Electron cloud studies for the FCC-ee

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Many Thanks: Luca Sabato, Tatiana Pieloni, Karla Cantún, Humberto Maury, and the FCC-ee optics team

June 8, 2023
• FCC-ee machine & beam parameters used in the simulations

• Parameters obtained from electron density distributions at the pipe center

• FCC-ee Collider Arc Dipole and Drift Build-up Results

• Wake Potentials due to Electron Clouds

• Conclusions & Future Plans
FCC-ee Collider Arc Dipole Parameters

**Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
</tr>
<tr>
<td>bunches per train</td>
<td>150</td>
</tr>
<tr>
<td>trains per beam</td>
<td>1</td>
</tr>
<tr>
<td>r.m.s. bunch length ($\sigma_z$) [mm]</td>
<td>5.40</td>
</tr>
<tr>
<td>hor. emittance [nm]</td>
<td>0.71</td>
</tr>
<tr>
<td>ver. emittance [pm]</td>
<td>1.4</td>
</tr>
<tr>
<td>number of particles / bunch (10^{11})</td>
<td>1.5</td>
</tr>
<tr>
<td>bend field [T]</td>
<td>0.01415</td>
</tr>
<tr>
<td>circumference C [m]</td>
<td>90.65</td>
</tr>
<tr>
<td>synchrotron tune Qs</td>
<td>0.0299</td>
</tr>
<tr>
<td>average beta function $\beta_y$ [m]</td>
<td>91.044</td>
</tr>
<tr>
<td>threshold density (10^{12} [m^{-3}])</td>
<td>0.018</td>
</tr>
</tbody>
</table>

- bunch spacings, BS : (15, 17.5, 20) ns
- circular beam pipe radii, $r$ : 30 mm
- SEY Models: ECloud, Furman-Pivi
- Total SEY : (1.1, 1.2, 1.3, 1.4)
- PE generation (# photoelectrons to be generated per positron and per unit length), $n'_\gamma$ : (1e-3, 1e-4, 1e-5) m^{-1}
- threshold density (single-bunch instability):

\[
\rho_{th} = \frac{2\gamma Q_s \omega_c \sigma_z / c}{\sqrt{3 K Q} r_e \beta_y C} \\
\omega_c = \left( \frac{N_b r_e c^2}{\sqrt{2\pi} \sigma_z \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2}
\]

\[
Q = \min(\omega_c \sigma_z / c, 7) \quad K = \omega_c \sigma_z / c
\]

---


Parameters for electron density at the pipe center

**Dipole Region**

ECLoud SEY Model, bunch spacing: 15 ns,

\[ n'_{(\gamma)} = 1e-3 \text{ m}^{-1} \text{ SEY}=1.4 \]

**Drift Region**

FP SEY Model, bunch spacing: 15 ns,

\[ n'_{(\gamma)} = 1e-3 \text{ m}^{-1} \text{ SEY}=1.3 \]
Parameters for electron density at the pipe center

**Dipole Region**
ECLOUD SEY Model, bunch spacing: 15 ns,

\[ n'(\gamma) = 1 \times 10^{-3} \text{ m}^{-1} \text{ SEY}=1.4 \]

**Drift Region**
FP SEY Model, bunch spacing: 15 ns,

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Parameters for electron density at the pipe center

**Dipole Region**
ECLOUD SEY Model, bunch spacing: 15 ns, 
\( n'_(\gamma) = 1e^{-3} \text{ m}^{-1} \) SEY=1.4

**Drift Region**
FP SEY Model, bunch spacing: 15 ns, 
\( n'_(\gamma) = 1e^{-3} \text{ m}^{-1} \) SEY=1.3

![Graphs showing electron density over time for dipole and drift regions](https://via.placeholder.com/150)
Parameters for electron density at the pipe center

**Dipole Region**
ECLOUD SEY Model, bunch spacing: 15 ns,
\[ n'(\gamma) = 1 \times 10^{-3} \text{ m}^{-1}, \text{SEY} = 1.4 \]

**Drift Region**
FP SEY Model, bunch spacing: 15 ns,
\[ n'(\gamma) = 1 \times 10^{-3} \text{ m}^{-1}, \text{SEY} = 1.3 \]
Distributions of the Parameters in Saturation

**Dipole Region**
ECLOUD SEY Model, bunch spacing: 15 ns, 
\( n'_{(\gamma)} = 1 \times 10^{-3} \text{ m}^{-1} \) SEY=1.4

**Drift Region**
FP SEY Model, bunch spacing: 15 ns, 
\( n'_{(\gamma)} = 1 \times 10^{-3} \text{ m}^{-1} \) SEY=1.3
e⁻ density variations at bunch arrival and bunch center

- e⁻ density decrease
  15ns - 17.5ns > 17.5ns - 20ns

- e⁻ densities increase regularly w.r.t SEY

- bunch arrivals indicate close density values for each $n'_{(\gamma)}$

- effects of photoemission for $n'_{(\gamma)} = 1e-4 \text{ m}^{-1}$ and $1e-5 \text{ m}^{-1}$ are similar for bunch centers

- e⁻ densities increase after bunch arrivals, but how much?
e$^-$ density variations at bunch arrivals and bunch center

(ba) : bunch arrival
(bc): bunch center

- $n'_(γ) : 1e-3$ m$^{-1}$

Dipole, FP SEY Model, $n'_c = 1e − 3$

- $n'_(γ) : 1e-4$ m$^{-1}$

Dipole, FP SEY Model, $n'_c = 1e − 4$

- $n'_(γ) : 1e-5$ m$^{-1}$

Dipole, FP SEY Model, $n'_c = 1e − 5$

- density increase from bunch arrival to bunch center $\sim [1e10 - 8.1e10]$ e$^-$/m$^3$
- for $n'_(γ) = 1e-4$ m$^{-1}$ and 1e-5 m$^{-1}$ difference in values $\sim [2e9 - 12e9]$ e$^-$/m$^3$
- density increase is smaller for SEY=1.1
Max. and Min. e\(^-\) density variations

- min. e\(^-\) density values are over the single-bunch instability threshold

- max. e\(^-\) density values decrease more significantly w.r.t. bunch spacing as compared to min. values

- when we decrease 
  \[ n'_{(\gamma)} = 1e^{-4} \text{ m}^{-1} \text{ to } n'_{(\gamma)} = 1e^{-5} \text{ m}^{-1} \]
  e\(^-\) densities decrease in the range of
  \(~ [1e10 - 15e10] \text{ e}^/-\text{m}^3 \text{ for max.} ~\]
  \(~ [1e9 - 4e9] \text{ e}^/-\text{m}^3 \text{ for min.} ~\]
Max. and Min. e\(^-\) density variations

For the selected photoemission range, simulations with 15ns and 17.5ns bunch spacings and SEY=1.3 & SEY=1.4 exceed 1e13 e\(^-/m^3\).

The minimum reachable e\(^-\) density occurs as \(\sim 1e11\ e^-/m^3\) for \(n'_{(\gamma)} = 1e-5\ m^-1\) and SEY=1.1.
Comparisons for different regions and models

- Max. values in the density distributions are used for these comparisons

- e- density decrease between 17.5ns and 20ns is smaller with ECloud SEY model

- Factor $\sim 2.46$ between two SEY models

- Factor $\sim 5.43$ between Dipole and Drift Regions for Furman-Pivi SEY model
Reference densities

bunch spacing: 20 ns, SEY ≈ 0, \( n'(\gamma) : 1\text{e-6 m}^{-1} \)

- results via two SEY models agree well for SEY \(\approx 0\)
- reference center e- density \(\approx 5\text{e7 e-}/\text{m}^{3} \) for Dipole and \(\approx 3.25 \text{e8 e-}/\text{m}^{3} \) for Drift Region
- factor \(\sim 6.5\) between Dipole and Drift Regions
- factor \(\sim 1.5\) between \( n'(\gamma) : 1\text{e-2 m}^{-1}\) and \( n'(\gamma) : 1\text{e-3 m}^{-1}\) for the min.
Electron Cloud Simulations with CST-PIC

F. Yaman, F. Zimmermann Recent Advances on the FCC-ee Electron Cloud Build-up Studies, FCC-Week 2022
Wake Potential Post-Processor for PIC solver

**a typical RF Cavity example**

\[ W_{||}(r,s) = \frac{1}{Q} \int_{-\infty}^{\infty} dz \; E_z(r,z,t) \bigg|_{t=0, t=s+z/v} \]


[https://indico.cern.ch/event/125315/contributions/96596/](https://indico.cern.ch/event/125315/contributions/96596/)
Longitudinal Wake Potential Calculations (Preliminary)

- Wake Potential due to Electron Cloud

- HEAD of the bunch

- circular beam pipe

- zoom
According to initial results, winglets significantly decrease the magnitude of the wakes due to Ecloud.

Higher computational power needs for the accurate wake and impedance calculations.

Numerical noise should be reduced in the computations.
Conclusions and Future Plans

- Reference center e- density $\approx 5e7 \text{ e}^{-}/\text{m}^3$ for DIPOLE and $\approx 3.25 \text{e}8 \text{ e}^{-}/\text{m}^3$ for DRIFT (SEY $\approx 0$).

- Reference density by factor $\approx 2.5$ increased according to the former parameters ($\approx 2\text{e}7 \text{ e}^{-}/\text{m}^3$ for DIPOLE*)

- Min. values are over the single-bunch instability threshold level via Furman-Pivi model

- factor $\sim 2.46$ between two SEY models

- factor $\sim 5.43$ between Dipole and Drift Regions for Furman-Pivi SEY model

- Verifications and Accurate Wake Potential Calculations

- Longitudinal Impedance calculations due Electron Clouds

- Simulations with the measured SEY data

*F Yaman and F. Zimmermann  Updates on the Electron Cloud Build-up Results for the FCC-ee, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting, Nov.10, 2022
THANK YOU FOR ATTENTION!
Backup Slides
$n'_\gamma = Y_\gamma \frac{5 \alpha \gamma}{2 \sqrt{3} \rho}$

≈ 0.1

number of photoelectrons emitted per length

fine structure constant $\alpha \approx 1/137$

the Lorentz factor $\gamma \approx 10^5$

radius of curvature of the particle path $\rho \approx 11000 \text{ [m]}$
4 IPs \( (n'_{(y)} = 1e-6 \text{ m}^{-1}, \text{ bunch spacing: 32ns}) \) Dipole Region

- results via two SEY models agree well for SEY \( = 0 \) (min. \( = 2e7 \text{ e}^-/\text{m}^3 \))
- max. \( = 5e8 \text{ e}^-/\text{m}^3 \) is verified with both models for SEY \( = 1.1 \)

4 IPs Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
</tr>
<tr>
<td>bunches per train</td>
<td>150</td>
</tr>
<tr>
<td>trains per beam</td>
<td>1</td>
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<tr>
<td>r.m.s. bunch length ( (\sigma_z) ) [mm]</td>
<td>4.32</td>
</tr>
<tr>
<td>h. r.m.s. beam size ( (\sigma_h) ) [\mu m]</td>
<td>207</td>
</tr>
<tr>
<td>v. r.m.s. beam size ( (\sigma_v) ) [\mu m]</td>
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<td>number of particles / bunch ( (10^{11}) )</td>
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<tr>
<td>bend field [T]</td>
<td>0.01415</td>
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<tr>
<td>circumference C [m]</td>
<td>91.2</td>
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<tr>
<td>synchrotron tune Qs</td>
<td>0.037</td>
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<td>average beta function ( \beta_y ) [m]</td>
<td>50</td>
</tr>
<tr>
<td>threshold density ( (10^{12} \text{ m}^{-3}) )</td>
<td>0.043</td>
</tr>
</tbody>
</table>
Furman-Pivi & E CLOUD SEY Models

**Note that** \( \hat{\Delta}_t \approx \hat{\Delta}_t \) and \( \hat{\Delta}_t \approx \hat{\Delta}_t + P_{1,e}(\infty) + P_{1,r}(\infty) \) provided that \( \hat{E}_{1S} \gg \hat{E}_e, E_r \).
### Table I: Main parameters of the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Copper</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backscattered electrons (Sec. III.B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{st} (\infty)$</td>
<td>0.02</td>
<td>0.07</td>
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<tr>
<td>$E_s [eV]$</td>
<td>0.016</td>
<td>0.096</td>
</tr>
<tr>
<td>$W [eV]$</td>
<td>0.78</td>
<td>0.86</td>
</tr>
<tr>
<td>$p$</td>
<td>1.00</td>
<td>0.9</td>
</tr>
<tr>
<td>$\sigma_e [eV]$</td>
<td>2.00</td>
<td>1.90</td>
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<tr>
<td>$c_1$</td>
<td>0.26</td>
<td>0.29</td>
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<tr>
<td>$c_2$</td>
<td>2.00</td>
<td>2.00</td>
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<tr>
<td>Rediffracted electrons (Sec. III.C)</td>
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</tr>
<tr>
<td>$P_{st} (\infty)$</td>
<td>0.20</td>
<td>0.24</td>
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<tr>
<td>$E_s [eV]$</td>
<td>0.041</td>
<td>0.094</td>
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<tr>
<td>$r$</td>
<td>0.194</td>
<td>0.35</td>
</tr>
<tr>
<td>$q$</td>
<td>0.50</td>
<td>0.62</td>
</tr>
<tr>
<td>$r_1$</td>
<td>0.26</td>
<td>0.29</td>
</tr>
<tr>
<td>$r_2$</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>True secondary electrons (Sec. III.D)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_{st}$</td>
<td>1.8848</td>
<td>1.73</td>
</tr>
<tr>
<td>$E_0 [eV]$</td>
<td>276.8</td>
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<tr>
<td>$s$</td>
<td>1.51</td>
<td>1.8</td>
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<tr>
<td>$t_1$</td>
<td>0.66</td>
<td>0.60</td>
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<tr>
<td>$t_2$</td>
<td>0.8</td>
<td>0.80</td>
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<tr>
<td>$t_3$</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>$t_4$</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Total SEY*</td>
<td>$E_s [eV]$</td>
<td>271.0</td>
</tr>
<tr>
<td>$\delta_0$</td>
<td>2.1</td>
<td>2.00</td>
</tr>
</tbody>
</table>

*Note that $E_s \approx E_{st}$ and $\delta_0 \approx \delta_{st} + P_{st}(\infty) + P_{s,s}(\infty)$ provided that $E_{st} \gg E_s, E_t$.\

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In this study, total SEY = \{1.1, 1.2, 1.3, 1.4\}