

# On Electron Cloud Effects and Possible Mitigation Strategies

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Acknowledgments: Oide Katsunobu, Zimmermann Frank, Zobov Mikhail , Iadarola Giovanni

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# Outline

- Introduction
- Multipacting and Stability
- Photoelectrons
- Mitigation Techniques
- Conclusions and Outlooks

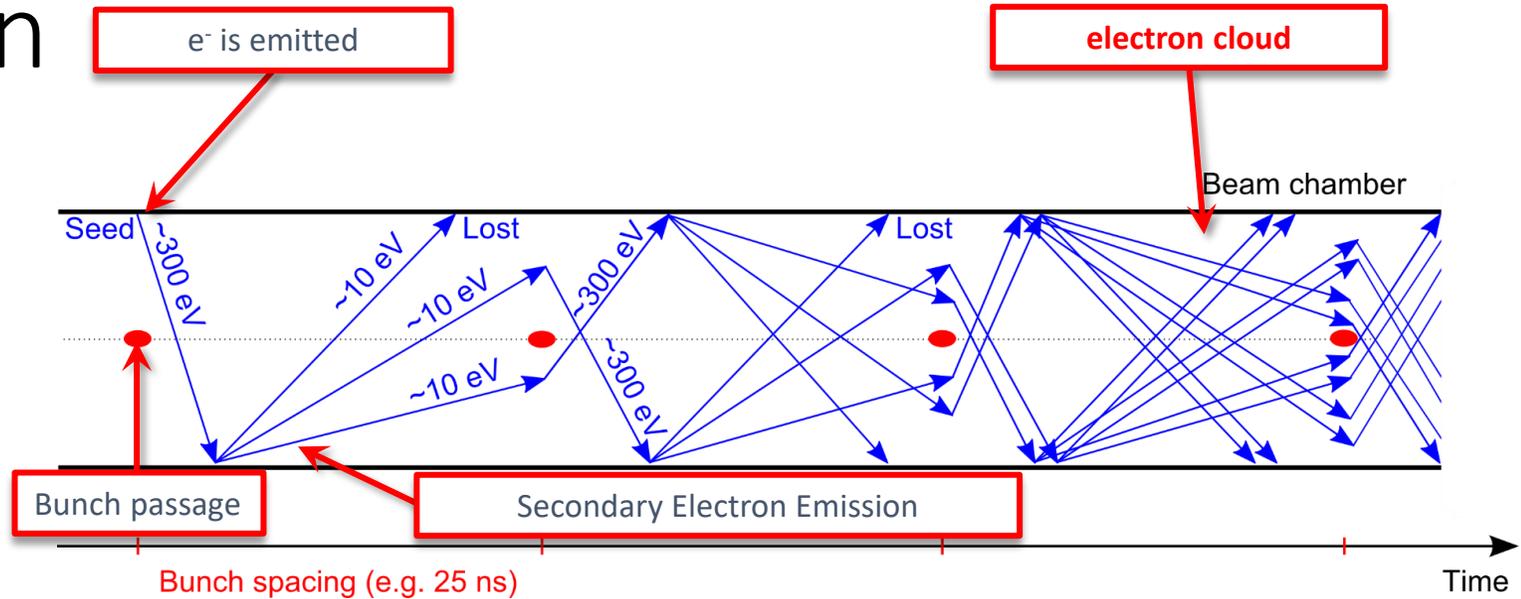
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# Motivation

- Electron cloud (**e-cloud**) effects have been observed in **several accelerators** all over the world (LHC, KEKB, DAΦNE, ...)
  - more commonly in those operated with **positively charged particles**
- Presently among the major **performance limitations** for high energy **collider**
  - transverse beam instabilities
  - incoherent beam effects
  - vacuum degradation
  - heat load
- E-cloud effects have to be studied for **FCC-ee**
  - to give input to chamber design and material properties to avoid e-cloud formation
  - define beam parameters and identify performance limitations

# E-Cloud Formation



Courtesy of G. Iadarola

- A circulating beam 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<sup>-</sup> acceleration and time of flight
- Surface properties have a primary role in the e<sup>-</sup> multiplication process

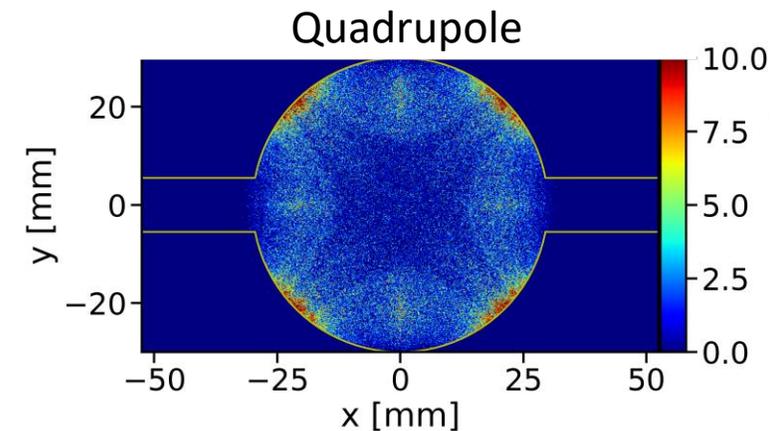
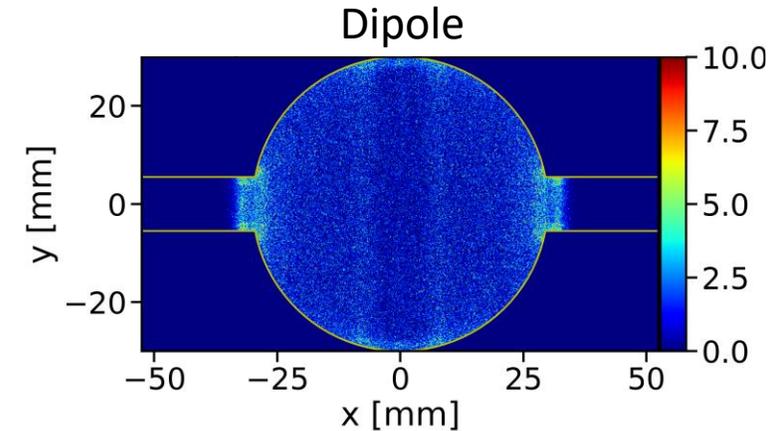
The main quantity involved is the Secondary Electron Yield (SEY):

depends on

- surface chemical properties
- history of the surface, in particular on accumulated electron dose

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

- Bunch spacing → It determines how many electrons survive between consecutive bunch passages and has direct impact on multipacting threshold
  - For FCC-ee: the strongest e-cloud effects are foreseen for the Z running mode due to the largest number of bunches (smallest bunch spacing)
- Bunch intensity and bunch length → affect the acceleration received by the electrons
- Magnetic fields → Electron trajectories are strongly influenced



Electron density 10<sup>3</sup> e<sup>-</sup>/mm<sup>3</sup>

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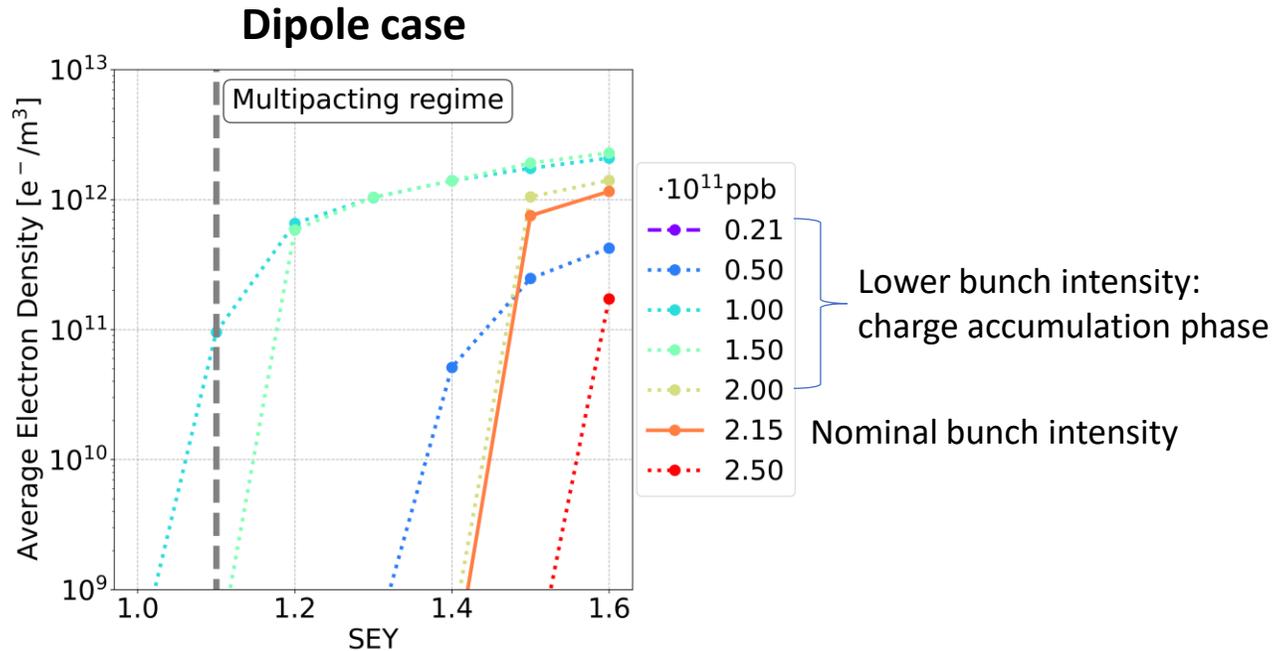
# E-Cloud Build-up Studies for FCC-ee baseline

*From Feasible Study Report*

Bunch Intensity [ $\times 10^{11}$ ppb]	Bunch Spacing [ns]	Number bunches / Train	Number Trains	Gap Length [ns] (gap/bunch spacing)
2.15	25	280	40	575 (23)

- Studies done for GHC Lattice by Ohmi-san
- Main collider
- Effects visible for positrons-electron beam effect negligible

- Extensive simulation campaign scanning all relevant parameters using Zimmerman-Rumolo model (PyEcloud)
- Simulations have been benchmarked versus Furman-Pivi model → [F. Yaman, “Electron cloud simulations using the Furman-Pivi model”, FCC-ee electron cloud meeting 18/03/2025](#)
- Important to understand the impact of lower bunch intensity (we will need to fill the ring and then top-up), chamber radius, magnetic fields of different elements
  - [“Electron cloud studies”, FCC week 2023](#)
  - [“Electron Cloud Studies”, FCC week 2025](#)
  - [“Update on the Electron Cloud Studies for FCC-ee”, FCC e-cloud meeting 12/09/2023](#)



Secondary Emission Yield (SEY)  $\delta(E) = \frac{I_{emit}}{I_{imp}(E)}$

Bunch population	SEY multipacting thresholds
nominal	1.4
below nominal	1.0

**Starting from an initial random seed of uniformly distributed electrons of  $10^7$  e/m**

**Avoid Multipacting:**

→ Compute the **Average electron density for different SEY** values and different magnetic elements (drift, dipole, quads, sextupoles)

→ Repeat **for intensities** in the range from 0.2-2.5  $10^{11}$  ppb to establish the intensity dependency and identify worse case during the accumulation phase

Element	Field	Bunch population	Thresholds
Drift Space	-	nominal	1.4
		below nominal	1.2
Dipole	15.2 mT	nominal	1.4
		below nominal	1.0
Quadrupole	1.45 T/m	nominal	1.1
		below nominal	1.0
Sextupole	72.5 T/m <sup>2</sup>	nominal	1.1
		below nominal	1.0

- **Non monotonic behaviour** versus intensity of the cloud formation (intensities  $[1.0-1.5] \cdot 10^{11}$  ppb most critical) → **problematic** during top-up and accumulation!
- **The SEY multipacting thresholds are extremely tight for baseline parameters**
  - difficult to satisfy using the baseline copper chamber with thin NEG coating (SEY 1.0-1.2) → might require more complex surface treatments
- **Dipole, Quadrupoles and sextupoles** have the **lowest SEY multipacting thresholds**

# E-Cloud Stability Threshold

- E-cloud could trigger **instabilities**, because the beams pass through the e-clouds and they receive transverse kicks
- Is the **central density above the stability threshold**? Which is the **e-cloud de**

## 1. Theoretical equation:

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

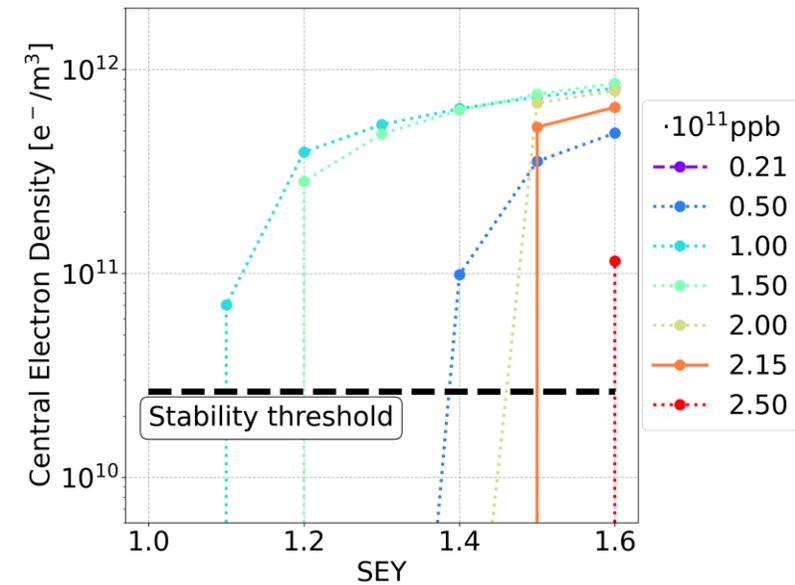
$$\rho_{e,th} = \frac{2\gamma v_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_e \beta_y L}$$

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y (\sigma_x + \sigma_y)}}$$

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

$$Q = \min(K, 7)$$

$$\lambda_p = \frac{i_b}{\sqrt{2\pi\sigma_z}}$$



- Simulations by means of **PyECLOUD-PyHEADTAIL** in order to track the beams through the e-clouds and observe instability rise and parameter evaluations (emittances)

Theoretical and numerical e-cloud density stability threshold have the same order of magnitude with strong vertical instability observed and with relevant emittance blow-up

# 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 → leads to beam instabilities
- **Sextupoles**
  - The central e-cloud density before the bunch passage is smaller than the e-cloud stability threshold (element length dependence)

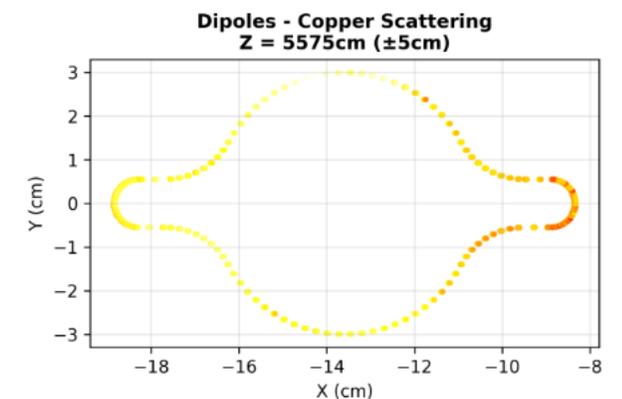
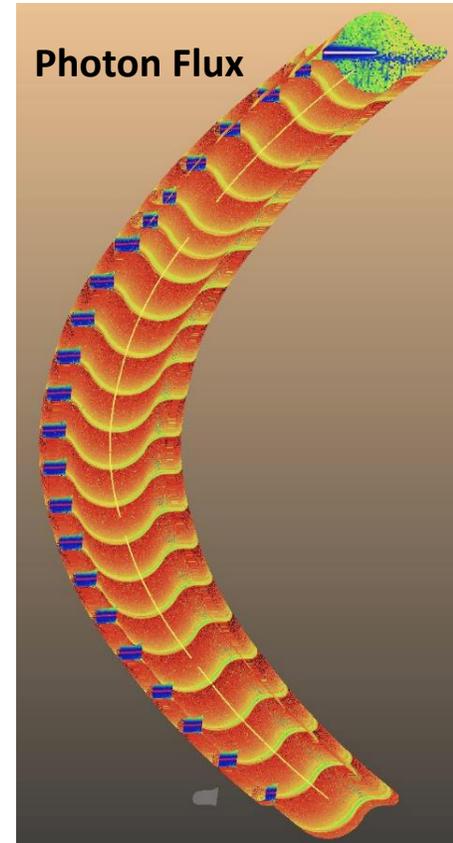
Above the SEY multipacting threshold, the e-cloud leads to beam instabilities, because the central density is above the stability threshold

# Outline

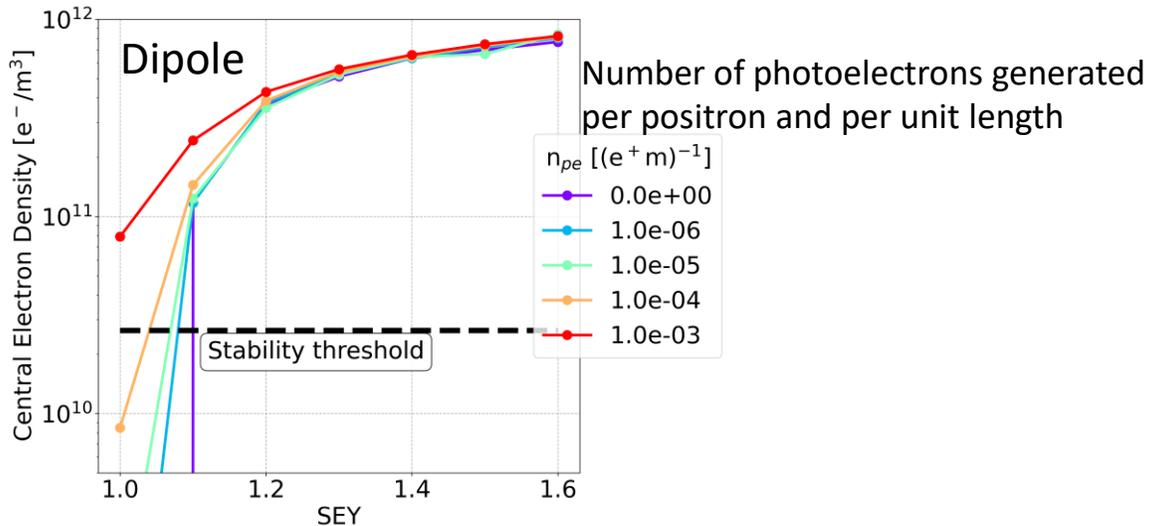
- Introduction
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- **Photoelectrons**
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# Photoelectron Emission

- The circulating beam particles can produce **primary electrons** via **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**?
- Material properties determine the conversion from **radiation** to **electrons**  
 Absorber structures control where most of the radiation impacts the walls
- The number of photoelectrons is determined by:
  - the amount of photons scattered into the main beam chamber
  - the **Photoelectron Yield (PY)**
    - property of the beam chamber
    - defined as the ratio between the emitted photoelectrons and the number of impinging photons



# Photoelectron Yield Limit



- The **central density** could be **larger** than the **stability threshold** even below the SEY multipacting threshold
- High values of  $n_{pe}$  should be avoided ( $< 1.0 \cdot 10^{-4} (e^+ m)^{-1}$ )
- The PY and the number of photoelectrons are related through the following equation

$$PY = \frac{In_{pe}}{\phi Le}$$

- $I$ : beam current (1.27 A)
- $L$ : chamber's perimeter (278 mm)
- $e$ : elementary charge

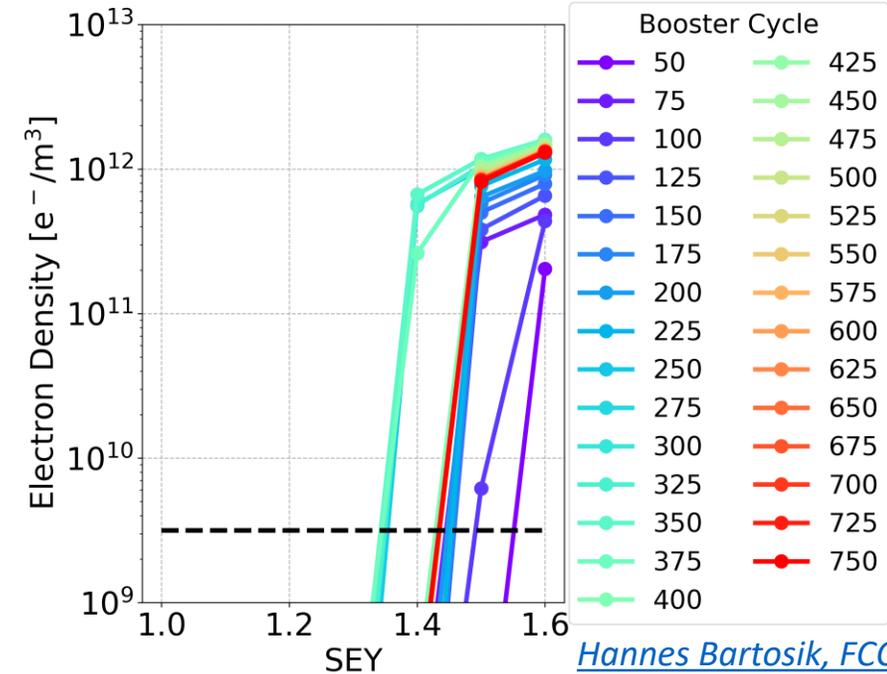
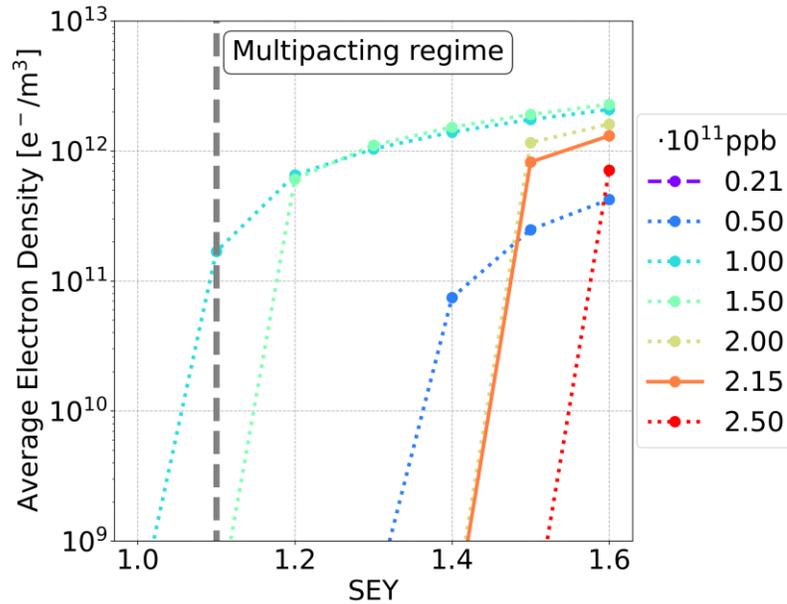
- $\phi$ : realistic photon flux -> from ray tracing codes (e.g., SYNRAD+ Marton-Saretti) in the order of  $10^{13} - 10^{14}$  photons/cm<sup>2</sup> s (not in the absorber areas)
- The constraint on the material is **very tight with  $PY \sim 2 \times 10^{-3}$**  → incompatible with the expected PY of the foreseen chamber surface (0.1-0.25 for NEG coated!) (in the absorber areas the photon flux is expected to be even higher!)
- **A new design of the photon absorbers** is under development and will **reduce the photon flux** inside the main beam chamber by a factor 100 !

**A detailed photoelectron emission model based on synchrotron radiation simulations will be developed and studies extended to understand the impact of photoelectrons in realistic configurations → new PhD student Adam Furman**

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- Photoelectron Impacts
- **Mitigation Techniques**
- Conclusions and Outlooks

# Mitigation I: Non-Uniform Bootstrap Injection



*Hannes Bartosik, FCC week 2024*

During the charge accumulation phase: **do not fill the bunches of the train uniformly**, in this way the **critical bunch intensities** will be reached with a **larger bunch spacing**

With special filling schemes during the charge accumulation phase, the **SEY multipacting thresholds** are **higher** and they tend to the SEY multipacting thresholds for the nominal bunch intensity

# Charge Accumulation Phase: Summary

Element	Field	Special filling schemes during charge accumulation phase	Uniform 25 ns	
Drift Space	-	1.4	nominal	1.4
			below nominal	1.2
Dipole	15.2 mT	1.3	nominal	1.4
			below nominal	1.0
Quadrupole	1.45 T/m	1.1	nominal	1.1
			below nominal	1.0
Sextupole	72.5 T/m <sup>2</sup>	1.1	nominal	1.1
			below nominal	1.0

A major concern with this approach is having **bunches** of significantly **different intensities** in the collider at the **same time**, which makes **difficult to find** a **working point** that **ensures stability** for all bunches

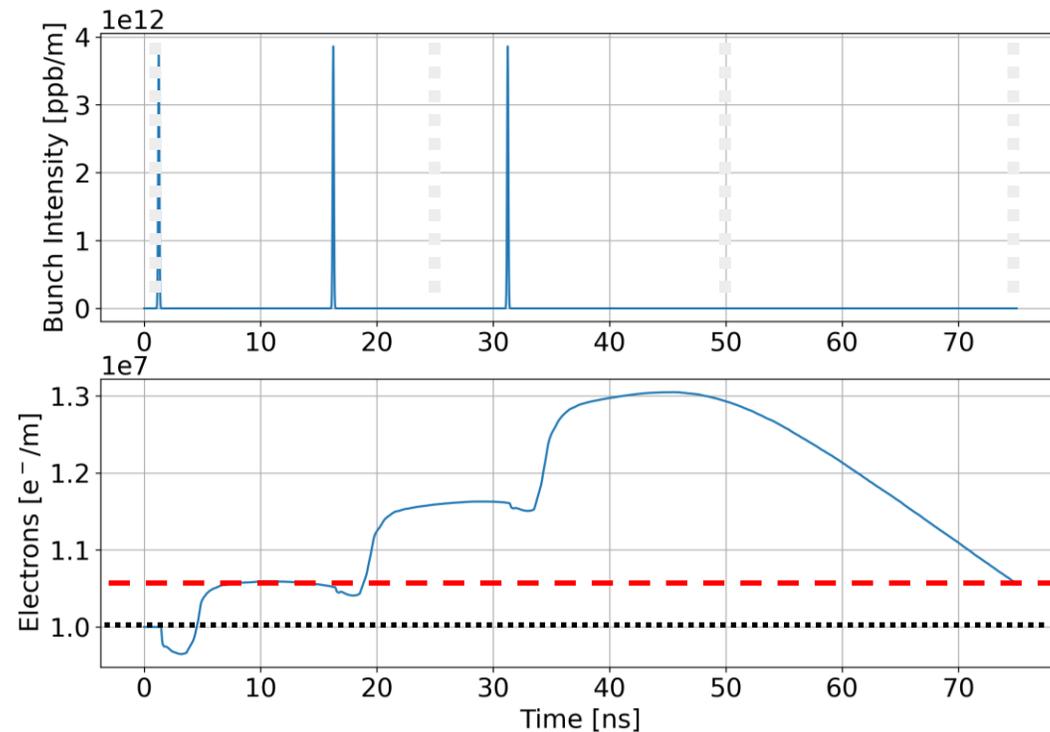
Studies on the interplay between beam-beam effects and impedance show that the horizontal plane is dominated by the coherent **x-z instability** → not **enough tune space** to accommodate the expected bunch-by-bunch intensity and voltage spread

[Roxana Soos et al., FCC week 2025](#)

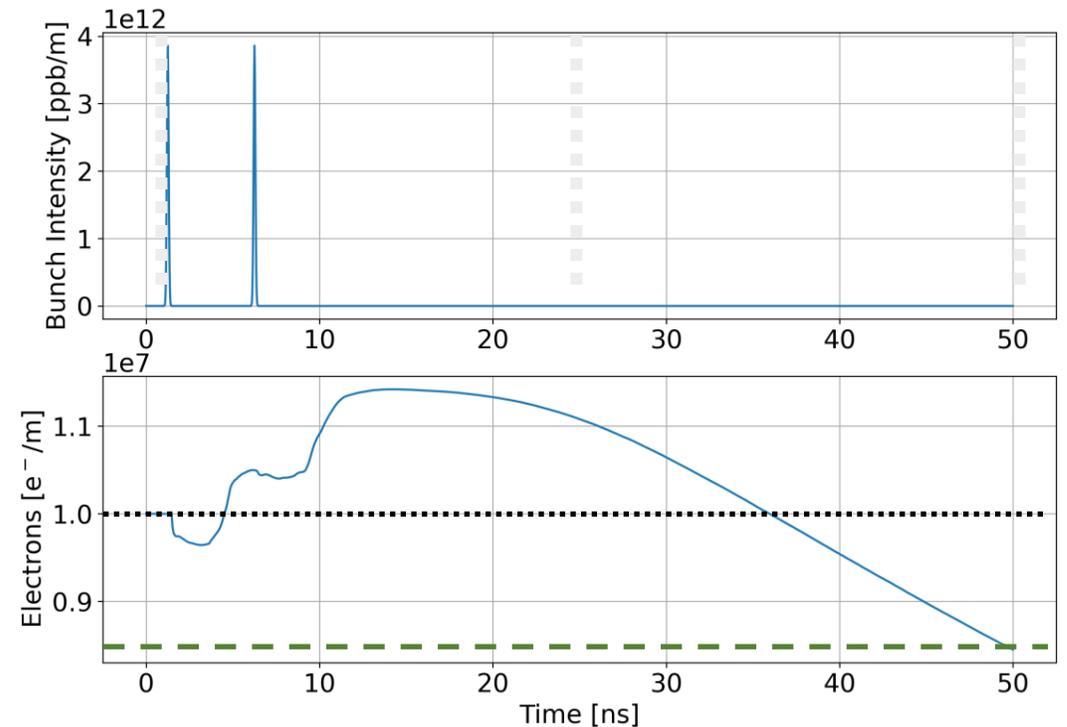
# Mitigation II: 5ns non-uniform Bunch Spacing

- Investigated possible filling schemes: reduced bunch spacing and small gaps after
- Considering **larger bunch spacing** (20 ns and 15 ns), the gap length is not long enough to mitigate the e-cloud
  - e-cloud after the bunch passages and the gap is larger than the initial e-cloud density
- Considering very **small bunch spacing** (10 ns and 5 ns), the gap is long enough to mitigate the e-cloud
  - e-cloud after the bunch passages and the gap is smaller than the initial e-cloud density

Bunch spacing 15 ns with 3 bunches and 2 empty



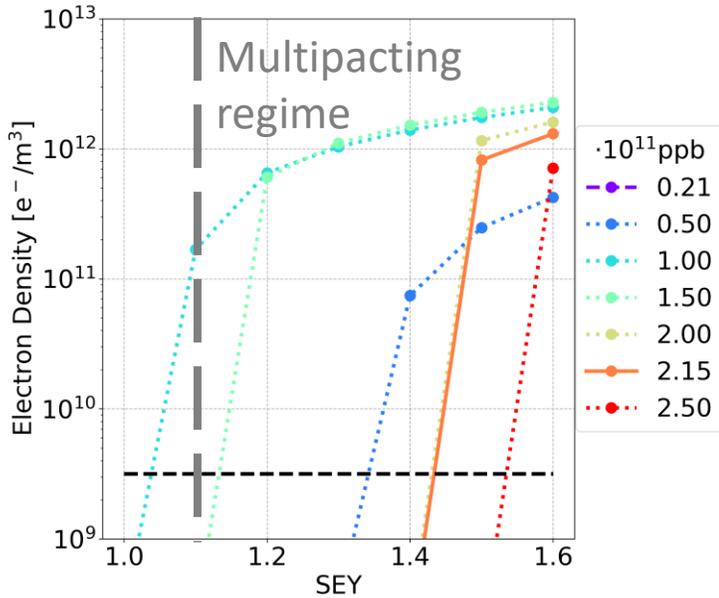
Bunch spacing 5 ns with 2 bunches and 8 empty



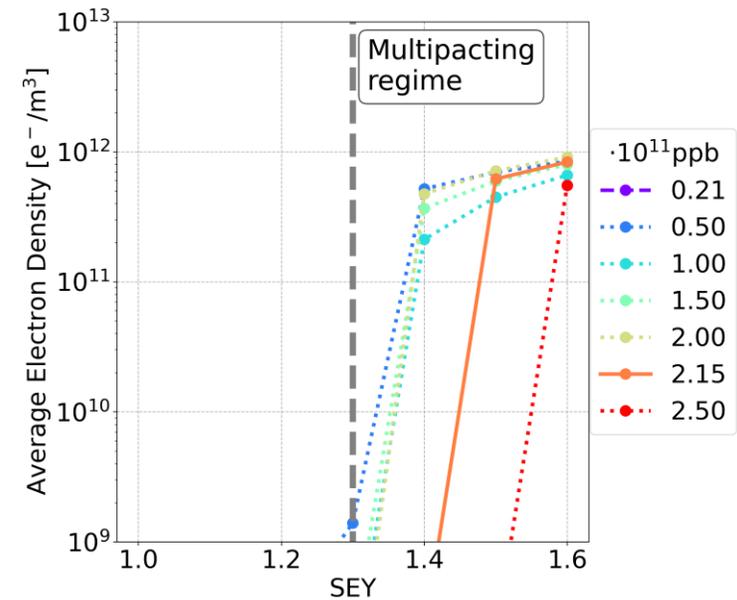
# Short Bunch Spacing: 10 ns vs 5 ns

Considering the passage a **full train** of 280 bunches and the following train gap

Bunch spacing 25 ns uniform



Bunch spacing 5 ns with 2 bunches and 8 empty

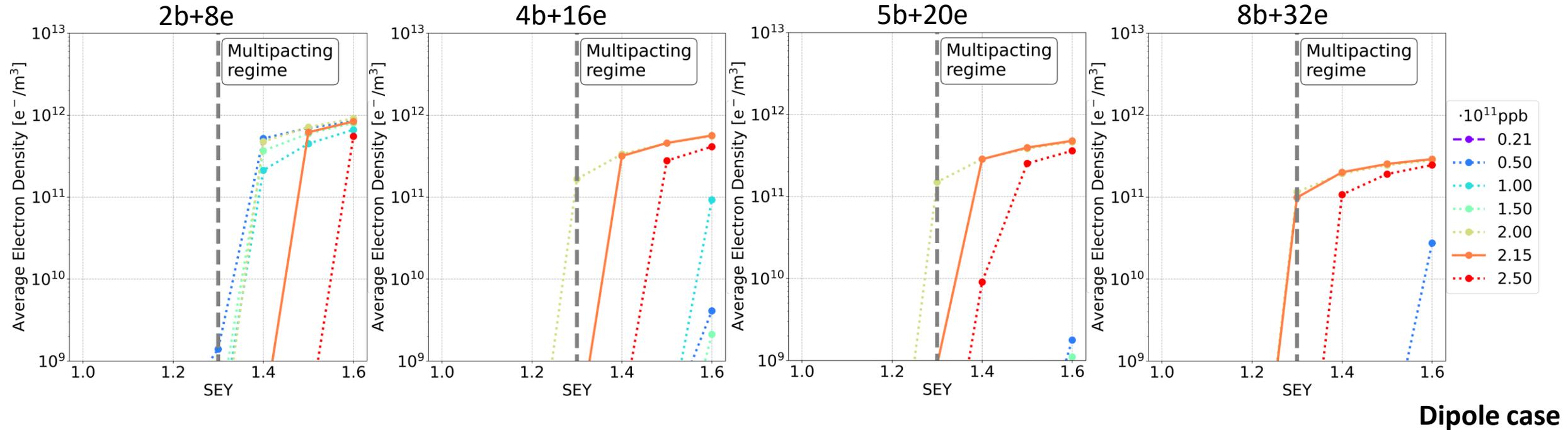


**Dipole case**

Higher SEY threshold for lower intensities is obtained using **NON-uniform** filling schemes with 5 ns bunch spacing

# Non-uniform Bunch Spacing 5 ns

Considering the passage of a **full train** of 280 bunches and the following train gap, a **better e-cloud mitigation** is obtained using filling schemes with **5 ns bunch spacing**



- Electron average densities are reduced
- **SEY multipacting thresholds** for critical bunch intensities are increased: **could mitigate!**

Element	Field	Bunch population	Uniform 25 ns	2b+8e	4b+16e	5b+20e	8b+32e
Drift Space	-	nominal	1.4	1.4	1.4	1.4	1.3
		below nominal	1.2	1.4	1.4	1.4	1.3
Dipole	15.2 mT	nominal	1.4	1.4	1.3	1.3	1.2
		below nominal	1.0	1.2	1.2	1.2	1.2
Quadrupole	1.45 T/m	nominal	1.1	1.3	1.3	1.3	1.3
		below nominal	1.0	1.2	1.3	1.3	1.3
Sextupole	72.5 T/m <sup>2</sup>	nominal	1.1	1.4	1.5	1.5	1.4
		below nominal	1.0	1.3	1.5	1.5	1.4

- Using filling schemes with **non-uniform bunch spacing**, the strict constraint on the **SEY multipacting thresholds could be mitigated**, for all the analysed magnetic elements
- No tighter constrains during accumulation
- Need to be further explored with photoelectrons
- Investigating possible implementation (impedance, injectors...)

# Outline

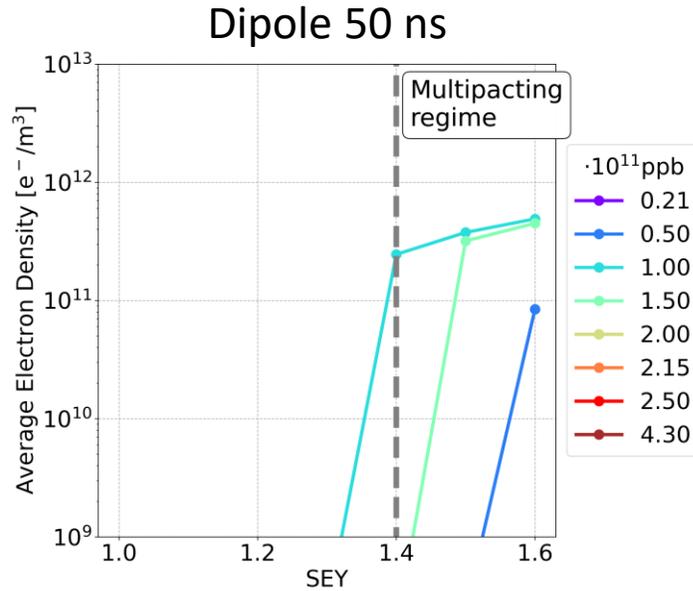
- Introduction
- Secondary Electron and Photoelectron Emission
- Electron Cloud Effects
- Mitigation Techniques
- **Conclusions and Outlooks**

# Conclusions and Outlooks

- The **material constraints** in order to avoid e-cloud avalanche multiplication and to control photoelectrons are **extremely tight** for baseline parameters and planned 150nm NEG coating (SEY 1.0-1.2, PY~0.1-0.2)
  - Above the SEY multipacting threshold (as low as below 1.0), the e-cloud leads to **beam instabilities** → for central densities above  $2 \times 10^{10} \text{ m}^{-3}$
  - Considering the additional contribution of the **photoemission** on the e-cloud formation process, the beam could be **unstable even below the SEY multipacting threshold**: PY  $\sim 10^{-3}$  required for existing photon flux → New **photo absorbers** are underdevelopment to improve by factor 100 the photon absorption → very challenging
  - Further systematic studies and the **development** of a **more detailed model** describing the impact of photoelectrons on electron cloud effects have started
- **Incoherent ecloud effects have to be addressed** → Electron and positron beams will experience different electron-cloud effects → slightly different parameters for the two beams with consequences for other collective effects
- **Non-uniform 5ns bunch spacing filling schemes mitigates** the e-cloud formation process
  - Discussions and studies on-going to evaluate possible implementation
- Investigation of the effectiveness of various active mitigation strategies of the e-cloud instabilities, such as the use of a **transverse feedback system** in combination with **chromaticity** and **octupole** settings are also under going

# Thanks for your attention

- E-cloud could be mitigated using **larger bunch spacing**



Larger bunch spacing

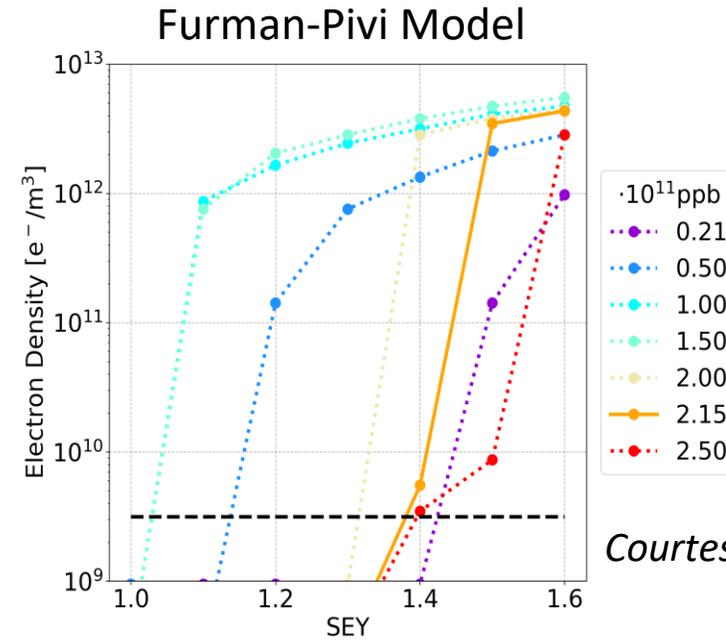
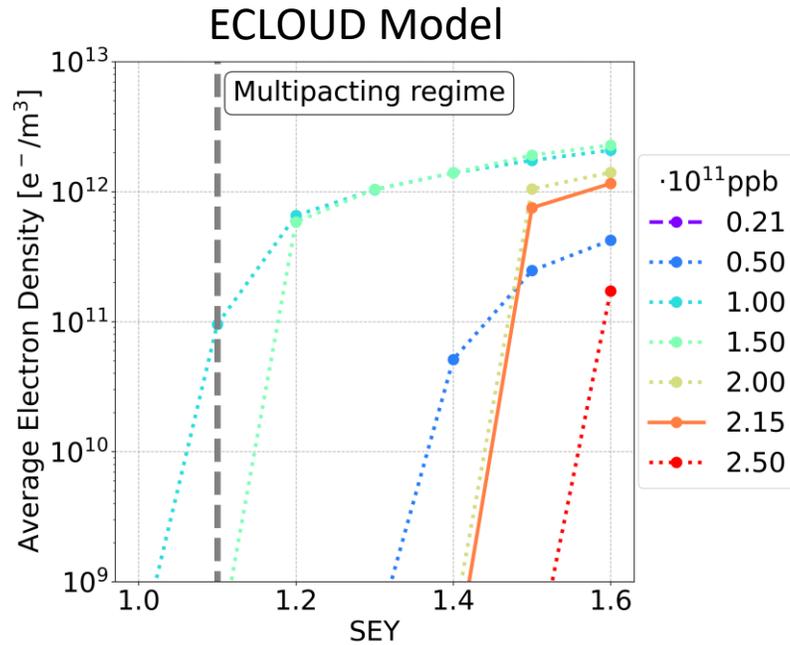
Element	25 ns	30 ns	40 ns	50 ns
Drift Space	1.2	1.3	1.5	> 1.6
Dipole (15.2 mT)	1.0	1.1	1.2	1.3
Quadrupole (1.45 T/m)	1.0	1.0	1.1	1.3
Sextupole (72.5 T/m <sup>2</sup> )	1.0	1.1	1.3	1.4

Increasing the bunch spacing **requires increasing the bunch intensity** to maintain a **constant beam current**

→ Larger bunch intensities could **lead to problems due to other collective effects**, such as beam-beam and beam-coupling impedance ([Mauro Migliorati FCC week 2024](#))

# SEY Models

Simulations based on different parametrisations of the surface SEY



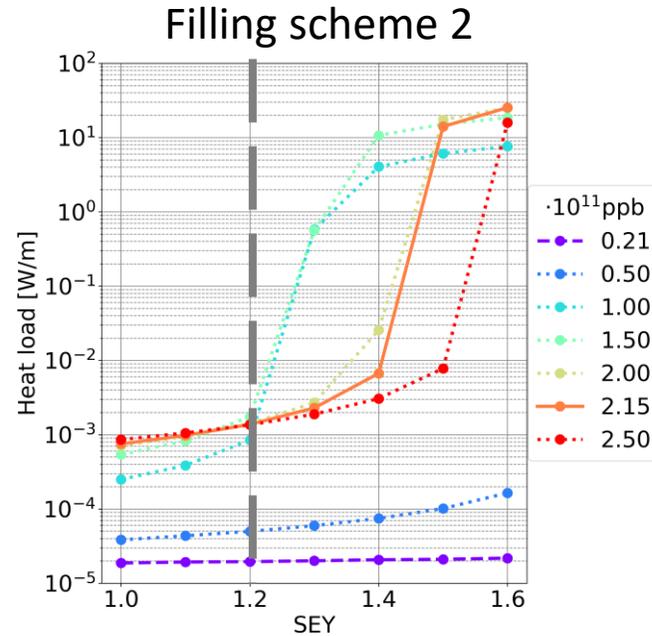
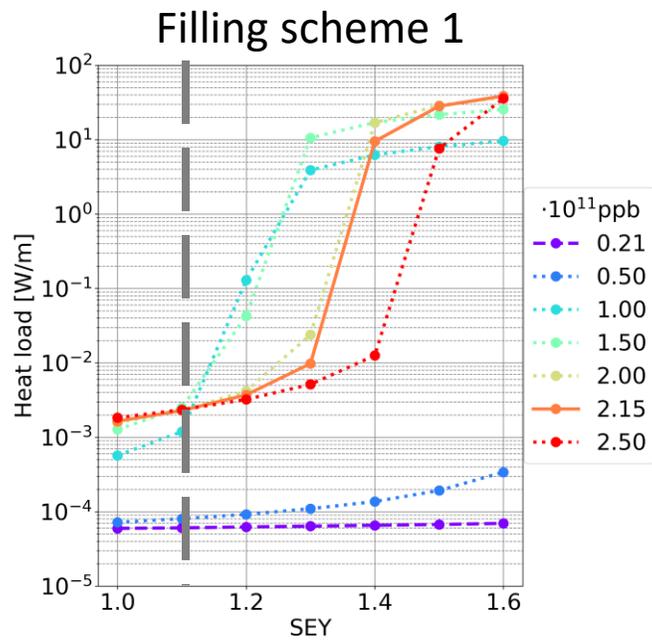
Courtesy of Fatih Yaman

Furman-Pivi model is more pessimistic:

- Multipacting occurs for lower SEY
- Larger e-cloud density

More details in: [F. Yaman, "Electron cloud simulations using the Furman-Pivi model", FCC-ee electron cloud meeting 18/03/2025](#)

# Heat Loads: Drift Space



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

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

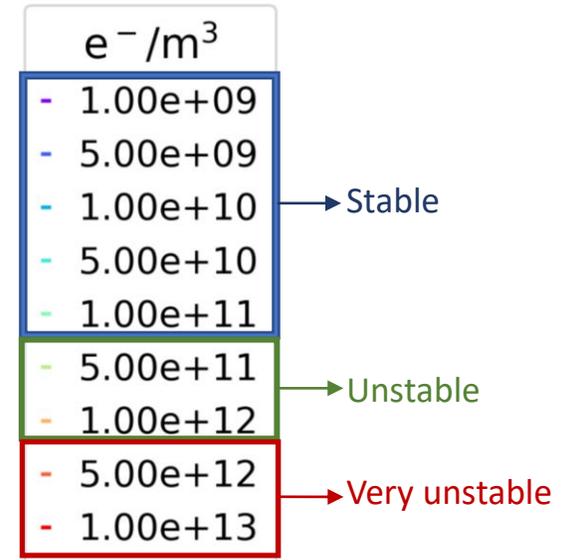
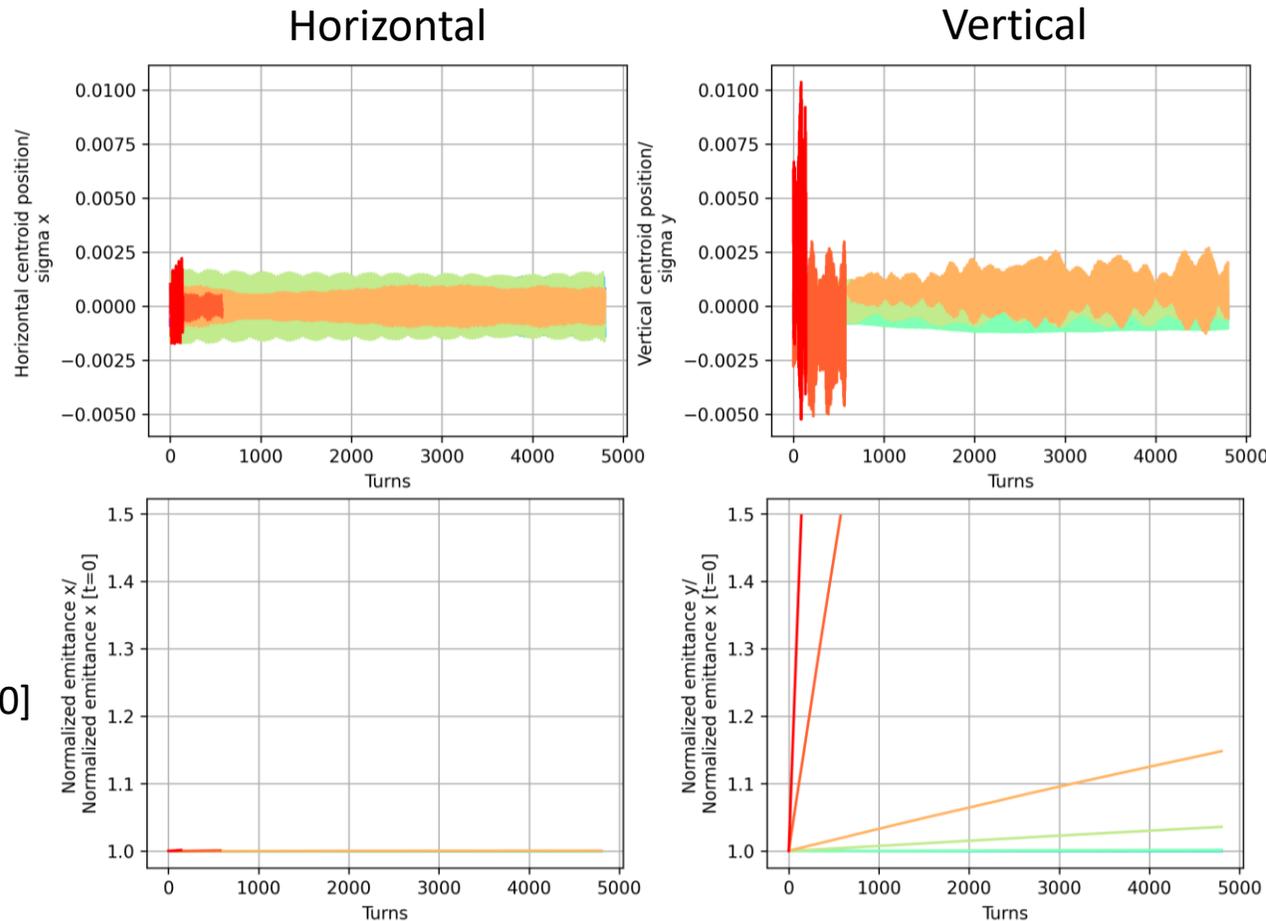
# Heat Loads: Summary

- In case there is **multipacting**, the **total heat loads** are in the order of:
  - 5-7% of **synchrotron radiation** power for the **filling scheme 1**
  -
- **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

# E-Cloud Stability Simulation Threshold

**Drift Space case:** considering only the drift length  $L_{\text{drift}} = 17.4 \text{ km}$  ( $L_{\text{drift}}/L = 19.18\%$ )

Centroid/  
Sigma

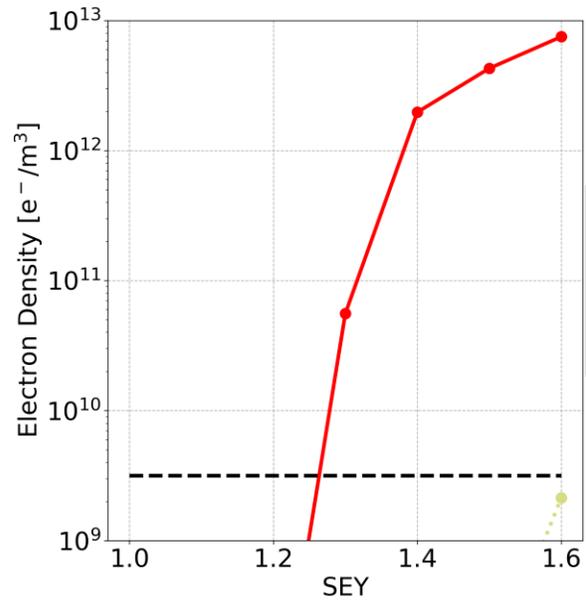


- Theoretical and numerical e-cloud density stability threshold have the same order of magnitude:

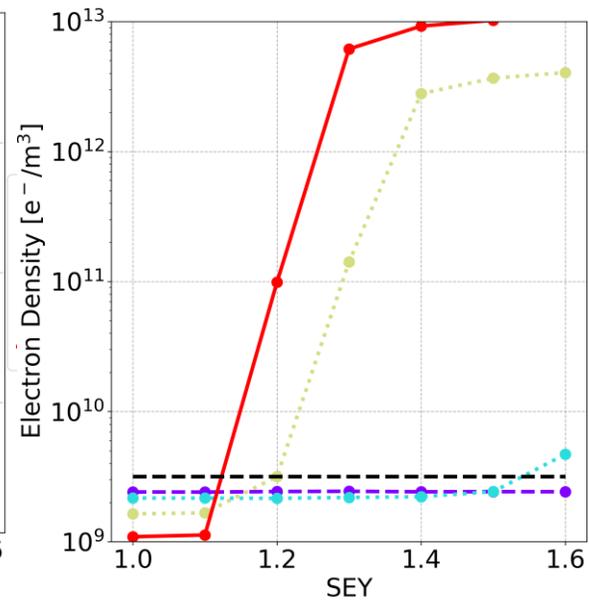
$$\rho_{e,\text{th}} = 9.53 \cdot 10^{10} \text{ e}^-/\text{m}^3$$

- Vertical plane is unstable

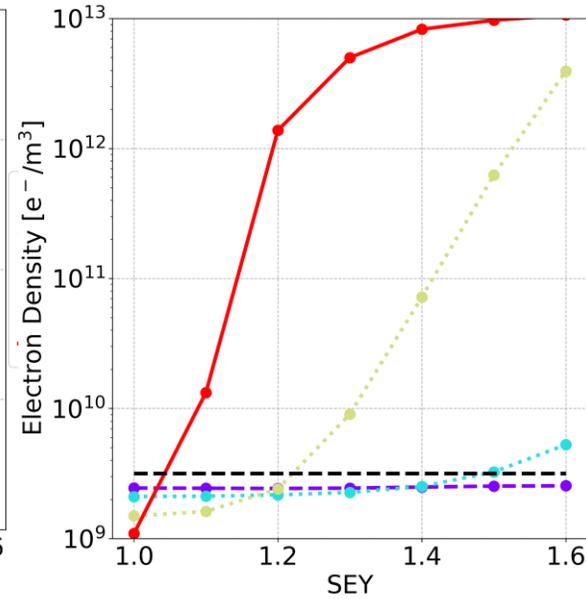
Drift



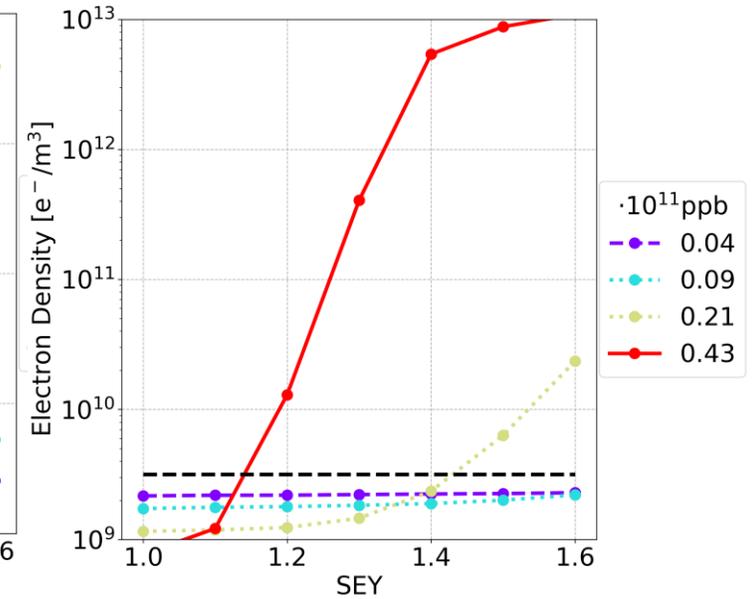
Dipole



Quadrupole



Sextupole



## Analysed ranges

- Bunch spacing: from 25 ns down to 5 ns
- Total number of bunches per train: from 280 up to 1,400 (Number of trains 40)
- Nominal bunch intensity: from 0.43e11 ppb down to 4.3e10

# Comparison 25 and 5ns Uniform Bunch Spacing

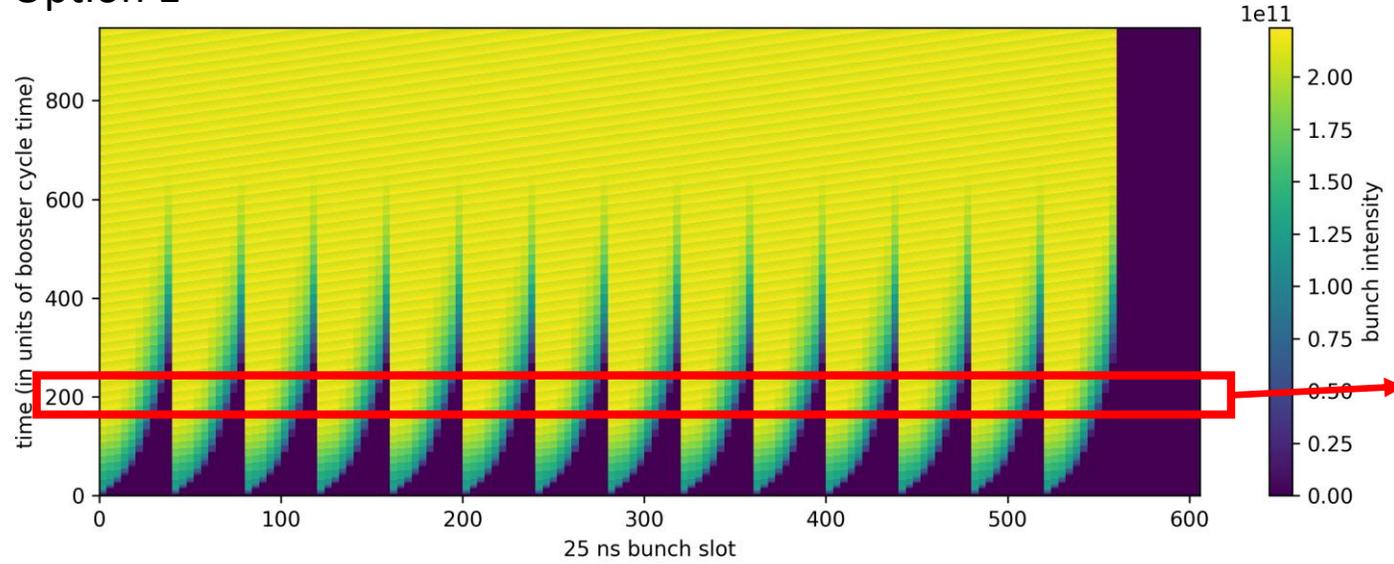
Element	Field	Bunch population	25 ns	5 ns
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		below nominal	1.0	
Drift Space	-	nominal	1.4	1.1
		below nominal	1.2	
Quadrupole	1.45 T/m	nominal	1.1	1.0
		below nominal	1.0	
Sextupole	72.5 T/m <sup>2</sup>	nominal	1.1	1.1
		below nominal	1.0	

5 ns uniform bunch spacing

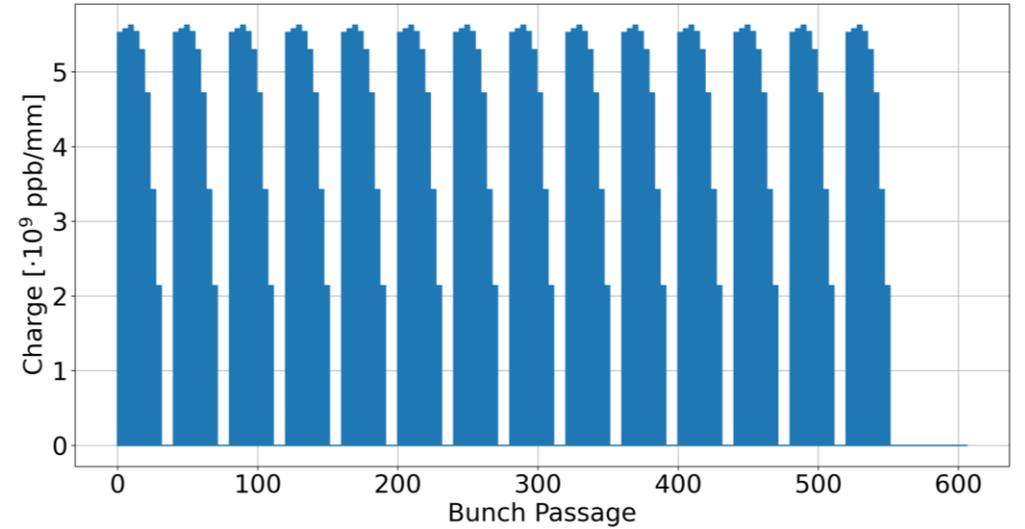
- **e-cloud density are higher when there is multipacting**
- Considering the nominal case the SEY multipacting thresholds are lower

# Charge Accumulation Phase

## Option 1

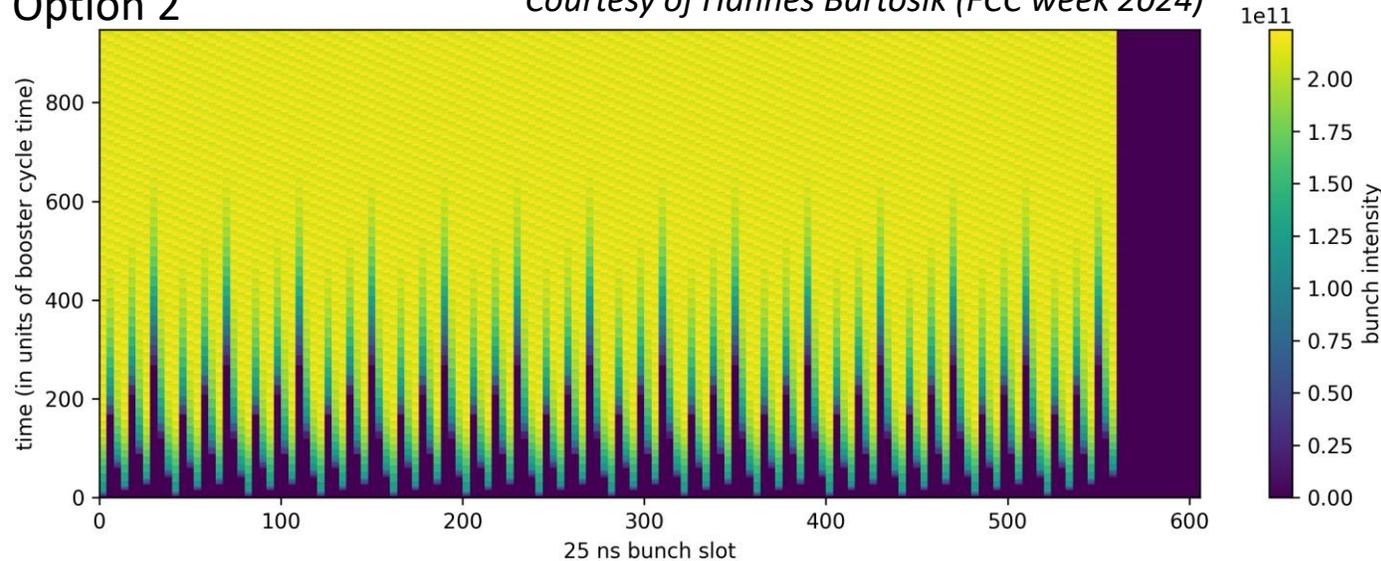


Option: 1 Booster Cycle: 200



## Option 2

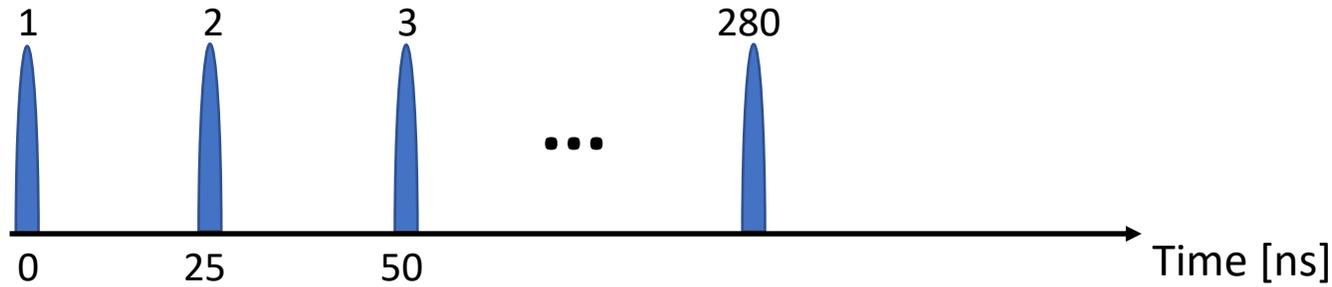
*Courtesy of Hannes Bartosik (FCC week 2024)*



# Mitigation: Non-Uniform reduced bunch spacing

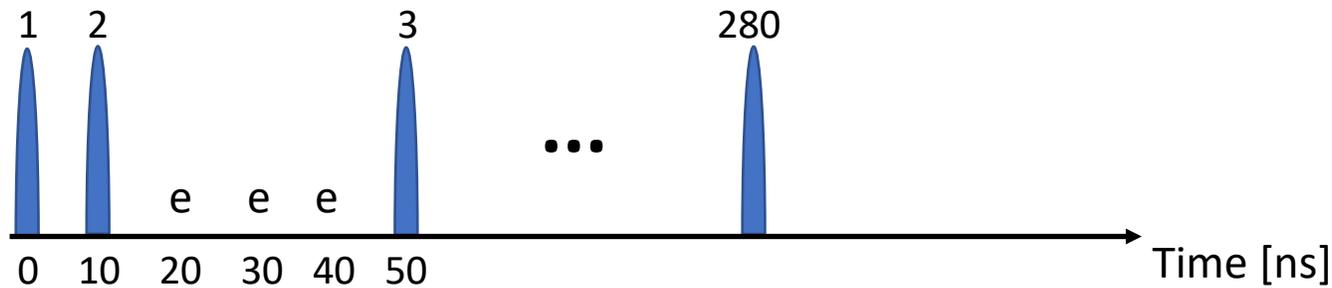
Analysed trains with uniform bunch spacing

- Trains with 25 ns bunch spacing



Trains with smaller bunch spacing and with small gaps in order to mitigate the e-cloud (keeping the same train duration):

- Trains with 10 ns bunch spacing (2 bunches + 3 empty bunches)



# 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**

