Estimation and scaling laws of impedances and beam instabilities from LHC to FCC-hh

Daria Astapovych*, Oliver Boine-Frankenheim
TEMF, Schloßgartenstraße 8, 64289 Darmstadt, Germany

TECHNISCHE UNIVERSITÄT DARMSTADT

Abstract

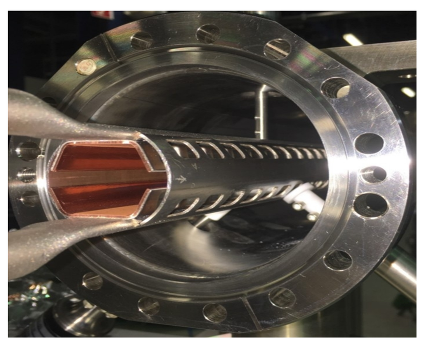
Beam instabilities caused by electron clouds and the resistive wall impedance are potential intensity limitations for a possible FCC-hh. Similar to LHC, the short relativistic proton bunches and their small spacing can lead to an electron cloud buildup. The FCC-hh beam screen will be coated partially with a low SEY layer, which might affect the impedance. We study the FCC-hh resistive wall impedance as well as the electron cloud buildup for realistic pipe geometries and different SEY models. We also analyze the scaling of the resulting effects, like the instability growth rate and the heat load, with beam energy and pipe dimensions.

Analysis of impedance and collective effects

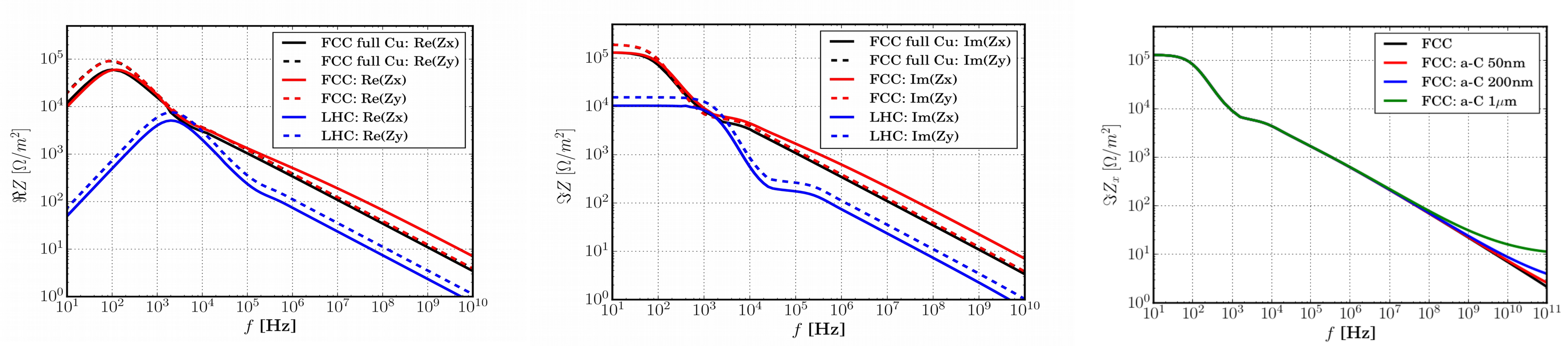
The FCC-hh resistive wall instability will be critical at both injection and top-energy due to the very low revolution frequency, the smaller beam screen radius, the increased resistivity of the inner copper layer (at 50 K) and higher magnetic fields together with the complex opening slits, relative to the LHC.

Parameters	LHC	FCC-hh
Circumference (km)	27	100
E_{inj} / E_{top} (TeV)	0.45 / 7	3.3 / 50
B_{inj} / B_{top} (T)	0.54 / 8.3	1.06 / 16
f_{rev} (Hz)	2942	3067
Q_x / Q_y	59.28/63.31	111.28/109.31
N_b (p/b)	10^{11}	10^{11}
N of bunches	2808	13068
τ_b (ns)	1	1
Bunch spacing (ns)	25	25
ϵ_{norm} (μm)	3.75	2.2

LHC



FCC-hh



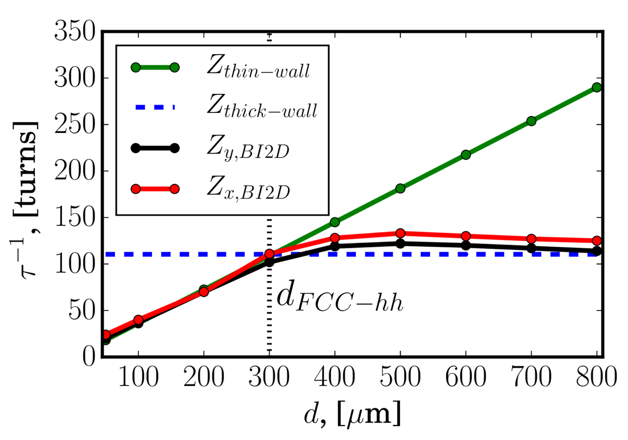
Transverse resistive wall impedance in case of top energy for the LHC and energy injection for the FCC-hh.

In order to prevent EC buildup the amorphous carbon (a-C) coating is the present design choice for the FCC-hh. It has a low SEY and a relatively weak effect on the machine impedance.

TCBI growth rate

$$\tau_0^{-1} = \frac{j}{2Q\omega_0} \frac{e\beta I_0}{\gamma m_0 L} \Re(Z_{tr,0})$$

$$\frac{\tau_{\mathrm{FCC}}^{-1}}{\tau_{\mathrm{LHC}}^{-1}} \approx \begin{matrix} 20 \text{ at injection/flat top} \\ 2 \text{ at flat top/flat top}. \end{matrix}$$



TMCI threshold

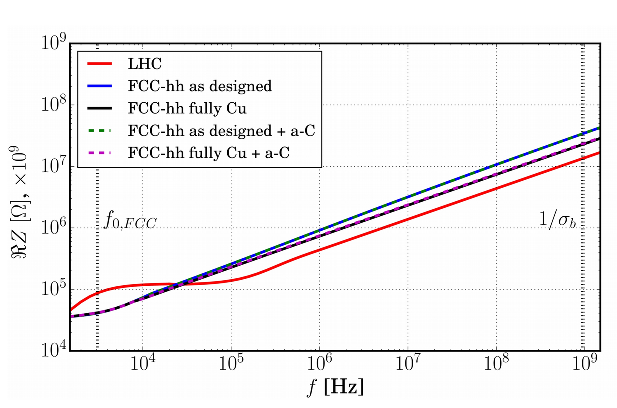
$$N_{th} = \frac{16\pi m_p \gamma Q_s \omega_0 \sigma_z Q_{x,y}}{\Im(Z_{tr}) e^2}$$

$$\frac{N_{\mathrm{th,FCC}}}{N_{\mathrm{th,LHC}}} \approx \begin{matrix} 1.1 \text{ at injection/flat top} \\ 13.5 \text{ at flat top/flat top}. \end{matrix}$$

a-C coating: in the horizontal plane

$$\frac{N_{\mathrm{th,FCC}}}{N_{\mathrm{th,FCC+a\text{-}C}}} \approx \begin{matrix} 1 \text{ for 50-200 nm coating}, \\ 0.9 \text{ for } 1\,\mu m \text{ coating}. \end{matrix}$$

In case of the vertical plane, the influence on the TMCI is negligible.



Longitudinal resistive wall impedance in case of top energy for the LHC and energy injection for the FCC-hh.

Heat load

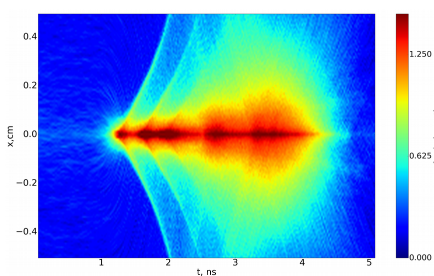
$$P = -2\pi e^2 N_b^2 \omega_0 \frac{c}{L l_{\mathrm{bb}}} \int_{-\infty}^{\infty} Z_{\|}(\omega) h(\omega,\sigma) d\omega.$$

$$\frac{P_{\mathrm{FCC}}}{P_{\mathrm{LHC}}} \approx \begin{matrix} 0.54 \text{ at injection/flat top} \\ 0.43 \text{ at flat top/flat top}. \end{matrix}$$

Impedance is obtained with ***BeamImpedance2D*** (U. Niedermayer).

Electron cloud study

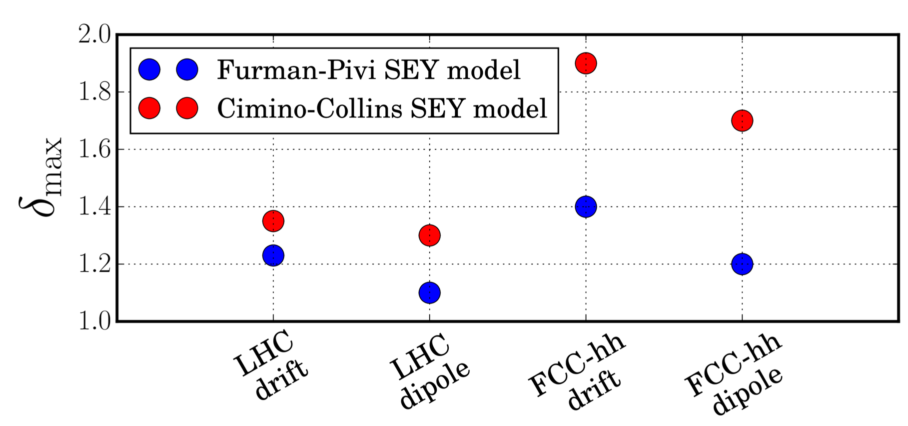
The electron clouds is one of the factors limiting the intensity of the proton beams. These limitations can arise from the EC heat load and instabilities. Thus, the EC can cause the emittance growth, tune shift and tune spread, beam instabilities and losses, vacuum degradation.



Electron cloud pinch in the absence of B-field

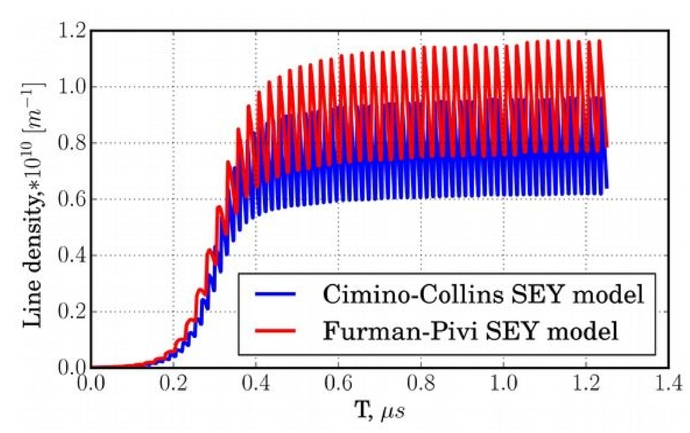
The FCC-hh, in comparison to the LHC, will have smaller beam pipe and, due to the higher energy, higher synchrotron radiation. On the other hand, the EC buildup depends on the beam screen geometry and the SEY of the beam screen surface. Therefore, the ECE can be more critical for the potentially new machine.

The sufficiently low SEY is needed to avoid the effect of the EC saturation
→ to find the maximum SEY value δ_{max} below which the EC do not saturate
→ based on the measurement two SEY models for the copper are used: Cimino-Collins and Furman-Pivi models

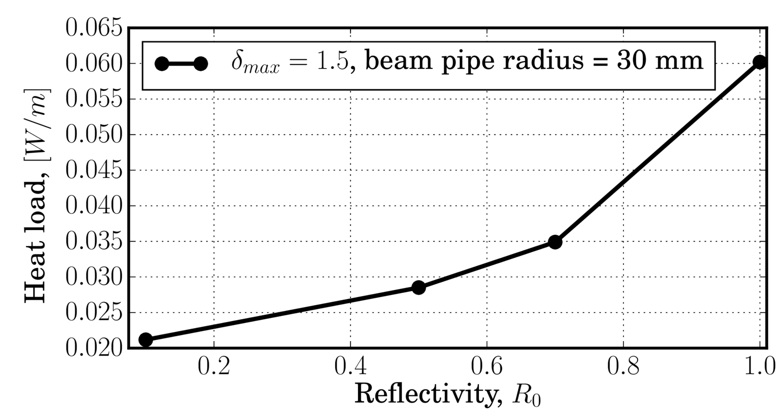


SEY threshold δ_{max} for the LHC and the FCC-hh in the drift and arc dipole.

A discrepancy in the simulation results can be due to:
– the fit to the experimental data;
– models have different values for the elastic electron reflectivity at zero primary electron energy: in the Cimino-Collins model R_0=0.7 and in the Furman-Pivi model R_0≈0.5;
– different electron distribution.

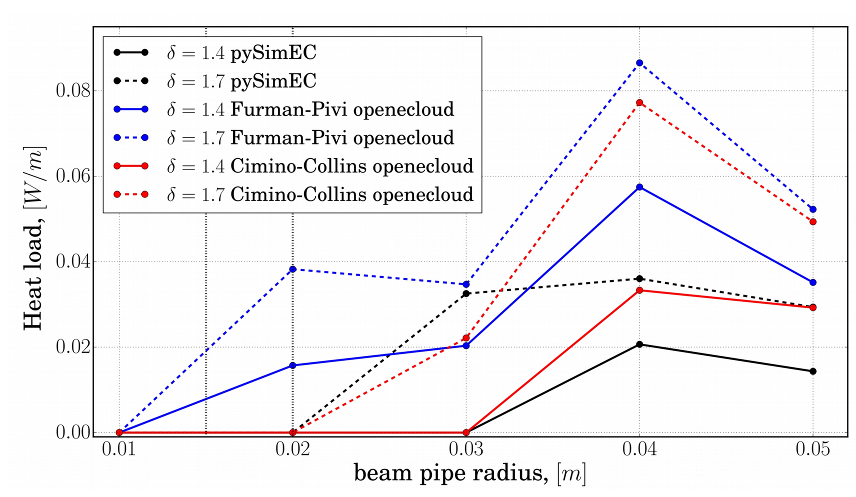


Electron cloud buildup in the 40 mm circular beam pipe, in the arc dipole and δ_{max} = 1.7.



Heat load as a function of reflectivity R0.

The EC results in an energy loss and corresponding heat load, that was previously observed in the LHC. In order to gain an understanding of the scaling of EC induced effects with energy and different pipe geometries, the heat load study for different beam pipe radii in case of the round beam pipe is done.



Heat load as the function of the beam pipe radius in the presence of the dipole magnetic field B = 1T.

Conclusion

• 200 nm of a-C coating, without an external sublayer, can be sufficient to avoid the electron clouds in the beam pipe and will not cause a large impact on the TMCI threshold.
• The results from the openECLOUD simulations for the FCC-hh and the LHC show the sensitivity to the chosen SEY model.

*astapovych@temf.tu-darmstadt.de

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