Electron Cloud Studies for FCC-ee

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Acknowledgement: *Cantún Karla*[5], *Maury Humberto*[4], *Paraschou Konstantinos*[2], *Yaman Fatih*[3], *Zimmermann Frank*[2]

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FCC week 2023

6th June 2023

Swiss Accelerator Research and Technology

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Outline

- Introduction
- Build-up Simulation Results
- Stability Simulations
- Conclusions and Outlook

Outline

- **Introduction**
  - FCC-ee Configuration Z
  - New Parameters
  - E-Cloud Formation Process
- Build-up Simulation Results
- Stability Simulations
- Conclusions and Outlook

FCC-ee Configuration Z

- A study to identify the parameters, in the range of the values of FCC-ee case, which play a significant role in the e-cloud formation has been performed

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	40
bunch intensity [10^{11}]	2.43	2.91	2.04	2.37

[ ] FCC week 2022, "Accelerator overview", Frank Zimmermann, Tor Raubenheimer

The Z configuration has been investigated, because the strongest e-cloud effects are foreseen for this configuration due to the highest number of bunches (smallest bunch spacing)

New Parameters

- New machine and beam parameters
  - More bunches -> smaller bunch spacing (max 18.9 ns)
  - Smaller bunch intensity
  - Bunch length

Table 1: FCC-ee collider parameters for Z as of Mar. 16, 2023

Beam energy	[GeV]	45.6	
Version		Mar. 11	Feb. 07
Layout		PA31-3.0	
# of IPs		4	
Circumference	[km]	90.658816	
Bending radius of arc dipole	[km]	9.936	
Energy loss / turn	[GeV]	0.0394	
SR power / beam	[MW]	50	
Beam current	[mA]	1270	
Colliding bunches / beam		16000	9200
Colliding bunch population	[10^{11}]	1.50	2.60
Horizontal emittance at collision ε_x	[nm]	0.71	
Vertical emittance at collision ε_y	[pm]	1.4	
Arc cell		Long 90/90	
Momentum compaction α_p	[10^{-6}]	28.6	
Arc sextupole families		75	
$\beta^*_{x/y}$	[mm]	150 / 0.8	100 / 0.8
Transverse tunes/IP $Q_{x/y}$		53.560 / 53.595	53.565 / 53.595
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0/086	0.039 / 0.143
Bunch length (SR/BS) σ_z	[mm]	5.40 / 11.8	4.37 / 15.9
RF voltage 400/800 MHz	[GV]	0.084 / 0	0.120 / 0
Harmonic number for 400 MHz		121200	
RF freuqeuncy (400 MHz)	MHz	400.786684	
Synchrotron tune Q_s		0.0299	0.0370
Long. damping time	[turns]	1158	
RF acceptance	[%]	1.1	1.6
Energy acceptance (DA)	[%]	±1.0	
Beam crossing angle at IP	mrad	±15	
Crab waist ratio	%	70–80	97
Beam-beam ξ_x/ξ_y [a]		0.0036 / 0.110	0.0023 / 0.139
Luminosity / IP	[10^{34}/cm^{2}s]	140	186
Lifetime (q + BS + lattice)	[sec]	10000–1500	20
Lifetime (lum) [b]	[sec]	1340	1010

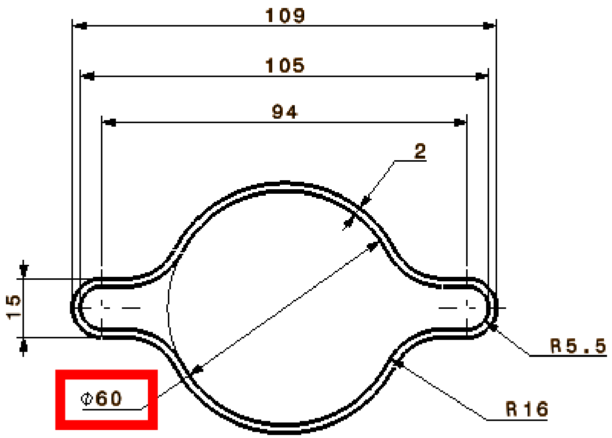
[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

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

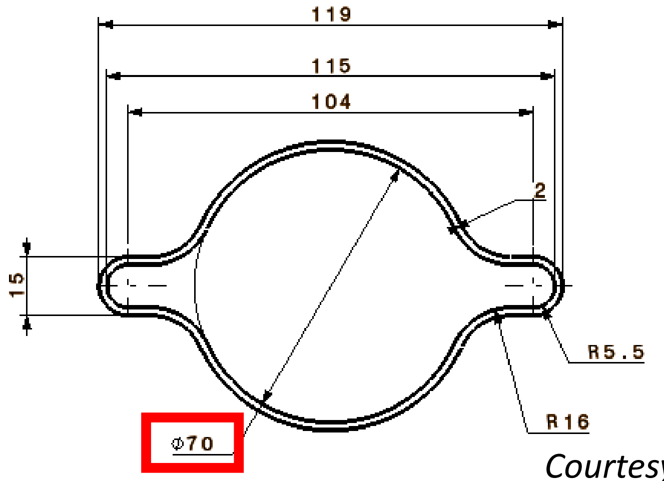
New Parameters

- New vacuum chamber

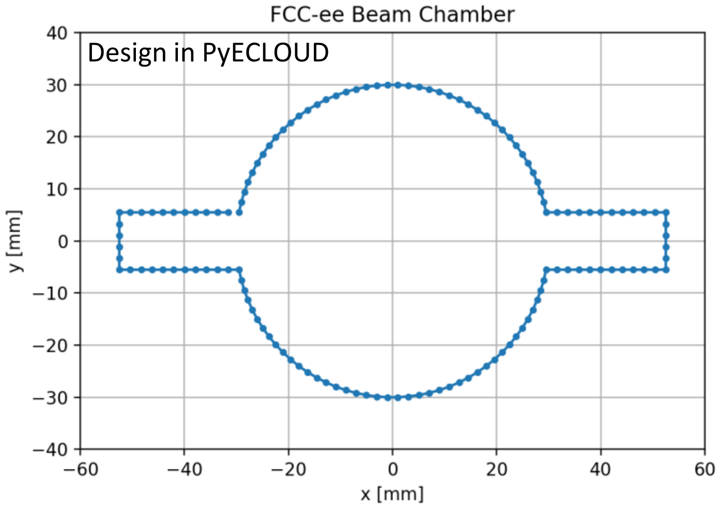
NEW

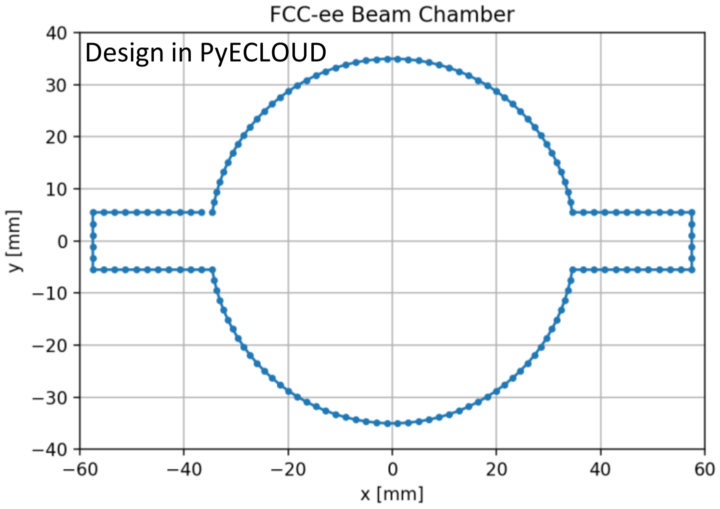


OLD



Courtesy of R. Kersevan and F. Santangelo





Motivation

- The scientific goal of the research activity is to check the stability limits by means of self-consistent beam stability simulations for the different arc elements with realistic e-cloud distributions obtained from build-up simulations

- What is the impact of the new parameters on the e-cloud single-bunch stability?

Strategy

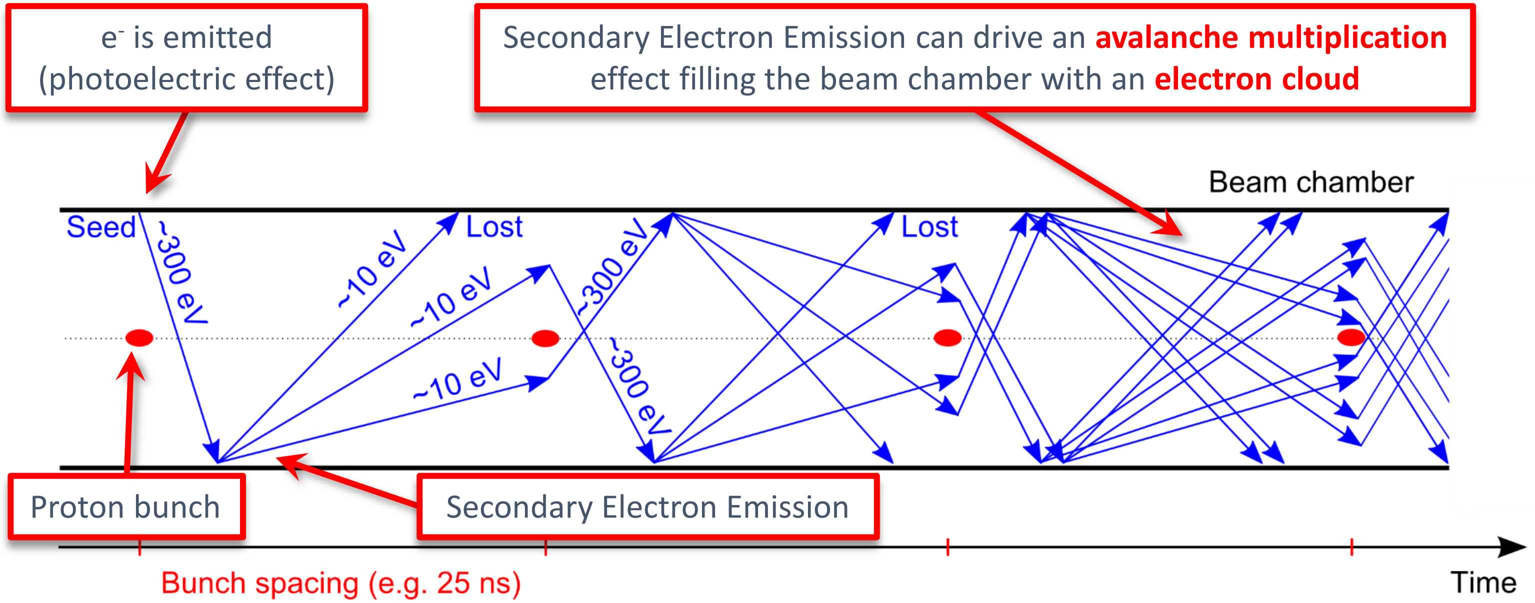
- The first campaign of build-up simulation studies with the old parameters has been used to identify which parameters play a significant role in e-cloud formation process

- A second campaign of build-up simulation has been performed in order to assess the effect of the new parameters on the e-cloud formation process
  - comparison between the new parameters and the old ones

- Stability simulations using the build-up simulation results with the new parameters

E-Cloud Formation Process

- Trailing bunches of the train are in a dense electron-cloud (e-cloud)
  - Transverse instabilities
  - Transverse emittance blow-up
  - Particle losses



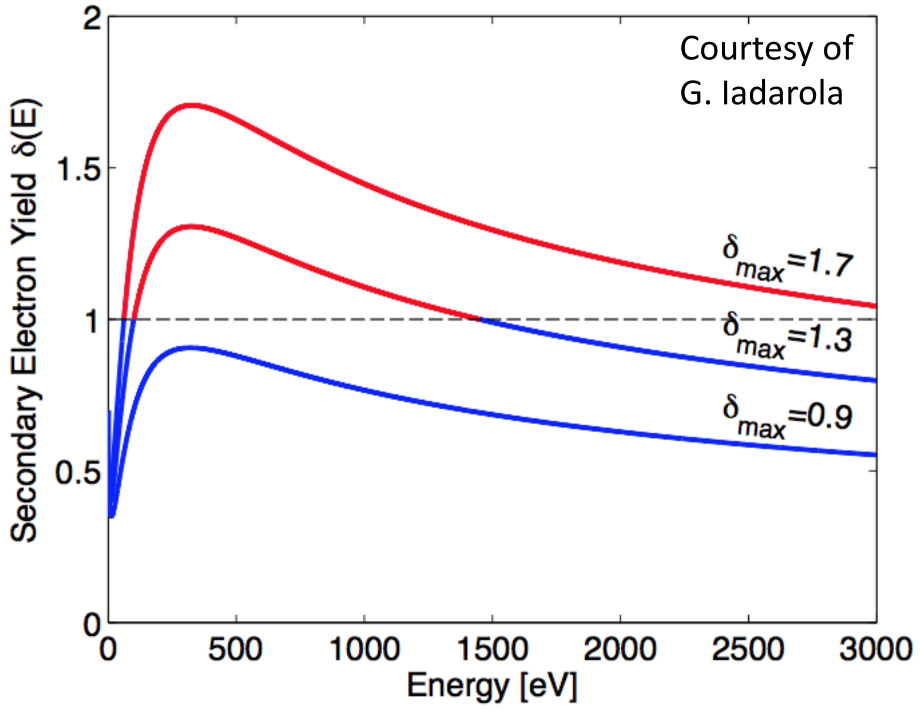
Courtesy of G. Iadarola

- e-cloud induces other unwanted effects like:
  - Heat load on the beam chambers
  - Vacuum degradation

- Affects mainly machine operating with positively charged particles (p^+, e^+, positive ions…)

E-Cloud Formation Process

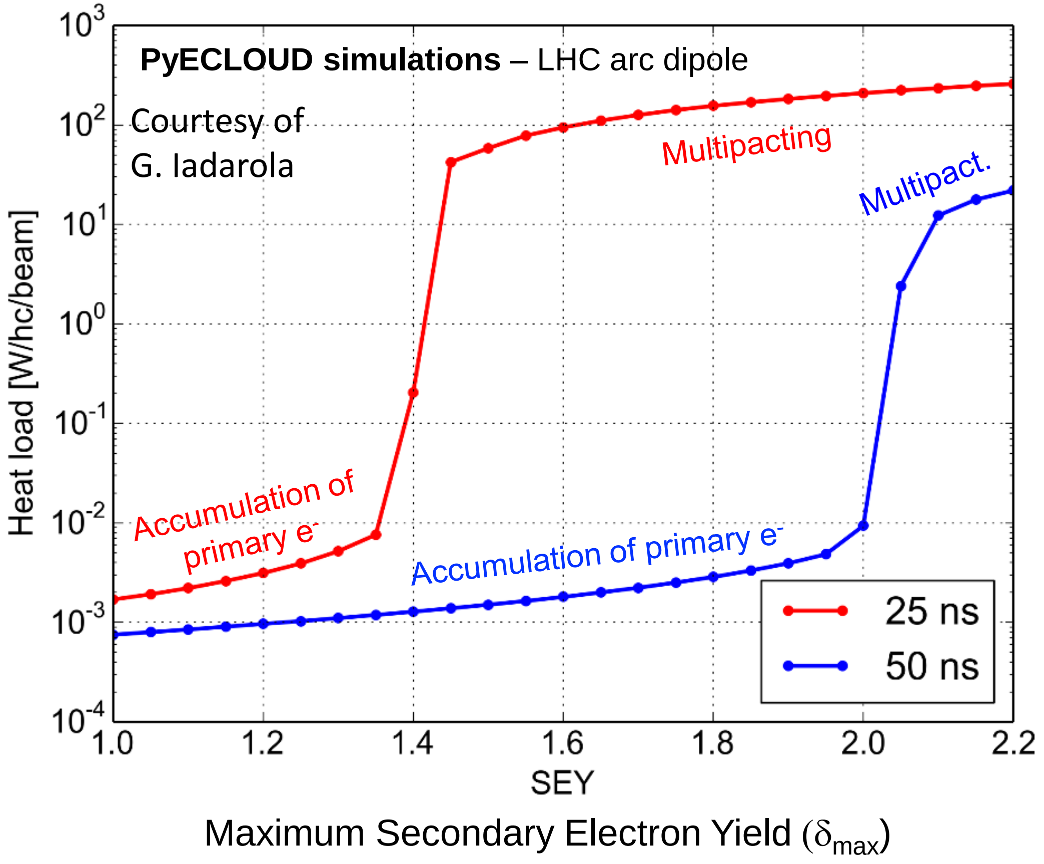
- The chamber geometry influences e⁻ acceleration and time of flight
- Surface properties have a primary role in the e⁻ multiplication process
  - The main quantity involved is the Secondary Electron Yield (SEY): $$\delta(E) = \frac{I_{\mathrm{emit}}}{I_{\mathrm{imp}}(E)}$$
  - The SEY is the ratio between emitted and impacting electron current as a function of the energy of the impinging electrons
  - It depends on surface chemical properties
  - it depends on the history of the surface, in particular on accumulated electron dose -> to a certain extent the e-cloud cures itself (beam induced scrubbing)



E-Cloud Formation Process

- A key ingredient is the bunch spacing:
  - It determines how many electrons survive between consecutive bunch passages
  - Significant impact on multipacting threshold, i.e. SEY above which avalanche multiplication (multipacting) is triggered

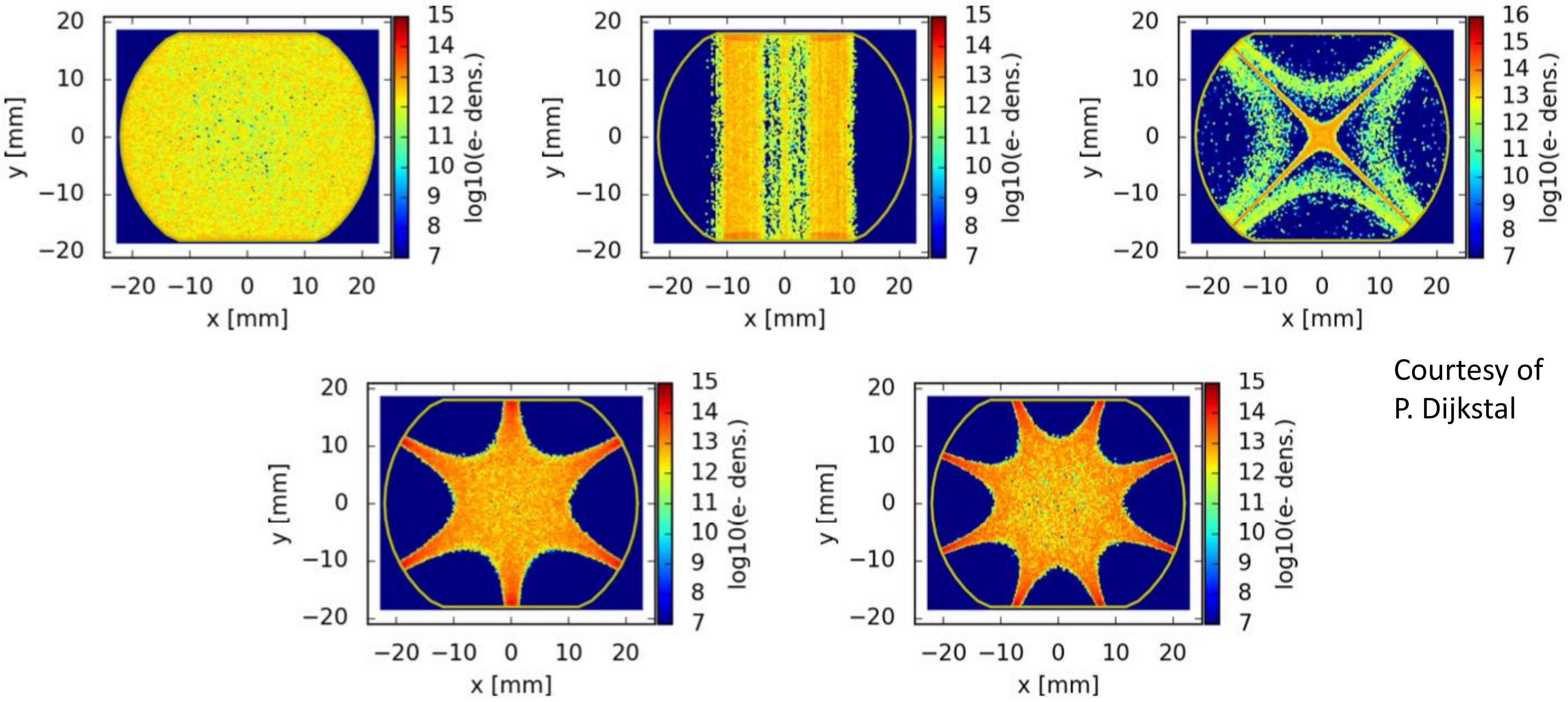
- Bunch intensity and bunch length also have an important effect as they affect the acceleration received by the electrons



E-Cloud Formation Process

Electron trajectories are strongly influenced by externally applied magnetic fields (Electrons spin around the field lines)

E-cloud distribution in the LHC arc magnets



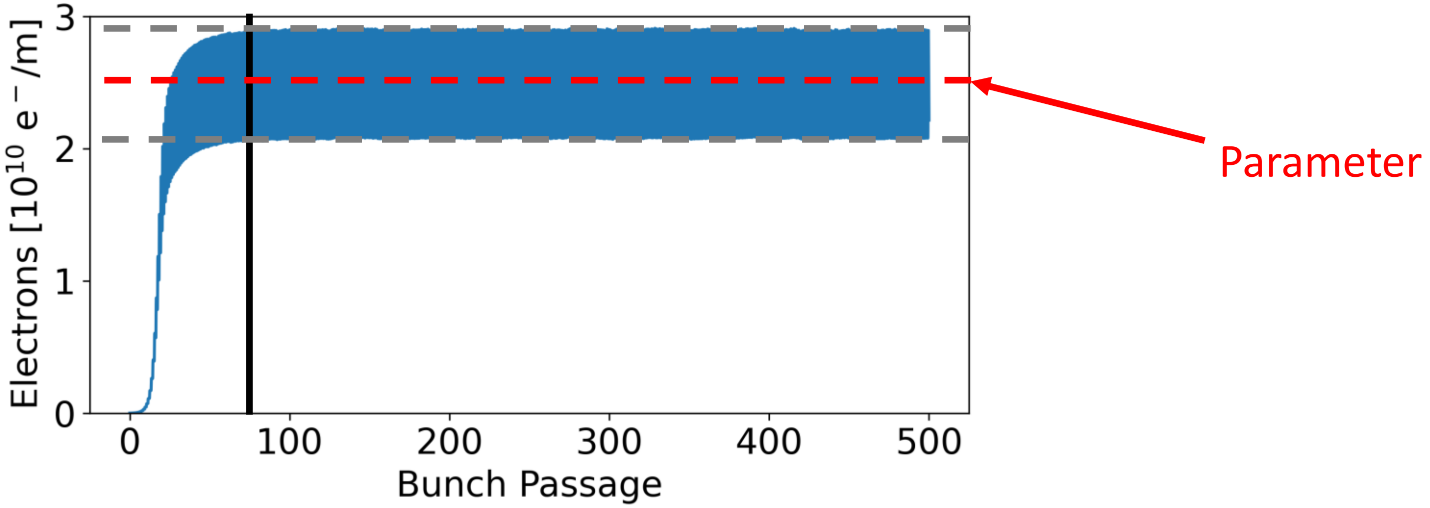
Courtesy of
P. Dijkstal

Outline

- Introduction
- **Build-up Simulation Results**
  - Parameter Overview
  - Summary Previous Results
  - Results for New Parameters
- Stability Simulations
- Conclusions and Outlook

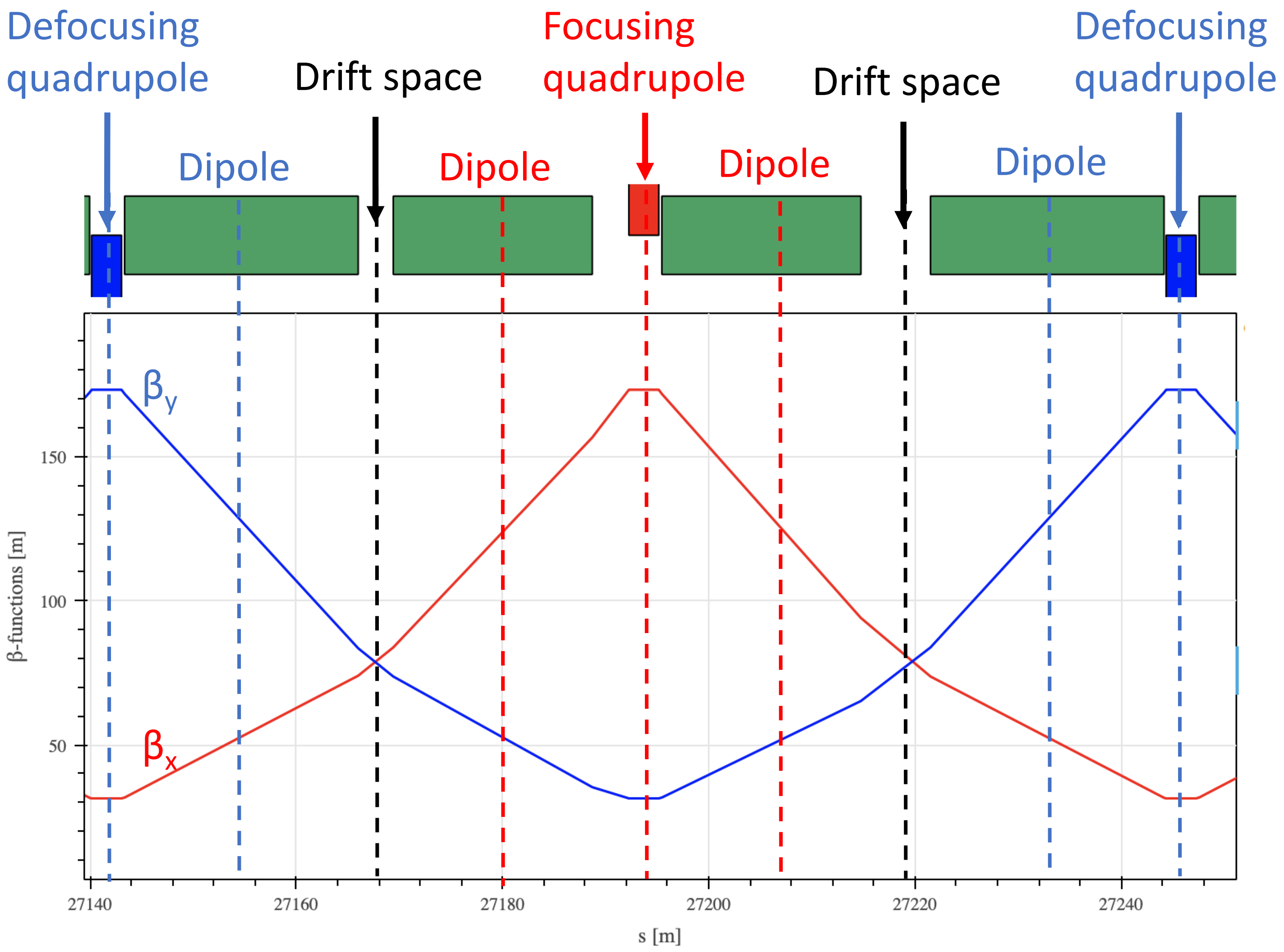
Parameter Overview

- For the summary plots the average density after saturation is used



Parameter Overview

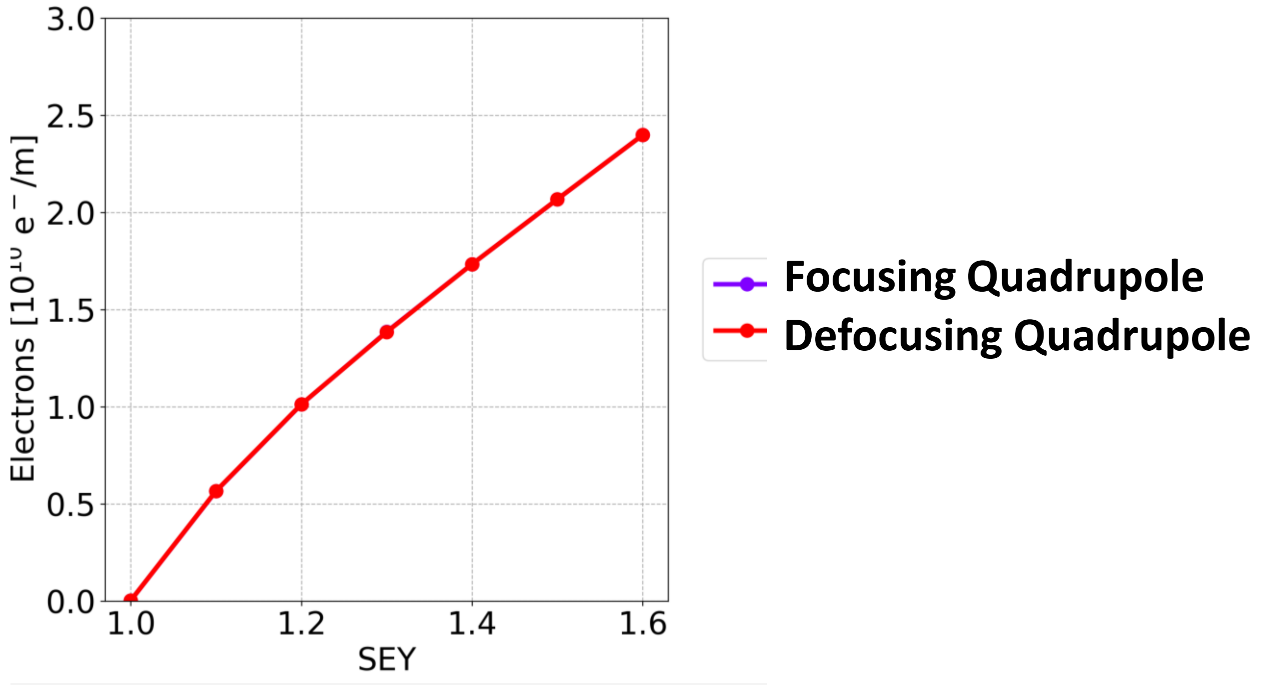
- **Element:**
  - Drift space
  - Quadrupole (5.65 T/m)
    - focusing
    - defocusing
  - Dipole (1.415 mT)
    - close to focusing quadrupole
    - close to defocusing quadrupole



The version V22.2 has been used

[] https://acc-models.web.cern.ch/acc-models/fcc/fccee/V22.2/z/

Dependence on Beta Function

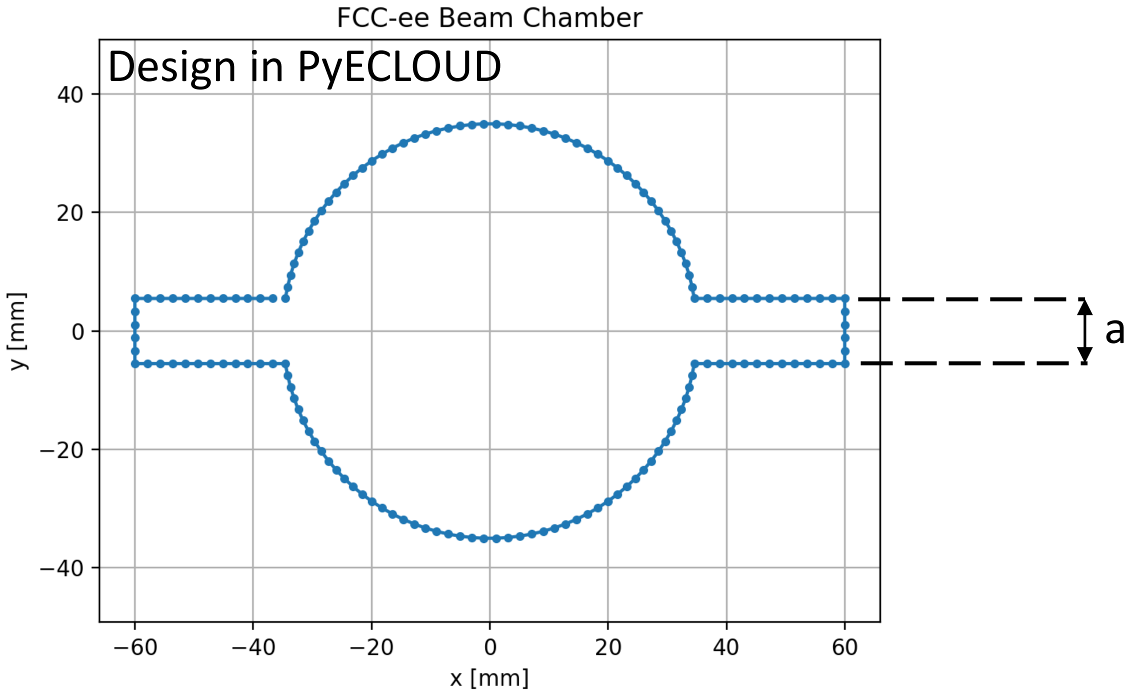


- No dependence on beta functions found in quadrupoles and dipoles

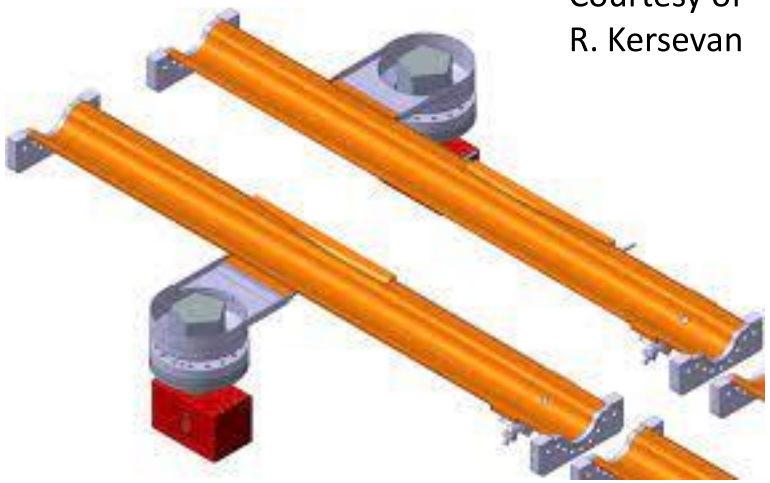
For more details: L. Sabato, 20th November 2022, "E-cloud studies in the FCC-ee"*, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Dependence on Winglet Geometry

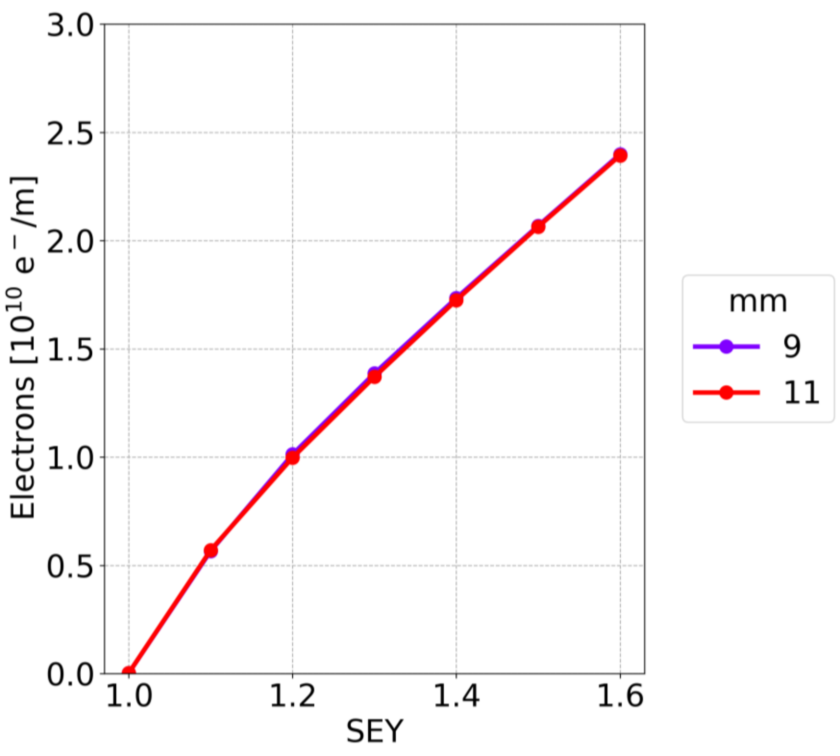
- **Beam chamber winglet geometry**
  - a = 9 mm
  - a = 10 mm
  - a = 11 mm



Courtesy of
R. Kersevan



Dependence on Winglet Geometry



- No dependence on the beam chamber winglet height

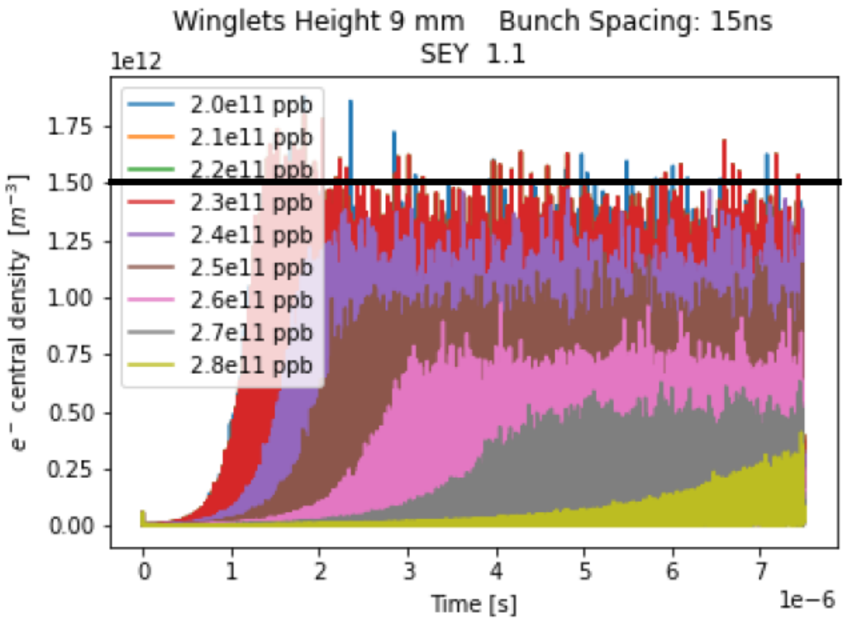
For more details: L. Sabato, 20th November 2022, "E-cloud studies in the FCC-ee"*, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Dependence on Winglet Geometry

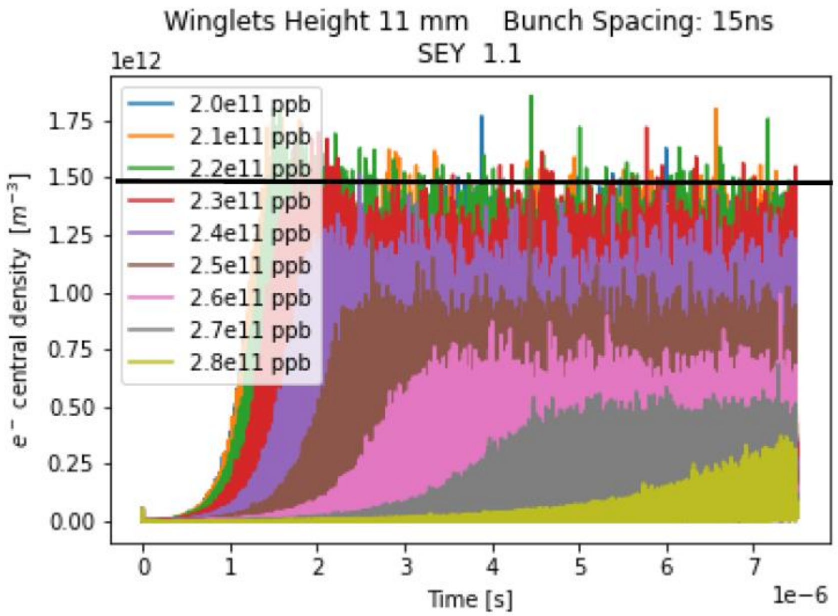
- No dependence on the beam chamber winglet height
- Recently confirmed also for the sextupoles

from the studies of *H. Maury, Universidad de Guanajuato*, and *K. Cantún, Universidad Autónoma de Yucatán*

9 mm



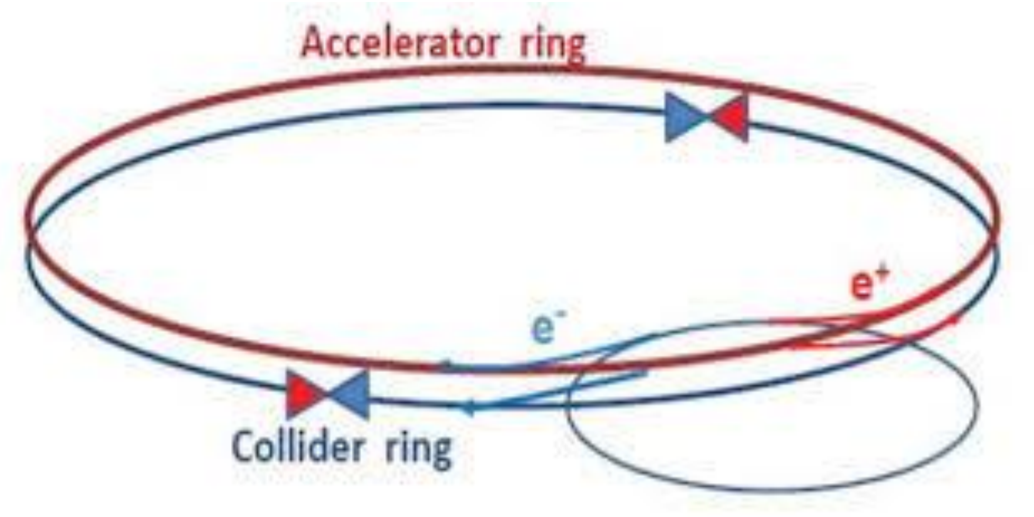
11 mm



Courtesy of H. Maury and K. Cantún

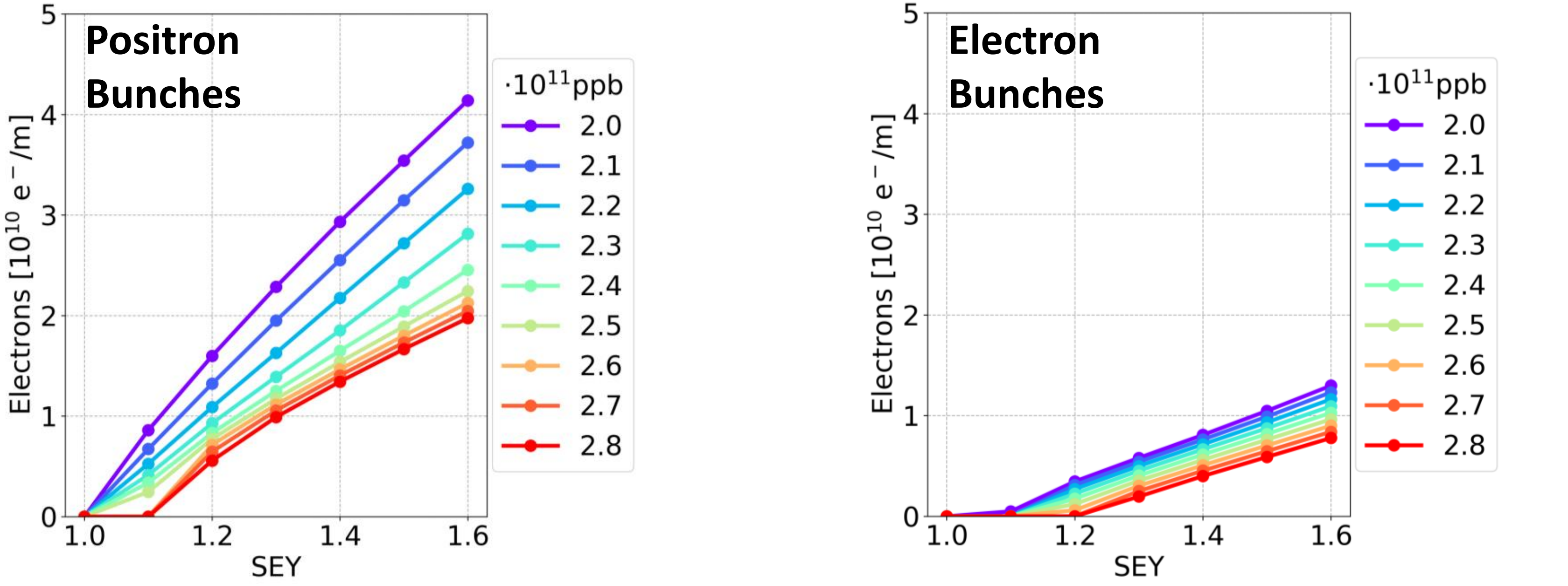
Build-up with Electron Beam

- E-cloud build-up has also been seen for machine operating with electron beam
- Investigated effects also for FCC-ee



Build-up with Electron Beam

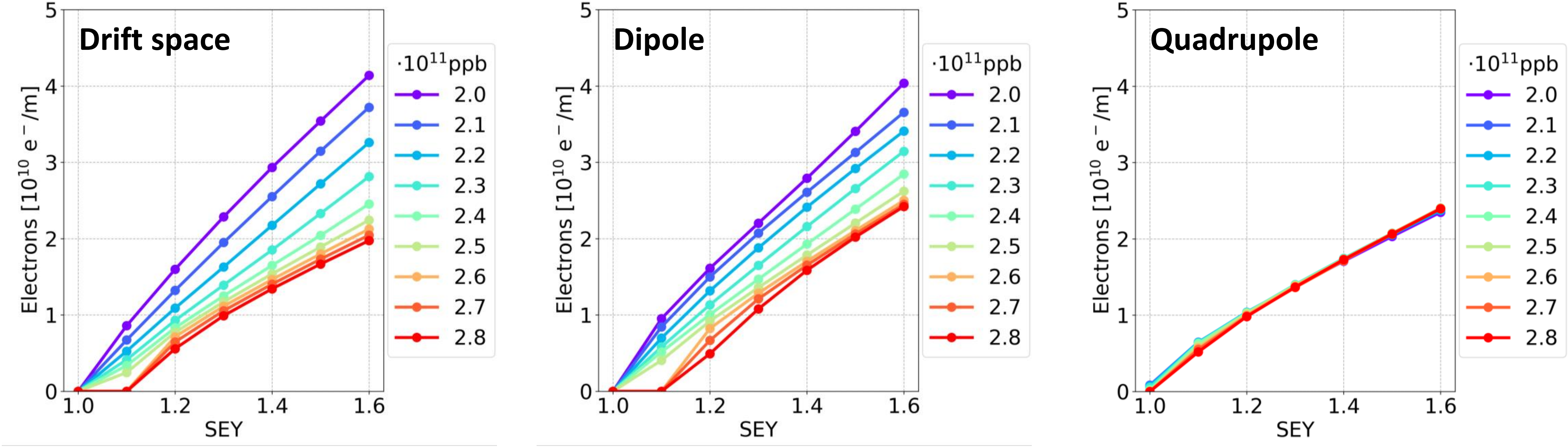
Drift space, bunch spacing 10 ns



- Multipacting occurs in a few cases
- In the case of electron bunches,
  - the e-cloud density is smaller
  - the electrons are mainly located far from the beam chamber centre → less concerning for stability

For more details: L. Sabato, 20th November 2022, “E-cloud studies in the FCC-ee”*, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Dependence on Bunch Intensity

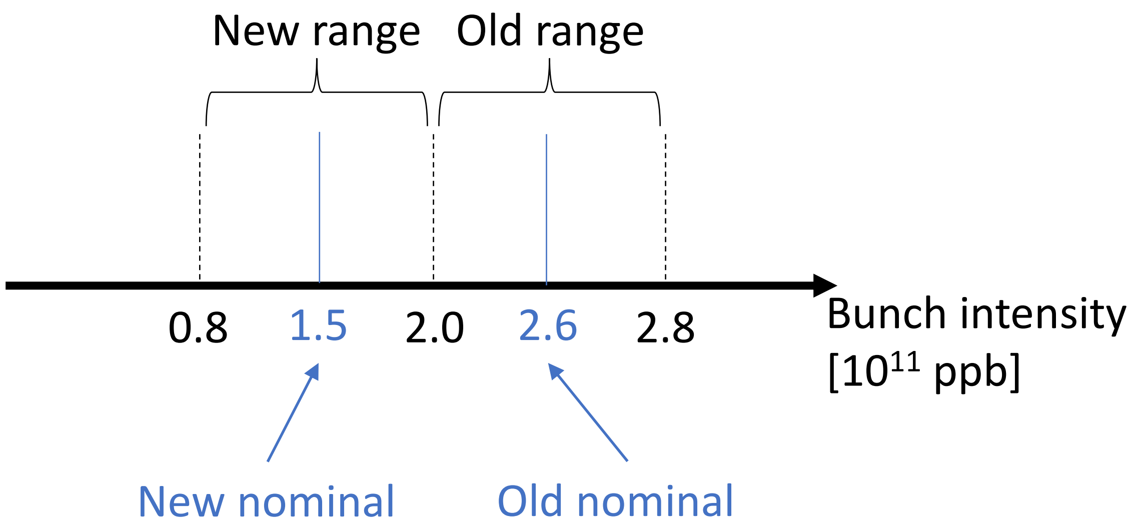


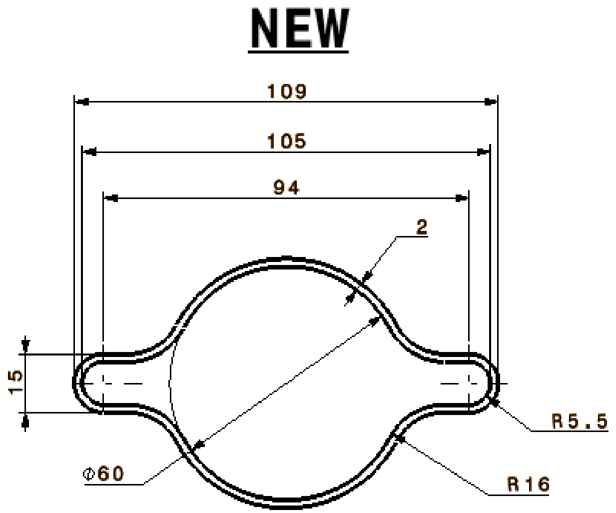
- In the drift space, monotonic increase in electron density with decreasing bunch intensity in studied range
- In dipole, the electron density has a similar behaviour with respect to the bunch intensity
- In the quadrupole, the bunch intensity has a negligible effect on the electron density

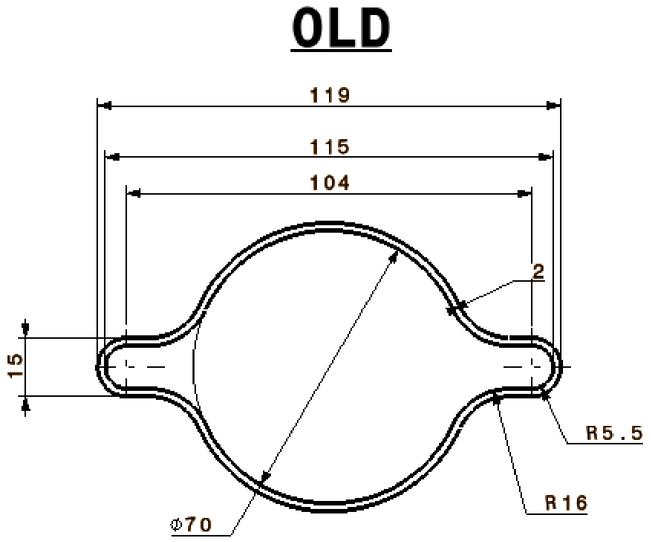
For more details: L. Sabato, 20th November 2022, "E-cloud studies in the FCC-ee"*, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Parameter Changes

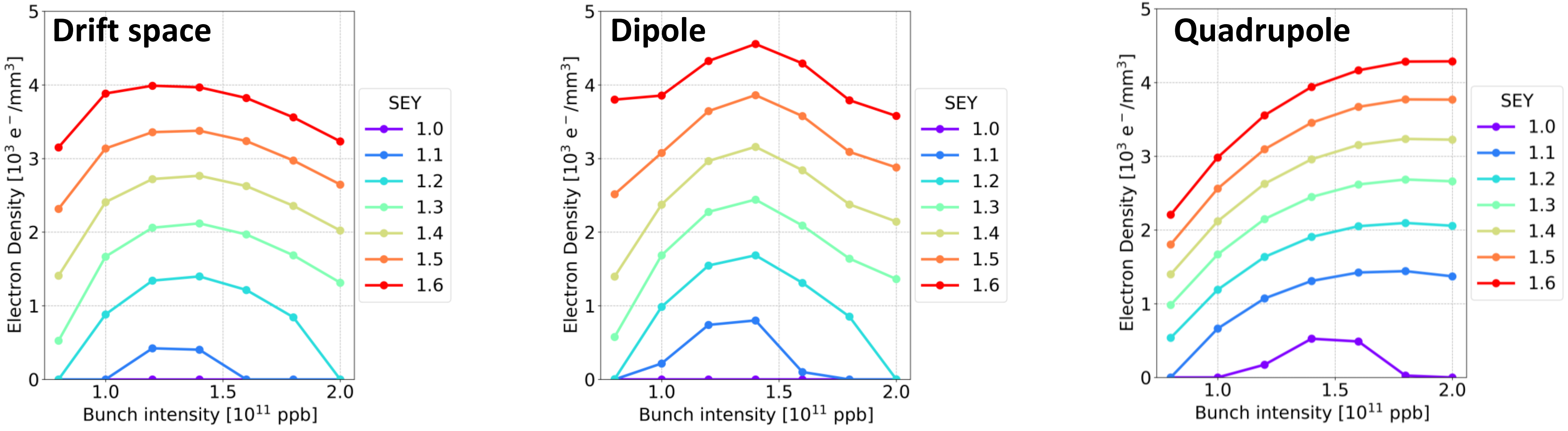
Parameter	New	OLD
Colliding bunches (beam)	16,000	9,200
Bunch intensity [10^{11} ppb]	1.50	2.60
Bunch length (SR/BS) [mm]	5.40/11.8	4.37/15.9





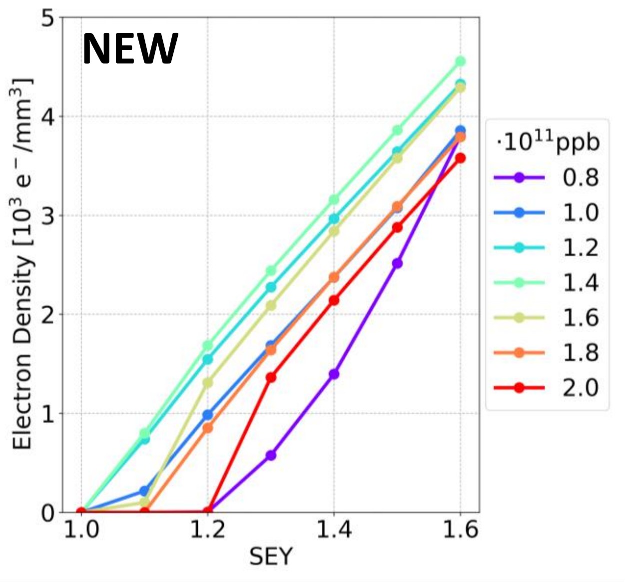


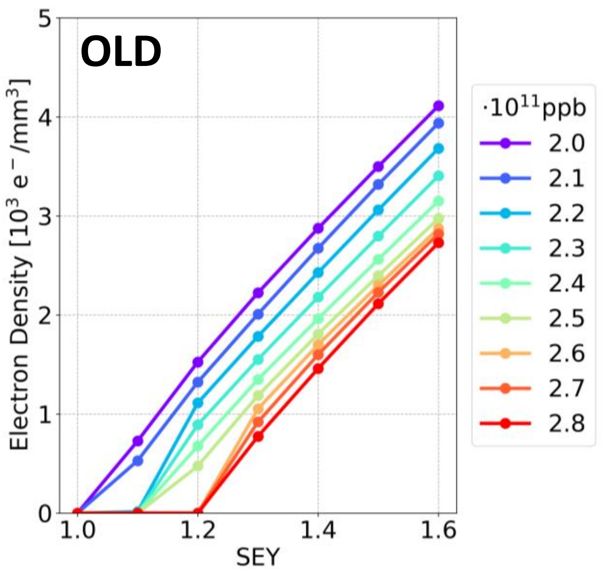
New Parameters



- In the drift space, the dependence on the bunch intensity is non-monotonic
- In the dipole, the electron density has a similar behaviour with respect to the bunch intensity
- In the quadrupole, the bunch intensity has a non-negligible effect on the electron density

Comparison: New vs Old Parameters



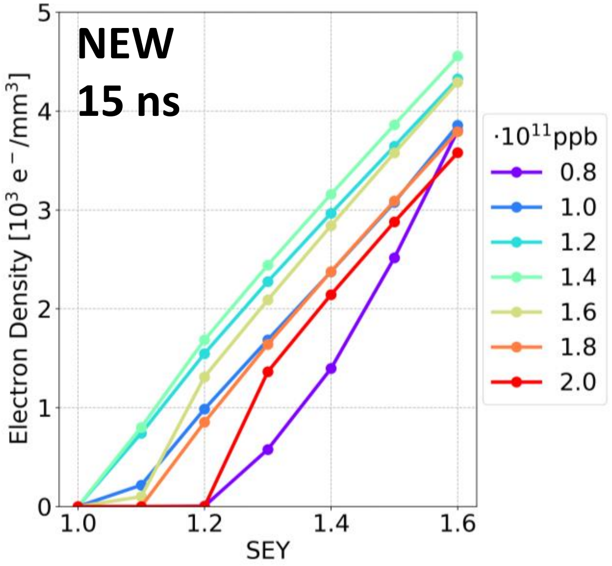


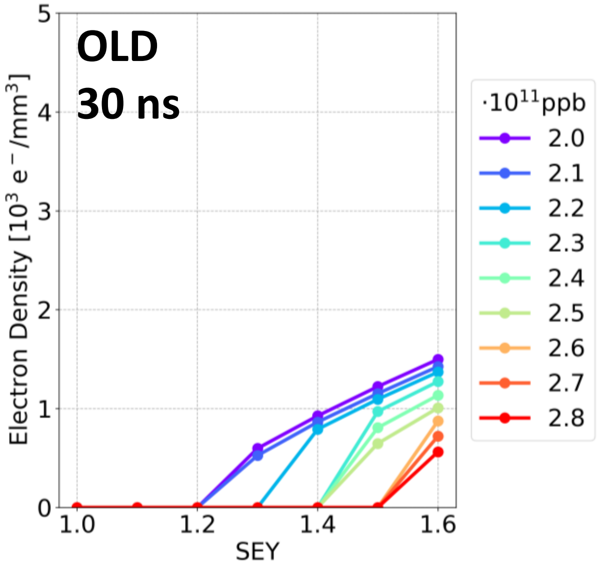
- For a fixed bunch spacing there is not a large difference in the range of multipacting threshold nor in the e-cloud density for the considered intensity range

  →The new configuration of beam chamber / bunch length / bunch intensity does not have a strong impact

Comparison: New vs Old Parameters

- With the new parameters the max bunch spacing reachable becomes 18.9 ns (16,000 bunches) instead of 32.9 ns (9,200 bunches)





- Comparing the new configuration and the old configuration with the max bunch spacing reachable there is a clear difference both in the range of multipacting threshold and in the e-cloud density

→E-cloud build-up can only be suppressed with SEY < 1.0

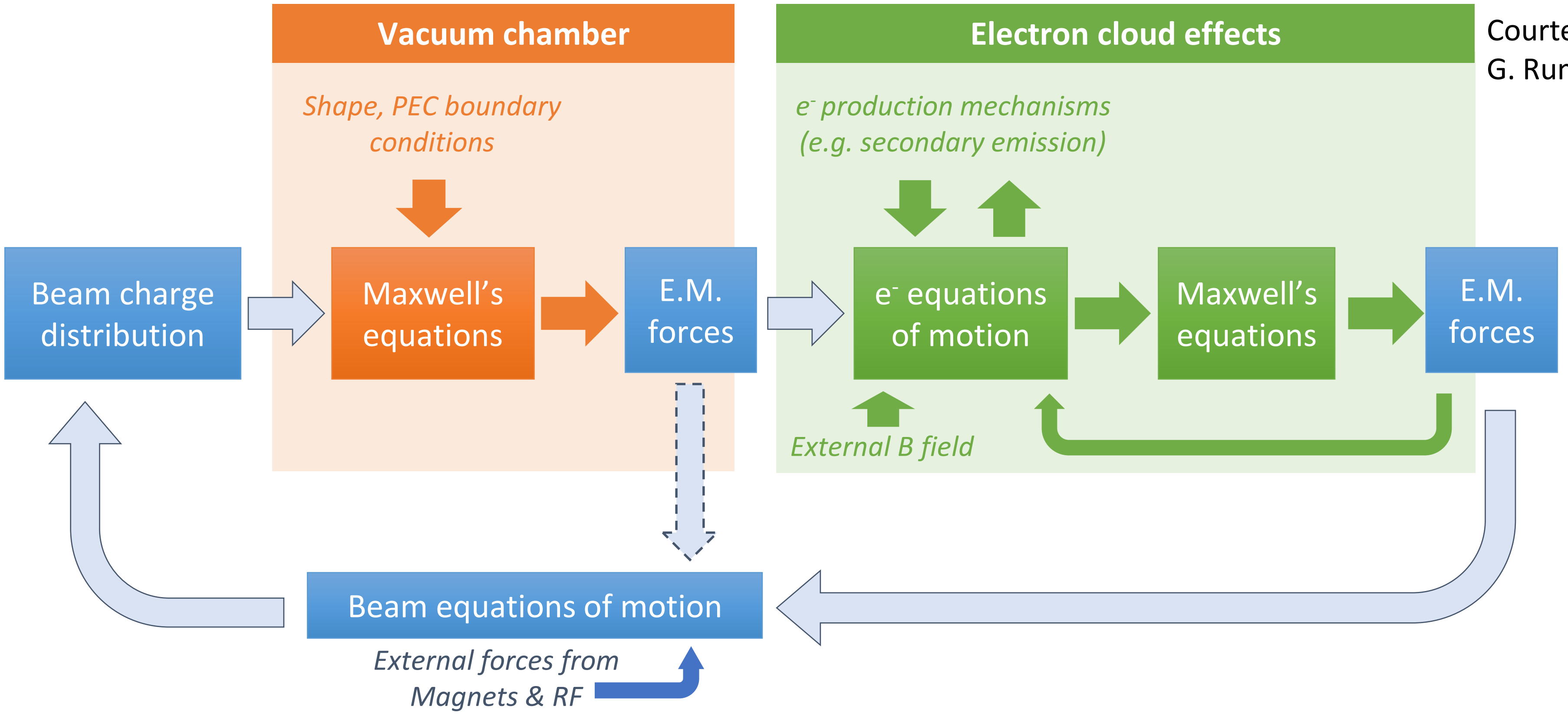
→Impact of higher electron density to be determined by stability simulations

Outline

- Introduction
- Build-up Simulation Results
- **Stability Simulations**
- Conclusions and Outlook

Stability Simulations

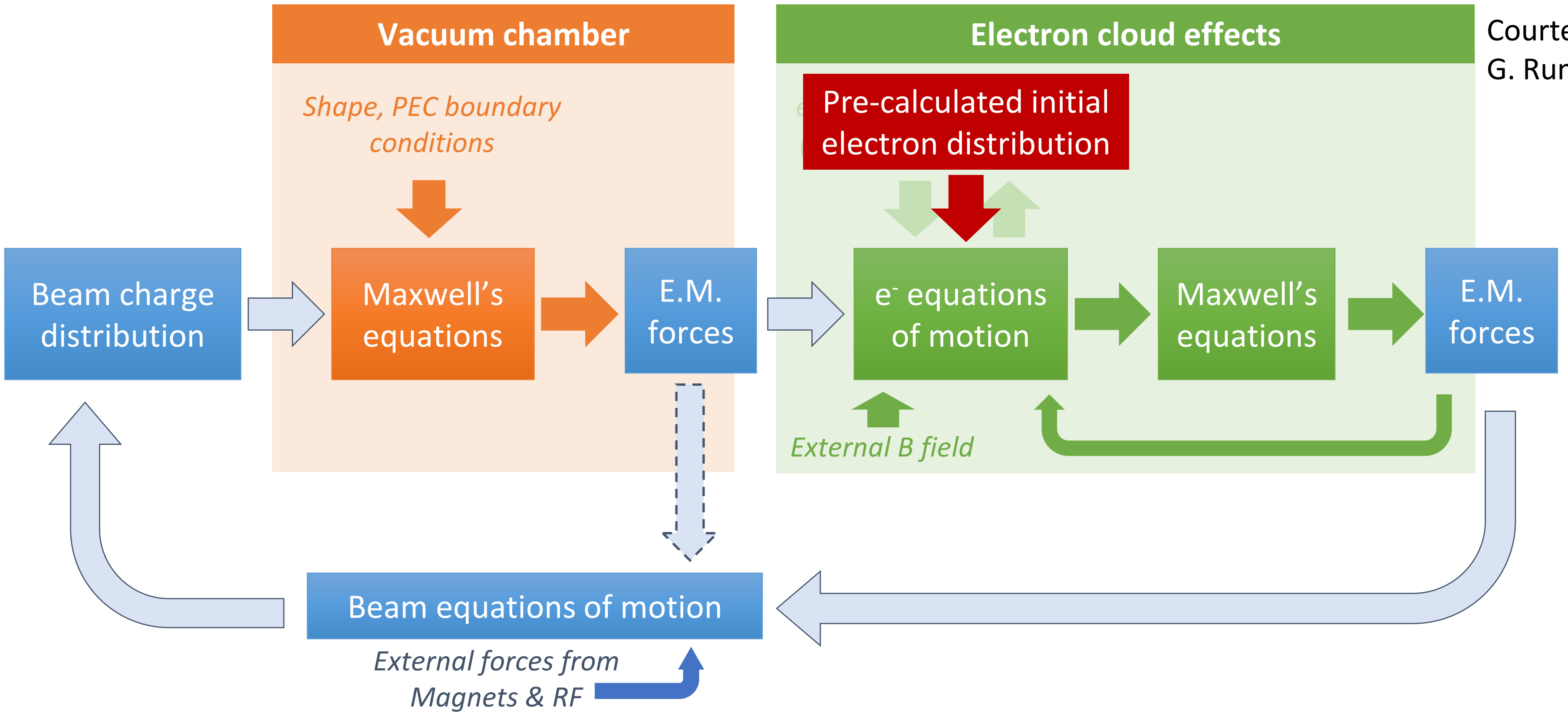
- A complex problem involving two sets of particles mutually interacting



Courtesy of G. Rumolo

Stability Simulations

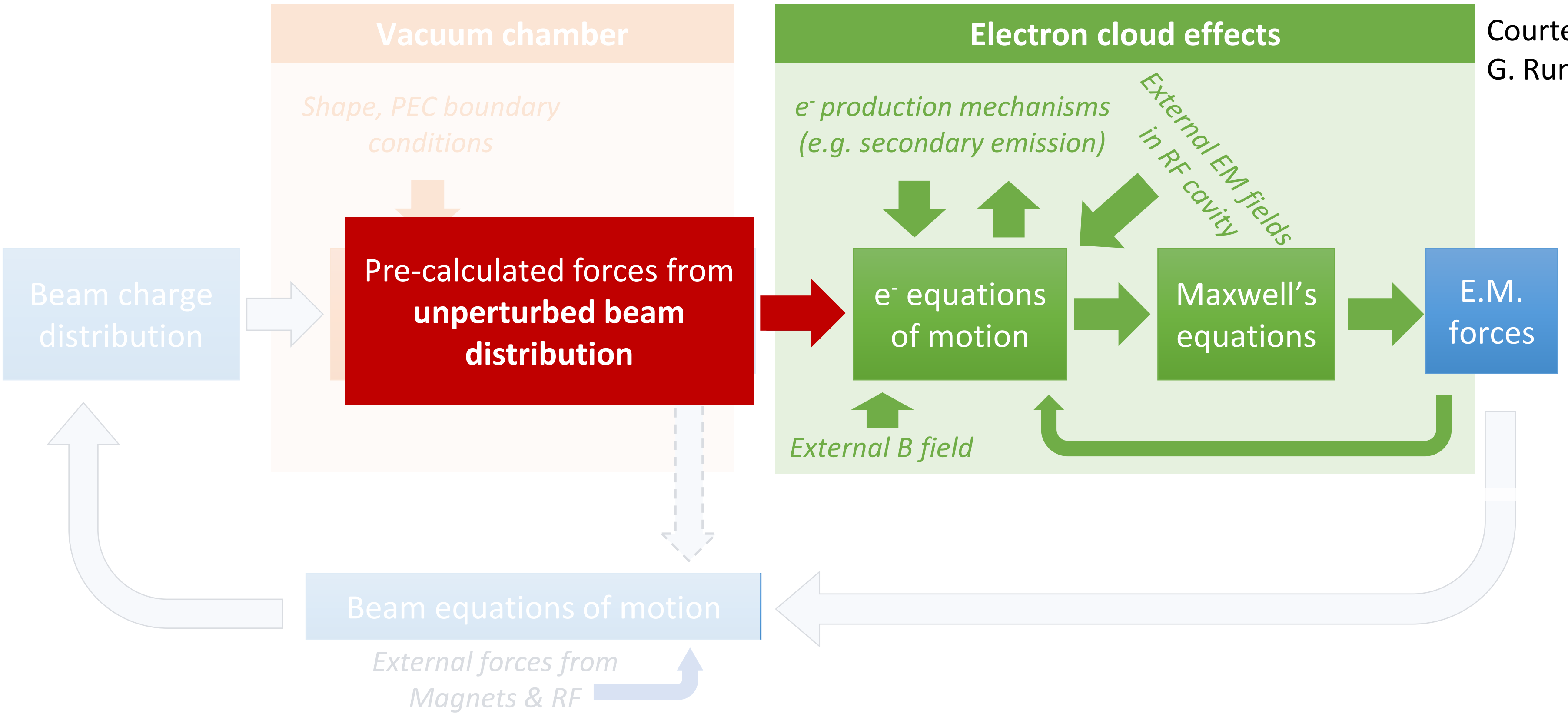
- Beam dynamics simulations → Model the interaction of the beam (typically a single bunch) with a given initial electron distribution



Courtesy of G. Rumolo

Stability Simulations

- E-cloud build-up → Solely focuses on electron dynamics with an unperturbed beam distribution to determine how the e-cloud forms and where it saturates

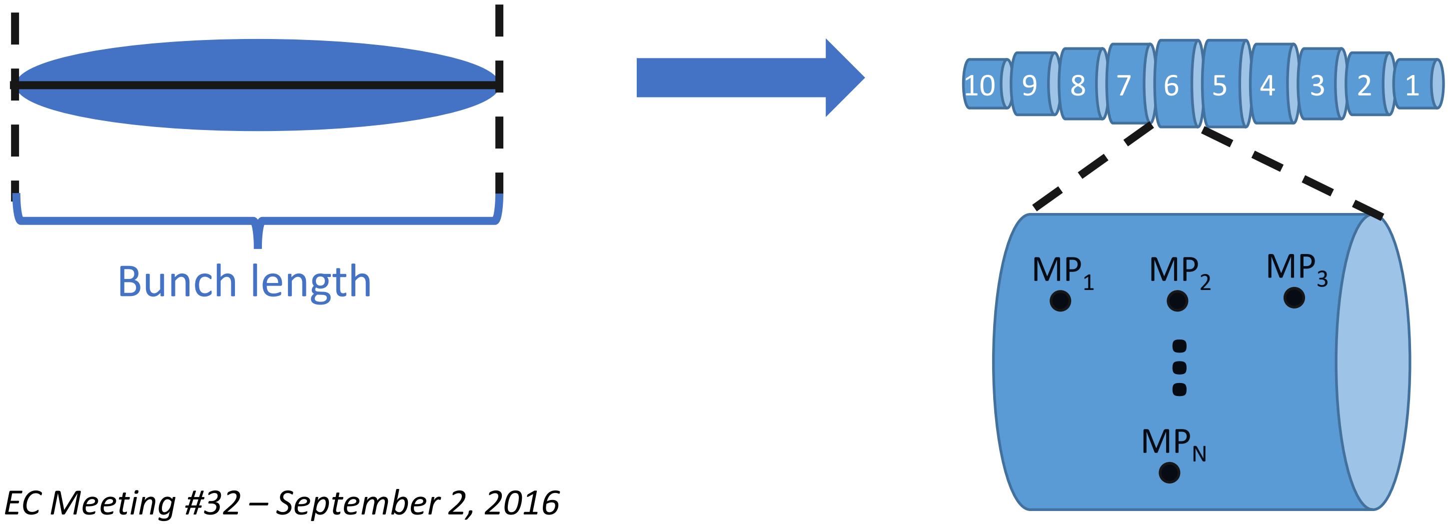


Courtesy of G. Rumolo

Stability Simulations

- Convergence studies on the numerical parameters are needed:

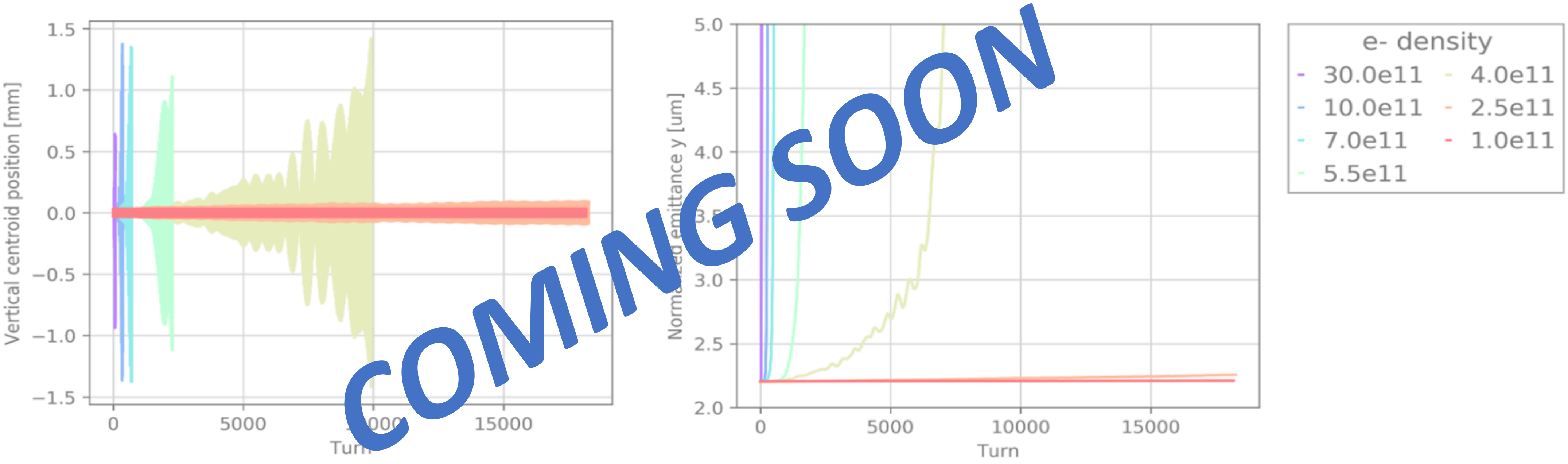
1. the number of longitudinal slices along the bunch
2. the average number of MPs/slice used to model the positron bunch
3. the number of e-cloud interactions (kicks) along the ring
4. the number of MPs used to model the e-cloud at each interaction
5. the configuration of the transverse grids used to compute the fields generated by the beam and by the electrons through the PIC method [ ])



[ ] E. Belli, "PyPIC: the multigrid solver", EC Meeting #32 – September 2, 2016

Stability Simulations

Single-bunch stability simulations



Stability Simulations

- For the first considerations on the stability, see the presentation of Fatih Yaman on Thursday 8th June at 14:30

14:30 **Electron cloud studies for the FCC-ee** 15m

We investigate the effects of the updated beam and machine parameters on the electron cloud instability for the FCC-ee arc dipole & drift regions by considering ‘ECLOUD’ and ‘Furman-Pivi’ secondary emission yield models and realistic photoemission yield values.

Speaker: Fatih Yaman (Izmir Institute of Technology (IYTE))

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Conclusions and Outlook

- The first studies identified the impact of various parameters on the e-cloud formation
  - Weak impact: beta-functions, winglet chamber geometry, electron beam
  - Strong impact: bunch intensity, bunch spacing and magnetic field
- Largest impact of the new parameters comes from tighter constraint on the bunch spacing
  - Due to the non-monotonic dependence on the bunch intensity a less critical range of intensity could be found, but this would also depend strongly on the chamber size, bunch length etc.
- The impact on the beam stability is being assessed by means of self-consistent beam stability simulations with realistic e-cloud distributions obtained from build-up simulations
- For future studies, consider also combined effect of e-cloud, beam-beam, impedance
  - Tools under development

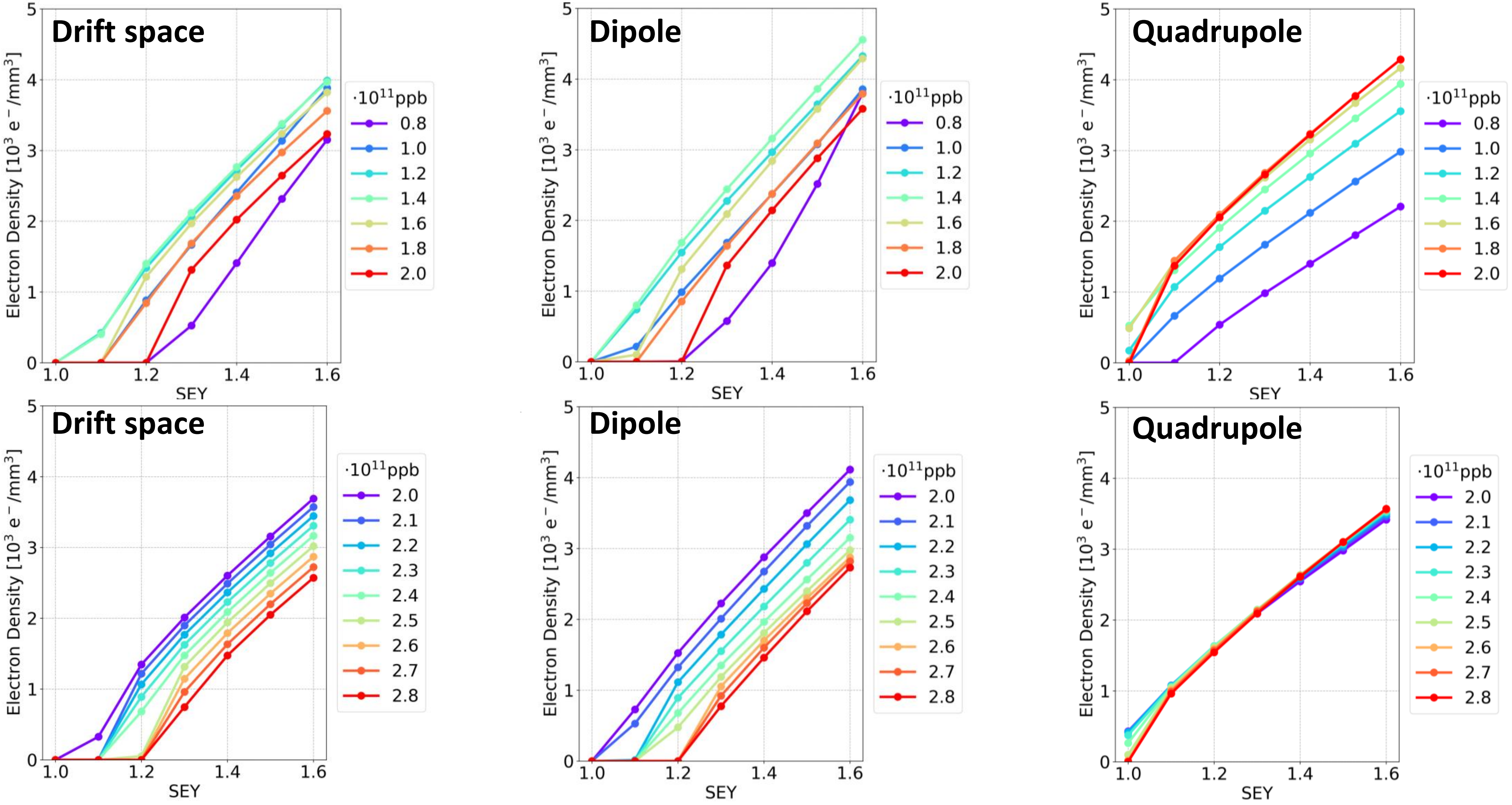
Thank you for your attention

New Parameters

- Bunch spacing 15 ns, longer bunch length

NEW

OLD

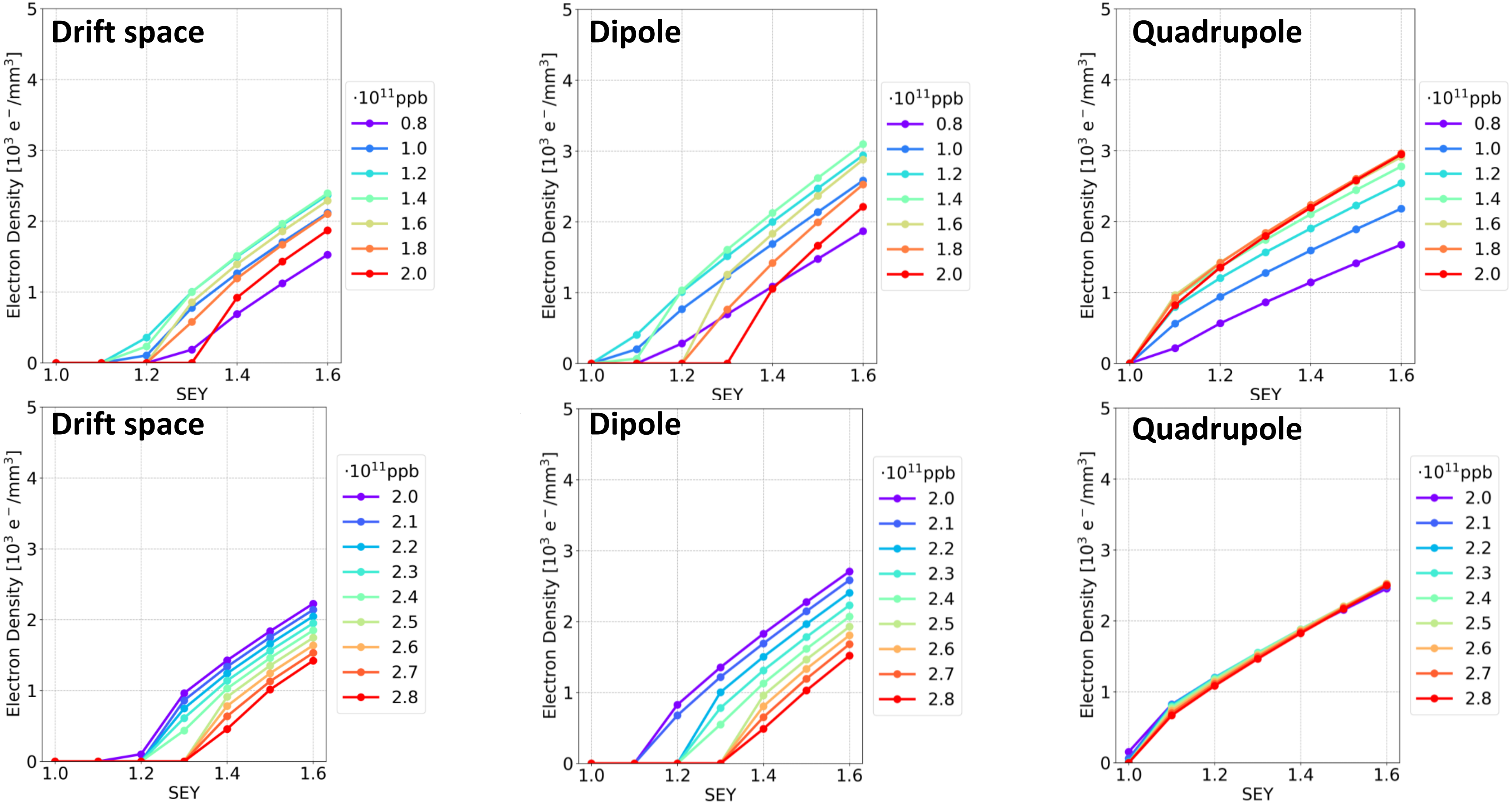


New Parameters

- Bunch spacing 20 ns, longer bunch length

NEW

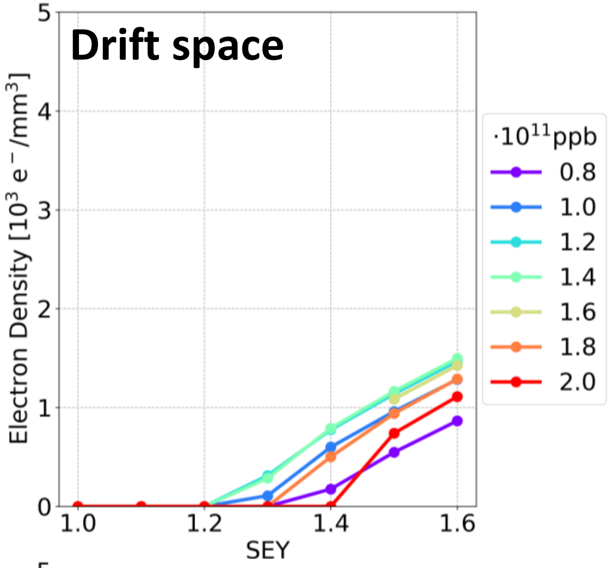
OLD

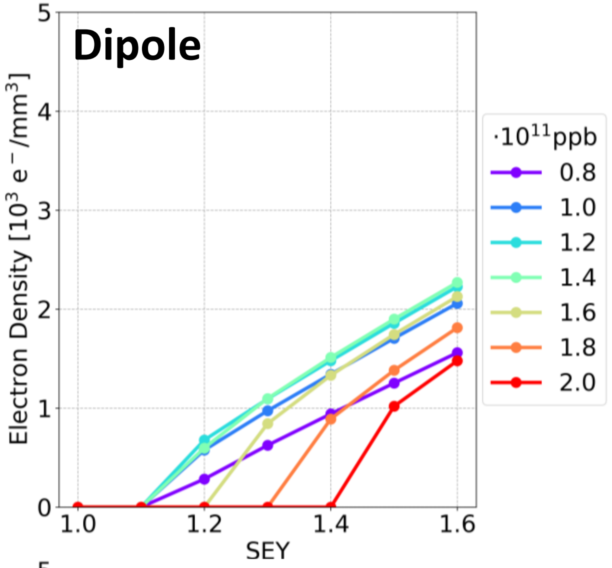


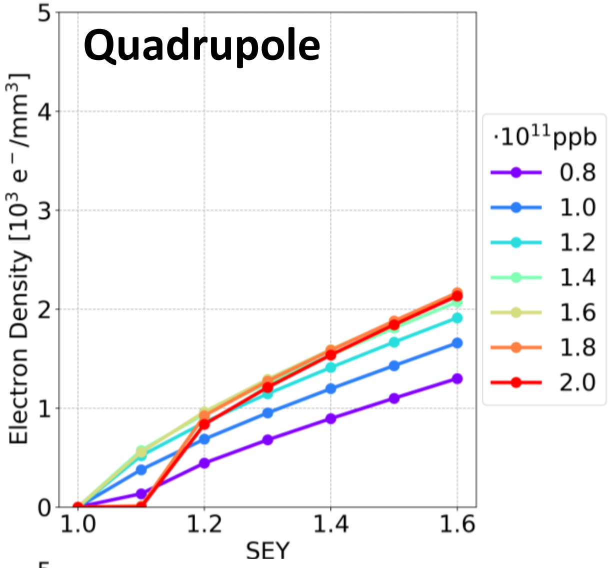
New Parameters

- Bunch spacing 25 ns, longer bunch length

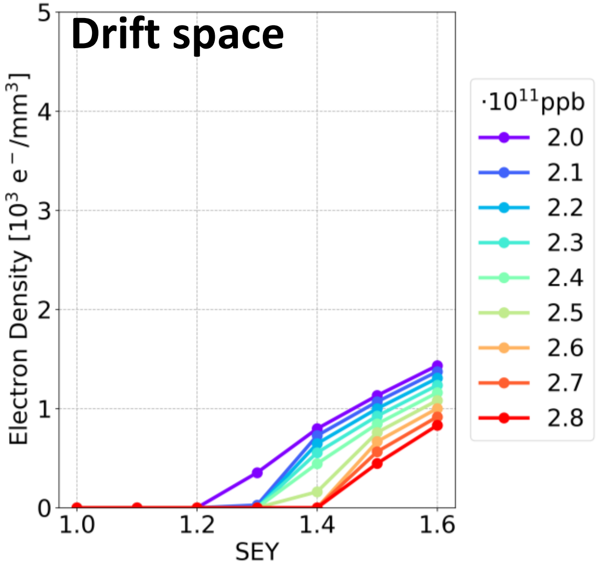
NEW

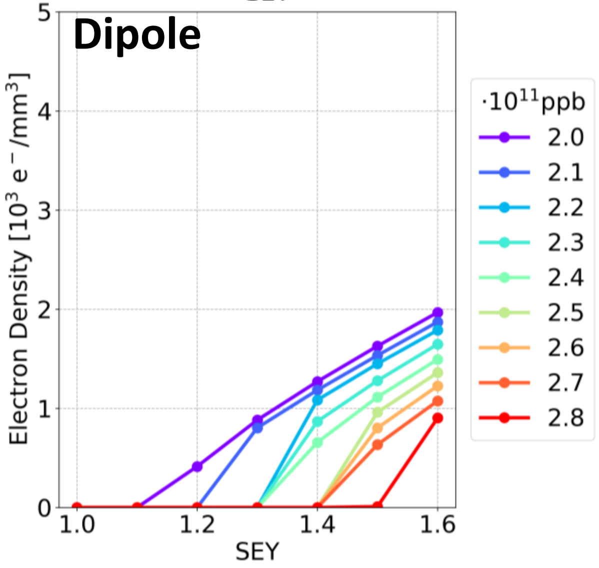


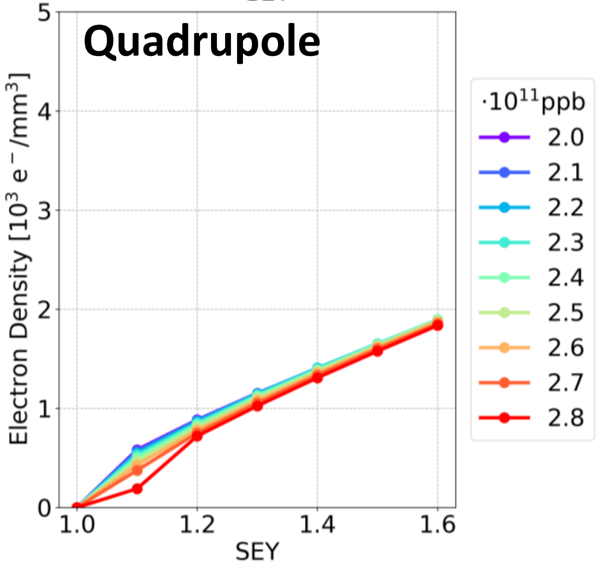




OLD

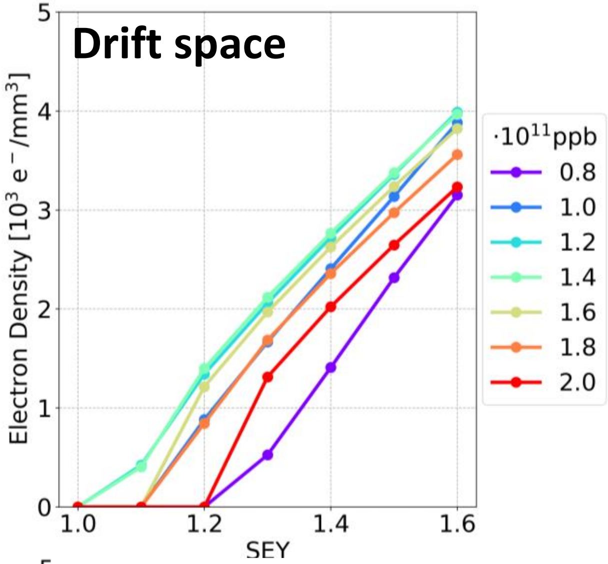


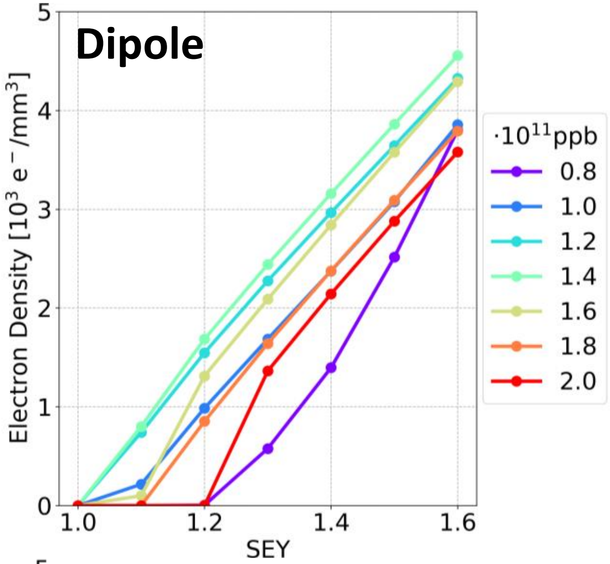


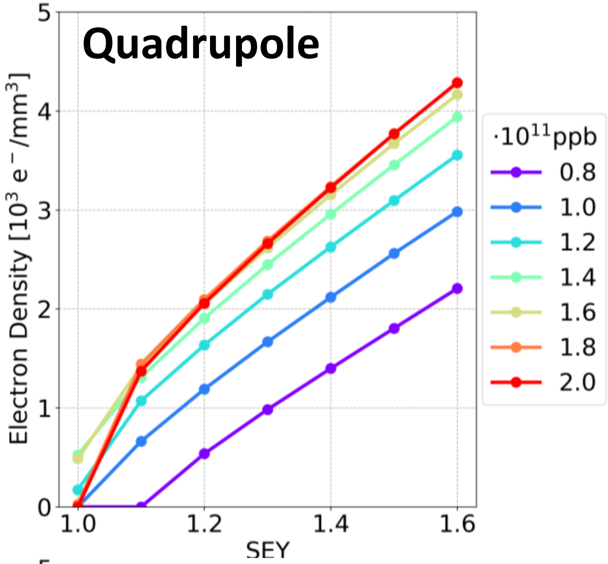


New Parameters

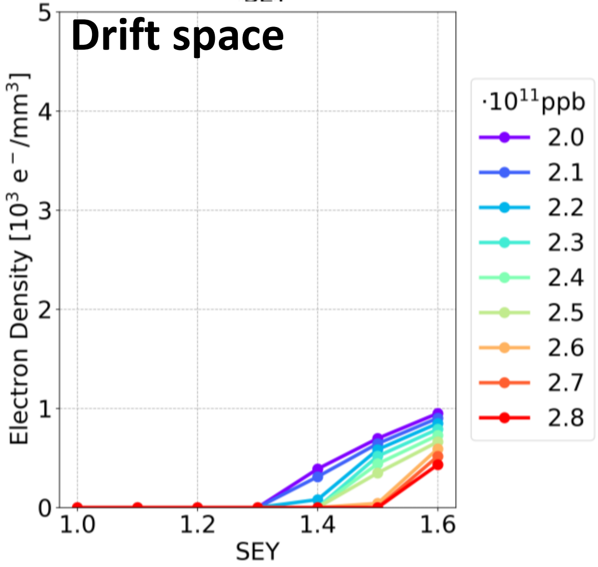
NEW
15 ns

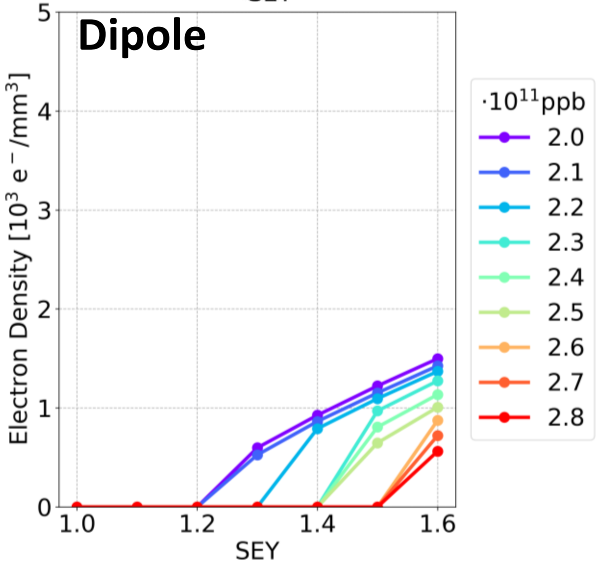


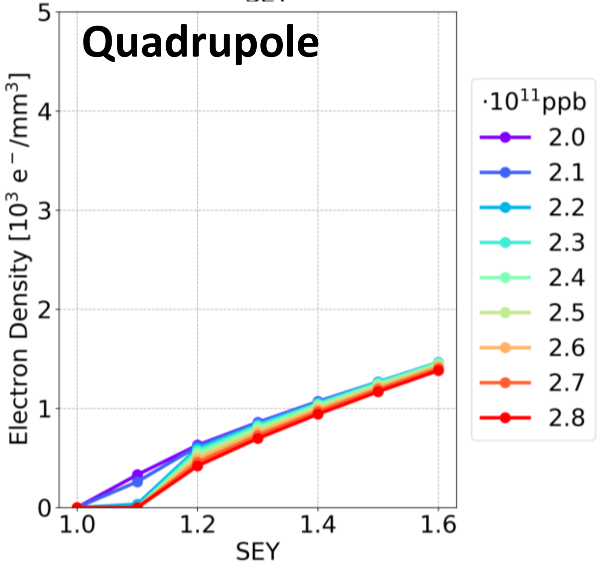




OLD
30 ns



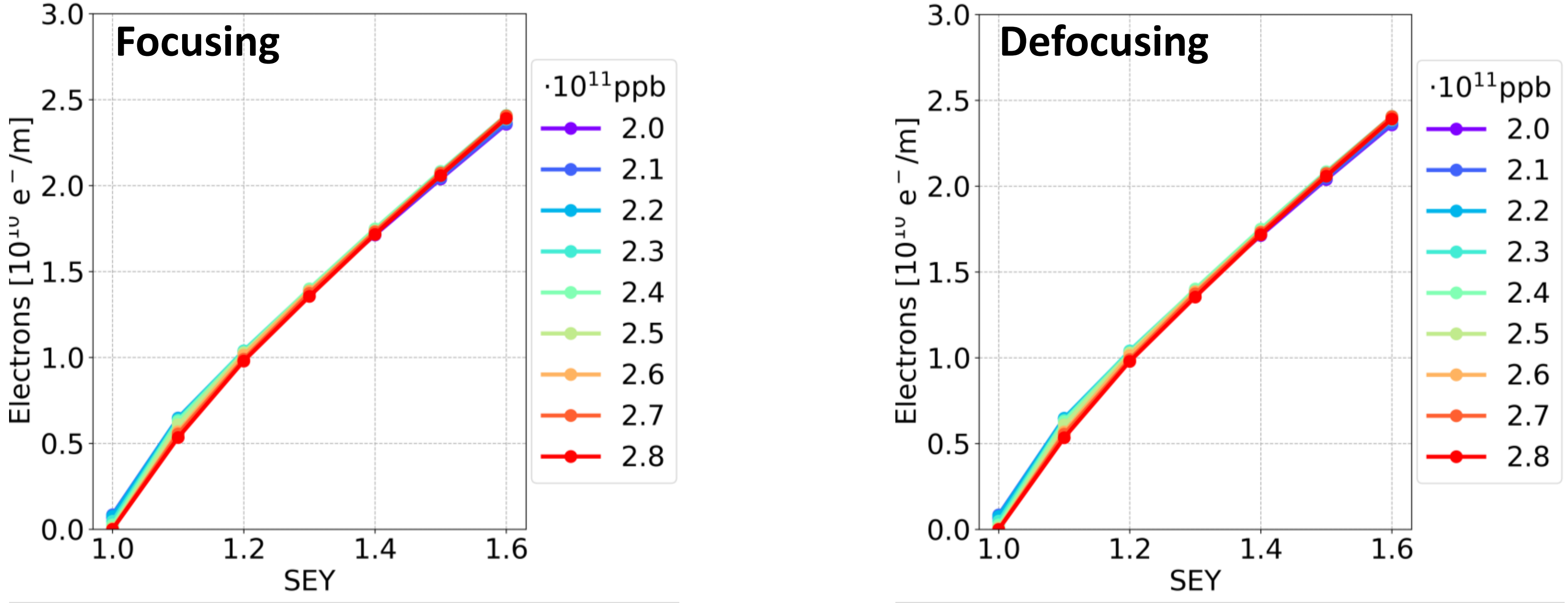




Summary Previous Results

- No dependence on beta functions found in quadrupoles and dipoles

positrons, beam chamber 9 mm, bunch spacing 10 ns

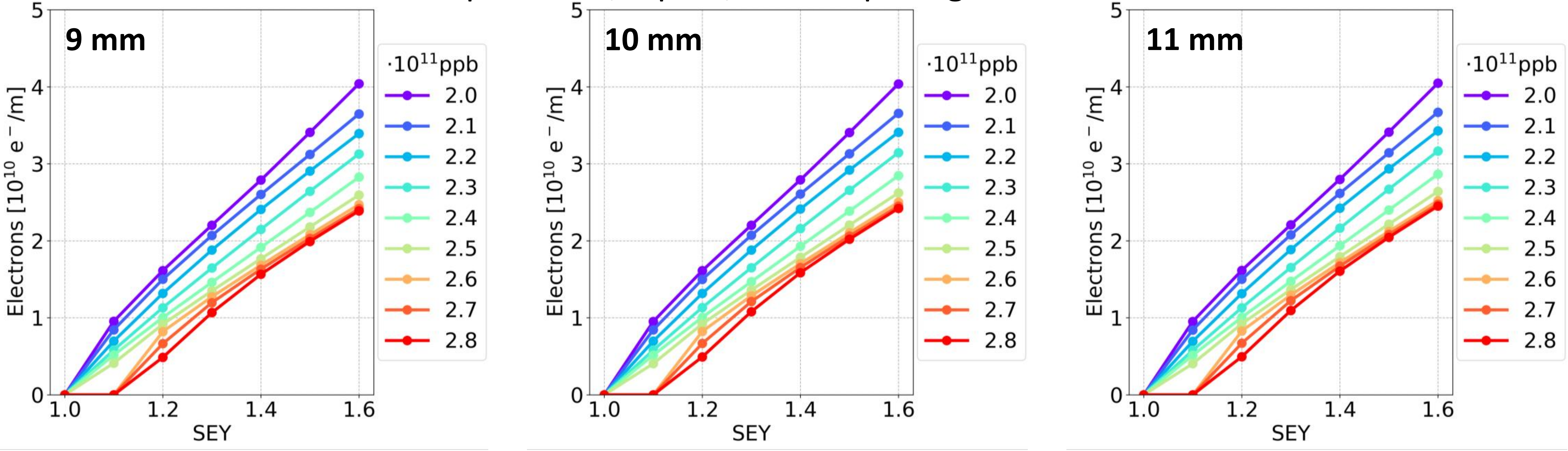


For more details: L. Sabato, 20th November 2022, “E-cloud studies in the FCC-ee”*, 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Summary Previous Results

- No dependence on the beam chamber winglet height

positrons, dipole, bunch spacing 10 ns

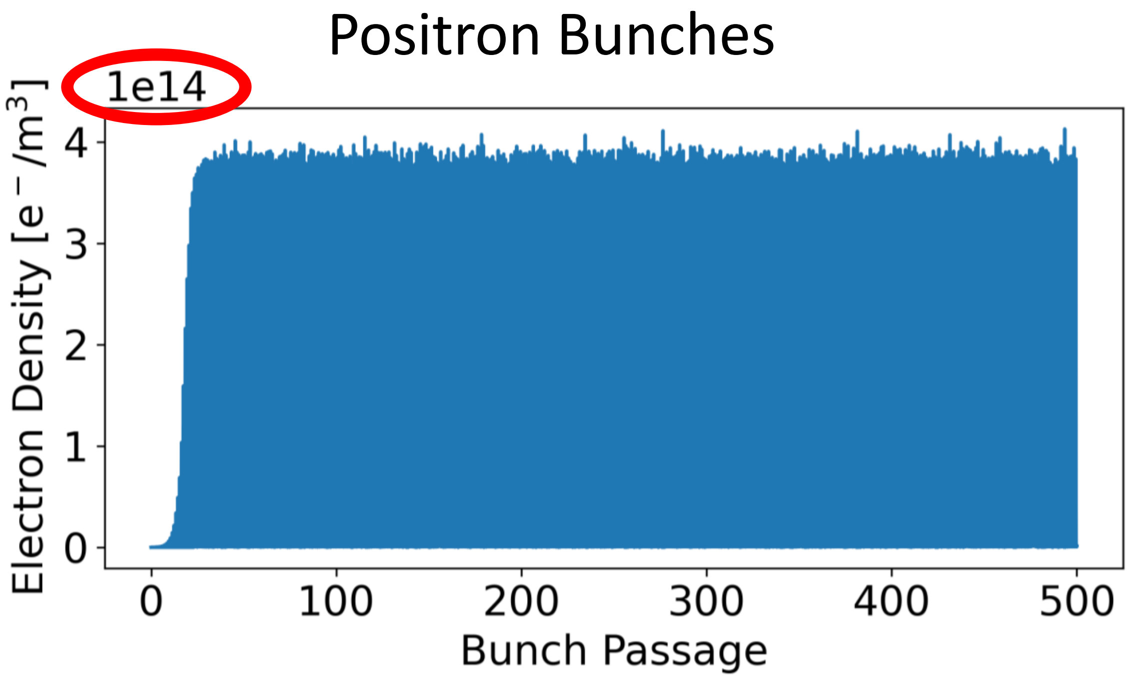


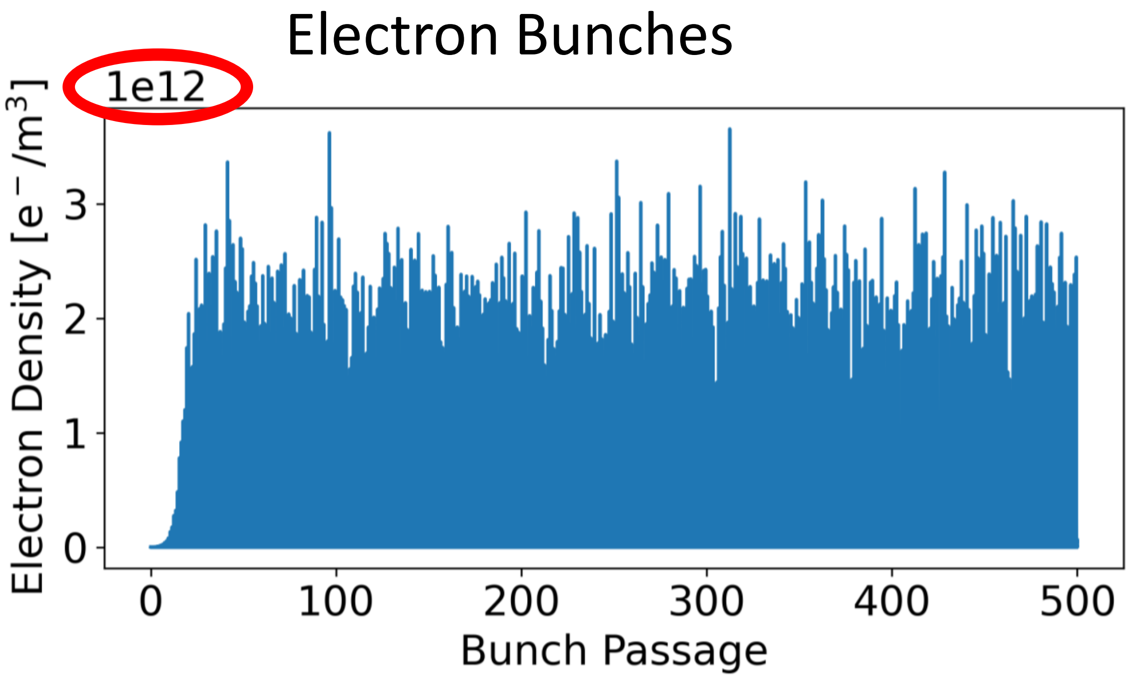
For more details: L. Sabato, 20th November 2022, "E-cloud studies in the FCC-ee", *159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting*

Summary Previous Results

- Dependence on the bunch species:

(Drift space, bunch spacing 10 ns, bunch intensity 2.0e11 ppb, SEY 1.6)





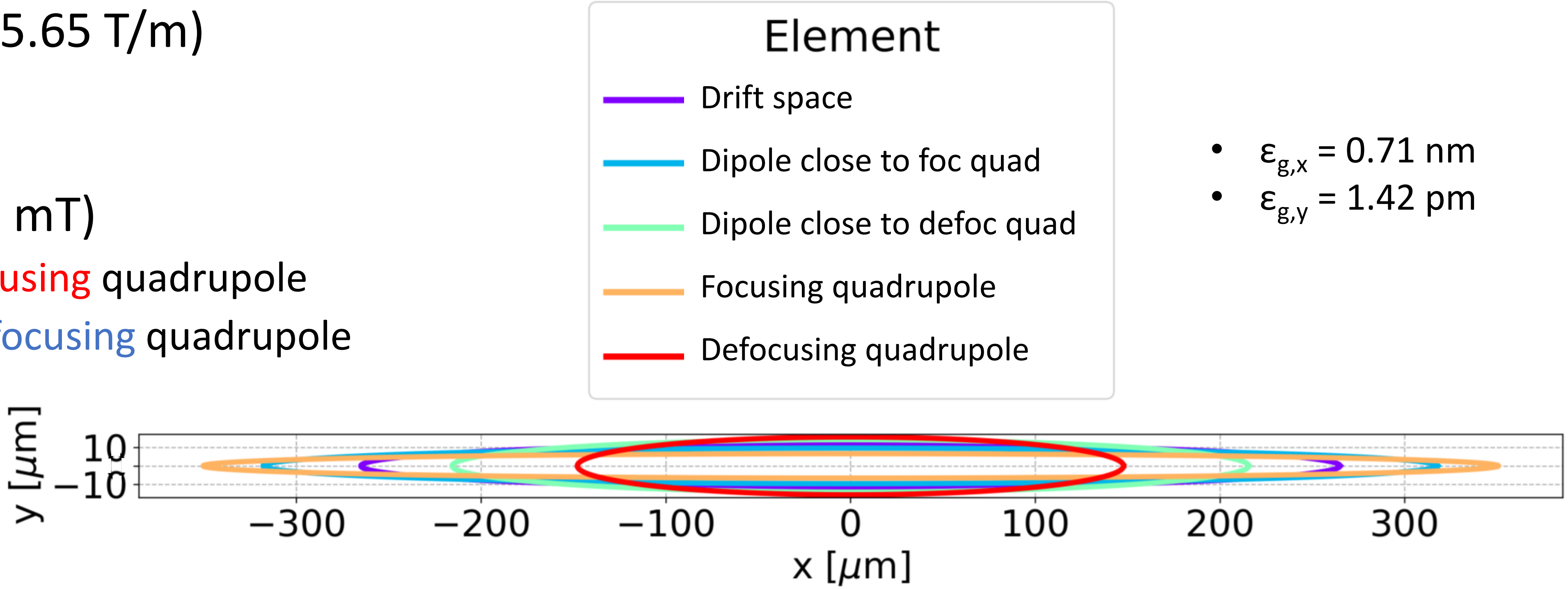
- In the case of electron bunches, the electrons are mainly located far from the beam chamber centre

For more details: L. Sabato, 20th November 2022, "E-cloud studies in the FCC-ee", 159th FCC-ee Optics Design Meeting & 30th FCCIS WP2.2 Meeting

Simulation Results: Parameter Overview

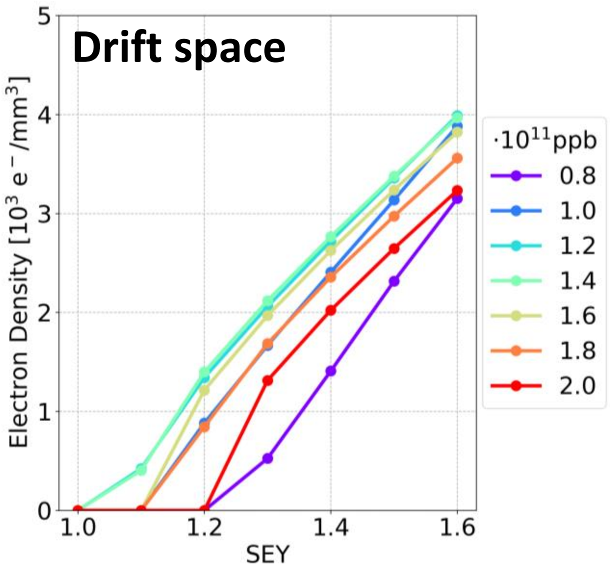
- **Element:**
  - Drift space
  - Quadrupole (5.65 T/m)
    - focusing
    - defocusing
  - Dipole (1.415 mT)
    - close to focusing quadrupole
    - close to defocusing quadrupole

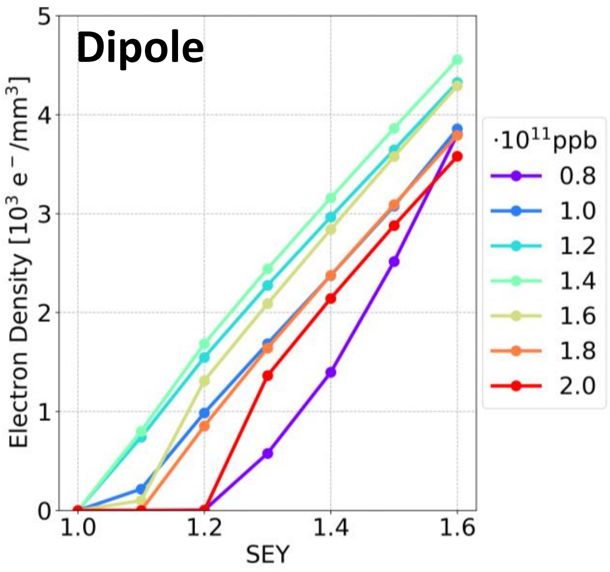
- $\varepsilon_{g,x}$ = 0.71 nm
- $\varepsilon_{g,y}$ = 1.42 pm

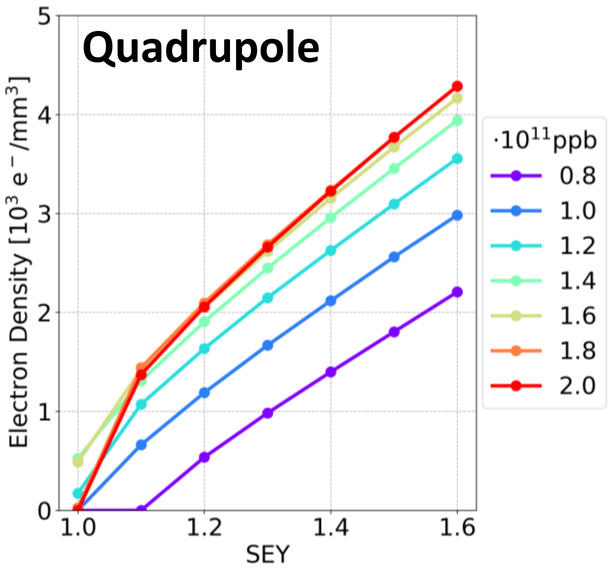


Simulation Results: New Parameters

bunch spacing 15 ns, longer bunch length



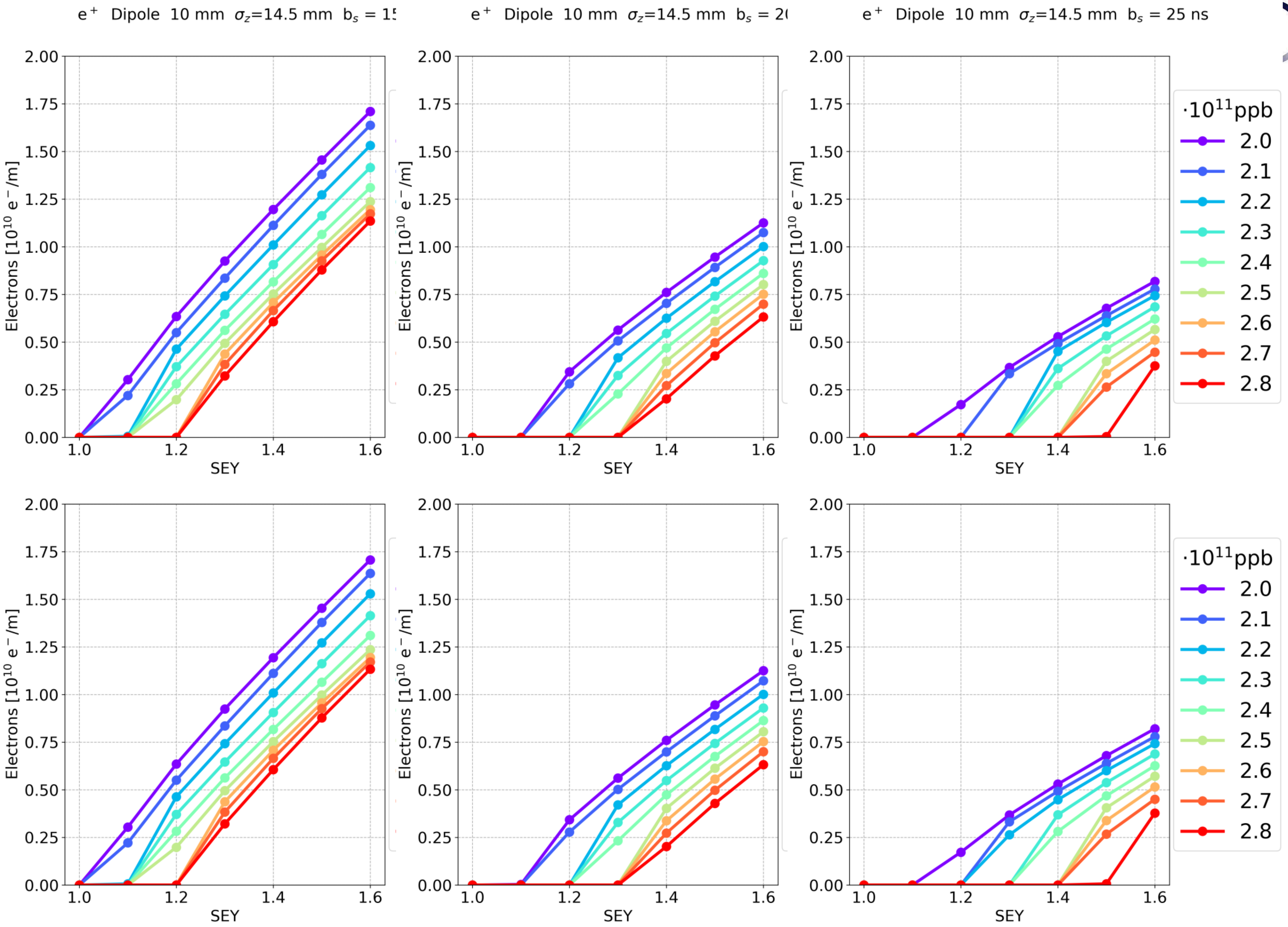




- In the drift space and dipole, the electron density has a similar behaviour with respect to the bunch intensity
  - the dependence on the bunch intensity is not monotonic
- In the quadrupole,
  - the bunch intensity has a non-negligible effect on the electron density
  - less bunch intensity less electron density

Dipole

Dipole with quadrupolar component (-9 mT/m)



In order to reduce the horizontal emittance of 10%-20%

Simulation Results: Summary Previous Results

- **Particle**
- **Beam chamber winglet geometry**
- **Element**
- **Bunch spacing:** 10 – 30 ns (step 5 ns)
- **Bunch intensity:** 2.0 – 2.8e11 ppb (step 0.1e11 ppb)
- **SEY:** 1.0 – 1.6 (step 0.1)

Total: 9,450 simulations

Simulation Results: New Parameters

- **Element:** Drift space, Dipole, Quadrupole
- **Bunch spacing:** 15 – 25 ns (step 5 ns)
- **Bunch intensity:** 0.8 – 2.0e11 ppb (step 0.2e11 ppb)
- **SEY:** 1.0 – 1.6 (step 0.1)
- **Bunch Length:** 11.8 mm

Total: 441 simulations

Stability Simulations

- The beam stability simulations are heavy from the computational point of view

- HPC cluster at INFN-CNAF (Bologna, Italy) allowing for Message Passing Interface (MPI) applications across multiple nodes
  - The cluster presently features a total of about 800 CPU-cores

Background: Case Study

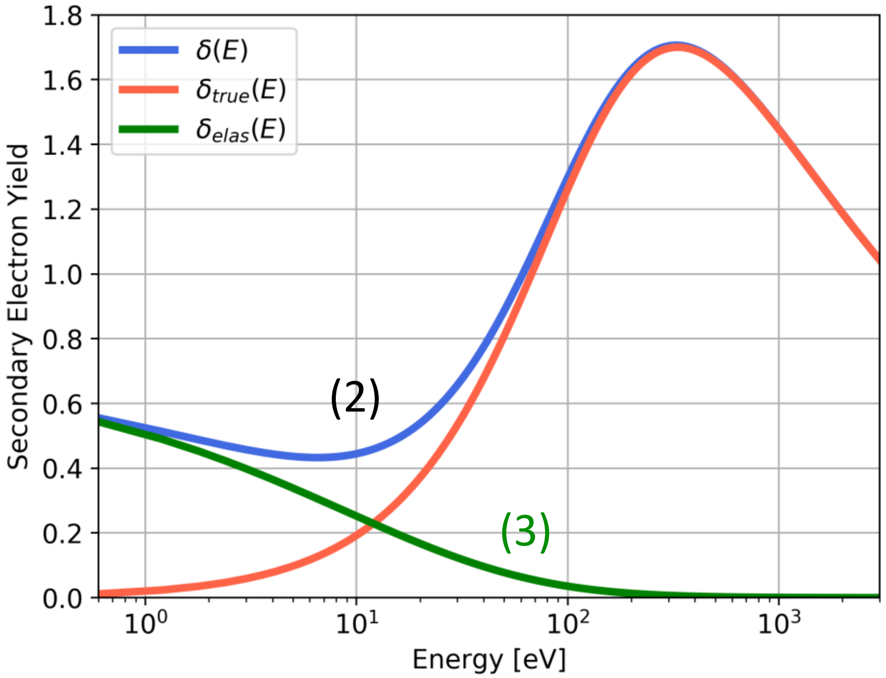
$$\delta(E) = \delta_{elas}(E) + \delta_{true}(E) \quad (2)$$

$$\delta_{elas}(E) = R_0 \left(\frac{\sqrt{E} - \sqrt{E+E_0}}{\sqrt{E} + \sqrt{E+E_0}} \right)^2 \quad (3)$$

E_0 and R_0: shape parameters.

For the LHC beam chambers:

- E_0 = 150 eV
- R_0 = 0.7

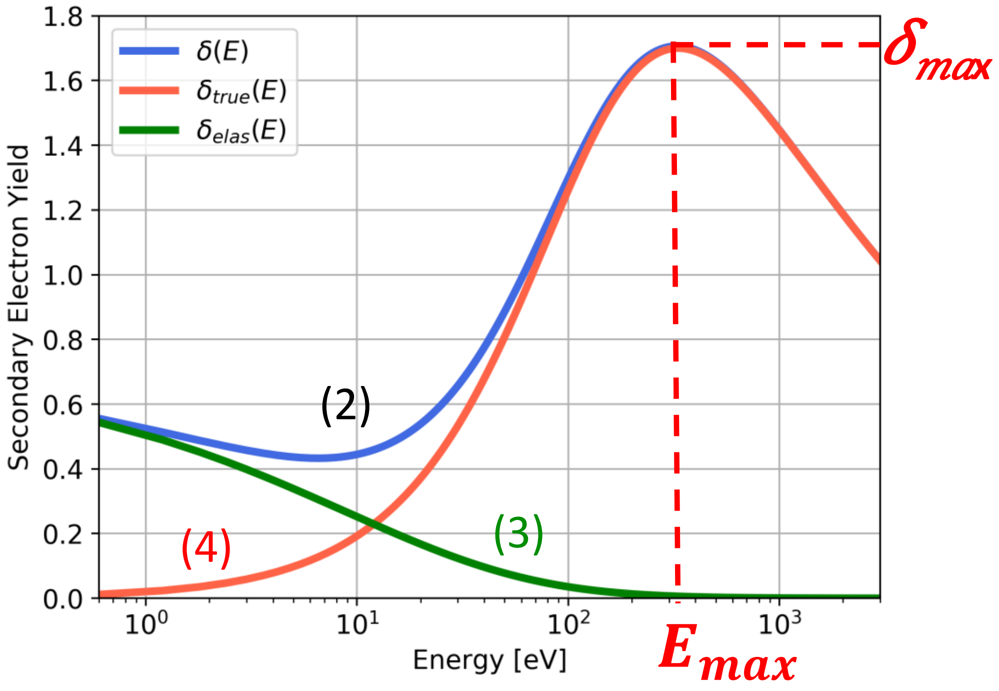


Background: Case Study

$$\delta(E) = \delta_{elas}(E) + \delta_{true}(E) \quad (2)$$

$$\delta_{true}(E) = \delta_{max} \frac{s\frac{E}{E_{max}}}{s-1+\left(\frac{E}{E_{max}}\right)^{s}} \quad (4)$$

- s: shape parameter;
- δ_{max}: maximum of the SEY curve dependent on the surface material, roughness and history
- E_{max}: electron energy, where the SEY reach the maximum δ_{max}: $\delta(E_{max}) \cong \delta_{true}(E_{max}) = \delta_{max}$



For the LHC beam chambers:

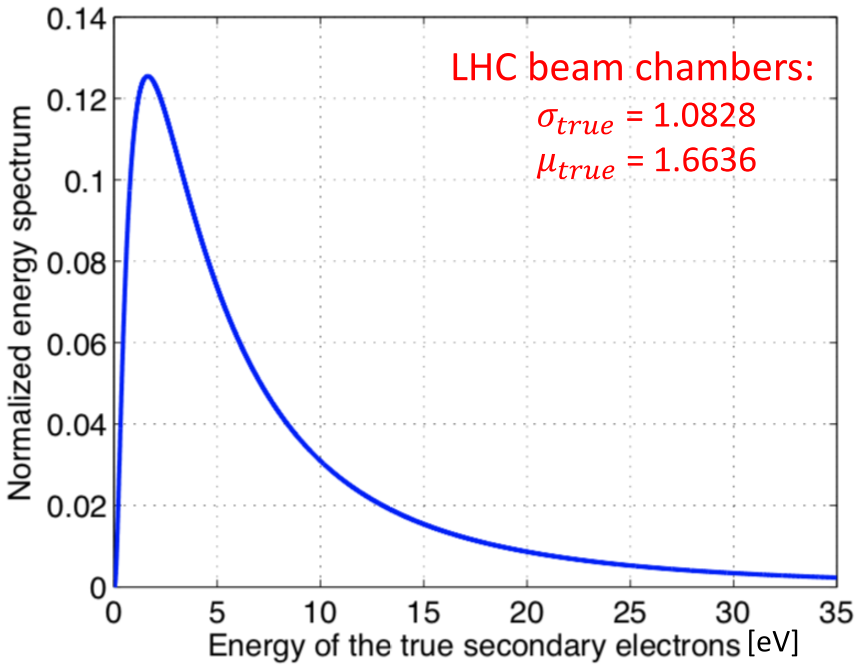
- s = 1.35
- E_{max} = 332 eV

Background: Case Study

Parameter Overview

Secondary emission model:

$$\frac{dn_{true}}{dE} = \frac{1}{E\sigma_{true}\sqrt{2\pi}} e^{-\frac{(ln(E)-\mu_{true})^2}{2\sigma_{true}{}^2}}$$



[] B. Henrist et al., "Secondary Electron Emission Data for the Simulation of Electron Cloud", cds 2002.

Project Goals

The goal is to go below the SEY threshold for instabilities driven by e-cloud

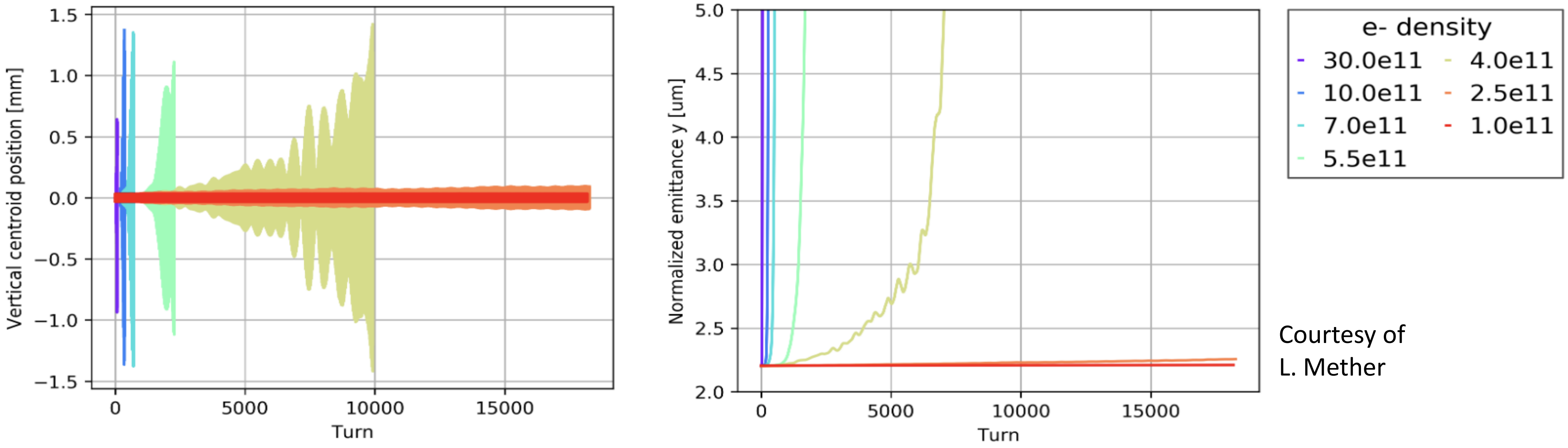
Comparison between the analytical central electron density threshold for single bunch instability and the simulation results

Analytical equation

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} \quad \text{with} \quad \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}, \qquad K = \omega_e\sigma_z/c, \quad Q = \min(\omega_e\sigma_z/c, 7)$$

[] K. Ohmi et al., "Study of Electron Cloud Instabilities in FCC-hh", Proc. of IPAC2015

Single-bunch stability simulations in dipoles



Courtesy of L. Mether