Electron Source Development for FCC-ee: Exploring the Pre-Accelerator Complex and Refilling Scheme

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Future Colliders for Early-Career Researchers: CZ/SK Edition

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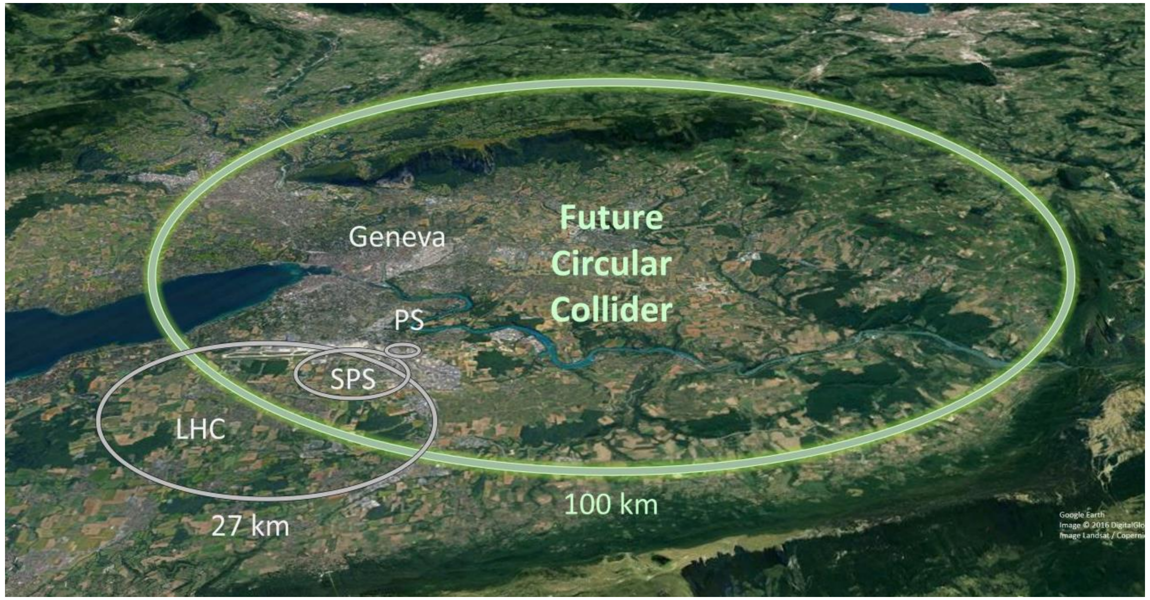
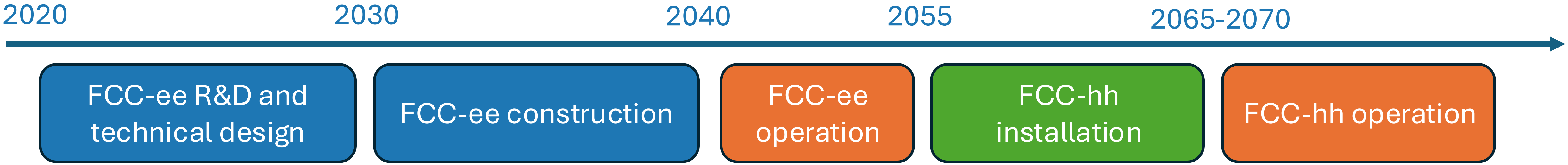
Overview

- FCC-ee (pre-)accelerator complex
- The electron source for the FCC-ee
- Filling scheme of the collider rings

Future Circular Collider (FCC) roadmap

- ~ 91 km long circular accelerator
- Feasibility study
- ~ 2030 tunnel construction
- ~ 2040 FCC-ee operation
  - Electron, positrons, up to 182 GeV
- ~ 2065-2070 FCC-hh
  - Protons, 50 TeV



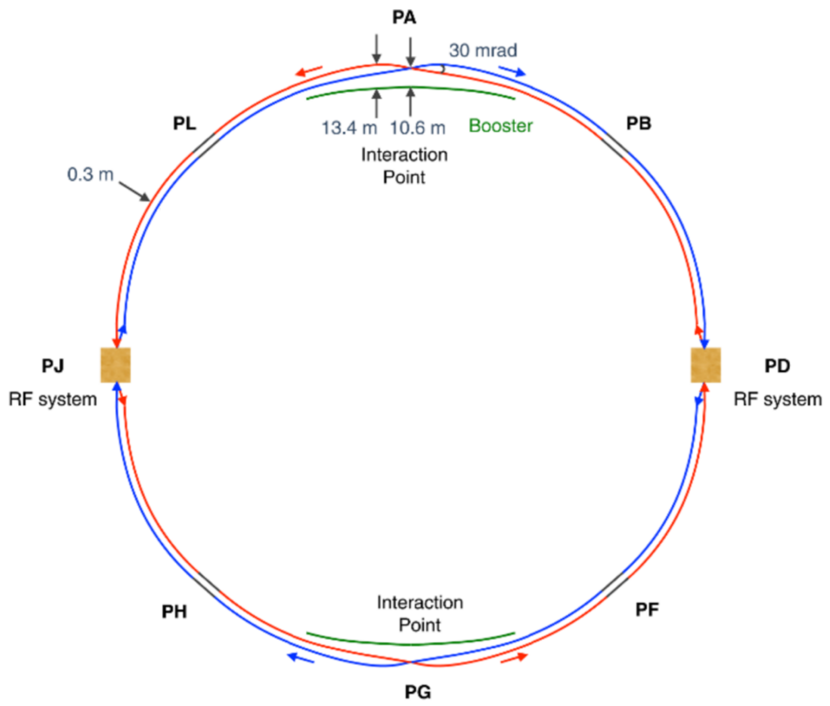


Cost estimate

Item	Cost estimate [milion CHF]
FCC-ee (including civil engineering)	10 500
FCC-hh (if replacing FCC-ee)	17 000
Electron source	7.9
CERN yearly budget (2022)	1 400

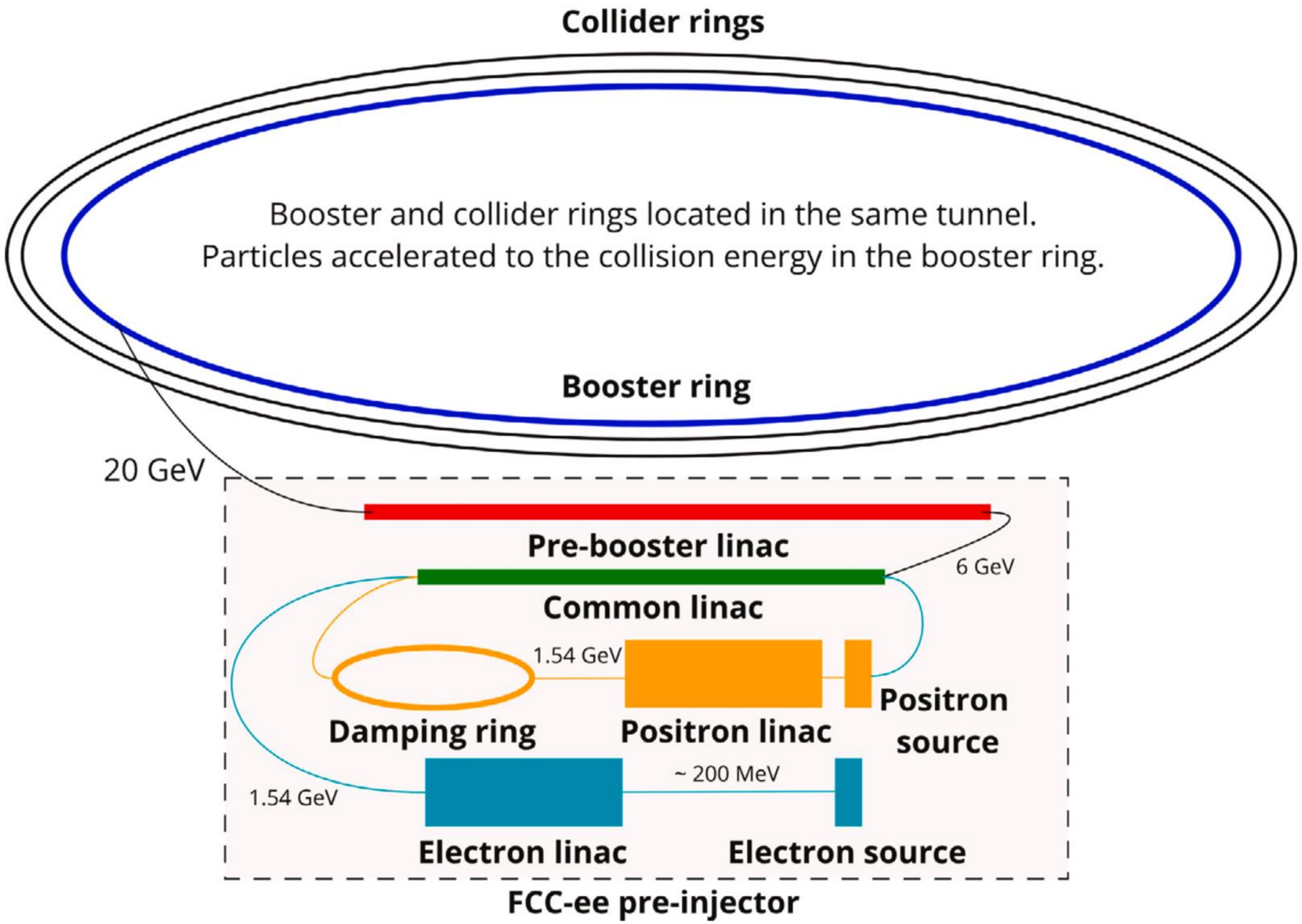
FCC-ee collider tunnel

- **Collider**: Two rings, two interaction points
- **Booster ring**: One ring, serves as injector
- All located in the same tunnel
- **Target physics** (energies per electron/positron)
  - Z pole measurements: 45.6 GeV
  - W pair: 80 GeV
  - Higgs factory: 120 GeV
  - Top-antitop production: 182.5 GeV

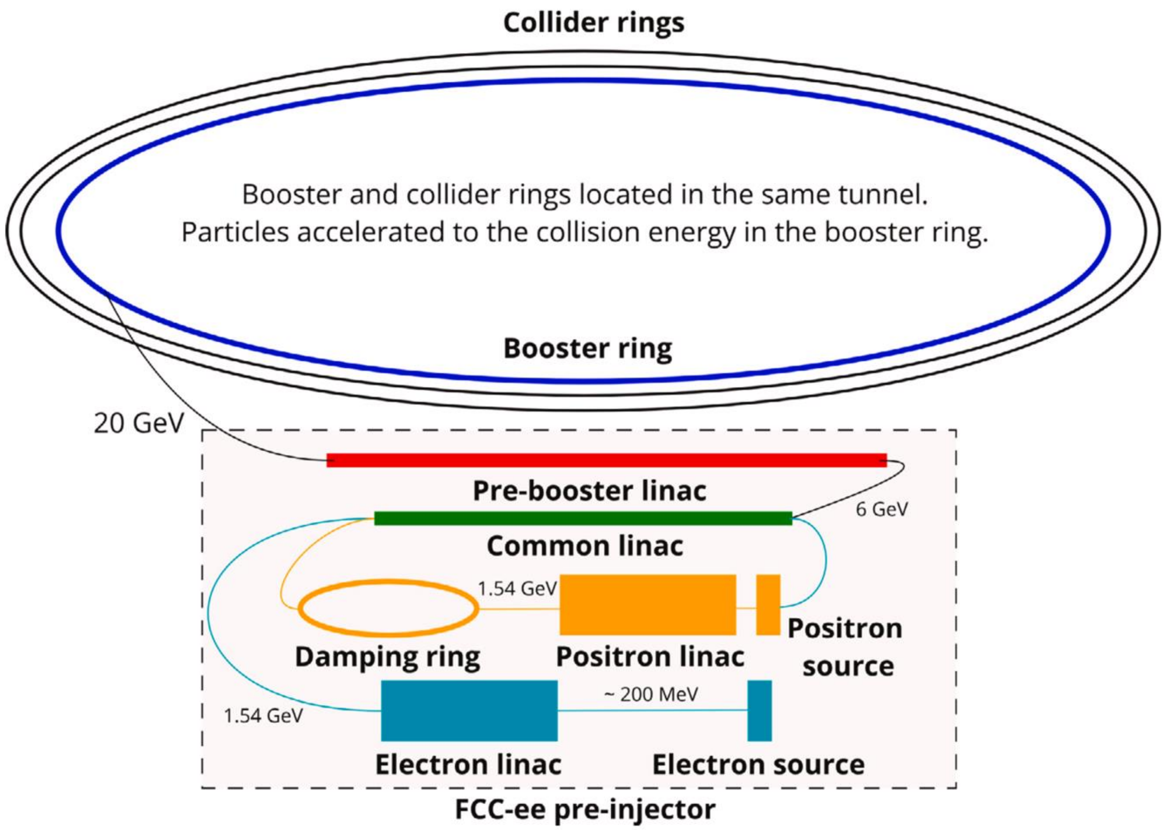


FCC-ee accelerator complex

- Preinjector study performed by within the CHART FCC-ee collaboration: CERN, PSI, IJCLab, INFN-LNF
- Studies of reusing SPS instead of building new HE linac
- LHC is not part of the complex



FCC-ee filling scheme

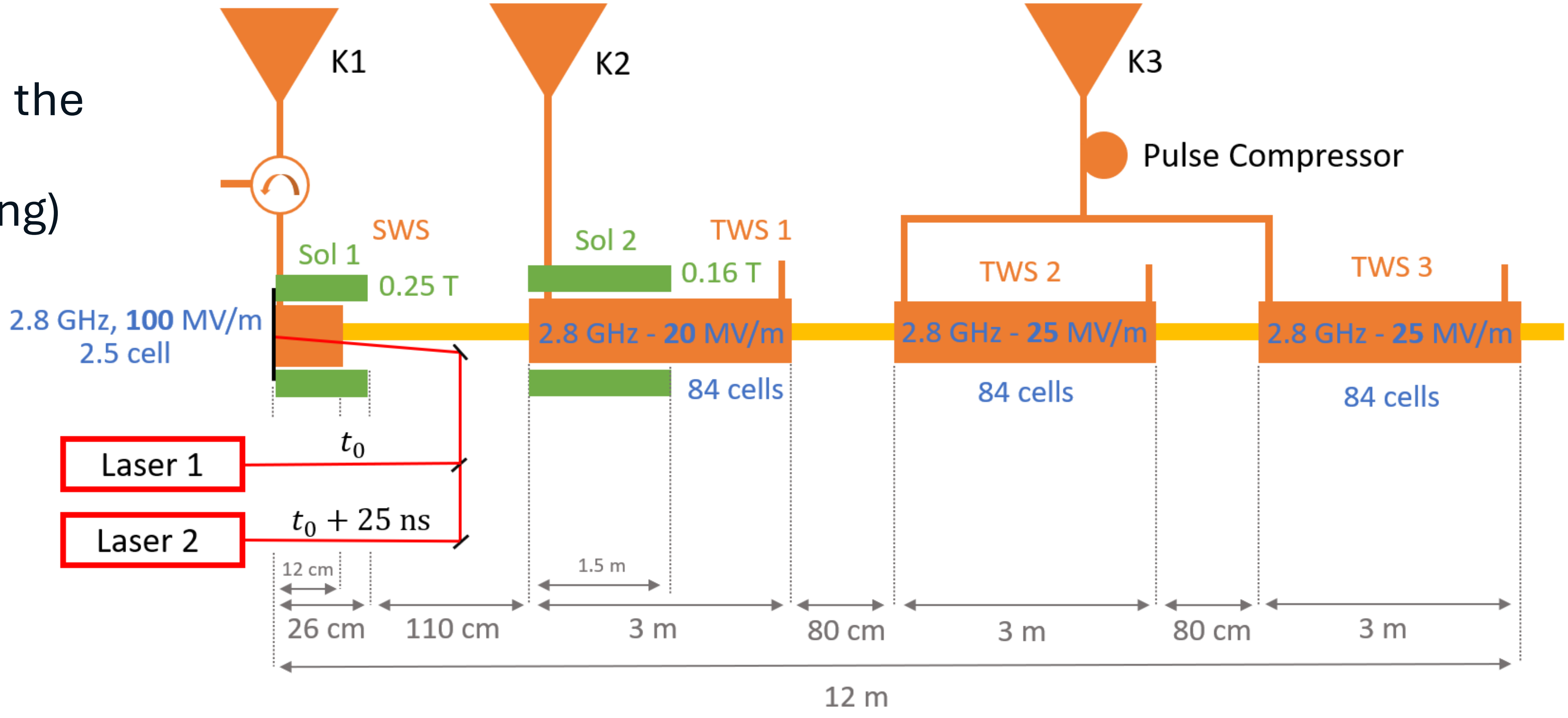


- CR filling in several cycles
- Limited by the maximum synchrotron radiation power (100 MW)
- Injector complex provides bunches with smaller charge
- Bunch merging in the CR

Parameter	Z pole	WW pair	Higgs factory	tt production
Energy [GeV]	45.6	80	120	182.5
No. of CR bunches	16000	1800	450	48
CR bunch charge [nC]	24	23	18	25
No. of BR cycles	10	10	10	20
Filling time [min]	17	4	2	4

Design of the electron source

- Inspired by the SwissFEL electron gun
- Two lasers to comply with the generation rate (200 Hz, 2 bunches with 25 ns spacing)
- 4 accelerating structures
- Two focusing solenoids

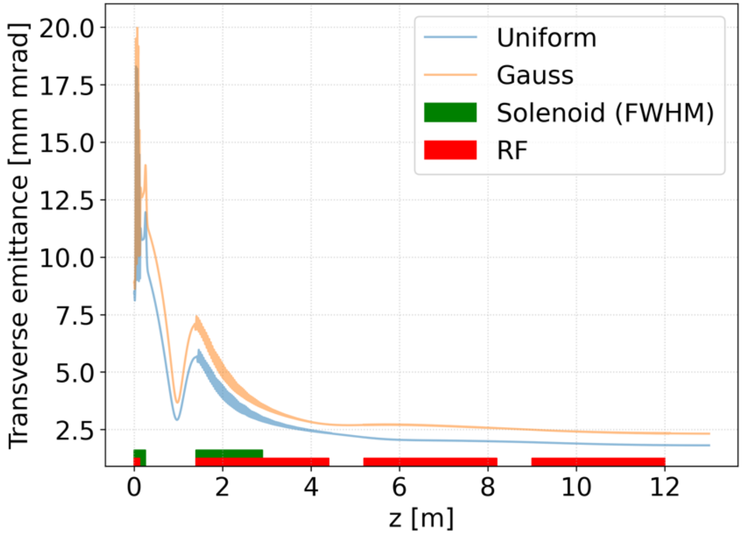


Design of the electron source

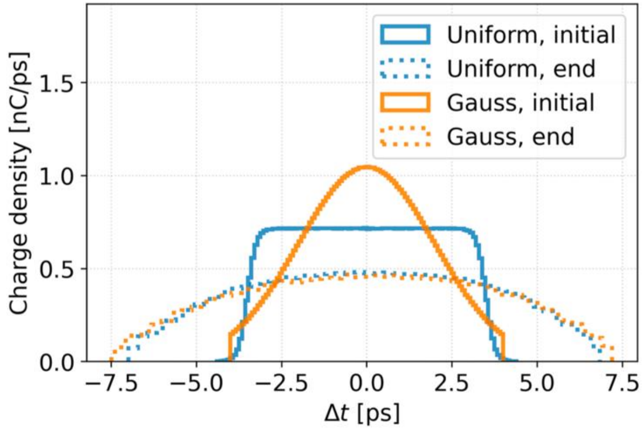
- Simulations in ASTRA
- Assigned bunch parameter budget
- FCC-ee needs subject to change → important margins

Bunch parameter	Limit	Achieved with Uniform	Achieved with Gaussian
Transverse emittance	< 4 mm mrad	1.81 mm mrad	2.39 mm mrad
Bunch length (rms)	~ 1 mm or shorter	1.01 mm	1.06 mm
Energy	~ 200 MeV	168 MeV	168 MeV
Energy spread	< 5 %	0.21 %	0.25 %

Emittance evolution within the electron source

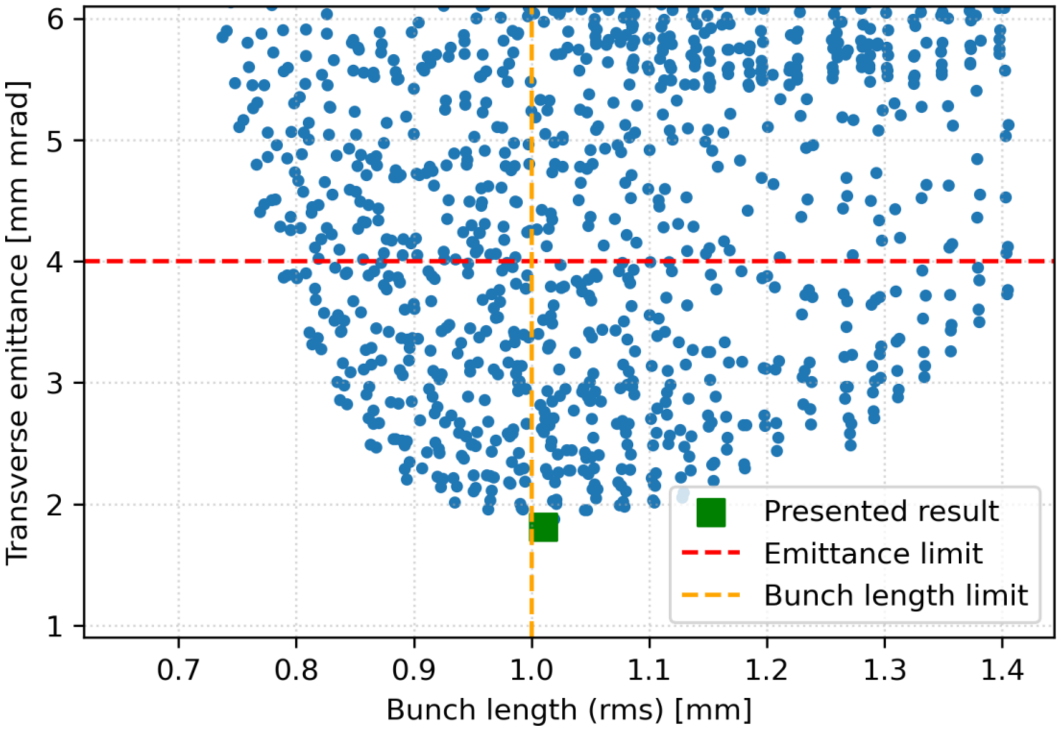


Longitudinal charge distributions



Trading emittance for bunch length

Emittance and bunch length scan



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- Changing the initial distribution (emission radius and length)
- Optimised magnetic field

Stability of the electron source

- Error study performed to assess the stability of the setup
- Required precisions can be reached
- Emittance / bunch length exchange

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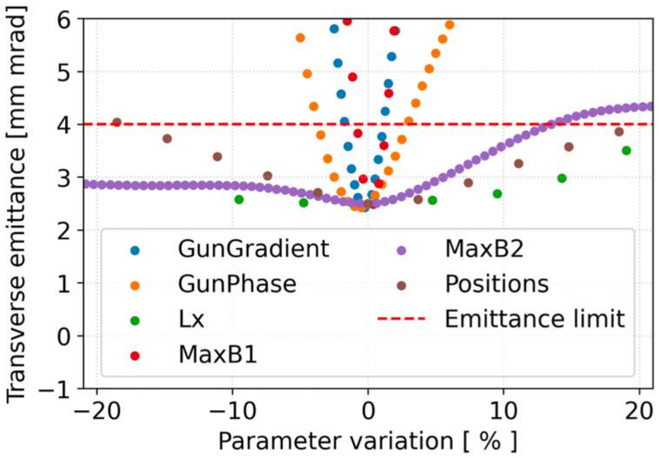
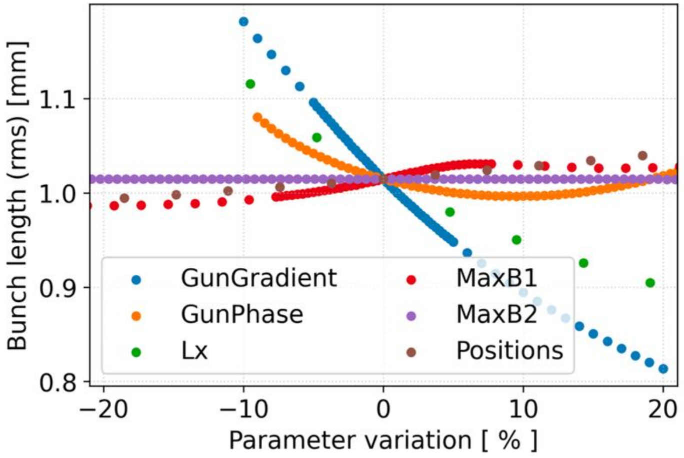
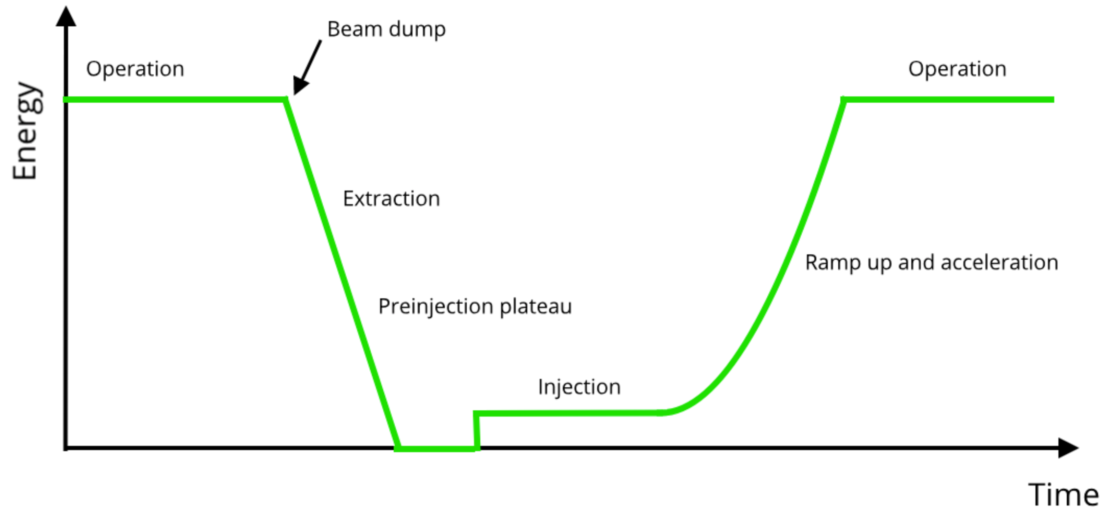




Beam lifetime in the collider rings

- Loss of particles due to collisions, beam-to-beam effects, imperfections …
- Stable conditions → luminosity limit
- **Beam lifetime**
- **Hadron Colliders** (LHC): beam dumping + filling from scratch
- **Lepton Colliders**?



Operation region	Lifetime [min]	Filling time [min]
Z pole	68	17
W pair	59	4
Higgs production	18	2
Top-antitop production	18	4

Beam refilling

- To achieve higher integrated luminosity
- FCC-ee: charge of individual CR bunches is measured, and the beam is refilled when needed (goal: bunch charge within ± of design charge)
- **How to achieve this?**

Beam refilling

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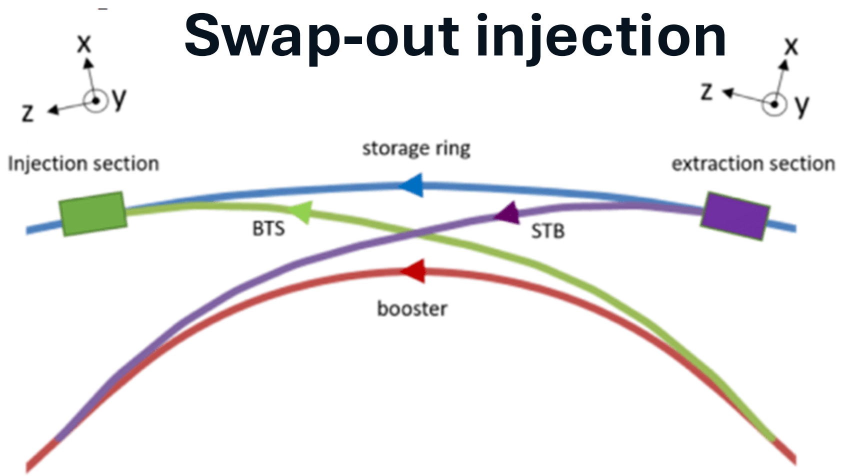
Swap-out injection



- Pre-accelerators would have to provide full-charge bunches
- Problems with synchrotron radiation power

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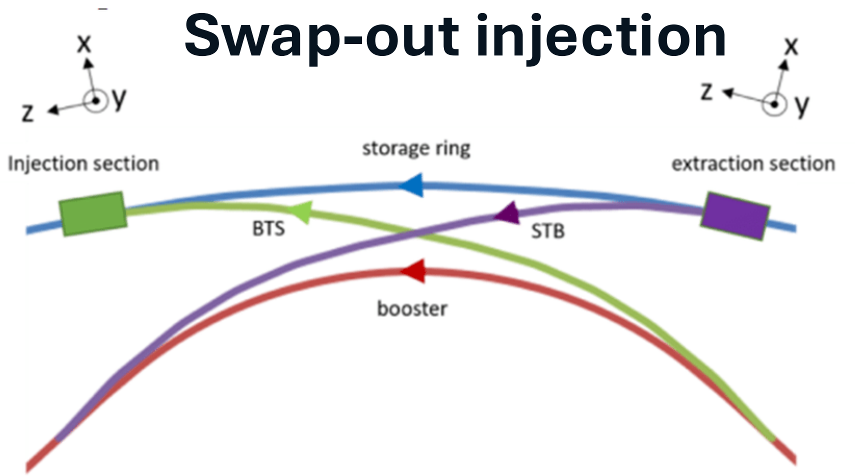
Swap-out injection



- Pre-accelerators would have to provide full-charge bunches
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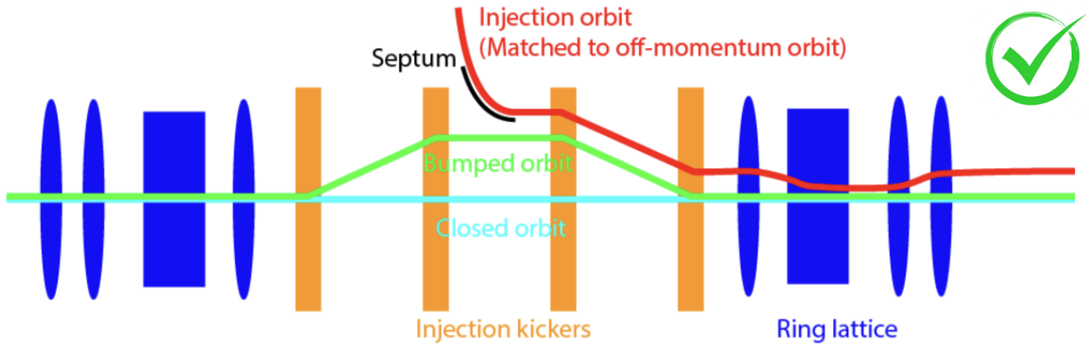
Top-up injection

- Pre-accelerators **provide just enough charge to replenish to design charge, for each bunch individually**

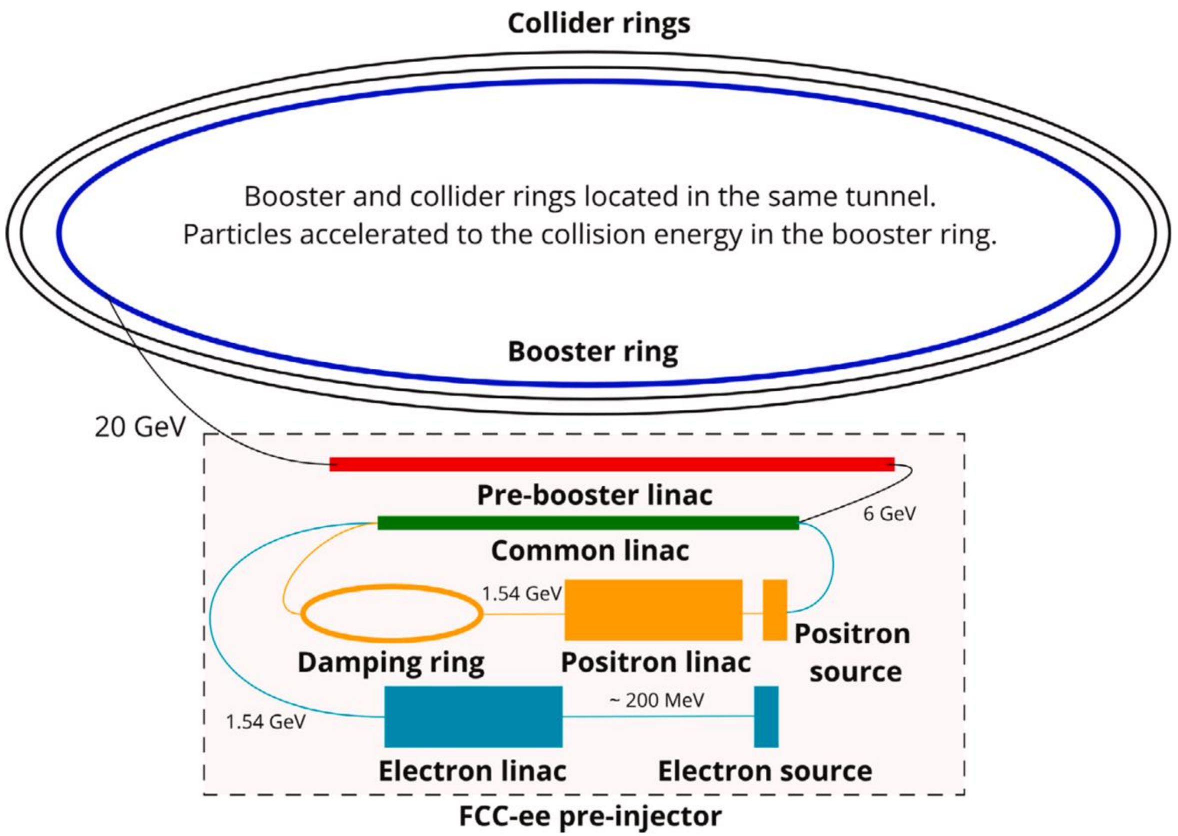


Top-up injection and the pre-accelerator complex

- Top-up = providing specific amount of charge for each bunch individually
- Some numbers:
  - CR bunch charge: ~ 20 nC
  - Target: stay around 5 % (1 nC)
  - Electron source peak charge: 5 nC
- **Electron / positron sources need to generate arbitrary charge in range 10-100 % on a shot-to-shot basis**

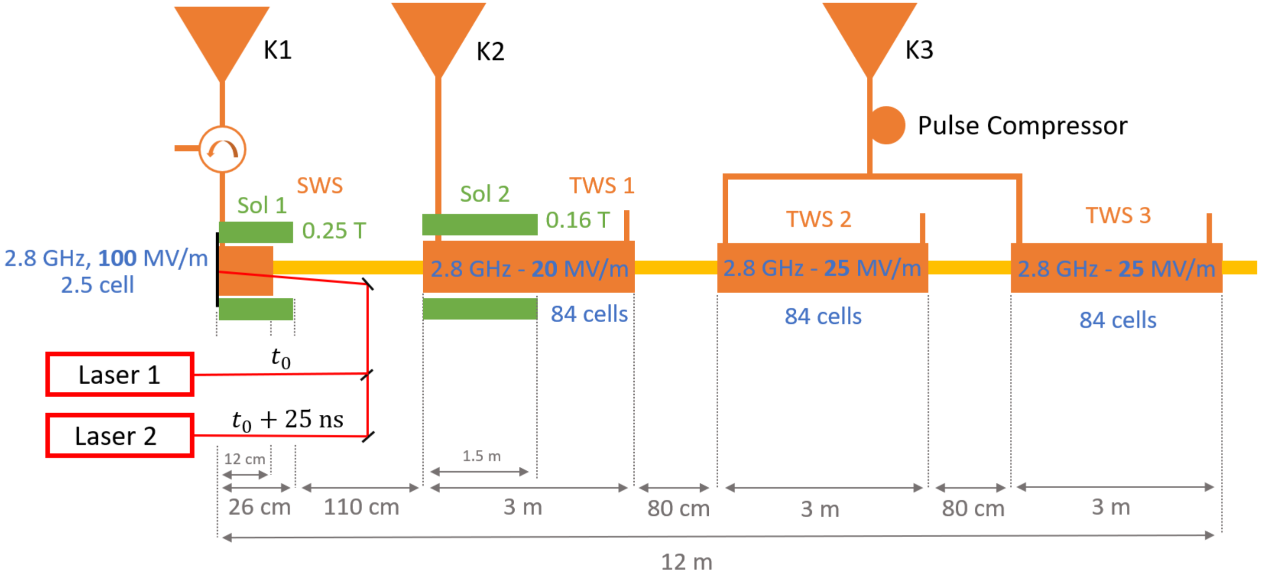
Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

How can we generate the different charge?
How can we reoptimise the gun?



Charge variation at the electron gun

- **Gun setup cannot be optimized to each charge individually**
- From performed simulations: solenoid focusing field is crucial
- **Our proposal**: keep charge density fixed, decrease the charge by decreasing emission area



Charge scaling with emission radius
(constant charge density)

$$R = \sqrt{\frac{Q}{Q_0}} R_0$$

Q … Wanted charge
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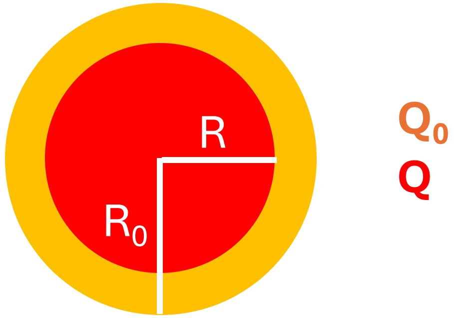
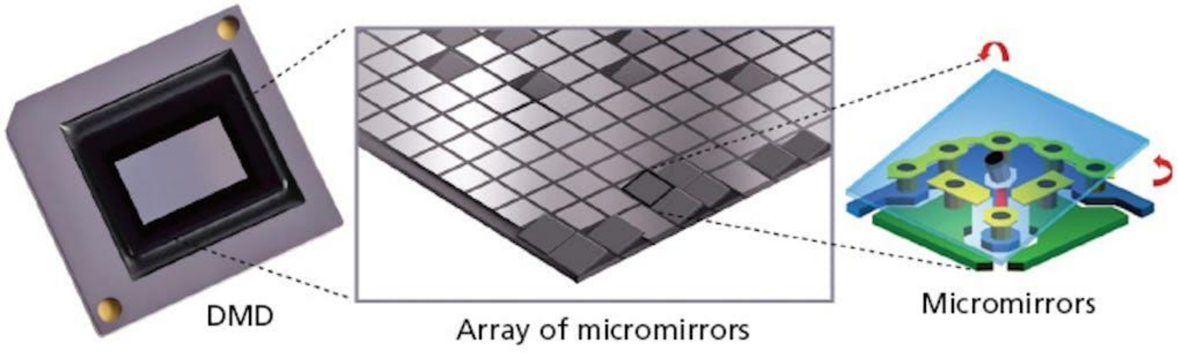


Charge variation at the electron gun

Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

- **Laser needs to be adjusted**
  - Continuous charge spectrum → ~~set of lasers~~
- Dynamically changing laser radius:
  - Possible to use commercial **Digital Micro-mirror device (DMD)**
- **Using DMD to scale down emission area with target charge**



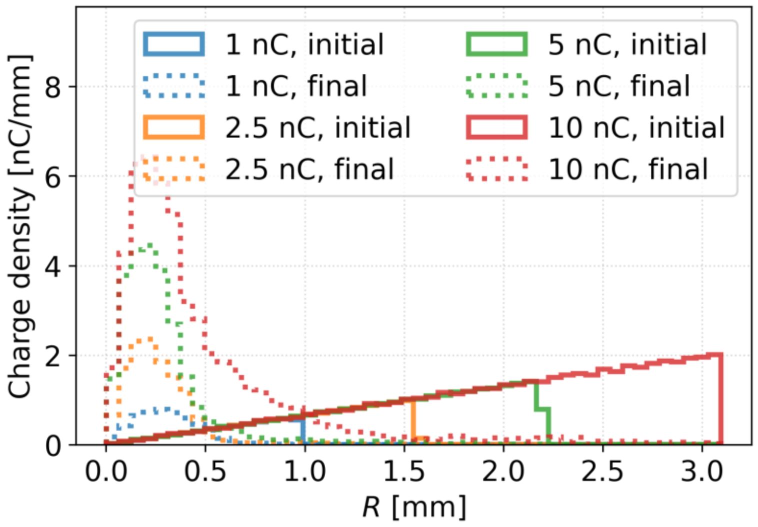
Parameter	Value
Operational frequency	Up to 32 kHz
Mirror (pixel) dimension	~ 7 μm

Charge variation at the electron gun

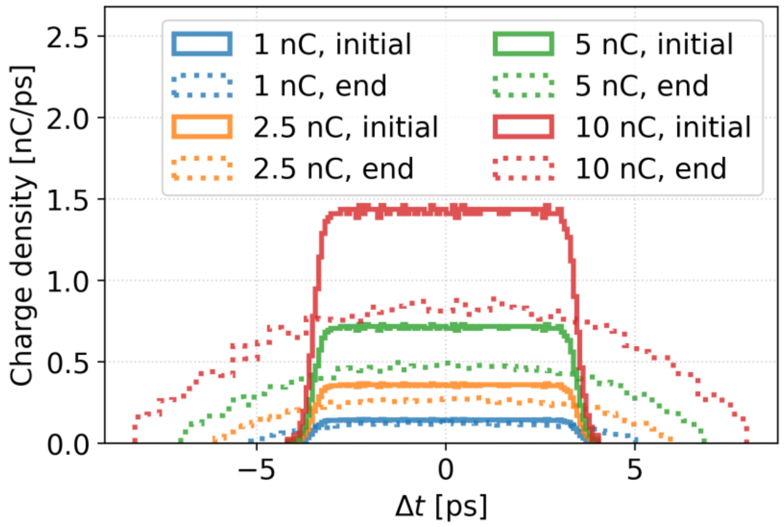
Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

- Emission radius scaled down with target charge
- Starting point: optimized setup for 5 nC
- **Gun setup remains fixed**
- Possibility to generate higher charges than the peak design charge

Transverse distribution



Longitudinal distribution



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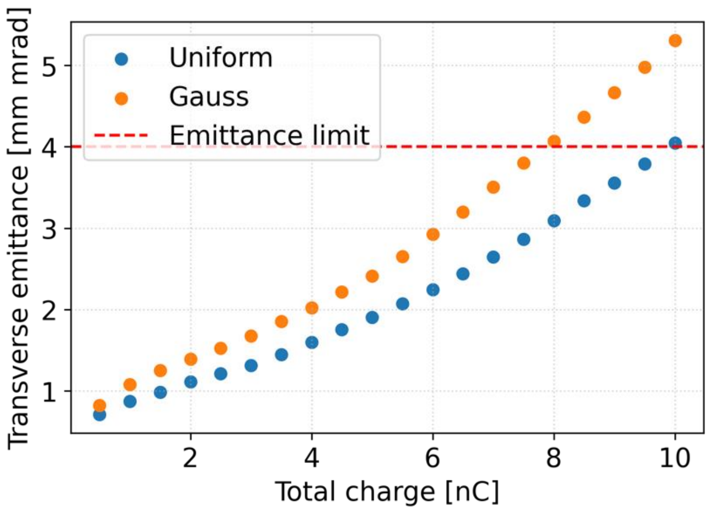
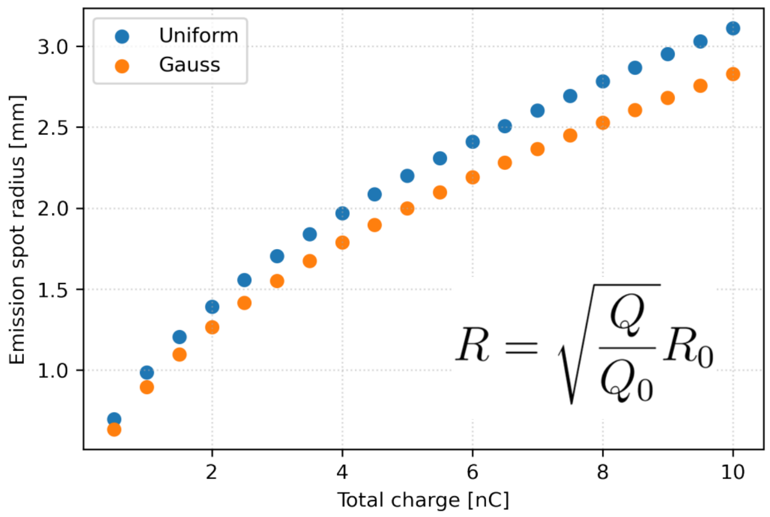
Emittance scaling with the charge



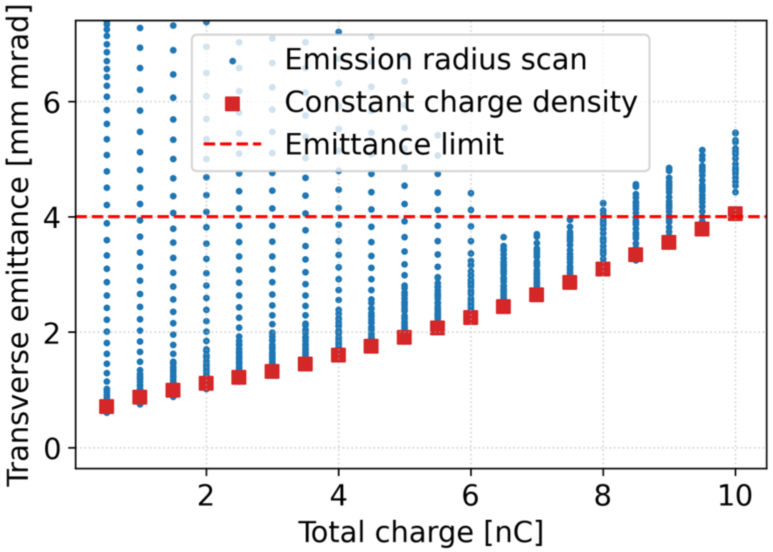
Emission radius scaling with charge

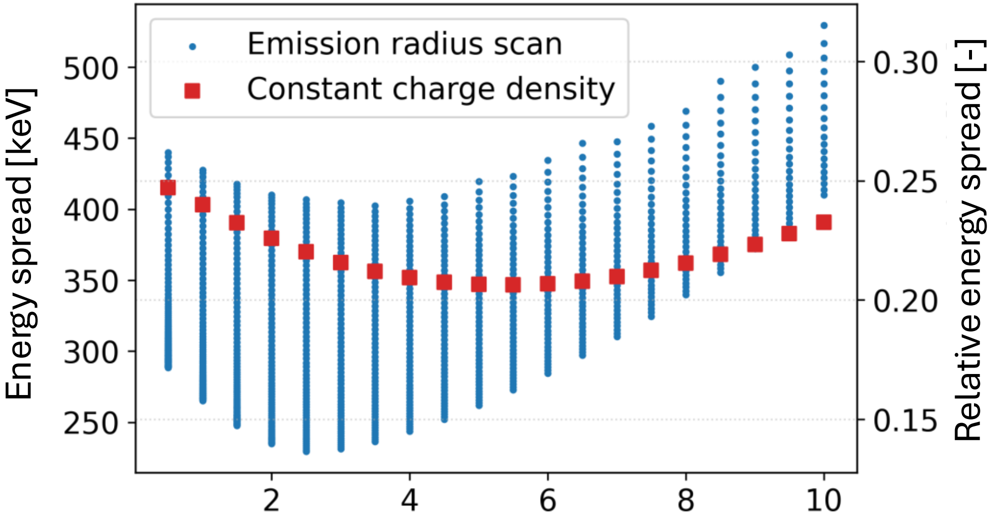


Is this charge variation the optimal?

Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

- Squares: our charge variation
- Dots: other charge-emission area combination
- **Presented method minimizes the emittance**





Summary and outlook

- FCC is in the phase of feasibility study
- Large number of parameters is subject to change
- A top-up refilling scheme is required to maintain high integrated luminosity
- Demonstration of compatibility of an electron source with the needs of the accelerator complex and top-up injection scheme
- **And outlook?**
  - Feasibility study → do we have technology to build the FCC-ee?
  - Prototype construction: electron source is an ideal candidate

Backup slides

Emittance

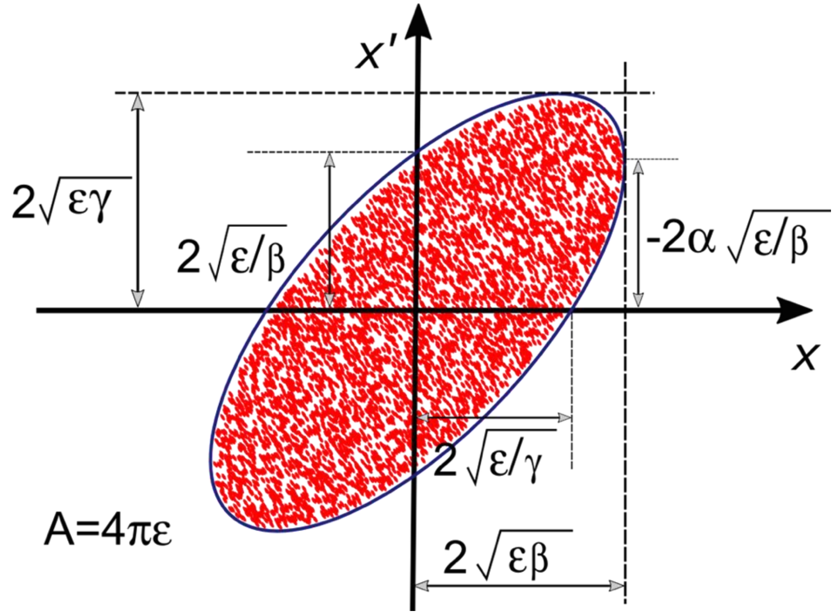
- Single stable particle → ellipse in the x,x' space

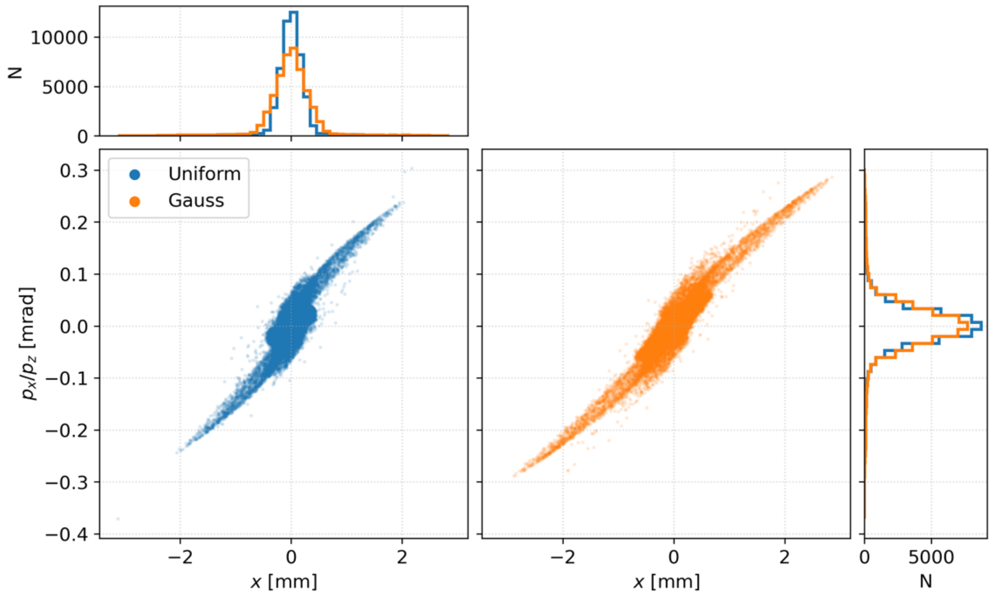
$$\frac{\varepsilon}{\pi} = \gamma x^2 + 2\alpha x x' + \beta x'^2$$

- Collective properties of beam → ellipse that encloses fraction of total particles

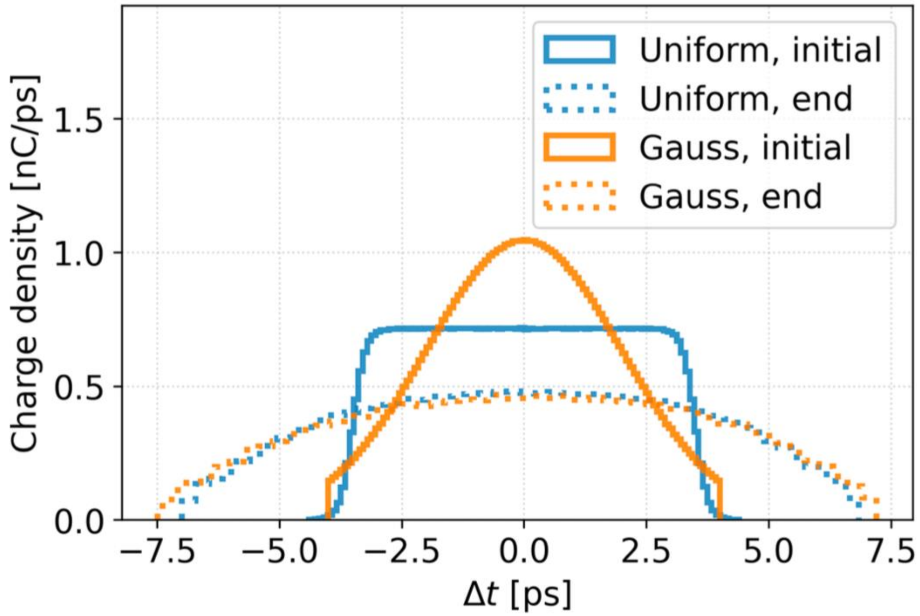
- The distribution is not always ellipse-like → statistical definition

$$\varepsilon_{\mathrm{RMS}} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2}$$

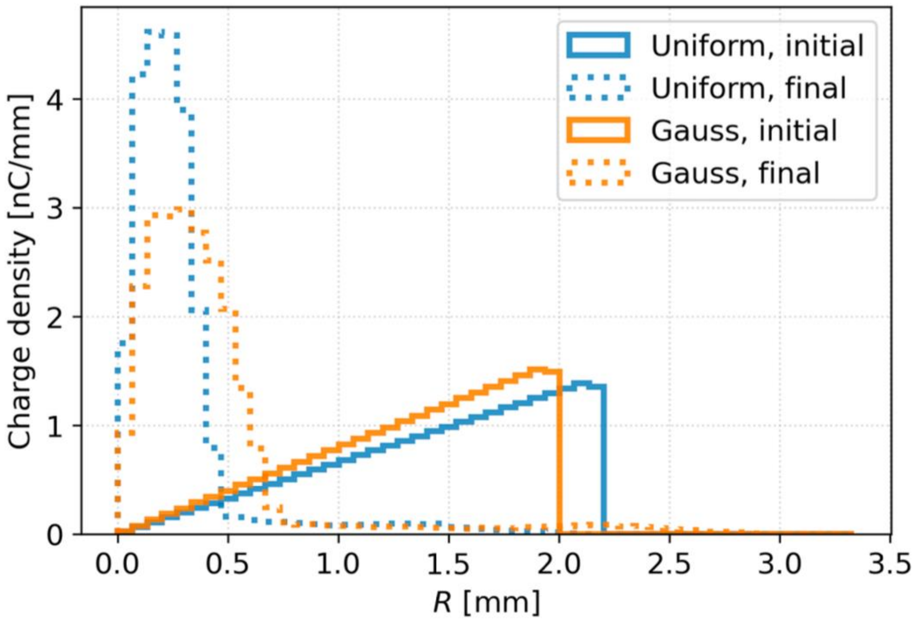




Transverse and temporal particle distributions

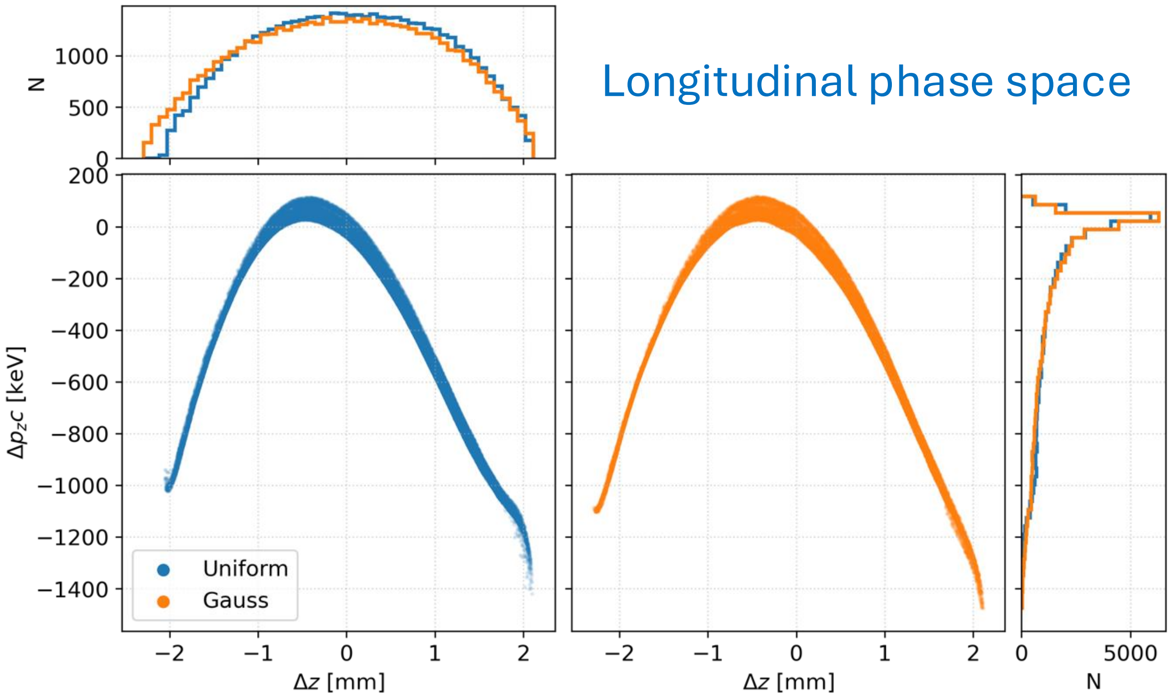


(a) Temporal particle distributions

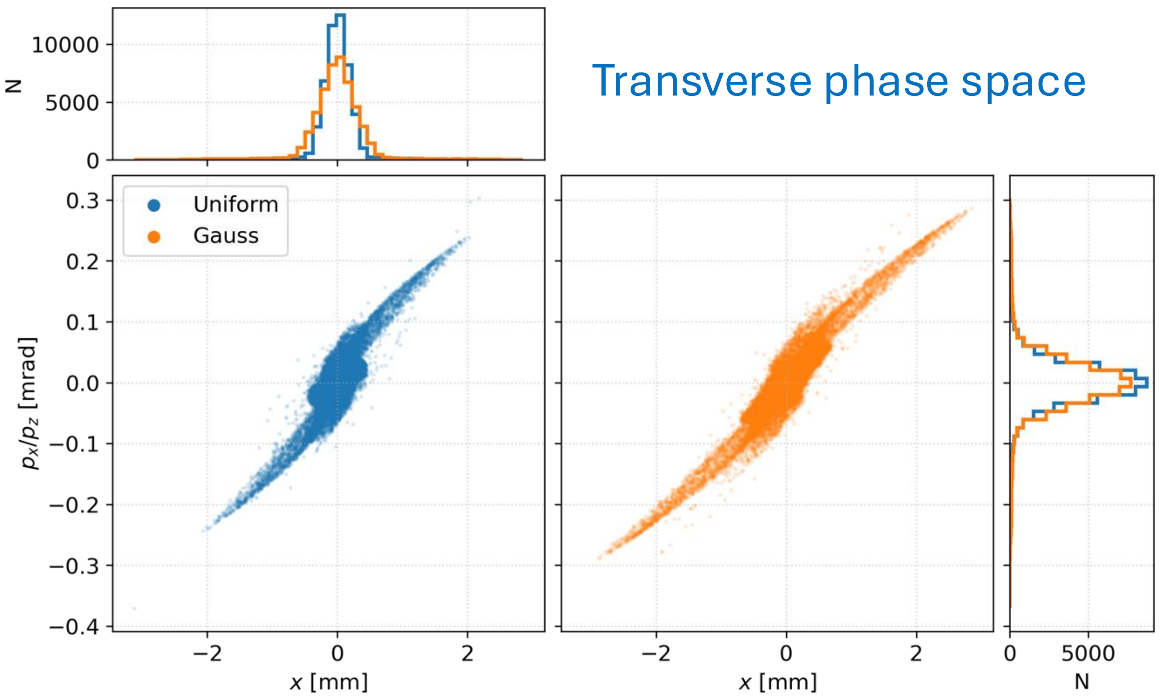


(b) Transverse particle distributions in polar coordinates ($R^2 = x^2 + y^2$).

Transverse and longitudinal phase space



Longitudinal phase space



Transverse phase space

Charge variation at the gun

Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

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Charge scaling with emission radius (constant charge density)

$$R = \sqrt{\frac{Q}{Q_0}} R_0$$

Q ... Wanted charge
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Q_0, R_0 ... Peak charge and corresponding emissin radius

Linear charge density

$$\lambda(l) = \frac{\mathrm{d}Q}{\mathrm{d}l} = \frac{\mathrm{d}}{\mathrm{d}l}\left(Q_0 \frac{R^2}{R_0^2}\right) = \frac{\mathrm{d}Q_0}{\mathrm{d}l}\frac{R^2}{R_0^2} = \lambda_0(l)\frac{R^2}{R_0^2}$$

Transverse space charge forces

$$F_T(r,l) = \frac{e}{\gamma^2}\frac{\lambda(l) r}{2\pi\epsilon_0 R^2} = \frac{e}{\gamma^2}\frac{\lambda_0(l) r}{2\pi\epsilon_0 R_0^2} = F_{T,0}(r,l)$$

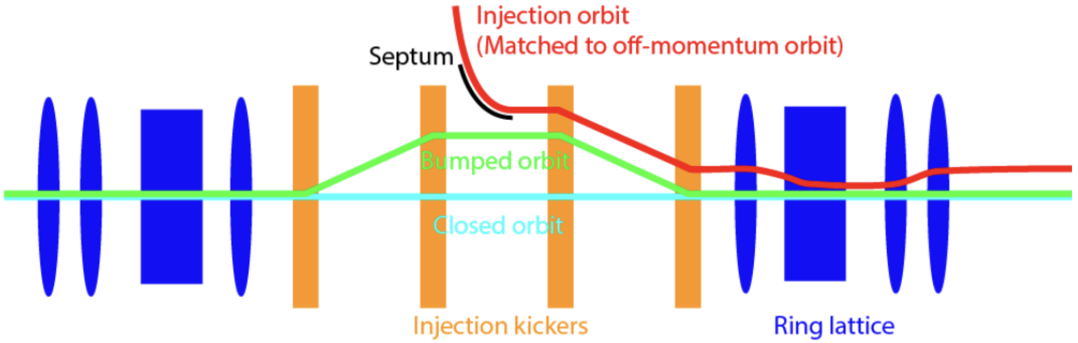
e ... Elementary charge
γ ... Lorentz factor
λ ... Linear charge density
ε ... Vacuum permittivity
r ... Radial position inside the bunch
l ... Longitudinal position inside the bunch
R ... Bunch radius

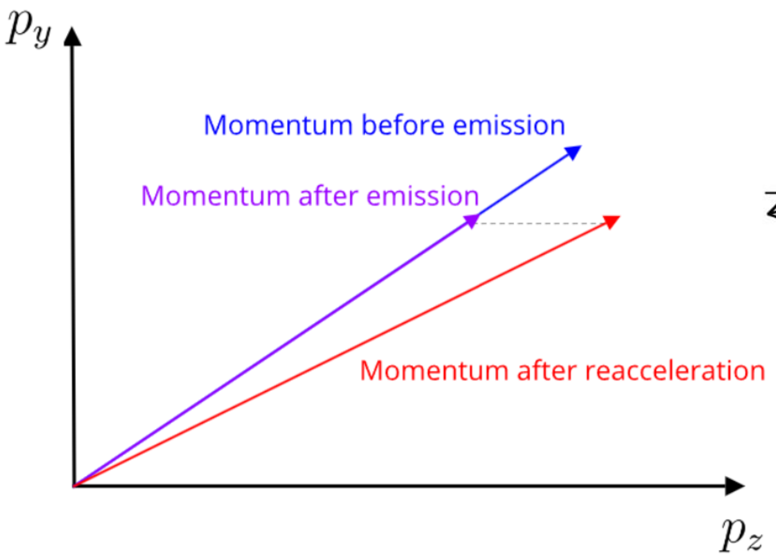
Continuous refilling scheme

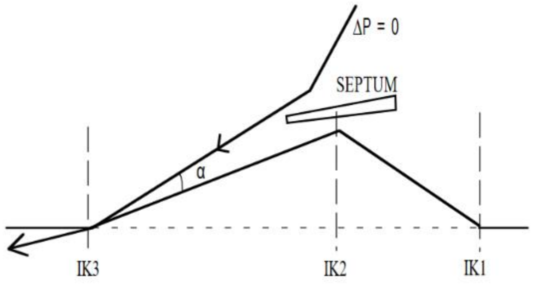
- Due to the short lifetime
- **On-demand system**: each bunch will be refilled individually
- → specific amount of charge to be delivered to each bunch
- **→ shot-to-shot charge variation at the gun**

Shot-to-shot = 200 Hz, 2 bunches with 25 ns spacing

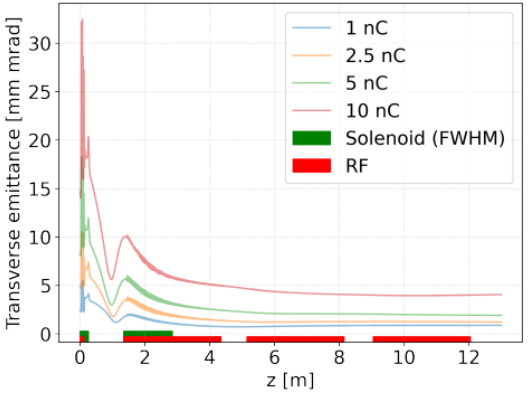
How can we generate the different charge?
How can we reoptimise the gun?



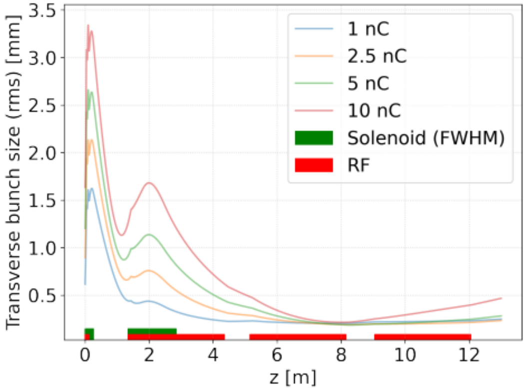




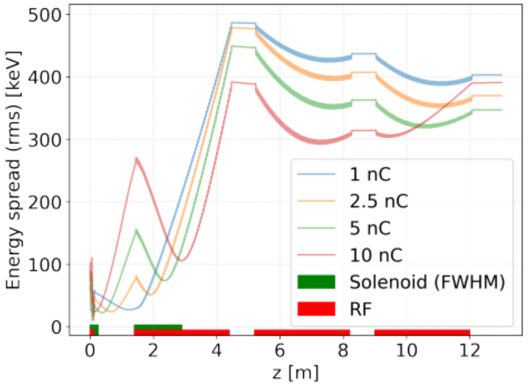
Parameter development in the electron source



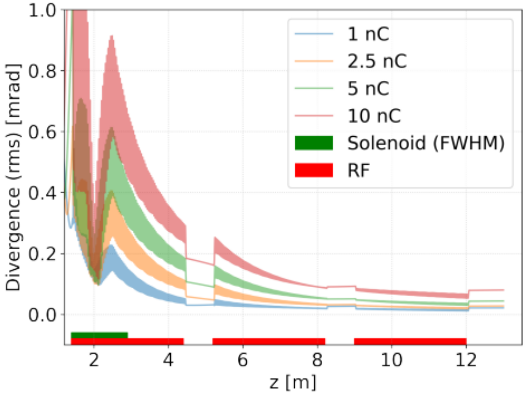
(a) Emittance development.



(b) Transverse bunch size (rms) development.



(c) Energy spread (rms) development.



(d) Beam divergence (rms) development. The gun part is removed due to large oscillations.