E-cloud studies for FCC-hh

D. Astapovych (for EuroCirCol Task 2.4)

O. Boine-Frankenheim (TU Darmstadt)
S. Arsenyev, L. Mether, B. Salvant, D. Schulte (CERN)
V. Kornilov (GSI)
T. Pieloni, C. Tambasco (EPFL, Lausanne)
Outline

- FCC-hh study
- FCC-hh impedance and instabilities
- Electron cloud study:
  - SEY threshold
  - Stopping power
- Summary
FCC-hh vs LHC: Beam stability

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

Larger circumference (3:1) -> 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) -> photoelectrons

Larger average \( \beta \)-function (2:1) -> growth rates

LHC-like bunches and 25 ns spacing (1:1)

Electron Cloud: ..........
FCC-hh study

Design challenges for high luminosity:
- High stored energy and losses
- **Impedance** (optics, materials, laser treatment, etc...) and **electron cloud** (sawtooth or laser treatment, coating)
- Aperture should be minimized for dipole cost
- High synchrotron radiation load due to high beam energy → special screen
Resistive wall impedance: LHC and FCC-hh

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

\[ \omega_{min} = (n - Q_y)\omega_0 \]

(lowest sideband)

**growth time at 3.3 TeV:**
approx. 100 turns

**at 50 TeV:**
approx. 800 turns

**LHC at 7 TeV:**
approx. 2000 turns

\[ Z_{\perp}(\omega) = \frac{c}{\pi\omega b^3 \delta_s \sigma_c} \]

(Thick) resistive wall impedance

BeamImpedance2D (U. Niedermayer)
Electron cloud studies for FCC-hh

Electron cloud in the FCC-hh can cause:
coherent instabilities, incoherent emittance growth, heat load, vacuum degradation, tune shift and spread

Motivation and Aims of this study:
- Estimate build-up thresholds, SEYs, heat load
- Predict tune shifts, spreads and instability thresholds
- Effect of residual photo electrons
- Compare LHC vs. FCC-hh, understand energy scaling.
Electron cloud study

Assumptions:
1. Electrostatic field solver for electron space charge field
2. Ultra relativistic approximation of primary beam: Rigid bunch approximation
3. LHC/FCC bunches

Simulation 2D tool openEcloud for electron cloud studies:
- Finite Integration Technique (field solver)
- 2D LU Poisson Solver with arbitrary cut-cell boundaries
- Standard Particle-In-Cell for electrons
- Boundary interaction models for electrons

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
Secondary emission yield model

Cimino/Collins SEY model: \( \delta = \delta_e + \delta_{ts} \)

Furman/Pivi SEY model: \( \delta = \delta_e + \delta_r + \delta_{ls} \)

Same model, but different parametrization!

R. Cimino et al., Phys. Rev. Lett. 93, 014801
G. Iadarola’s PhD Thesis; P. Dijkstal Master Thesis
Secondary emission yield model

Furman/Pivi SEY model: \( \delta = \delta_e + \delta_r + \delta_{ts} \)
\[ \delta_{\text{max}} \approx 1.88 \]

Cimino/Collins SEY model: \( \delta = \delta_e + \delta_{ts} \)
\[ \delta_{\text{max}} \approx 1.7 \]

\[
\begin{align*}
\delta_{ts}(E_0, \theta_0) &= \hat{\delta}(\theta_0) D(E_0/\hat{E}(\theta_0)) \\
D(x) &= \frac{sx}{s-1+x^2} \\
\hat{\delta}(\theta_0) &= \hat{\delta}_{ts}[1+t_1(1-\cos^r \theta_0)] \\
\delta_{bs} &= \hat{\delta}_{bs}(E_0, \theta_0)[1+e_1(1-\cos^e \theta_0)] \\
\delta_{rd} &= \hat{\delta}_{rd}(E_0, \theta_0)[1+r_1(1-\cos^r \theta_0)]
\end{align*}
\]

\[
\begin{align*}
\delta_{\text{elax}}(E) &= R_0 \left( \sqrt{\frac{E}{E_0}} - \frac{\sqrt{E}}{\sqrt{E} + \sqrt{E + E_0}} \right)^2 \\
\delta_{\text{true}}(E, \theta) &= \delta_{\text{max}}(\theta) \frac{s}{E_0} \frac{E}{E_{\text{max}}(\theta)} \frac{1}{s-1+\left(\frac{E}{E_{\text{max}}(\theta)}\right)^s} \\
\delta_{\text{true}}'(\theta) &= \delta_{\text{max}} \left(1-\cos^e \theta_0\right) \frac{1}{2} \\
R_0 &= 1 ?
\end{align*}
\]
**SEY threshold: from LHC to FCC-hh**

Thresholds are defined as the highest SEY without build-up

<table>
<thead>
<tr>
<th>Arc element</th>
<th>Furman/Pivi SEY model</th>
<th>Cimino/Collins SEY model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCC-hh</td>
<td>LHC</td>
</tr>
<tr>
<td>Drift</td>
<td>1.3</td>
<td>1.23</td>
</tr>
<tr>
<td>Dipole [injection/top energy]</td>
<td>1.25/1.25</td>
<td>1.1/1.1</td>
</tr>
</tbody>
</table>

Dependence of SEY:
- energy and angle incidence of the primary particles
- geometry and material of the beam pipe

**Electron cloud build-up** by multipacting can be suppressed by sufficiently long scrubbing or coatings (laser-treated Copper, which increase the impedance at high frequencies, or amorphous Carbon).
Electron cloud pinch in the FCC-hh

The effect is occurred if there is already an electron cloud when the bunch passes it is attracted towards the center of the bunch.

Density profile of electron cloud pinched in the field of the bunch in the absence of external B-field

The longitudinal electric field induced by a FCC-hh bunch in the saturated cloud
Stopping power and heat load

The electron clouds can be the source of the energy loss as a result of the observed dependence in the LHC between the rf phase shift on the bunch spacing.

Stopping power – is a total energy loss of the bunch per length unit:

\[ \frac{dW}{ds} = - \int \rho_i(r) E_z(r) dr = -q \int \lambda(z) E_z(z) dz \]

- \( \rho_i \) – bunch charge density
- \( E_z(z) \) – longitudinal electric field induced by the bunch
- \( \lambda(z) \) – line density of the bunch
- \( q = e \) – particle charge

Energy loss per turn and particle:

\[ \Delta W_z = \frac{L}{N_i} \frac{dW}{ds} \]

RF phase shift:

\[ \sin(\Delta \phi_s) = \frac{\Delta W_p}{qV_{rf}} \]

Heat load:

\[ P \left[ \frac{W}{m} \right] = \frac{cS}{l_{bb}} \]

- \( l_{bb} \) – bunch spacing
In conclusion, both simulations and experiments show that the ECI becomes more severe with increasing beam energy. As a consequence, upgrade plans with higher injection energy for proton machines which suffer from ECI must foresee a program of EC suppression. Promising EC


FIG. 3 (color online). Simulated ECI thresholds at different momenta, study done with quasi-self-consistent e-cloud distribution.
Stopping power and heat load (is in progress)

How can the high beam energy/gamma affect the stopping power?

The transverse beam size:

\[ \sigma = \sqrt{\epsilon \beta^*} \propto \frac{1}{\sqrt{\gamma}} \]

\[ E_{\text{inj}} : \sigma \approx 10^{-3} \text{ m} \]

\[ \epsilon_n = \text{const} \]

\[ E_{\text{top}} : \sigma \approx 10^{-4} \text{ m} \]

Requires a high resolution → a lot of memory to run simulations

Analytical model:

Energy loss of a short bunch in an (initially homogeneous) electron cloud:

\[ \frac{d\epsilon}{ds} \approx \frac{q^2 N_b^2 n_e r_e}{\epsilon_0} \ln \left( \frac{b}{a} \right) \]

Summary

SEY threshold depends on the chosen model:
- energy and angle incidence of the primary particles
- geometry and material of the beam pipe

<table>
<thead>
<tr>
<th>Arc element</th>
<th>Furman/Pivi SEY model</th>
<th>Cimino/Collins SEY model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>FCC-hh: 1.3</td>
<td>FCC-hh: 1.6</td>
</tr>
<tr>
<td></td>
<td>LHC: 1.23</td>
<td>LHC: 1.3</td>
</tr>
<tr>
<td>Dipole [injection/top energy]</td>
<td>FCC-hh: 1.25/1.25</td>
<td>FCC-hh: 1.56/1.56</td>
</tr>
<tr>
<td></td>
<td>LHC: 1.1/1.1</td>
<td>LHC: 1.32/1.32</td>
</tr>
</tbody>
</table>

Next steps:
- to estimate the stopping power from an analytical model and with the simulation tool
- to estimate the tune shift and tune spread as a function of beam energy
- implementation and estimation of the residual photoelectrons effect
Thank you for your attention!
### Back up: FCC-hh vs LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [km]</td>
<td>27</td>
<td>100</td>
</tr>
<tr>
<td>$E_{\text{inj}}$ [TeV]</td>
<td>0.45</td>
<td>3.3</td>
</tr>
<tr>
<td>$E_{\text{c.o.m.}}$ [TeV]</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Arc dipole field [T]</td>
<td>0.54...8.33</td>
<td>1...16</td>
</tr>
<tr>
<td>Bunch length [ns]</td>
<td>1.07(8cm)</td>
<td>1.07(8cm)</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25, 5</td>
<td>25</td>
</tr>
<tr>
<td>Bunch population [$10^{11}$]</td>
<td>1.0</td>
<td>1.15</td>
</tr>
<tr>
<td>$Q_x/Q_y$ at injection</td>
<td>64.28/59.31</td>
<td>111.28/109.31</td>
</tr>
<tr>
<td>$Q_x/Q_y$ at collision</td>
<td>64.31/59.32</td>
<td>111.31/109.32</td>
</tr>
<tr>
<td>Revolution frequency, $f_0$ [Hz]</td>
<td>11245</td>
<td>3067</td>
</tr>
</tbody>
</table>