FCC-hh impedances and instabilities

O. Boine-Frankenheim (for EuroCirCol Task 2.4)

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

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FCC-hh vs LHC: Beam stability

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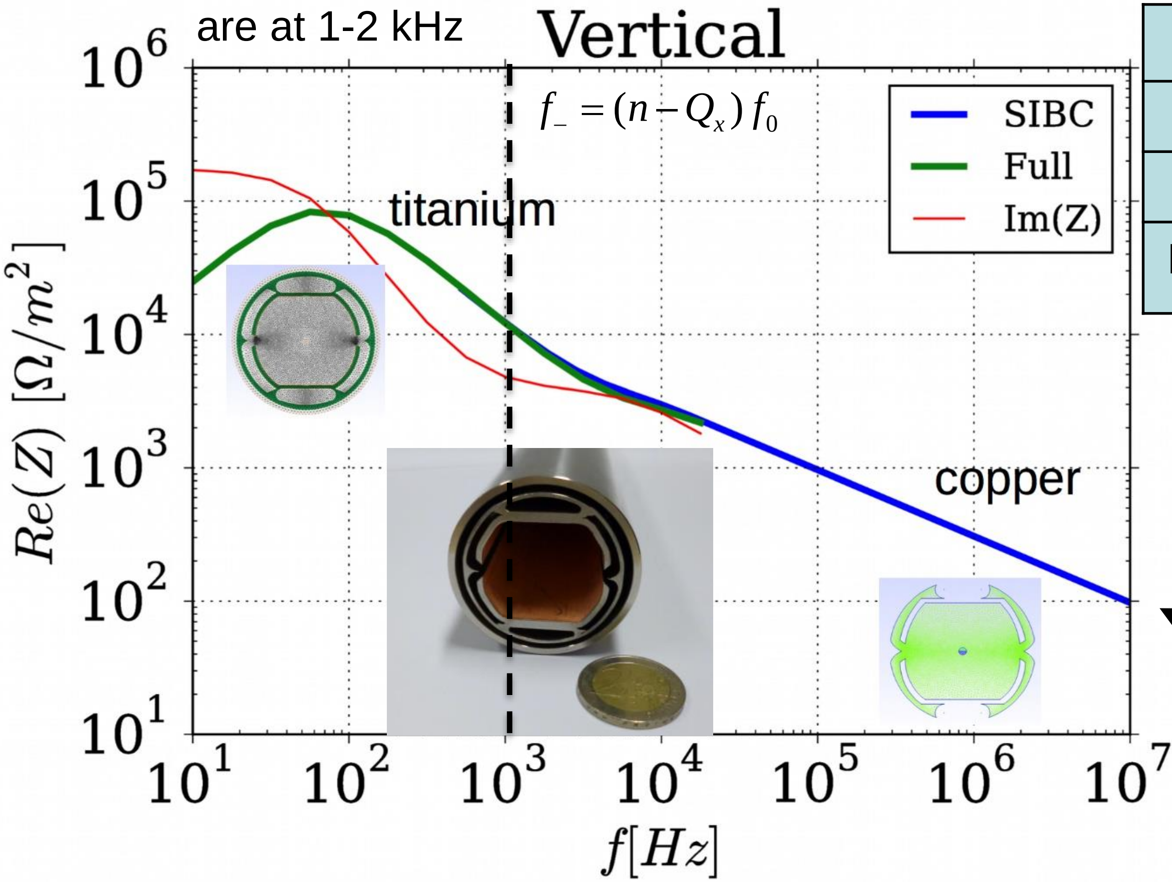
Growth rate for transverse instabilities: $\tau^{-1} = \mathrm{Im}\left(\Delta\Omega\right) \propto \frac{q^2 N}{m\gamma} \hat{\beta}_\perp \Re Z_\perp$

- Larger circumference (5:1) -> lower frequency: **1 kHz vs 8 kHz**
- Smaller screen diameter (2:3) -> **larger impedance** (factor 3), **e-cloud density ?**
- 20 W/m synchrotron radiation (100:1) -> **photo electrons**
- 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)

FCC beam screen and impedance

Betatron side-bands
are at 1-2 kHz



See poster: Daria Astapovych

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.

At 3 TeV: resitive wall instability ≈ 100 turns -> feedback (+ octupoles) required !

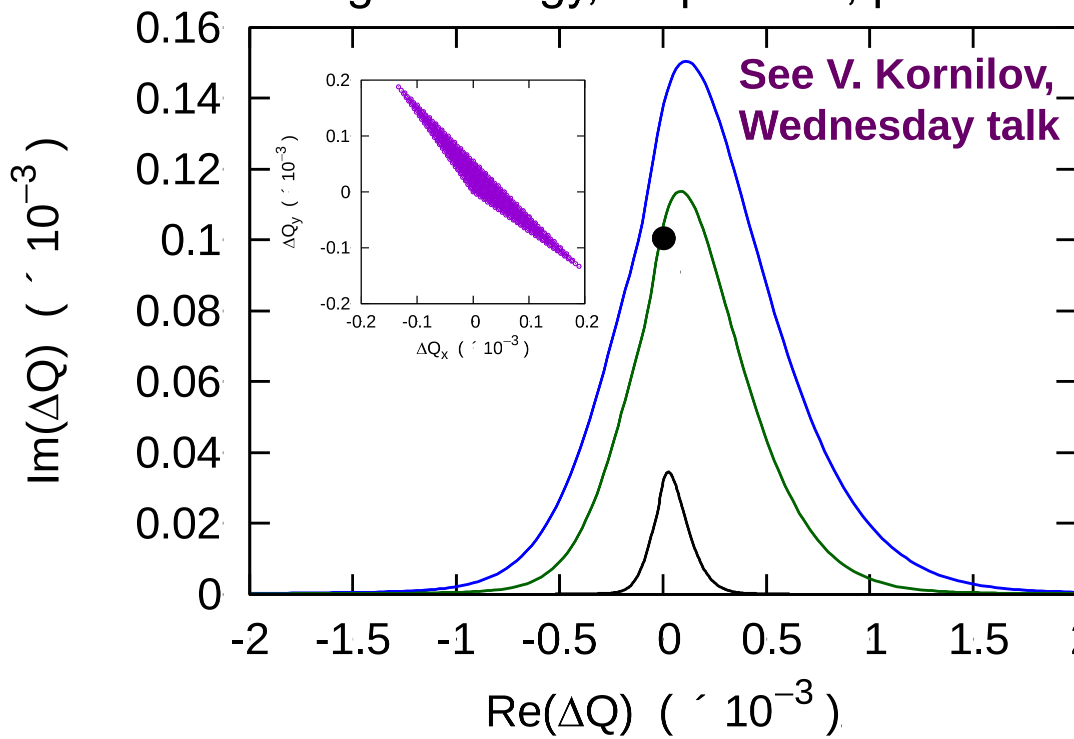
Landau damping: Octupoles

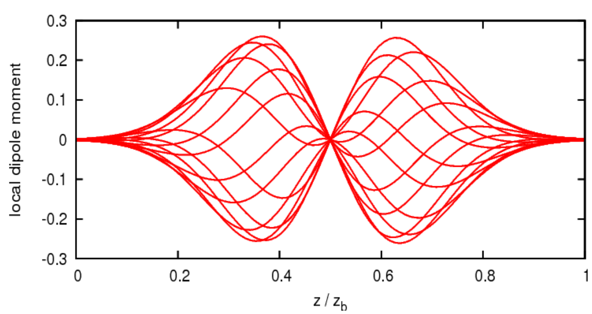
The expected coherent tune shifts in FCC are similar to those in LHC.
The total octupole power should be ≈ 20 times stronger: energy, amplitudes, β-functions

Blue: ΔQ_{coh}−Damping as in LHC. **3554** Octupoles.

Green: enough damping for the (•) included impedances. **2686** octupoles.

Black: $N_{MO} = N_{MQ} =$ **814**



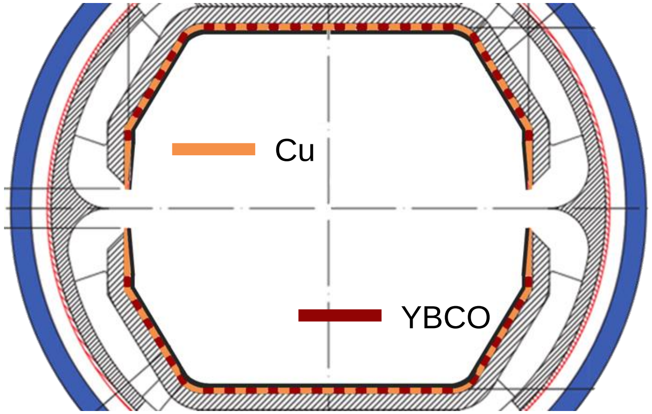


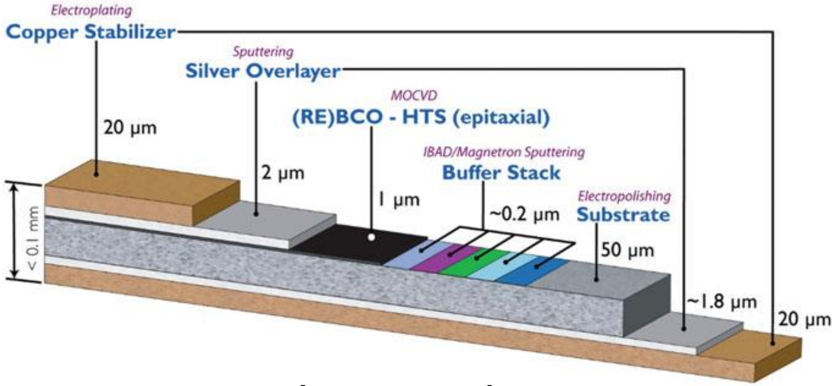
Same damping rates also for k>0

Octupoles vs. RFQ: Simulations indicate that the RFQ requires larger tune spreads.

HTS screen coating for impedance reduction

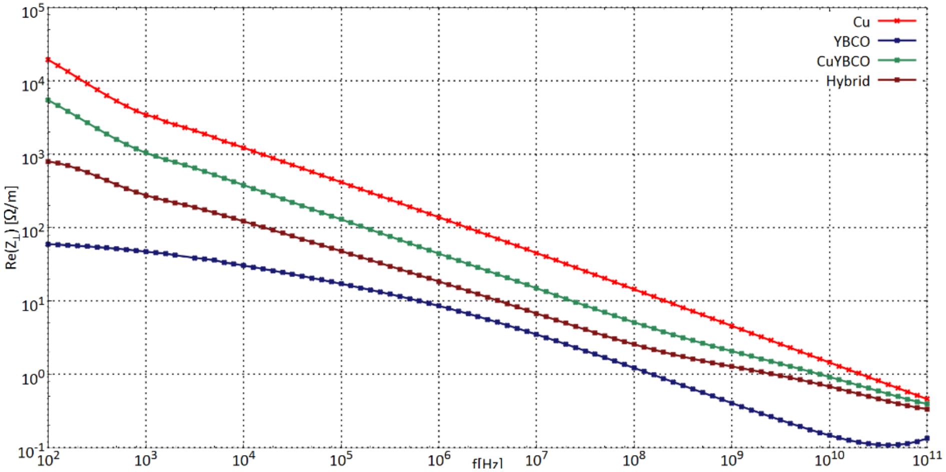
Potential impedance reduction by factor 10 !





See poster by Francis Perez

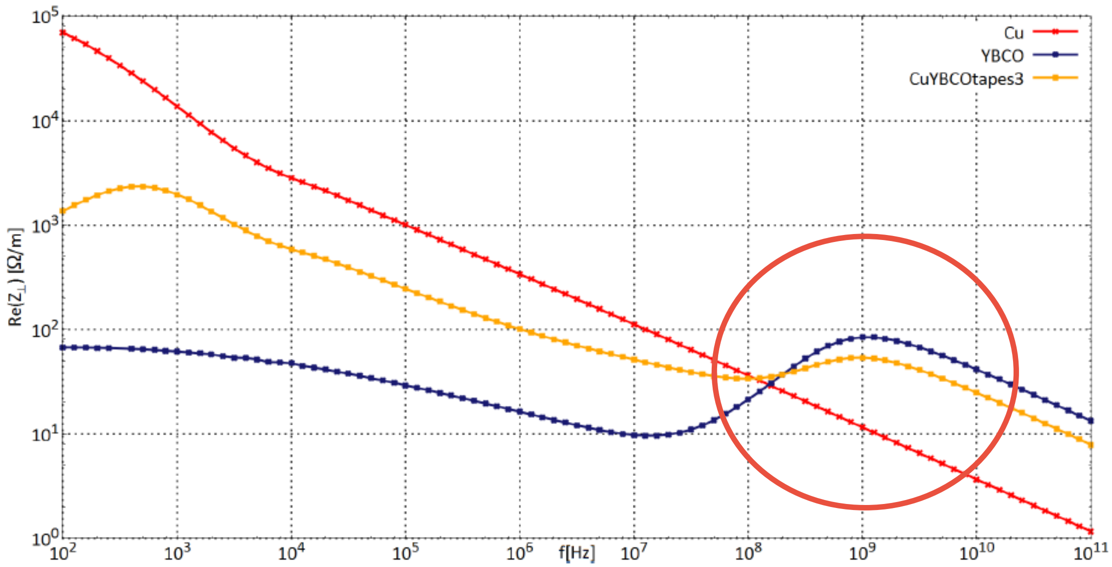
Steel beam screen:	YBCO coating:	Copper coating:
$\kappa = 180$ MS/m	$\kappa_n = 1.37$ MS/m	$\kappa = 6$ GS/m
Thickness: 1 mm	Thickness: 1 µm	Thickness: 300 µm



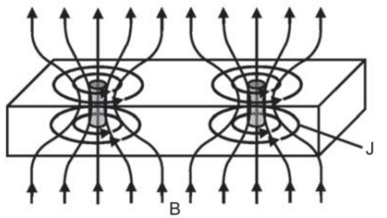
See poster: Patrick Krkotic

HTS coating: Effect on the magnetic field

Larger impedance at high frequencies for large magnetic fields (16 T.)



Flux line lattice



$$\rho_{fl} = \rho_{ns} \frac{B_0}{B_{c2}} \frac{\omega^2 + i\omega\omega_{dep}}{\omega^2 + \omega_{dep}^2}$$

$$\rho_{TFM} = \frac{1}{\kappa_n - i\kappa_{sc}}$$

$$\rho_{eff} = \rho_{fl} + \rho_{TFM}$$

$$Z_s = (1+i)\sqrt{\frac{\mu_0 \omega}{2}\rho_{eff}}$$

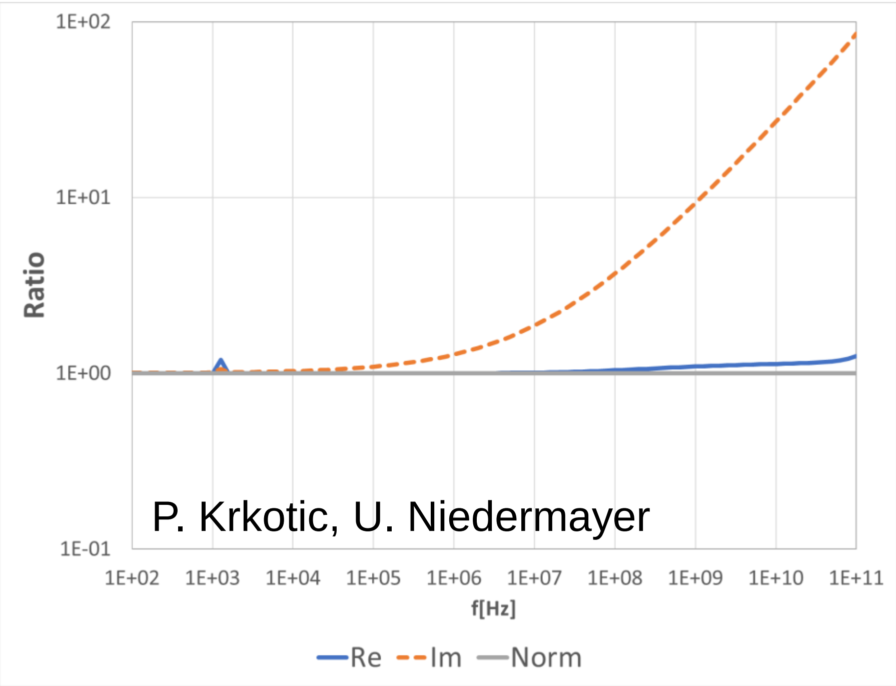
See poster: Patrick Krkotic

Superconductor surface resistance in the presence of a dc magnetic field: frequency and field intensity limits
Sergio Calatroni – (submitted to IEEE)

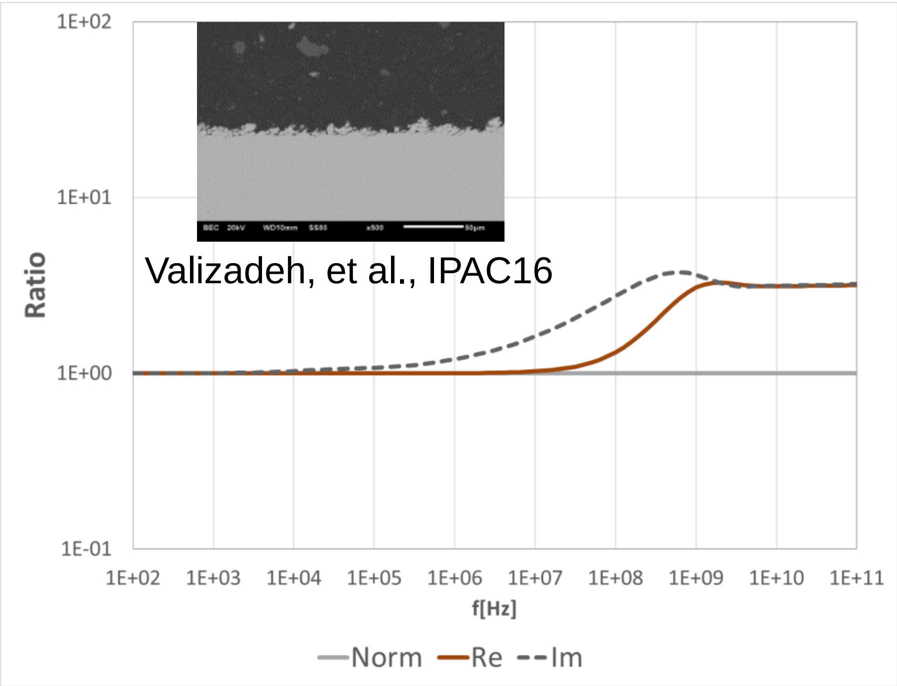
Screen coating for SEY reduction

Both type of coatings, a-C and laser treatment, reduce the SEY to values below 1.

1 µm a-Carbon coated surface



8 µm laser treated surface



Enlarged impedance at > 1 GHz
might lead to TMCI-like instabilities.

Transverse mode coupling instabilities

(Laser) coating: Impedance contributions above 1 GHz.

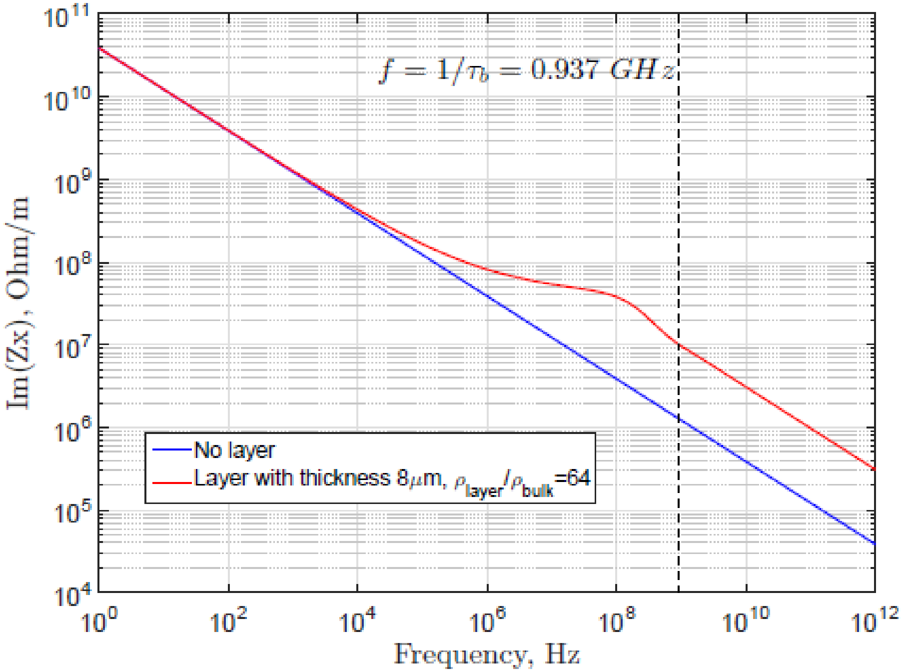
Threshold bunch intensity for BB-like impedances (k=0 couples with k=-1):

$$N_{TMCI} \approx \frac{16\pi m_p \gamma Q_x \omega_0 \sigma_z Q_s}{e^2 Z_{\perp,0}} \propto \frac{1}{\gamma_t}$$

At 3 TeV (no coating): $N_{TMCI} \approx 10^{12}$

At 3 TeV (coating): $N_{TMCI} \approx 10^{11}$

S. Arsenyev: talk on Wednesday



Collimator impedance and TMCI:
D. Amorim

If necessary, TMCI threshold could be increased by larger bunch area or “nonlinear rf”.

Electron cloud: Buildup (no coating)

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

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

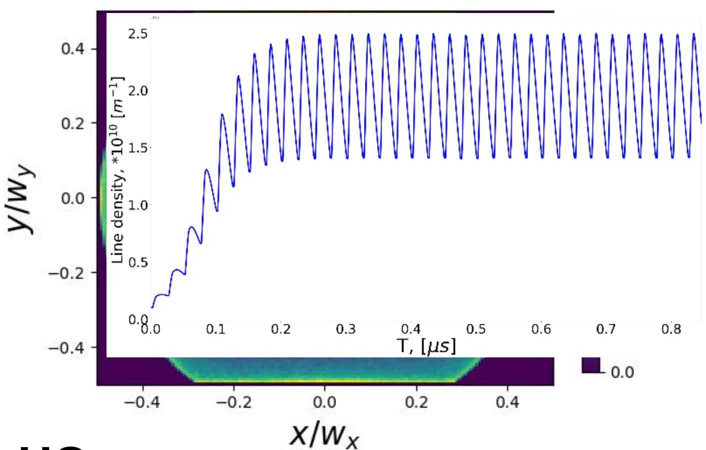
$$n_{es} \approx \frac{E_s}{\pi m_e c^2 r_e R_p^2}$$

Saturated electron cloud density depends on pipe radius R_p

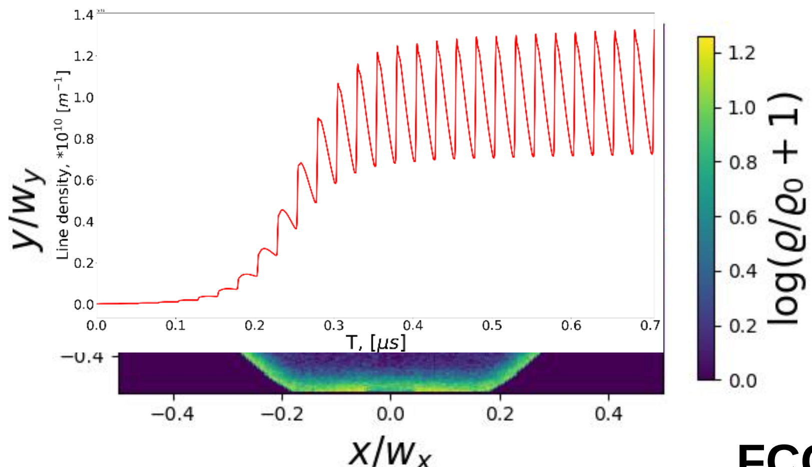
Lower electron energies for smaller R_p

-> Simulation studies using detailed FCC screen started (poster: Daria Astapovych)!

https://github.com/openecloud/openecloud



LHC



FCC

See also L. Mether's talk: shorter bunch spacing.

Electron cloud density: Instability thresholds

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

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

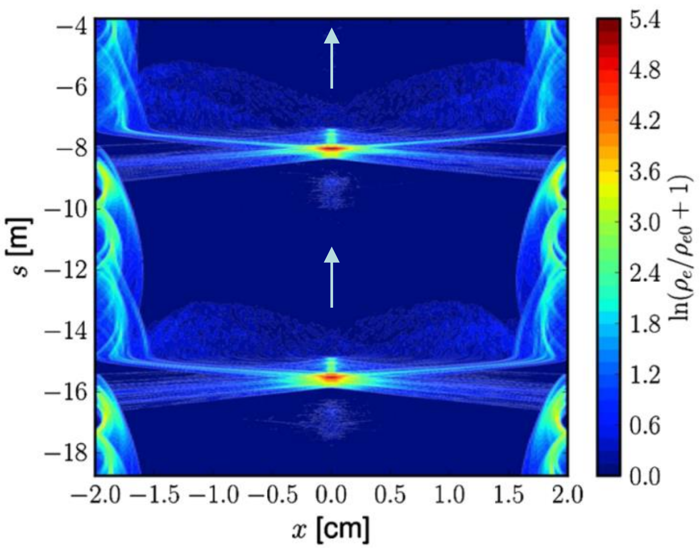
(focusing strength for electrons in the bunch potential)

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

-> Detailed simulations required to determine 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
- ✓ Holes/slits in the screen: Analytical estimates (see B. Riemann today)
- ✓ Collimators: Important at top energy
- o Interconnects,…

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

- ✓ Screen/Collimators: Coupled bunch damped by Octupoles (k>=0) and Feedback
  - - > HTS coating might allow to operate with Octupoles only
- ✓ TMCI (might be an issue with laser coating and collimators)

Ecloud buildup and instability thresholds:

- ✓ Estimates for buildup in simplified geometries
- o Buildup in detailed FCC screen geometry (-> allowed residual photoelectrons)
- o Required SEY for instability supression.

Scaling of thresholds/budgets from LHC to FCC using analytical/simulations tools.

Backup

Collimator impedances

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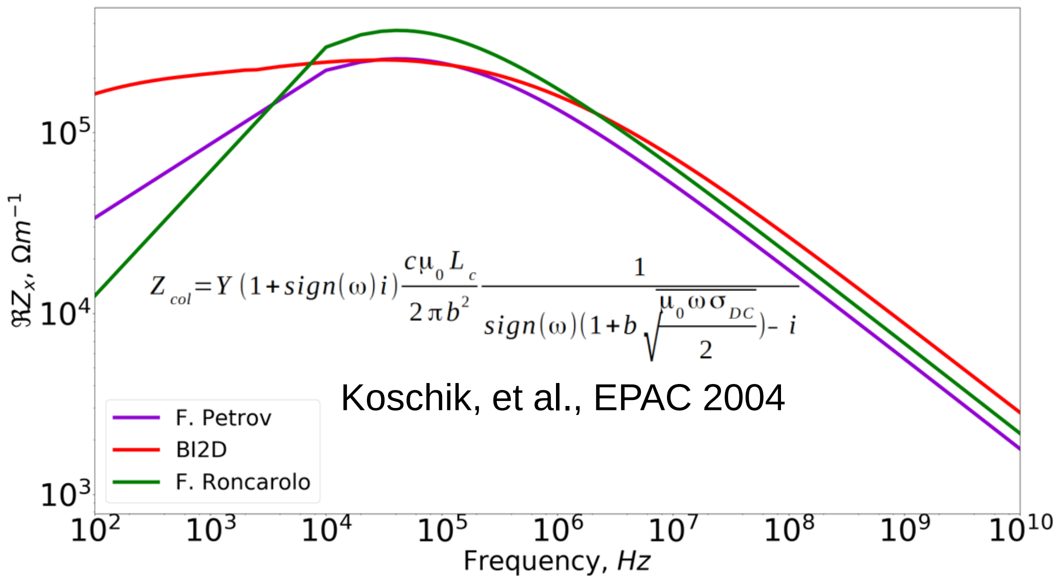
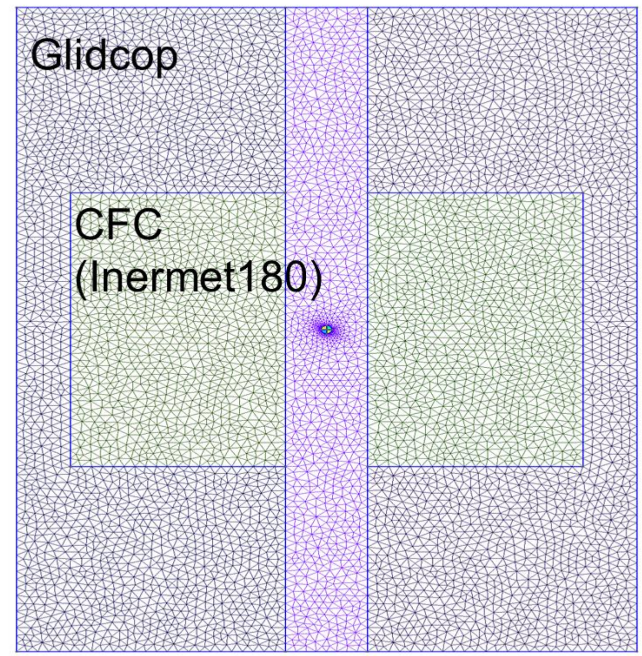


E [TeV]	Growth rate [Turns]
1.5	1729
3.3	3805
50	8018

Betatron collimation (CFC)
3 primaries (7.6 σ) 11 secondaries (8.8 σ) 5 absorbers (12.6 σ)



Ecloud with B=1T