FIRST STUDIES ON THE ELECTRON CLOUD BUILD-UP IN THE BOOSTER OF THE FCC-ee

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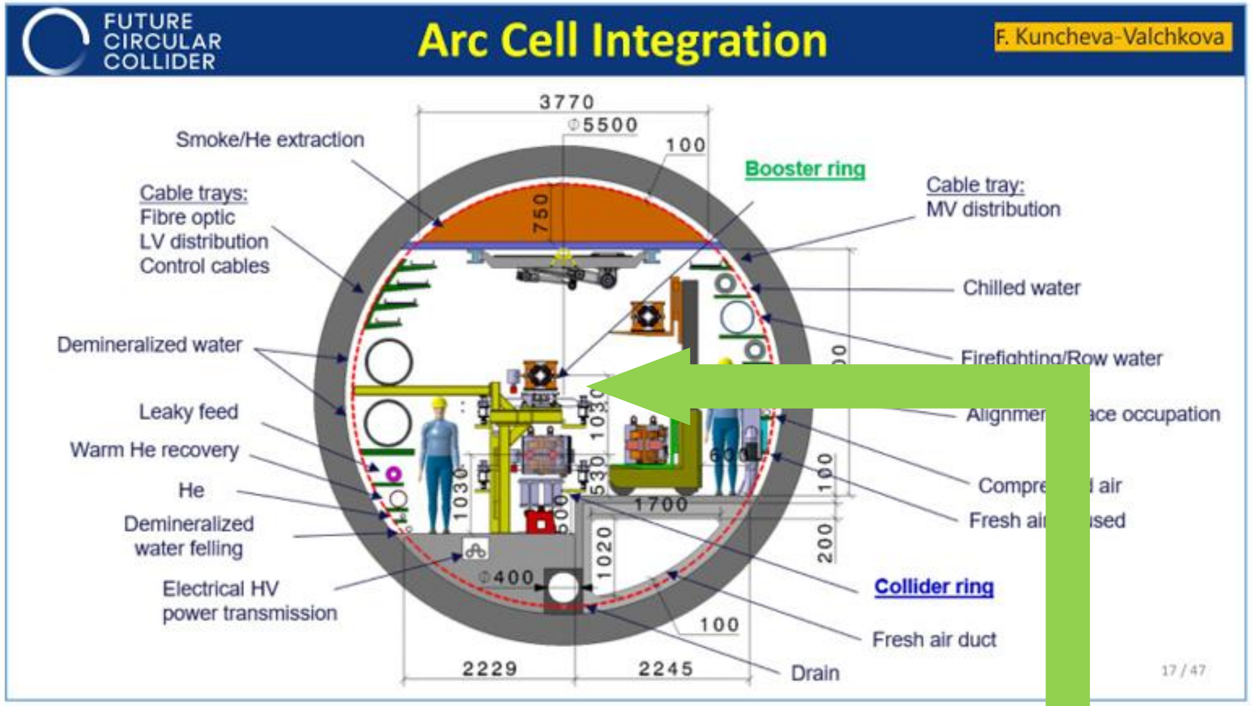

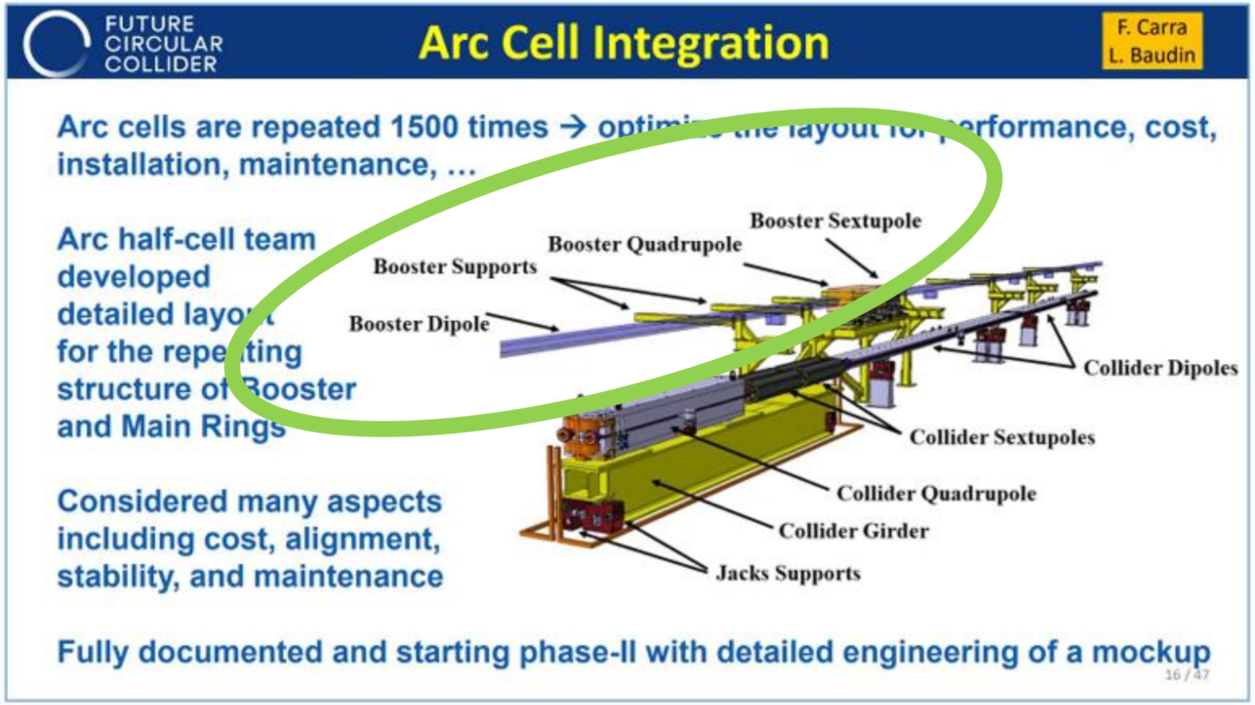

- Above the two rings of the collider, there is a THIRD ring, the full-energy injection BOOSTER, which injects both e- and e+ (in opposite directions) whenever necessary

R Kersevan, *Vacuum system and photoelectron distributions in the booster,*
FCCIS WP2 Workshop, Nov 2023

Booster Elements:

- ✓ **Drift sections**
- ✓ **Dipoles**
- ✓ **Quadrupoles**
- ✓ **Sextupoles**

General Consideration **(all this is the result of the Cost Review exercise)**

1. The vacuum chamber cross-section in the booster is NOW 50 mm circular (ID). The specific conductance of a 50 mm ID circular tube is only ~41 l·m/s → LOWER CONDUCTANCE
2. Material is stainless steel (probably 316L or LN) with NO welding seam (extruded, not bent and welded like the LHC beam-screen)
3. NO copper coating → RW IMPEDANCE???
4. NO NEG-coating → HIGH PRESSURE
5. NO bakeout system → HIGHER MASS SPECIES (ineffective water vapo
6. NO RF fingers in the bellows → GEOMETRIC IMPEDANCE/HOMs???
7. No SR Absorbers possible (the booster accelerates both beams in opposite directions) → SLOWER CONDIT.
8. It is a rather "conventional" design (other than its size) as implemented for decades in e.g. light sources worldwide
9. Same sectoring as for the 2 storage rings (i.e. 400 m between adjacent gate valves)

It is necessarily to work on e-Cloud mitigation requirements

If you put together some of these poin

e-cloud build-up will be possible at FCC-ee booster

along the booster won't be very low very quickly, as it is expected to be in the storage rings.

Also the booster will be prone to several instabilities due to high(er) pressure, high(er) gas ionization (ion-trapping) and high(er) photoelectron yield and SEY, and e-cloud effects

R Kersevan, *Vacuumsystem and photoelectron distributions in the booster,* FCCIS WP2 Workshop, Nov 2023

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Booster parameter table (mid-term report)

Running mode		Z	W	ZH	$t\bar{t}$
Injection option		LINAC/SPS			
Circumference	[km]	91.174			
Injection energy	[GeV]	20/[illegible]6			
Extraction energy	[GeV]	45.6	80	120	182.5
Number bunches / ring		11200	1780	440	60
Maximum particle number / bunch Nmax	[10^{10}]	≥ 2.5 (4 nC)			
Particles / bunch in top-up	[10^{10}]	2.14	0.87	0.69	[illegible]
RF frequency	[MHZ]	800			
Arc optics FODO		60°/60°		90°/90	
Momentum compaction		14.9×10^{-6}		7.34×10	
Coupling		2×10^{-3}			
Injection horizontal emittance (norm.)	[μm]	10/190			

Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26	0.81	0.
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53	1.62	1.
Injection Energy loss / turn	[MeV]	1.514/0.6203		
Extraction Energy loss / turn	[MeV]	40.93	387.7	1
Injection bunch length	[mm]	4/5.5		
Extraction bunch length	[mm]	4.38	3.55	3.
[illegible]				1.
[illegible] energy acceptance				0.
Injection RF voltage	[MV]	104.9/82.97		
Extraction RF voltage	[MV]	49.48	458.6	2

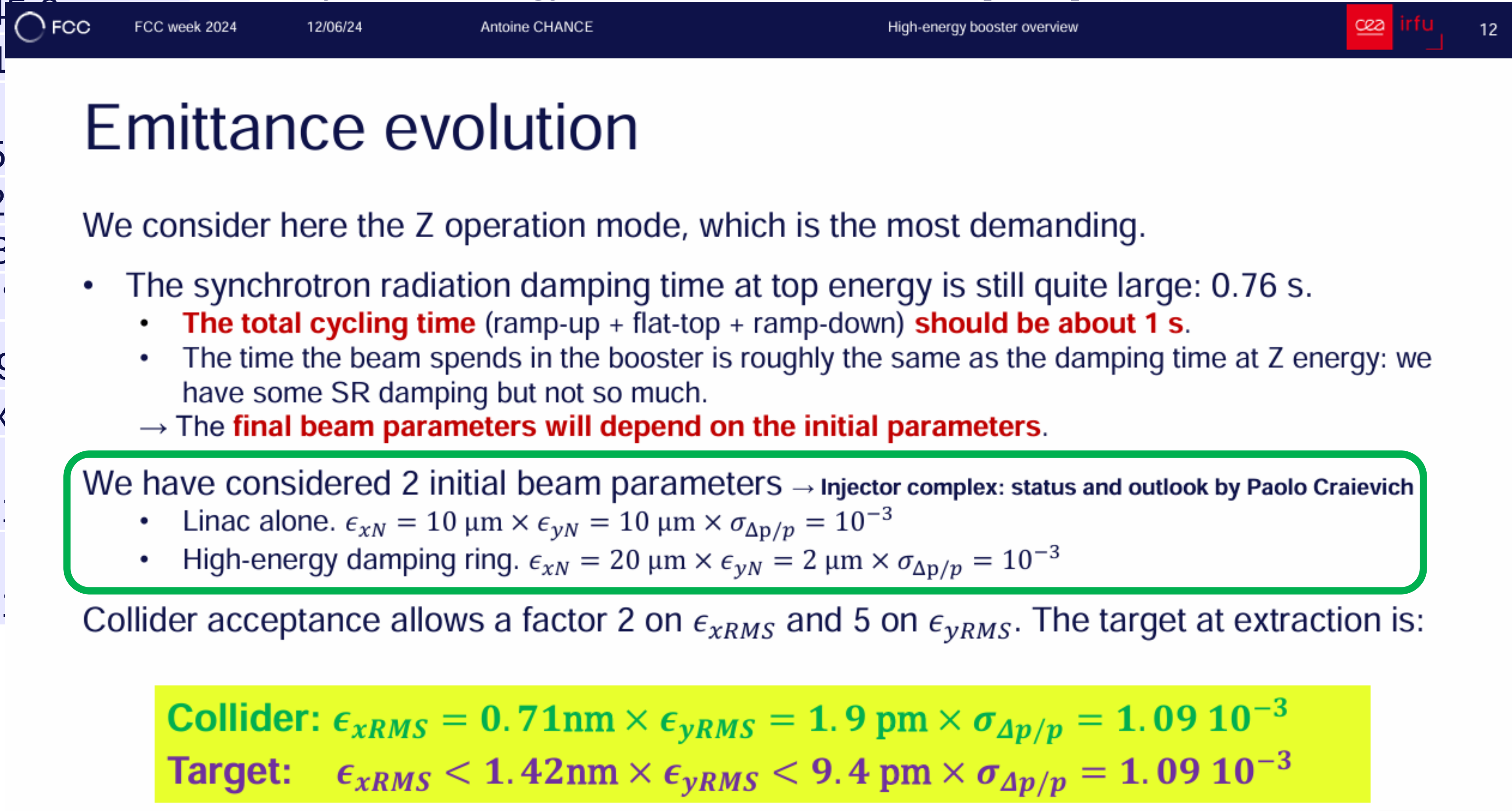
Stages of study:
- Injection of bunches into the booster
- Injection of bunches into the collider

Atoine Chance, *High energy booster overview,* FCC-ee week 2024

Parameters of the booster design Z operation mode

Running mode		Z
Injection option	LINAC alone and High Energy Damping ring	
Circumference	[km]	91.174
Injection energy	[GeV]	20
Extraction energy	[GeV]	4
Number bunches/ring		11
Maximum particle number/ bunch N max	[10^{10}]	>2.5
Particles / bunch in top-up	[10^{10}]	2
RF frequency	[MHZ]	8
Arc optics FODO		60
Momentum compaction		14.
Coupling		2x
Injection horizontal emittance (norm.)	[μm]	
Injection vertical emittance (norm.)	[μm]	

Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53
Injection Energy loss /turn	[MeV]	1.514


FCC FCC week 2024 12/06/24 Antoine CHANCE High-energy booster overview irfu 12

Emittance evolution

We consider here the Z operation mode, which is the most demanding.

- The synchrotron radiation damping time at top energy is still quite large: 0.76 s.
  - **The total cycling time** (ramp-up + flat-top + ramp-down) **should be about 1 s**.
  - The time the beam spends in the booster is roughly the same as the damping time at Z energy: we have some SR damping but not so much.

→ The **final beam parameters will depend on the initial parameters**.

We have considered 2 initial beam parameters → **Injector complex: status and outlook by Paolo Craievich**
- Linac alone. $\epsilon_{xN} = 10\ \mu\text{m} \times \epsilon_{yN} = 10\ \mu\text{m} \times \sigma_{\Delta p/p} = 10^{-3}$
- High-energy damping ring. $\epsilon_{xN} = 20\ \mu\text{m} \times \epsilon_{yN} = 2\ \mu\text{m} \times \sigma_{\Delta p/p} = 10^{-3}$

Collider acceptance allows a factor 2 on ϵ_{xRMS} and 5 on ϵ_{yRMS}. The target at extraction is:

Collider: $\boldsymbol{\epsilon_{xRMS} = 0.71\text{nm} \times \epsilon_{yRMS} = 1.9\ \text{pm} \times \sigma_{\Delta p/p} = 1.09\ 10^{-3}}$

Target: $\boldsymbol{\epsilon_{xRMS} < 1.42\text{nm} \times \epsilon_{yRMS} < 9.4\ \text{pm} \times \sigma_{\Delta p/p} = 1.09\ 10^{-3}}$

A Chance, *High energy booster overview,* FCC-ee week 2024

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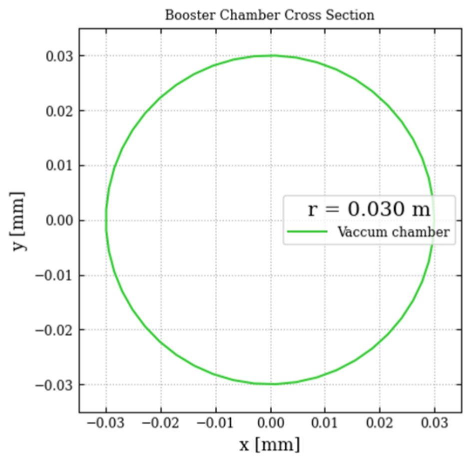
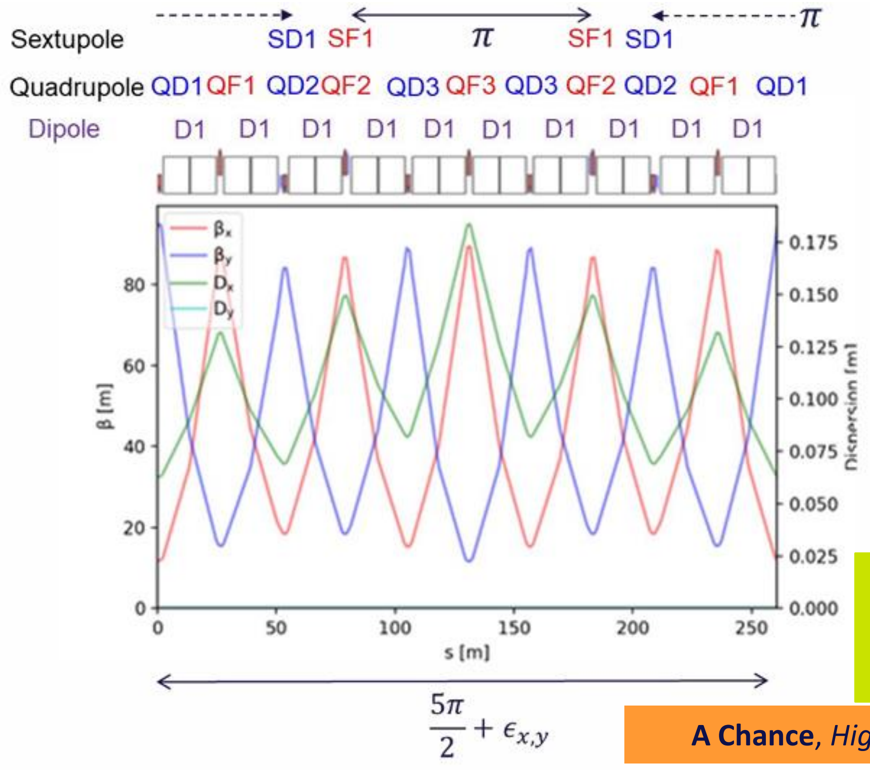
Stages, baseline optics of FODO cells and scan parameters

Stage		Extraction	Injection	
			LINAC	Damping Ring
Energy (extraction, injection)	[GeV]	45.6	20	20
Momentum spread (RMS)	$[10^{-3}]$	0.38	1	1
Normalized transvese emittance of the beam x	[µm]	23.2	10	20
Normalized transvese emittance of the beam y	[µm]	0.047	10	2
Bunch length	[mm]	4.38	4	4





Elements of the FODO Cell	Drift	Dipole	Quadrupoles	Sextupoles
Injection Magnetic Field/Gradient LINAC and Damping Ring		6.4 [mT]	2.7 [T/m]	125 $[T/m^2]$
Extraction Magnetic Momenta		14.6[mT]	6.16[T/m]	285 $[T/m^2]$

Scan parameters	Range	Steps
Bunch spacing [ns]	[5 , 25]	5
Secondary-emission yield	[1 .0, 2.0]	0.1

Positron beam
No photoelectrons considered

A Chance, *High energy booster overview*, FCC-ee week 2024

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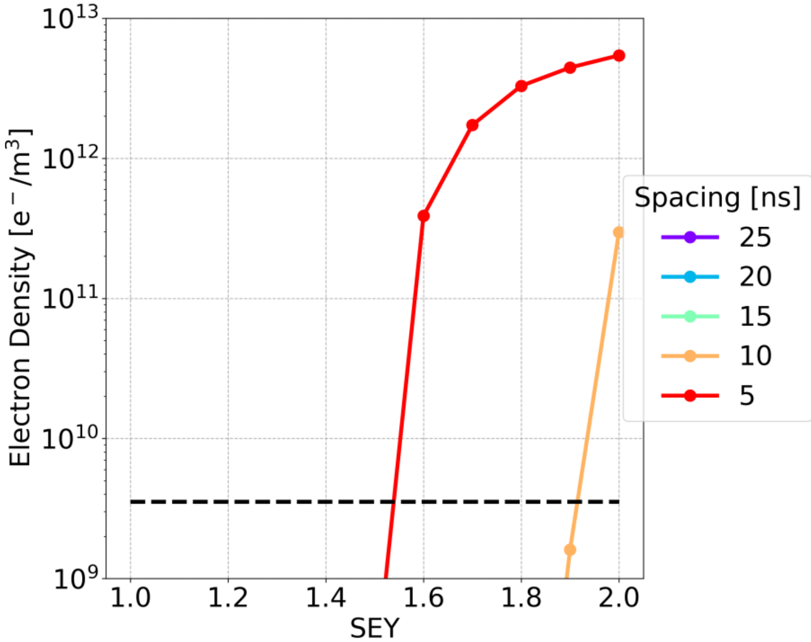
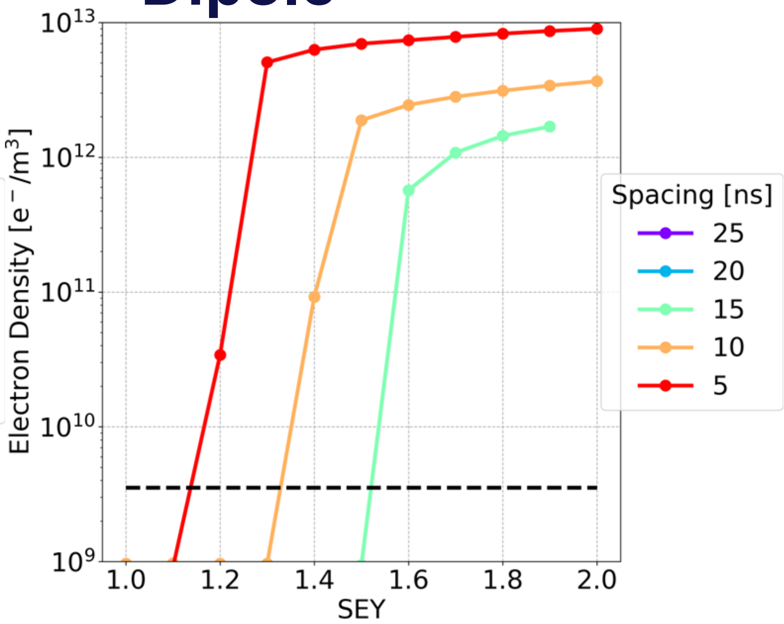
Booster at extraction

Drift



Dipole



Element	Bunch spacing [ns]				
	5	10	15	20	25
Drift	1.5	1.9	>2.0	>2.0	>2.0
Dipole	1.1	1.3	1.5	>1.8	>2.0

For **drift section,** multipacting occurs for few cases:
- small bunch spacing (<15 ns) at large SEY (>1.5).

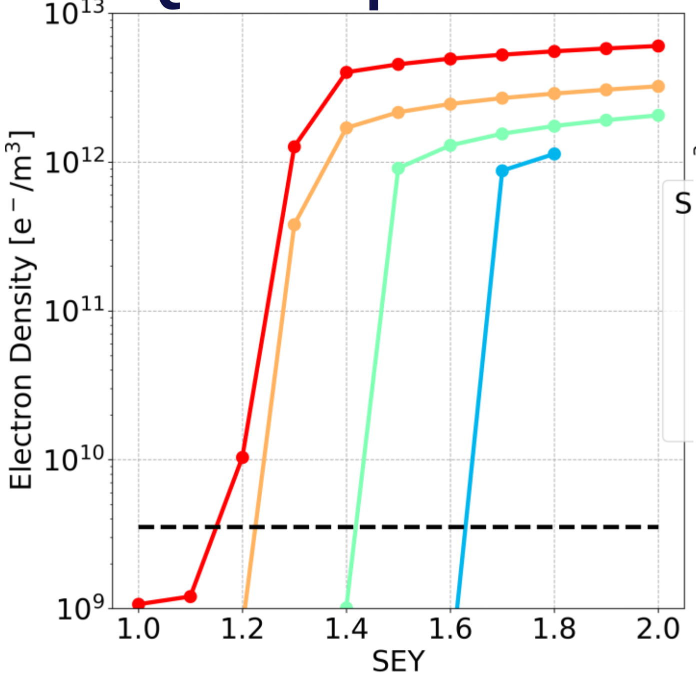
The magnetic elements are more critical from the e-cloud point of view.

For dipole magnet, multipacting could occur in more cases:
- with larger bunch spacing (even for 15 ns and SEY 1.6)

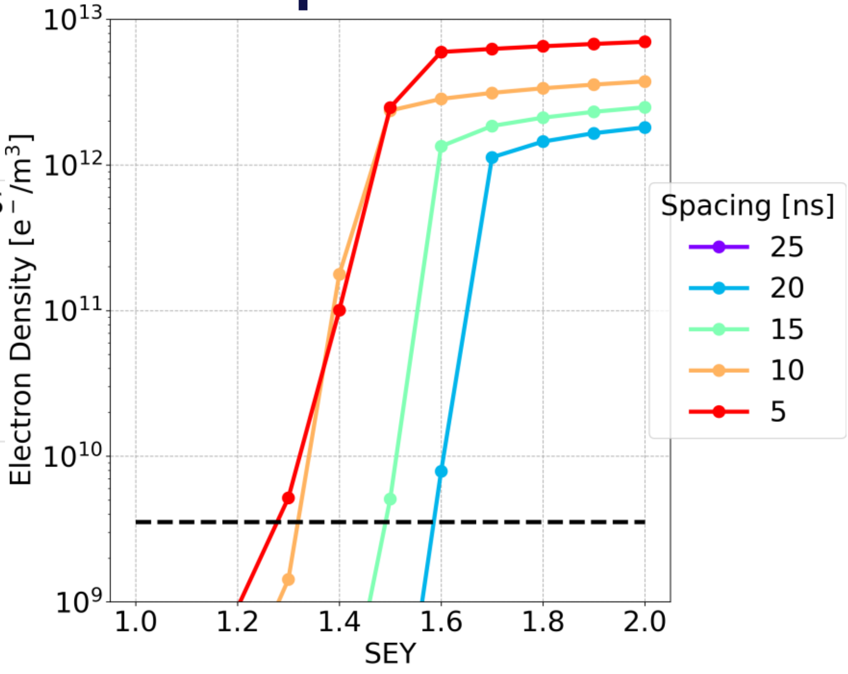
On going simulations

Booster at extraction

Quadrupole



Sextupole



In the **quadrupoles and sextupoles**, multipacting could occur even for 20 ns bunch spacing with a SEY >1.5 on both cases.

Considering smaller bunch spacing, the e-cloud could occur with smaller SEY, for example: 15 ns bunch spacing SEY> 1.4 for both elements

Element	Bunch spacing [ns]				
	5	10	15	20	25
Quadrupole	1.1	1.2	1.4	1.6	>1.6
Sextupole	1.2	1.3	1.4	1.5	>1.5

On going simulations

Preliminary SEY Multipacting Thresholds

Booster at extraction

On going simulations

Booster at Extraction					
Element	Bunch spacing [ns]				
	5	10	15	20	25
Drift	1.5	1.9	>2.0	>2.0	>2.0
Dipole	1.1	1.3	1.5	>1.8	>2.0
Quadrupole	1.1	1.2	1.4	1.6	>1.6
Sextupole	1.2	1.3	1.4	1.5	>1.5

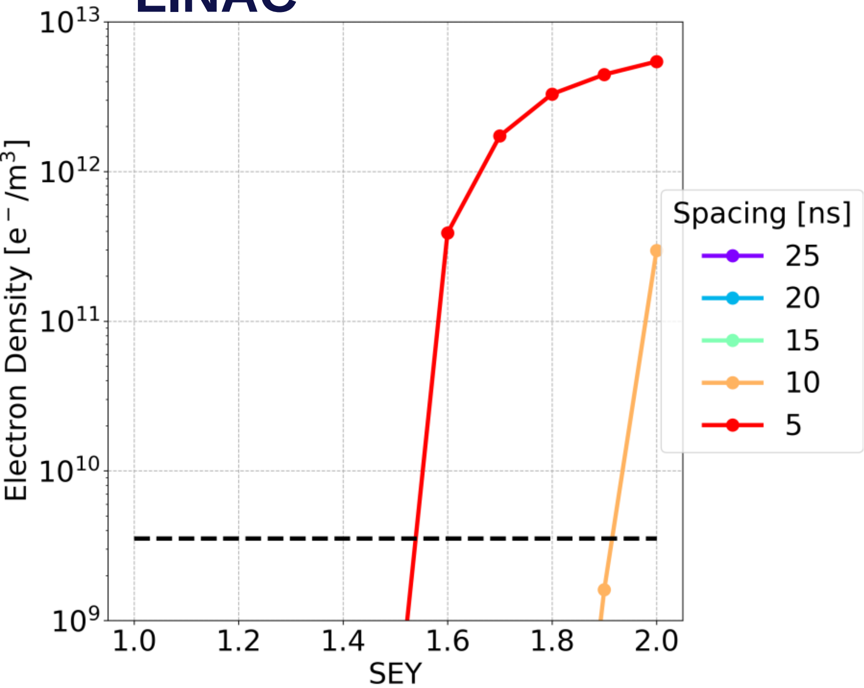
The drift space has the largest SEY multipacting thresholds and the magnetic elements have the lowest thresholds

For bunch spacing 25 ns, the simulations are on going…
For bunch spacing 20 ns, to avoid e-cloud multipacting a surface with an SEY 1.5 is needed.

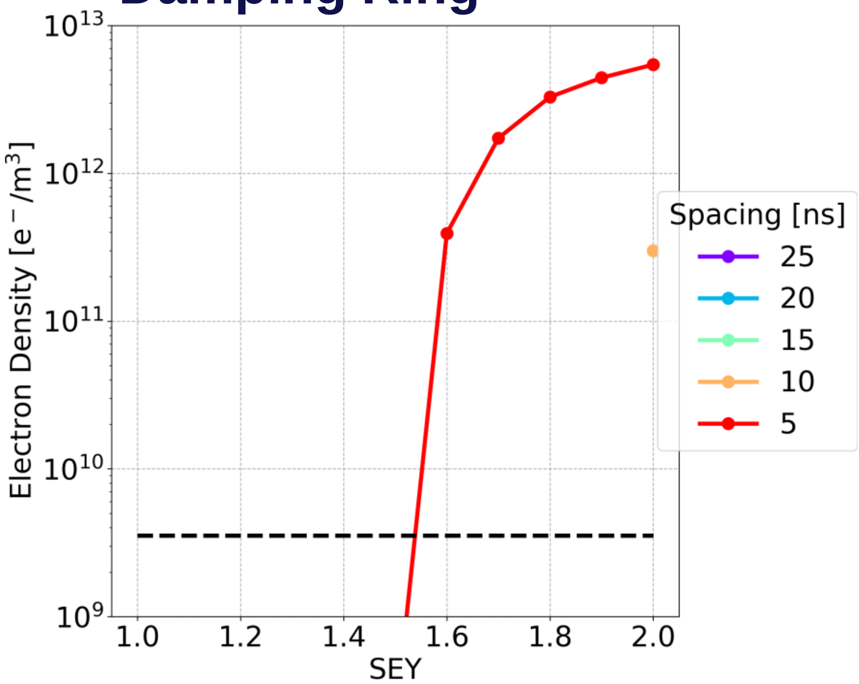
Considering filling schemes with **smaller bunch spacing, the required material constraint is tighter**, for example with a bunch spacing of 15 ns the required SEY is 1.4

Booster at injection at Drift space

LINAC



Damping Ring



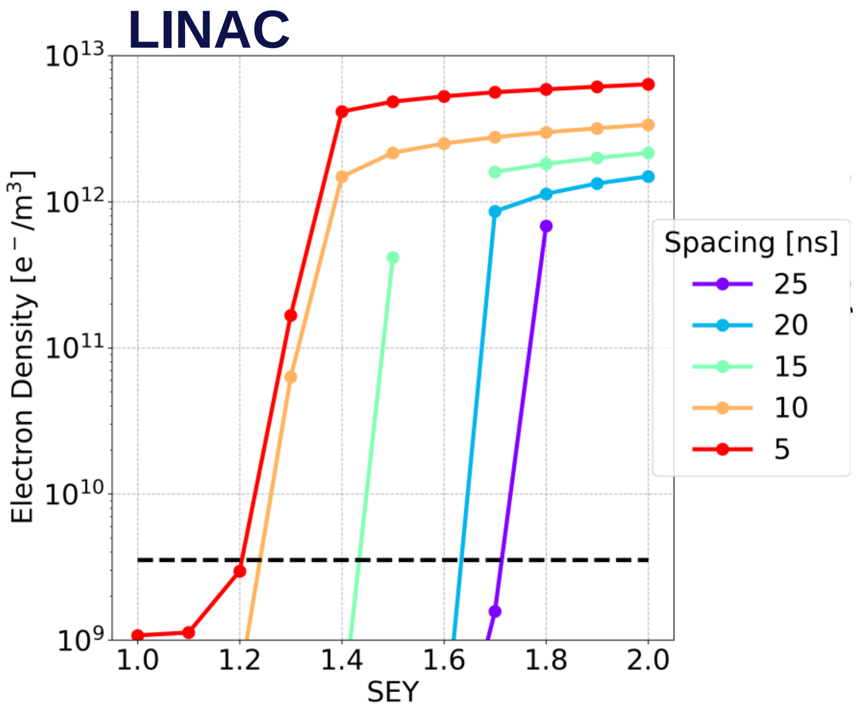
The scene is similar to extraction stage.

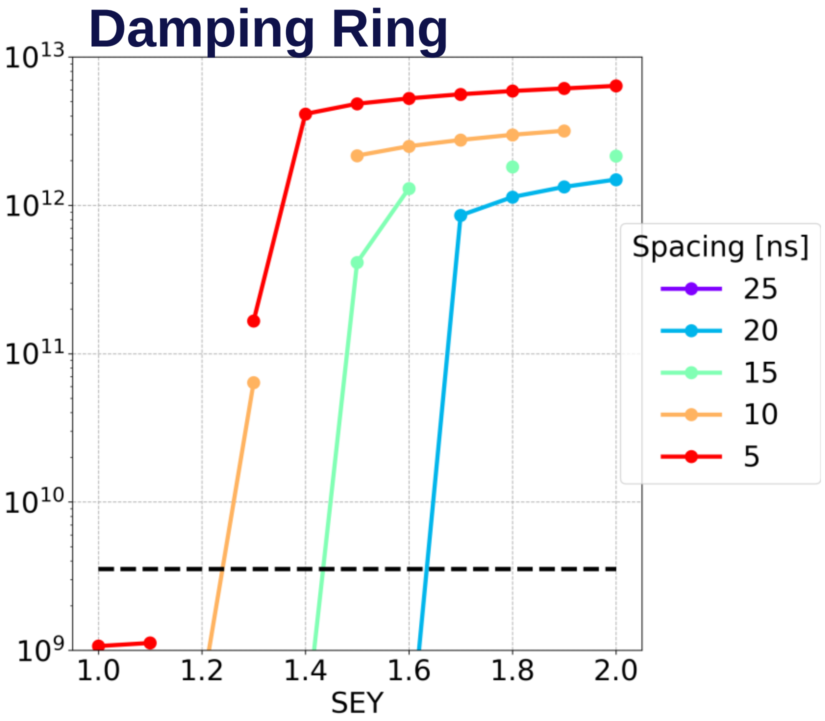
Multipacting occurs for very small bunch spacing (<15 ns) and large SEY (>1.5)

Injection Option	Bunch spacing [ns]				
	5	10	15	20	25
LINAC	1.5	1.9	>2.0	>2.0	>2.0
Damping ring	1.5	1.8/1.9	>2.0	>2.0	>2.0

On going simulations

Booster at injection at quadrupoles





Multipacting occurs even for 25 ns with SEY >1.7 taking the LNAC option.

For lower bunch spacing, both options of beam injection to the booster have similar behavior.

Considering smaller bunch spacing, the e-cloud could occur with smaller SEY (for example: 10 ns bunch spacing SEY= 1.2)

Injection Option	Bunch spacing [ns]				
	5	10	15	20	25
LINAC	1.2	1.2	1.4	1.6	1.7
Damping ring	1.1/1.2	1.2	1.4	1.6	>1.6

On going simulations

Booster at Injection

On going simulations

Option LINAC					
Element	Bunch spacing [ns]				
	5	10	15	20	25
Drift	1.5	1.9	>2.0	>2.0	>2.0
Dipole	1.4	1.5	…1.6/1.7/1.8	>2.0	…>1.6
Quadrupole	1.2	1.2	1.4	1.6	1.7
Sextupole	1.3	1.4	1.6	1.6/1.7	>1.6

Option damping ring					
Element	Bunch spacing [ns]				
	5	10	15	20	25
Drift	1.5	1.8/1.9	>2.0	>2.0	>2.0
Dipole	1.4	1.5	1.7	…	…
Quadrupole	1.1/1.2	1.2	1.4	1.6	>1.6
Sextupole	1.3	1.4	1.5/1.6/1.7	>1.6	>1.6

The drift space has the largest SEY multipacting thresholds for the baseline optics at injection stage.
The element with the lowest SEY thresholds is quadrupole at most of the scanned time of buch spacing.
For bunch spacing 25 ns, most of the simulations are on going, but we may say from the first option of injection SEY threshold could be around 1.7
Considering filling schemes with smaller bunch spacing, the required material constraint is tighter, for example, with a bunch spacing of 15 ns the required SEY is 1.4
From the e-cloud point of view, both options of injection of the beam offer similar quota to avoid multipacting effect in the entire optic baseline

Comparison injection and extraction stages

Element	Option LINAC					Option damping ring					Extraction				
	Bunch spacing [ns]					Bunch spacing [ns]					Bunch spacing [ns]				
	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
Drift	1.5	1.9	>2.0	>2.0	>2.0	1.5	1.8/1.9	>2.0	>2.0	>2.0	1.5	1.9	>2.0	>2.0	>2.0
Dipole	1.4	1.5	1.6/1.7/1.8	>2.0	>1.6	1.4	1.5	1.7	…	…	1.1	1.3	1.5	>1.8	>2.0
Quadrupole	1.2	1.2	1.4	1.6	1.7	1.1/1.2	1.2	1.4	1.6	>1.6	1.1	1.2	1.4	1.6	>1.6
Sextupole	1.3	1.4	1.6	1.6/1.7	>1.6	1.3	1.4	1.5/1.6/1.7	>1.6	>1.6	1.2	1.3	1.4	1.5	>1.5

Injection options present slightly larger values for the SEY multipacting threshold than those presented for the extraction stage most of the times, for several bunch spacing scanned

As a very **preliminary value to avoid the e-Cloud build up** in the booster chamber, we may suggest:

For the scheme of bunch spacing of 25 ns a surface with maximum SEY = 1.7
For the scheme of bunch spacing of 15 ns a surface with maximum SEY = 1.4

Is this SEY value achieved for a NEG coating copper surface?

On going simulations

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Future Work

- Implement the photoemission .
- Verify the effects, if there are any, on the variation of the bunch intensity.
- Review the instability considerations and heat load studies.
- Study the effect of implement the Hybrid FODO lattice(HFD) on the booster.
- Among others…

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Conclusions

The FCC-ee booster has been analyzed and bring us **preliminary results** from the e-cloud point of view. It was conduced considering baseline optic elements.

→ The preliminary material constraints in terms of SEY multipacting thresholds have been presented.

→ The two options for injections (LINAC or damper ring) results suggest to similar behavior for all elements.

→ The e-cloud buld-up is similar both stages: injection and extraction.

Conclusions

The drift space has the largest SEY multipacting thresholds and the magnetic elements are more critical from the e-cloud point of view.

→ For bunch spacing 25 ns, we still have some simulations ongoing. However, until now we observe: 1.5 < SEY multipacting thresholds < 1.7

→ Considering filling schemes with smaller bunch spacing, the required material constraint is tighter, for example with a bunch spacing of 15 ns the required SEY is 1.4.

THANK YOU!

Parameters of the booster design Z operation mode

Running mode	Z	
Injection option	LINAC alone and High Energy Damping ring	
Circumference	[km]	91.174
Injection energy	[GeV]	20
Extraction energy	[GeV]	45.6
Number bunches/ring		11200
Maximum particle number/ bunch N max	$[10^{10}]$	>2.5(4 nC)
Particles / bunch in top-up	$[10^{10}]$	2.14
RF frequency	[MHZ]	800
Arc optics FODO		60°/60°
Momentum compaction		14.9×10^{-6}
Coupling		2×10^{-3}
Injection horizontal emittance (norm.)	[μm]	10
Injection vertical emittance (norm.)	[μm]	10

Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53
Injection Energy loss /turn	[MeV]	1.514
Extraction Energy loss /turn	[MeV]	40.93
Injection bunch length	[mm]	4
Extraction bunch length	[mm]	4.38
Injection RMS energy spread	$[10^{-3}]$	1
Extraction RMS energy spread	$[10^{-3}]$	0.38
Injection Maximum relative energy acceptance	[%]	3
Extraction Maximum relative energy ac		
Inj		
Ex		
Fil		
Ra		
Flat top	[s]	1.9
Total cycling time	[s]	30.54/34.14

Stages of study:

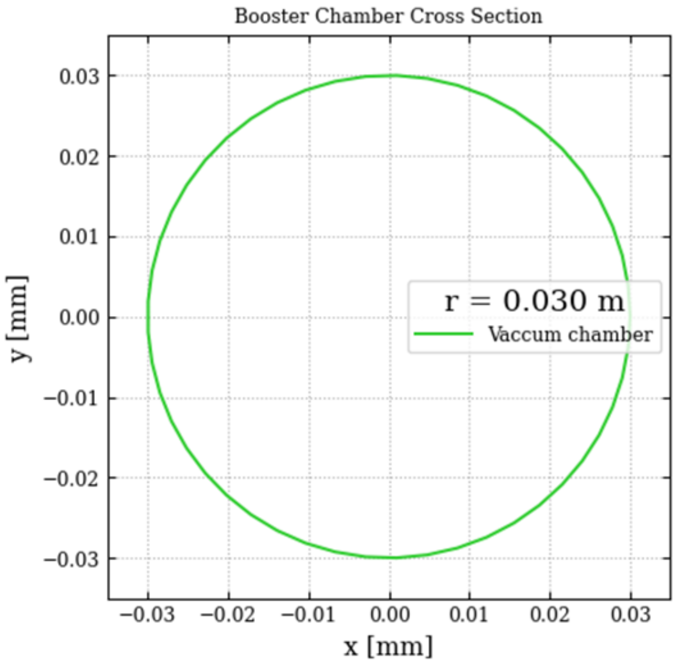
- Injection of bunches into the booster
- Injection of bunches into the collider

A Chance, *High energy booster overview,* FCC-ee week 2024

FCC FCC week 2024 12/06/24 Antoine CHANCE High-energy booster overview cea irfu 4

Major changes since FCC week 2023

- **Same circumference as the collider**.
- **Better second order matching** in the insertions.
- **Reduced number of stored bunches** in the booster (safer injection to the collider).
  - Maximum number of stored bunches at Z/W/ZH/ttar operation: 1120/890/380/56.
  - Requires 10/2/1/1 booster cycles to give the total number of bunches to the collider.
  - Shorter accumulation time.
  - Enlarges the pressure tolerance and TCBI threshold (reduced average current).
- **Reduces maximum bunch charge** for **ZH/ttbar** operation: 4 nC → 1.6 nC.
  - Reduces the peak radiated power.
  - Enlarges the allowed impedance budget for ZH/ttbar operation.
- **Larger beam pipe** aperture: 50 mm → 60 mm (Copper).
  - Smaller contribution of the beam pipe to the impedance budget.
  - Enlarges the TMCI/TCBI threshold: same optics possible for all modes.
- **Larger misaligment errors** (150 um pre-alignment in the arcs → 200 um girder-to-girder + 50 um girder pre-alignement) and **orbit tuning procedures**



Circular cross section of the booster vacuum chamber, with 60 mm of diameter.

A. **Chance**, *High-energy booster overview,* FCC Week 2024, Junio 2024

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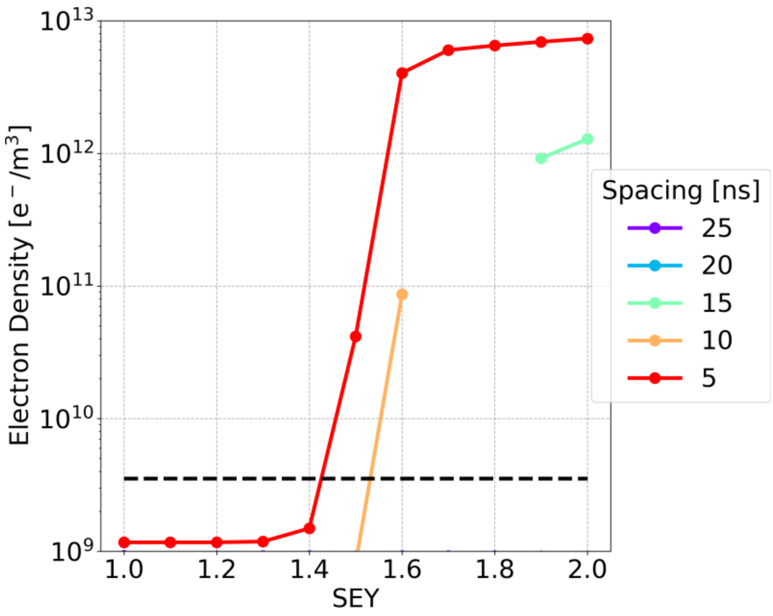
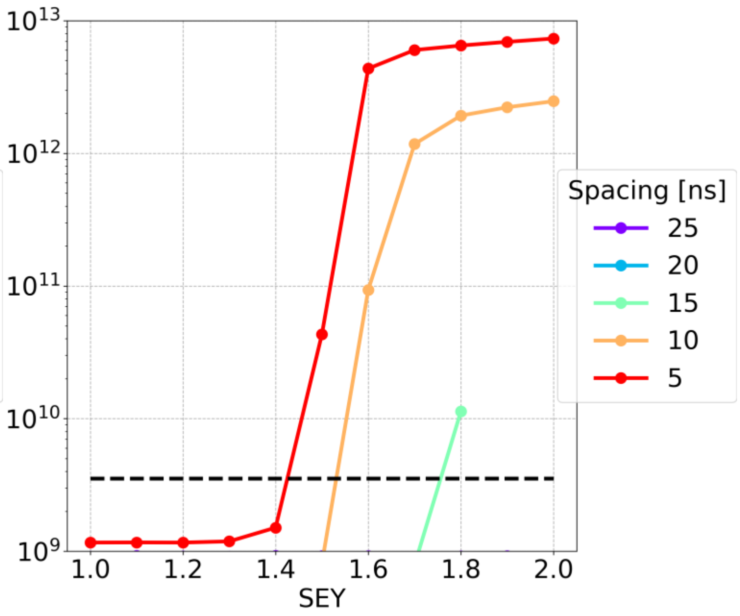
Booster at injection at dipoles

LINAC



Damping Ring



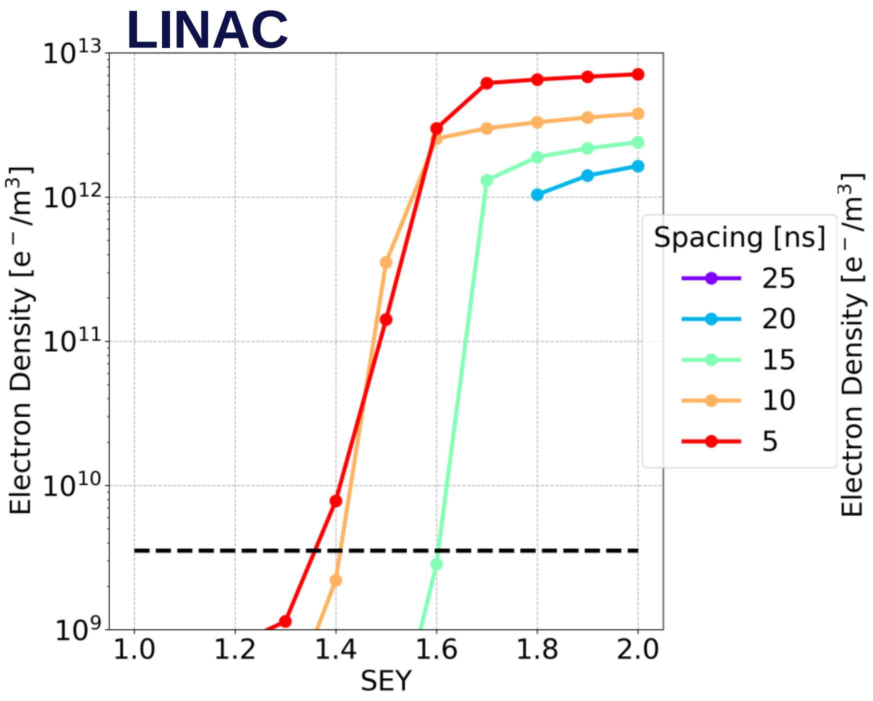
Injection Option	Bunch spacing [ns]				
	5	10	15	20	25
LINAC	1.4	1.5	>1.6	>2.0	>1.6
Damping ring	1.4	1.5	1.7		

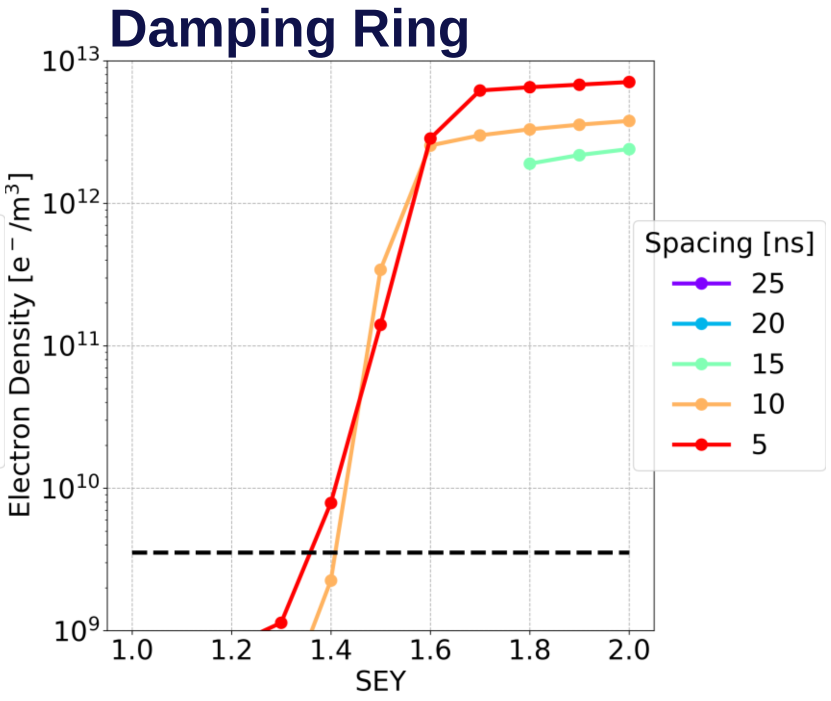
Considering both options for injection of the beam at the booster, it is clear that for the lowest bunch spacing values scanned, both options present similar behavior.

For example: 10 ns bunch spacing the preliminary SEY multipacting threshold is1.5

For larger values, we have ongoing studies

Booster at injection at sextupoles





Multipacting occurs for 15 ns with SEY >1.5 for both options of injection of the beam to the booster.

For lower bunch spacing, both options of beam injection to the booster have similar behavior.

Injection Option	Bunch spacing [ns]				
	5	10	15	20	25
LINAC	1.3	1.4	1.6	>1.6	>1.6
Damping ring	1.3	1.4	>1.5	>1.6	>1.6