Electron cloud scaling: from LHC to FCC-hh

D. Astapovych, O. Boine-Frankenheim
Electron cloud studies for FCC-hh

Motivation and Aims of this study:
- Estimate build-up thresholds, SEYs, heat load
- Predict tune shifts, spreads and instability thresholds
- Estimate the effect of residual photoelectrons
- Compare LHC vs. FCC-hh, understand energy scaling.

Will electron cloud still be a concern in FCC-hh?
FCC-hh vs LHC beam screen

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>$27 \times 10^3$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$E_{inj}$ [TeV]</td>
<td>0.45</td>
<td>3.3</td>
</tr>
<tr>
<td>$B_{inj}$ [T]</td>
<td>0.54</td>
<td>1.06</td>
</tr>
<tr>
<td>$E_{top}$ [TeV]</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>$B_{top}$ [T]</td>
<td>8.4</td>
<td>16</td>
</tr>
<tr>
<td>Beam screen Temperature [K]</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

- Bunch length, $\sigma z$ [m] | 0.1
- Bunch radius, $\sigma r$ [m] | $10^{-3}$
- Bunch population, $N_i$ | $10^{11}$
- Bunch spacing [ns] | 25
- Maximum total SEY $\delta_{max}$ | 1.8
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

**Furman model:**  \( \delta = \delta_e + \delta_r + \delta_{ts} \)

\[
\delta_{ts}(E_0, \theta_0) = \delta_0 D(E_0', E_0) D(x) = \frac{sx}{s-1+x^2} \\
\delta_0 = \delta_{ts}[1 + t_1 (1 - \cos^2 \theta_0)] \\
\delta_{bs} = \delta_{bs}(E_0, \theta_0)[1 + e_1 (1 - \cos^2 \theta_0)] \\
\delta_{rd} = \delta_{rd}(E_0, \theta_0)[1 + r_1 (1 - \cos^r \theta_0)]
\]

**Simple SEY model:**  \( \delta = \delta_e + \delta_{ts} \)

\[
\delta_{elas}(E) = R_0 \left( \frac{\sqrt{E} - \sqrt{E + E_0}}{\sqrt{E} + \sqrt{E + E_0}} \right)^2 \\
\delta_{true}(E, \theta_i) = \delta_{max} \frac{s \frac{E}{E_{max}(\theta_i)}}{s-1 + \left( \frac{E}{E_{max}(\theta_i)} \right)^s} \\
\delta_{max}(\theta_i) = \delta_{max} e^{\frac{1 - \cos \theta_i}{2}} \\
\delta_{bs}(E_0, \theta_0) = \delta_{bs}(E_0, \theta_0) \\
\delta_{rd}(E_0, \theta_0) = \delta_{rd}(E_0, \theta_0)
\]

**Main differences:**
- \( \delta_{max} \)
- angle dependence
- redifused electrons
- free parameters

M. A. Furman and M. T. F. Pivi, Phys. Rev. ST Accel. Beams 5, 124404
R. Cimino et al., Phys. Rev. Lett. 93, 014801
G. Iadarola’s PhD Thesis; P. Dijkstal Master Thesis
Electron cloud study: Furman model vs Simple SEY model

The threshold approaches $\text{SEY} \sim 1.3$ with Furman and $\sim 1.6$ with simple SEY models in FCC-hh in the absence of Bfield.

Possible reasons of the difference:
– rediffused electrons (only in Furman model)
– angle dependence
– free parameters
– etc.

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<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
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<tr>
<td>Number of bunches</td>
<td>100</td>
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SEY threshold: from LHC to FCC-hh

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– etc.

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<th>Simple SEY model</th>
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<tr>
<td>LHC</td>
<td>1.23</td>
<td>1.3</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Drift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection</td>
<td>1.1</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>1.42</td>
</tr>
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Electron cloud pinch in the FCC-hh

Electron cloud pinch in the absence of B-field

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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The longitudinal electric field induced by a FCC-hh bunch in the saturated cloud
Stopping power

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

\[
\frac{dW}{ds} = - \int \rho_i(r) E_z(r) d^3r \approx -q \int \rho(z) E_z(z) dz
\]

Heat load \([\text{W/m}] = \frac{cS}{I_{bb}}\)

\(I_{bb}\) is the bunch distance

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<td>Bunch radius, (\sigma r) [m]</td>
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<td>(\delta_{\text{max}})</td>
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Stopping power as a function of the bunch radius in the saturated cloud
Higher gamma/energy → stronger electron cloud pinch → tune spread

Let’s assume that the ecloud is the only source of tune shifts/spreads.

The kick due to an electron cloud:

$$\Delta x_e' = \frac{e E_x^e(x, y) L}{\gamma_0 m_p c^2}$$

Tune shift/spread depends strongly on gamma/beam energy - 1/γ scaling
Conclusions and Outlook

Conclusions
- SEY threshold depends a lot on the chosen model
- Tune shift depends strongly on gamma/beam energy
- Stopping power: asymptotic limit is at beam radius = 1e-4 m

Next steps:
- electron cloud study with the bunch offset
- implementation of the electron cloud to tracking code (PATRIC/pyOrbit)
- electron cloud study w.r.t. instabilities, etc. in FCC-hh/LHC
- implementation of the photoelectrons

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Thank you for your attention!