

05 – 09 June

**FCC
WEEK
2023**

Electron cloud studies for the FCC-ee

Fatih Yaman, Izmir Institute of Technology & STFC – ASTeC, Daresbury Lab.

Frank Zimmermann, CERN

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

Outline

- 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 | |
|---|---------|
| beam energy [GeV] | 45.6 |
| bunches per train | 150 |
| trains per beam | 1 |
| r.m.s. bunch length (σ_z) [mm] | 5.40 |
| hor. emittance [nm] | 0.71 |
| ver. emittance [pm] | 1.4 |
| number of particles / bunch (10^{11}) | 1.5 |
| bend field [T] | 0.01415 |
| circumference C [m] | 90.65 |
| synchrotron tune Qs | 0.0299 |
| average beta function β_y [m] | 91.044 |
| threshold density (10^{12} [m^{-3}]) | 0.018 |

 K. Oide 16th March 2023, "Impact of beamstrahlung on crab sextupole compensation", 163rd FCC-ee Optics Design Meeting & 34th FCCIS WP2.2 Meeting

 L. Sabato, private comm.

- 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) :

$$\rho_{\text{thr}} = \frac{2\gamma Q_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_e \beta_y C}$$

$$\omega_e = \left(\frac{N_b r_e c^2}{\sqrt{2\pi} \sigma_z \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2}$$

$$Q = \min(\omega_e \sigma_z / c, 7) \quad K = \omega_e \sigma_z / c$$

PyECloud

Drift region
is included

-  K. Ohmi, Beam-beam and electron cloud effects in CEPC / FCC-ee, Int. Journal of Modern Physics A, 31(33), 1644014 (2016).
-  K. Ohmi, F. Zimmermann and E. Perevedentsev, Wake-field and fast head-tail instability caused by an electron cloud, Phys. Rev. E 65, 016502 (2001).
-  F. Yaman, G. Iadarola, R. Kersevan, S. Ogur, K. Ohmi, F. Zimmermann and M. Zobov, Mitigation of Electron Cloud Effects in the FCC-ee Collider, EPJ Tech. and Inst. 2022 9:9

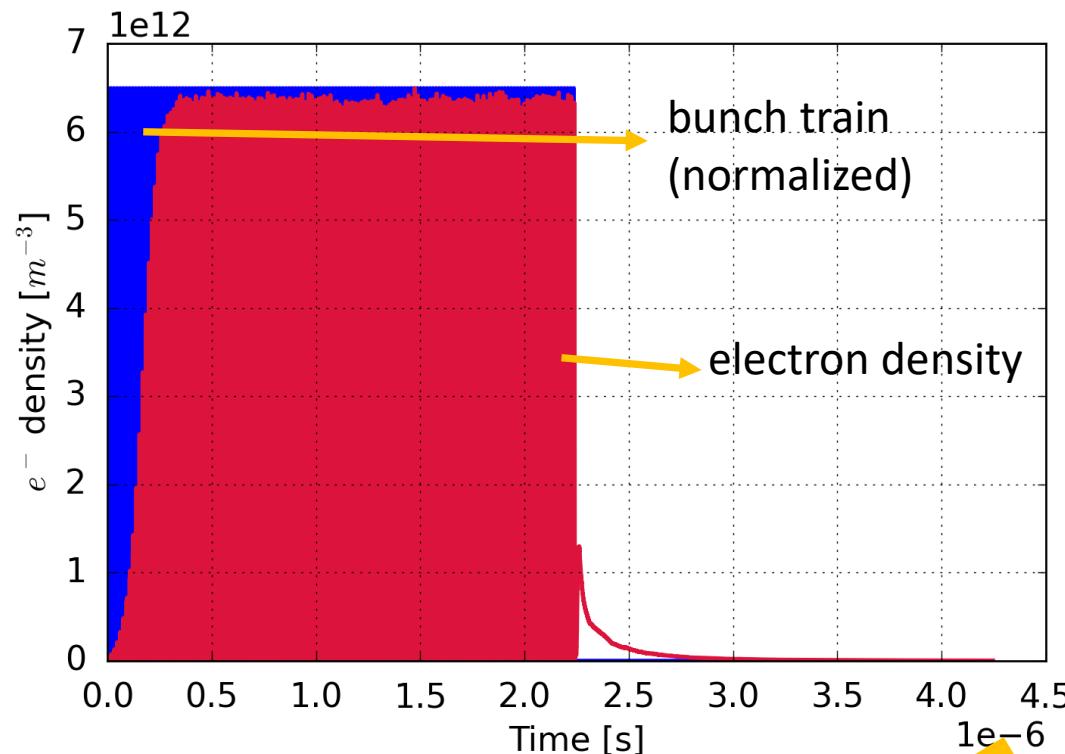
Parameters for electron density at the pipe center

PyECloud

Dipole Region

ECLOUD SEY Model, bunch spacing: 15 ns,

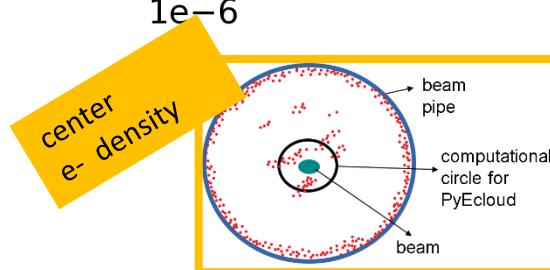
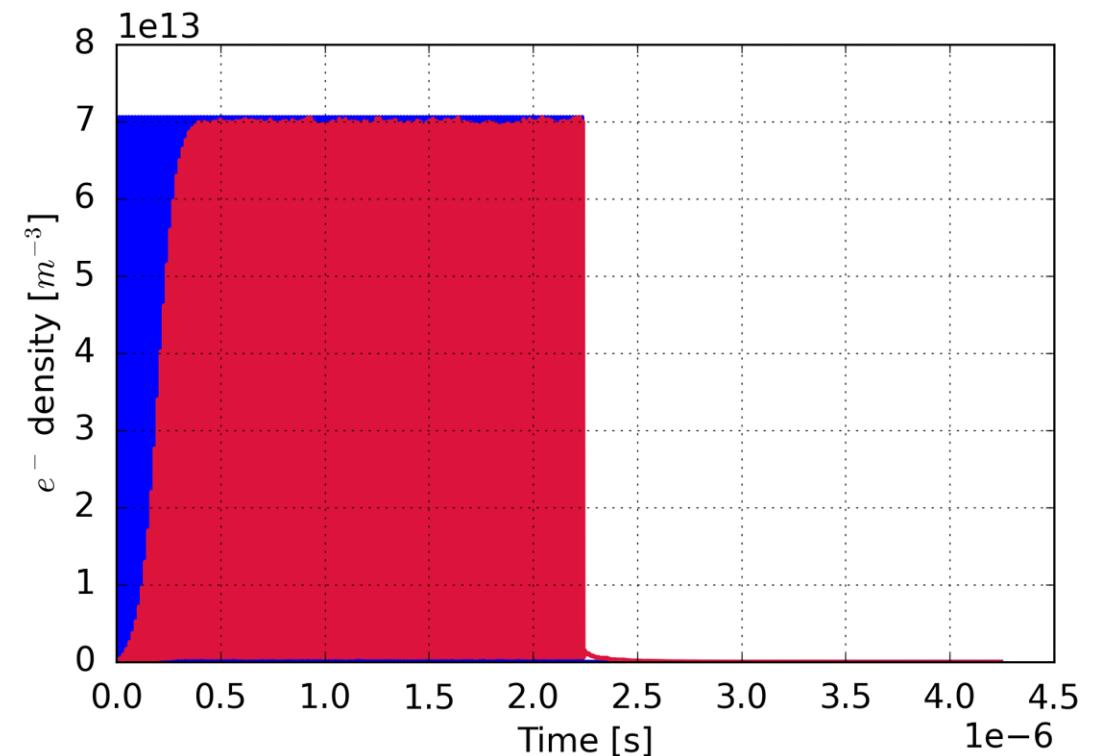
$$n'_{(\gamma)} = 1\text{e-}3 \text{ m}^{-1} \text{ SEY}=1.4$$



Drift Region

FP SEY Model, bunch spacing: 15 ns,

$$n'_{(\gamma)} = 1\text{e-}3 \text{ m}^{-1} \text{ SEY}=1.3$$

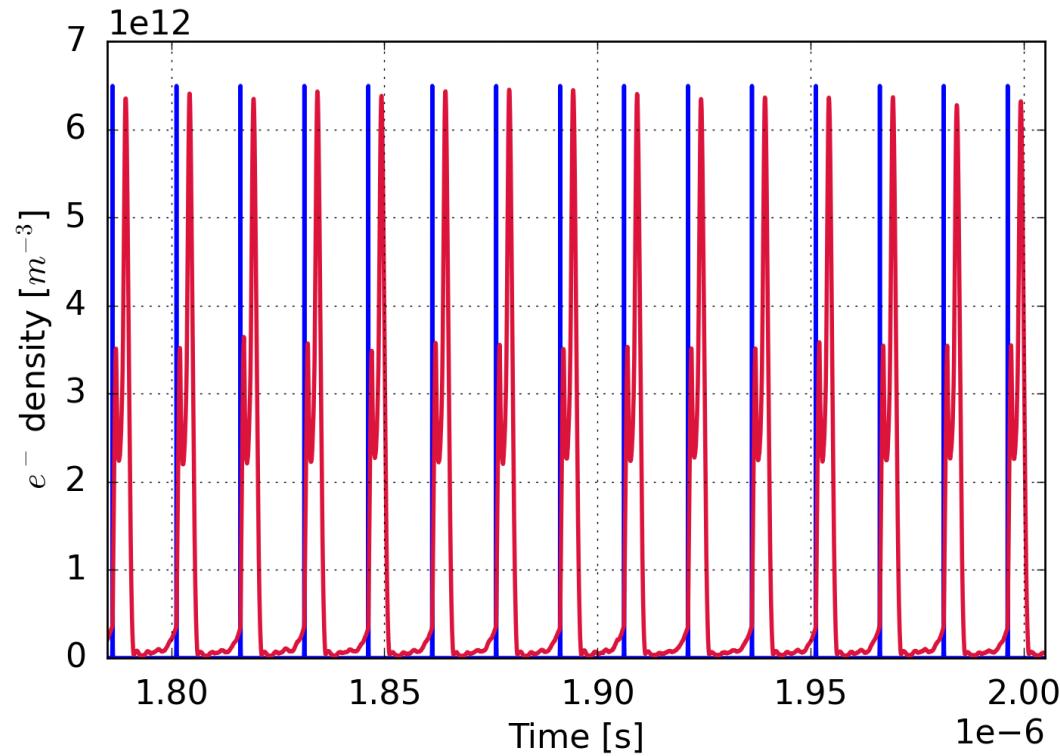


Parameters for electron density at the pipe center

Dipole Region

ECLOUD SEY Model, bunch spacing: 15 ns,

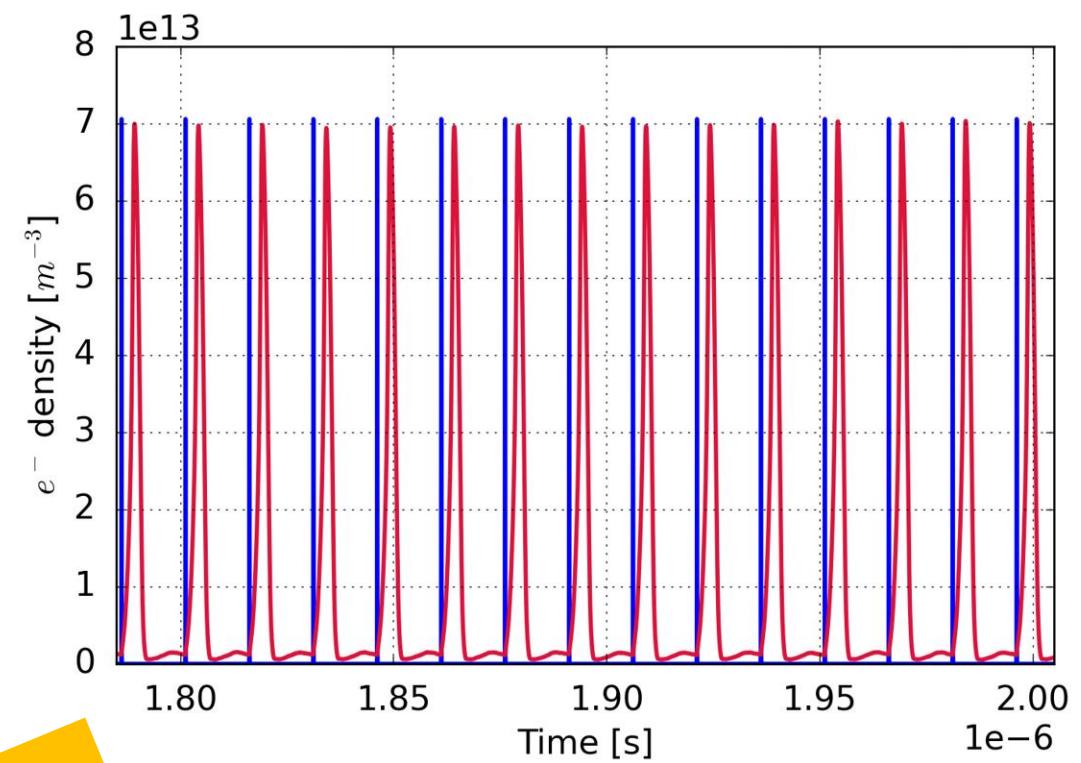
$$n'_{(\gamma)} = 1\text{e-}3 \text{ m}^{-1} \text{ SEY}=1.4$$



Drift Region

FP SEY Model, bunch spacing: 15 ns,

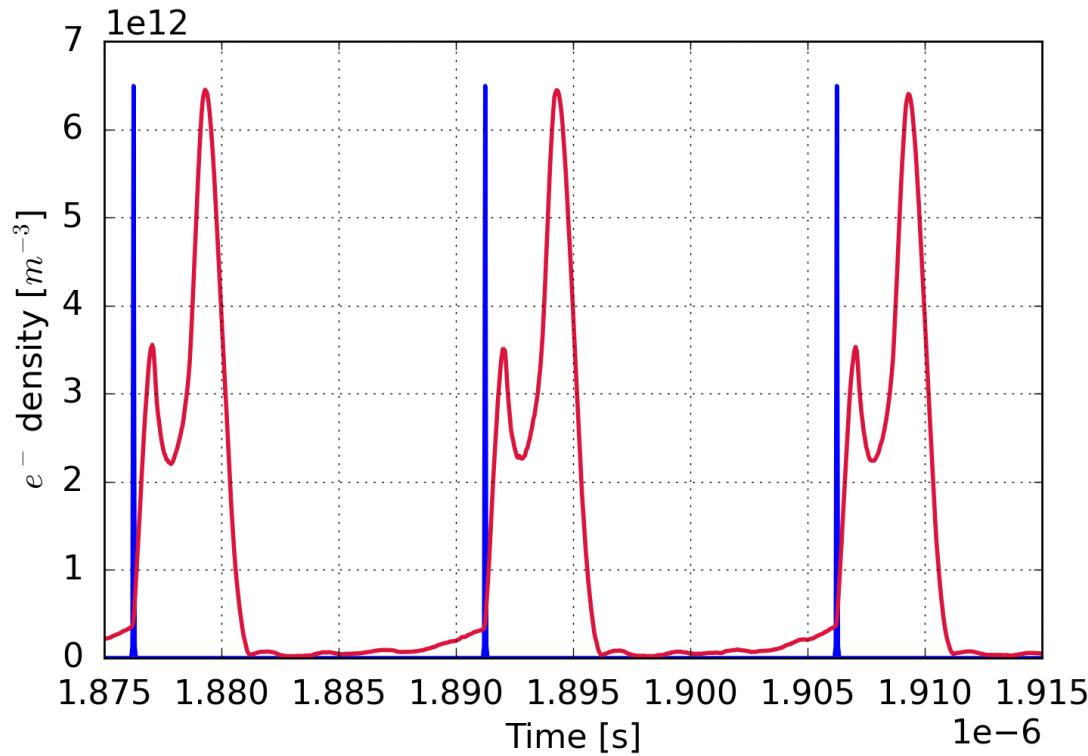
$$n'_{(\gamma)} = 1\text{e-}3 \text{ m}^{-1} \text{ SEY}=1.3$$



Parameters for electron density at the pipe center

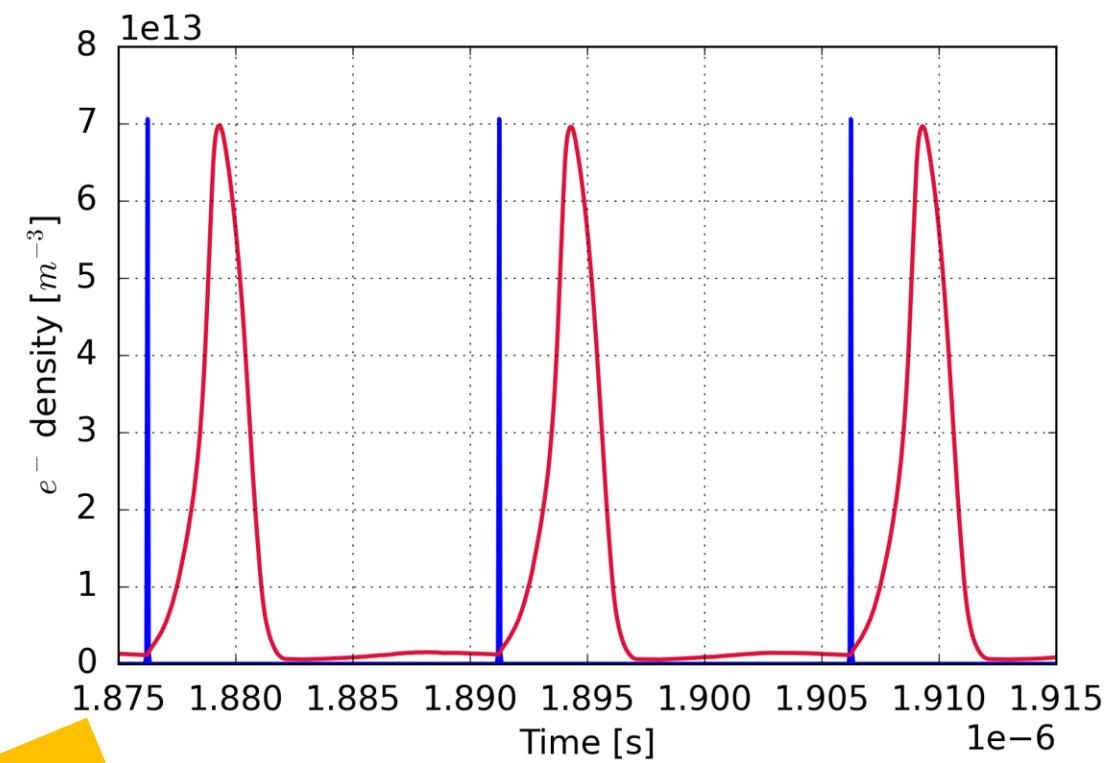
Dipole Region

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



Drift Region

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



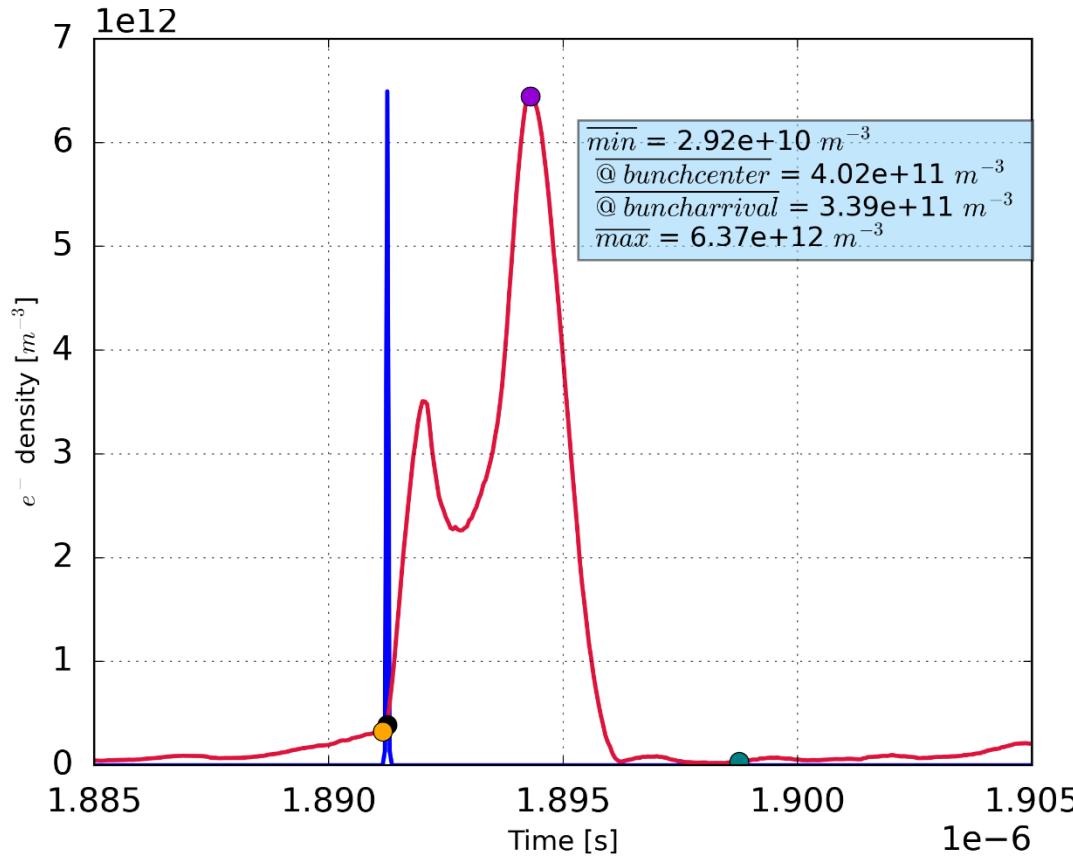
zoom

Parameters for electron density at the pipe center

Dipole Region

ECLOUD SEY Model, bunch spacing: 15 ns,

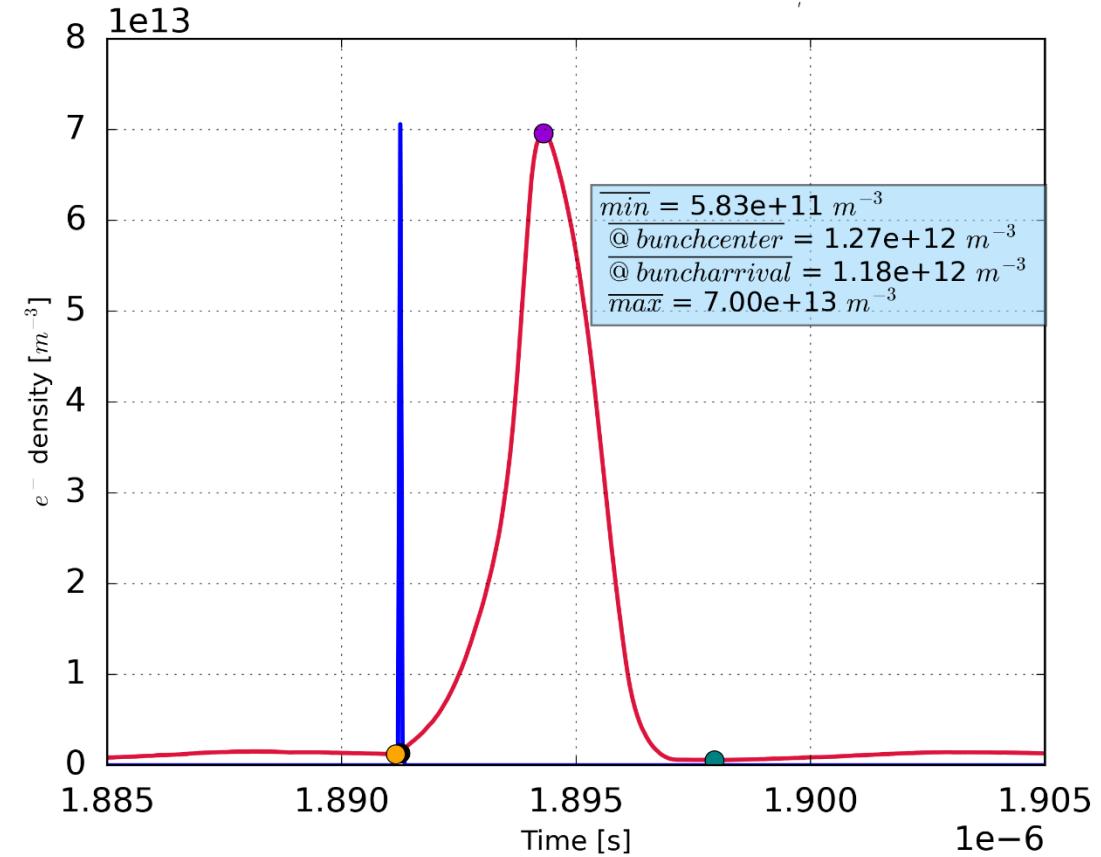
$$n'_{(\gamma)} = 1 \text{e-}3 \text{ m}^{-1} \text{ SEY}=1.4$$



Drift Region

FP SEY Model, bunch spacing: 15 ns,

$$n'_{(\gamma)} = 1 \text{e-}3 \text{ m}^{-1} \text{ SEY}=1.3$$



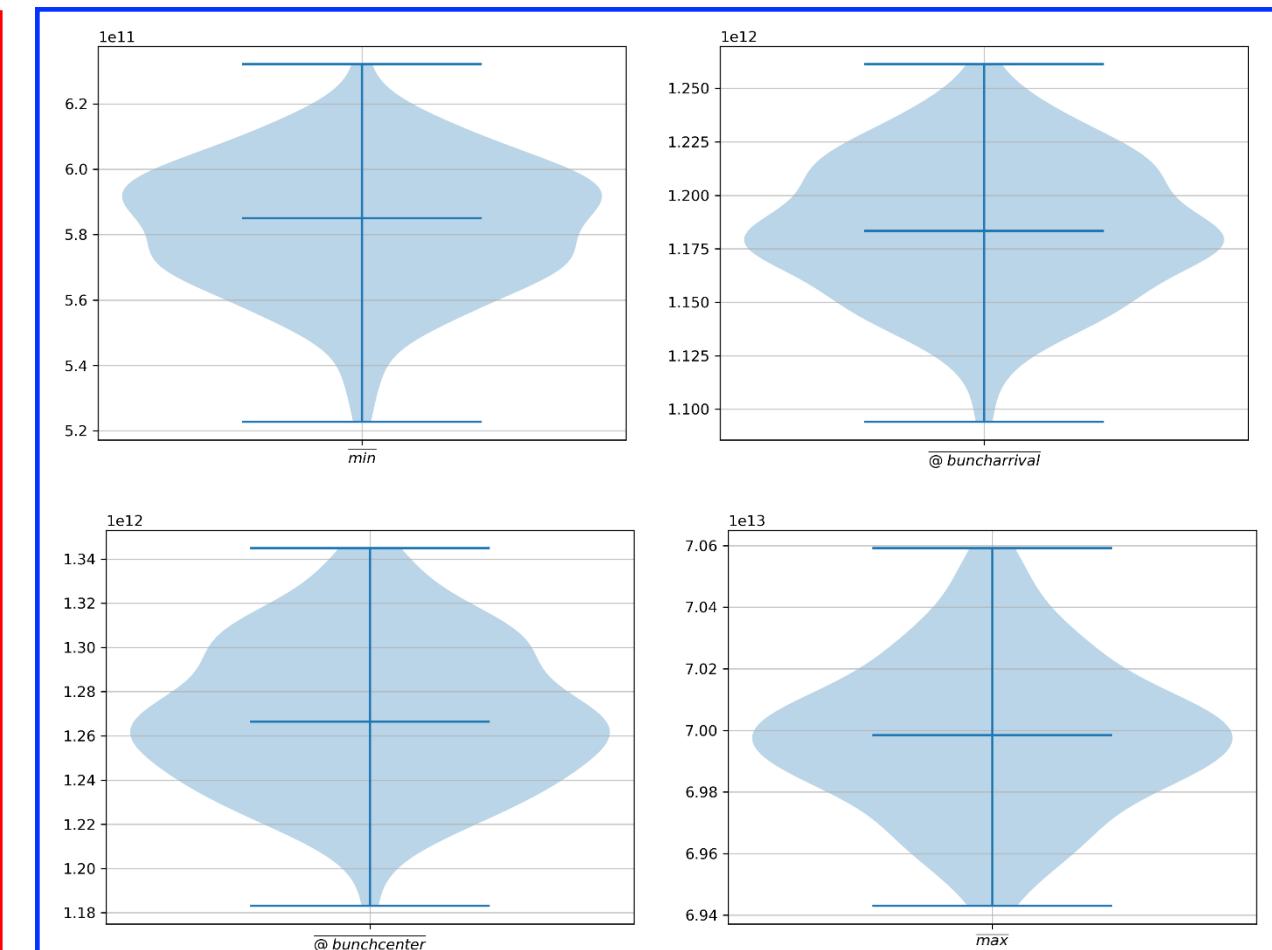
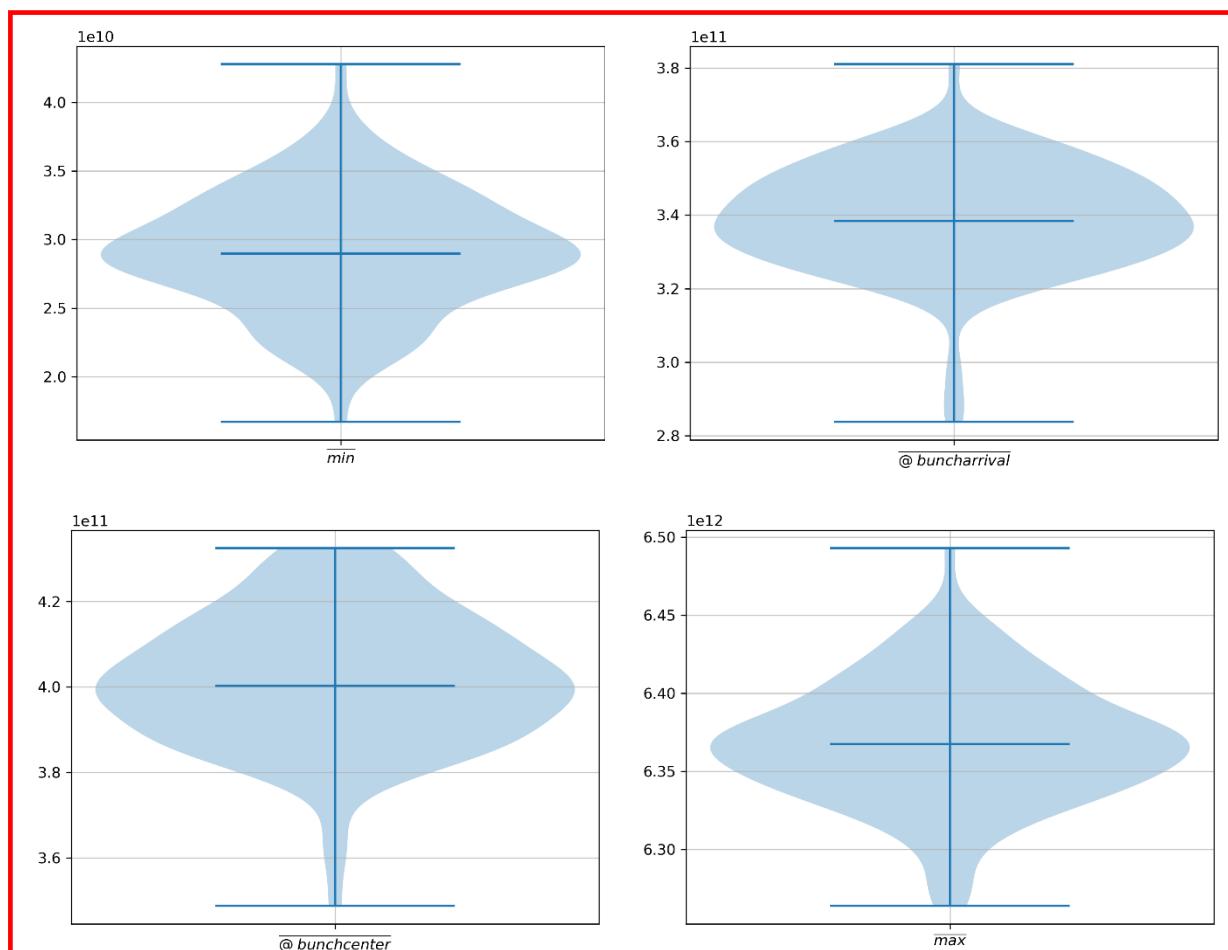
Distributions of the Parameters in Saturation

min = $2.92\text{e+}10 \text{ m}^{-3}$
@ bunchcenter = $4.02\text{e+}11 \text{ m}^{-3}$
@ bунчarrival = $3.39\text{e+}11 \text{ m}^{-3}$
max = $6.37\text{e+}12 \text{ m}^{-3}$

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

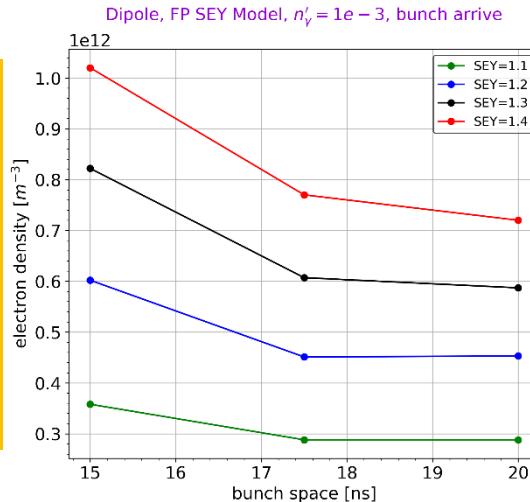
min = $5.83\text{e+}11 \text{ m}^{-3}$
@ bunchcenter = $1.27\text{e+}12 \text{ m}^{-3}$
@ bунчarrival = $1.18\text{e+}12 \text{ m}^{-3}$
max = $7.00\text{e+}13 \text{ m}^{-3}$

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

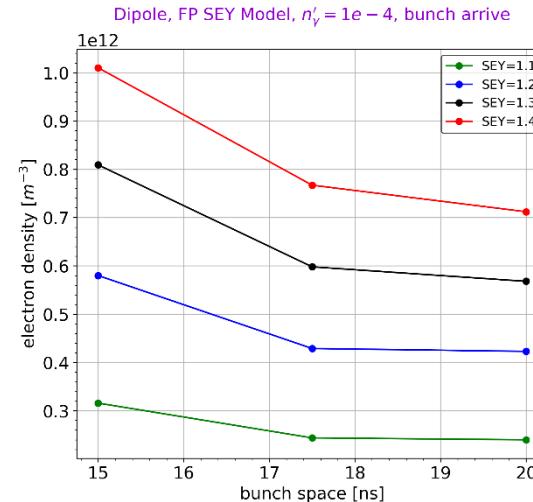


e^- density variations at bunch arrival and bunch center

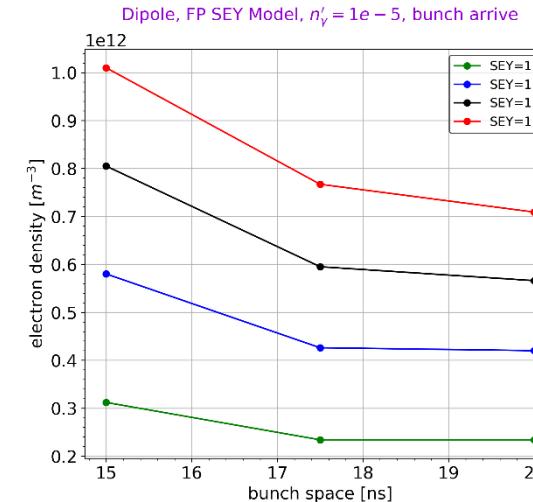
$$n'_{(\gamma)} : 1e-3 \text{ m}^{-1}$$



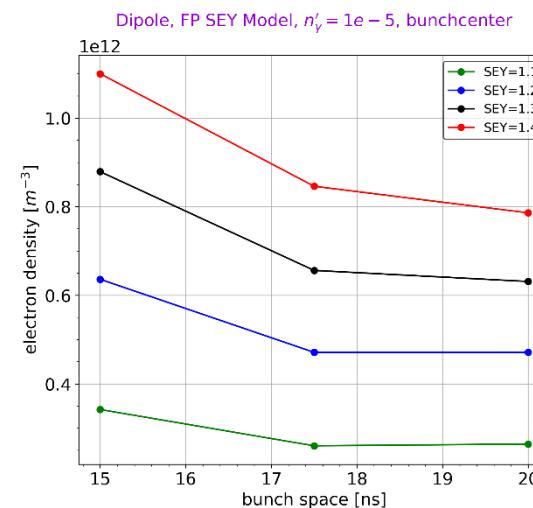
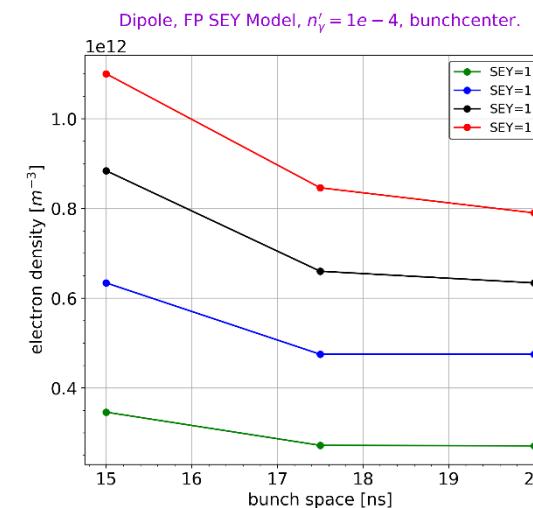
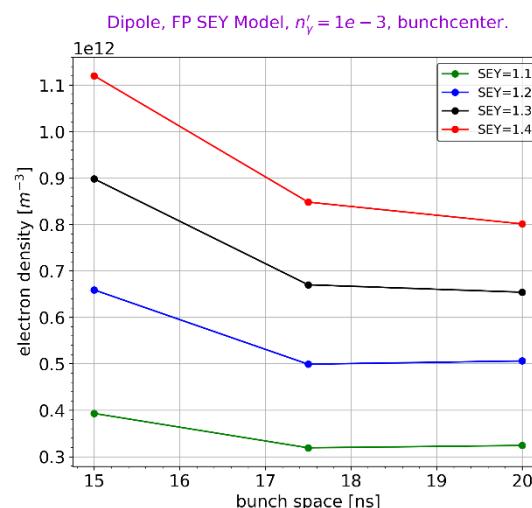
$$n'_{(\gamma)} : 1e-4 \text{ m}^{-1}$$



$$n'_{(\gamma)} : 1e-5 \text{ m}^{-1}$$



@ bunch arrive



@ bunch center

- e^- density decrease
 $15\text{ns} - 17.5\text{ns} > 17.5\text{ns} - 20\text{ns}$
- 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?

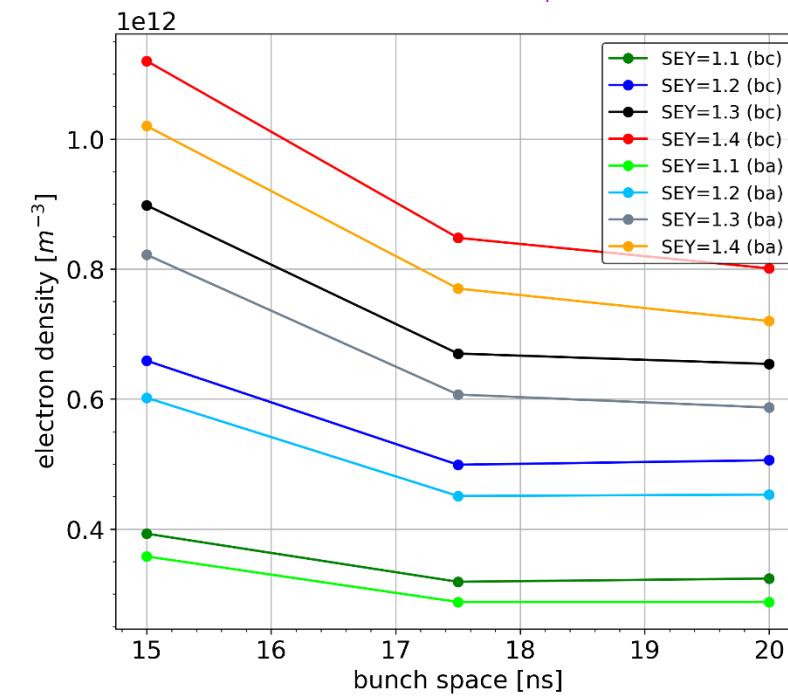
e⁻ density variations at bunch arrivals and bunch center

(ba) : bunch arrival

(bc): bunch center

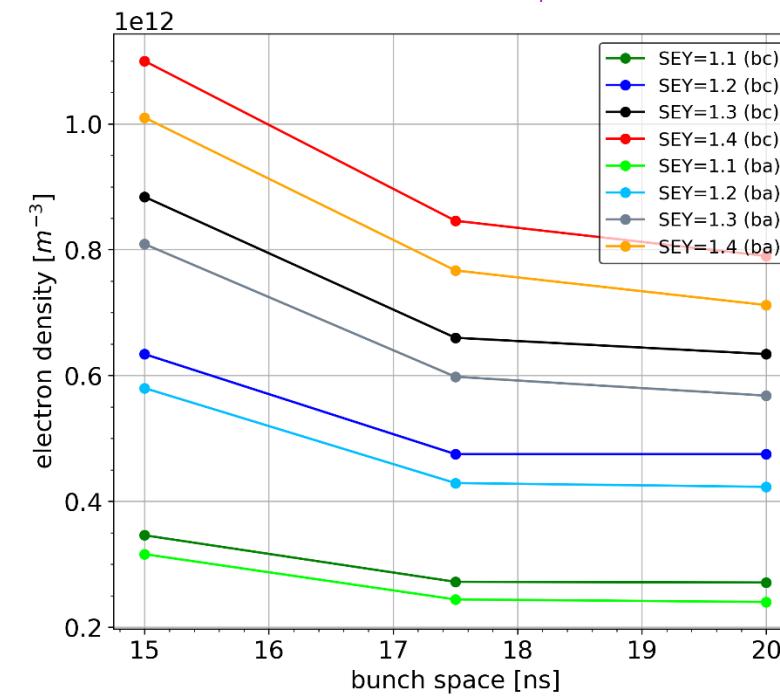
$$n'_{(\gamma)} : 1\text{e-}3 \text{ m}^{-1}$$

Dipole, FP SEY Model, $n'_{\gamma} = 1\text{e-}3$



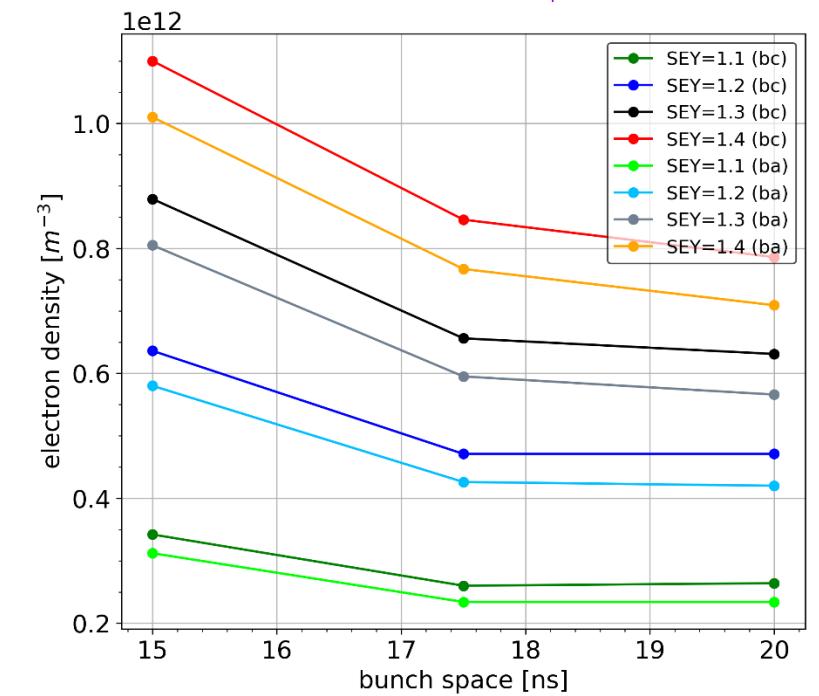
$$n'_{(\gamma)} : 1\text{e-}4 \text{ m}^{-1}$$

Dipole, FP SEY Model, $n'_{\gamma} = 1\text{e-}4$



$$n'_{(\gamma)} : 1\text{e-}5 \text{ m}^{-1}$$

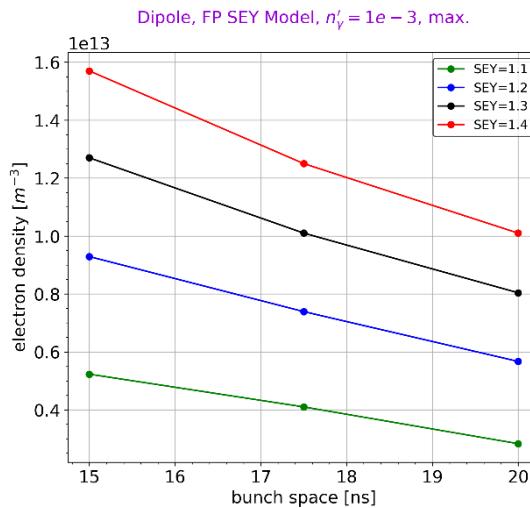
Dipole, FP SEY Model, $n'_{\gamma} = 1\text{e-}5$



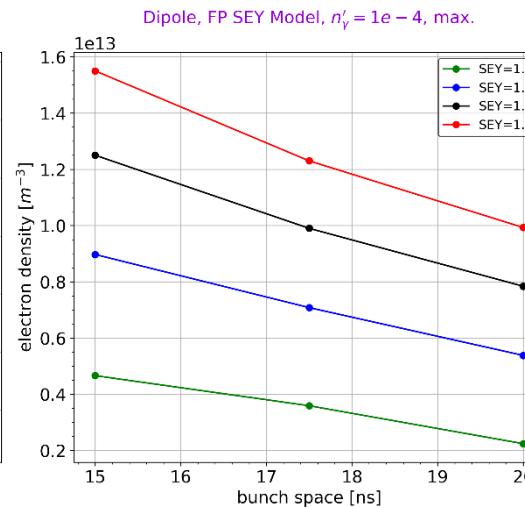
- density increase from bunch arrival to bunch center $\sim [1\text{e}10 - 8.1\text{e}10] \text{ e}^-/\text{m}^3$
- for $n'_{(\gamma)} = 1\text{e-}4 \text{ m}^{-1}$ and $1\text{e-}5 \text{ m}^{-1}$ difference in values $\sim [2\text{e}9 - 12\text{e}9] \text{ e}^-/\text{m}^3$
- density increase is smaller for SEY=1.1

Max. and Min. e⁻ density variations

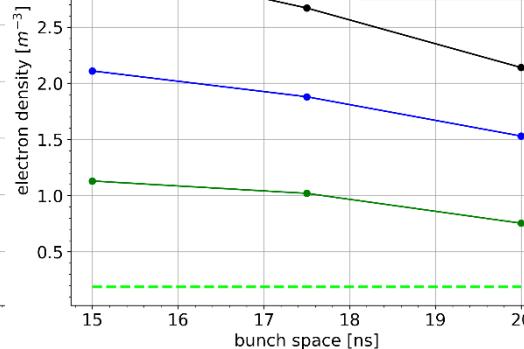
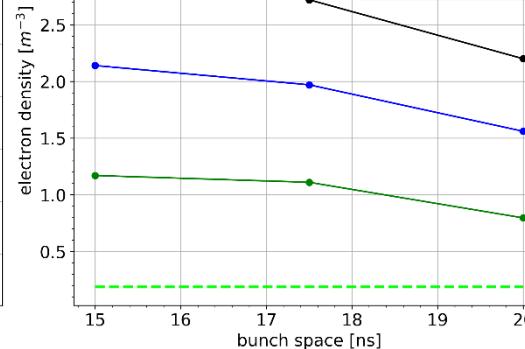
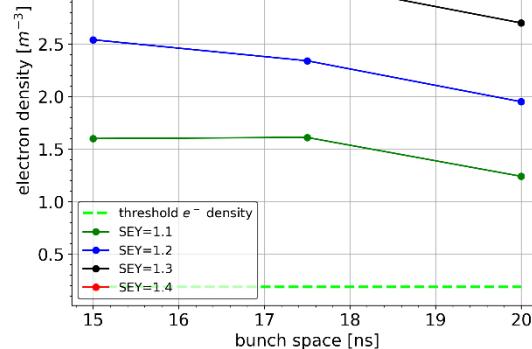
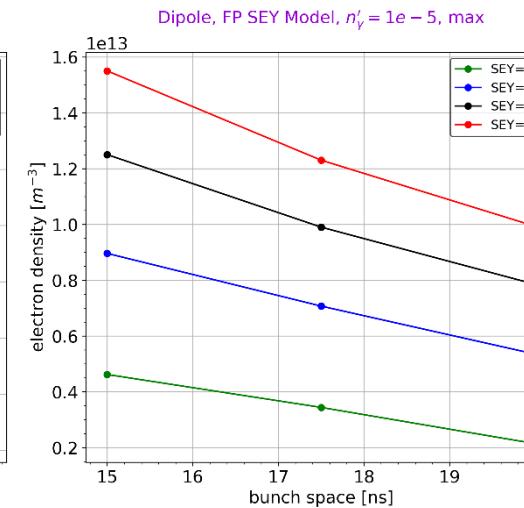
$$n'_{(\gamma)} : 1\text{e-}3 \text{ m}^{-1}$$



$$n'_{(\gamma)} : 1\text{e-}4 \text{ m}^{-1}$$

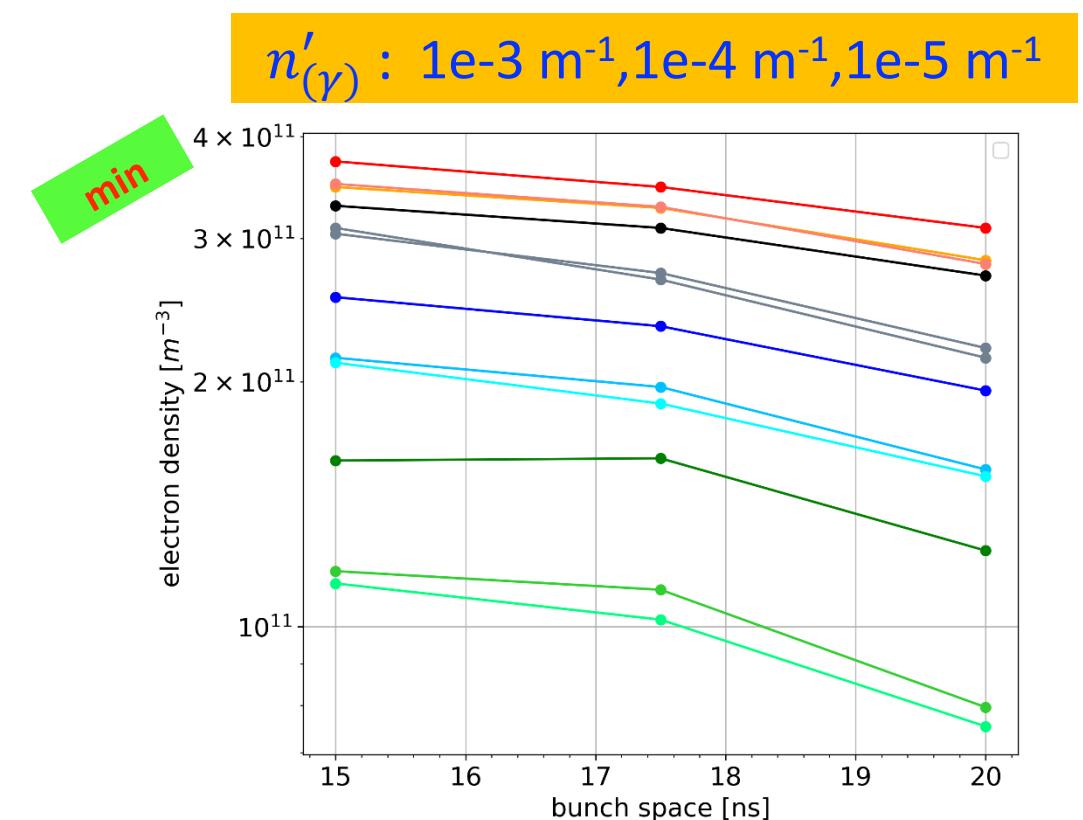
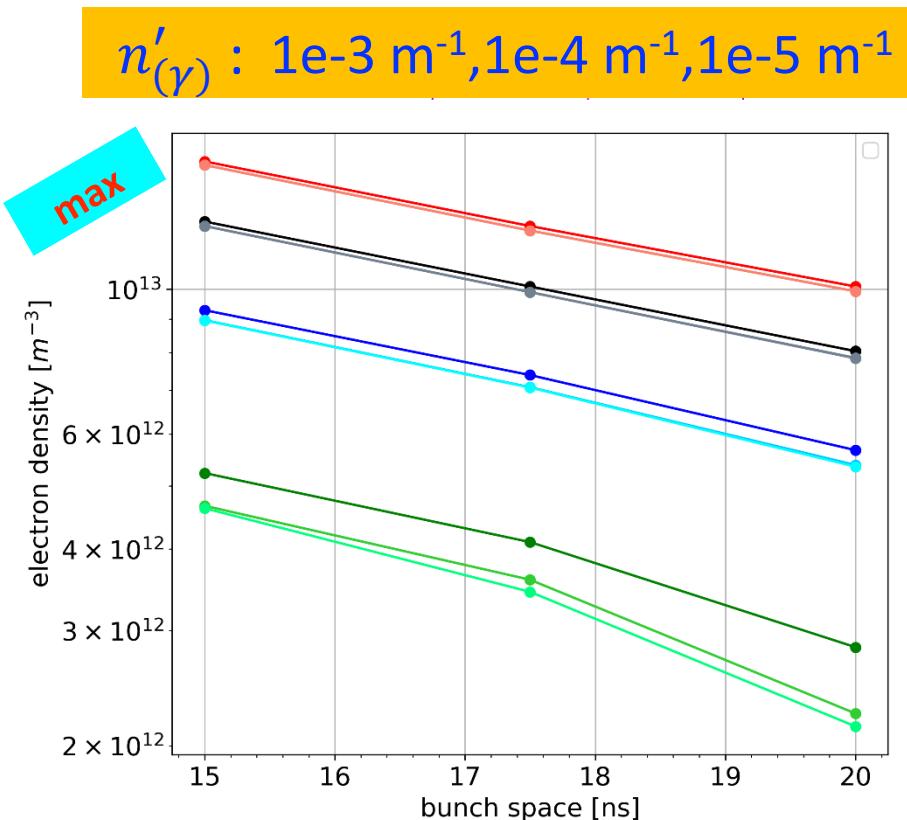


$$n'_{(\gamma)} : 1\text{e-}5 \text{ m}^{-1}$$



- 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 $n'_{(\gamma)}$ = $1\text{e-}4 \text{ m}^{-1}$ to $n'_{(\gamma)} = 1\text{e-}5 \text{ m}^{-1}$ e⁻ densities decrease in the range of ~ $[1\text{e}10 - 15\text{e}10] \text{ e}^-/\text{m}^3$ for max. ~ $[1\text{e}9 - 4\text{e}9] \text{ e}^-/\text{m}^3$ for min.

Max. and Min. e⁻ density variations

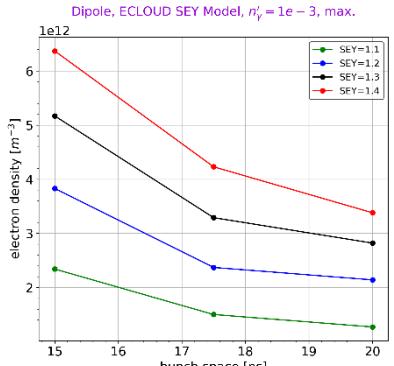


- for the selected photoemission range, simulations with 15ns and 17.5ns bunch spacings and SEY=1.3 & SEY=1.4 exceed $1\text{e}13 \text{ e}^-/\text{m}^3$
- the minimum reachable e⁻ density occurs as $\sim 1\text{e}11 \text{ e}^-/\text{m}^3$ for $n'_{(\gamma)} = 1\text{e-}5 \text{ m}^{-1}$ and SEY=1.1

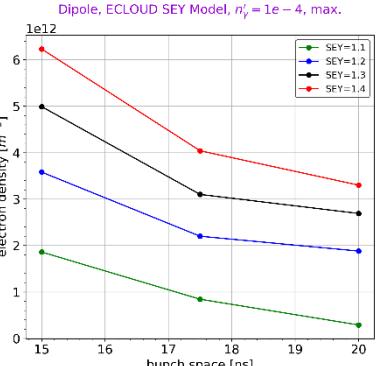
Comparisons for different regions and models

Dipole, ECLOUD SEY

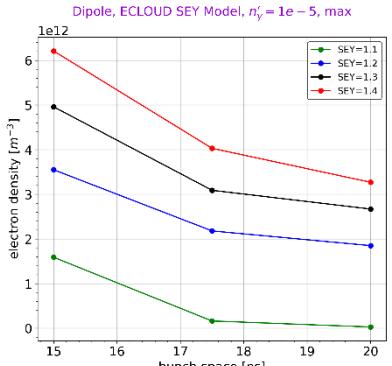
$$n'_{(\gamma)} : 1e-3 \text{ m}^{-1}$$



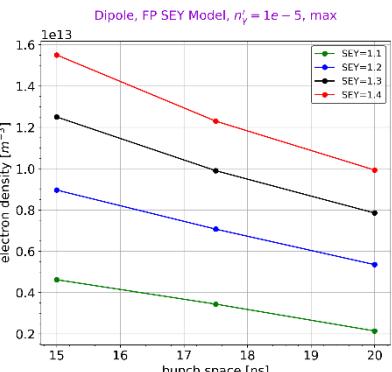
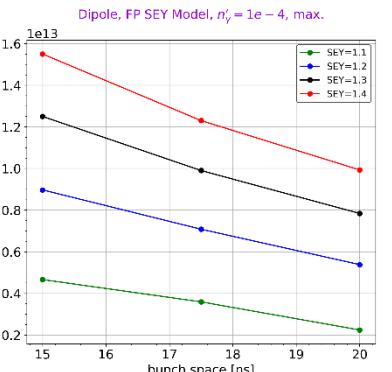
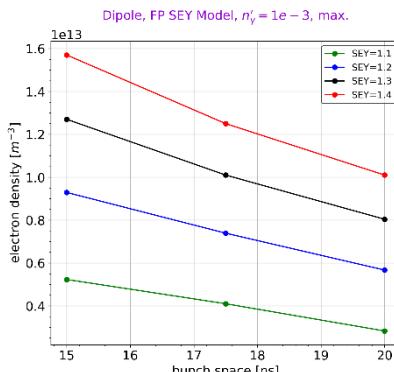
$$n'_{(\gamma)} : 1e-4 \text{ m}^{-1}$$



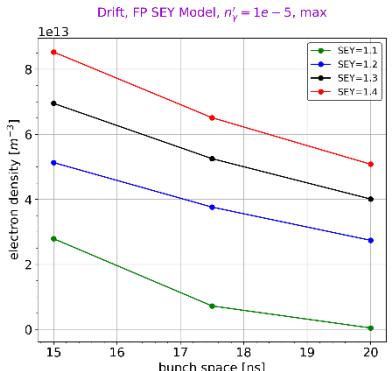
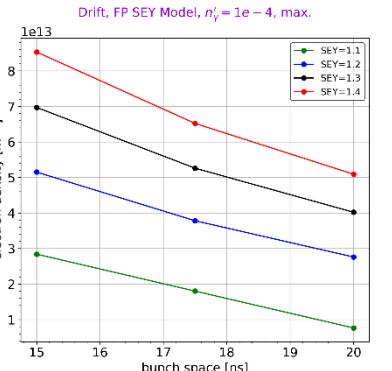
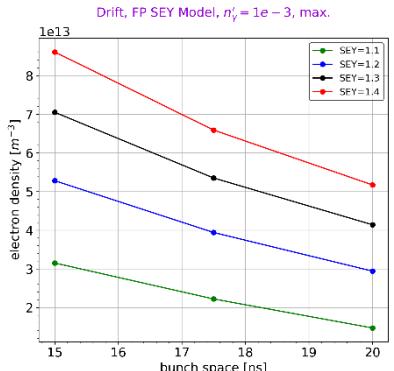
$$n'_{(\gamma)} : 1e-5 \text{ m}^{-1}$$



Dipole, FP SEY



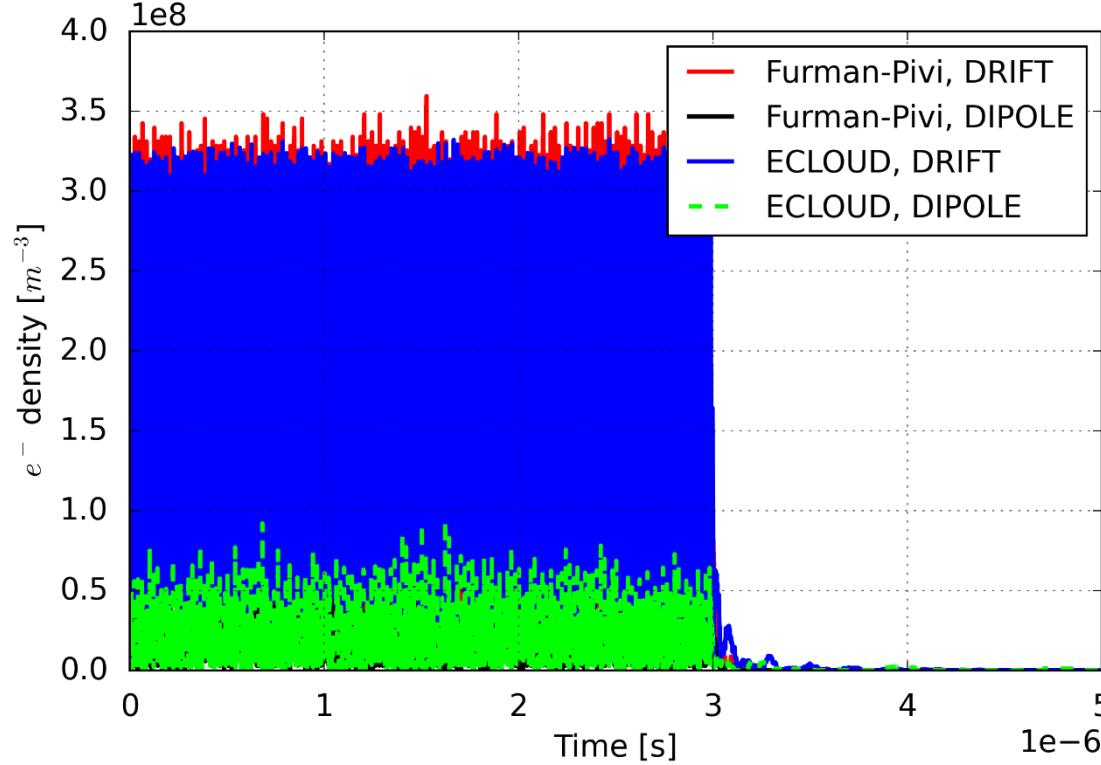
Drift, FP SEY



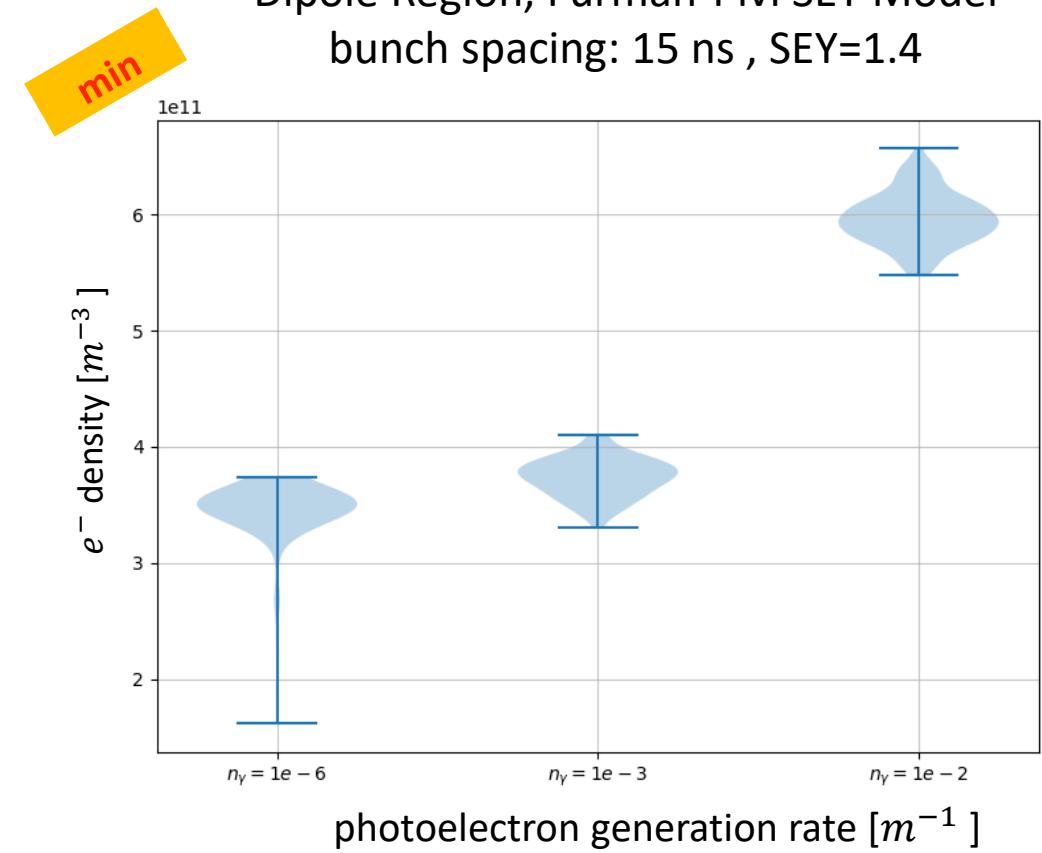
- Max. values in the density distributions are used for these comparisons
- e- density decrease between 17.5ns and 20ns is smaller with ECLOUD SEY model
- factor ~ 2.46 between two SEY models
- factor ~ 5.43 between Dipole and Drift Regions for Furman-Pivi SEY model

Reference densities

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

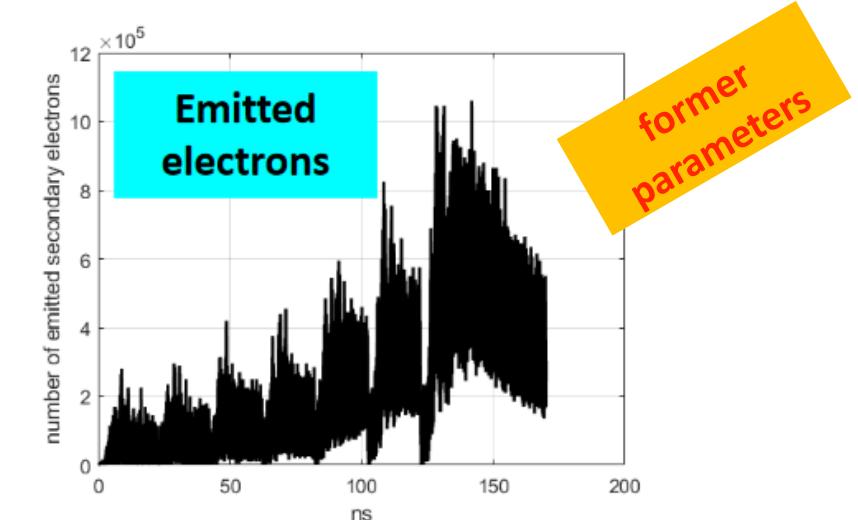
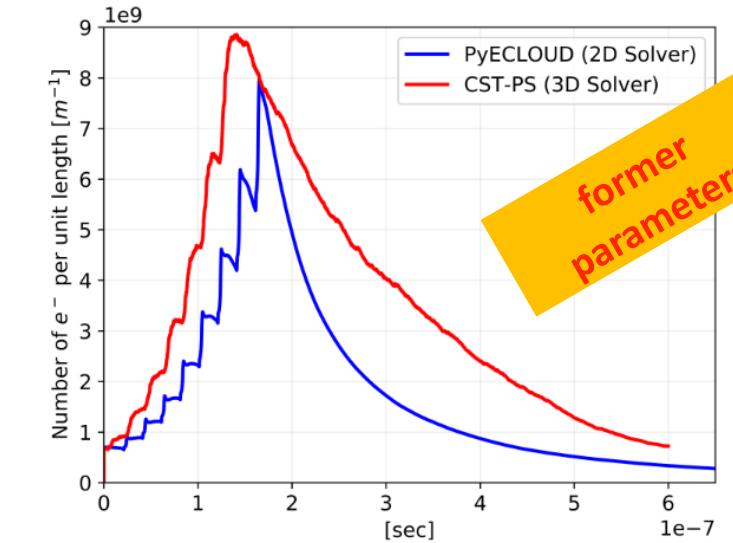
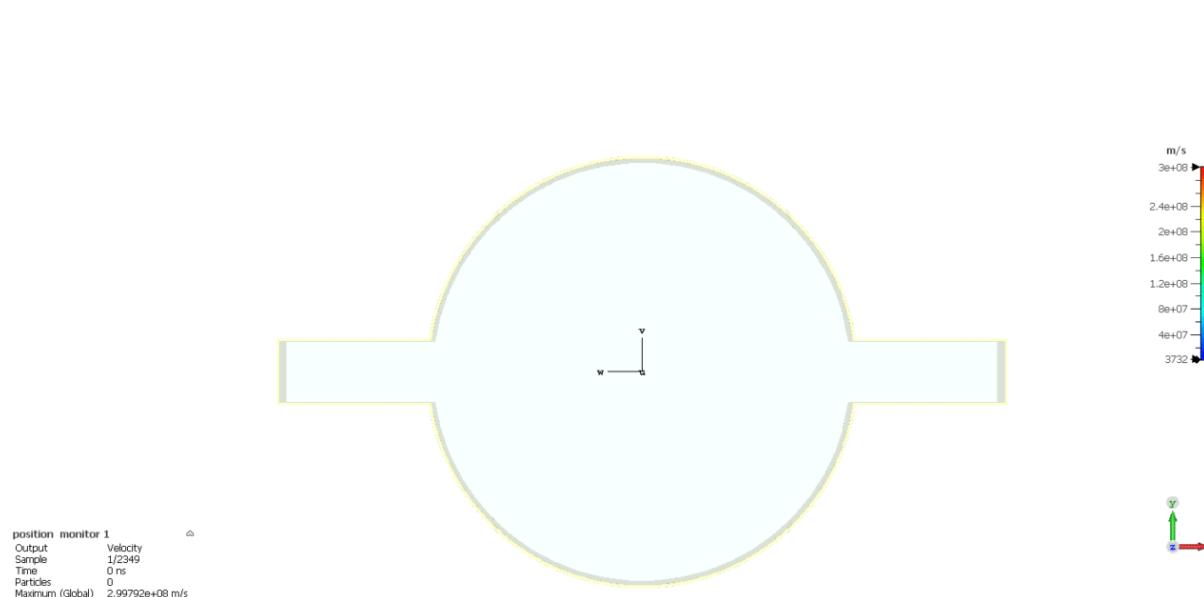
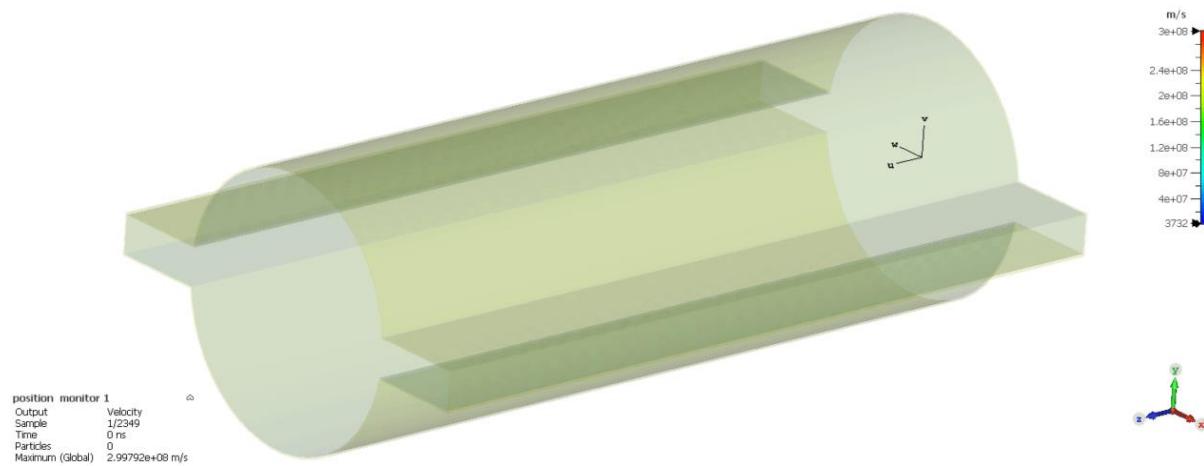


Dipole Region, Furman-Pivi SEY Model
bunch spacing: 15 ns , SEY=1.4



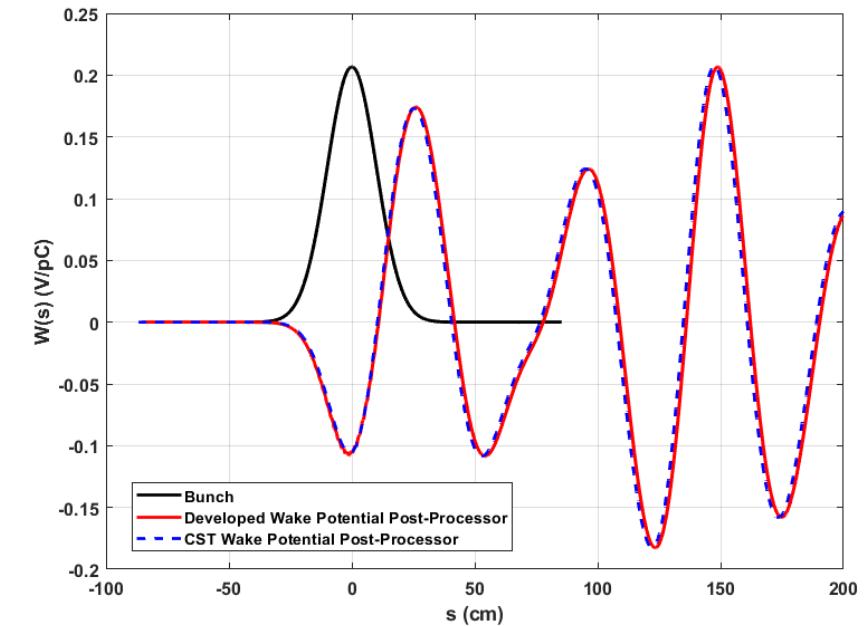
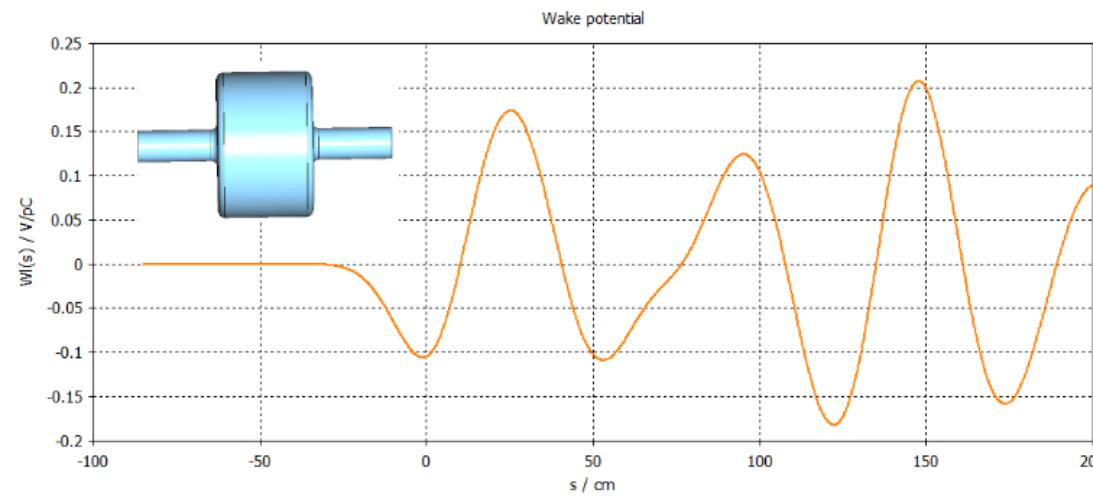
- results via two SEY models agree well for $\text{SEY} \simeq 0$
- reference center e^- density $\simeq 5\text{e}7 \text{ e-/m}^3$ for Dipole and $\simeq 3.25 \text{ e}8 \text{ e-/m}^3$ for Drift Region
- factor ~ 6.5 between Dipole and Drift Regions
- factor ~ 1.5 between $n'_{(\gamma)} : 1\text{e-}2 \text{ m}^{-1}$ and $n'_{(\gamma)} : 1\text{e-}3 \text{ m}^{-1}$ for the min.

Electron Cloud Simulations with CST-PIC



Wake Potential Post-Processor for PIC solver

a typical RF Cavity example



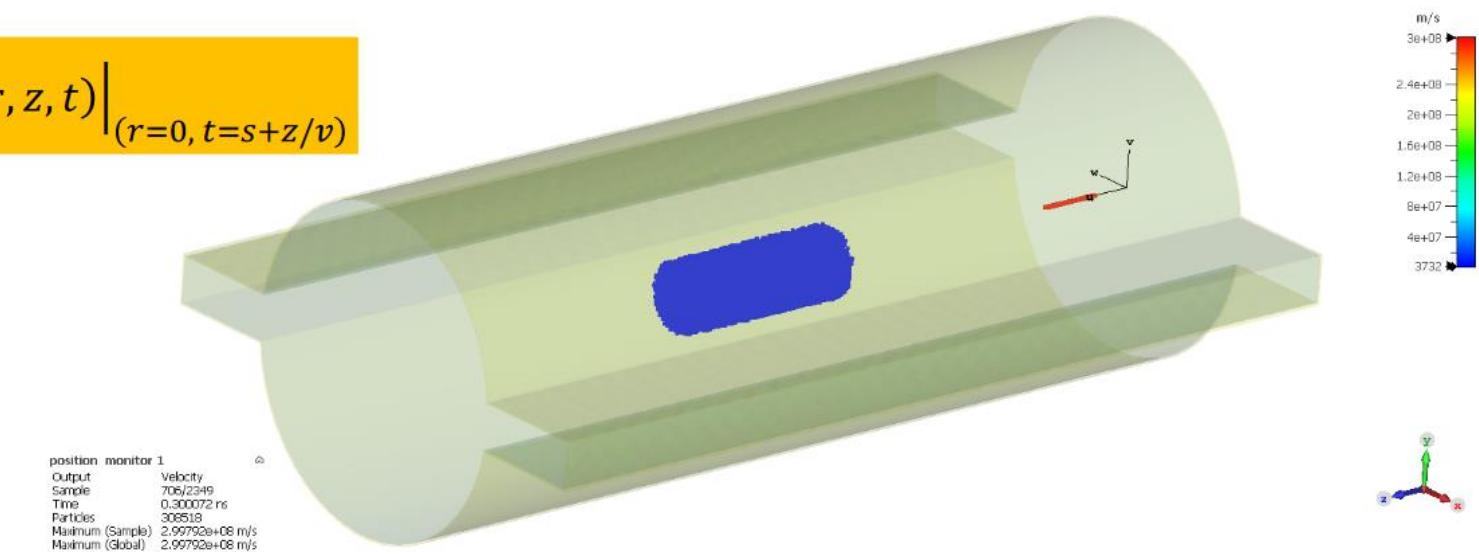
$$W_{||}(r, s) = \frac{1}{Q} \int_{-\infty}^{\infty} dz \ E_z(r, z, t) \Big|_{(r=0, t=s+z/v)}$$



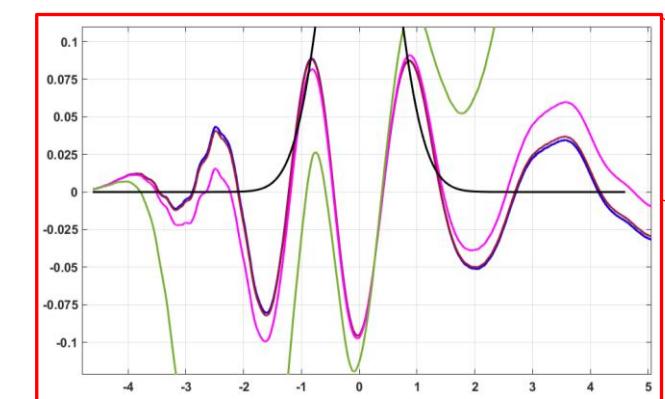
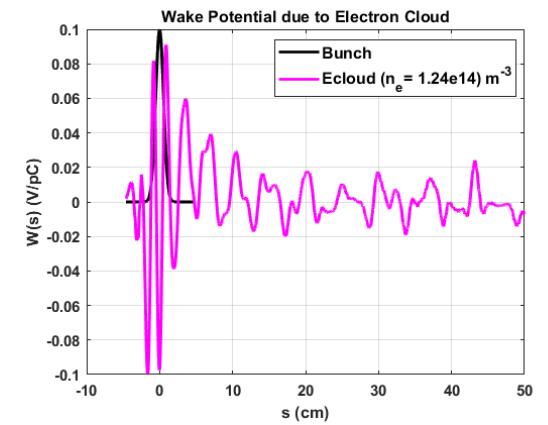
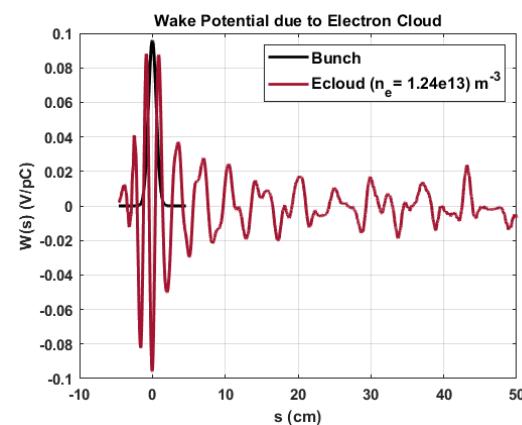
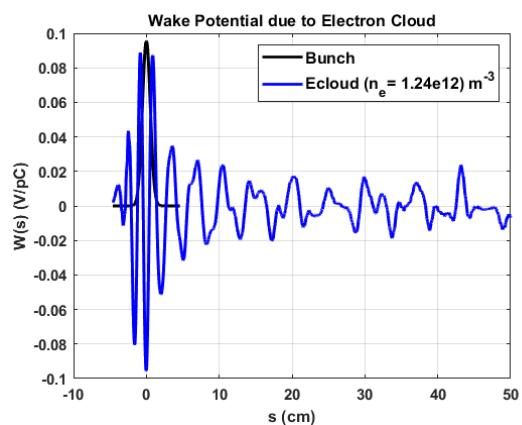
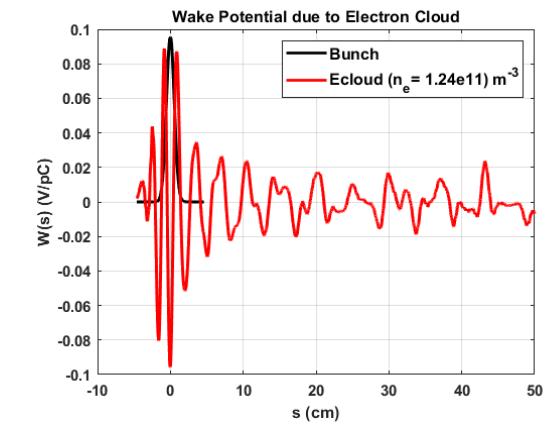
K. Ohmi, F. Zimmermann, and E. Perevedentsev, 'Wake-field and fast head-tail instability caused by an electron cloud,' Phys. Rev. E 65, 016502 – Published 17 December 2001



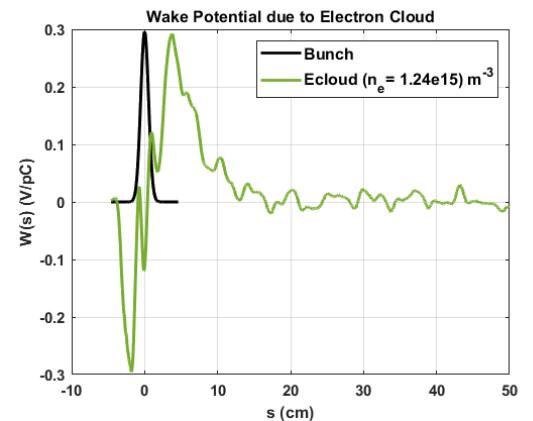
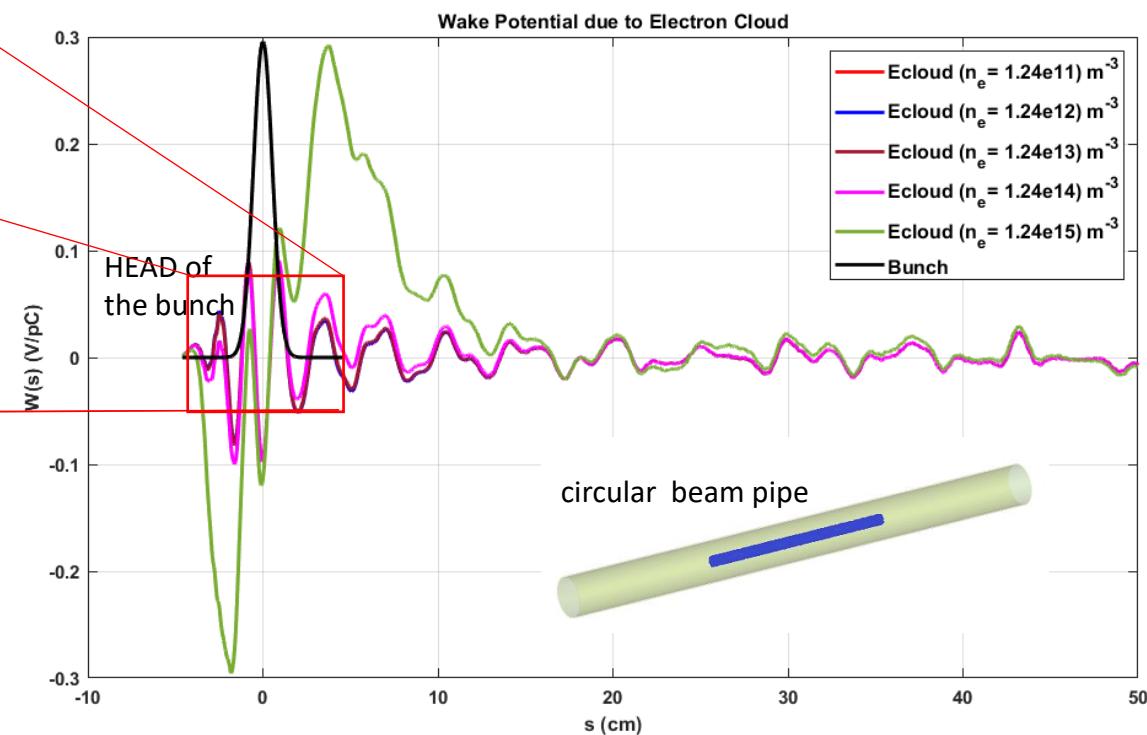
F. Yaman, E.Gjonaj, Th. Weiland, '3D EM PIC code to study e- Cloud effects for short bunches (<50ns)', CERN - GSI Electron Cloud Workshop 2011, Geneve, Switzerland, 2011
<https://indico.cern.ch/event/125315/contributions/96596/>



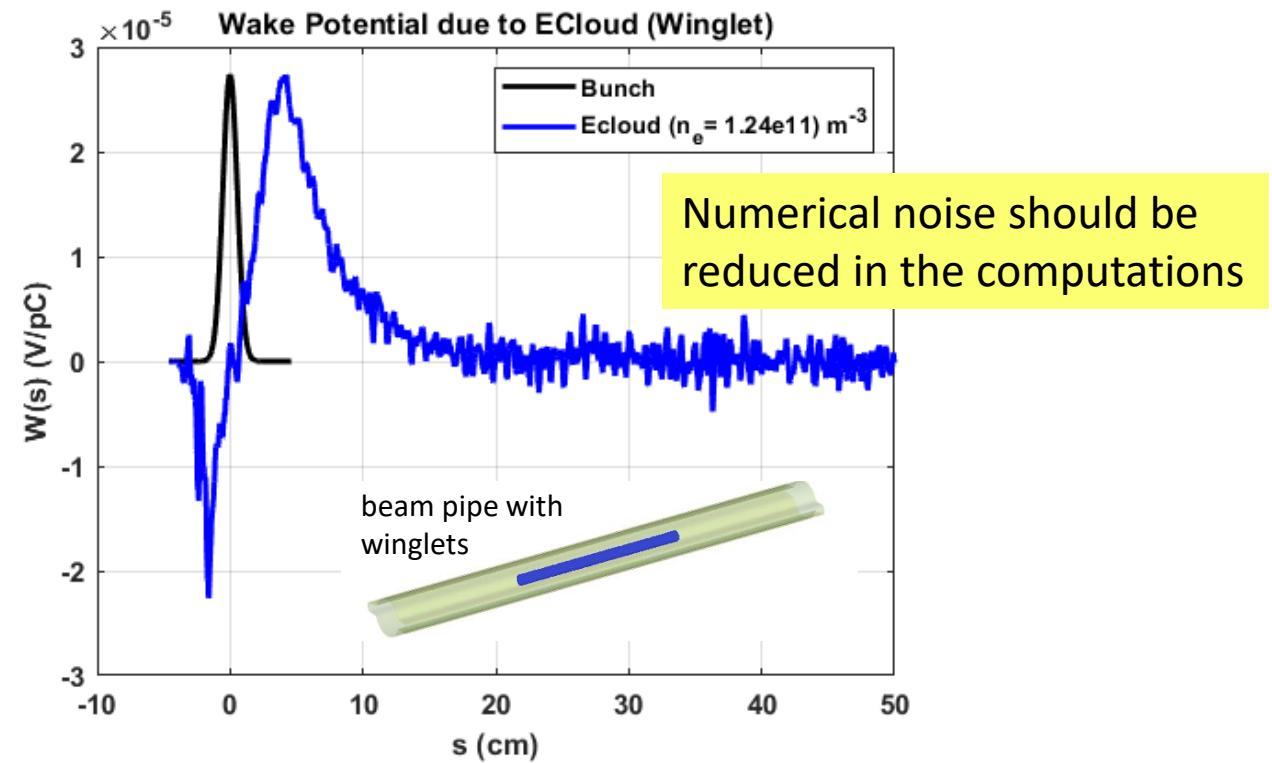
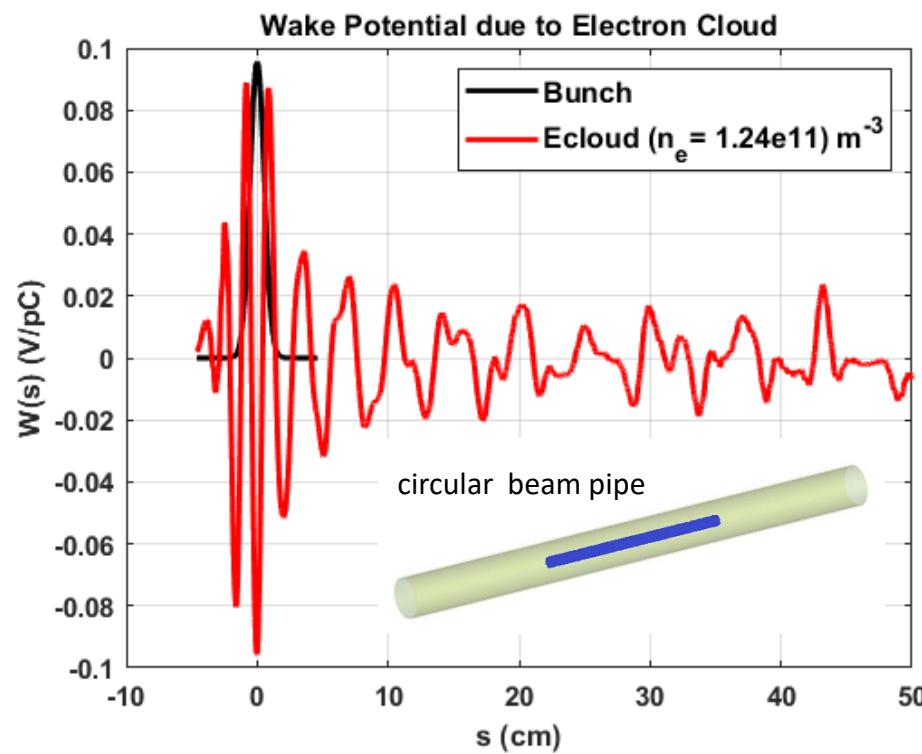
Longitudinal Wake Potential Calculations (Preliminary)



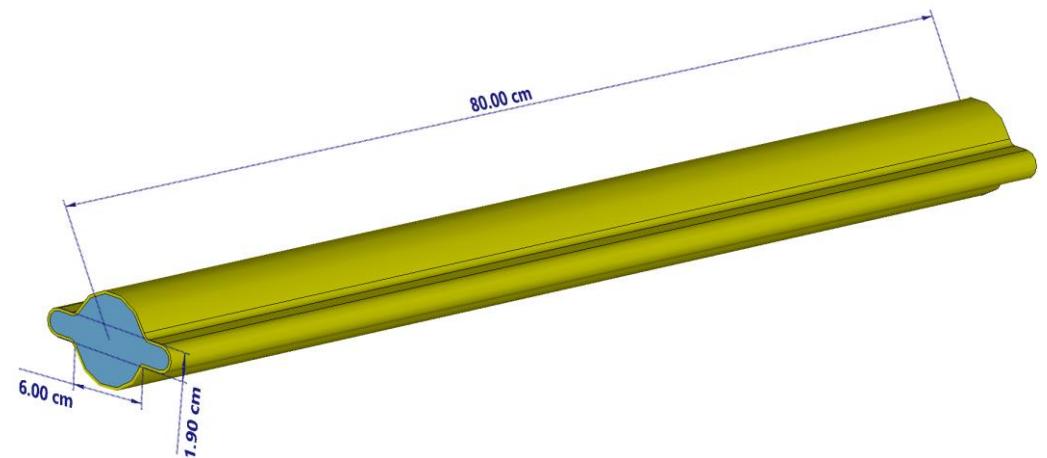
zoom



Longitudinal Wake Potential Calculations (Preliminary)



- 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



Conclusions and Future Plans

- Reference center e- density $\simeq 5e7 \text{ e-}/\text{m}^3$ for DIPOLE and $\simeq 3.25 e8 \text{ e-}/\text{m}^3$ for DRIFT (SEY $\simeq 0$).
- Reference density by factor $\simeq 2.5$ increased according to the former parameters ($\simeq 2e7 \text{ e-}/\text{m}^3$ for DIPOLE*)
- Min. values are over the single-bunch instability threshold level via Furman-Pivi model
- factor ~ 2.46 between two SEY models
- factor ~ 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



THANK YOU FOR ATTENTION!



fatihyaman@iyte.edu.tr
Fatih.Yaman@stfc.ac.uk

Backup Slides

PE generation rate

$$n'_\gamma = Y_\gamma \frac{5 \alpha \gamma}{2\sqrt{3}\rho}$$

≈ 0.1

number of
photoelectrons
emitted
per length

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

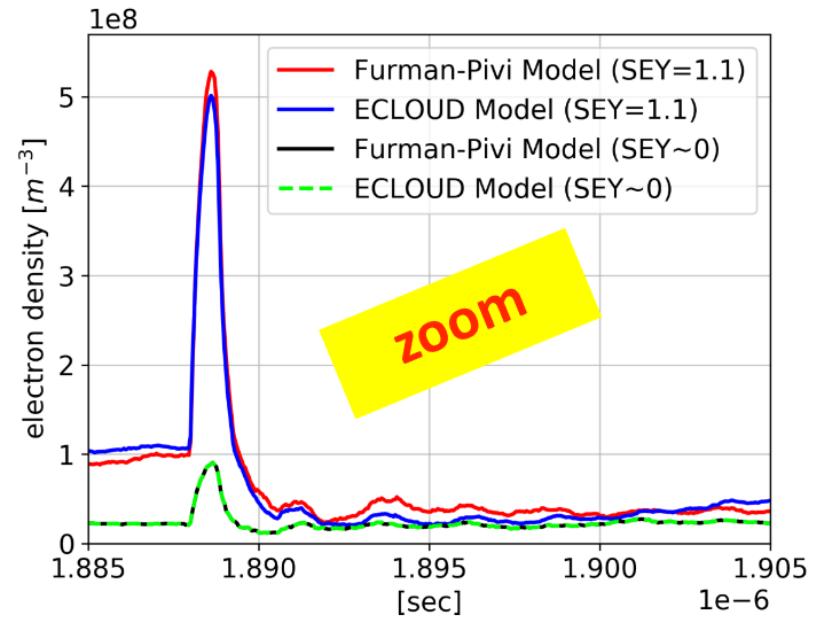
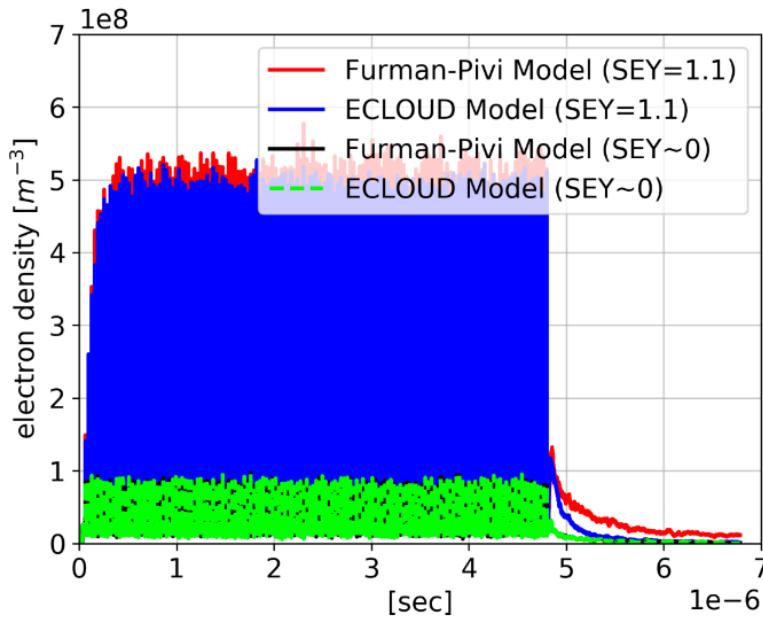
the Lorentz factor

$\gamma \approx 10^5$

radius of curvature of
the particle path

$\rho \approx 11000$ [m]

4 IPs ($n'_{(\gamma)} = 1\text{e-}6 \text{ m}^{-1}$, bunch spacing: 32ns) Dipole Region



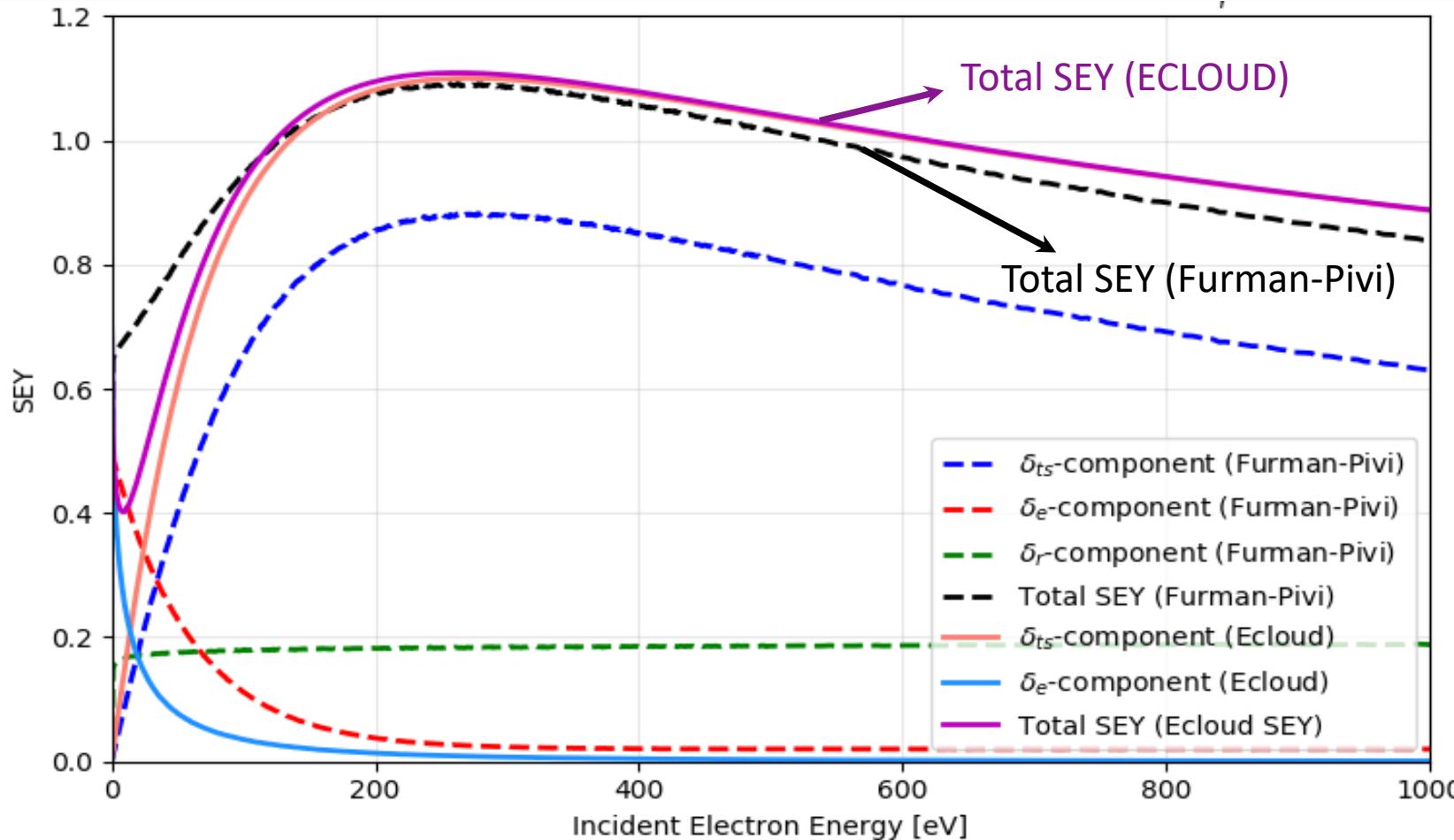
- results via two SEY models agree well for $\text{SEY} \simeq 0$ (min. $\simeq 2\text{e}7 \text{ e}^-/\text{m}^3$)
- max. $\simeq 5\text{e}8 \text{ e}^-/\text{m}^3$ is verified with both models for $\text{SEY} = 1.1$

3

| 4 IPs Parameters | |
|--|----------------|
| beam energy [GeV] | 45.6 |
| bunches per train | 150 |
| trains per beam | 1 |
| r.m.s. bunch length (σ_z) [mm] | 4.32 |
| h. r.m.s. beam size (σ_x) [μm] | 207 |
| v. r.m.s. beam size (σ_y) [μm] | 12.1 |
| number of particles / bunch (10^{11}) | 2.76 |
| bend field [T] | 0.01415 |
| circumference C [m] | 91.2 |
| synchrotron tune Q_s | 0.037 |
| average beta function β_y [m] | 50 |
| threshold density (10^{12} [m^{-3}]) | 0.043 |



Furman-Pivi & ECLOUD SEY Models



^aNote that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

1.1

0.88

0.02

0.2

TABLE I: Main parameters of the model.

| | Copper | Stainless Steel |
|---|--------|-----------------|
| Emitted angular spectrum (Sec. II C 1) | | |
| α | 1 | 1 |
| Backscattered electrons (Sec. III B) | | |
| $P_{1,e}(\infty)$ | 0.02 | 0.07 |
| $\hat{P}_{1,e}$ | 0.496 | 0.5 |
| \hat{E}_e [eV] | 0 | 0 |
| W [eV] | 60.86 | 100 |
| p | 1 | 0.9 |
| σ_e [eV] | 2 | 1.9 |
| e_1 | 0.26 | 0.26 |
| e_2 | 2 | 2 |
| Ridiffused electrons (Sec. III C) | | |
| $P_{1,r}(\infty)$ | 0.2 | 0.74 |
| E_r [eV] | 0.041 | 40 |
| r | 0.104 | 1 |
| q | 0.5 | 0.4 |
| r_1 | 0.26 | 0.26 |
| r_2 | 2 | 2 |
| True secondary electrons (Sec. IIID) | | |
| $\hat{\delta}_{ts}$ | 1.8848 | 1.22 |
| \hat{E}_{ts} [eV] | 276.8 | 310 |
| s | 1.54 | 1.813 |
| t_1 | 0.66 | 0.66 |
| t_2 | 0.8 | 0.8 |
| t_3 | 0.7 | 0.7 |
| t_4 | 1 | 1 |
| Total SEY^a | | |
| \hat{E}_t [eV] | 271 | 292 |
| $\hat{\delta}_t$ | 2.1 | 2.05 |

^aNote that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.



Furman-Pivi & ECLOUD SEY Models

M.A. Furman and M.T.F. Pivi, 'Probabilistic Model for the Simulation of Secondary Electron Emission', SLAC-PUB-9912, 2003

TABLE I: Main parameters of the model.

| | Copper | Stainless Steel |
|---|--------|-----------------|
| Emitted angular spectrum (Sec. II C 1) | | |
| α | 1 | 1 |
| Backscattered electrons (Sec. III B) | | |
| $P_{1,e}(\infty)$ | 0.02 | |
| $\hat{P}_{1,c}$ | 0.496 | |
| \hat{E}_e [eV] | 0 | |
| W [eV] | 60.86 | |
| p | 1 | 0.9 |
| σ_e [eV] | 2 | 1.9 |
| e_1 | 0.26 | 0.26 |
| e_2 | 2 | 2 |
| Rediffused electrons (Sec. III C) | | |
| $P_{1,r}(\infty)$ | 0.2 | 0.74 |
| E_r [eV] | 0.041 | 40 |
| r | 0.104 | 1 |
| q | 0.5 | 0.4 |
| r_1 | 0.26 | 0.20 |
| r_2 | 2 | 2 |
| True secondary electrons (Sec. III D) | | |
| $\hat{\delta}_{ts}$ | 1.8848 | 1.22 |
| \hat{E}_{ts} [eV] | 276.8 | 310 |
| s | 1.54 | 1.813 |
| t_1 | 0.66 | 0.66 |
| t_2 | 0.8 | 0.8 |
| t_3 | 0.7 | 0.7 |
| t_4 | 1 | 1 |
| Total SEY^a | | |
| \hat{E}_t [eV] | 271 | 292 |
| $\hat{\delta}_t$ | 2.1 | 2.05 |

^aNote that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

$$\delta_e(E_0, \theta_0) = \delta_e(E_0, \theta_0 = 0)[1 + e_1(1 - \cos^{e_2} \theta_0)]$$

$$\delta_r(E_0, \theta_0) = \delta_r(E_0, \theta_0 = 0)[1 + r_1(1 - \cos^{r_2} \theta_0)]$$

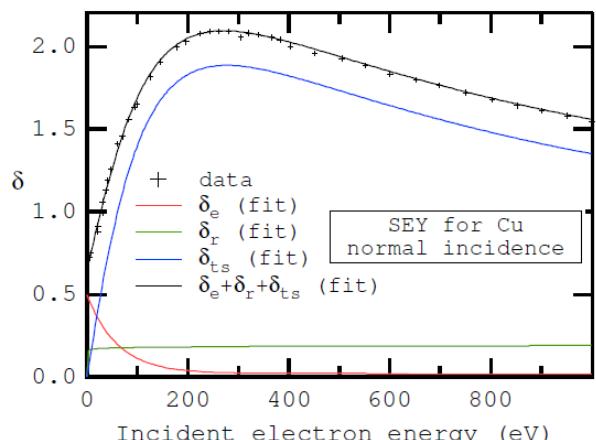
$$\delta_{ts}(E_0, \theta_0) = \hat{\delta}(\theta_0)D(E_0/\hat{E}(\theta_0)),$$

$$\delta(E_0, \theta_0) = \delta_e(E_0, \theta_0) + \delta_r(E_0, \theta_0) + \delta_{ts}(E_0, \theta_0)$$

^aNote that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

1.1
0.88
0.02
0.2

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



E.G. T. Wulff and G. Iadarola, 'Implementation and benchmarking of the Furman-Pivi model for Secondary Emission in the PyEcloud simulation code', CERN-ACC-2019-0029, 2019

