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Landau Damping Using Electron Lenses in Future Circular Colliders

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Disclaimer

- This talk mostly follows recent PRL article:

Landau Damping of Beam Instabilities by Electron Lenses

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Landau Damping of Beam Instabilities by Electron Lenses

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Modern and future particle accelerators employ increasingly higher intensity and brighter beams of charged particles and become operationally limited by coherent beam instabilities. Usual methods to control the instabilities, such as octupole magnets, beam feedback dampers, and use of chromatic effects, become less effective and insufficient. We show that, in contrast, Lorentz forces of a low-energy, magnetically stabilized electron beam, or “electron lens,” easily introduce transverse nonlinear focusing sufficient for Landau damping of transverse beam instabilities in accelerators. It is also important to note that, unlike other nonlinear elements, the electron lens provides the frequency spread mainly at the beam core, thus allowing much higher frequency spread without lifetime degradation. For the parameters of the Future Circular Collider, a single conventional electron lens a few meters long would provide stabilization superior to tens of thousands of superconducting octupole magnets.

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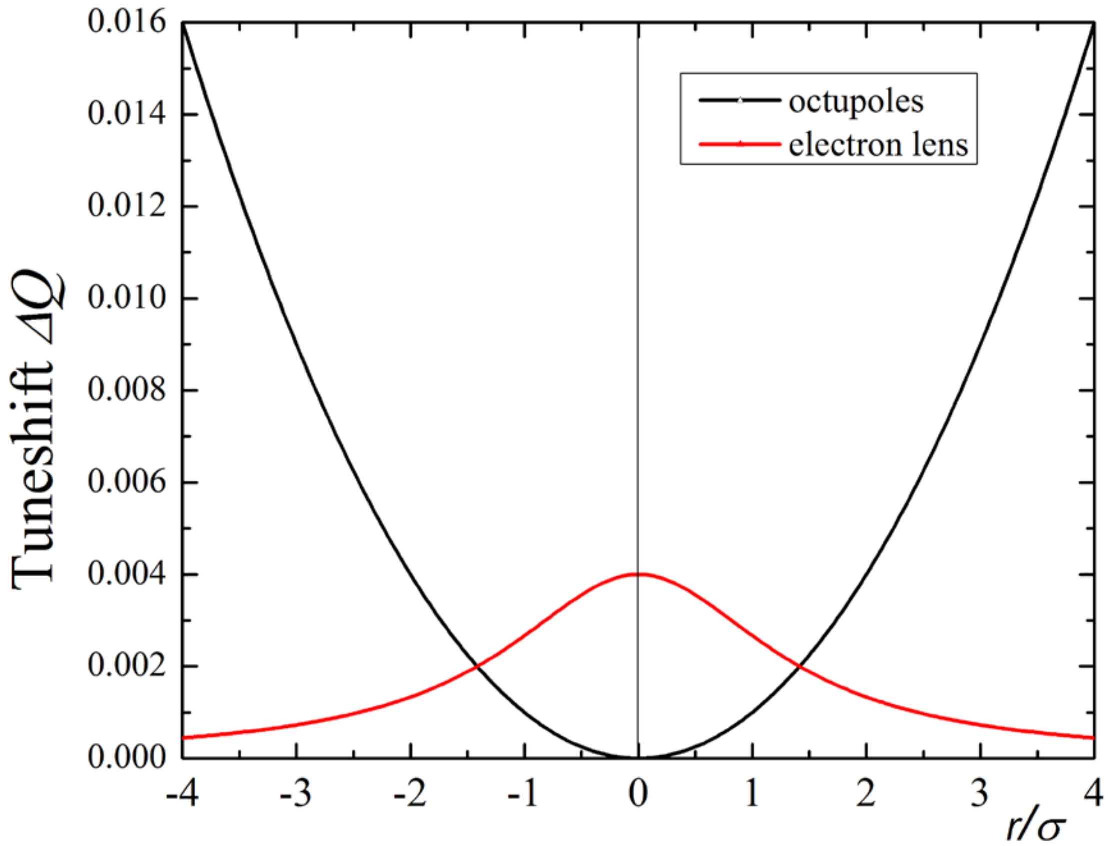
Electron Lenses for Landau Damping

(the concept, circa 2006)

- Landau damping needs incoherent betatron frequency spread
- Two issues with octupoles – required strength grows approx as ***~E²*** leads to Dynamic Aperture degradation
- (Gaussian) electron lens ~2 m and 2 A – would give enough stabilization even for the 50 TeV FCC without detrimental effects on particles with larger amplitudes *A*

Betatron frequency shift versus amplitude



V. Shiltsev, in *Proceedings of the CARE-HHH-APD LHC-LUMI-06 Workshop* (Valencia, Spain, 2006); CERN Yellow Report No. CERN-2007-002 (2007), p. 92.

Let's Start with Octupoles : Stability Diagram (SD)

$$D(\Delta\nu) = -\left(\int \frac{J_x \partial F / \partial J_x}{\Delta\nu - \delta\nu_x + io} dJ_x dJ_y\right)^{-1}$$

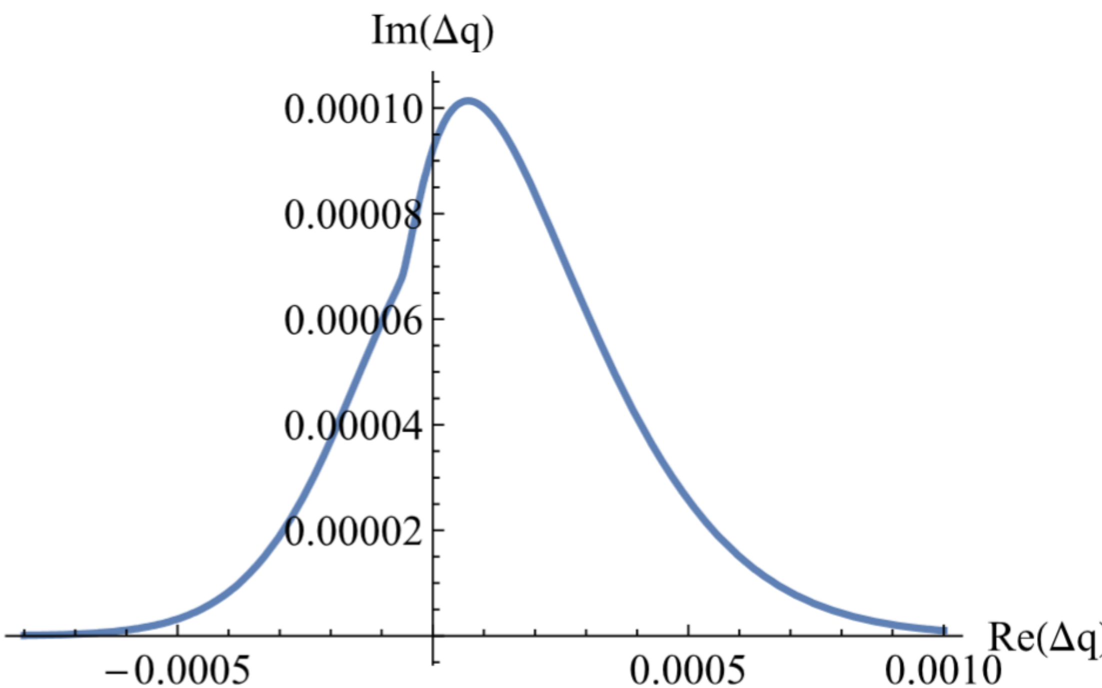
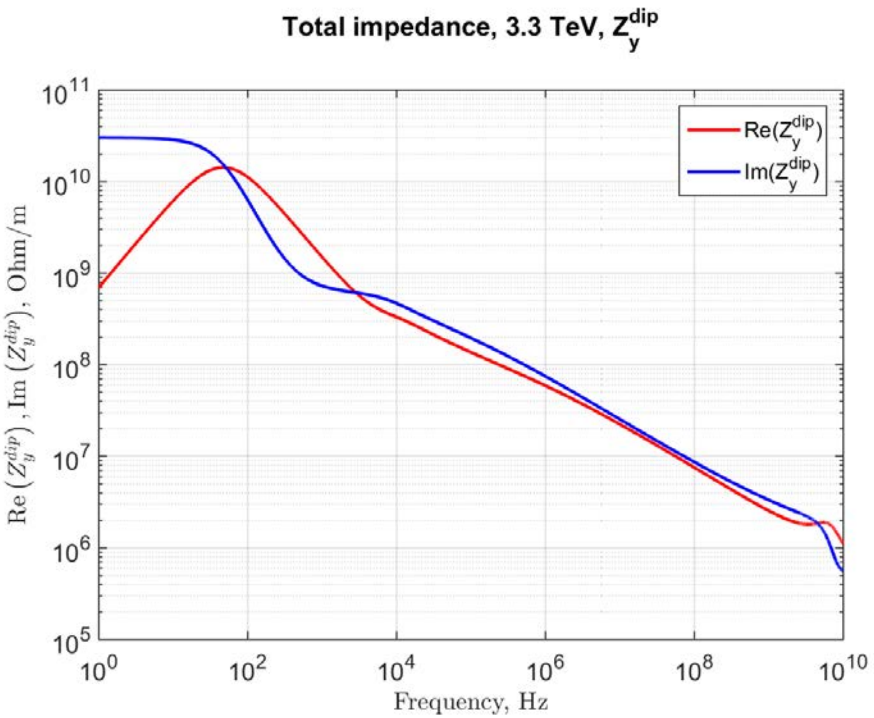


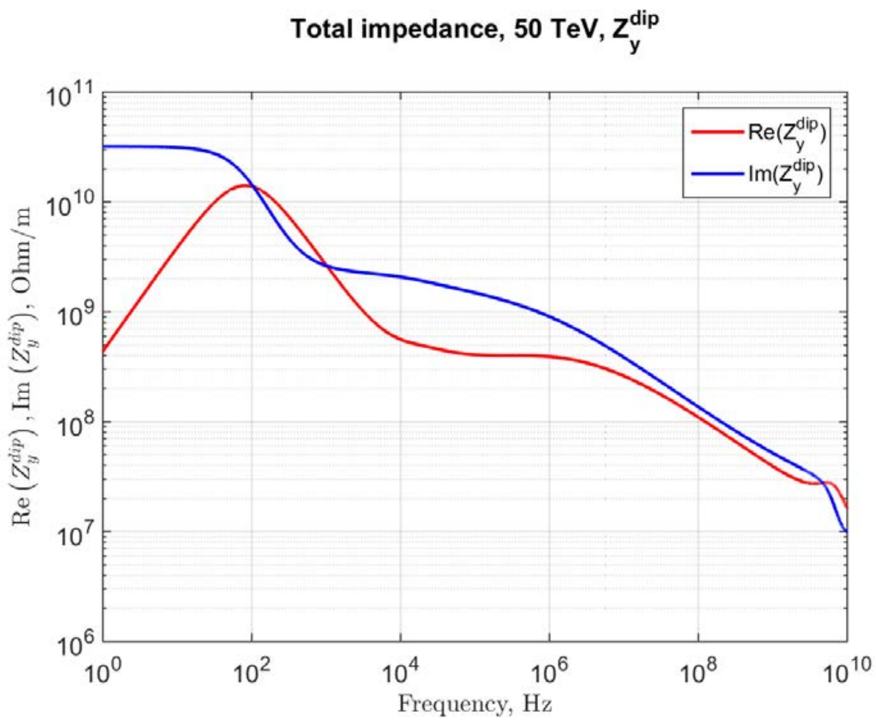
FIG. 2. Stability diagram for the 7 TeV proton beams in LHC at the maximal strength of the Landau octupoles.

Worrisome FCC Impedance Estimates

Current is high, aperture is small, collimators are close, electron cloud with SR uncertain

by Sergey Arsenyev





On top of that:
CC HOM (the most dangerous)

f=1.3GHz, Q=2.3 $\times 10^4$, R_s= 3.7 / 65 MOhm/m

So, the Concern is VERY Real

For the FCC beams the growth rates are (approx.):

06-06-2017

FCC-hh parameters based on Antoine Chance's presentation in Berlin

	At Injection	At Top Energy
Beam energy	3.3 TeV	50 TeV
Circumference	97.74914 km	
Revolution frequency	3066.95745 Hz	
RMS bunch length σ_z	8 cm (τ_4σ=1.06741 ns)	
Single bunch intensity N	10^{11}	
Betatron tunes Qx / Qy	111.28 / 109.31	111.31 / 109.32
Momentum compaction factor α_p	1.01354×10^{-4}	
Transition gamma γ_tr	99.33	
Slippage factor η	1.01273×10^{-4}	1.01353×10^{-4}
RF harmonic number h	130680	
RF frequency	400.79 MHz	
RF Voltage V	12 MV	32 MV
Synchrotron tune Qs	2.76754×10^{-3}	1.16151×10^{-3}

	Injection, 3.3TeV	Top, 50 TeV	damping
CB, low-f	100 turns	500 turns	damper
CB, HOM	10^5 turns	10^5 turns	Landau
SB	5000 turns	5000 turns	Landau

CB = coupled-bunch
SB = single-bunch

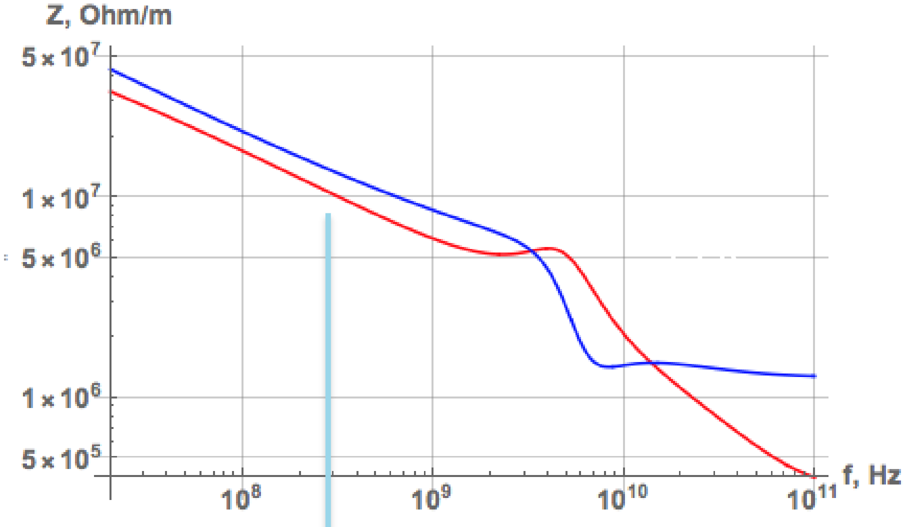
https://impedance.web.cern.ch/impedance/fcchbeam_dynamics_parameters.html

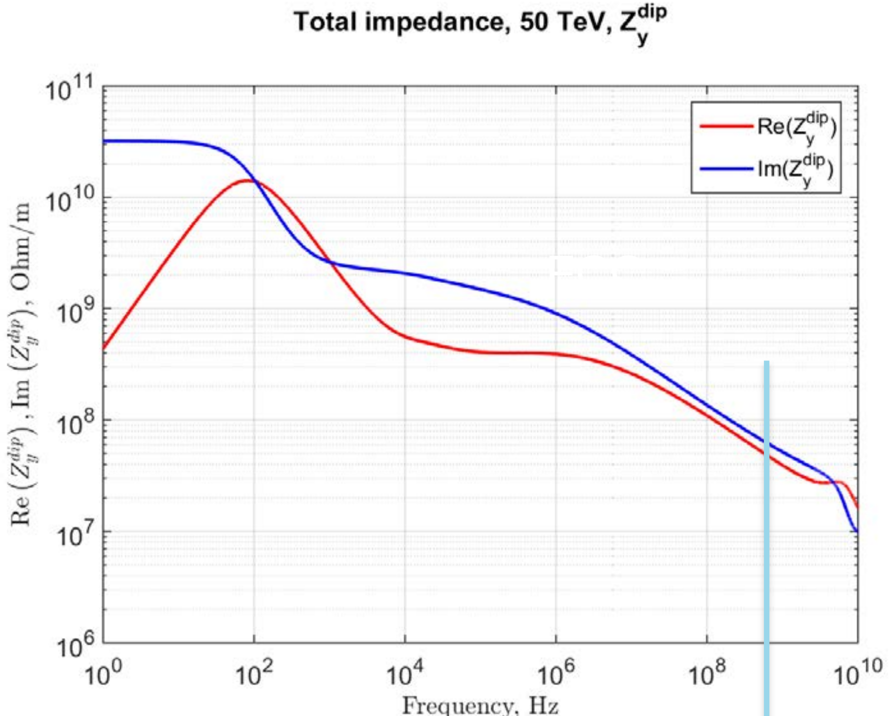
Number of Octupoles to Ensure Stability

$$\frac{N_{FCC}^{oct}}{N_{LHC}^{oct}} = \frac{Z_{SB}\beta_y\gamma\big|_{FCC}}{Z_{SB}\beta_y\gamma\big|_{LHC}} = 5\cdot 2\cdot 7 = 70$$

$$N_{FCC}^{oct} = 168\cdot 70 \approx 12000$$

at 50 TeV





So the problem is:

- Impedances grow
- DA concerns grow
- Spread diminishes

$$\delta\nu_x = c_{xx} J_x/\varepsilon_n + c_{xy} J_y/\varepsilon_n$$

As the result:

- Tevatron – 1 TeV beams – 35 SC octupoles (1m, 50 A)
- LHC – 7 TeV beams – 336 SC octupoles (0.32 m, 550A)
- FCC – 50 TeV beams – 12,000 "LHC-type" octupoles

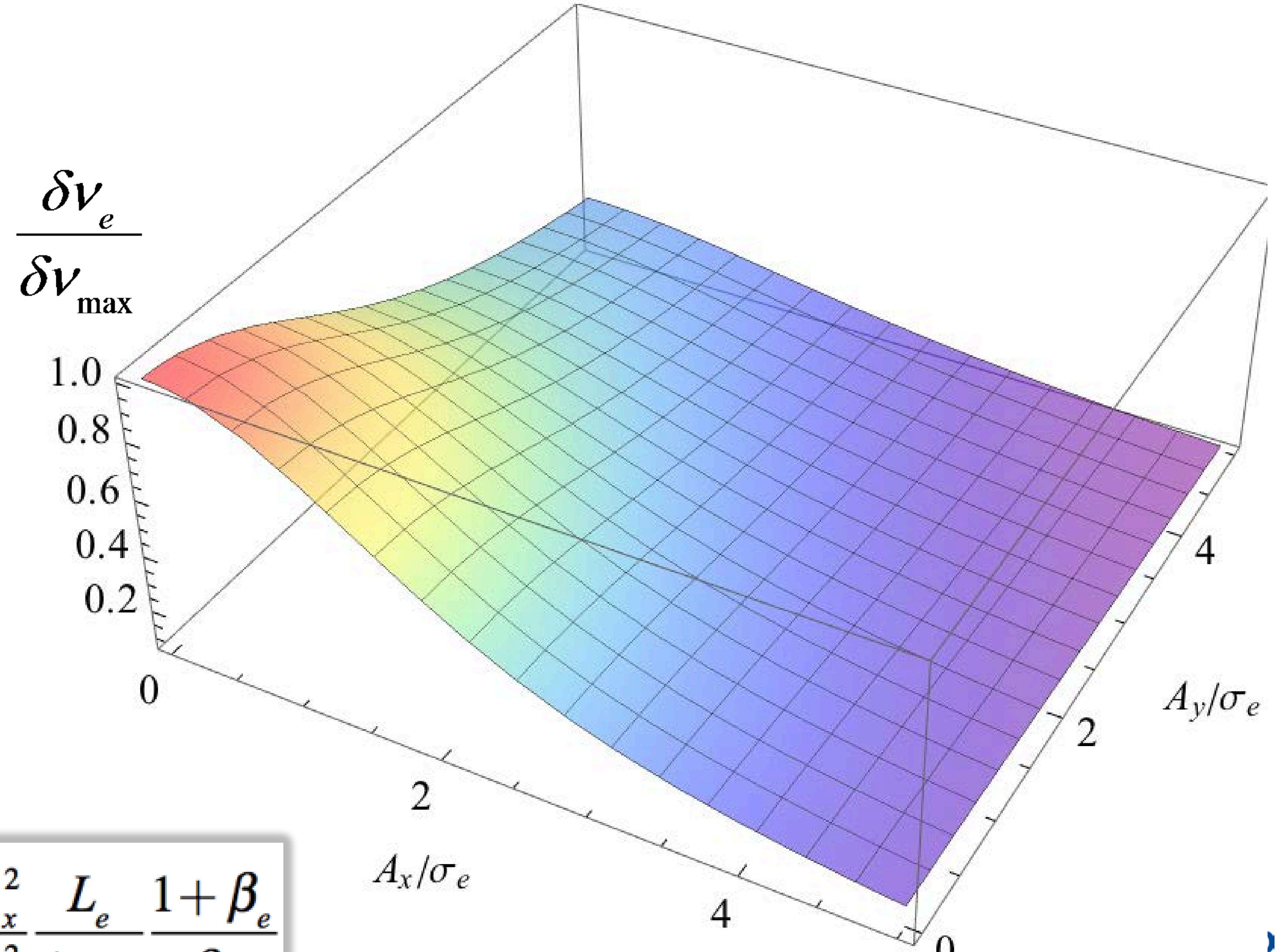
All that makes octupoles unsuitable

Octupoles provide too little non-linearity where it is needed and too high where it is detrimental

- Too many are needed
- Unreliable: tail-sensitive
- Stability diagram collapse problem
  - Experienced recently in the LHC (interplay of LR beam-beam and octupoles during the squeeze)
- Cannot vary along the beam
- Dynamic aperture problems

E-Lens as a Perfect Landau Element

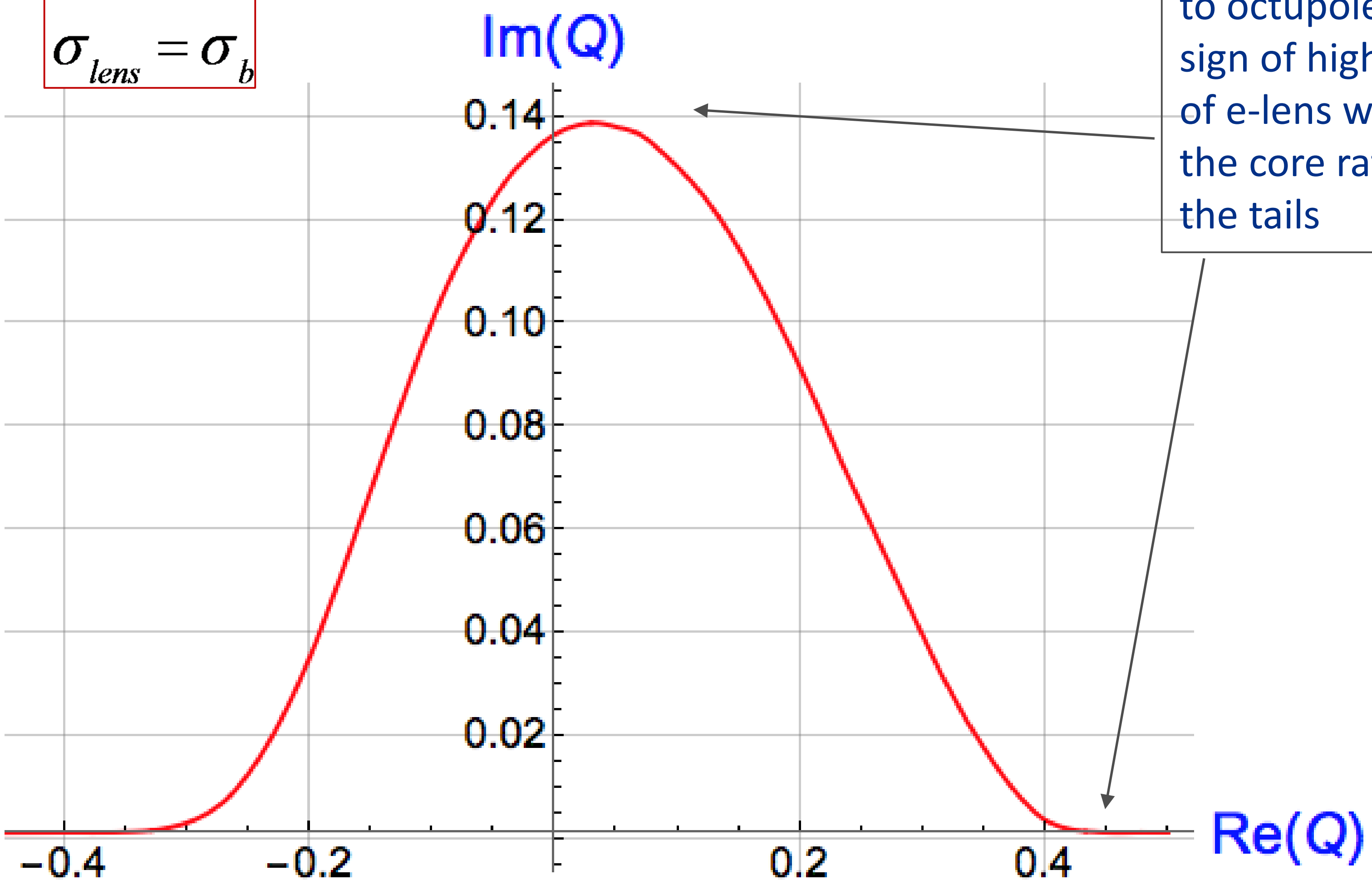
E-Lens can deliver nonlinearity just where it is needed:



$$\delta\nu_{\max} = \frac{I_e}{I_A}\frac{m_e}{m_p}\frac{\sigma_x^2}{\sigma_e^2}\frac{L_e}{4\pi\varepsilon_n}\frac{1+\beta_e}{\beta_e}$$

Stability Diagram with e-lens

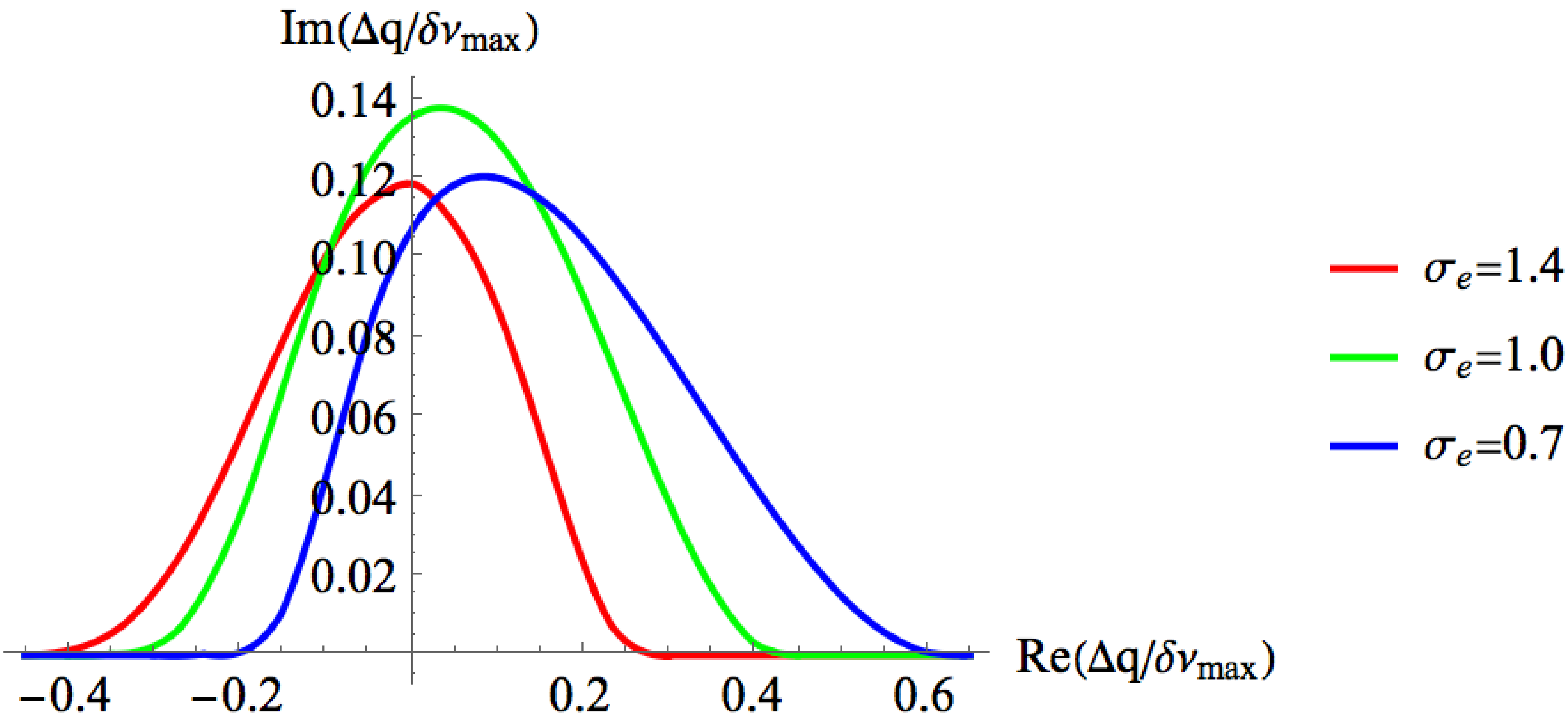
$$\sigma_{lens} = \sigma_b$$



In the units of max betatron tuneshift

Note high ratio of Im/Re (~1/3) compared to octupoles (~1/10) = sign of higher efficiency of e-lens which acts on the core rather than on the tails

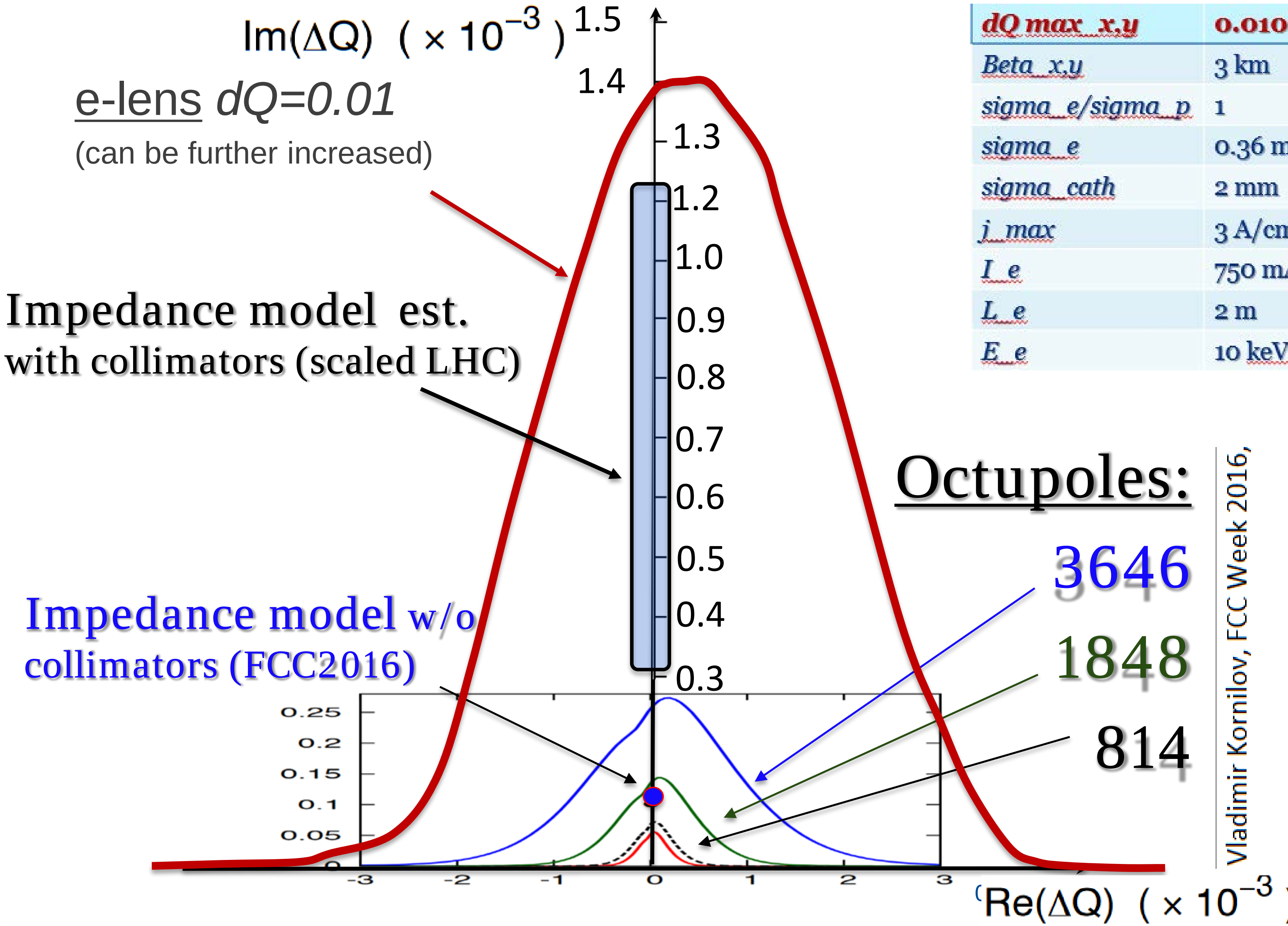
E-Lens Stability Diagrams for Different Sizes



SDs for various lens sizes with the same max current density

FCC Stability Diagram

dQ max_x,y	0.010
Beta_x,y	3 km
sigma_e/sigma_p	1
sigma_e	0.36 mm
sigma_cath	2 mm
j_max	3 A/cm^2
I_e	750 mA
L_e	2 m
E_e	10 keV



Vladimir Kornilov, FCC Week 2016,

Possible e-Lens Parameters

Length	2 m
Beta-function at e-lens	1.5 km
Electron current	0.7 A
Electron energy	10 kV
E-lens rms radius	0.25 mm
Fields in main/gun solenoids	6.5 T / 0.2 T
Max tune shift	0.01

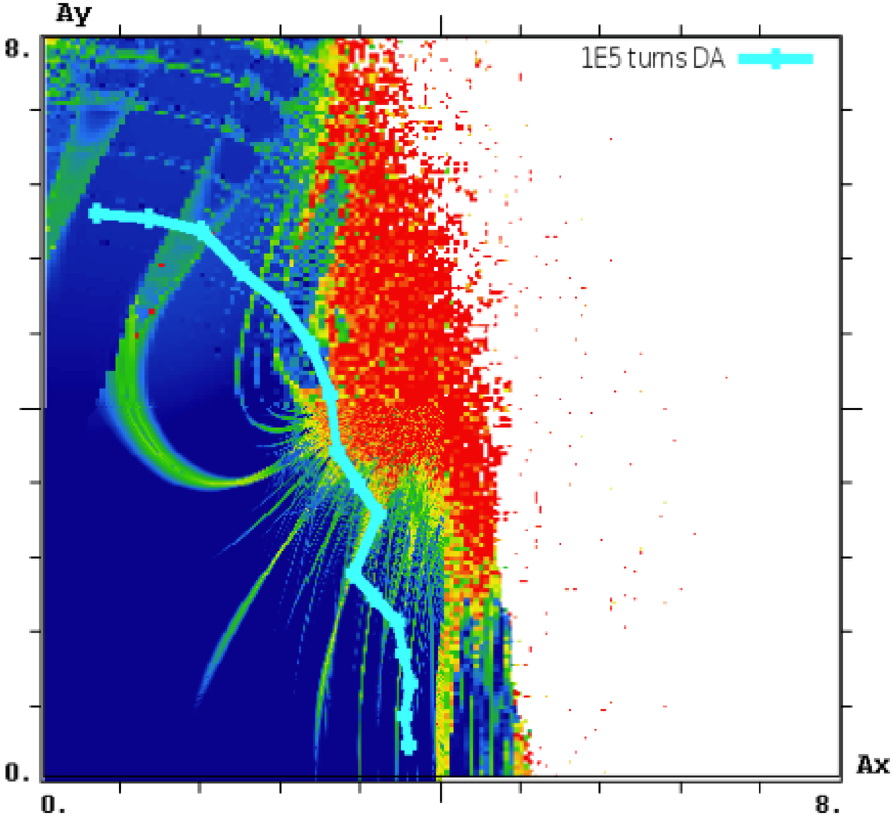
E-Lens parameters for the proton emittance 2.2 microns, at 50 TeV

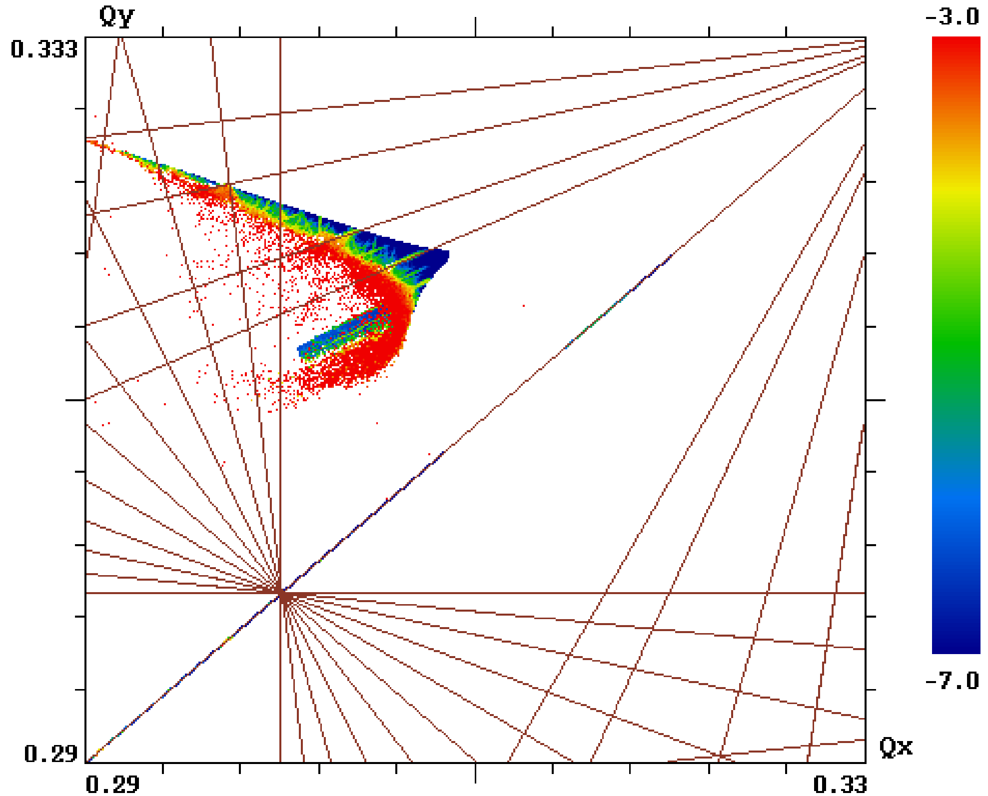
At the injection, the same tune shift is achieved at lower e-current.

Effect of Stabilizing Elements on Dynamic Aperture

HL-LHC with octupoles

$DA_{min} = 3.7\,\sigma$





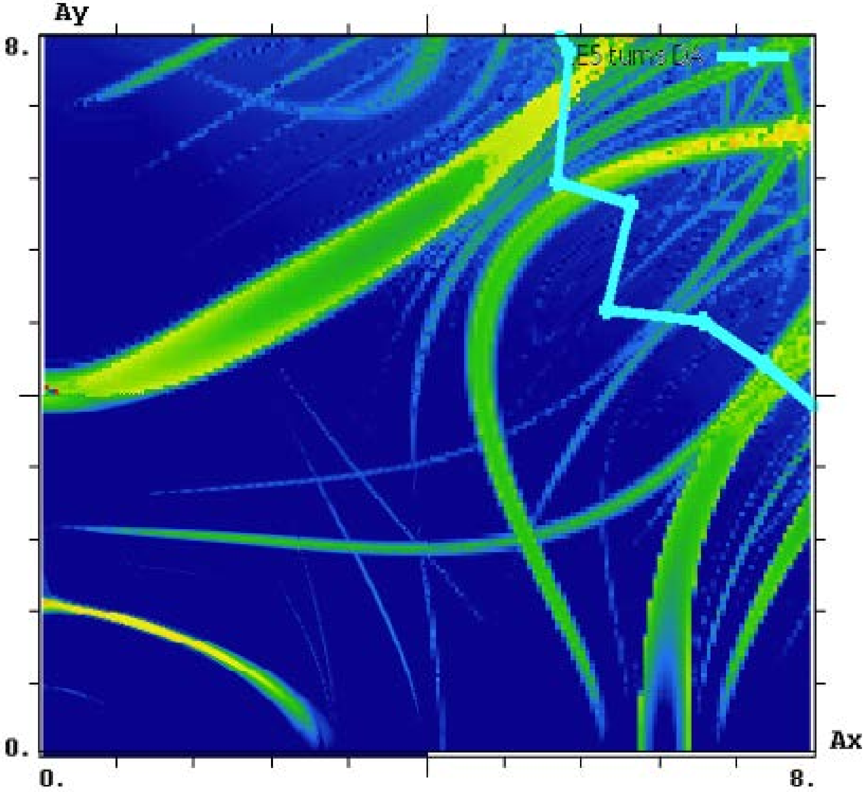
Energy 7TeV, no collisions, HL-LHC optics Version 1.0 with multipole errors (1 seed), Chromaticity = 3

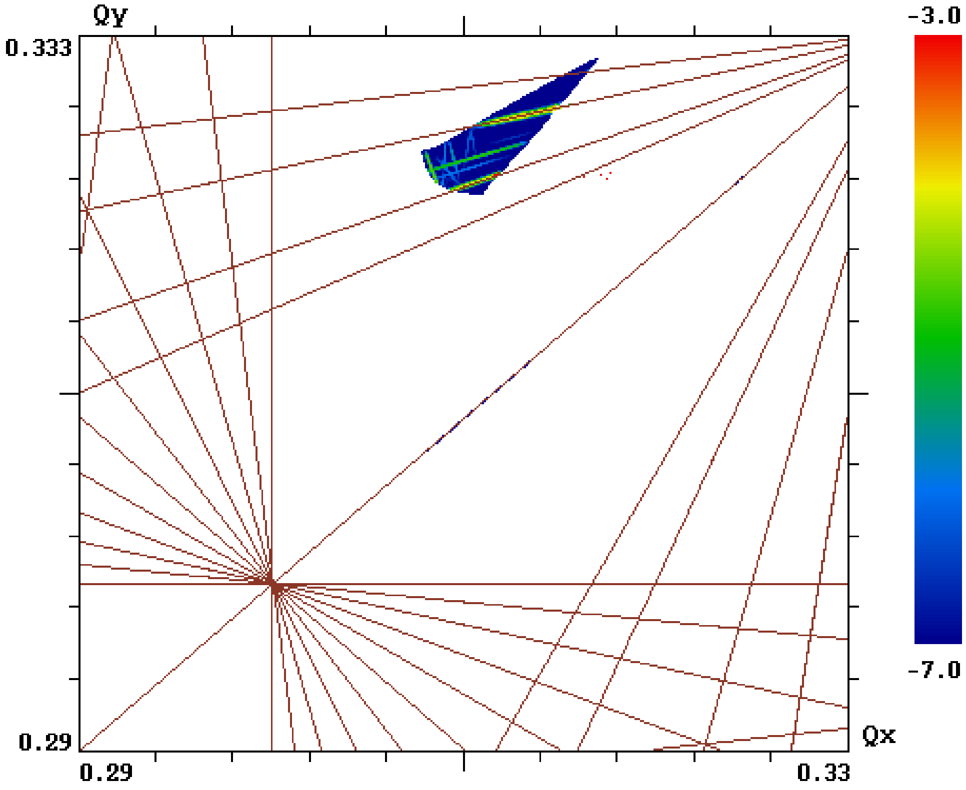
- For simulation with octupoles, current increased to -2000 A to create tune spread of 0.005 at 2.5 sigma
- Single electron lens at IR4 – the location of Hollow Electron Beam Collimator, Electron beam size matched to size of proton beam (sigma=0.28 mm). Current of EL corresponds to tune spread of 0.005 at 2.5 sigma

Effect of Stabilizing Elements on Dynamic Aperture

HL-LHC with E-Lens

$DA_{min} = 8.0\ \sigma$





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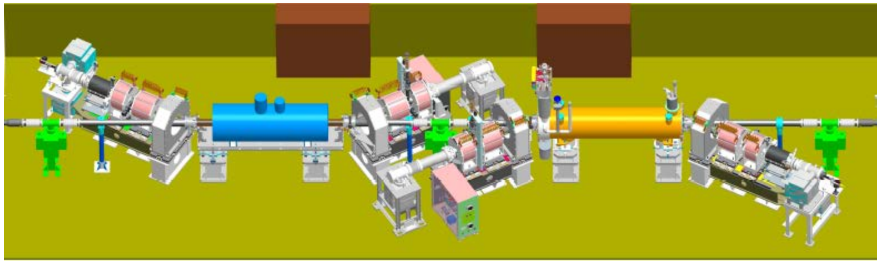
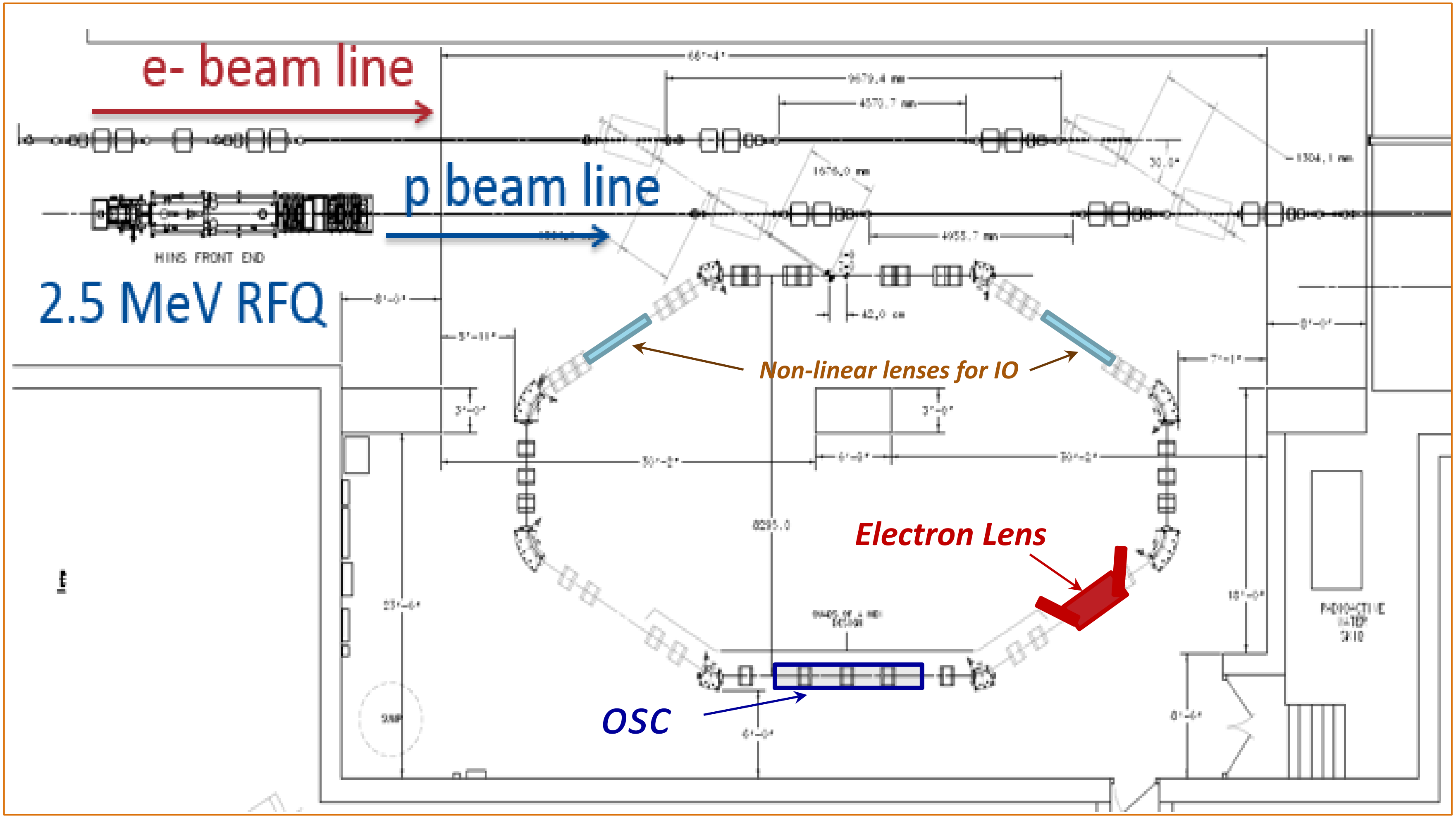
Landau lens test at RHIC?



- Two Gaussian lenses operational in RHIC
- Questions that can be answered:
  - Predicted SD vs. measurement
  - Effects of imperfections in implementation
  - Is E-Lens different from head-on beam-beam?
- RHIC beams are generally stable, the 2 possible ways to make the beam unstable are
  - Injection damper
  - Chromaticity
- Store is preferred due to better alignment. A likely experiment (W.Fischer)
  1. ramp to store
  2. align hadron beam with electron beam at given current
  3. lower chromaticity until beam becomes unstable
  4. repeat with: new ramp, lower electron beam current

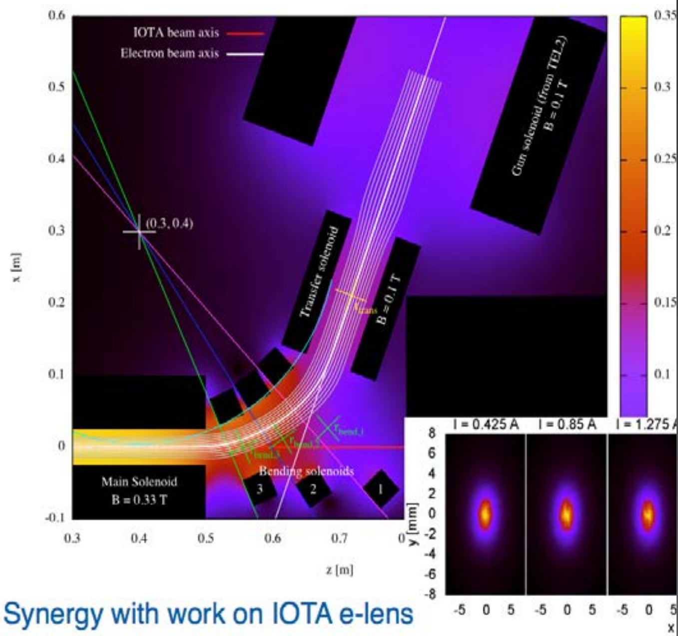
Landau Lens test at IOTA

40 м, *e-* 150 MeV/c *p+* 70 MeV/c

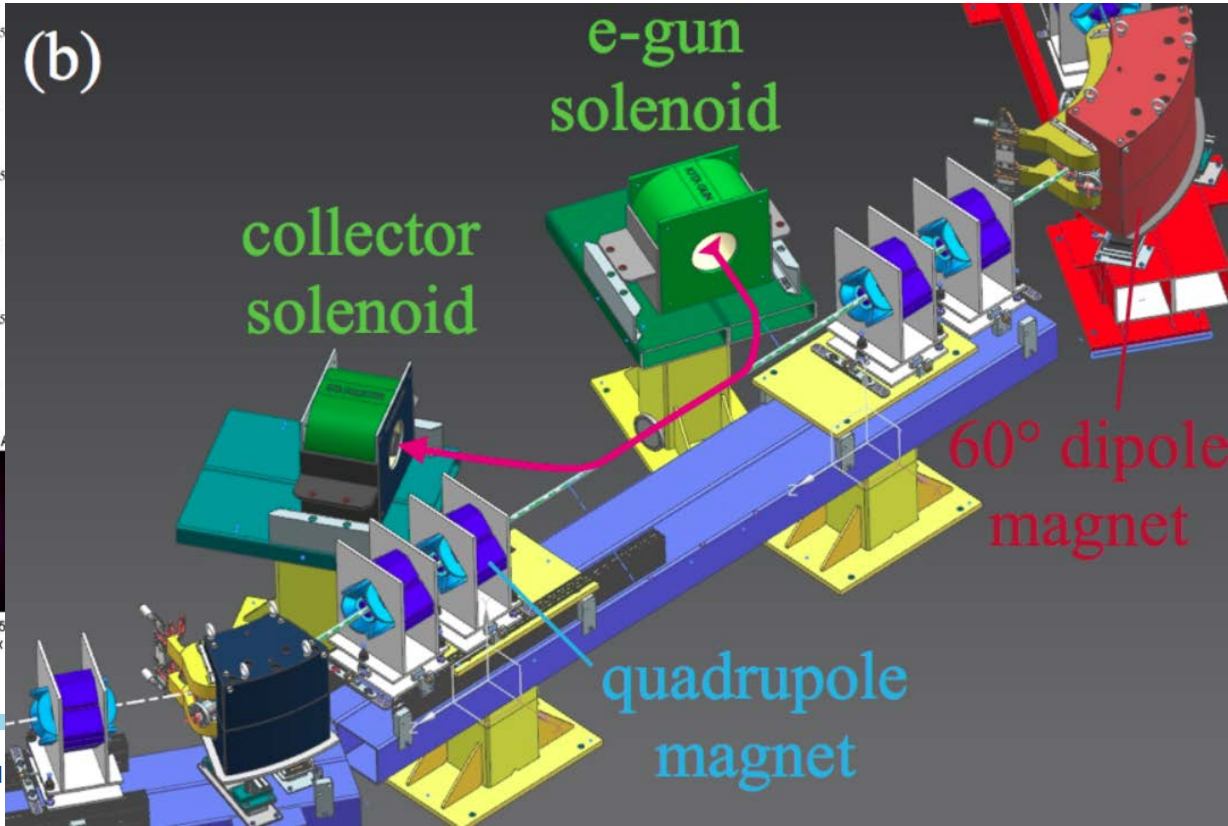


IOTA Electron Lens

- Capitalize on the Tevatron and RHIC experience, LARP work
- Re-use Tevatron Electron Lens components:
  - Removed TEL-2 gun & collector from Tev tunnel
  - Refurbishment in progress
- Computer modeling for IOTA e-Lens in progress



Synergy with work on IOTA e-lens



Summary

- Higher the energy of hadron beams, the harder to maintain coherent stability with octupoles (eg $O(10^4)$ in FCC-hh)
- A “standard technology”, few meters long e-lens would do the job of ~20 000 LHC-type octupoles for the LHC or FCC.
- E-lens SD is core-based, so it is robust, little effect on DA
  - Contrary to octupoles
- E-Lens can be bunch-dependent
- A problem of SD collapse can be fully excluded
  - E.g. like those due to LR beam-beam in the LHC squeeze
- Experimental studies would be very interesting
  - RHIC, or IOTA

BACK UP SLIDES

RF Quads ?

RF Quads (A. Grudiev et al.) are novel interesting Landau elements.

There are serious beam-lifetime and DA concerns related to synchrobetatron coupling induced by the RFQ

Their effectiveness of the RFQ is sensitive to predictability and reproducibility of the longitudinal tails of the bunches.

An ideal Landau element would be independent on the distribution tails.

Stability Diagram, weak head-tail, No SC

Stability diagram (SD) is defined as a map of real axes ν on the complex plane Δq:

$$\Delta q = \left(-\int \frac{J_x \partial F / \partial J_x}{\nu - \delta\nu_x + io} d\Gamma \right)^{-1} \qquad d\Gamma = dJ_x dJ_y$$

$$\delta\nu_x(\kappa_x,\kappa_y) = 2\delta\nu_{\max} \int_0^{1/2} \frac{I_0(\kappa_x u) - I_1(\kappa_x u)}{\exp(\kappa_x u + \kappa_y u)} I_0(\kappa_y u)\, du;$$

$$\kappa_{x,y} = \frac{a_{x,y}^2}{2\sigma_e^2}; \quad \delta\nu_{\max} = \frac{I_e}{I_A} \frac{m_e}{m_p} \frac{\sigma_x^2}{\sigma_e^2} \frac{L_e}{4\pi\varepsilon_n} \frac{1+\beta_e}{\beta_e},$$

To be stable, the coherent tune shift has to be below the SD.