Recent Advances on the FCC-ee Electron Cloud Build-up Studies

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Many Thanks: *Giovanni Iadarola, Roberto Kersevan, Salim Ogur, Kazuhito Ohmi and Mikhail Zobov*

Acknowledgments: *the FCC-ee optics team*

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Outline

- FCC-ee machine & beam parameters for the simulations
- Overview of SEY Models & Simulation Tools
- FCC-ee Collider Arc Dipole (4IPs) Build-up Results
- Preliminary Wakefield Results
- Conclusions & Future Plans

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)

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

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

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

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

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}

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

$Y_\gamma \approx 0.1$

$\frac{5 \alpha \gamma}{2\sqrt{3}\rho}$: 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 $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

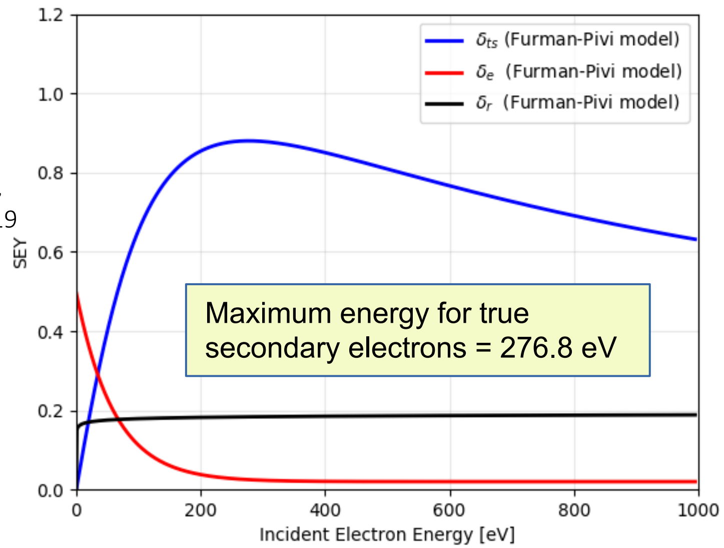
$$\delta_e(E_0,\theta_0) = \delta_e(E_0,\theta_0=0)[1+e_1(1-\cos^{e_2}\theta_0)]$$
$$\delta_r(E_0,\theta_0) = \delta_r(E_0,\theta_0=0)[1+r_1(1-\cos^{r_2}\theta_0)]$$
$$\delta_{ts}(E_0,\theta_0) = \hat{\delta}(\theta_0)D(E_0/\hat{E}(\theta_0)),$$

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

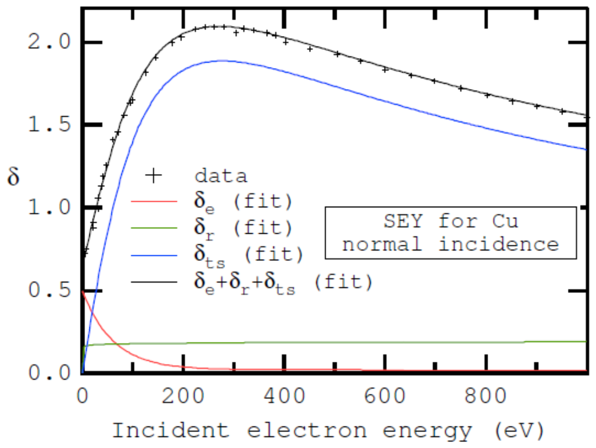
[a]Note that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

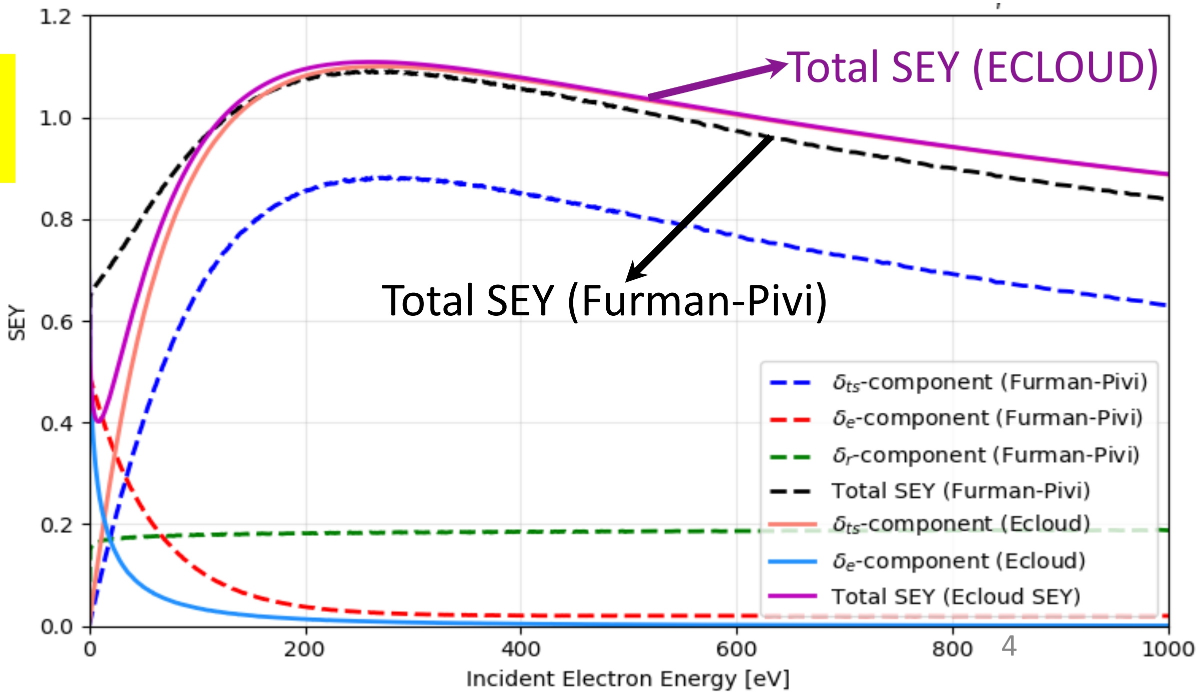
1.1 0.88 0.02 0.2

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 Tools: PyECLOUD, CST

PyECLOUD

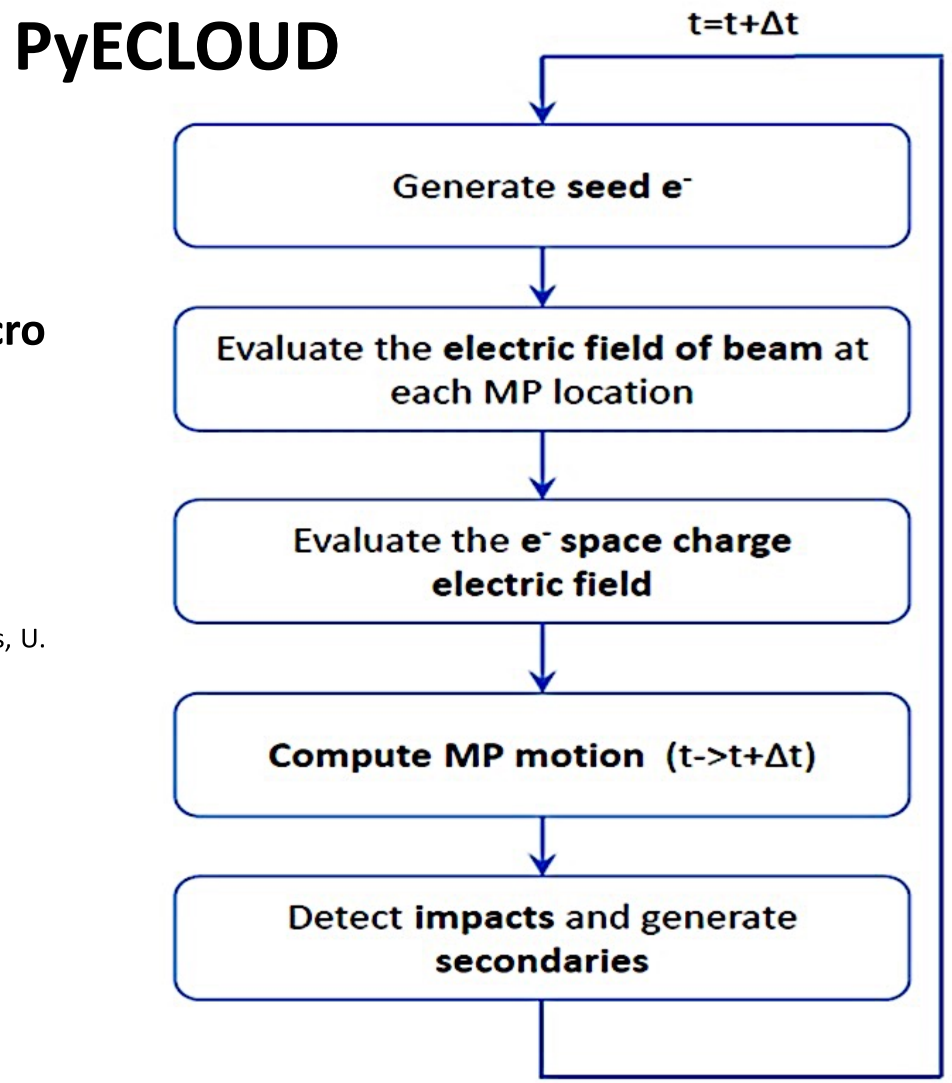
- **2D Electrostatic PIC simulation**
- **effects of space charge and secondary electrons are included**
- **adaptive scheme to control the number of electrons per macro particle during the simulation**
- **ECLOUD and Furman-Pivi SEY models**

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).

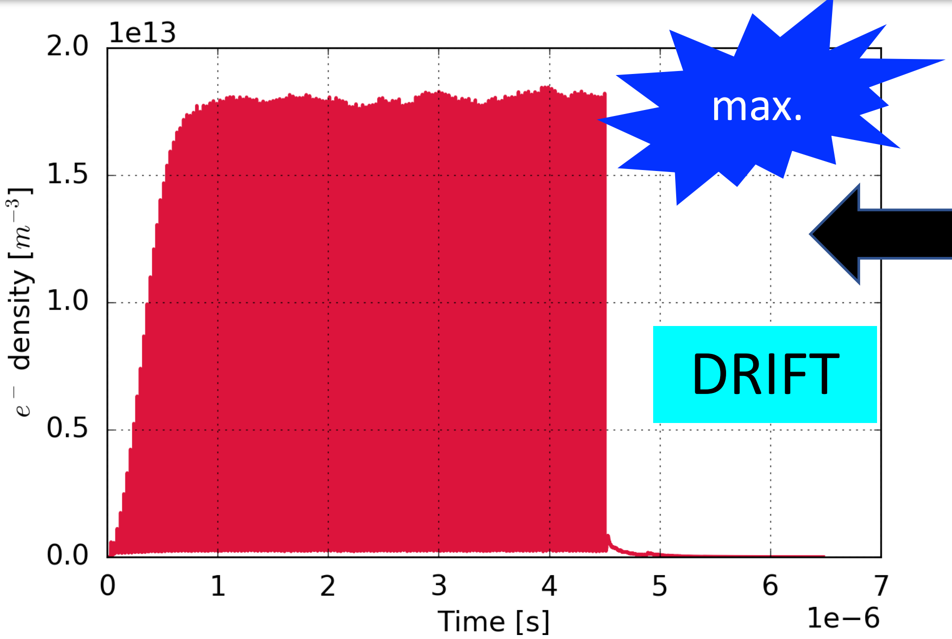
CST-PS

- **3D Electromagnetic PIC simulation**
- **effects of space charge and secondary electrons are included**
- **Furman-Pivi SEY model**
- **Photoemission mechanism is not included in this work**



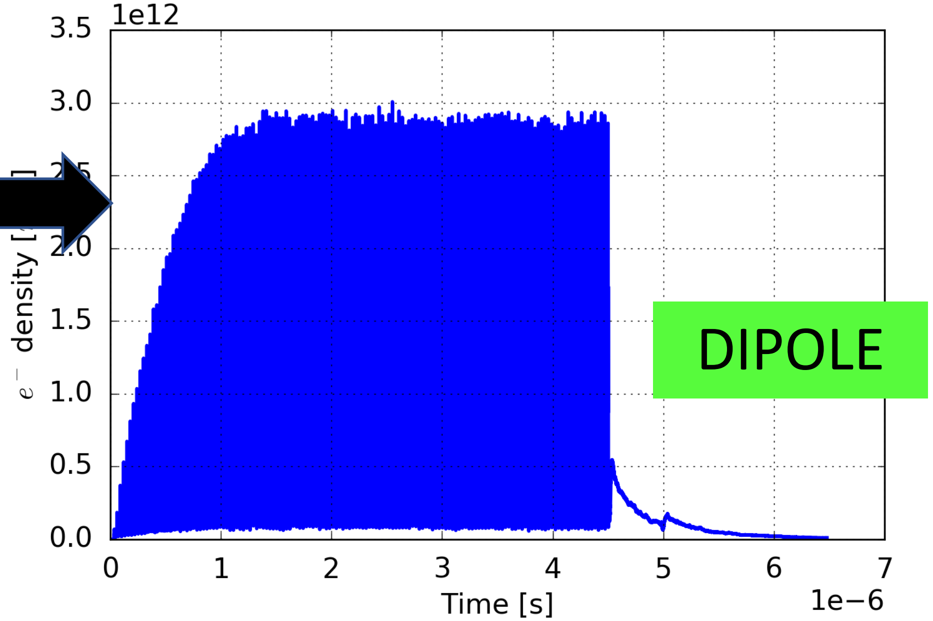
with the courtesy of G. Iadarola

Center e⁻ density, min. max. values

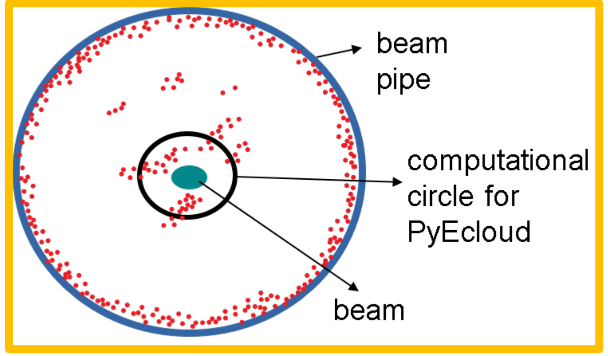


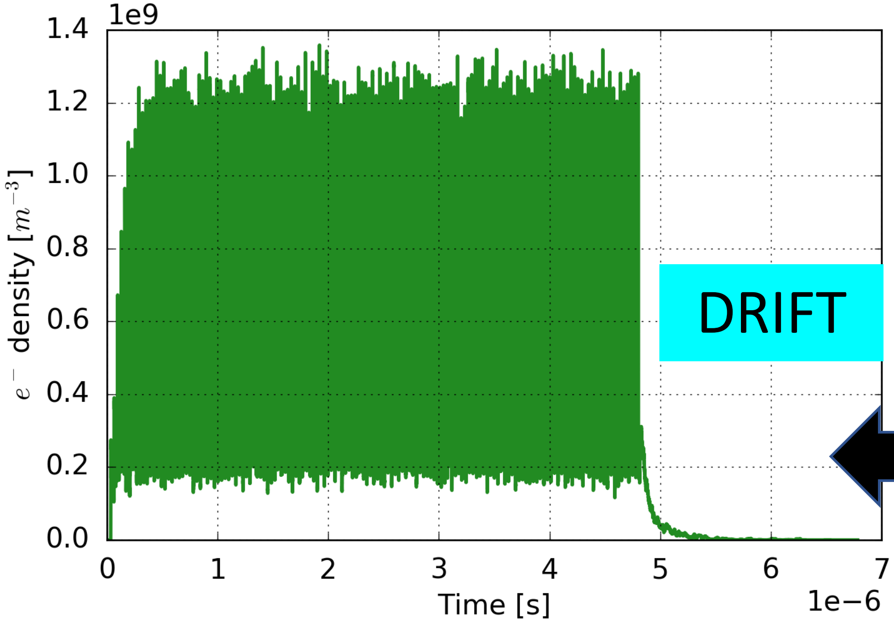
- BS: 30 [ns]
- FP SEY

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



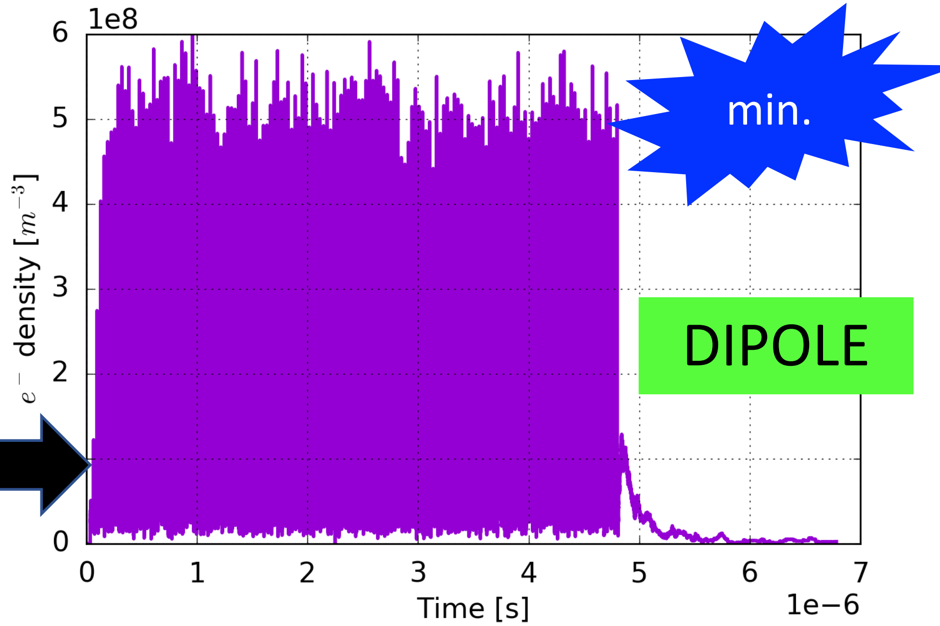
center e⁻ density



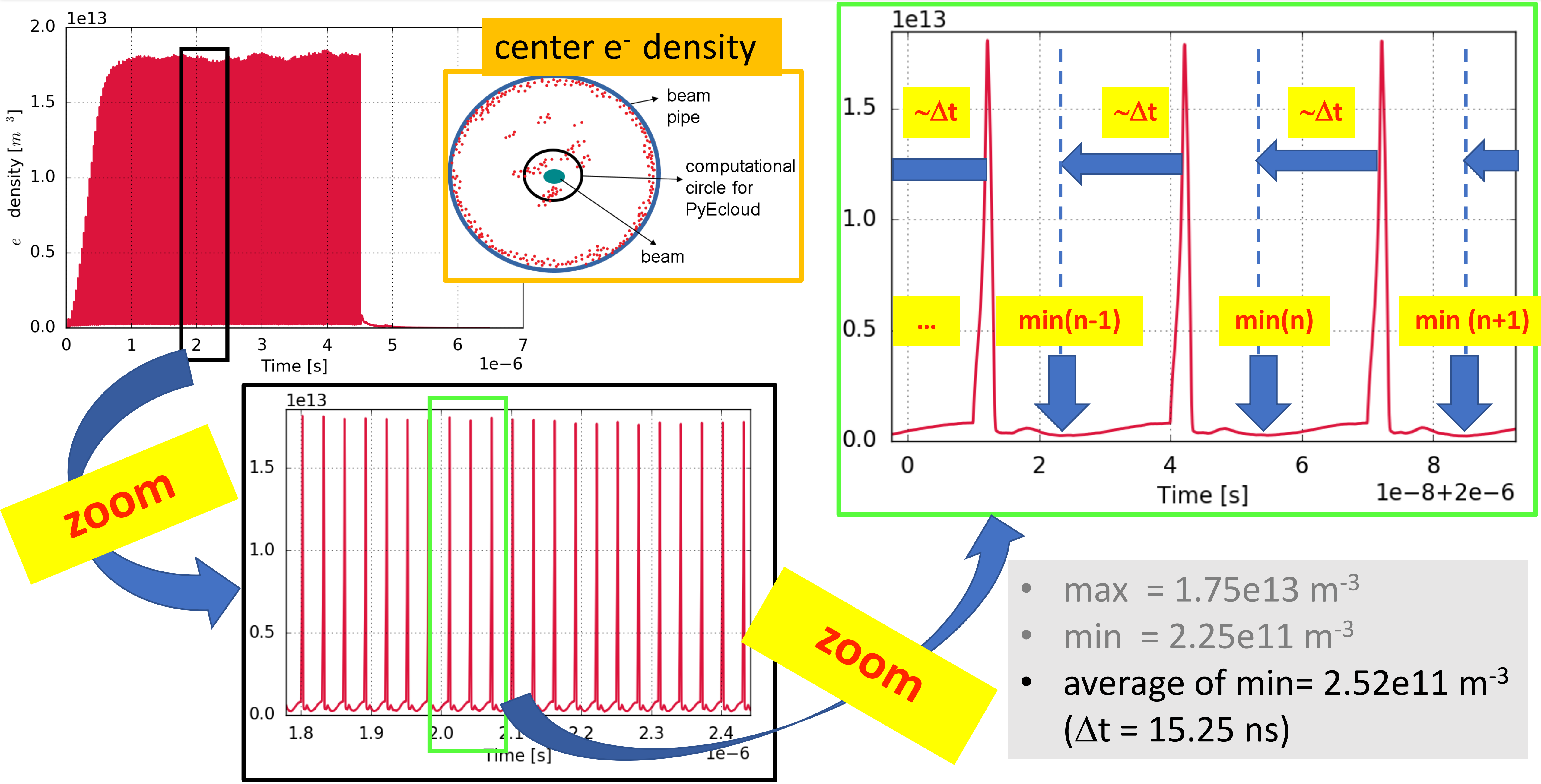


- BS: 32 [ns]
- ECLOUD SEY

  SEY=1.1
- $n'_{(\gamma)}$ =1e-6 [m⁻¹]



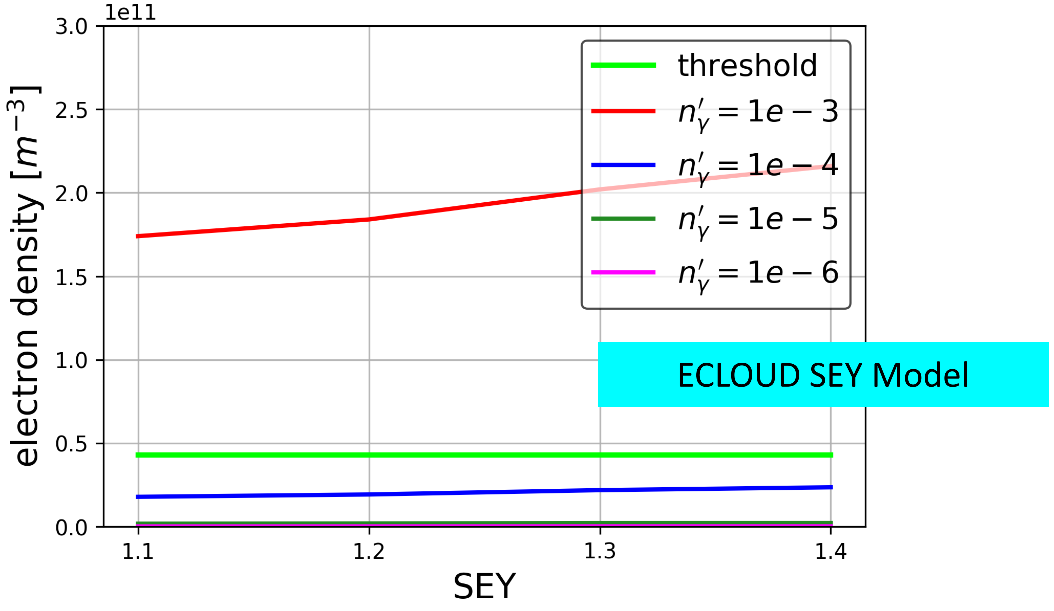
Average of minimum's for center electron density

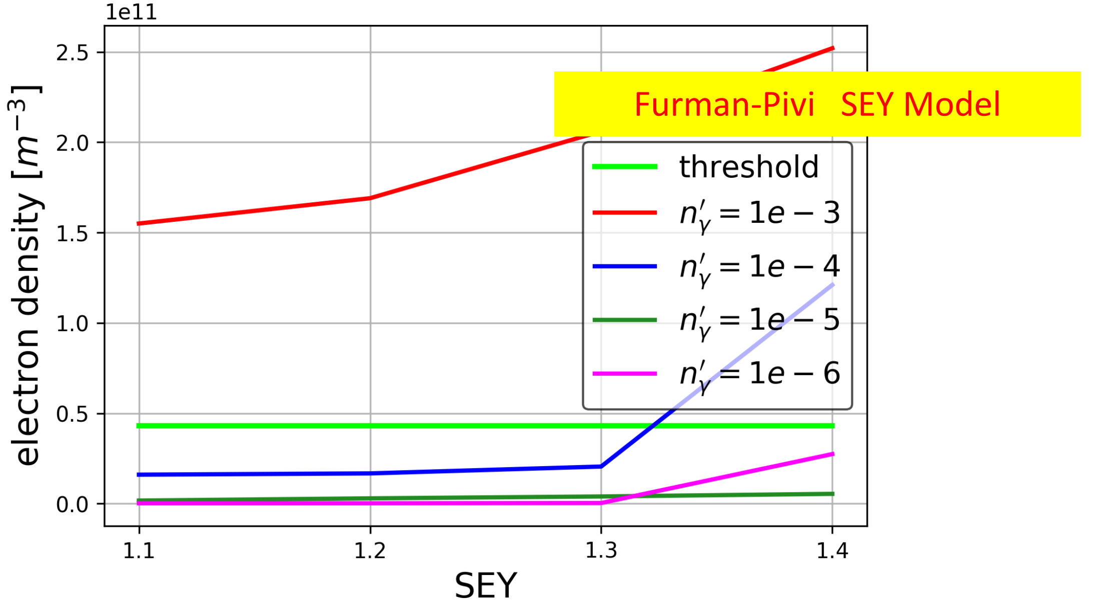


- max = 1.75e13 m^{-3}
- min = 2.25e11 m^{-3}
- average of min= 2.52e11 m^{-3} (Δt = 15.25 ns)

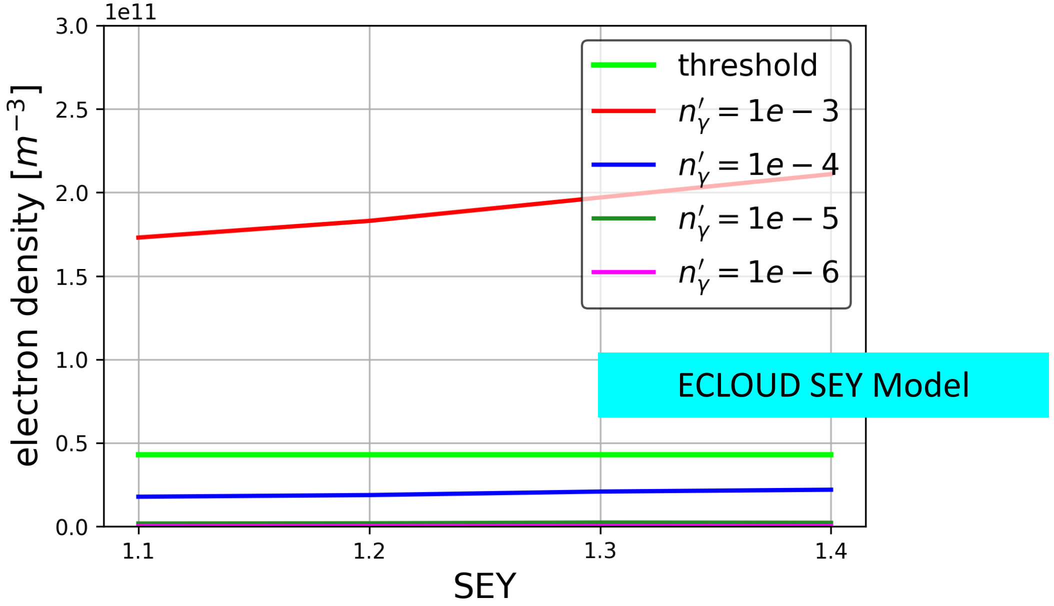
Average of min. for center e⁻ density, FCCee Collider Drift

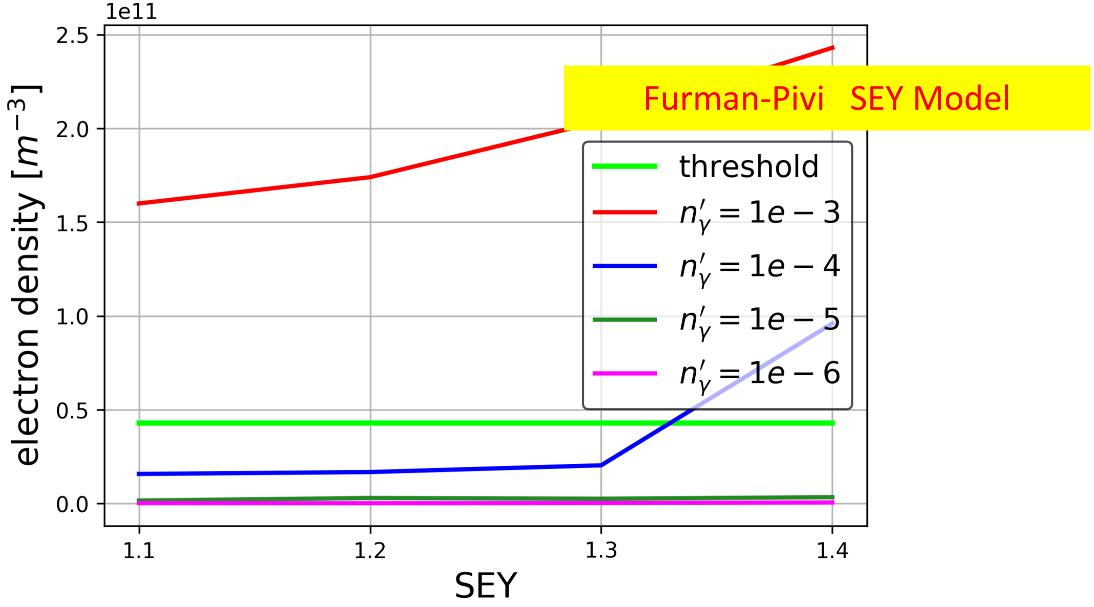
bunch space : 30 [ns]





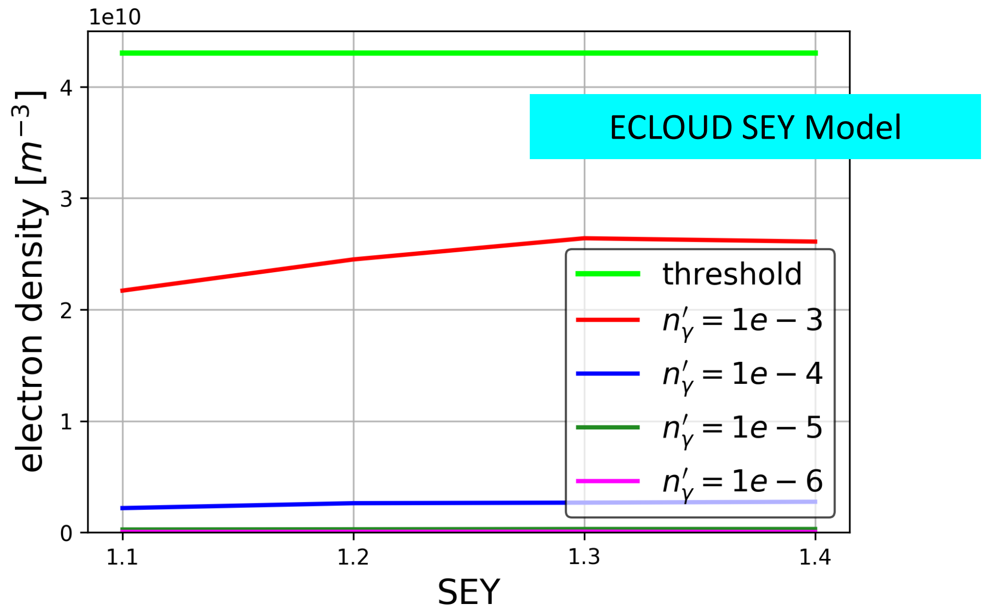
bunch space : 32 [ns]

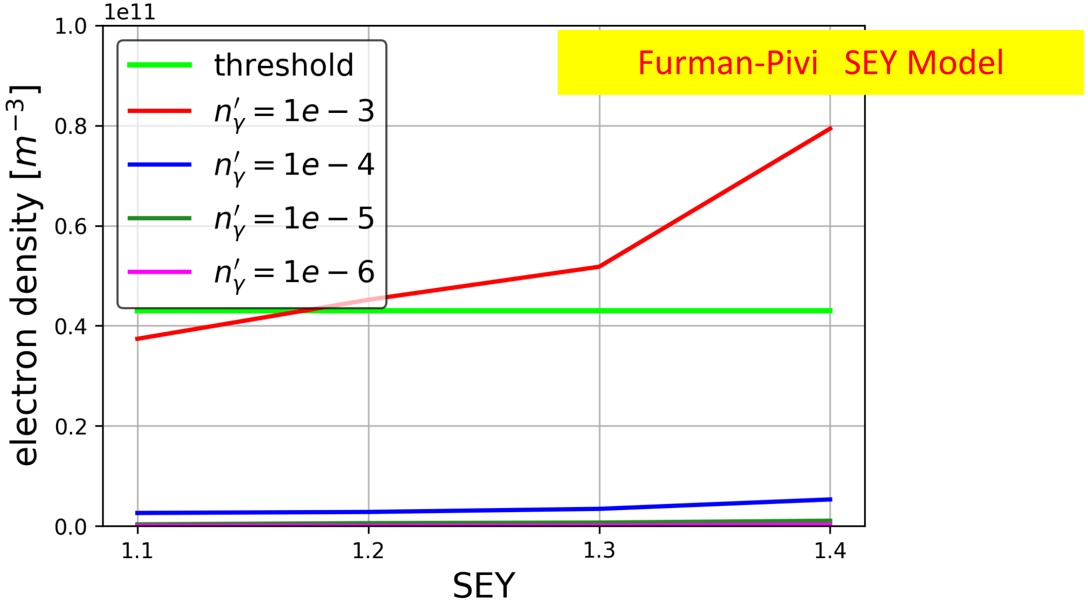




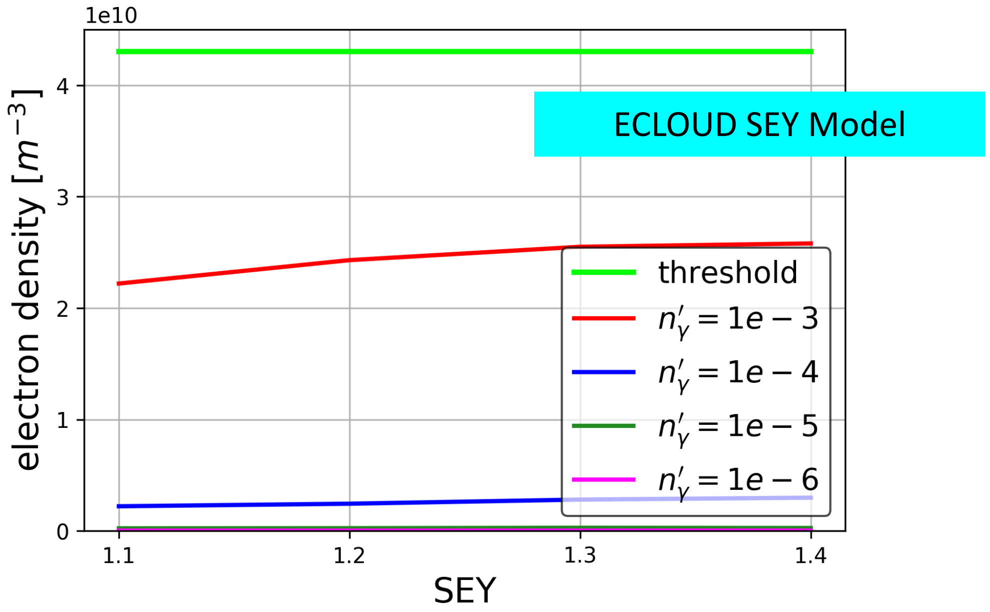
Average of min. for center e⁻ density, FCCee Collider Arc Dipole

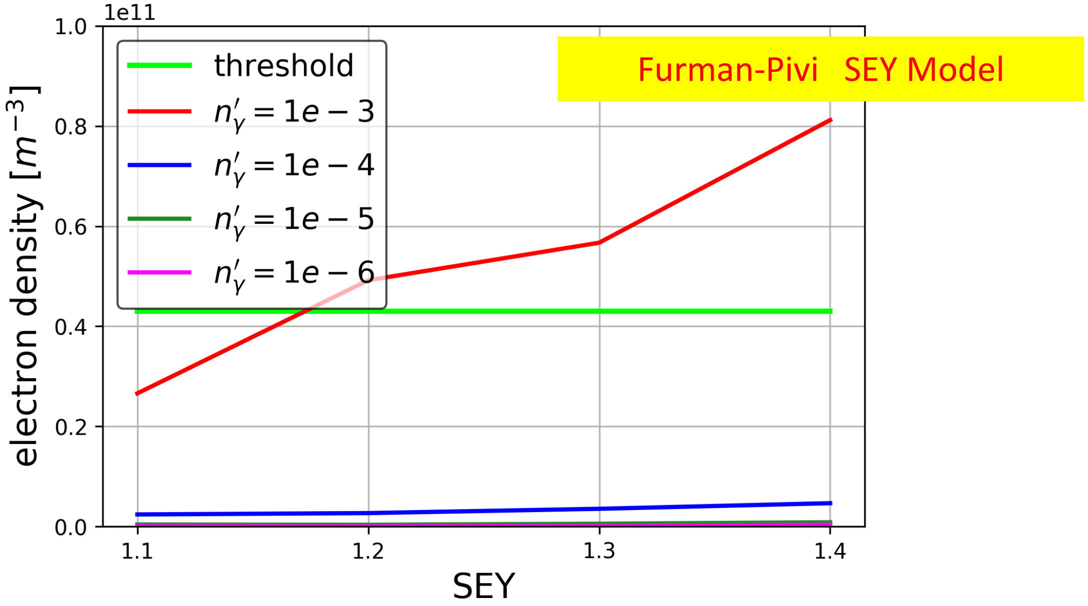
bunch space : 30 [ns]



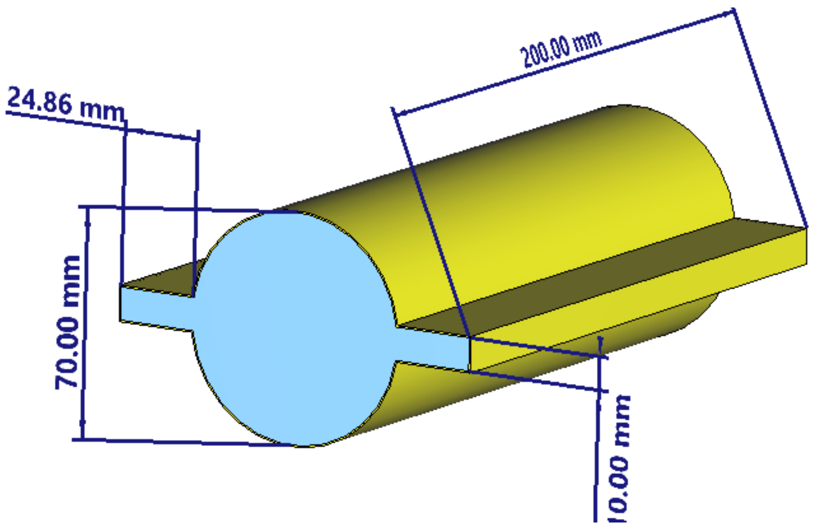


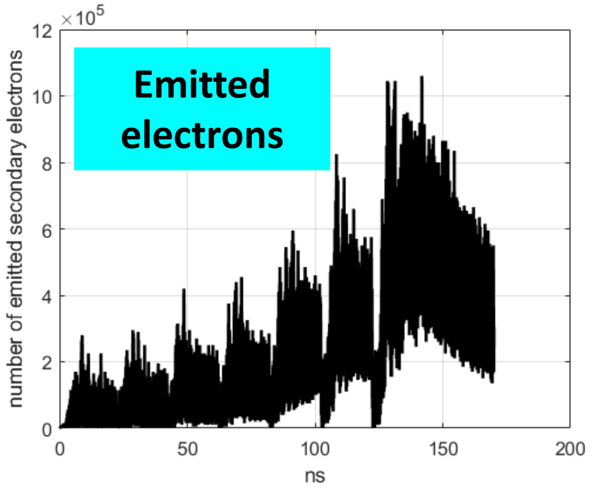
bunch space : 32 [ns]



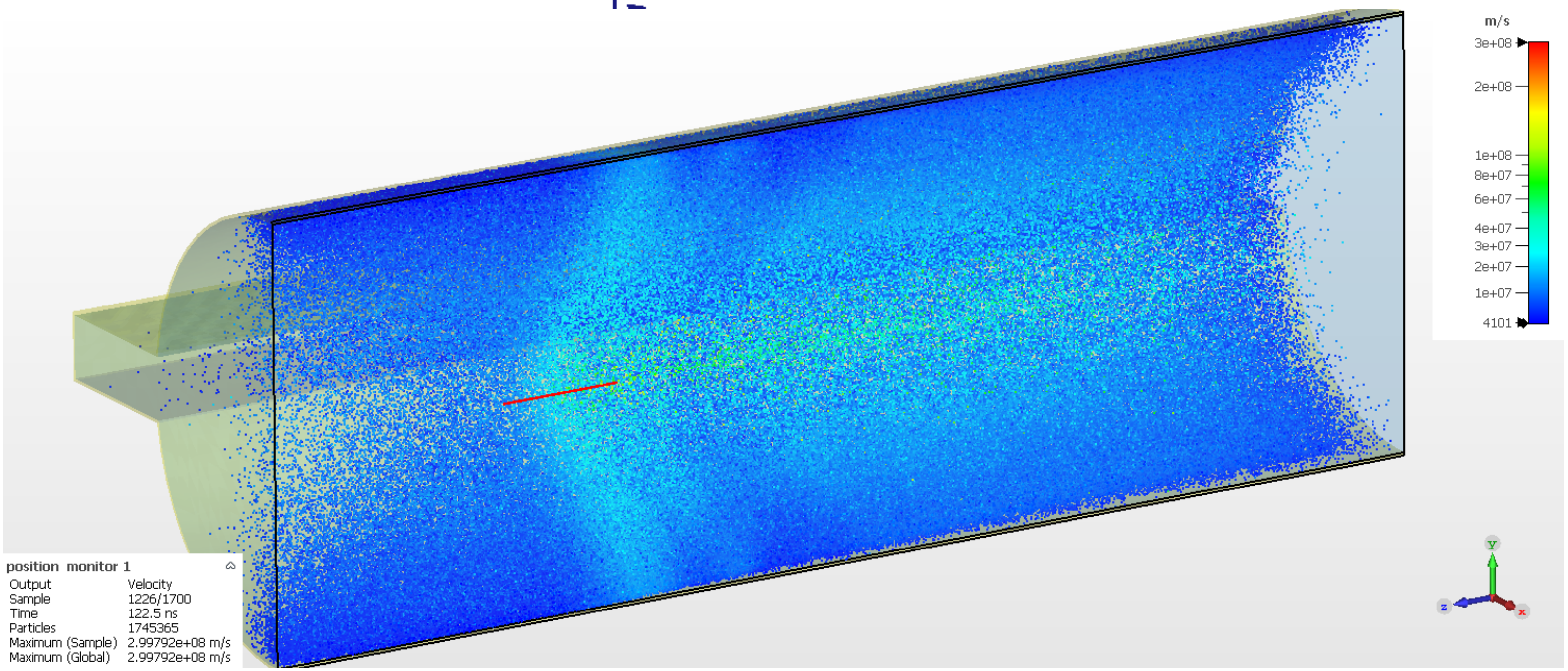


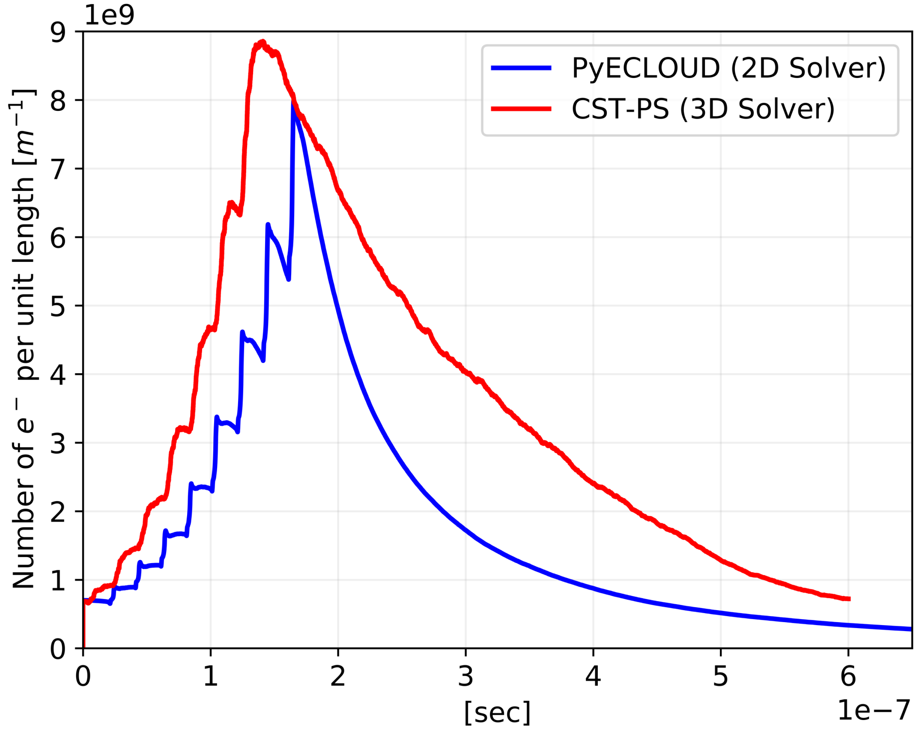
Electron Cloud Build-up Simulations with CST-PS





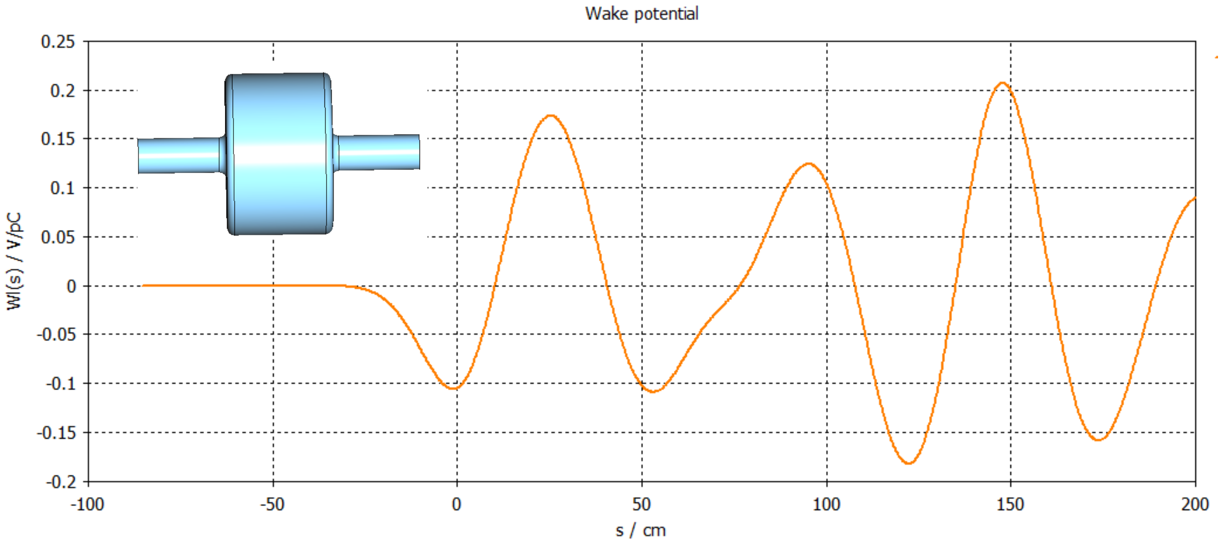
FCCee 2IPs Arc Dipole test (circular beam pipe)





Wakefield computations with CST: RF Cavity Analogy

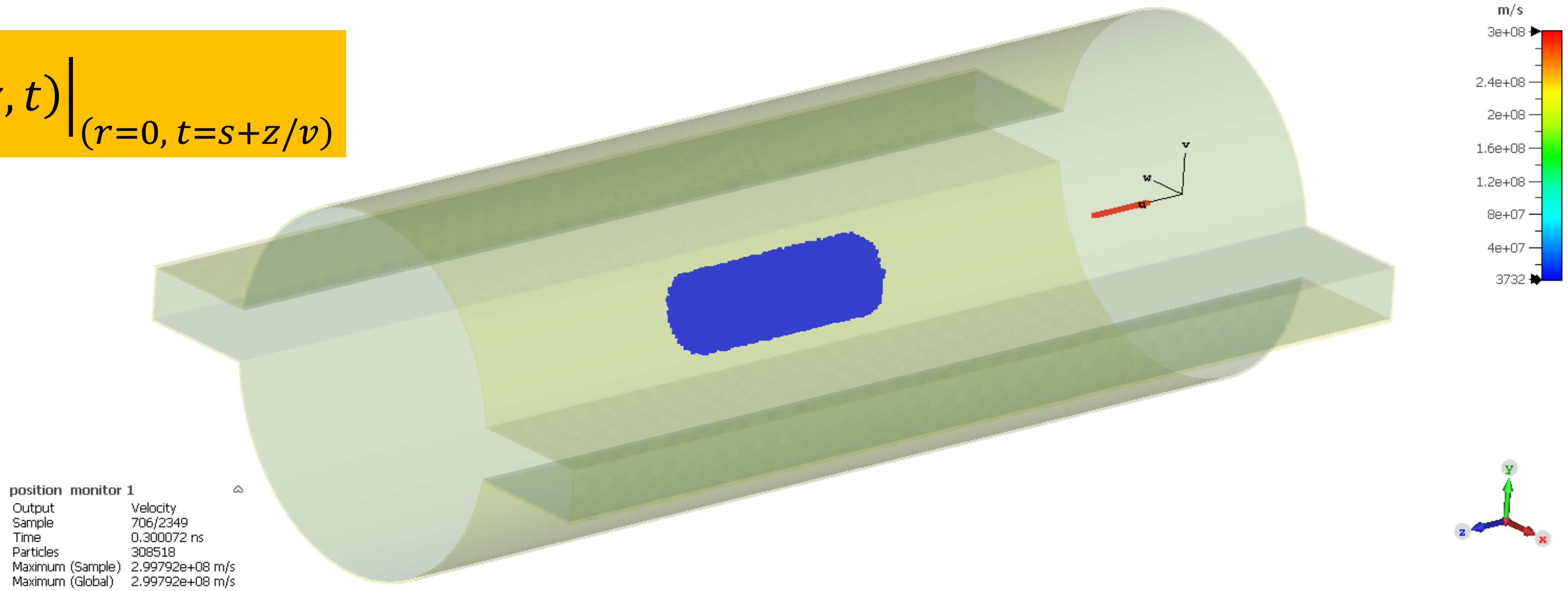
a typical RF Cavity example



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

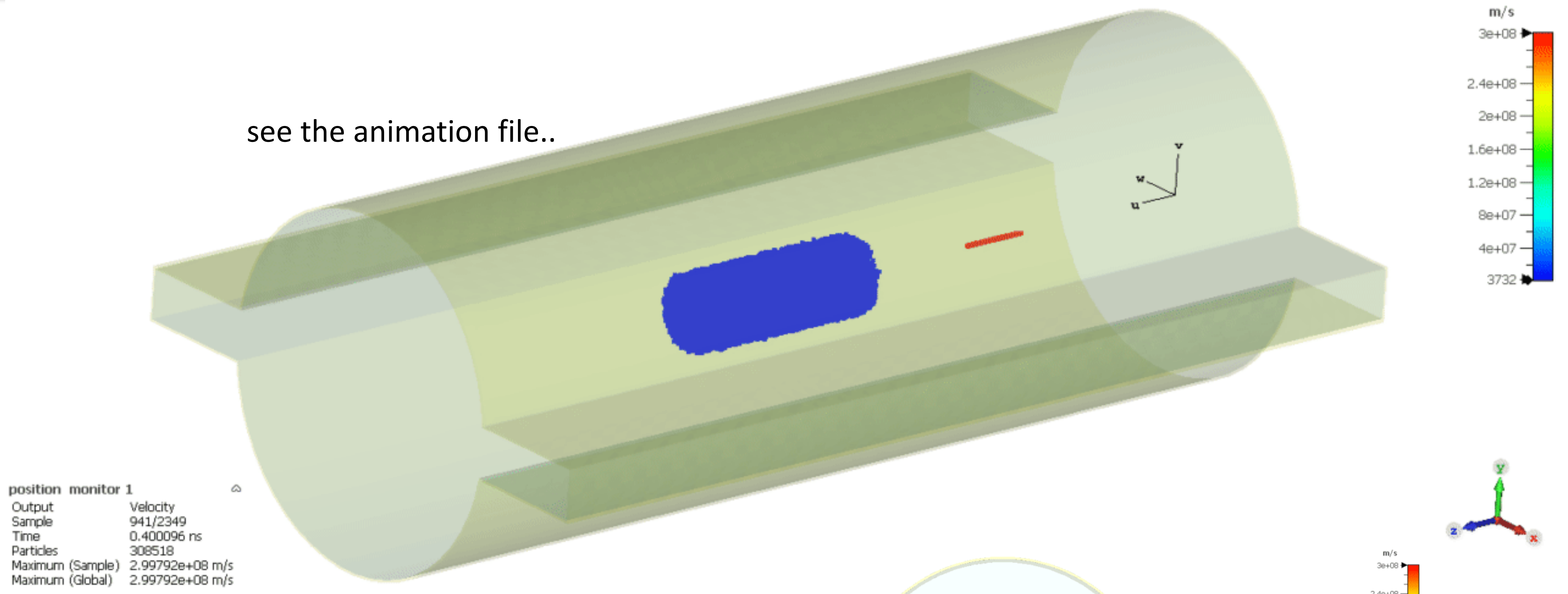
F. Yaman, E.Gjonaj, Th. Weiland, '3D EM PIC code to study e-Cloud effects for short bunches (<50ns) ', **CERN - GSI Electron Cloud Workshop 2011, Geneve,Switzerland, 2011** https://indico.cern.ch/event/125315/contributions/96596/

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

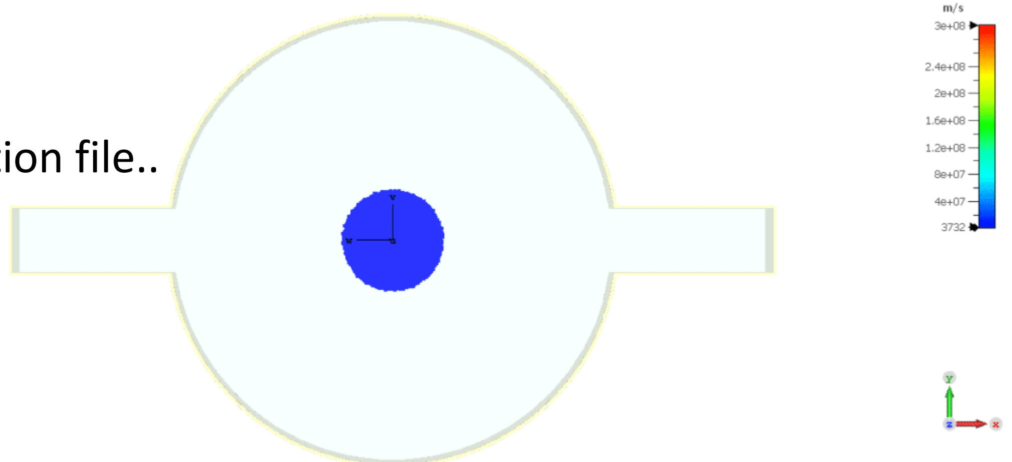


Wakefield computations with CST-PS

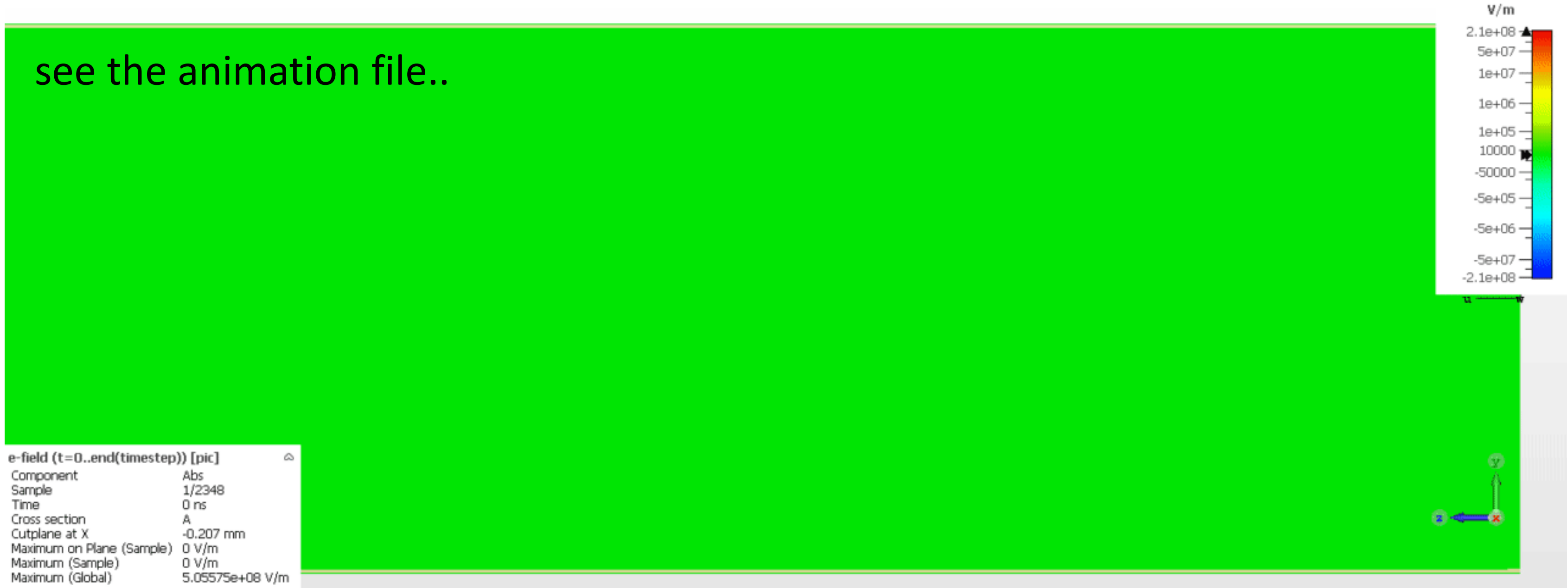
see the animation file..



see the animation file..

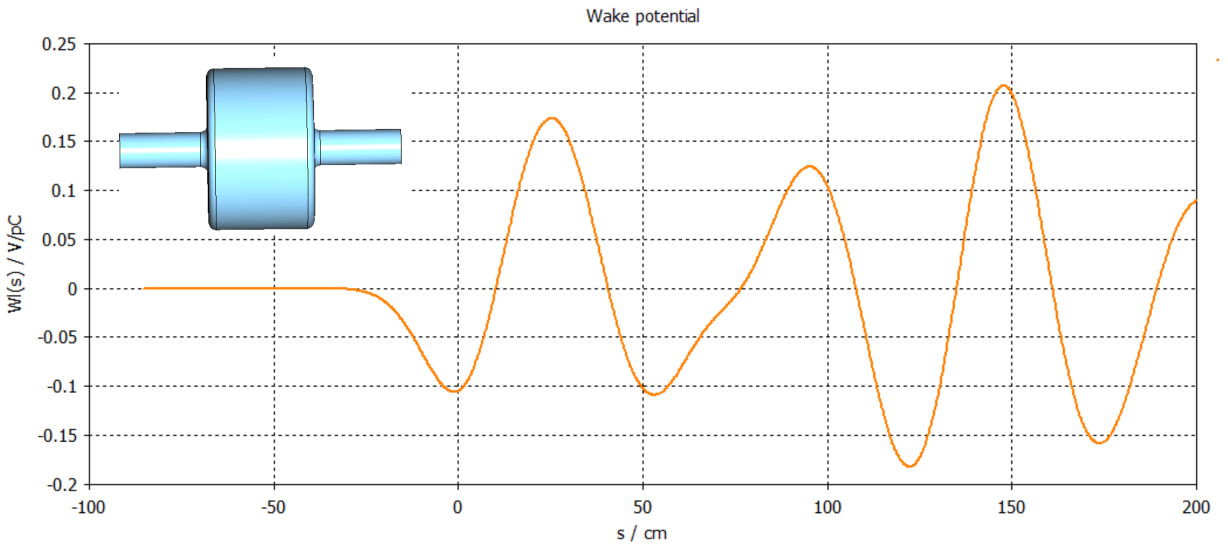


Longitudinal Component of the Electric Field



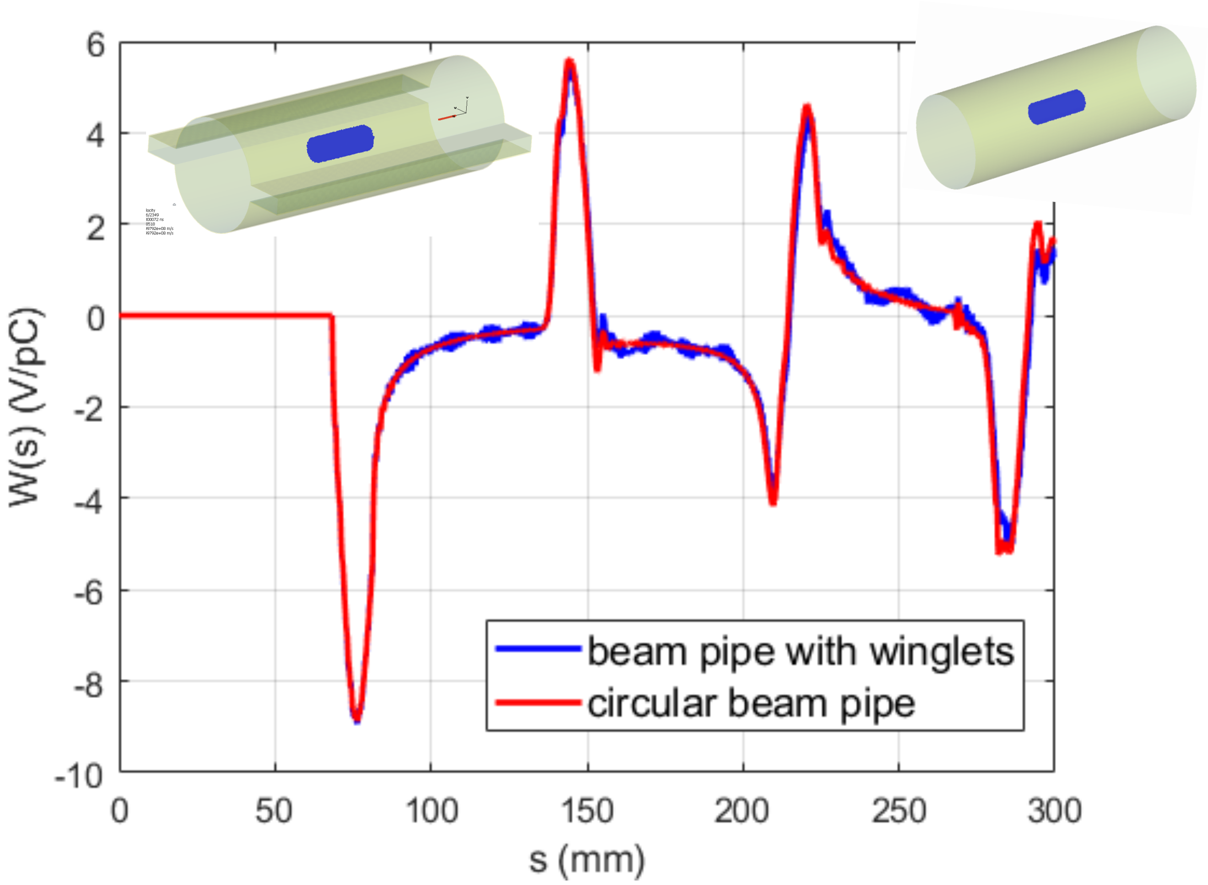
Longitudinal Wakefield (in progress)

a typical RF Cavity example result



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

Preliminary Result !



Conclusions and Future Plans

- 4IPs parameters + (30ns, 32ns) bunch spacing relax Ecloud build up
- Max. center electron density = 1.75e13 m^{-3}

  (bunch spacing: 30 ns, Furman-Pivi SEY, SEY=1.4 , n'_{γ} =1e-3, DRIFT region)
- Min. center electron density = 6e8 m^{-3}

  (bunch spacing: 32 ns, ECLOUD SEY , SEY=1.1 , n'_{γ} =1e-6, DIPOLE region)
- Simulations are performed in the realistic photon flux regimes
- Preliminary Ecloud build up comparisons with 2D and 3D codes
- Verification of Wakefield calculations, Impedance calculations
- Simulations with the measured SEY data

THANK YOU FOR ATTENTION!

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