

FCC-hh single beam stability



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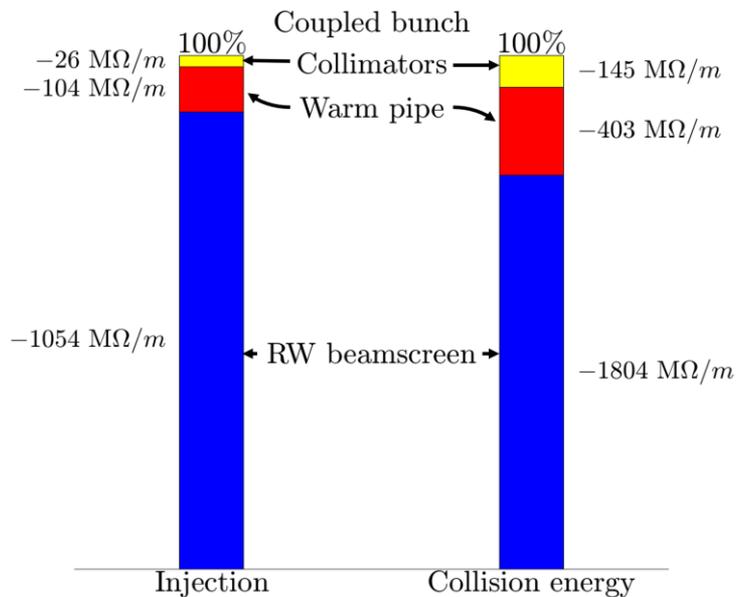


Impedance contributions and database

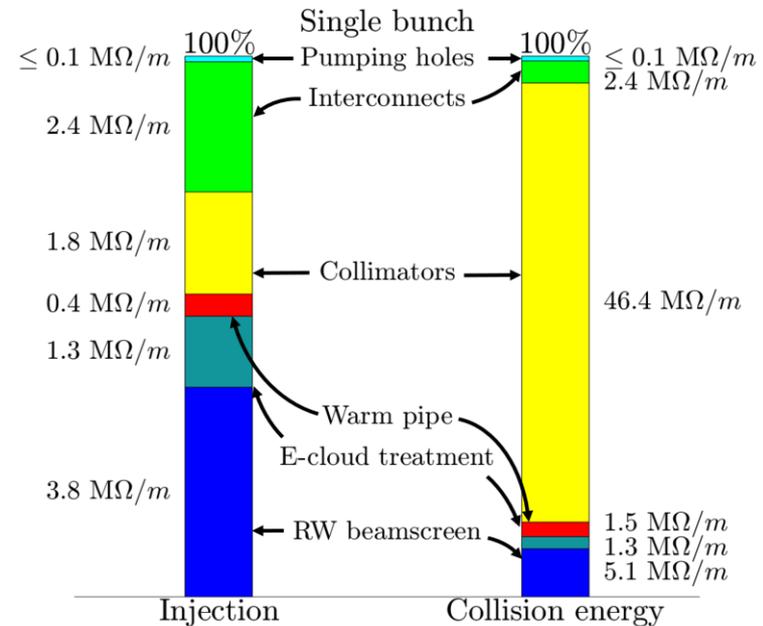
$$Z_{x,k}^{eff} = \frac{\sum_p \hat{\beta}_x Z_x(\omega_p) |\Delta_k(\omega_p - \omega_\xi)|^2}{\langle \hat{\beta}_x \rangle |\Delta_k(\omega_p - \omega_\xi)|^2}$$

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

Example: Coupled bunch instability



Example: TMCI



S. Arsenyev (2018)

Resistive wall impedance: LHC and FCC-hh

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

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

FCC

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

(chromatic phase shift)

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

(lowest sideband)

Transverse impedances (only real part)

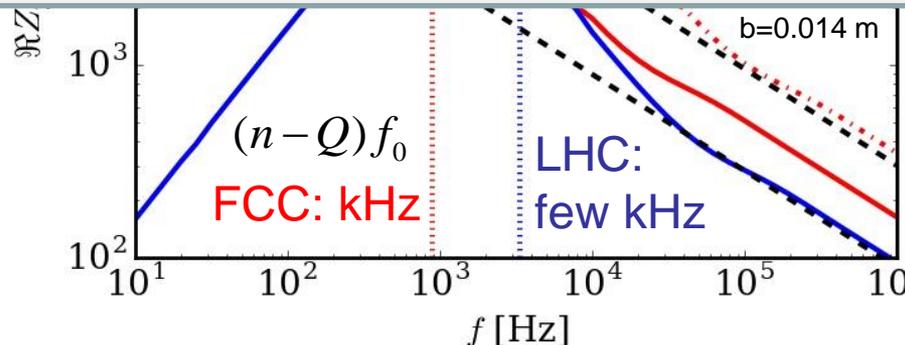


P. Krkotic *et al.*, **High-temperature superconductor coating for coupling impedance reduction in the FCC-hh beam screen**, Nucl. Instr. Meth. A, (2018)



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

LHC

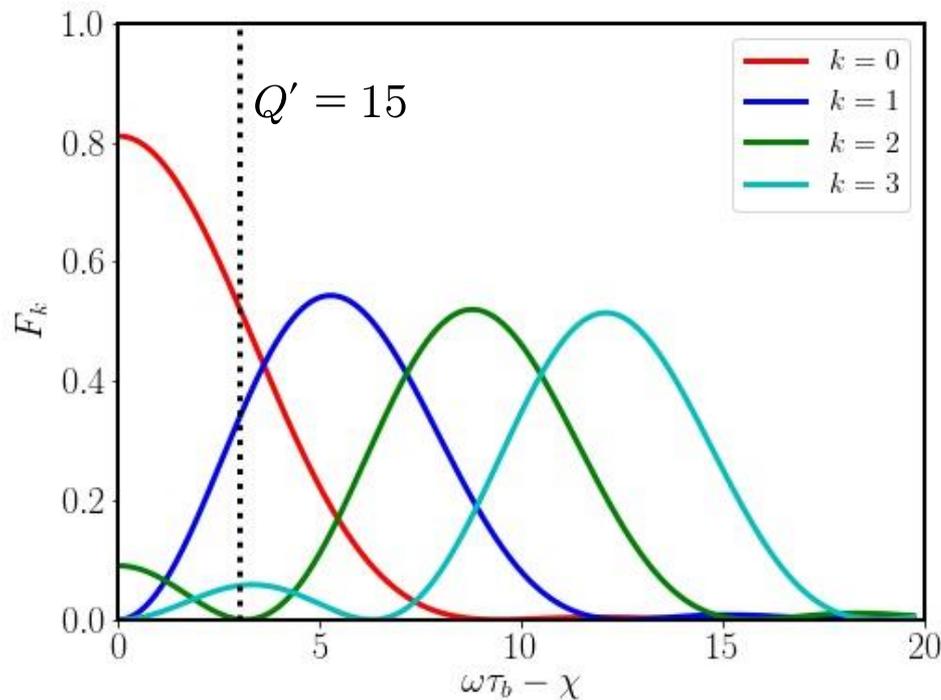


LHC at 7 TeV.
approx. 2000 turns

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

(Thick) resistive wall impedance

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)

Octupoles and Landau damping

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:

$$\Rightarrow N_{oct} L_m \propto E_0^2$$

From LHC to FCC-hh:
7² x 168 octupoles

$$E_0 = \gamma_0 m c^2$$

L_m : length of magnet

N_{oct} : # of magnets

2D dispersion relation [1-3]:

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

[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:

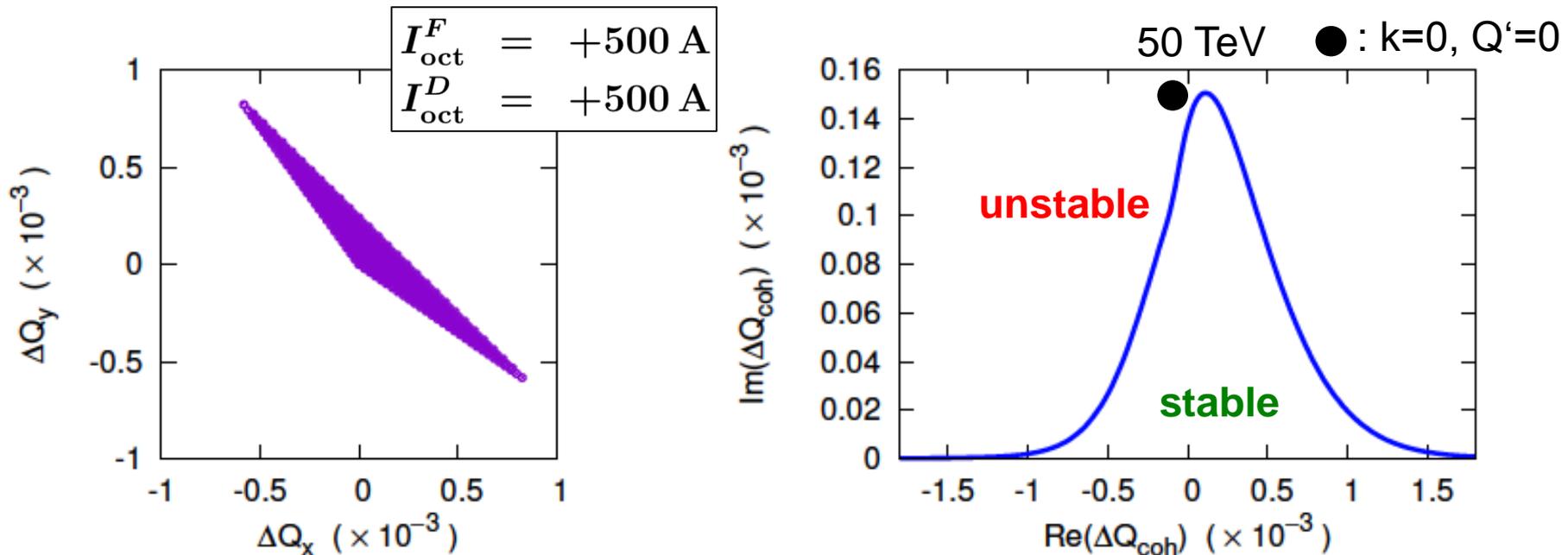
$$\delta Q_{x,y} = \langle \Delta Q_{x,y}(J_x, J_y) \rangle$$

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

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

Very approximate stability condition

Stability with octupoles: FCC top energy

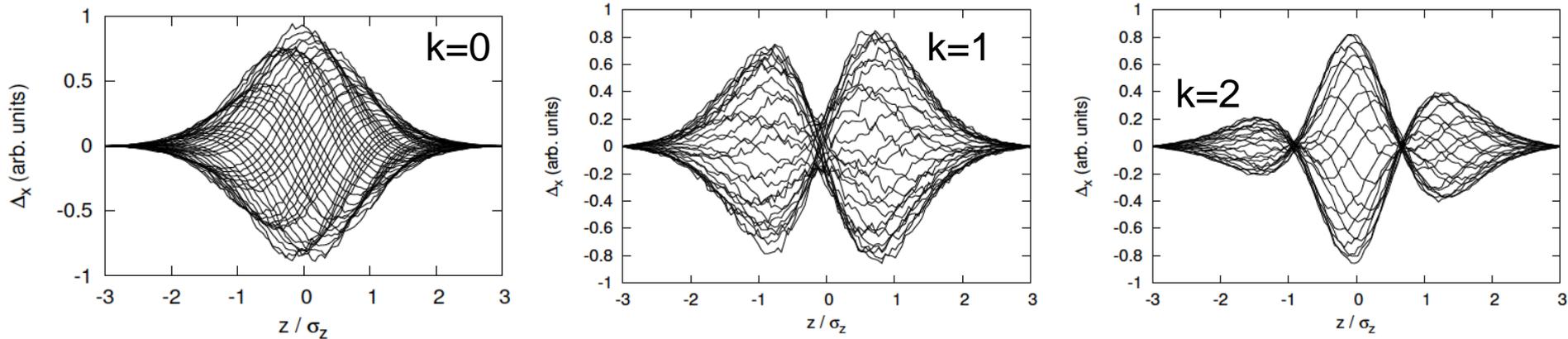


FCC-hh
For the ΔQ_{coh} -Damping as in LHC:
3554 LHC-octupoles.
508 Advanced-technology octupoles.

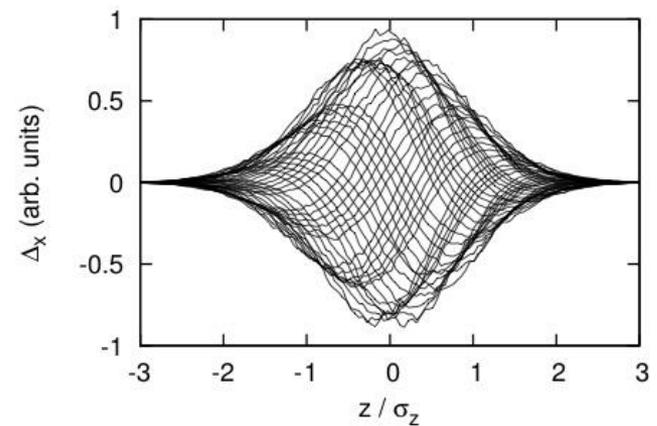
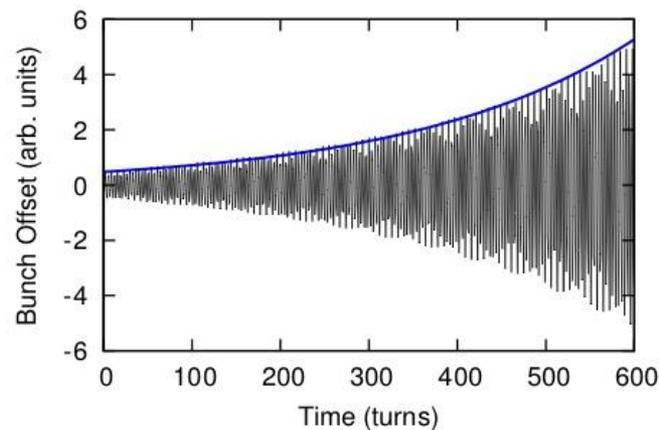
V.Kornilov

Landau damping of head-tail modes

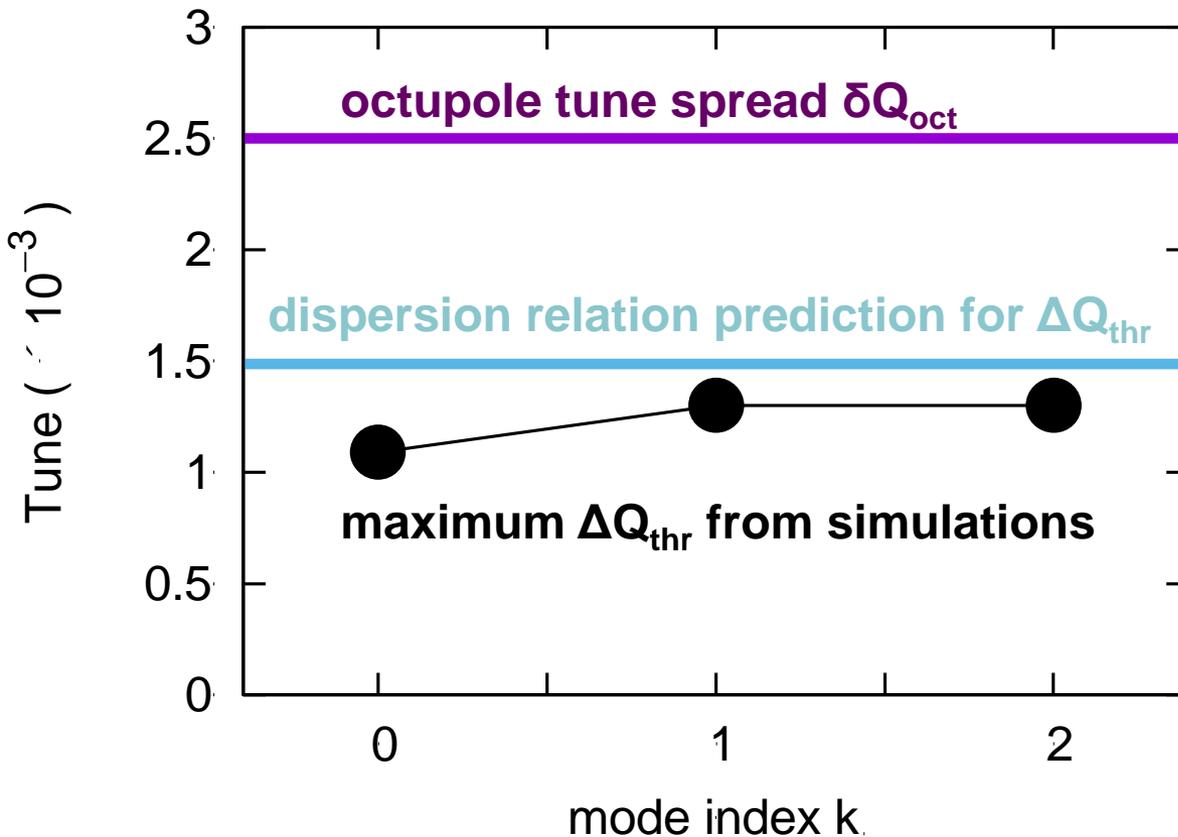
Head-tail modes (including the $k=0$ mode) are not rigid-bunch modes:



Particle tracking
with octupoles
and resistive wall
wake.



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.

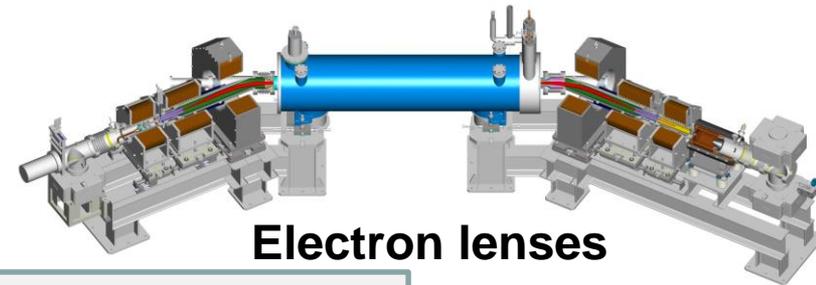
V. Kornilov, to be published

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 !

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



Electron lenses

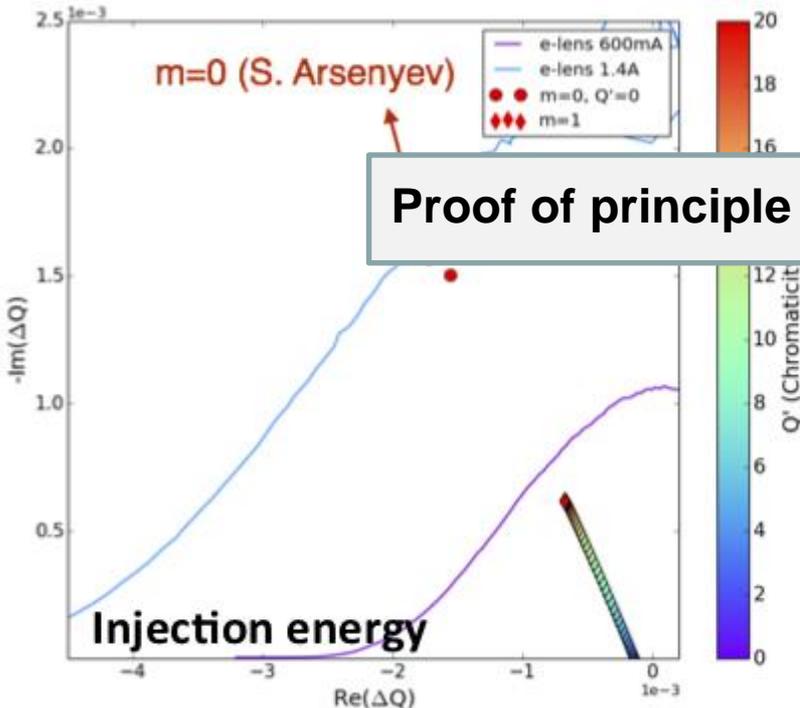
Proof of principle experiment in LHC required !

ed by a counter-propagating electron beam:

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

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.



T. Pieloni, C. Tambasco (2018)

Electron cloud: Tune shift and relativistic limit

Tune shift induced by the pinch along the bunch

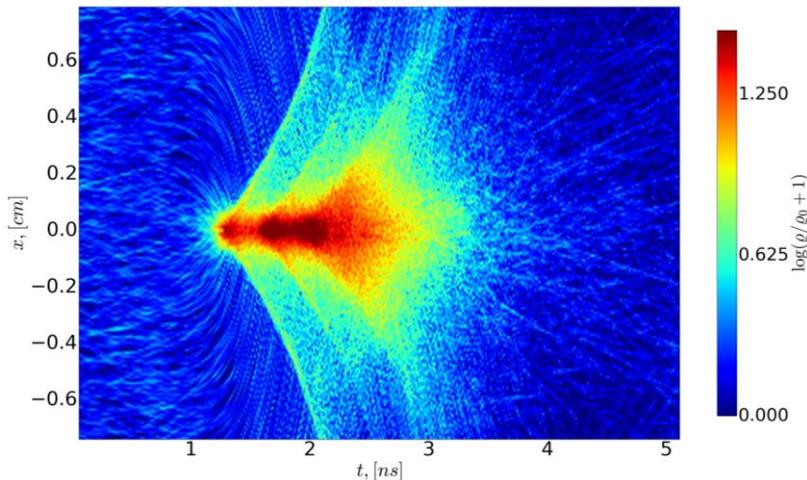
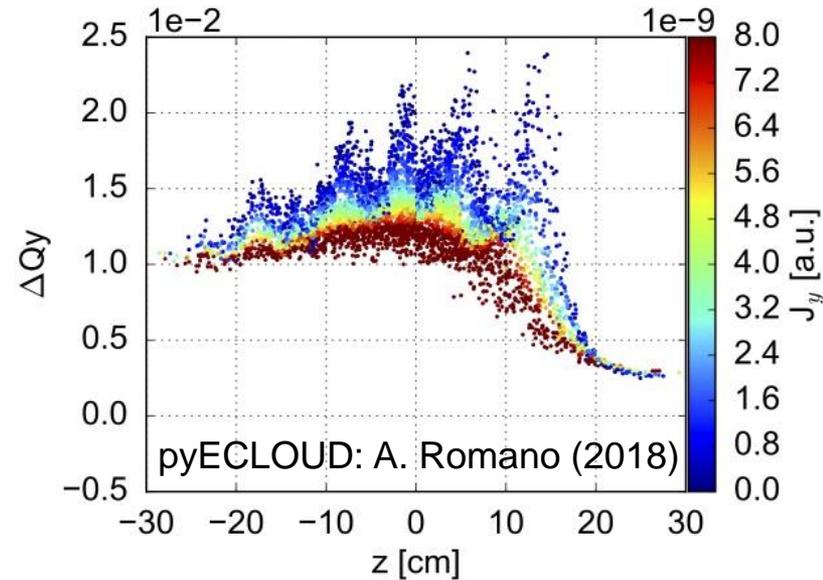
$$\Delta Q_x(z) = \frac{r_p L b_y}{\gamma_0 (b_x + b_y)} \bar{\rho} \lambda_e(z) \quad \bar{\rho} \approx \frac{E_s}{\pi m_e c^2 r_e b^2}$$

(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 \mathbf{E} and instability thresholds in the **ultrarelativistic limit** $a \rightarrow 0$

$$\rho_b(r, z) \rightarrow \delta(r) \lambda(z) \quad \epsilon_0 \nabla \cdot \mathbf{E} = \rho_e$$

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

D. Astapovych

Summary and outlook

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

To do:

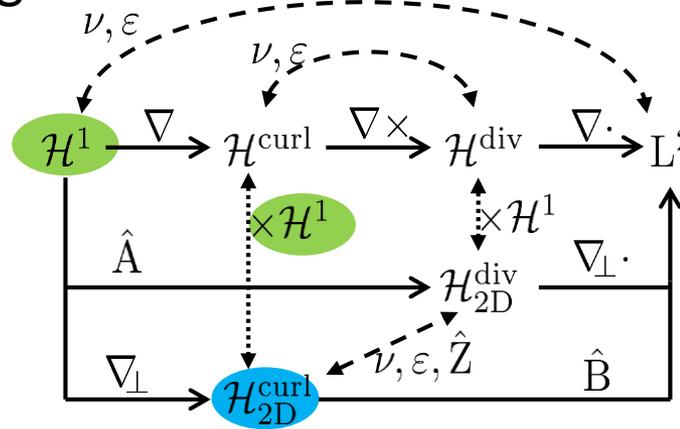
- Proof of principle experiments with electron lenses
- Interplay of electron cloud with other sources of tune shifts
-

Backup

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)

$$-\nabla \cdot \underline{\underline{\epsilon}} \nabla \underline{\underline{\Phi}} = \underline{\underline{\rho}}$$



$$\mathbf{e}_{\text{curl}} = \begin{bmatrix} \mathbf{e}_{\perp}^r \\ \mathbf{e}_{\perp}^i \\ \mathbf{e}_z^r \\ \mathbf{e}_z^i \end{bmatrix}$$

Nodal functions

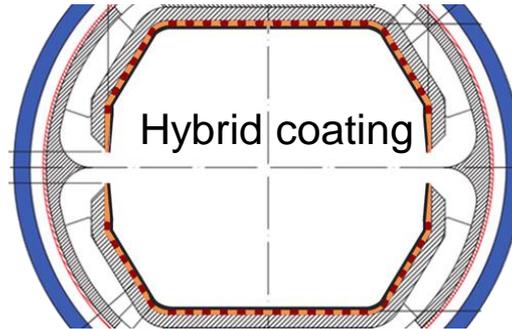
Nedelec edge functions

$$\nabla \times \underline{\underline{\mu}}^{-1} \nabla \times \underline{\underline{E}}_{\text{curl}} - \omega^2 \underline{\underline{\epsilon}} \underline{\underline{E}}_{\text{curl}} = \omega^2 \underline{\underline{\epsilon}} \nabla \underline{\underline{\Phi}} - i\omega \underline{\underline{J}}_s$$

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

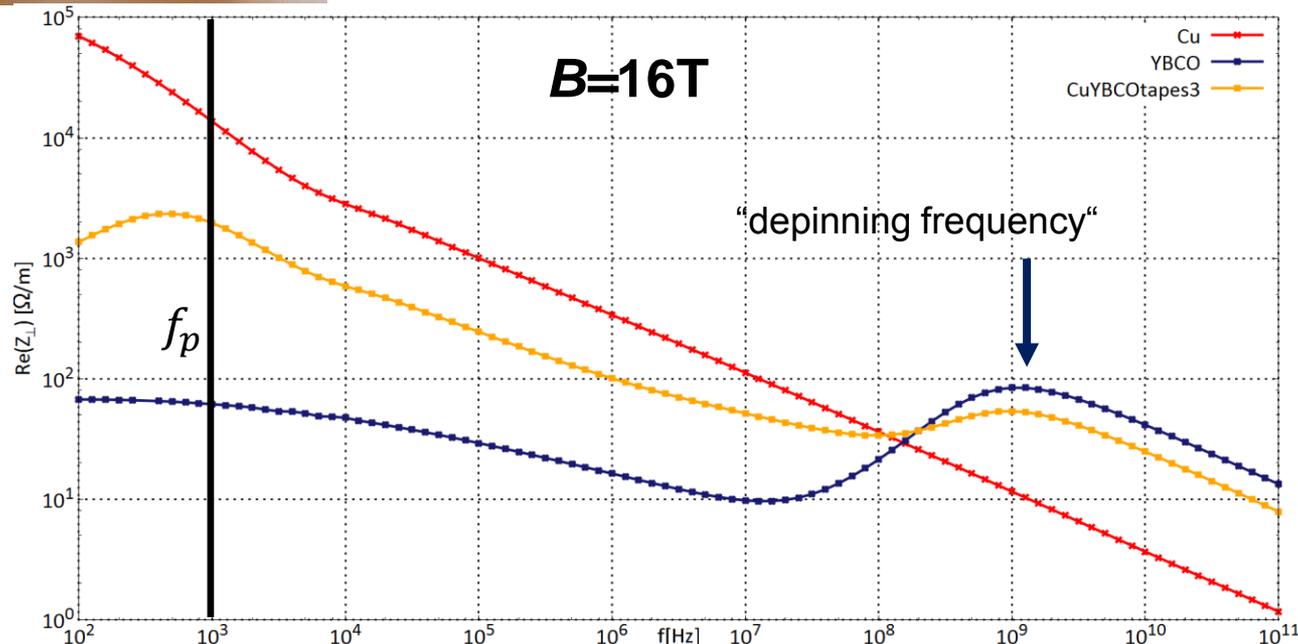
BeamImpedance2D (PYTHON): <https://bitbucket.org/uniederm/beamimpedance2d.git>

Option: HTS coated screen



Hybrid coating (HTS stripes):

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



P. Krkotic,
U. Niedermayer

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

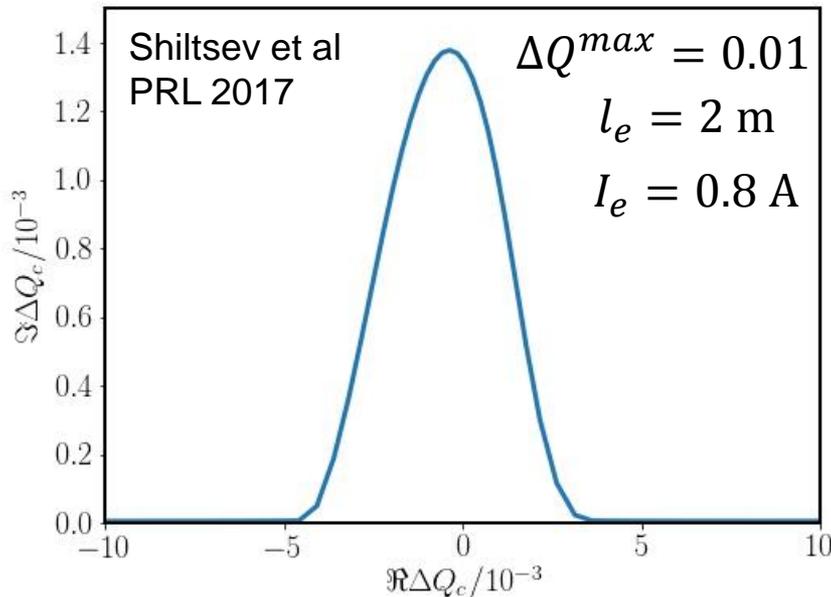
$$\Rightarrow N_{oct} L_m \propto E_0^2$$

From LHC to FCC-hh: $7^2 \times 168$ octupoles

Landau damping: Possible alternative schemes

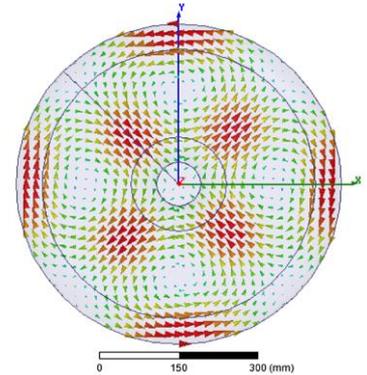
FCC-hh: Active feedback for $k=0$ modes, Landau damping for $k>1$.
Still, additional Landau damping concepts are helpful !

LHC: 10 x larger stability area then with octupoles



Radio-Frequency Quadrupole (RFQ)

Grudiev PRAB 2014
Schenk et al, IPAC17



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

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

No local spread (in z) !

Dispersion relation and Landau damping ?

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

Electron cloud studies: Buildup

See also L. Mether

Photoelectrons without mitigation would dominate the buildup (L. Mether, 2016)

FCC beam pipe design: Photoelectrons stay in antechamber (first approximation)

$$n_{es} \approx \frac{E_s}{\pi m_e c^2 r_e R_p^2}$$

Saturated electron cloud
density depends on pipe radius R_p

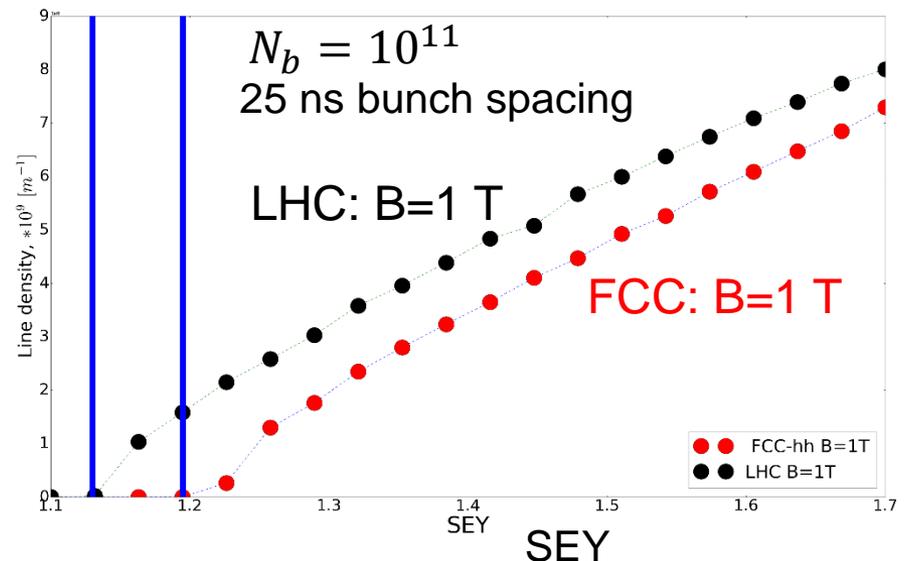
Lower electron energies
for smaller R_p

Differences between different simulation models and codes:

- SEY model
- Pipe geometry and mesh
- Particle pusher and field solver
-

Next step: (residual) photoelectron

SEY \approx 1.1 SEY \approx 1.2 SEY threshold for buildup



D. Astapovych