Dynamic Aperture in Electron and Ion Colliders

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U.S. DEPARTMENT OF ENERGY
Office of Science

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Outline

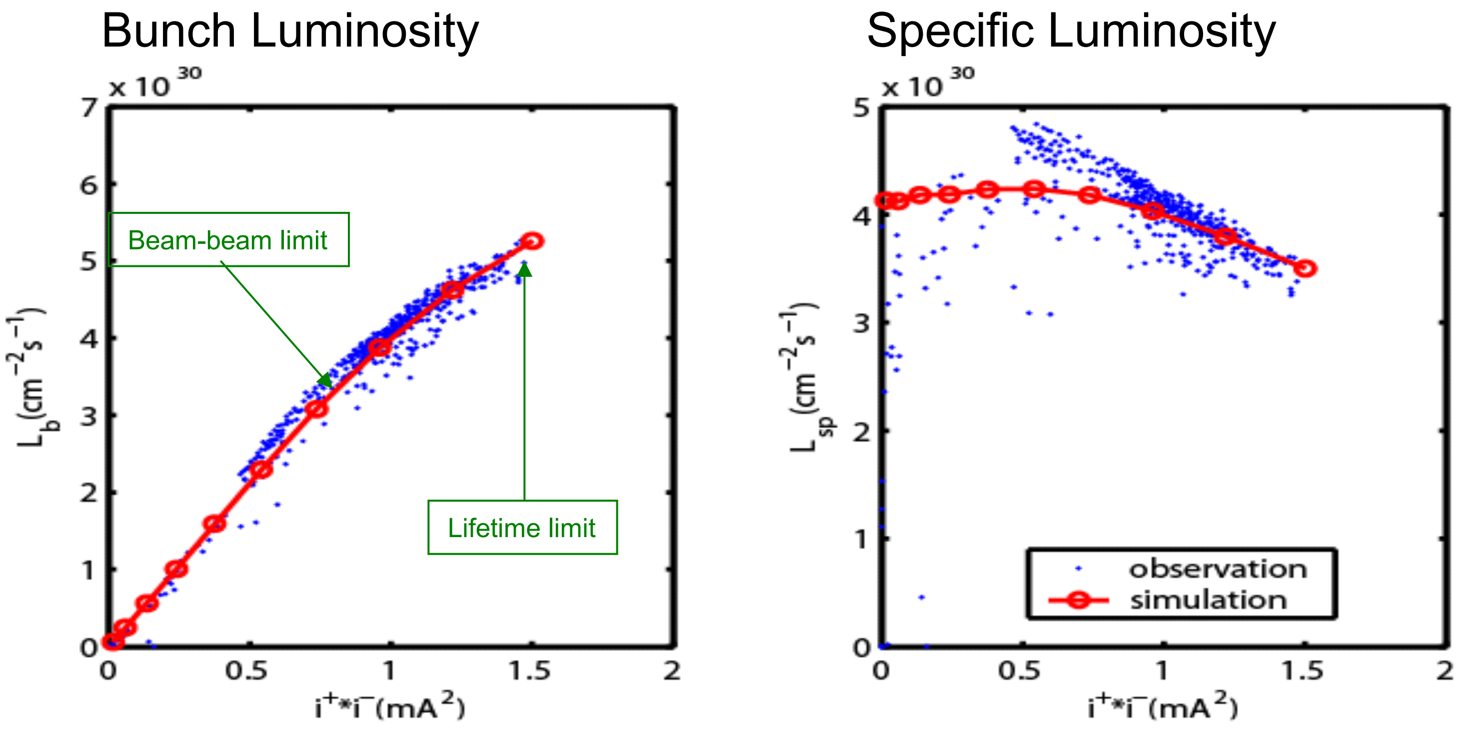
- Introduction
- Version 5.0 lattice of the electron ring in ERHIC
  - Evaluation
  - Requirements
- Simplified lattices
  - 60° cells of six arcs and six straights
  - Replace a straight with a low-beta interaction region
- Chromatic compensation
  - Global scheme
  - Semi-Local scheme
- Conclusion

Electron Rings

Parameters	Units	PEP-II HER	JLEIC ERING	ERHIC ERING
Energy	GeV	9	5	10
Circumference	m	2200	2256	3834
Beam current	A	2	3	2.5
Emittance	nm	47.5	4.6	24.0
Energy spread	10^{-4}	6.0	4.6	5.5
Tunes		24.57/23.64	57.22/50.16	45.12/36.10
Chromaticity		43/57	125/129	83/91
IP betas	m	0.50/0.015	0.10/0.02	0.42/0.05
L*	m	0.9	3.0	5.3

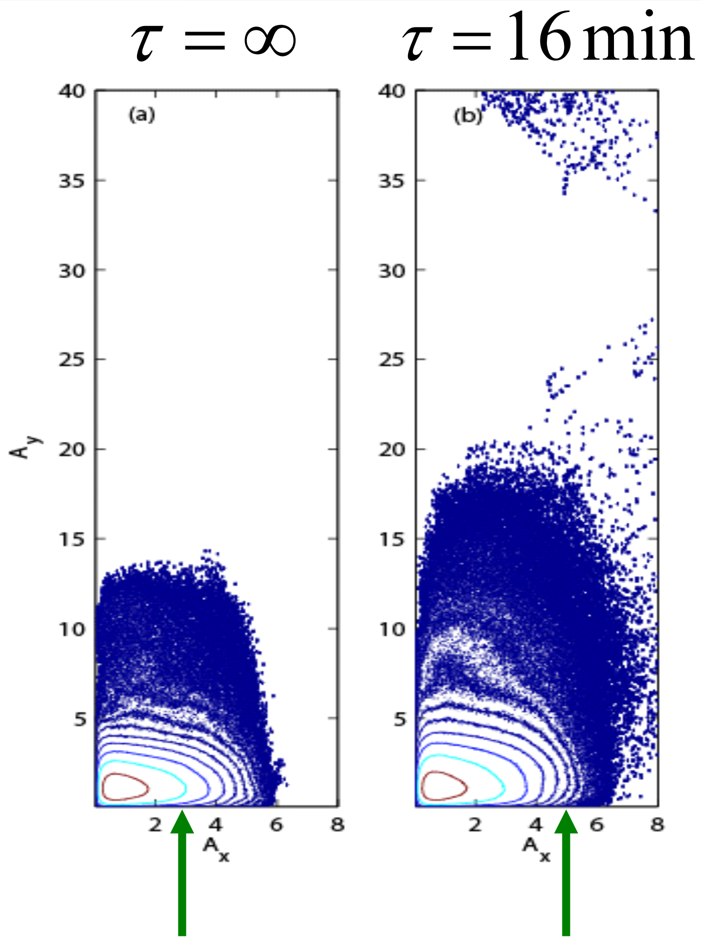
PEP-II achieved luminosity is 1.2×10^{34} $cm^{-2}s^{-1}$

Beam-Beam Interaction in PEP-II



Data was taken in 24 hour period: between 21-NOV-2003 18:49:00 to 22-NOV-2003 18:49:00. The number of bunch was 1230 and bunch spacing was every two buckets. The ratio of currents in the measurement was not fixed as a constant but the agreements are surprisingly good.

e+ Distributions with Beam-Beam Interaction



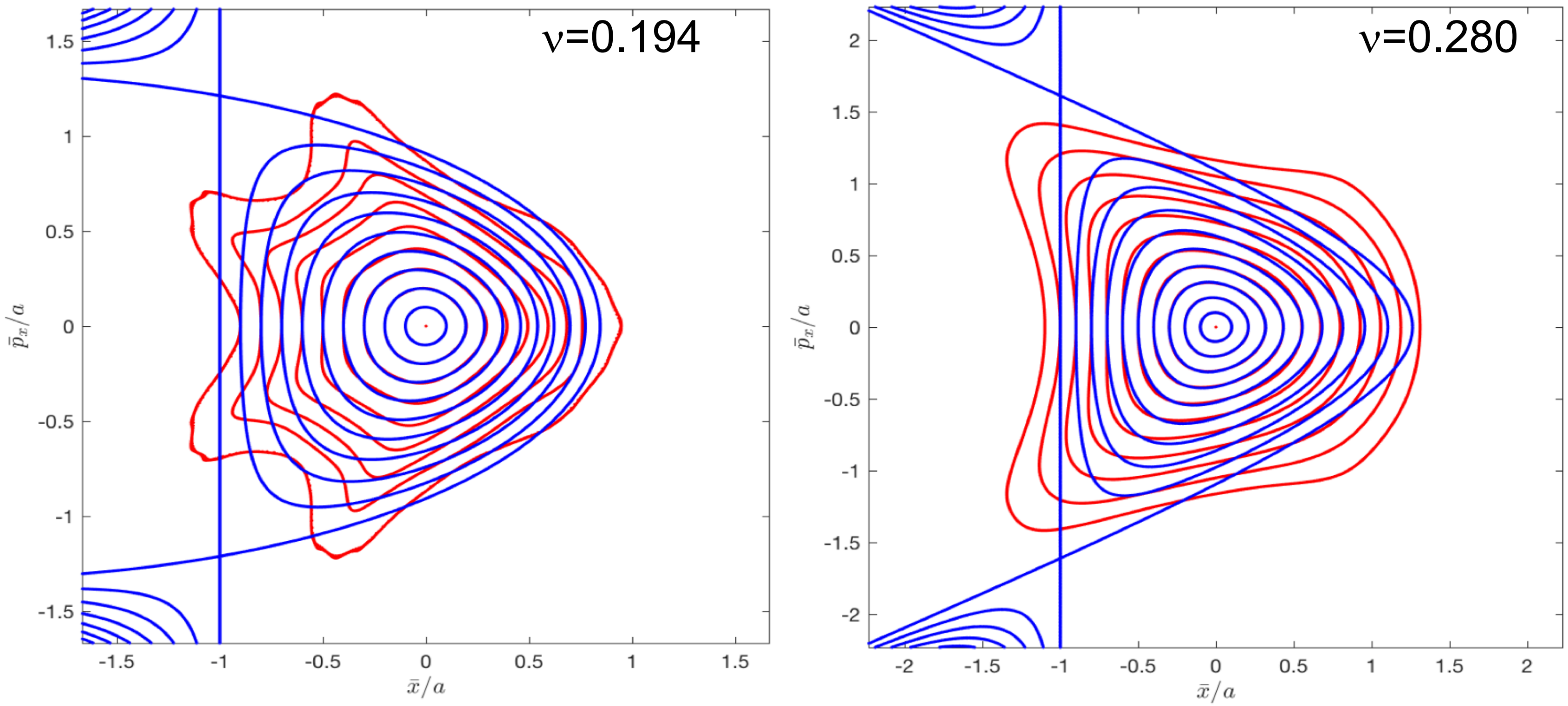
The distributions are averaged after 40,000 turns to improve the statistics.

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.

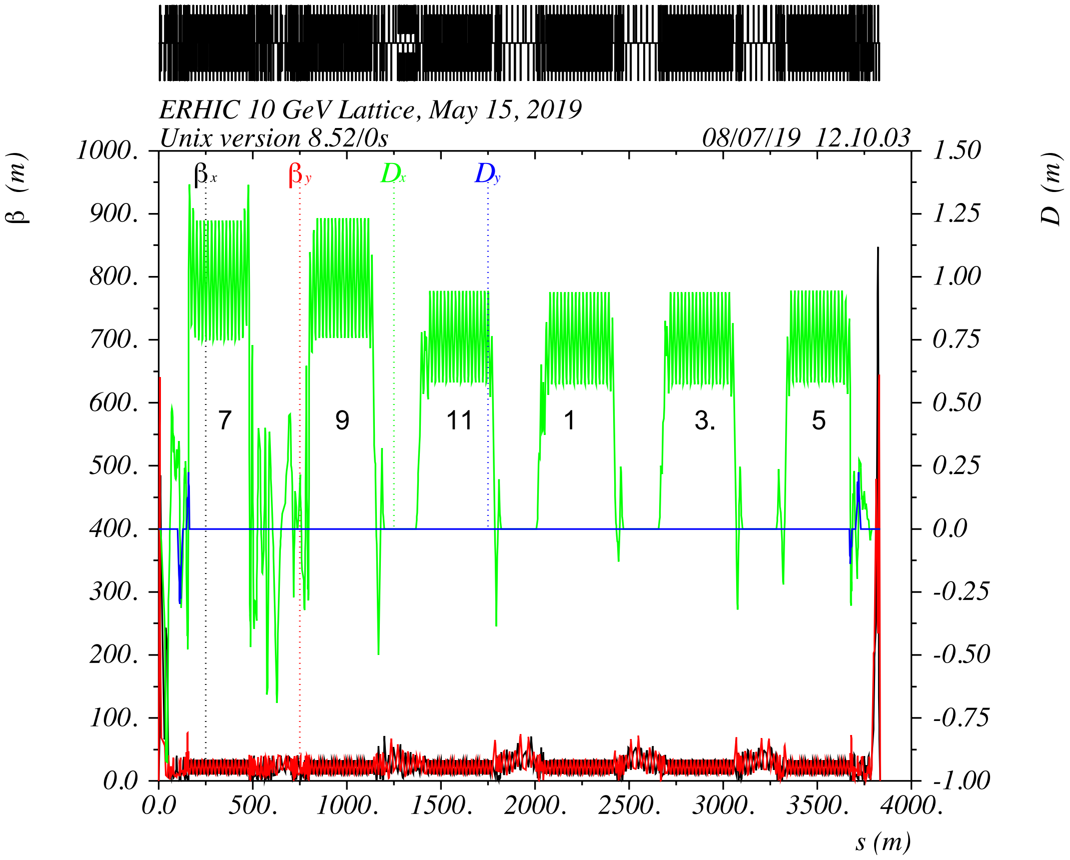
Persistence



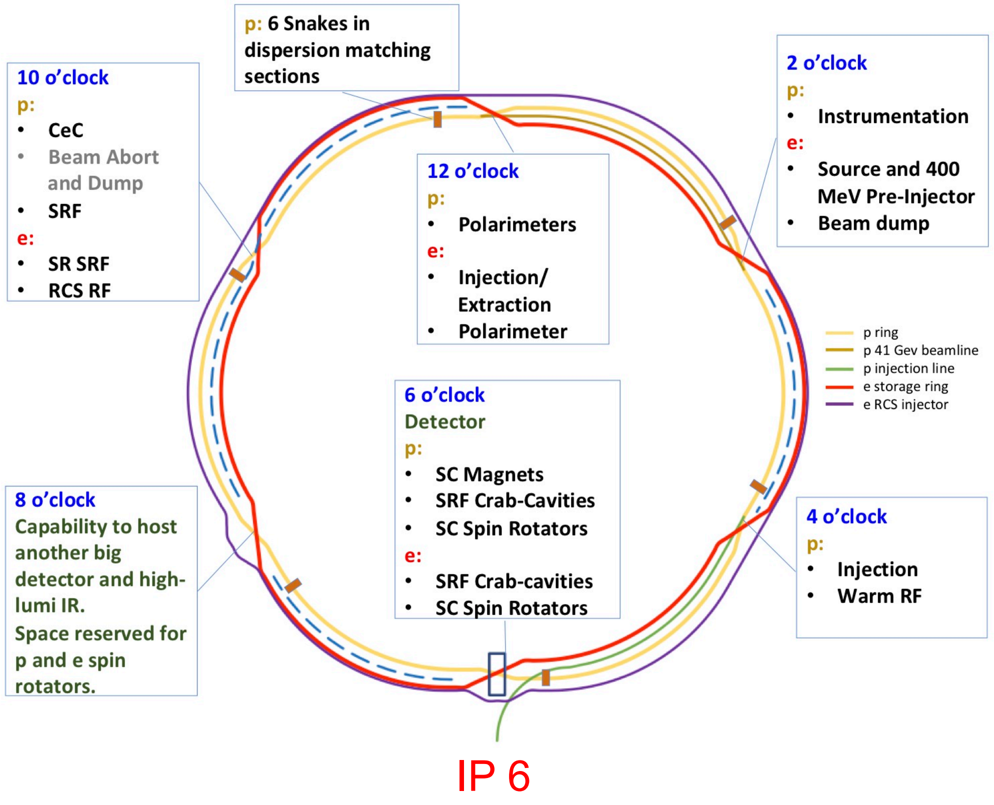
The higher order perturbation distorted the contours but not break them when the tune is sufficiently away from the resonances, Yunhai Cai, PRAB, 21, 054002 (2018)

Electron Ring Lattice

Version 5.0, Tepikian



Layout



Dynamic Aperture of the Design Lattice

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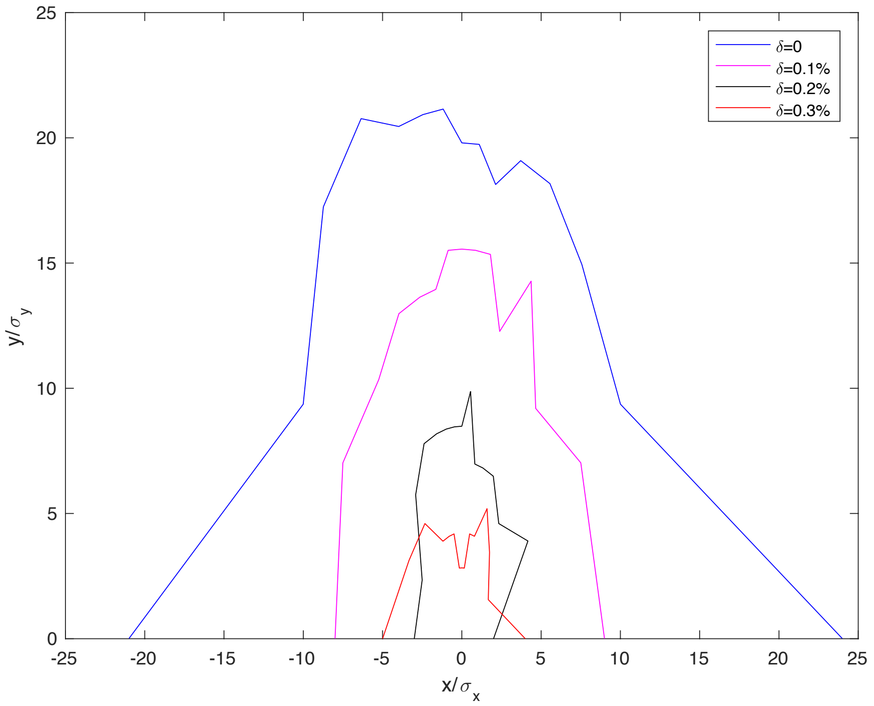
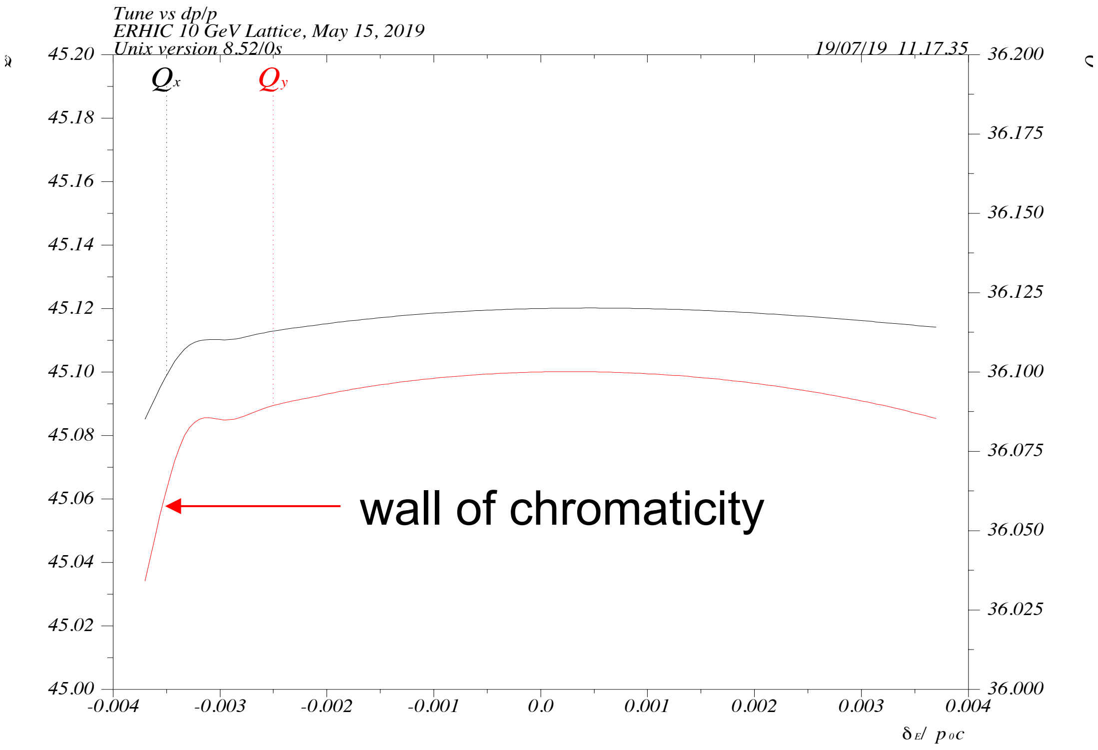
Momentum Aperture



Tunes vs. $\delta=(p-p_0)/p_0$



- Reference emittances
  - horizontal 24 nm
  - vertical 12 nm
- Synchrotron oscillation: on

Momentum aperture is 0.3% consistent with momentum bandwidth

Chromatic Optics at Interaction Point

β[m]	α	ν	η[m]	η'
order: 0				
4.196942e-01	7.887650e-05	4.511995e+01	-2.749660e-07	-4.306417e-05
4.999994e-02	-3.011440e-05	3.609997e+01	5.122667e-12	1.409070e-09
order: 1				
-6.245835e+01	-1.318125e+01	9.893213e-01	1.584850e+00	-2.436665e+00
-9.968913e+00	-6.445416e+01	9.800348e-01	-6.596413e-01	3.116056e+00
order: 2				
8.755505e+03	-4.907347e+03	-1.640191e+03	-6.116449e+02	-6.788702e+02
1.495831e+03	1.287648e+04	-2.702967e+03	2.520371e+02	1.214073e+03
order: 3				
-1.135232e+06	1.384366e+05	1.186107e+05	3.108798e+05	1.414246e+04
-4.281689e+05	-7.511489e+05	1.238044e+05	-6.923175e+04	8.527815e+05

Second- and third- order chromaticity are huge

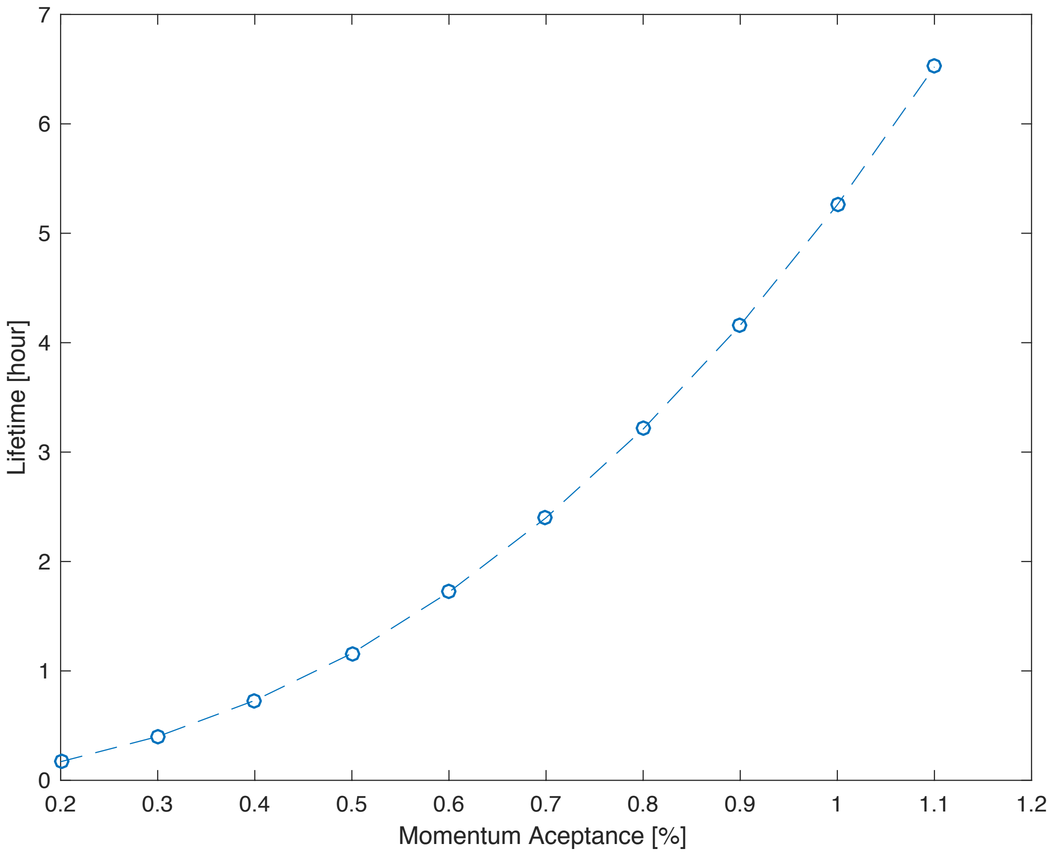
Yunhai Cai, Nucl. Instrum. Methods Phys. Res. Sect. **A** 707 (2015) 172-181

- Differential algebra
- Symplectic maps
- Accurate derivatives
- Arbitrary order
- Include coupling
- Written in C++

Touschek Lifetime

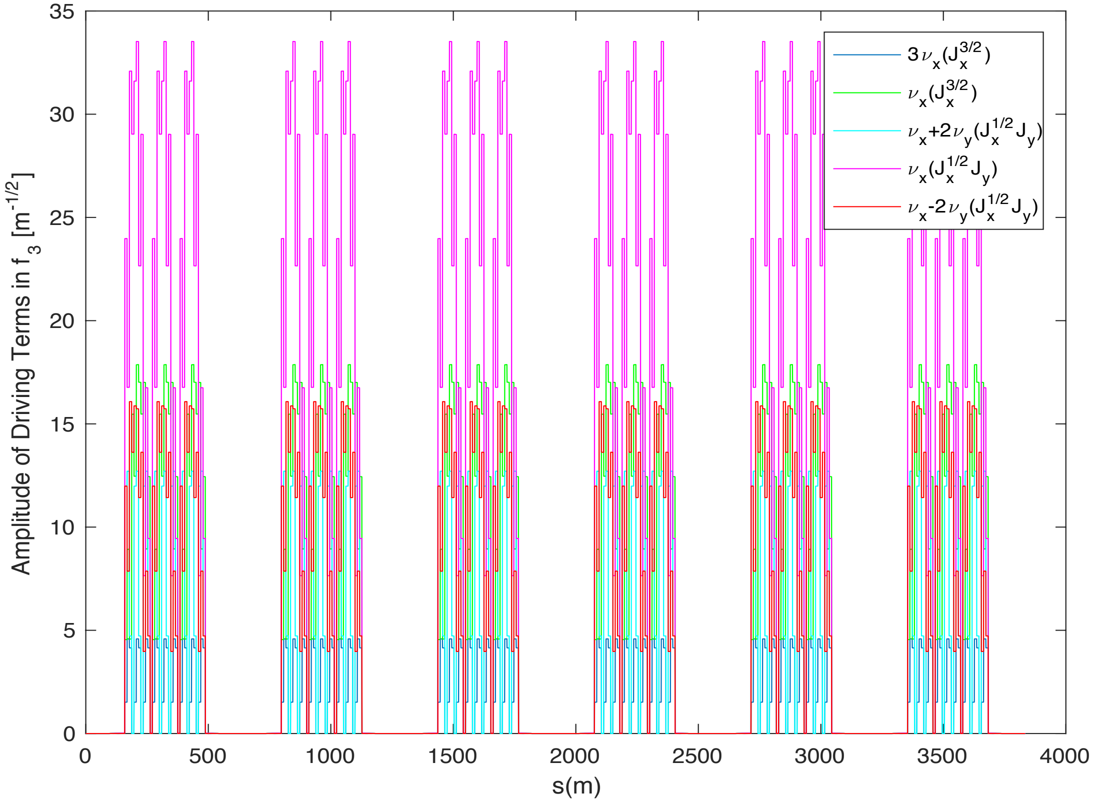
- Assumptions
  - 10% coupling
  - Beam current: 2.5 A
  - 1320 Bunches
  - Bunch length: 7.36 mm
  - Lattice V 5.0

- Momentum Acceptance
  - ❖ Quantum: 0.33%
  - ❖ Injection: 1%

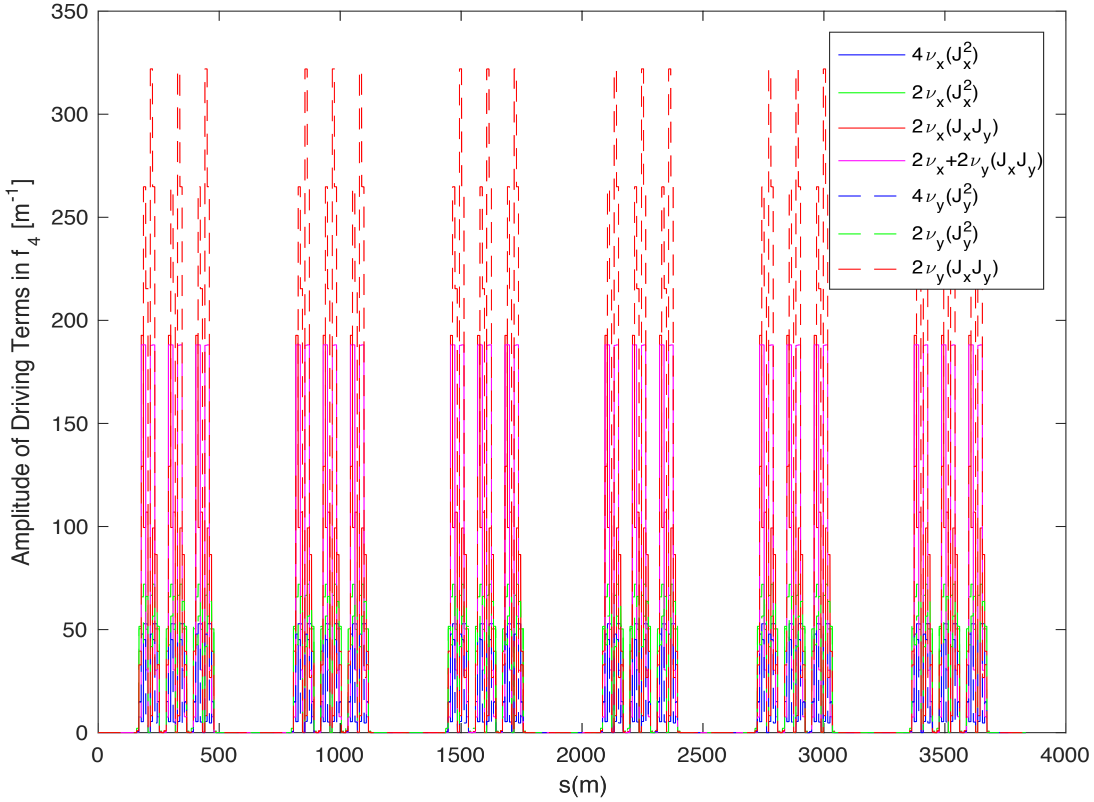


Storage Ring with 60^0 Phase Advance in Arcs

Third-Order Resonance Driving Terms



Fourth-Order Resonance Driving Terms

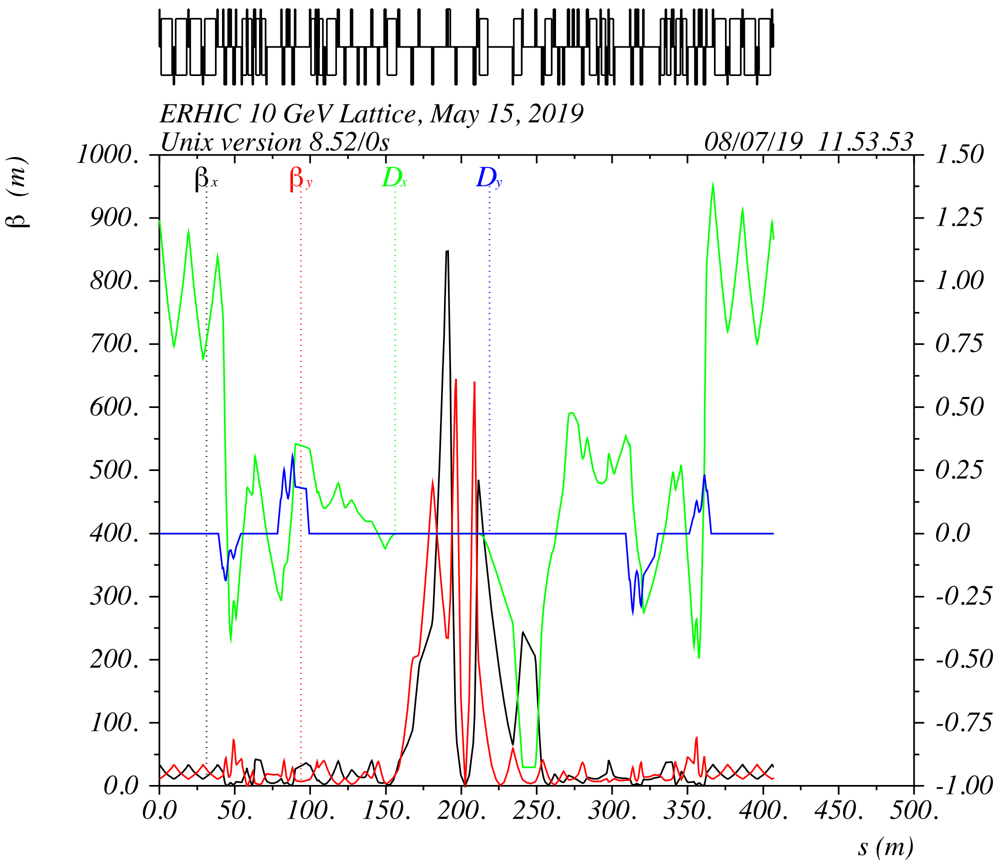


K.L. Brown & R.V. Servranckx
Nucl. Inst. Meth., A258:480–502, 1987

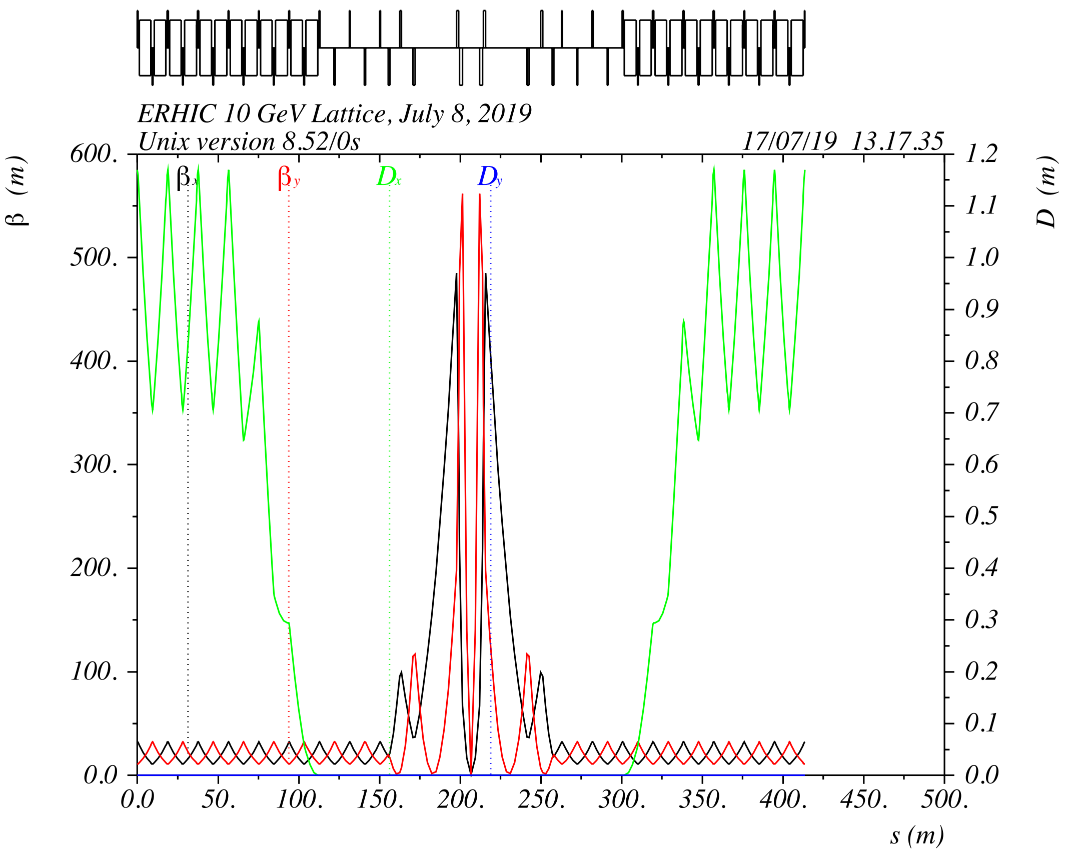
Yunhai Cai
Nucl. Inst. Meth., A645:168–174, 2011

Interaction Region

Design lattice: V 5.0



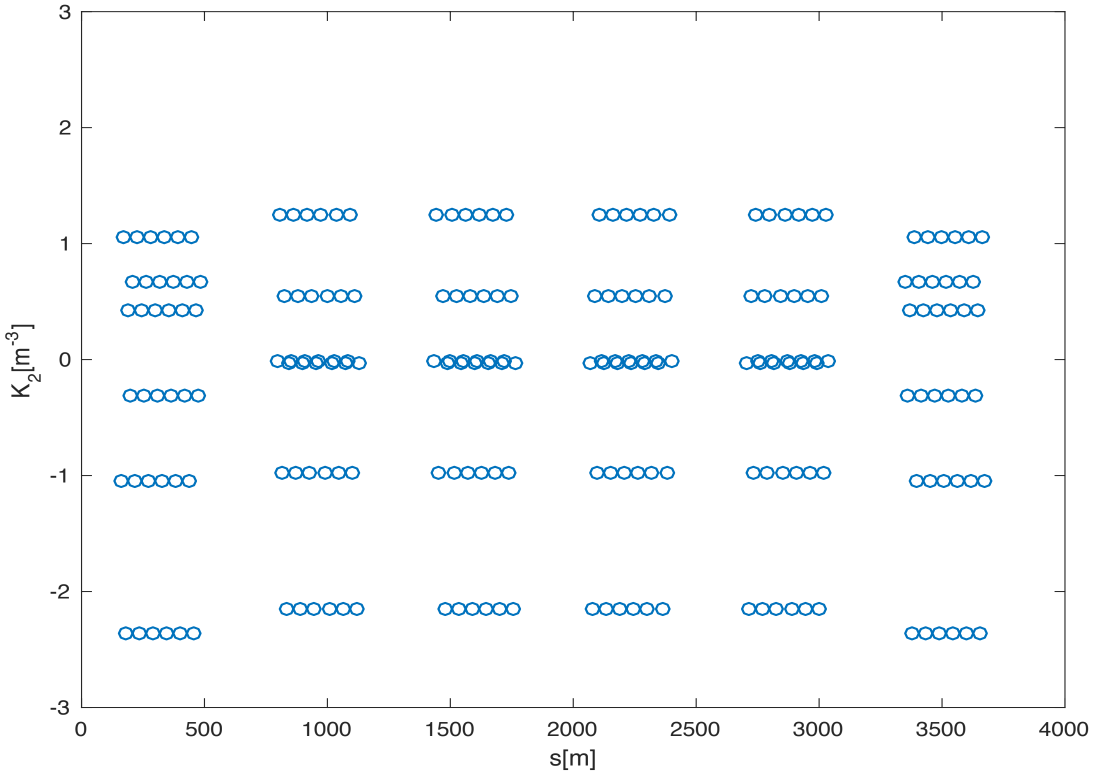
Simplified IR



β_x*=0.42 m, β_y*=0.05 m, L*=5.3 m

Chromatic Compensation Scheme

Sextupole strengths



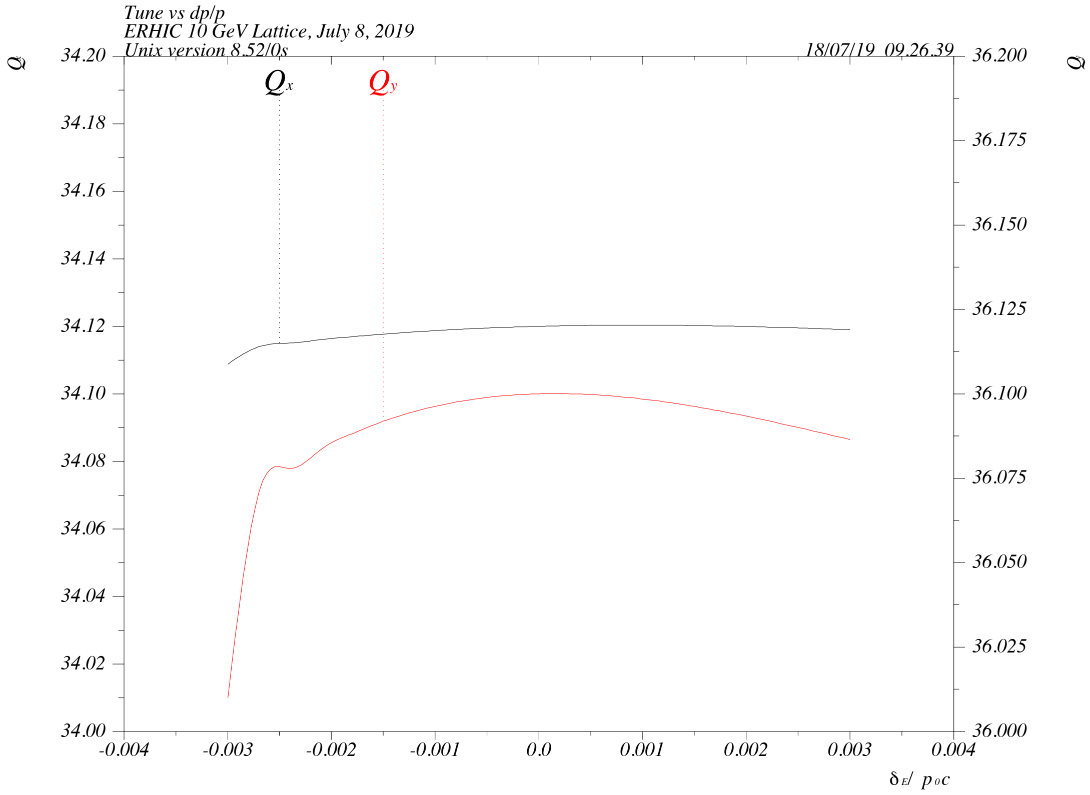
with a simplified interaction region

Recipe

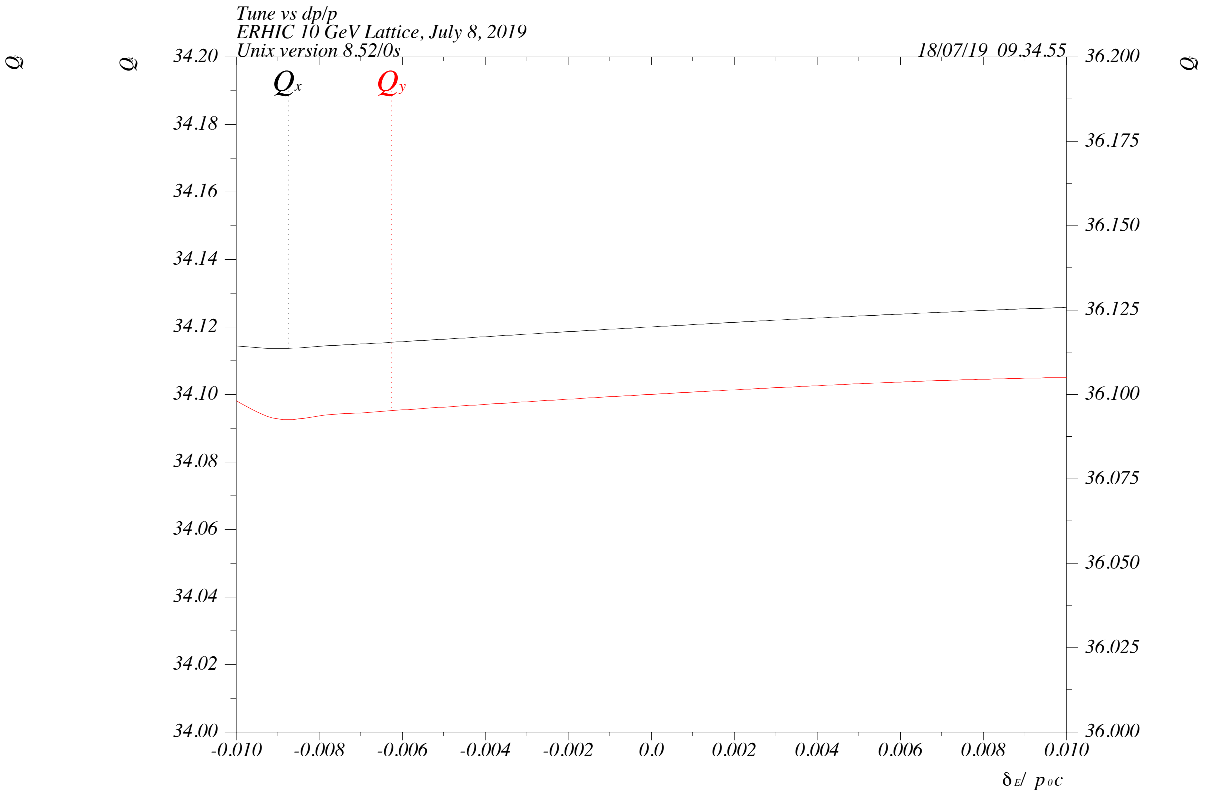
- Reflection Symmetry
- Three families/plane in arc
- All members in phase: 180^0 or 360^0 in terms of beta beating
- Zero out high-order derivatives of tune with respect to δ up to 6^{th} order in each plane using twelve sextupole families
- High-precision derivatives computed using differential algebra
- Find solution using the Levenberg-Marquardt algorithm
- Perturbative approach

Correction of Chromatic Betatron Tunes

Two families of sextupoles



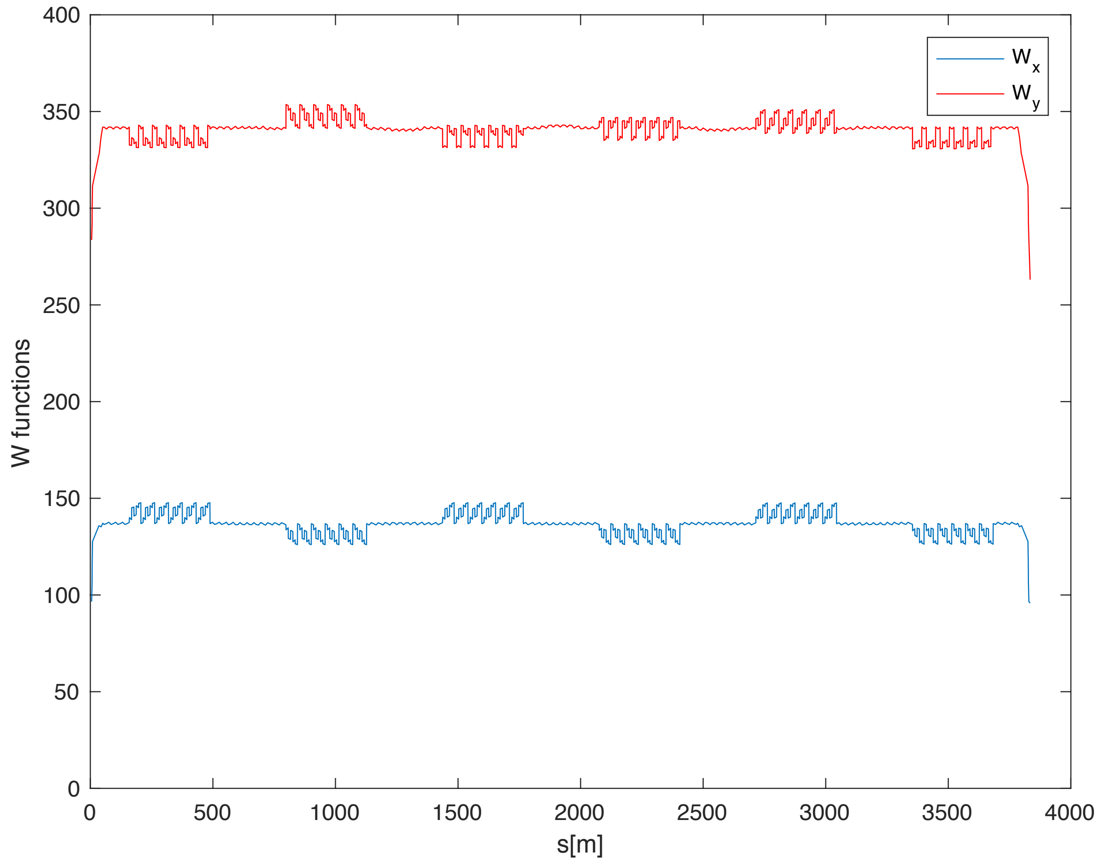
Twelve families of sextupoles



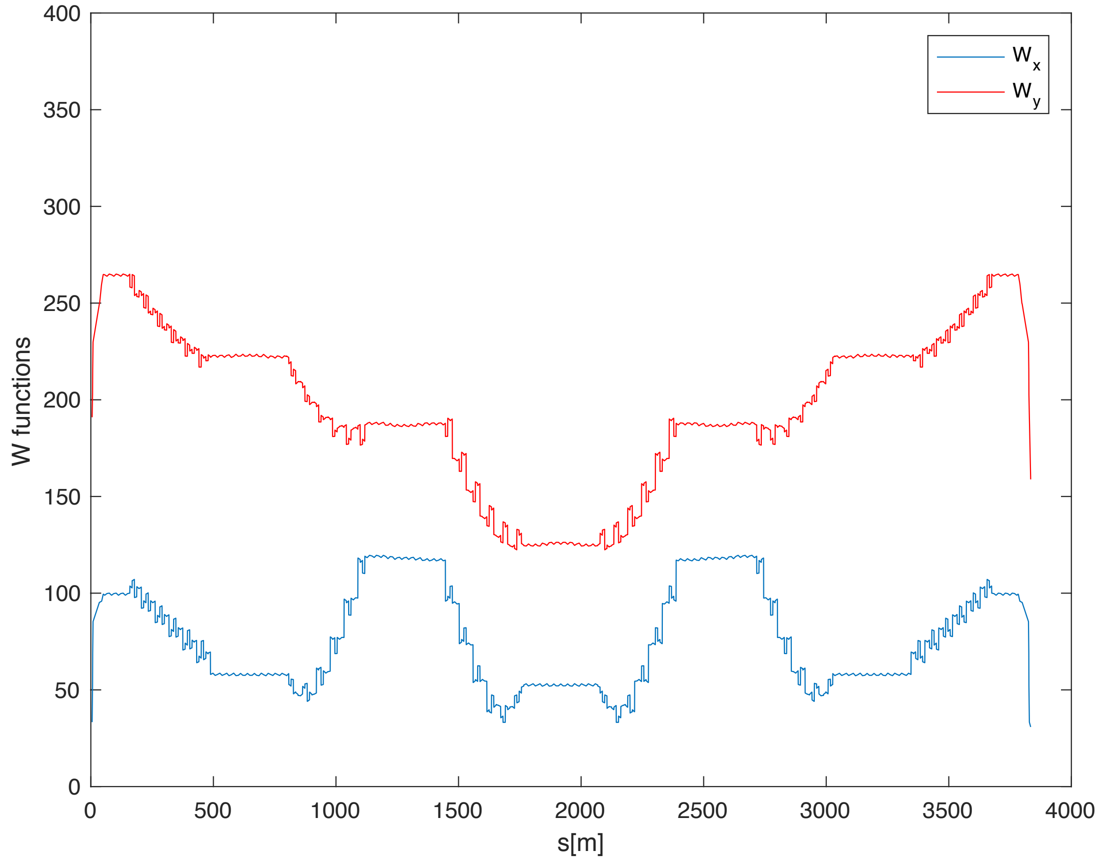
with a simplified interaction region

Improvement of Chromatic Beta Beating

Two families of sextupoles



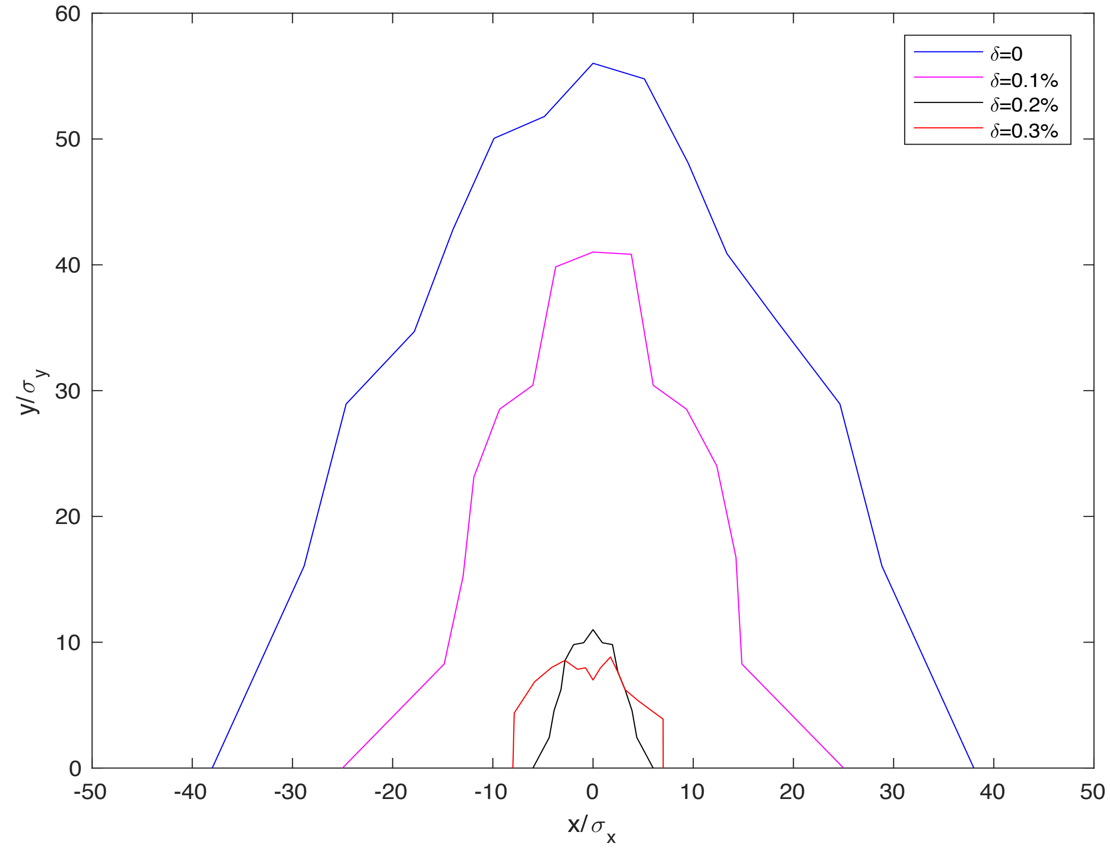
Twelve families of sextupoles



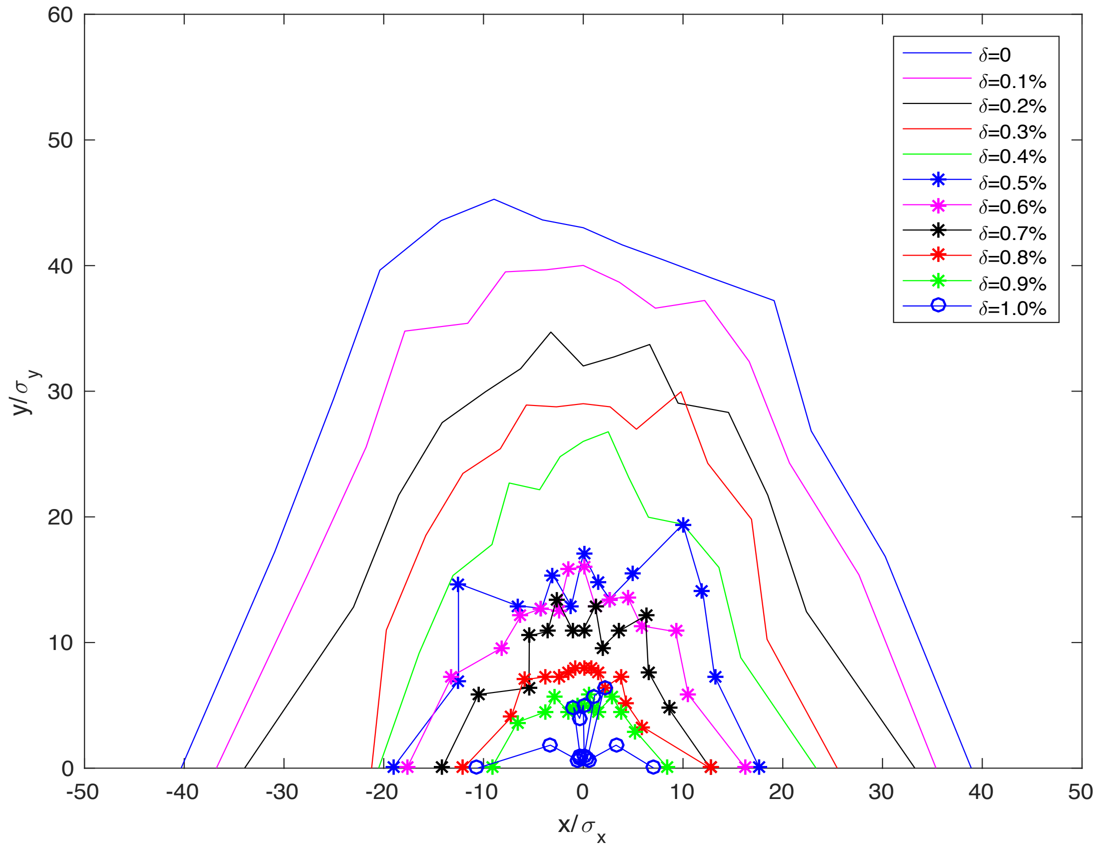
with a simplified interaction region

Improvement of Momentum Aperture

Two families of sextupoles



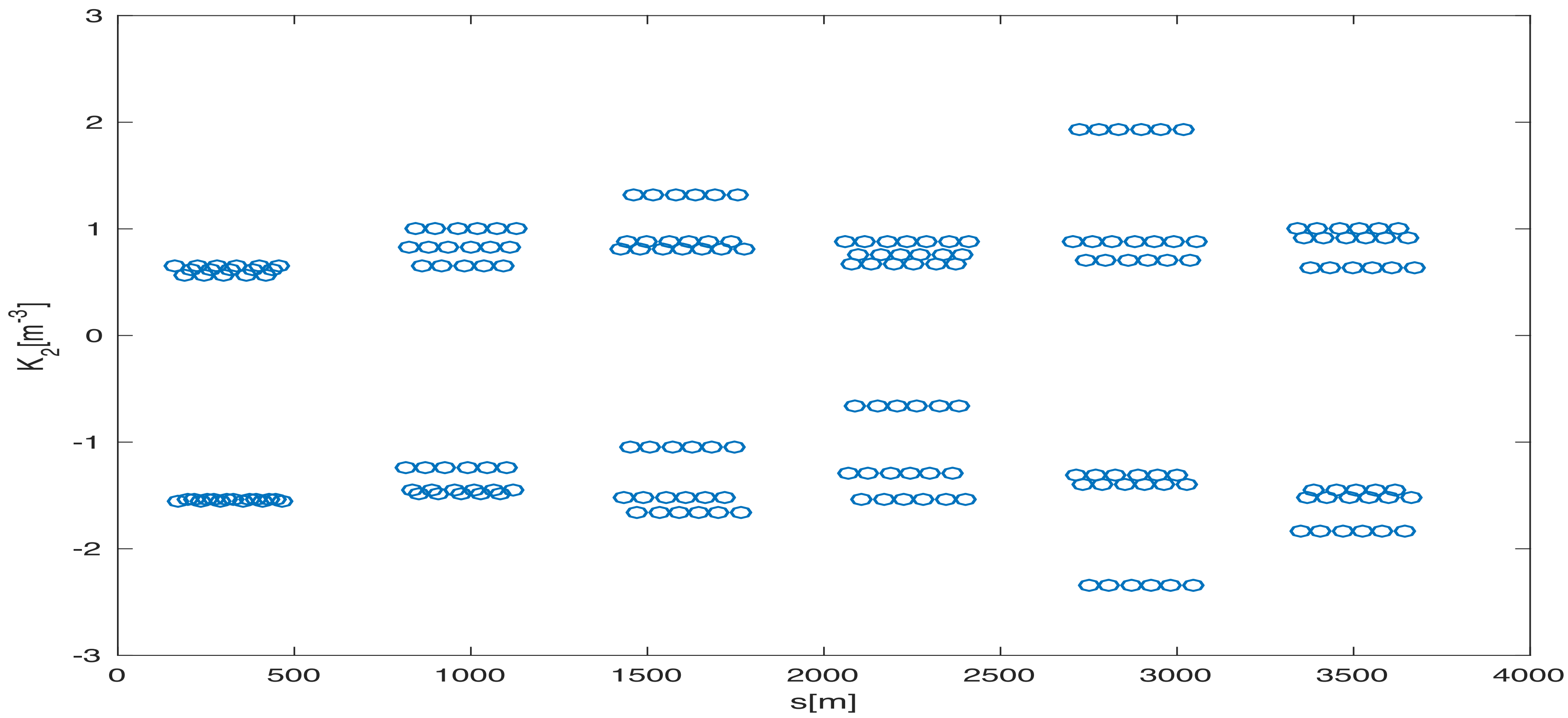
Twelve families of sextupoles



With a simplified interaction region, 1% momentum acceptance is within reach.

Global Chromatic Compensation for Design Lattice V 5.0

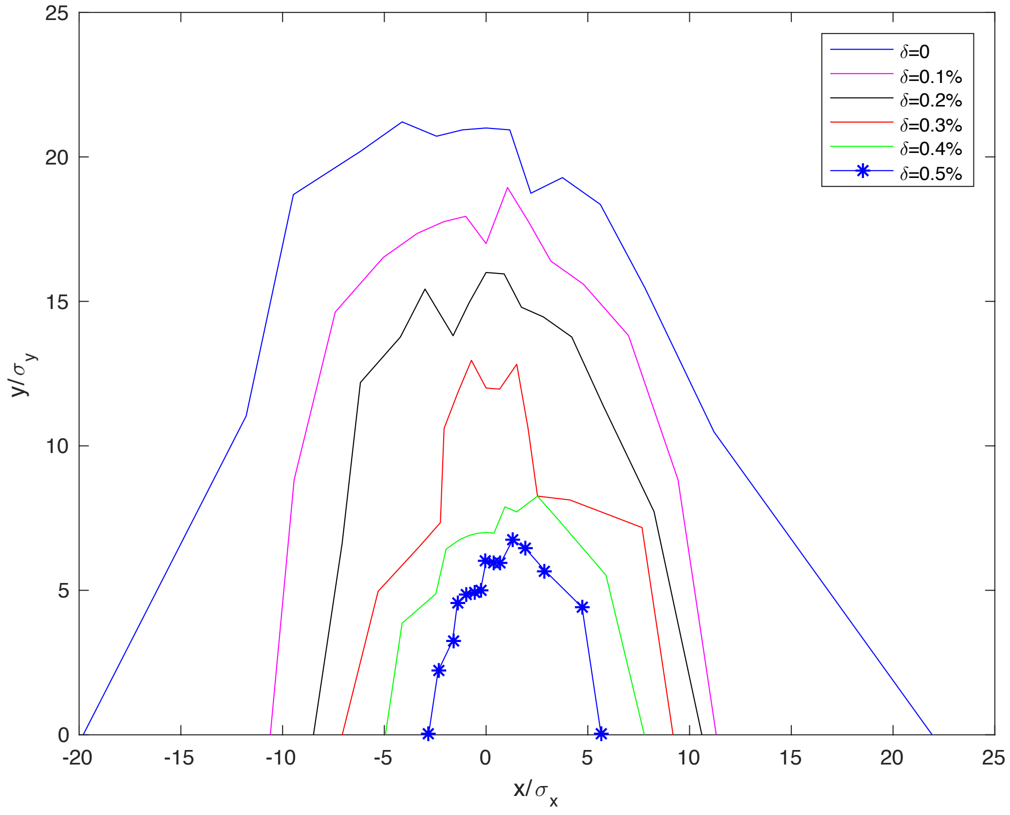
Strengths of thirty six families of sextupoles



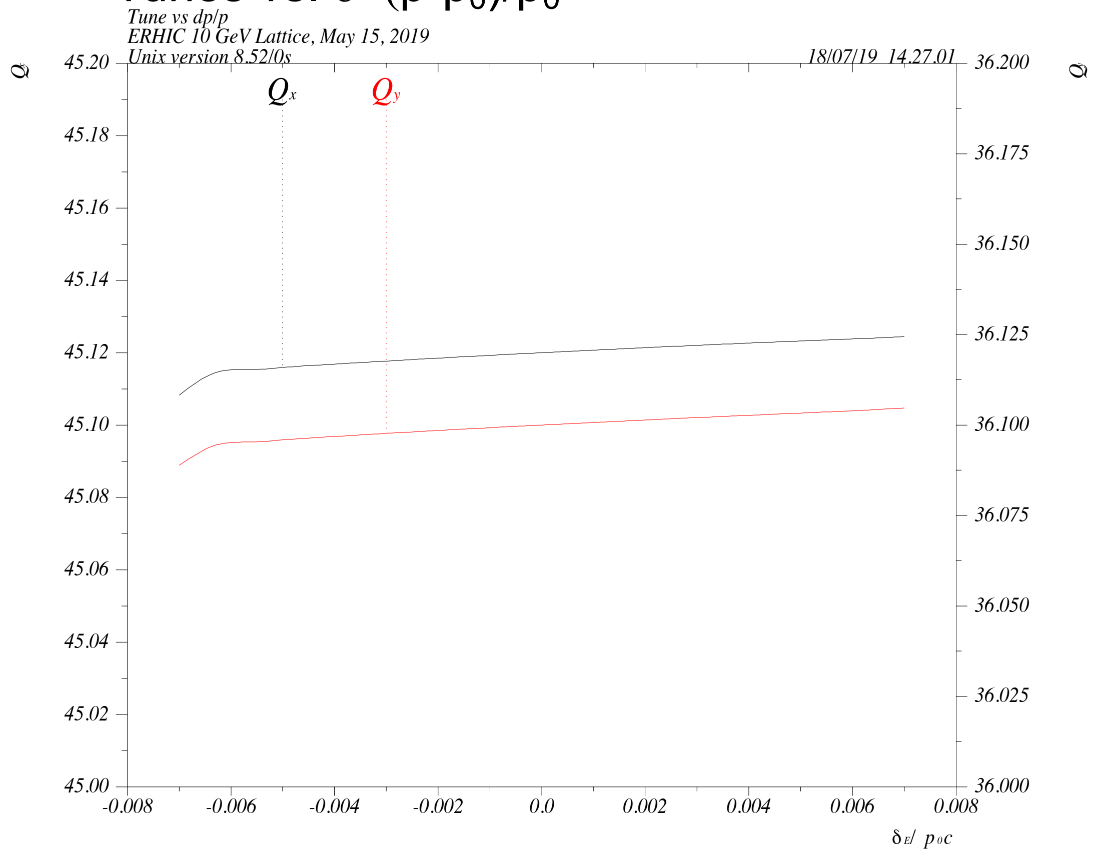
Nelder-Mead algorithm, slow converge taking 8 days on iMac

Improvement of Momentum Aperture

Momentum Aperture

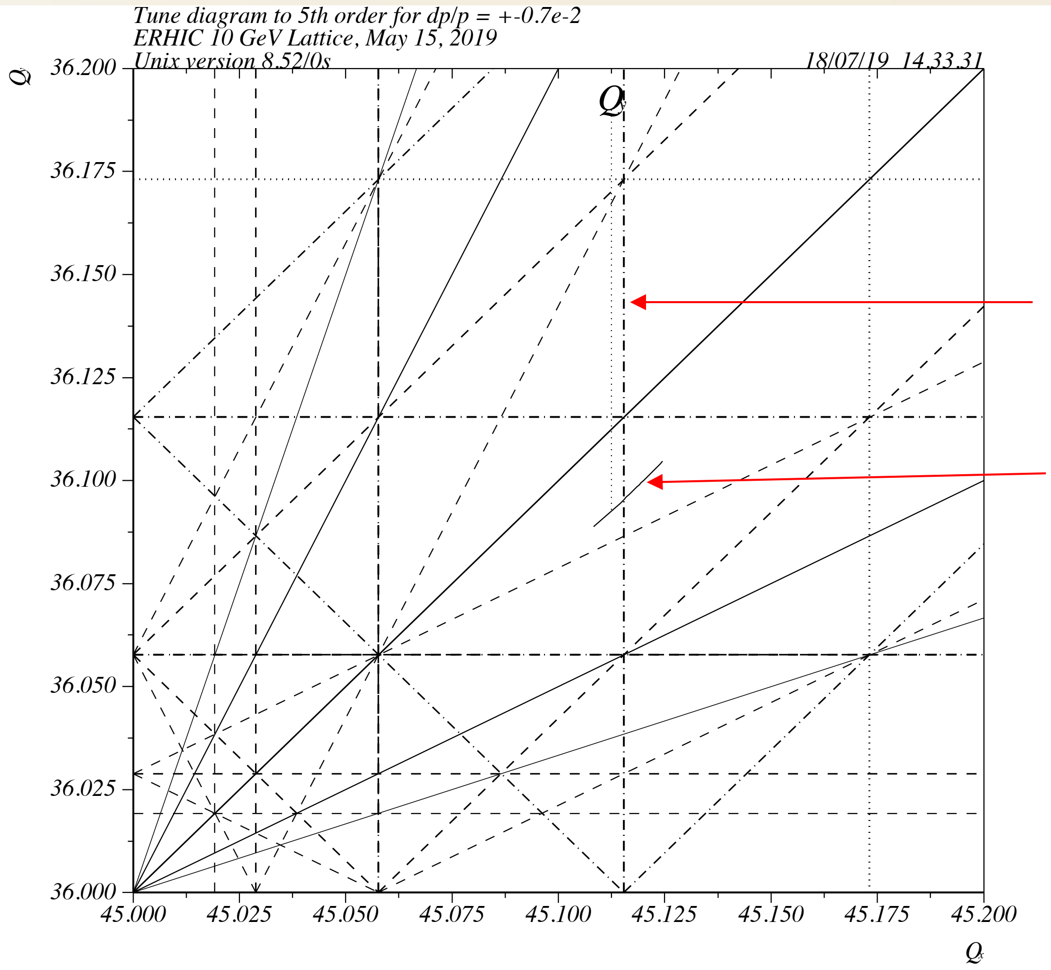


Tunes vs. $\delta=(p-p_0)/p_0$



Momentum aperture increases from 0.3% to 0.5% but smaller than bandwidth

Synchro-Betatron Resonance



ν_x-2ν_s=45

operating point

Mitigation

- Change the working point
- Reduce the second-order dispersion at RF locations

Resonance: ν_x-2ν_s=45 is a limiting factor

Semi-Local Chromatic Compensation for Design Lattice V 5.0

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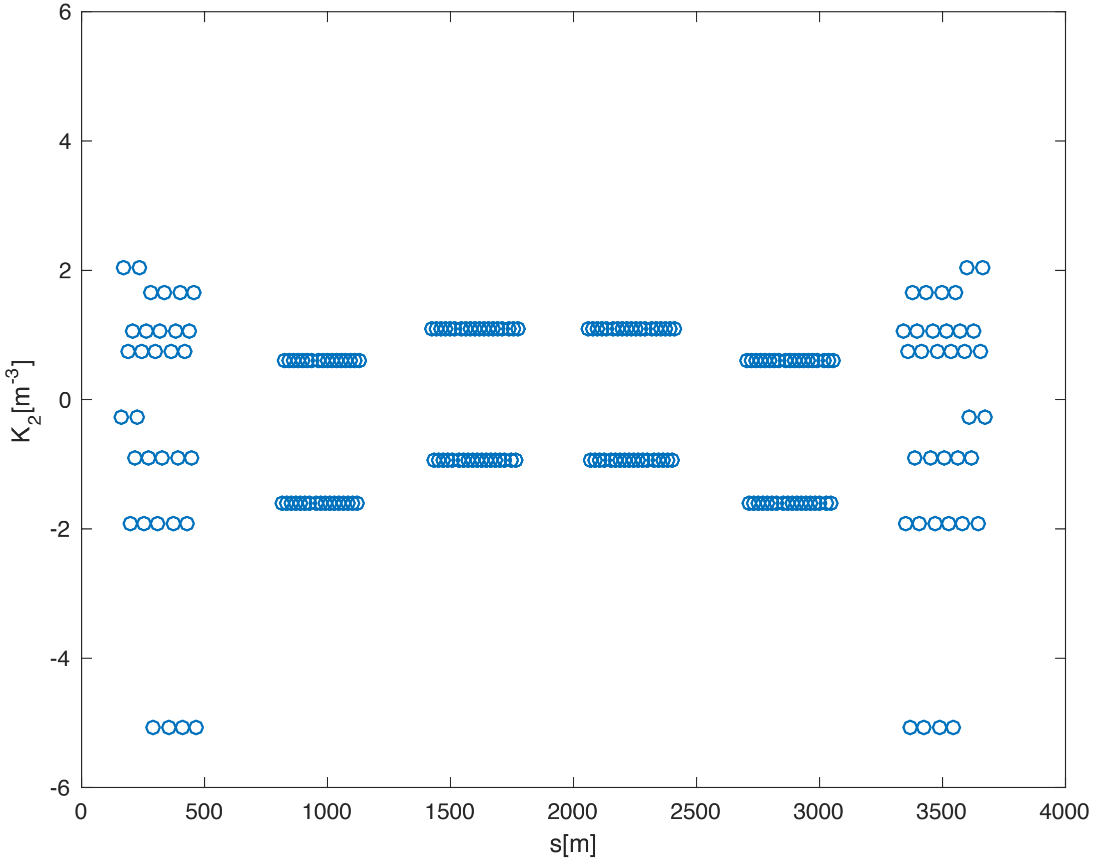
Procedure

1) Phase trombones in straights and between the final doublets in the arc sextupoles to minimize the second-order chromaticity
2) Three families/plane in the adjacent arcs to zero out chromaticity up to the third order
3) Split the strongest one into two families and zero out up to the fourth order
4) Add two families in the four remaining arcs and zero out up to the fifth order
5) Split two families to four families in the far arcs and zero out up to the sixth order

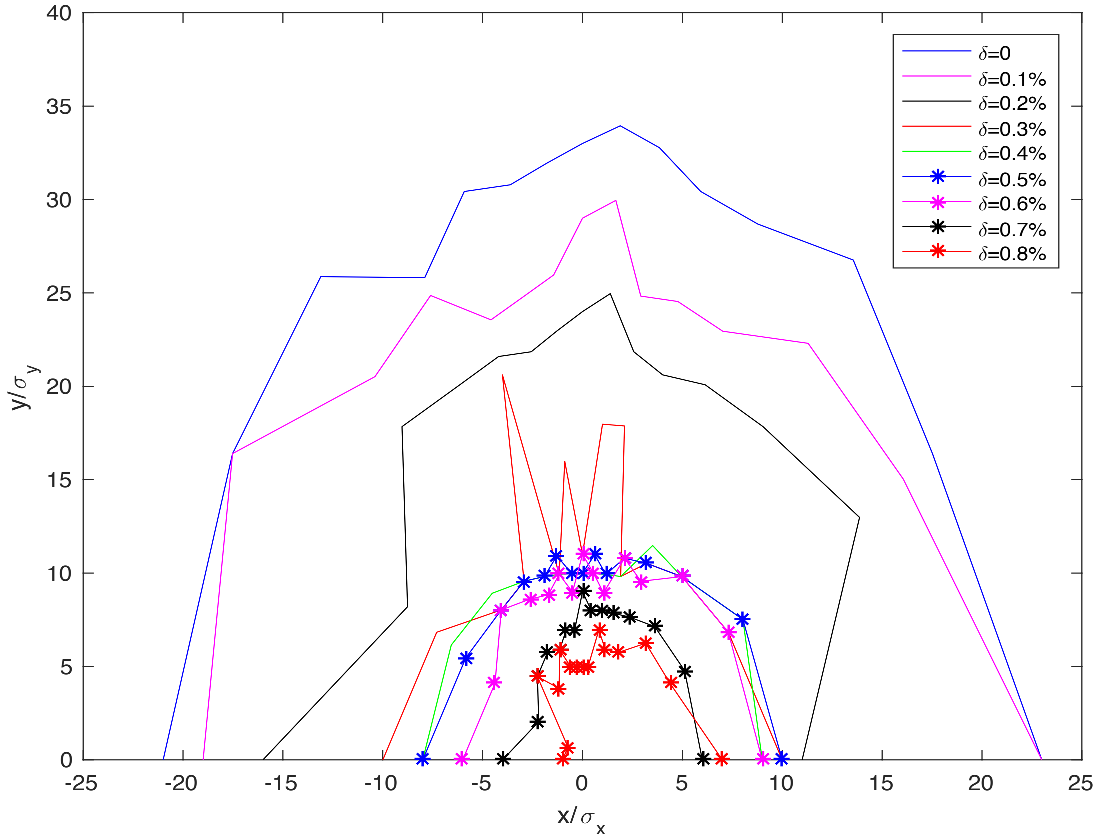
The low-order solutions are found using the Nelder-Mead algorithm while the high-order on with the Levenberg-Marquardt algorithm

Strengths of twelve families of sextupoles

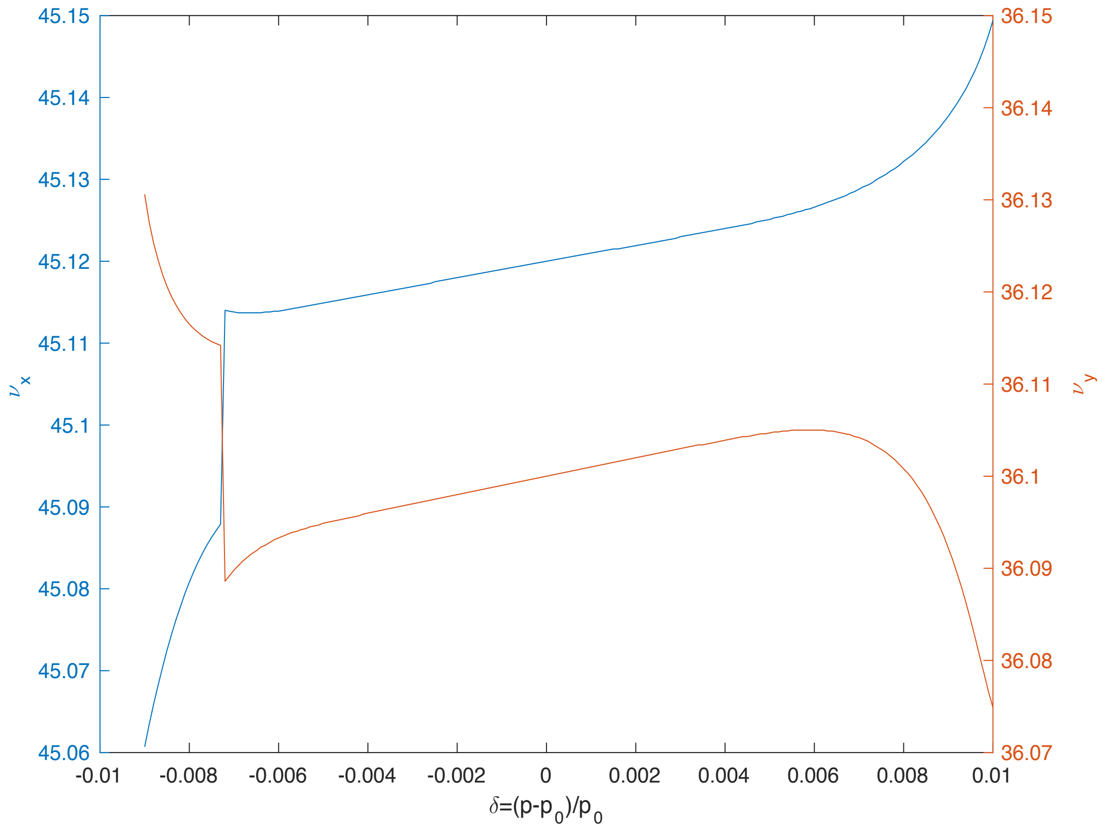


Improvement of Momentum Aperture (Design Lattice V 5.0)

Momentum Aperture



Tunes vs. δ=(p-p0)/p0

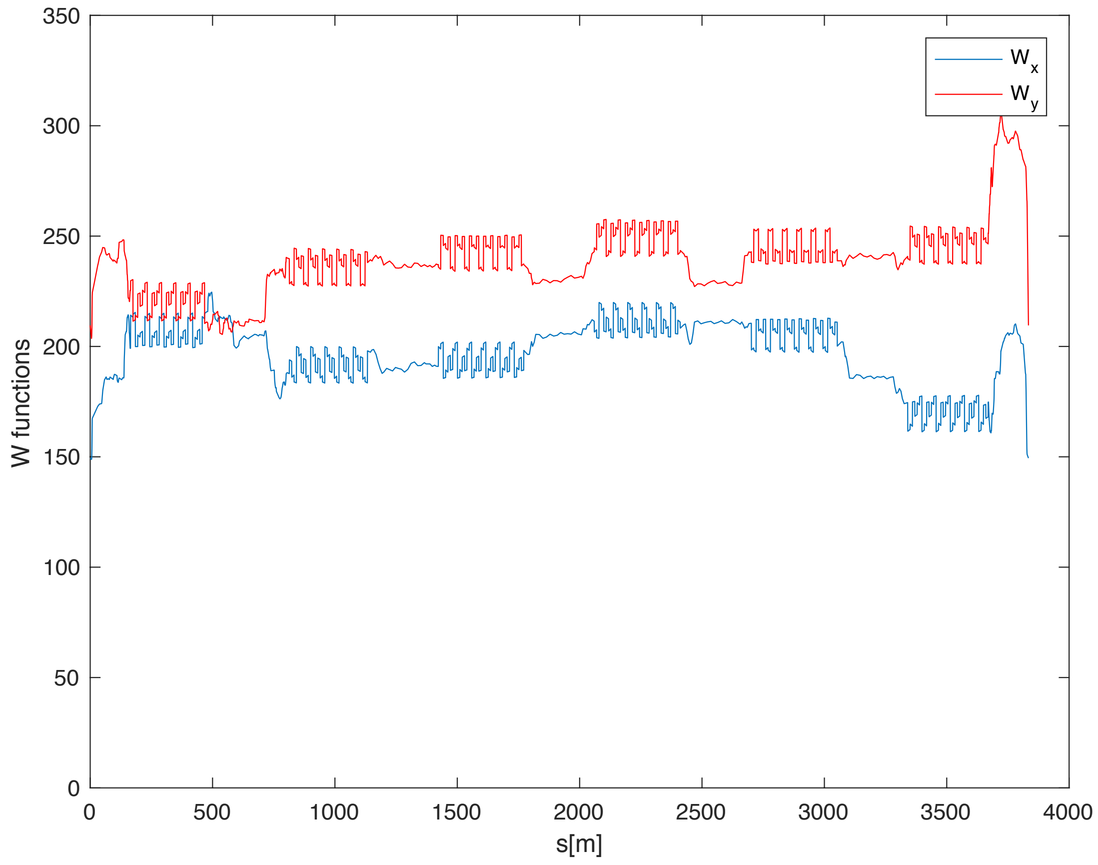


Momentum aperture increases from 0.3% to 0.8%

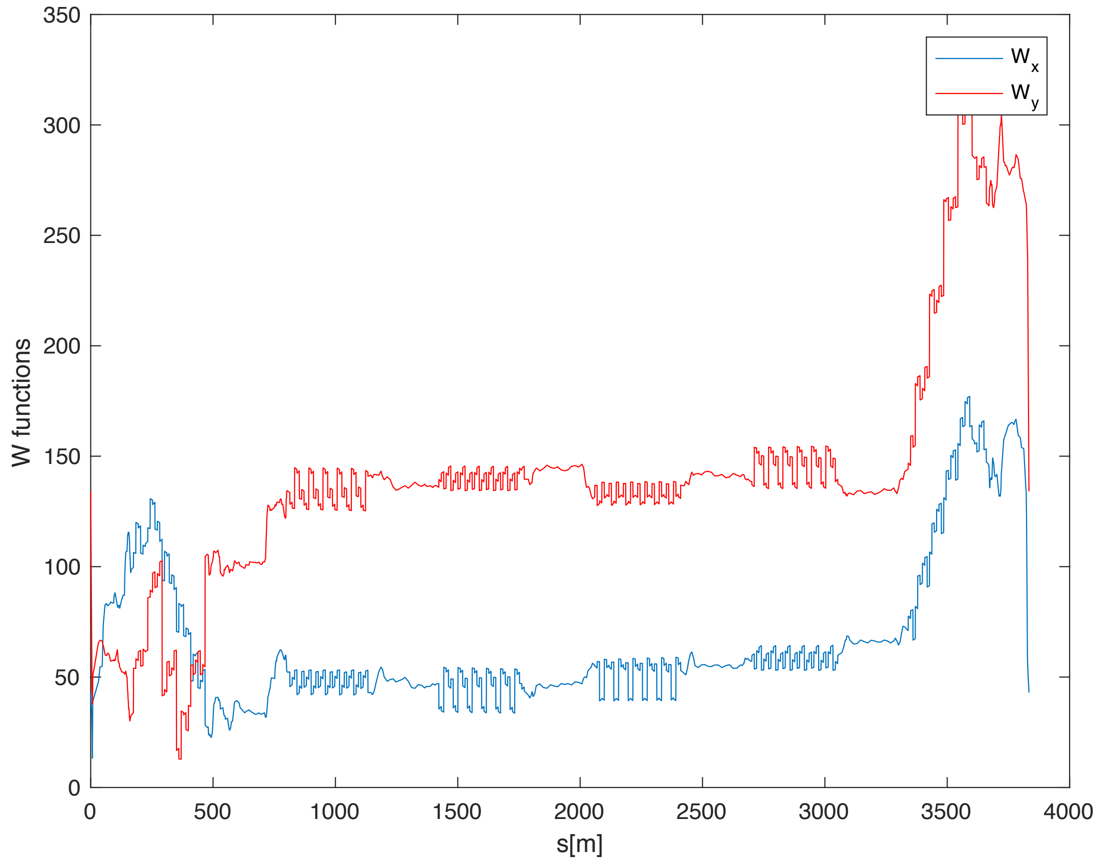
Chromatic coupling resonance is seen

Improvement of Chromatic Beta Beating

Two families of sextupoles



Twelve families of sextupoles



Design Lattice V 5.0

Conclusions

- Accurate and fast computation of chromatic optics is developed, allowing an arbitrary order of $\delta = (p-p_0)/p_0$
- Two optimizing algorithms, namely the Nelder-Mead and Levenberg-Marquardt, are implemented for chromatic compensation
- Dynamic aperture for is 20 σ in the horizontal plane and increases from 20 σ to 35 σ in the vertical plane
- Chromaticity up to sixth-order of δ is well compensated and controlled
- Momentum aperture with synchrotron oscillation increases from 0.3% to 0.8%. 1% goal seems achievable but remains as challenging

More work to be done

- Implement the phase trombones (Tepikian will visit SLAC August)
- Two interaction regions

Acknowledgement

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BNL:

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