Electron Cloud Studies for the FCC-ee

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Outline

- Introduction
- E-Cloud Build-Up Studies
- Heat Loads
- Stability Studies
- Photoemission
- Conclusions and Outlooks

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- **Introduction**
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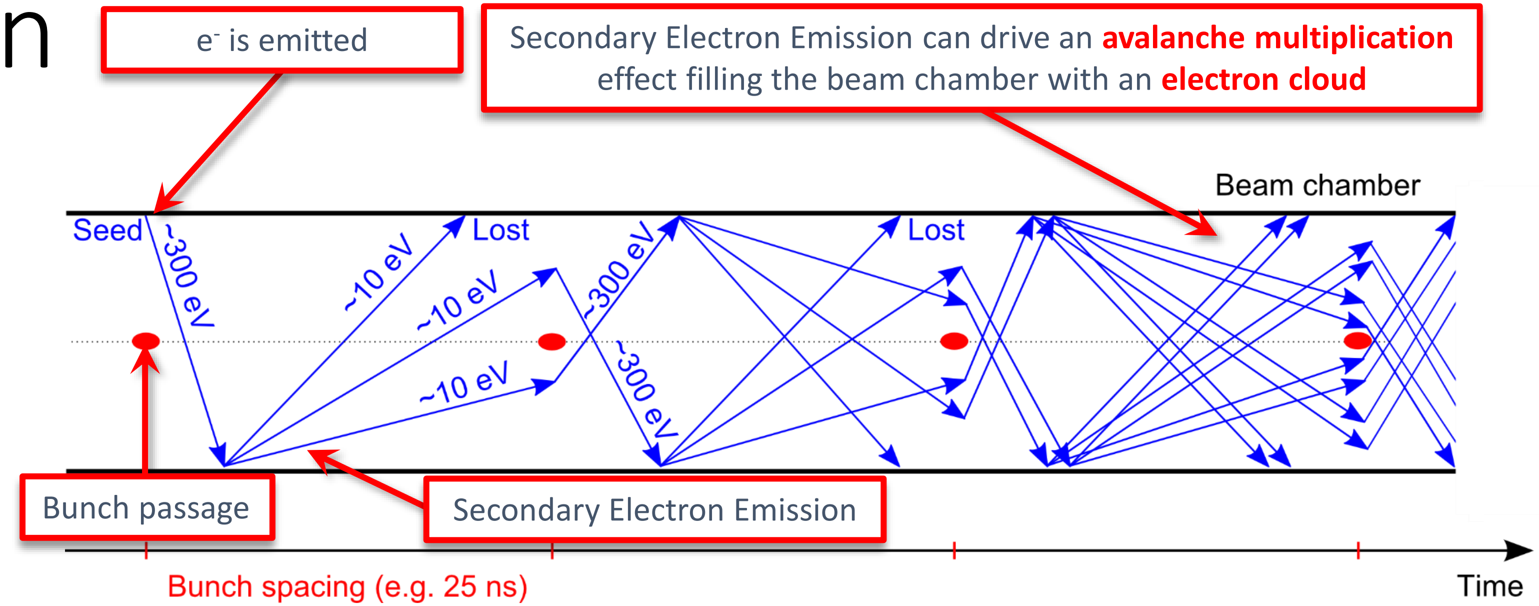
E-Cloud Formation



Courtesy of G. Iadarola

- The circulating beam particles can produce primary electrons (seed)
  - ionisation of the residual gas in the beam chamber
  - photoemission from the chamber's wall due to the synchrotron radiation emitted by the beam
- With the particle bunch passage
  - primary electrons can be accelerated to energies up to hundreds of eV
  - after impacting the wall, secondary electrons can be emitted
- Secondary electrons have energies of tens of eV
  - after impacting the wall, they can be either absorbed or elastically reflected
  - if they survive until the passage of the following bunch, they can be accelerated, projected onto the wall and produce secondaries
- Secondary electron emission can drive an avalanche multiplication effect

E-Cloud Parameters

- 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):

$$\delta(E) = \frac{I_{\mathrm{emit}}}{I_{\mathrm{imp}}(E)}$$

  - SEY depends on
    - surface chemical properties
    - history of the surface, in particular on accumulated electron dose -> to a certain extent the e-cloud cures itself (beam induced scrubbing)
- 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 is triggered
- Bunch intensity and bunch length also have an important effect as they affect the acceleration received by the electrons
- Electron trajectories are strongly influenced by externally applied magnetic fields (e.g., dipoles, quadrupoles, and so on)

FCC-ee MidTerm Report Parameters

Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]		100		
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Hor. IP beam size σ_x^* [μm]	9	21	13	40
Vert. IP beam size σ_y^* [nm]	36	47	40	51
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Total beam lifetime [min.]	15	12	12	11
Int. annual luminosity / IP [ab^{-1}/yr]	17†	2.4†	0.6	0.15‡

† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;
‡ The integrated luminosity in the first year, at a lower beam energy of about 173 GeV, is assumed to be about 65% of this value to account for the machine commissioning and beam tuning. The smaller time for commissioning compared with the lower energy running reflects the LEP/LEP-2 experience.

From FCC MidTerm Report

- 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)

Possible Filling Schemes

Filling schemes (with constant total number of particles per beam)

From Tor Raubenheimer

Filling Scheme Number	Bunch Intensity [x10^{11} ppb]	Bunch Spacing [ns]	Number bunches / Train	Number Trains	Gap Length [ns] (gap/bunch spacing)
1	2.15	20	280	40	1980 (99)
2	2.15	25	560	20	1175 (47)

- Important to understand the impact of lower bunch intensity (we will need to fill the ring)

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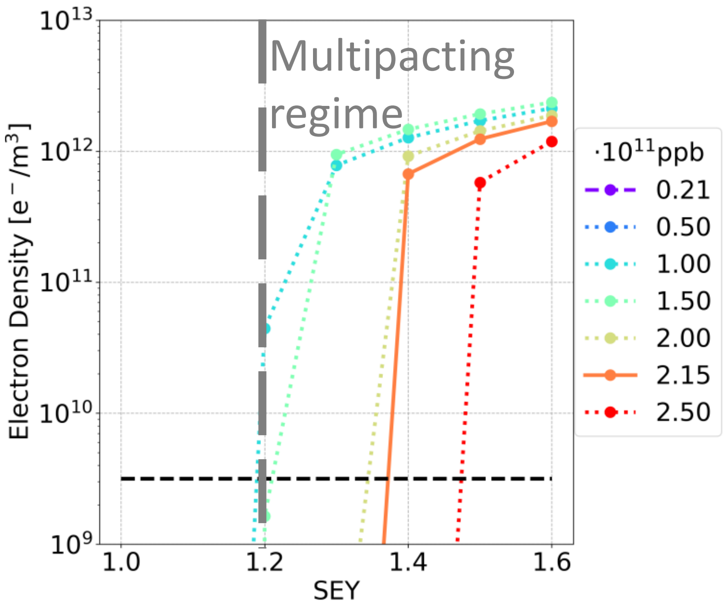
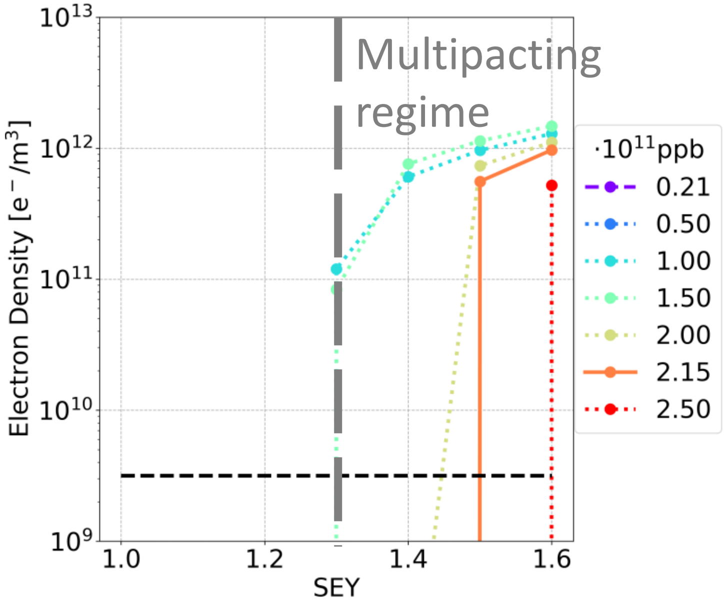
E-Cloud Build-Up Studies: Drift Space

Find the material propriety constraints to avoid e-cloud avalanche multiplication (multipacting)

Filling scheme 1



Filling scheme 2



The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.3	1.4
SEY threshold (all intensity below nominal one)	1.1	1.2

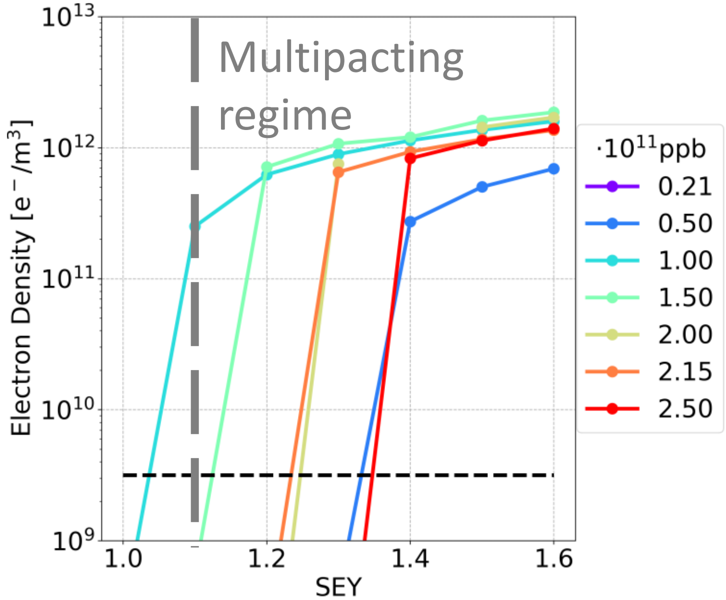
E-Cloud Build-Up Studies: Summary

- Quadrupoles and sextupoles are the most critical elements from the e-cloud point of view
- Larger SEY multipacting thresholds considering the filling scheme 2 (25 ns bunch spacing)
- Bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

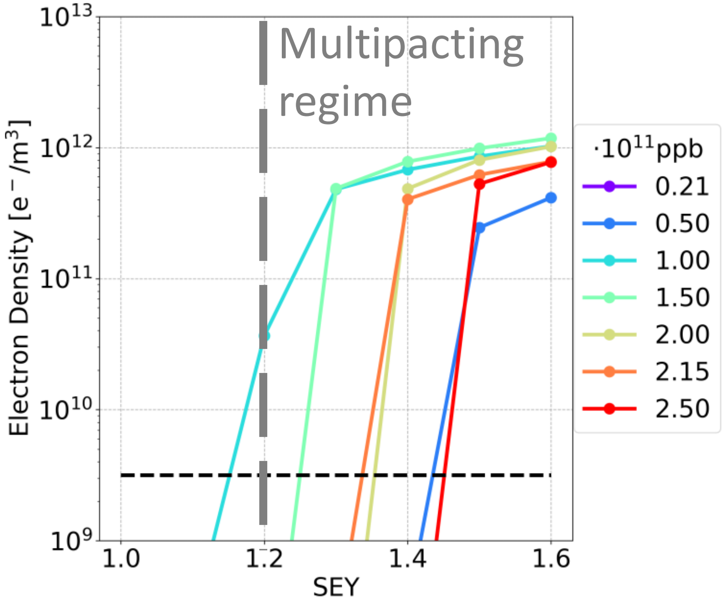
Element	SEY Threshold	Filling Scheme 1	Filling Scheme 2
Drift Space	nominal intensity	1.3	1.4
	all intensity below nominal one	1.1	1.2
Dipole (15.2 mT)	nominal intensity	1.3	1.4
	all intensity below nominal one	1.0	1.0
Quadrupole (1.45 T/m)	nominal intensity	1.1	1.2
	all intensity below nominal one	1.0	1.0
Sextupole (72.5 T/m^2)	nominal intensity	1.1	1.1
	all intensity below nominal one	1.0	1.0

Bunch Spacing

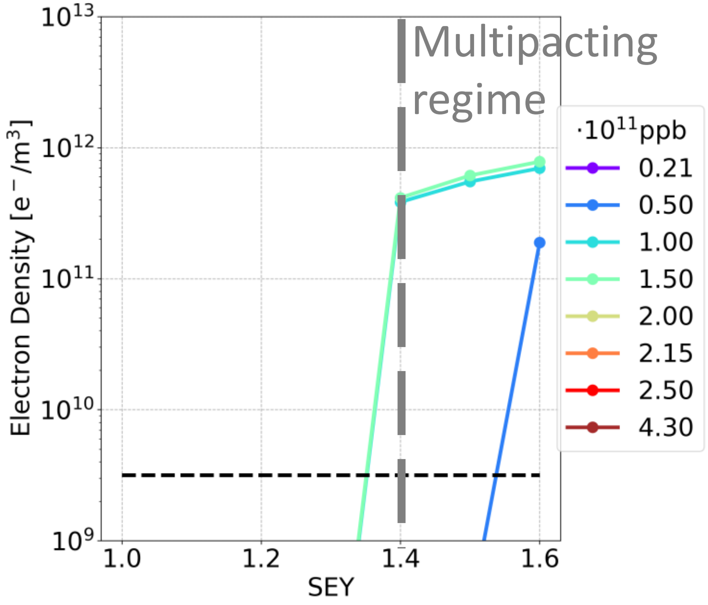
30 ns



40 ns



50 ns



- Choosing a larger bunch spacing -> larger SEY multipacting thresholds
- For example, for the most critical element (quadrupole):
  - the SEY multipacting threshold is 1.0 with a bunch spacing of 25 ns
  - the SEY multipacting threshold is 1.0 with a bunch spacing of 30 ns
  - the SEY multipacting threshold is 1.1 with a bunch spacing of 40 ns
  - the SEY multipacting threshold is 1.3 with a bunch spacing of 50 ns

Bunch Spacing: Summary

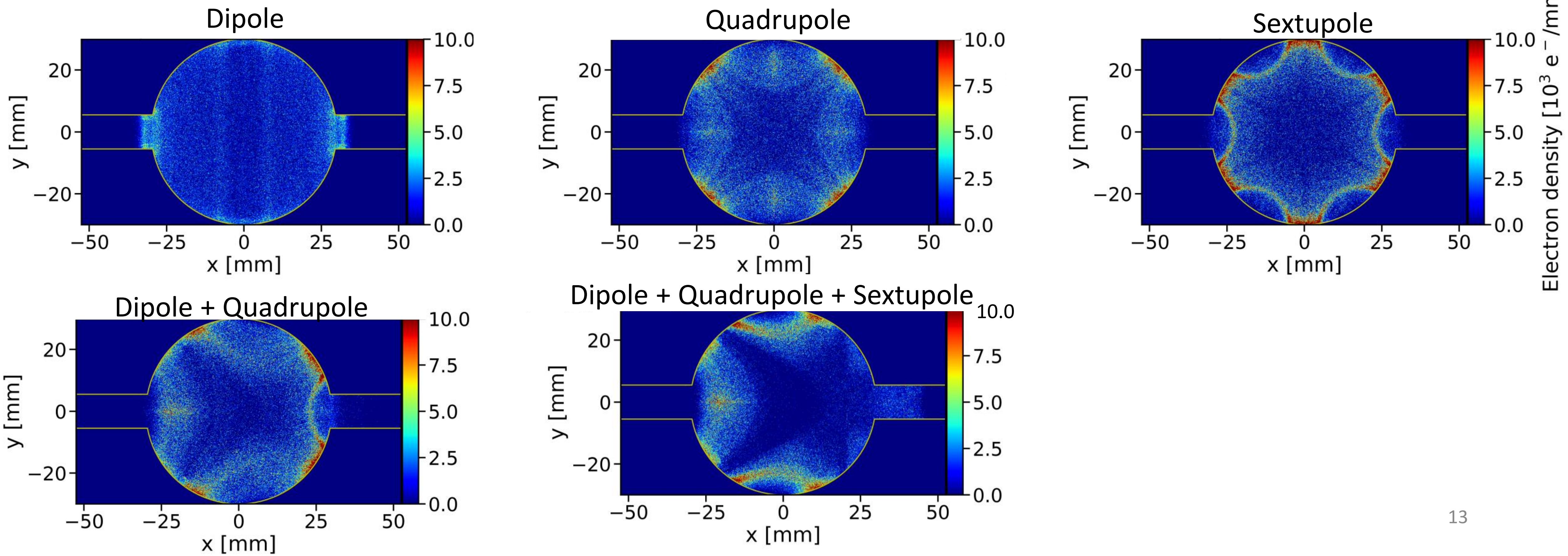
SEY Multipacting thresholds
(considering all intensity below nominal one)

Larger bunch spacing

Element	20 ns	25 ns	30 ns	40 ns	50 ns
Drift Space	1.1	1.2	1.3	1.5	> 1.6
Dipole (15.2 mT)	1.0	1.0	1.1	1.2	1.3
Quadrupole (1.45 T/m)	1.0	1.0	1.0	1.1	1.3
Sextupole (72.5 T/m^2)	1.0	1.0	1.1	1.3	1.4

Outlooks: Nested Magnets

- Nested Magnets under exploration by overlapping dipole fields with arc quadrupoles and sextupoles
  - Thereby increasing the dipole filling factor and reducing the synchrotron radiation
- On going development on HTS SSS magnets development (Koratzinos et al.)
- On going studies on nested magnet alternative optics (more details in L. Van Riesen-Haupt presentation)
- The configurations with nested magnets have to be studied from the e-cloud point of view



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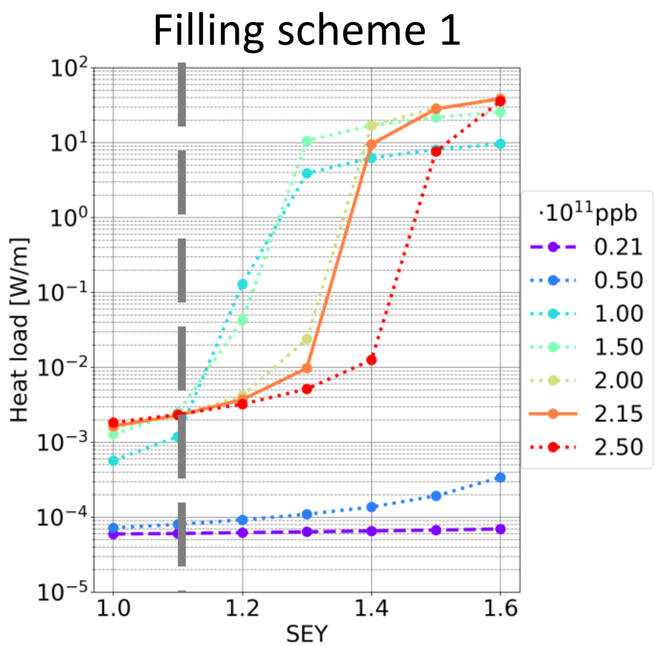
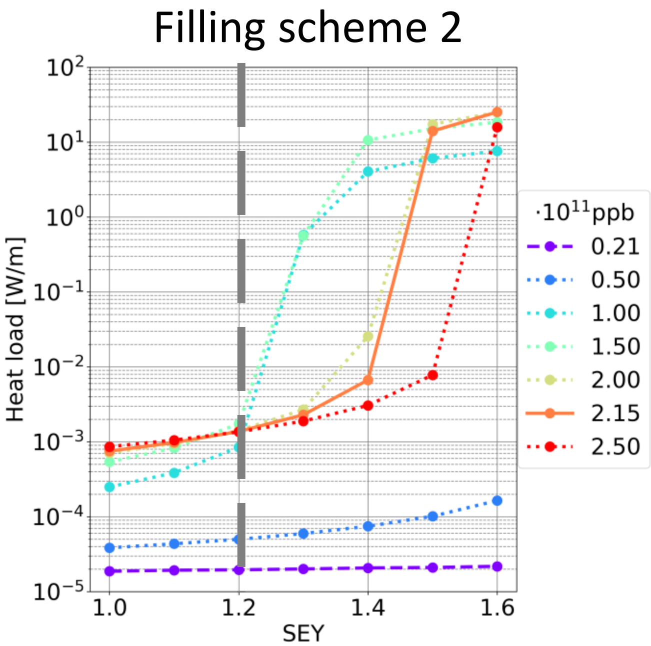
Heat Loads: Drift Space





L_{drift} = 17.4 km (L_{drift} /L = 19.18%)

Synchrotron radiation power: ~50 MW per beam

If multipacting (considering nominal bunch intensity and maximum simulated SEY=1.6):

Filling scheme 1: ~38.7 W/m -> full circumference ~673 kW ~1.35% of synchrotron radiation power

Filling scheme 2: ~25.3 W/m -> full circumference ~439 kW ~0.88% of synchrotron radiation power

If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

Filling scheme 1 (SEY<=1.1) & 2 (SEY<=1.2): smaller than 0.01 W/m -> full circumference smaller than 200 W ~0.0004% of synchrotron radiation power

Heat Loads: Summary

- In case there is multipacting, the total heat loads are in the order of:
  - 7% of synchrotron radiation power for the filling scheme 1
  - 5% of synchrotron radiation power for the filling scheme 2
- Heat loads are smaller considering the filling scheme 2 (25 ns bunch spacing)
- Dipoles are the main contributors to the total heat loads
- If there is no multipacting, the total heat loads are negligible compared to the synchrotron radiation power

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E-Cloud Stability Threshold

- E-cloud could trigger instabilities, because the beams pass through the e-clouds and they receive transverse kicks

- Which is the e-cloud density stability threshold?

1. Theoretical equation:

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L} \qquad \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}} \qquad \begin{matrix} K = \omega_e\sigma_z/c \\ Q = \min(K,7) \end{matrix} \qquad \lambda_p = \frac{i_b}{\sqrt{2\pi}\sigma_z}$$

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

2. Simulations by means of PyECLOUD-PyHEADTAIL suite in order to track the beams through the e-clouds

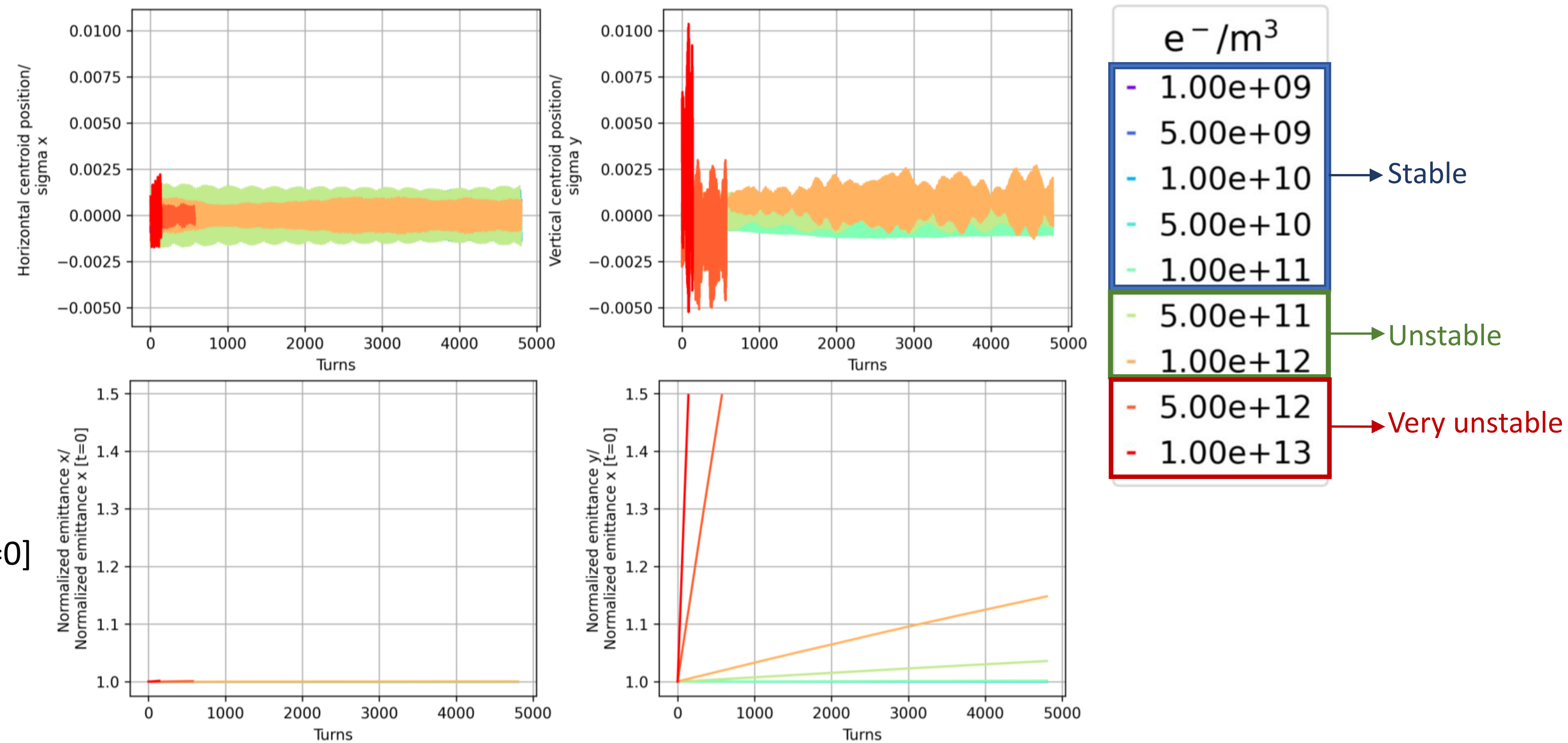
E-Cloud Stability Simulation Threshold: Drift Space

- $\rho_{e,th} = 9.53 \cdot 10^{10}\ e^{-}/m^3$ considering only the drift length L_{drift} = 17.4 km (L_{drift}/L = 19.18%)

Horizontal Vertical

Centroid/
Sigma

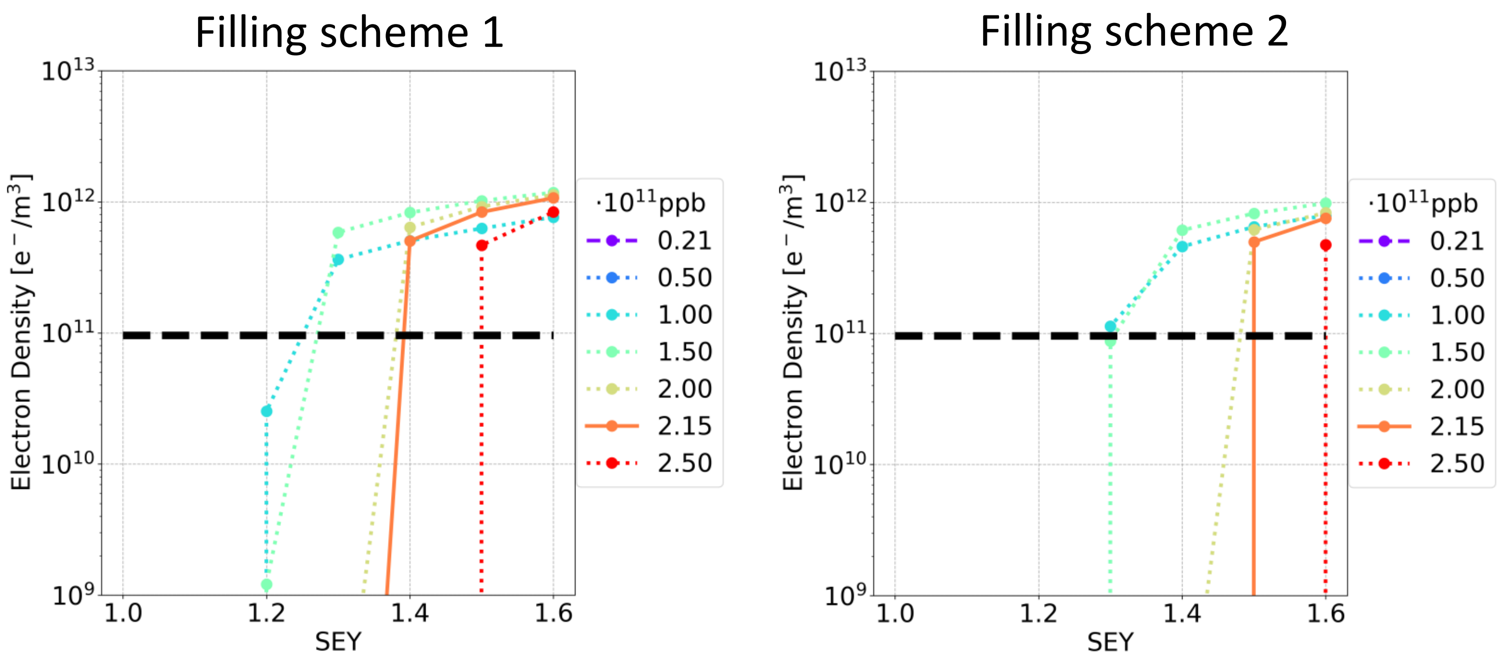
Normalised emittance/
Normalised emittance [t=0]



- Theoretical and numerical e-cloud density stability threshold have the same order of magnitude
- Vertical plane is unstable

E-Cloud Stability: Drift Space

- E-cloud stability threshold has to be compared with the e-cloud density
  - before the bunch passage
  - close to the vacuum chamber centre



- Above the SEY multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold -> lead to beam instabilities

E-Cloud Stability: Summary

- Dipoles and Quadrupoles
  - Above the SEY multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold -> lead to beam instabilities

- Sextupoles
  - The central e-cloud density before the bunch passage is smaller than the e-cloud stability threshold (element length dependence)

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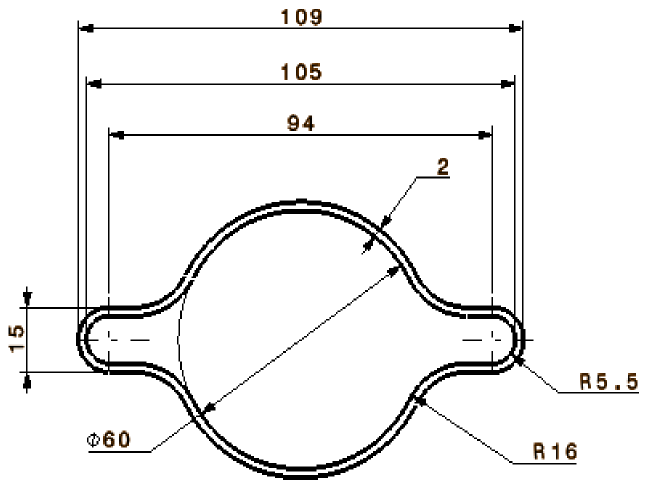
Photoemission

- The circulating beam particles can produce primary electrons (seed)
  - ionisation of the residual gas in the beam chamber
  - **photoemission** from the chamber's wall due to the synchrotron radiation emitted by the beam

- The results presented in the previous slides do not take into account the photoemission What is the impact of the photoelectrons on the e-cloud formation process?

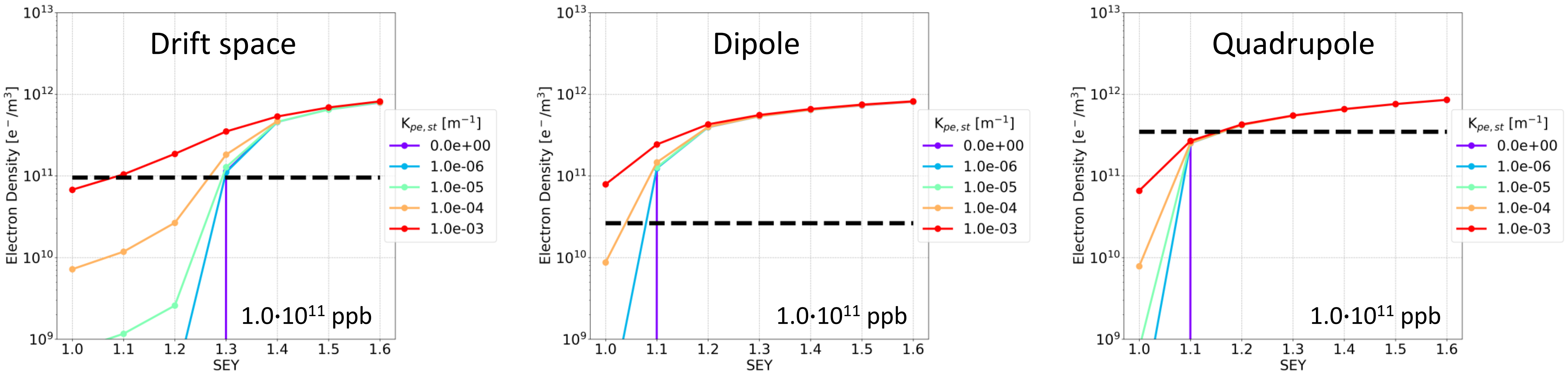
- In PyECLOUD:
  - $K_{pe,st}$: [m^{-1}] Number of photoelectrons to be generated per beam particle (positron) and per unit length
  - Photoelectrons uniformly generated per segment of the vacuum chamber



More details in *Pyziak Lucas'* presentation:
https://indico.cern.ch/event/1412362/contributions/5936228/attachments/2852012/4987248/EC_sim_studies_photoemission.pdf

Photoemission

- Taking into account the photoemission in the e-cloud formation process
  - the e-cloud density saturation value could be reached in less bunch passages and it could be larger
  - the gap length, needed to clean the vacuum chamber, could be larger



- The central e-cloud density before the bunch passage could be larger than the e-cloud stability threshold even below the SEY multipacting threshold (even in the case of 25 ns bunch spacing)
- High values of $K_{pe,st}$ should be avoided ($<10^{-4}$ m^{-1})

Photoemission

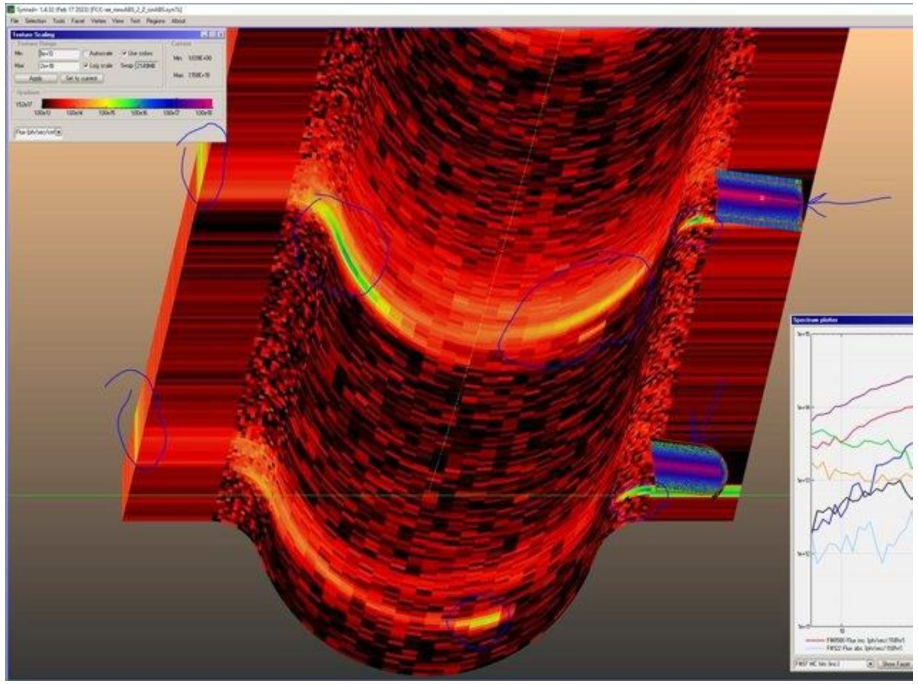
- Photoelectron Yield Y: number of photoelectrons emitted per impinging photon
  - property of the beam chamber surface

$$Y = \frac{I K_{pe,st}}{\phi L e}$$

- $K_{pe,st}$: [m^{-1}] Number of photoelectrons to be generated per beam particle (positron) and per unit length
- ϕ: photon flux
- *I:* beam current (1.27 A)
- *L:* chamber's perimeter (278 mm)
- *e:* elementary charge

Courtesy of Roberto Kersevan

ϕ: realistic photon flux -> from raytracing codes (e.g., SYNRAD+)



- From previous simulations of Roberto Kersevan (ongoing studies):
  - Photon flux around 10^{13} - 10^{14} photons/cm^2 s (not in the absorber areas)

High values of $K_{pe,st}$ should be avoided ($<10^{-4}$ m^{-1})

↓

$Y < 2.86 \cdot 10^{-3}$ (considering photon flux 10^{14} photons/cm^2s, most conservative)

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Conclusions

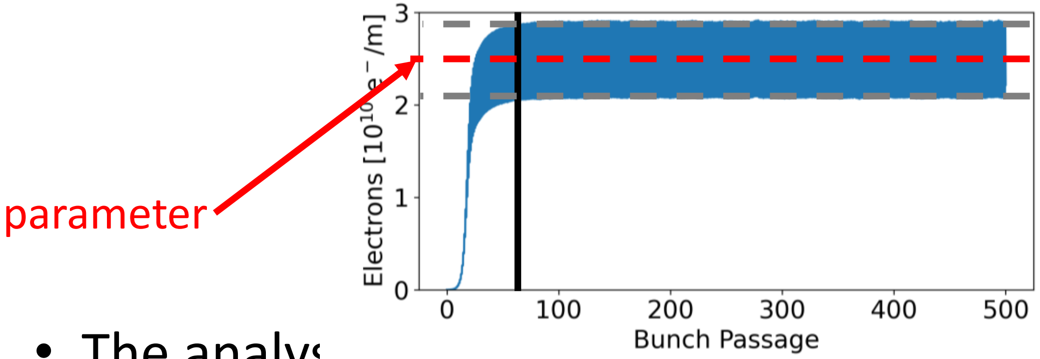
- An extensive study related to the effects of the e-cloud for FCC-ee with the midterm report parameters and alternative scenarios has been presented
- Material constraints in order to avoid e-cloud avalanche multiplication have been provided in terms of SEY multipacting thresholds
  - Extremely tight for baseline parameters
  - Quadrupoles and sextupoles are the most critical elements
  - Bunch intensities in the range of 1/10 of the nominal intensity to the nominal intensity are the most critical cases
  - SEY multipacting thresholds are better considering larger bunch spacing
- E-cloud avalanche multiplication could lead to additional heat loads
  - In the order of some percent of synchrotron radiation power
  - Dipoles are the main contributors to the heat loads
- E-cloud could lead to transverse beam instabilities
  - Simulations show that the vertical plane is the most unstable
  - In all the studied elements (except sextupoles): above the SEY multipacting thresholds, the beam is unstable
- Considering the additional contribution of the photoemission on the e-cloud formation process, the beam could be unstable even below the SEY multipacting threshold
- Methods to mitigate e-cloud instabilities can be investigated: increase bunch spacing, use filling schemes to avoid critical bunch intensities in the accumulation phase (more details in H. Bartosik presentation), feedback systems, chromaticity, …

Thanks for your attention

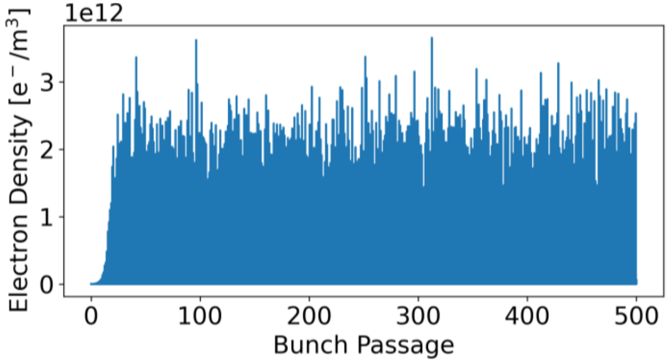
E-Cloud Build-Up Studies

- To find the SEY multipacting threshold, we considered the e-cloud density in the full chamber (less noisy than the central e-cloud density)

Total electrons in the chamber



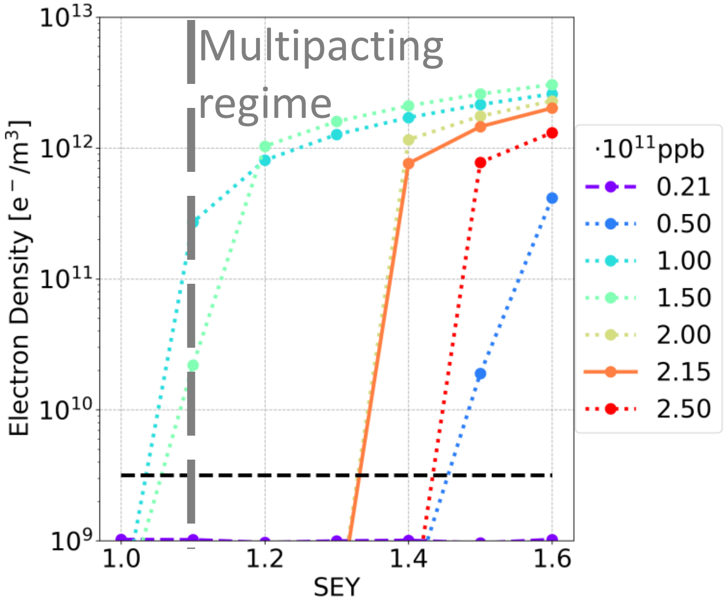
Electrons close the chamber centre



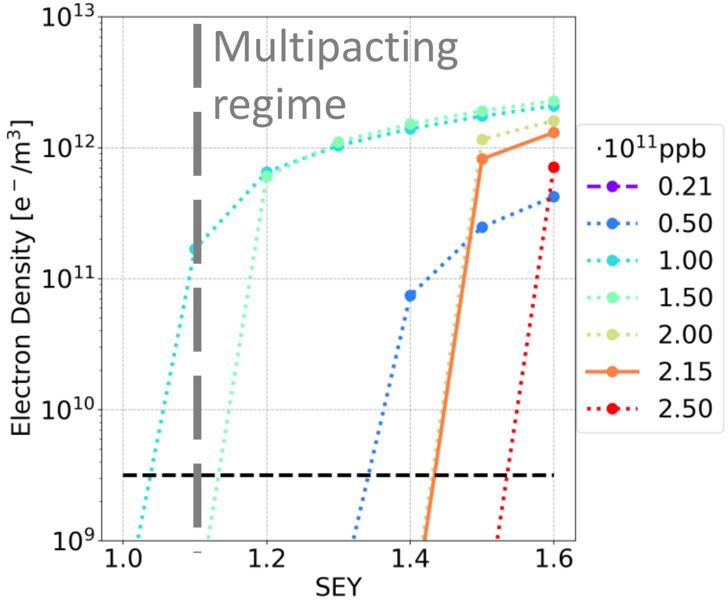
- The analys the ave aturation value is reached

E-Cloud Build-Up Studies: Dipole

Filling scheme 1



Filling scheme 2

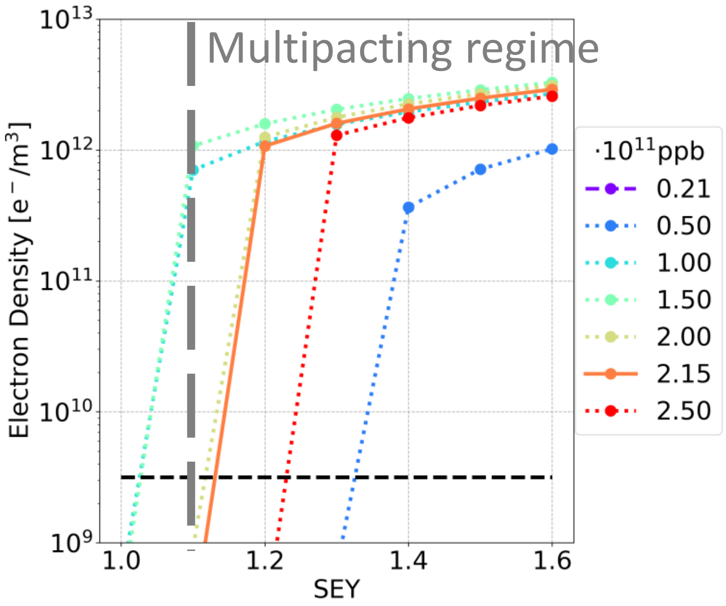


The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

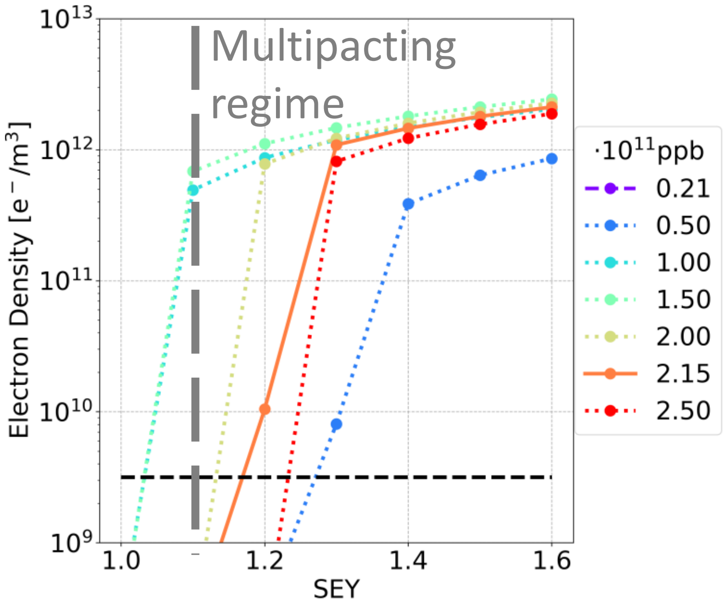
	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.3	1.4
SEY threshold (all intensity below nominal one)	1.0	1.0

E-Cloud Build-Up Studies: Quadrupole

Filling scheme 1



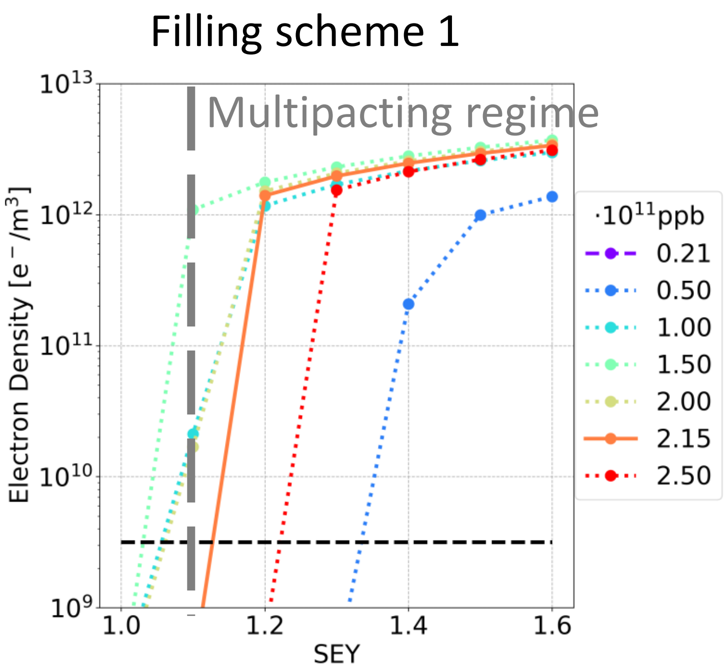
Filling scheme 2

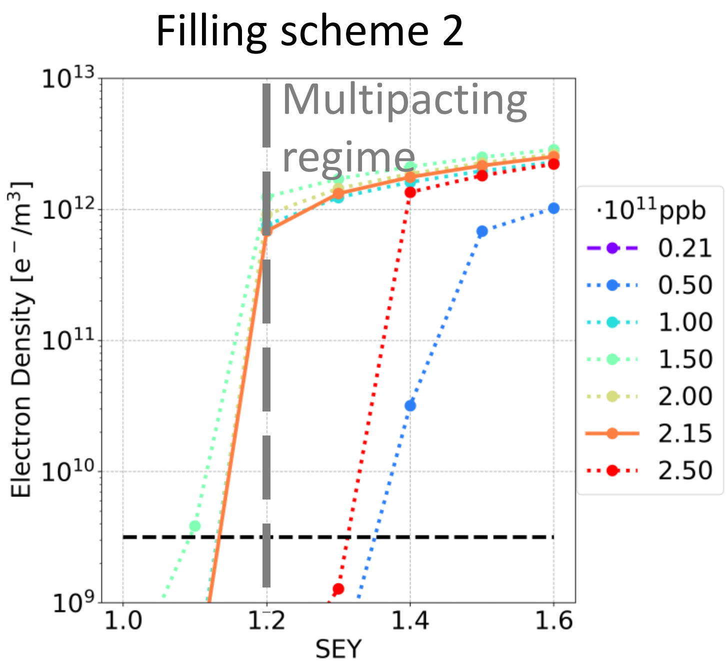


The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.1	1.2
SEY threshold (all intensity below nominal one)	1.0	1.0

E-Cloud Build-Up Studies: Sextupole



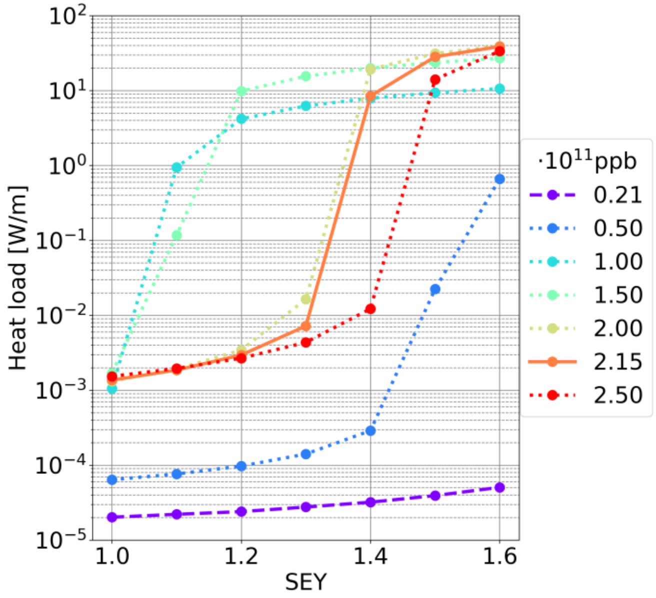


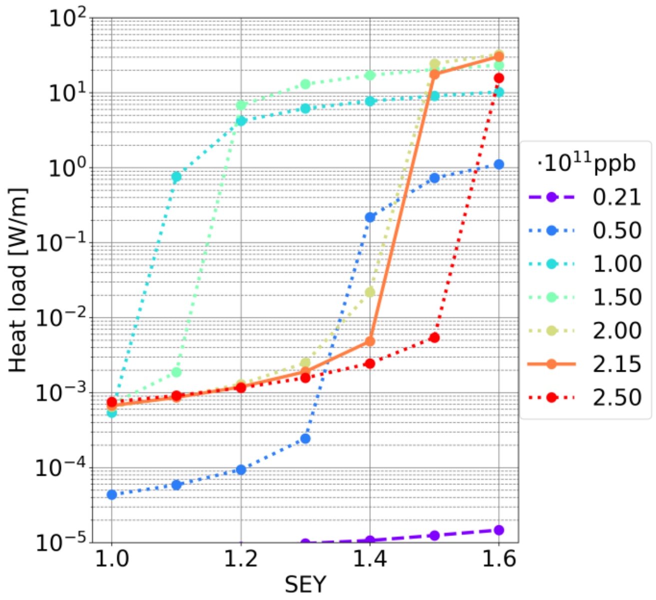
The bunch intensities 1.00e11 and 1.50e11 ppb, 2.00e11 and 2.15e11 ppb are the most critical cases

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.1	1.1
SEY threshold (all intensity below nominal one)	1.0	1.0

Heat Loads: Dipole

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.3	1.4
SEY threshold (all intensity below nominal one)	1.0	1.0





L_{dipole} = 62.8 km (L_{dipole}/L = 69.24%)

Synchrotron radiation power: ~50 MW per beam

If multipacting (considering nominal bunch intensity and maximum simulated SEY=1.6):

Filling scheme 1: ~38.7 W/m -> full circumference ~2.43 MW ~4.87% of synchrotron radiation power

Filling scheme 2: ~30.4 W/m -> full circumference ~1.91 MW ~3.82% of synchrotron radiation power

If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

Filling scheme 1 (SEY<=1.0) & 2 (SEY<=1.0): smaller than 0.01 W/m -> full circumference smaller than 700 W ~0.002% of synchrotron radiation power

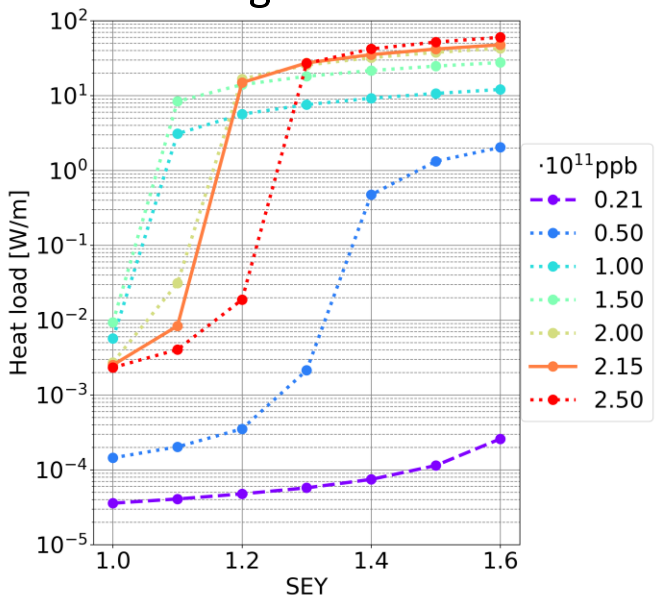
Heat Loads: Quadrupole

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.1	1.2
SEY threshold (all intensity below nominal one)	1.0	1.0

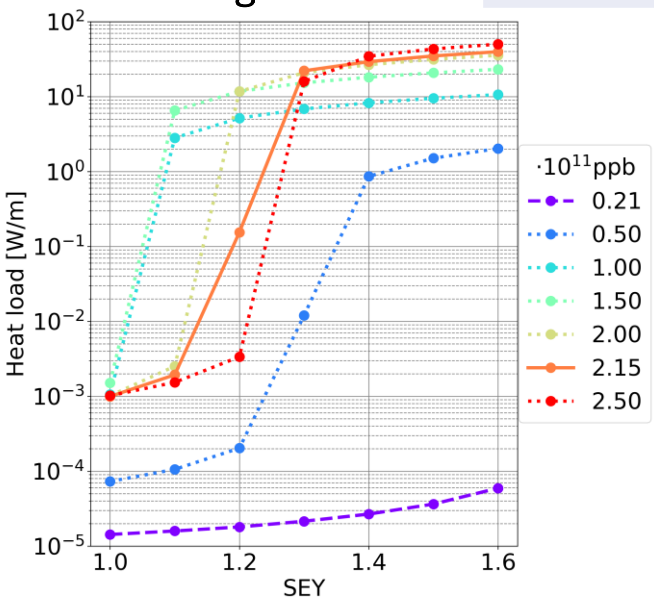
L_{quad} = 4.77 km (L_{quad}/L = 5.26%)

Synchrotron radiation power: ~50 MW per beam

Filling scheme 1



Filling scheme 2



If multipacting (considering nominal bunch intensity and maximum simulated SEY=1.6):

Filling scheme 1: ~47.7 W/m -> full circumference ~227 kW ~0.45% of synchrotron radiation power

Filling scheme 2: ~39.8 W/m -> full circumference ~190 kW ~0.38% of synchrotron radiation power

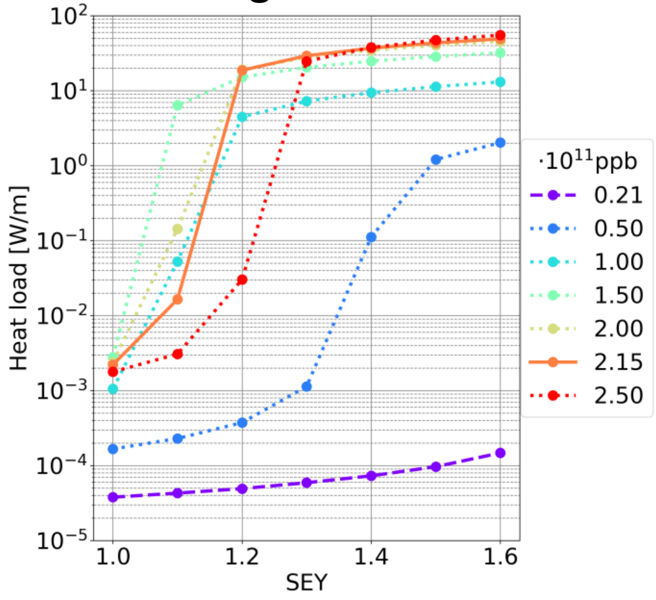
If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

Filling scheme 1 (SEY<=1.0) & 2 (SEY<=1.0): smaller than 0.01 W/m -> full circumference smaller than 50 W ~0.0001% of synchrotron radiation power

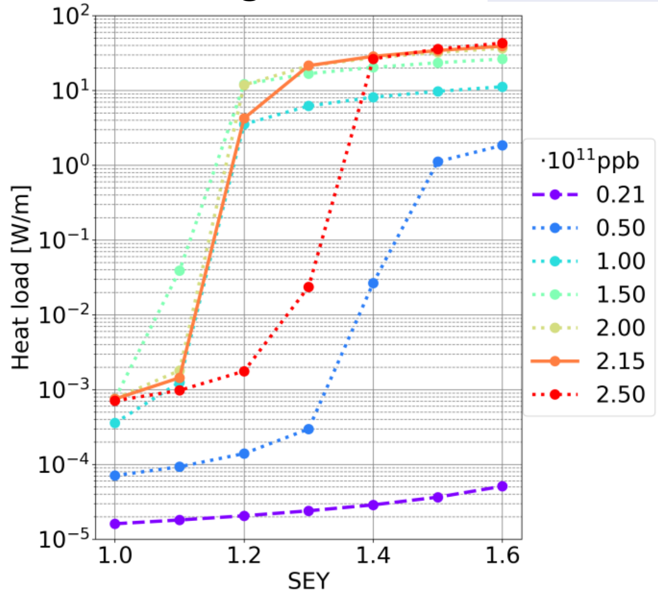
Heat Loads: Sextupole

	Filling Scheme 1	Filling Scheme 2
SEY threshold (nominal intensity)	1.1	1.1
SEY threshold (all intensity below nominal one)	1.0	1.0

Filling scheme 1



Filling scheme 2



L_{sex} = 0.900 km (L_{sex}/L = 0.99%)

Synchrotron radiation power: ~50 MW per beam

If multipacting (considering nominal bunch intensity and maximum simulated SEY=1.6):

Filling scheme 1: 49.2 W/m -> full circumference 44.3 kW ~0.09% of synchrotron radiation power

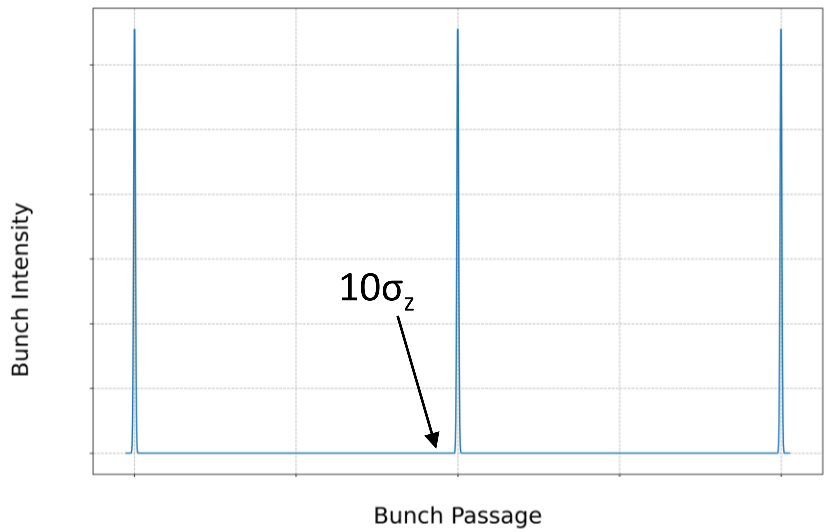
Filling scheme 2: 39.1 W/M -> full circumference 35.2 kW ~0.07% of synchrotron radiation power

If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

Filling scheme 1 (SEY<=1.0) & 2 (SEY<=1.0): smaller than 0.01 W/m -> full circumference smaller than 10 W ~0.00002% of synchrotron radiation power

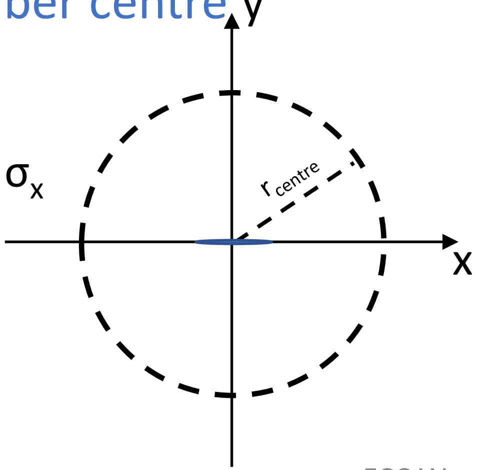
E-Cloud Central Density

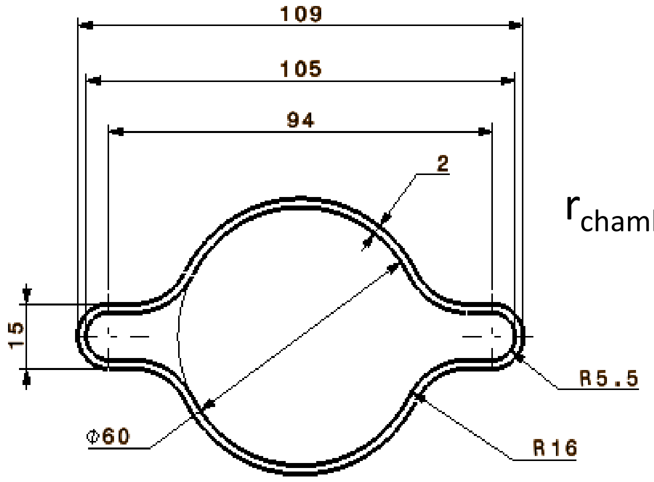
- E-cloud stability threshold has to be compared with the e-cloud density
  - before the bunch passage



  - close to the vacuum chamber centre

$r_{centre} \approx 10\ \sigma_x$





$r_{chambre} \approx 600\ \sigma_x$

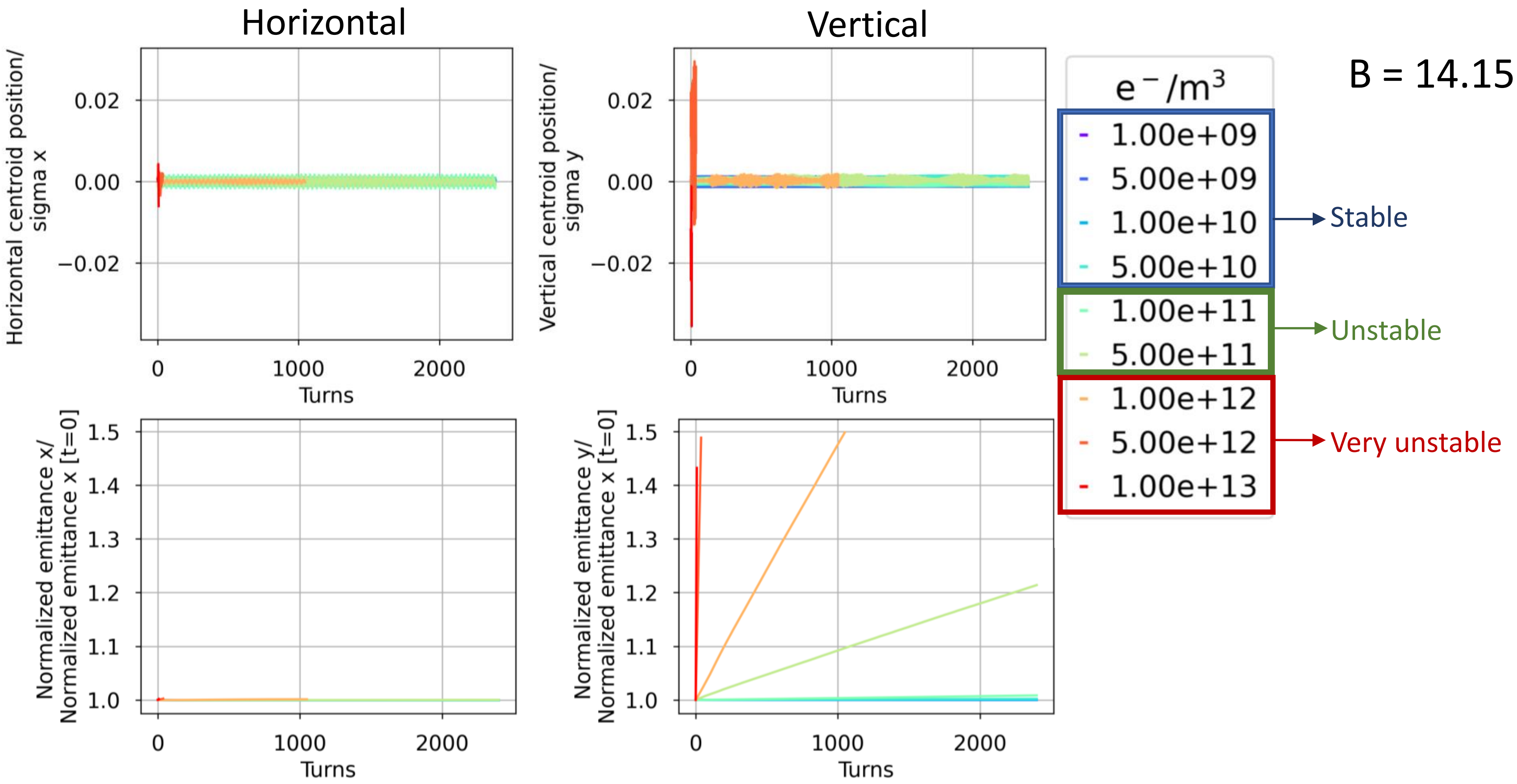
E-Cloud Stability Simulation Threshold: Dipole

- $\rho_{e,th}$ =2.42 $\cdot 10^{10}$ e^{-}/m^{3} considering only the dipole length L_{dipole} = 62.8 km (L_{dipole}/L = 69.24%)

B = 14.15 mT

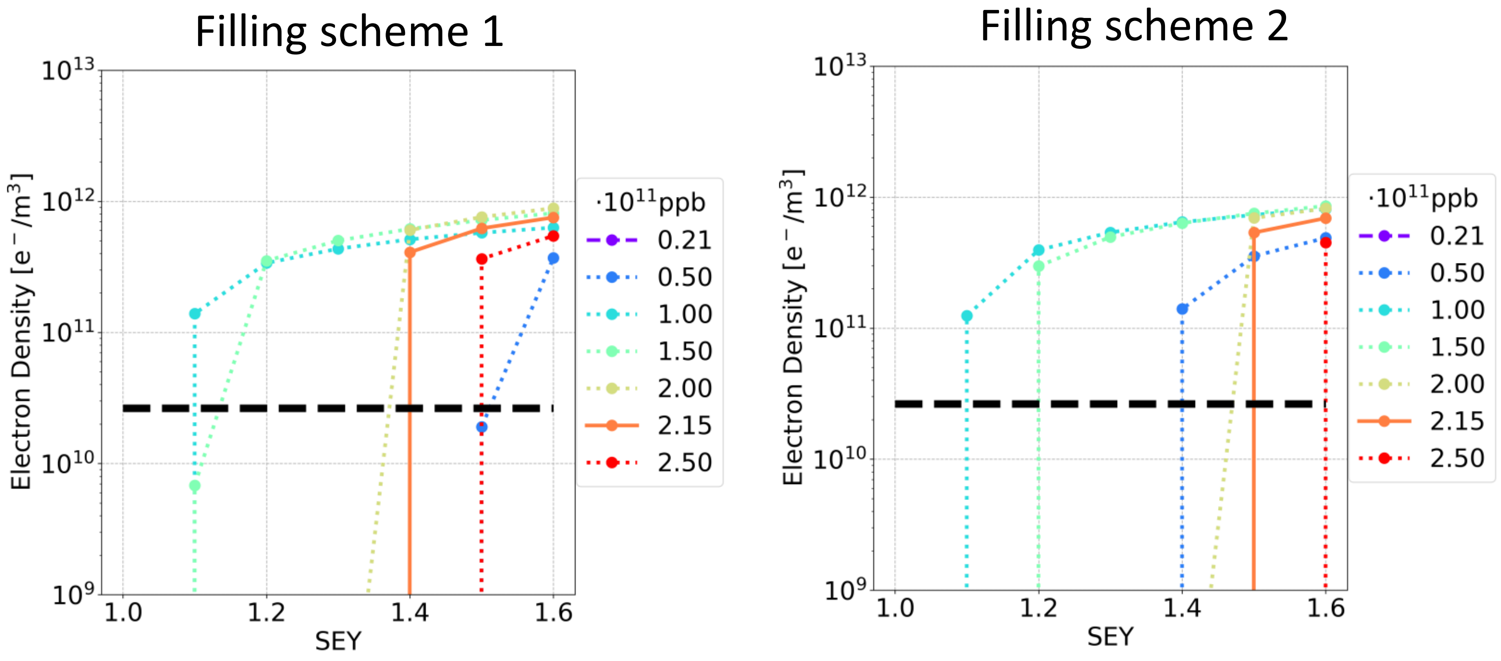
Centroid/ Sigma

Normalised emittance/ Normalised emittance [t=0



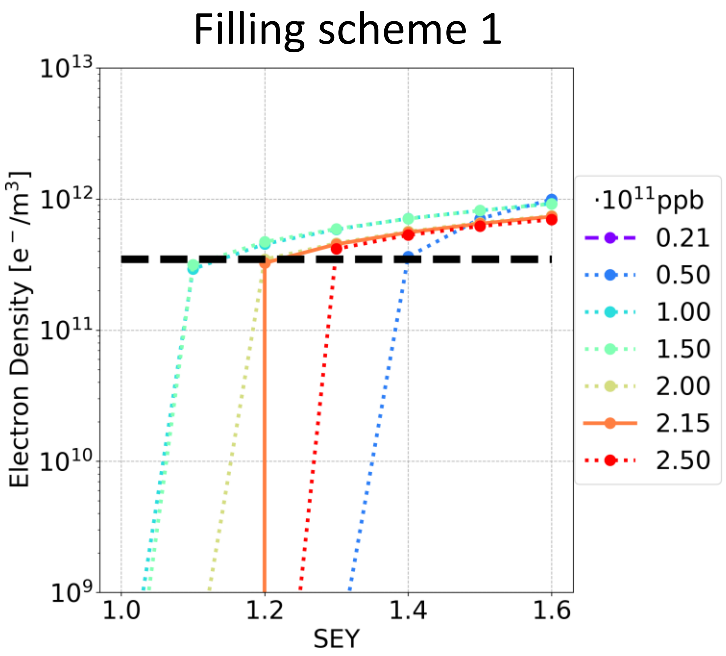
- Theoretical and numerical e-cloud density stability threshold have the same order of magnitude
- Vertical plane is unstable

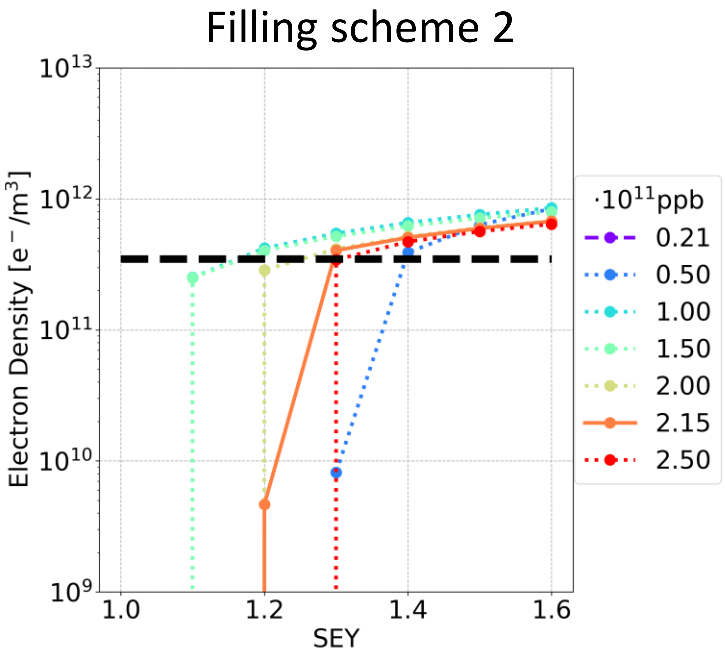
E-Cloud Stability: Dipole



- Above the SEY multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold -> lead to beam instabilities

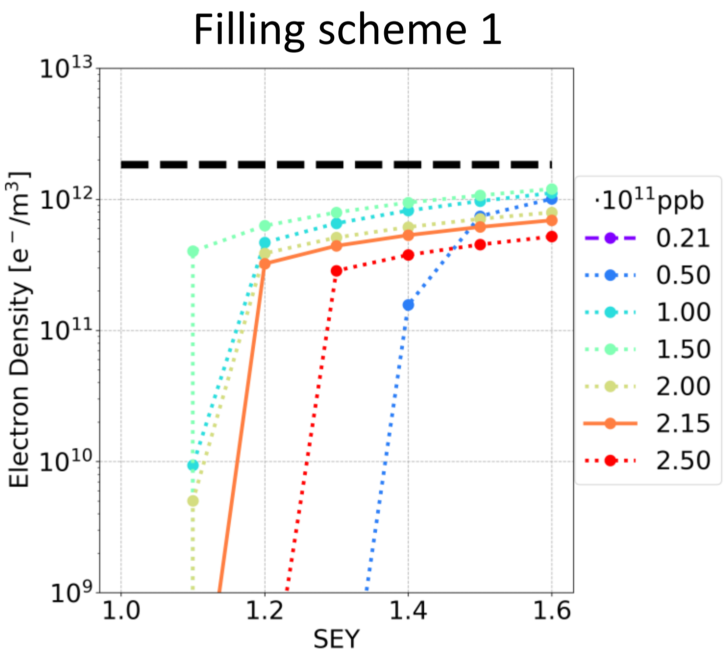
E-Cloud Stability: Quadrupole

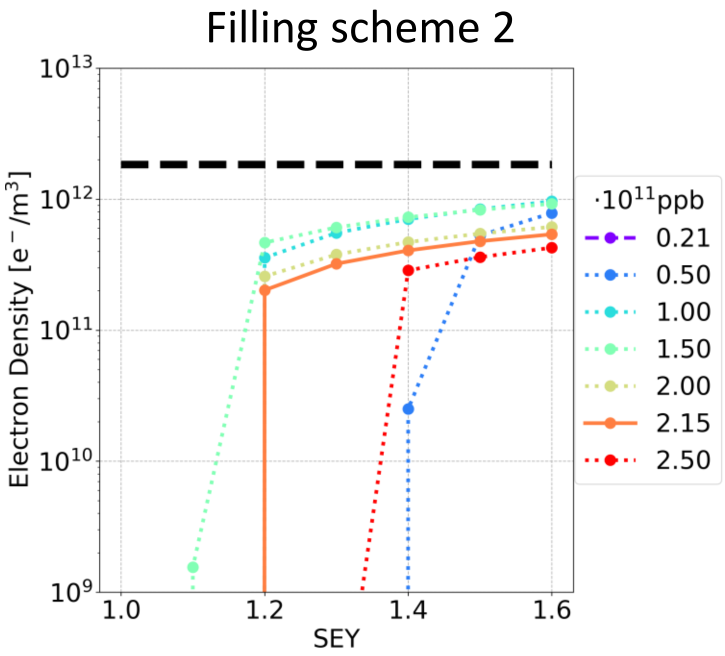




- Above the SEY multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold -> lead to beam instabilities

E-Cloud Stability: Sextupole





- The central e-cloud density before the bunch passage is smaller than the e-cloud stability threshold (element length dependance)

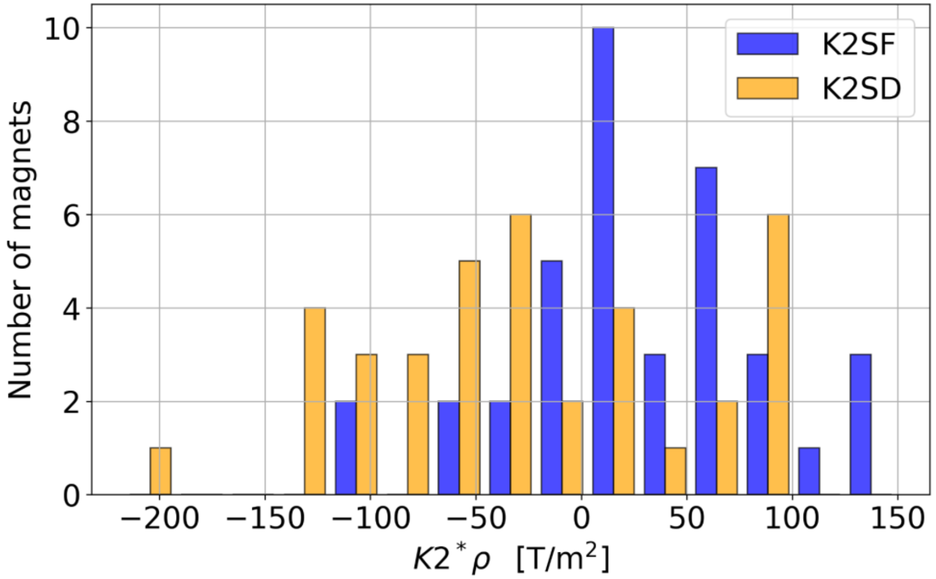
Magnetic Field Elements

Update values from FCC-ee optics team

Table 1: The magnetic field strengths for the baseline and CFM cell in the Z mode are shown, at a reference radius of 10 mm.

Magnetic field & gradient	Baseline	Nested Magnets	length [m]
B1	0.0152 T	- - -	22.654
B1S	0.0152 T	- - -	19.304
B1L	0.0152 T	- - -	20.954
B1CF	- - -	0.0129 T	23.155
BTT	- - -	0.0066 T	2.9
BD	- - -	0.0125 T	2.9
BF	- - -	0.0059 T	2.9
Orbit Corrector	- - -	0.00844 T	2.9
Sextupoles			2.9
Quad F		1.450 T/m	2.9
Quad D		-1.450 T/m	2.9

Distribution of the magnetic field of the sextupoles
Z mode 45.6 GeV



Courtesy of Cristobal Garcia and Leon Van Riesen-Haupt

Largest number:

149.503 T/m2

Average:

27.714 T/m2

Smallest number:

-216.550 T/m2

RMS for k2sf: 63.316 T/m2

RMS for k2sd: 81.560 T/m2

- Dipoles 15.2 mT (previous value used for e-cloud simulations 14.15 mT *[1]*)
- Quadrupoles 1.45 T/m (previous value used for e-cloud simulations 5.65 T/m *[2]*)
- Sextupoles 72.5 T/m^2 (previous value used for e-cloud simulations 200-800 T/m^2 *[3]*)

[1] Fatih Yaman, "Electron Cloud Simulations for the FCC-ee", June 30, 2021 @ FCC week
[2] Jaime Rocha, Humberto Maury, Karla Cantún, "ELECTRON CLOUD IN THE ARC QUADRUPOLES", December 8,2021 @ FCCIS WP2 Workshop 2021
[3] Humberto Maury, Karla Cantún, "STUDIES ON THE ELECTRON CLOUD BUILD-UP FORTHE FCC-ee MAIN SEXTUPOLES UNDER DIFFERENT SCENARIOS", November 2nd, 2023 @ 174th FCC-ee Optics Design Meeting & 45th FCCIS WP2.2 Meeting

E-Cloud Stability Theoretical Threshold

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_e\beta_y L} \qquad \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}} \qquad \begin{array}{c} K = \omega_e\sigma_z/c \\ Q = \min(K,7) \end{array} \qquad \lambda_p = \frac{i_b}{\sqrt{2\pi}\sigma_z}$$

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

- $\rho_{e,th} = 1.89\cdot10^{10}$ e^-/m^3 considering the full circumference L = 90.7 km

- $\gamma = E/E_0$, where *E* is the beam energy, E_0 is the particle rest energy.
- ν_s is the synchrotron tune.
- σ_z is the bunch length.
- *c* is the light velocity.
- r_e is the classical electron radius.
- σ_x *and* σ_y are the bunch horizontal and vertical dimension, respectively.
- λ_p is the line density of the proton bunch.
- ω_e is the electron angular oscillation frequency.
- *K* characterizes how many electrons contribute to the instability.
- *Q* is the quality factor of the wake field.
- β_y is the vertical beta function.
- *L* is the circumference length.

Photoemission

- Taking into account the photoemission in the e-cloud formation process
  - the e-cloud density saturation value could be reached in less bunch passages and it could be larger
  - the gap length, needed to clean the vacuum chamber, could be larger