FCC Stability

Long term coherent stability for the Future Circular Colliders: E-Cloud

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Outline

- Introduction
- Design and Parameter Inputs for FCC Mid-Term Report
- Stability
- Conclusions and Outlooks

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- **Introduction**
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Motivation

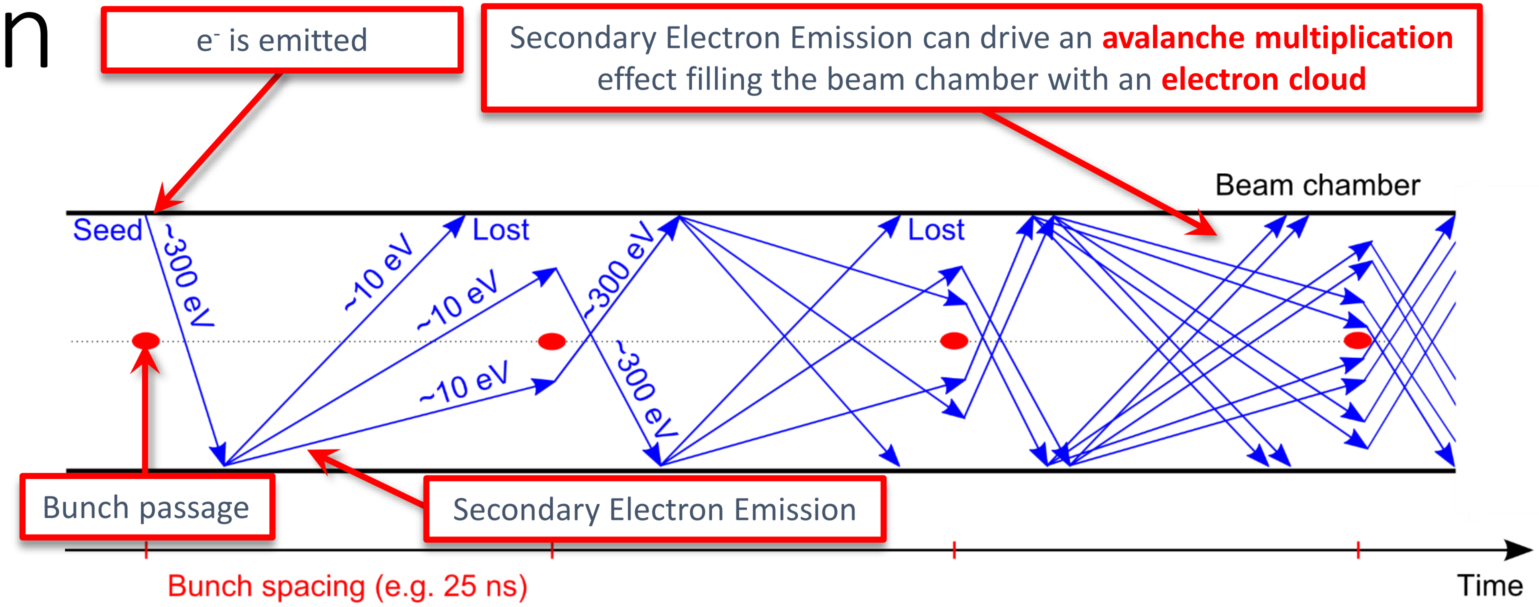
- Electron cloud (e-cloud) effects have been observed in several accelerators all over the world (LHC, KEKB, DAϕNE, …)
  - much more commonly in those operated with positively charged particles

- 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

- 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



Courtesy of G. Iadarola

- 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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FUTURE CIRCULAR COLLIDER

Important Parameters for E-Cloud Formation

- Design stage of FCC-ee
- 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)

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	40
bunch intensity [10^{11}]	2.43	2.91	2.04	2.37

FCC week 2022, "Accelerator overview", Frank Zimmermann, Tor Raubenheimer

Parameters for E-Cloud Formation

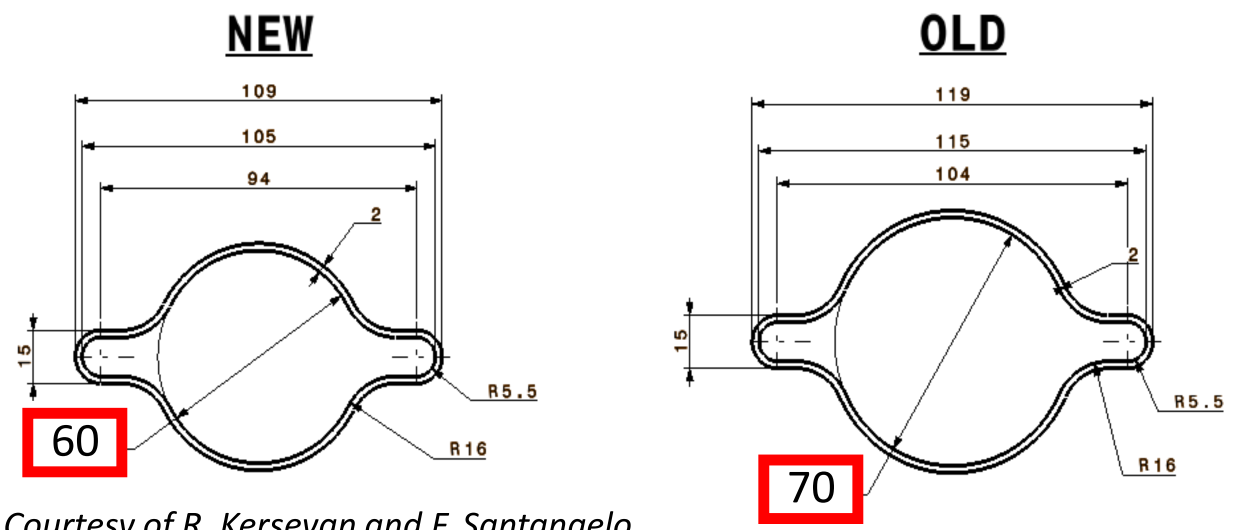
- After an extensive simulation study campaign in the range of FCC-ee parameters the main results are the following:

- Some parameters play a significant role in the e-cloud formation process:
  - Bunch spacing
  - 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
  - Bunch length

New Parameters

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



Courtesy of R. Kersevan and F. Santangelo

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

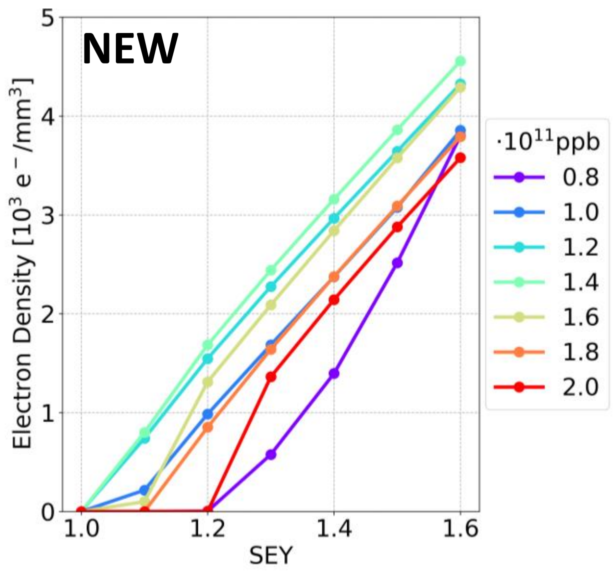
Beam energy	[GeV]	45.6	
Version		Mar. 11	Feb. 07
Layout		PA31-3.0	
# of IPs		4	
Circumference	[km]	90.658816	
Bending radius of arc dipole	[km]	9.936	
Energy loss / turn	[GeV]	0.0394	
SR power / beam	[MW]	50	
Beam current	[mA]	1270	
Colliding bunches / beam		16000	9200
Colliding bunch population	$[10^{11}]$	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 ξ_x/ξ_y [a]		0.0036 / 0.110	0.0023 / 0.139
Luminosity / IP	$[10^{34}/\text{cm}^2\text{s}]$	140	186
Lifetime (q + BS + lattice)	[sec]	10000–1500	20
Lifetime (lum) [b]	[sec]	1340	1010

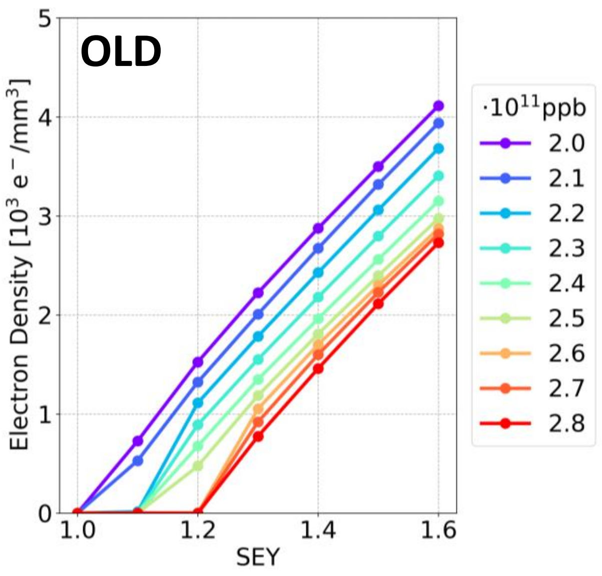
[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

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

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

Comparison: New vs Old Parameters



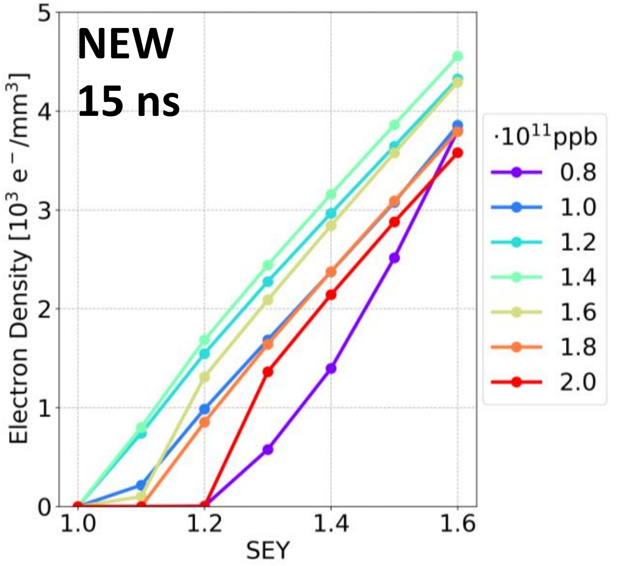


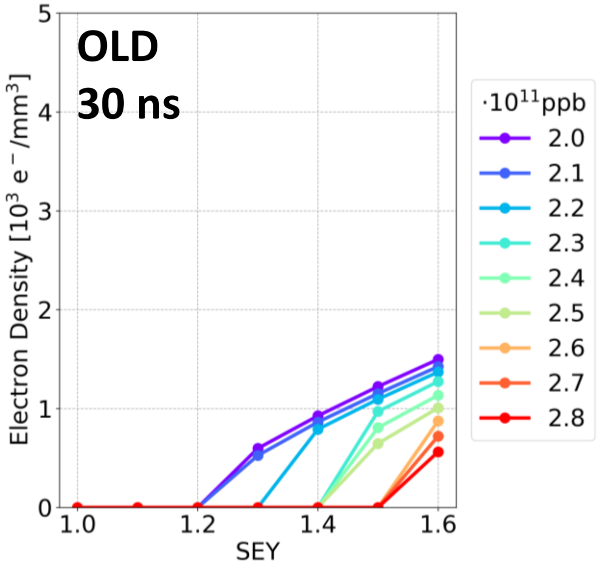
- For a fixed bunch spacing there is not a large difference in the range of multipacting threshold nor in the e-cloud density for the considered intensity range

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

Comparison: New vs Old Parameters

- 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 new configuration and the old configuration 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

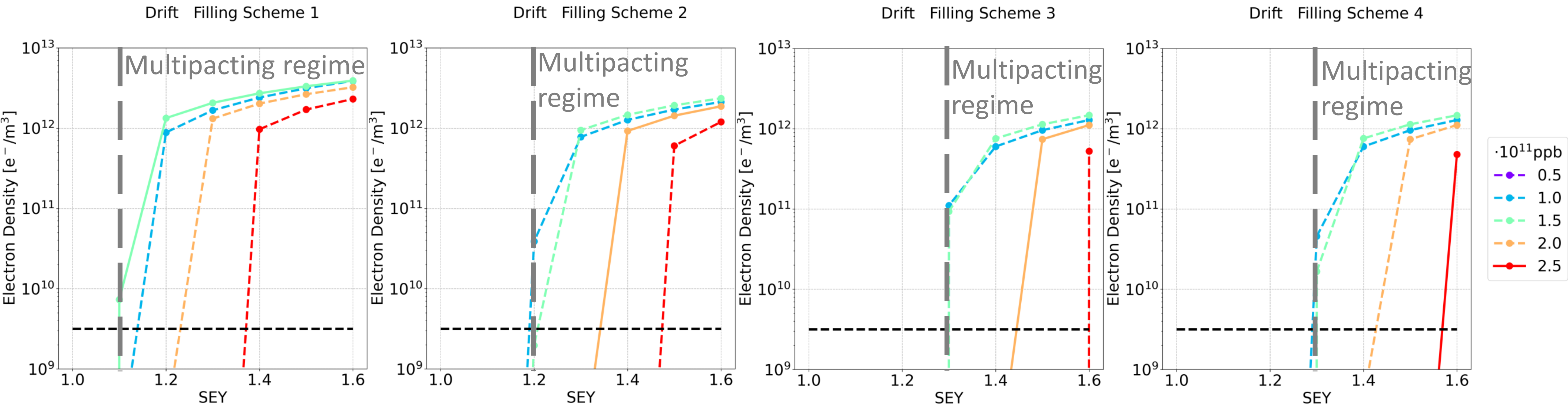
Filling schemes (with constant total number of particles per beam)

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
- Considering the nominal bunch intensity the filling scheme 4 is preferable

Simulation Results: Summary

- Filling scheme 4 is preferable
  - 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
- Input for the FCC mid-term report

Heat Loads

- The total heat loads due to the e-cloud are in order of a small percentage of the synchrotron radiation (considering high values SEY)

    for drift spaces, dipoles, quadrupoles

    considering the max simulated SEY 1.6 and for the nominal bunch intensity

    - Filling scheme 1: ~3.3 MW (~7% of synchrotron radiation)
    - Filling scheme 2: ~3.3 MW (~7% of synchrotron radiation)
    - Filling scheme 3: ~2.4 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:

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

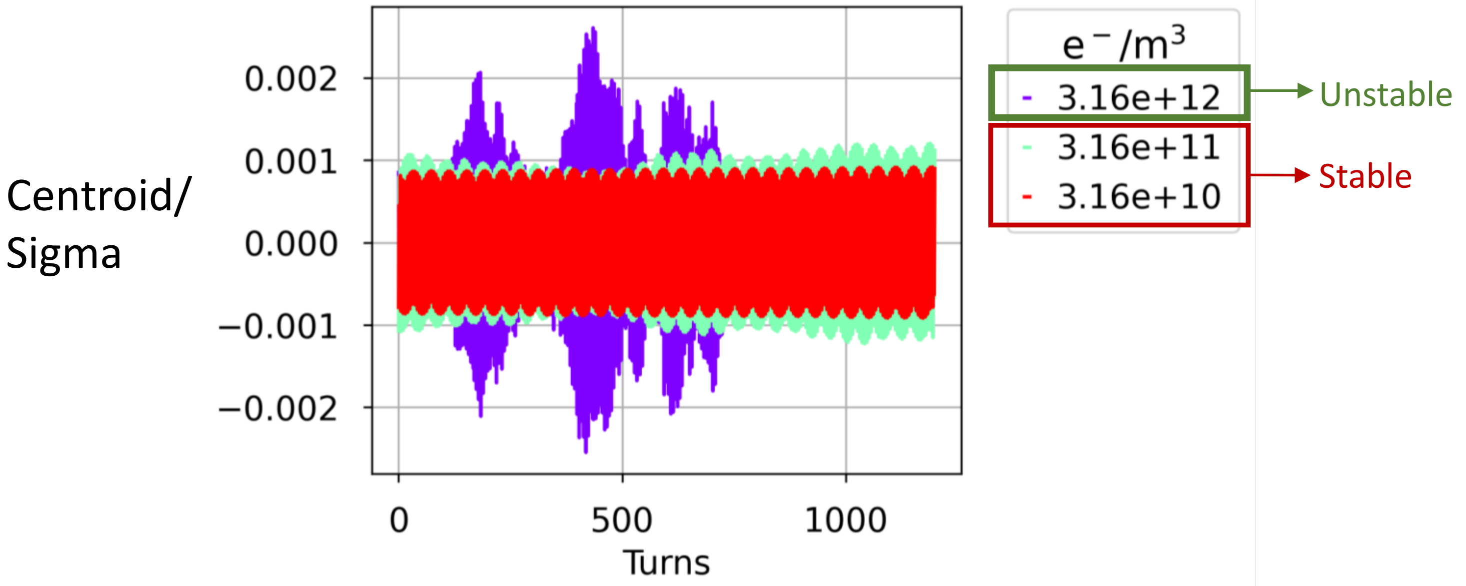
From K. Ohmi et al., "Study of Electron Cloud Instabilities in FCC-hh", Proc. of IPAC2015

2. Simulations by means of PyECLOUD-PyHEADTAIL suite in order to track the beams through the e-cloud
   - 1,200 turns have been simulated (damping time)

E-Cloud Stability Numerical Threshold

Drift Space

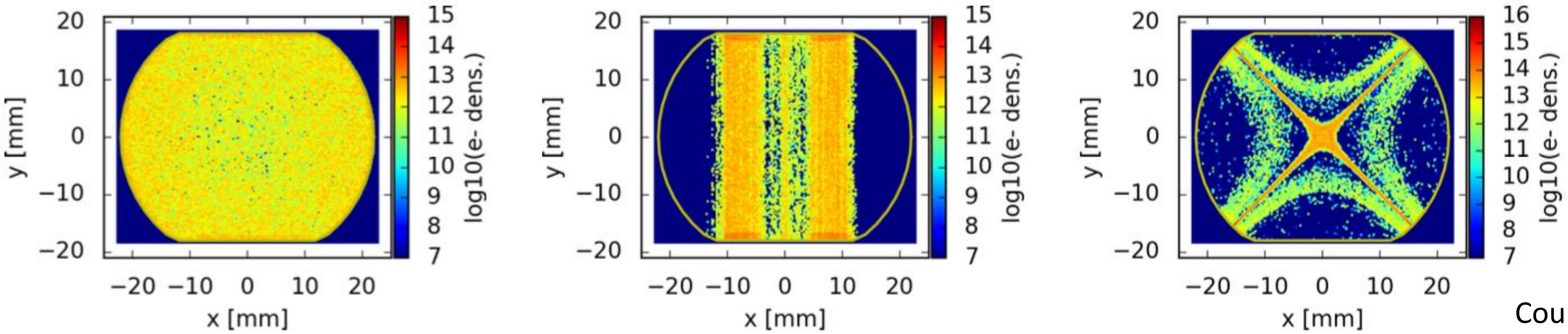
- $\rho_{e,th} = 9.85 \cdot 10^{10}\ e^-/m^3$ considering only the drift length L_{drift} = 17.4 km (L_{drift}/L = 19.2%)



- Theoretical and numerical e-cloud density stability threshold same order of magnitude
- Theoretical threshold more conservative

E-Cloud Stability

E-cloud distribution in the LHC arc magnets



Courtesy of
P. Dijkstal

- In drift space, all the electrons are free to move
- In magnetic elements, electron trajectories are strongly influenced by externally applied magnetic fields (electrons spin around the field lines)
  - Dipole:
    - the electrons are trapped in two vertical strips
    - only the electrons in the area between the two strips are close to the bunch and free to move
  - Quadrupole:
    - the electrons are trapped in an area with a shape of a cross passing through the vacuum chamber centre
    - the real e-cloud map has to be simulated

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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
    - bunch spacing, externally applied magnetic field, bunch intensity
    - negligible contribution: beam chamber winglet height, beta function in the arcs, dispersion, bunch length
- FCC mid-term report inputs
    - e-cloud build-up more severe in quadrupoles
        - can only be suppressed with SEY < 1.1 (avoiding bunch spacing < 20 ns)
        - Non-Evaporable getter (NEG) coated surface
    - heat loads have been estimated
        - in order of a small percentage of the synchrotron radiation (considering high values SEY)
- E-cloud single-bunch stability theoretical and numerical thresholds have been estimated for drift spaces and dipoles
    - from the preliminary studies per elements, the numerical and theoretical thresholds have the same order of magnitude

List of Presentations

- Presentation at EPFL-LPAP Activity Meeting 2023/10/05
  https://indico.cern.ch/event/1321724/
- Presentation at Electron Cloud Studies for FCC-ee 2023/09/12
  https://indico.cern.ch/event/1324913/contributions/5575351/attachments/2713113/4711737/2023_09_12_FCC_ecloud_meeting.pdf
- Presentation at FCC Week 2023 2023/06/06
  https://indico.cern.ch/event/1202105/contributions/5390895/attachments/2659031/4607694/2023_06_06_FCC_week.pdf
- Presentation at ABP-CEI Section Meeting 2022/06/01
  https://indico.cern.ch/event/1281953/contributions/5385854/attachments/2657397/4602982/2023_06_01_CEI_section_meeting.pdf
- Presentation at Electron Cloud Studies for FCC-ee 2023/05/15
  https://indico.cern.ch/event/1287085/contributions/5408619/attachments/2647970/4583936/2023_05_15_FCCee_ecloud_meeting.pdf
- Presentation at FCCIS 2022 workshop 2022/12/07
  https://indico.cern.ch/event/1203316/contributions/5125374/attachments/2562368/4416763/2022_12_07_Sabato_Luca_FCCIS_2022_Workshop.pptx
- Presentation at 159th FCC-ee Optics Design Meeting 2022/11/10
  https://indico.cern.ch/event/1205924/contributions/5080961/attachments/2544998/4382481/2022_11_10_Sabato_Luca_FCC-ee%20Optics_Design_Meeting.pdf
- Presentation at ECLOUD22 workshop 2022/09/25
  https://agenda.infn.it/event/28336/contributions/176811/attachments/97052/133885/2022_09_26_Sabato_Luca_ECLOUD22.pptx
- Presentation at EPFL-LPAP Activity Meeting 2022/09/23
  https://indico.cern.ch/event/1200207/contributions/5046762/attachments/2514699/4323463/2022_09_23_Sabato_Luca_EPFL-LPAP.pdf

List of Publications

- Sabato L, Pieloni T, Mether L, Iadarola G, “Electron Cloud Build-up Studies for FCC-ee”, 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, 2023.

  https://www.ipac23.org/preproc/pdf/WEPA092.pdf

- Mether L, Sabato L, et al., “Electron cloud observations and mitigation for the LHC Run 3”, 14th Int. Particle Accelerator Conf. (IPAC’23), Venice, Italy, 2023.

  https://www.ipac23.org/preproc/pdf/WEPA091.pdf

Thanks for your attention

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Outlooks

- The e-cloud density thresholds have to be compared with the e-cloud density obtained from build-up simulations, considering the e-cloud transverse distribution due to the different magnetic configurations

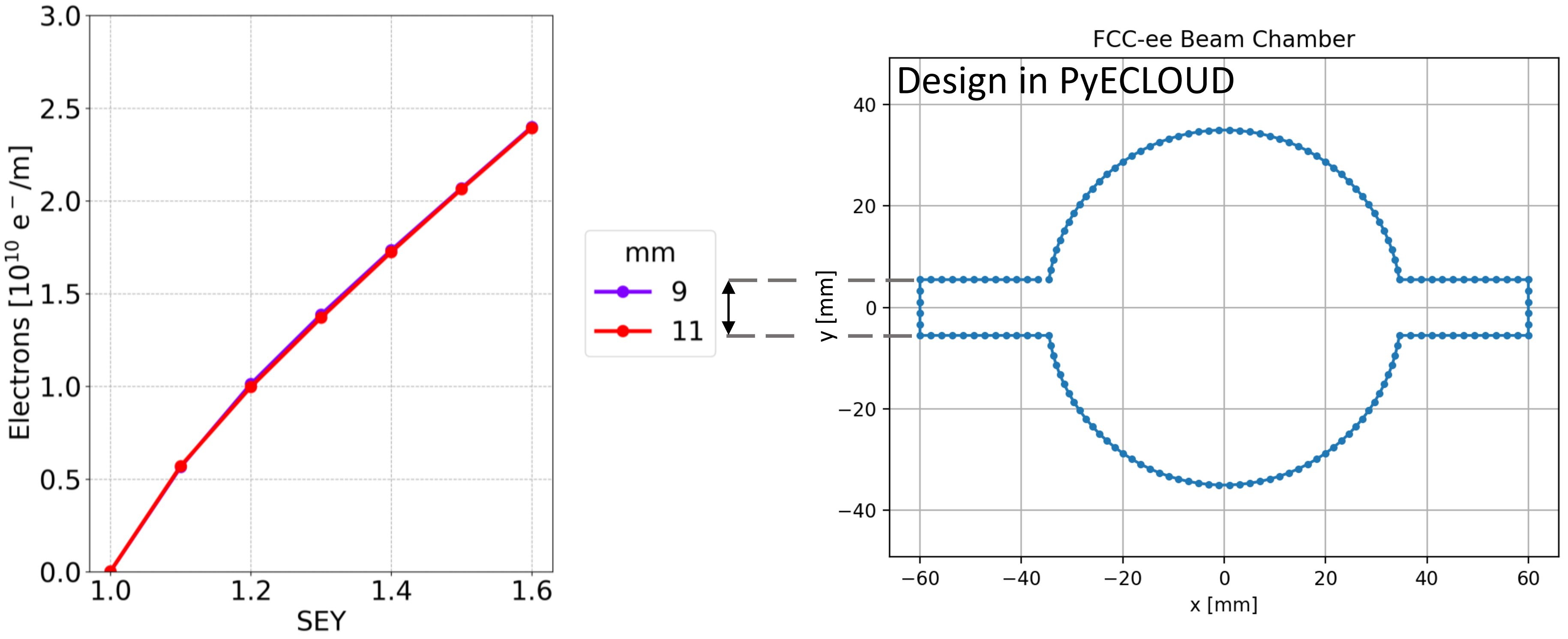
- In the cases where the electrons, which play a significant role for the stability (i.e., electrons close to the vacuum chamber centre) are trapped in the magnetic field lines, stability simulations with realistic e-cloud distributions have to be performed

- The impact of the photoemission in the e-cloud formation process has to be assessed

- For future studies, consider also combined effect of e-cloud, beam-beam, impedance
  - Tools under development

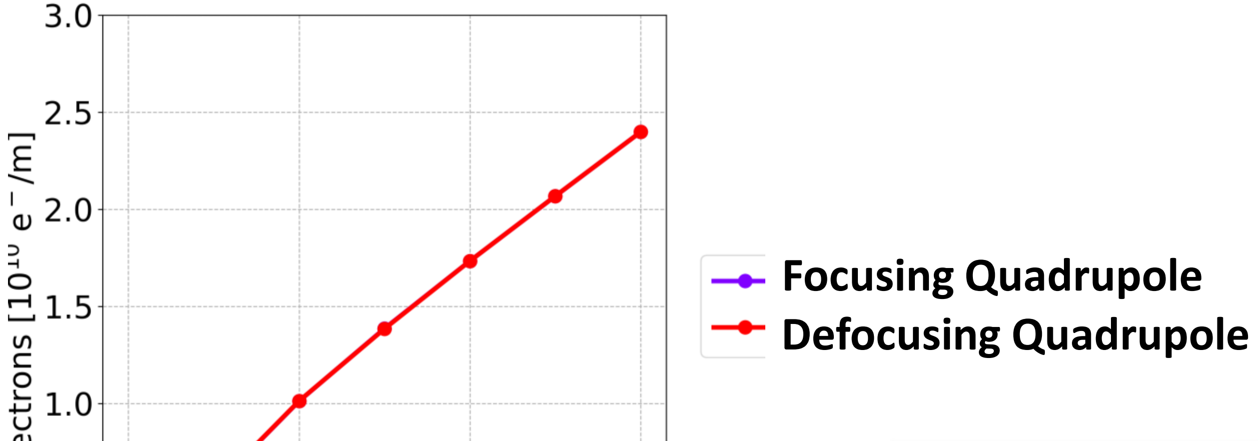
Negligible Contribution

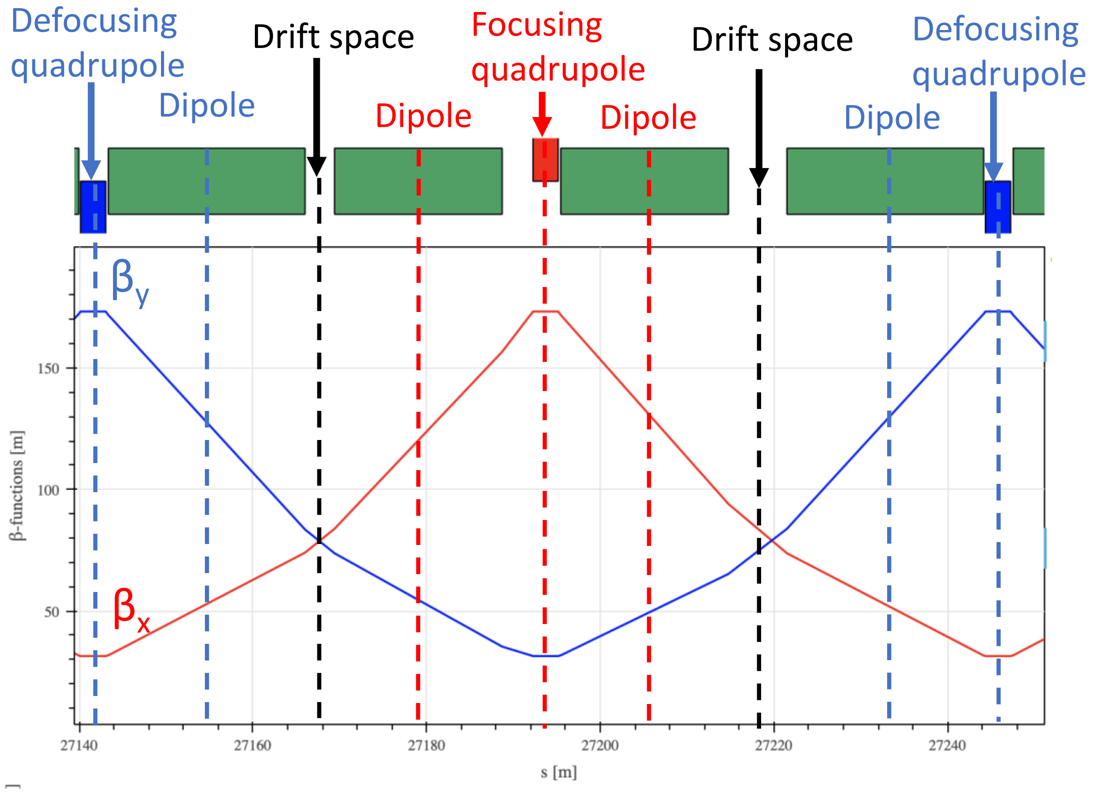
- Some parameters make a negligible contribution to the e-cloud formation process:
  - Beam chamber winglet height

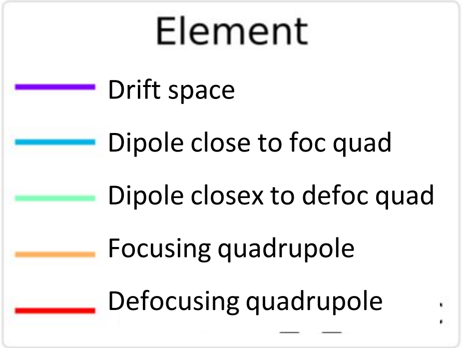


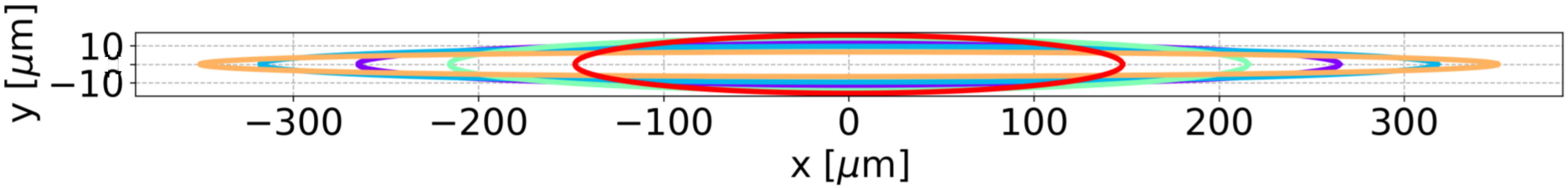
Negligible Contribution

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







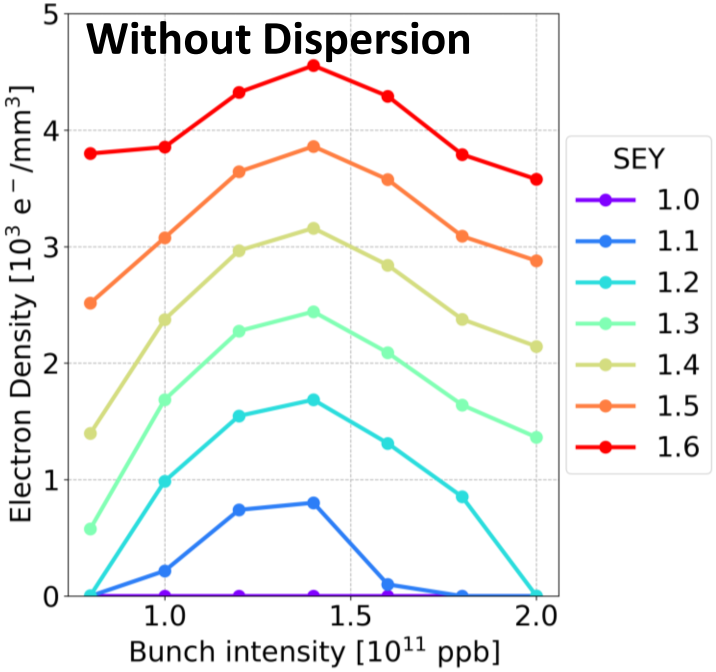


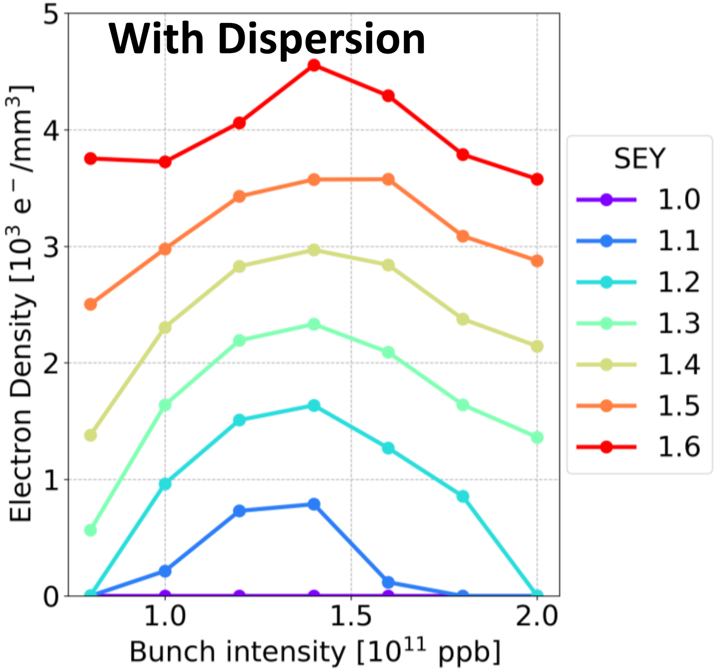
$\varepsilon_{g,x} = 0.71$ nm

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

Negligible Contribution

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





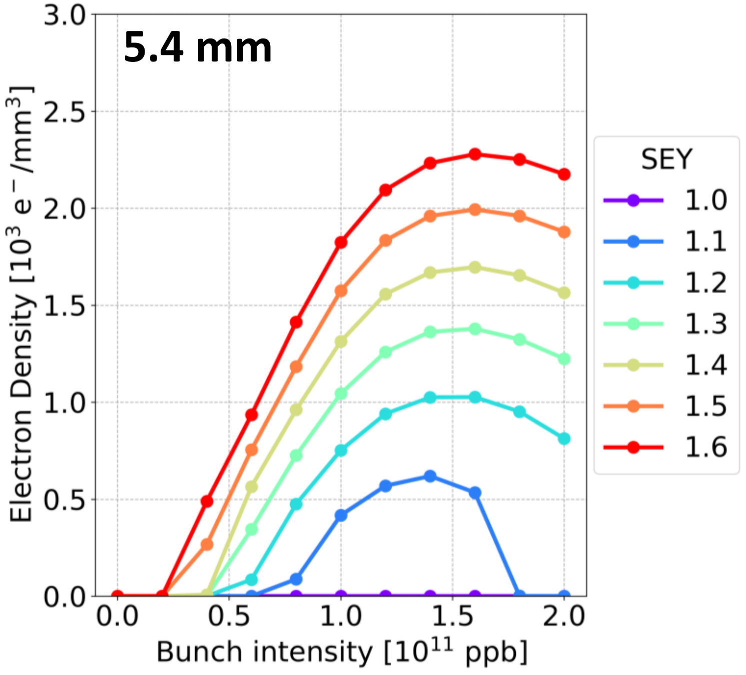
Average in the arcs
$D_x = 0.433$ m

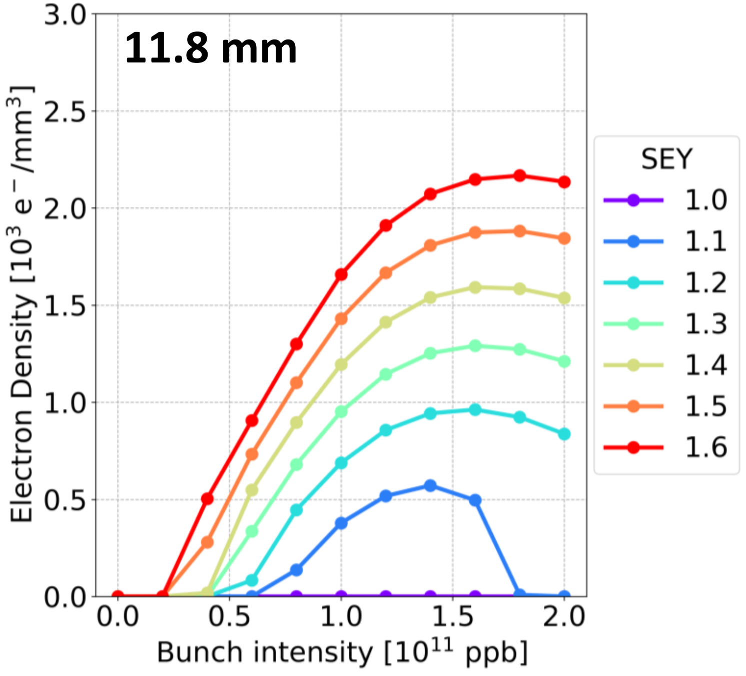
Consistent results:

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

Negligible Contribution

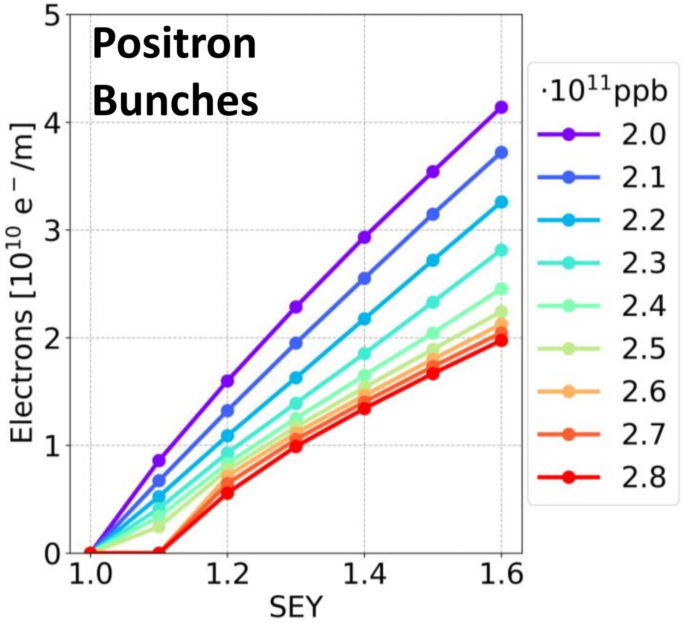
- Some parameters make a negligible contribution to the e-cloud formation process:
  - Bunch length

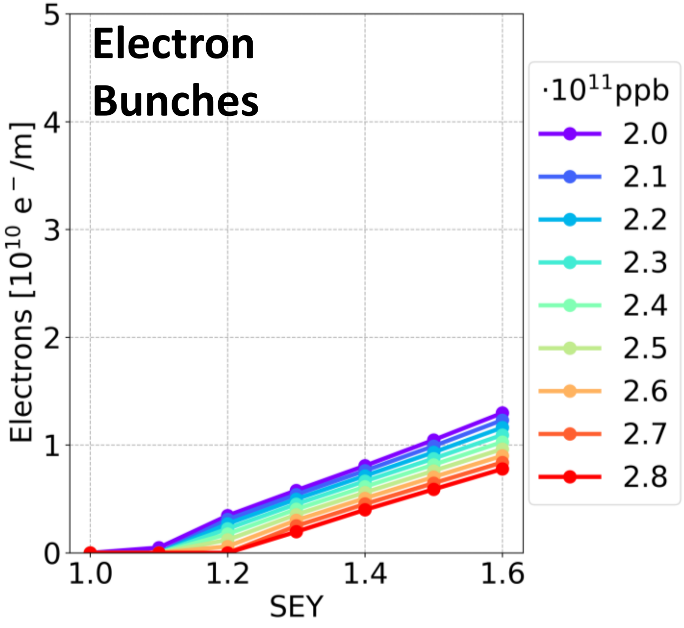




Electron Beam

- 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

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

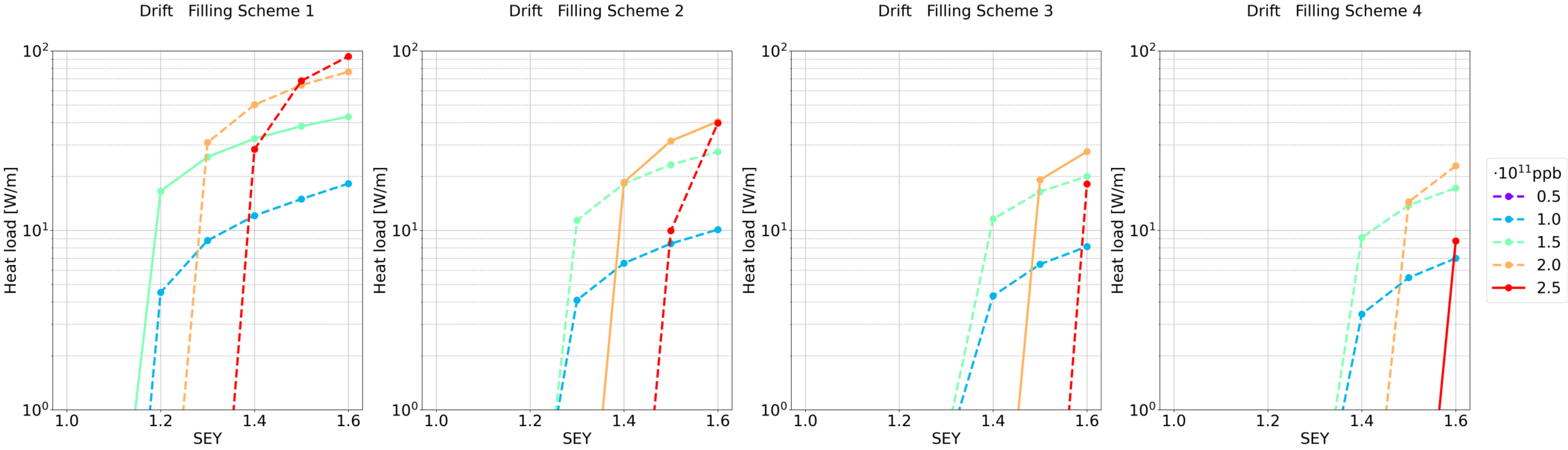
Parameter Overview

- **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/

Heat Loads



- Synchrotron radiation ~50 MW per beam
- For the max simulated SEY and for the nominal bunch intensity (in most of the cases there is multipacting), the total heat loads (for drift spaces, dipoles, quadrupoles) is in the order of:
  - Filling scheme 1: ~3.3 MW (~7% of synchrotron radiation)
  - Filling scheme 2: ~3.3 MW (~7% of synchrotron radiation)
  - Filling scheme 3: ~2.4 MW (~5% of synchrotron radiation)
  - Filling scheme 4: ~0.7 MW (~1% of synchrotron radiation)

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E-Cloud Stability Theoretical Threshold

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

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

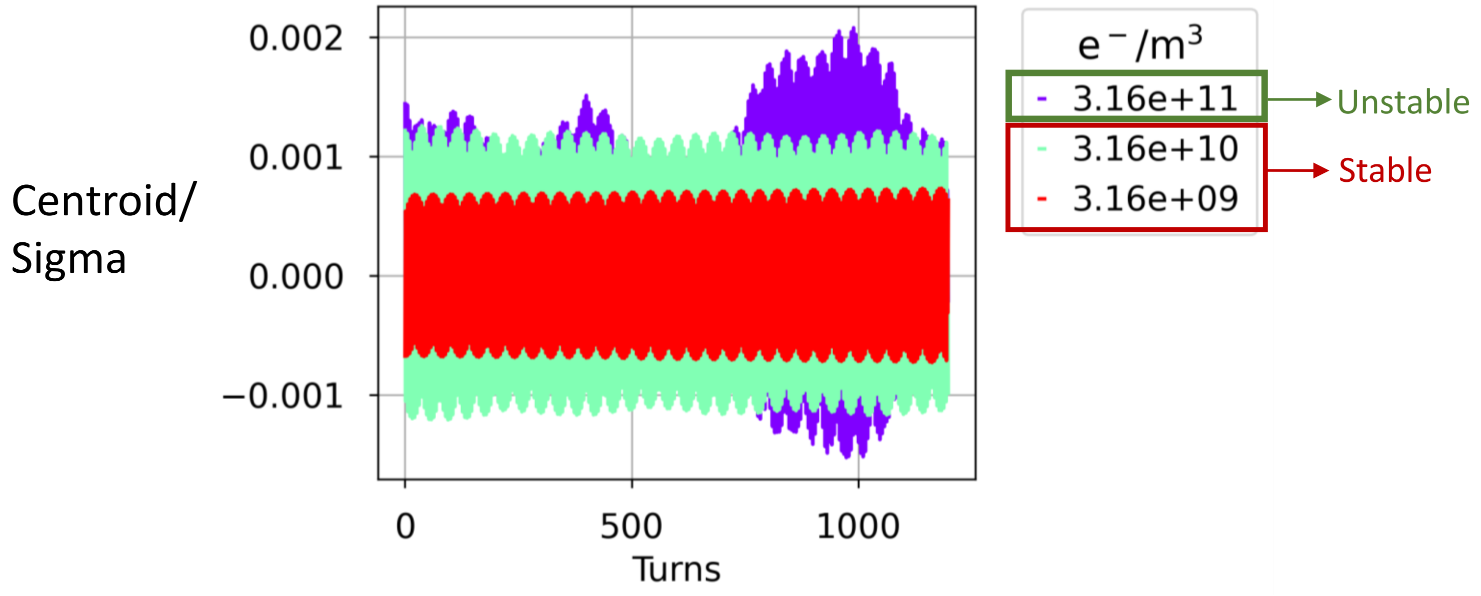
- $\rho_{e,th} = 1.89\cdot10^{10}$ e^-/m^3 considering the full circumference L = 90.7 km

- $\gamma = E/E_0$, 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.

E-Cloud Stability Numerical Threshold

Dipole

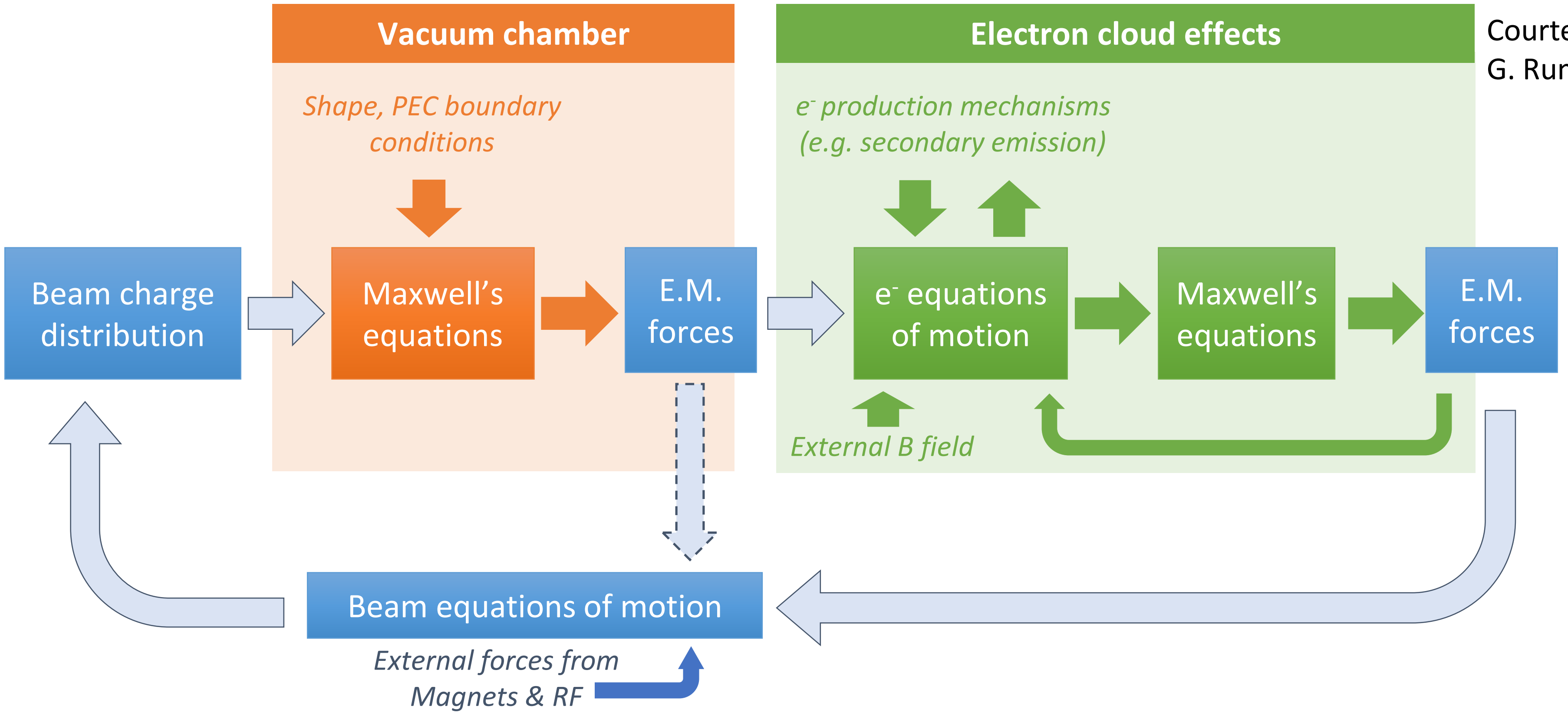
- $\rho_{e,th}$ = 2.73 ·10^{10} e^-/m^3 considering only the dipole length L_{dipole} = 62.8 km (L_{dipole}/L = 69.2%)



- Theoretical and numerical e-cloud density stability threshold same order of magnitude
- More simulations between 3.16·10^{10} and 3.16·10^{12} e^-/m^3

Stability Simulations

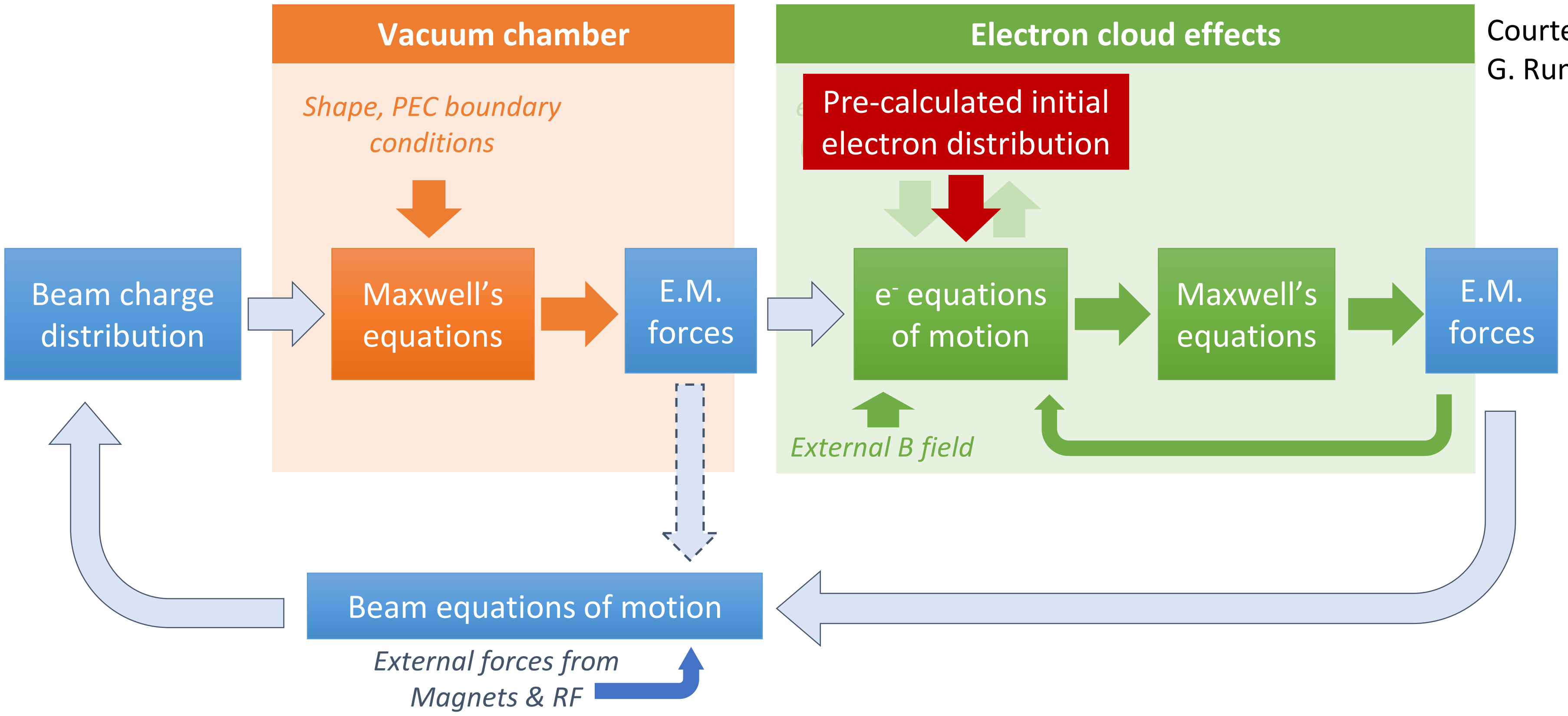
- A complex problem involving two sets of particles mutually interacting



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



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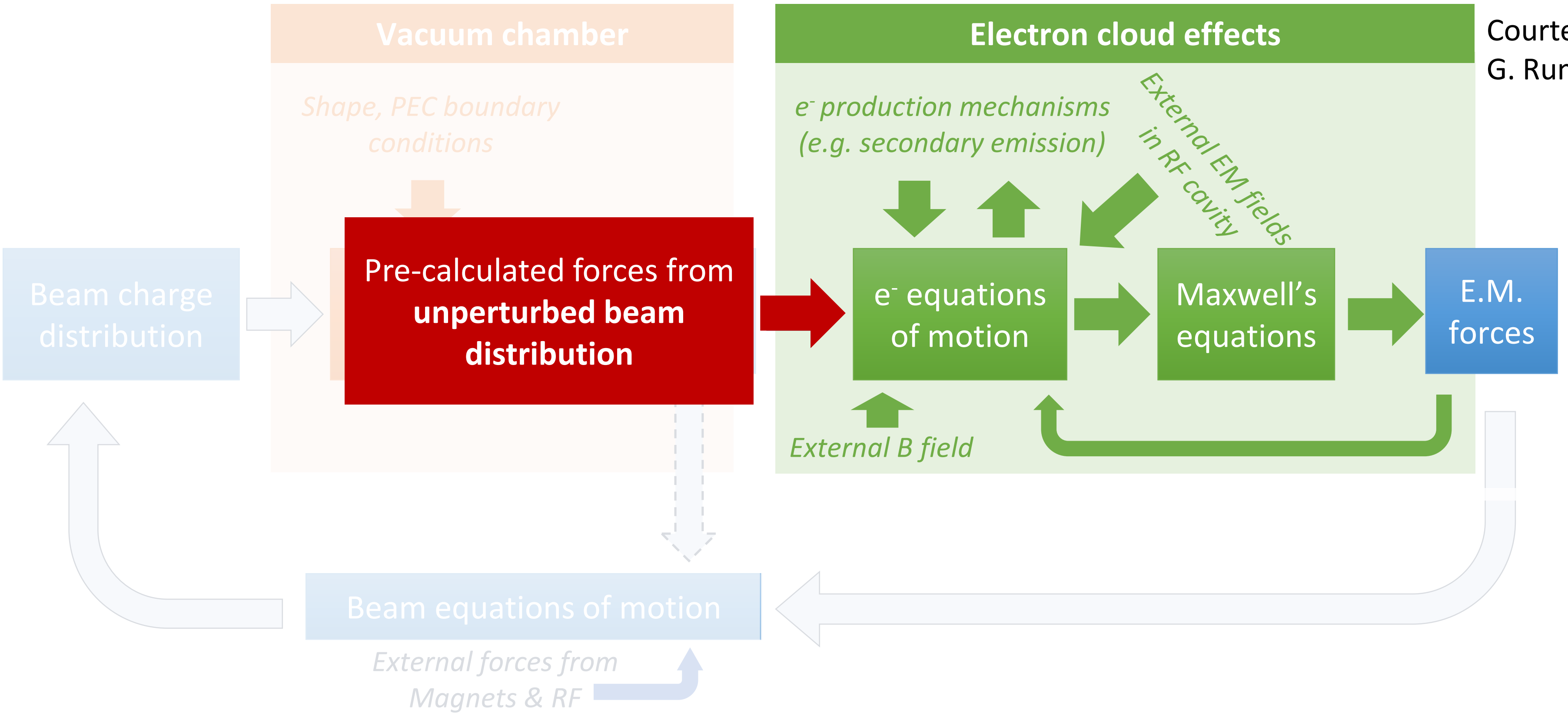
Stability Simulations

- 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



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