E-Cloud Studies and Instability Threshold

Sabato Luca[1], *Iadarola Giovanni*[2], *Mether Lotta*[2], *Tatiana Pieloni*[1]

Acknowledgement: *Cantún Karla*[5], *Michael Hofer*[2], *Maury Humberto*[4], *Paraschou Konstantinos*[2], *Yaman Fatih*[3], *Léon Van Riesen-Haupt*[1], *Zimmermann Frank*[2]

1 EPFL
2 CERN
3 IZMIR INSTITUTE OF TECHNOLOGY IZTECH
4 UNIVERSIDAD DE GUANAJUATO
5 UADY UNIVERSIDAD AUTÓNOMA DE YUCATÁN

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Outline

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

Outline

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

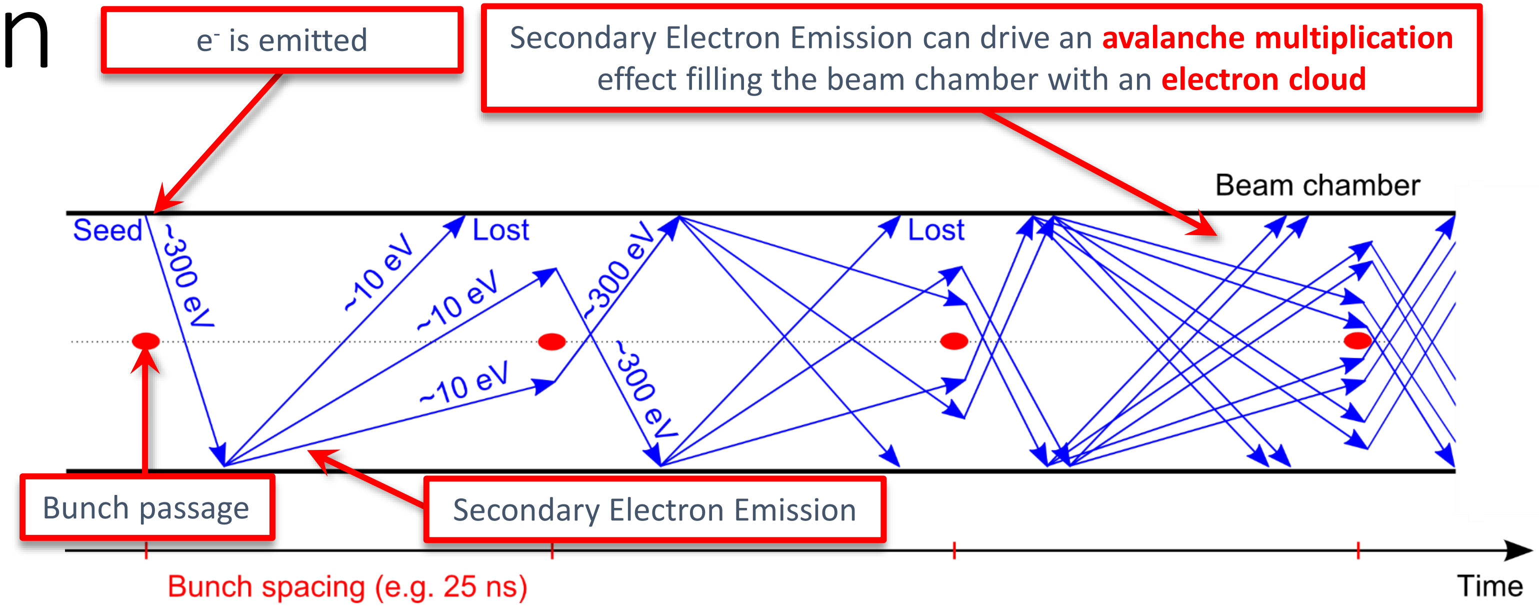
Motivation

- Electron cloud (e-cloud) effects have been observed in several 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
  - impact on beam diagnostics

- E-cloud effects have to be studied for FCC-ee
  - to give input to chamber design, material properties

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)

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FCC-ee Parameters

- Design stage of FCC-ee

Previous versions

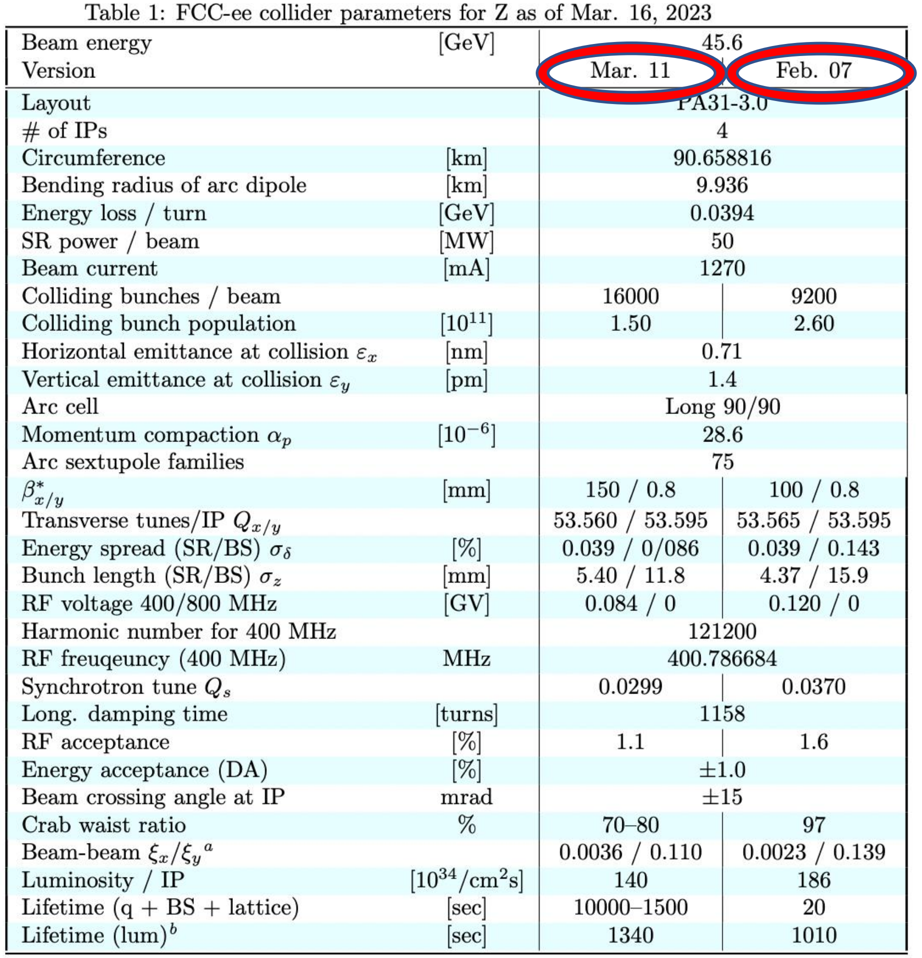


Table 1: FCC-ee collider parameters for Z as of Mar. 16, 2023

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

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

Latest version

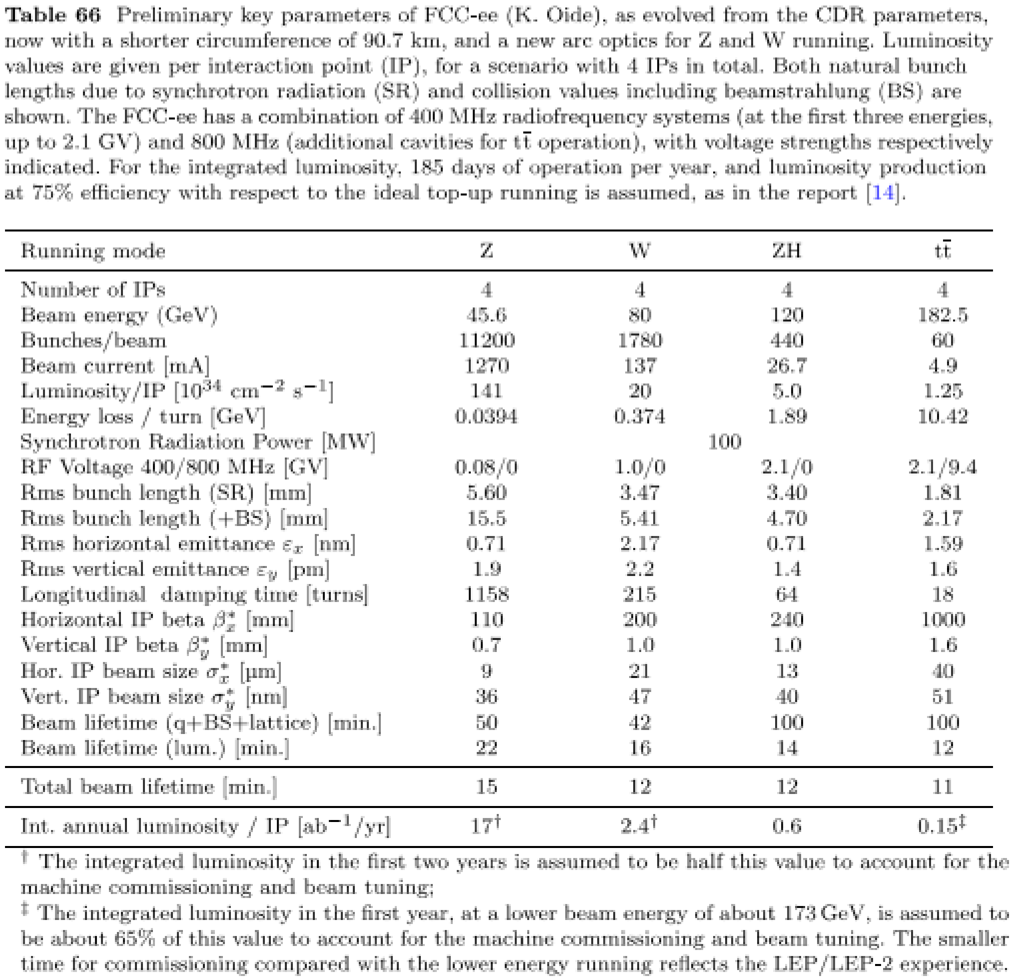


Table 66 Preliminary key parameters of FCC-ee (K. Oide), as evolved from the CDR parameters, now with a shorter circumference of 90.7 km, and a new arc optics for Z and W running. Luminosity values are given per interaction point (IP), for a scenario with 4 IPs in total. Both natural bunch lengths due to synchrotron radiation (SR) and collision values including beamstrahlung (BS) are shown. The FCC-ee has a combination of 400 MHz radiofrequency systems (at the first three energies, up to 2.1 GV) and 800 MHz (additional cavities for $t\bar{t}$ operation), with voltage strengths respectively indicated. For the integrated luminosity, 185 days of operation per year, and luminosity production at 75% efficiency with respect to the ideal top-up running is assumed, as in the report [14].

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‡

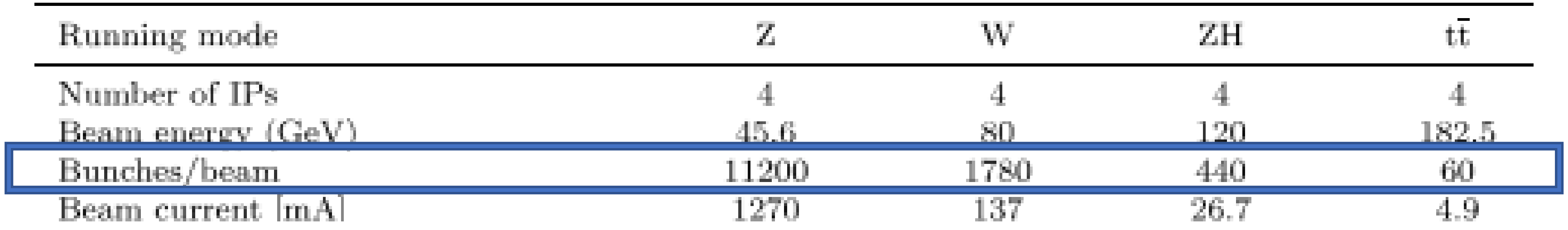
† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;

‡ 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 Frank Zimmermann

Important Parameters for E-Cloud Formation

- A preliminary study to identify the parameters, in the range of the values of FCC-ee case, which play a significant role in the e-cloud formation has been performed
- The Z configuration has been investigated, because the strongest e-cloud effects are foreseen for this configuration due to the highest number of bunches (smallest bunch spacing)



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Important Parameters for E-Cloud Formation

- After an extensive simulation study campaign in the range of FCC-ee parameters the main results are the following:

- Some parameters play a significant role in the e-cloud formation process:
    - Bunch spacing
    - SEY
    - Bunch intensity
    - Externally applied magnetic field

- Some parameters make a negligible contribution to the e-cloud formation process:
    - Beam chamber winglet height
    - Beta function in the arcs
    - Dispersion

Important Parameters for E-Cloud Formation

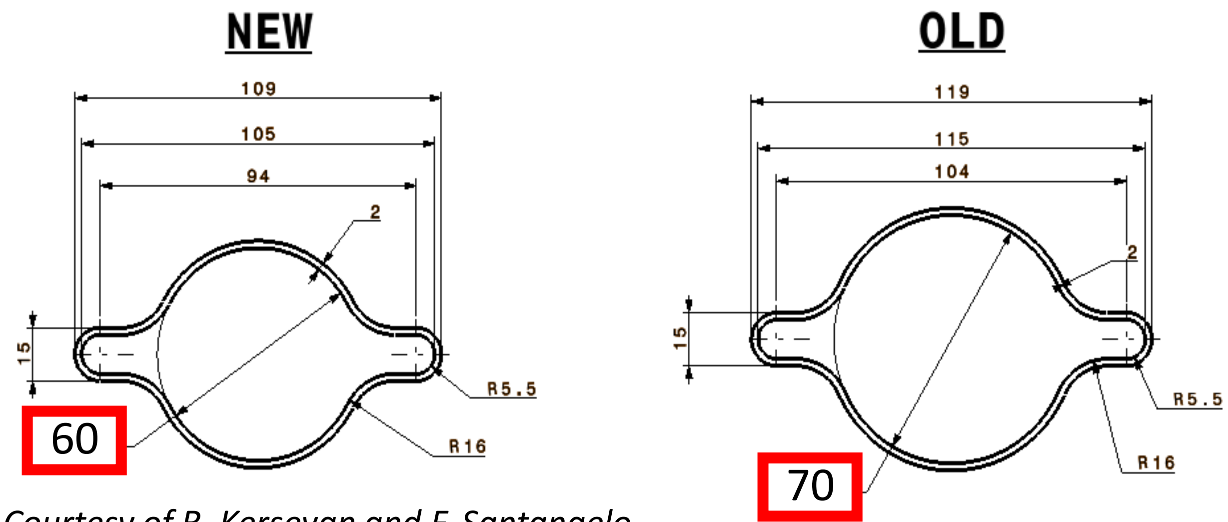
- After an extensive simulation study campaign in the range of FCC-ee parameters the main results are the following:

- The dependence of the e-cloud density on some parameters is monotonic:
  - SEY: larger SEY -> larger e-cloud density
  - Bunch spacing: larger bunch spacing -> larger multipacting thresholds and smaller e-cloud density

- In general the dependence of the e-cloud density on the other parameters is complex

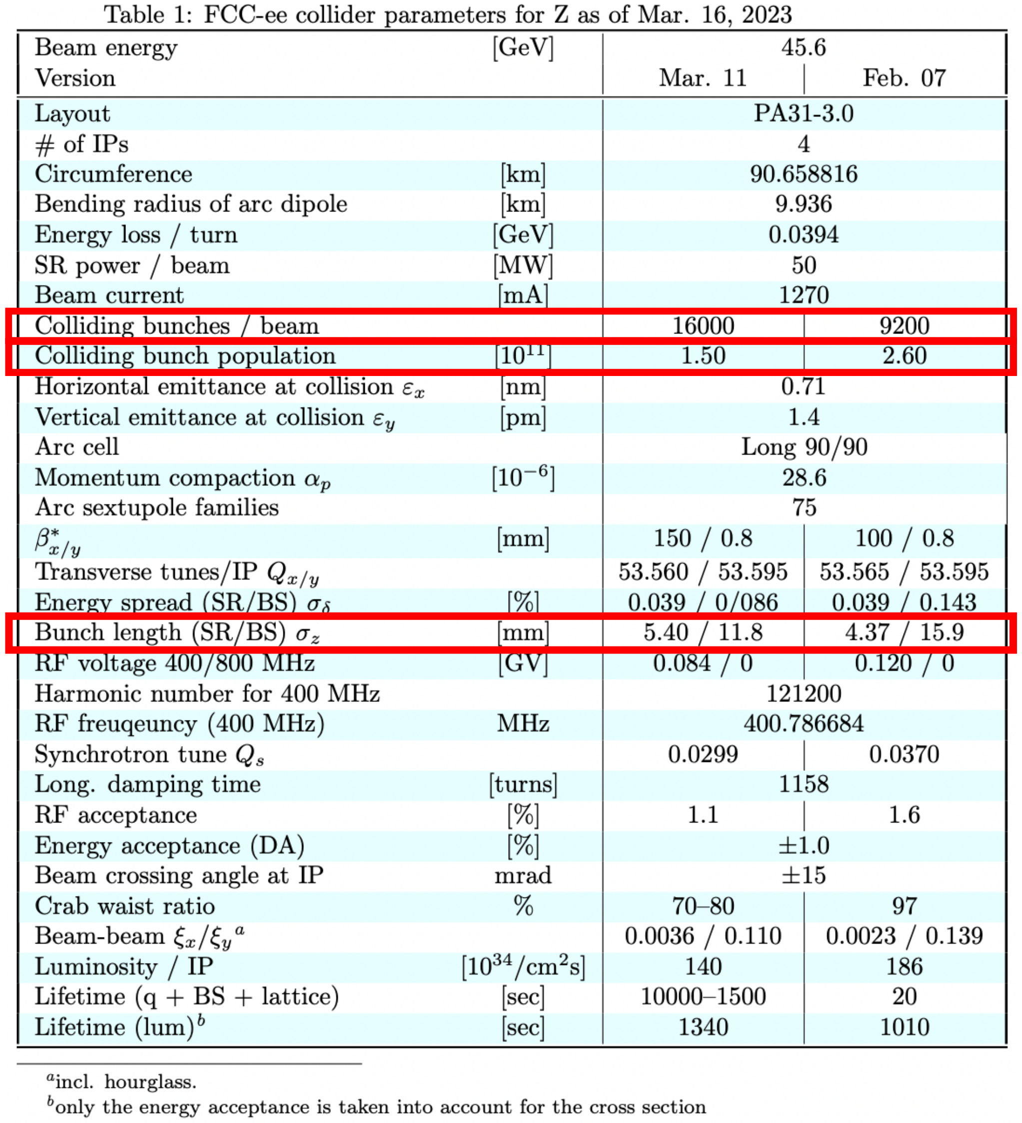
Parameters in March

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



Courtesy of R. Kersevan and F. Santangelo

- What is the impact of the new parameters on the e-cloud formation process?



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Lifetime (q + BS + lattice)	[sec]	10000–1500	20
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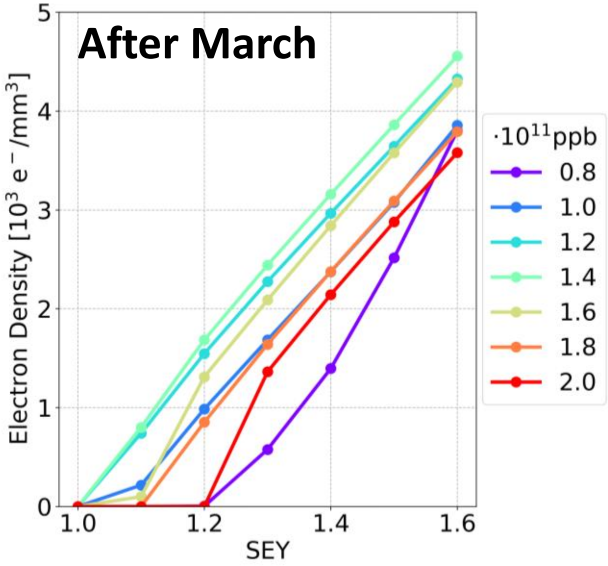
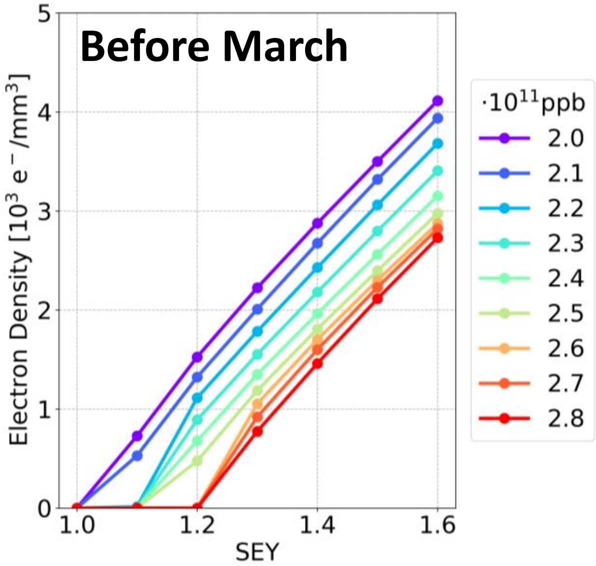
[a] incl. hourglass.

[b] only the energy acceptance is taken into account for the cross section

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

Comparison: Before vs After March



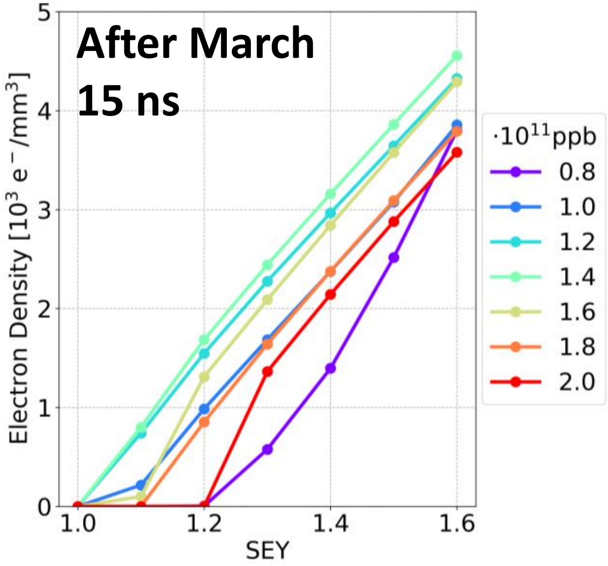


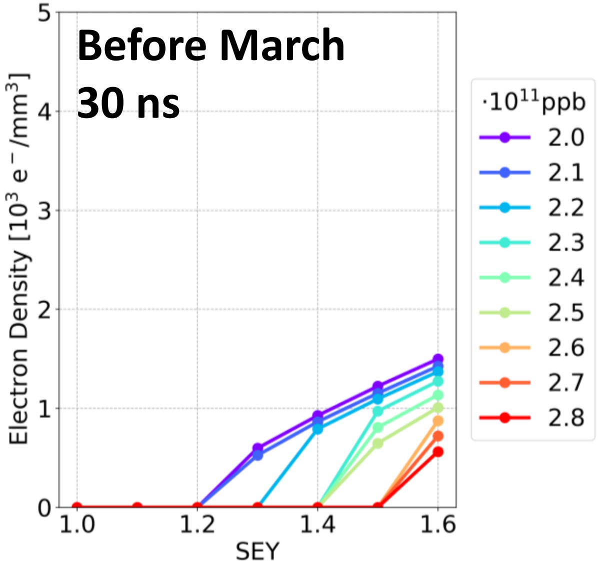
- For a fixed bunch spacing there is not a large difference in the range of multipacting threshold nor in the e-cloud density for the considered intensity range

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

Comparison: Before vs After March

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





- Comparing the version after March and the version before March with the max bunch spacing reachable there is a clear difference both in the range of multipacting threshold and in the e-cloud density

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

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

Possible Filling Schemes

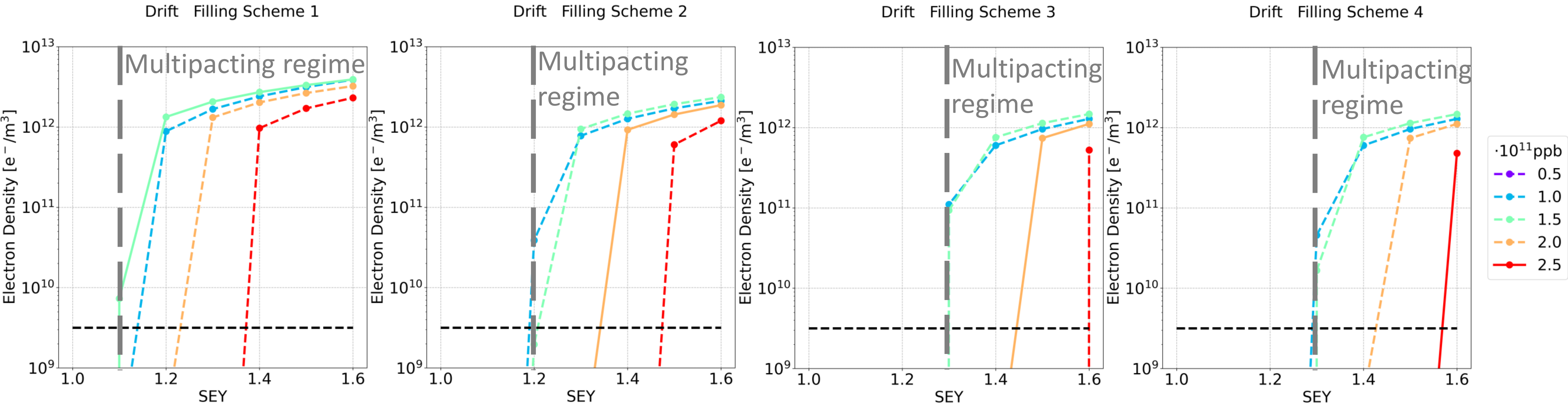
Filling schemes (with constant total number of particles per beam)

From Tor Raubenheimer

Filling Scheme Number	Bunch Intensity [x10^{11} ppb]	Bunch Spacing [ns]	Number bunches / Train	Number Trains	Gap Length [ns] (gap/bunch spacing)
1	1.51	15	320	50	1275 (85)
2	2.15	20	280	40	1980 (99)
3	2.15	25	560	20	1175 (47)
4	2.43	25	255	40	1225 (49)

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

Simulation Results: Drift Space



	Filling Scheme 1	Filling Scheme 2	Filling Scheme 3	Filling Scheme 4
SEY threshold (nominal intensity)	1.0	1.3	1.4	1.5
SEY threshold (all intensity below nominal one)	1.0	1.1	1.2	1.2

- Filling scheme 3 and 4 (with longer bunch spacing) are better: multipacting threshold higher

Simulation Results: Summary

- With larger bunch spacing the required SEY threshold (to suppress the e-cloud build-up) is higher

Element	**SEY Threshold**	**Filling Scheme 1**	**Filling Scheme 2**	**Filling Scheme 3**	**Filling Scheme 4**
Drift Space	nominal intensity	1.0	1.3	1.4	1.5
	all intensity below nominal one	1.0	1.1	1.2	1.2
Dipole	nominal intensity	1.0	1.3	1.4	1.5
	all intensity below nominal one	1.0	1.0	1.1	1.1
Quadrupole	nominal intensity	<1.0	1.0	1.1	1.2
	all intensity below nominal one	<1.0	1.0	1.0	1.0

- Quadrupoles have the lowest thresholds: most critical elements from the e-cloud point of view

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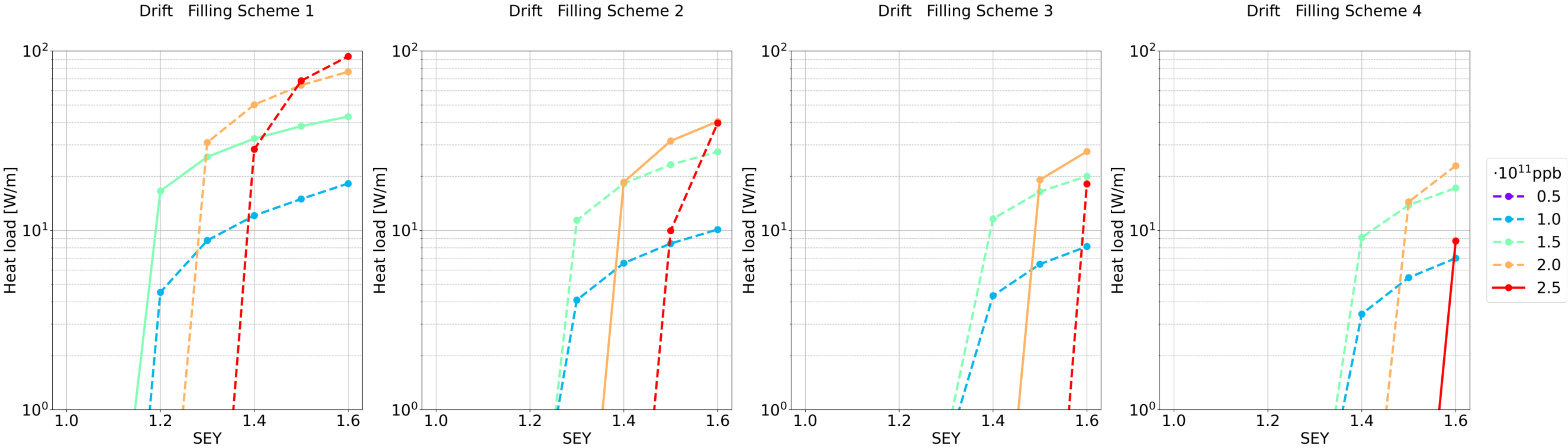
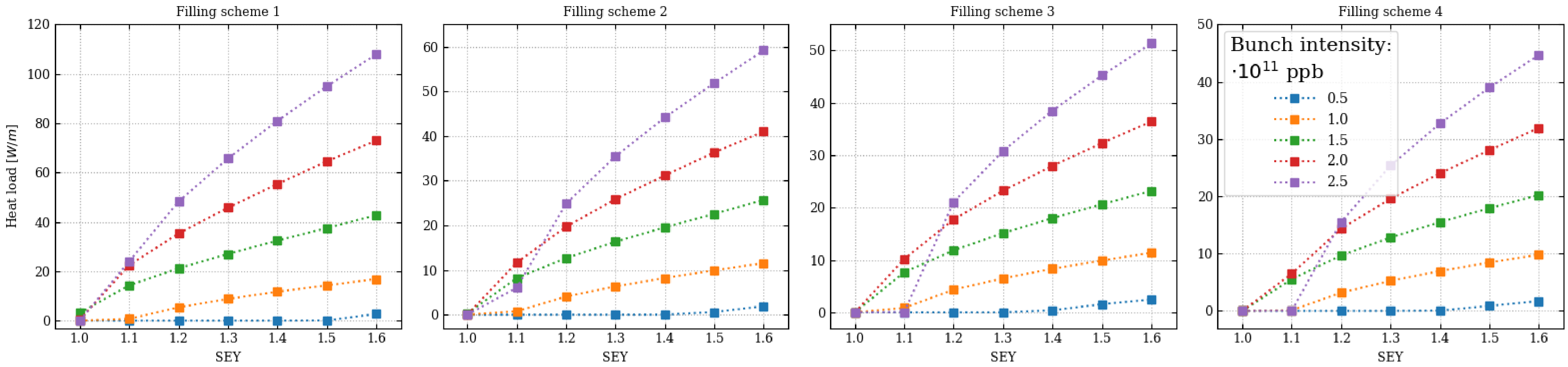
Heat Loads



- Filling scheme 3 and 4 (with larger bunch spacing) show lower heat loads
- Same results for dipoles, quadrupoles

Heat Loads

Courtesy of K. Cantún and H. Maury
02/11/2023, "Studies on the electron cloud build-up for the FCC-ee main sextupoles under different scenarios"
174th FCC-ee Optics Design Meeting & 45th FCCIS WP2.2 Meeting



- Same results for sextupoles
- For the max simulated SEY and for the nominal bunch intensity (in most of the cases there is multipacting), the total heat loads (drift spaces, dipoles, quadrupoles, sextupoles) is in the order of a few percent of the synchrotron radiation:
    - Filling scheme 1: ~3.4 MW (~7% of synchrotron radiation)
    - Filling scheme 2: ~3.4 MW (~7% of synchrotron radiation)
    - Filling scheme 3: ~2.5 MW (~5% of synchrotron radiation)
    - Filling scheme 4: ~0.7 MW (~1% of synchrotron radiation)

Synchrotron radiation ~50 MW per beam

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E-Cloud Stability Threshold

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

- Which is the e-cloud density stability threshold?

1. Theoretical equation:

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

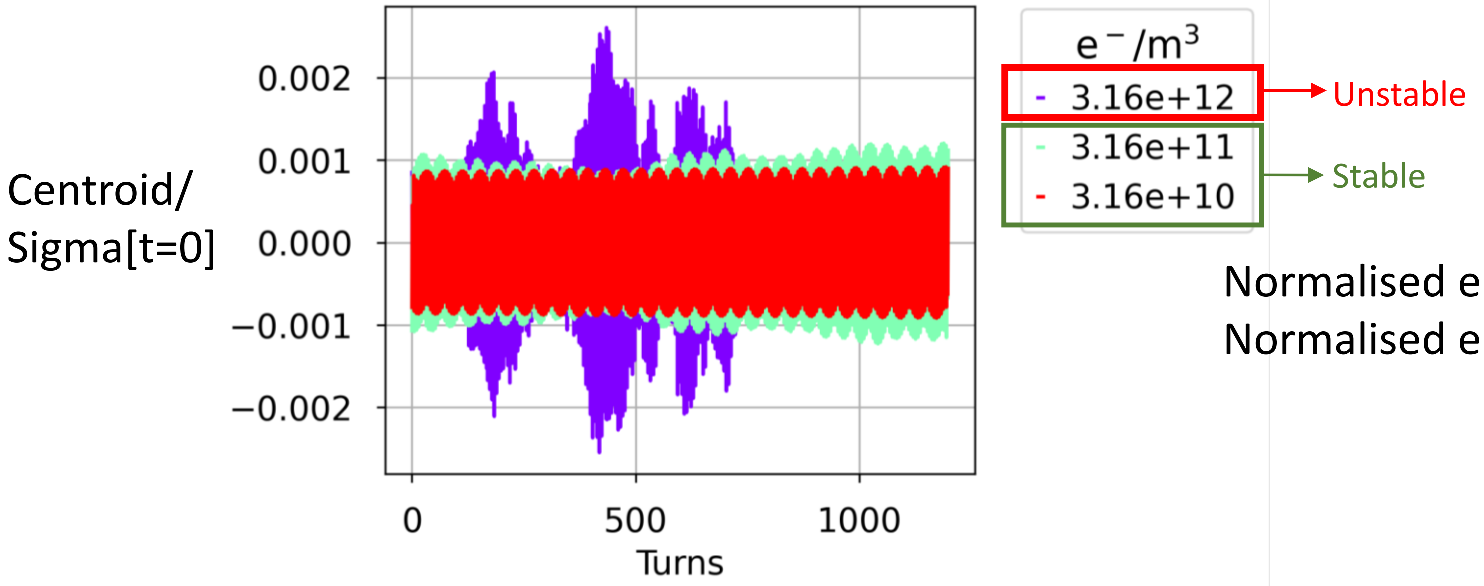
From K. Ohmi et al., "Study of Electron Cloud Instabilities in FCC-hh", Proc. of IPAC2015

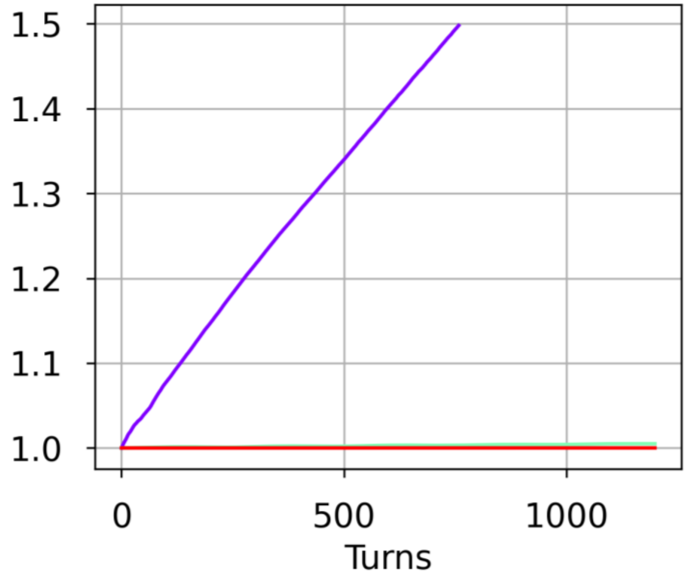
2. Simulations by means of PyECLOUD-PyHEADTAIL suite in order to track the beams through the e-clouds

E-Cloud Stability Numerical Threshold

Drift Space

- $\rho_{e,th}$ = 9.85 ·10^{10} e^-/m^3 considering only the drift length L_{drift} = 17.4 km (L_{drift} /L = 19.2%)

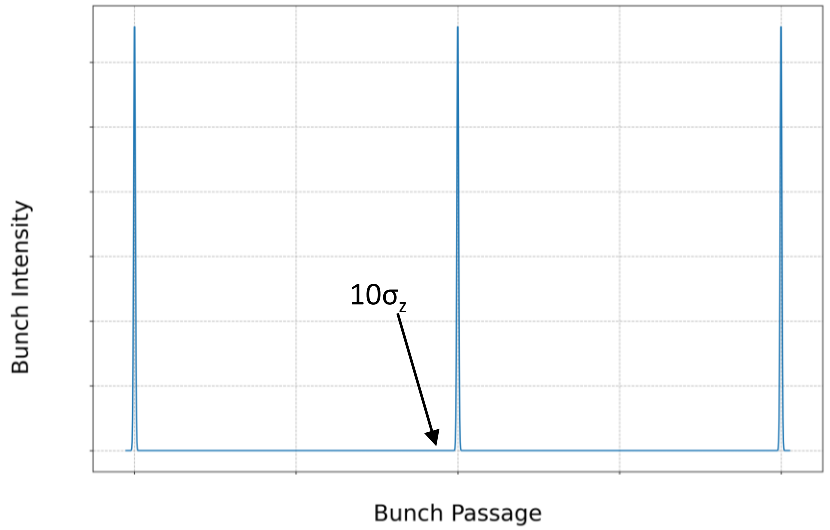




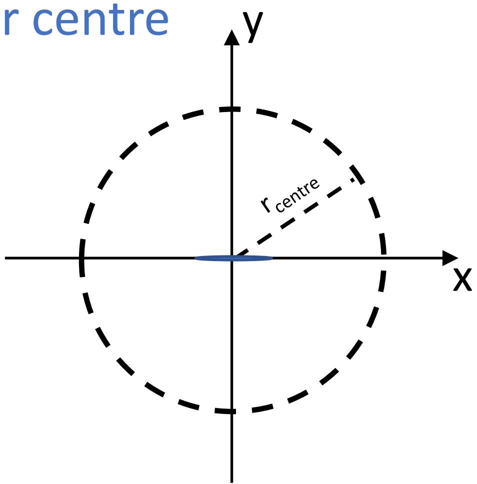
- From preliminary results:
  - Theoretical and numerical e-cloud density stability threshold same order of magnitude
  - Theoretical threshold more conservative

E-Cloud Central Density

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

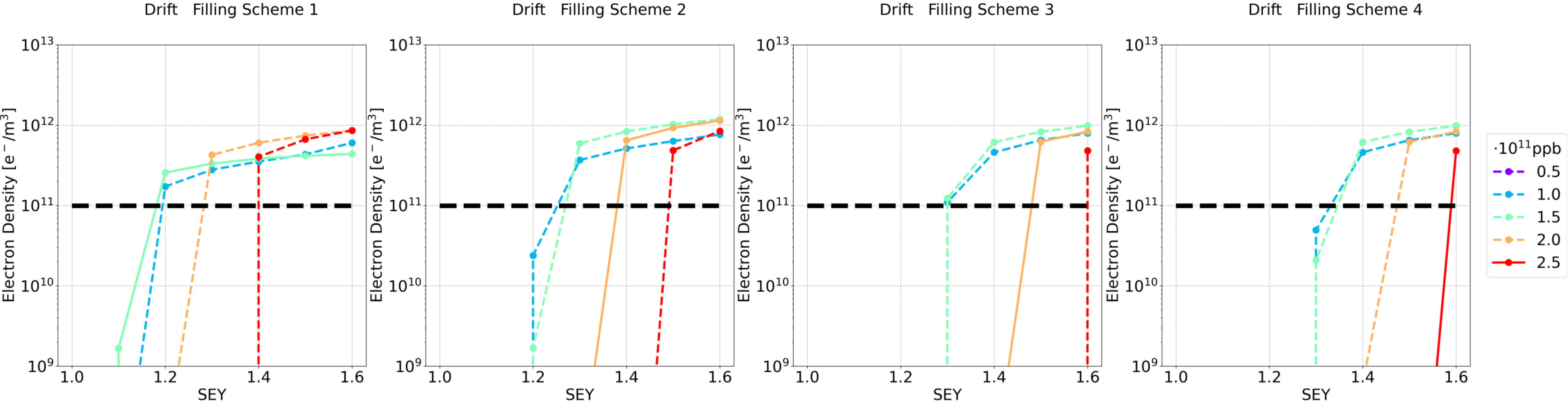


  - close the vacuum chamber centre



E-Cloud Stability

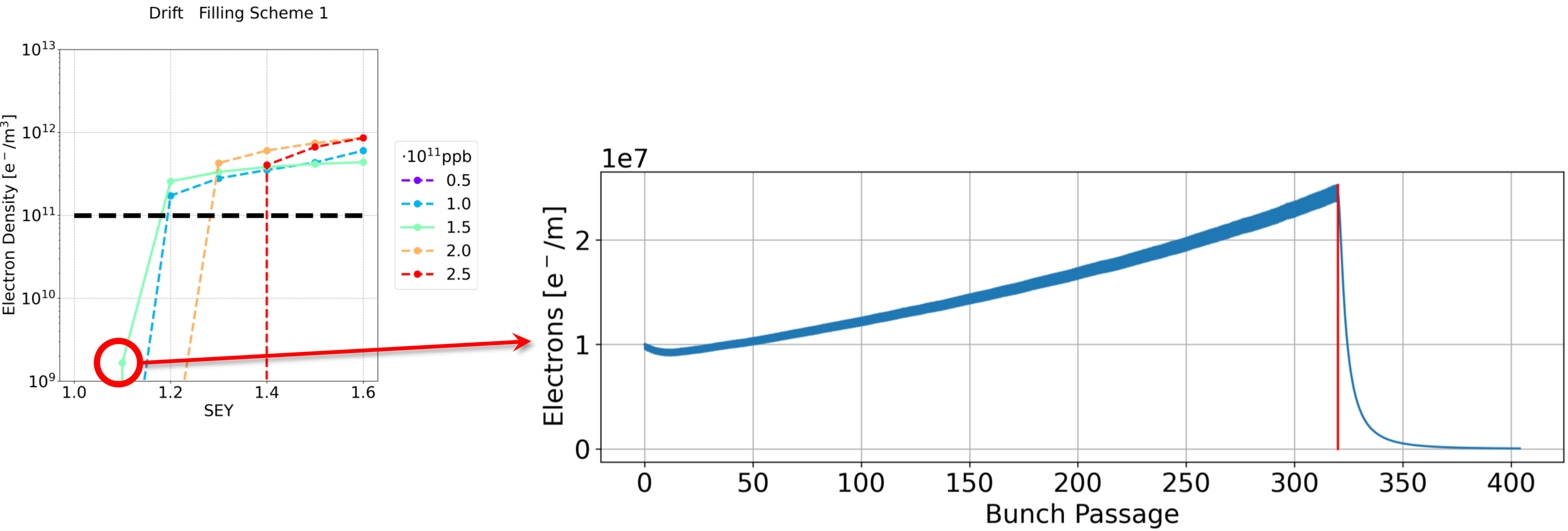
Drift Space



- Above the multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold

E-Cloud Stability

Drift Space

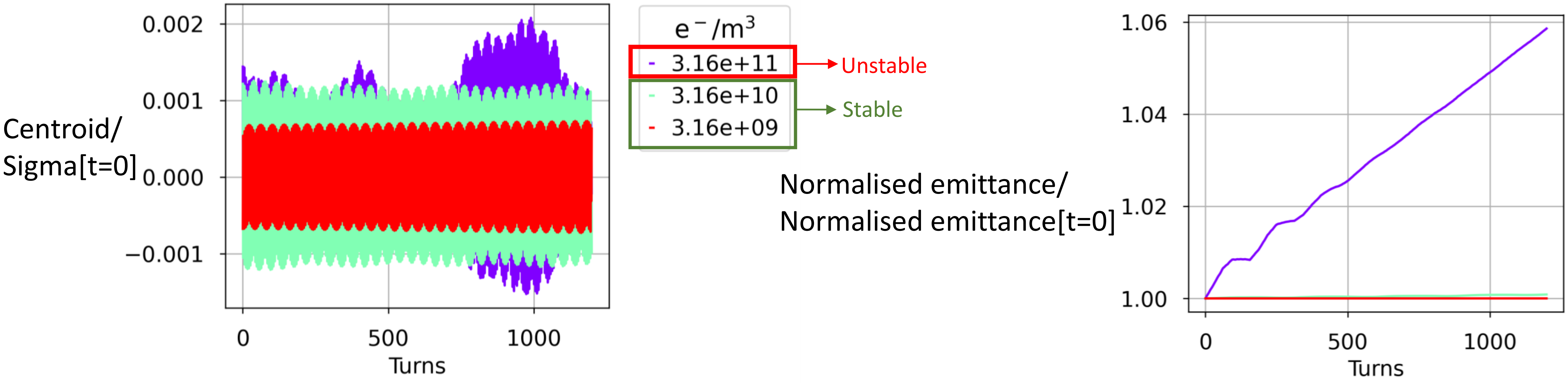


- Some simulations do not reach the multipacting saturation value
- With larger values of the photoemission generation rate, the saturation value can be reached within less bunch passages

E-Cloud Stability Numerical Threshold

Dipole

- $\rho_{e,th} = 2.73 \cdot 10^{10}\ e^-/m^3$ considering only the dipole length L_{dipole} = 62.8 km (L_{dipole}/L = 69.2%)



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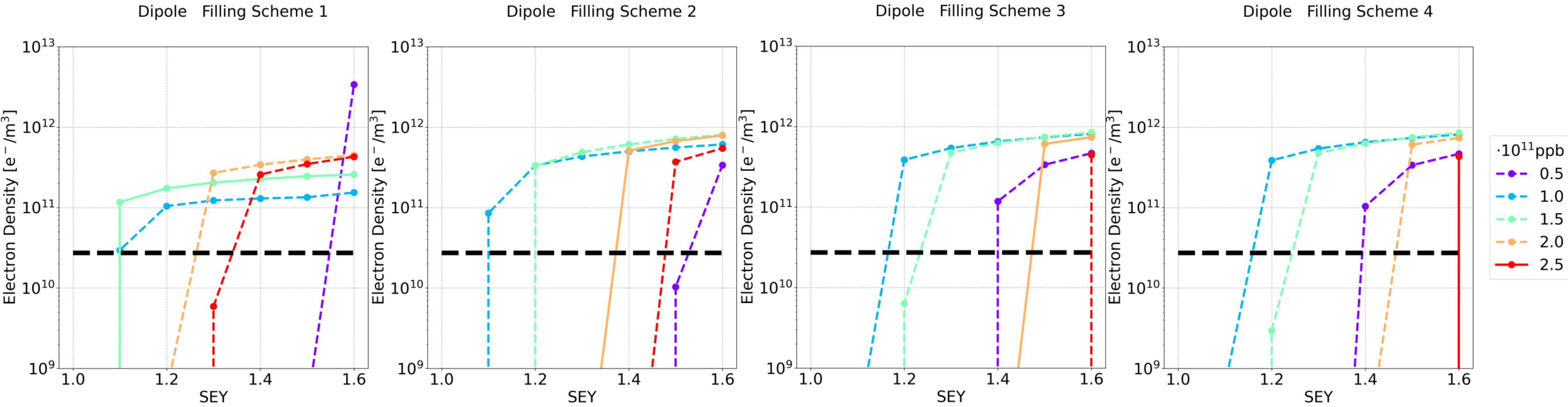
E-Cloud Stability

Dipole



- Above the multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold
- The multipacting has to be avoided

E-Cloud Stability

Sextupoles

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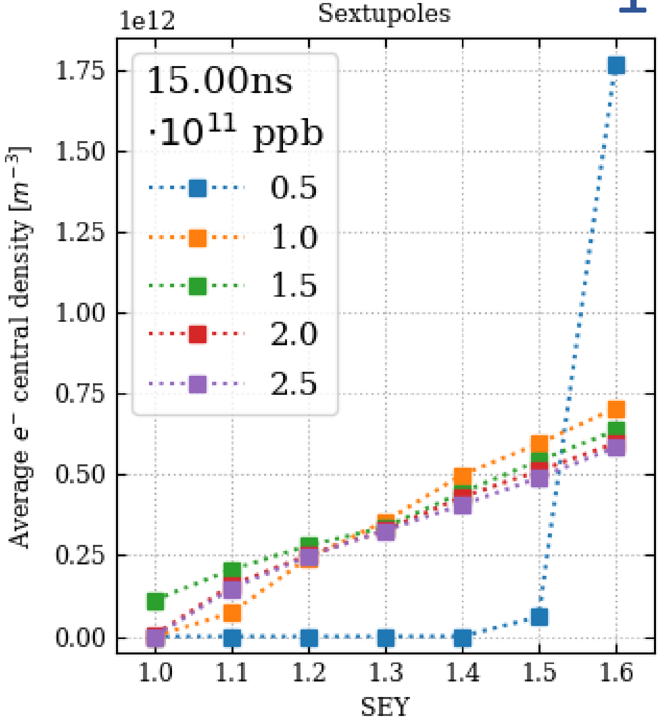

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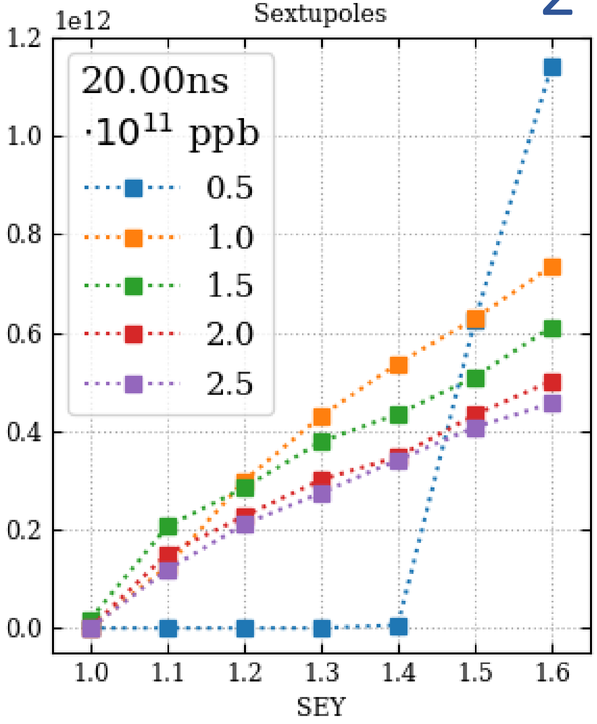

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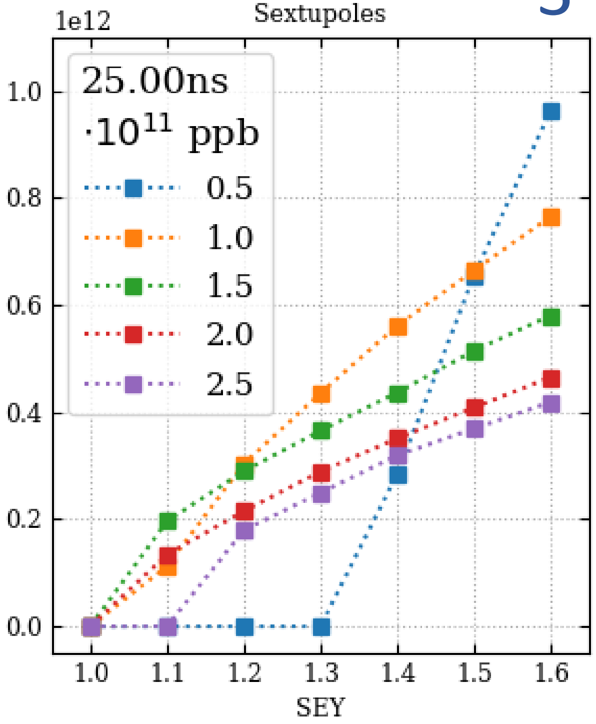

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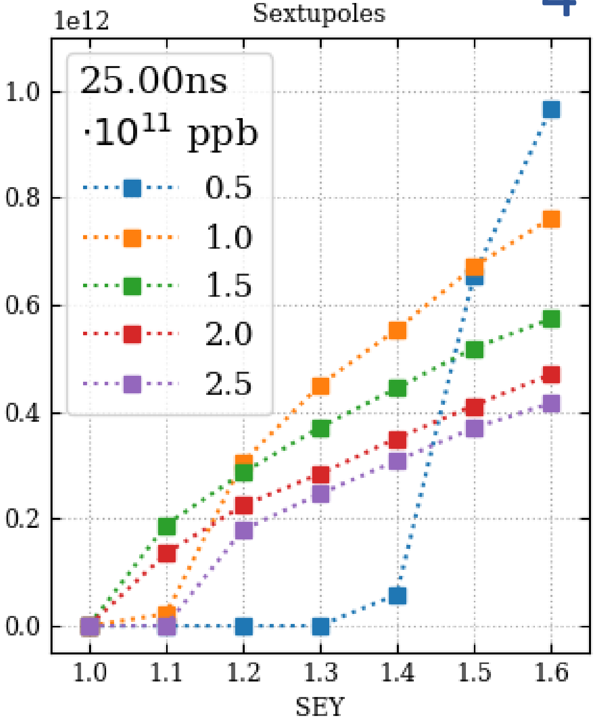

- The central e-cloud density before the bunch passage is smaller than the e-cloud theoretical stability threshold ($1.91 \cdot 10^{12}$ e^-/m^3)

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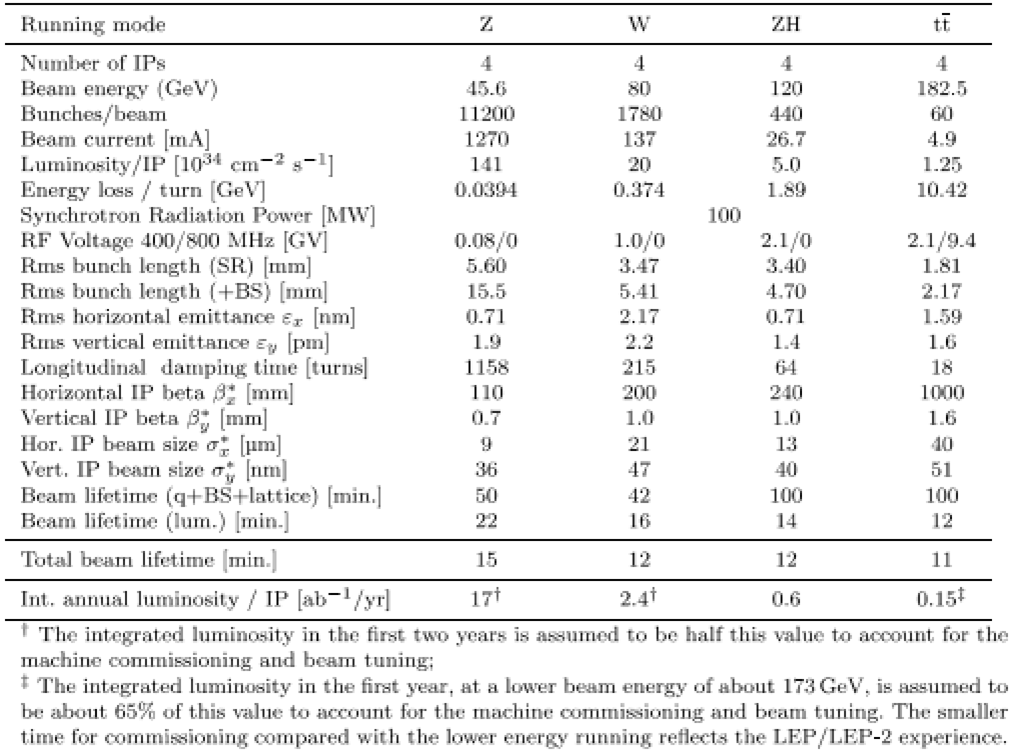
- Heat Loads
- Stability Studies
- **Conclusions and Outlooks**

Conclusions

- A preliminary study to identify the parameters, in the range of the values of FCC-ee case, which play a significant role in the e-cloud formation has been performed
- E-cloud build-up studies
  - with larger bunch spacing the required SEY threshold (to suppress the e-cloud build-up) is higher
  - e-cloud build-up is more severe in quadrupoles
    - multipacting can only be suppressed with SEY < 1.1 (avoiding bunch spacing < 20 ns)
    - Non-Evaporable getter (NEG) coated surface
- Heat loads have been estimated
  - larger bunch spacing -> lower heat loads
  - above multipacting, the total heat loads (drift spaces, dipoles, quadrupoles, sextupoles) is in the order of a few percent of the synchrotron radiation
- Stability studies
  - E-cloud single-bunch stability theoretical and numerical thresholds have been estimated for drift spaces and dipoles
    - same order of magnitude from the preliminary studies per element
    - above the multipacting threshold, the central e-cloud density before the bunch passage is larger than the e-cloud stability threshold: multipacting has to be avoided
  - Sextupoles: the central e-cloud density before the bunch passage is smaller than the e-cloud theoretical stability threshold

Outlooks

- The stability has to be checked for the other magnetic elements: quadrupoles, …
- The impact of the photoemission in the e-cloud formation process has to be assessed
- The latest version of parameters has to be studied from the e-cloud point of view



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‡

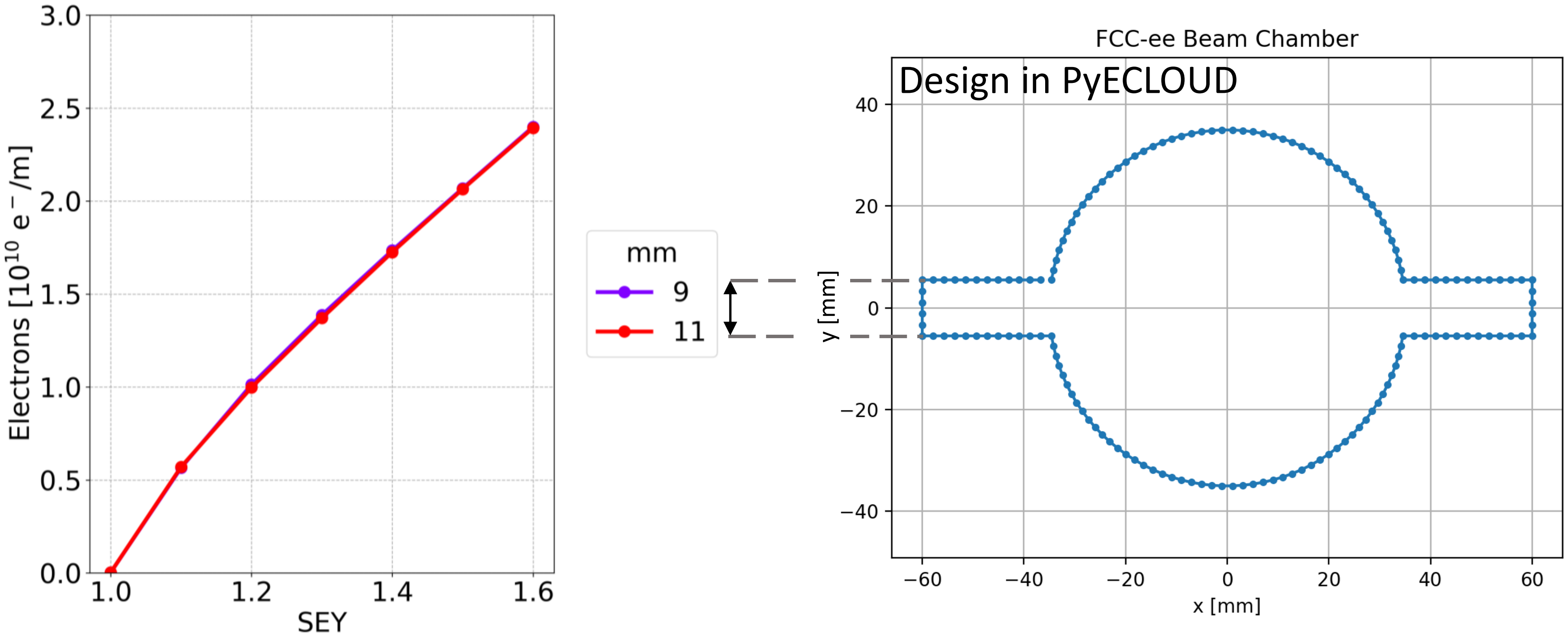
† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;

‡ 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.

Thanks for your attention

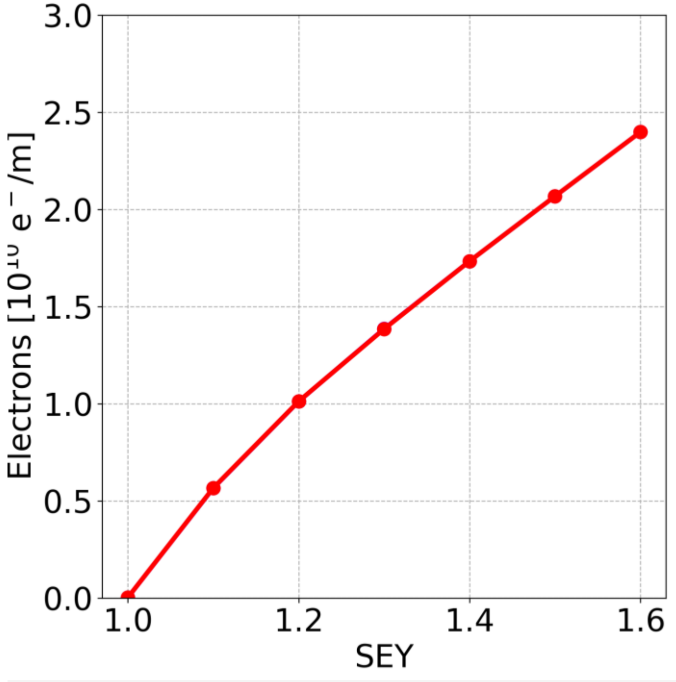
Negligible Contribution

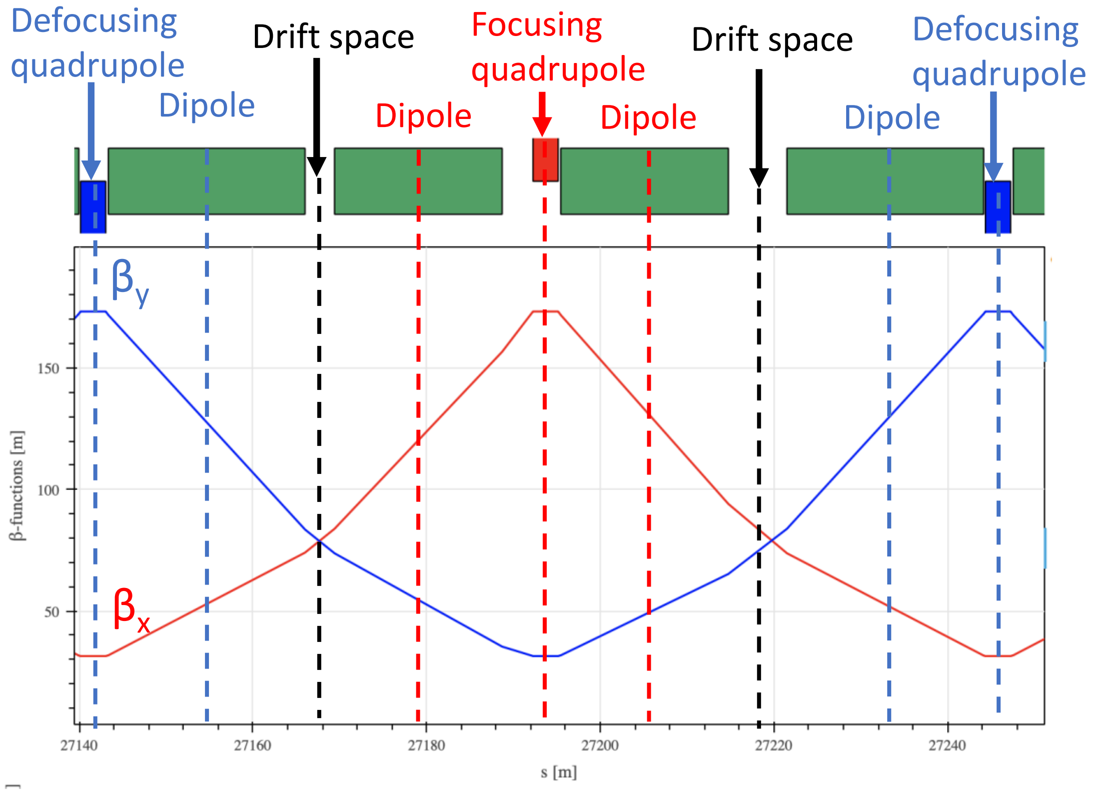
- Some parameters make a negligible contribution to the e-cloud formation process:
    - Beam chamber winglet height

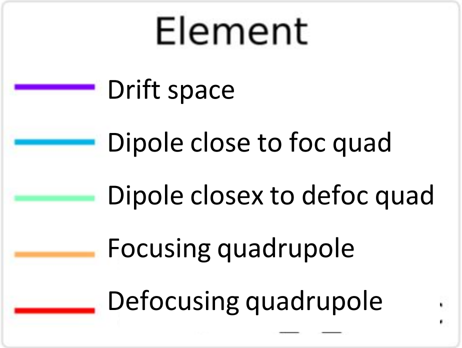


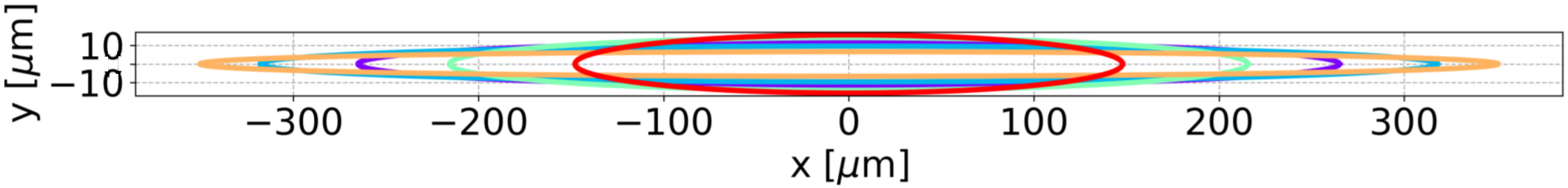
Negligible Contribution

- Some parameters make a negligible contribution to the e-cloud formation process:
  - Beta function







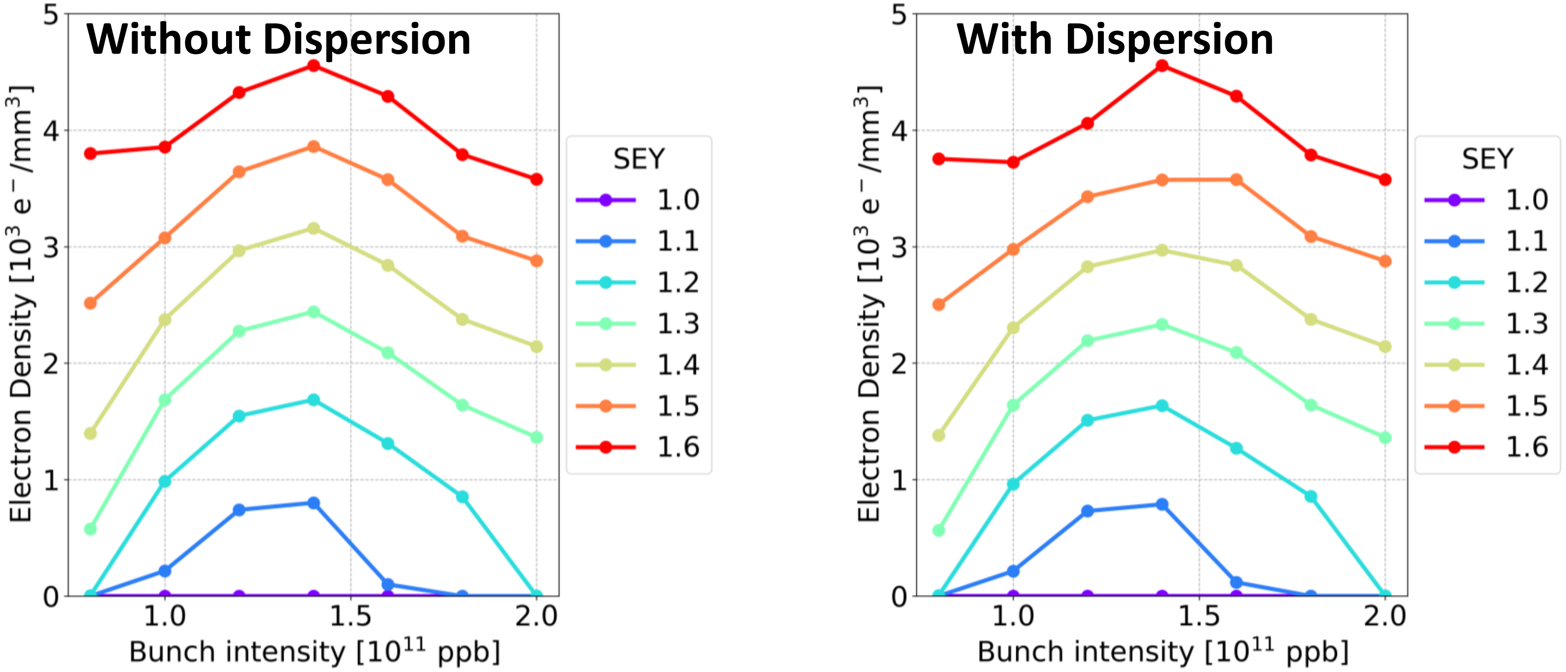


$\varepsilon_{g,x}$ = 0.71 nm

$\varepsilon_{g,y}$ = 1.42 pm

Negligible Contribution

- Some parameters make a negligible contribution to the e-cloud formation process:
  - Dispersion



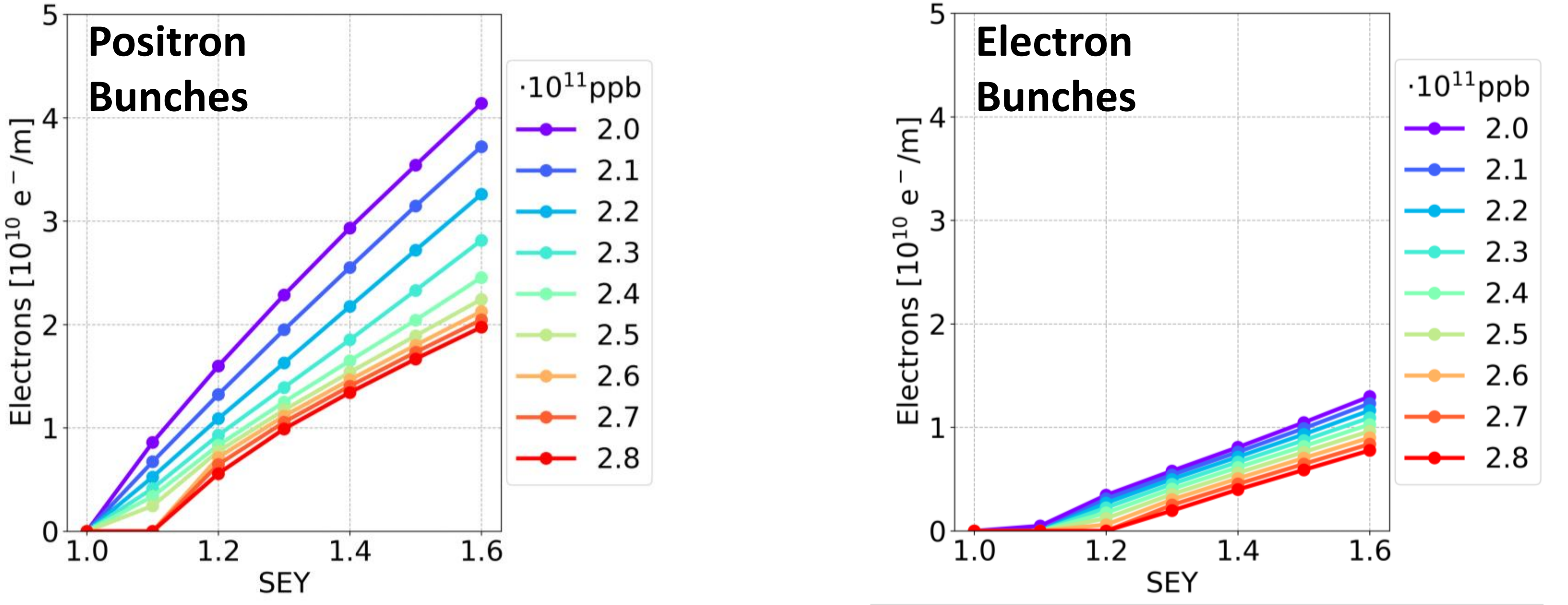
Average in the arcs
D_x = 0.433 m

Consistent results:

introducing the dispersion -> the horizontal dimension becomes larger
variation of the beta-functions -> negligible effect on the e-cloud formation process

Electron Beam

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



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

Arc Element Length

FCC-ee total length: 90.7 km

Arc elements:

- Drift spaces –> 17.4 km (19,2%)
- Dipoles –> 62.8 km (69,2%)
- Quadrupoles –> 4.77 km (5.26%)
- Sextupoles –> 0.900 km (0.992%)

Parameter Overview

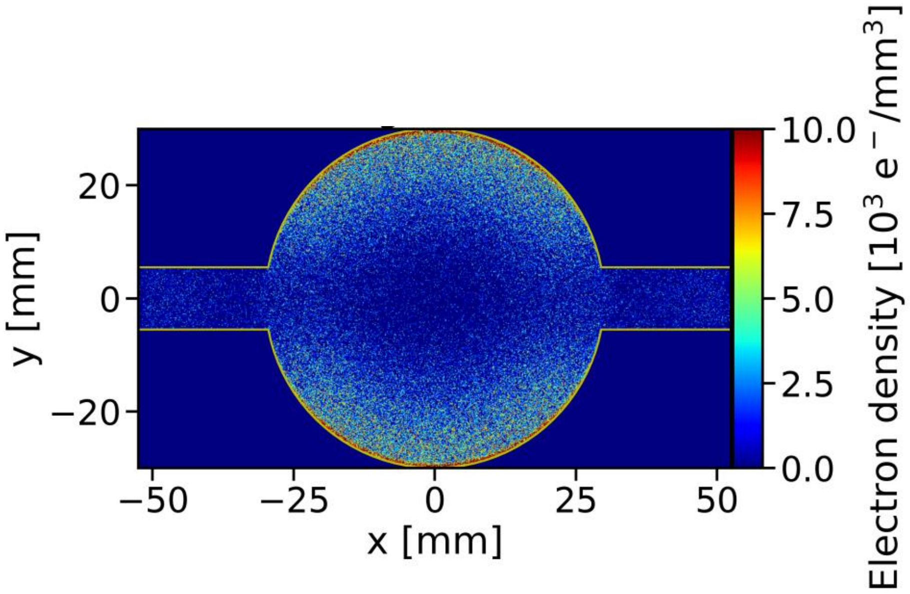
- **Element**:
  - Drift space
  - Quadrupole (5.65 T/m)
    - focusing
    - defocusing
  - Dipole (14.15 mT)
    - close to focusing quadrupole
    - close to defocusing quadrupole

The version V22.2 has been used

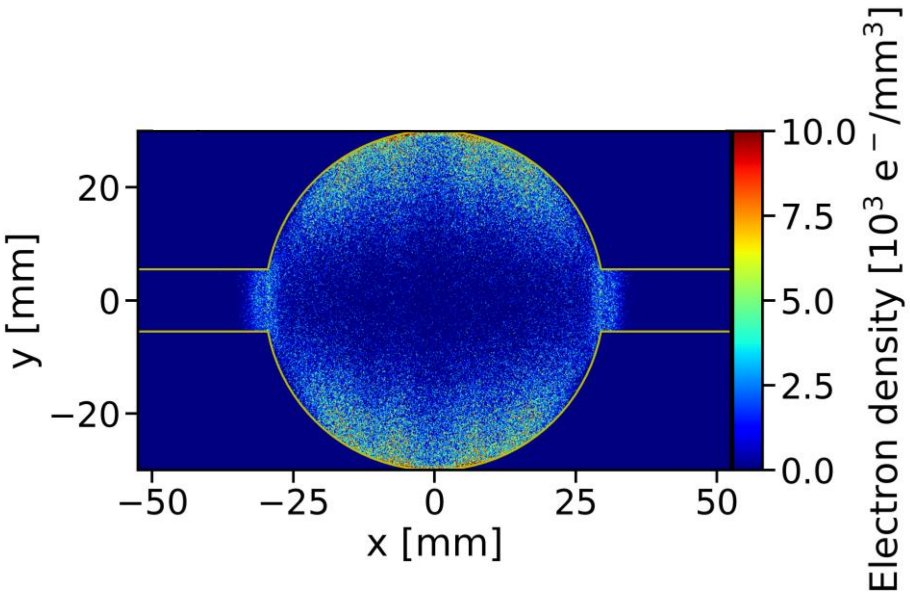
[] https://acc-models.web.cern.ch/acc-models/fcc/fccee/V22.2/z/

E-Cloud Transverse Distribution

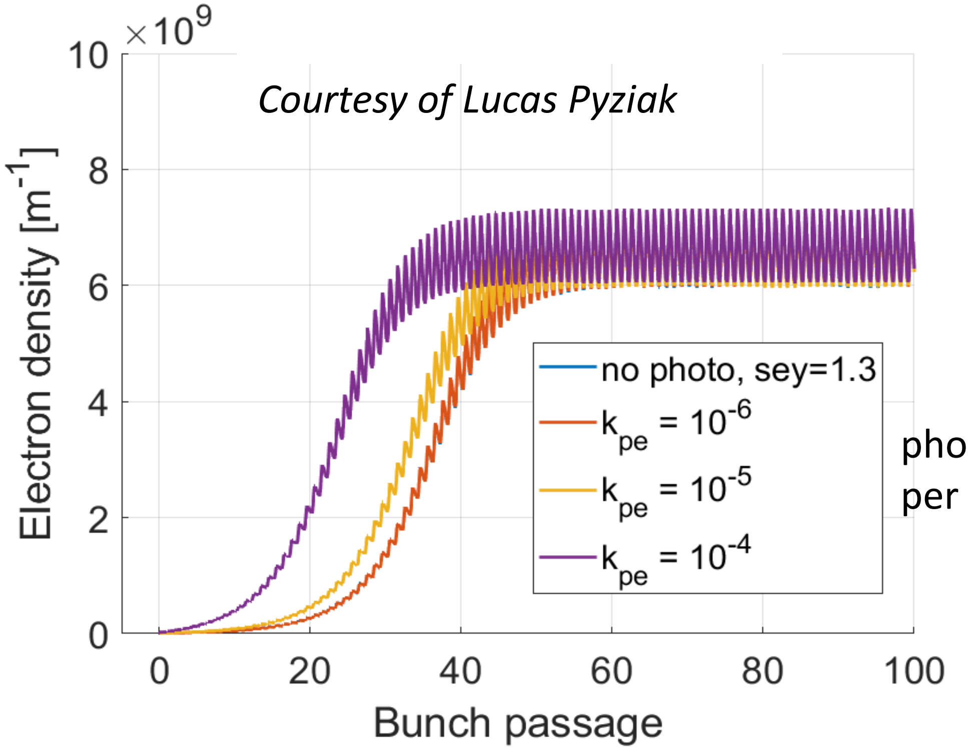
Drift Space



Dipole



Photoemission: Preliminary Results



Courtesy of Lucas Pyziak

photoelectrons generated
per proton per unit of length [m^{-1}]

E-Cloud Stability Theoretical Threshold

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

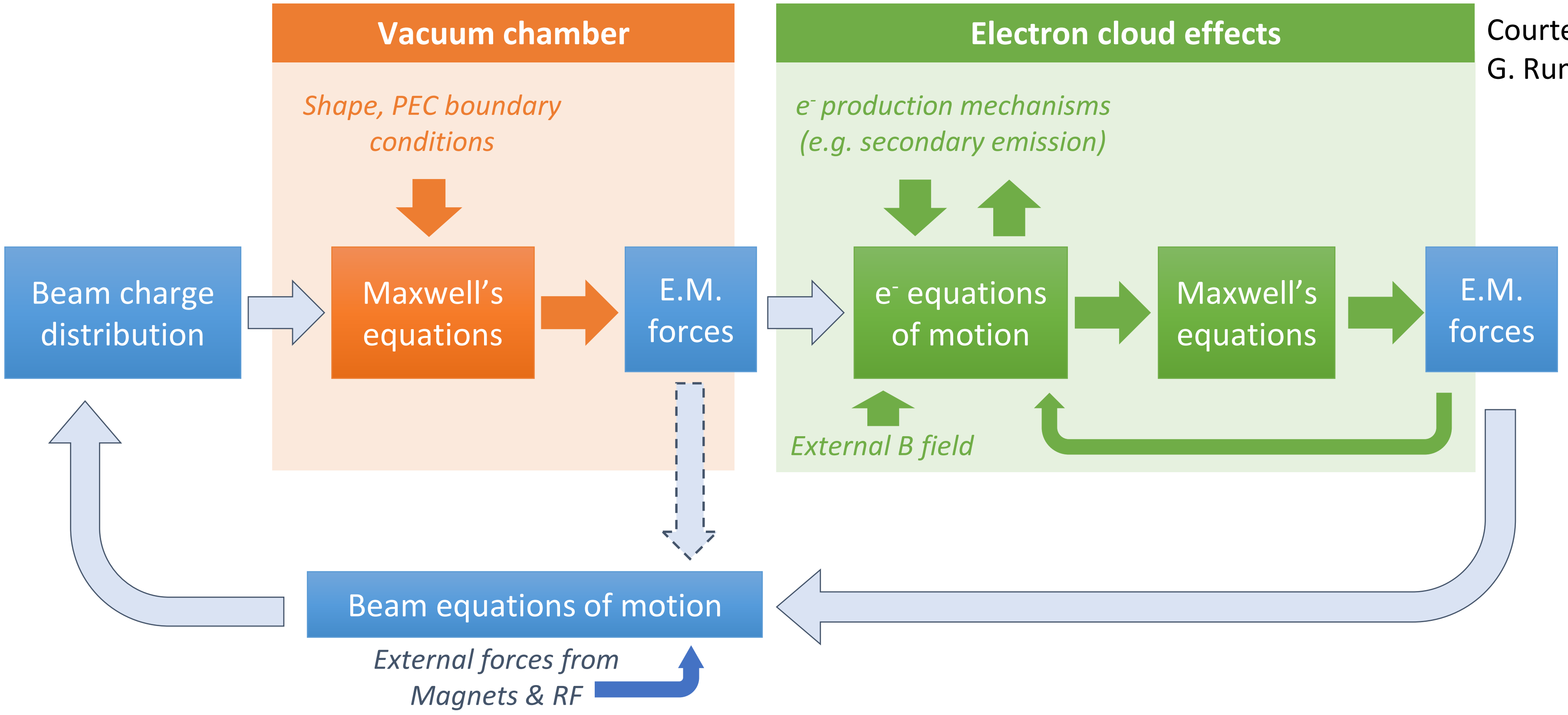
From K. Ohmi et al., "Study of Electron Cloud Instabilities in FCC-hh", Proc. of IPAC2015

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

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

Stability Simulations

- A complex problem involving two sets of particles mutually interacting



Vacuum chamber

Shape, PEC boundary conditions

Electron cloud effects

e^- production mechanisms (e.g. secondary emission)

Beam charge distribution

Maxwell's equations

E.M. forces

e^- equations of motion

Maxwell's equations

E.M. forces

External B field

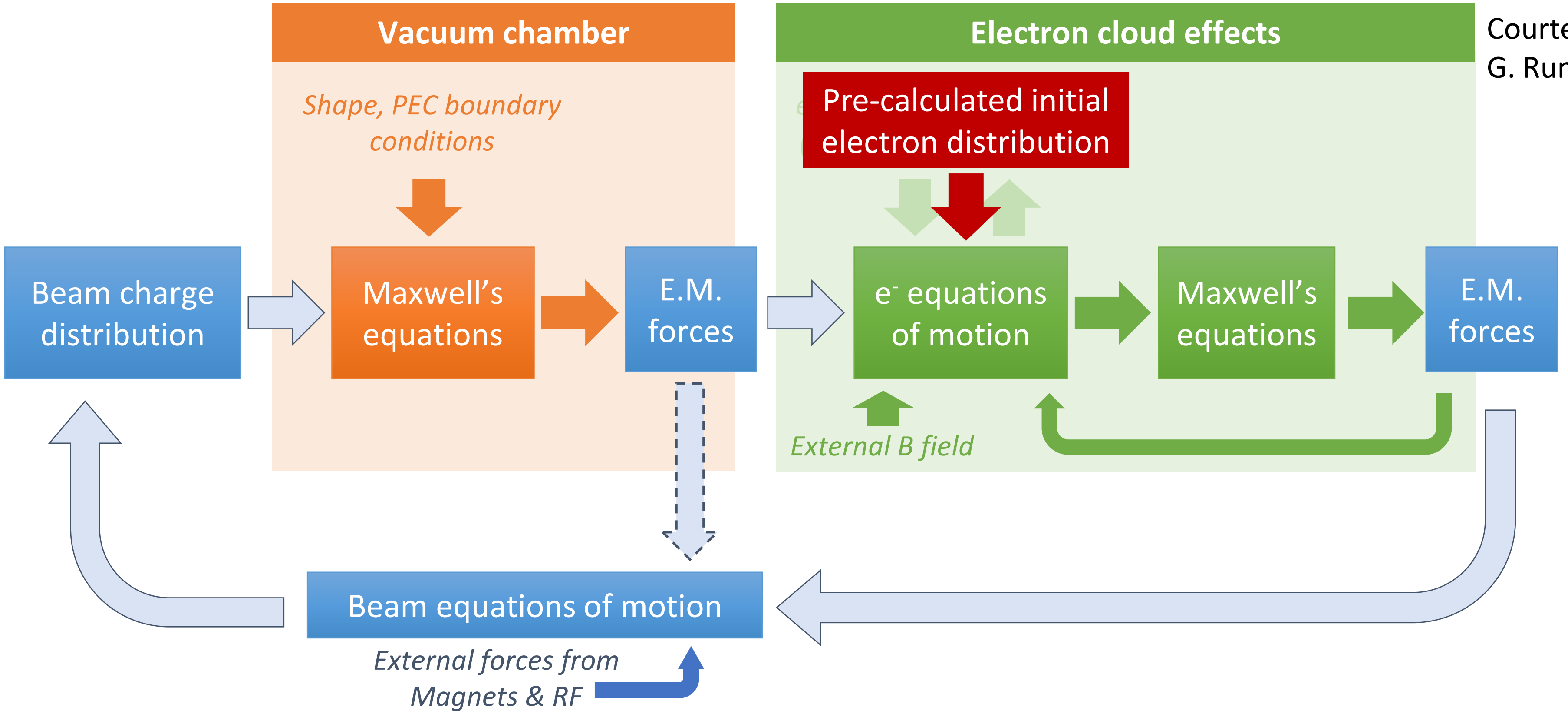
Beam equations of motion

External forces from Magnets & RF

Courtesy of G. Rumolo

Stability Simulations

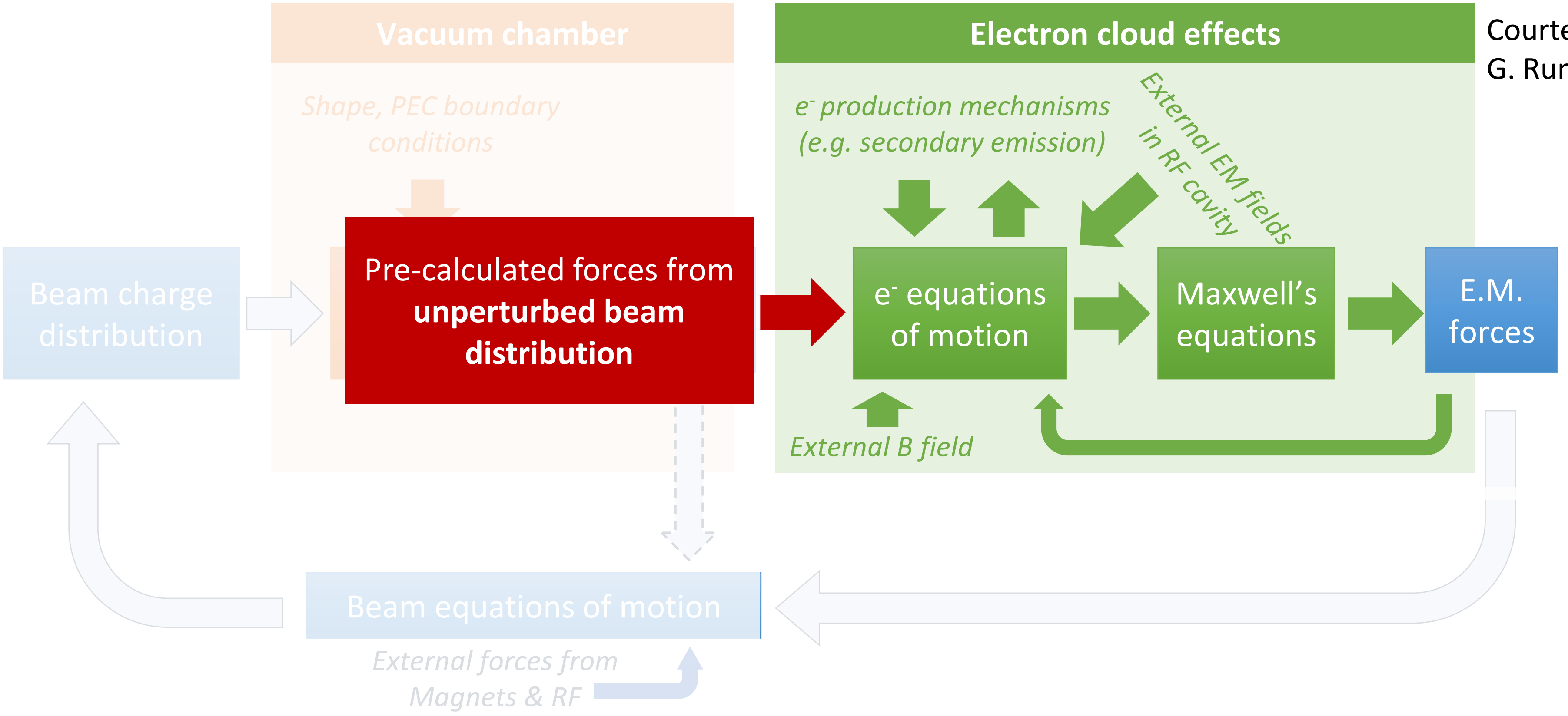
- Beam dynamics simulations → Model the interaction of the beam (typically a single bunch) with a given initial electron distribution



Courtesy of G. Rumolo

Stability Simulations

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



Courtesy of
G. Rumolo