Electron cloud studies for FCC-hh and HE-LHC – status and plans

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Outline

- Introduction
  - FCC-hh and HE-LHC parameters

- FCC-hh electron cloud
  - E-cloud build-up and multipacting thresholds
  - Effect of photoelectrons
  - Instability studies
  - Summary & plans

- HE-LHC electron cloud
  - E-cloud in dipoles for chamber options
  - E-cloud build-up and multipacting thresholds
  - Evolution during fill
  - Summary & plans

Parameter overview

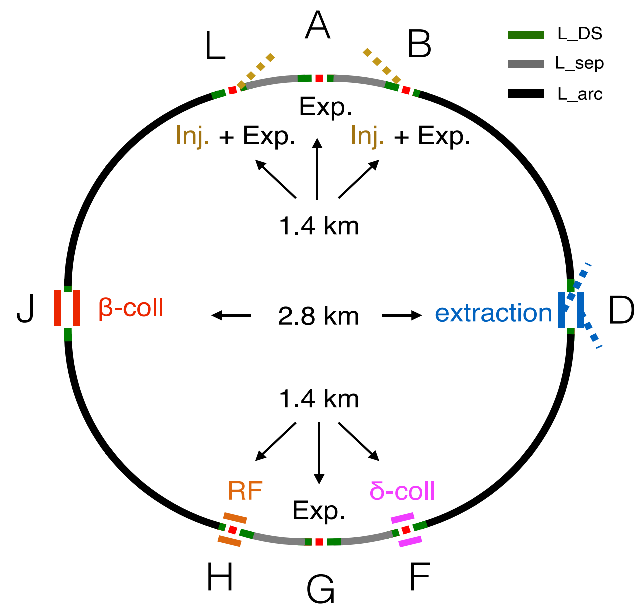
	FCC-hh	HE-LHC	HL-LHC	LHC
Collision energy cms [TeV]	100	27	14	14
Circumference [km]	97.75		27	
Bunch intensity [10^{11}]	1 (0.2)	2.2 (0.44)	2.2	1.15
Bunch spacing [ns]	25 (5)	25 (5)	25	
Norm. emittance [mm]	2.2 (0.4)	2.5 (0.5)	2.5	3.75
Injection energy [TeV]	3.3	1.3	0.45	0.45
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5 - 30	25	5	1
Beta* [m]	1.1 - 0.3	0.25	0.2	0.55
Initial beam lifetime [h]	3	3	15	40
Stored energy/beam [GJ]	8.4	1.3	0.7	0.36
SR power / length [W/m/ap.]	28.4	4.6	0.33	0.17
Long damping time [h]	0.54	1.8	12.9	12.9

FCC-hh

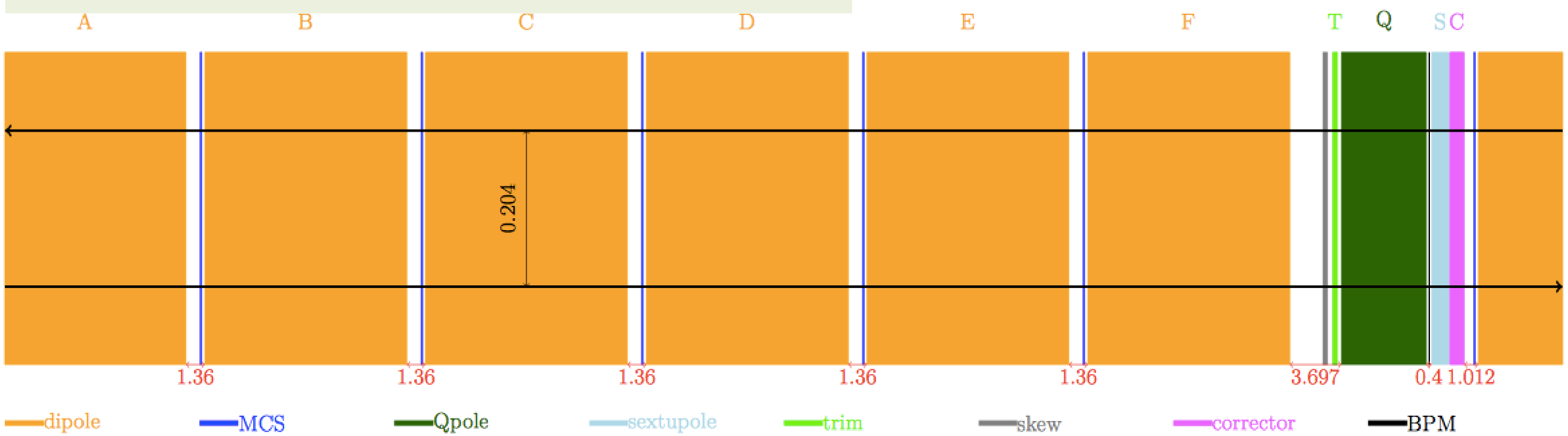
Layout

90° FODO cells, L_{cell} = 211.986 m

- 12 (straight) dipoles of 14.3 m, maximum dipole field: 15.71 T
- 2 quadrupoles of 6.3 m, maximum quadrupole gradient: 381 T/m
- 12 *b*3 correctors (MCS), 2 sextupoles (MS), 2 BPMs, 2 dipole correctors.



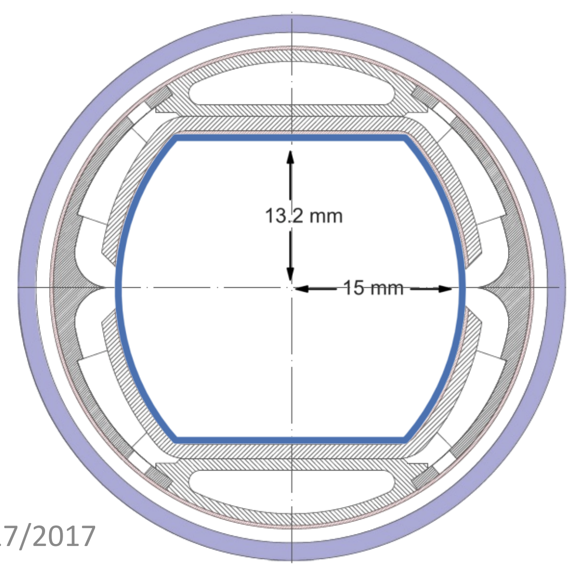
A. Chance, B. Dalena et al.



Simulation overview

Beam parameters			
Bunch spacing [ns]	25	12.5	5
Bunch intensity [p^+]	10×10^{10}	5×10^{10}	2×10^{10}
Norm. emittance [m]	2.2e-6	1.1e-6	0.44e-6
Bunch length [m]	0.08		
Bunch train pattern	(50b +	(100b + 24e)*4	(250b + 60e)*4

Main chamber of FCC beam screen (2015 version), with Cu surface



Arc elements			
	Dipole	Quad	Drift
Field	16 T	444 T/m	-
Length [m]	171.6	12.6	26.6

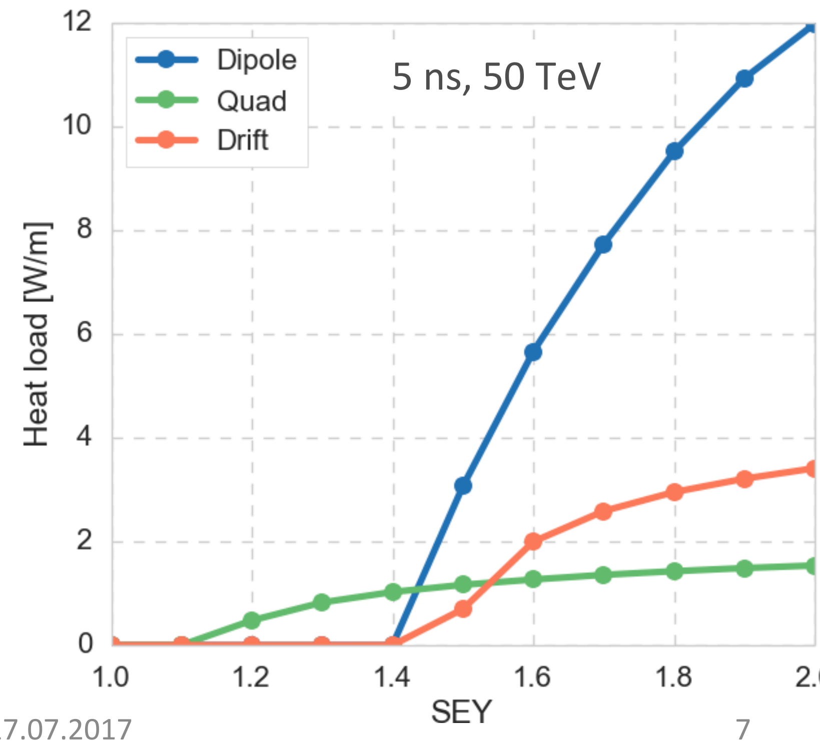
E-cloud build-up

- Multipacting thresholds
  - Build-up from uniform initial distribution
  - Threshold defined as lowest confirmed SEY with build-up

	25 ns		12.5 ns		5 ns	
E [TeV]	3.3	50	3.3	50	3.3	50
Dipole	1.7	1.7	1.3	1.3	1.6	1.5
Quadrupole	1.3	1.4	1.1	1.2	1.2	1.2
Drift	1.9	1.9	1.3	1.3	1.6	1.5

- Lowest thresholds for 12.5 ns beam
- Highest heat load for 5 ns beam: lower than heat load from SR ~30 W/m/b → Stability more critical than heat load
- SEY < 1.1 needed to fully suppress e-cloud

Heat load scaled to device length in half-cell



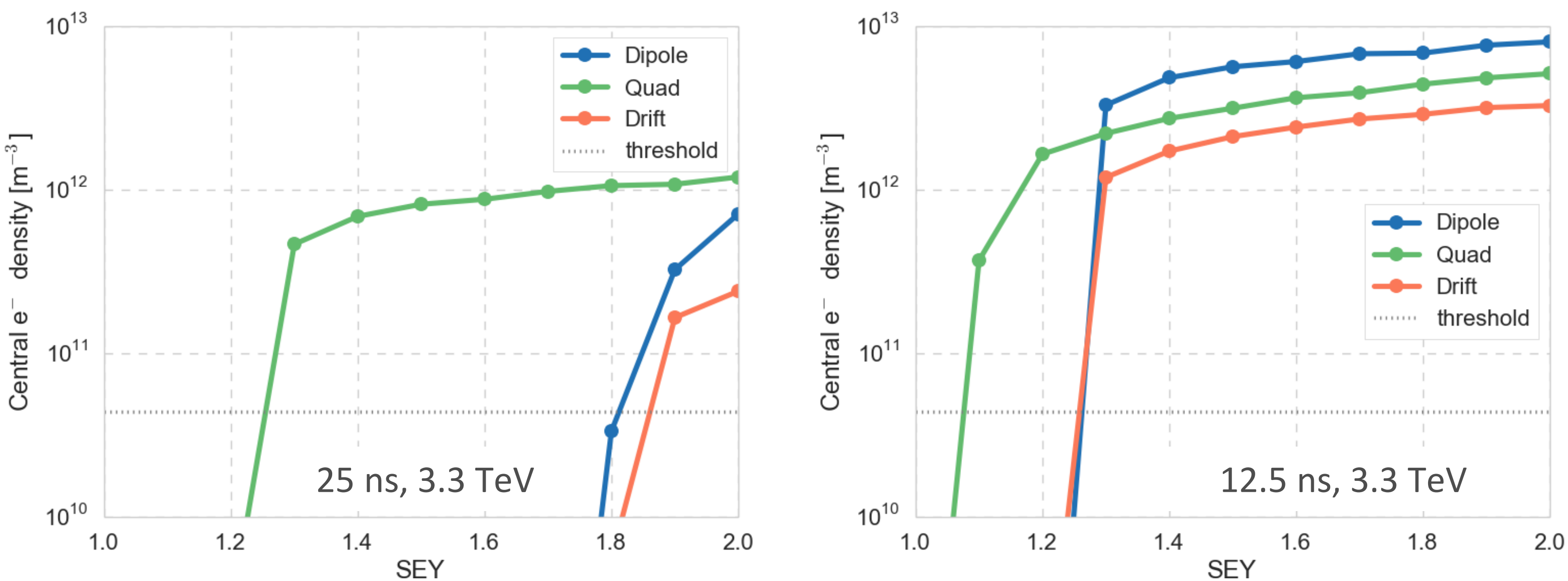
Single bunch instability

- Analytical estimate of **threshold electron density** for instability

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} \quad \text{with} \quad \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}, \quad K = \omega_e\sigma_z/c \quad Q = \min(\omega_e\sigma_z/c, 7)$$

  - Thresholds: 6×10^{10} m^{-3} at 3.3 TeV, 3.6×10^{11} m^{-3} at 50 TeV

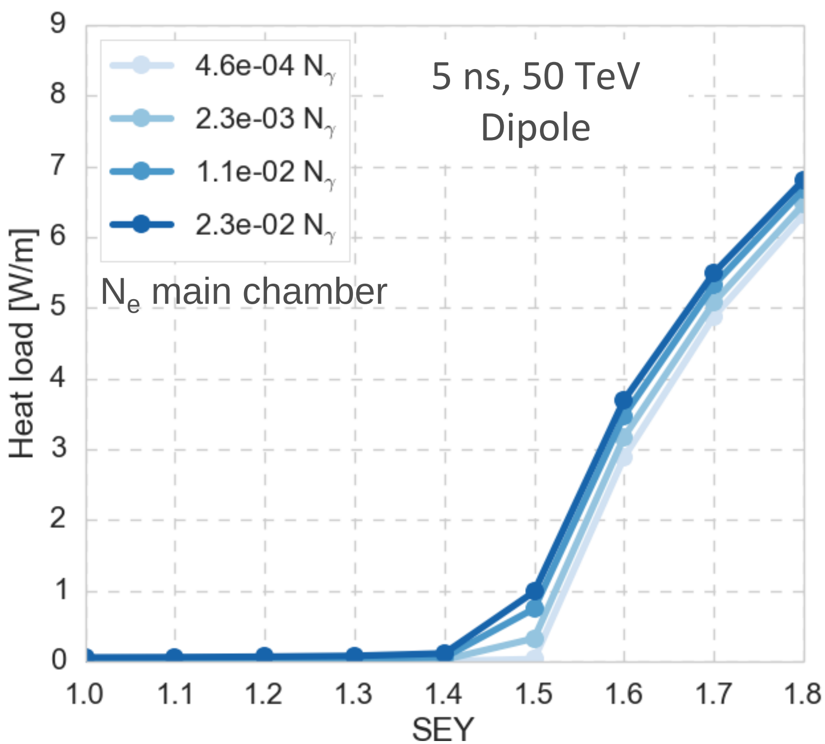
Above the multipacting threshold, central electron densities are above instability threshold

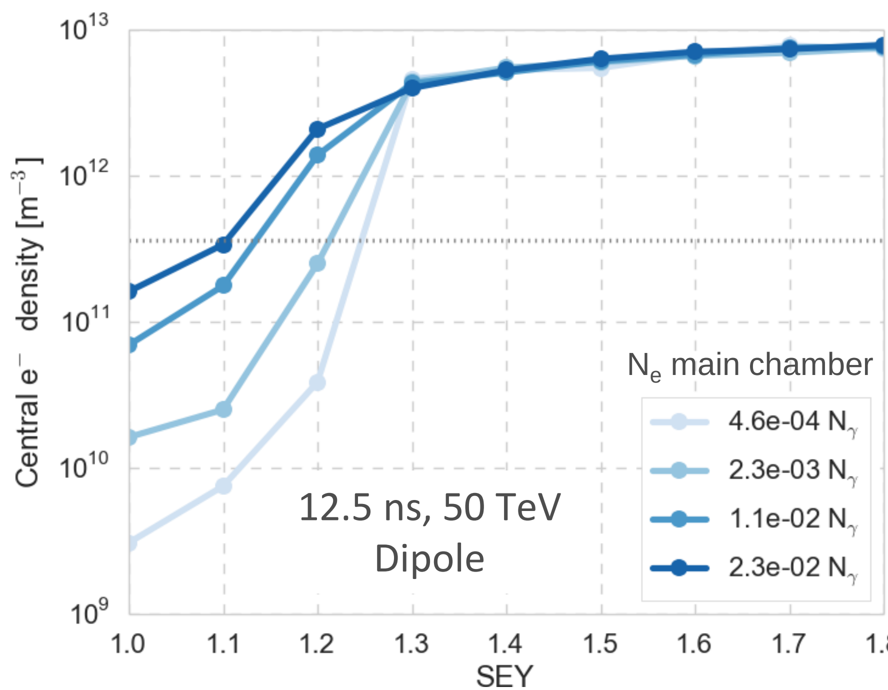


Central electron densities scaled to device length in half-cell

Effect of photoelectrons

- Only marginal effect on heat loads, more significant for central densities
  - Even with SEY = 1-1.1, electron densities can reach instability threshold due to photoelectrons, depending on the number of photons that reach the main chamber and the photoelectron yield





Heat load and central electron densities scaled to device length in half-cell

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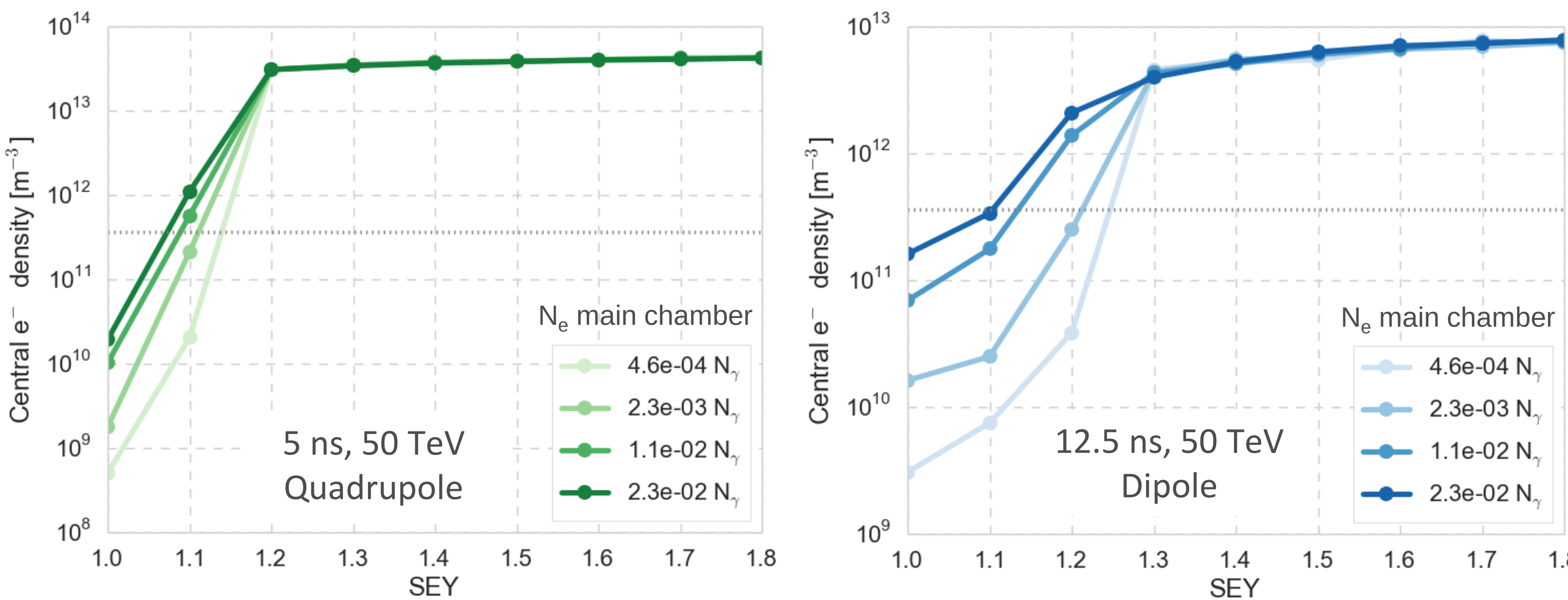
- For 5 and 12.5 ns, the threshold is approached for N_e ~ 1-5 % of photon number

→ For up to 5% photons in main chamber (vacuum estimate) yields > 0.2 problematic



Central electron densities scaled to device length in half-cell

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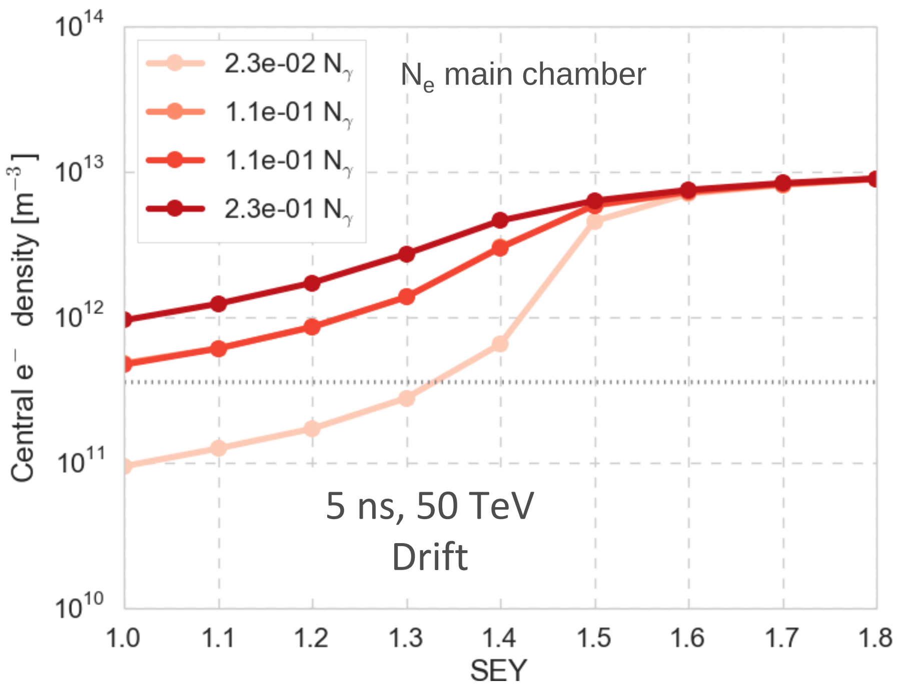


- In drifts, also electrons potentially produced in ante-chamber may move into main chamber and lead to increased electron density

→ more detailed studies needed
Beam screen geometry?
(Photoelectrons in ante-chamber)
Amount of synchrotron radiation?
(Absorbers at end of dipoles)

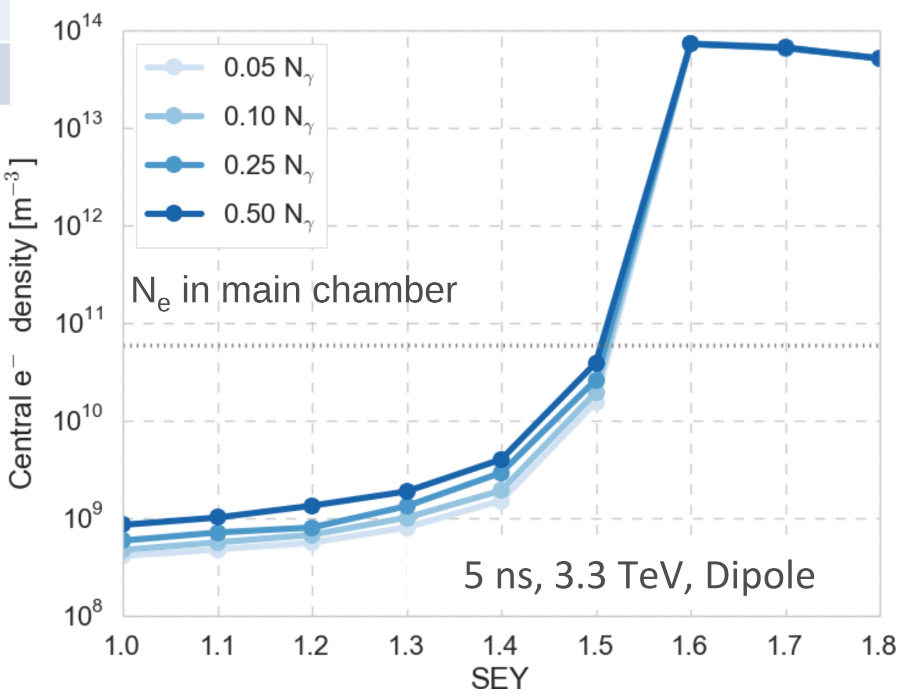
Central electron densities scaled to device length in half-cell

Injection

- Electron densities at 3.3 TeV much below instability threshold
  - Due to smaller number of photons, and critical energy below Cu work function

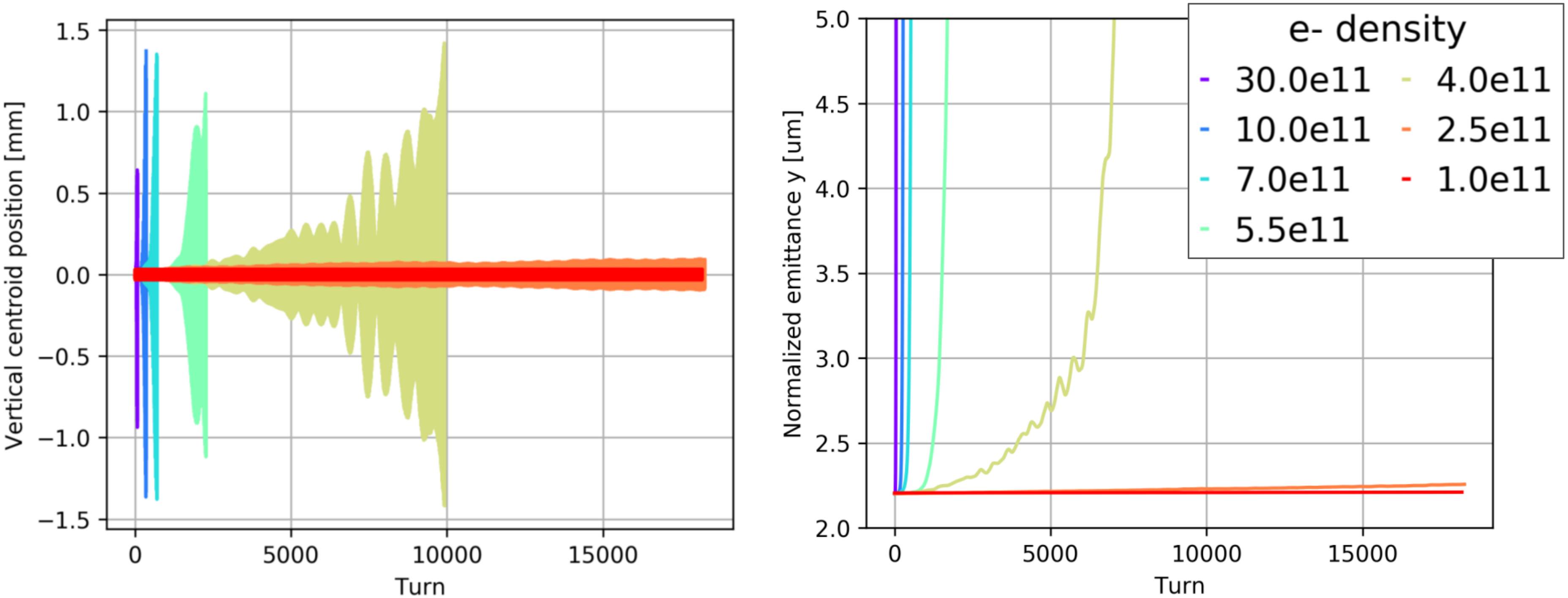
	FCC	FCC Injection		
E [TeV]	50	1.5	3.3	5.5
E_c [eV]	4030	0.11	1.14	5.26
N_γ/p^+m	0.050	0.0015	0.0033	0.0055
N_{eff}/N_{tot}	0.88	6.1e-20	2.5e-3	0.11
N_{eff}/p^+m	0.044	9.1e-23	8.2e-6	5.9e-3

Most critical case for stability may be at some intermediate energy



Single bunch instability simulations

- First instability simulation study: 25 ns beam at 3.3 TeV in dipole field – no stabilizing mechanisms

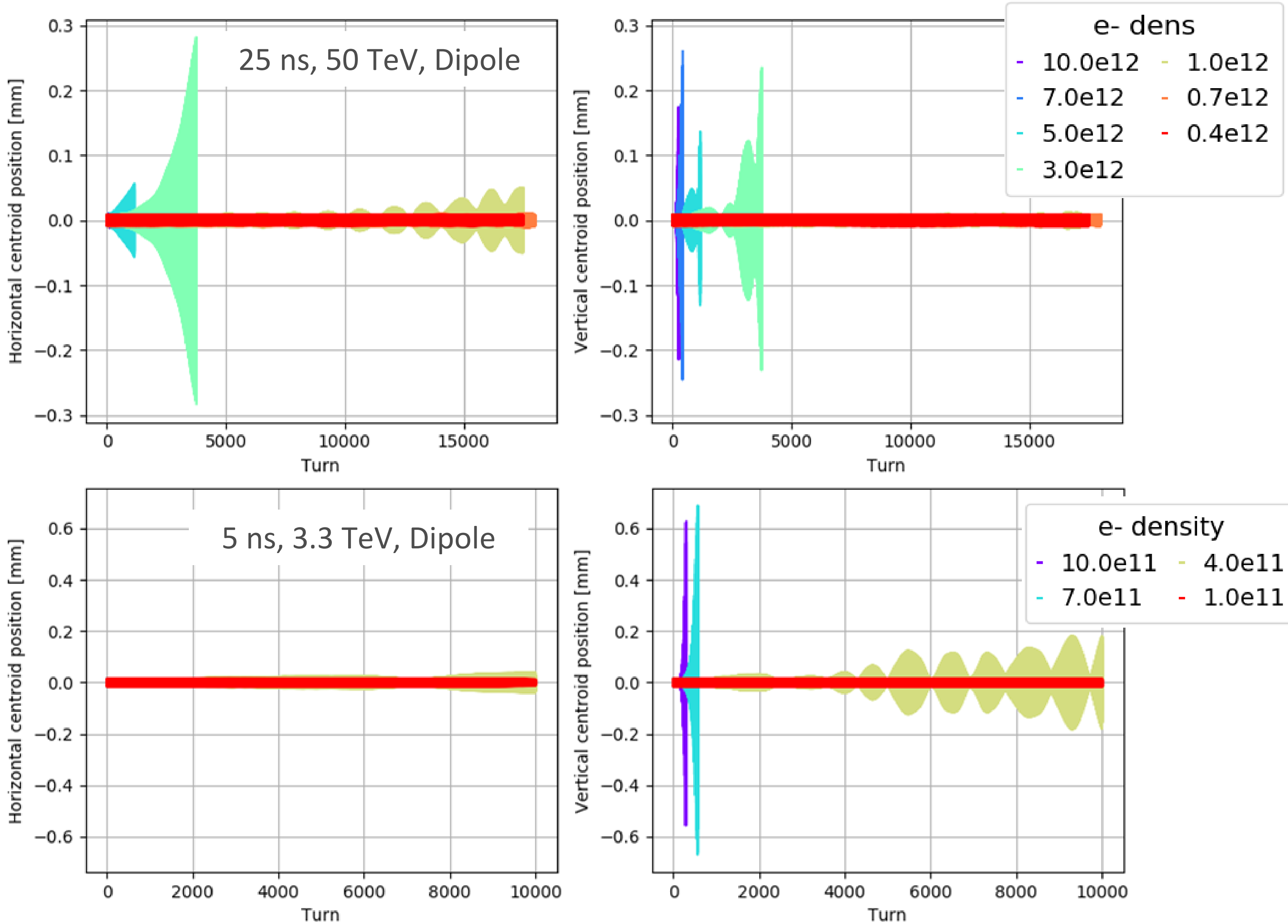


Over 17 000 turns (~ 5 s): instability threshold around 1-2.5 x 10^{11} m^{-3}

- Compare to analytic estimate scaled to dipole length: 7.5 x 10^{10} m^{-3}

→ Analytic estimate slightly pessimistic, by factor 2-3

Single bunch instability simulations



Summary FCC-hh

- Stability more critical than heat load
  - Low-SEY coating is needed to avoid e-cloud completely
- Based on first results of single bunch instability simulations:
  - Analytic threshold is slightly pessimistic, but correct order of magnitude
  - Studies continuing: beam configurations, energy, arc elements and their combined effect, stabilizing mechanisms…
- Enhanced electron densities due to photoelectrons at low SEY give some cause for concern
  - Not extremely critical, but close enough that many details matter: surface properties, their accurate implementation in simulations, understanding of quantitative effect of model assumptions

Future plans and issues FCC-hh

- New build-up studies
  - Updated chamber geometry (with ante-chambers, non-trivial)
  - Updated bunch pattern (more likely (80b. + 17e.) * N)
  - Updated quadrupole field

- Photoelectrons
  - Generate photoelectrons per wall segment
    - → full control over number of photons generated on different parts of the chamber
    - → allows for complex geometry like ante-chamber
  - Accuracy of seeding below threshold?
    - Currently beam ionization + photoelectrons
    - Ionization from electrons?
  - SEY curve for treated surface?

Future plans and issues FCC-hh

- Instability studies
  - Complete study with quadrupoles, drifts, damper (intra-bunch?), Q', octupoles?, RFQ?...

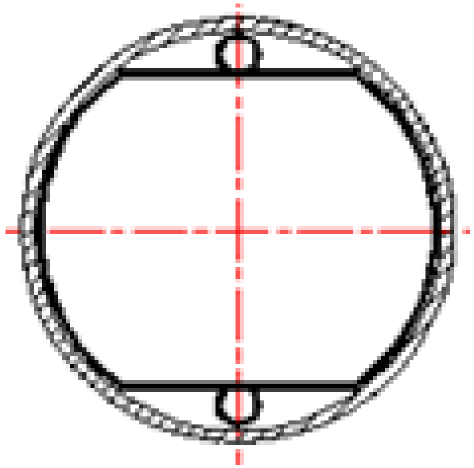
- Further instability studies?
  - Horizontal instability
  - Effect of different beam/machine parameters to explore differences between LHC and FCC

- E-cloud in injectors
  - The baseline for FCC-hh is to inject from the LHC at 3.3 TeV
  - After the HL-LHC it's probably safe to assume there will be no problems with the 25 ns beam in the LHC, but it is less clear whether this will be true also for the 12.5 and 5 ns beam

HE-LHC

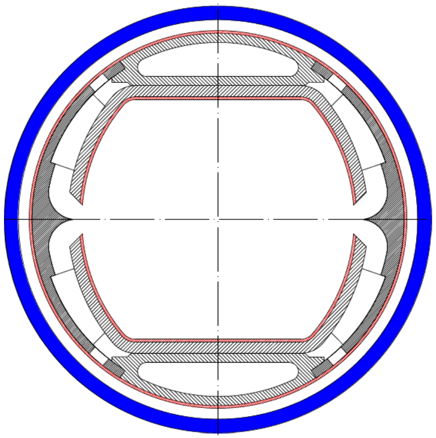
Beam screen for HE-LHC

- Two options for HE-LHC beam screen
  - E-cloud build-up studies in dipoles for the two chamber options



Scaled LHC beam screen

- Pumping slots in main chamber
- Saw-tooth structure at impact of synchrotron radiation fan

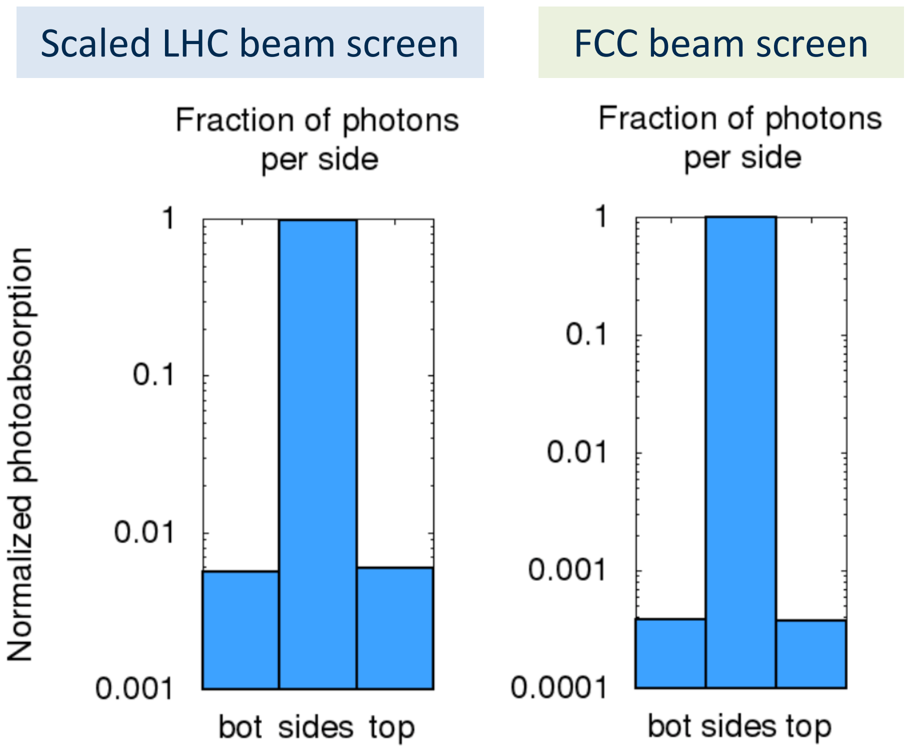


FCC beam screen

- Shielded pumping slots
- Minimized photon absorption in main chamber

Synchrotron radiation

Synchrotron radiation absorption ratios



G.Guillermo

	LHC	HE-LHC	FCC
E [TeV]	7	12.5	50
γ	7400	13375	53300
ρ [m]	2800		11300
N_γ/p^+m	0.028	0.051	0.05
E_c [eV]	43	250	4030
N_{eff}/p^+m	0.013	0.03	0.044

In both chambers the fraction of photons absorbed on the top and bottom of the pipe are very low

- A factor 10 lower for FCC beam screen

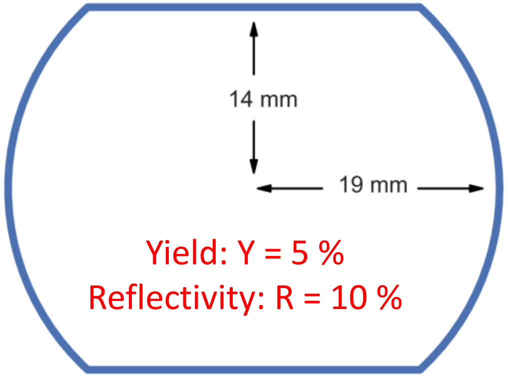
Simulation setup

Simulation parameters		
Energy [TeV]	12.5	
Bunch spacing [ns]	25	5
Bunch intensity [p^+]	2.5×10^{11}	0.5×10^{11}
Norm. emittance [um]	2.5×10^{-6}	0.5×10^{-6}
Bunch length [m]	0.0755	
Bunch train pattern	72 b + 9 e	360 b + 45 e
Arc elements considered	**Dipole:** 16 T $beta_{x,y} \approx 88$ m	

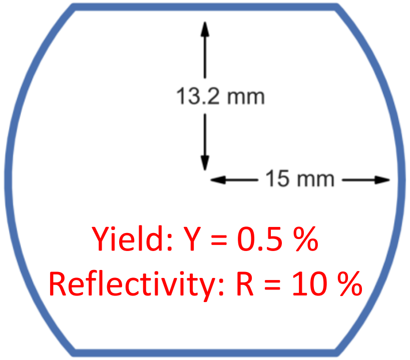
With the chosen Y and R parameters, the number of electrons scattered in the chamber is similar to the number of photons absorbed on the top and bottom of the chamber in the SR studies → distributed with $\cos^2$

Photoemission parameters

Scaled LHC beam screen

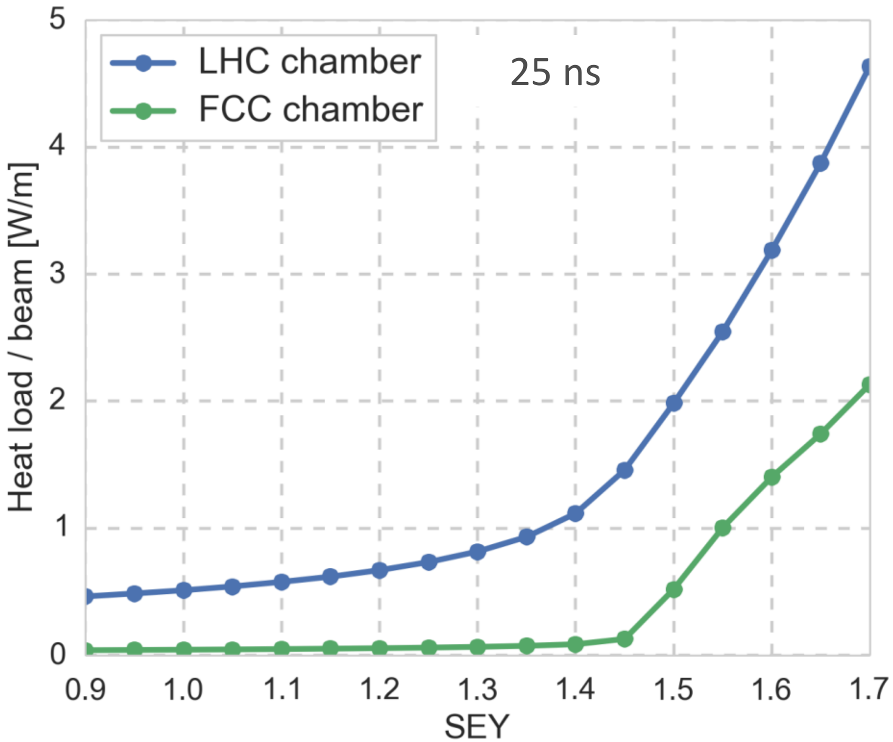


FCC beam screen

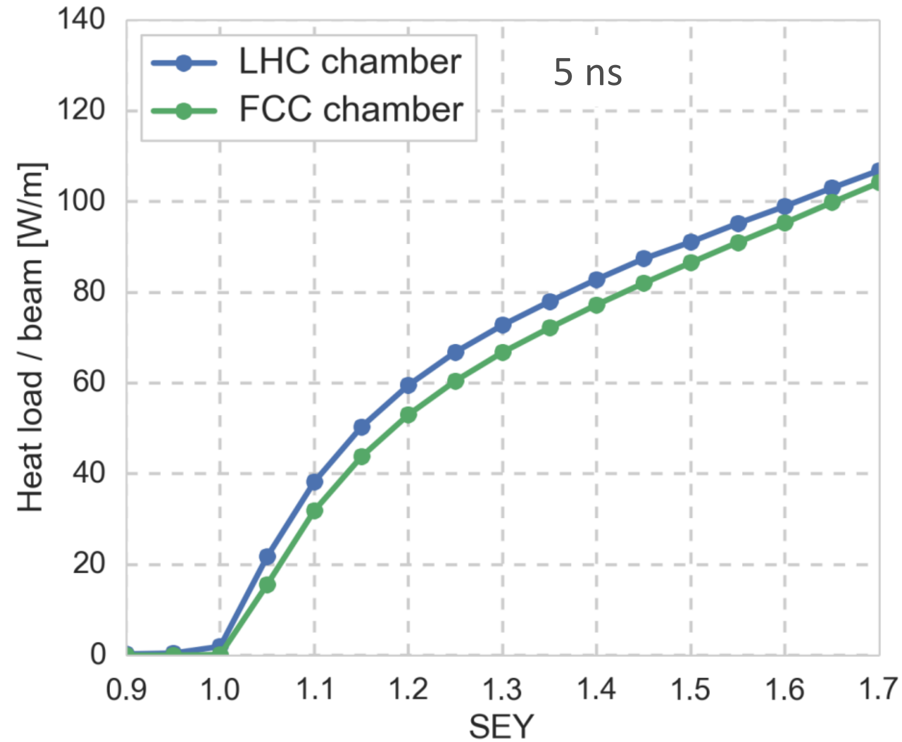


Heat load

- The bunch spacing has a stronger impact on the heat load than the chamber
  - Heat load from synchrotron radiation: 4.6 W/m/beam



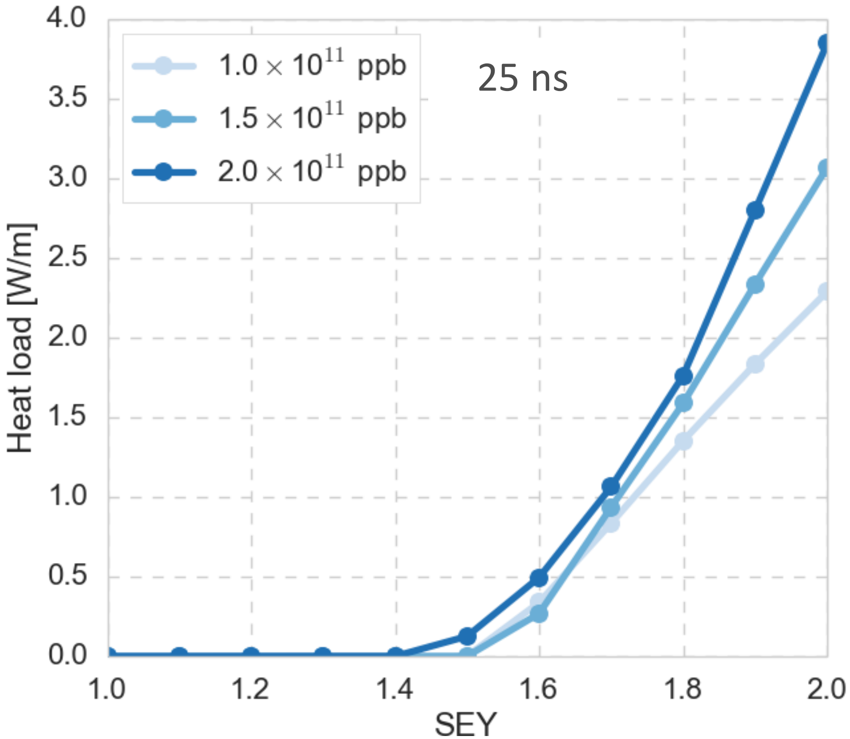
- Multipacting threshold at SEY ~ 1.45
- Higher heat load for scaled LHC chamber

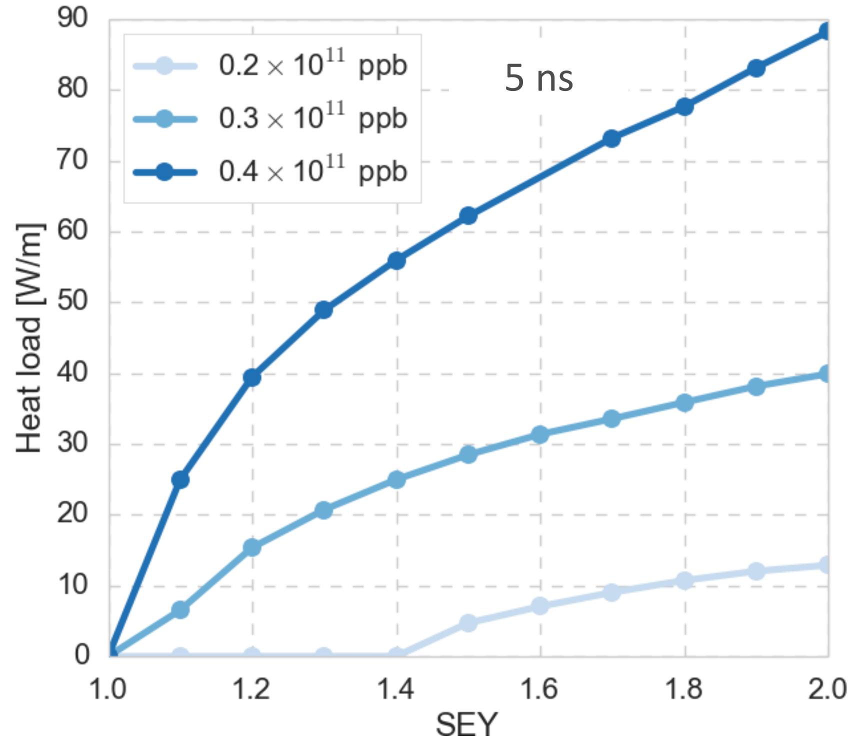


- Multipacting threshold at SEY ~ 1
- Very high heat load for both chambers

Intensity dependence

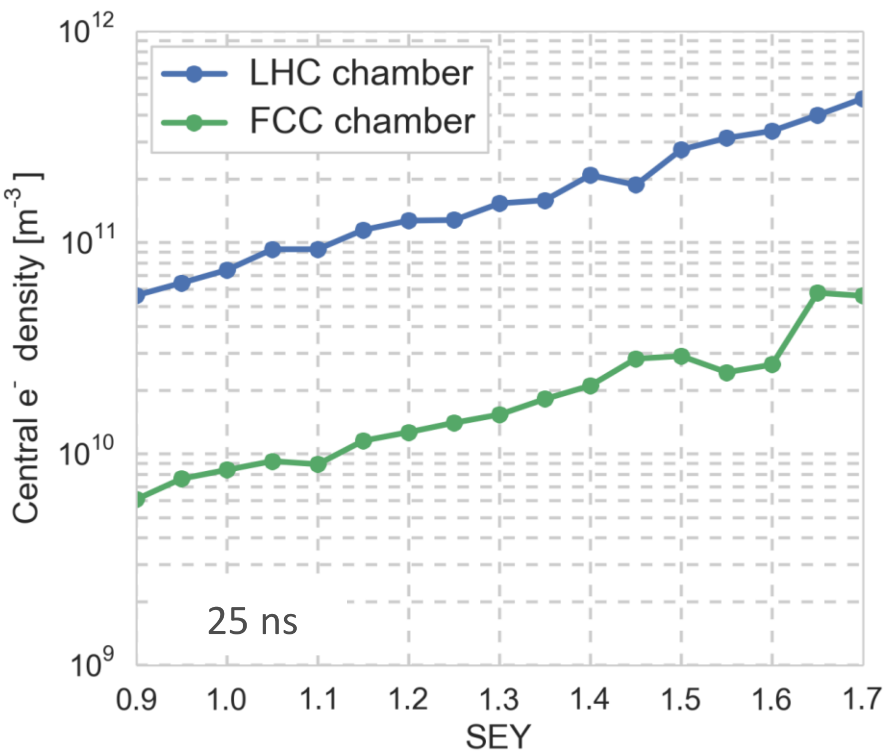
- Simulations scanning the bunch intensity in FCC-hh show that the threshold for e-cloud build-up for the 5 ns beam depends strongly on the bunch intensity

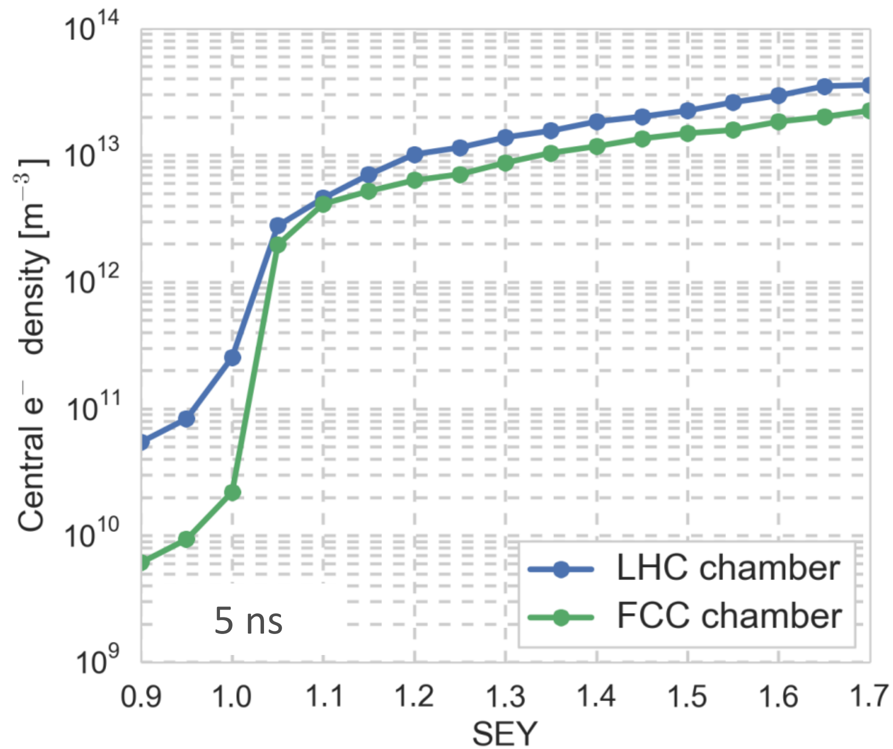




Central electron densities

- Difference in central densities for the two chambers for 25 ns beam is comparable to the difference in photoelectron seeding between the two chambers
- For 5 sn beam effect of photoelectron seeding only below multipacting threshold: SEY ~ 1





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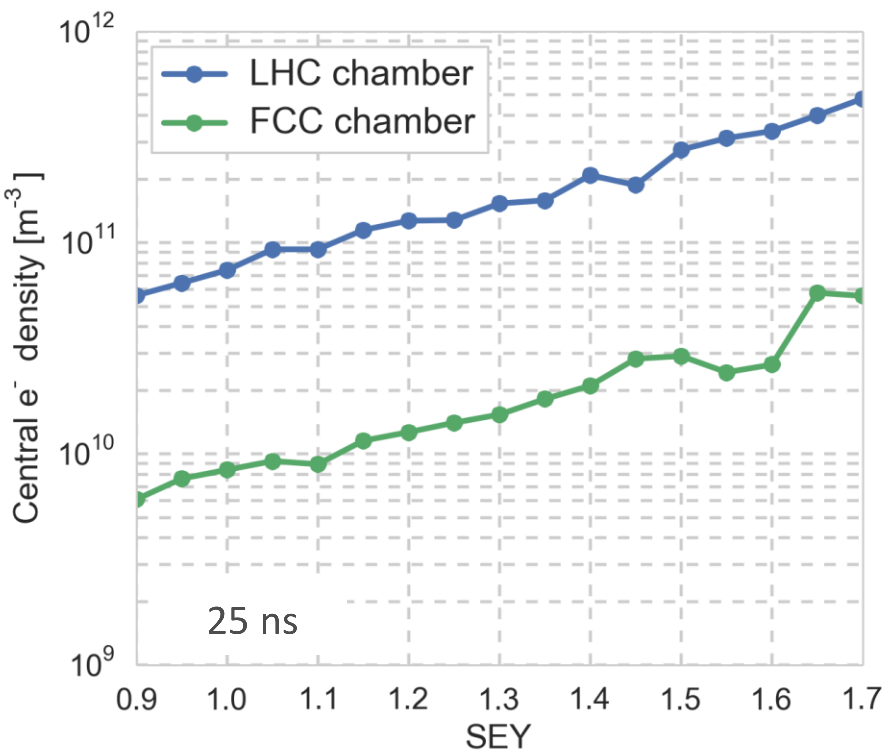
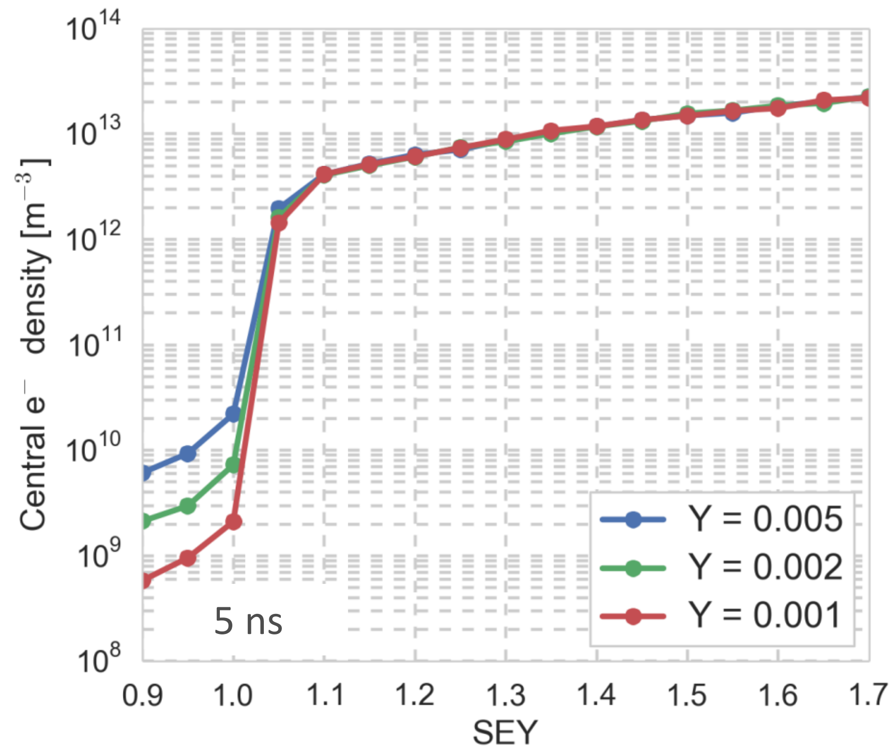


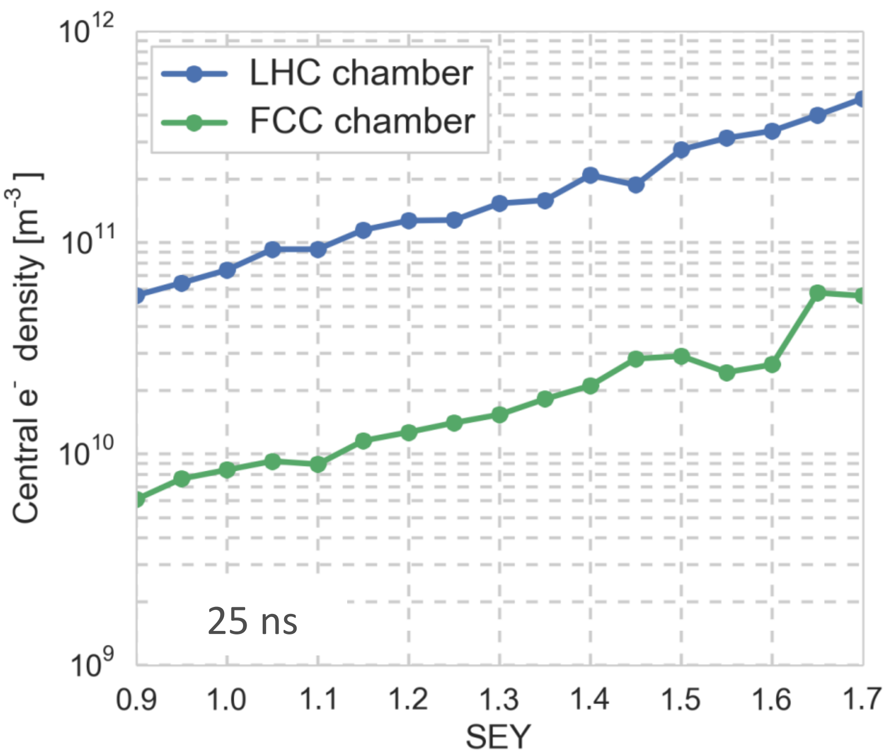


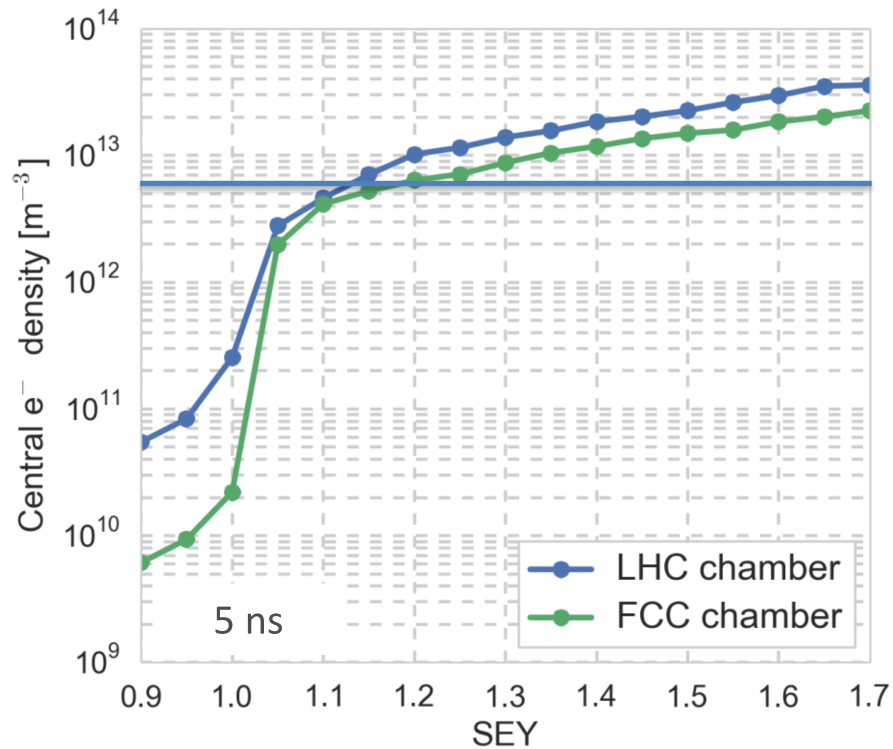
Central electron densities

- Threshold electron density for single bunch instability
  - Central density below threshold for 25 ns beam
  - For 5 ns density below threshold for SEY < 1.1

K. Ohmi

	450 GeV	13.5 TeV
Analytic	1.4×10^{11}	8.1×10^{12}
Simulation	3×10^{11}	6×10^{12}





Summary HE-LHC

- Photon absorption in main chamber a factor 10 lower for FCC beam screen

- Heat load lower for FCC beam screen due to lower photoelectron seeding
- Heat load for 25 ns beam moderate compared to SR and impedance contributions for SEY < 1.5
- Very high heat loads for 5 ns beam above SEY ~ 1

- At top energy, electron densities below instability threshold for 25 ns beam in both chambers
- For 5 ns beam threshold reached for SEY ~1.1 in both chambers

→ FCC-hh beam screen chosen for the HE-LHC

Future plans HE-LHC

- Build-up studies
  - Complete build-up studies like for FCC-hh (no scan in photoelectrons)
  - Build-up for beam variants (25, 12.5 and 5 ns) with updated parameters in dipole and quadrupole arc elements at injection and top energy
  - Scan over intensity and emittance during fill
  - Done, but currently uncertain what the final parameters are (intensity, injection energy, beam size)

- Instability studies
  - Complete instability scans like for FCC-hh
  - Longitudinal parameters yet to be determined