FUTURE CIRCULAR COLLIDER EPFL

E-Cloud Studies for FCC-ee

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ABP-CEI Section Meeting

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CHART Swiss Accelerator Research and Technology

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Outline

- Introduction
- SEY Multipacting Thresholds
- Heat Loads
- Stability Studies
- Photoemission
- Nested Magnets
- Conclusions and Outlooks

Outline

- **Introduction**
- SEY Multipacting Thresholds
- Heat Loads
- Stability Studies
- Photoemission
- Nested Magnets
- Conclusions and Outlooks

Motivation

- The FCC-ee is a future circular positron-electron collider

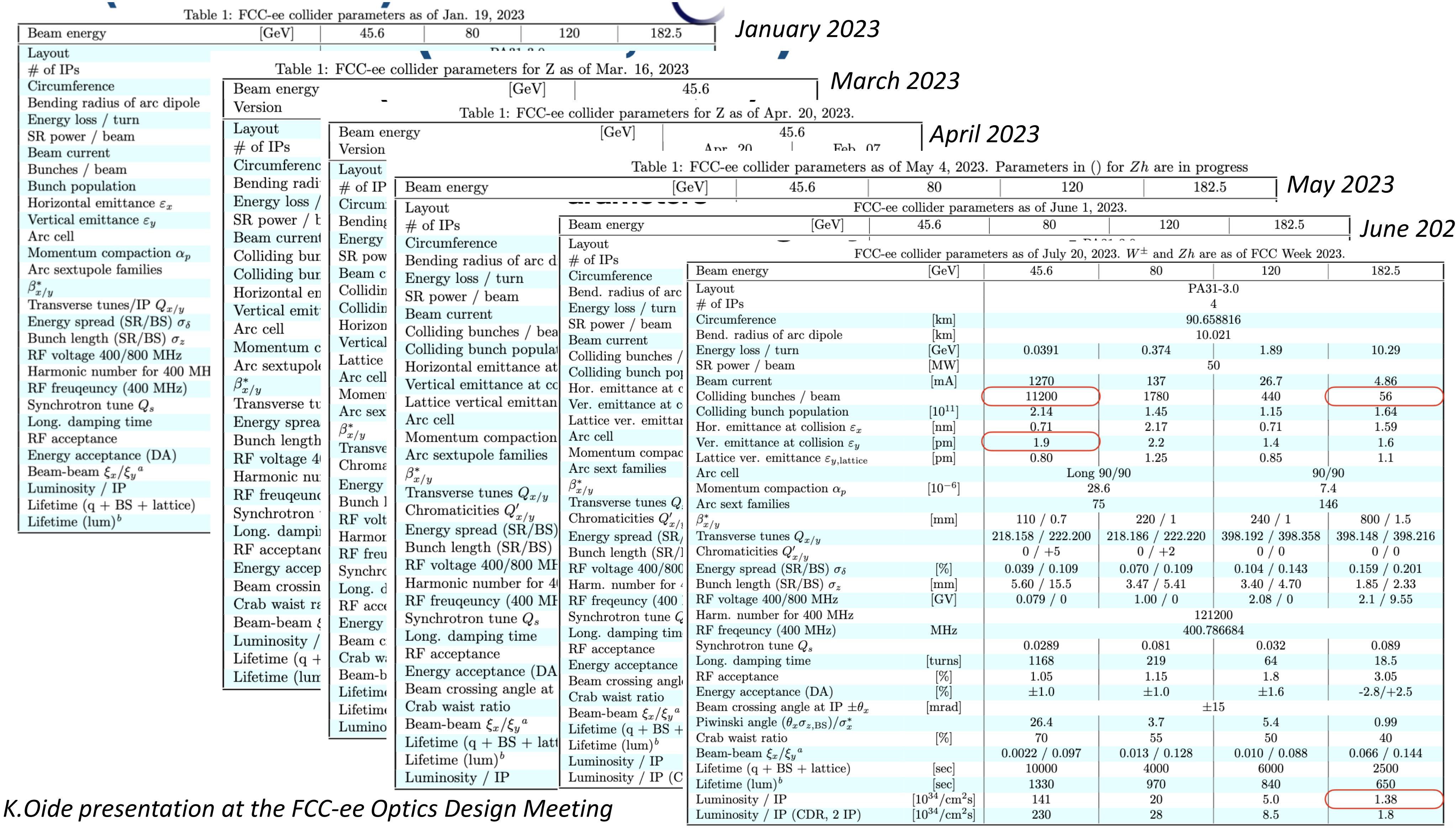
- Electron cloud (e-cloud) effects have been observed in several circular accelerators all over the world (LHC, KEKB, DAϕNE, …)
  - much more commonly in those operated with positively charged particles

- Presently among the major performance limitations for high energy collider
  - transverse beam instabilities, incoherent beam effects, vacuum degradation, heat load, …

- It is important to study how to supress the e-cloud in the design stage of a particle accelerator
  - the e-cloud depends on many key parameters of the accelerator and the beams
  - the e-cloud effects have to be studied for FCC-ee to give input to chamber design, material properties, filling schemes, and so on

FCC-ee Design Stage

In the last years, different versions of the FCC-ee parameters (important from the e-cloud point of view)



January 2023

Table 1: FCC-ee collider parameters as of Jan. 19, 2023

Beam energy	[GeV]	45.6	80	120	182.5
Layout					
# of IPs					
Circumference					
Bending radius of arc dipole					
Energy loss / turn					
SR power / beam					
Beam current					
Bunches / beam					
Bunch population					
Horizontal emittance ε_x					
Vertical emittance ε_y					
Arc cell					
Momentum compaction α_p					
Arc sextupole families					
$\beta^*_{x/y}$					
Transverse tunes/IP $Q_{x/y}$					
Energy spread (SR/BS) σ_δ					
Bunch length (SR/BS) σ_z					
RF voltage 400/800 MHz					
Harmonic number for 400 MH					
RF freuqeuncy (400 MHz)					
Synchrotron tune Q_s					
Long. damping time					
RF acceptance					
Energy acceptance (DA)					
Beam-beam ξ_x/ξ_y [a]					
Luminosity / IP					
Lifetime (q + BS + lattice)					
Lifetime (lum)[b]					

March 2023

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

Beam energy	[GeV]	45.6
Version		
Layout		
# of IPs		
Circumferenc		
Bending radi		
Energy loss /		
SR power / b		
Beam current		
Colliding bur		
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Horizontal en		
Vertical emit		
Arc cell		
Momentum c		
Arc sextupol		
$\beta^*_{x/y}$		
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Energy sprea		
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RF voltage 4		
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Synchrotron		
Long. dampi		
RF acceptanc		
Energy accep		
Beam crossin		
Crab waist ra		
Beam-beam ξ		
Luminosity /		
Lifetime (q +		
Lifetime (lun		

April 2023

Table 1: FCC-ee collider parameters for Z as of Apr. 20, 2023.

Beam energy	[GeV]	45.6	
Version		Apr. 20	Feb. 07
Layout			
# of IP			
Circum			
Bending			
Energy			
SR pow			
Beam c			
Collidin			
Collidin			
Horizon			
Vertical			
Lattice			
Arc cell			
Momen			
Arc sex			
$\beta^*_{x/y}$			
Transve			
Chroma			
Energy			
Bunch l			
RF volt			
Harmor			
RF freu			
Synchro			
Long. d			
RF acce			
Energy			
Beam c			
Crab w			
Beam-b			
Lifetim			
Lifetim			
Lumino			

May 2023

Table 1: FCC-ee collider parameters as of May 4, 2023. Parameters in () for Zh are in progress

Beam energy	[GeV]	45.6	80	120	182.5
Layout					
# of IPs					
Circumference					
Bending radius of arc d					
Energy loss / turn					
SR power / beam					
Beam current					
Colliding bunches / bea					
Colliding bunch populat					
Horizontal emittance at					
Vertical emittance at cc					
Lattice vertical emittan					
Arc cell					
Momentum compaction					
Arc sextupole families					
$\beta^*_{x/y}$					
Transverse tunes $Q_{x/y}$					
Chromaticities $Q'_{x/y}$					
Energy spread (SR/BS)					
Bunch length (SR/BS)					
RF voltage 400/800 MH					
Harmonic number for 4					
RF freuqeuncy (400 MH					
Synchrotron tune Q_s					
Long. damping time					
RF acceptance					
Energy acceptance (DA					
Beam crossing angle at					
Crab waist ratio					
Beam-beam ξ_x/ξ_y [a]					
Lifetime (q + BS + latt					
Lifetime (lum)[b]					
Luminosity / IP					

June 2023

FCC-ee collider parameters as of June 1, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout					
# of IPs					
Circumference					
Bend. radius of arc					
Energy loss / turn					
SR power / beam					
Beam current					
Colliding bunches /					
Colliding bunch pop					
Hor. emittance at c					
Ver. emittance at c					
Lattice ver. emittar					
Arc cell					
Momentum compac					
Arc sext families					
$\beta^*_{x/y}$					
Transverse tunes Q					
Chromaticities $Q'_{x/y}$					
Energy spread (SR/					
Bunch length (SR/I					
RF voltage 400/800					
Harm. number for 4					
RF freqeuncy (400					
Synchrotron tune Q					
Long. damping tim					
RF acceptance					
Energy acceptance					
Beam crossing angl					
Crab waist ratio					
Beam-beam ξ_x/ξ_y [a]					
Lifetime (q + BS +					
Lifetime (lum)[b]					
Luminosity / IP					
Luminosity / IP (C					

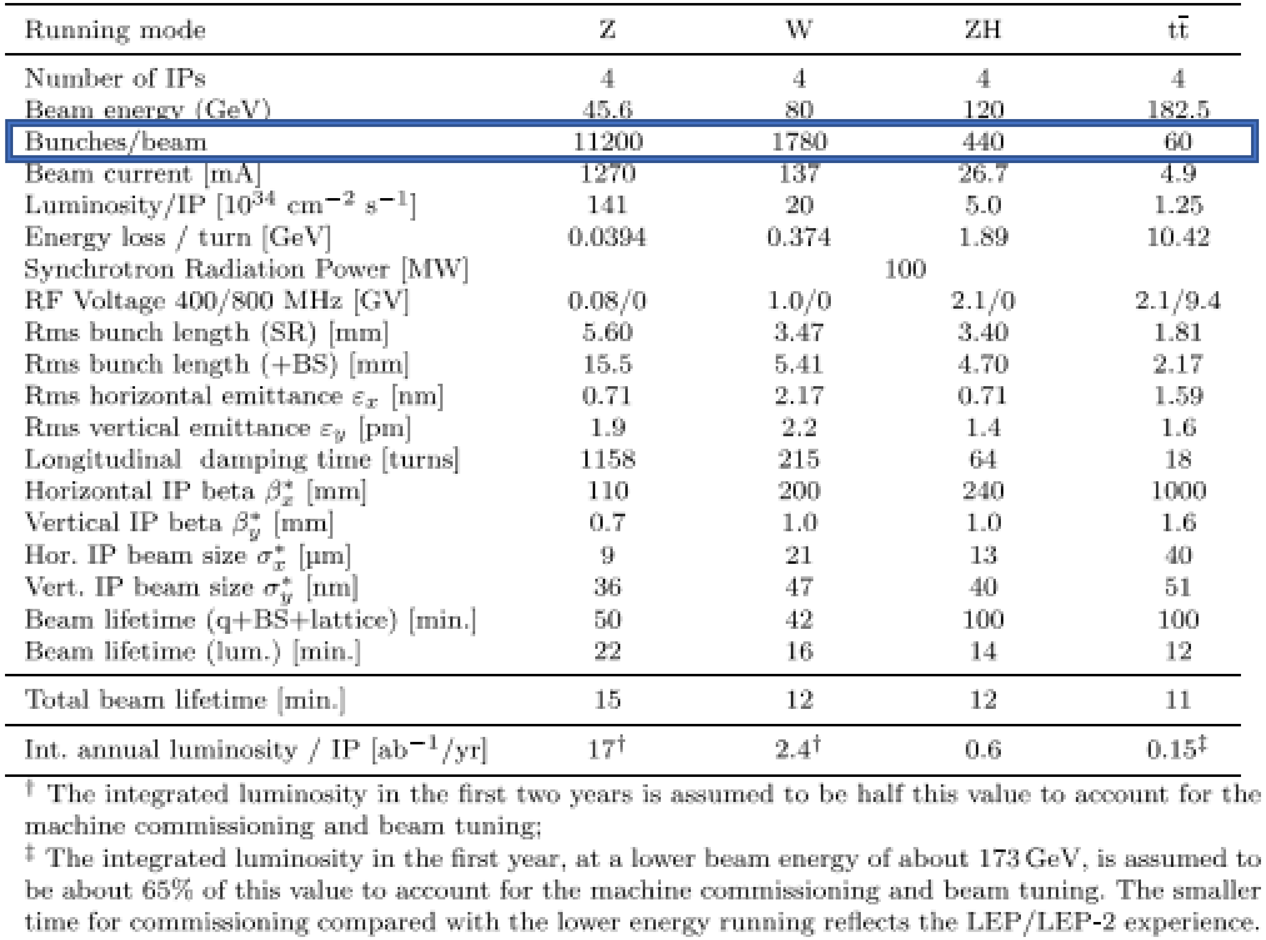
July 2023

FCC-ee collider parameters as of July 20, 2023. $W^\pm$ and Zh are as of FCC Week 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.89	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.86
Colliding bunches / beam		11200	1780	440	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.15	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.80	1.25	0.85	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.104 / 0.143	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.47 / 5.41	3.40 / 4.70	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.55
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0289	0.081	0.032	0.089
Long. damping time	[turns]	1168	219	64	18.5
RF acceptance	[%]	1.05	1.15	1.8	3.05
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma_x^*$		26.4	3.7	5.4	0.99
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Lifetime (q + BS + lattice)	[sec]	10000	4000	6000	2500
Lifetime (lum)[b]	[sec]	1330	970	840	650
Luminosity / IP	[10^{34}/cm^{2}s]	141	20	5.0	1.38
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

From K.Oide presentation at the FCC-ee Optics Design Meeting

FCC-ee Mid-Term Review 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 Feasibility Study Mid-Term Review Autumn 2023

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

Possible Filling Schemes

Filling schemes (with constant beam current)

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)
- The bunches are gradually filled from the booster at collision energy (top-up injection)

Magnetic Field Elements

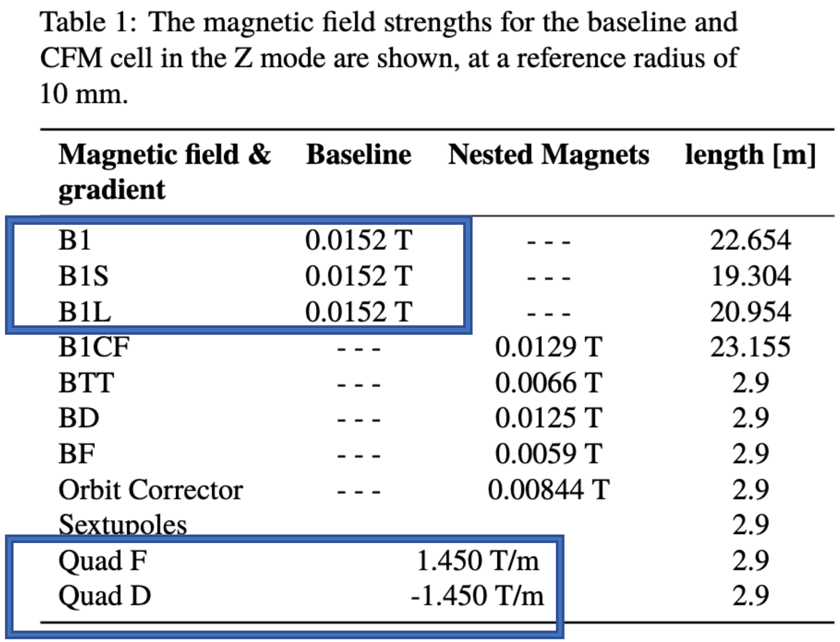
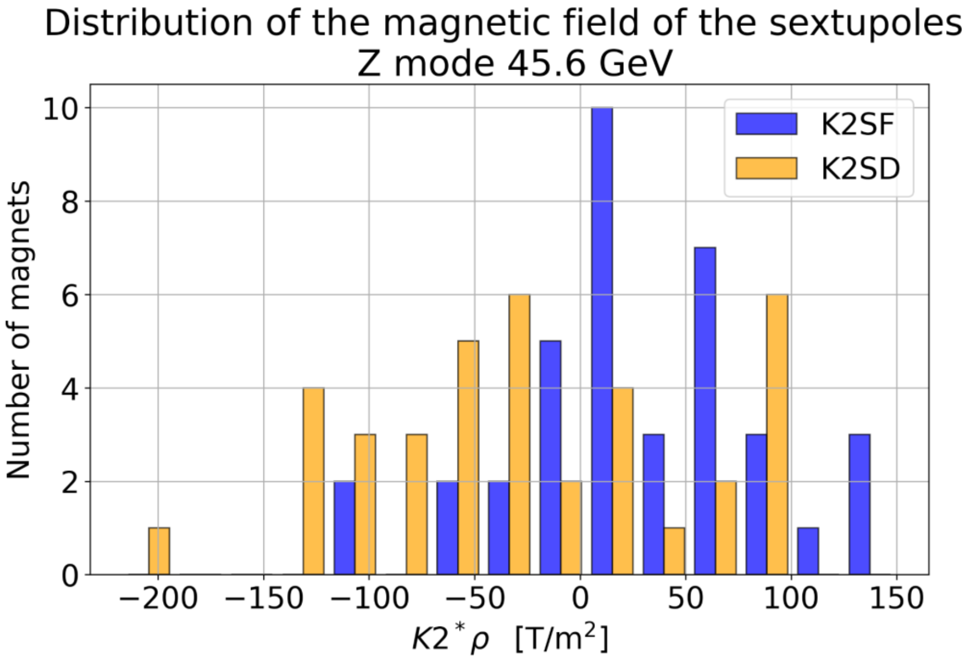


Table 1: The magnetic field strengths for the baseline and CFM cell in the Z mode are shown, at a reference radius of 10 mm.

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



Courtesy of Cristobal Garcia and Leon Van Riesen-Haupt

- Dipoles 15.2 mT
- Quadrupoles 1.45 T/m
- Sextupoles 72.5 T/m^2

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- **SEY Multipacting Thresholds**
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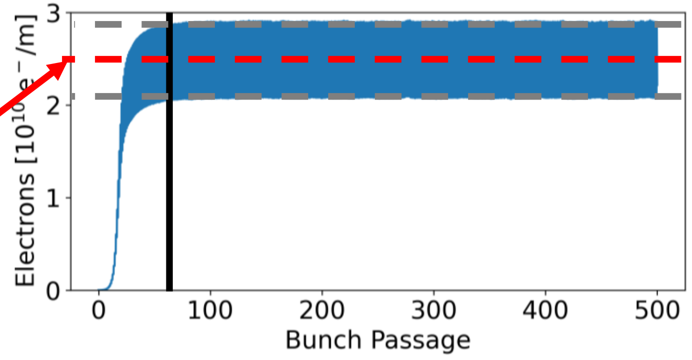
E-Cloud Build-Up Studies

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

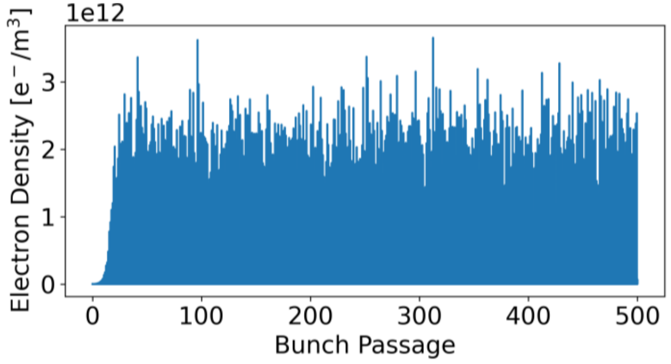
- The main quantity involved is the Secondary Electron Yield (SEY):

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

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

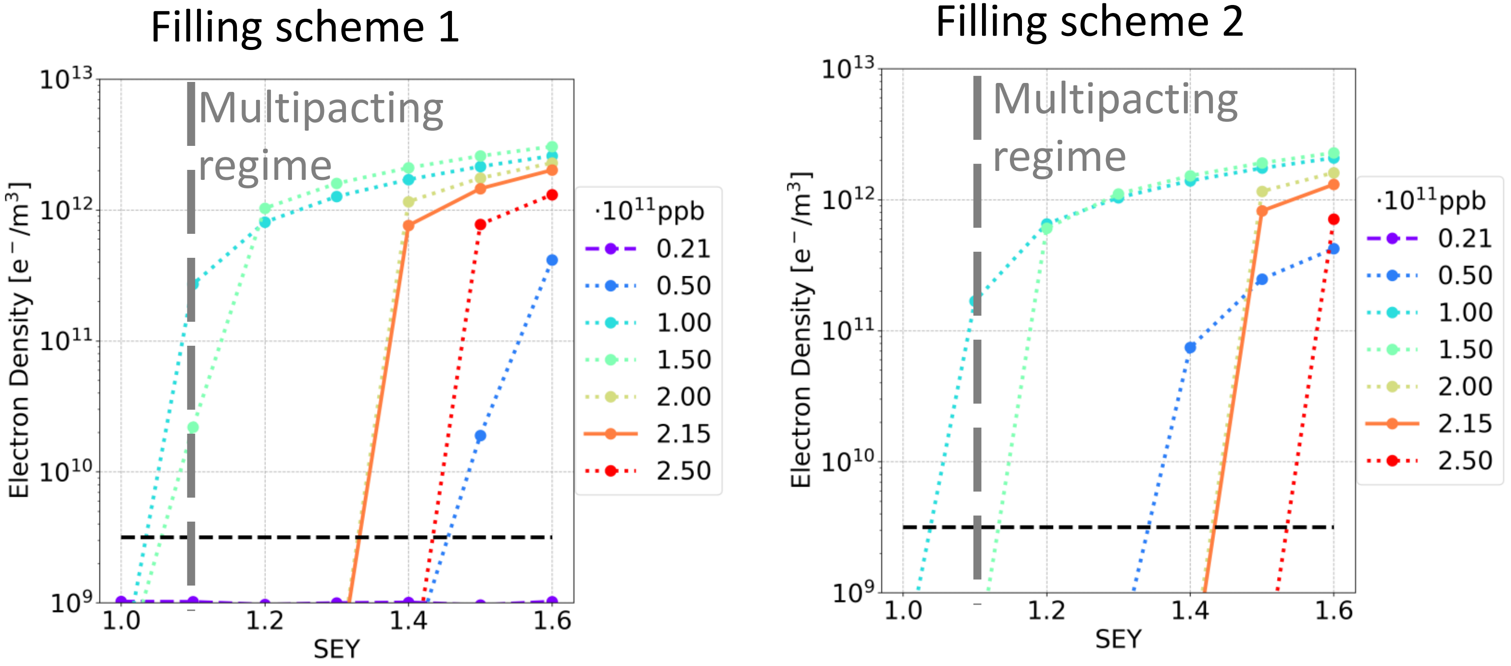

Total electrons in the chamber

parameter


Electrons close the chamber centre

- The analysed parameter in the next plots is the average e-cloud density when the saturation value is reached

E-Cloud Build-Up Studies: Dipole



The bunch intensities 1.00 and 1.50 x 10^{11} 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

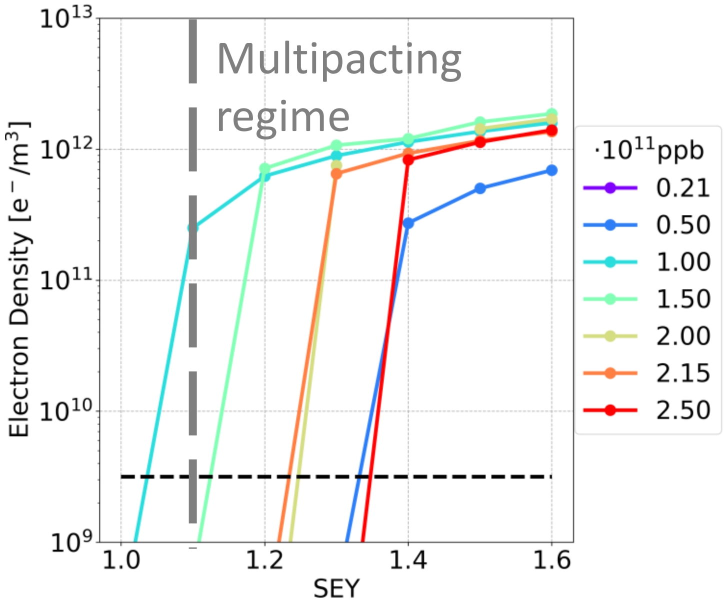
E-Cloud Build-Up Studies: Summary

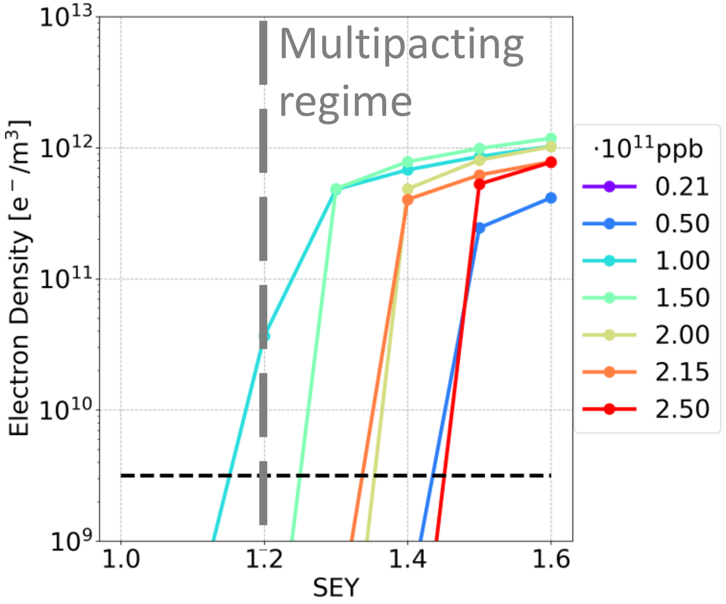
- Quadrupoles and sextupoles have the lowest SEY multipacting thresholds
- Larger SEY multipacting thresholds considering the filling scheme 2 (25 ns bunch spacing)
- Bunch intensities 1.00 and 1.50 x 10^{11} ppb are the most critical cases

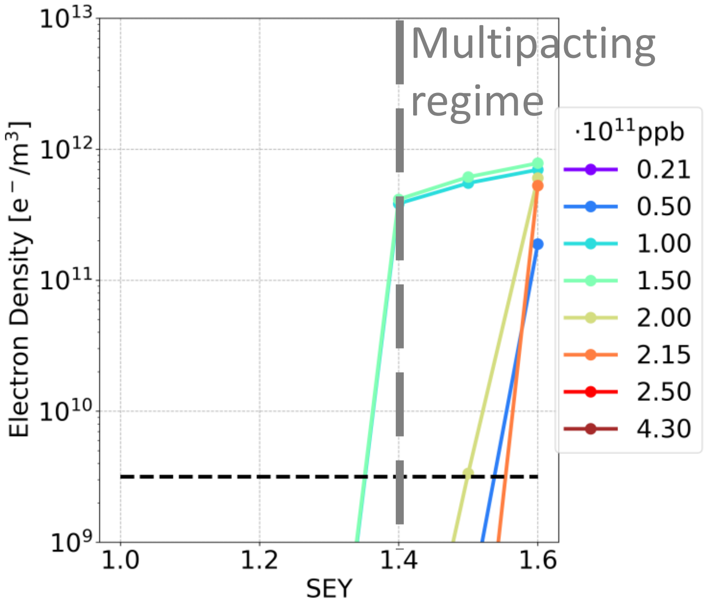
Element	**SEY Threshold**	**Filling Scheme 1**	**Filling Scheme 2**
Drift Space	nominal intensity	1.3	1.4
	all intensity below nominal one	1.1	1.2
Dipole (15.2 mT)	nominal intensity	1.3	1.4
	all intensity below nominal one	1.0	1.0
Quadrupole (1.45 T/m)	nominal intensity	1.1	1.1
	all intensity below nominal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

Mitigation: Bunch Spacing

The SEY multipacting thresholds are extremely tight for baseline parameters


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

Bunch Spacing: Negative Aspects

If the bunch spacing is larger (e.g., 2 times: 25 ns -> 50 ns)

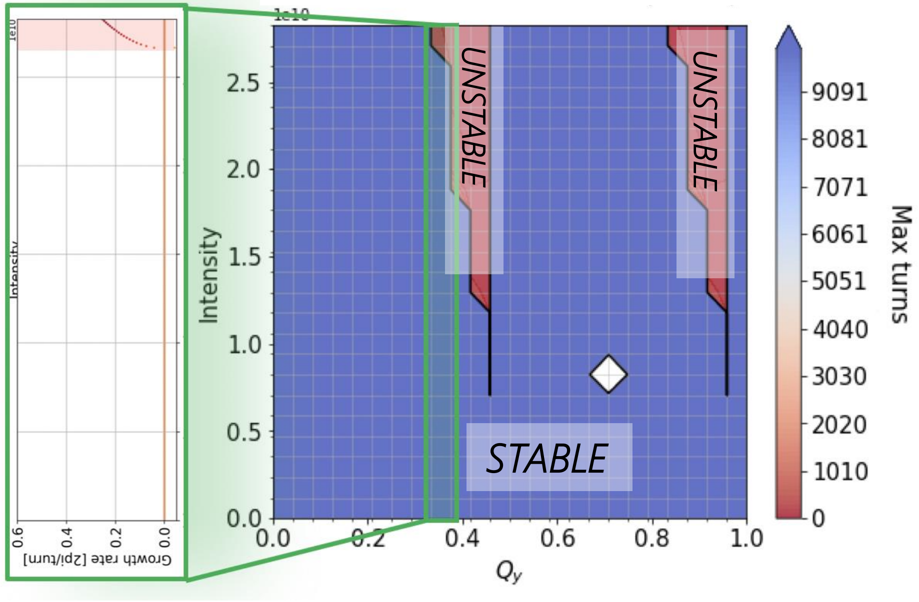
in order to keep the beam current constant

larger bunch intensities (e.g., 2 times: 2.15×10^{11} ppb -> 4.30×10^{11} ppb)

It could lead to issues with other collective effects:

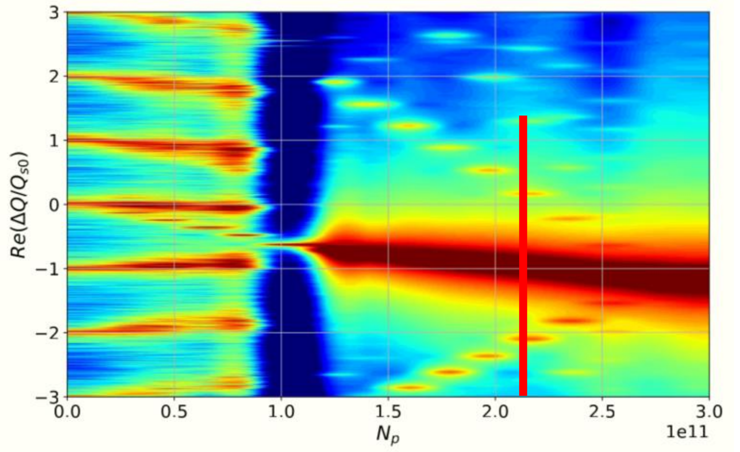
Beam-Beam

Courtesy of Roxana Roos (FCC week 2024)

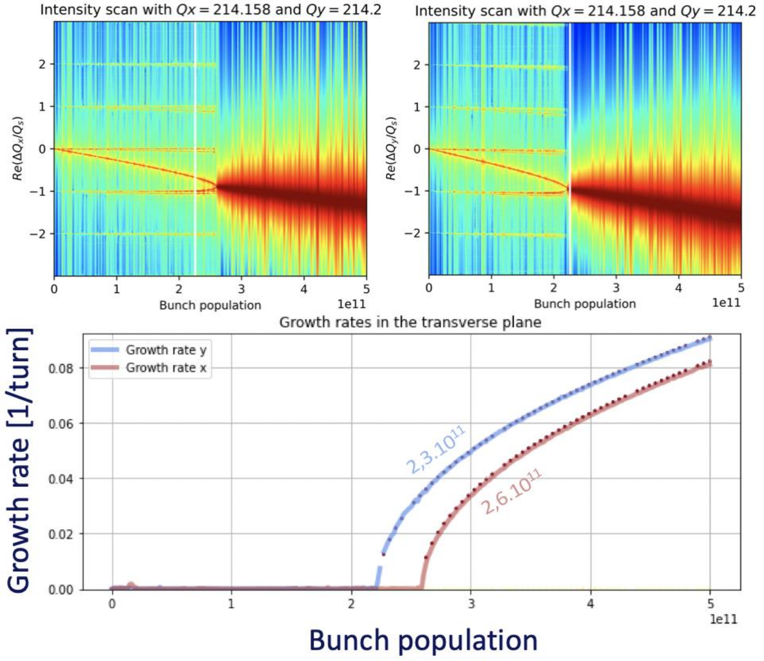


Wake-fields and coupling impedance

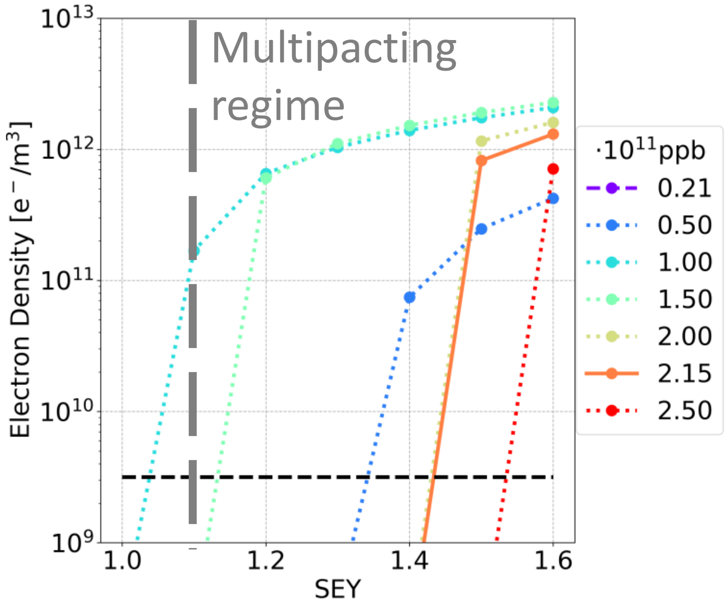
Courtesy of Mauro Migliorati (FCC week 2024)

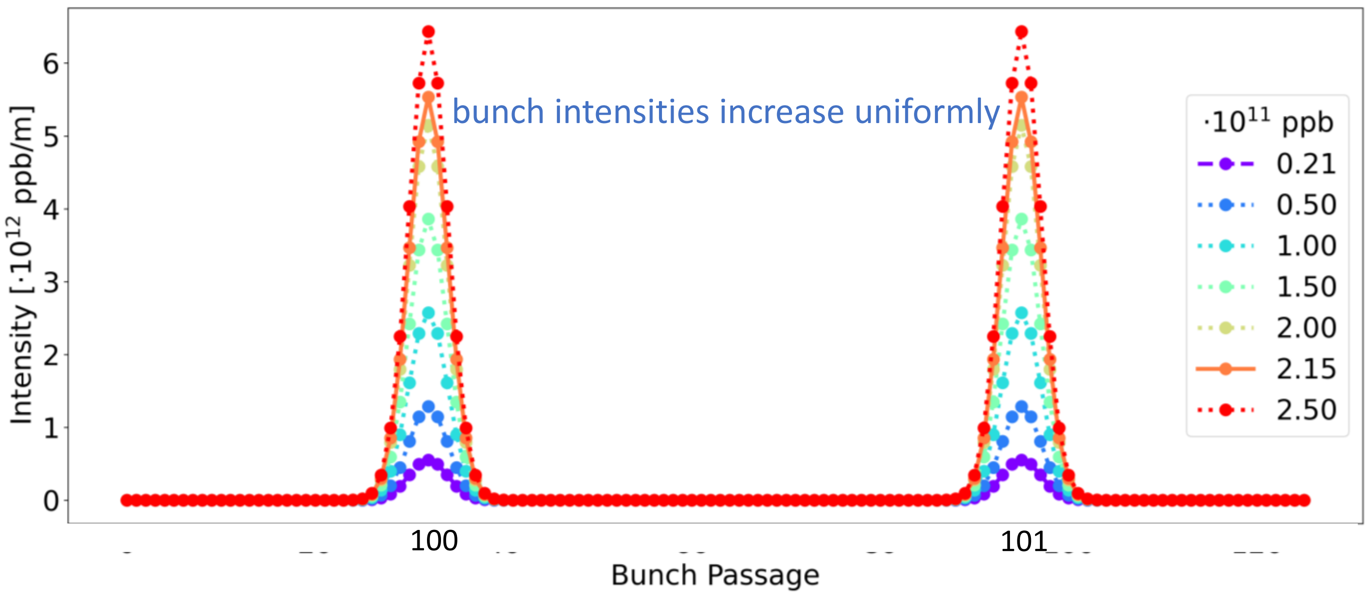


Courtesy of Roxana Roos (FCC week 2024)



Mitigation: Charge Accumulation Phase





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

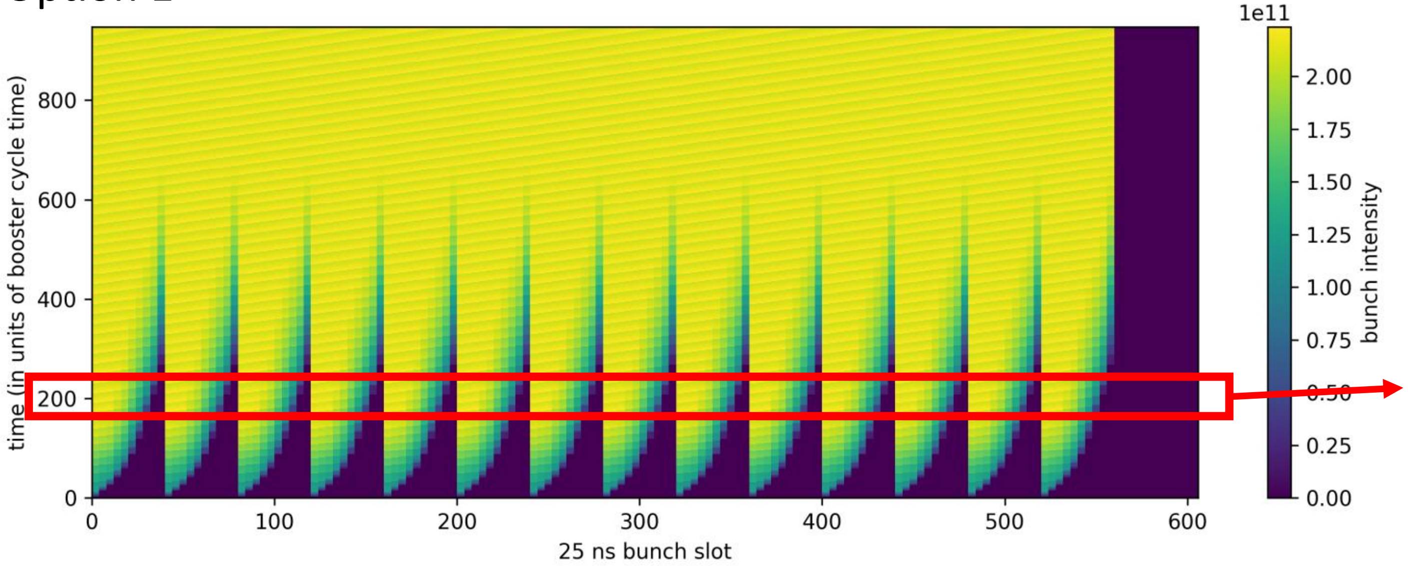
During the charge accumulation phase: do not fill the bunches of the train uniformly

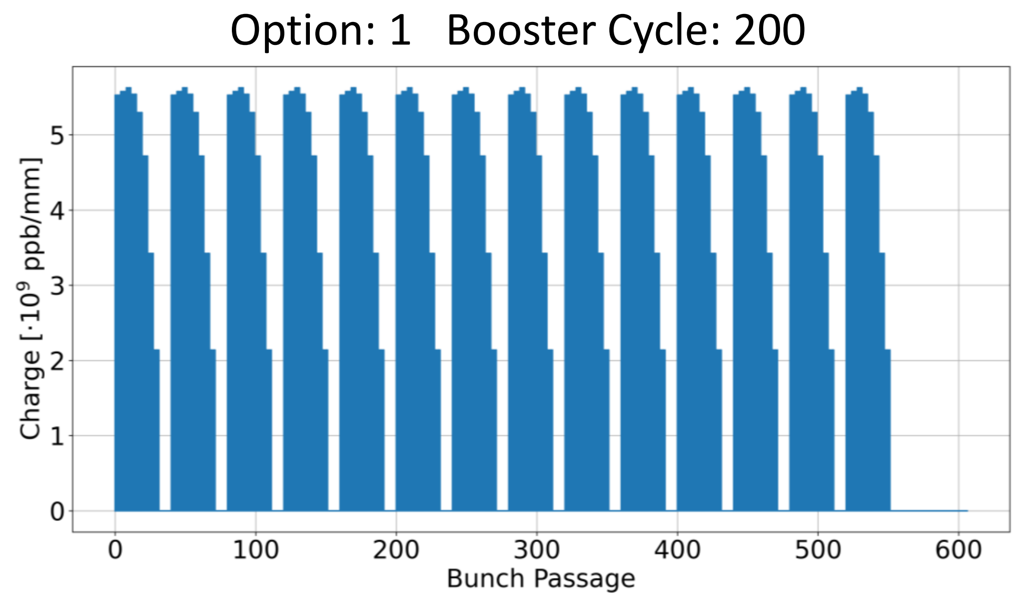
(Now it is possible because the injection scheme from booster changed from full ring to 1/10)

In this way the critical bunch intensities will be reached with a larger bunch spacing

Charge accumulation phase

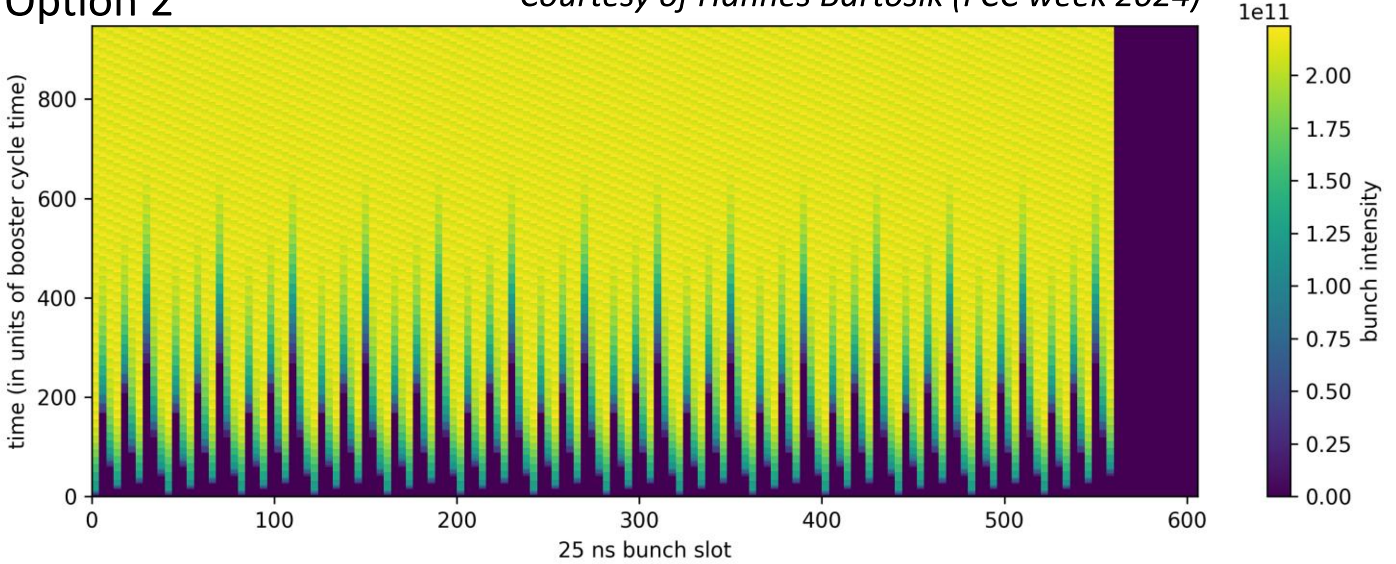
Option 1





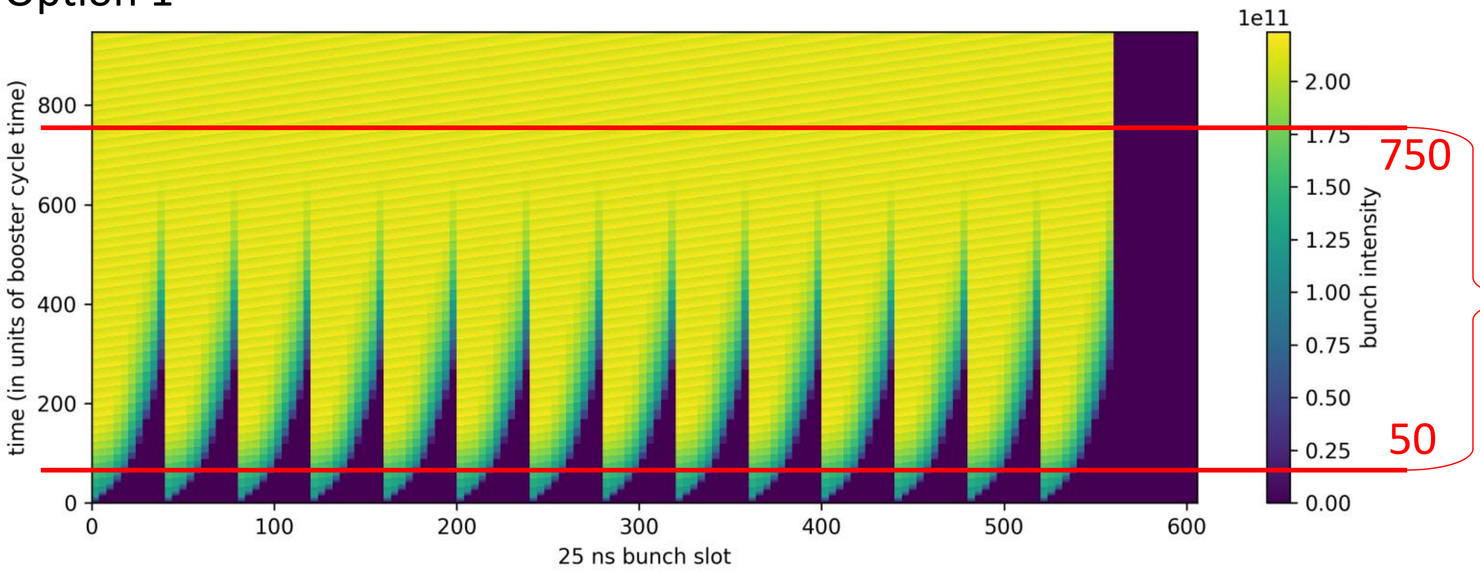
Option 2

Courtesy of Hannes Bartosik (FCC week 2024)



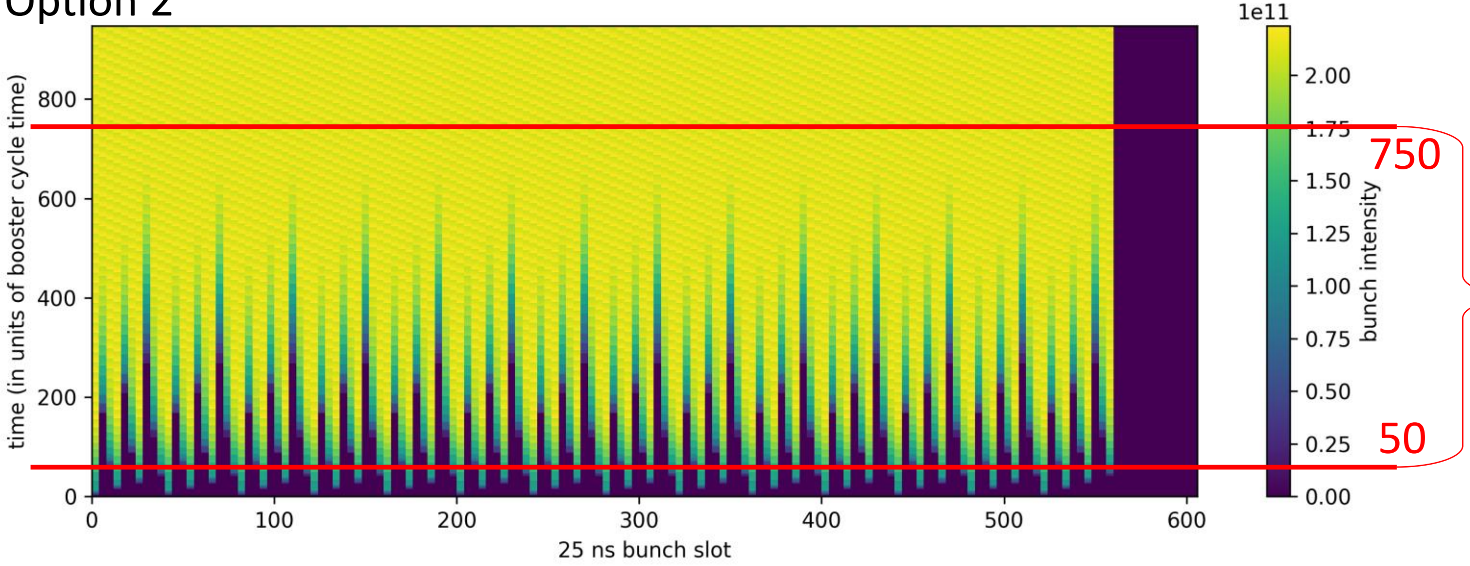
Charge accumulation phase

Option 1



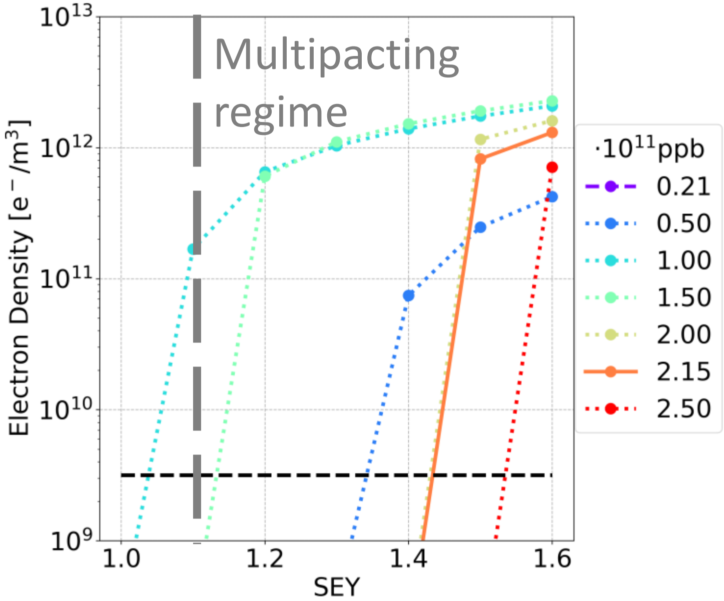
Analysed range (step 25 booster cycles)

Option 2

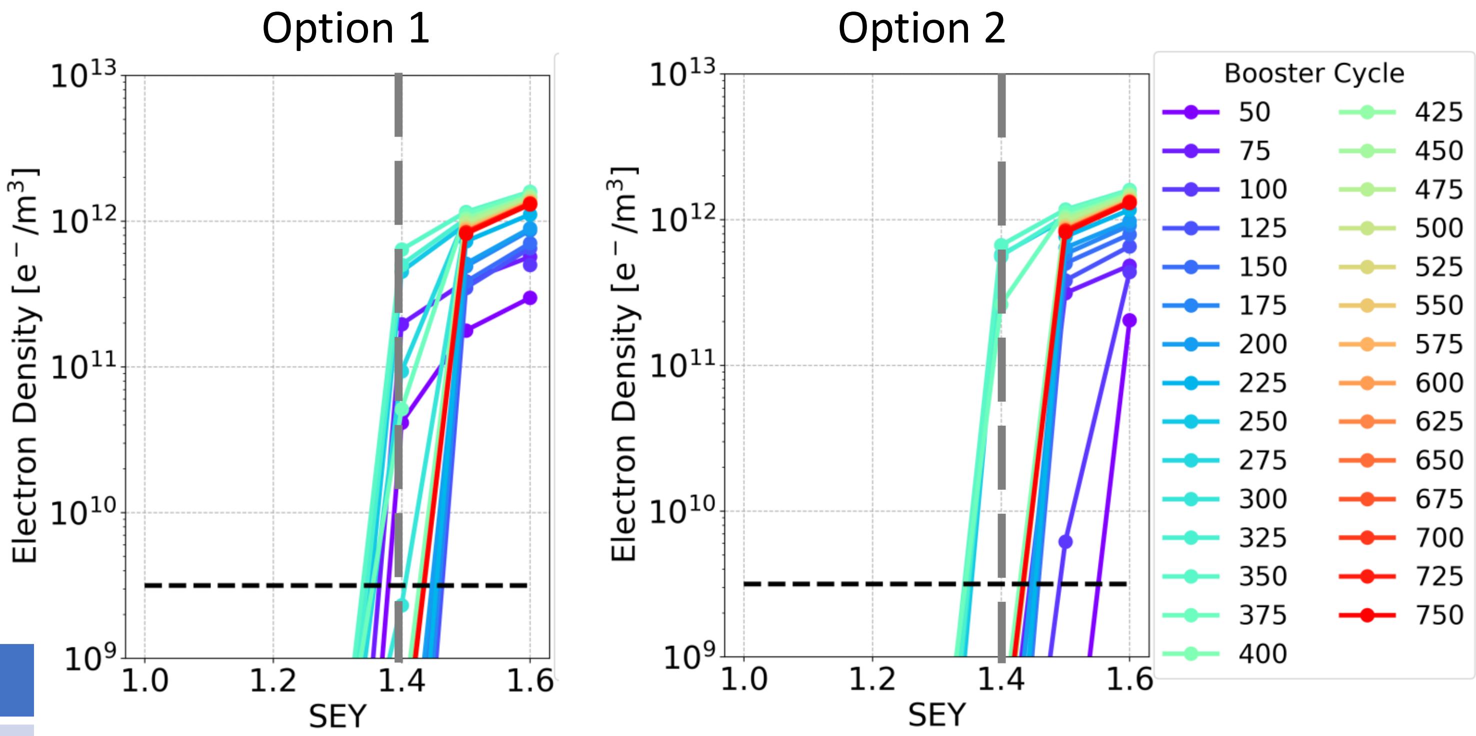


Analysed range (step 25 booster cycles)

Charge accumulation phase: Dipole



Bunch Spacing	25 ns
SEY threshold (nominal intensity)	1.4
SEY threshold (all intensity below nominal one)	1.0



Charge accumulation Phase	Non-uniform
SEY threshold	1.3

Using the two options with special filling schemes during the charge accumulation phase, the SEY mutipacting 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	Special Filling schemes during charge accumulation phase	Uniform Bunch Spacing (25 ns)	
Drift Space	1.4	nominal intensity	1.4
		all intensity below nominal one	1.2
Dipole (15.2 mT)	1.3	nominal intensity	1.4
		all intensity below nominal one	1.0
Quadrupole (1.45 T/m)	1.1	nominal intensity	1.1
		all intensity below nominal one	1.0
Sextupole (72.5 T/m^2)	1.1	nominal intensity	1.1
		all intensity below nominal one	1.0

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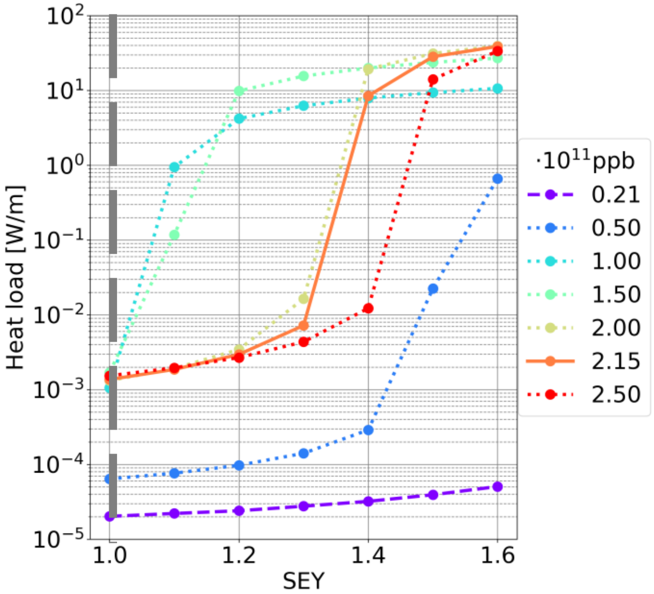
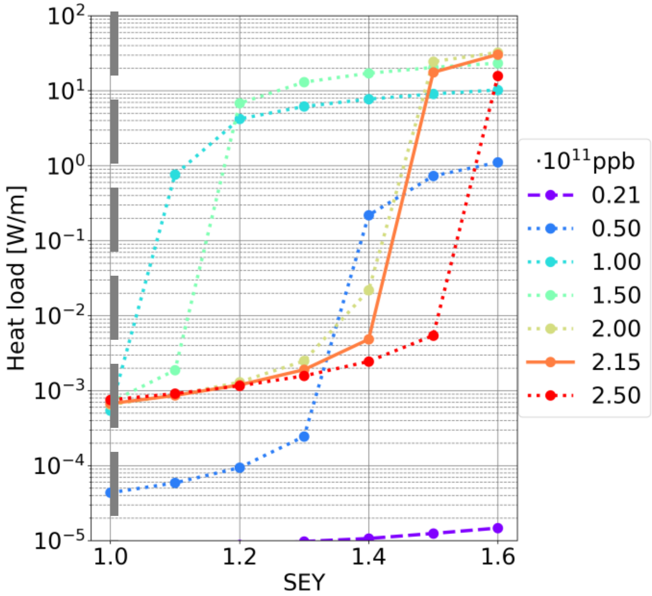
Heat Loads: Dipole

Filling scheme 1



Filling scheme 2



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: 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

Outline

- Introduction
- SEY Multipacting Thresholds
- Heat Loads
- **Stability Studies**
- Photoemission
- Nested Magnets
- Conclusions and Outlooks

E-Cloud Stability Threshold

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

- What is the e-cloud density stability threshold?

1. Theoretical equation:

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

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

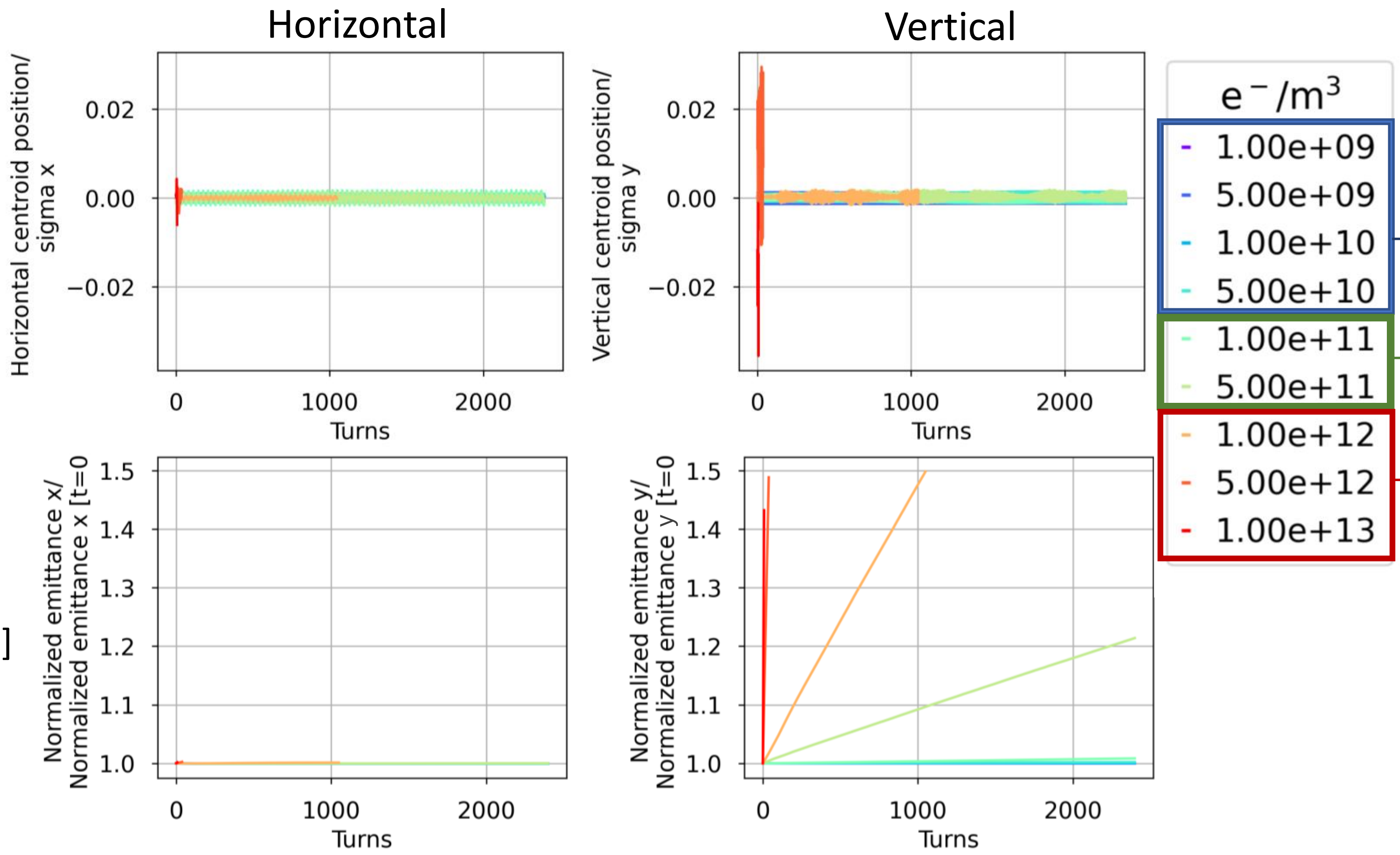
E-Cloud Stability Simulation Threshold: Dipole

- $\rho_{e,th} = 2.42 \cdot 10^{10}$ 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]



→ Stable

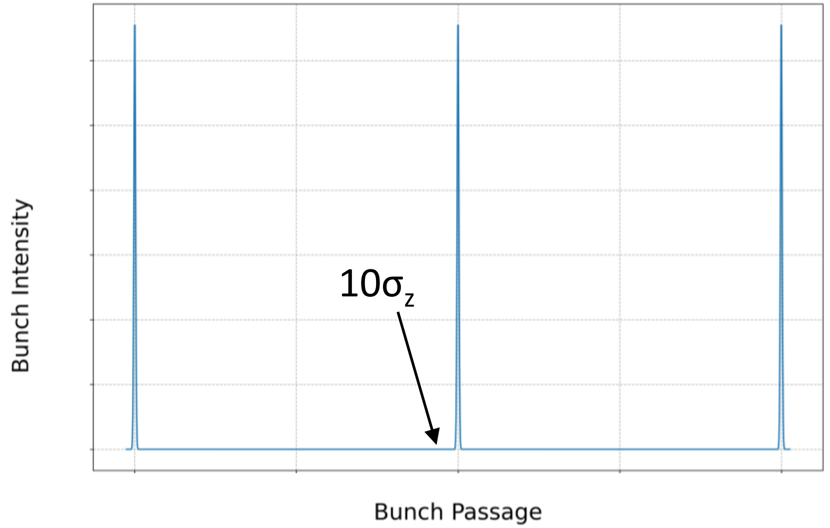
→ Unstable

→ Very unstable

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

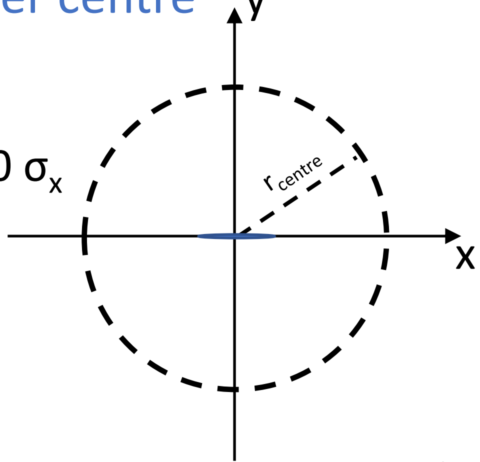
E-Cloud Central Density

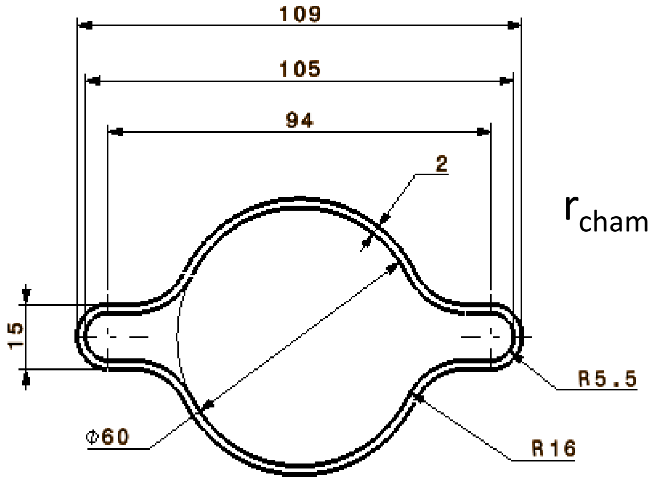
- E-cloud stability threshold has to be compared with the e-cloud density
  - before the bunch passage



  - close to the vacuum chamber centre

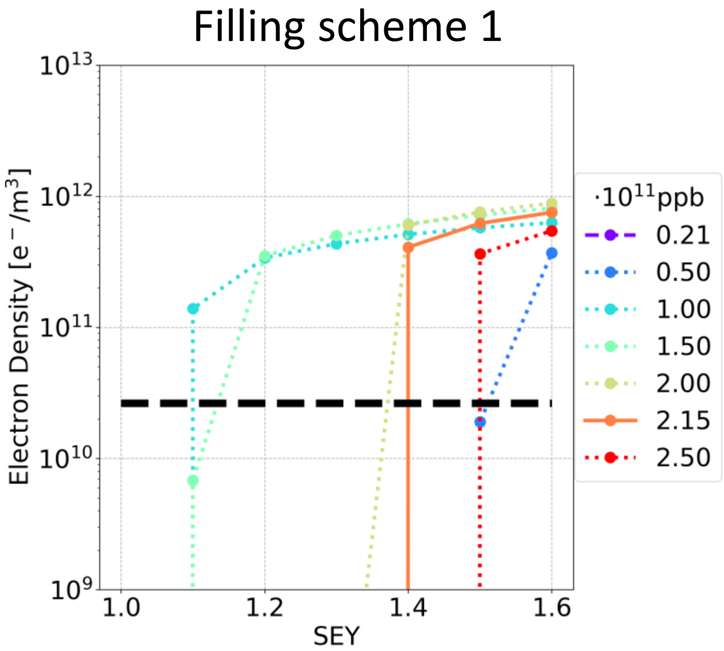
$r_{centre} \approx 10\ \sigma_x$

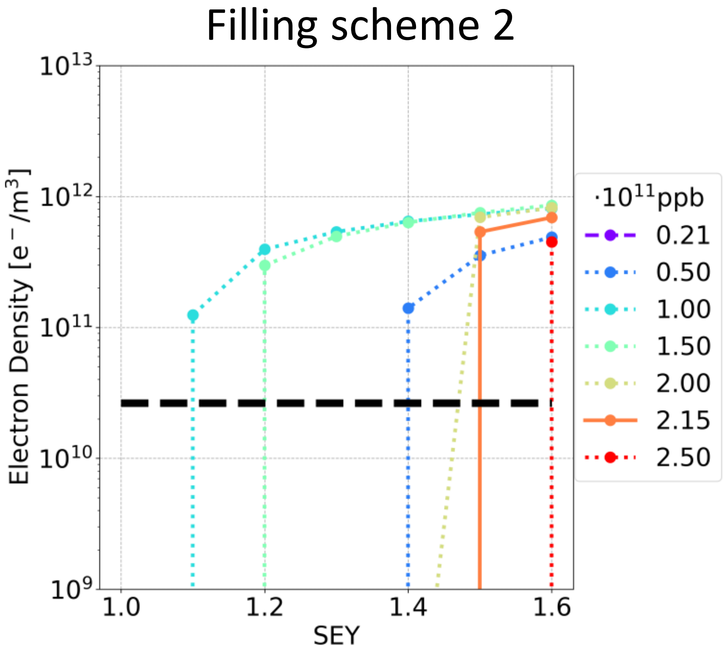




$r_{chambre} \approx 600\ \sigma_x$

E-Cloud Stability: Dipole


Filling scheme 1


Filling scheme 2

- Above the SEY multipacting threshold, the central density is above the stability threshold -> It could lead to beam instabilities

E-Cloud Stability: Summary

- Drift Spaces and Quadrupoles
  - Above the SEY multipacting threshold, the central density is above the stability threshold -> It could lead to beam instabilities

- Sextupoles
  - Even above the SEY multipacting threshold, the central density is below the stability threshold (short total length of the sextupoles in the arcs)

Outline

- Introduction
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- Stability Studies
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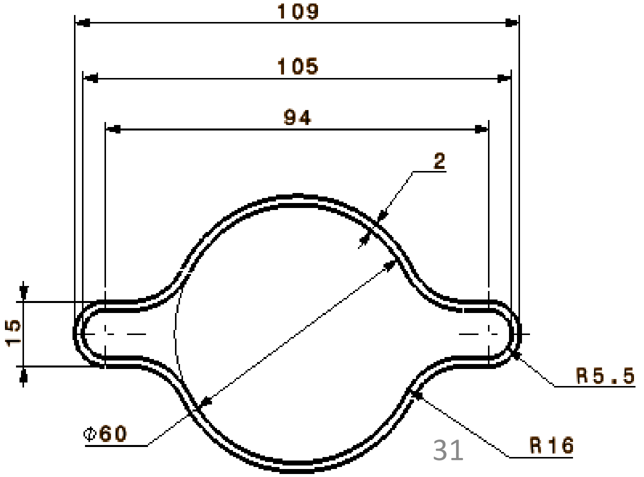
Photoemission

- 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 directly the photoemission
  - What is the impact of the photoelectrons on the e-cloud formation process?

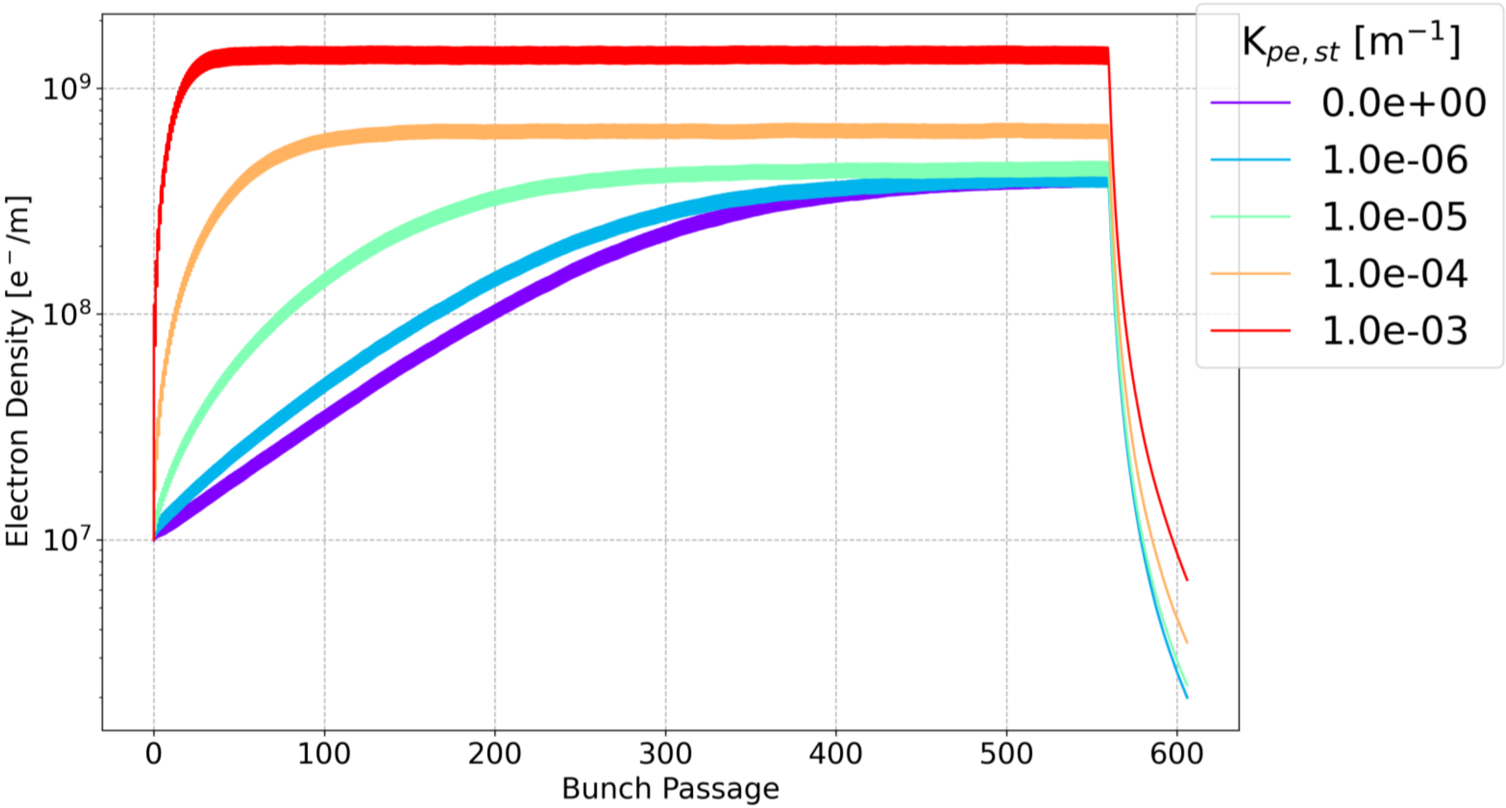
- In PyECLOUD:
  - $K_{pe,st}$: [m^{-1}] Number of photoelectrons generated per beam particle (positron) and per unit length
  - Photoelectrons uniformly generated per segment of the vacuum chamber
    - motivated by the ray tracing simulations (from the vacuum team)



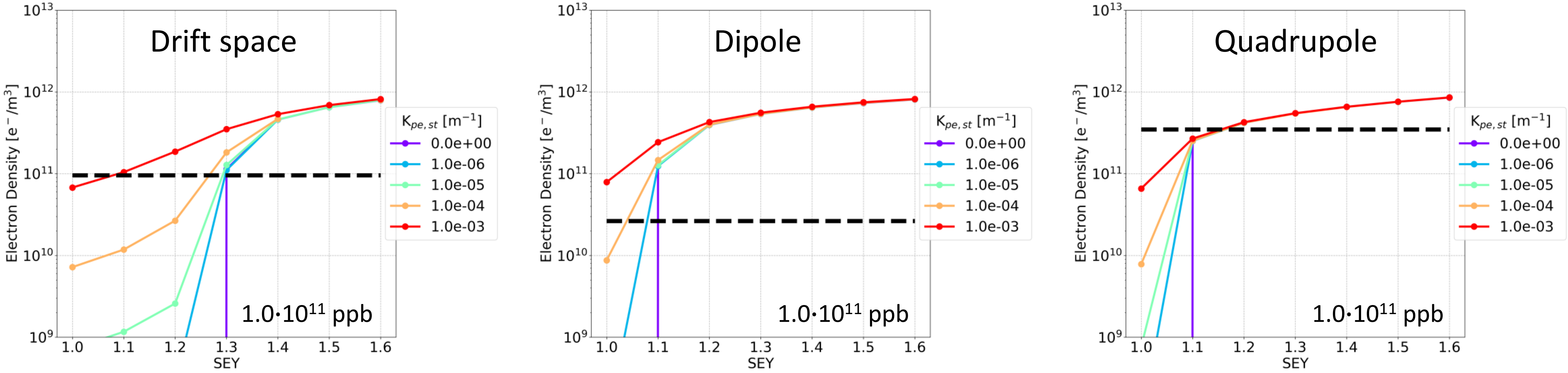
More details in *Pyziak Lucas'* presentation:
https://indico.cern.ch/event/1412362/contributions/5936228/attachments/2852012/4987248/EC_sim_studies_photoemission.pdf

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



Photoemission



- The central density could be larger than the 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} with margin)

Photoemission

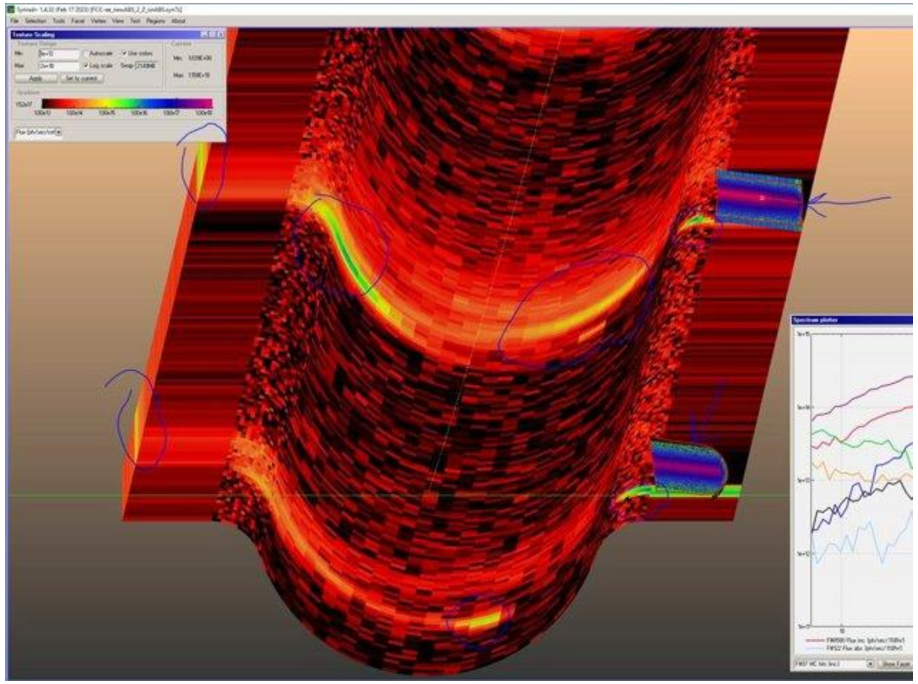
- Photoelectron Yield Y: number of photoelectrons emitted per impinging photon
  - property of the vacuum chamber surface

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

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

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

Courtesy of Roberto Kersevan



- 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/cm²s, most conservative)

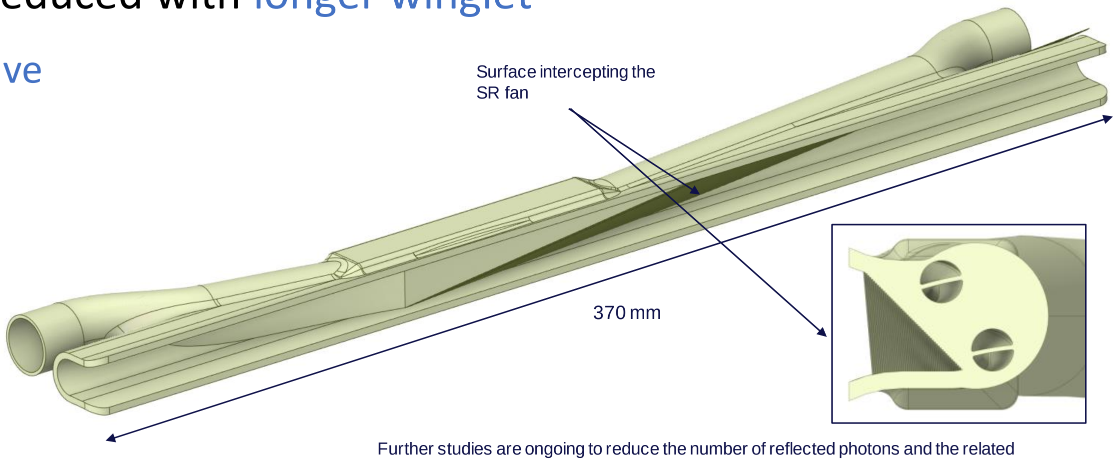
Photoelectron yield should be between 3‰ – 3%
Based on preliminary ray tracing simulations

Photoemission

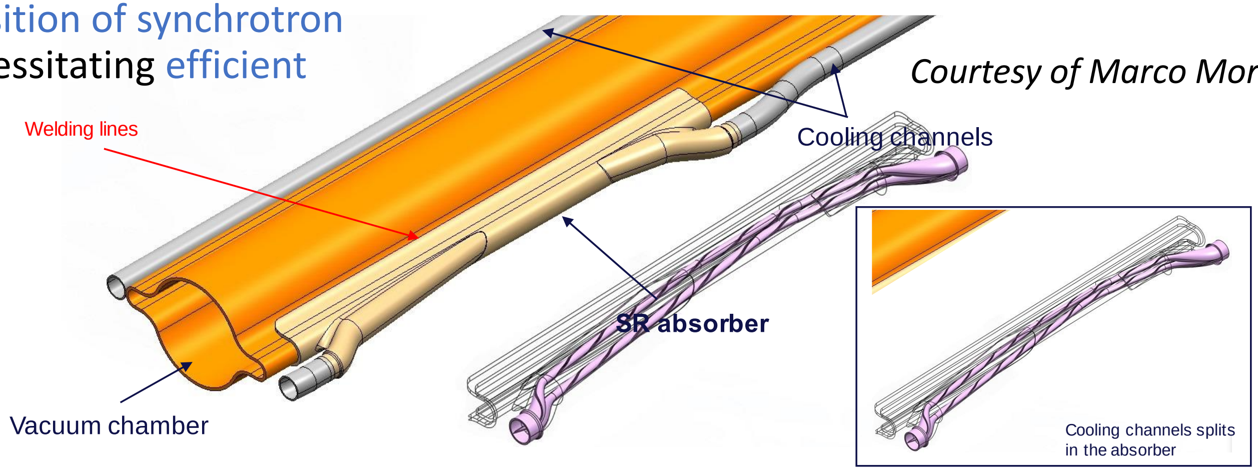
- The constraint on the material is very tight (in the absorber areas the photon flux is expected to be even higher!)

- The synchrotron radiation leakage to the main chamber might be reduced with longer winglet
  - Vacuum team (R. Kersevan) says there is no space and it is not effective

- Another solution is under development by the vacuum group
  - Design of a new synchrotron radiation absorber with a saw-tooth profile along the primary facet (where the primary synchrotron radiation photons hit)
  - with the saw-tooth profile oriented in a specific way, only a much smaller fraction of the impinging photons are actually reflected
  - This solution results in a much larger deposition of synchrotron radiation power in the absorber areas, necessitating efficient cooling methods



Further studies are ongoing to reduce the number of reflected photons and the related photoelectron generation in the main chamber.



Courtesy of Marco Morrone (FCC week 2024)

Outline

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- **Nested Magnets**
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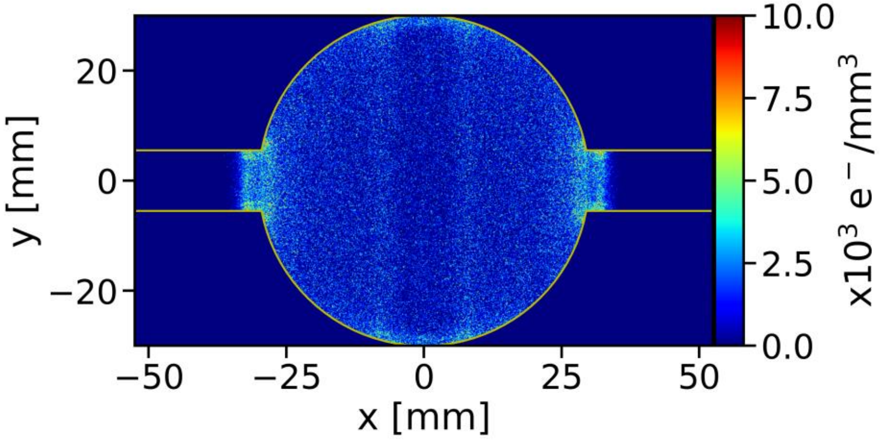
Nested Magnets

- Nested Magnets under exploration by overlapping dipole fields with arc quadrupoles and sextupoles
    - Thereby increasing the dipole filling factor and reducing the synchrotron radiation (more details in the presentation of Leon Van Riesen-Haupt at FCC week 2024)

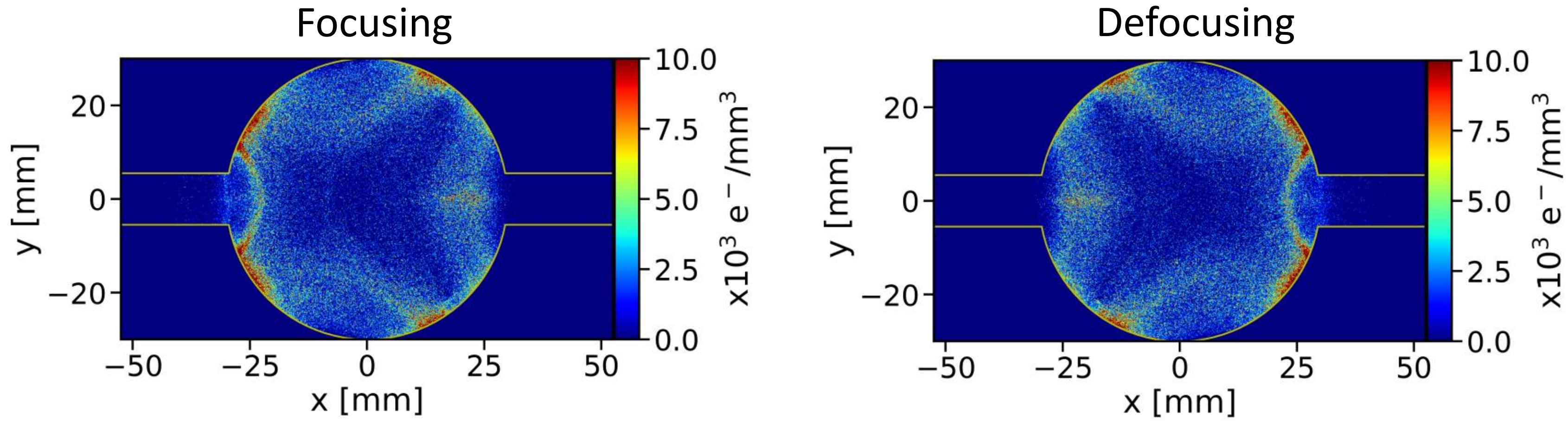
- What is the impact on the e-cloud in a dipole magnet adding a quadrupolar and/or a sextupolar gradient?

Dipole (15.2 mT)



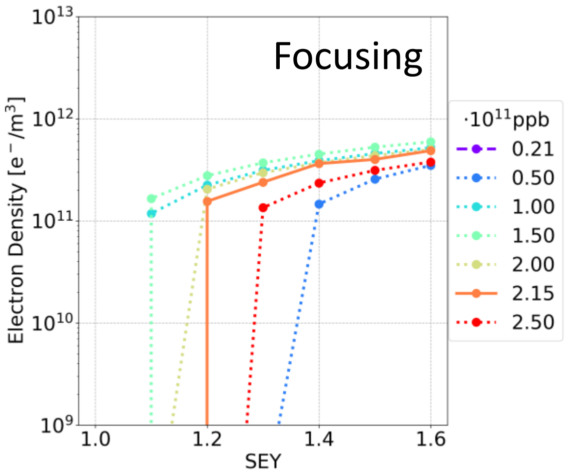
Nested Magnets

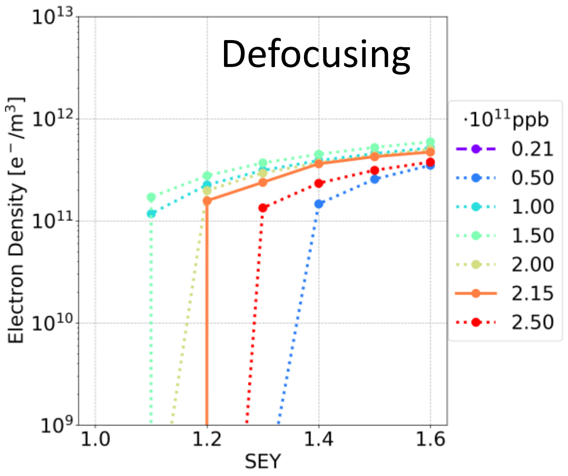
Dipole (15.2 mT) + Quadrupole (1.45 T/m)



Changing the polarity (focusing-defocusing) of the quadrupole

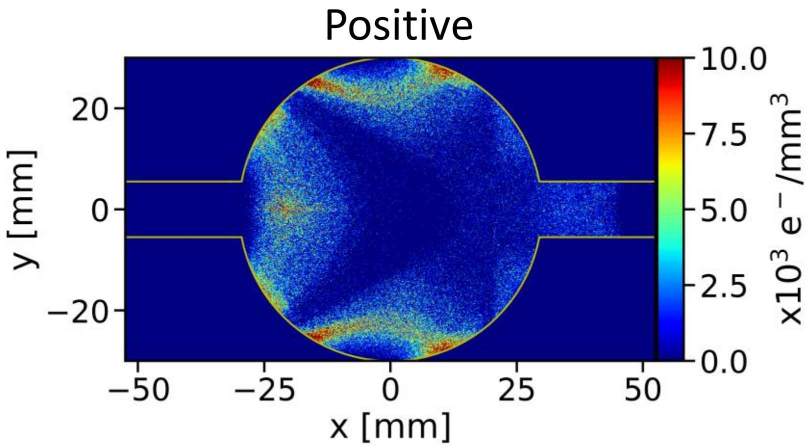
- inverts the symmetry (left-right) of the e-cloud transverse distribution
- does not alter the central e-cloud density before the bunch passage

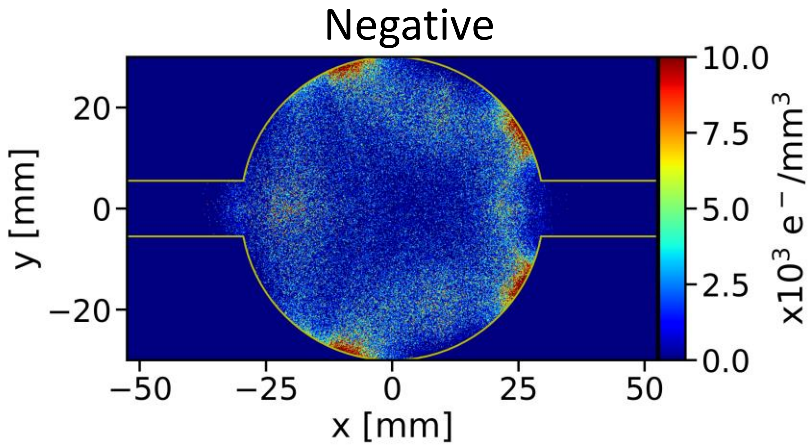




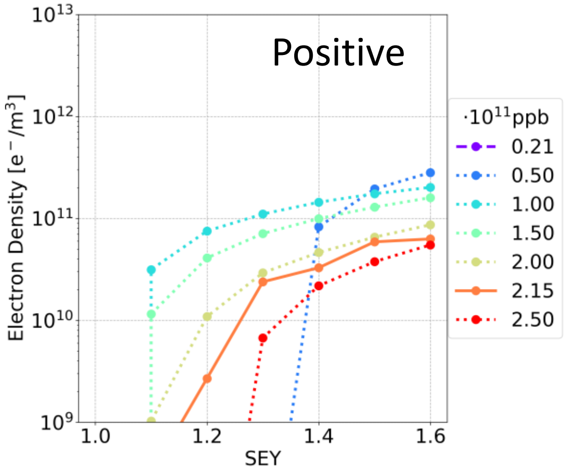
Nested Magnets

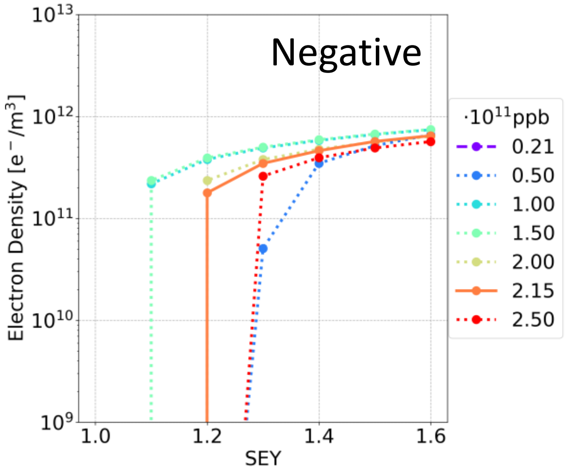
Dipole (15.2 mT) + Quadrupole (1.45 T/m) + Sextupole (72.5 T/m^2)



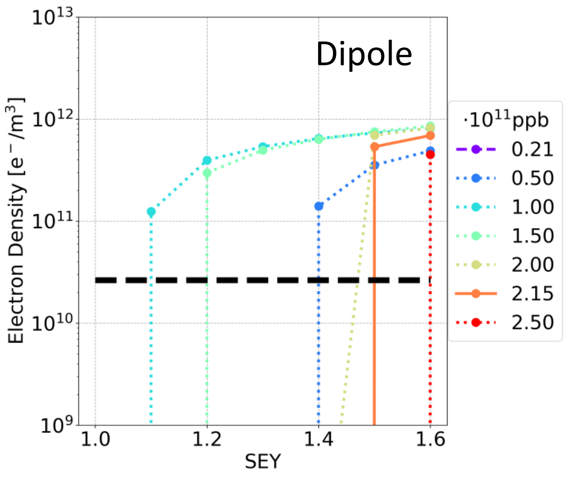


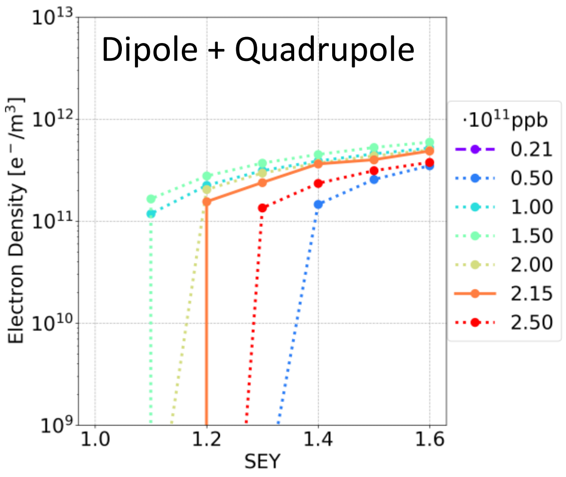
By adding a positive sextupolar component, the e-cloud transverse distribution is pushed away from the vacuum chambre centre

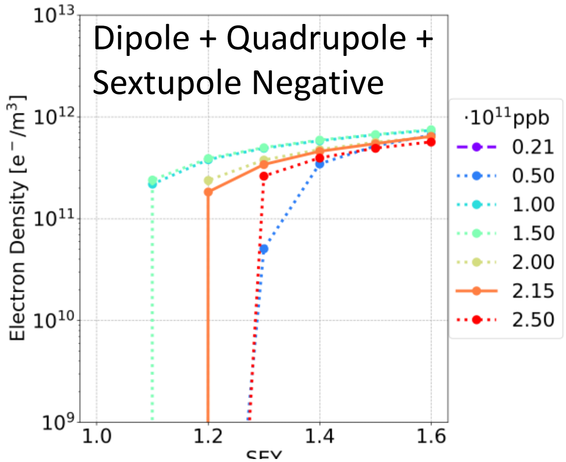




Nested Magnets: Summary

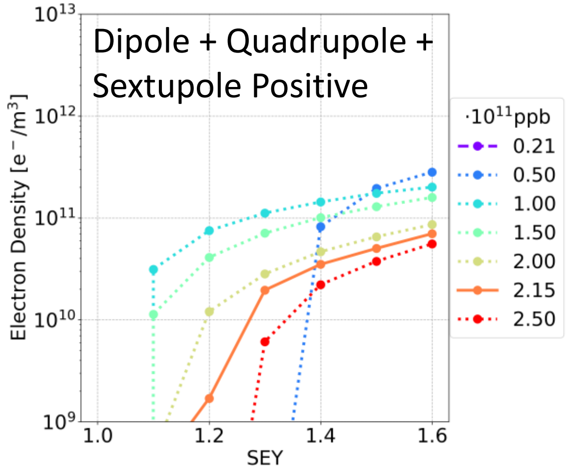






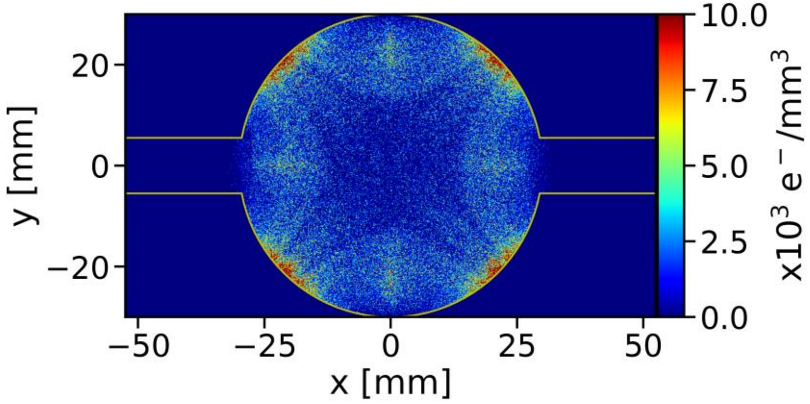
SEY multipacting thresholds worsen with nested magnets

	Dipole	Dipole+Quadrupole	Dipole+Quadrupole+Sextupole
SEY threshold (nominal intensity)	1.4	1.1	1.1
SEY threshold (all intensity below nominal one)	1.0	1.0	1.0

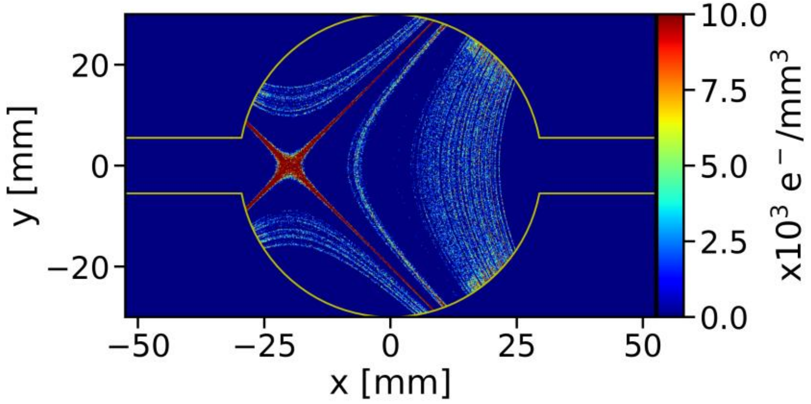


Nested Magnets

Quadrupole (1.45 T/m)



Quadrupole (1.45 T/m) + Sextupole (72.5 T/m^2)



By adding a sextupolar component to a quadrupole magnet

a large number of electrons are trapped in an off-centre cross shape

positioned to the right or left of the vacuum chamber centre depending on the combination of the gradient sign of the quadrupole and sextupole

Outline

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Conclusions and Outlooks

- 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 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
  - Methods to mitigate the material constraints have been investigated
    - increase bunch spacing, but it could lead to issues with other collective effects (keeping constant the beam current)
    - special filling schemes during the accumulation phase avoid tight constraints for the critical bunch intensities
  - On going Other methods to mitigate the material constraints could be studied
    - filling schemes with non-uniform bunch spacing with holes to avoid e-cloud multipacting (already used for LHC)

- 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

Conclusions and Outlooks

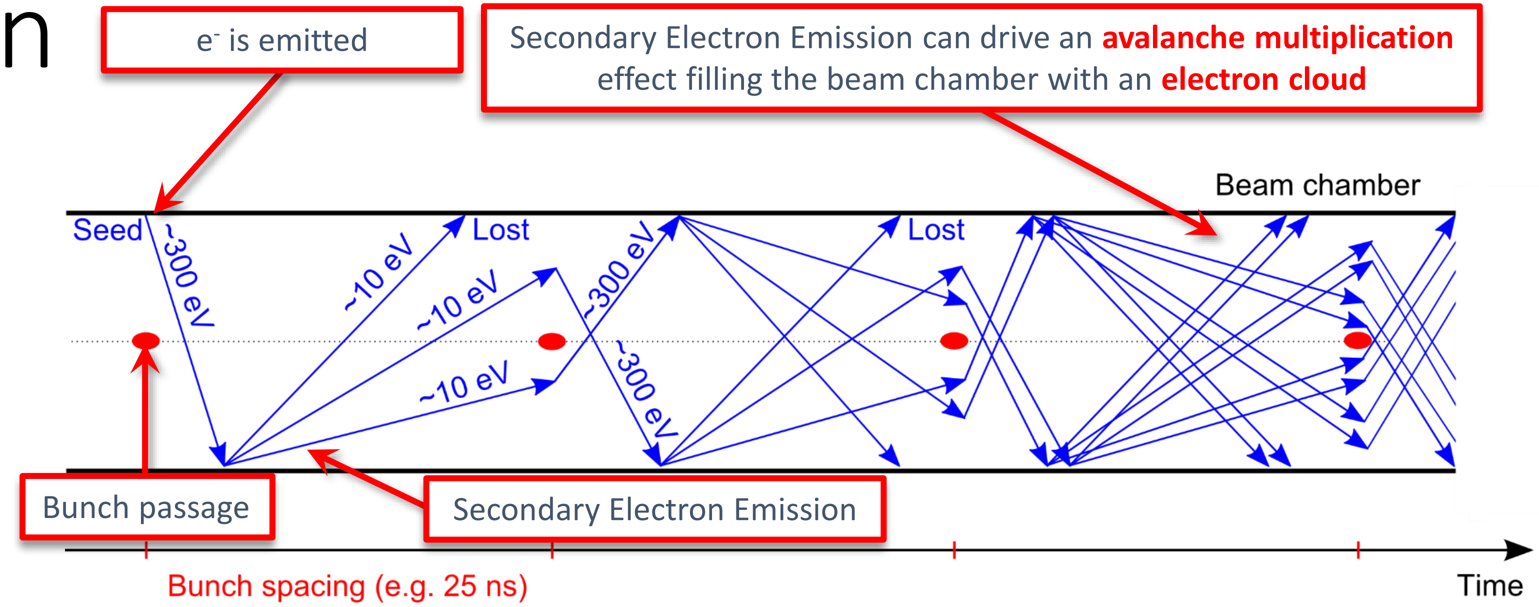
- E-cloud could lead to transverse beam instabilities
  - In all the studied elements (except sextupoles): above the SEY multipacting thresholds the beam is unstable
  - The theoretical and numerical stability thresholds agree (order of magnitude) for the drift space and dipole magnets

- Considering the additional contribution of the photoemission on the e-cloud formation process, the beam could be unstable even below the SEY multipacting threshold
  - The constraint on the material is very tight
  - On going A solution is under development by vacuum group: design of a new synchrotron radiation absorber to reduce the reflected photons
  - On going The vacuum team could provide a realistic distribution of photoelectron generation using ray tracing codes, allowing for more realistic simulations of the e-cloud formation process

- Preliminary results on the nested magnets have been presented
  - SEY multipacting thresholds are smaller for the nested magnets than the single dipole magnets
  - On going exploring other nested magnet configurations could help determine how dependent the observations are on the magnetic and gradient fields

Thanks for your attention

E-Cloud Formation


e$^-$ is emitted

Secondary Electron Emission can drive an **avalanche multiplication** effect filling the beam chamber with an **electron cloud**

Bunch passage

Secondary Electron Emission

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

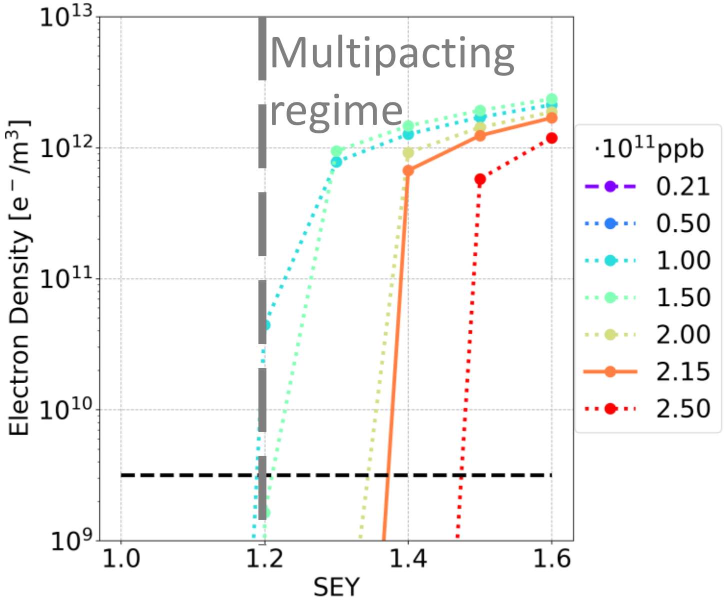
- Chamber geometry influences e^- acceleration and time of flight
- Surface properties have a primary role in the e^- multiplication process
  - The main quantity involved is the Secondary Electron Yield (SEY):

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

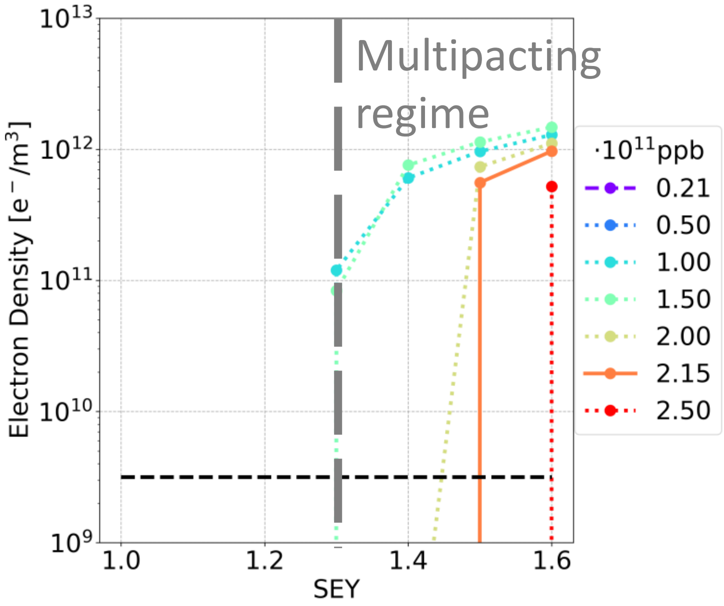
  - SEY depends on
    - surface chemical properties
    - history of the surface, in particular on accumulated electron dose -> to a certain extent the e-cloud cures itself (beam induced scrubbing)
- A key ingredient is the bunch spacing:
  - It determines how many electrons survive between consecutive 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)

E-Cloud Build-Up Studies: Drift Space

Filling scheme 1



Filling scheme 2

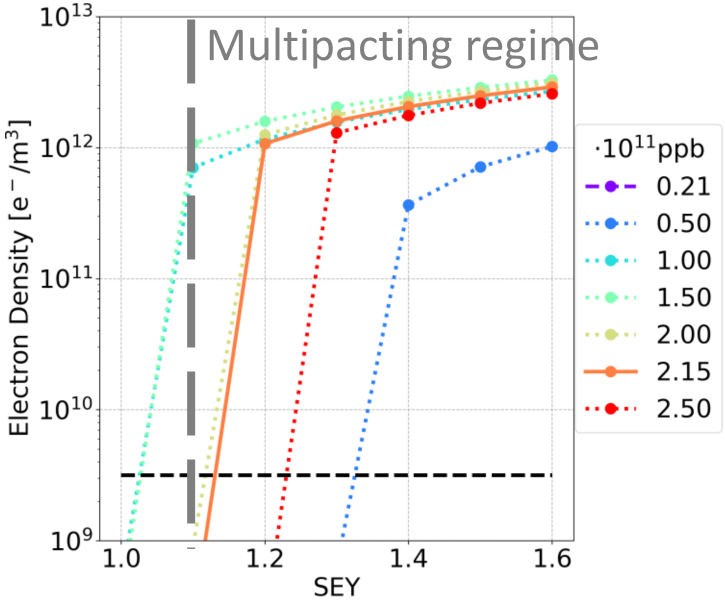


The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

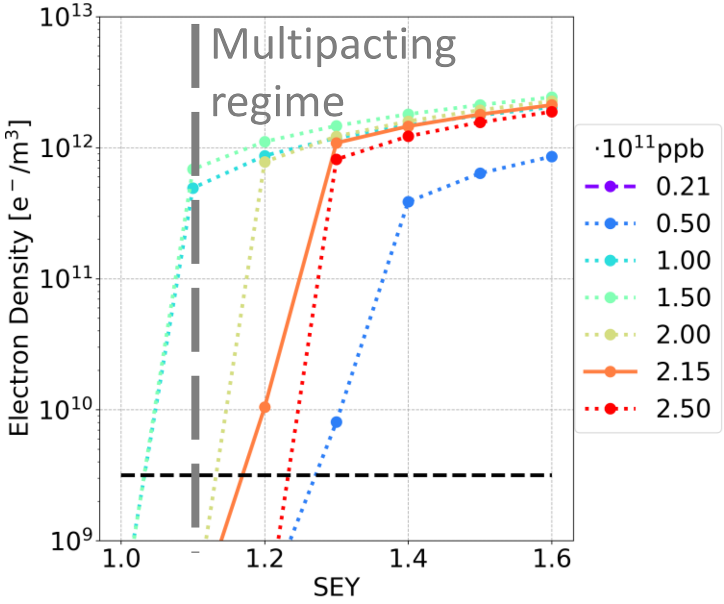
	Filling Scheme 1	**Filling Scheme 2**
SEY threshold (nominal intensity)	1.3	1.4
SEY threshold (all intensity below nominal one)	1.1	1.2

E-Cloud Build-Up Studies: Quadrupole

Filling scheme 1



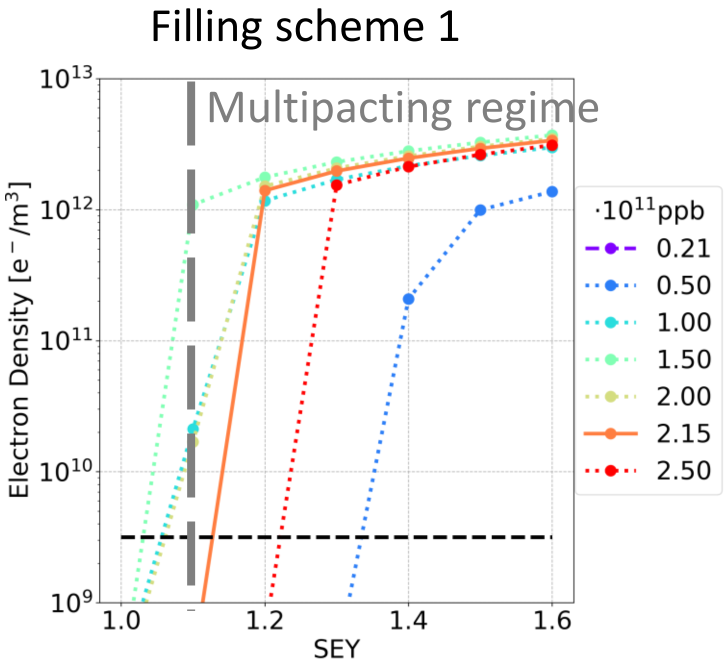
Filling scheme 2

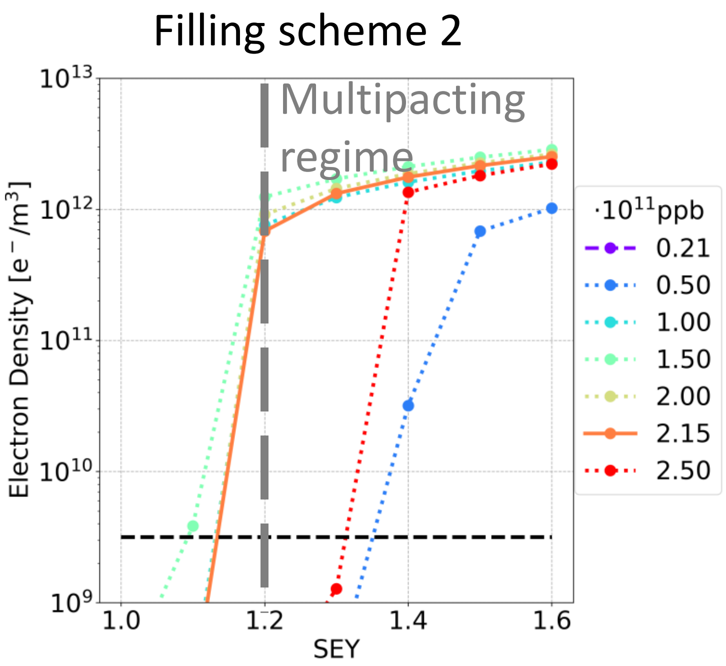


The bunch intensities 1.00e11 and 1.50e11 ppb are the most critical cases

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

E-Cloud Build-Up Studies: Sextupole



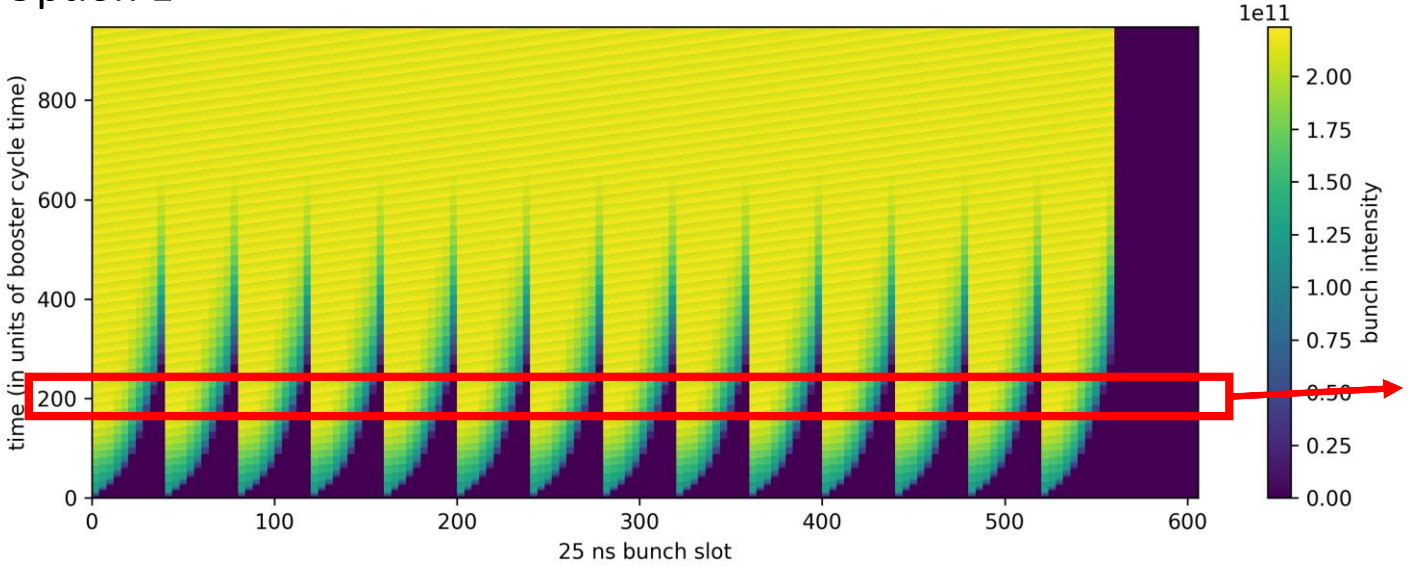


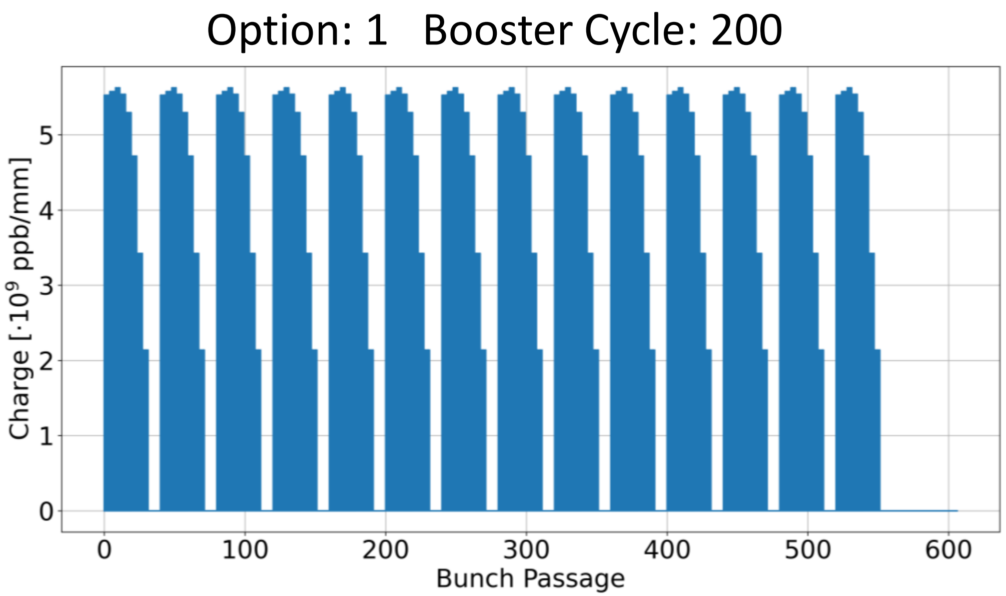
The bunch intensities 1.00e11 and 1.50e11 ppb, 2.00e11 and 2.15e11 ppb are the most critical cases

	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

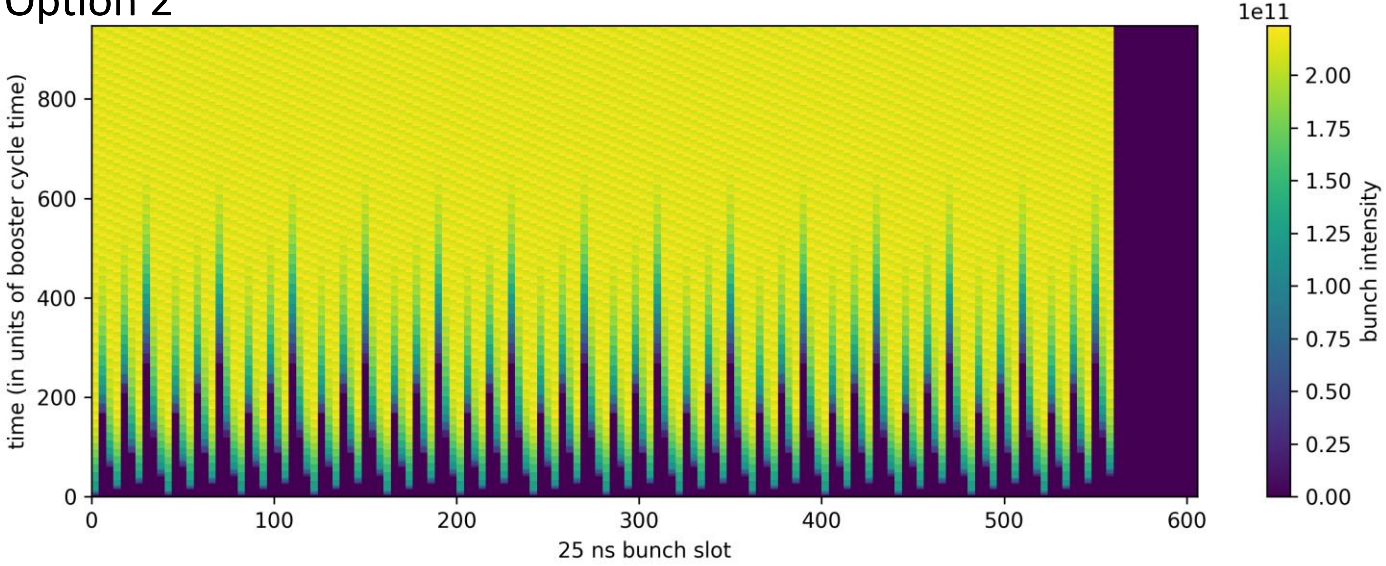
Charge accumulation phase

Option 1




Option: 1 Booster Cycle: 200

Option 2



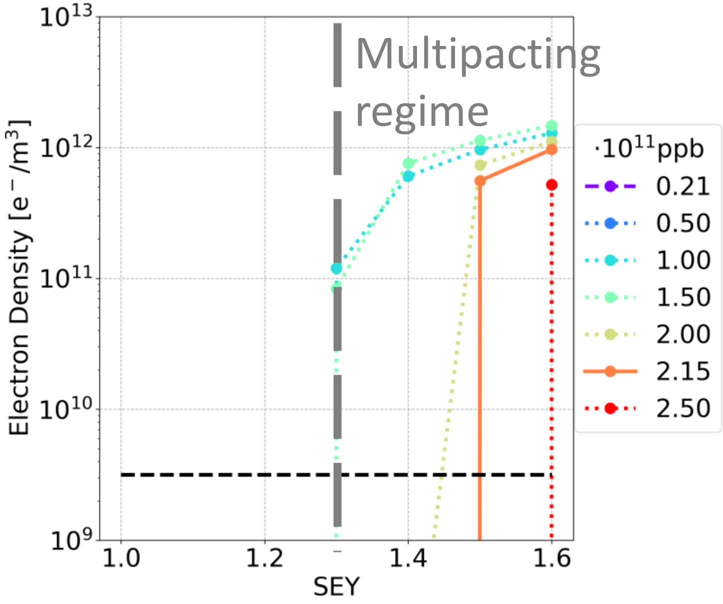
$$int(z) = \frac{int_{tot}}{\sqrt{2\pi}\sigma_z} e^{-\frac{1}{2\sigma_z{}^2}(z-\mu_z)^2}$$

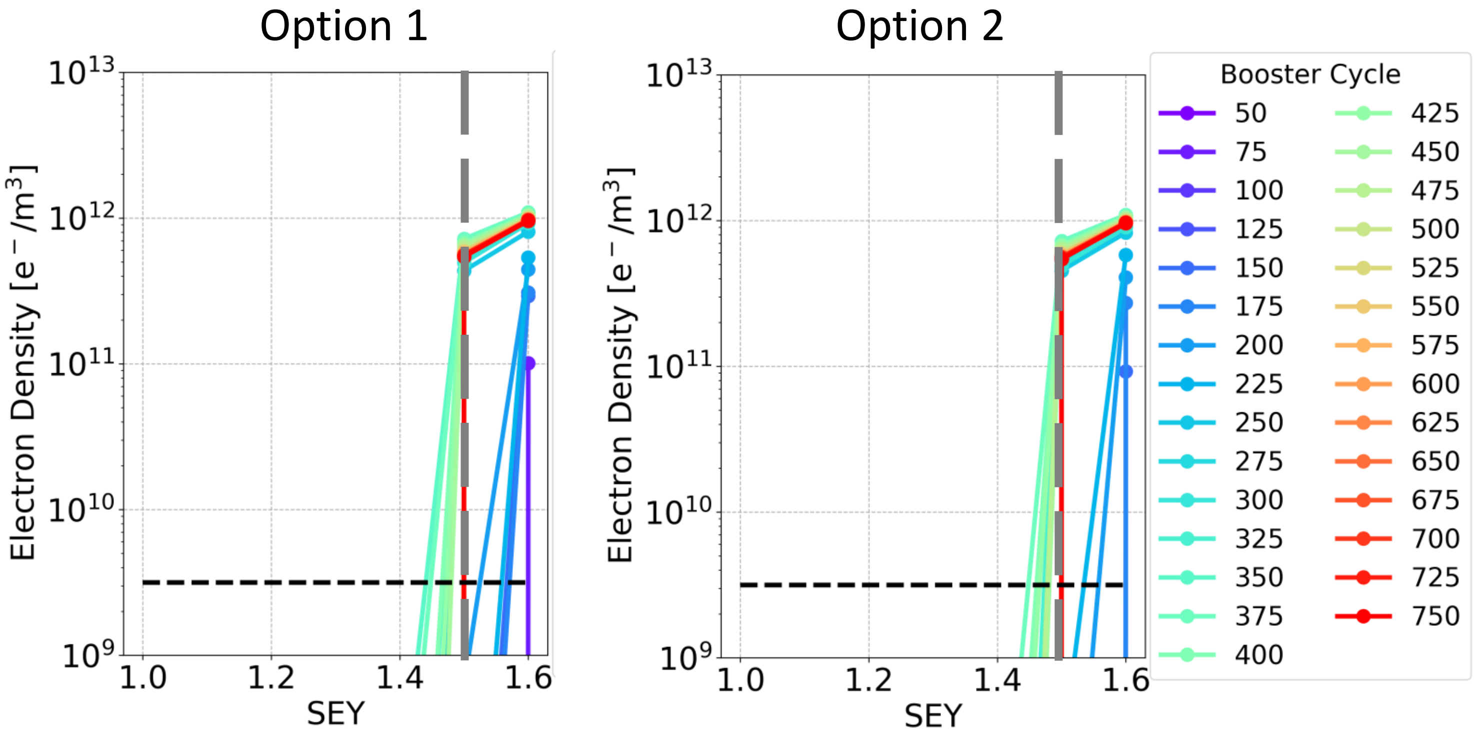
$$int(\mu_z) = \frac{int_{tot}}{\sqrt{2\pi}\sigma_z}$$

σ_z = 15.5 mm

int_{tot}=2.15 10^{11} ppb

Simulation Results: Drift Space

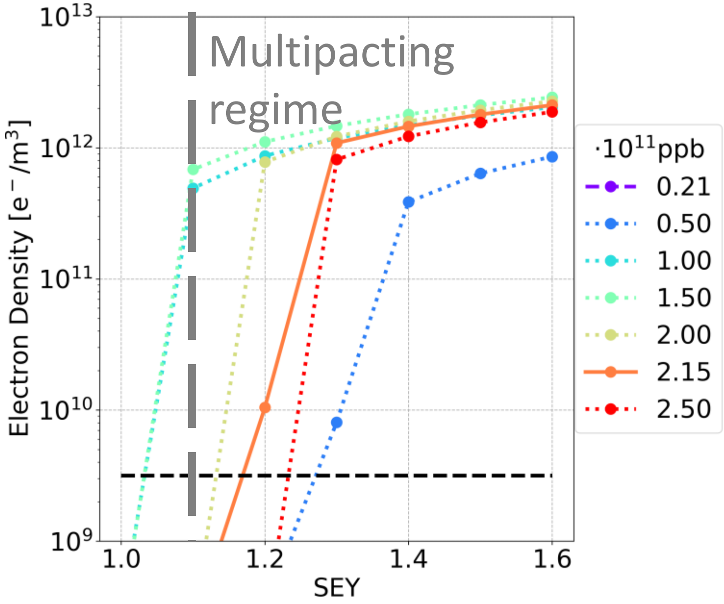


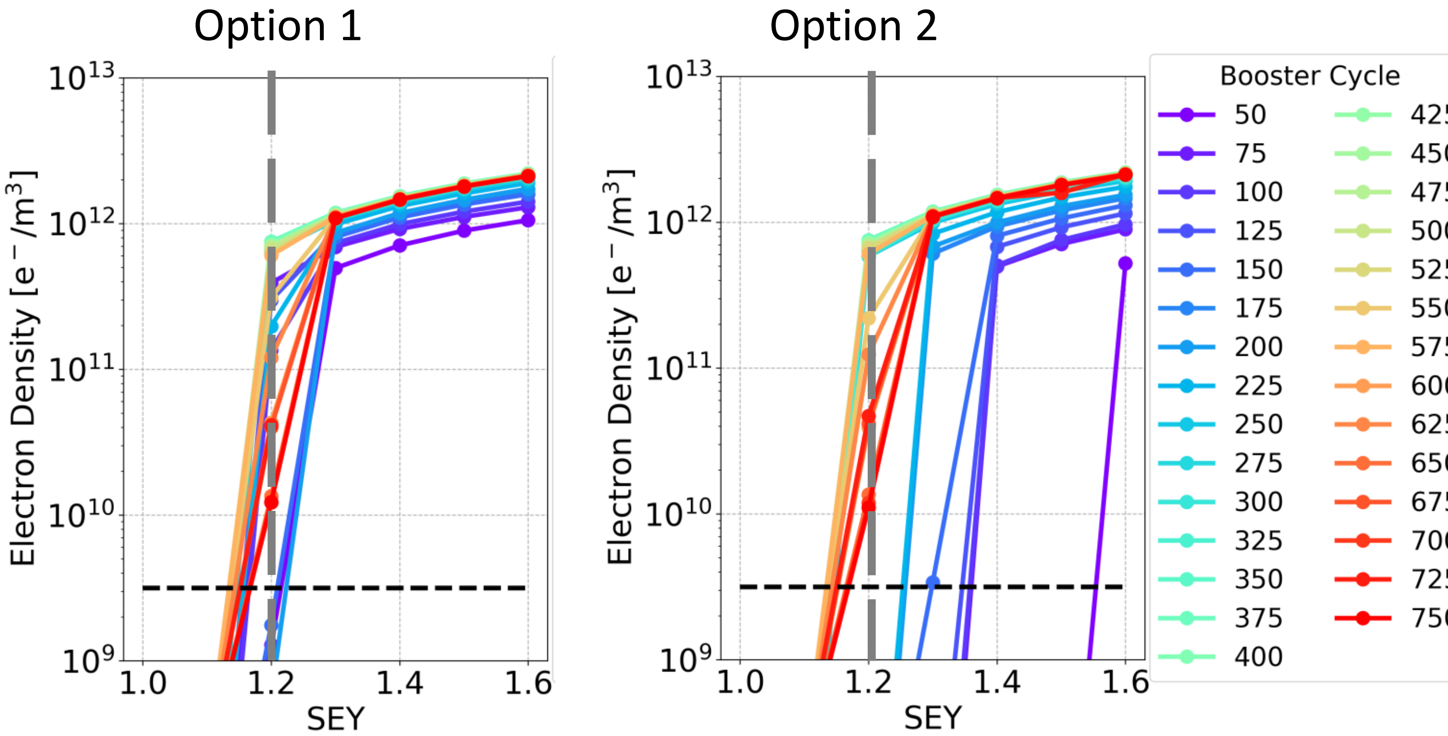


Bunch Spacing	25 ns
SEY threshold (nominal intensity)	1.4
SEY threshold (all intensity below nominal one)	1.2

Charge accumulation Phase	Non-uniform
SEY threshold	1.4

Simulation Results: Quadrupole

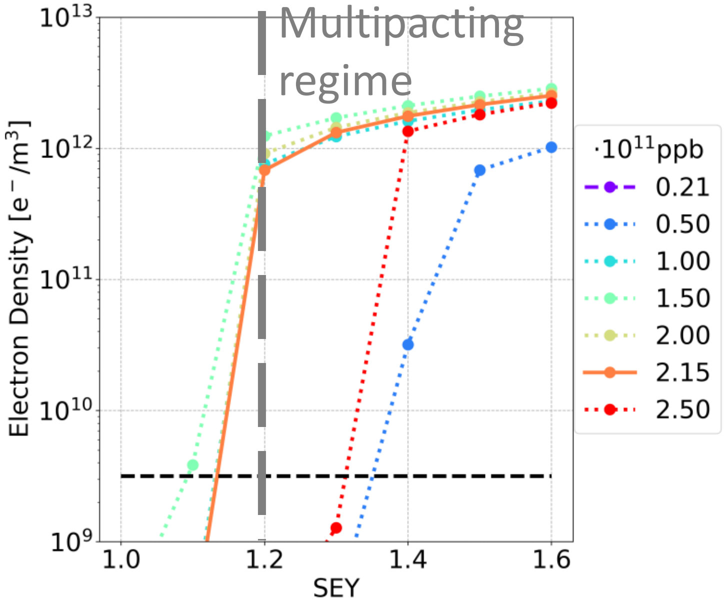


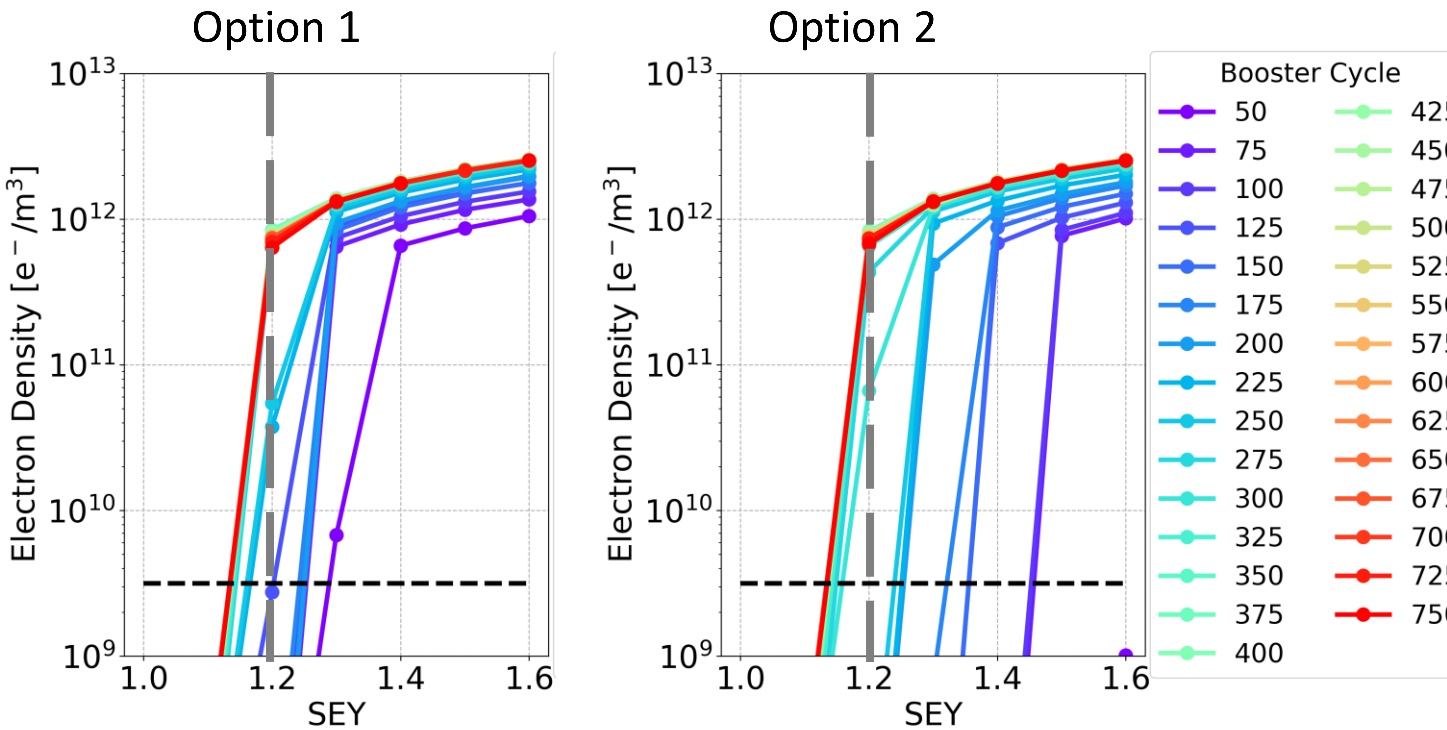


Bunch Spacing	25 ns
SEY threshold (nominal intensity)	1.1
SEY threshold (all intensity below nominal one)	1.0

Charge accumulation Phase	Non-uniform
SEY threshold	1.1

Simulation Results: Sextupole



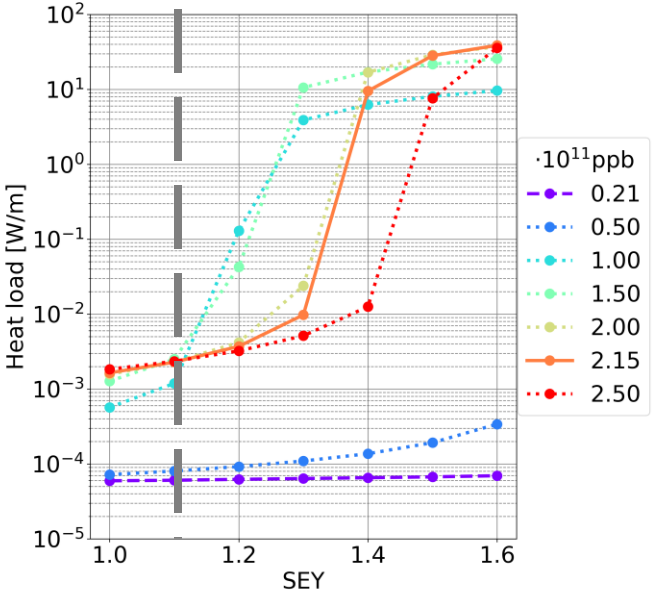


Bunch Spacing	25 ns
SEY threshold (nominal intensity)	1.1
SEY threshold (all intensity below nominal one)	1.0

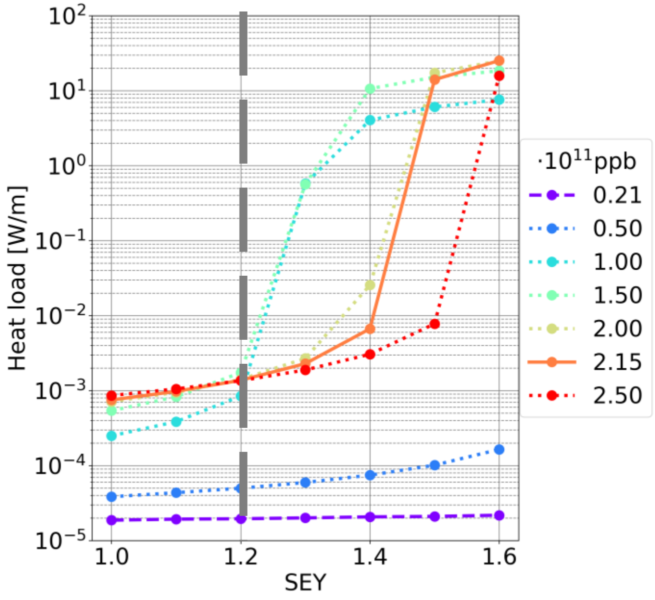
Charge accumulation Phase	Non-uniform
SEY threshold	1.1

Heat Loads: Drift Space

Filling scheme 1



Filling scheme 2



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

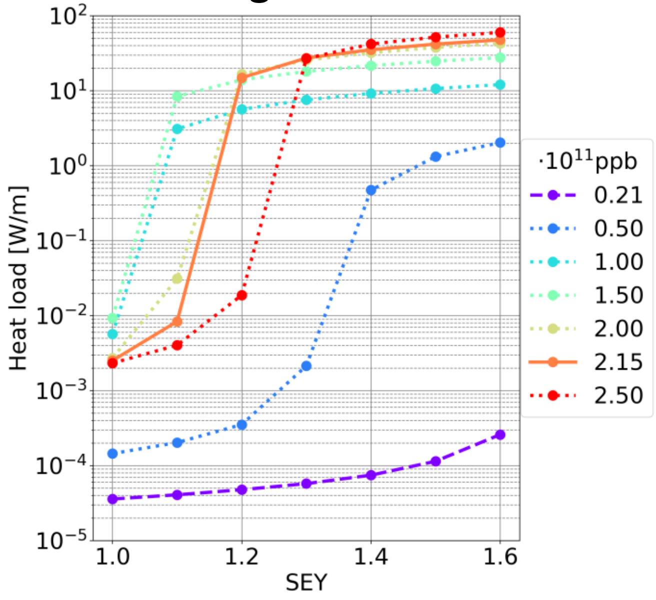
If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

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

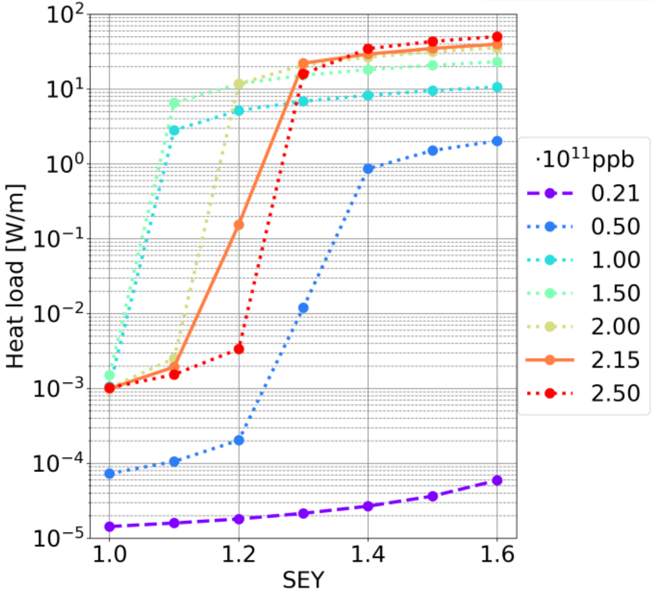
Heat Loads: Quadrupole

	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

Filling scheme 1



Filling scheme 2



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

Synchrotron radiation power: ~50 MW per beam

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

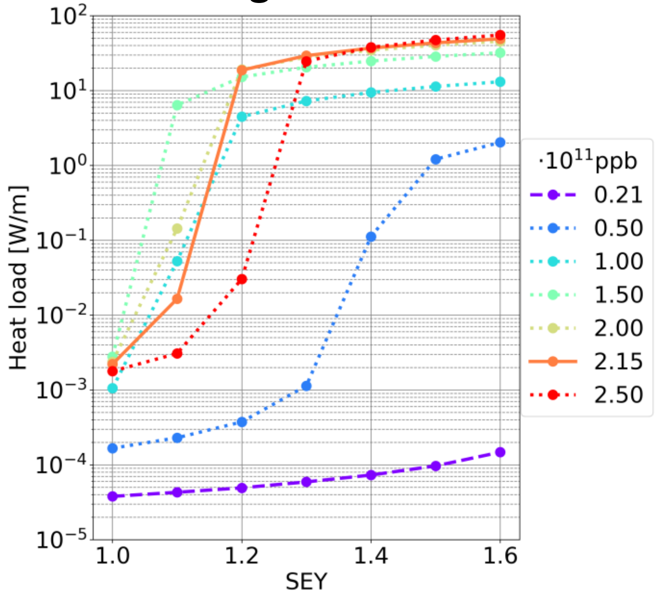
Filling scheme 2: ~39.8 W/m -> full circumference ~190 kW ~0.38% of synchrotron radiation power

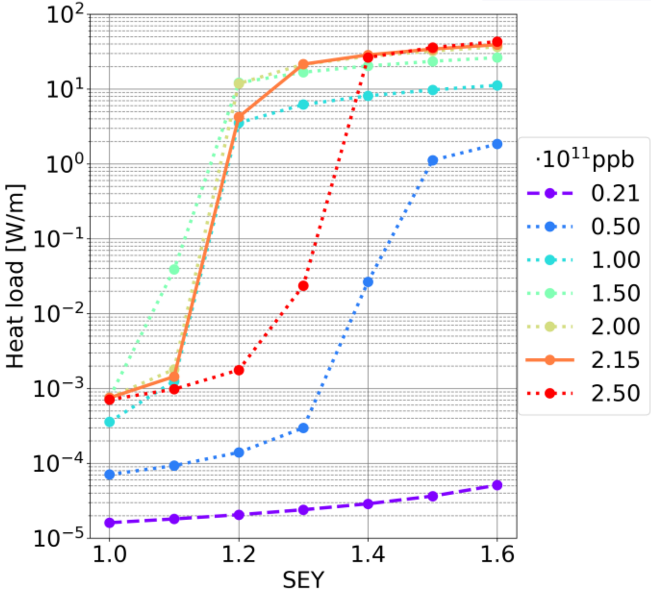
If no multipacting (considering SEY smaller the SEY multipacting threshold, all simulated bunch intensities):

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 Stability Theoretical Threshold

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

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

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

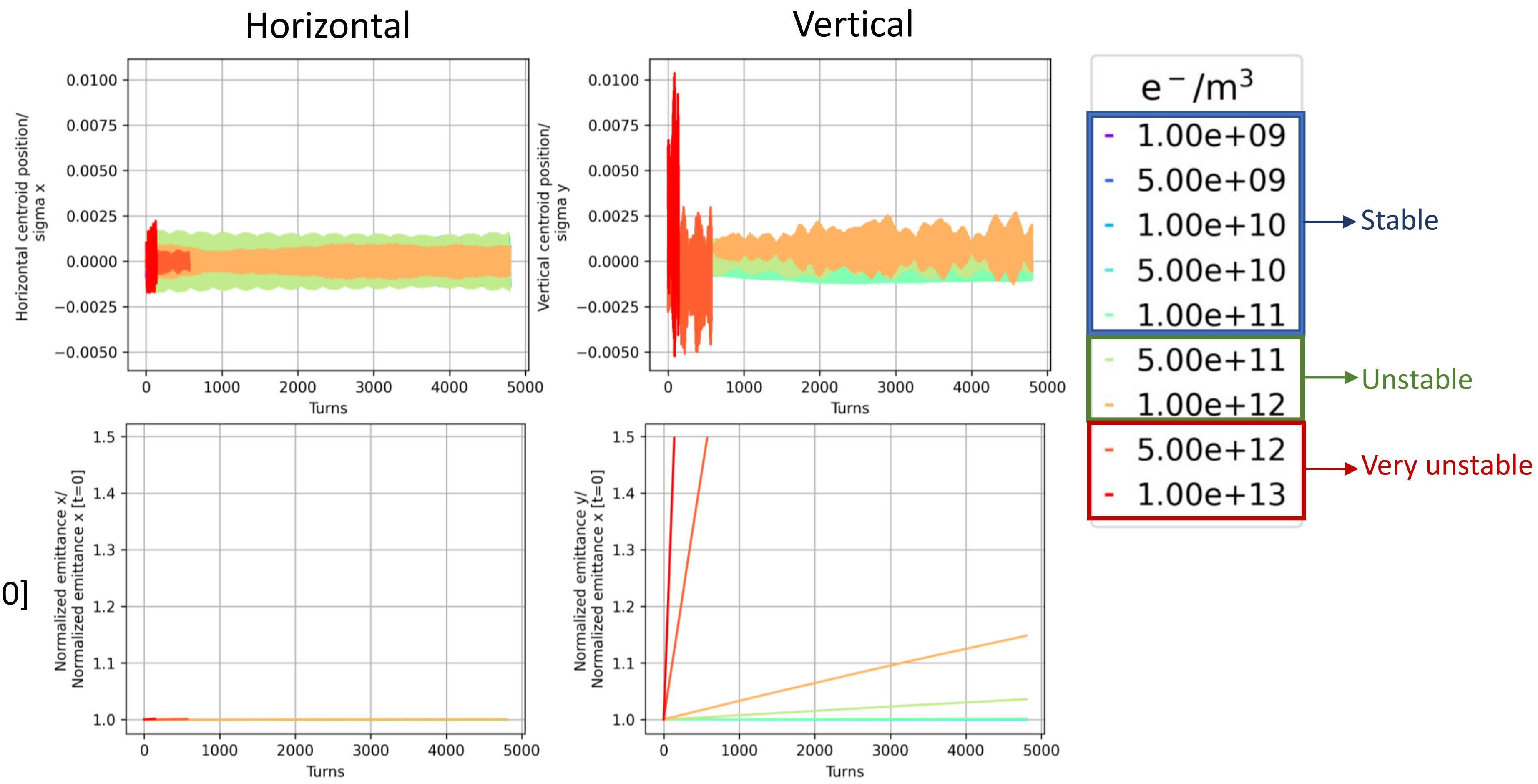
- $\gamma = E/E_0$, where *E* is the beam energy, E_0 is the particle rest energy.
- ν_s is the synchrotron tune.
- σ_z is the bunch length.
- *c* is the light velocity.
- r_e is the classical electron radius.
- σ_x *and* σ_y are the bunch horizontal and vertical dimension, respectively.
- λ_p is the 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.

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%)

Centroid/ Sigma

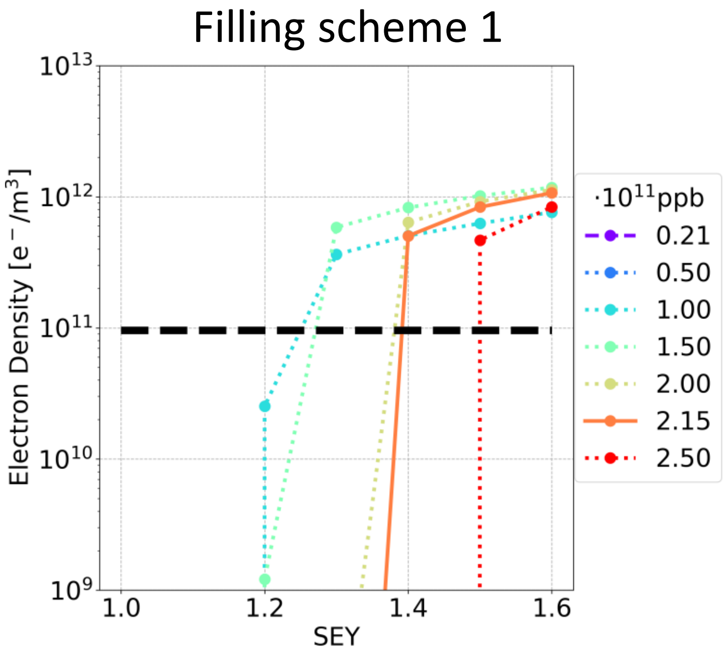
Normalised emittance/ Normalised emittance [t=0]



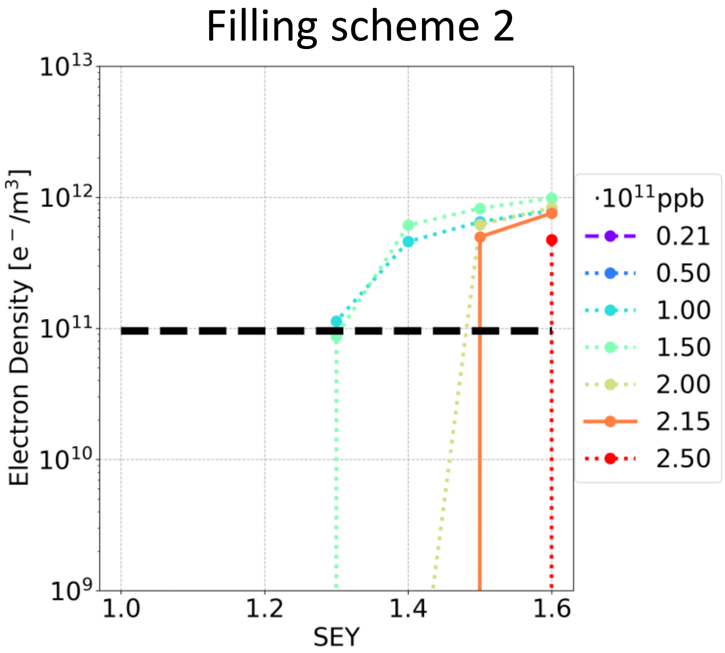
- Theoretical and numerical e-cloud density stability threshold have the same order of magnitude
- Vertical plane is unstable

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



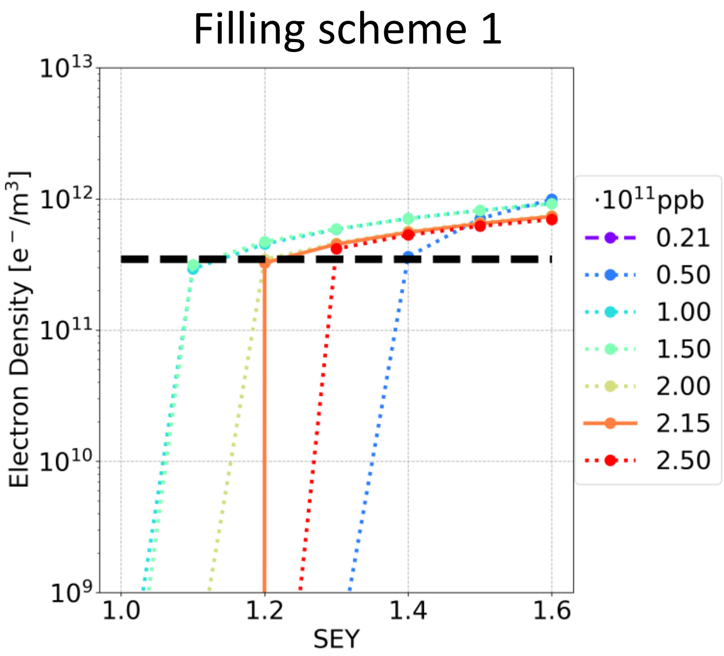
Filling scheme 1

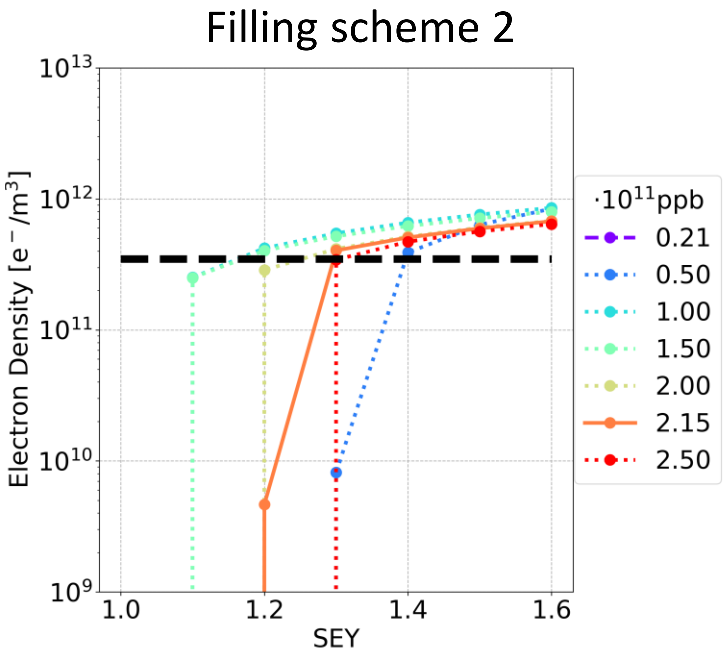


Filling scheme 2

- 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

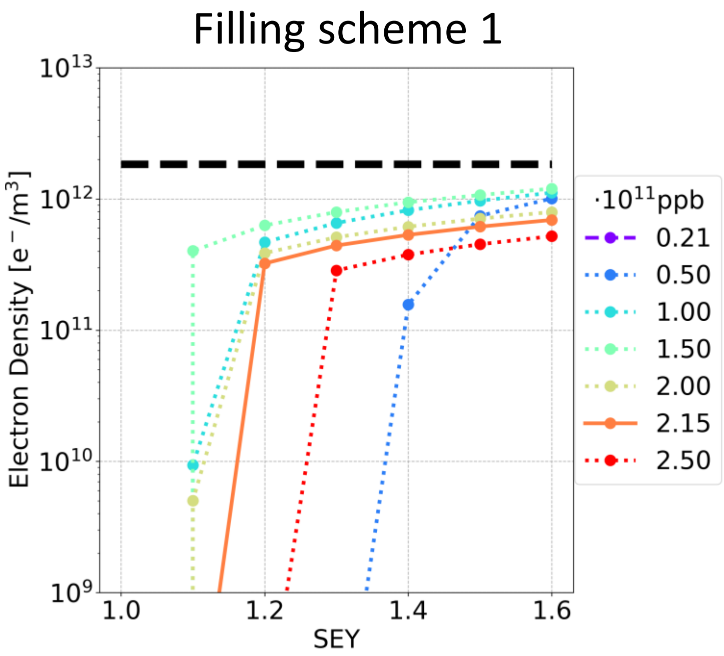
E-Cloud Stability: Quadrupole

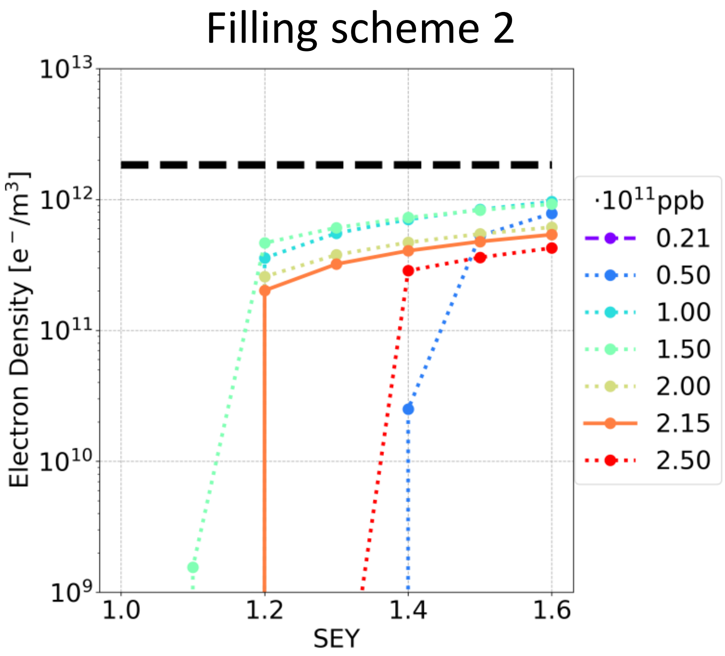

Filling scheme 1


Filling scheme 2

- 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


Filling scheme 1


Filling scheme 2

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