# Landau Damping by Electron Lenses: Outperforming Thousands of Octupoles

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Fermilab

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# Landau Damping of Beam Instabilities by Electron Lenses

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## ABSTRACT

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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# Landau Damping

Landau damping, caused by a frequency spread, is an indispensable means of beam stabilization.

For bunched beams this spread is normally provided by either sextupoles ($2^{nd}$ order) or octupoles ($1^{st}$ order)

There are 168 Landau octupoles in each of the LHC rings.

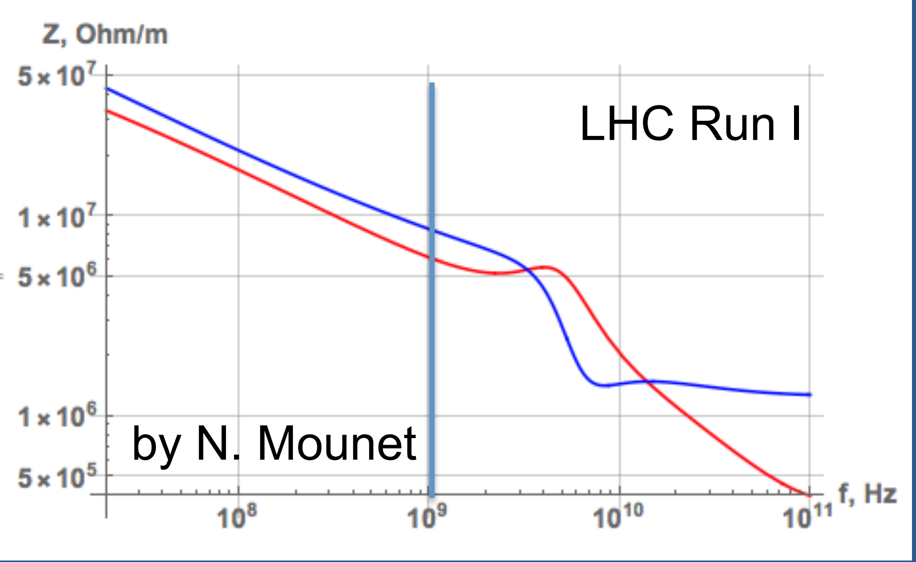
How many of them do we need in the FCC?

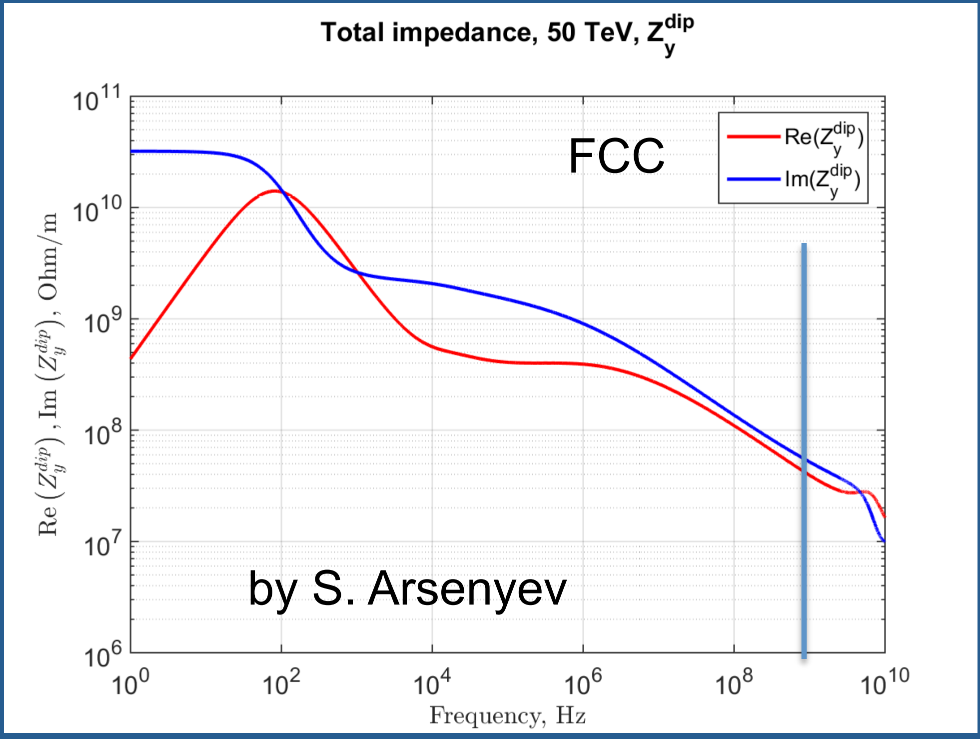
Maybe we should rather use something better?

# How many octupoles?

$$\frac{N^{oct}_{FCC}}{N^{oct}_{LHC}} = \frac{Z_{SB}\beta_y^{-1}\gamma(a^3_{oct}/L_{oct})\Big|_{FCC}}{Z_{SB}\beta_y^{-1}\gamma(a^3_{oct}/L_{oct})\Big|_{LHC}} = 7\cdot 2^{-1}\cdot 7\cdot 0.2 = 5$$

$$N^{oct}_{FCC} = 168\cdot 5 \approx 800$$



# What 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
- Vaccaro diagram reduction problem
- Cannot vary from bunch to bunch
- Dynamic aperture problems

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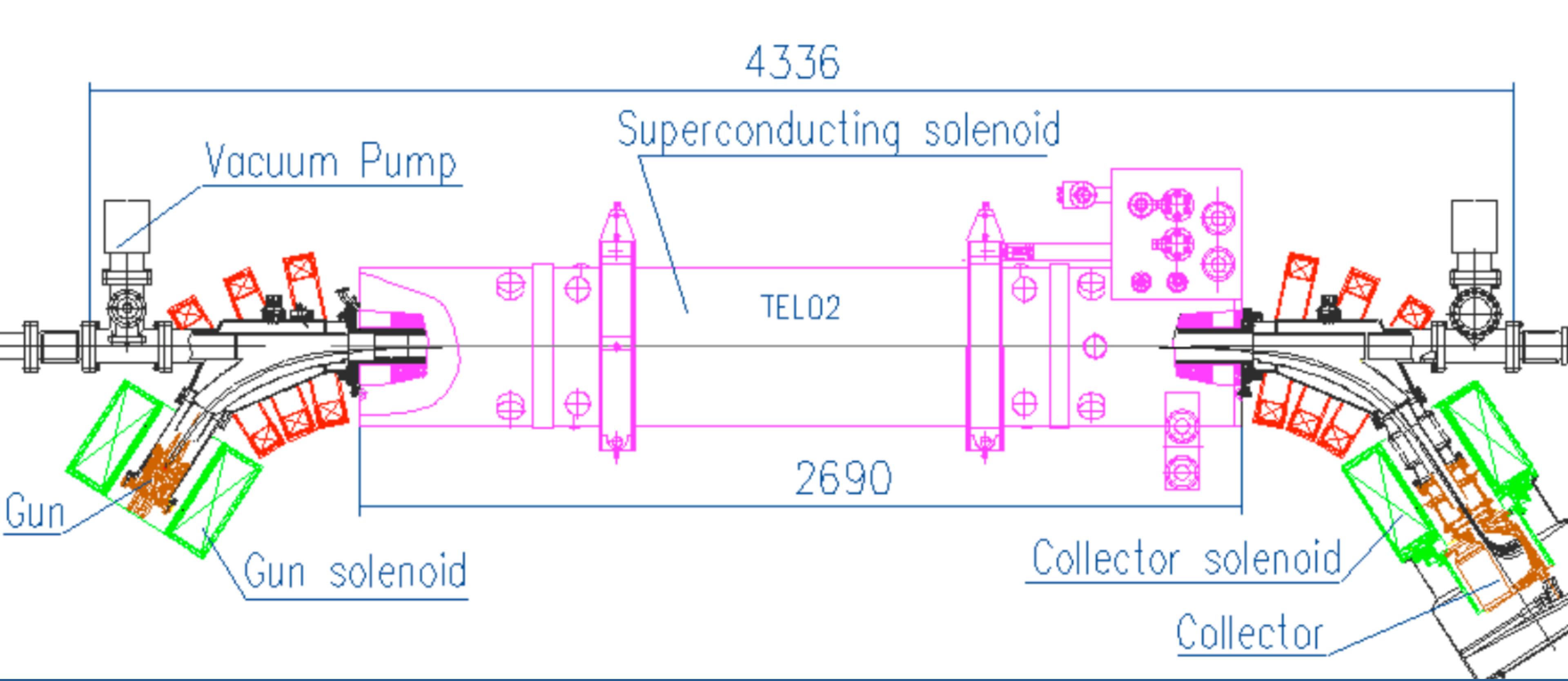
# Electron lens

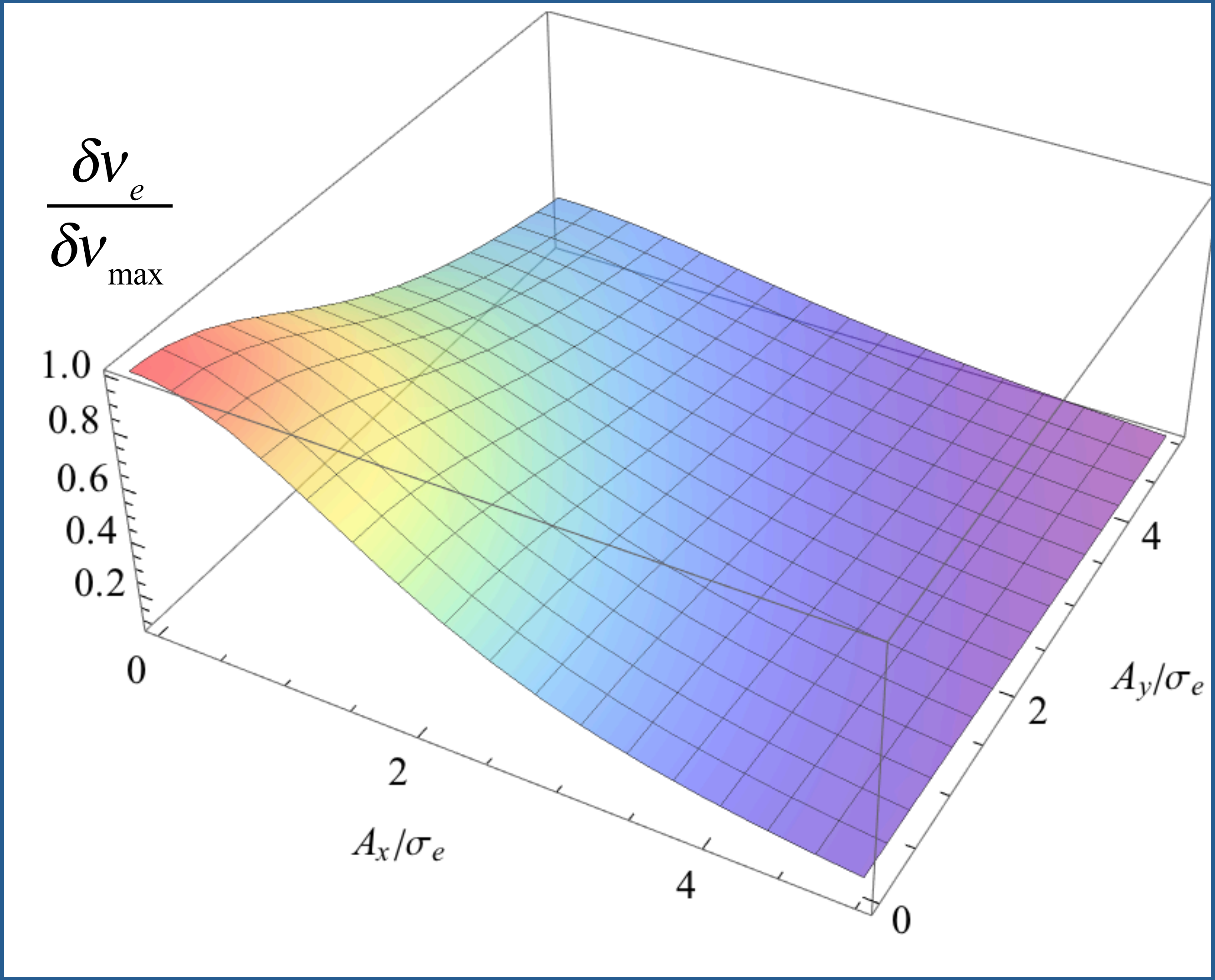
Electron lens is an e-beam guided by magnetostatic field




Tevatron e-lens

# E-Lens as a Landau Element

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



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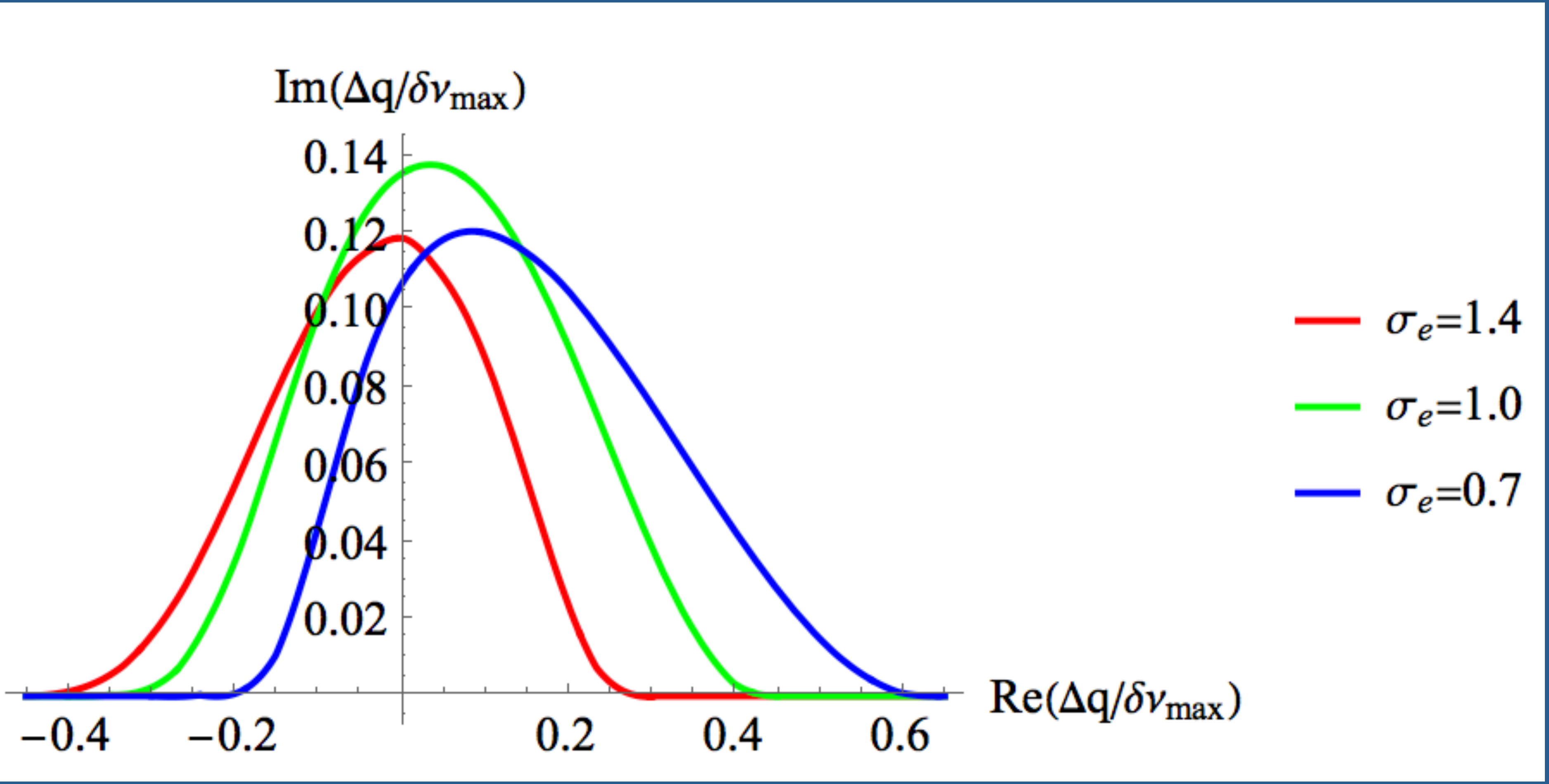
# E-Lens Vaccaro Diagrams, round beam




VDs for various lens sizes with the same max current density



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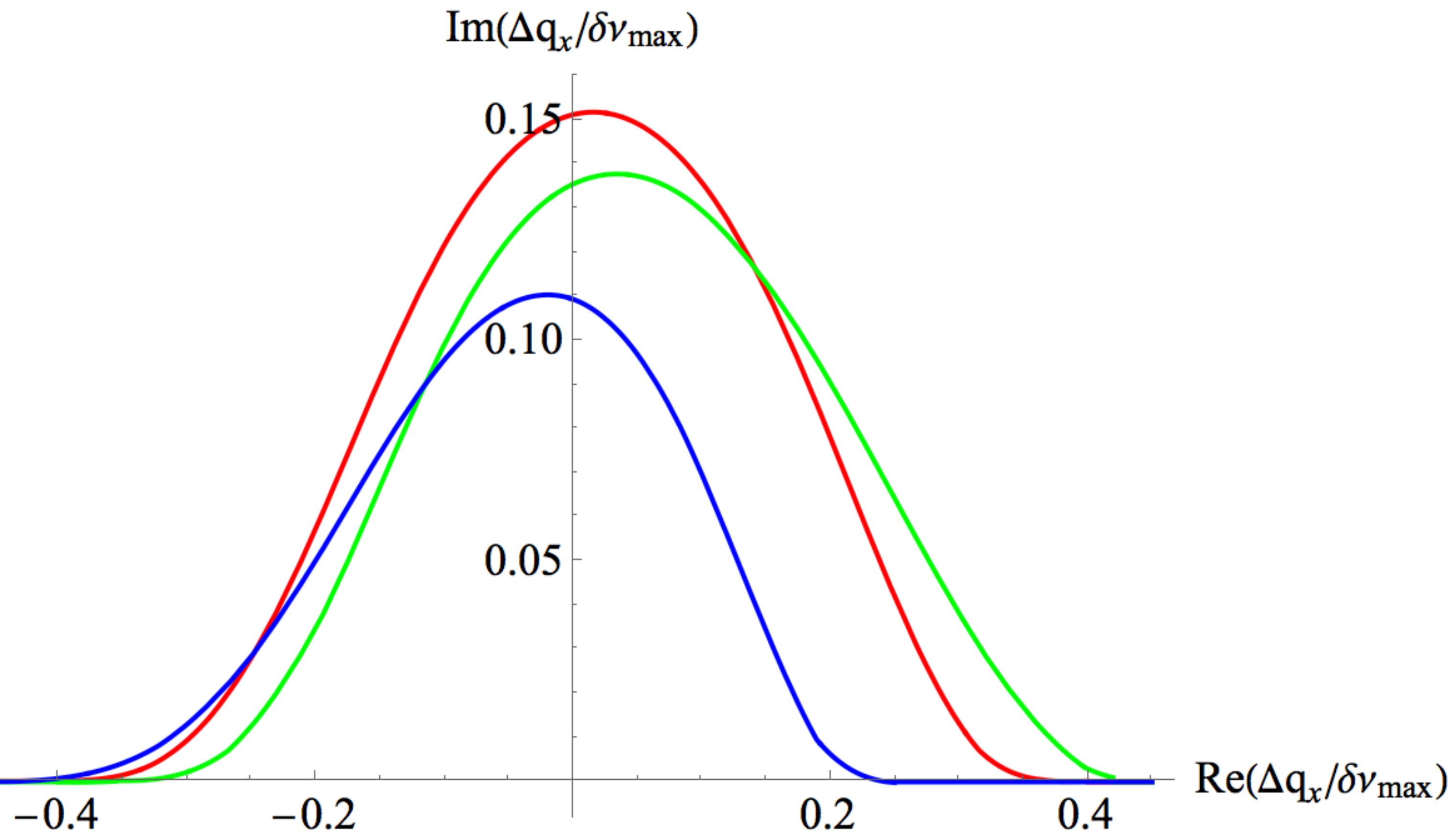
# Vaccaro Diagrams for non-round beam




VDs for non-round beams

# Possible e-lens parameters

| Length | 2 m |
|---|---|
| Beta-functions at e-lens | 1.5 km |
| Electron current | 0.7 A |
| Electron energy | 10 kV |
| E-lens rms radius, $\sigma_e = \sigma_\perp$ | 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.



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# E-Lens Summary

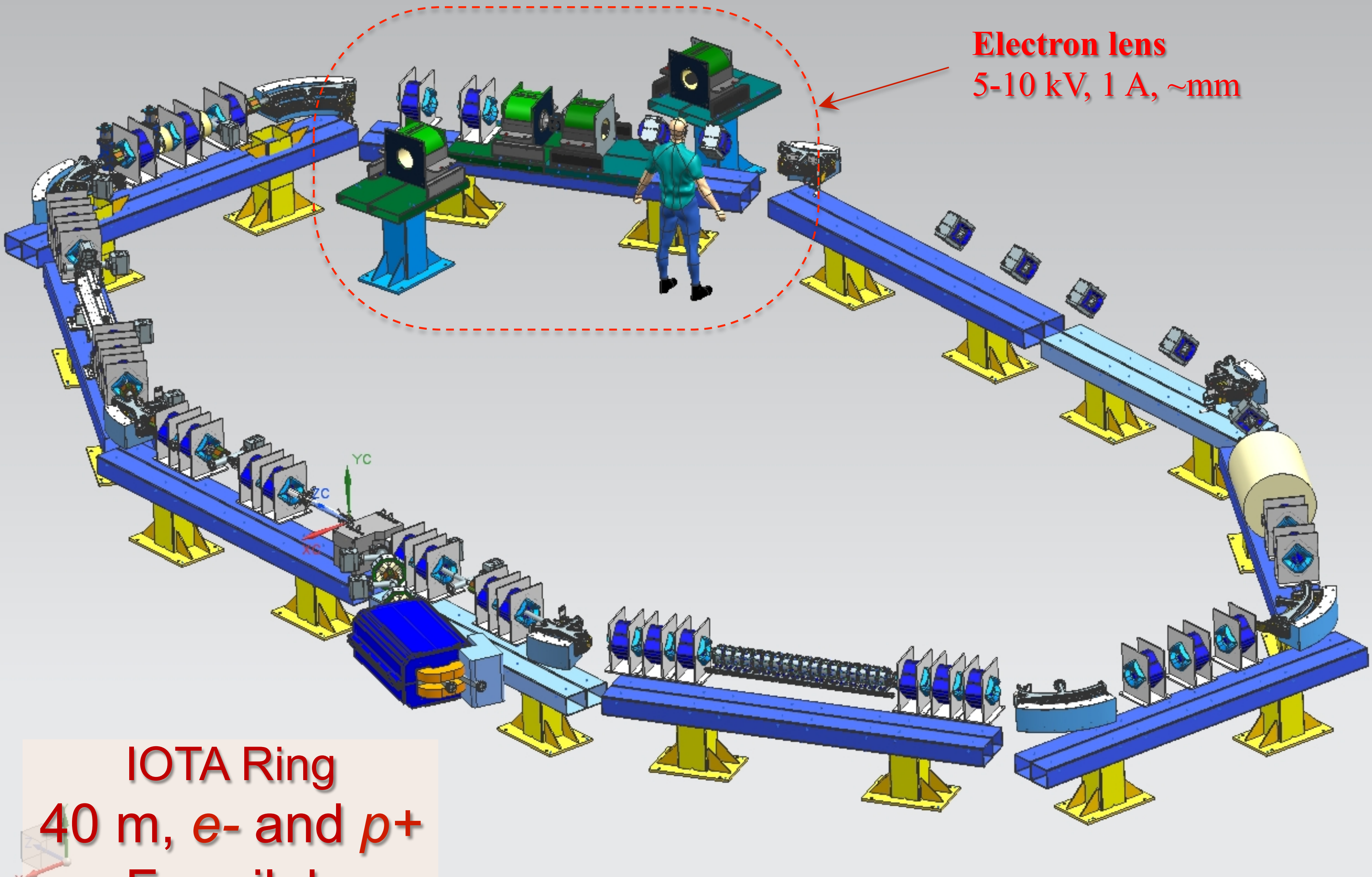
A standard, few meters long e-lens would do the job of 20 000 LHC-type octupoles for the LHC or FCC.

E-lens VD is core-based, so it is robust

E-Lens can vary along the train

A problem of VD reduction can be fully excluded.

# Beam tests possible at RHIC and IOTA

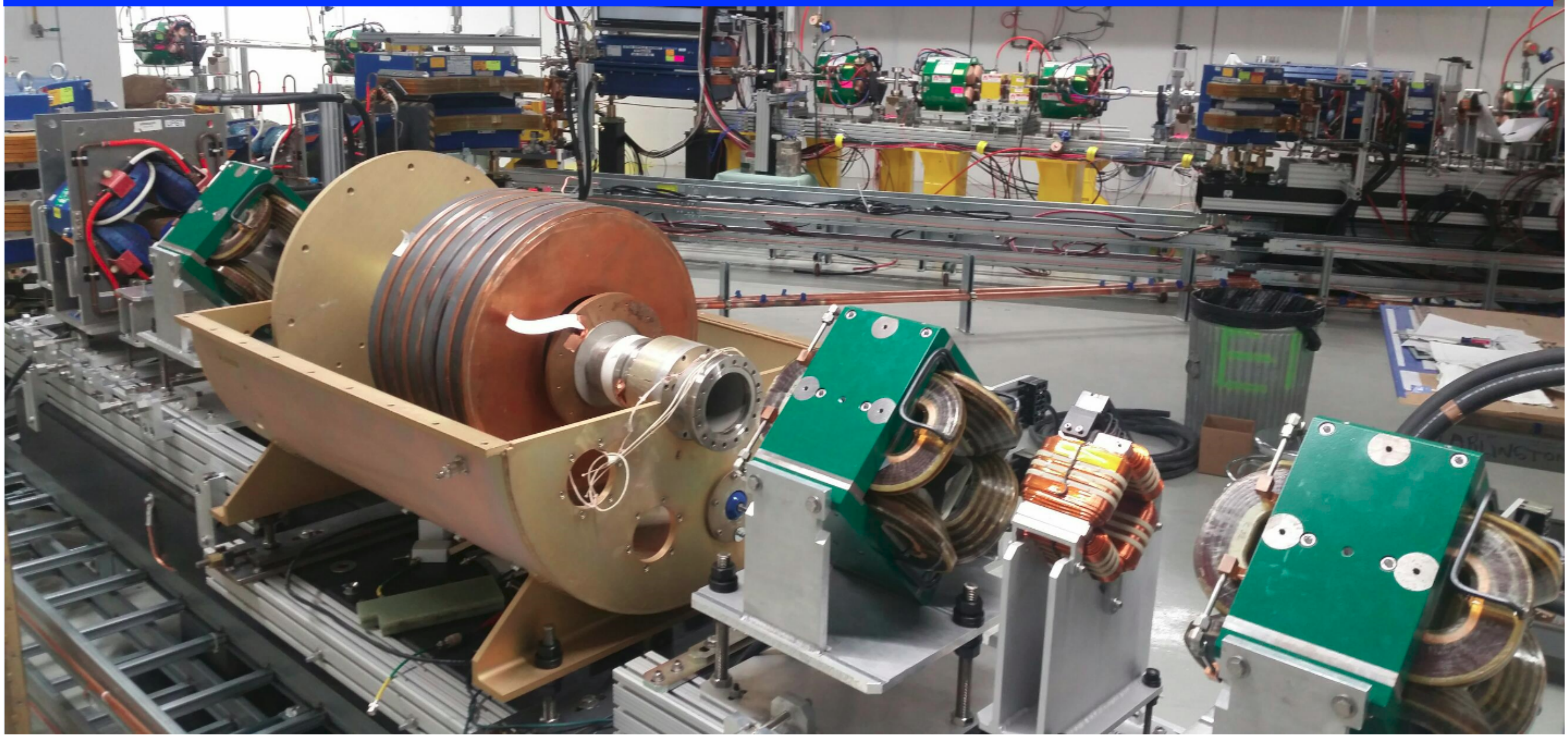



**Electron lens**
5-10 kV, 1 A, ~mm

IOTA Ring
40 m, *e*- and *p*+
Fermilab

# IOTA Ring : Beam Start-up This Summer

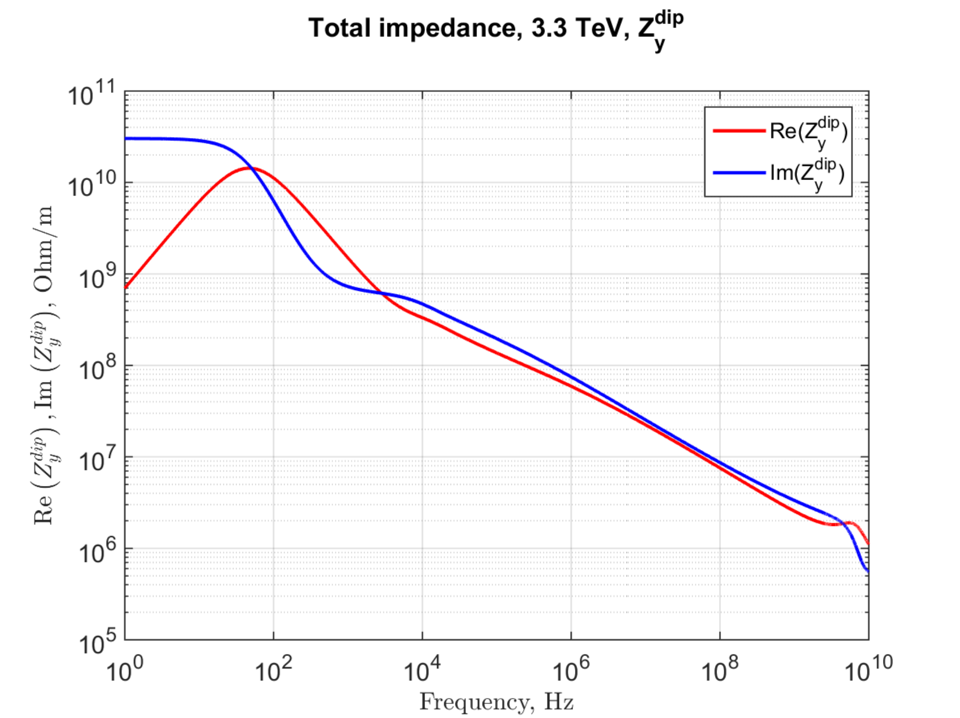
THPMF024  Commissioning and Operation of FAST Electron Linac at Fermilab (A.Romanov)
THPMF025  Emittance Study at FAST (J.Ruan)
THPAF068  Suppression of Instabilities by an Anti-Damper in IOTA (A.Macridin)

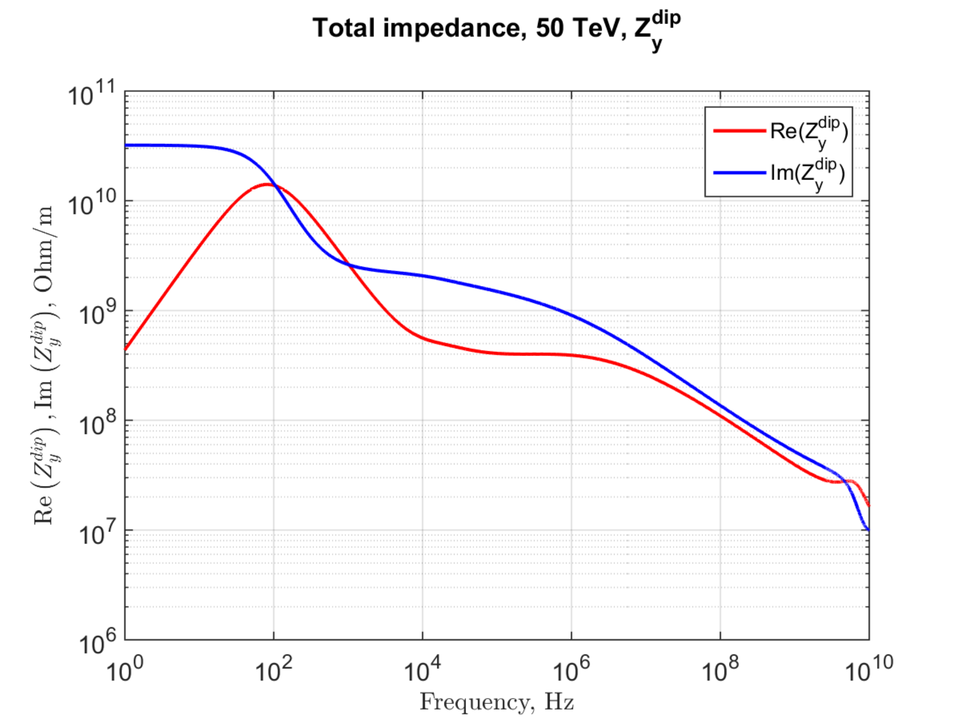


*Many thanks!*

# Transverse Impedances

*by Sergey Arsenyev*




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

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

# Beam Parameters

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 | $1.01354\times10^{-4}$ | |
| Transition gamma γ_tr | 99.33 | |
| Slippage factor η | $1.01273\times10^{-4}$ | $1.01353\times10^{-4}$ |
| RF harmonic number h | 130680 | |
| RF frequency | 400.79 MHz | |
| RF Voltage V | 12 MV | 32 MV |
| Synchrotron tune Qs | $2.76754\times10^{-3}$ | $1.16151\times10^{-3}$ |

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

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# How strong should be the instabilities?

Growth times, rough numbers

| | Injection, 3.3TeV | Top, 50 TeV | damping |
|---|---|---|---|
| CB, 2kHz — 20 MHz | ≥ 100 turns | ≥ 500 turns | damper |
| CB, HOMs, ≥ 1 GHz | ≥ $10^5$ turns | ≥ $10^5$ turns | Landau |
| SB, ≥ 0.5 GHz | ~5000 turns | ~5000 turns | Landau |

CB = coupled-bunch, SB = single-bunch

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# Vaccaro Diagram

Vaccaro diagram (VD) is defined as a map of real axes $\nu$ on the complex plane $\Delta q$ :

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

$$d\Gamma = dJ_x dJ_y$$

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

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

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



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# RF Quads ?

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

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

DA reduction due to the synchro-betatron coupling?