65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)

IZMIR INSTITUTE OF TECHNOLOGY
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Studies and possible mitigation of electron cloud effects in FCC-ee

Fatih Yaman, Izmir Institute of Technology

Frank Zimmermann, CERN

Many Thanks: the FCC-ee optics team

Sept. 14, 2022

FUTURE CIRCULAR COLLIDER

Outline

- **FCC-ee parameters :** machine, beam
- **Overview :** SEY Models, PyECLOUD
- **Electron densities at pipe center :** reference, min. and max.
- **Average of min.'s vs estimated threshold :** Drift, Dipole regions
- **Mitigation Ideas**
- **Conclusions**

FCC-ee Collider Arc Dipole Parameters

Parameters	2 IPs	4 IPs
beam energy [GeV]	45.6	45.6
bunches per train	150	150
trains per beam	1	1
circular beam pipe radius [mm]	35	35
r.m.s. bunch length (σ_z) [mm]	3.5	4.32
h. r.m.s. beam size (σ_x) **[μm]**	120	207
v. r.m.s. beam size (σ_y) **[μm]**	7	**12.1**
number of particles / bunch (**10^{11}**)	1.7	2.76
bend field [T]	0.01415	**0.01415**
circumference *C* [m]	97.76	**91.2**
synchrotron tune Qs	0.025	**0.037**
average beta function $\boldsymbol{\beta}_y$ [m]	50	**50**
threshold density (**10^{12} [m^{-3}]**)	0.027	**0.043**

threshold density (single-bunch instability)

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

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

$$K = \omega_e \sigma_z / c$$

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

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, arXiv:2203.04872, (2022).

PE generation rate

{1e-3, 1e-4, 1e-5, 1e-6} m^{-1}

$$n'_\gamma = \underbrace{Y_\gamma}_{\approx 0.1} \underbrace{\frac{5\,\alpha\,\gamma}{2\sqrt{3}\rho}}_{\text{number of photoelectrons emitted per length}}$$

fine structure constant

$$\alpha \approx 1/137$$

the Lorentz factor

$$\gamma \approx 10^5$$

radius of curvature of the particle path

$$\rho \approx 11000 \text{ [m]}$$

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	
$\hat{P}_{1,e}$	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	0.26
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

[a]Note 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 $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

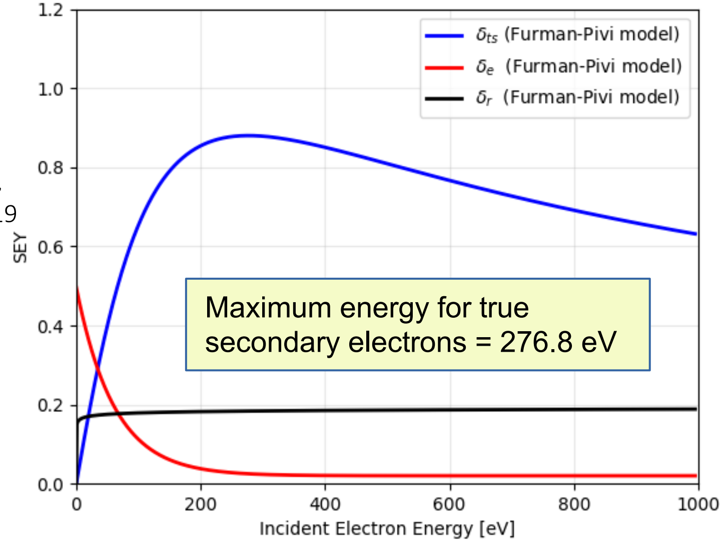
$$\delta_e(E_0,\theta_0) = \delta_e(E_0,\theta_0=0)[1+e_1(1-\cos^{e_2}\theta_0)]$$
$$\delta_r(E_0,\theta_0) = \delta_r(E_0,\theta_0=0)[1+r_1(1-\cos^{r_2}\theta_0)]$$
$$\delta_{ts}(E_0,\theta_0) = \hat{\delta}(\theta_0)D(E_0/\hat{E}(\theta_0)),$$

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

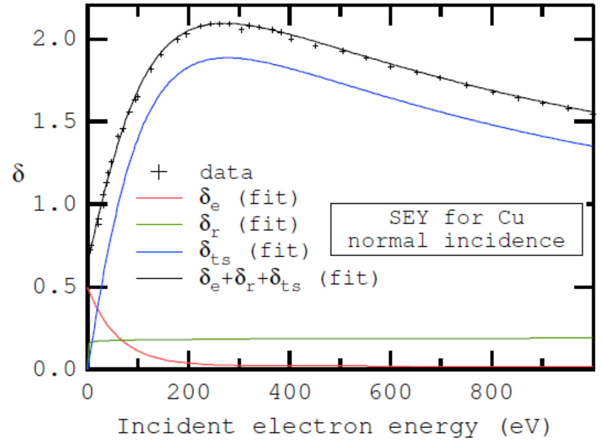
[a]Note that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

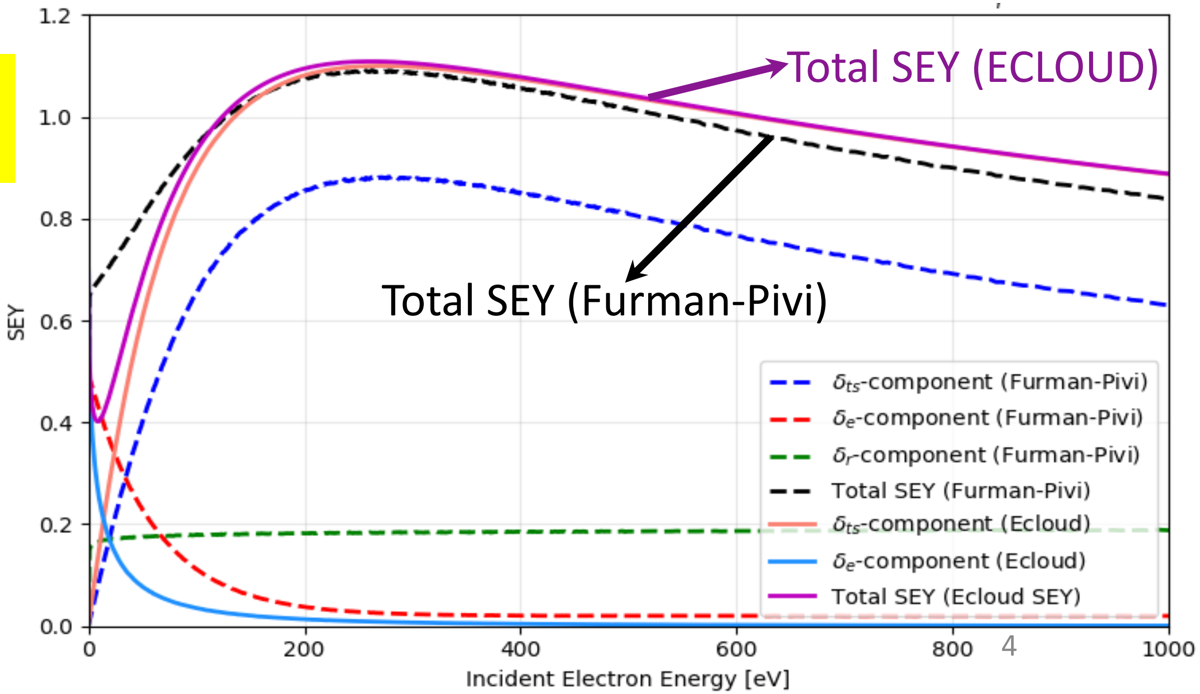
1.1 0.88 0.02 0.2

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



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





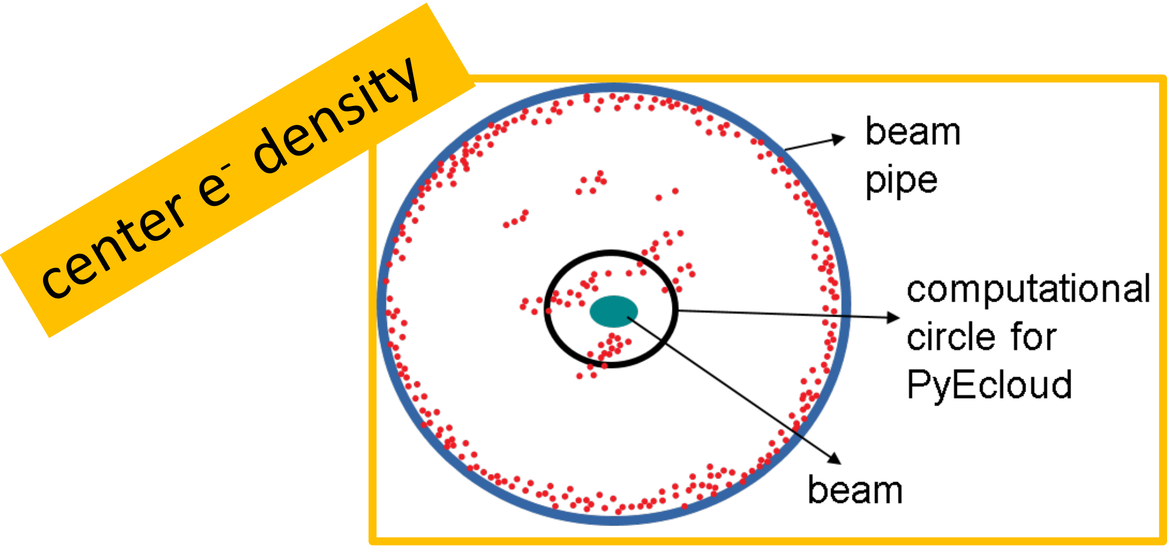
Simulation Tool: PyECLOUD

PyECLOUD

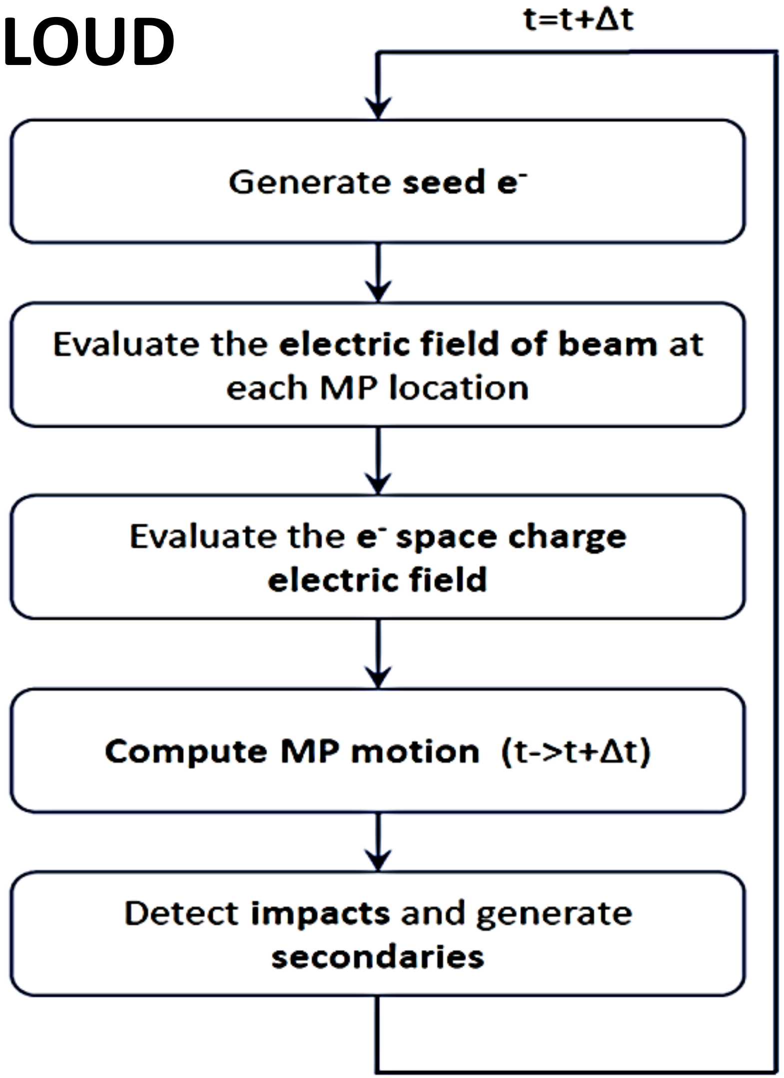
- **2D Electrostatic PIC simulation**
- **effects of space charge and secondary electrons are included**
- **adaptive scheme to control the number of electrons per macro particle during the simulation**
- **ECLOUD and Furman-Pivi SEY models**

G. Iadarola, "Electron cloud studies for CERN particle accelerators and simulation code development" PhD Thesis, U. Naples, CERN-THESIS-2014-047, (2014).

N.Hilleretetal.,"Secondary electron emission data for the simulation of electron cloud", Proc. of ECLOUD’02, Geneva, Switzerland, CERN-2002-001, (2002).

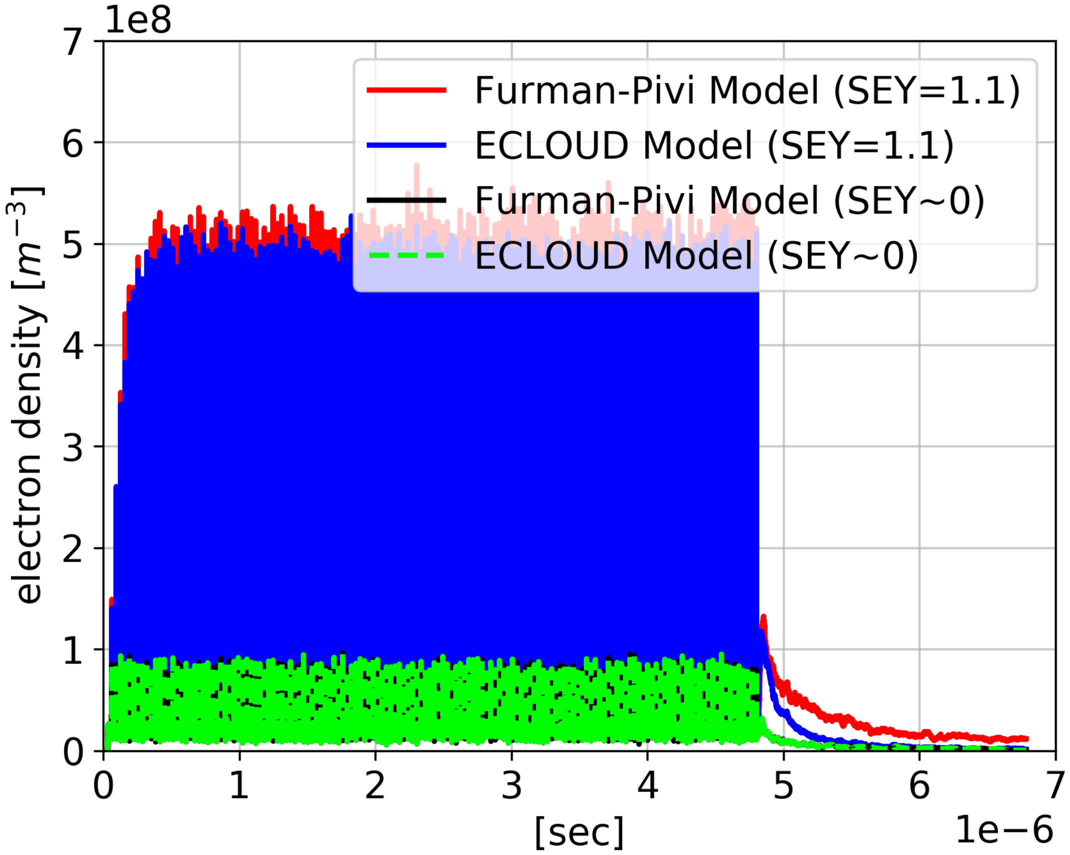


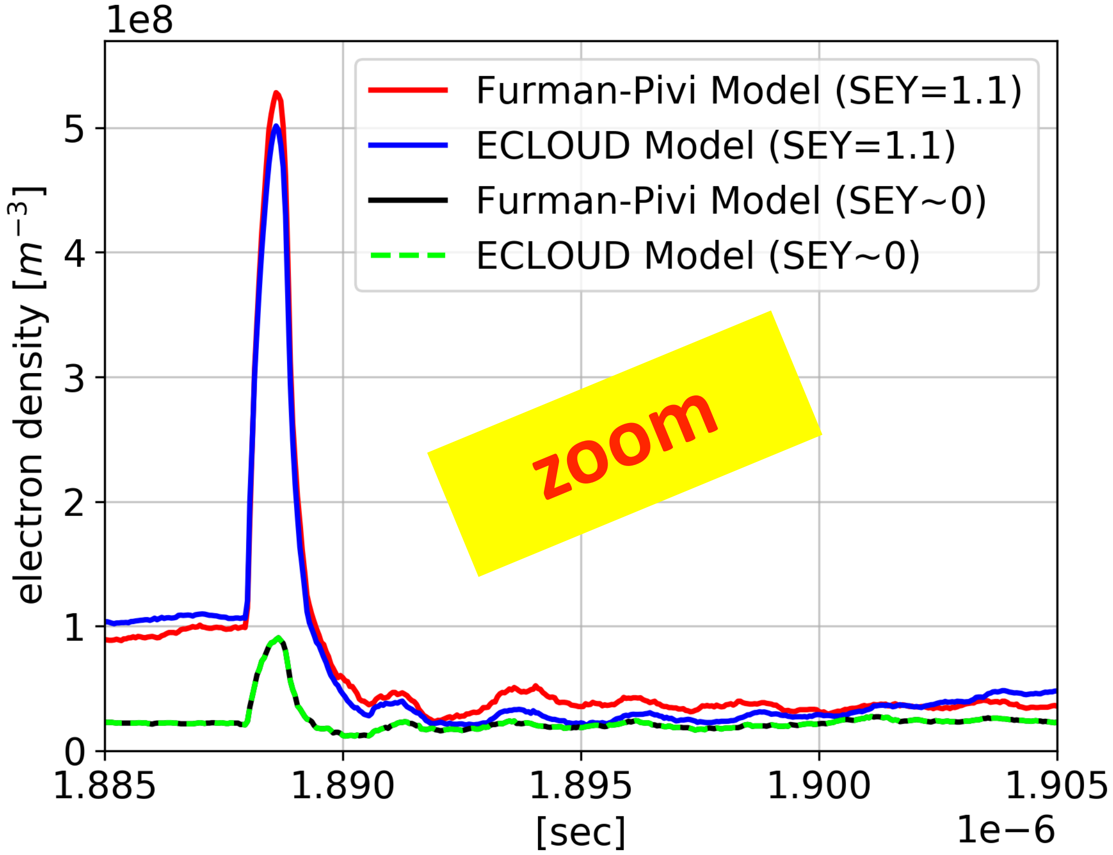
PyECLOUD



with the courtesy of G. Iadarola

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

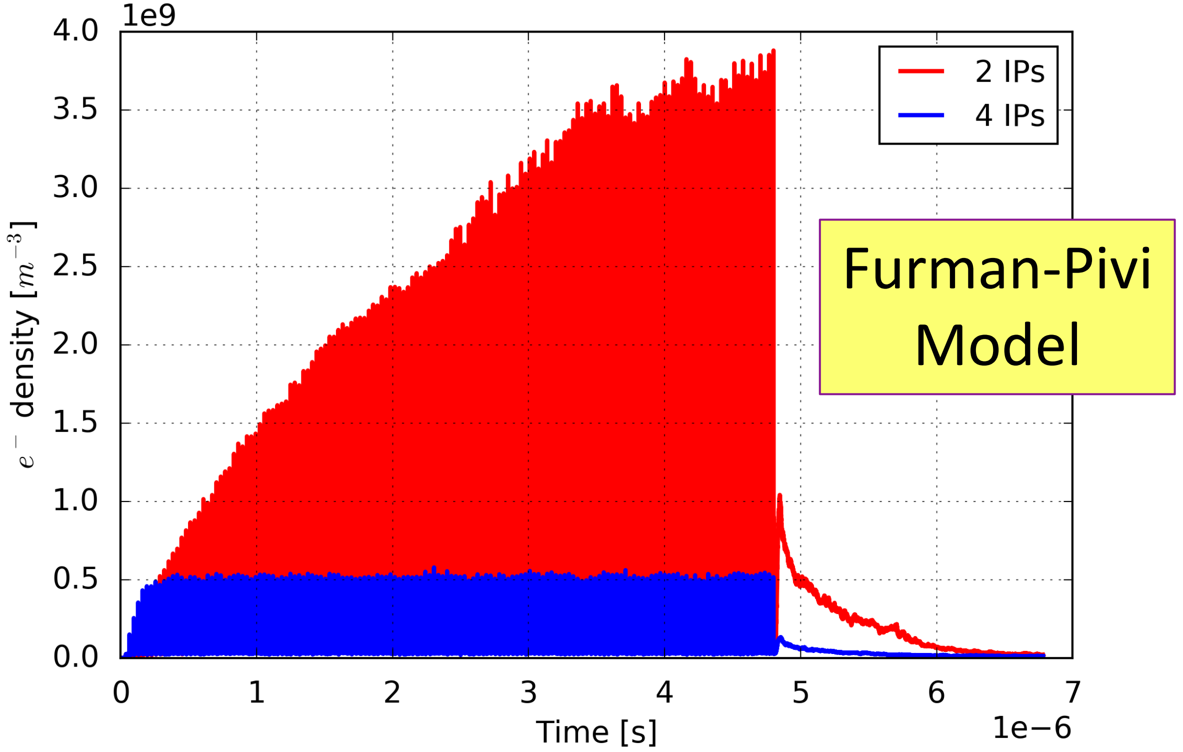


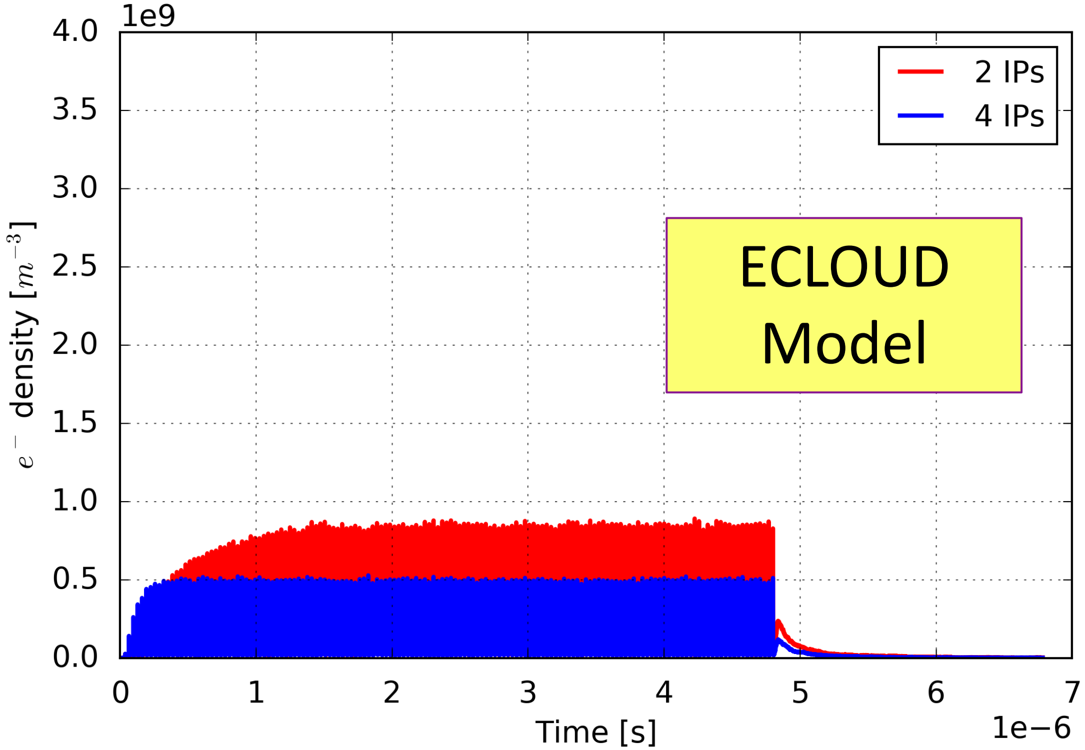


- results via two SEY models agree well for SEY ≃ 0 (min. ≃ 2e7 e^-/m^3)
- max. ≃ 5e8 e^-/m^3 is verified with both models for SEY = 1.1

e^- densities for Arc Dipole at the pipe center

SEY $\backsimeq$ 1.1 , $n'_{(\gamma)} \rightarrow$ 1e-6 m^{-1} , bunch spacing: 32ns

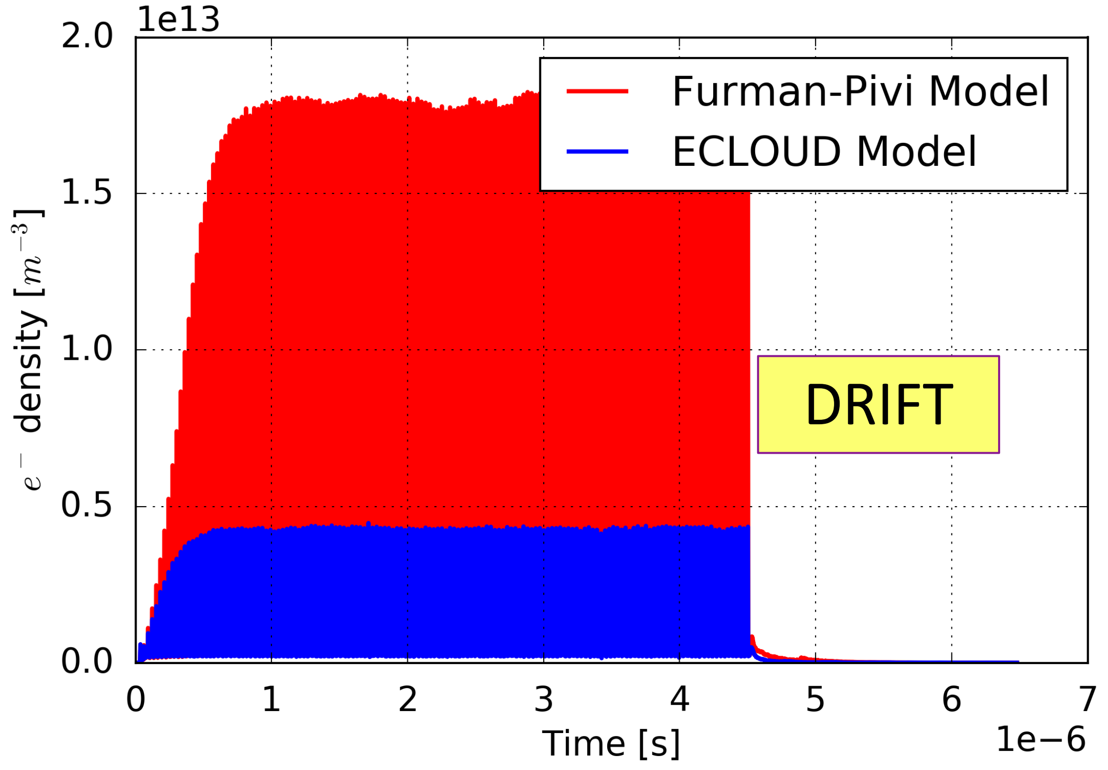


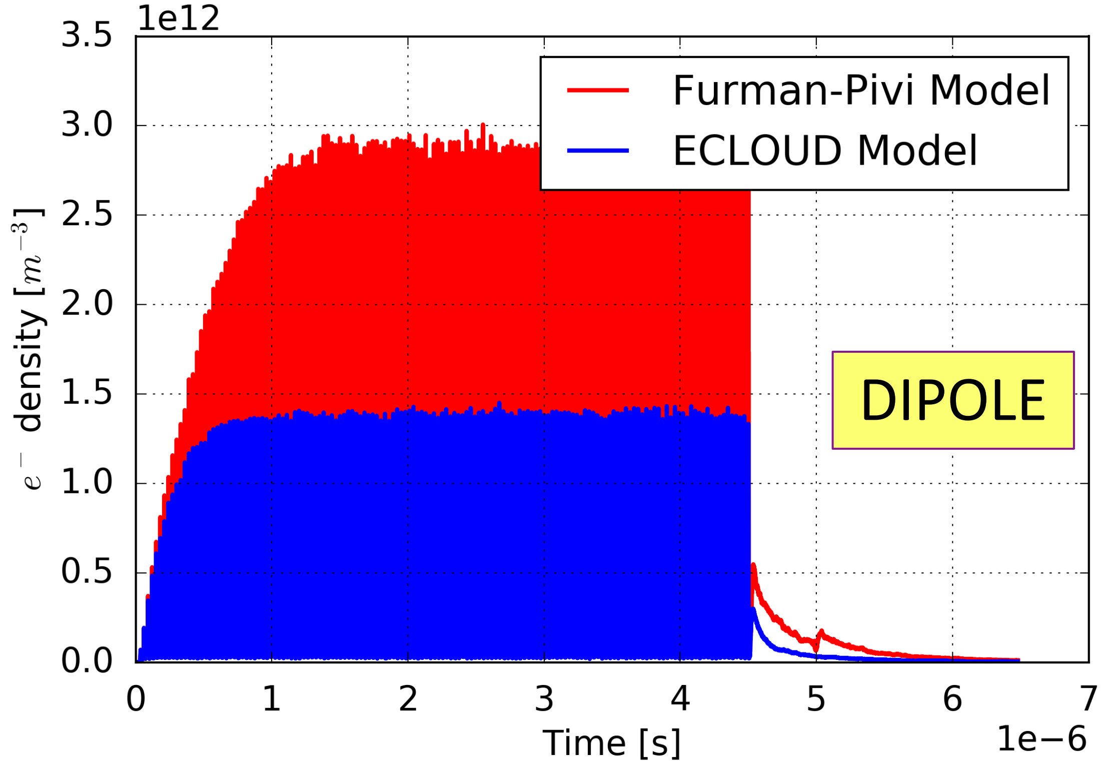


- exponential-like growth for 2 IPs parameters via Furman-Pivi model
- results via two SEY models agree for 4 IPs parameters

4 IPs max. densities for Drift and Dipole regions

SEY =1.4 , $n'_{(\gamma)}$ =1e-3 m^{-1} , bunch spacing: 30 ns

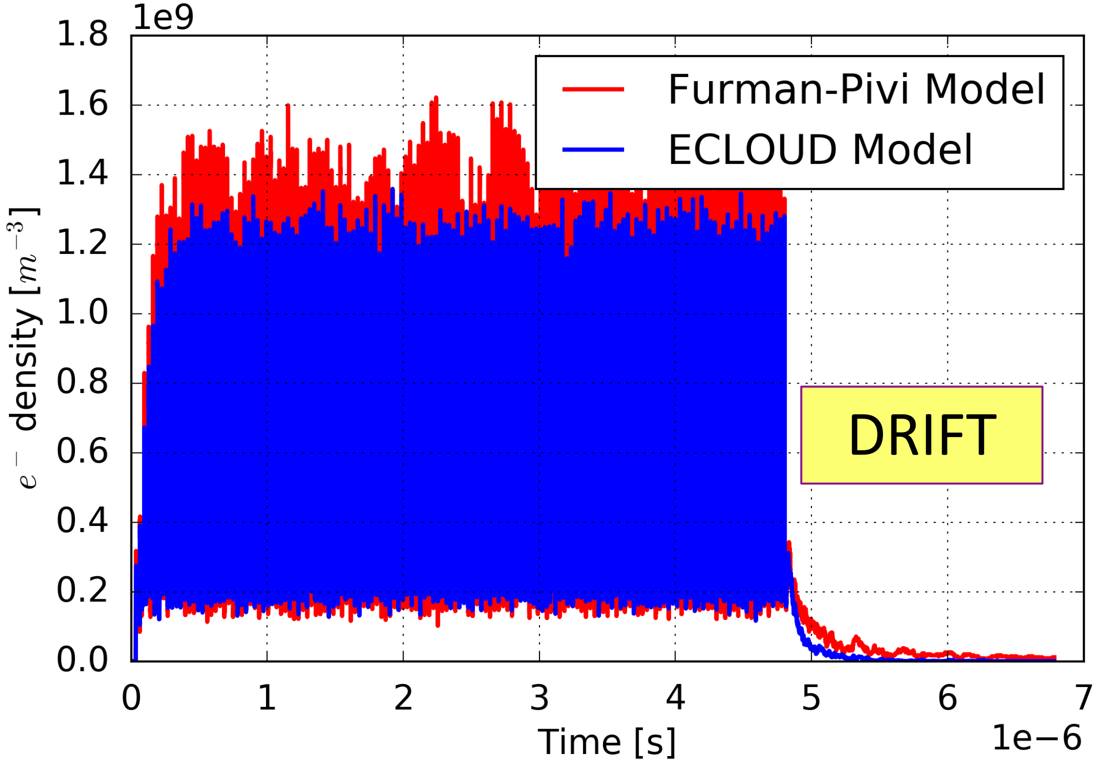


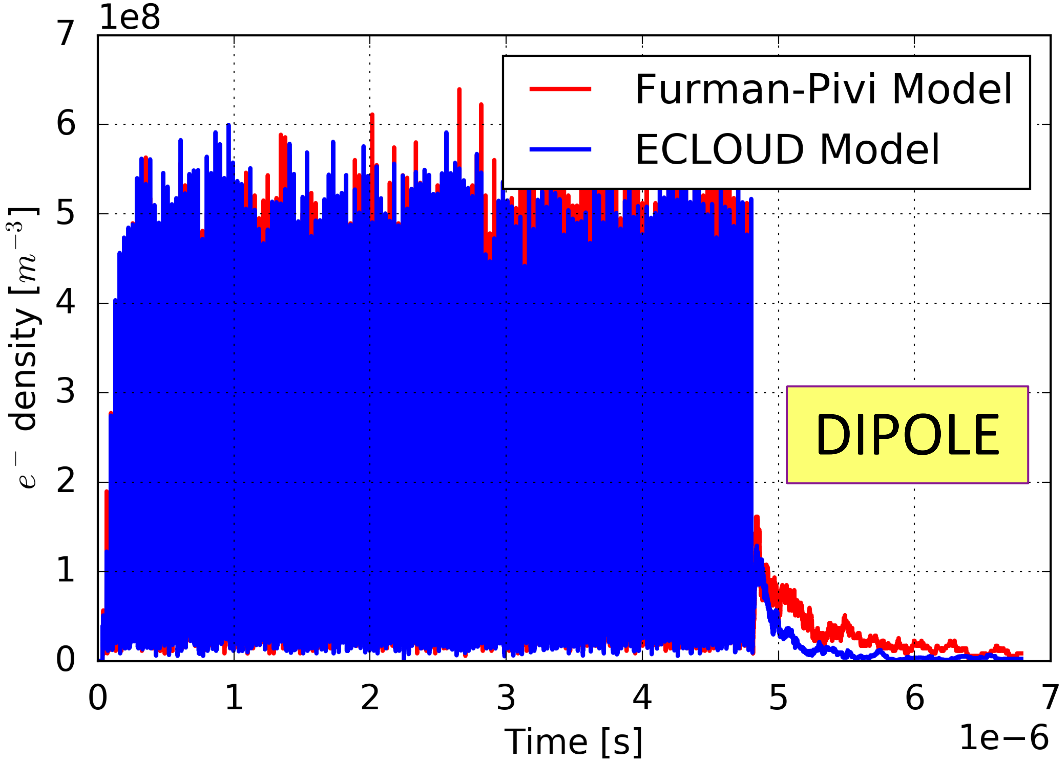


- computations via Furman-Pivi SEY model is more sensitive to external magnetic field
- ECLOUD SEY model may yield lower densities up to $\simeq$ 4 times

4 IPs min. densities for Drift and Dipole regions

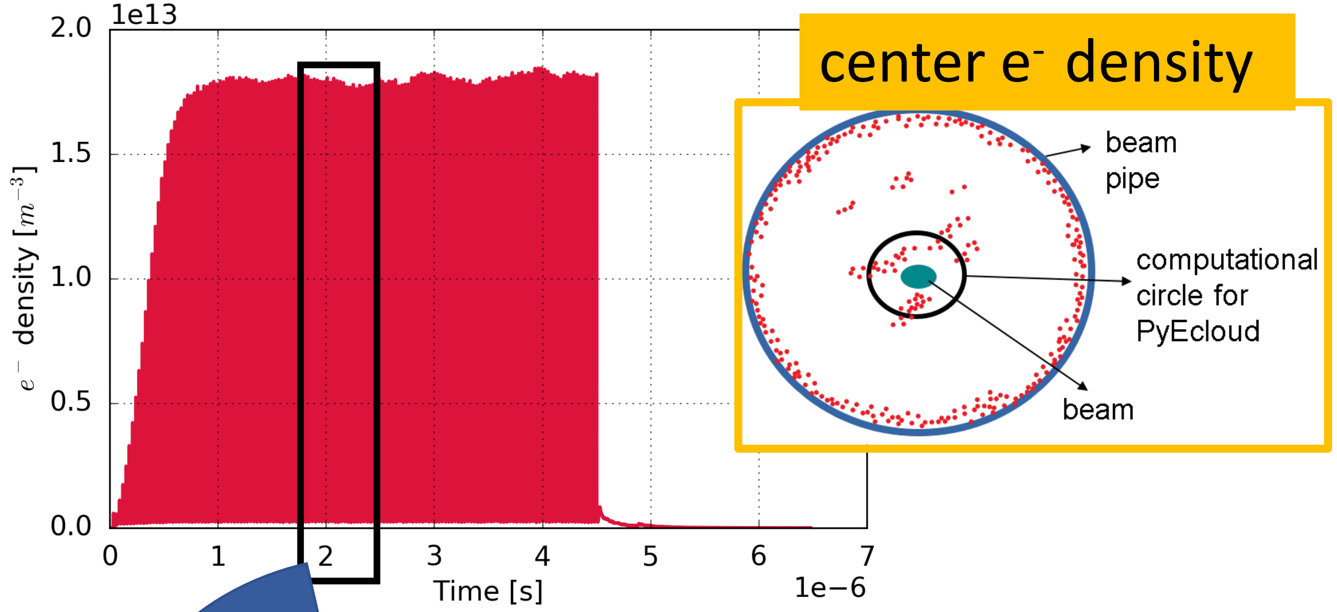
SEY =1.1 , $n'_{(\gamma)}$ =1e-6 m^{-1} , bunch spacing: 32 ns

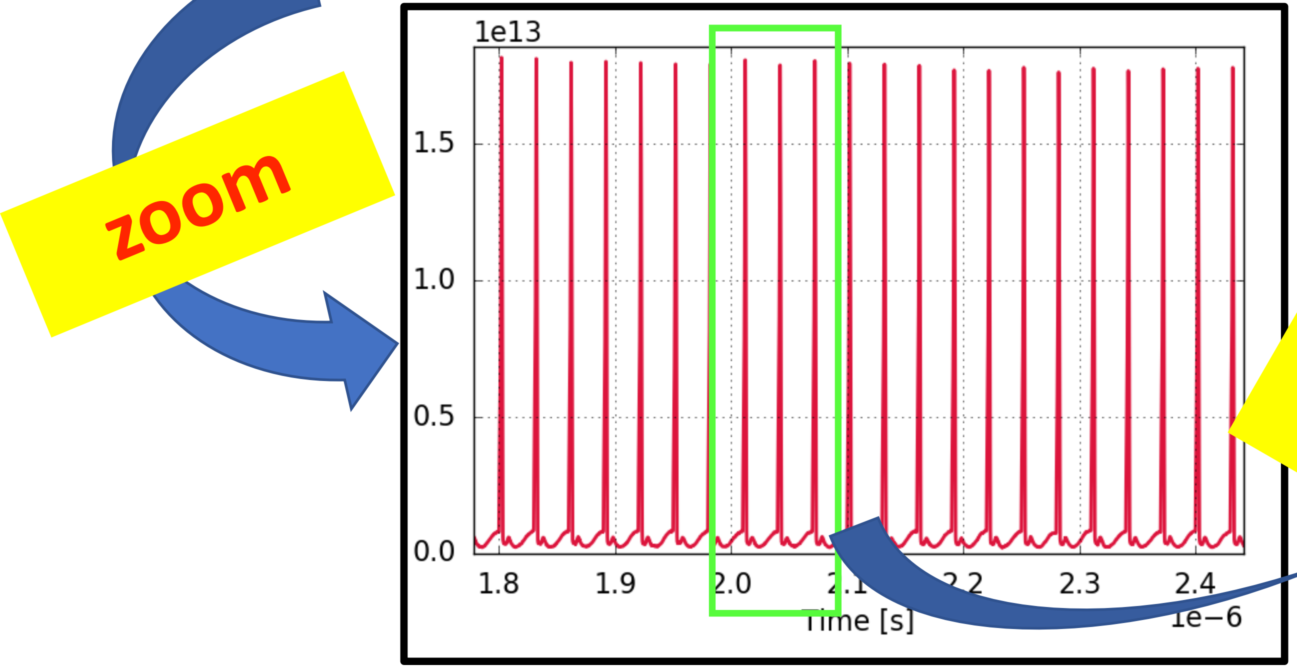


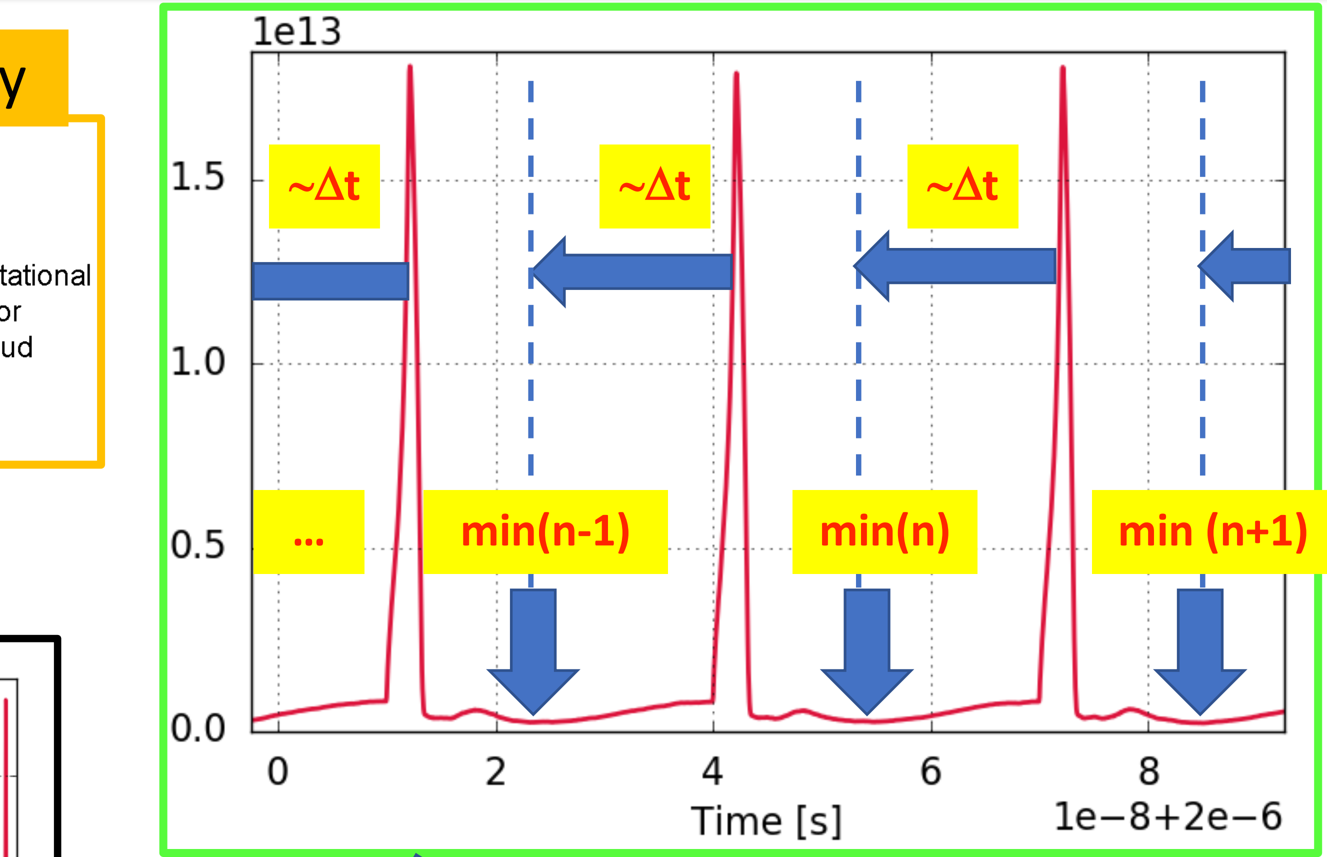


- both models yield similar results w.r.t. regions due to low SEY & PE (similar behaviours for 30ns bunch spacing)
- 0.01415 [T] external magnetic field ≃ 2.5 times lowers the densities for the weakest SEY & PE

Average of min.’s for center electron density

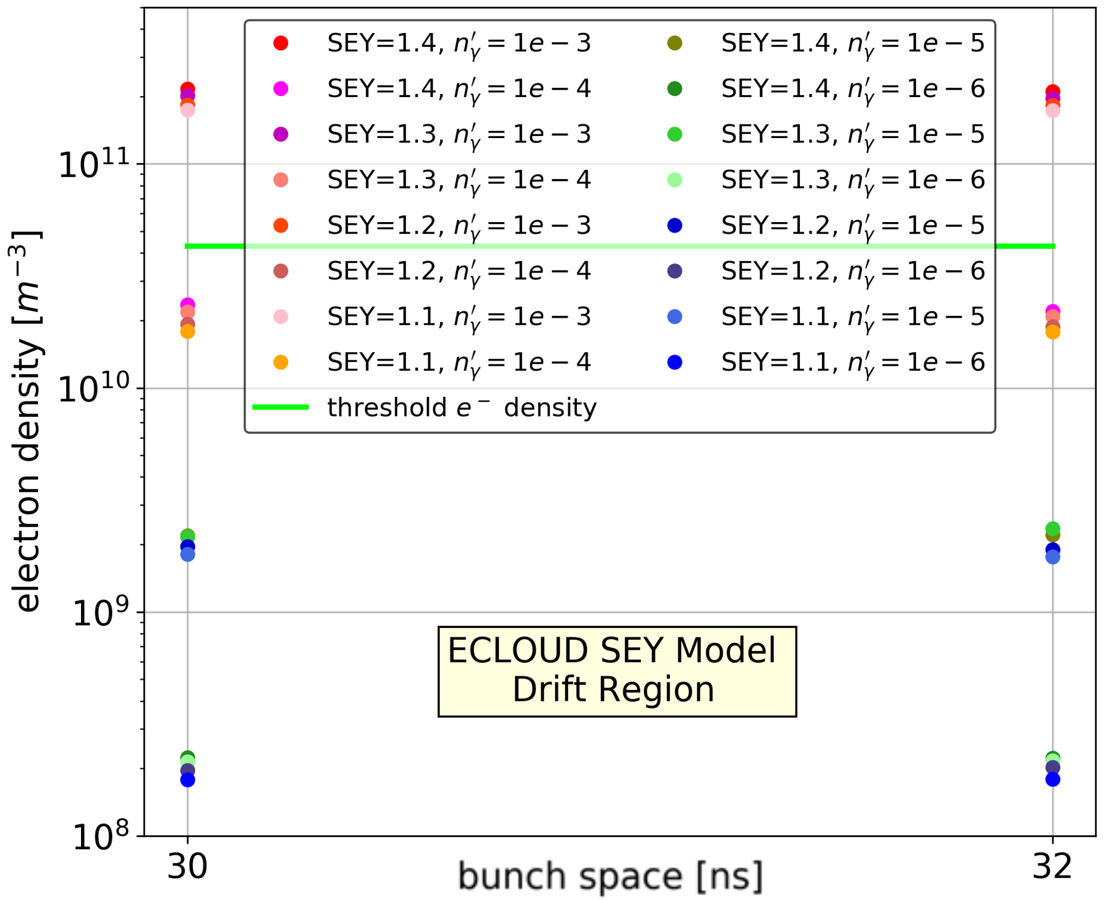


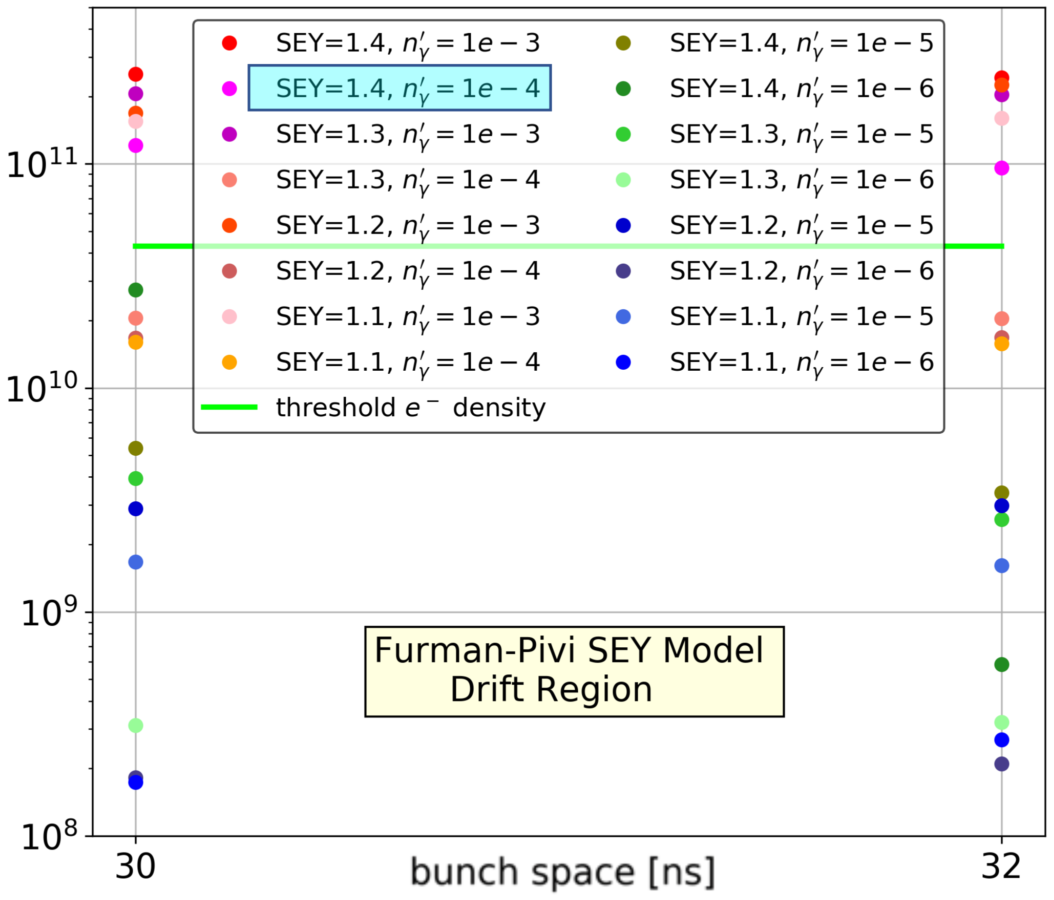




- max = 1.75e13 m^{-3}
- min = 2.25e11 m^{-3}
- average of min= 2.52e11 m^{-3} (Δt = 15.25 ns)

Threshold density and average min.'s for Drift

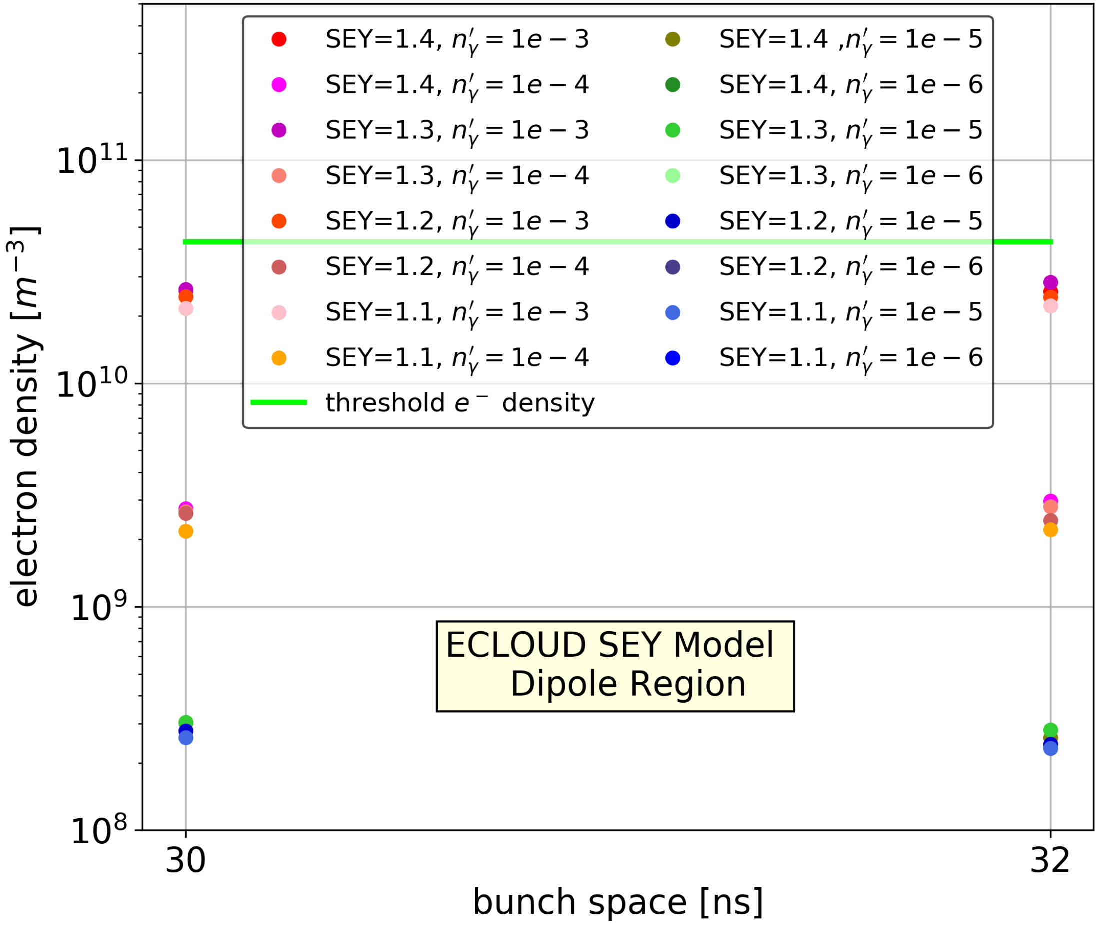


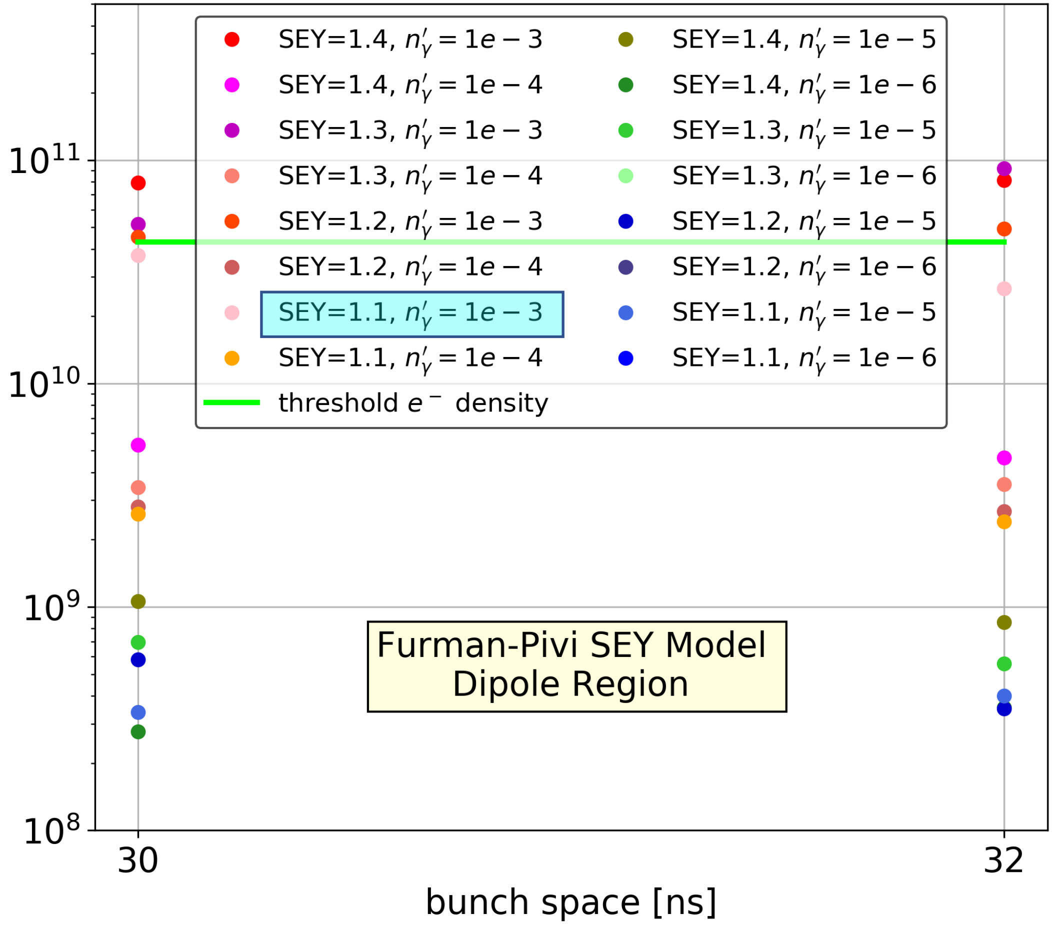


- $n'_{(\gamma)}$ < 1e-3 m^{-1} is necessary to keep average minimums lower than the threshold for both SEY models and bunch spacings
- ($n'_{(\gamma)}$ = 1e-4 m^{-1}, SEY = 1.4, Furman-Pivi Model) indicates set of parameters for a value larger than threshold for both bunch spacings

F.Yaman, G. Iadarola, R. Kersevan, S. Ogur, K. Ohmi, F. Zimmermann, M. Zobov, 'Mitigation of electron cloud effects in the FCC-ee collider, EPJ Tech. Inst., 9:9, 2022

Threshold density and average min.'s for Dipole





- all parametric scans using ECLOUD SEY model refer values lower than the estimated threshold
- $n'_{(\gamma)}$ < 1e-3 m^{-1} is necessary to keep average minimums lower than the threshold for Furman-Pivi model (exceptional case: $n'_{(\gamma)}$ = 1e-3 m^{-1} , SEY=1.1)

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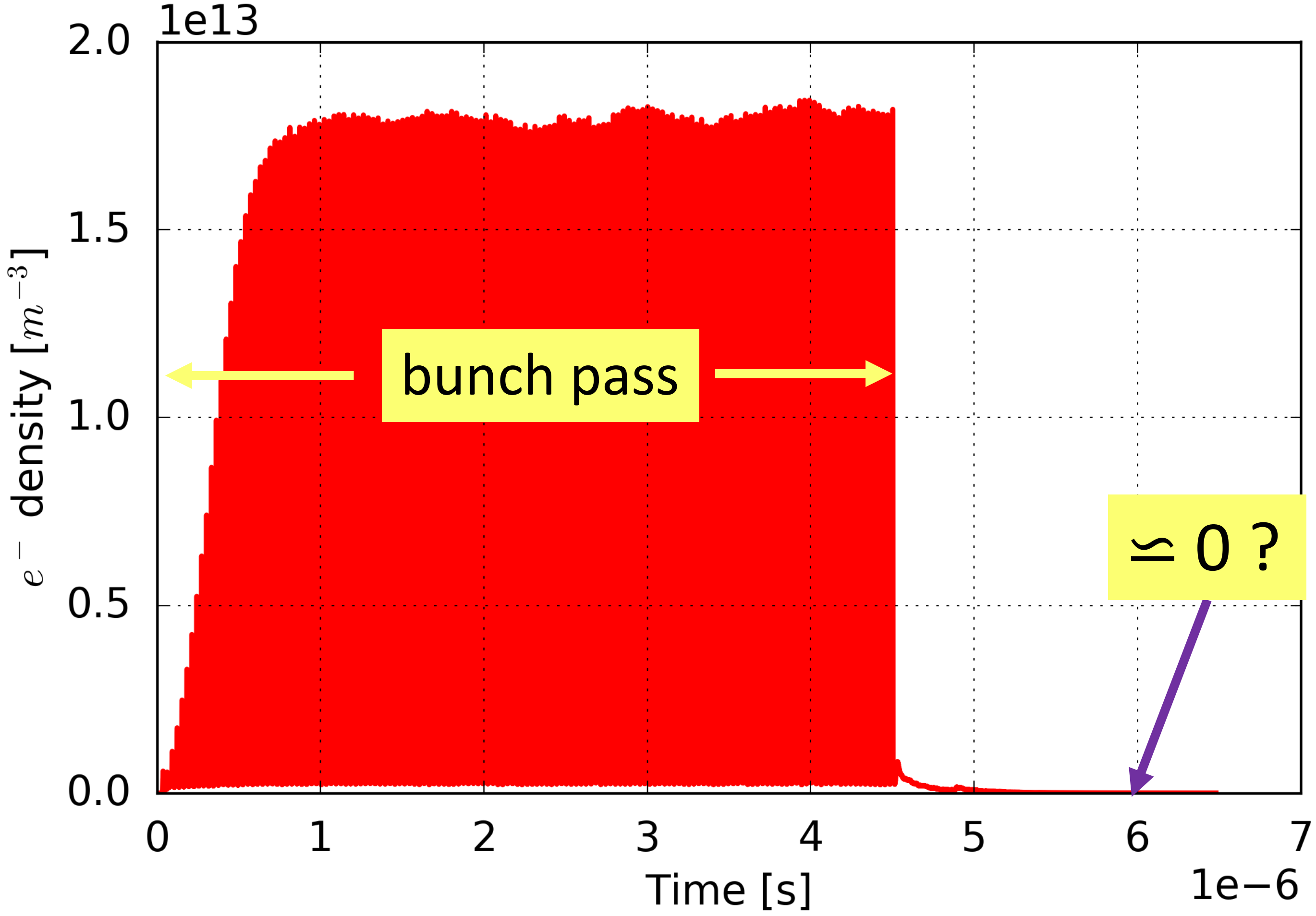
Electron Cloud Mitigation

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

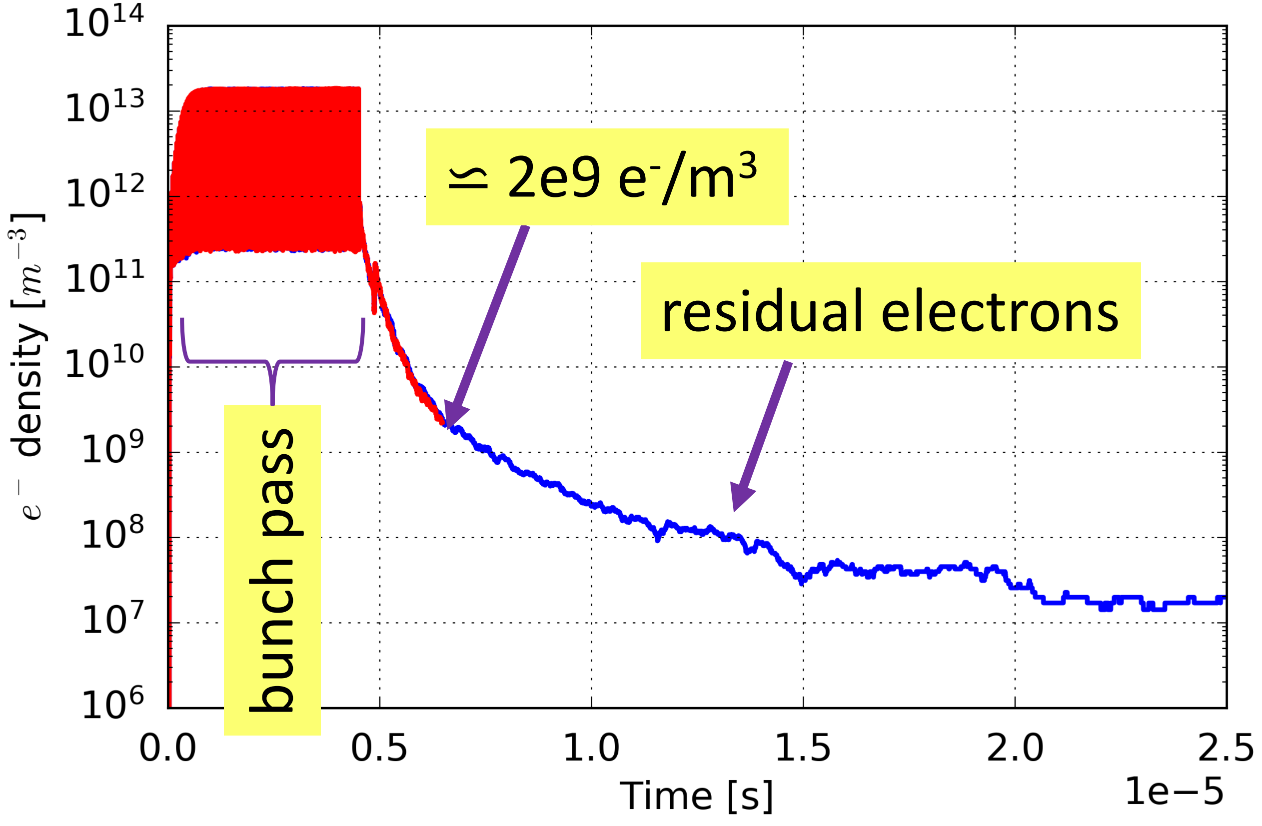
bunch spacing: 30 ns, Furman-Pivi Model, Drift Region

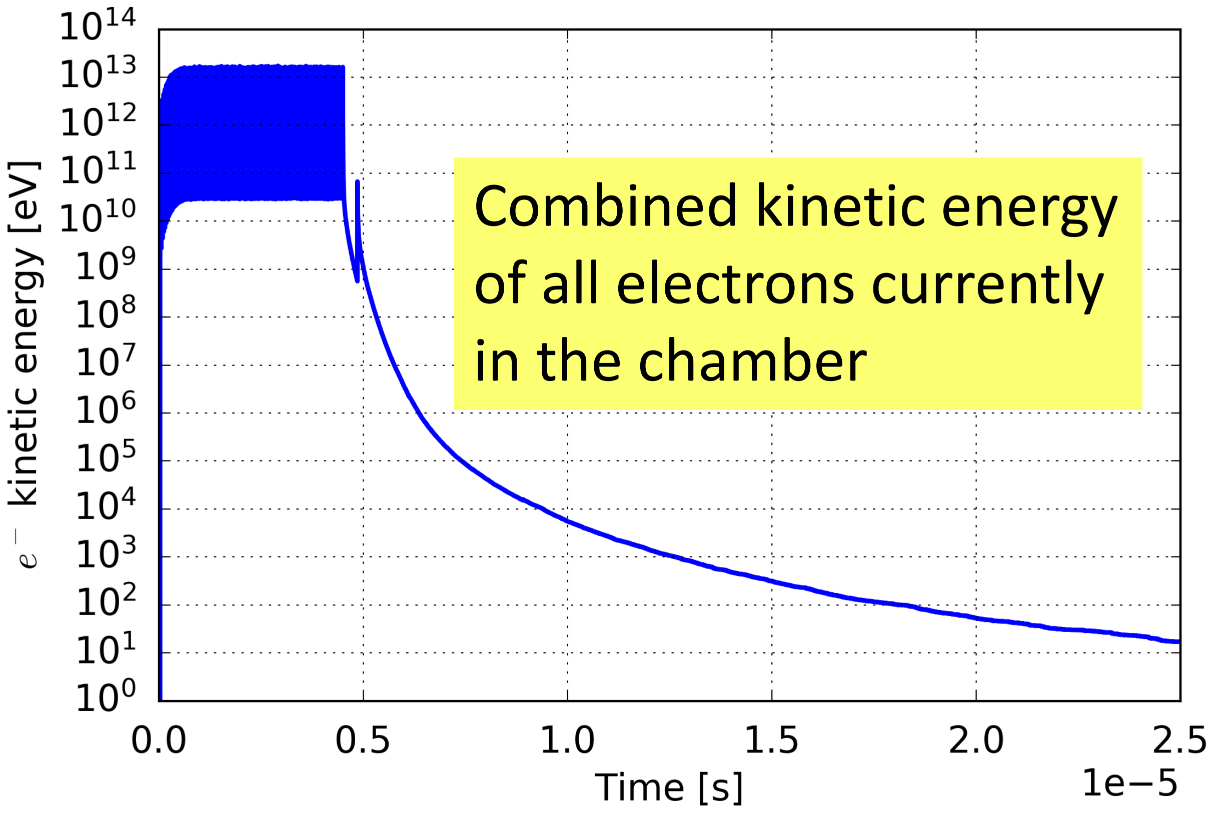


Electron Cloud Mitigation

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

bunch spacing: 30 ns, Furman-Pivi Model, Drift Region

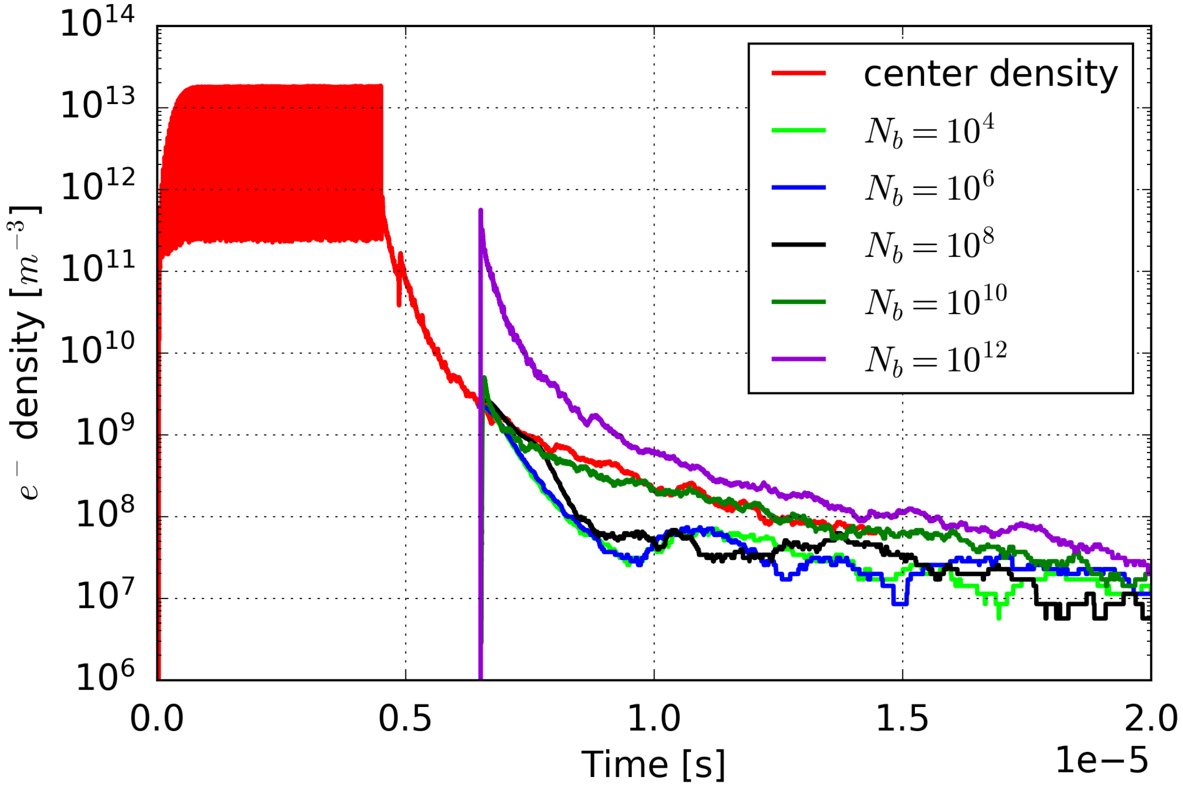


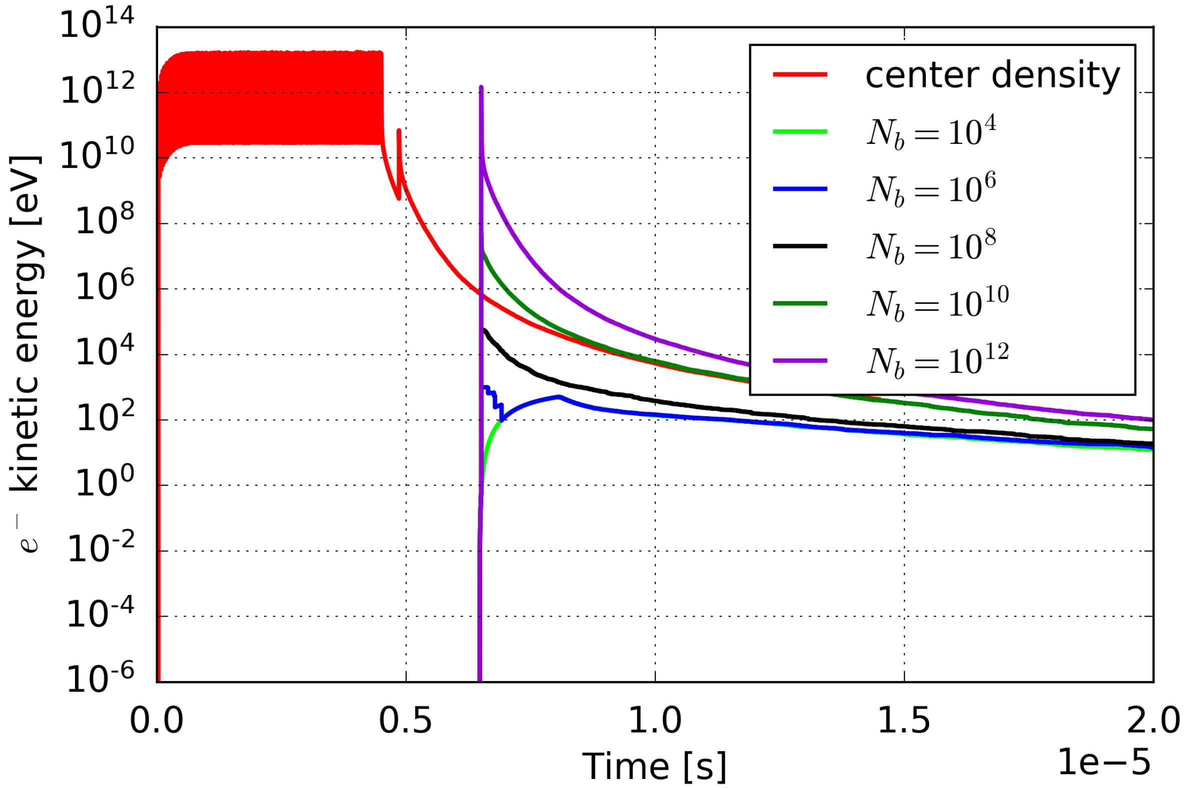


Mitigation tests via single trailing bunch

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

bunch spacing: 30 ns, Furman-Pivi Model, Drift Region



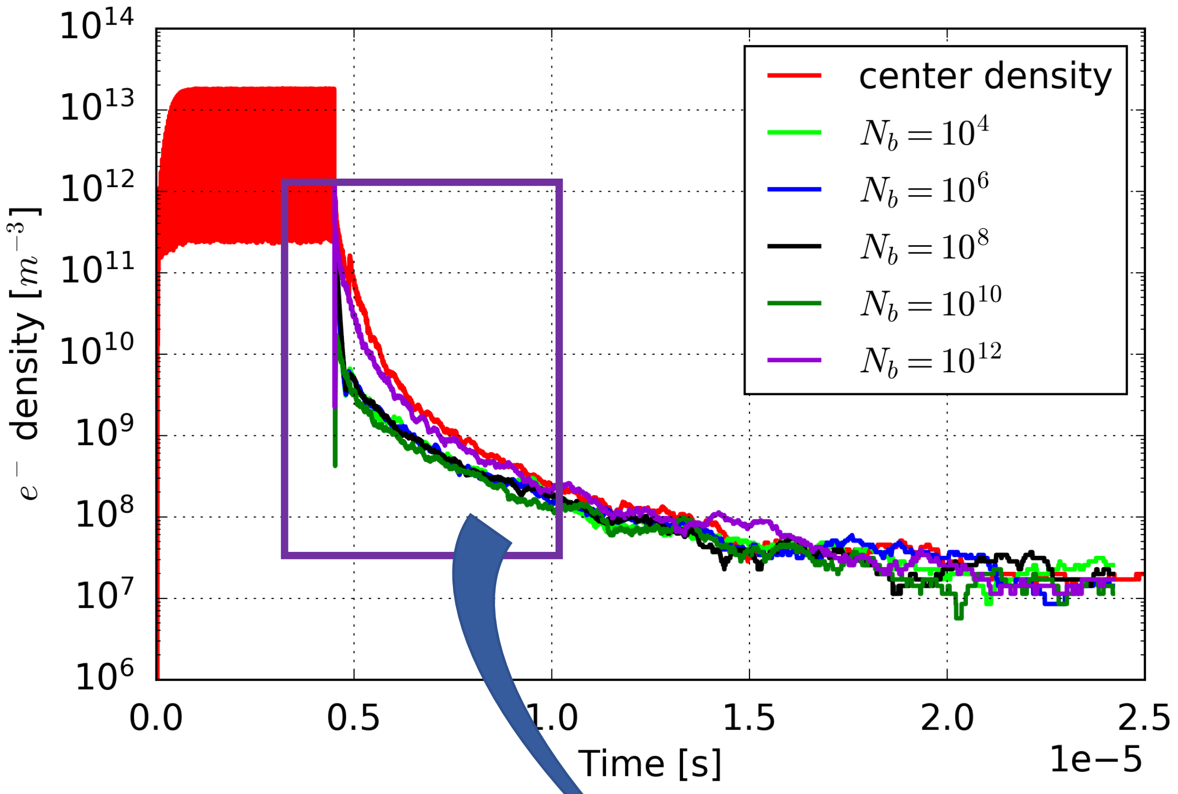


Clearing the residual electrons via low-charge trailing bunch

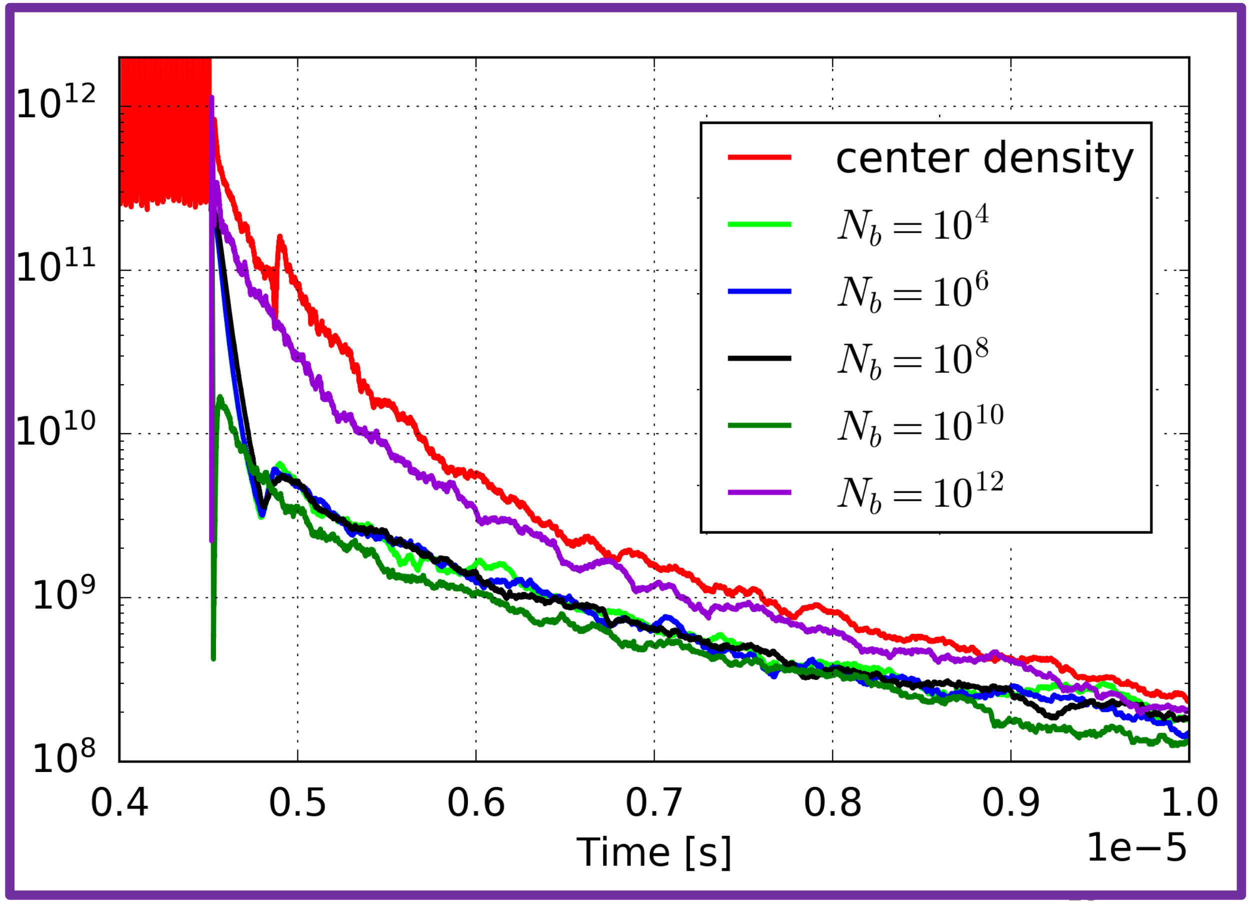
private communication with S. Veitzer (Tech-X), July 2021

Mitigation tests via single trailing bunch

SEY =1.4 , $n'_{(\gamma)}$ =1e-3 m^{-1} ,
bunch spacing: 30 ns,
Furman-Pivi Model, Drift Region



zoom



Conclusions and Future Plans

- 4IPs parameters & (30ns, 32ns) bunch spacing relax Ecloud build up
- $\backsimeq$ [6e8 - 1.75e13] m^{-3} center electron density values for 4IPs parameter scope
- Simulations are performed in the realistic photon flux regimes
- $n'_{(\gamma)}$ < 1e-3 m^{-1} is necessary to keep average minimums lower than the estimated threshold for both SEY models, bunch spacings, dipole & drift regions
- In Drift Region a particular case for both bunch spacings : ($n'_{(\gamma)}$ = 1e-4 m^{-1}, SEY = 1.4, FP) indicates set of parameters for a value larger than threshold
- Clearing the residual electrons
- Verification of Wakefield calculations, Impedance calculations
- Simulations with the measured SEY data

THANK YOU FOR ATTENTION!

fatihyaman@iyte.edu.tr