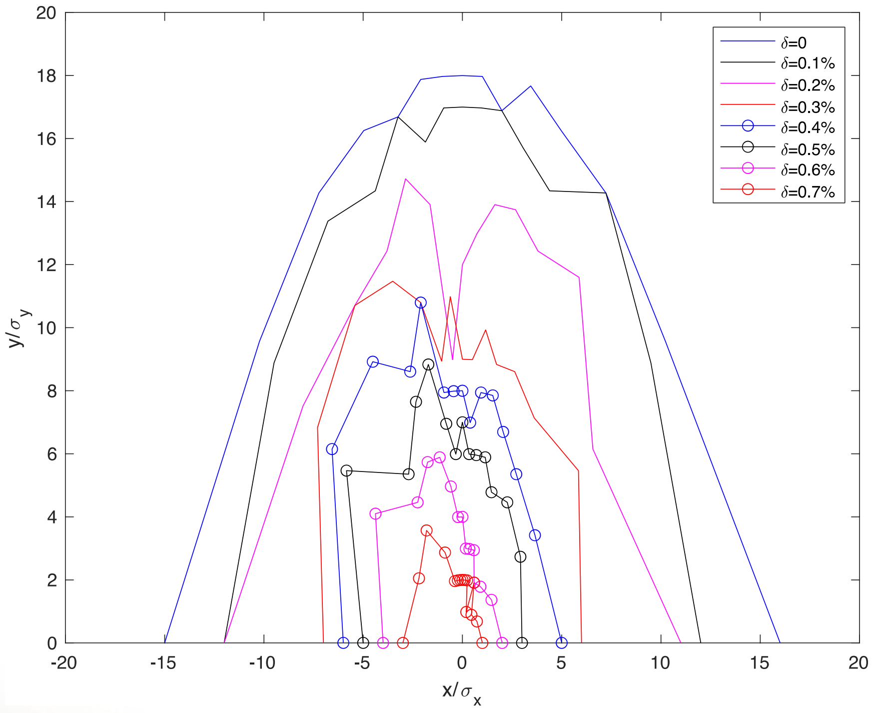
1) Four variables: strengths of two sextupole families, ν_x and ν_y
2) Four goals: β_x', α_x', β_y', α_y' setting at zeros
3) Two free parameters: ratio of strenghts of two families in each plane
4) Solutions are found with a downhill simplex optimizer

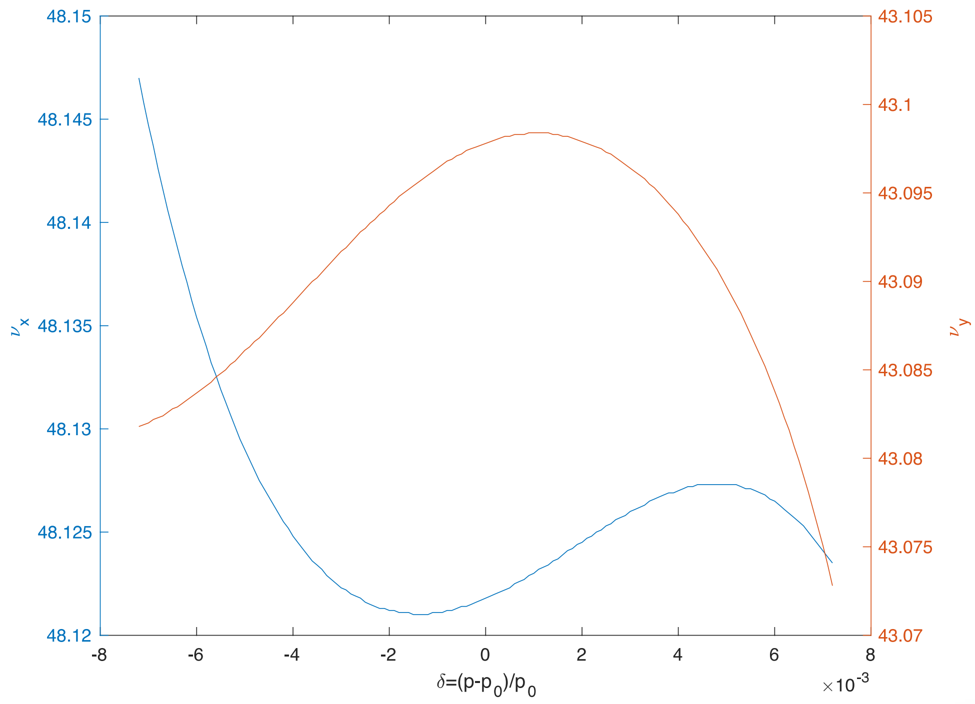
Semi-Local Chromatic Compensation in the 90^0 Lattice



1) Add two more trombones to restore the phase advances at the beginning of the second arcs, retaining the tunes
2) Two families of sextupoles in remaining four arcs to set chromaticity to 1 unit
3) Use 10 families of sextupoles in the arcs
4) Solutions are parameterized with the local chromaticity

Dynamic Aperture of the 90^0 Lattice with Semi-Local Correction

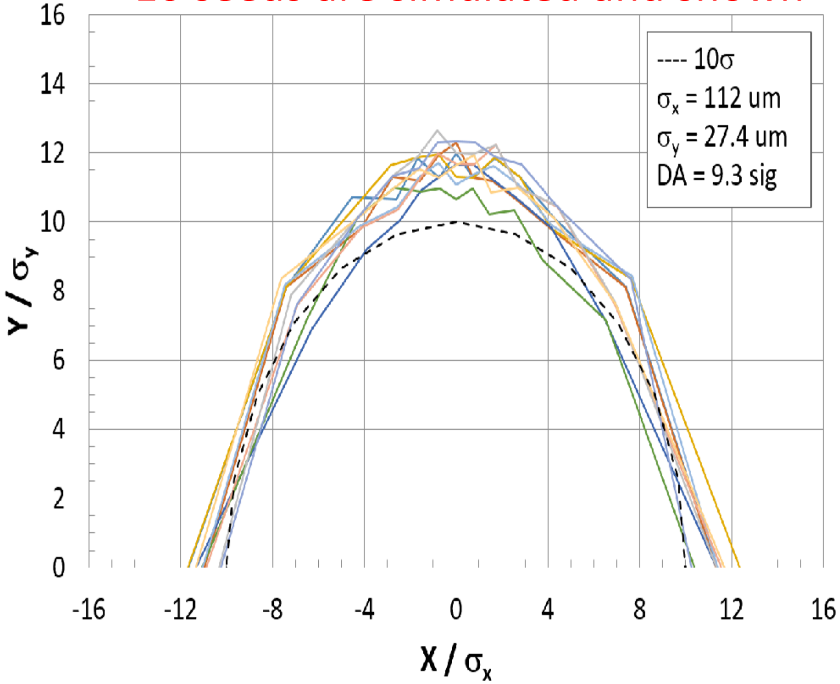




- The trombones are implemented by rematching of the optics
- Momentum aperture is increased to 0.7%, or 7 σ

Machine Tolerances
(Yuri Nosochkov)

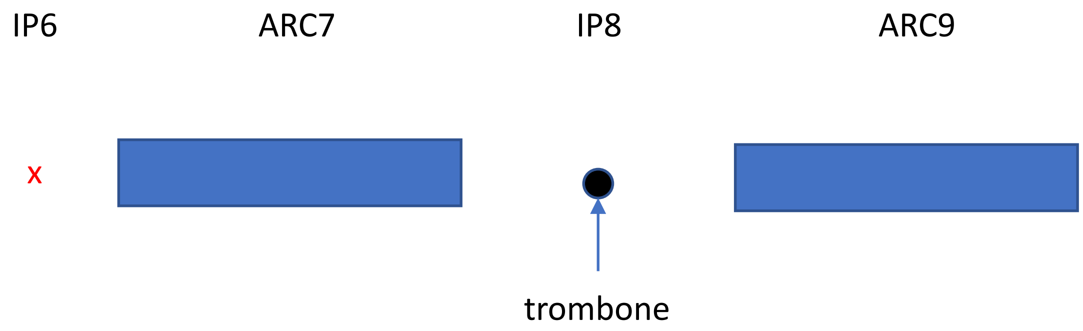
10 seeds are simulated and shown



- Include alignment and magnetic errors
- Correct orbit, dispersion, coupling, and beta beatings
- Specify multipole errors for all magnets

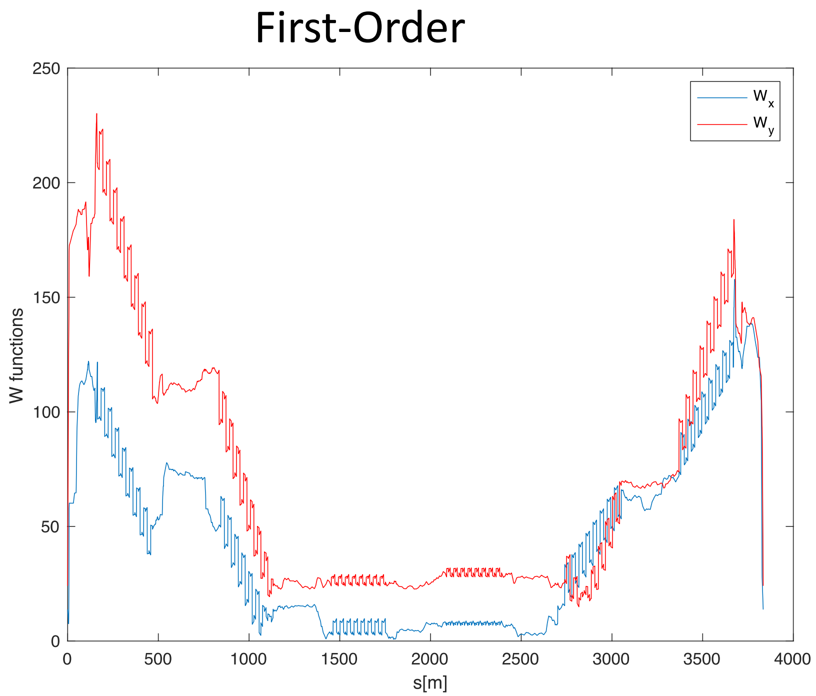
Quadrupoles in high-beta regions require tighter tolerances.

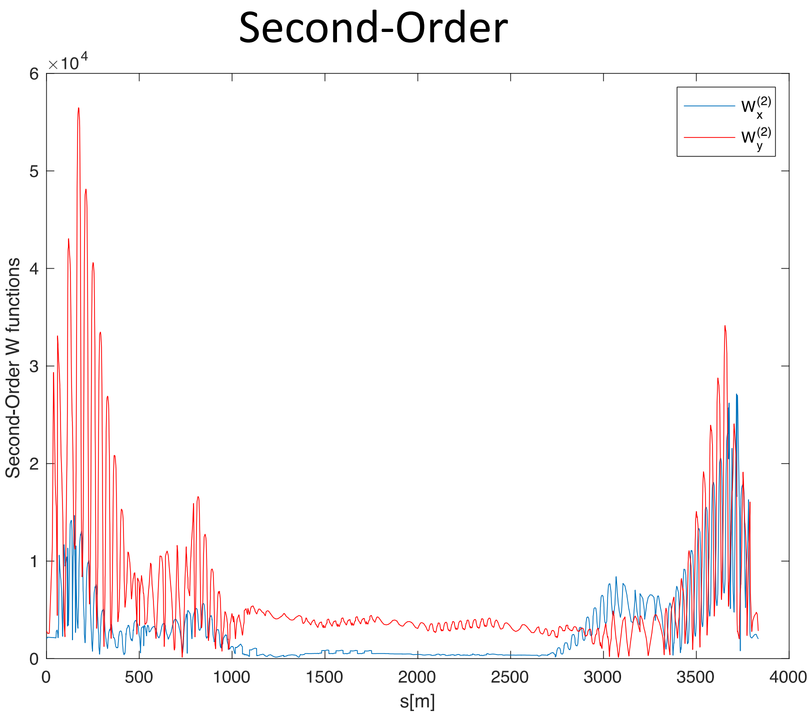
Chromatic Compensation Scheme with Two Arcs



1) Starting from the previous optimized semi-local solution with the arc 7
   a) The phases of the sextupoles in the arc 7 have been optimized.
   b) Strenghts of sextupoles reduced by a half initially because of two arcs
2) Four families of sextupoles in arc 7 and arc 9
3) A trombone in IP8, the middle of the straight
4) Correct both chromaticity and first-order beta beating

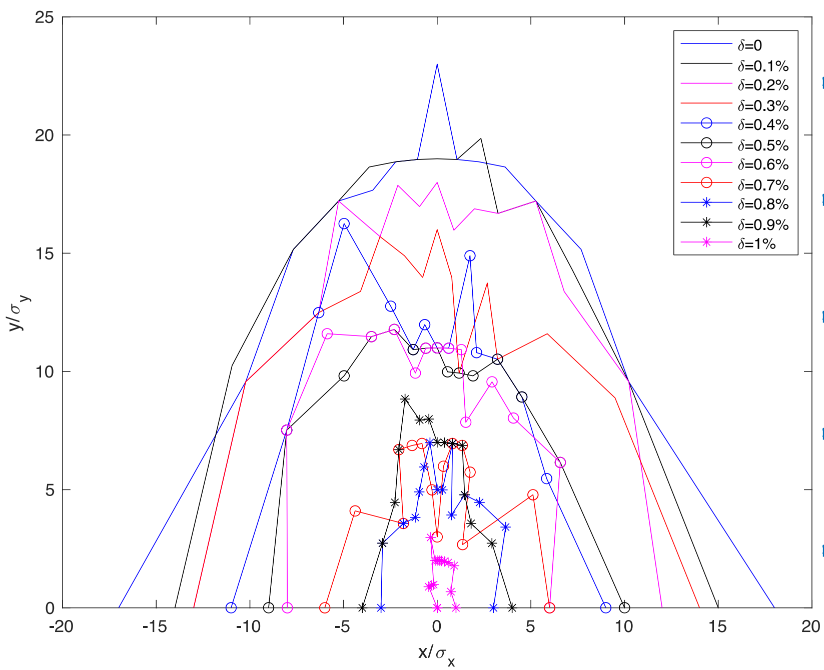
Chromatic Optics of the 90^0 Lattice

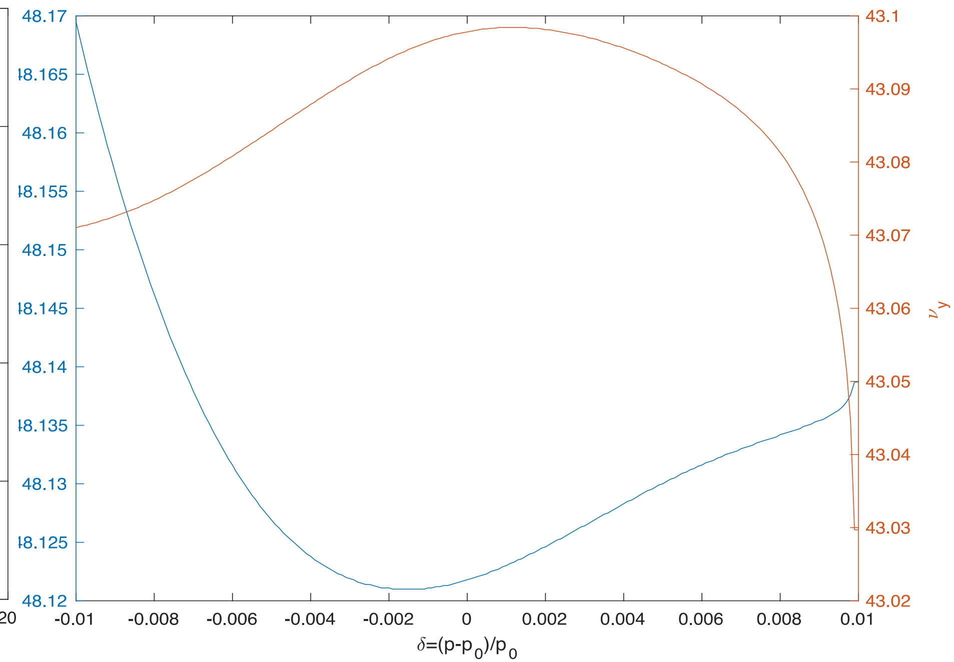




Reduction of both the first-order and second-order chromatic beatings is important

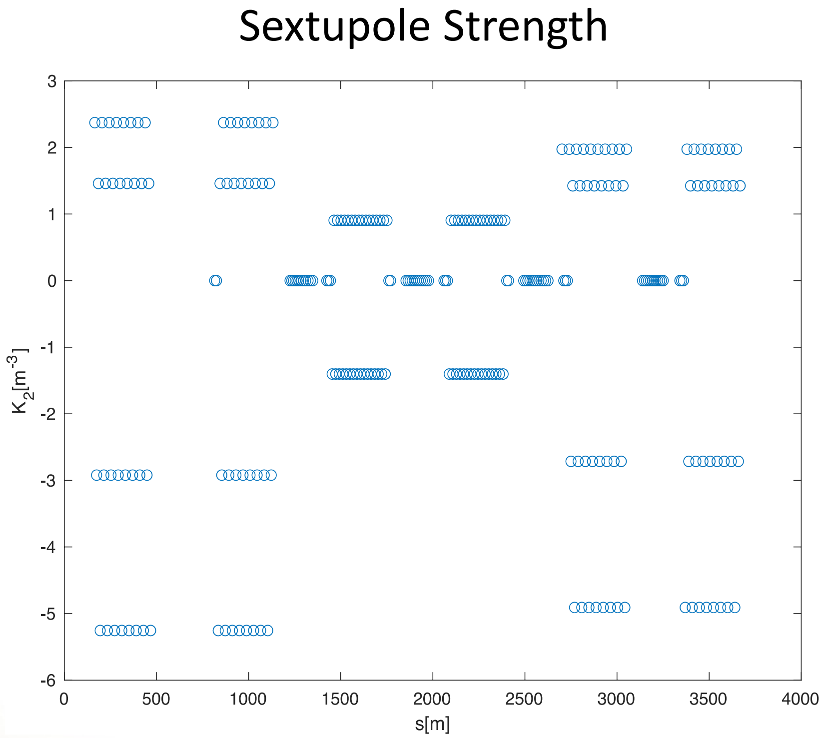
Dynamic Aperture of the 90^0 Lattice





Increased from 0.7% to 1%, mostly because more over chromaticity compensation in arc 7, 9 and arc 3,5 to reduce the second-order chromatic beta beatings and therefore the third-order chromaticity

Chromatic Solution



- 10 families of sextupoles with much reduced peak sextupoles
- Parameterized solutions, excellent for the tuning in the real accelerator

	IP4	IP8
$\Delta\nu_x$	0.264	0.027
$\Delta\nu_y$	-0.178	0.131

Conclusion

- The design criteria of dynamic aperture, namely 10 σ in all three dimensions, are achieved for both the 60-degree and the 90-degree lattices with single interaction region.
- Various chromatic compensation schemes, including global and semi-local, are investigated. The semi-local solutions are well understood and parameterized in terms of the local chromaticity. In particular, the minimization of the second-order chromatic beta beatings is the key for the success. Most importantly, the scheme can be easily deployed in the online tuning and optimization of the collider.
- For the optimization of dynamic aperture, it is essential to reduce the third-order resonance driving terms and to minimize the peak strengths of the sextupoles.
- The next challenge is to find adequate solutions with two interaction regions. Currently, we are halfway there.

Acknowledgements

- SLAC: Yuri Nosochkov for many years of collaboration on lattice design
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- Cornell University: Georg Heinz Hoffstaetter and Jonathan Unger for the EIC collabortion

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