FCC-hh single beam stability

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Updates on:

- Beam pipe impedance
- Beam stability estimates
- Electron cloud buildup estimates and scaling
- Other collective effects

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Resistive wall impedance: LHC and FCC-hh

Growth rate: $\tau^{-1} = \omega_0 \Im \Delta Q$ (Sacherer 1974)

$$\frac{1}{\tau_k} = -\frac{1}{1+k}\frac{\omega_0 q M I_b}{4\pi E_0}\hat{\beta}_y \Re Z_y(\omega_{\min}) F'_k(\omega_{\min} - \chi/\tau_b)$$

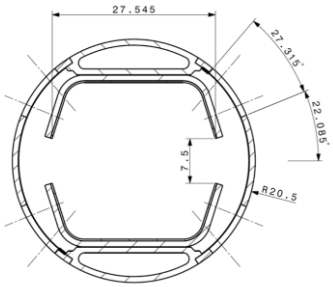
$\chi = Q'\gamma_t^2 \omega_0 \tau_b$

(chromatic phase shift)

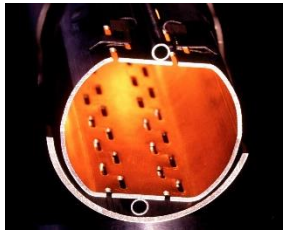
$\omega_{min} = (n - Q_y)\omega_0$

(lowest sideband)

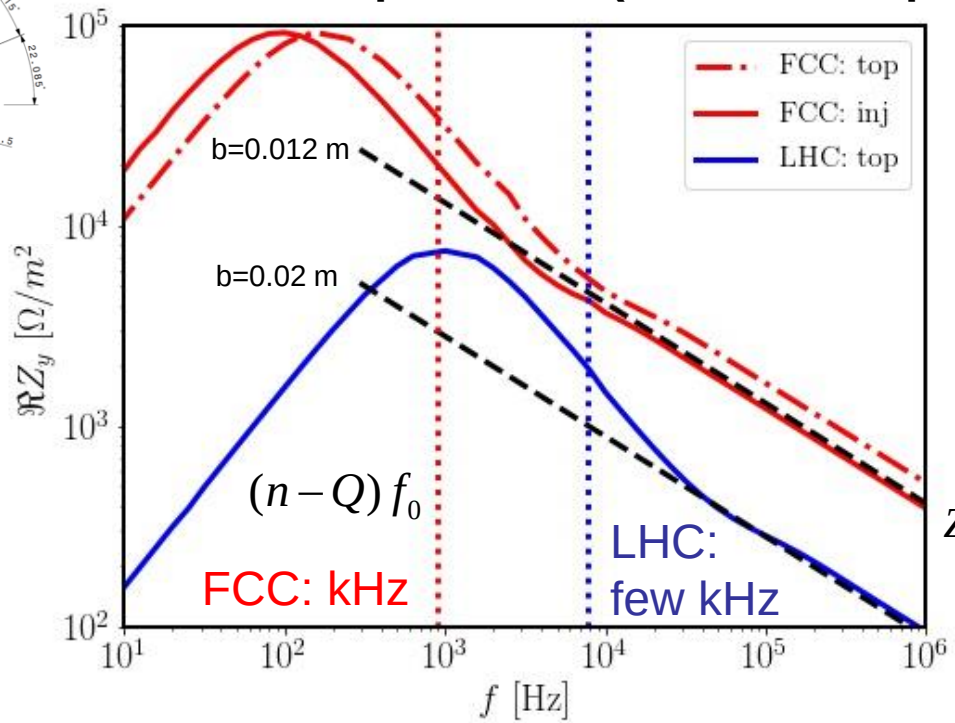
FCC



LHC



Transverse impedances (vertical real part)



$\chi = 0$:

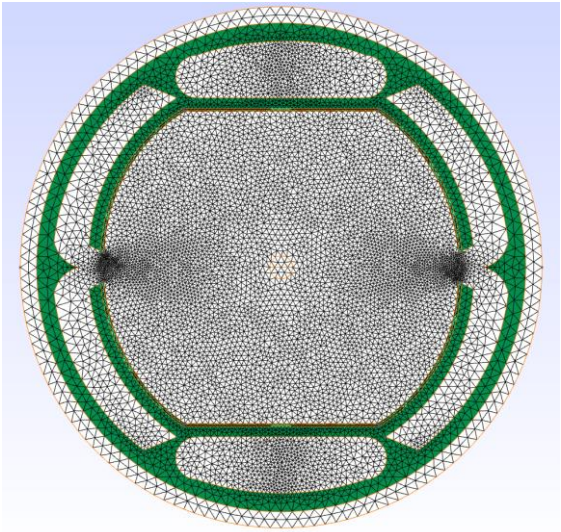
growth time at 3.3 TeV:
approx. 50 turns
at 50 TeV:
approx. 500 turns
LHC at 7 TeV:
approx. 2000 turns

$$Z_\perp(\omega) = (1-i)\frac{c}{\pi\omega b^3 \delta_s \sigma_c}$$

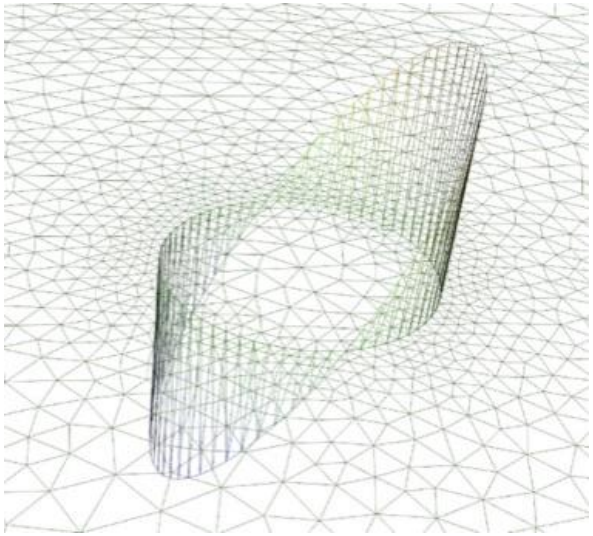
(Thick) resistive wall impedance

2D impedance code in frequency space

- Open source package FEniCS
  (A. Logg, K. Mardal, G. Wells et al.)
- Mesh from GMSH
  (C. Geuzaine, J. Remacle)



(Just an example mesh:
old design !)



Dipolar current source term

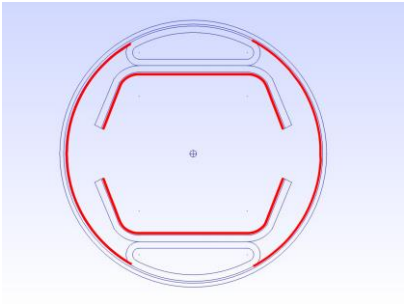
$$\nabla \times \mu^{-1} \nabla \times \mathbf{E} - \omega^2 \epsilon \mathbf{E} = -i\omega \mathbf{J}_s$$

U. Niedermayer *et al*., **Space charge and resistive wall impedance computation in the frequency domain using the finite element method**, Phys. Rev. ST-AB 18, 032001, 2015

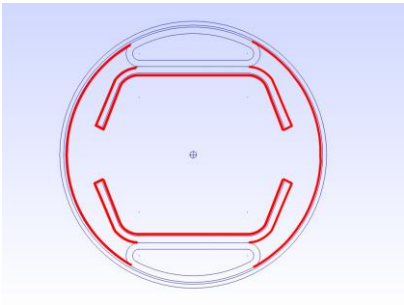
BeamImpedance2D (PYTHON): https://bitbucket.org/uniederm/beamimpedance2d.git

FCC pipe: Vertical vs Horizontal

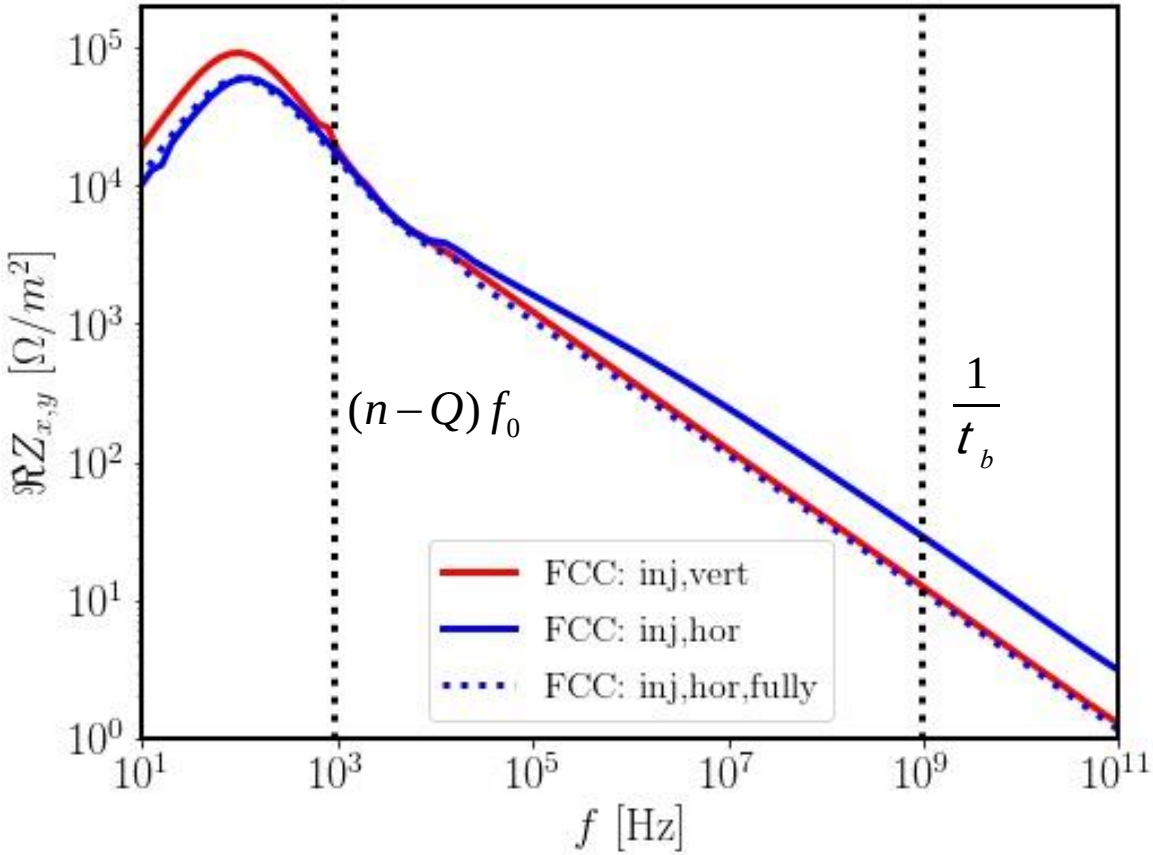
Design Cu coating (d=0.3/0.1 mm)



‚Full' Cu coating (d=0.3/0.1 mm)



Design vs Full: Increased horizontal impedance



Single bunch TMCI threshold: Imaginary part

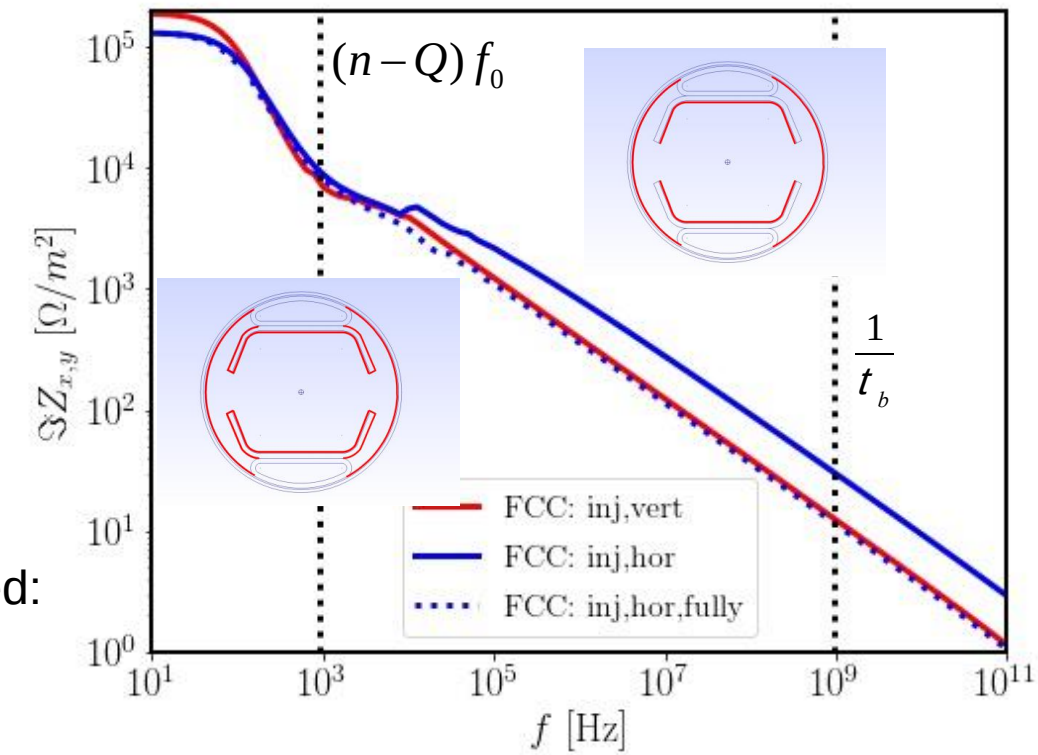
$$\Re \Delta Q_{k=0} \approx Q_s$$

(tune shift)

$$Q_s = \frac{\Delta E}{g_t^2 w_0 E_0 t_b}$$

(synchrotron tune)

$$Z_{x,k}^{eff} = \frac{\sum_p \hat{\beta}_x Z_x(\omega_p) \,|\, \Delta_k(\omega_p - \omega_\xi) \,|^2}{\langle \hat{\beta}_x \rangle \,|\, \Delta_k(\omega_p - \omega_\xi) \,|^2}$$



TMCI threshold bunch intensity:

$$N_b^{th} \approx \frac{4\pi \Delta E}{w_0 e^2 \hat{b}_y g_t^2 \Im Z_{y,0}^{\text{eff}}}$$

Fully Cu coated:

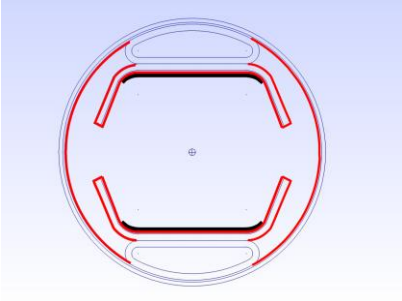
$$\frac{N_b^{th}}{N_b} \gg 6$$

Partially Cu coated:

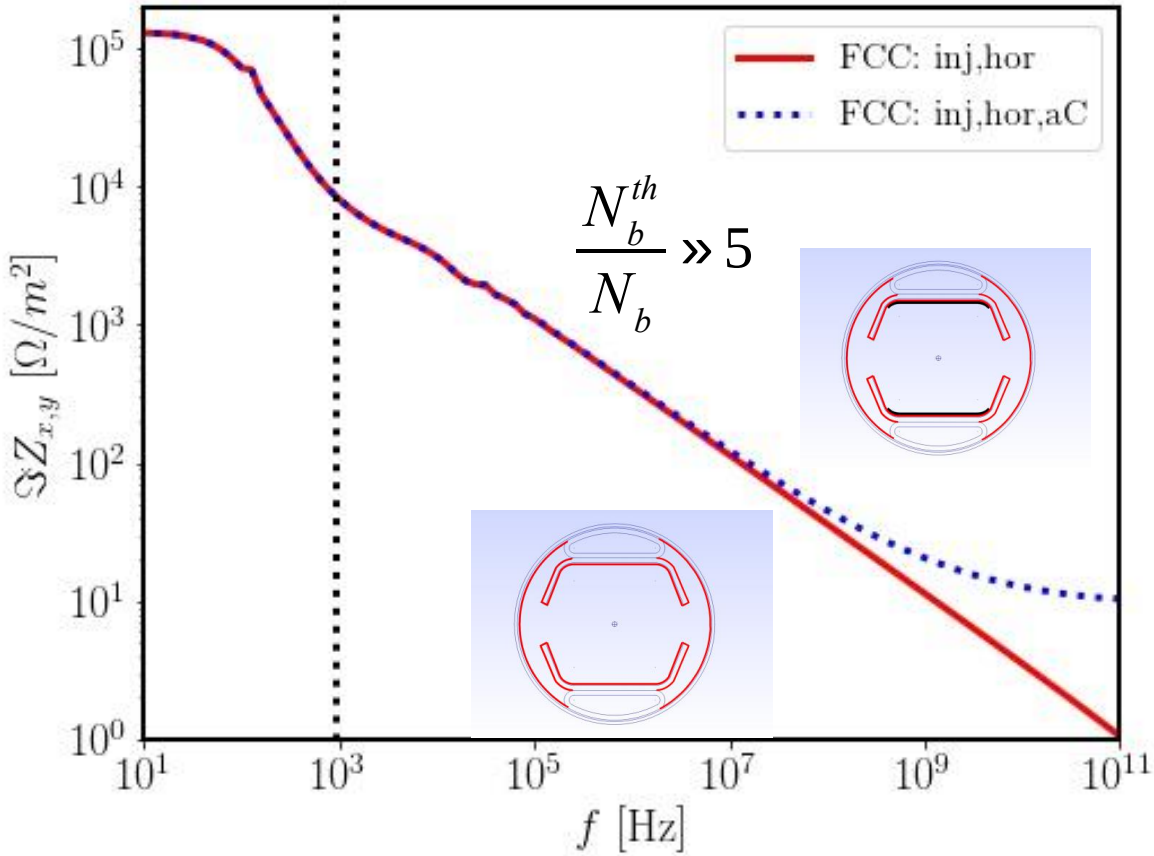
$$\frac{N_b^{th}}{N_b} \gg 3$$

FCC pipe: a-C coating

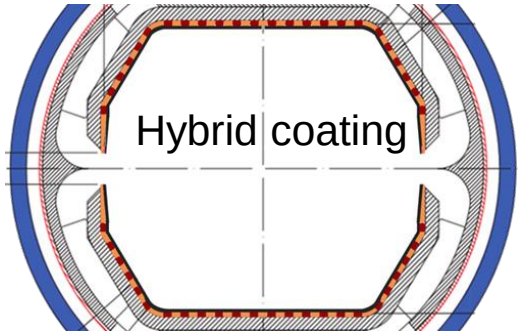
Pipe with a-C coating (1 μm)



Remark: For an SEY of about 1 the coating can be much thinner, for example only 30 nm.
P.Pinto (CERN)

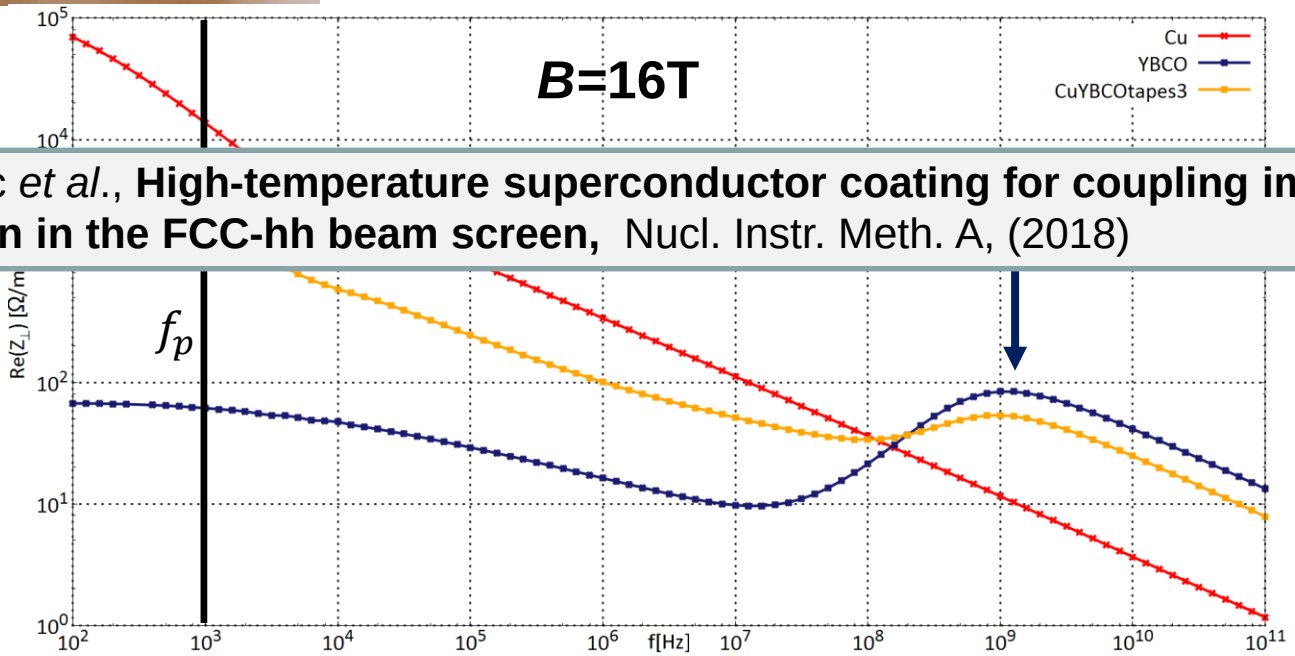


HTS coated FCC screen



Hybrid coating (HTS stripes):

- Possible reduction of the resistive wall instability growth rates by factor 5-6.
- TMCI thresholds !



P. Krkotic *et al*., **High-temperature superconductor coating for coupling impedance reduction in the FCC-hh beam screen,** Nucl. Instr. Meth. A, (2018)

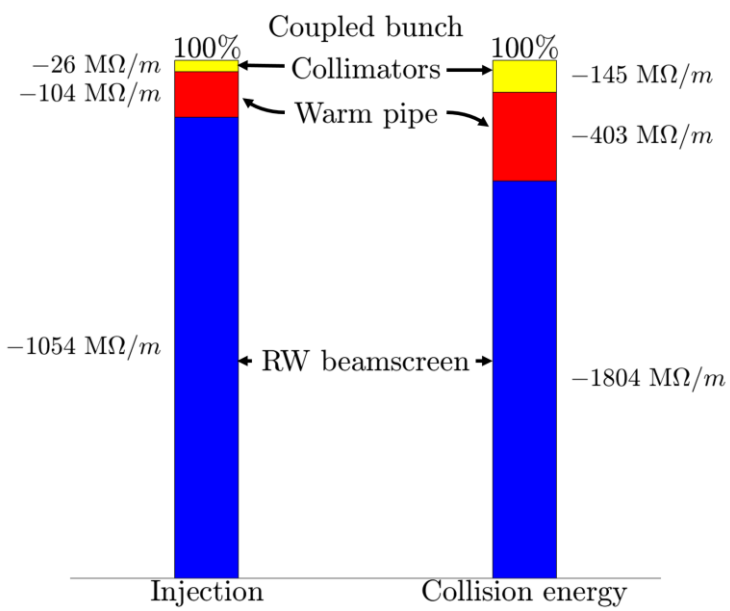
P. Krkotic,
U. Niedermayer

Impedance contributions and database

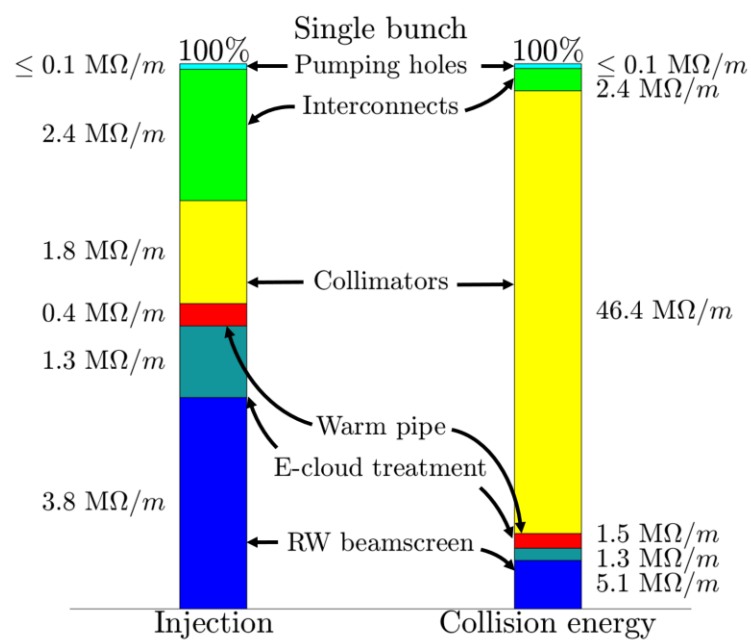
$$Z_{x,k}^{eff} = \frac{\sum_p \hat{\beta}_x Z_x(\omega_p) \mid \Delta_k(\omega_p - \omega_\xi) \mid^2}{\langle \hat{\beta}_x \rangle \mid \Delta_k(\omega_p - \omega_\xi) \mid^2}$$

$\Delta_k(\omega)$: Spectrum of head-tail modes

Example: Coupled bunch instability



Example: TMCI



S. Arsenyev (IPAC 18)

Beam stability: LHC vs FCC

Growth rate for transverse coupled bunch instabilities: $\tau^{-1} \mu \omega_0 \frac{q^2 N_b}{m\gamma l_{bb}} \hat{\beta}_y \hat{A} Z_\wedge$

TMCI single bunch threshold bunch intensity: $N_b^{th} = \frac{4\pi \Delta E}{\omega_0 e^2 \hat{\beta}_y \gamma_t^2 \Im Z_{y,0}^{\mathrm{eff}}}$

- Larger circumference (5:1) -> lower frequency: **1 kHz vs 8 kHz**
- Smaller screen diameter (2:3) -> **larger impedance** (factor 3)
- screen temperature: 50 K (5:2), maximum field 16 T (2:1) -> **changed conductivites**
- Larger average β-function (2:1) -> **growth rates**
- Smaller beams (1:3) -> weaker **Landau damping**, **e-cloud thresholds**
- LHC-like bunches and 25 ns spacing (1:1)

Space charge in the FCC ?

$$\Delta Q_{sc} \propto \frac{q^2 N_b}{\tau_b \varepsilon_{n,y} \gamma^2}$$

(space charge tune shift)

$$Q_s = \frac{\Delta E}{\gamma_t^2 \omega_0 E_0 \tau_b}$$

(synchrotron tune shift)

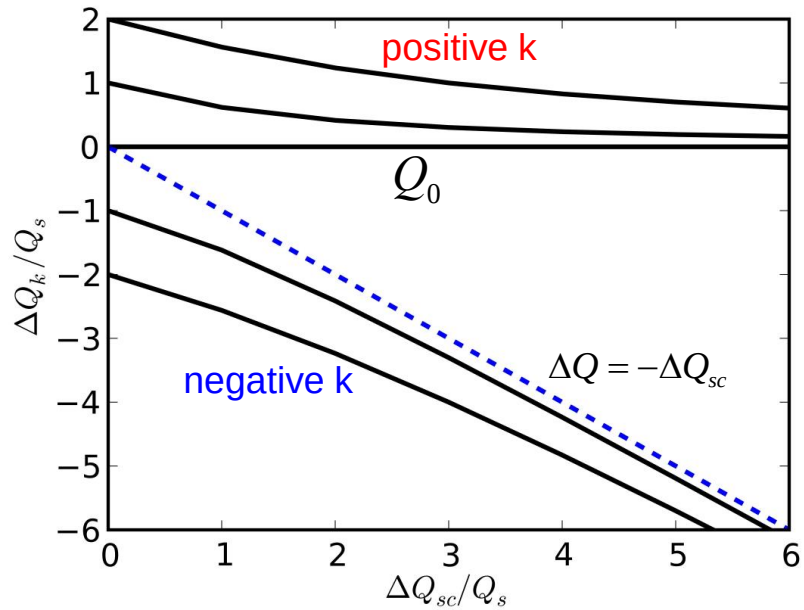
$$\frac{\Delta Q_k}{Q_s} \approx -\frac{1}{2}\frac{\Delta Q_{sc}}{Q_s} + k$$

with

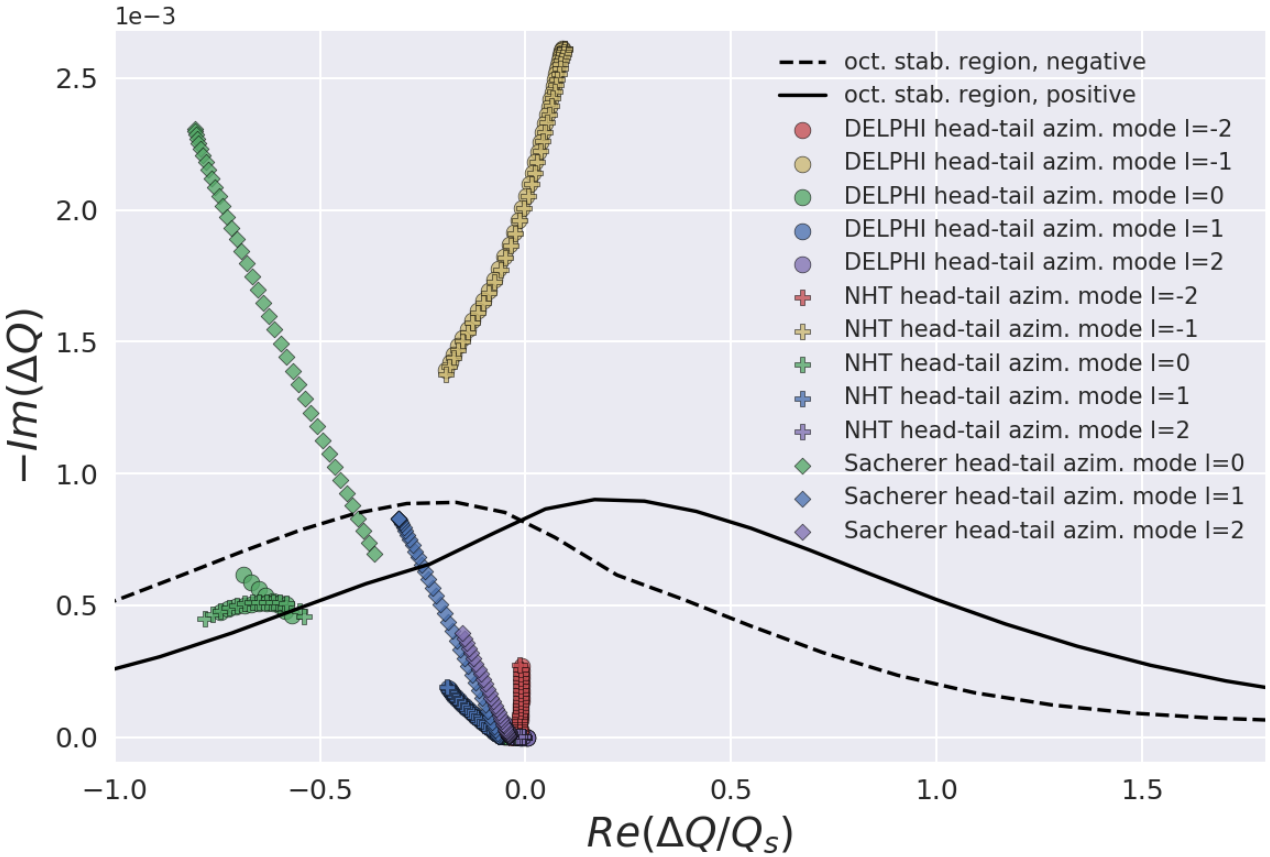
$$\frac{\Delta Q_{sc}}{Q_s} \propto \frac{\gamma_t^2 \omega_0 N_b}{\gamma \Delta E}$$

Head-tail tune shift with space charge:

$$\Delta Q_k = Q_k - Q_0 = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{(\Delta Q_{sc}/2)^2 + (k Q_s)^2}$$



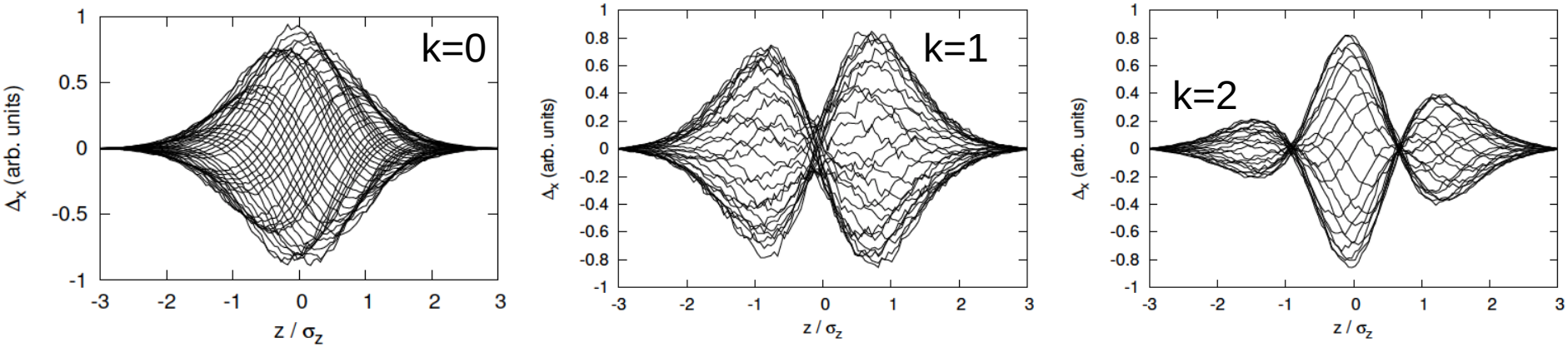
Multibunch mode coupling vs Sacherer‘s formula



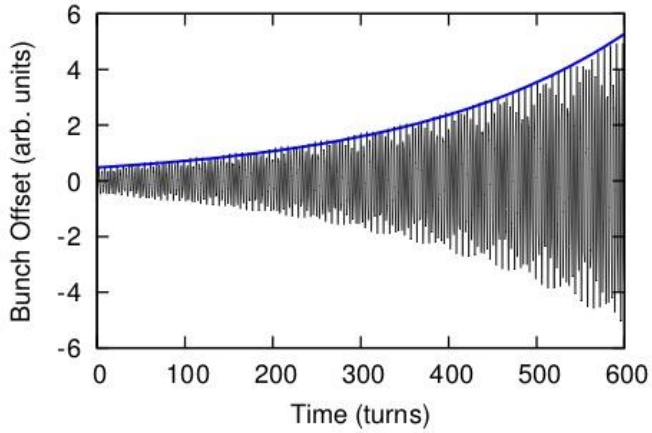
Klinkenberg, Arsenyev, Schulte

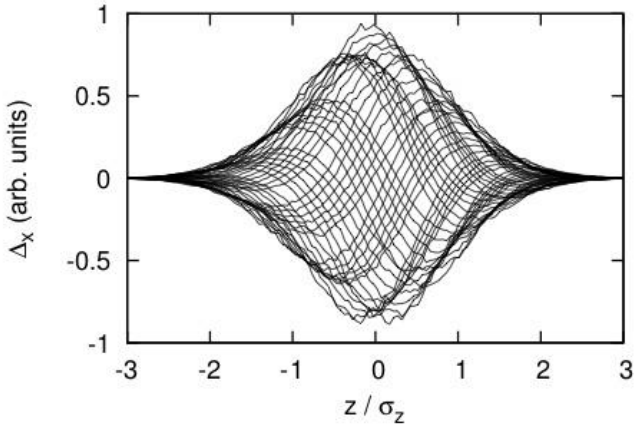
Landau damping of head-tail modes

Head-tail modes (including the k=0 mode) are not rigid-bunch modes:

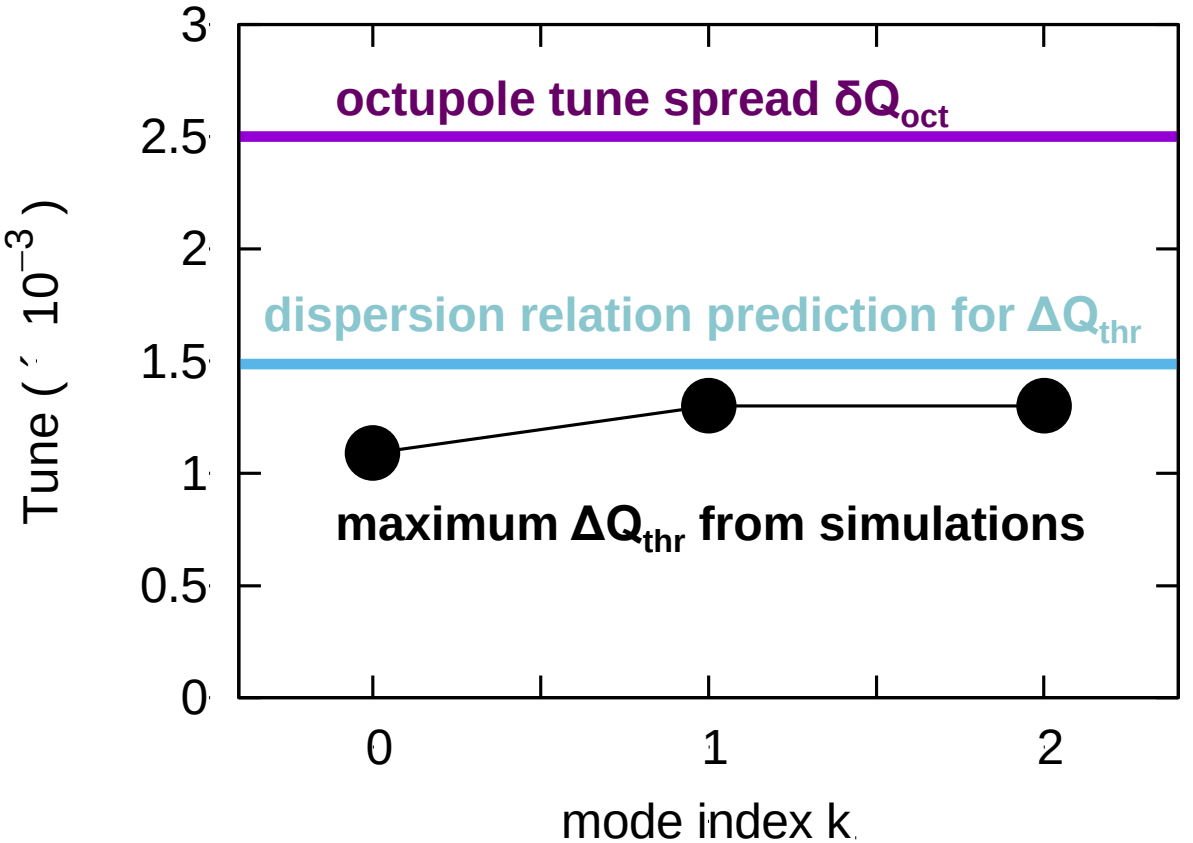


Particle tracking with octupoles and resistive wall wake.





Landau damping with octupoles: Results of particle tracking



- Octupoles provide a similar stabilization for higher-order modes
- The 2D “rigid-bunch” dispersion relation can be applied to ”non-rigid” modes
- Octupoles: reliable well-understood damping mechanism
- For k>0: fewer octupoles needed (lower growth rates)
- The k=0 mode will be stabilized by feedback systems.

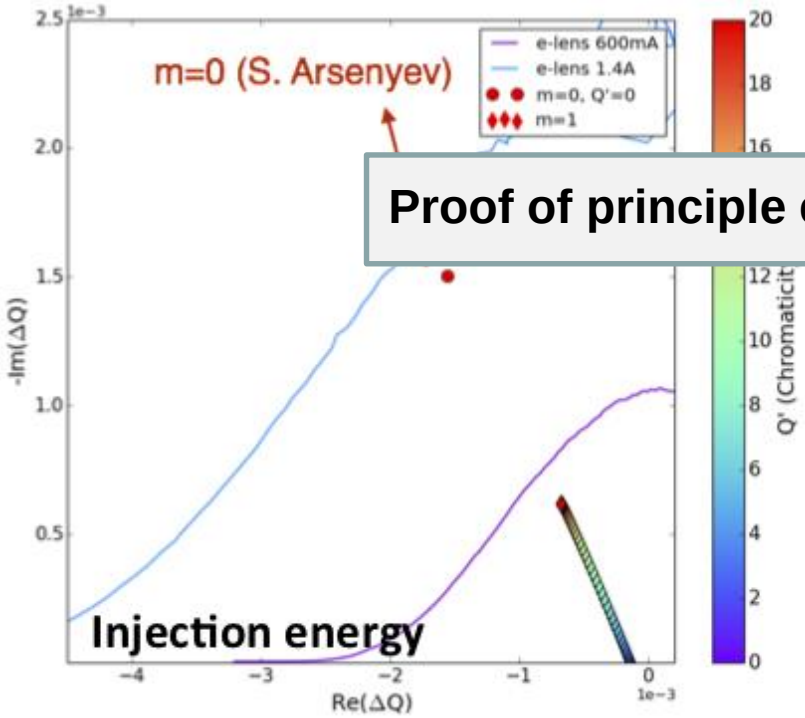
V. Kornilov

Landau damping: Electron lenses

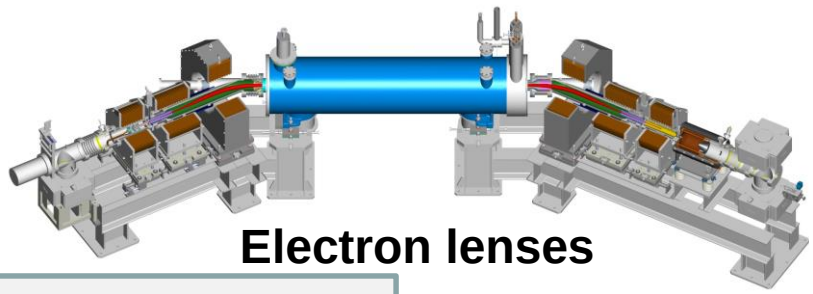
Tune shift: $\Delta Q_x^e(J_x,J_y) \approx 2\Delta Q^e(1 - aJ_x - aJ_y)$

Similar to the beam-beam force !

$$\Delta Q_x^e(J_x,J_y) = 2\Delta Q^e \int_0^{1/2} \frac{I_0(\hat{J}_x u) - I_1(\hat{J}_x u)}{\exp(\hat{J}_x u + \hat{J}_y u)} I_0(\hat{J}_y u)\, du$$



T. Pieloni, C. Tambasco (2018)



Electron lenses

Proof of principle experiment in LHC required !

ed by a counter-propagating electron beam:

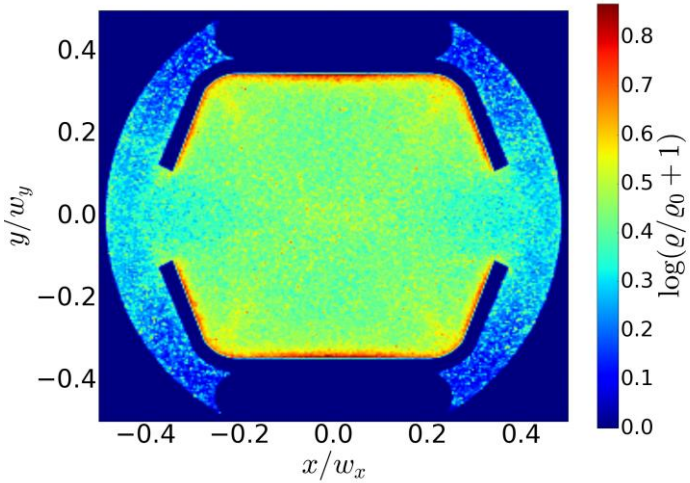
$$\Delta Q_x^e = \frac{1+\beta_e}{\beta_e} \frac{I_e l r_p}{2\pi e c \varepsilon_x}$$

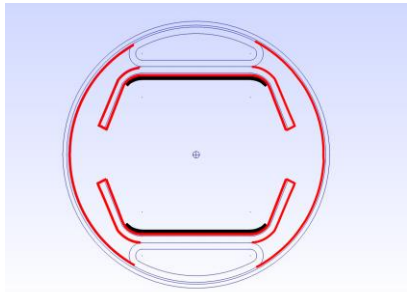
V. Shiltsev et al., PRL (2017)

Example: One lens (l=2 m, I_e=1 A) in LHC would provide a tune spread similar to the 168 octupoles.

Electron cloud buildup and scaling

Example from openECLOUD:
Saturated e-cloud density in FCC drift section without a-C coating

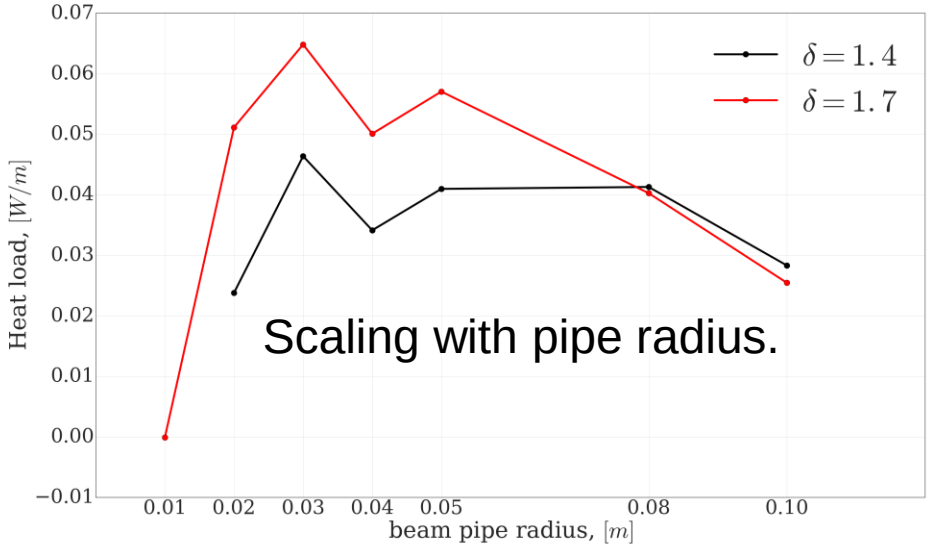




D. Astapovych

Questions (to the simulations):

- Minimum a-C coated area
- Scaling of buildup / heat-load with beam energy (and pipe radius)



Scaling with beam energy (beam radius):
A new <u>gridless</u> ecloud-code code has been developed !

Summary and outlook

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- ✓ Impedance contributions and database
- ✓ Landau damping and requirements: Octupoles and electron lens
- ✓ Electron cloud buildup thresholds (SEY requirements)

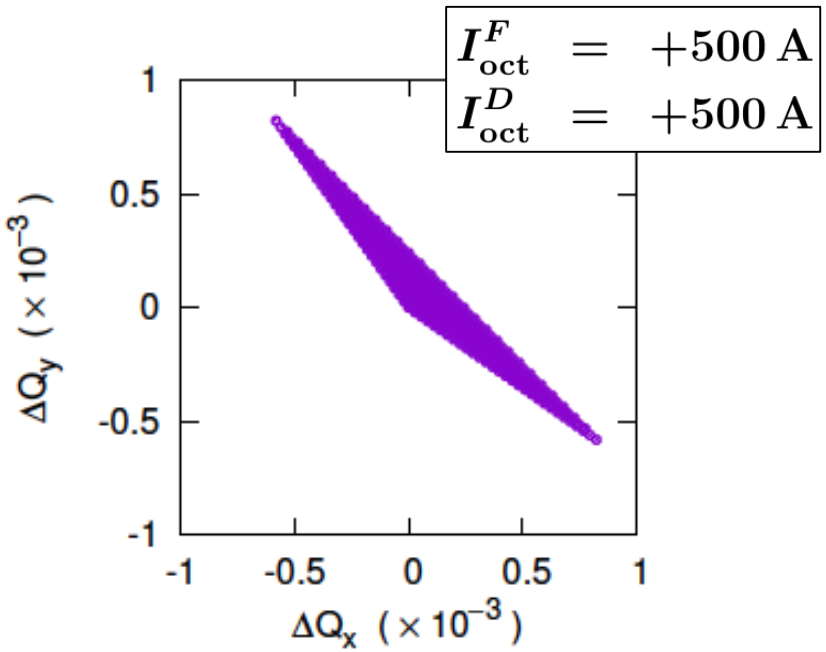
-> CDR input

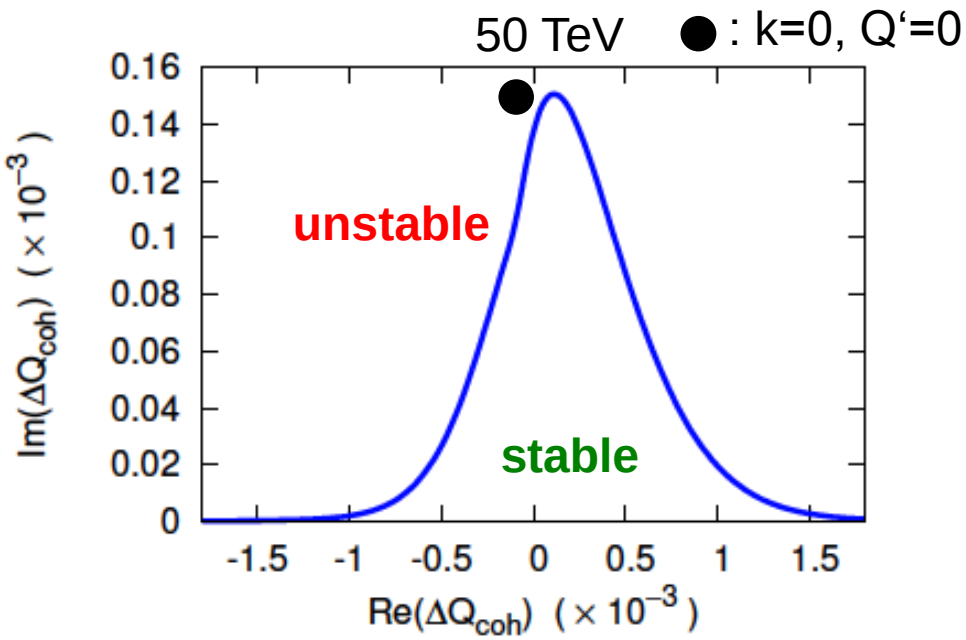
To do:

- Role of mode coupling for coupled bunches in FCC
- Proof of principle experiments with electron lenses
- Electron cloud and other sources of tune shifts: Beam stability
- ….

Backup

Stability with octupoles: FCC top energy





FCC-hh

For the ΔQ_{coh}−Damping as in LHC:
3554 LHC-octupoles.
508 Advanced-technology octupoles.

V.Kornilov

Octupoles and Landau damping

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Tune shifts from octupoles:

$$\Delta Q_x = a_x J_x - b_{xy} J_y$$
$$\Delta Q_y = a_y J_y - b_{xy} J_x$$

($J_{x,y}$: actions variables)

Scaling with energy:

$$\Rightarrow N_{oct} L_m \propto \mathrm{E}_0^2$$

From LHC to FCC-hh:
7^2 x 168 octupoles

$E_0 = \gamma_0 mc^2$

L_m: length of magnet

N_{oct}: # of magnets

2D dispersion relation [1-3]:

$$1 = \Delta Q_{\mathrm{coh}} \int \frac{1}{\Delta Q_{\mathrm{oct}} - \Omega/\omega_0} J_x \frac{\partial \psi_\perp}{\partial J_x} dJ_x dJ_y$$

[1] H. G. Hereward, CERN 65-20 (1965)
[2] J. S. Berg, F. Ruggiero, CERN SL-AP-96-71 (1996)
[3] J. Gareyte, CERN-LHC-Project-Report-91 (1997)

2D beam distribution: $\psi_\perp(J_x, J_y) = e^{-(J_x + J_y)}$

rms tune spread: $\delta Q_{x,y} = \langle \Delta Q_{x,y}(J_x, J_y) \rangle$

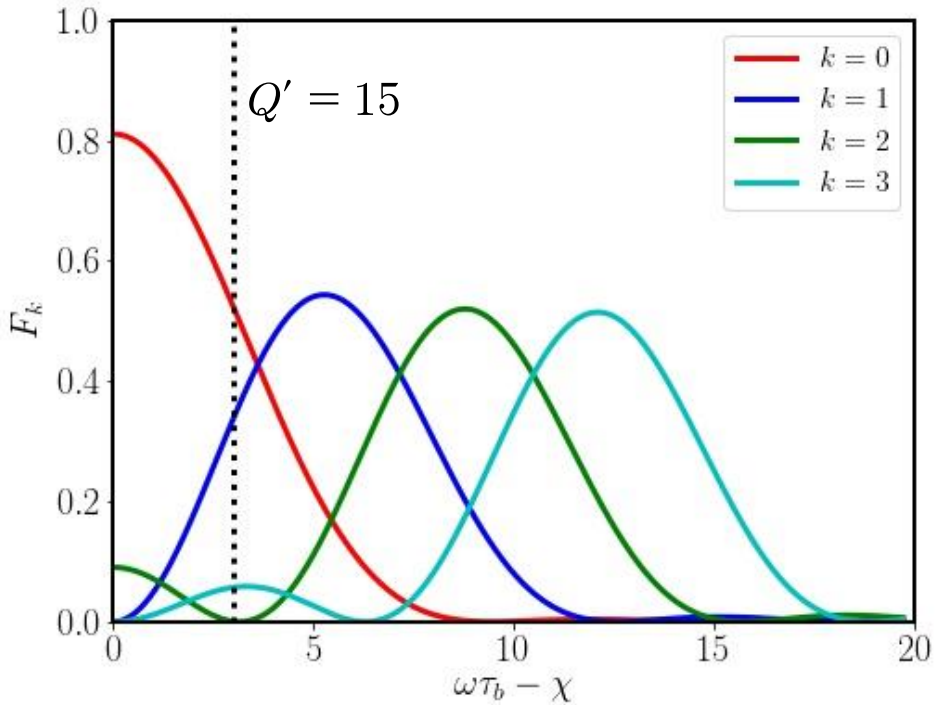
$$|\Delta Q| \lesssim \delta Q$$

$$\tau^{-1} = \omega_0 \Im \Delta Q$$

Very approximate stability condition

Finite chromaticity

Form factor for different k



Example case Q'=15: the growth rates for the k=0 coupled bunch mode would be lower by a factor 0.6, but the k=1 mode would be present in addition (growth rate corresponding to 650 turns at injection).

(Sacherer 1974)

Landau damping: Scaling with energy

The good news: $\frac{1}{\tau} \propto \frac{1}{E_0}$ (instability growth rate)

The OK news: $\delta Q_{oct} \approx (\omega_0 \tau)^{-1} \propto \frac{L}{E_0}$ (tune spread required for LD)

The bad news: $\delta Q_{oct} \approx N_{oct} L_m \frac{\varepsilon}{E_0^2}$ (tune spread provided by octupoles)

$E_0 = \gamma_0 m c^2$

L: circumference

L_m: length of magnet

N_{oct}: # of magnets

ε: normalized emittance

$$\Rightarrow N_{oct} L_m \propto \mathrm{E}_0^2$$

From LHC to FCC-hh: 7^2 x 168 octupoles

Landau damping: Possible alternative schemes

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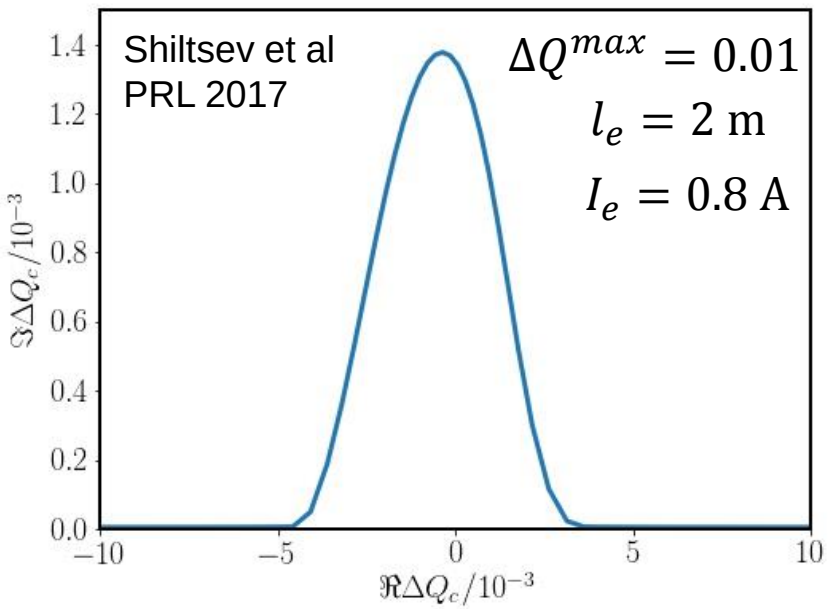
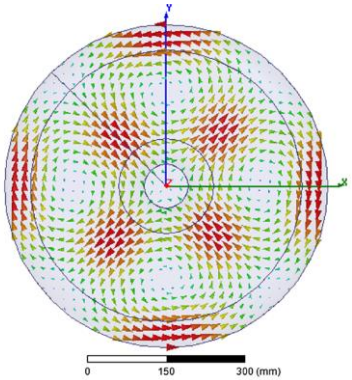
FCC-hh: Active feedback for k=0 modes, Landau damping for k>1.
Still, additional Landau damping concepts are helpful !

LHC: 10 x larger stability area then with octupoles



Radio-Frequency Quadrupole (RFQ)



Grudiev PRAB 2014
Schenk et al, IPAC17

$$\Delta Q_{x,y}(z) = \pm \frac{q\hat{\beta}_{x,y} k^{(2)}}{4\pi m \gamma_0} \cos\left(\frac{\omega_{rf} z}{c} + \phi\right)$$

$\delta Q_{x,y} \propto J_z$ (longitudinal action)

No local spread (in z) !
Dispersion relation and Landau damping ?

Detailed particle tracking studies are ongoing (see also V. Kornilov).

Electron cloud: Tune shift and relativistic limit

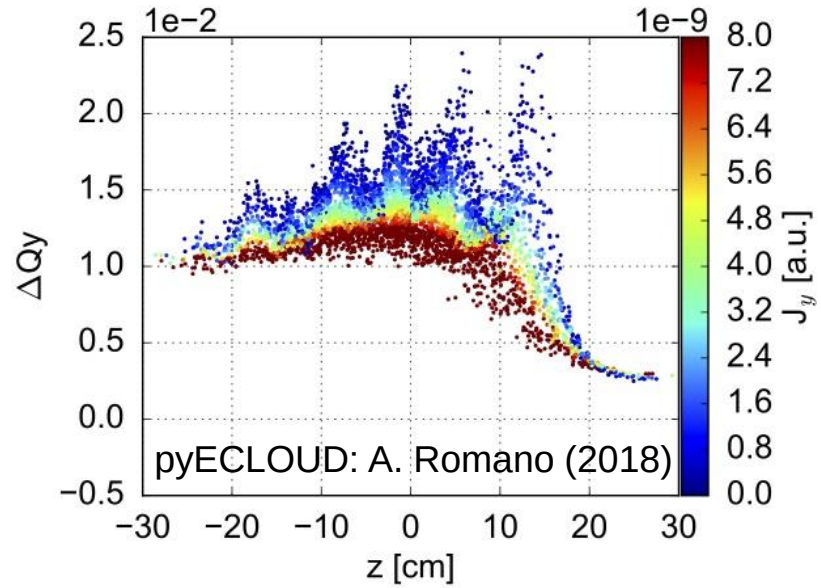
Tune shift induced by the pinch along the bunch

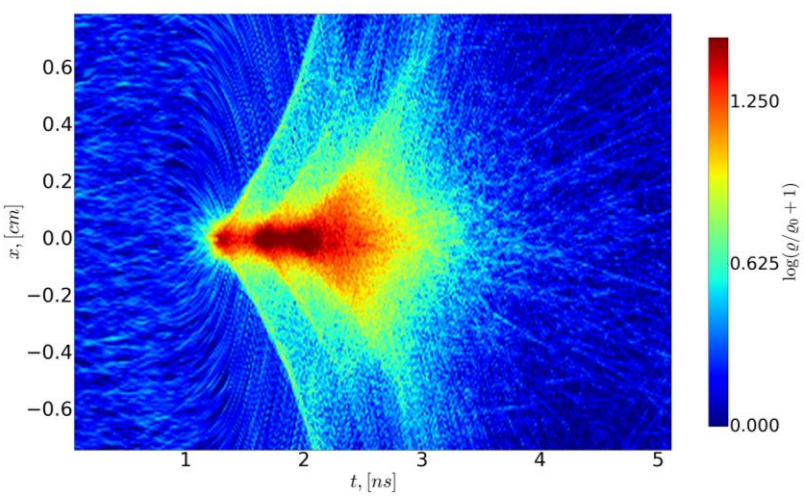
$$\Delta Q_x(z) = \frac{r_p L b_y}{\gamma_0 (b_x + b_y)} \bar{\rho} \lambda_e(z) \qquad \bar{\rho} \approx \frac{E_s}{\pi m_e c^2 r_e b^2}$$

(b: pipe radius)

Furman, Zholents, PAC 1999
Petrov, Boine-Frankenheim, PRAB 2014

Tune shift potentially effects Landau damping (see for example Burov 2013).





Electron space charge field **E** and instability thresholds in the **ultrarelativistic limit** $a \to 0$

$$\rho_b(r,z) \to \delta(r)\lambda(z) \qquad \epsilon_0 \nabla \cdot \mathrm{E} = \rho_e$$

$$\omega_e = \frac{\sqrt{\lambda_b r_e c^2}}{a} \to \infty$$

D. Astapovych