FCC-hh impedances and instabilities

O. Boine-Frankenheim (for EuroCirCol Task 2.4)

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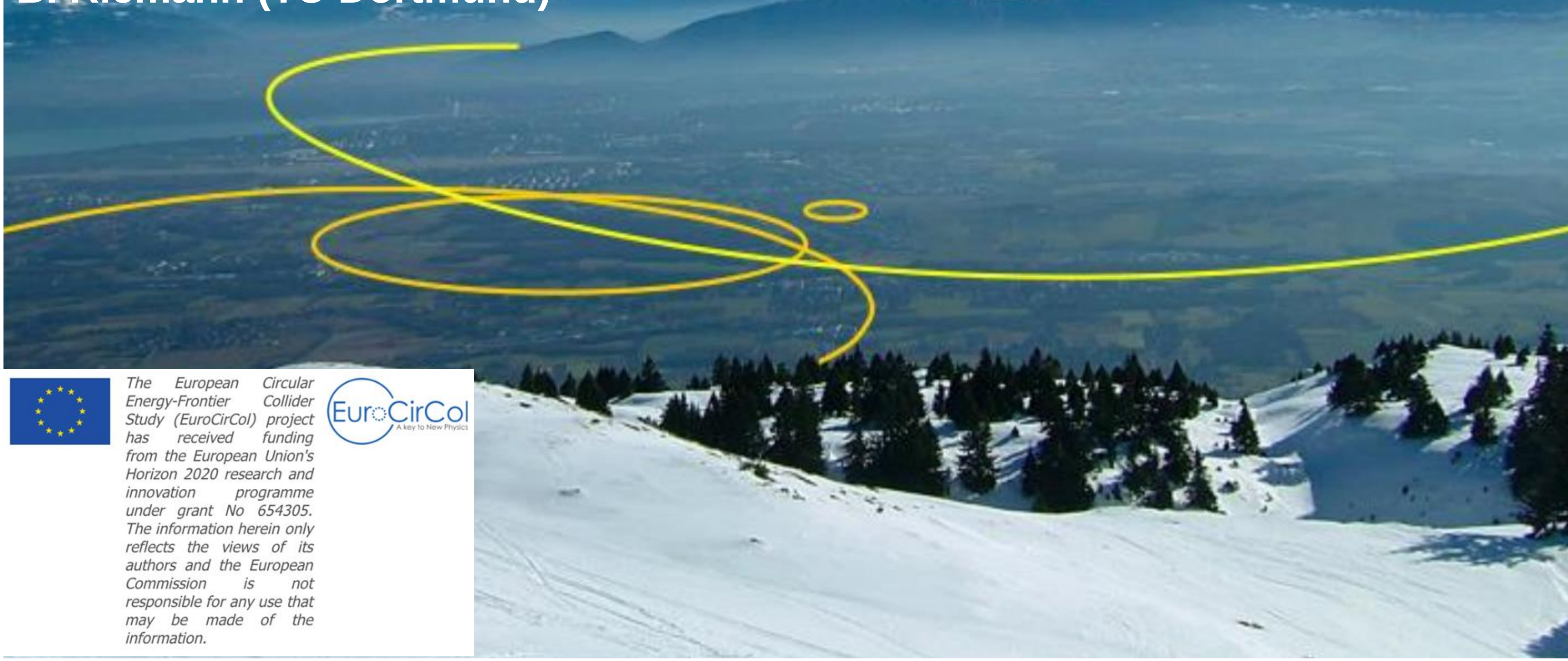
S. Arsenyev, L. Mether, B. Salvant, D. Schulte (CERN)
D. Astapovych, U. Niedermayer (TU Darmstadt)
V. Kornilov (GSI)
B. Riemann (TU Dortmund)

EuroCirCol
A key to New Physics



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A key to New Physics

Task 2.4 Single Beam Stability

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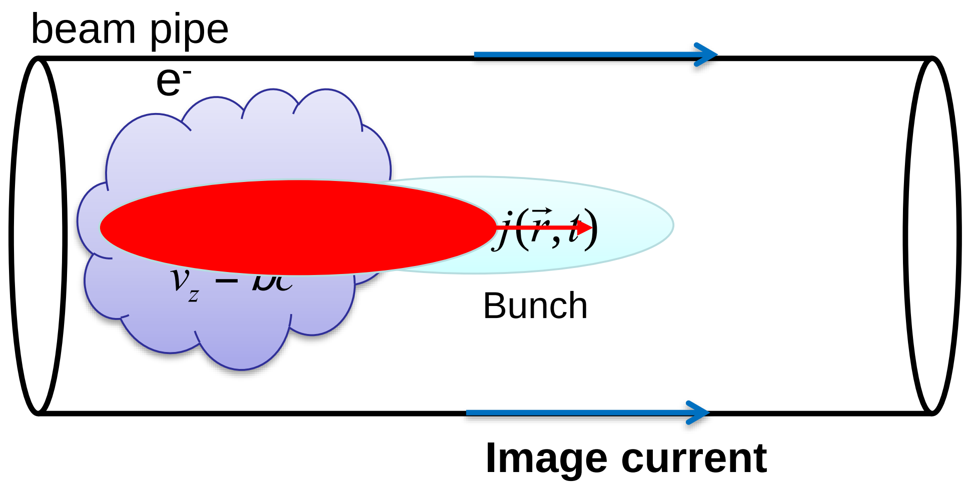
Wakefields and impedances:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \times \vec{B} = \mu_0 \vec{j} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

2D and 3D simulation codes



Beam-beam interaction:
Not part of this work package
(but, electron lenses for LD are)

Electron clouds:
created by residual gas or wall emission.

Instabilty thesholds (Landau damping):
Dispersion relations and tracking studies

Compare with LHC observations and simulations as much as possible.

-> Scaling with beam energy,…

2D impedance code in frequency space

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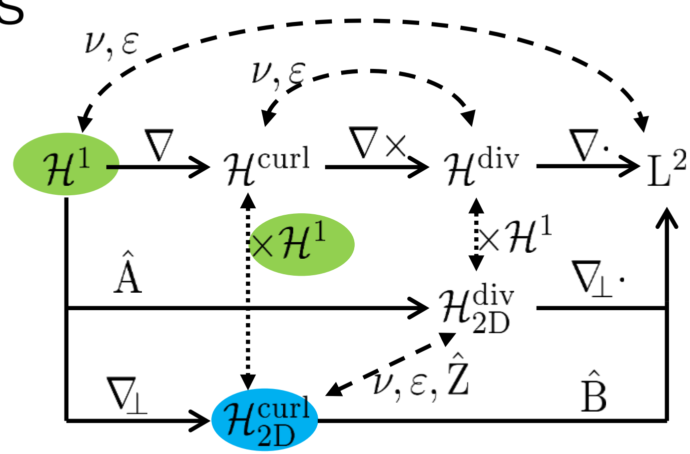
- Open source package FEniCS *(A. Logg, K. Mardal, G. Wells et al.)*
- Mesh from GMSH *(C. Geuzaine, J. Remacle)*

$$-\nabla \cdot \underline{\varepsilon} \nabla \underline{\Phi} = \underline{\varrho}$$



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

Nodal functions

Nedelec edge functions

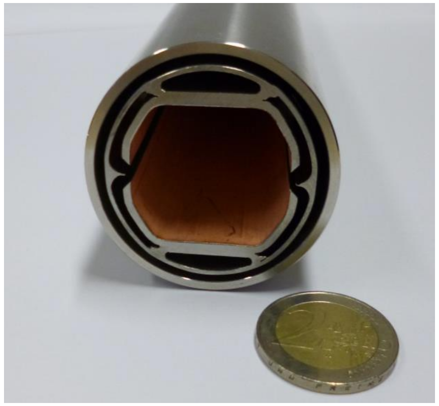
$$\nabla \times \underline{\mu}^{-1} \nabla \times \underline{\vec{E}}_{\mathrm{curl}} - \omega^2 \underline{\varepsilon}\, \underline{\vec{E}}_{\mathrm{curl}} = \omega^2 \underline{\varepsilon}\, \nabla \underline{\Phi} - i\omega \underline{\vec{J}}_{\mathrm{s}}$$

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

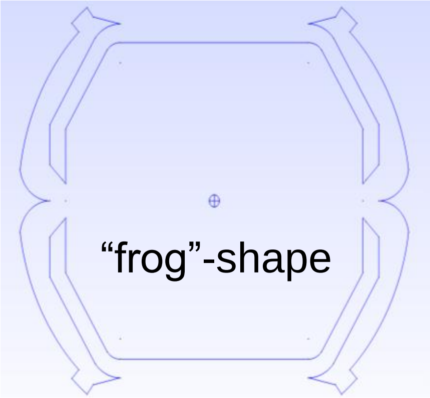
BeamImpedance2D (PYTHON): https://bitbucket.org/uniederm/beamimpedance2d.git

Impedance of the FCC-hh beam screen

FCC

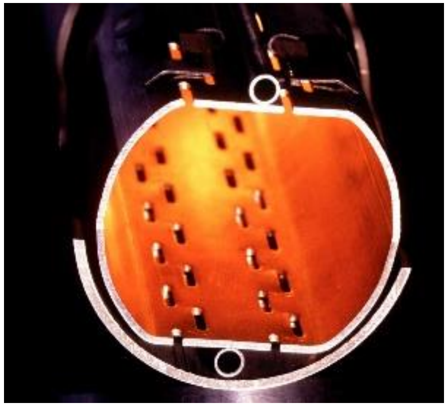


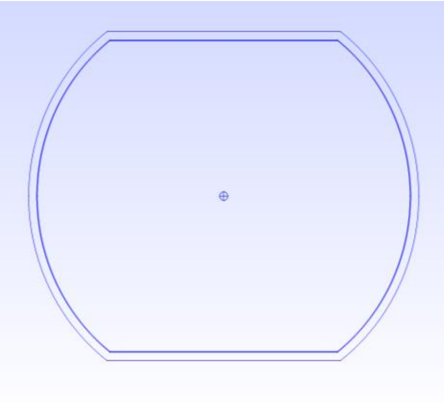
Boundaries and parameters for impedance calculations with BeamImpedance2D



	LHC	FCC-hh
Circumference [m]	27×10^3	10^5
E_{inj} [TeV]	0.45	3.3
B_{inj} [T]	0.54	1.06
E_{top} [TeV]	7	50
B_{top} [T]	8.4	16
Beam screen Temperature [K]	20	50

LHC

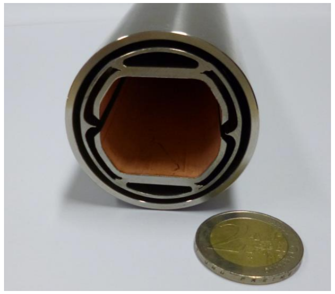




Material/ thickness [mm]	LHC	FCC-hh
Stainless Steel	1.	1.25
Copper (RRR=100)	0.75	0.3
Laser treated Copper	-	$10^{-3} - 10^{-1}$

Coupled bunch instability: FCC vs. LHC

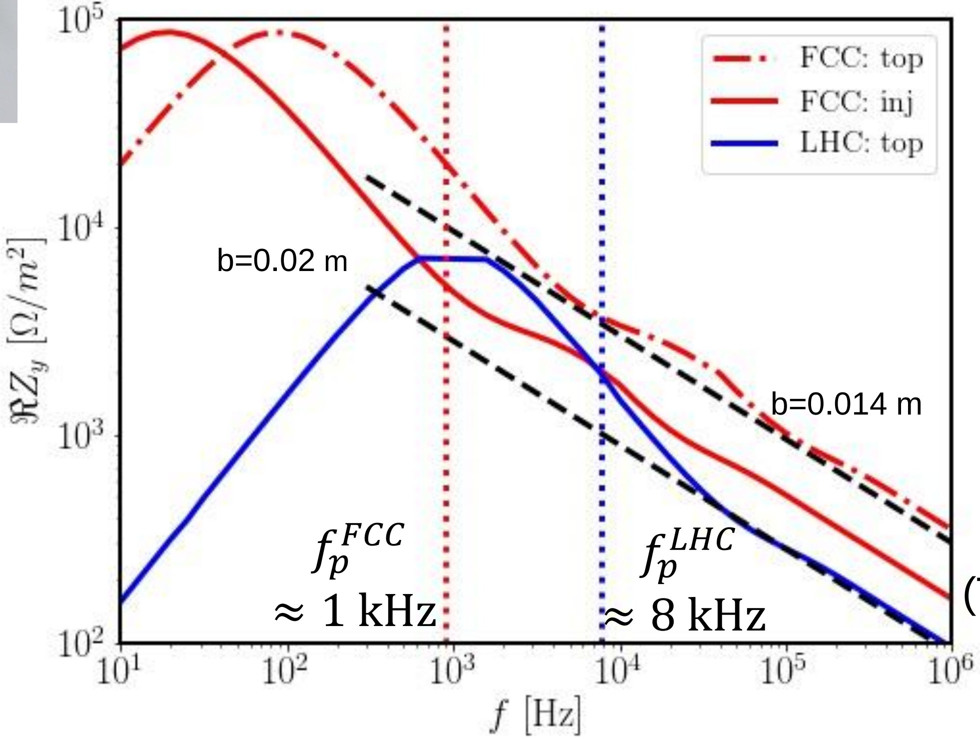
FCC



LHC

Growth rate: (Sacherer 1974) $\frac{1}{\tau_k} = -\frac{1}{1+k}\frac{qIc}{2E_0B_f}\hat{\beta}_\perp \Re[Z(\omega_p)]F_k'(\omega_p - \chi/\tau_b)$ $\omega_p \approx (n-Q)\omega_0$

Transverse impedances (only real part)



growth time at 3.3 TeV:
approx. 200 turns
at 50 TeV:
approx. 1000 turns

(LHC at 7 TeV: 2000 turns)

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

(Thick) resistive wall impedance

Dispersion relation and Landau damping

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$$\Delta Q_{\mathrm{coh}} \int \frac{1}{\delta Q_{\mathrm{oct}}(J_x, J_y) - \Omega / \omega_0} J_x \frac{\partial F(J_x, J_y)}{\partial J_x} dJ_x dJ_y = 1$$

$$\Delta Q_{\mathrm{coh}} \propto L \frac{Z_\perp \hat{\beta}_\perp}{\gamma}$$ (coherent tune shift)

$$\delta Q_x = a_x J_x - b_{xy} J_y$$ (octupoles)

see V. Kornilov

$$N_{\mathrm{oct}} O_3 L_{\mathrm{m}} \propto \frac{\gamma^2}{\hat{\beta}^2 \varepsilon} \delta Q_{\mathrm{oct}}$$

(incoherent tune spread)

$$\delta Q_{\mathrm{oct}} \approx \Delta Q_{\mathrm{coh}}$$

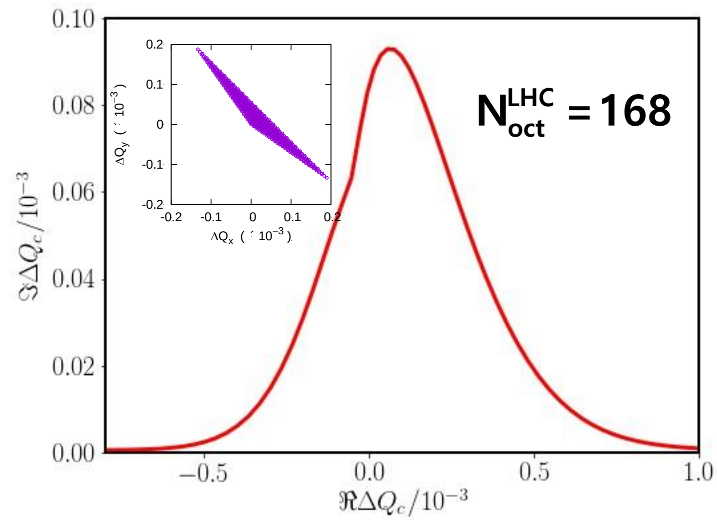
(for stability)

LHC (7 TeV) vs FCC-hh (50 TeV):

$$\frac{\Delta Q_{\mathrm{coh}}^{\mathrm{FCC}}}{\Delta Q_{\mathrm{coh}}^{\mathrm{LHC}}} = \frac{L_{\mathrm{FCC}}}{L_{\mathrm{LHC}}} \times \frac{\hat{\beta}_{\mathrm{FCC}}}{\hat{\beta}_{\mathrm{LHC}}} \times \left(\frac{\gamma_{\mathrm{FCC}}}{\gamma_{\mathrm{LHC}}}\right)^{-1} \times \frac{Z_{\mathrm{FCC}}}{Z_{\mathrm{LHC}}} \approx 2 - 3$$

$$\delta Q_{\mathrm{oct}} \approx \Delta Q_{\mathrm{coh}} \quad \Rightarrow \frac{(N_{\mathrm{oct}} O_3 L_{\mathrm{m}})^{\mathrm{FCC}}}{(N_{\mathrm{oct}} O_3 L_{\mathrm{m}})^{\mathrm{LHC}}} \approx 50 \qquad N_{\mathrm{oct}}^{\mathrm{FCC}} \approx 8000$$

Example stability plot for LHC (7 TeV)



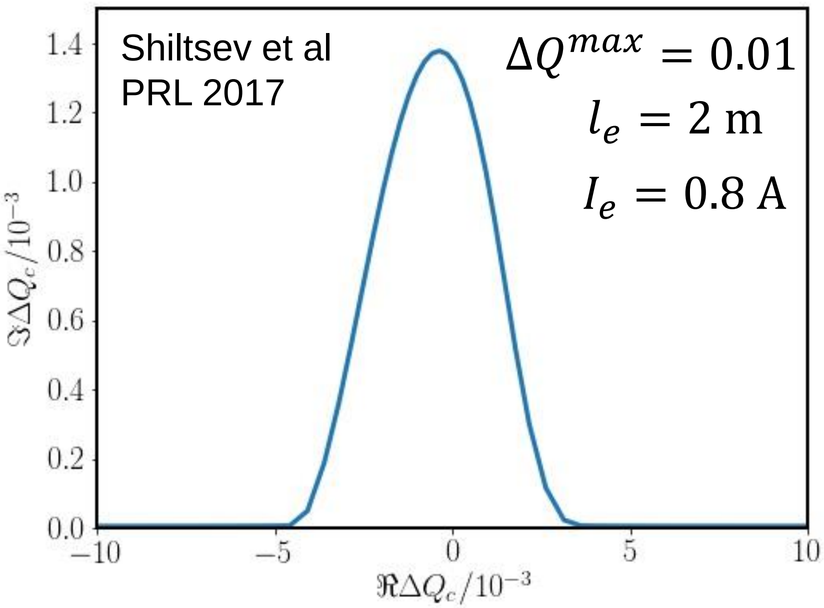
Undesired effects: Reduction of dynamic aperture,…

Possible strategy: Active dampers for k=0, octupoles for k>0.

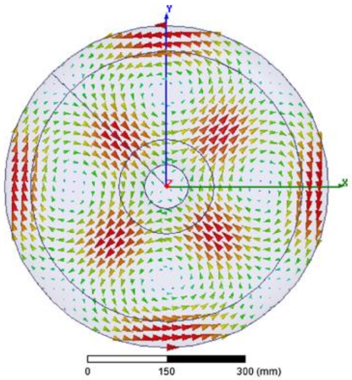
Landau damping: Possible alternative schemes

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

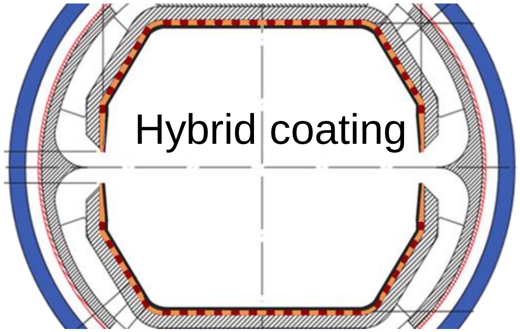
$$\Delta Q_{x,y}(z) = \pm \frac{q\hat{\beta}_{x,y}k^{(2)}}{4\pi m\gamma_0}\cos\left(\frac{\omega_{rf}z}{c}+\phi\right)$$

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

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

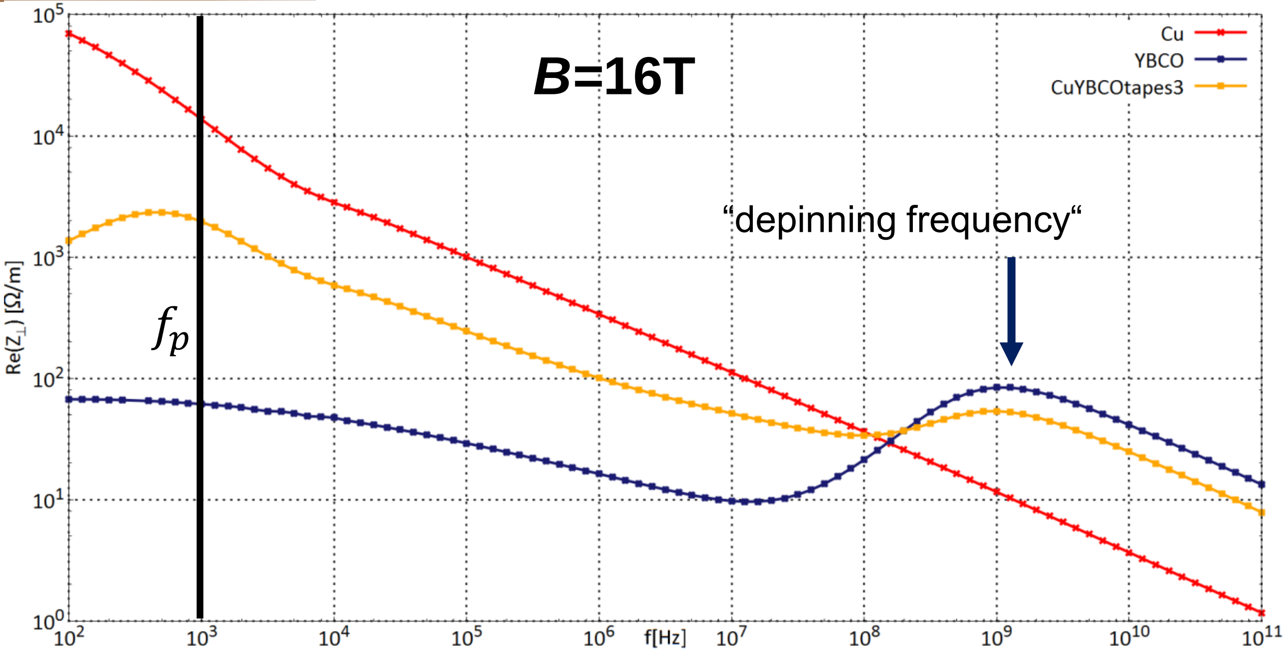
Detailed particle tracking studies are ongoing (see also V. Kornilov).

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

Electron cloud studies

openEcloud : https://github.com/openecloud

e.g. F. Petrov, O. Boine-Frankenheim, O. Haas, PRAB (2014)

Fast 2D Poisson solver, PIC solver, SEY model, interfaces to PATRIC/pyORBIT (to do)

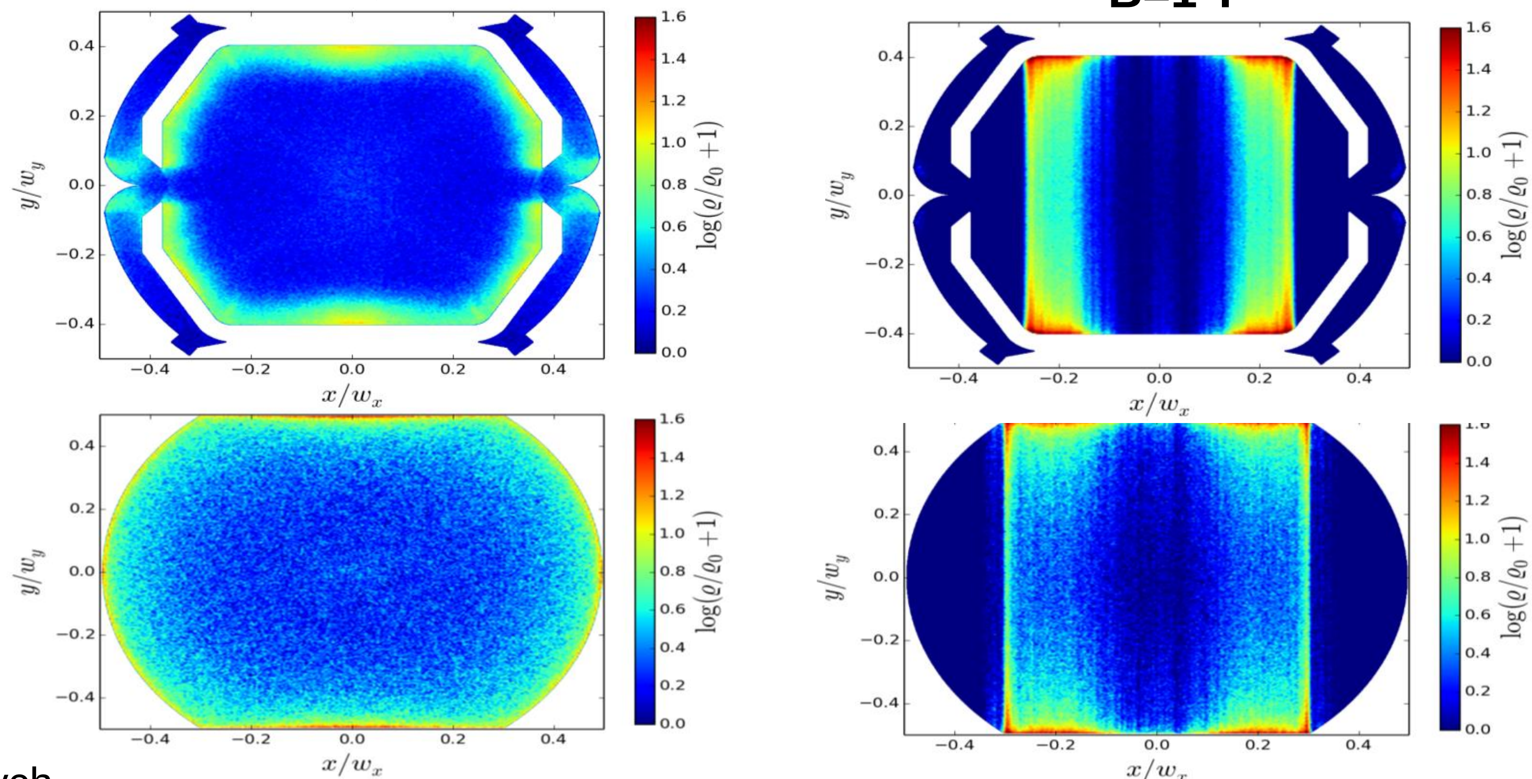
B=0 **B=1 T**

FCC

LHC

$N_b = 10^{11}$

25 ns bunch spacing



D. Astapovych

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

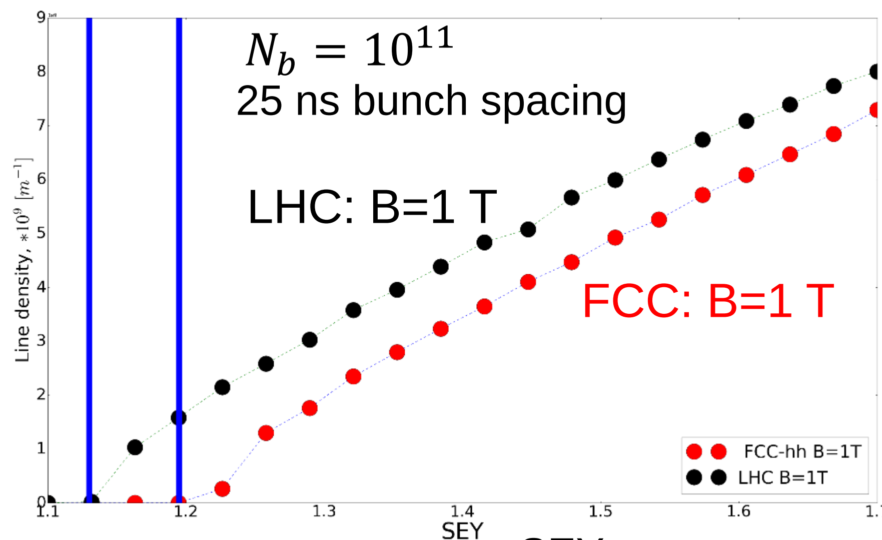
Lower electron energies for smaller R_p

Differences between different simulation models and codes:

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

Next step: (residual) photoelectron

$\mathrm{SEY} \approx 1.1$ $\mathrm{SEY} \approx 1.2$ **SEY threshold for buildup**



SEY

D. Astapovych

Electron cloud: instability thresholds

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Rumolo et al. PRL (2008): Electron cloud induced instability stronger at higher energies because of smaller beams.

$$\kappa_e(z) = \frac{\sqrt{2r_e\lambda(z)}}{a}$$

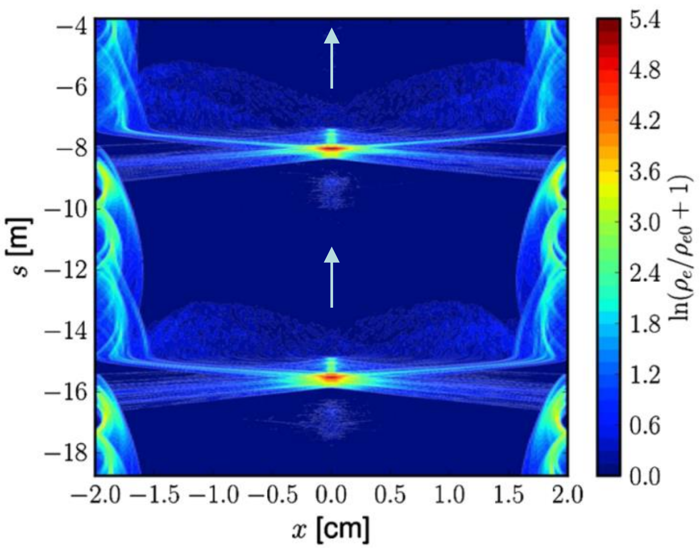
(focusing strength for electrons in the bunch potential)

Electron cloud density thresholds (K. Ohmi et al, IPAC2015)

$$n_{e,th} \approx \frac{\gamma Q_s}{\kappa_e r_e \hat{\beta} L}$$

3 TeV: $n_{e,th} = 4.4 \times 10^{10}\ m^{-3}$
50 TeV: $n_{e,th} = 5.7 \times 10^{11}\ m^{-3}$

-> Next step: Detailed simulations to determine instability threshold densities (and required SEY for FCC) !



Simulation for LHC (drifts), B-F., Petrov (PRAB 2012/2015)

If the the FCC screen will be a-C coated (with SEY lower/equal 1) and the chosen screen design avoids photoelectron entering in the pipe, electron could induced instabilities should be absent in the FCC.

Status and Plans (EuroCirCol WP 2.4)

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Impedances studies:

- ✓ Screen and coatings (HTS and laser): HTS for impedance, Laser for SEY
- ✓ Warm parts (see B. Riemann)
- ✓ Collimators: Important at top energy
- o Impedance library (see S. Arsenyev)

Impedance budgets -> from instability thresholds (!) or tolerable head loads.

- ✓ Screen/Collimators: Coupled bunch damped by Octupoles (k>=0) and Feedback
- ✓ TMCI (might be an issue with laser coating and collimators)
- o Other Landau damping mechanisms and combinations (see V. Kornilov)

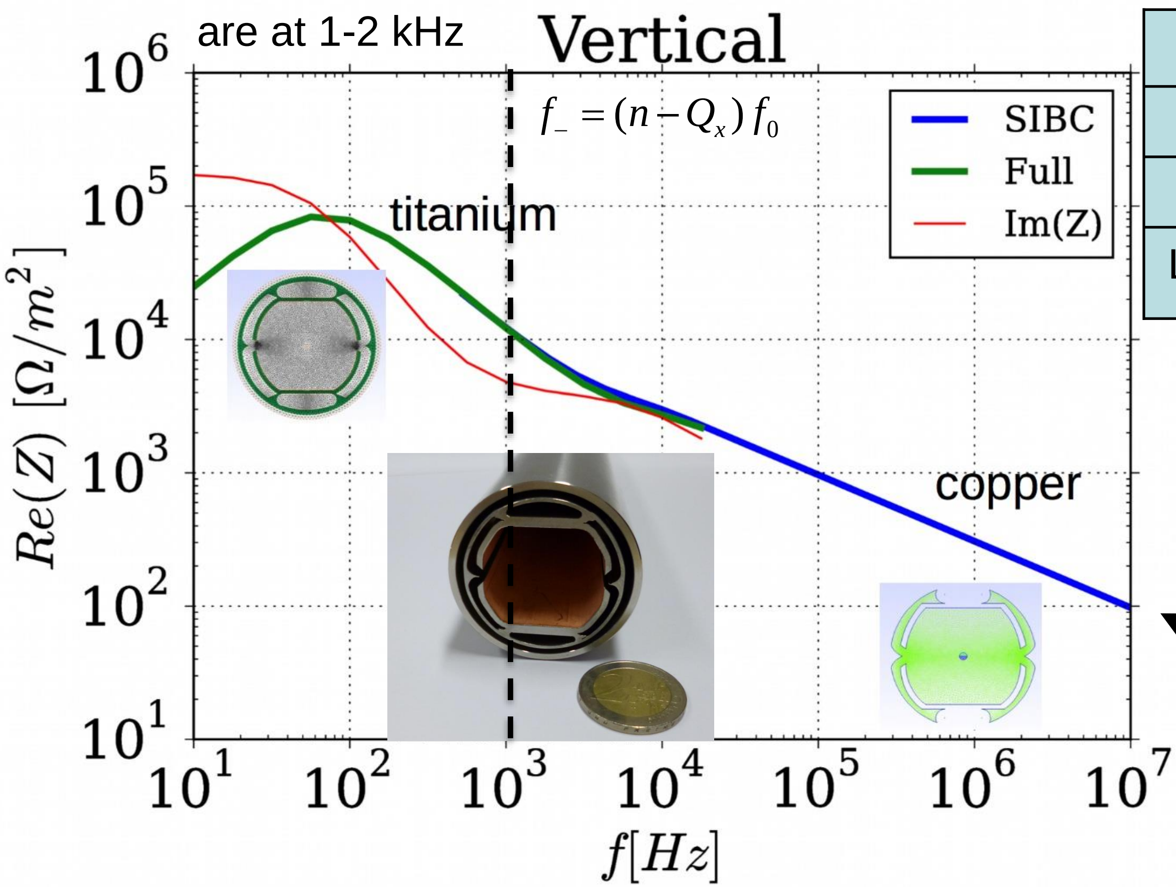
Ecloud buildup and instability thresholds:

- ✓ Estimates for buildup (see L. Mether)
- o Required SEY for instability supression.

Backup

FCC beam screen and impedance

Betatron side-bands are at 1-2 kHz



Beam pipe	
Material	Cu, SS
Cu thickness [μm]	**300**
Laser/a-C coating [μm]	**1-10**

Resistive wall instability:

$$\frac{1}{\tau} \approx \frac{MqI_b\omega_0}{4\pi m\gamma_0 c^2 B_f} \hat{\beta}_\perp \Re[Z(\omega_-)]$$

High-frequency parts and coatings treated separately.