Stability with electron lenses and lattice considerations

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Thanks to M. Blaskiewicz, W. Fischer and Y. Luo

Outline

Introduction

Principle of head-on compensation

coherent effects

Theoretical expectations and numerical simulations

machine impedance, electron lens driven TMCI

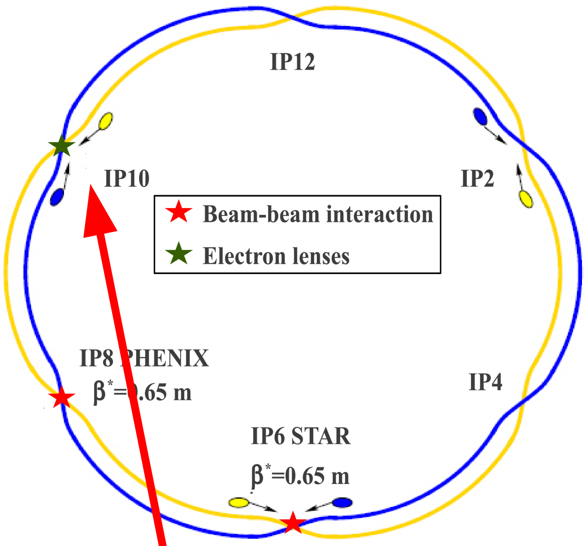
possible mitigations

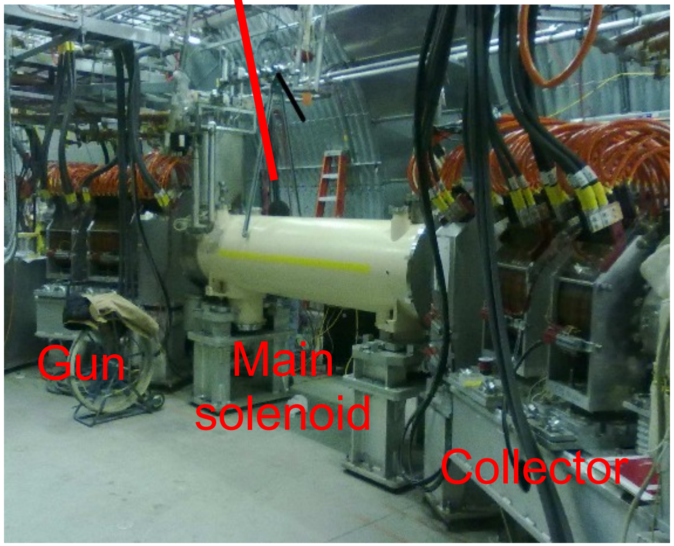
Electron lens lattice

phase advance

beta-function at the electron lens

RHIC electron lenses



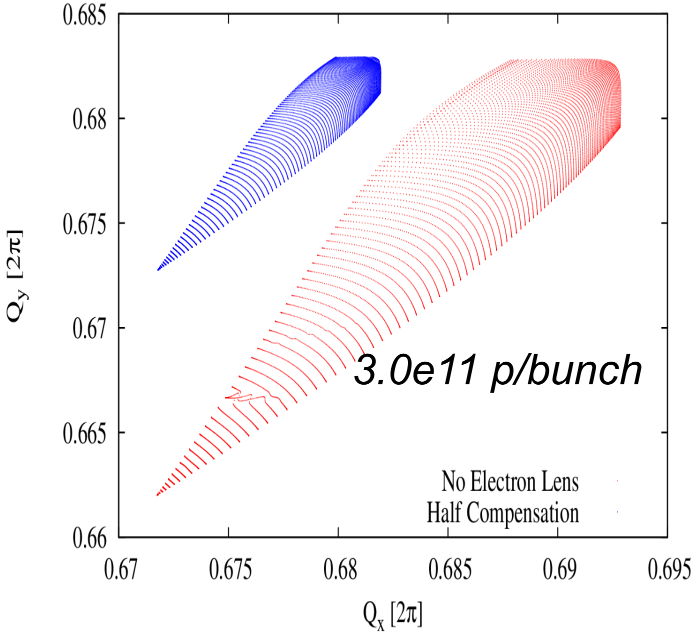


Yellow electron lens installed in 2013

→ Electron lenses for head-on compensation under installation at RHIC

→ Commissioning next run

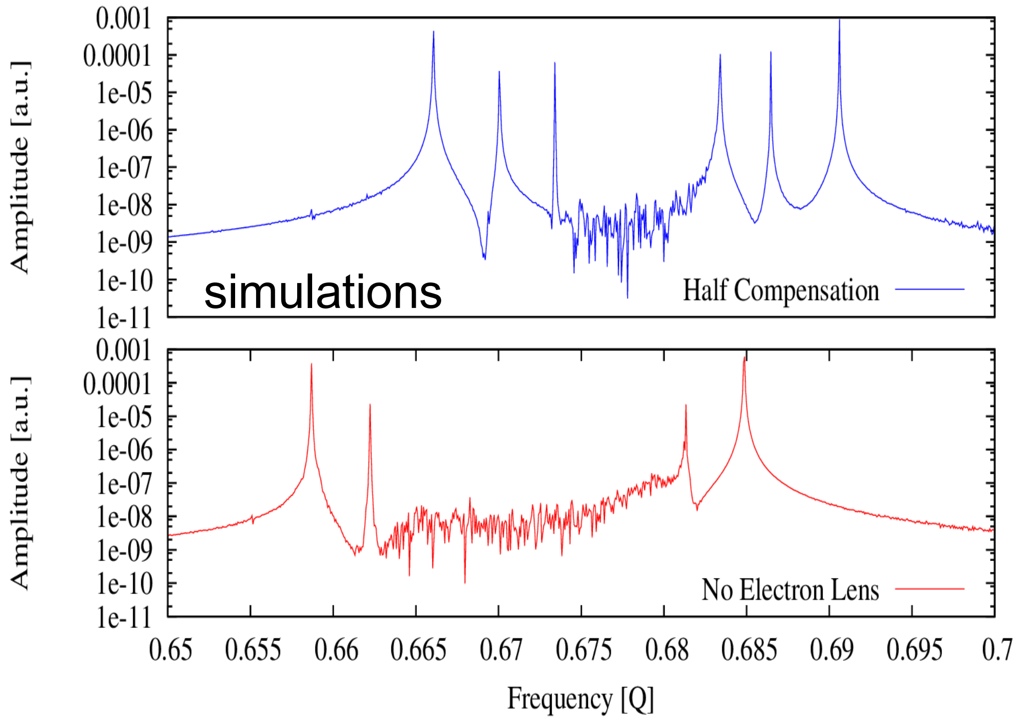
→ **Should allow to double the luminosity**

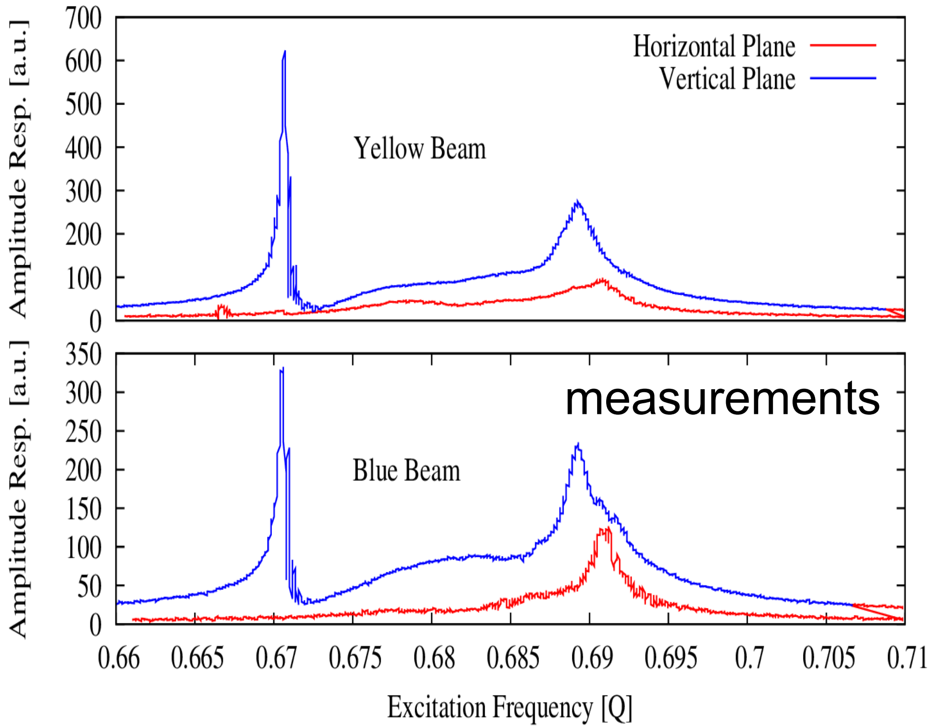


→ RHIC operates between 2/3rd and 7/10: very little room to increase intensity

→ **Electron lenses will compensate for half the beam-beam tune spread** and provide more space for increased intensity

Coherent effects





→ Due to the symmetry of collision points bunches couple 3x3 → expect 6 coherent beam-beam modes – without electron lens Landau damping acts on the inner modes

→ Head-on compensation reduces the tune spread and Landau damping is lost for all modes → coherent modes will be far outside the tune spread and overlap the $2/3^{rd}$ resonance: stability?

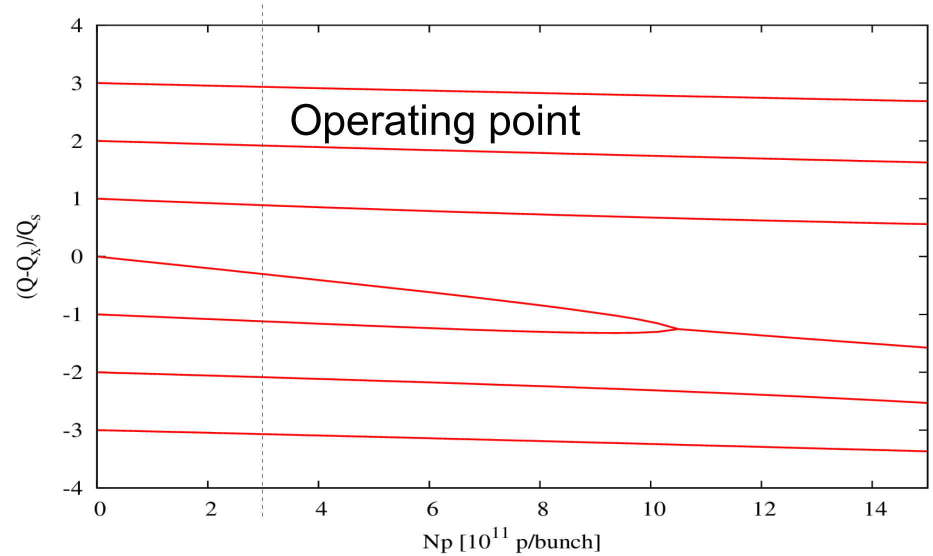
→ To be noted: π-mode is generally not observed in the horizontal plane – a possible explanation could be an exchange of Landau damping between planes

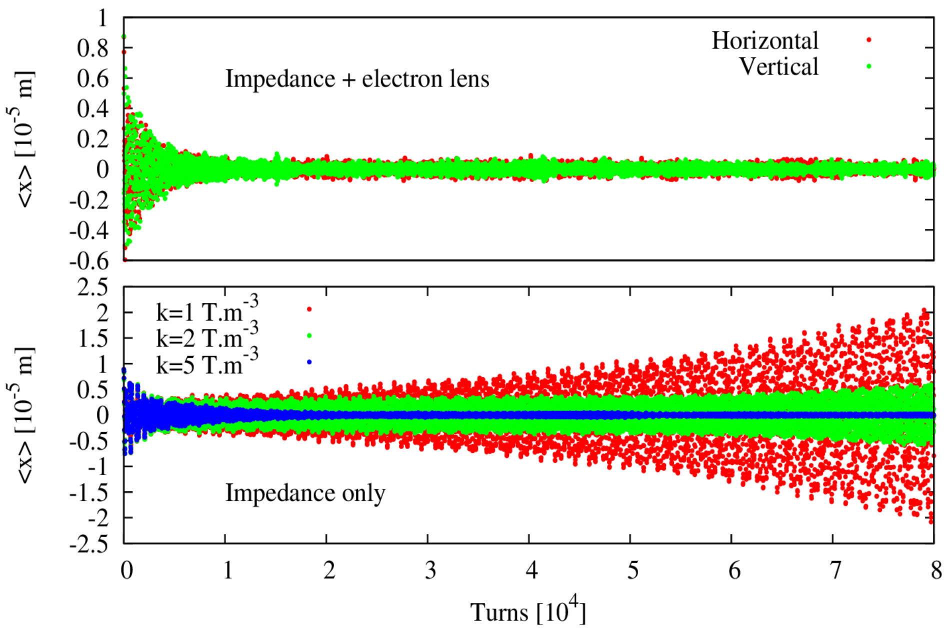
Machine impedance

→ RHIC impedance model includes BPM, bellows and resistive wall contributions computed from analytical formulas

→ Using this model one can compute the TMCI threshold at Q'=0.0 for a longitudinal airbag Distribution

→ RHIC operates far off the threshold (250 GeV)





	δQx/δJx	δQy/δJy	δQx/δJy
Tracking	607	607	417
NL model	314	387	463

→ Stabilizing octupolar detuning found to be close to what is provided by machine non-linearities: with electron lens fully stable

→ Last year measurements seem to agree with the model within a factor ~2

Electron lens driven TMCI

- Low energy electrons acquire a transverse momentum when interacting with the protons and as a result will start spiraling around the solenoid field lines. The kick received by the protons will therefore depend on their longitudinal position. This electron lens transverse impedance was introduced in: *A. Burov et al. "Transverse beam stability with an electron lens", Phys/Rev. E, 59.*

- The s-dependent momentum change of the protons can then be modeled using a wake function:

$$\Delta p_{x,y} = W[\Delta_{x,y}\sin(ks) \pm \Delta_{y,x}(1-\cos(ks))],\ k = \frac{\omega_L}{(1+\beta_e)c}$$

W is a constant and ω_L is the Larmor angular frequency which depends on the field. The kick depend on both the horizontal and vertical displacement of preceding slices.

- Using a linearized model (no Landau damping or chromaticity) one can derive a threshold field required to provide stability:

$$B_{th} = \frac{1.3\, eN_p \xi_{el}}{r^2 \sqrt{\Delta Q Q_s}}$$

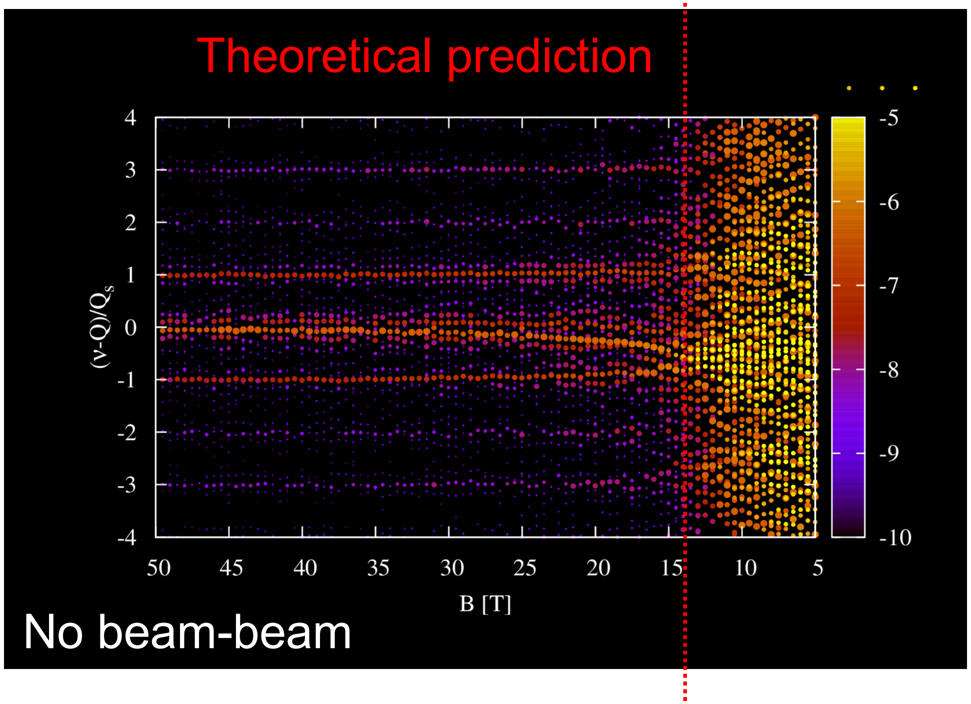
- For RHIC parameters (N_p = 3.0e11, ξ_{el} = 0.011, ΔQ = 0.011, Q_s = 5.0e-4, r = 2σ) we find a threshold of about 14T. Well above the design field of 6T.

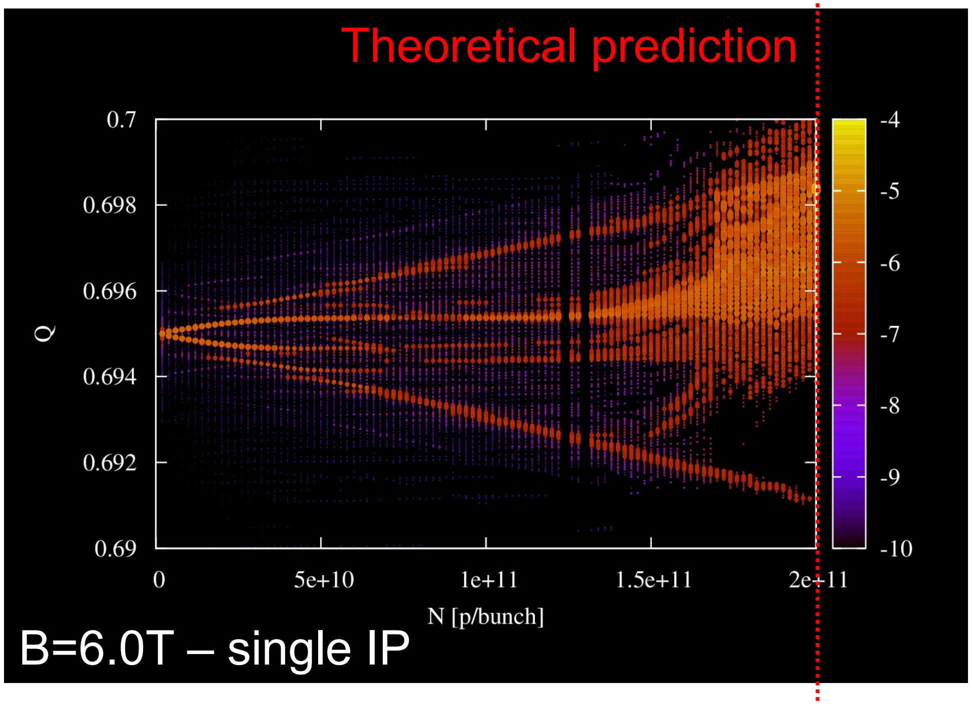
Tracking simulations

- The electron lens is now modeled by a zero length electron beam going against the 6D proton beam sliced longitudinally

→ Solenoid field scan with Gaussian distributions and linear beam-beam kicks

→ The mode coupling at 14T which is in agreement with theory





→ Coherent beam-beam effects further Degrade the situation

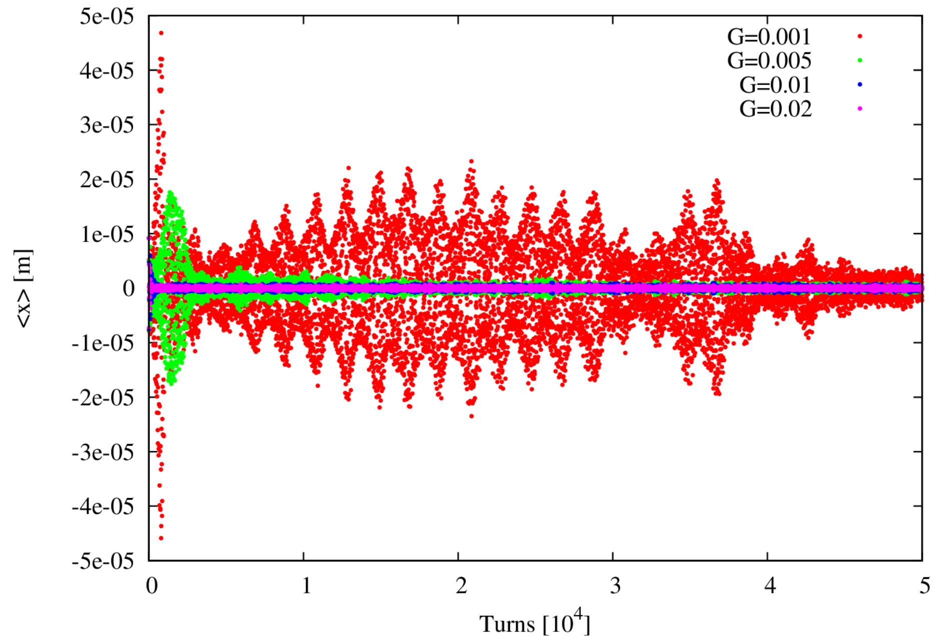
→ Not described by the theory

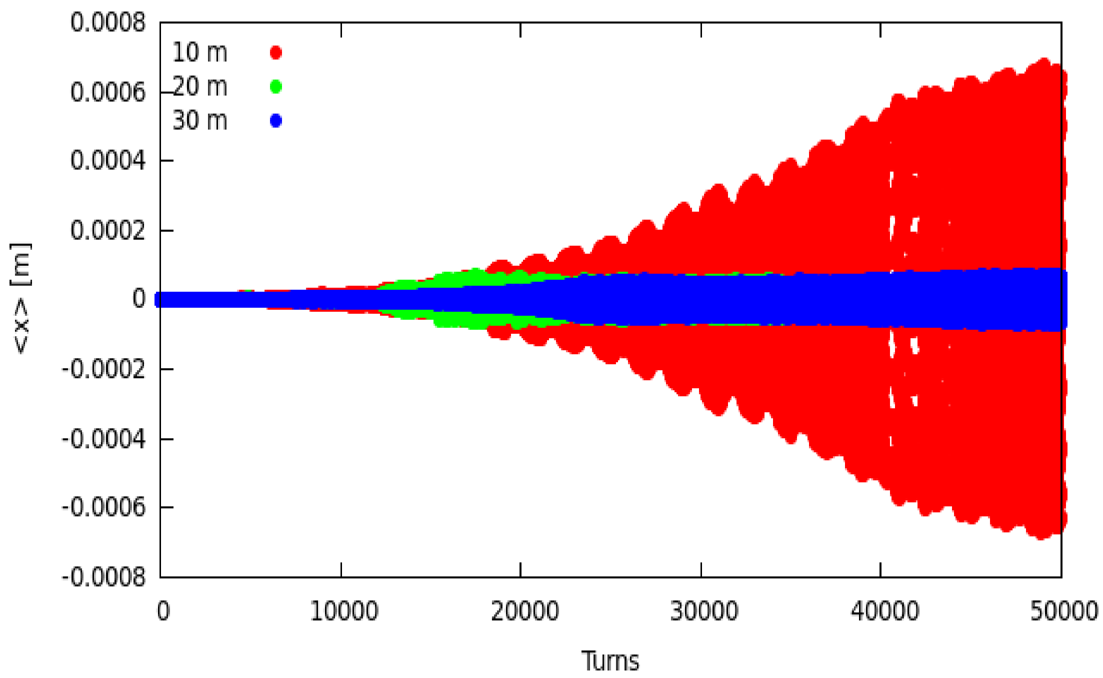
Mitigations

- A combination of transverse bunch-by-bunch feedback and chromaticity should mitigate the instability:

→ Here example of Q'=5.0 at 250 GeV

→ Commissioning should start next run





→ 100 GeV, 2.5e11 p/bunch, Q'=0.0
B_{sol} = 6T

→ Increasing the beam size at the elens strongly mitigates the fast instability

→ Could be used as a counter measure. More studies required: **chromaticity, emittance, long term?**

Summary and possible experiments

- **The electron lenses will reduce the beam-beam tune spread and hence Landau damping:**
  - Coherent modes far outside the tune spread
  - **Simulation in the presence of machine impedance show no sign of instabilities**

- **Interaction inside the electron lens can drive a TMCI a low solenoid field:**
  - **RHIC is by design below the threshold** and coherent beam-beam further degrades the situation
  - Simulations indicate that either a transverse bunch-by-bunch damper or an increased β-function at the electron lens could mitigate the instability

- **Experiments:**
  - Instability threshold as function of electron current and solenoid field
  - Impact of the damper and chromaticity
  - Correlation with β-function at the electron lens is more difficult but one could think of having a knob to tune β* in IP10 allowing for some beta-beating around the ring

Electron lens lattice - constraints

- **Phase advances for DA optimization:**

→ **$\pi/2$ between two low β insertions** will compensate for chromatic aberrations due to the β_{max} in Q2

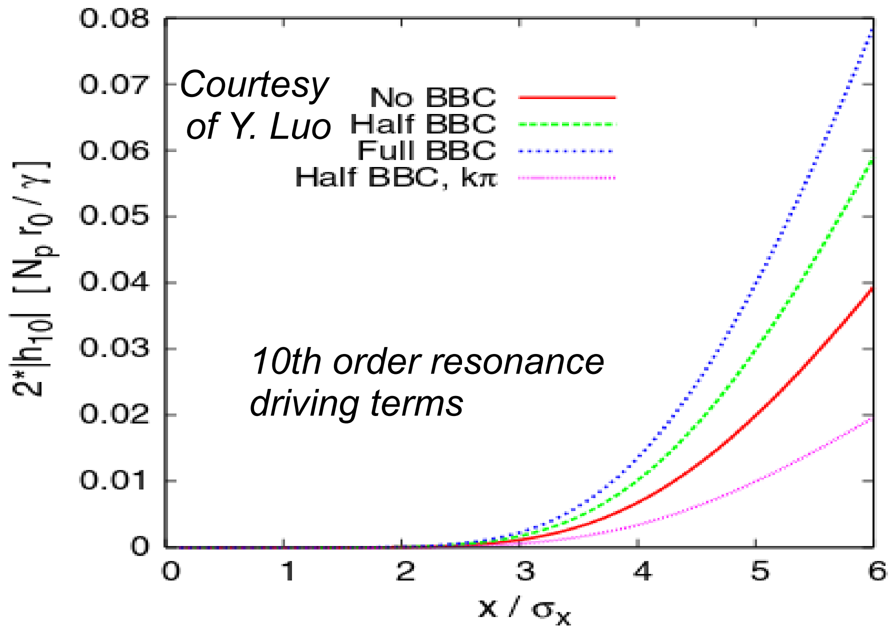
→ $\pi/2$ between two p-p collisions compensates for beam-beam driven non-linear resonances

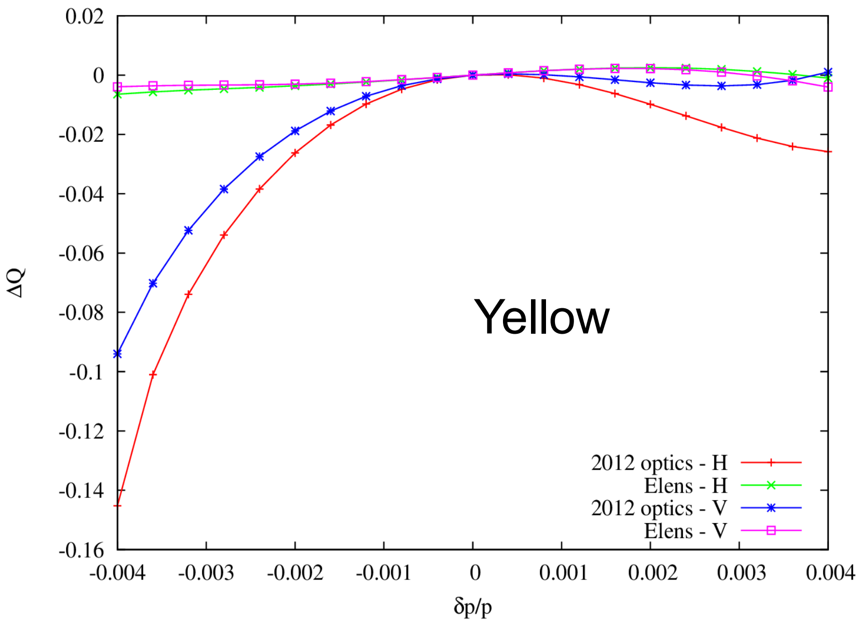
→ **π between electron lens and p-p collision** compensates for beam-beam driven non-linear resonances

- **Achievable by modifying the integer tune and with phase shifter:**

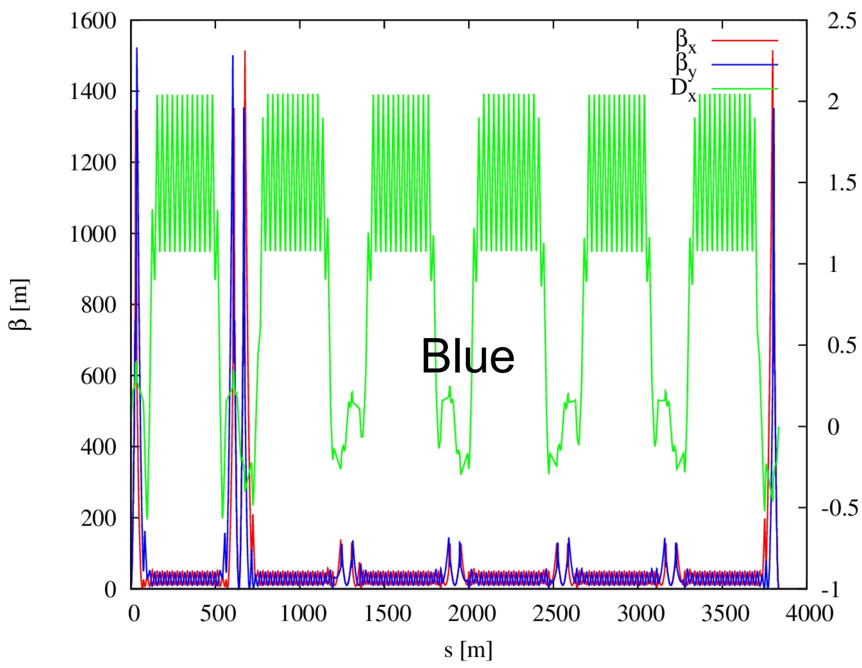
→ Changes the FODO cell phase advance (in all or one arc)

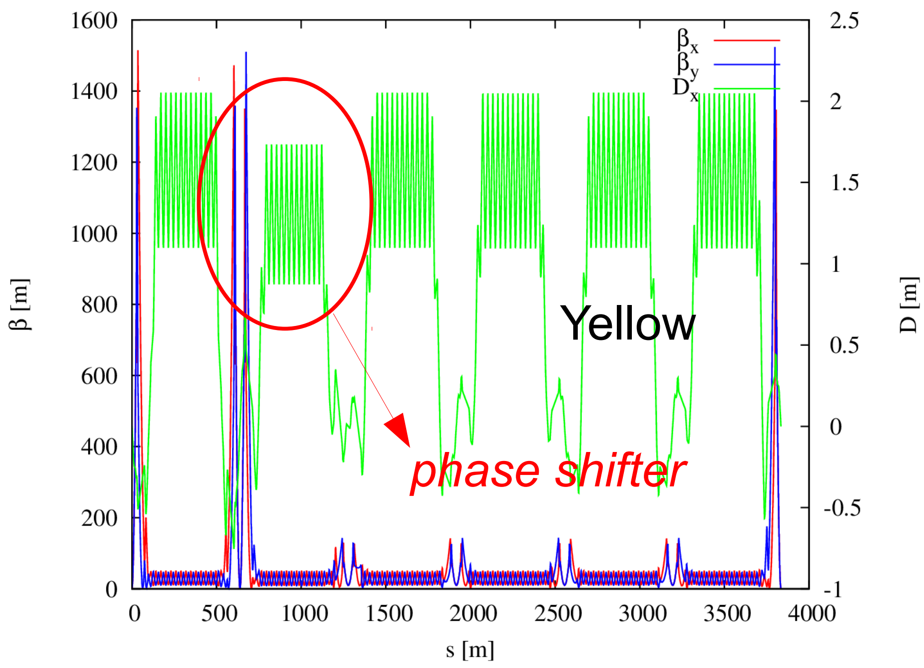
→ **Issue with the 3rd order resonance? It was a major issue with the elens lattice tried this year**





Preliminary Lattices





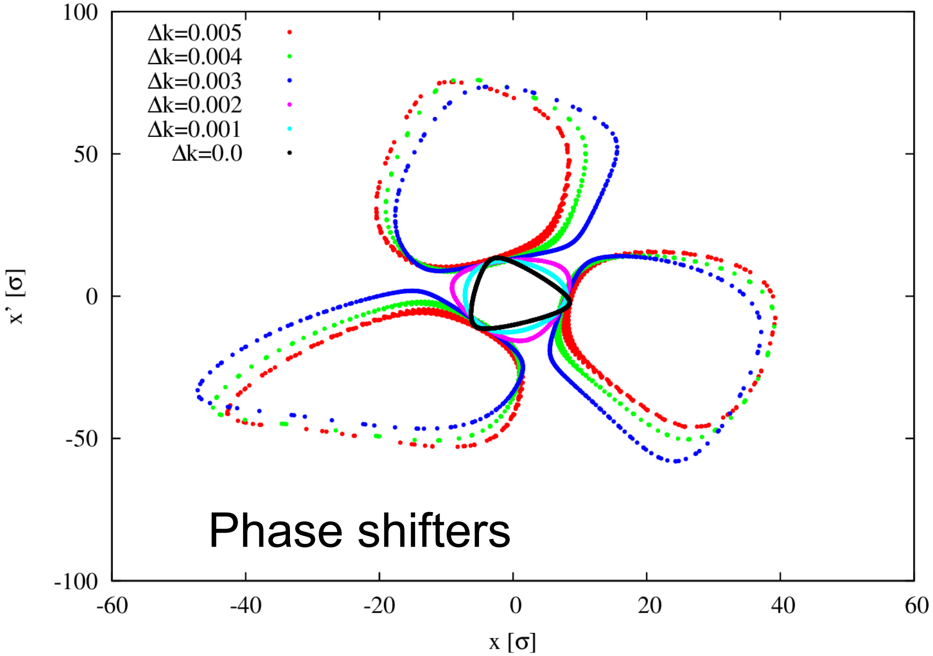
	Q_{xb}	Q_{yb}	Q_{xy}	Q_{yy}
IP6	0.0	0.0	0.0	0.0
IP8	5.25	4.25	3.75	5.75
Elens	9.25	9.75	9.25	10.25
Ring	27.695	29.685	27.695	28.685

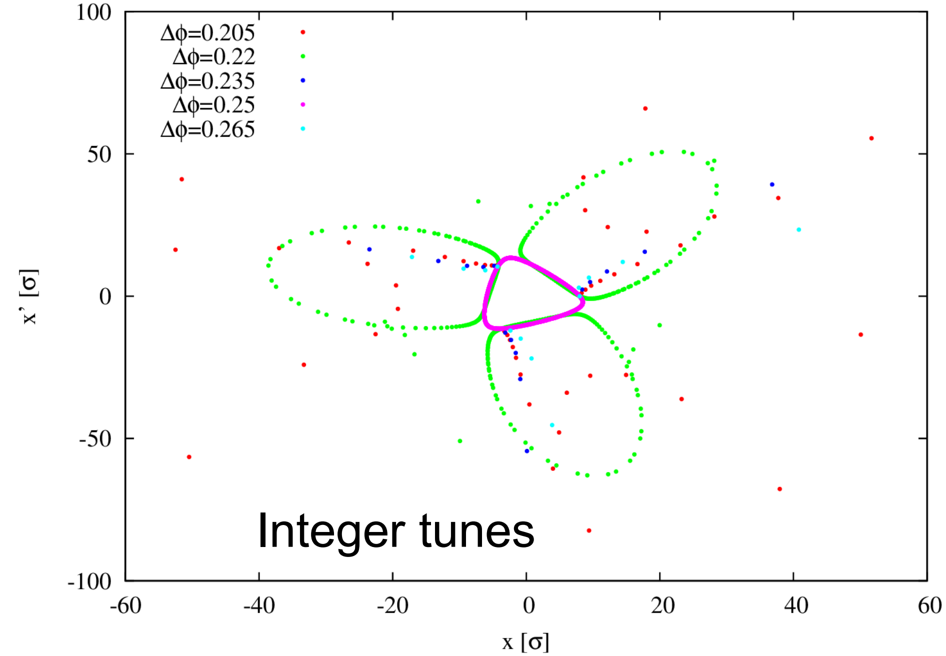
→ **Blue:** solution found without phase shifters

→ **Yellow:** phase shifters required. Power supply currents: (150,156)

→ Tried to minimize current in phase shifters: optics distortion in IR10

Phase advance per cell and phase shifter





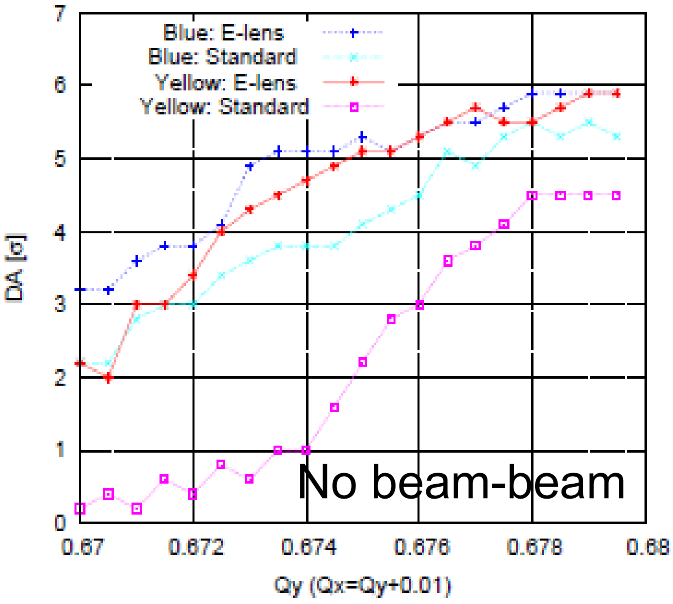
→ Keep both Q_x and Q_y with fractional tunes close to the resonance (0.67,0.685)

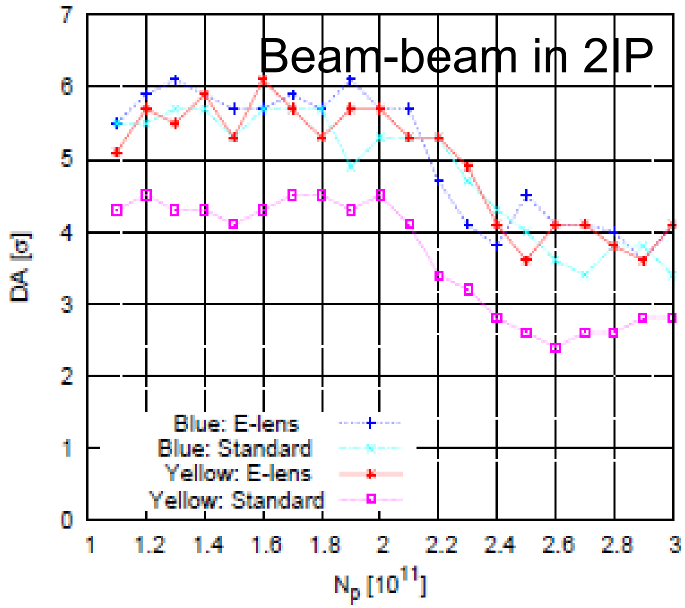
→ Phase space trajectory for an initial amplitude of 8σ, the phase advance per is changed using the integer tune. Δk=0.005 → ΔI~150A for the phase shifters

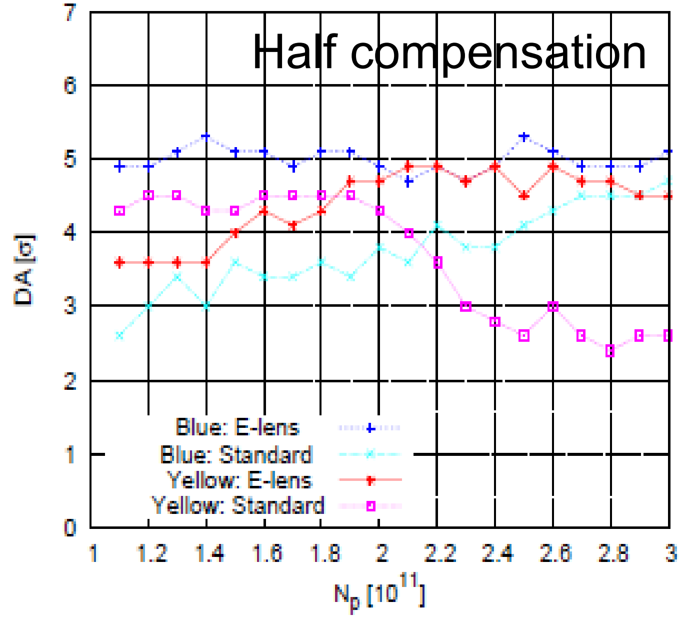
→ Both the phase shifter and the integer tune can have strong detrimental effects: expect some degradation of dynamic aperture with the elens lattice

→ Phase shifters are to be used with great care

Dynamic aperture







- **Off-momentum DA (no collisions):**

→ Clear improvement in the Yellow lattice due to the reduced non-linear chromaticity
→ Blue was already ok for the standard lattice: only minor improvements

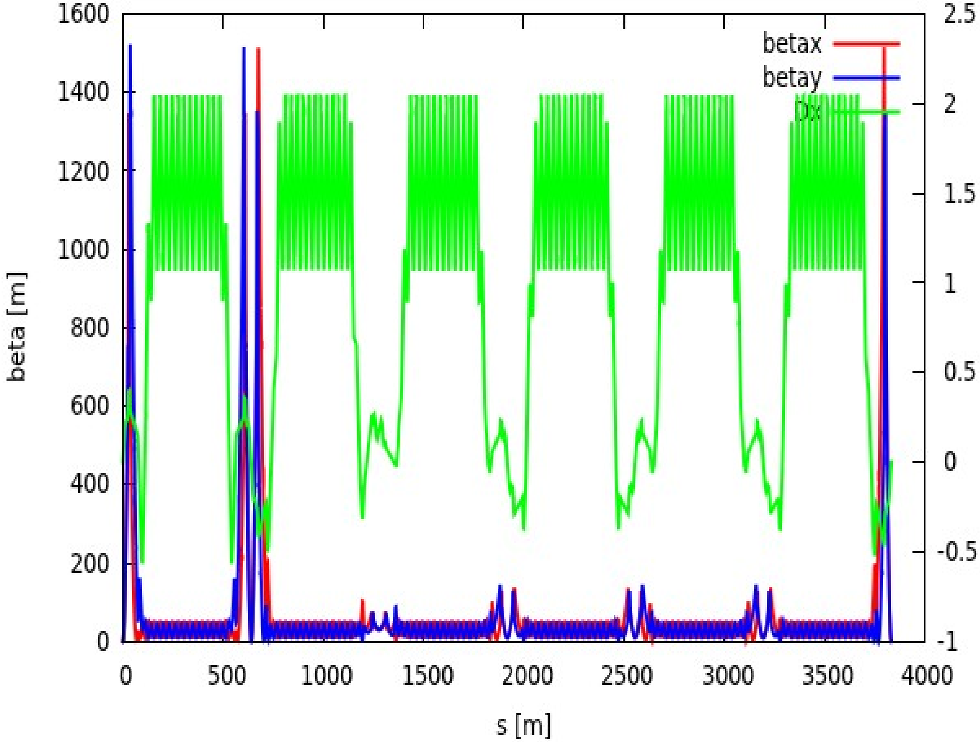
- **Beam-beam only (zero amplitude particles at 0.68,0.67):**

→ All lattices behave similarly except for the standard yellow: DA dominated by beam-beam

- **With half compensation(zero amplitude particles at 0.68,0.67):**

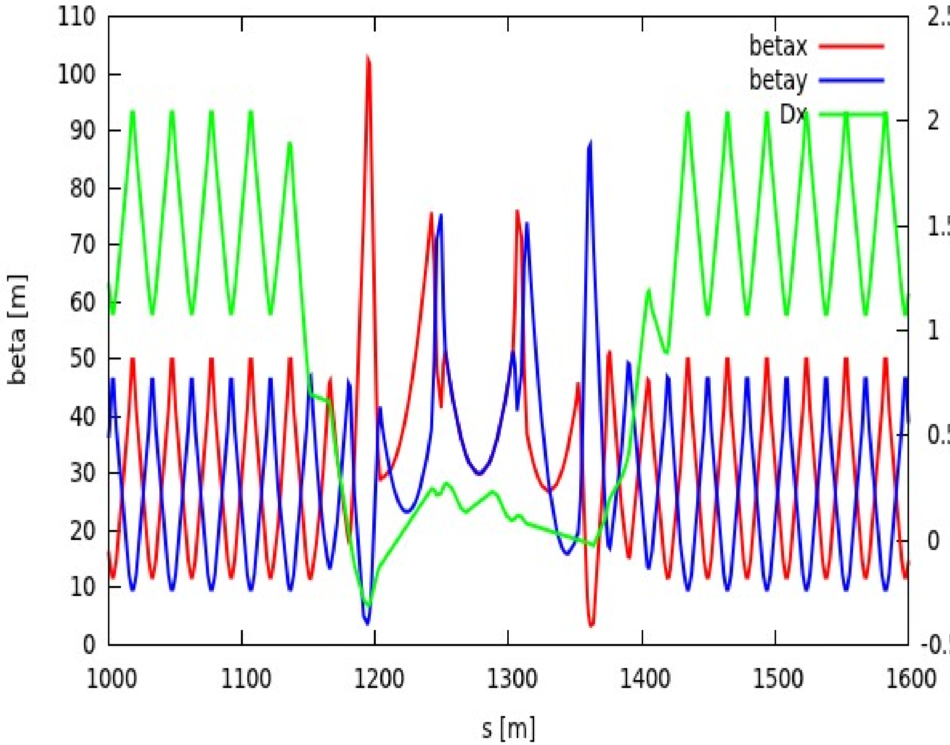
→ DA independent of the bunch intensity for Blue, in Yellow the 3rd order resonance could be the reason for the degradation at low intensity
→ Overall there is a degradation of DA with and w/o compensation: **tune optimization**

High-β at the electron lens?



→ A β* of 30 m could mitigate the fast stability

→ Existing optics solution including π/2 Phase advance between IP6 and IP8



→ Non negligible D* in IR10 (0.2m). Large β function in Q4 and Q5. Is that an issue? Could be fixed by relaxing α*

→ Still need to fix π phase advance. (0.8,0.53). Optimizations possible. Work ongoing.

Summary and possible experiments

- **The phase advances constraint for the electron lens poses a conceptual problem:**
  - Ideally adjust it with matching sections keeping the FODO cell to its optimum: not possible due to powering scheme
  - Changing the FODO cell (integer tune or phase shifter) drives the 3rd order resonance

→ Although improvements are seen with respect to the standard lattice, the current solutions are not fully satisfactory, especially in Yellow

- **Possible alternatives:**
  - Relax β^* and try rematching with insertions only, loss in luminosity compensated with higher bunch intensities
  - Give up $\pi/2$ between the two low β insertions: requires carefull correction of non linear chromaticity

- Solutions with high-β in the electron lenses were studied for stability: so far not possible to adjust phase advances

- **Experiments:**
  - 3rd order resonance driving terms as function of phase shifter current
  - Off momentum optics and lifetime as a function of the phase advance between IPs