FCC-hh single beam stability

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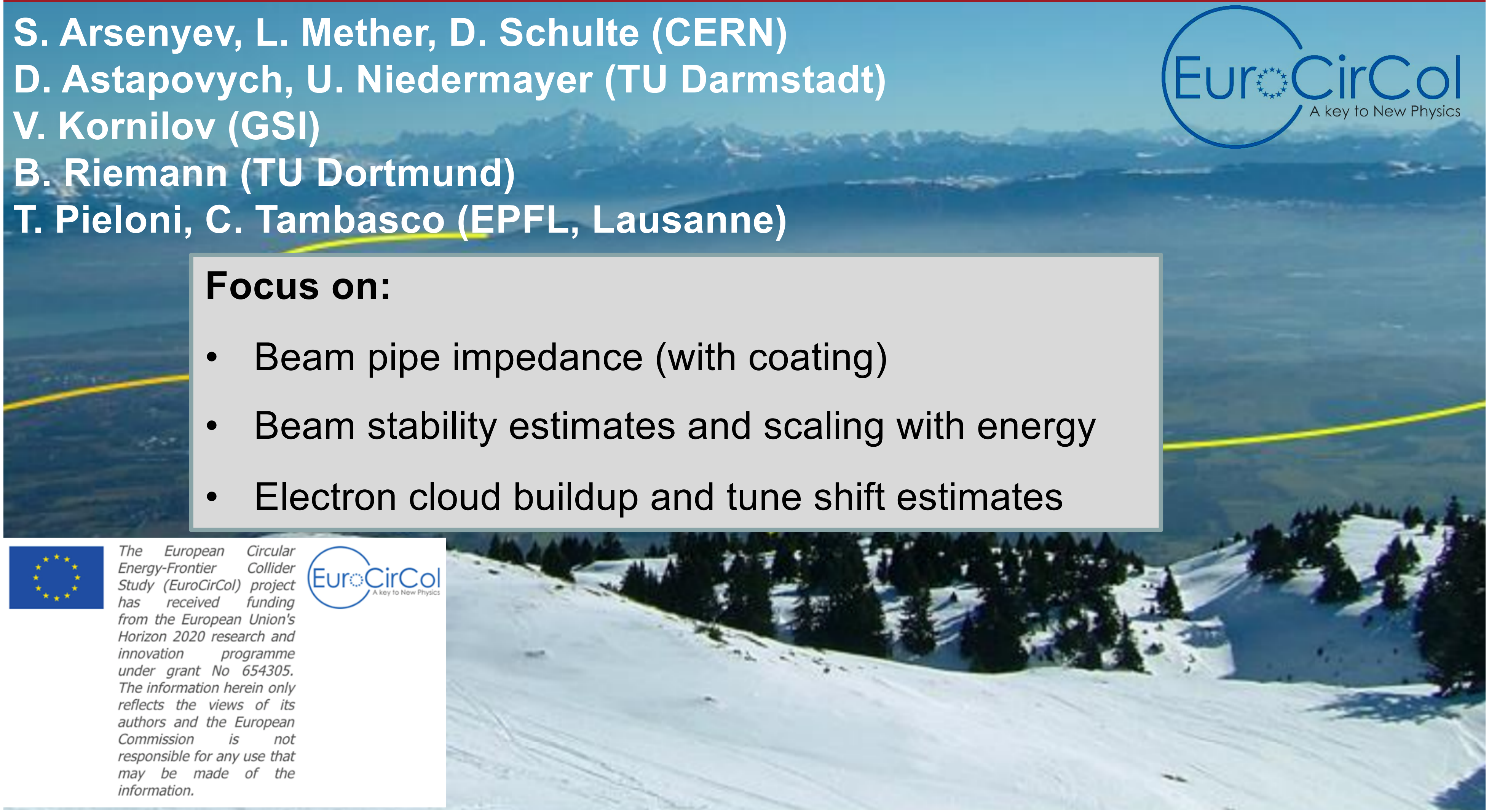

Focus on:

- Beam pipe impedance (with coating)
- Beam stability estimates and scaling with energy
- Electron cloud buildup and tune shift estimates

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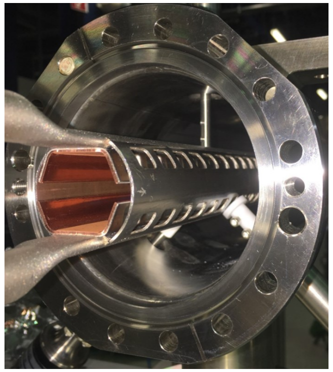
FCC-hh resistive wall impedance

Coupled bunch instability growth rate (Sacherer 1974):

$$\tau^{-1} = \omega_0 \Im \Delta Q_{\mathrm{coh}} \qquad \frac{1}{\tau_k} \approx -\frac{1}{1+k} \frac{\omega_0 q M I_b}{4\pi E_0} \hat{\beta}_y \Re Z_y(\omega_{\min}) \qquad \omega_{min} = (n - Q_y)\omega_0$$

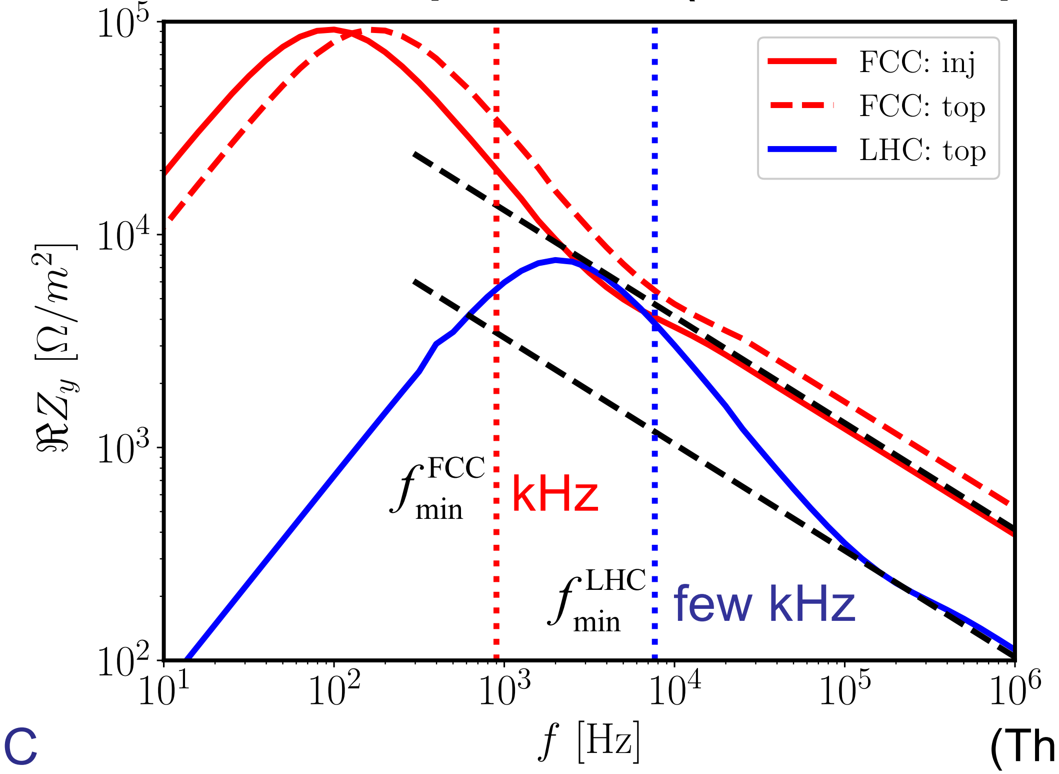
(lowest sideband)

Transverse impedances (vertical real part)



FCC

LHC



Uncertainties:

Copper conductivity
-> Factor 2-3

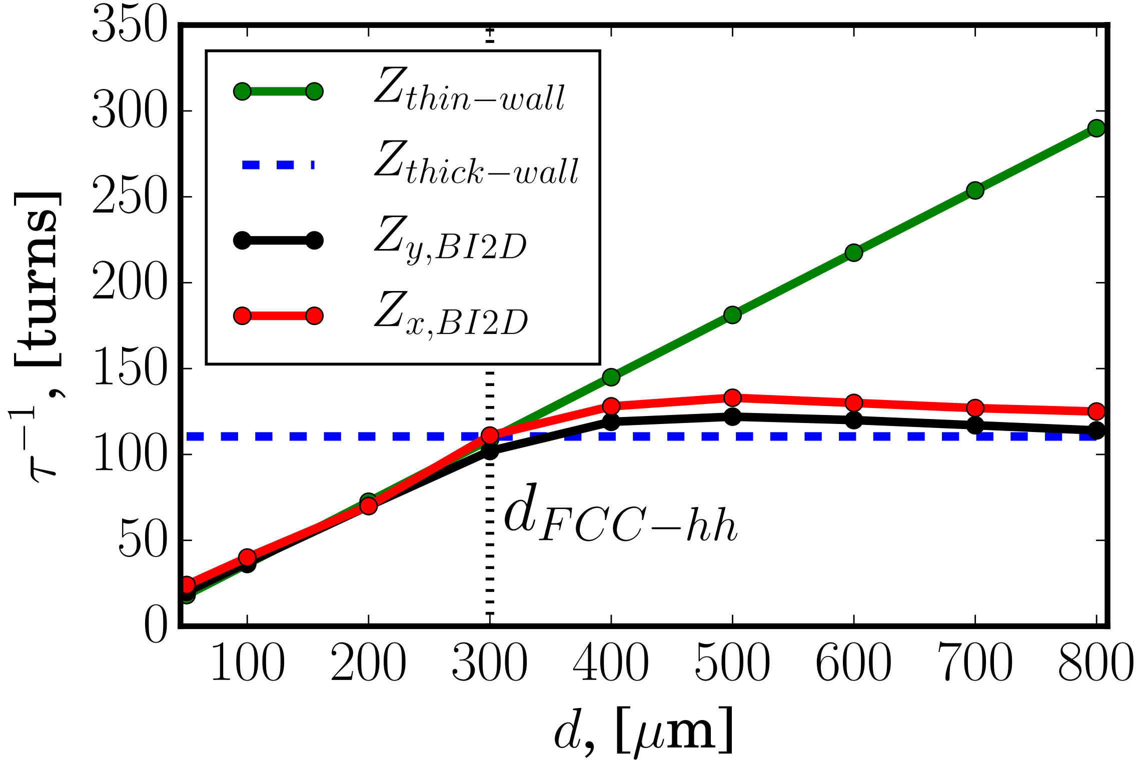
growth time at 3.3 TeV:
approx. 50 turns

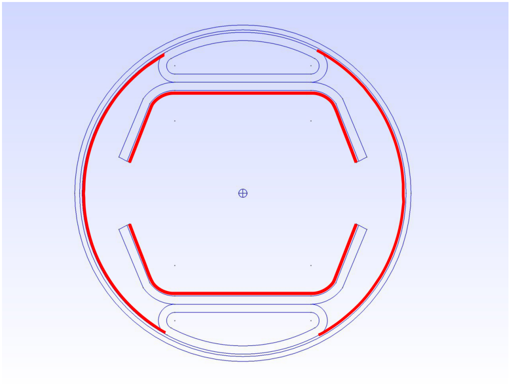
at 50 TeV:
approx. 500 turns

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

(Thick) resistive wall impedance

FCC beam screen: copper coating





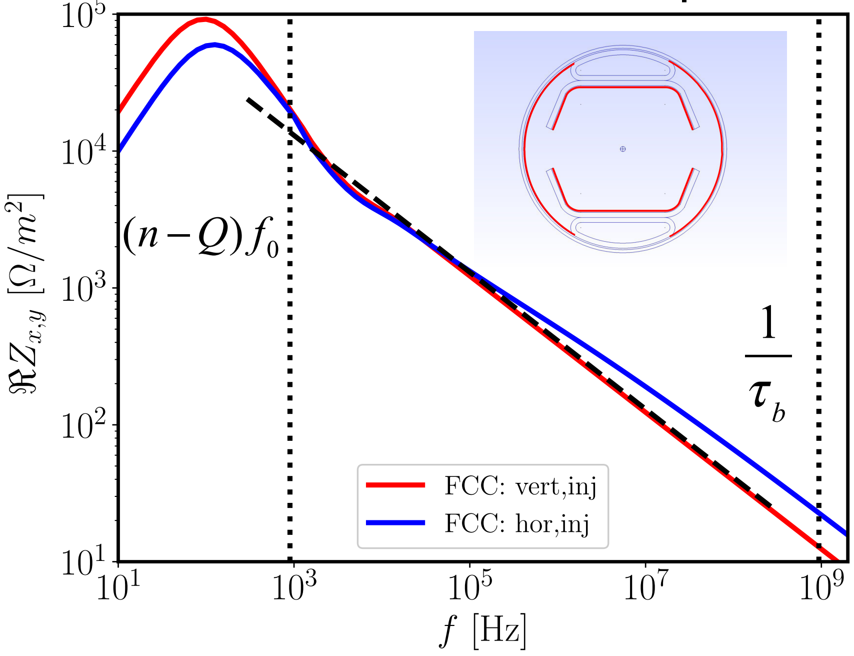
„Optimum“ thickness of the copper layer: 300 µm

D. Astapovych

FCC beam screen: single bunch instabilities

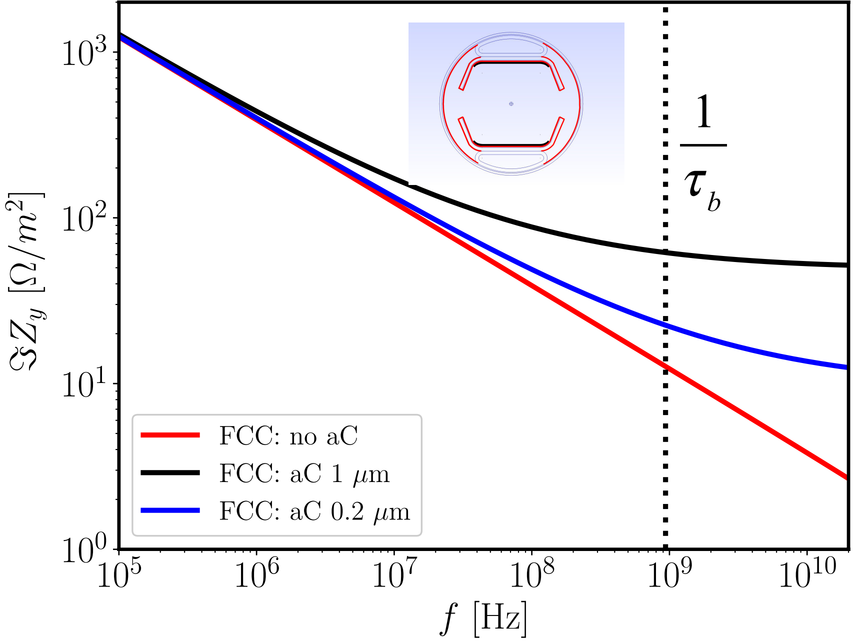
Large fields at the uncoated screen edges

Horizontal vs. vertical impedance



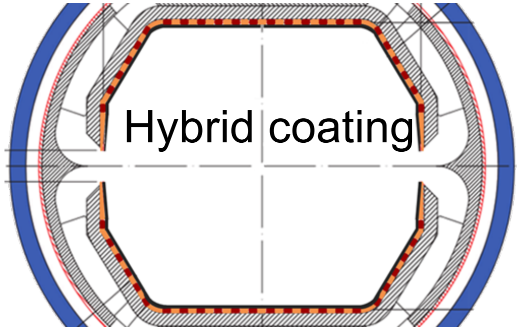
Low frequencies: Vertical impedance dominates
High frequencies: Horizontal impedance larger

Contribution of a-C coating



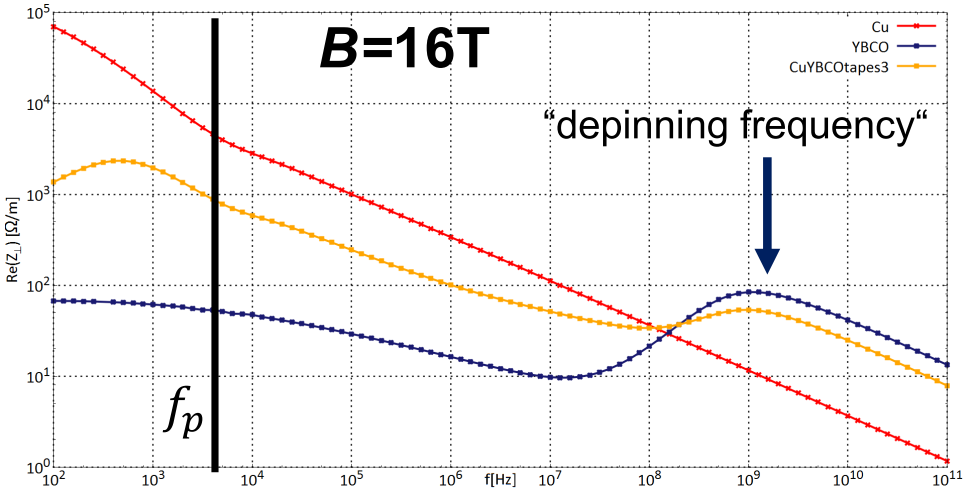
Remark: For an SEY of about 1 the coating can be much thinner, for example only 30 nm. P.Pinto (CERN)

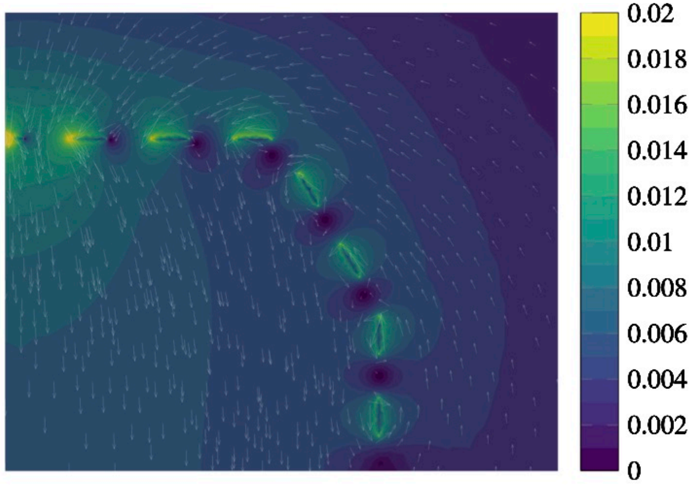
FCC beam screen: Possible HTS coating



Hybrid coating (HTS stripes):

- Possible reduction of the resistive wall instability growth rates by factor 5-6.
- Increase of high frequency part !
- Some effect on the field quality.





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

[2] S. Patsch et al, **Computation of the magnetization of type II superconductors for potential FCC beam screen coatings**, IEEE Trans. Appl. Superconductivity (2019)

Some very rough scaling laws (with energy)

Tune shifts and growth rate for transverse coupled bunch instabilities

$$\Delta Q \propto \frac{q^2 N_b}{m\gamma l_{bb}} \hat{\beta}_y \Re Z_\perp \qquad \tau^{-1} = \omega_0 \Delta Q$$

$$\frac{L_{\mathrm{FCC}}}{L_{\mathrm{LHC}}} \times \frac{\hat{\beta}_{\mathrm{FCC}}}{\hat{\beta}_{\mathrm{LHC}}} \times \left(\frac{\gamma_{\mathrm{FCC}}}{\gamma_{\mathrm{LHC}}}\right)^{-1} \approx 1 \quad \Rightarrow \quad \frac{\Delta Q^{\mathrm{FCC}}}{\Delta Q^{\mathrm{LHC}}} \approx 10$$

(at top energies)

-> Growth rates are rather similar, but damping becomes „tougher“ at higher energy.

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

(mode coupling)

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

(synchrotron tune)

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

Mode coupling threshold

-> Mode coupling more likely an issue in FCC.

Landau damping: Octupoles and others

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:

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

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

$E_0 = \gamma_0 m c^2$

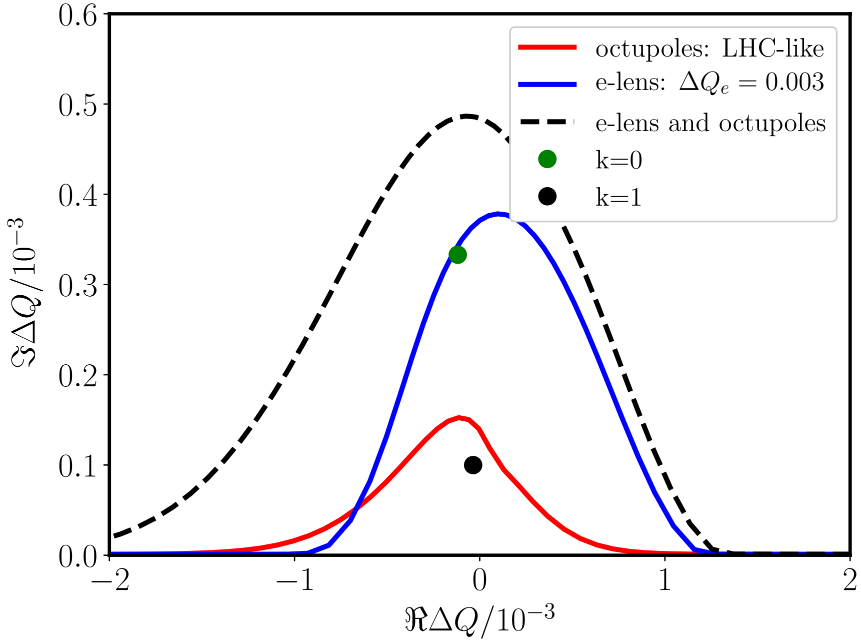
L_m: length of magnet

N_{oct}: # of magnets

2D dispersion relation [1-2]:

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

[1] H. G. Hereward, CERN 65-20 (1965)
[2] J. S. Berg, F. Ruggiero, CERN SL-AP-96-71 (1996)

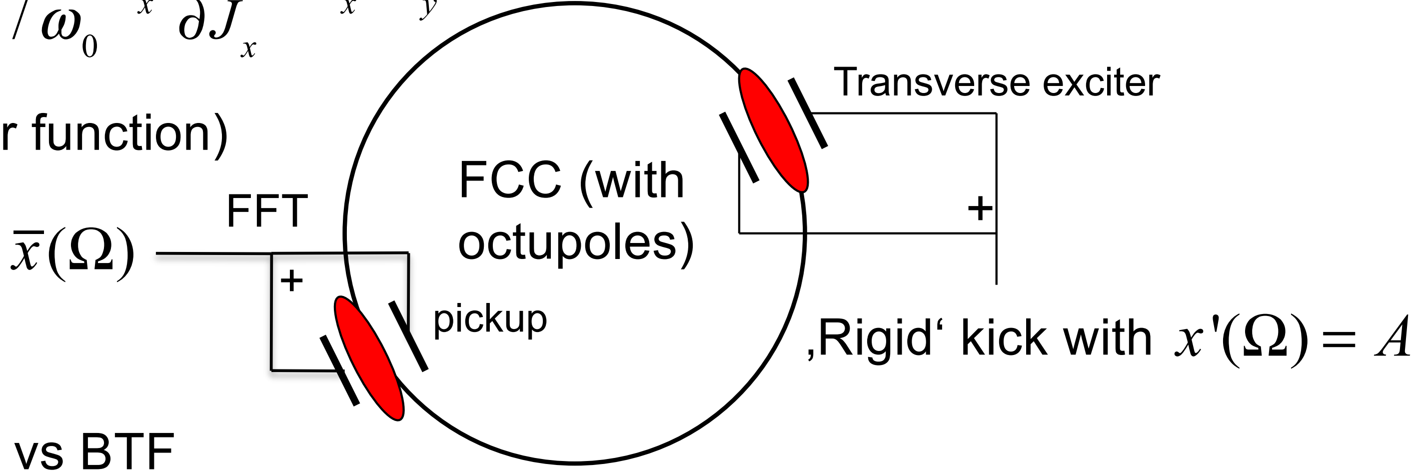


FCC-hh: Active feedback for k=0 modes, Landau damping for k>1.

Octupoles: Probing the beam transfer function

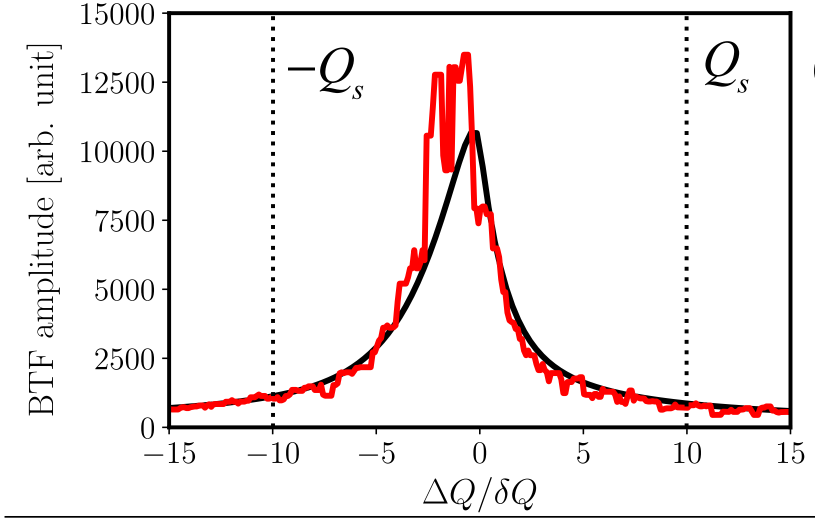
$$\bar{x}(\Omega) = A\int \frac{1}{\Delta Q_{oct} - kQ_s - \Omega/\omega_0} J_x \frac{\partial \psi_\perp}{\partial J_x} dJ_x dJ_y$$

(BTF: Beam transfer function)



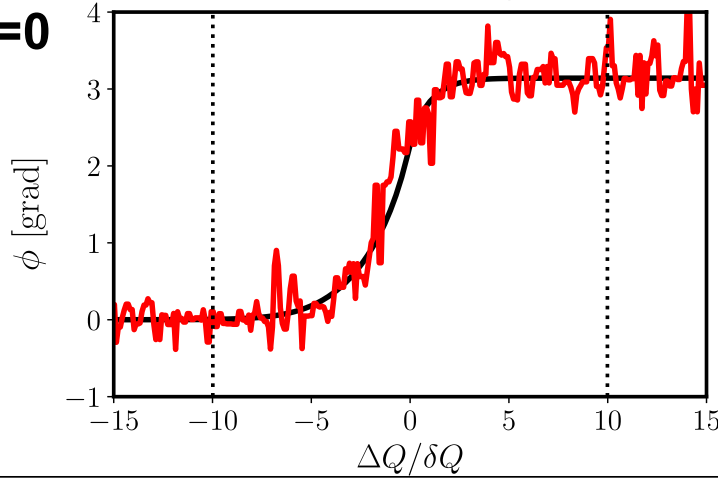
‚Rigid‘ kick with $x'(\Omega) = A$

3D particle tracking vs BTF



Chromaticity=0

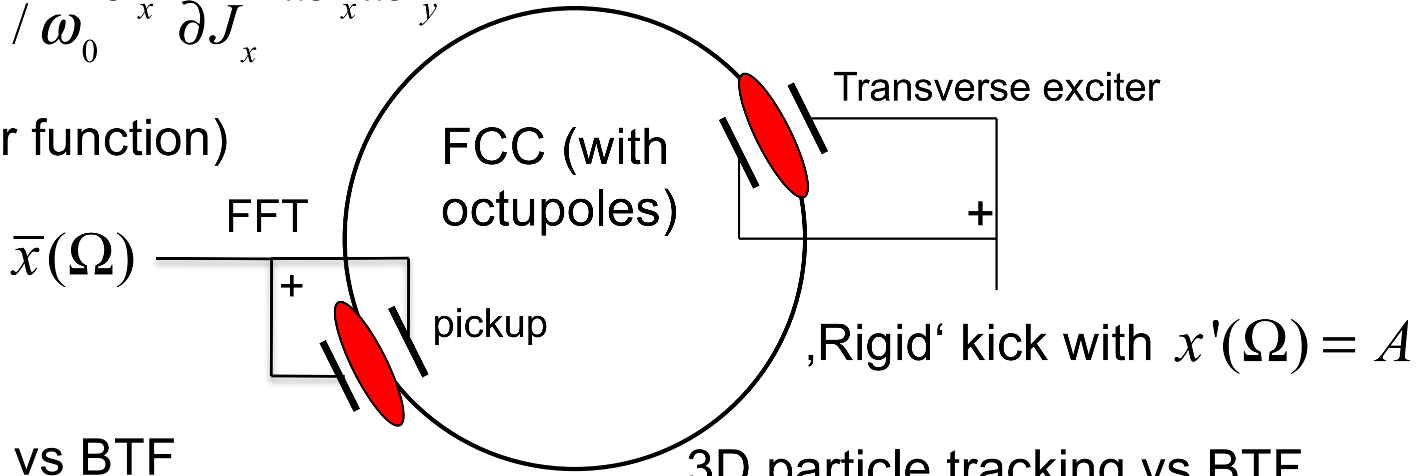
3D particle tracking vs BTF



Octupoles: Probing the BTF (finite chromaticity)

$$\bar{x}(\Omega) = A\int \frac{1}{\Delta Q_{oct} - kQ_s - \Omega / \omega_0} J_x \frac{\partial \psi_\perp}{\partial J_x} dJ_x dJ_y$$

(BTF: Beam transfer function)



$\bar{x}(\Omega)$

FFT

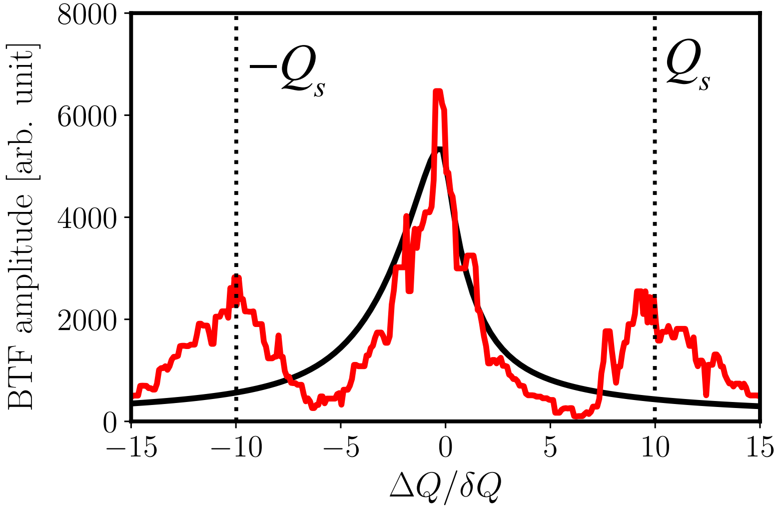
FCC (with octupoles)

Transverse exciter

pickup

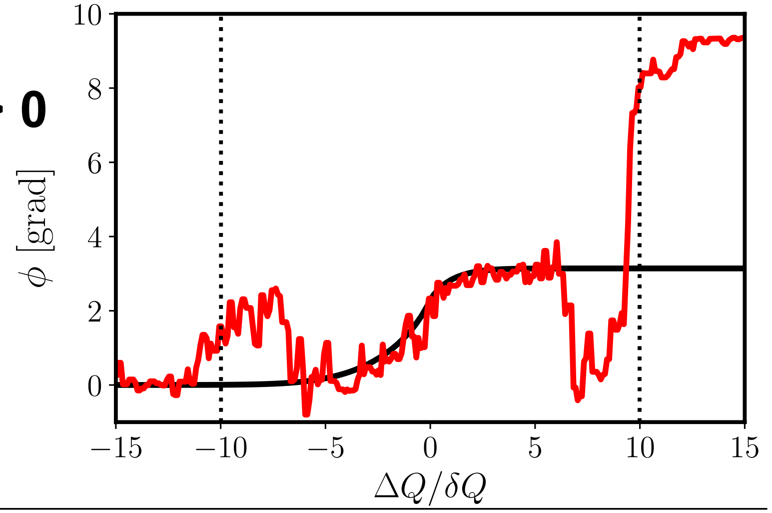
‚Rigid' kick with $x'(\Omega) = A$

3D particle tracking vs BTF



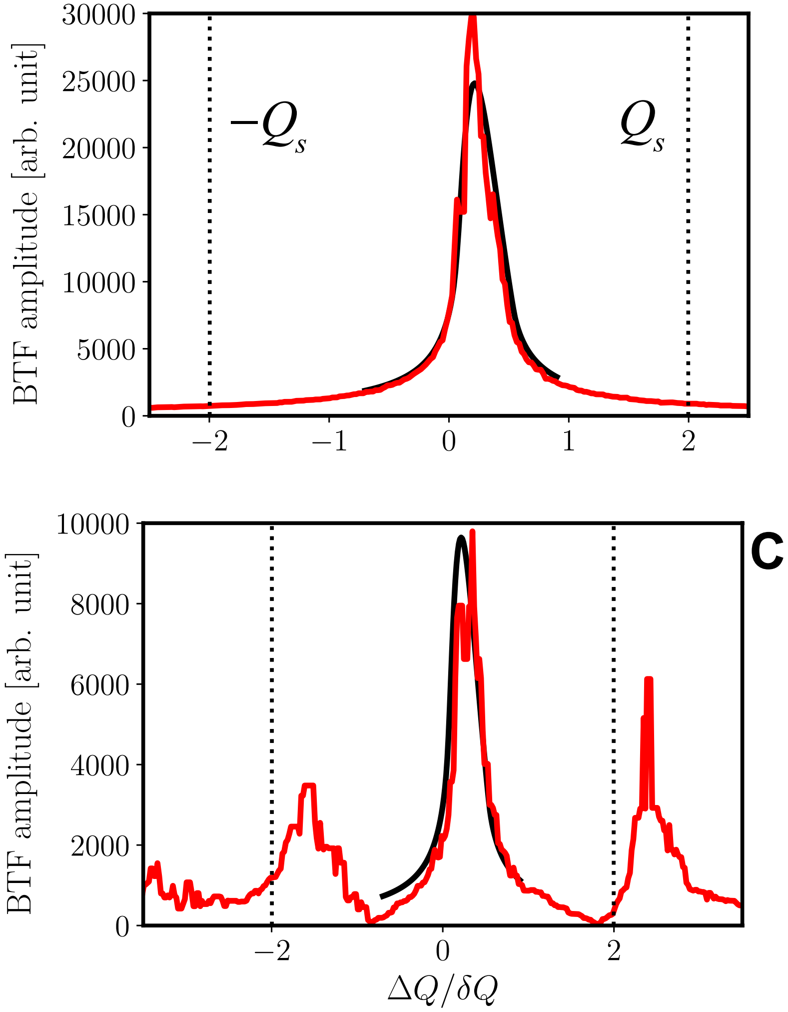
Chromaticity > 0

3D particle tracking vs BTF



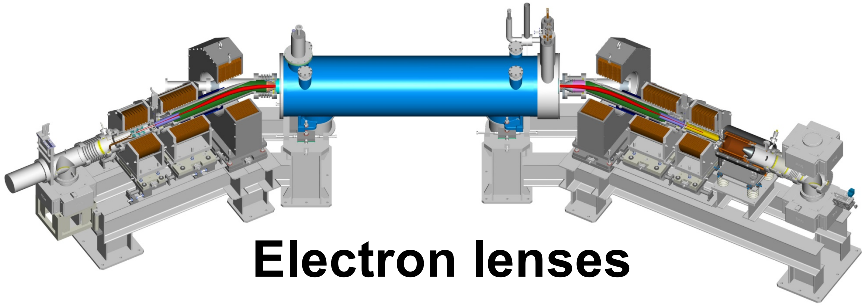
Landau damping: Electron lens

3D particle tracking vs BTF



Chrom > 0

Similar to the beam-beam force !



Electron lenses

Tune shift induced by a counter-propagating electron beam:

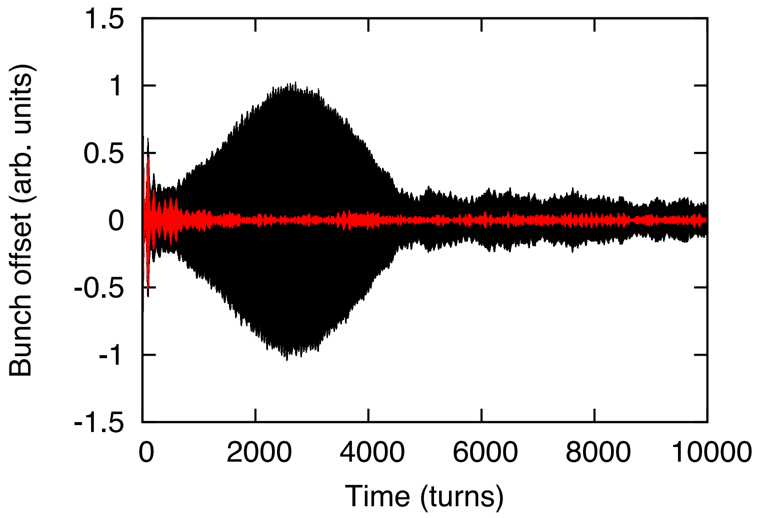
$$\Delta Q_x^e = \frac{1+\beta_e}{\beta_e}\frac{I_e l r_p}{2\pi e c \varepsilon_x}$$

V. Shiltsev et al., PRL (2017)

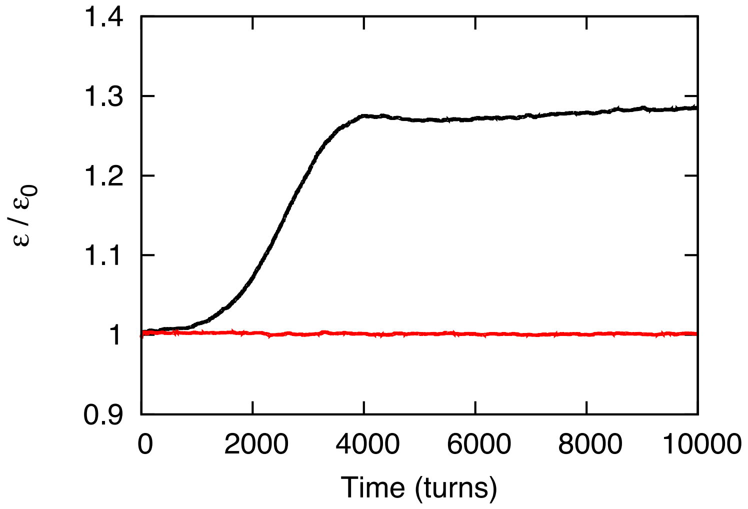
Example: One lens (l=2 m, I_e=1 A) in LHC would provide a tune spread similar to the 168 octupoles.

Octupoles: Initially unstable bunches

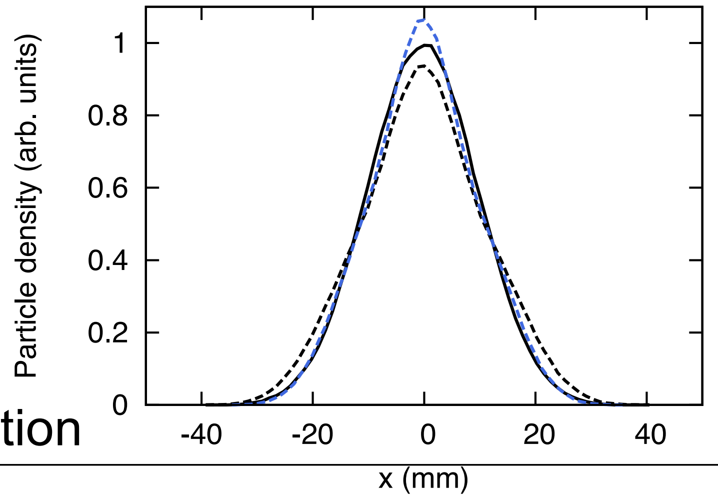
Growth and saturation of a transverse instability



Emittance growth



V. Kornilov et al., *Landau damping due to octupoles of non-rigid head-tail modes,* submitted to NIMA

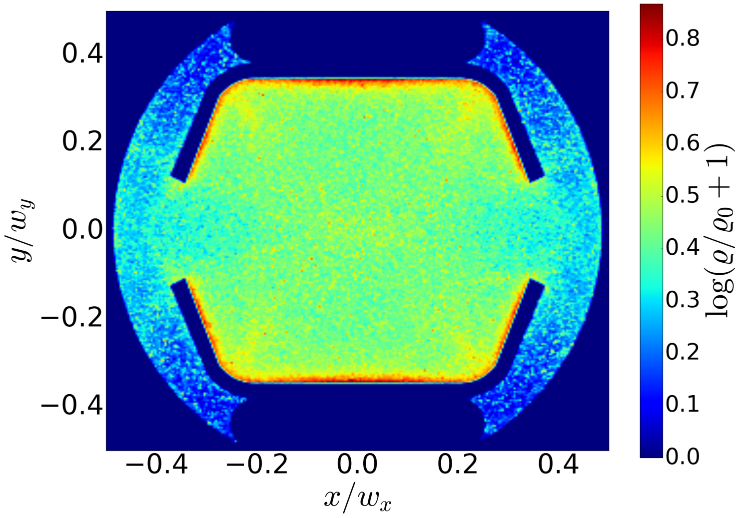


Beam distribution after saturation

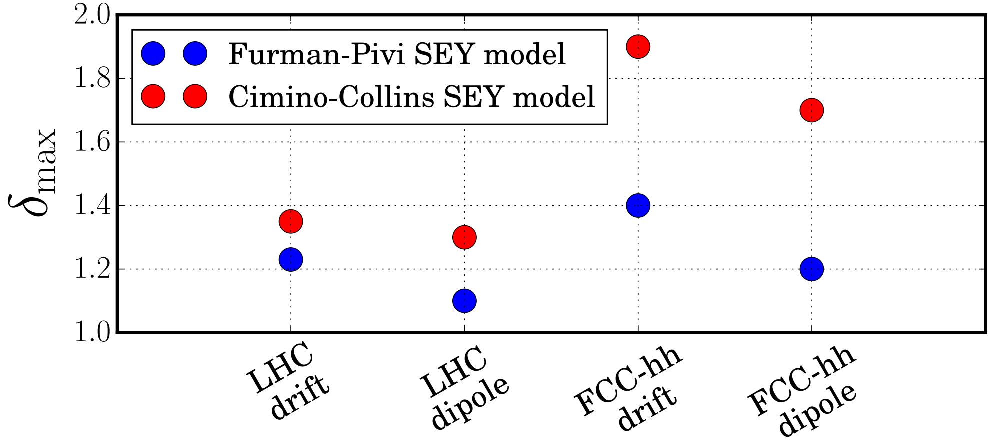
Electron clouds: Buildup

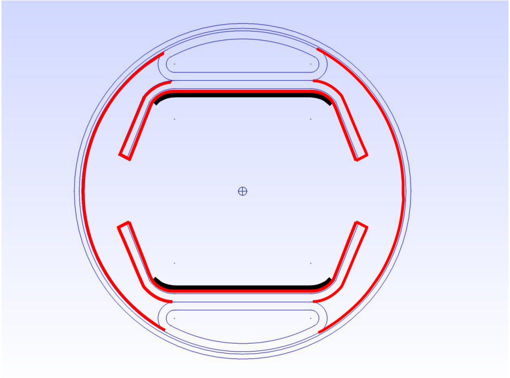
D. Astapovych (see poster)
L. Mether (see talk)

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



Buildup thresholds (SEY) from simulations





Remark: a-C coating should supress the e-cloud in the dipoles

Electron clouds: Tune shift and scaling

Tune shift induced by the pinching electrons along the bunch

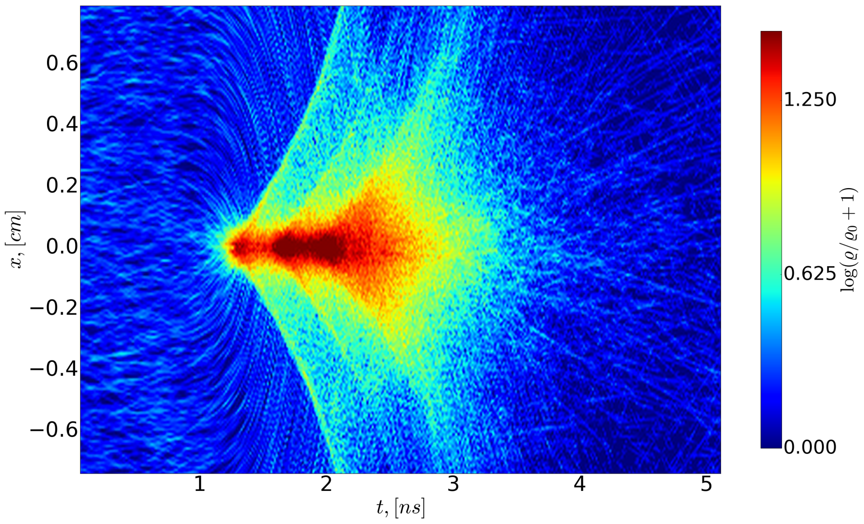
$$\Delta Q_x(z) = \frac{r_p L \hat{\beta}_x}{\gamma} \bar{n}_e \lambda_e(z)$$ $\lambda_e(z)$: Local electron line density inside the beam radius a

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

Scaling LHC to FCC:

$$\frac{\Delta Q_e^{\mathrm{FCC}}}{\Delta Q_e^{\mathrm{LHC}}} \approx \frac{L^{\mathrm{FCC}}}{L^{\mathrm{LHC}}} \frac{\hat{\beta}^{\mathrm{FCC}}}{\hat{\beta}^{\mathrm{LHC}}} \frac{\lambda_e}{\gamma} \approx 10 \frac{\lambda_e}{\gamma}$$

Pinching electrons



Tune shift in the ultrarelativistic limit ?

$$a_x = \sqrt{\hat{\beta}_x \varepsilon_x} \propto \frac{1}{\sqrt{\gamma}} \to 0$$

(beam radius)

$$\rho_b(r,z) \to \delta(r)\lambda(z)$$

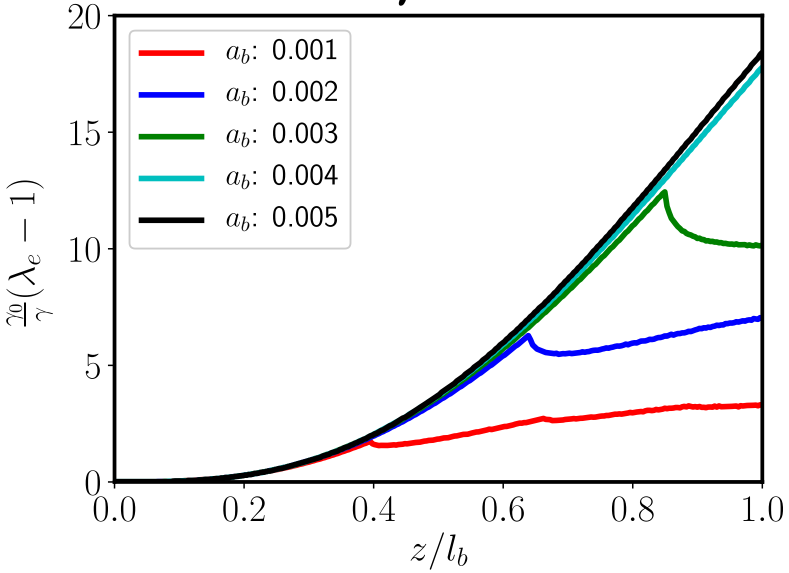
(beam density)

E-cloud simulation (particle tracking)

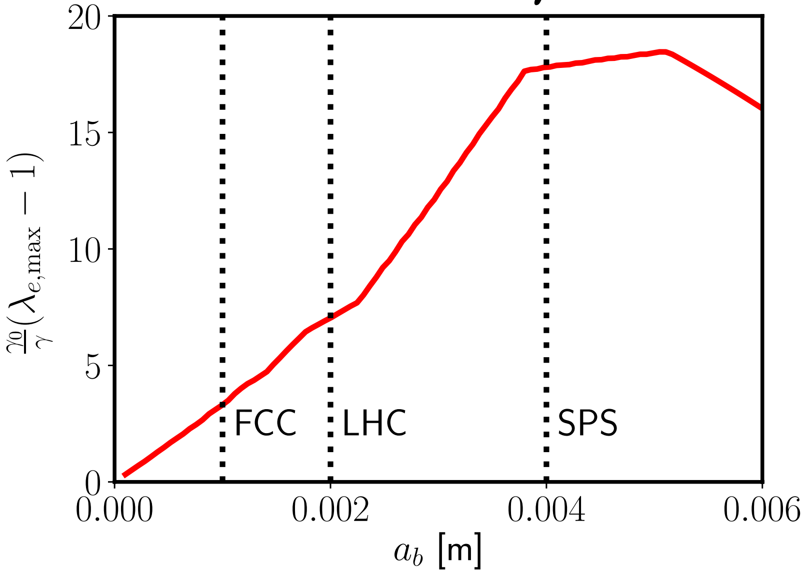
Scaling with beam energy (beam radius):

A new gridless e-cloud code has been developed !

$$\Delta Q_x(z) \propto \frac{\lambda_e(z)}{\gamma} \qquad \gamma \propto \frac{1}{\sqrt{a}}$$



$$\Delta Q_x(a) \propto \frac{\lambda_e^{\max}}{\gamma}$$



With increasing energy: Larger electron density at the beam center, but $\frac{1}{\gamma}$ wins.

E-cloud induced tune shift goes to zero in the ultrarelativisic limit.

Summary

Impedances and instability growth rates

Longitudinal and transverse impedances of the FCC beam screen, using a 2D FEM frequency domain solver

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 comparison, optimum Cu coating, a-C coating, „error bars“,….
-> possible HTS beam screen coating.

Landau damping

Octupoles, energy scaling and damping of „non-rigid“ bunch modes
Electron lenses and combinations.
-> BTF simulation of stable beams and time evolution of unstable beams

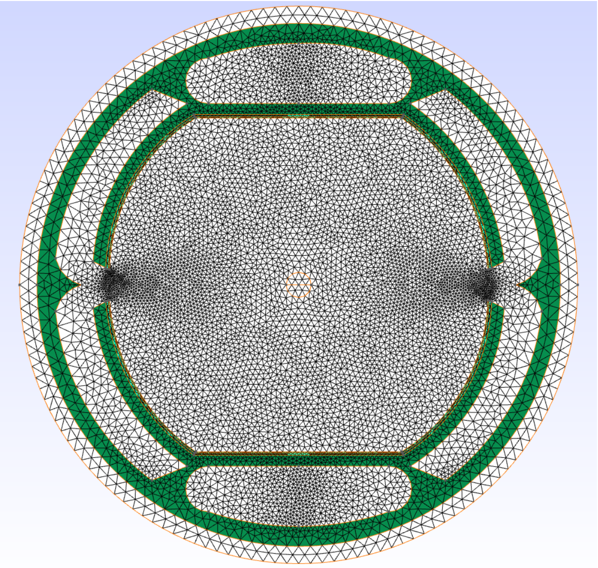
Electron clouds

Buildup studies using the detailed screen geometry and different SEY models.
-> Energy scaling of electron cloud induced effects.

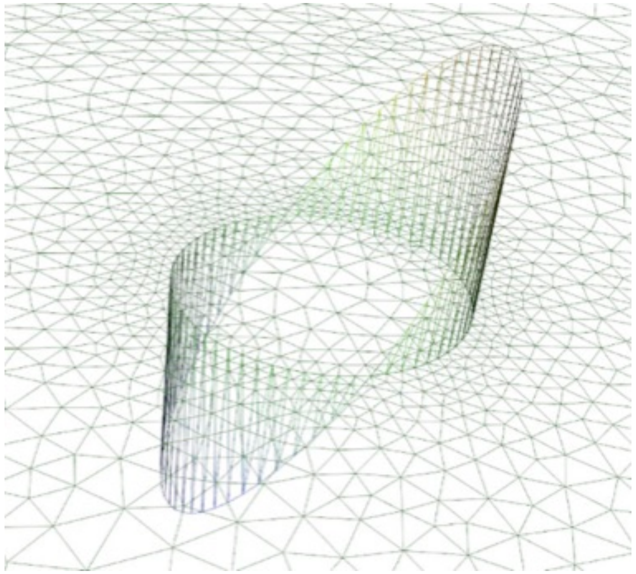
Backup

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)



(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

Single bunch TMCI threshold: Imaginary part

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

(tune shift)

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

(synchrotron tune)

TMCI threshold bunch intensity:

$$N_b^{th} \approx \frac{4\pi \Delta E}{\omega_0 e^2 \hat{\beta}_y \gamma_t^2 \Im Z_{y,0}^{\mathrm{eff}}}$$

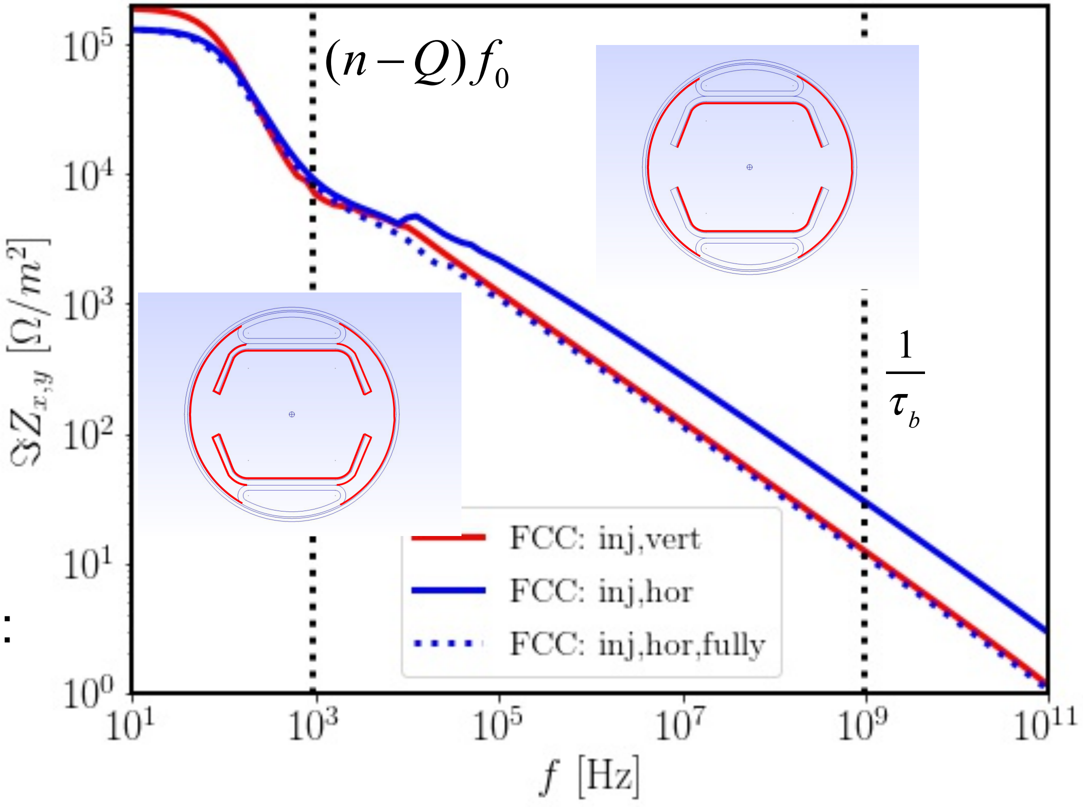
Fully Cu coated:

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

Partially Cu coated:

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

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



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

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

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

Stability curve: octupoles + e-lens