

Electron-Cloud Effects and Possible Mitigation Strategies

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Acknowledgments: Bartosik Hannes², Carli Christian², Iadarola Giovanni², Oide Katsunobu⁷, Seidel Mike¹, Zimmermann Frank¹, Zobov Mikhail⁶

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Swiss Accelerator Research and Technology

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Outline

- Baseline Scenario
- Mitigation Techniques
- Non-Uniform Bunch Spacing
- Conclusions and Outlooks

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- **Baseline Scenario**
- Mitigation Techniques
- Non-Uniform Bunch Spacing
- Conclusions and Outlooks

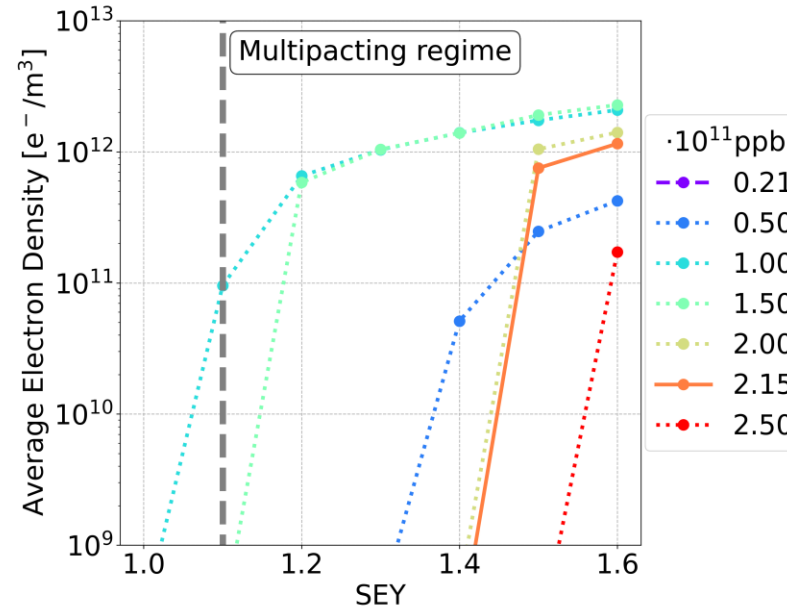
E-Cloud Build-up Studies for Baseline

From Feasible Study Report

Bunch Intensity [x10 ¹¹ ppb]	Bunch Spacing [ns]	Number bunches / Train	Number Trains	Gap Length [ns] (gap/bunch spacing)
2.15	25	280	40	575 (23)

- Important to understand the impact of **lower bunch intensity** (we will need to **fill the ring**)
- The bunches are gradually filled from the booster at collision energy (**top-up injection**)
- **E-cloud** becomes **too severe** with **bunch spacing < 25 ns**, more details in:
 - [“Electron cloud studies”, FCC week 2023](#)
 - [“Update on the Electron Cloud Studies for FCC-ee”, FCC e-cloud meeting 12/09/2023](#)

E-Cloud Build-Up Studies: Dipole



Secondary Emission Yield (SEY)

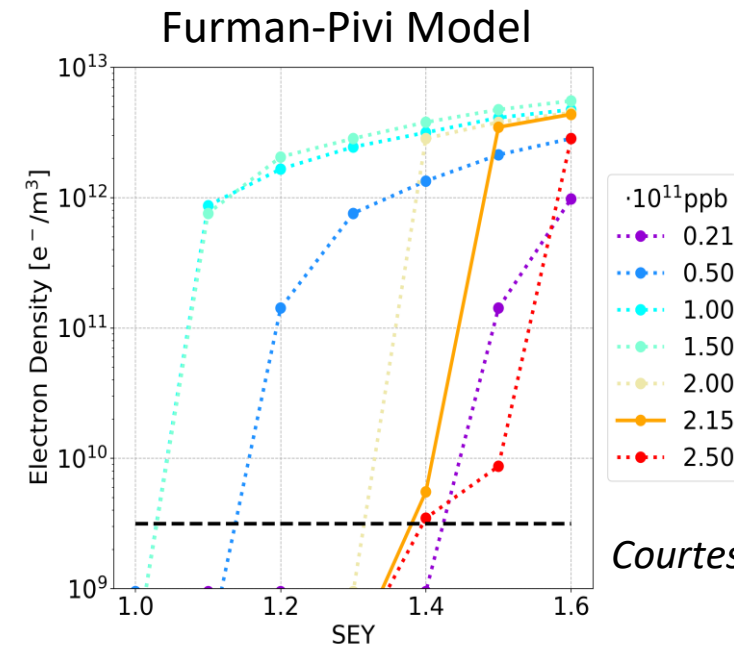
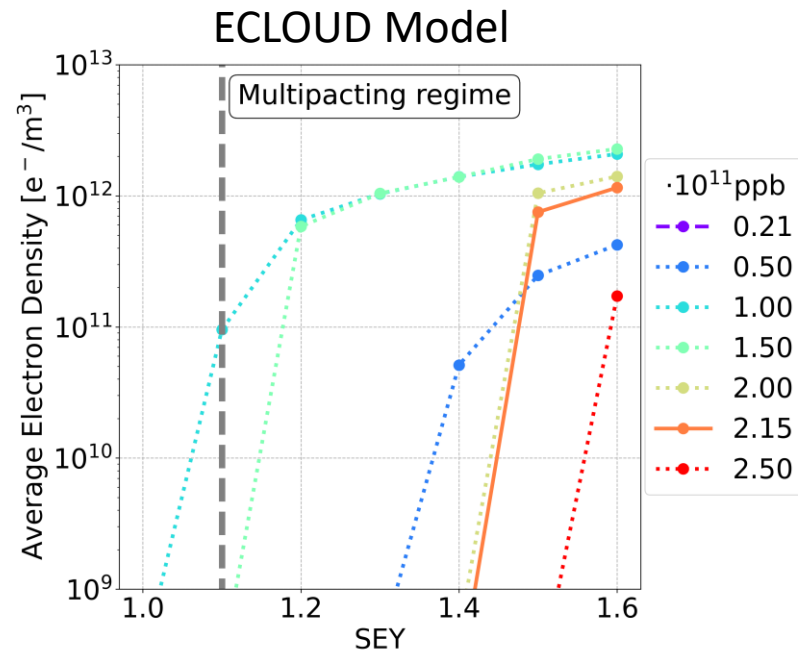
$$\delta(E) = \frac{I_{\text{emit}}}{I_{\text{imp}}(E)}$$

The bunch intensities 1.00 and 1.50 x 10¹¹ ppb are the most critical cases

Bunch population	SEY multipacting thresholds
nominal	1.4
below nominal	1.0

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](#)

E-Cloud Build-Up Studies: Summary

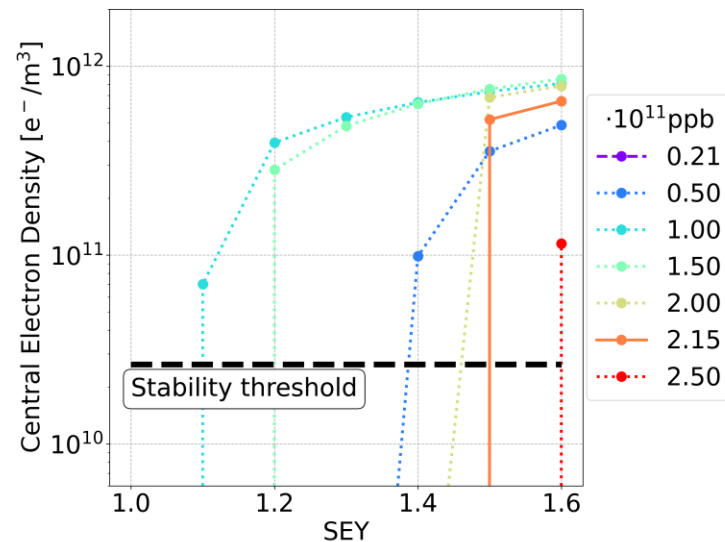
- The **SEY multipacting thresholds** are extremely **tight** for **baseline parameters**
- **Quadrupoles** and **sextupoles** have the **lowest SEY multipacting thresholds**
- Bunch intensities 1.00 and 1.50×10^{11} ppb are the most critical cases

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 ²	nominal	1.1
		below nominal	1.0

Stability

E-cloud multipacting has to be avoided

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



Theoretical stability threshold

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

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

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

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

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

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

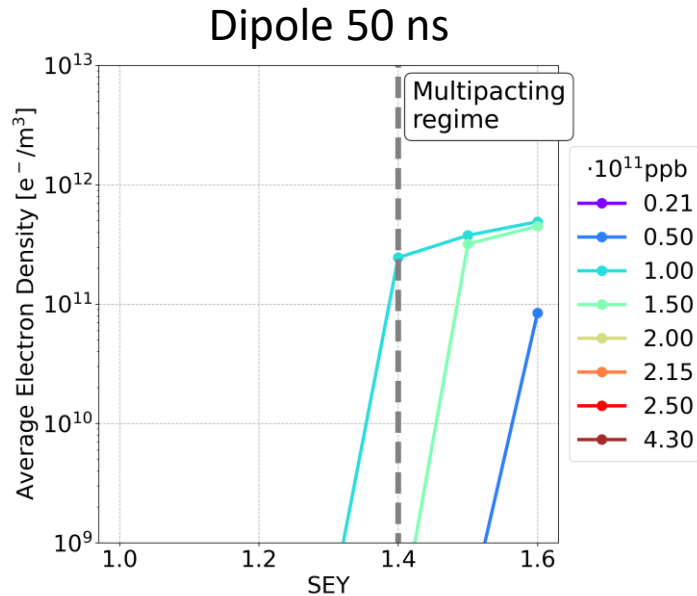
Theoretical threshold has been verified by means of [PyECLOUD-PyHEADTAIL](#) simulations, more details in: ["Electron Cloud studies for the FCC-ee", FCC week 2024](#)

Outline

- Baseline Scenario
- **Mitigation Techniques**
- Filling Pattern with Non-Uniform Bunch Spacing
- Conclusions and Outlooks

Mitigation: Bunch Spacing

- The SEY multipacting thresholds are extremely tight for baseline parameters
- E-cloud could be mitigated using larger bunch spacing

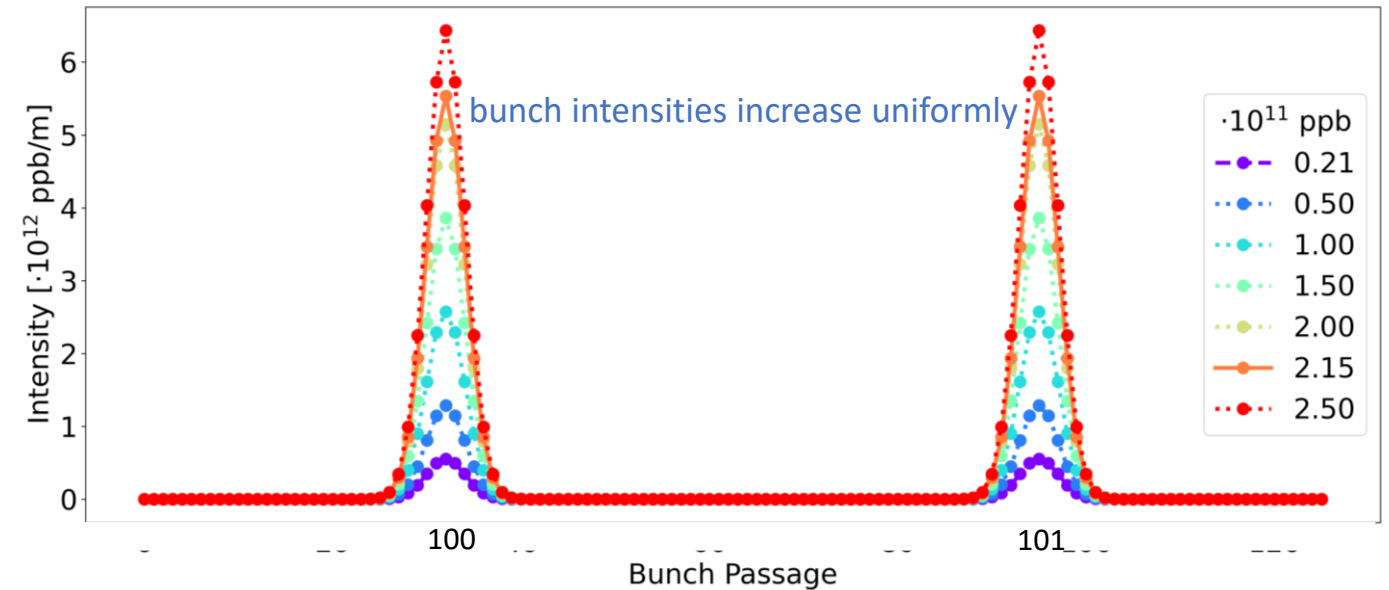
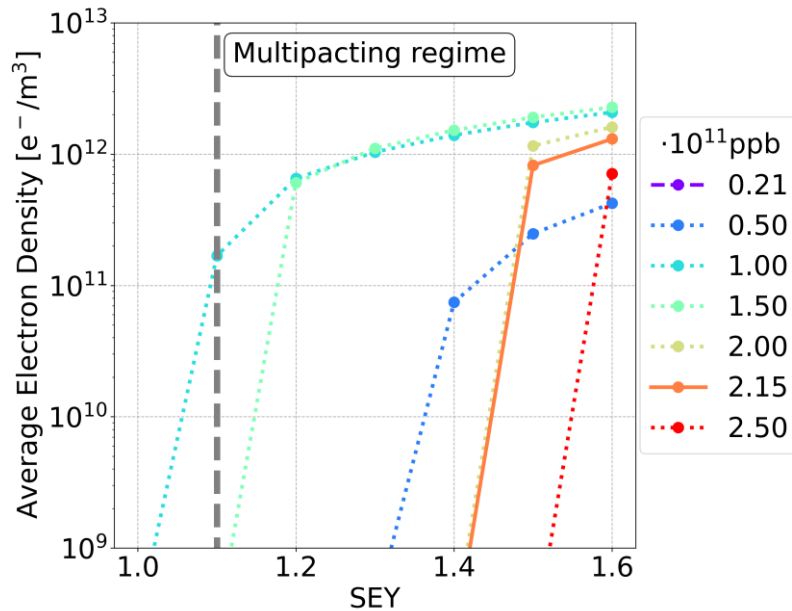


Larger bunch spacing

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 ²)	1.0	1.1	1.3	1.4

- If the bunch spacing is larger (e.g., 2 times: 25 ns -> 50 ns), in order to keep the beam current constant
- larger bunch intensities are needed (e.g., 2 times: 2.15×10^{11} ppb -> 4.30×10^{11} ppb)
- It could lead to issues with other collective effects (beam-beam, beam-coupling impedance), more details in:
 - [Mauro Migliorati, "FCC-ee single beam collective effects", FCC week 2024](#)
 - [Roxana Soos, "Xsuite simulations of beam-beam effects with impedance contribution", FCC week 2024](#)

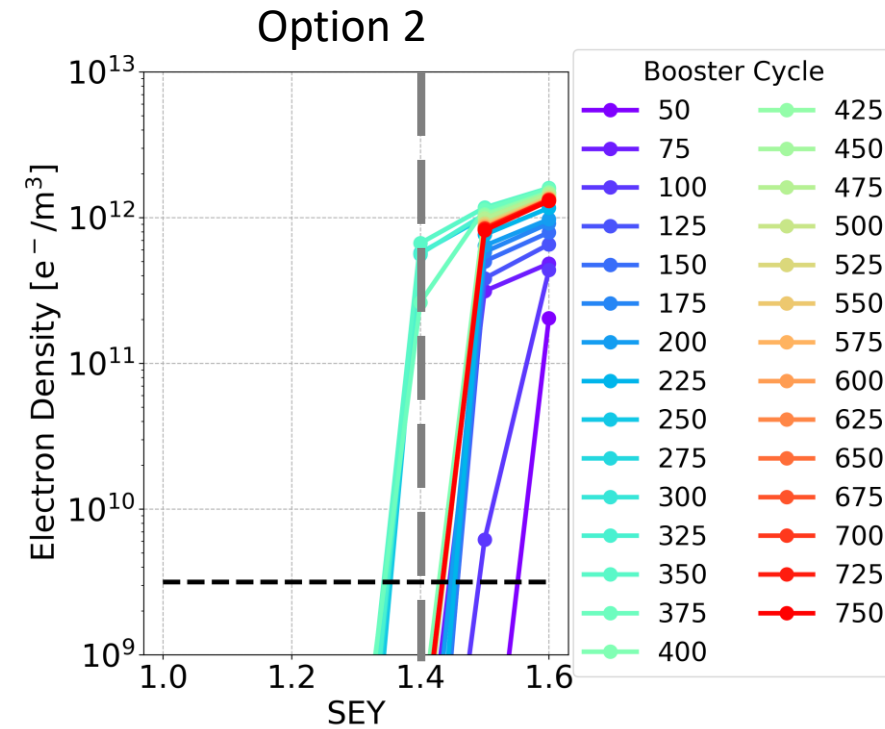
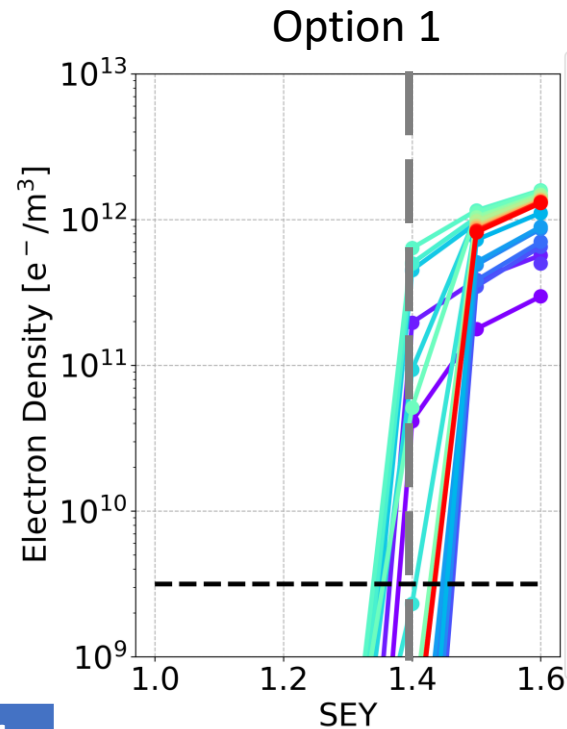
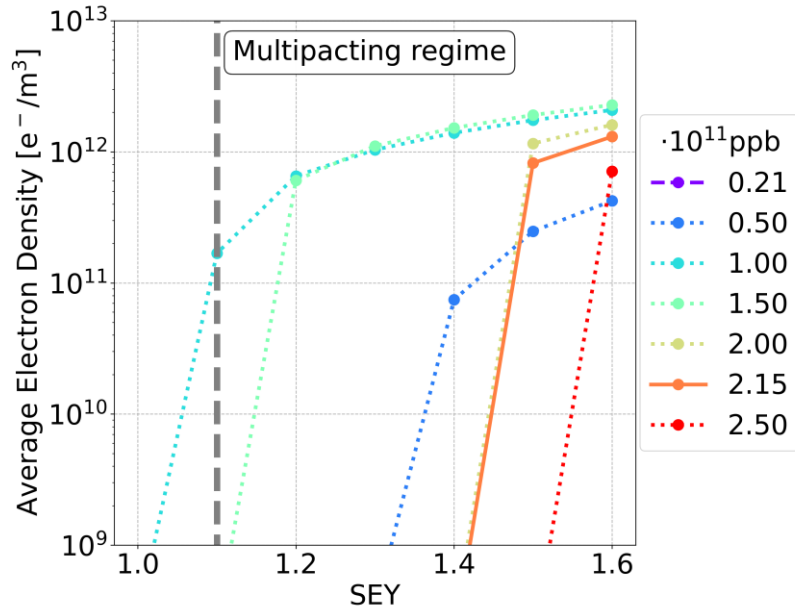
Mitigation: Charge Accumulation Phase



The bunch intensities 1.00 and 1.50×10^{11} ppb are the most critical cases

- 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**
- Two options were presented by [Hannes Bartosik, "Booster and collider filling scheme", FCC week 2024](#)

Charge Accumulation Phase: Dipole



Bunch population	SEY multipacting thresholds
nominal	1.4
below nominal	1.0

	SEY multipacting thresholds
During charge accumulation	1.3

Using the **two options** with special filling schemes during the charge accumulation phase, the **SEY multipacting thresholds** are **higher** and they tend to the SEY multipacting thresholds in the case of the nominal bunch intensity

Charge Accumulation Phase: Summary

- The **two options** with special filling schemes **are also effective** for the **other analysed elements**
- **Quadrupoles** and **sextupoles** have the lowest SEY multipacting thresholds

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 ²	1.1	nominal	1.1
			below nominal	1.0

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

See Roxana Soos, "Beam-Beam and Wakefield-Induced Collective Instabilities and Mitigation Strategies in the FCC-ee at Z Energy", FCC week 2025

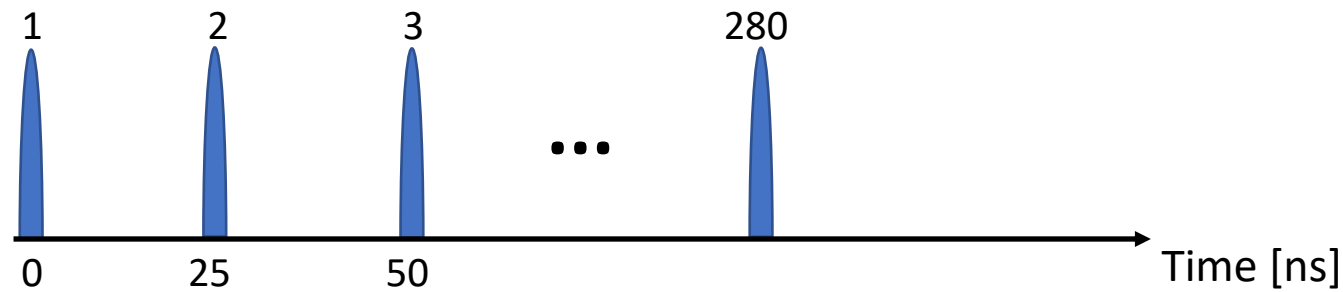
Outline

- Baseline Scenario
- Mitigation Techniques
- **Non-Uniform Bunch Spacing**
- Conclusions and Outlooks

Trains with Non-Uniform Bunch Spacing

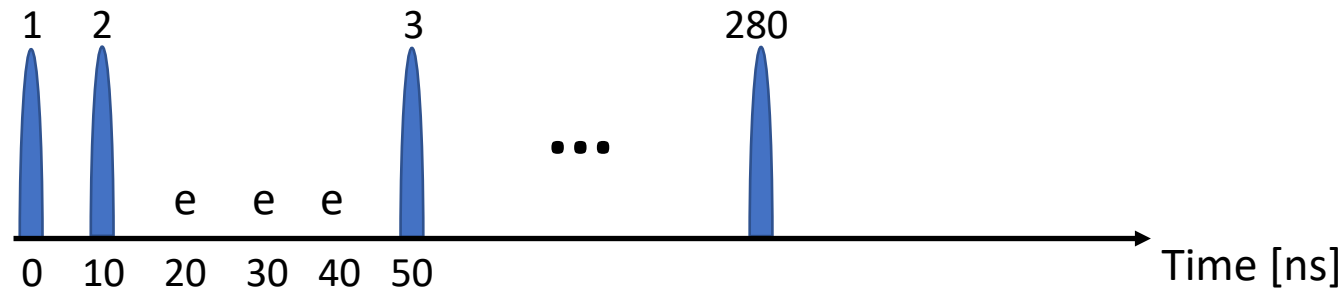
Analysed trains with uniform bunch spacing

- 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):

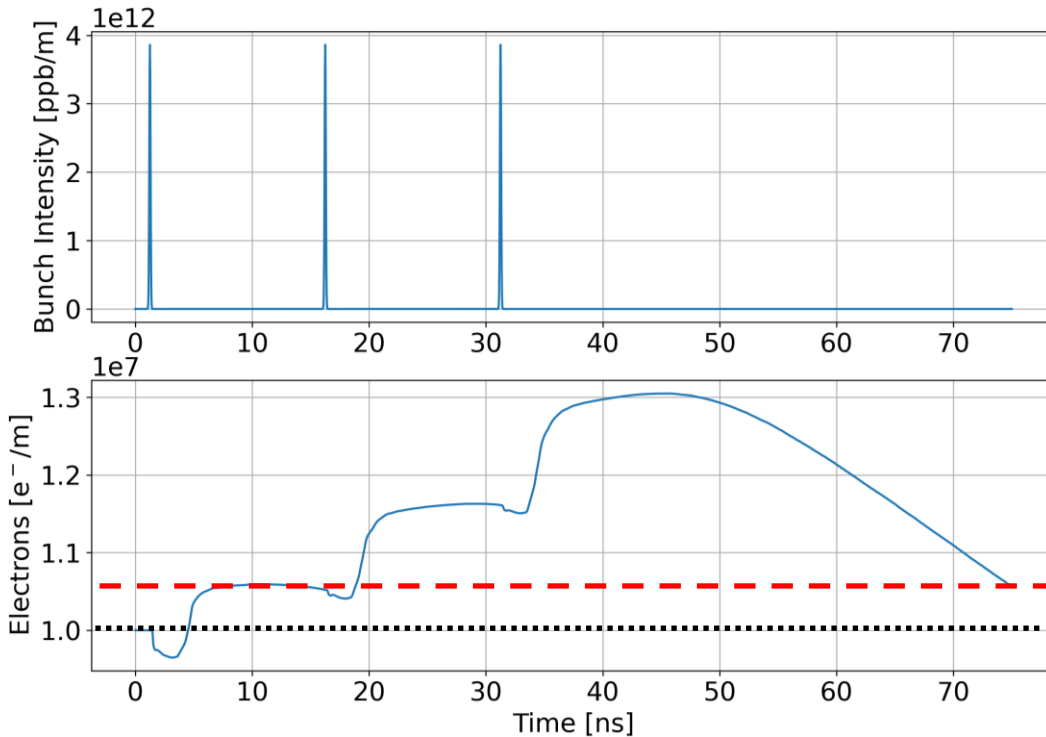
- Trains with 10 ns bunch spacing (2 bunches + 3 empty bunches)



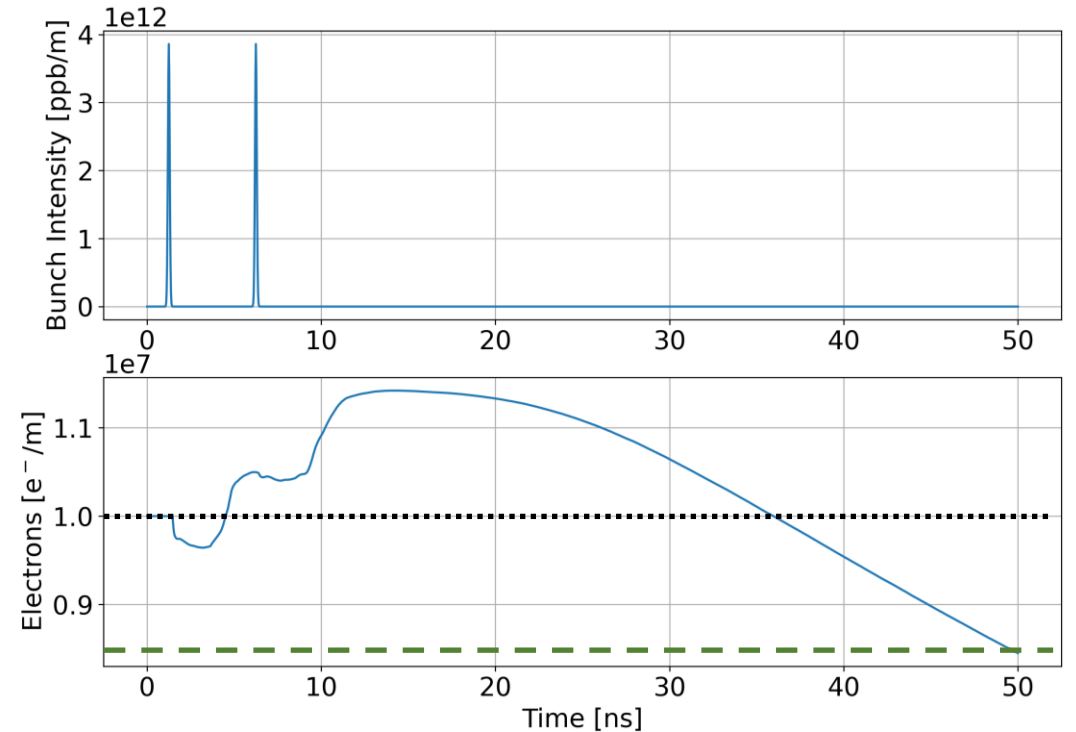
Bunch Spacing

- Analysed some cases with few bunch passages and a small gap
- Considering larger bunch spacing (20 ns and 15 ns), the small gap is not long enough to mitigate the e-cloud
 - e-cloud after the bunch passages and the small gap is larger than the initial e-cloud density
- Considering very small bunch spacing (10 ns and 5 ns), the small gap is long enough to mitigate the e-cloud
 - e-cloud after the bunch passages and the small gap is smaller than the initial e-cloud density

Bunch spacing 15 ns with 3 bunches and 2 empty



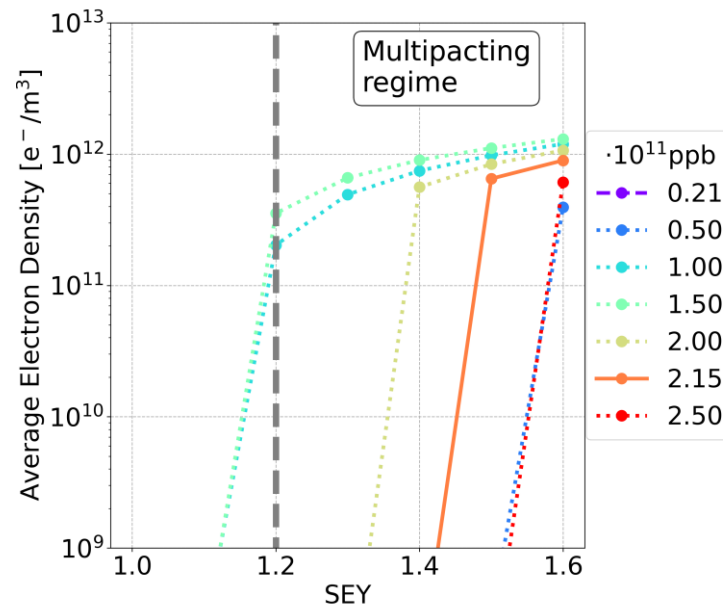
Bunch spacing 5 ns with 2 bunches and 8 empty



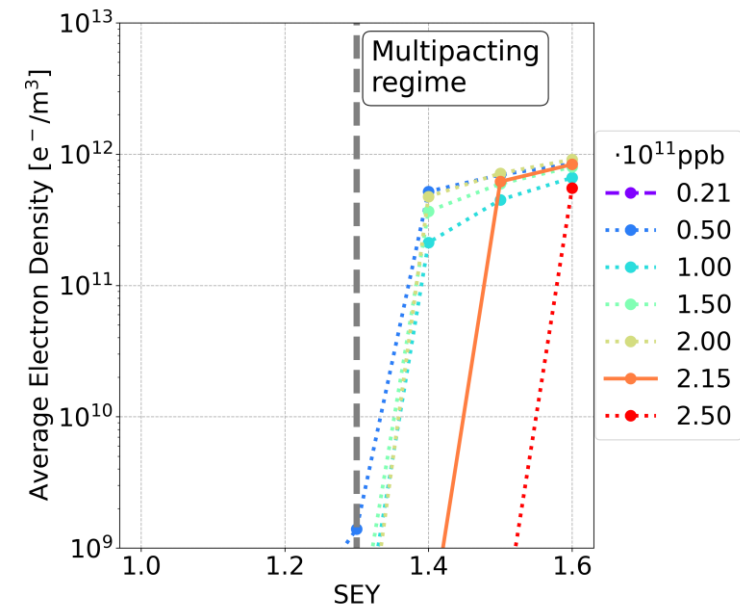
Short Bunch Spacing: 10 ns vs 5 ns

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

Bunch spacing **10 ns** with 2 bunches and 3 empty



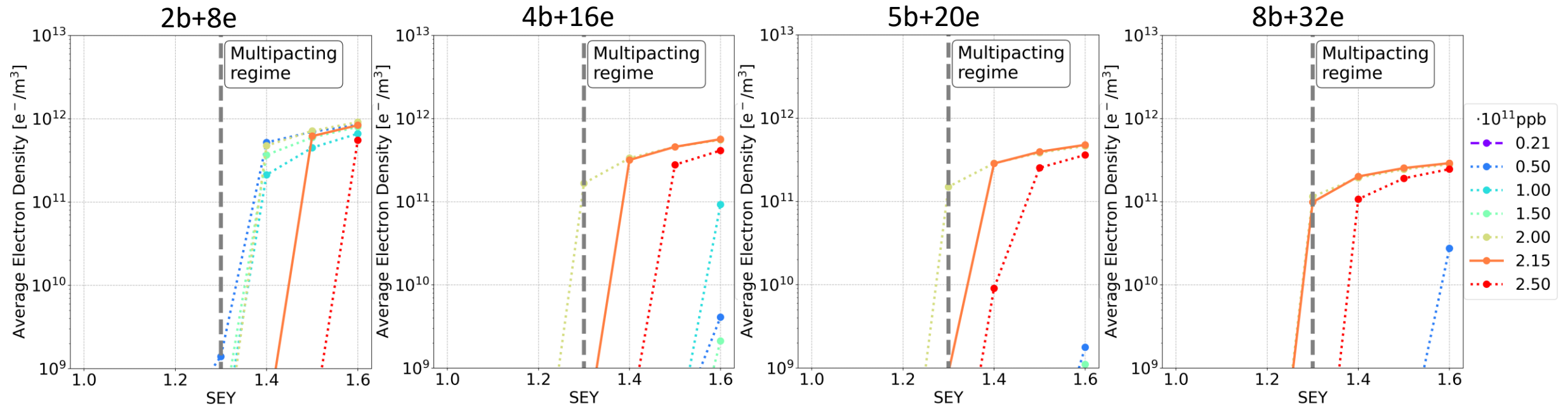
Bunch spacing **5 ns** with 2 bunches and 8 empty



A **better e-cloud mitigation** is obtained using filling schemes with **5 ns bunch spacing**

Short Bunch Spacing 5 ns: Dipole

Considering different filling patterns



Bunch population	Uniform 25 ns	2b+8e	4b+16e	5b+20e	8b+32e
nominal	1.4	1.4	1.3	1.3	1.2
below nominal	1.0	1.2	1.2	1.2	1.2

Using filling schemes with **non-uniform bunch spacing**, the strict constraint on the **SEY multipacting thresholds** for critical bunch intensities **could be mitigated**

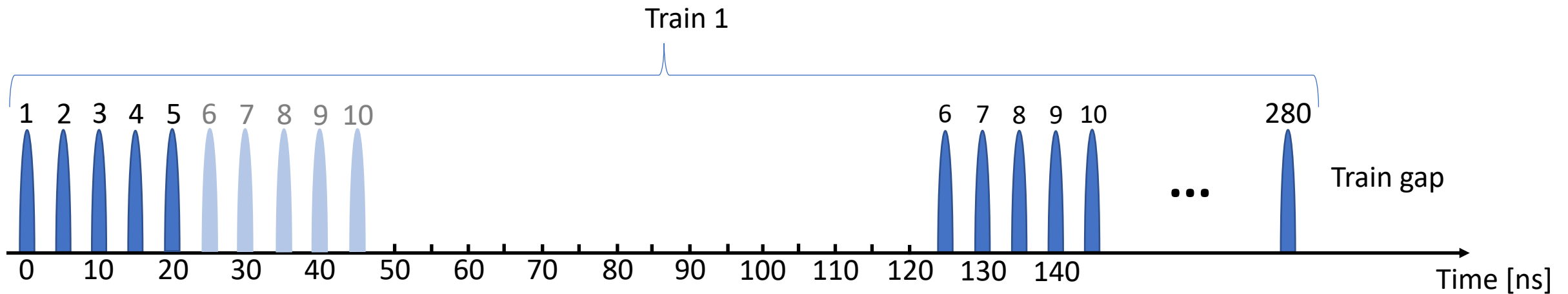
Short Bunch Spacing 5 ns: Summary

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 ²	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
- The filling schemes with the patterns **4b16e** and **5b20e** are the **most promising**

Higher Total Bunches

- Having a larger number of bunches
 - allows for a reduction in nominal bunch intensity while maintaining the same beam current
 - reducing the severity of other collective effects (beam-coupling impedance and beam-beam)
- The filling schemes with the patterns 5b20e has been analysed

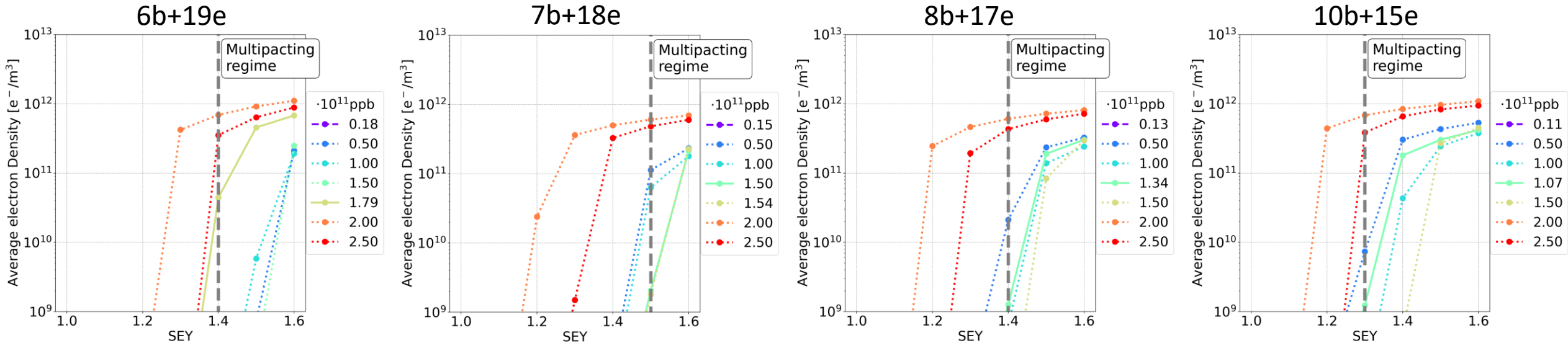


- Additional bunches are added, reducing the number of empty bunches that form the gap

Filling pattern	5b+20e	6b+19e	7b+18e	8b+17e	10b+15e
Total bunches	11,200	13,440	15,680	17,920	22,400
Nominal bunch intensity [$\times 10^{11}$ ppb]	2.15	1.79	1.54	1.34	1.08

Higher Total Bunches: Dipole

Considering different filling patterns with a larger number of bunches



Bunch population	Uniform 25 ns	5b+20e	6b+19e	7b+18e	8b+17e	10b+15e
nominal	1.4	1.3	1.3	1.4	1.3	1.2
below nominal	1.0	1.2	1.3	1.4	1.3	1.2

Filling schemes with non-uniform bunch spacing and a higher total number of bunches remain effective in alleviating the stringent requirements on the internal surface material of the vacuum chamber

Higher Total Bunches: Summary

Element	Field	Bunch population	Uniform 25 ns	5b+20e 11,200 2.15×10^{11} ppb	6b+19e 13,440 1.79×10^{11} ppb	7b+18e 15,680 1.54×10^{11} ppb	8b+17e 17,920 1.34×10^{11} ppb	10b+15e 22,400 1.08×10^{11} ppb
Drift Space	-	nominal	1.4	1.4	>1.6	>1.6	>1.6	1.4
		below	1.2	1.4	>1.6	>1.6	>1.6	1.4
Dipole	15.2 mT	nominal	1.4	1.3	1.3	1.4	1.3	1.2
		below	1.0	1.2	1.3	1.4	1.3	1.2
Quadrupole	1.45 T/m	nominal	1.1	1.3	1.2	1.2	1.2	1.2
		below	1.0	1.3	1.2	1.2	1.2	1.2
Sextupole	72.5 T/m ²	nominal	1.1	1.5	1.4	1.3	1.2	1.2
		below	1.0	1.5	1.4	1.3	1.2	1.2

- Filling schemes with non-uniform bunch spacing and a **higher total number** of bunches **remain effective** in **alleviating** the **stringent requirements** on the internal surface material of the vacuum chamber

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- Non-Uniform Bunch Spacing
- **Conclusions and Outlooks**

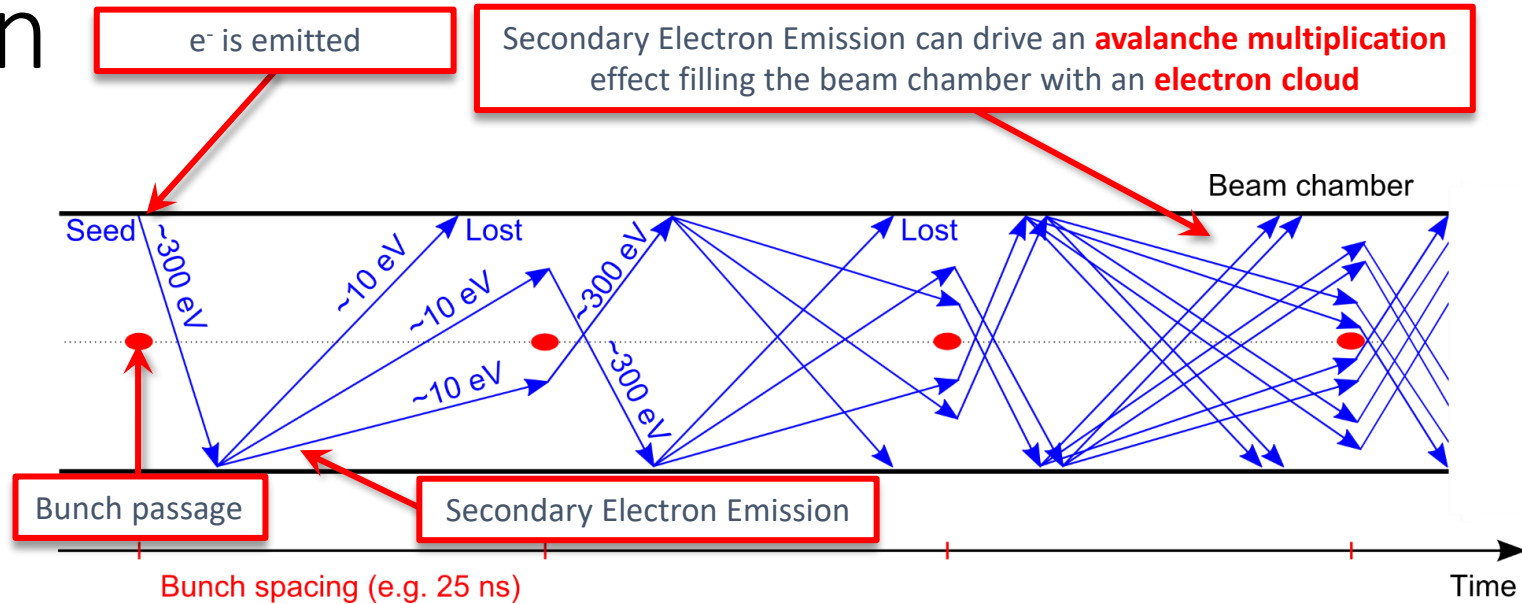
Conclusions

- The **material constraints** in order to avoid e-cloud avalanche multiplication are **extremely tight for baseline parameters**
 - E-cloud **mitigation techniques** are needed
- **Increase bunch spacing** could alleviate the stringent constraints
 - To keep the beam current constant, the bunch intensity has to be increased and it could lead to **issues with other collective effects**
- **Special filling schemes during the accumulation phase avoid** tight constraints for the **critical bunch intensities**
 - **to find a working point that ensures stability may be difficult**, having bunches of significantly different intensities in the collider at the same time
- Using **filling schemes with non-uniform bunch spacing the e-cloud formation process could be mitigated**
 - the total number of bunches could be increased, with a corresponding decrease of the bunch population, while keeping the surface requirements achievable
 - reducing the severity of other collective effects (beam-coupling impedance and beam-beam)

Thanks for your attention

E-Cloud Formation

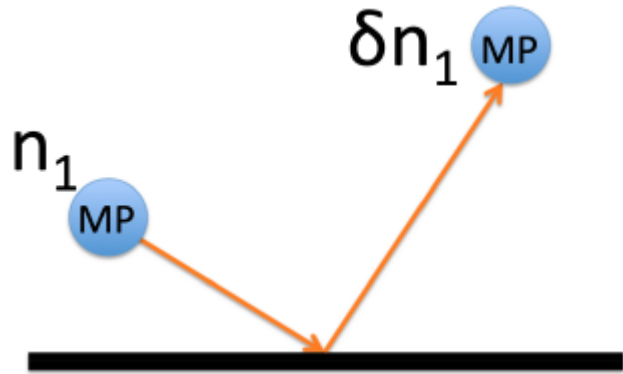
- The circulating beam particles can produce **primary electrons** (seed)
 - ionisation of the residual gas in the beam chamber
 - photoemission from the chamber's wall due to the synchrotron radiation emitted by the beam



- 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**

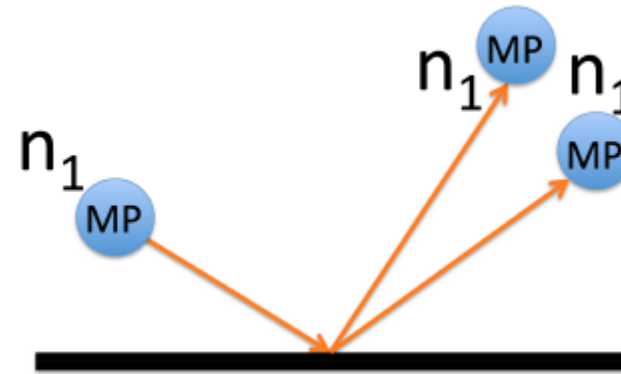
Courtesy of G. Iadarola

Furman-Pivi & ECLLOUD SEY Models



ECLLOUD Model:

- **resizes macroparticles** (MP) upon impact.
- elastically backscattered electrons are **emitted with the same energy** as the impact.
- the **rediffused** SEY component is not included

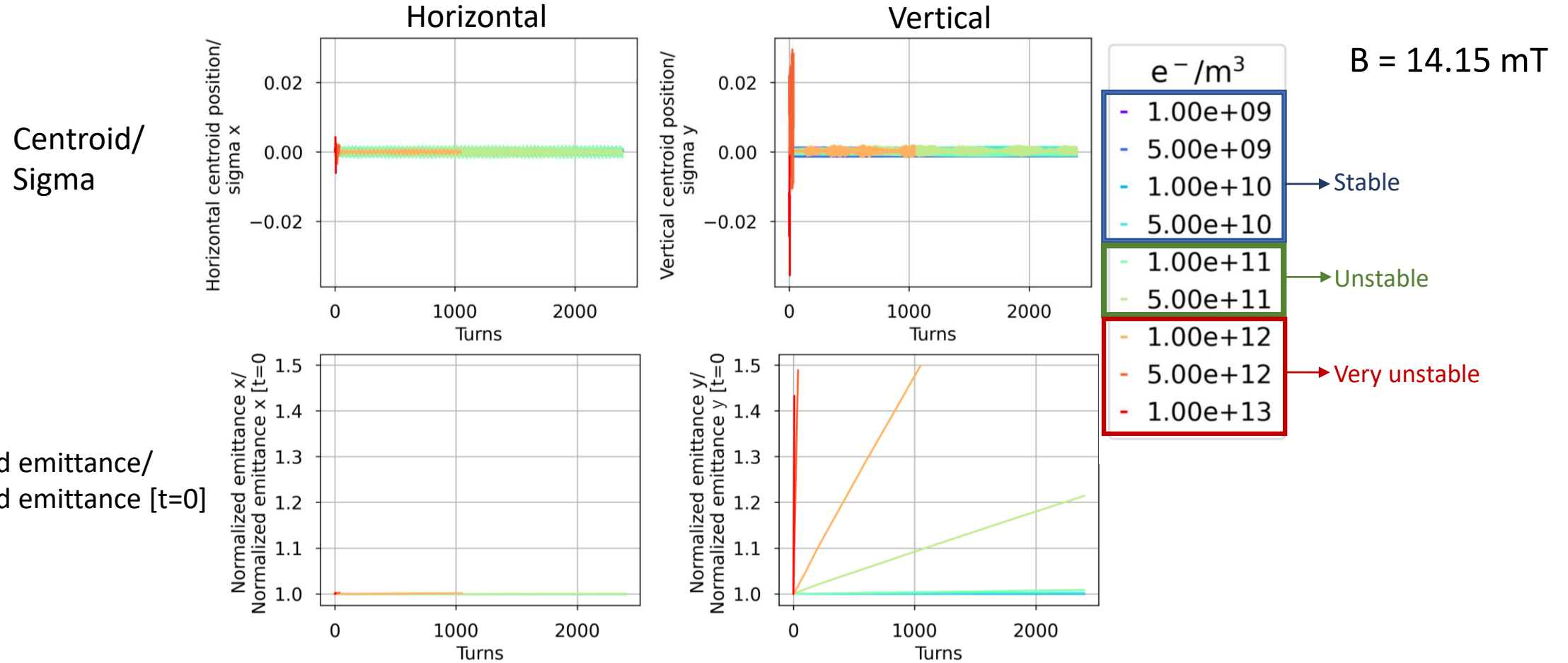


Furman-Pivi Model:

- **does not rescale macroparticles** (MP), and uses a **Poisson distribution**.
- **emitted energy** distribution depends on the **event type**
- the **rediffused** SEY component is **included**

E-Cloud Stability Simulation Threshold: Dipole

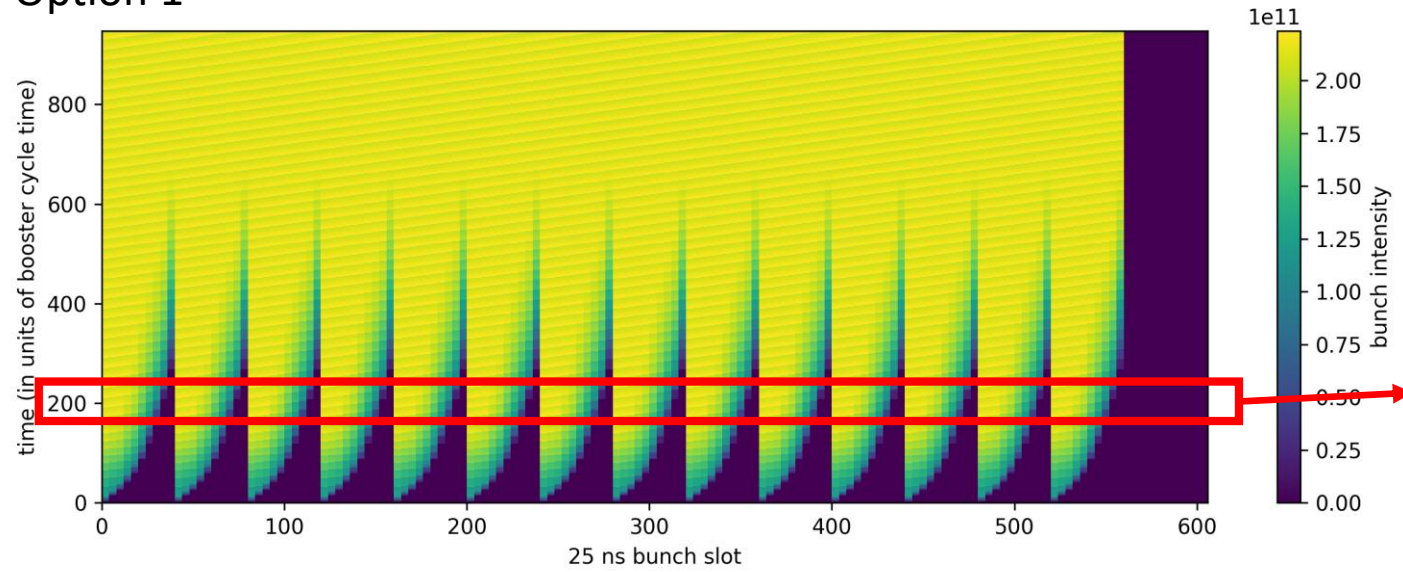
➤ $\rho_{e,th} = 2.42 \cdot 10^{10} \text{ e}^-/\text{m}^3$ considering only the dipole length $L_{dipole} = 62.8 \text{ km}$ ($L_{dipole}/L = 69.24\%$)



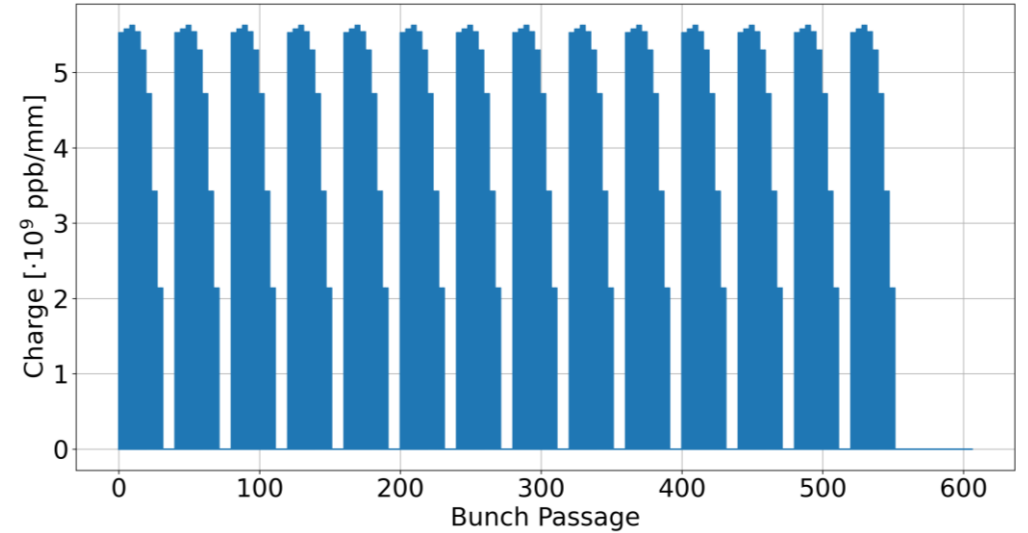
- Theoretical and numerical e-cloud density stability threshold have the same order of magnitude
- Vertical motion is unstable

Charge Accumulation Phase

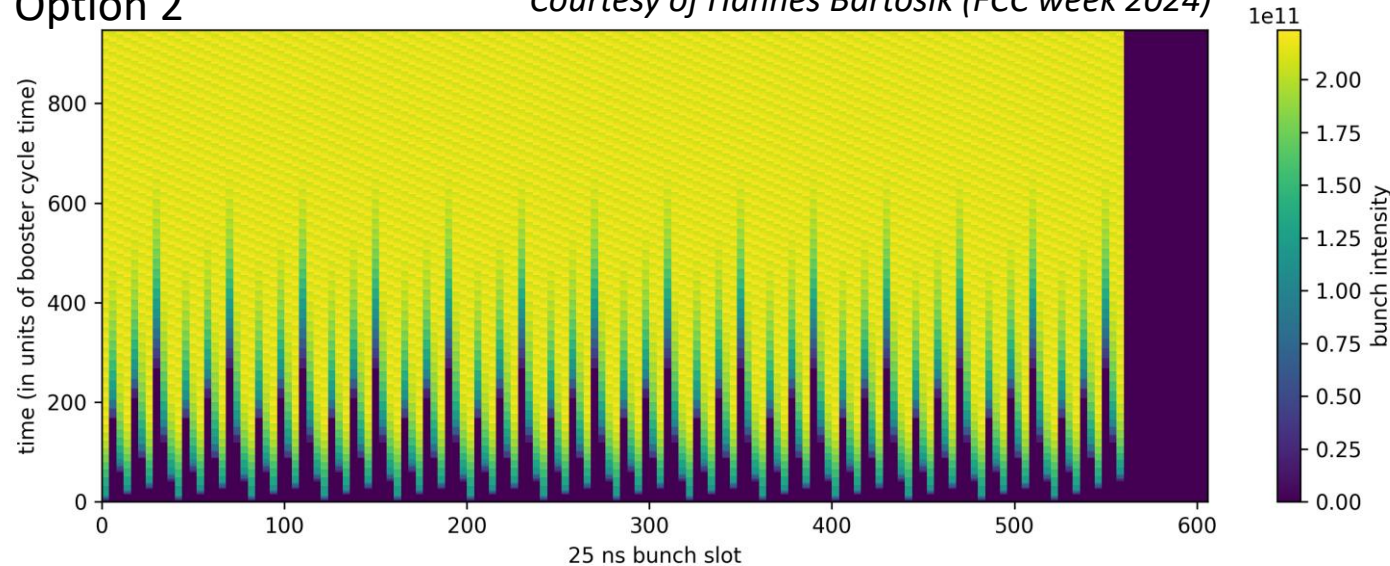
Option 1



Option: 1 Booster Cycle: 200



Option 2



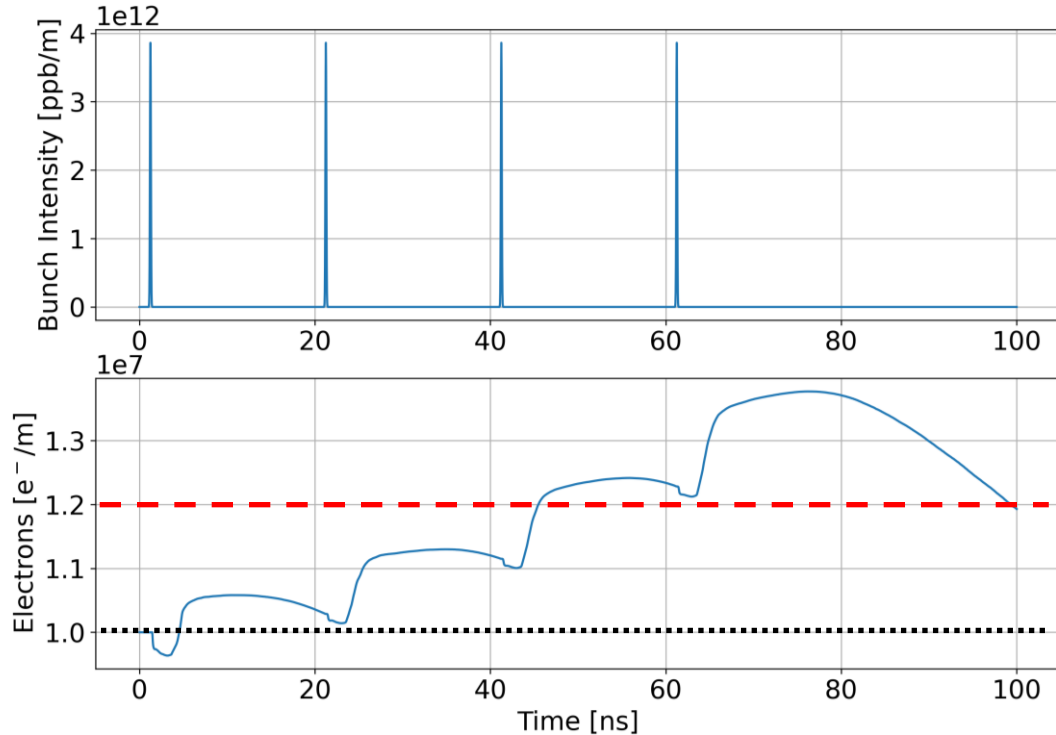
Courtesy of Hannes Bartosik (FCC week 2024)

Long Bunch Spacing

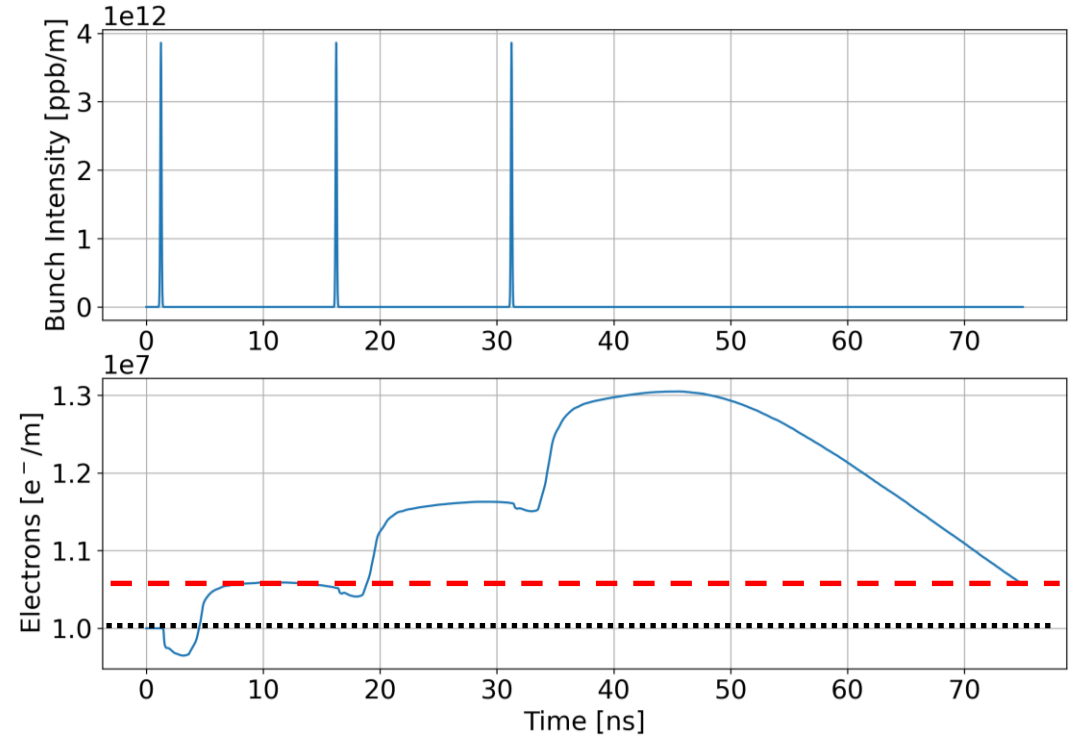
Analysed some cases with few bunch passages and a small gap

Considering larger bunch spacing (20 ns and 15 ns), the small gap is not long enough to mitigate the e-cloud
 e-cloud after the bunch passages and the small gap is larger than the initial e-cloud density

Bunch spacing 20 ns with 4 bunches and 1 empty



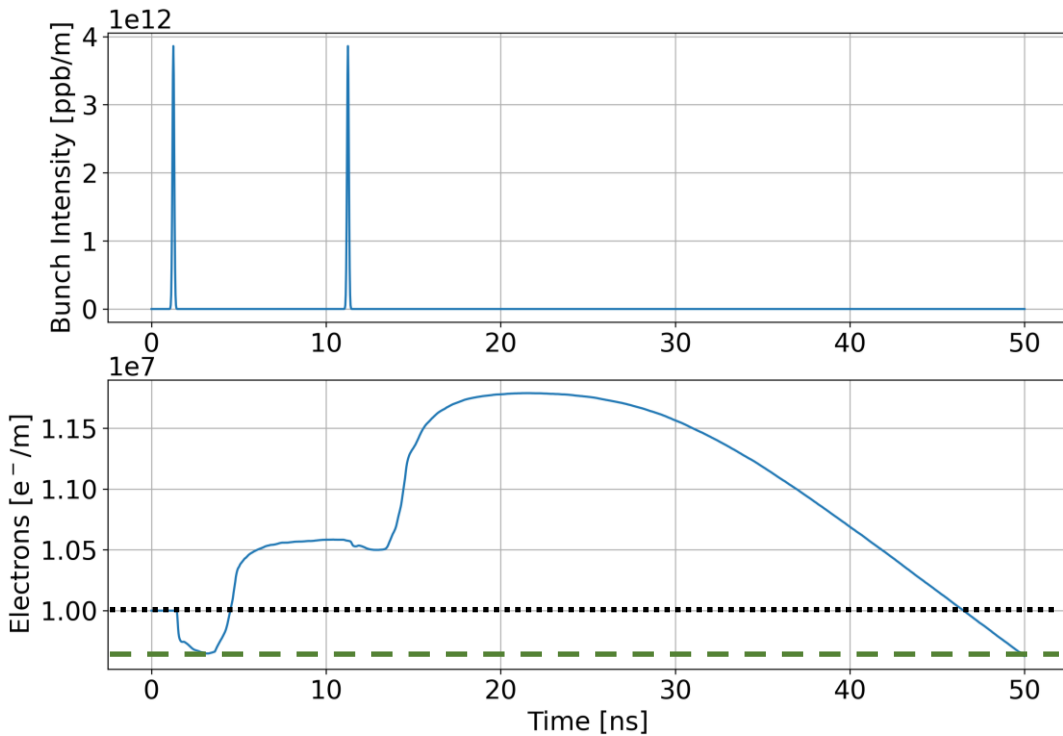
Bunch spacing 15 ns with 3 bunches and 2 empty



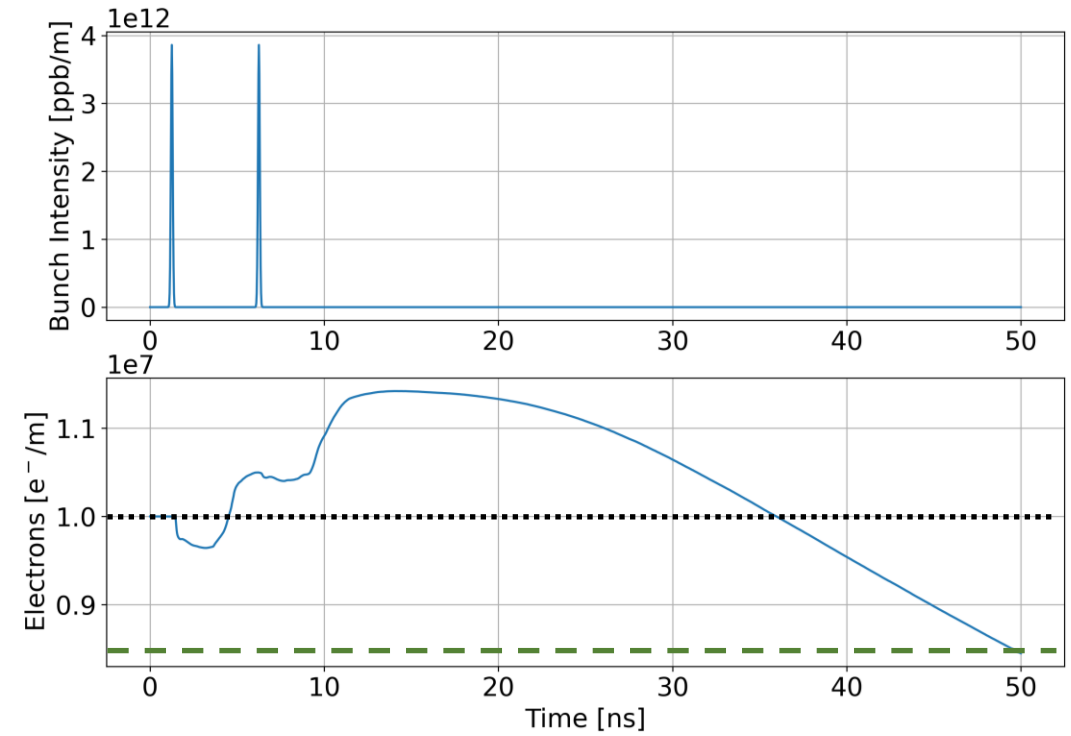
Short Bunch Spacing

Considering **very small bunch spacing (10 ns and 5 ns)**, the **small gap** is long enough to mitigate the e-cloud e-cloud **after the bunch passages** and the **small gap** is smaller than the initial e-cloud density

Bunch spacing **10 ns** with **2 bunches** and **3 empty**



Bunch spacing **5 ns** with **2 bunches** and **8 empty**

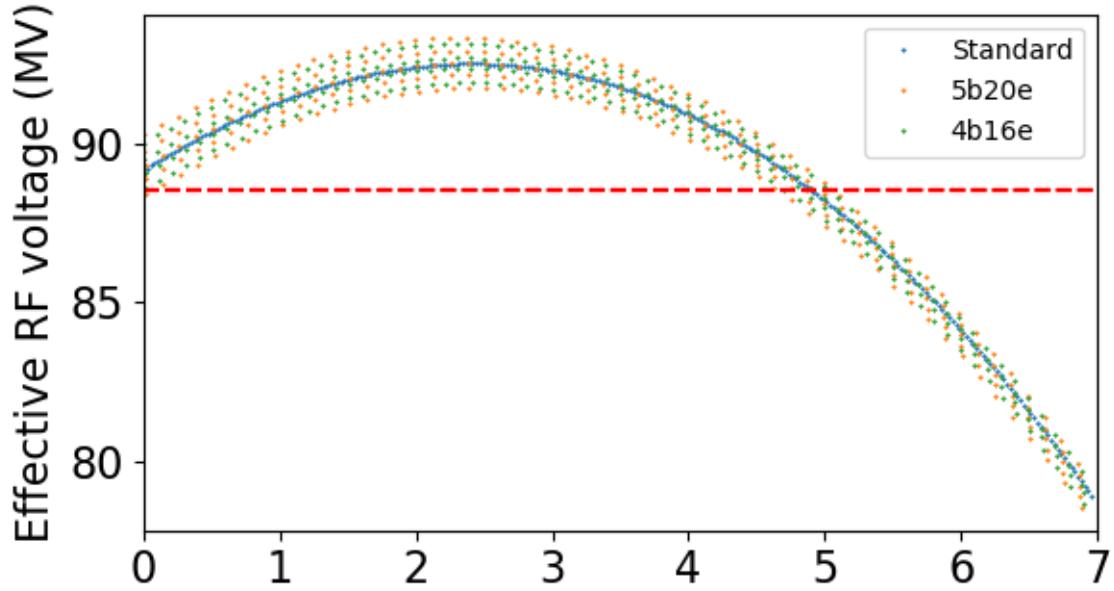


Outlooks

- Beam-beam
 - With smaller bunch intensity, the beam-beam parameter is smaller
 - With 5 ns bunch spacing, two long range beam-beam interactions per IP separations >100 sigma
- Impedance
 - Lower bunch intensities gives margin to the instability threshold
 - Filling patterns with non-uniform bunch spacing have to be studied
 - Two beams in common beam pipe needs an impedance evaluation
- Transient beam loading
 - The proposed filling schemes lead to a small change in the bunch-by-bunch effective RF voltage spread ($\sim 10\%$)
see Ivan Karpov, "FCC RF operation scenarios - new baseline", FCC week 2025
- Luminosity
 - Increasing the number of bunches and reducing the bunch intensity, keeping a constant beam current -> reduction of luminosity performance (e.g. -17% for 6b+19e)
 - The reduction could be compensated, for example, by decreasing the transverse beam size (e.g. -10% for 6b+19e)
- Is it possible to generate the proposed filling schemes using the injector chain?

The proposed filling schemes lead to a small change in the bunch-by-bunch effective RF voltage spread (~10%)

see Ivan Karpov, "FCC RF operation scenarios - new baseline", FCC week 2025



Courtesy of Ivan Karpov

