FCC-hh impedances and instabilities

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FCC-hh vs LHC: Beam stability

Growth rate for transverse instabilities: \[ \tau^{-1} = \text{Im}(\Delta \Omega) \propto \frac{q^2 N}{m\gamma} \hat{\beta} \Re Z \]

- 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 conductivities
- Larger average \( \beta \)-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

Vertical

\[ f_\bot = (n - Q_x) f_0 \]

- SIBC
- Full
- Im(Z)

Material
- Cu, SS

Cu thickness [μm]
- 300

Laser/a-C coating [μm]
- 1-10

Resistive wall instability:

\[
\frac{1}{\tau} \approx \frac{M q I_b \omega_0}{4 \pi m \gamma_0 c^2 B_f} \hat{\beta}_\bot \Re[Z(\omega_\bot)]
\]

High-frequency parts and coatings treated separately.

At 3 TeV: resistive 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: $\Delta Q_{coh}$ – 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.

See V. Kornilov, Wednesday talk.
HTS screen coating for impedance reduction

Potential impedance reduction by factor 10!

Steel beam screen:
\[ \kappa = 180 \text{ MS/m} \]
Thickness: 1 mm

YBCO coating:
\[ \kappa_{\text{YBCO}} = 1.37 \text{ MS/m} \]
Thickness: 1 \( \mu \)m

Copper coating:
\[ \kappa = 6 \text{ GS/m} \]
Thickness: 300 \( \mu \)m

See poster: Patrick Krkotic

See poster by Francis Perez
HTS coating: Effect on the magnetic field

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

\[ \rho_{\text{eff}} = \rho_{\text{fl}} + \rho_{\text{TFM}} \]

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

\[ \rho_{\text{TFM}} = \frac{1}{\kappa_n - i\kappa_{\text{sc}}} \]

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

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.

Valizadeh, et al., IPAC16
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”.

\[ f = \frac{1}{\tau_i} = 0.937 \text{ GHz} \]

\[ \text{Im}(Z_x), \text{Ohm/m} \]

\[ \text{Frequency, Hz} \]

\[ f = 1/\tau_i = 0.937 \text{ GHz} \]

\[ \text{No layer} \]

\[ \text{Layer with thickness 8\mu m, } \rho_{layer}/\rho_{bulk} = 64 \]
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](https://github.com/openecloud/openecloud)

LHC

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

FCC
Electron cloud density: Instability thresholds

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

Electron cloud density thresholds

\[ n_{e,\text{th}} \approx \frac{\gamma Q_s}{\kappa_e r_e \beta L} \]

3 TeV: \( n_{e,\text{th}} = 4.4 \times 10^{10} \text{ m}^{-3} \)

50 TeV: \( n_{e,\text{th}} = 5.7 \times 10^{11} \text{ m}^{-3} \)

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

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.

Simulation for LHC (drifts), B-F., Petrov (PRAB 2012/2015)
Status and Plans (EuroCirCol WP 2.4)

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

\[ Z_{\text{col}} = Y (1 + \text{sign}(\omega)) i \frac{c \mu_0 L_c}{2 \pi b^2} \cdot \frac{1}{\text{sign}(\omega) \sqrt{1 + b \frac{\mu_0 \omega \sigma_{DC}}{2}}} - i \]

Koschik, et al., EPAC 2004

Betatron collimation (CFC)
- 3 primaries (7.6 \( \sigma \))
- 11 secondaries (8.8 \( \sigma \))
- 5 absorbers (12.6 \( \sigma \))

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<th>E [TeV]</th>
<th>Growth rate [Turns]</th>
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Ecloud with B=1T