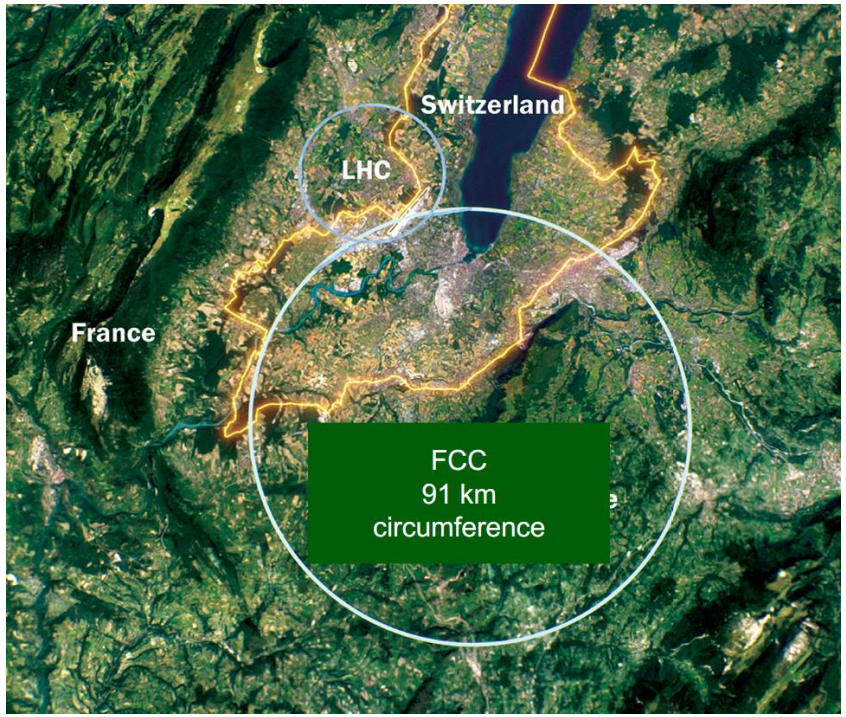


FCC-ee electron source(s) studies

Zdenek Vostrel, Steffen Doebert and Mike Seidel

9 October 2026

The Future Circular Collider (FCC)



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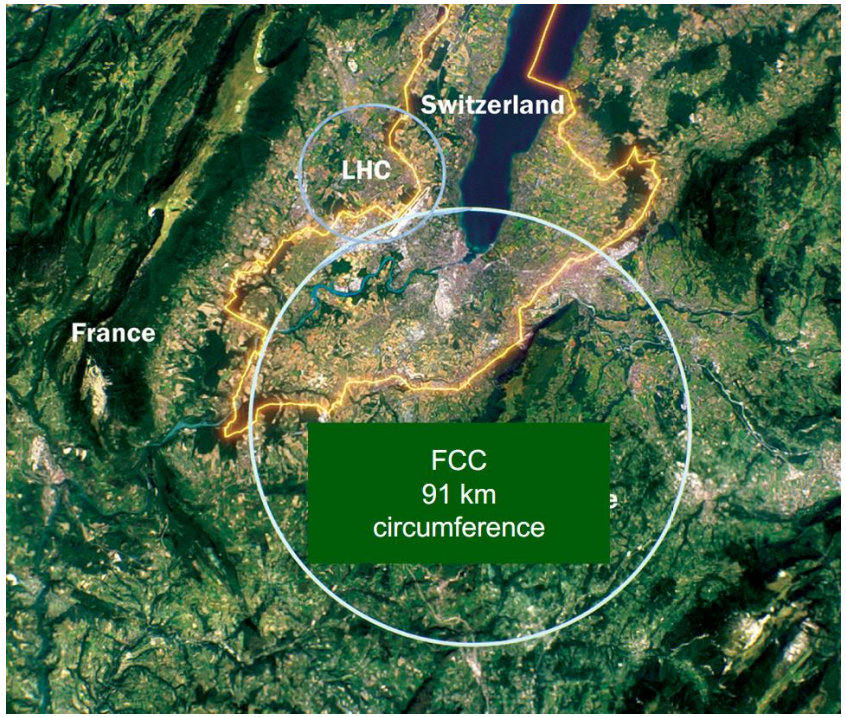
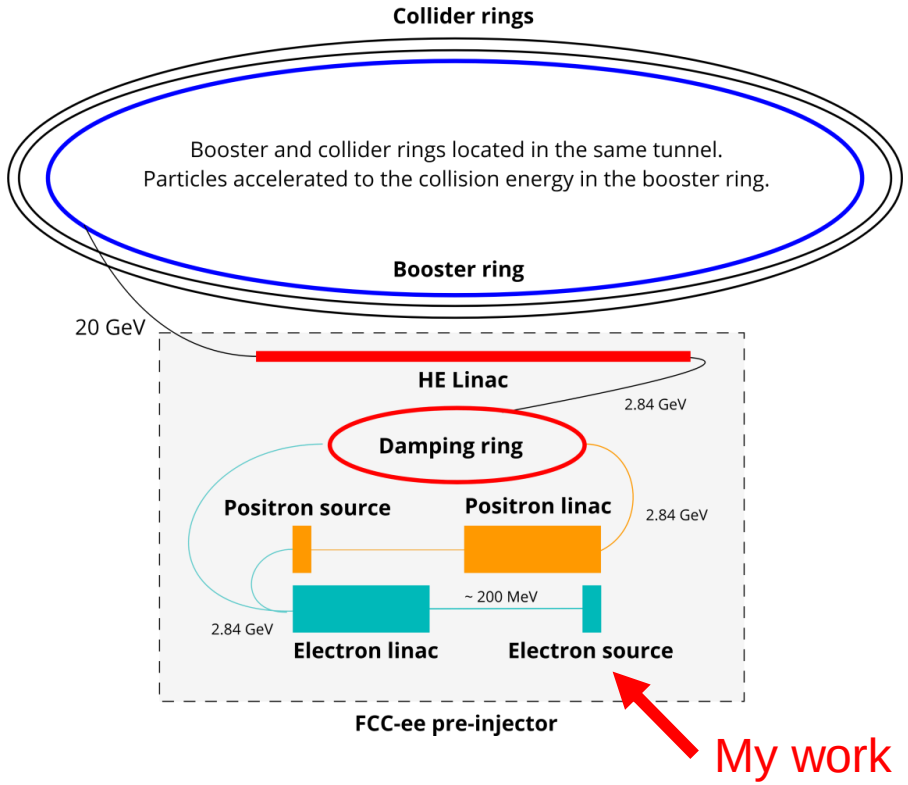
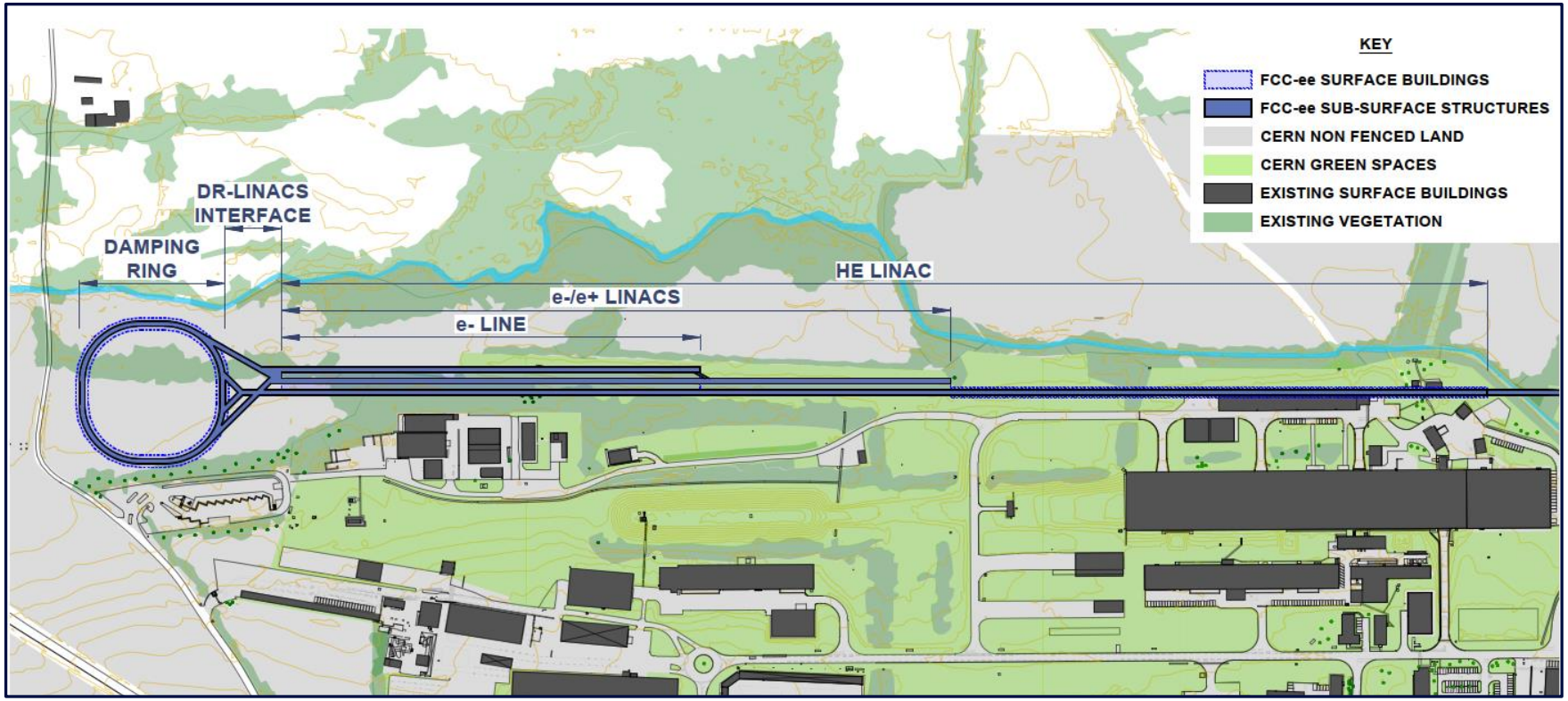
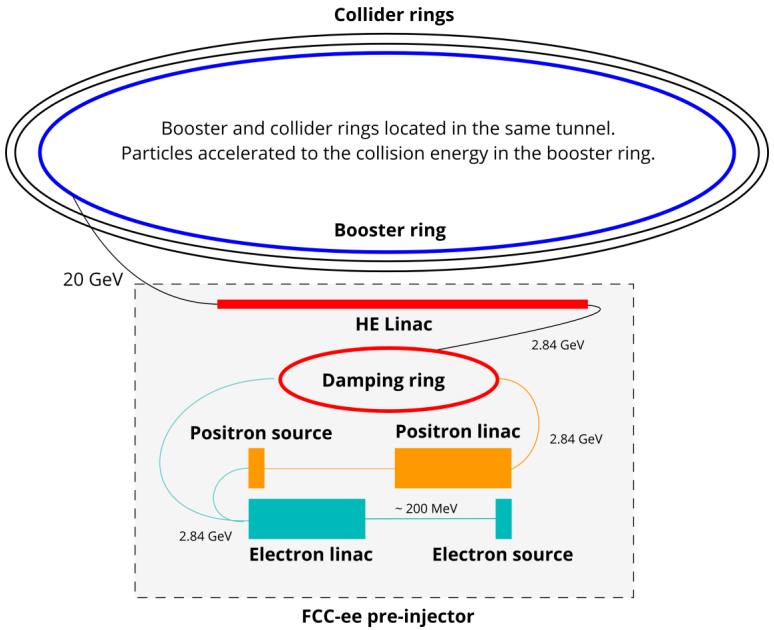




Pre-injector complex



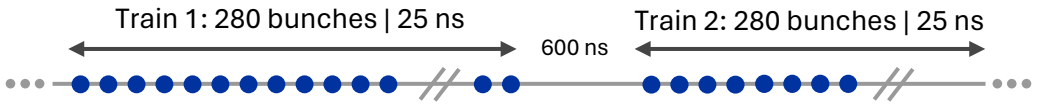


Tim WALSON (CERN), FCC Week 2026 - https://indico.cern.ch/event/1552126/contributions/7132567/attachments/3291464/5885452/260608_FCC_Week_CE_Injector_Complex.pdf

What do we need from the electron source?

Filling scheme – Z mode (91 GeV c.o.m.)

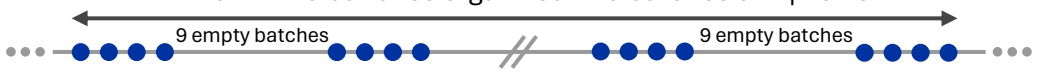
Collider ring



40 trains × **280** bunches per train = **11 200** bunches per specie
1 bunch = **34.4 nC**

Booster injection = **1/10** of nominal charge & **1/10** of bunches → **100 injection** needed

Booster



40 trains × **28** bunches per train = **1 120** bunches per specie
1 bunch = **3.44 nC** (at extraction)

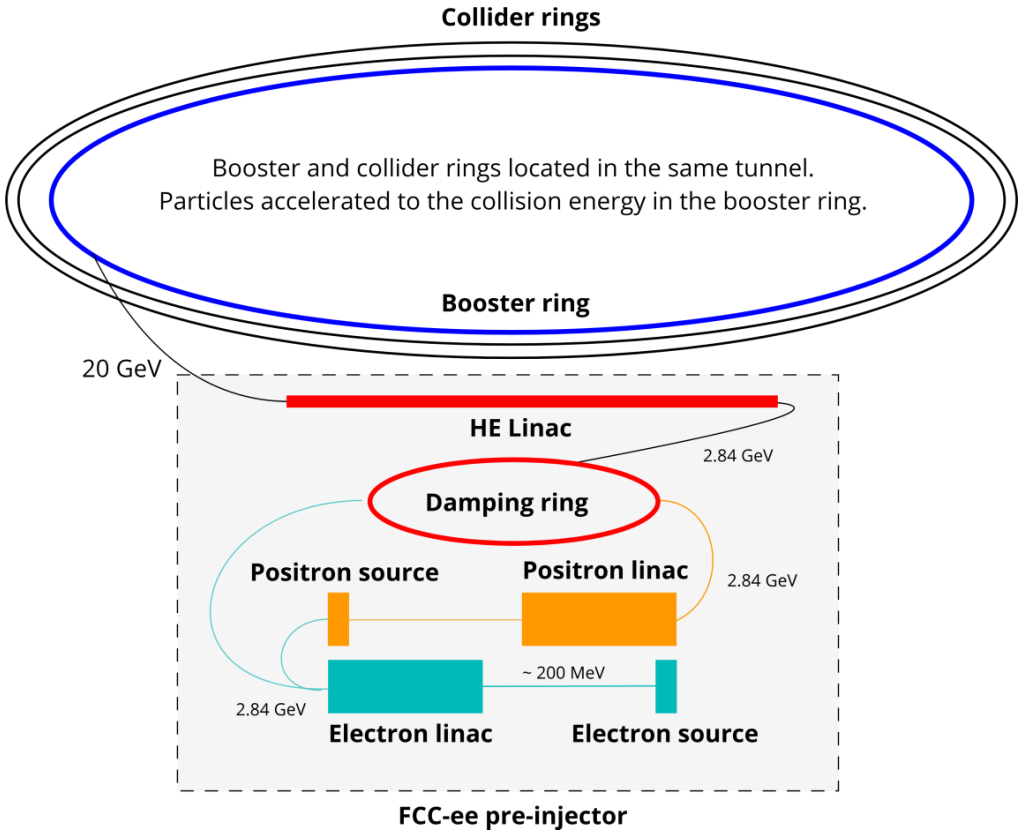
280 injections to fill the booster

Pre-injector complex

Pre-injector pulse: 4 bunches | 25 ns



100 Hz repetition frequency | up to **5 nC**

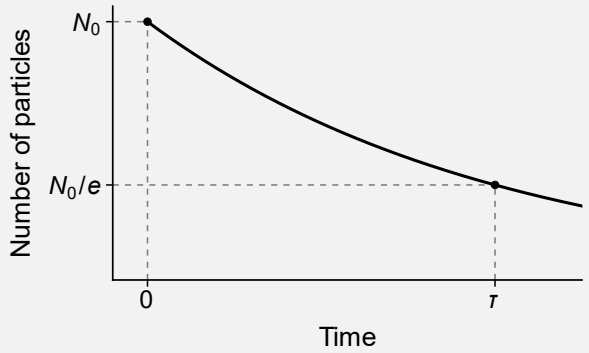


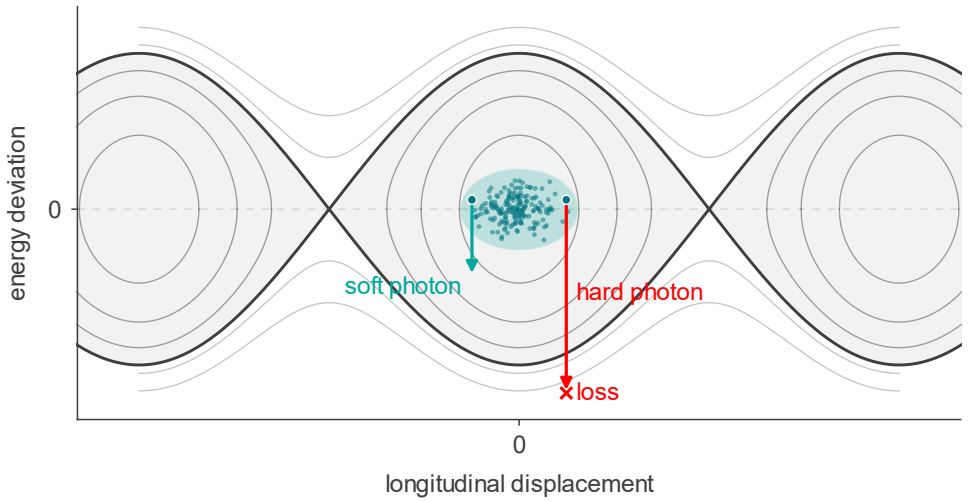
(**280** injection to booster × **10 ms** + **1 ms** booster ramp up)
× **100** booster injections = **6.3 min**

Beam lifetime in the collider rings

$$N(t) = N_0\, e^{-t/\tau}$$

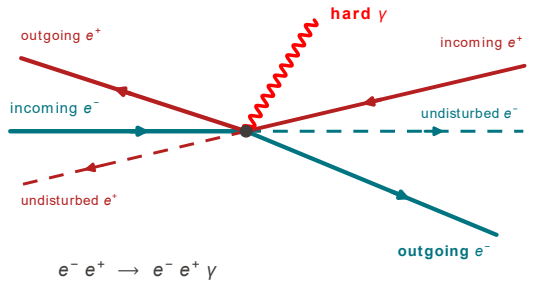
$N(t)$	number of particles at time t
N_0	initial number of particles at $t = 0$
t	elapsed time
τ	beam lifetime; $N(\tau) = N_0/e$





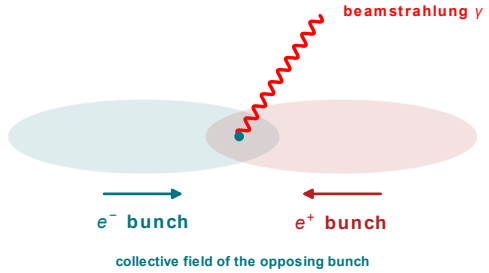
Radiative Bhabha scattering

Emission of photon during electron-positron collision



Beamstrahlung

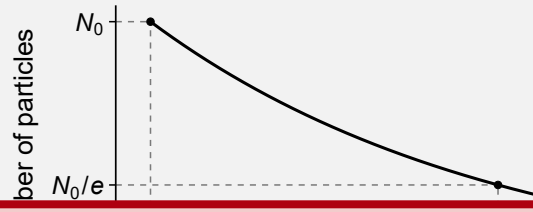
Emission of photon in the electric field of the counter-propagating bunch



Beam lifetime in the collider rings

$$N(t) = N_0\, e^{-t/\tau}$$

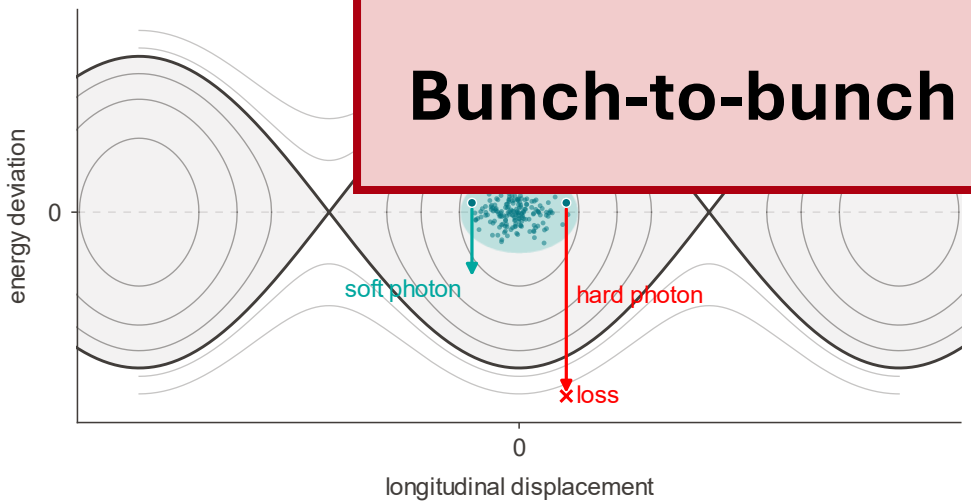
$N(t)$ number of particles at time t
N_0 initial number of particles at $t = 0$
t elapsed time

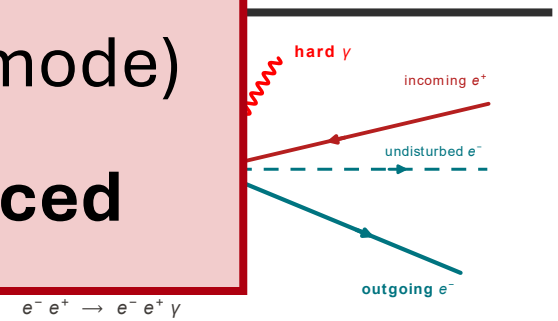


Beam lifetime: about **18 min** (Z mode)

Filling time: 6.3 min × 2 species = **12.6 min** (Z mode)

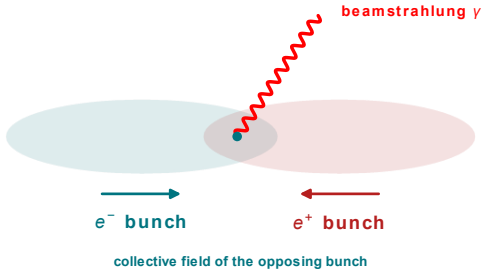
Bunch-to-bunch charge imbalances introduced





Beamstrahlung

Emission of photon in the electric field of the counter-propagating bunch



Top-up injection

- Continuous **response-based** refilling of the collider bunches
- **Charge of individual bunches measured, and injector tasked to provide exactly that charge**
- Pre-injector operating with 4 bunches with 25 ns spacing @ 100 Hz

Pre-injector complex

Pre-injector pulse: 4 bunches | 25 ns

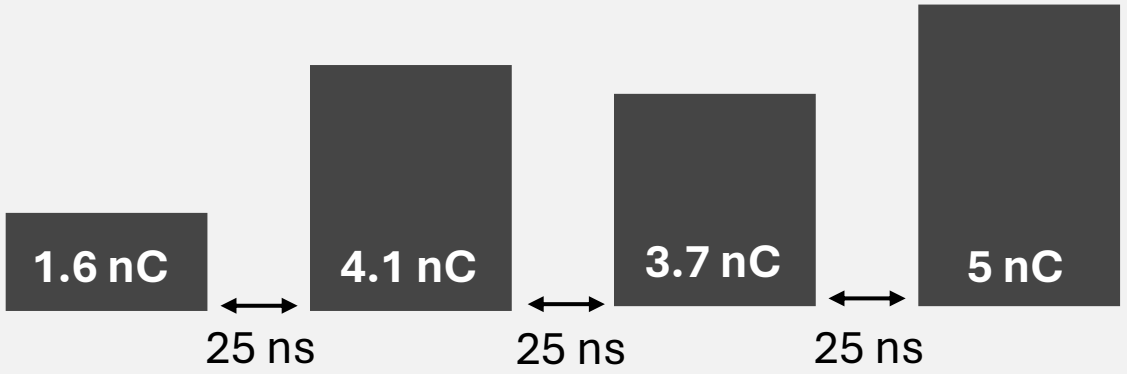


100 Hz repetition frequency | up to **5 nC**

Top-up injection and the electron source

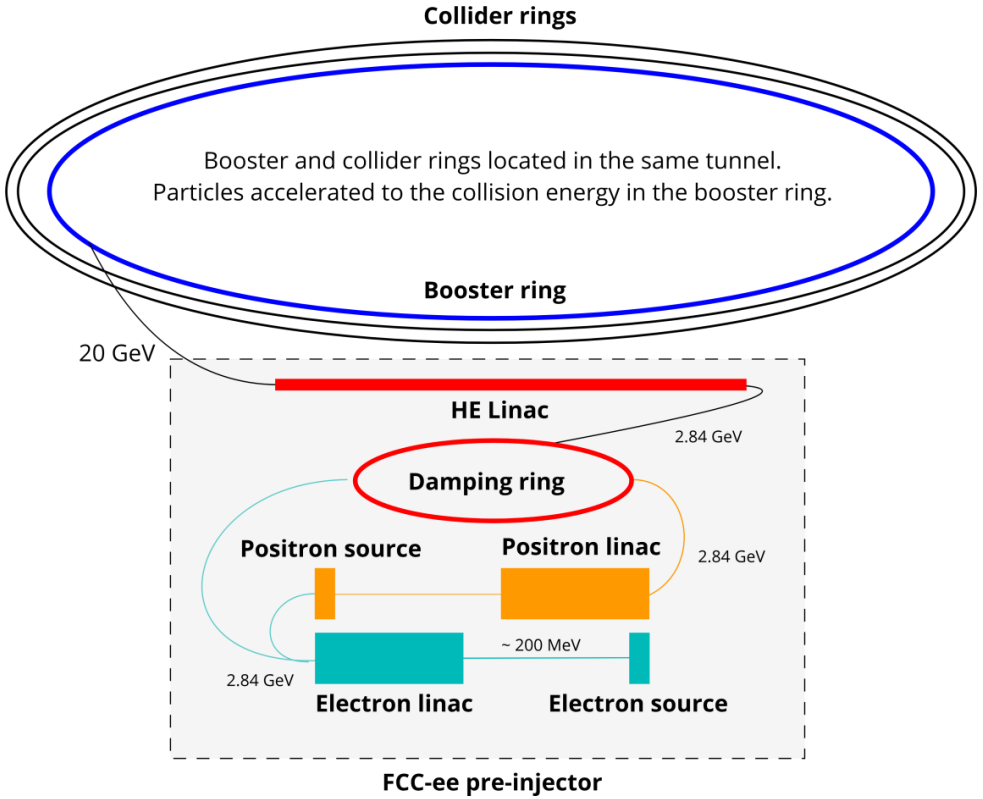
- **Shot-to-shot charge variation**
- Arbitrary in the range **5 – 100 %,** maximum charge **5 nC**
- Generating **4 bunches with 25 ns spacing at 100 Hz**

→ **fixed gun setup operating over large charge range**



So, to sum up what we need:

Provide up to 5 nC charge	Bunches for collider & positron source
4 bunches with 25 ns (?) spacing @ 100 Hz	To comply with the filling scheme
Shot-to-shot variation of the bunch charge	To facilitate the top-up injection



★ And we need a polarized electron source…

… and how to do that?

Electron source options

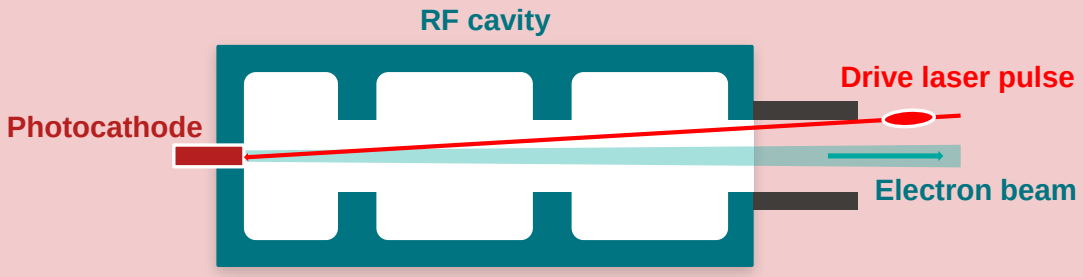
Photoemission RF gun

BASELINE

Emission induced by incoming laser

Very low emittance, short bunches

Complex design with laser systems

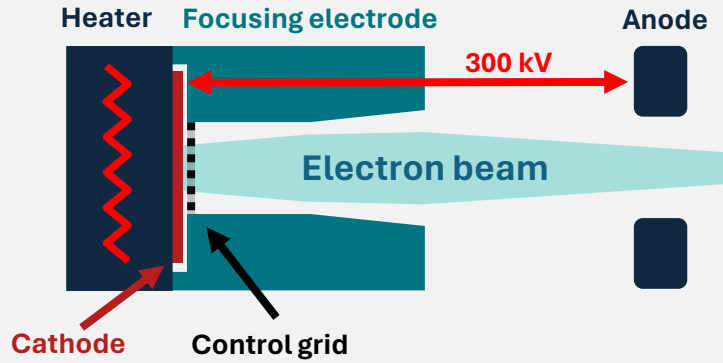


Thermionic DC gun

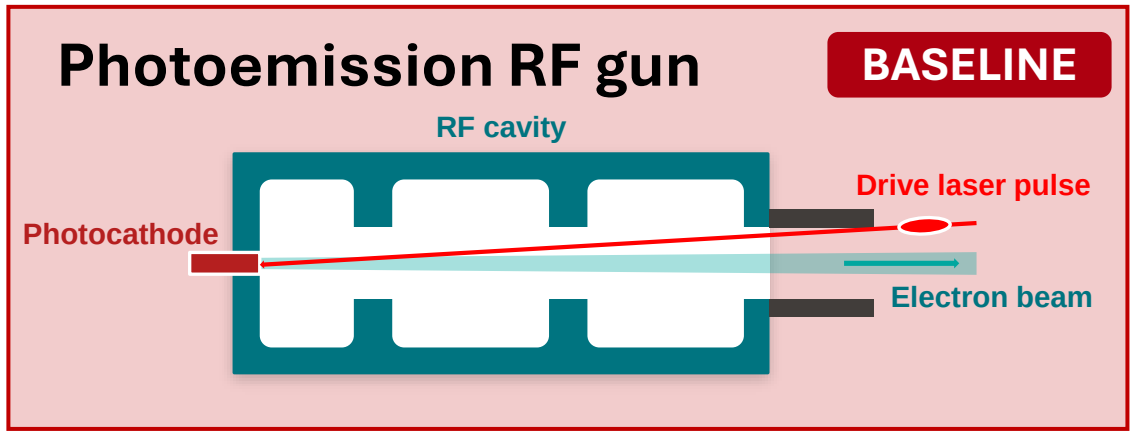
Emission induced by heating the cathode

Longer beams, higher emittance

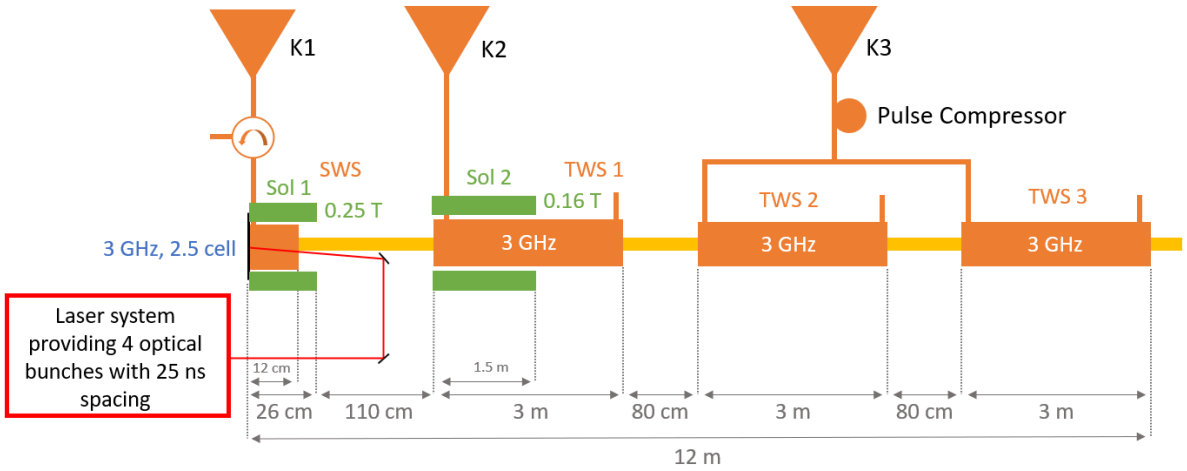
Standard, robust, simple



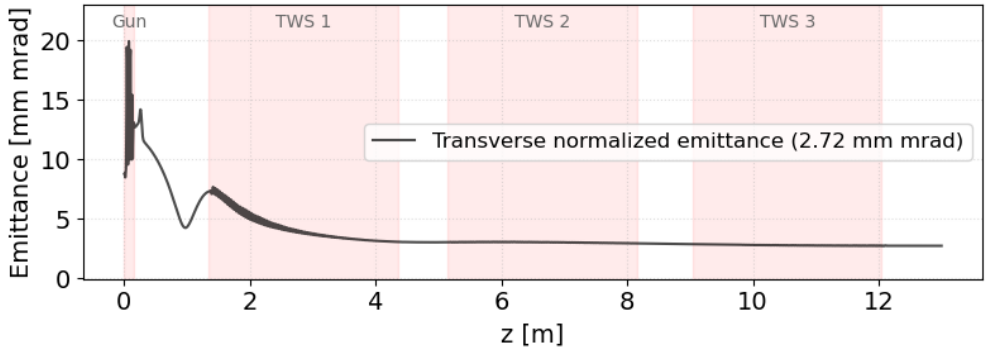
Photoemission RF gun



- Based on existing SwissFEL gun
- Simulation design study complete
  [Vostrel, Doebert, 2024]
- Experimental verification at PSI
  - Charge variation scheme
  - Photocathode lifetime

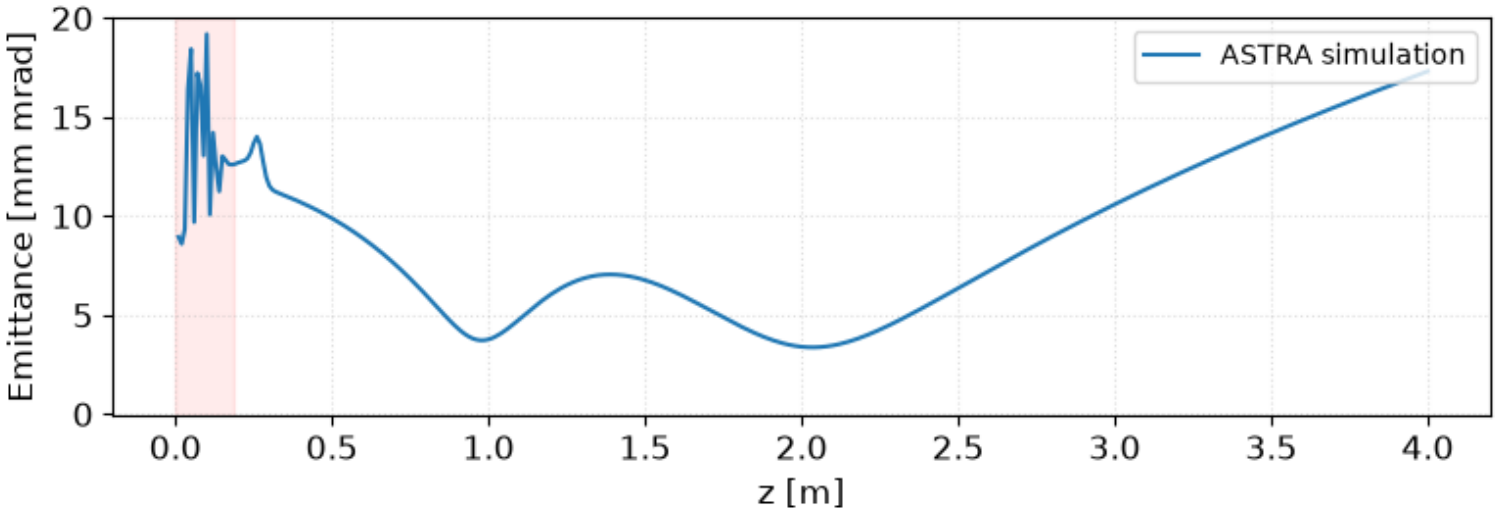


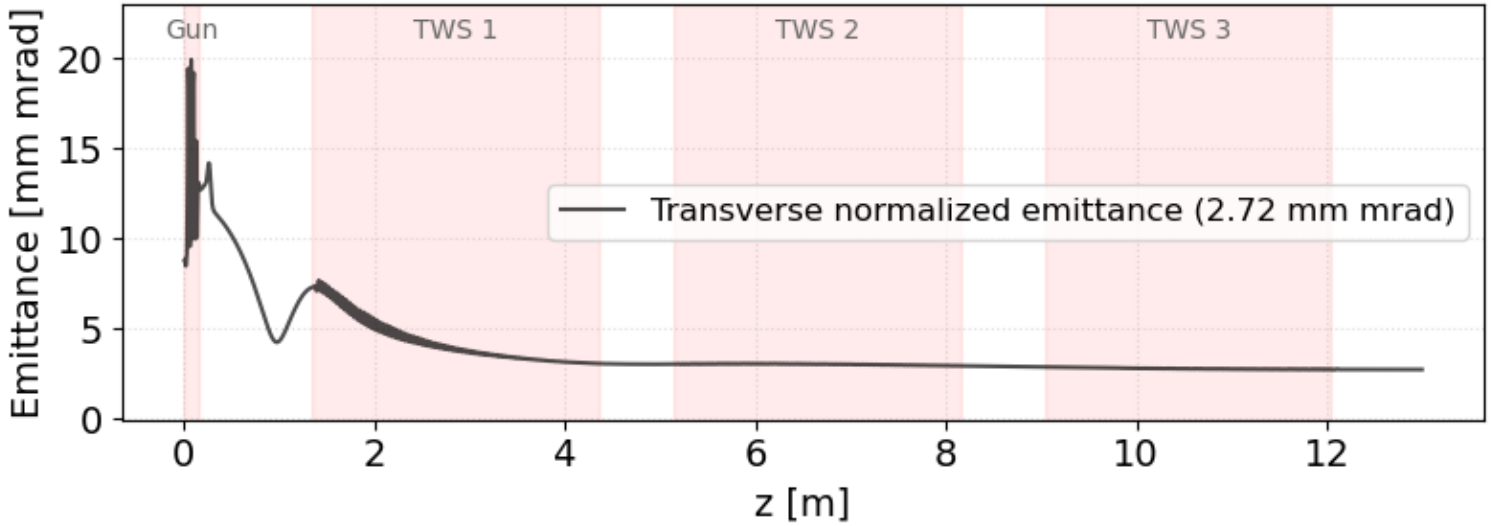
Schematic of the electron source layout



Emittance evolution in the electron source complex

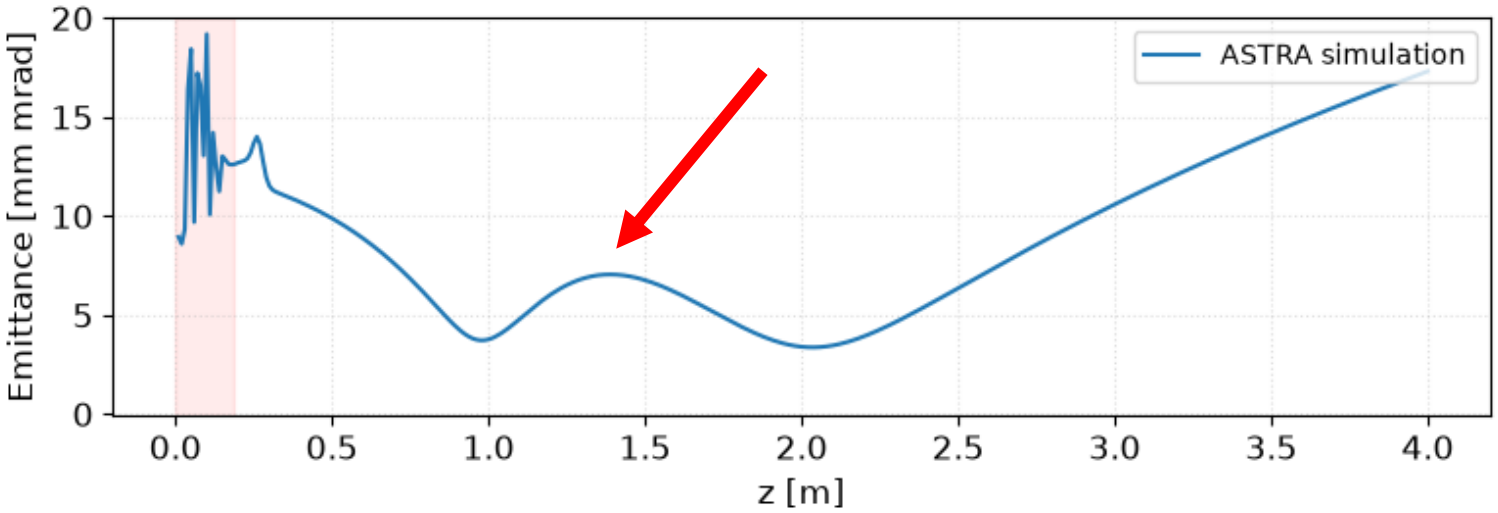
Photoemission RF gun

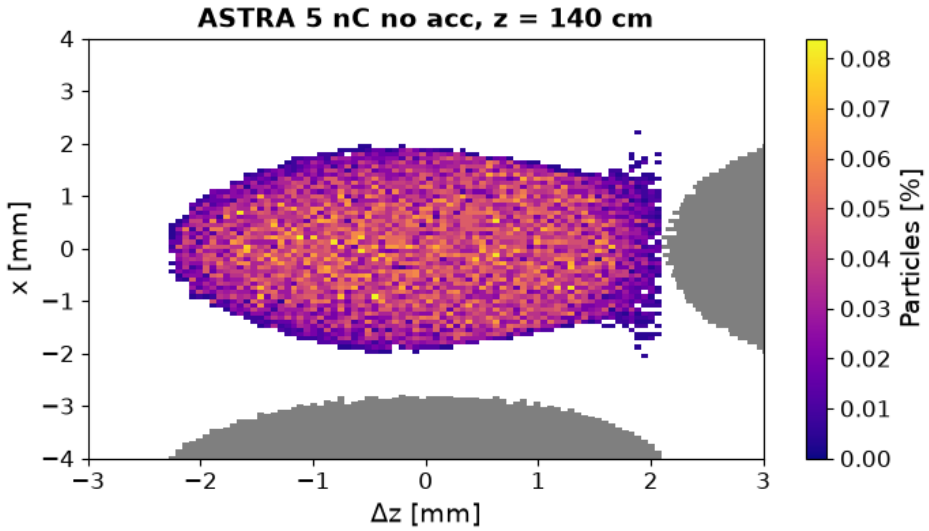




Note the different horizontal axis scales.

Photoemission RF gun





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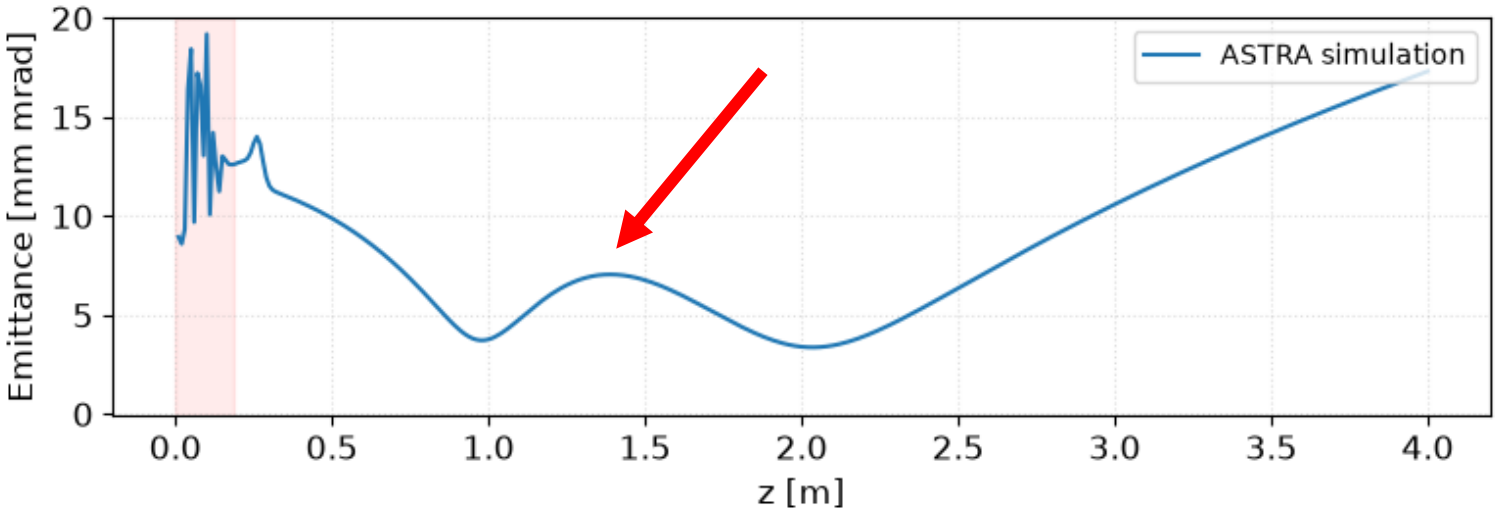
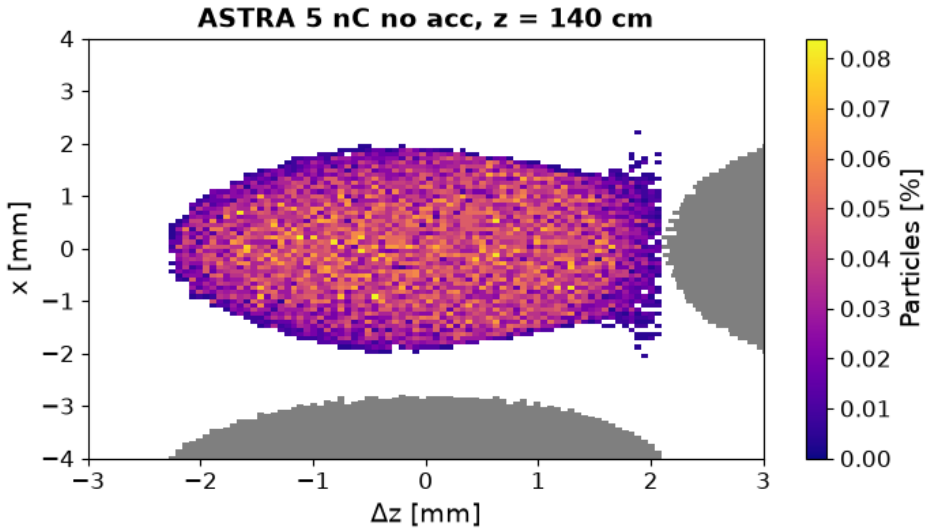
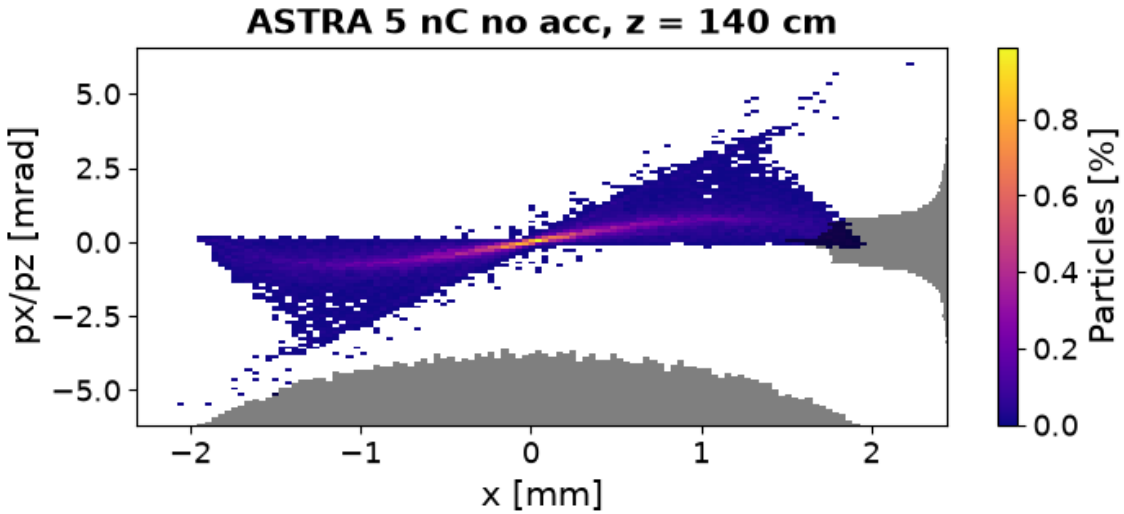
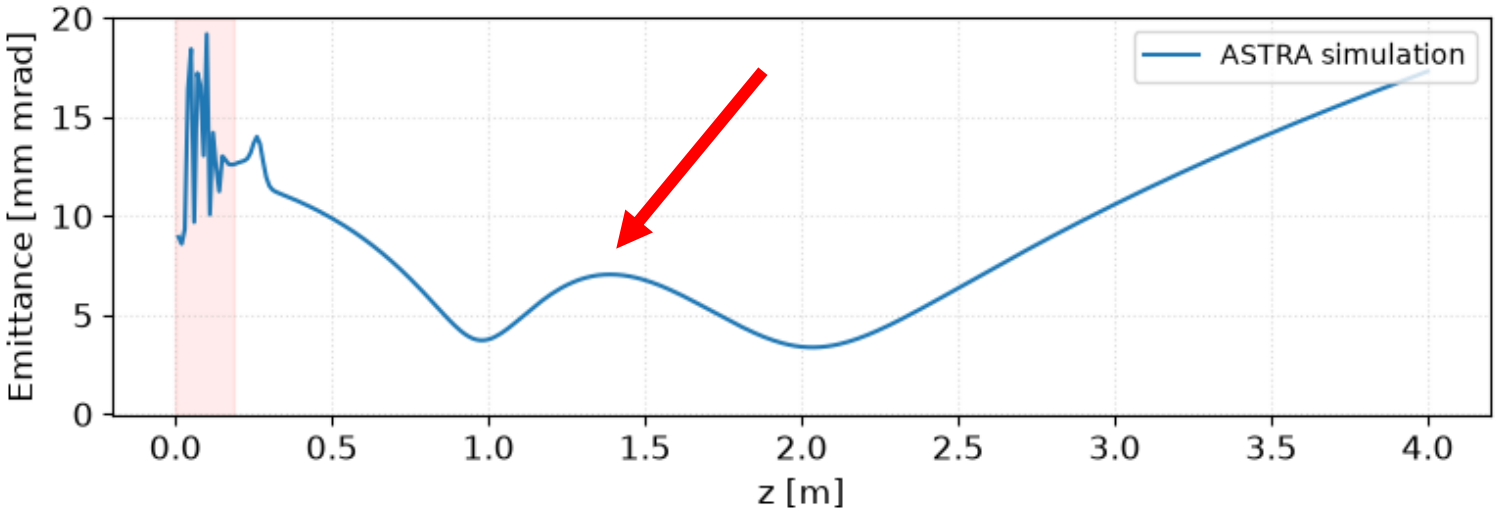
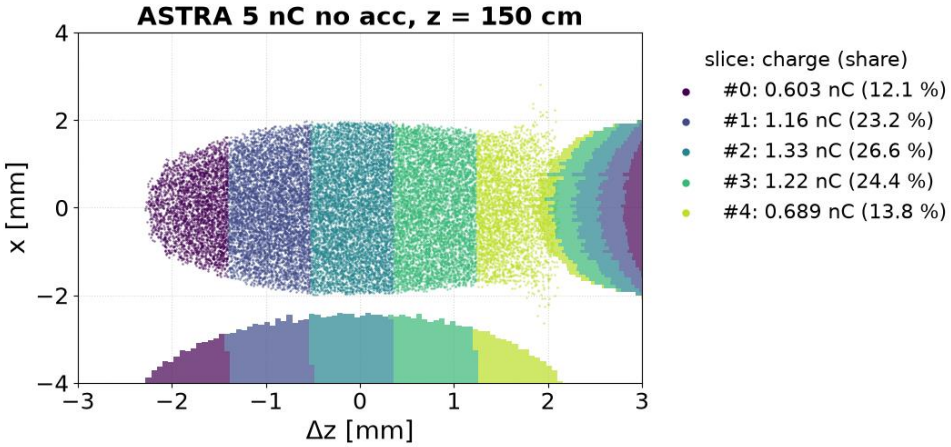


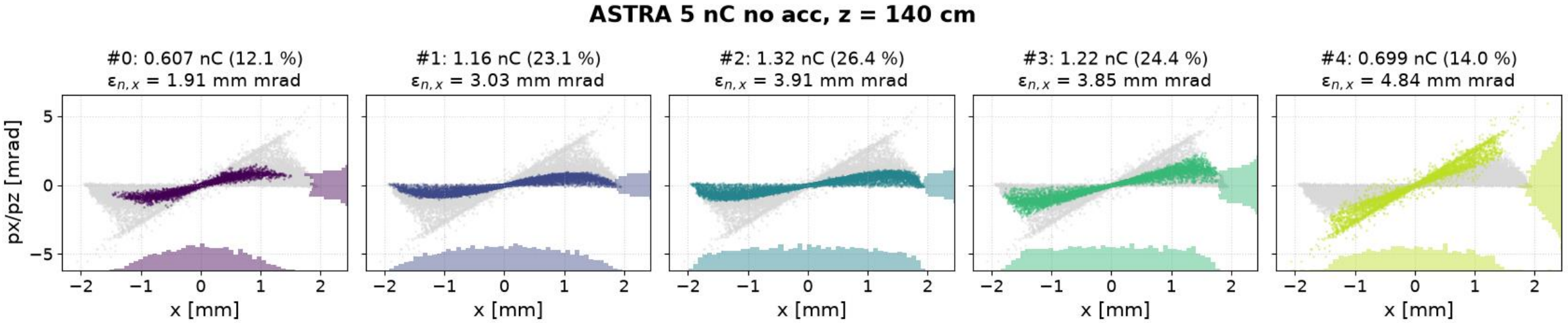




Photoemission RF gun







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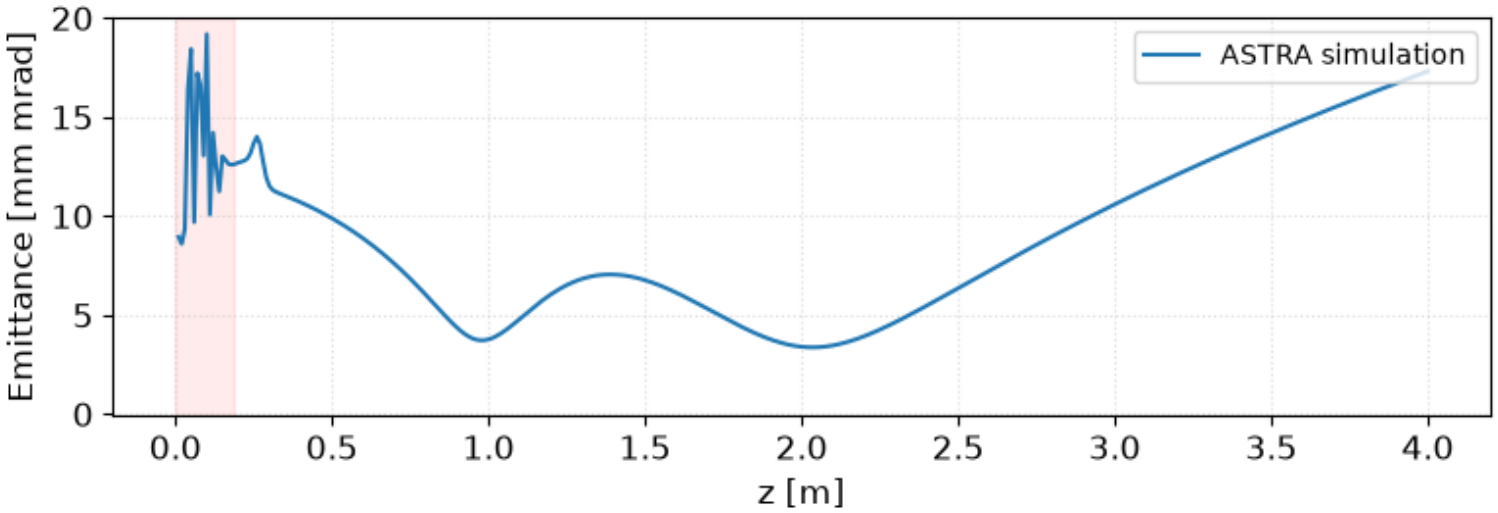

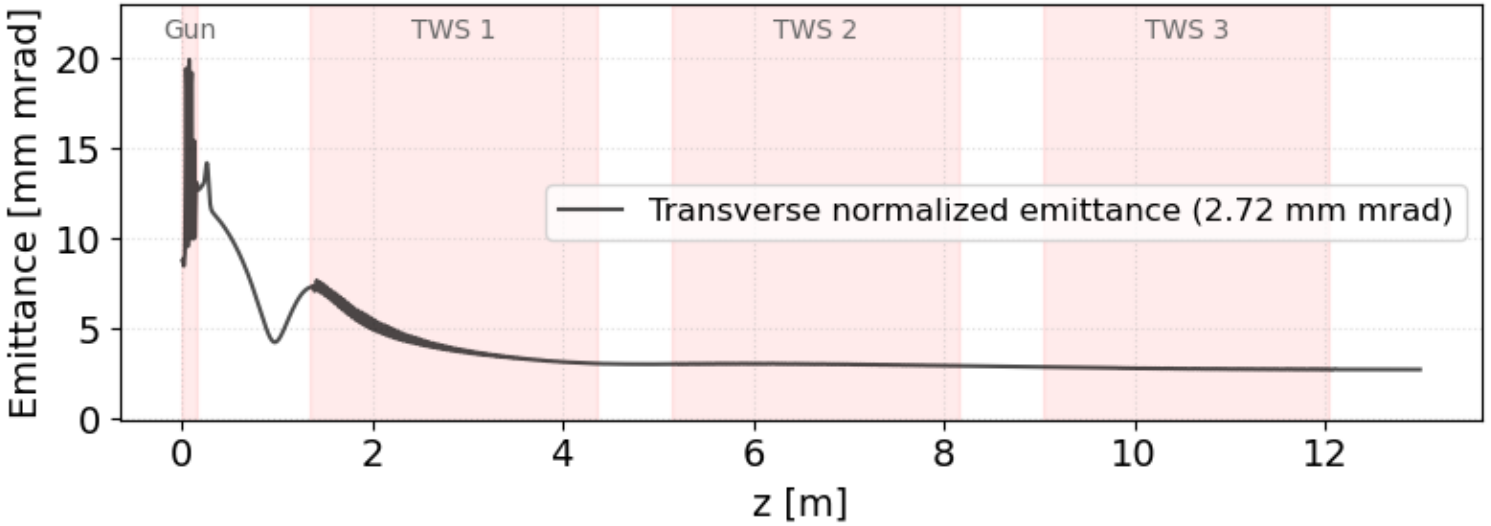

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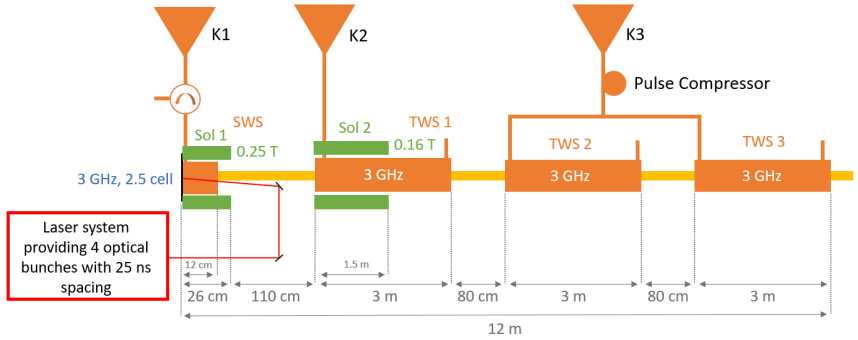


Photoemission RF gun

Charge variation proposal

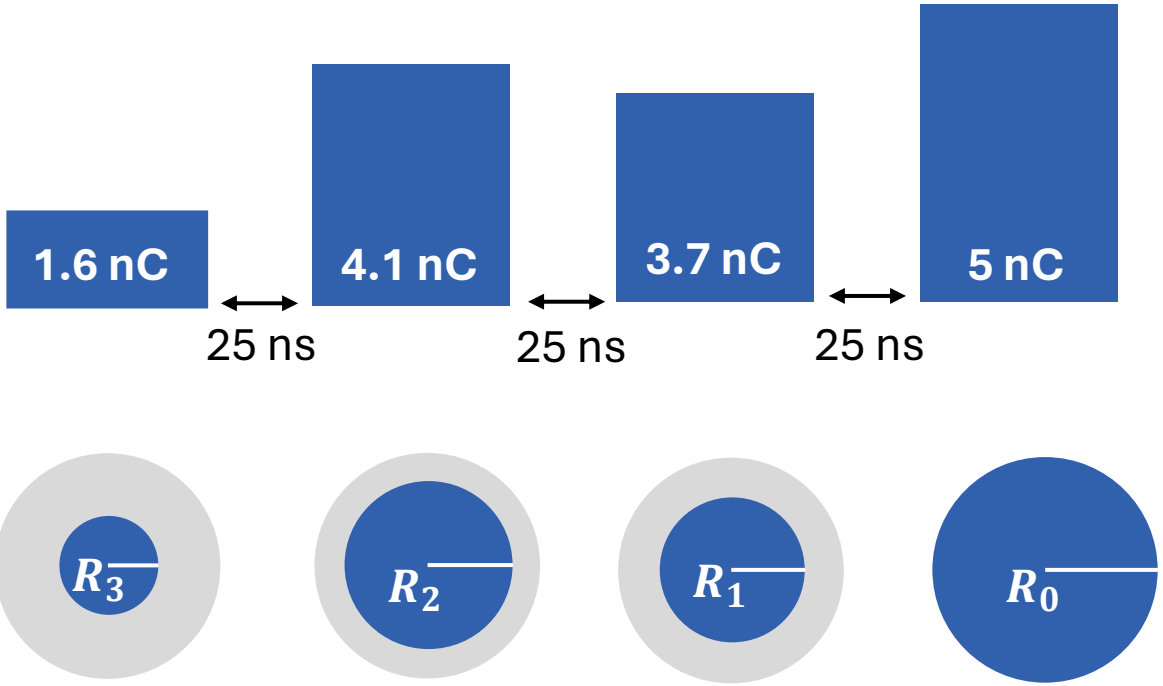
- Error study**: solenoid field is critical parameter**
- Used to compensate space charge in low energy region

Preserve the transverse charge density, modulate by changing the transverse emission radius

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

R, R_0 ... emission radius

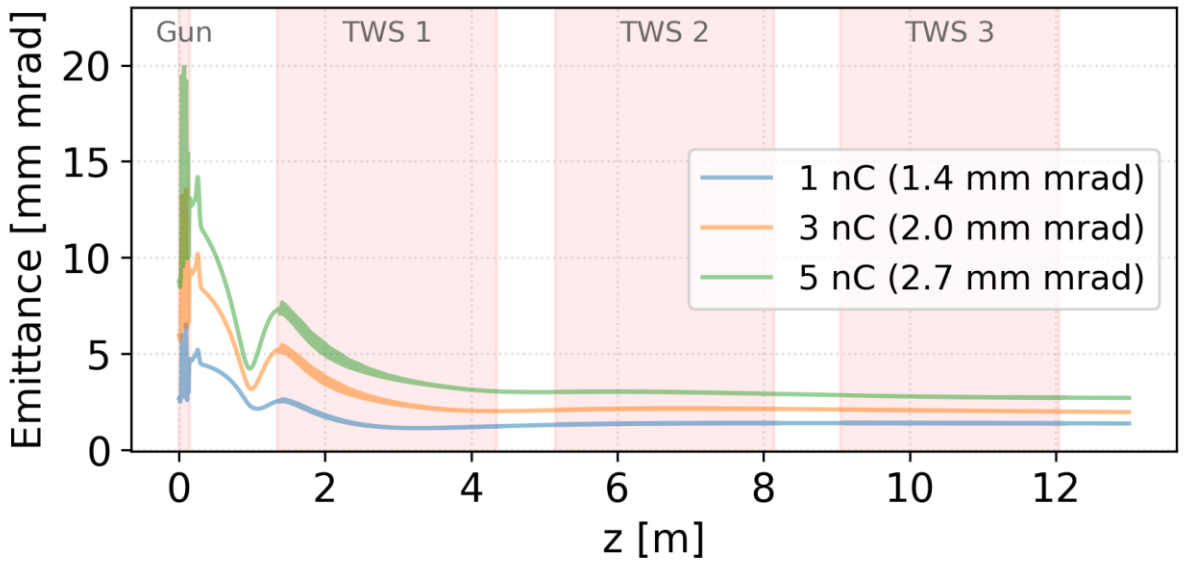
Q, Q_0 ... bunch charge



Exact emission models studied by Anahita OMOUMI (CERN)

★ Assuming uniform transverse charge density, setup optimized for 5 nC

Photoemission RF gun

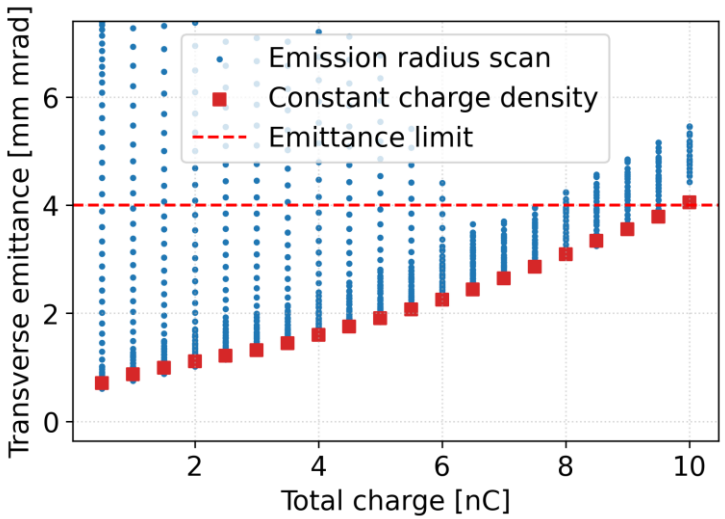


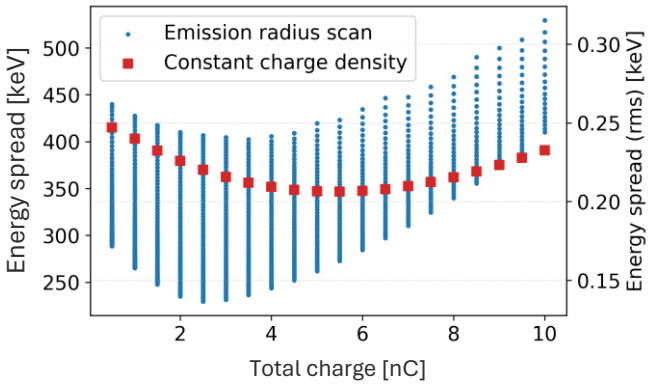
Emittance evolution along the fixed source complex, plotted for different charges

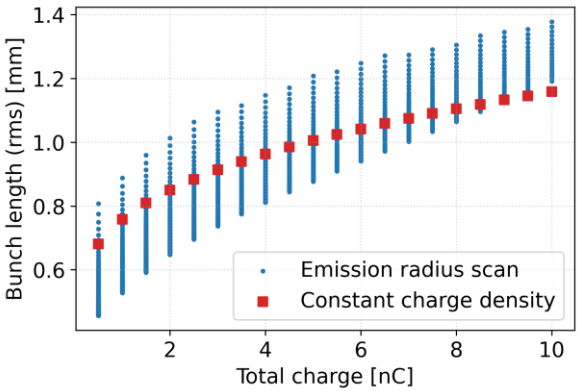
$$R = \sqrt{\frac{Q}{Q_0}} R_0$$

... emission radius

... bunch charge







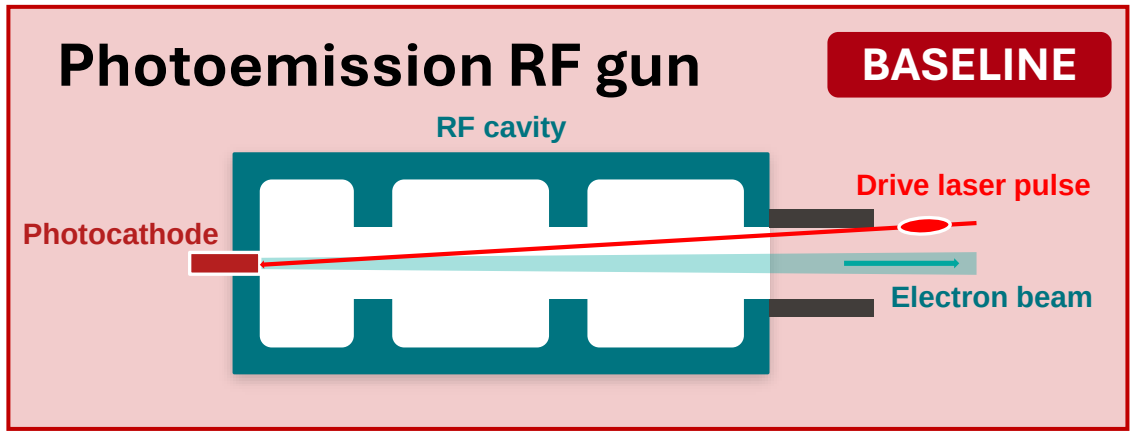
Squares: proposed variation

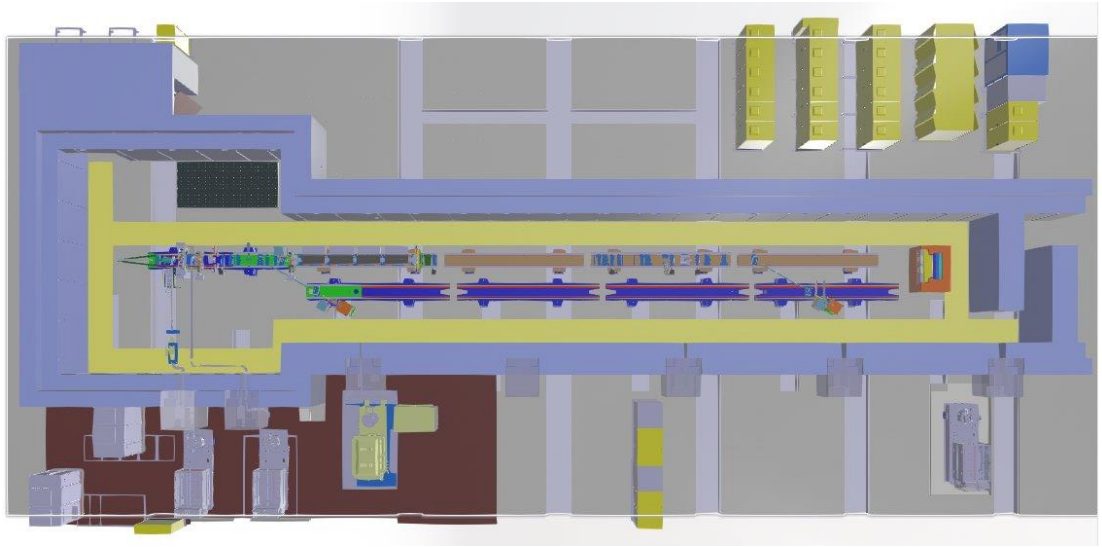
Dots: other charge-emission area combination

Presented method minimizes the emittance

★ Assuming uniform transverse charge density, setup optimized for 5 nC

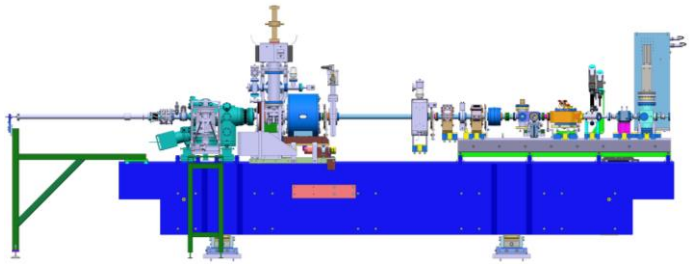
Photoemission RF gun



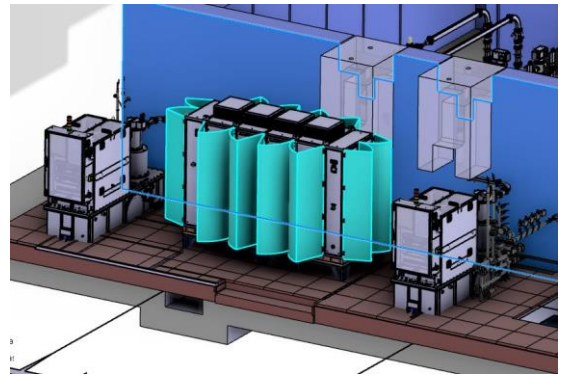


Test Stand Layout

- Based on existing SwissFEL gun
- Simulation design study complete
  [Vostrel, Doebert, 2024]
- Experimental verification at PSI
  - Charge variation scheme
  - Photocathode lifetime

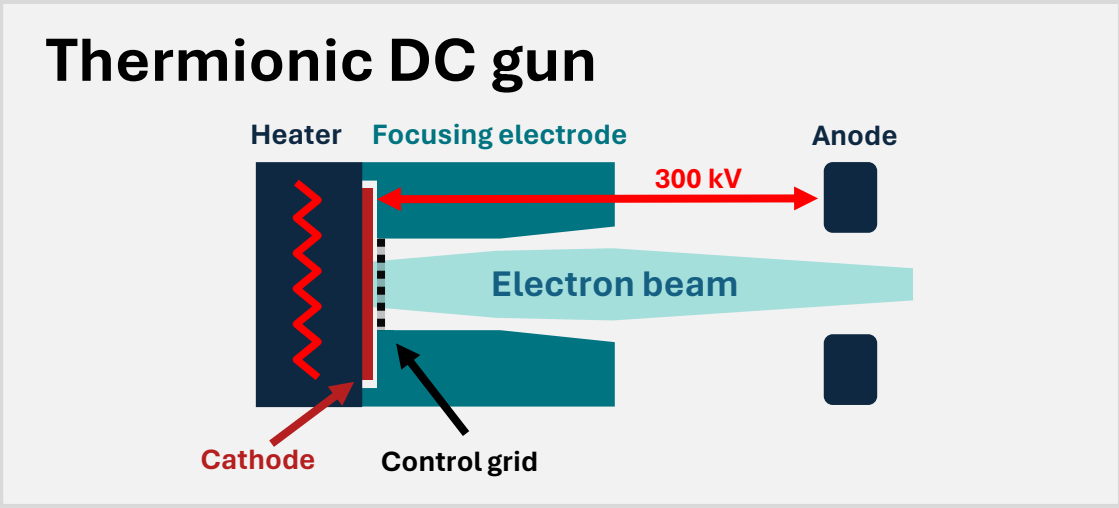


Electron source layout

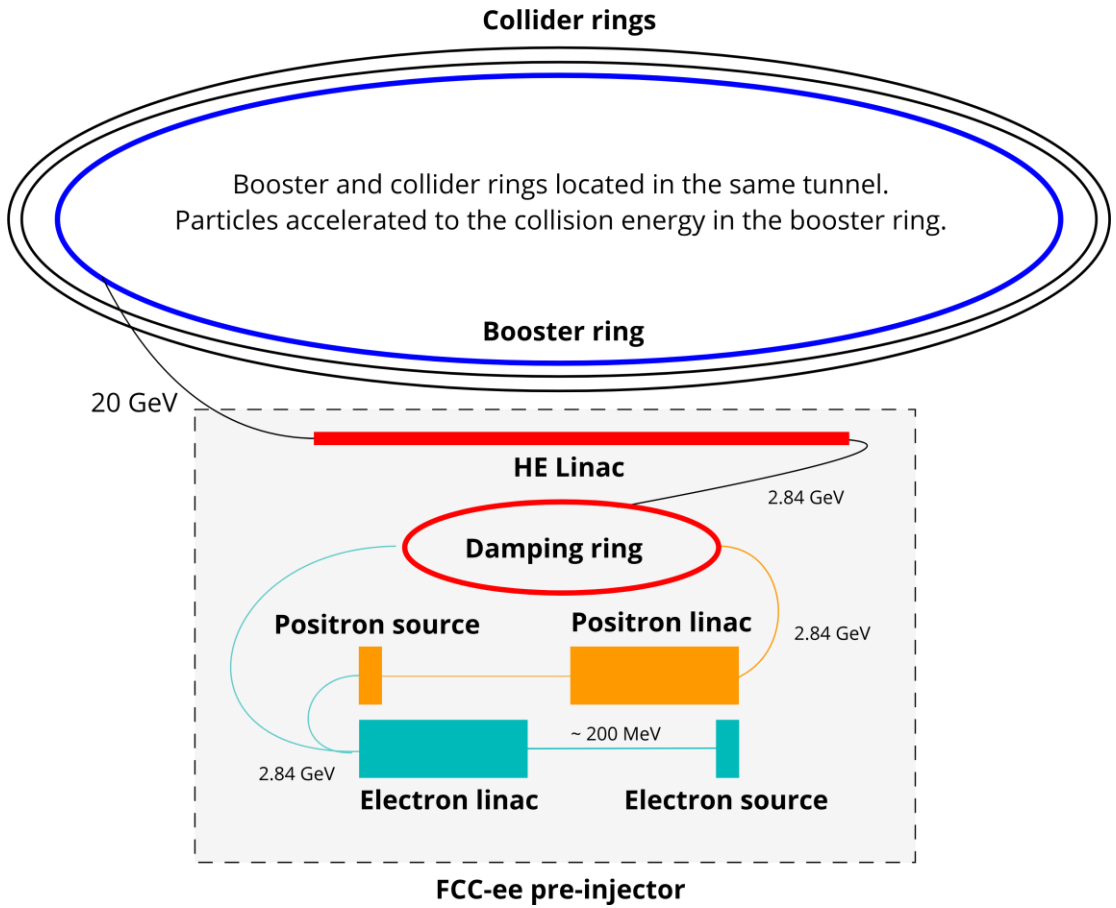


PSI Built Modulators

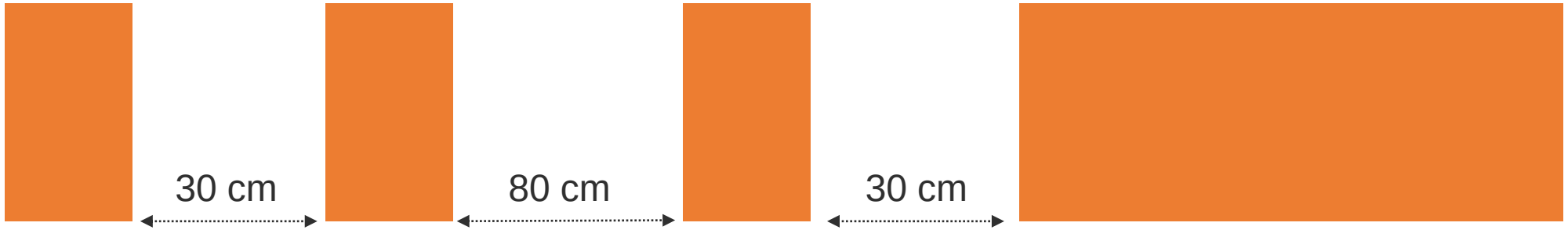
Thermionic DC gun



- Enabled by electron damping ring addition
- Easier construction and operation
- Worse quality beams
- Longer emitted bunches → need for bunching

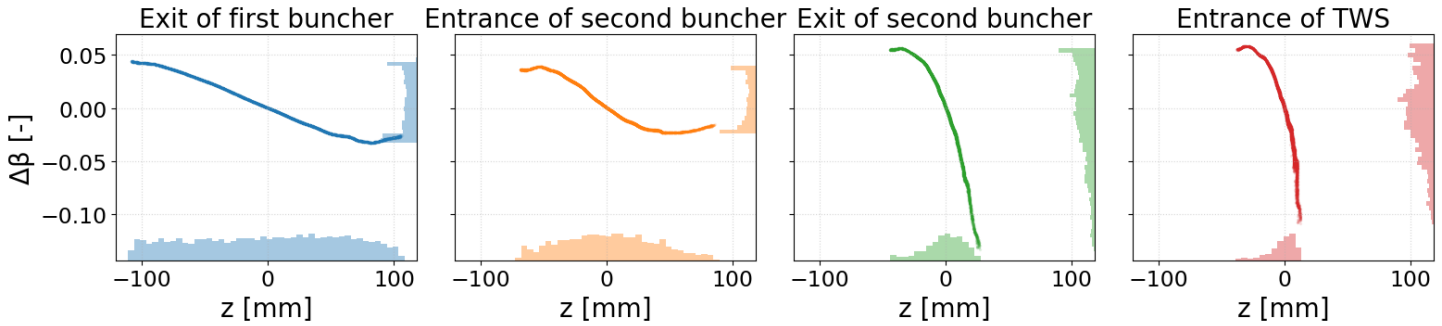


Thermionic DC gun

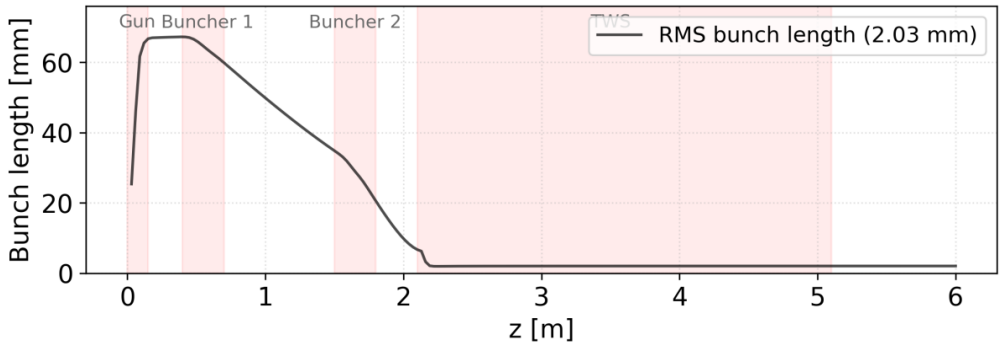


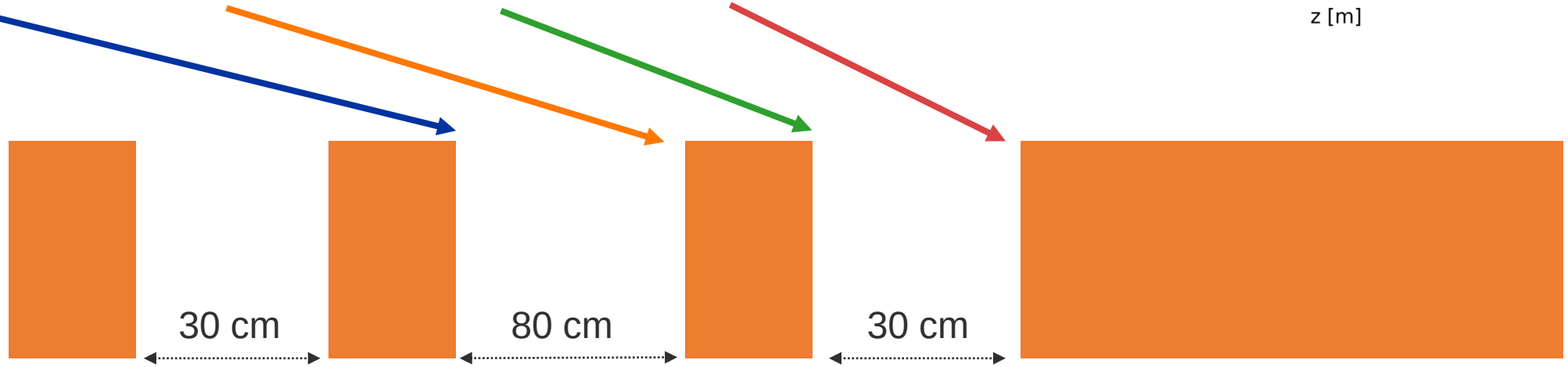
Thermionic DC gun

Longitudinal trace space snapshots (relativistic velocity | longitudinal positions)



Bunch length evolution along bunching system





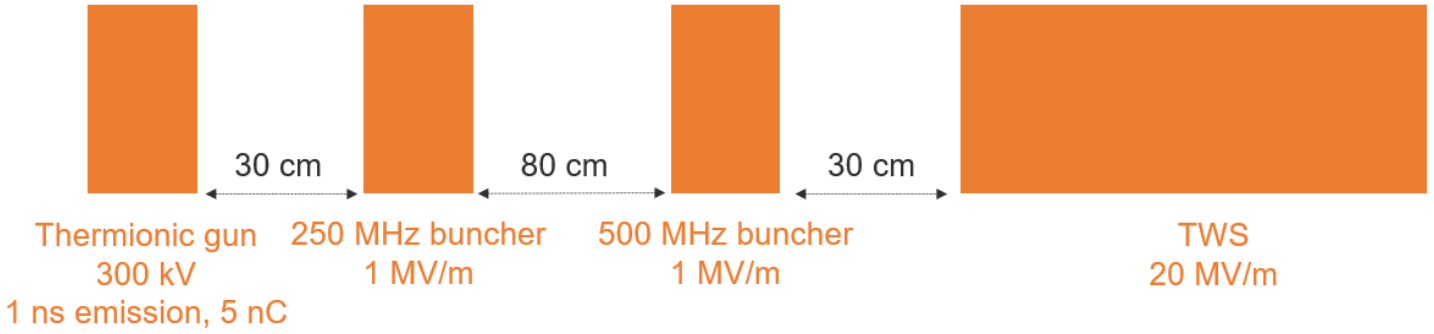
Thermionic gun
300 kV
1 ns emission, 5 nC

250 MHz buncher
1 MV/m

500 MHz buncher
1 MV/m

TWS
20 MV/m

Thermionic DC gun



$$x''(z) + k_s(z)\,x(z) - \frac{2I}{\beta^3\gamma^3 I_A 2\,x(z)} - \frac{\varepsilon_n^2}{\beta^2\gamma^2\,x^3(z)} = 0$$

Hill's equation

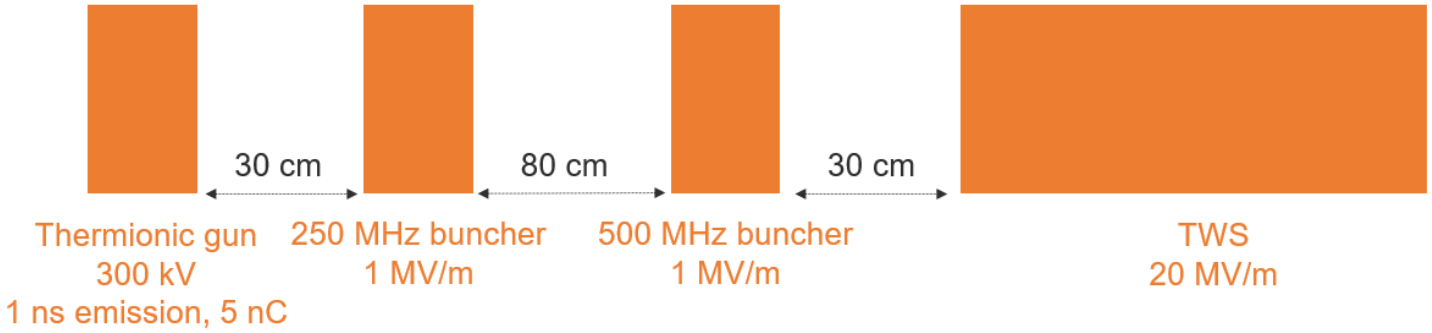
Space charge pressure

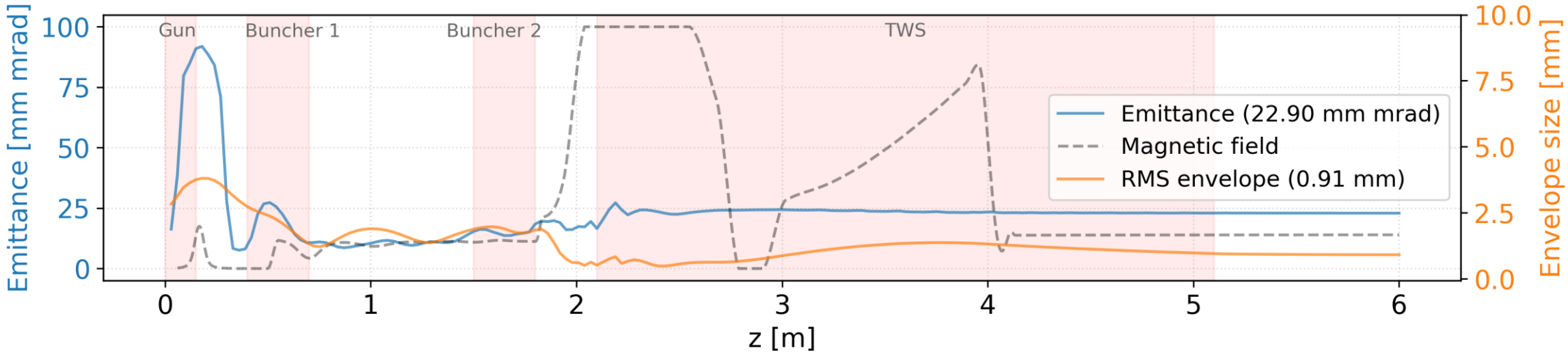
Emittance pressure

- $x(z)$: RMS transverse beam size
- $x''(z)$: envelope curvature (second derivative of beam size)
- $k_s(z)$: solenoid focusing strength
- β: relativistic velocity factor (v/c)
- γ: Lorentz factor
- ε_n: normalized transverse emittance (beam quality)
- K_{sc}: generalized perveance (space-charge strength)
- I: beam current
- I_A: Alfven current (~ 17 kA for electrons)
- $B(z)$: solenoid magnetic field
- e: electron charge
- m_e: electron mass
- c: speed of light

$$k_s = \left(\frac{eB}{2\beta\gamma m_e c}\right)^2$$

Thermionic DC gun





Thermionic DC gun

Longitudinal field of travelling wave structure

$$E(z,t) = \epsilon(z)\cos(\underbrace{\omega t - k_z z + \phi}_{\psi(z,t)})$$

Transverse component of Lorentz force

$$F_r(z,t) = -\frac{qr}{2}\left(\frac{\partial}{\partial z} + \frac{\beta}{c}\frac{\partial}{\partial t}\right) E_0(z,t)$$

… plugging the field into Lorentz equation

$$F_r = -\frac{qr}{2}\left[\epsilon'(z)\cos\psi + k_0\left(\frac{1}{\beta_\phi} - \beta\right)\epsilon(z)\sin\psi\right]$$

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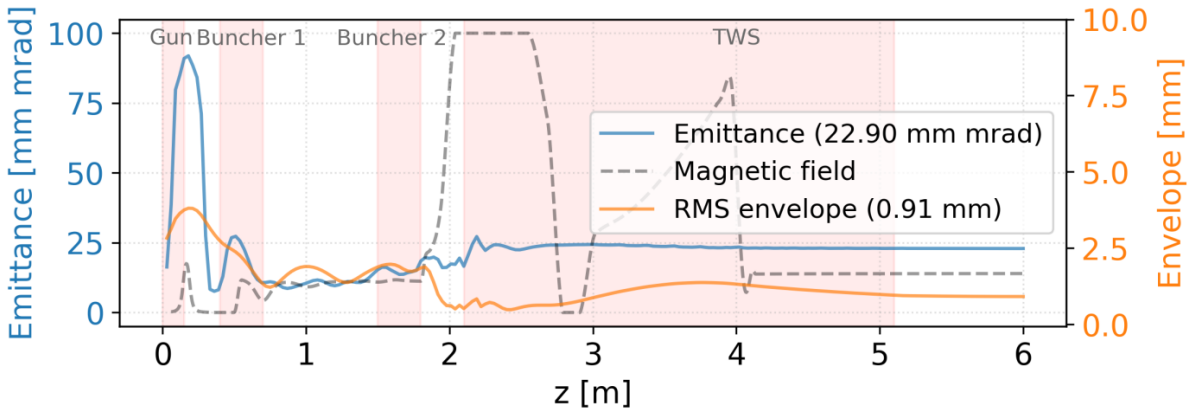
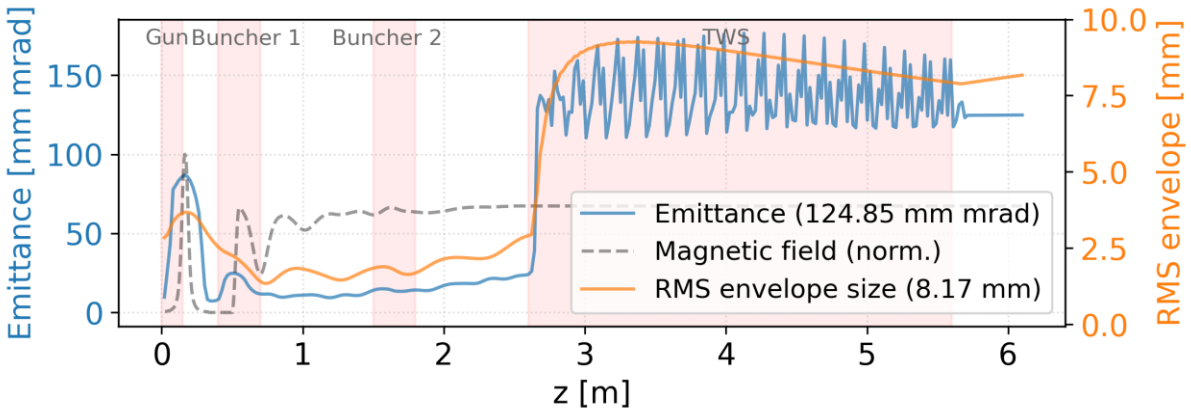
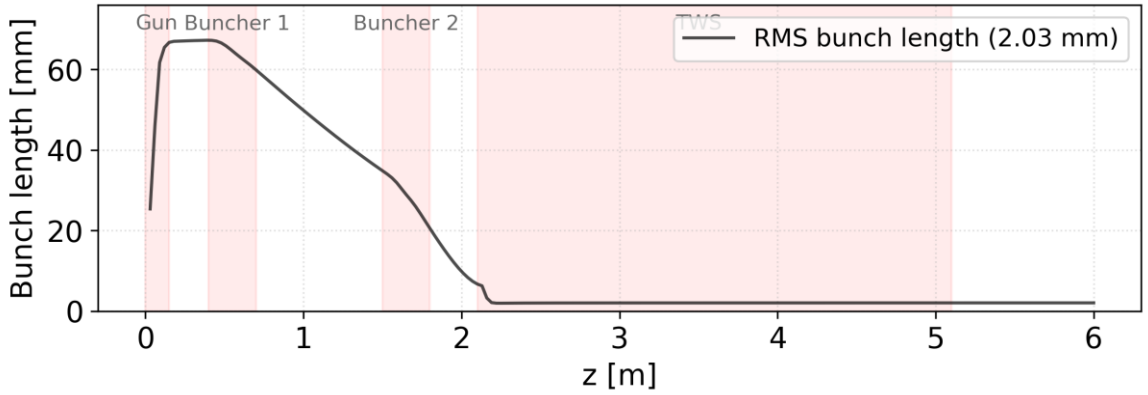
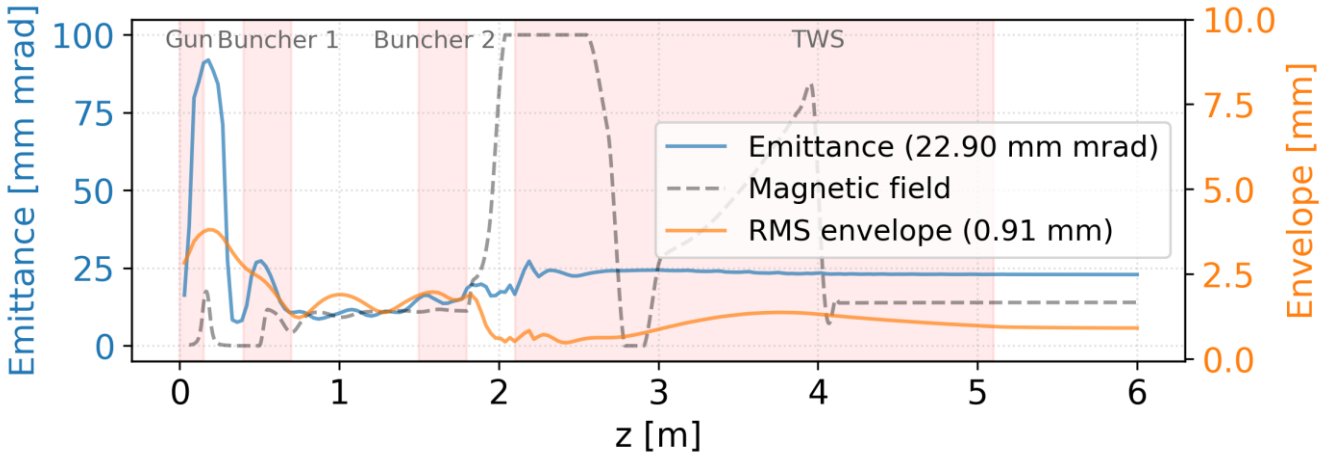
This is bad…





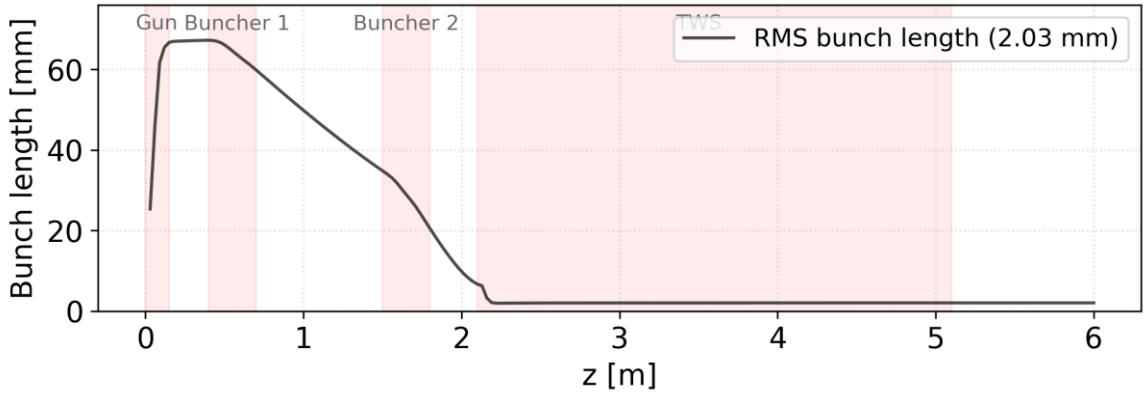
Thermionic DC gun

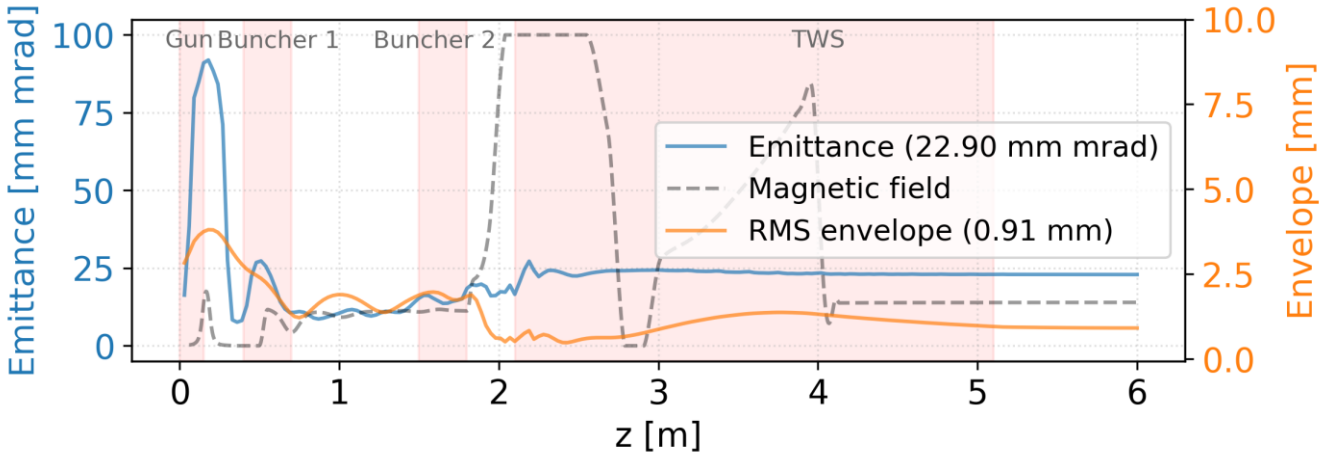




These are somewhat reasonable parameters…

Thermionic DC gun

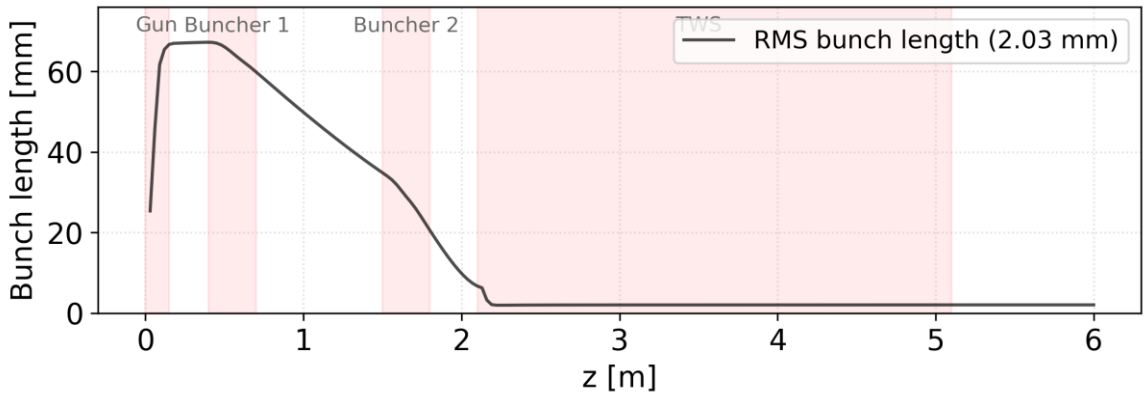


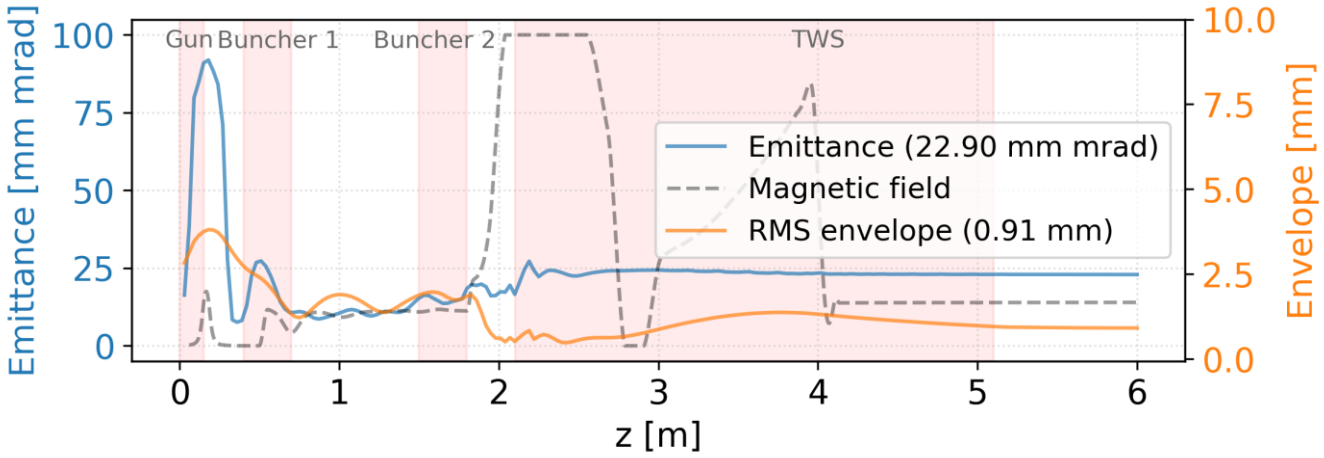


These are somewhat reasonable parameters…

… are they really?

Thermionic DC gun



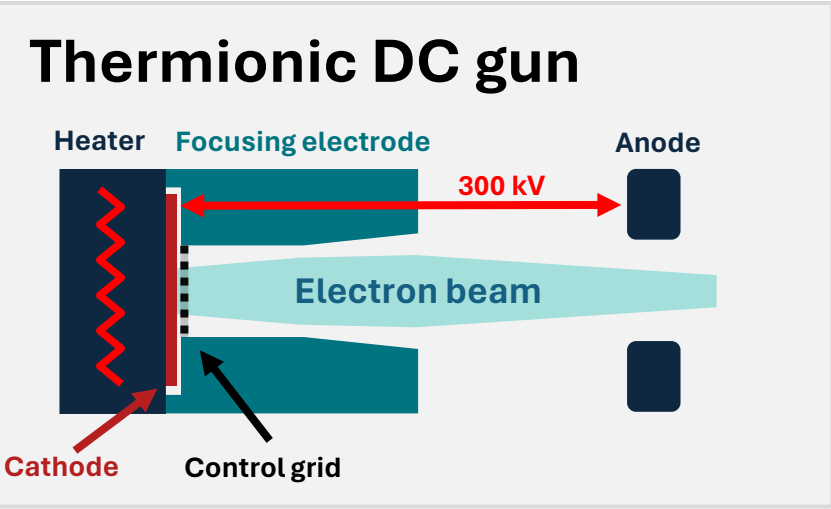


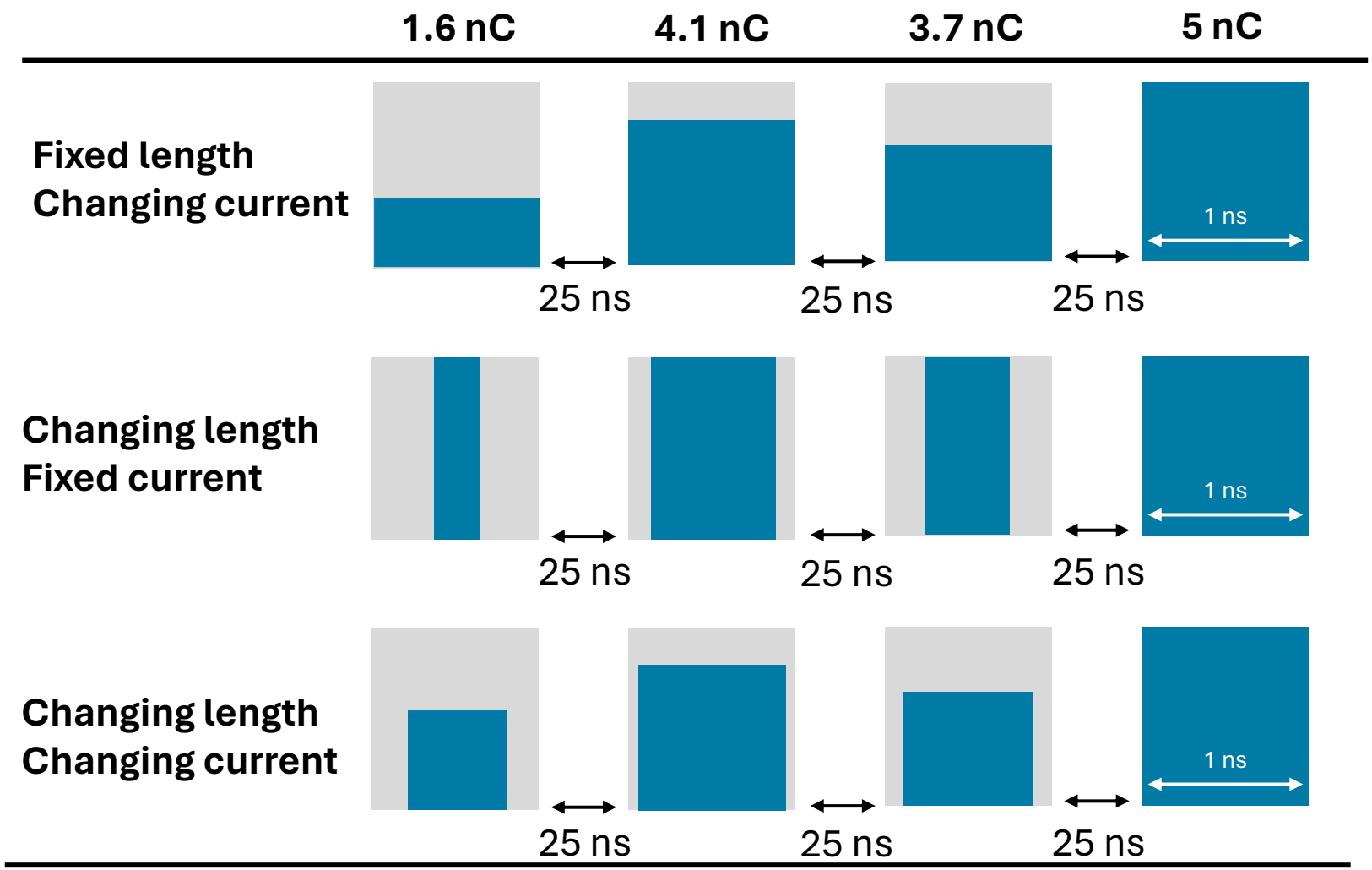
These are somewhat reasonable parameters…

… are they really?

… and what about the charge variation?

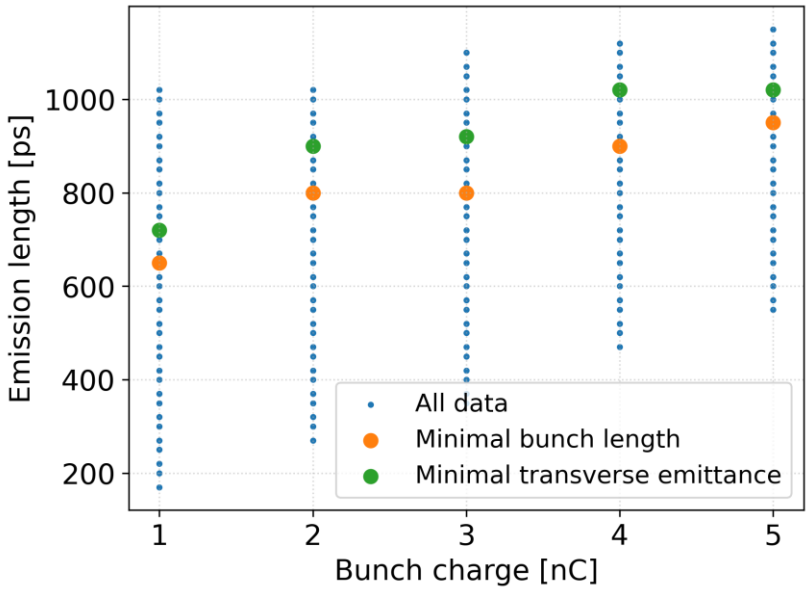
Thermionic DC gun



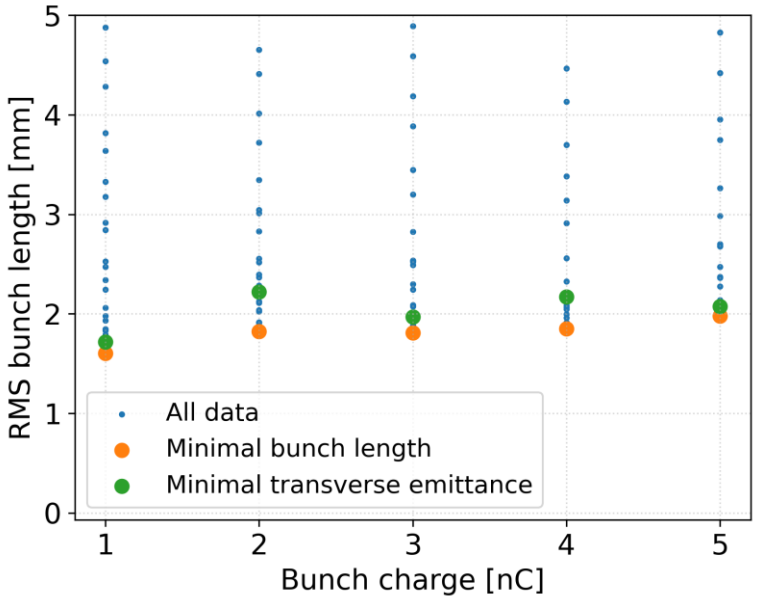


Thermionic DC gun

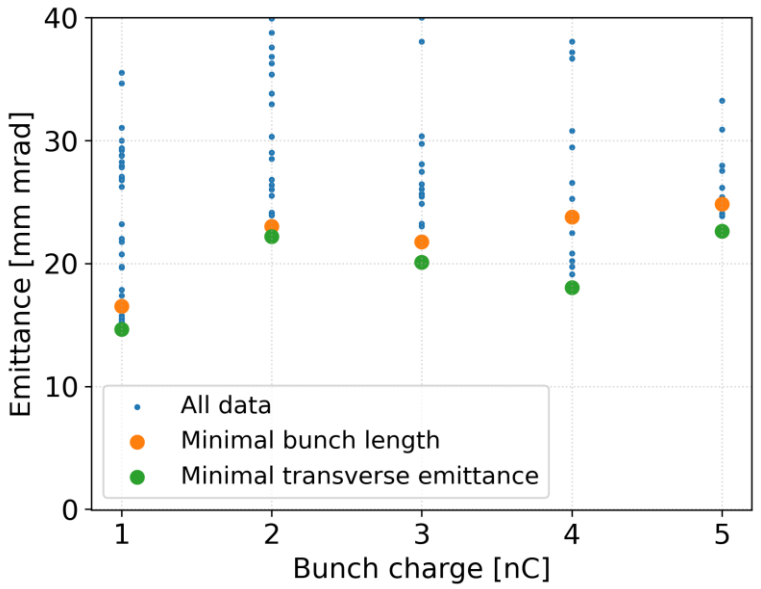
Preliminary results



Tested combinations of the emission length and total charge



Achievable RMS bunch length for different combinations of emission length and intensity



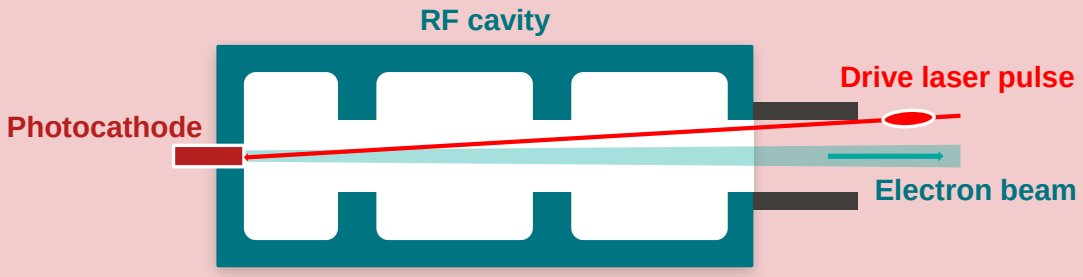
Achievable transverse normalized emittance for different combinations of emission length and intensity

So which one…?

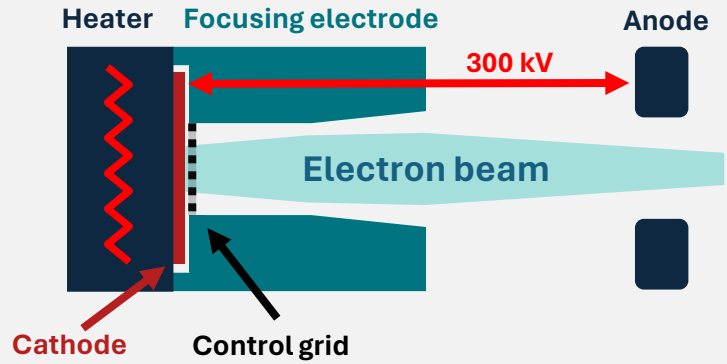
Compatibility with the downstream accelerators?
Feasibility of the charge variation?
Robustness

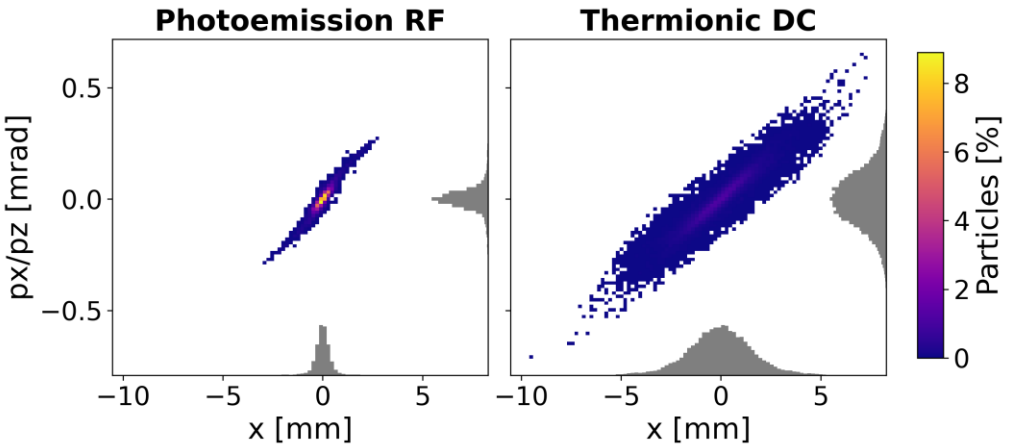
Photoemission RF gun

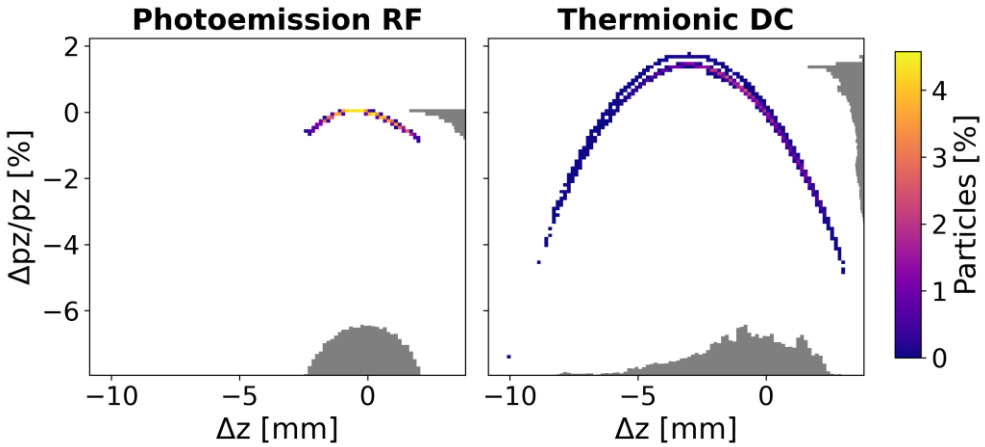
BASELINE



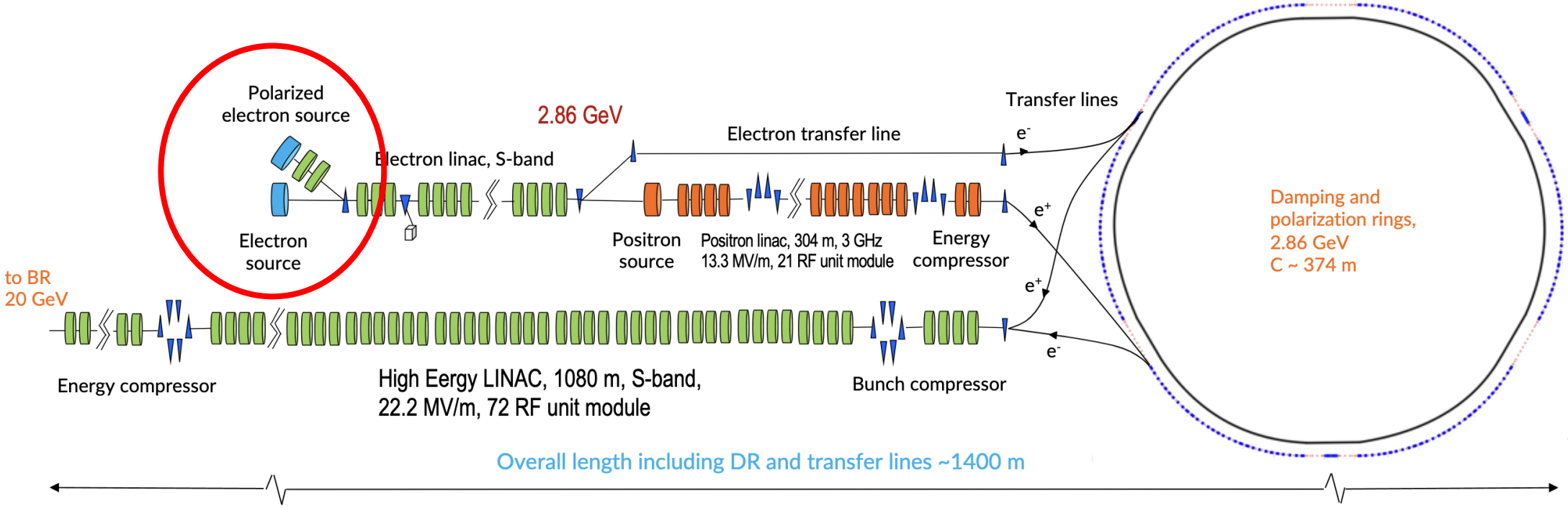
Thermionic DC gun







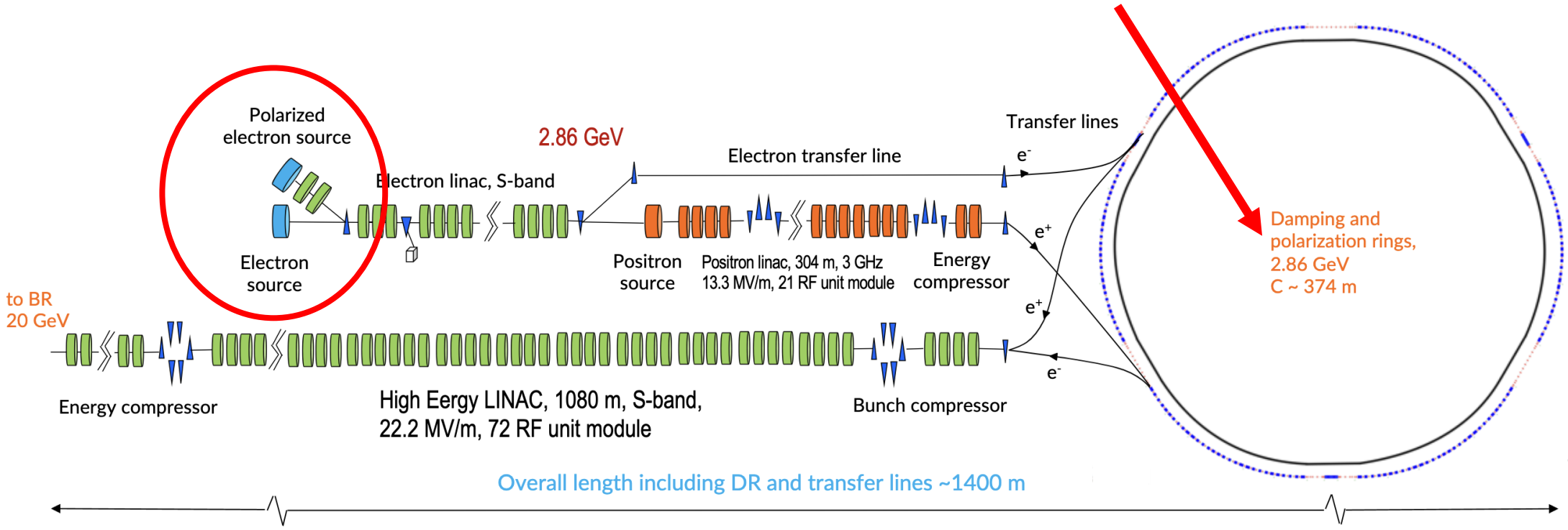
… and the polarized electrons?



Courtesy of Alexej Grudiev (CERN)

… and the polarized electrons?

positrons polarized in a ring, about
12 minutes, polarization above 90 %



Courtesy of Alexej Grudiev (CERN)

How to get polarized electrons, quickly

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   squeezed layers of GaAs and GaAsP – this separates different electron energy bands

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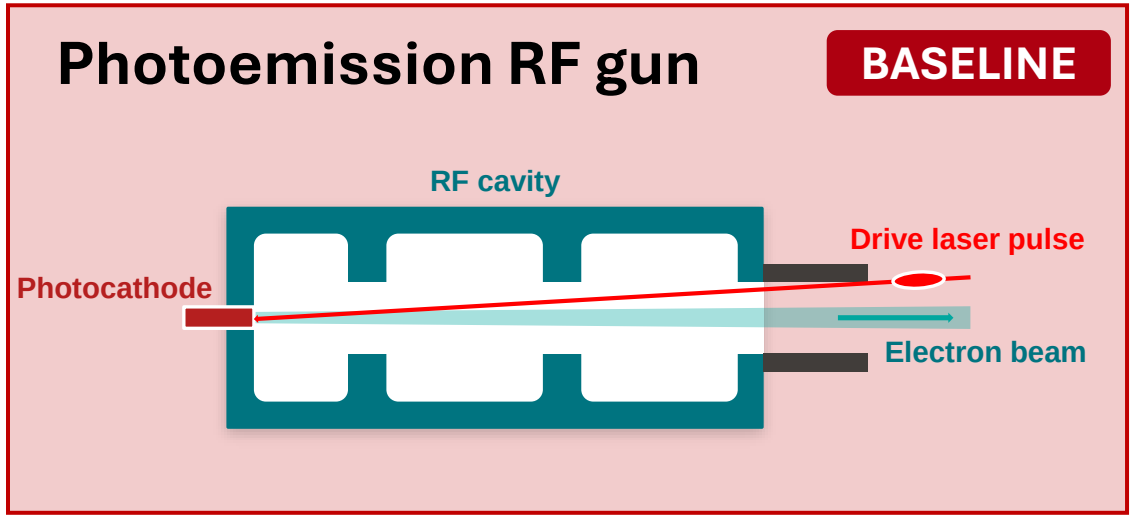
MAGIC



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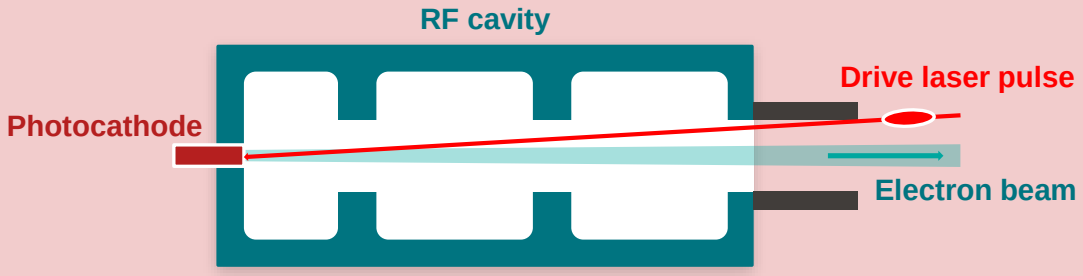
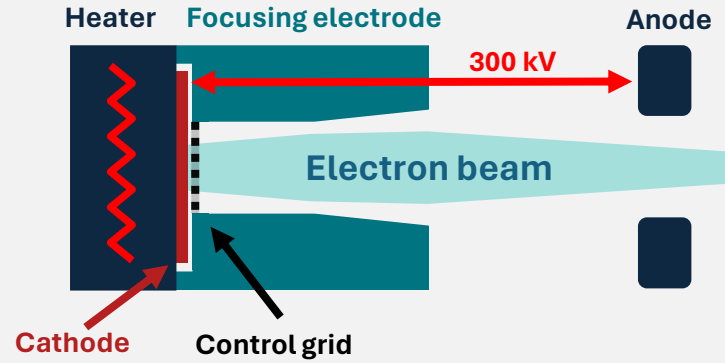
MAGIC

Photoemission RF gun

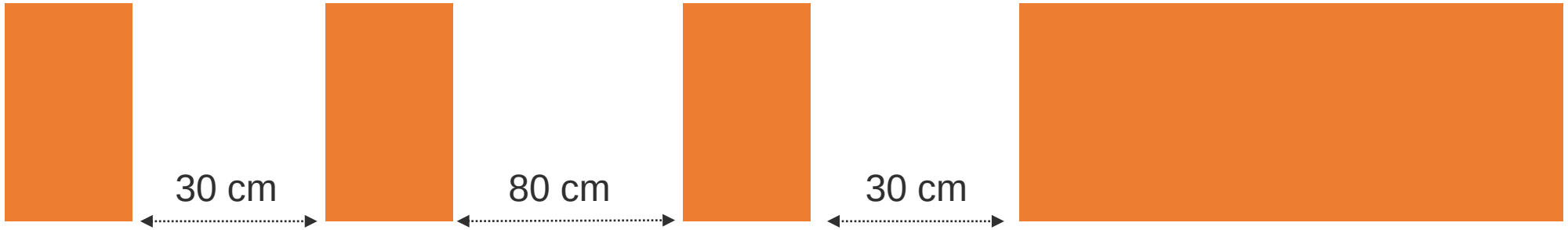
BASELINE



Thermionic DC gun



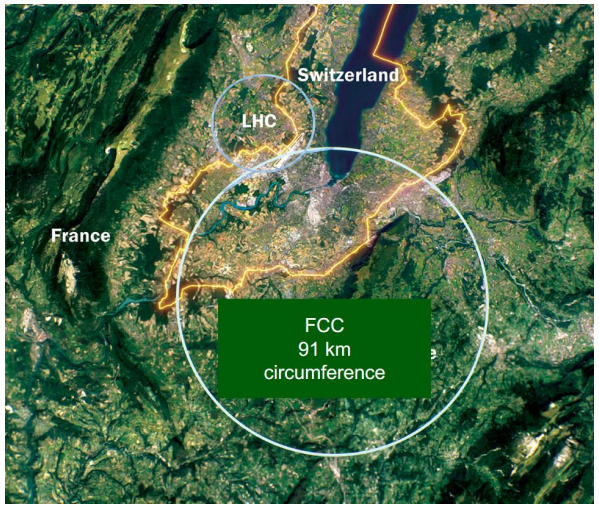
Polarized electron source

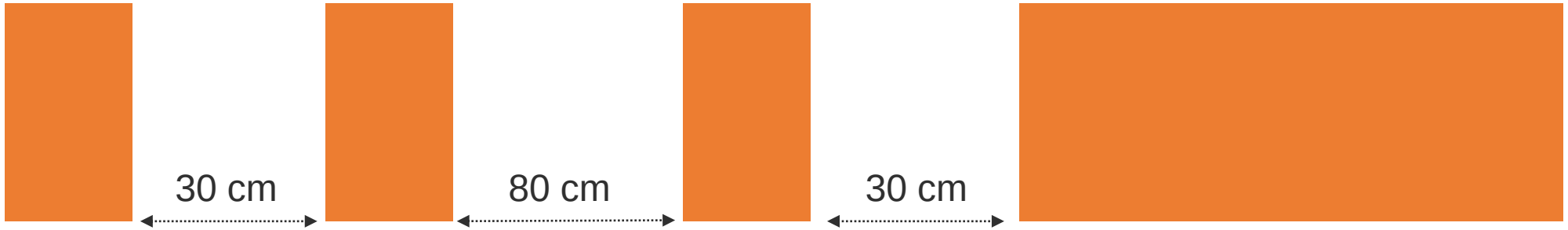


Polarized electron source

Polarization direction

Electron source	Longitudinal polarization	Given by the material properties
FCC complex	Vertical polarization	Because of the dipole magnets: vertical field





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Polarization vector (direction of polarization)

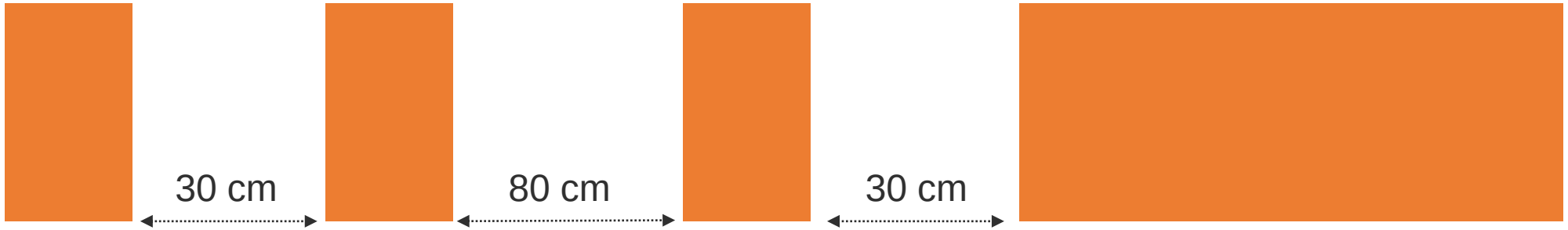
T-BTM equation

$$\frac{d\vec{P}}{dt} = \vec{\Omega} \times \vec{P}$$

$$\vec{\Omega} = -\frac{q}{m}\left[\left(a+\frac{1}{\gamma}\right)\vec{B} - \frac{a\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\cdot\vec{\beta} - \left(a+\frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Magnetic field

Electric field



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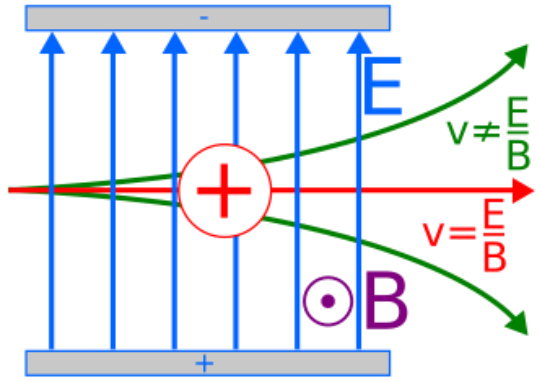
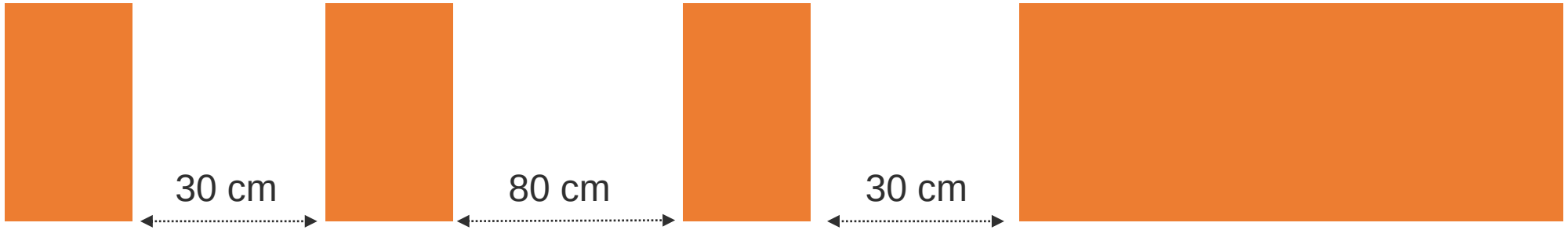
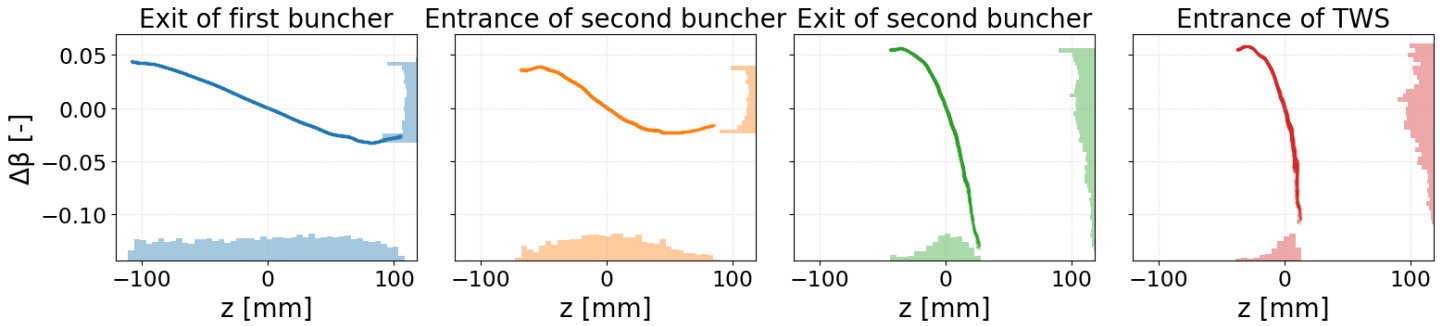
Wien filter



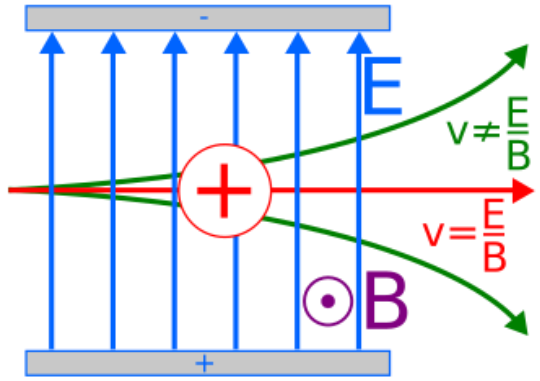


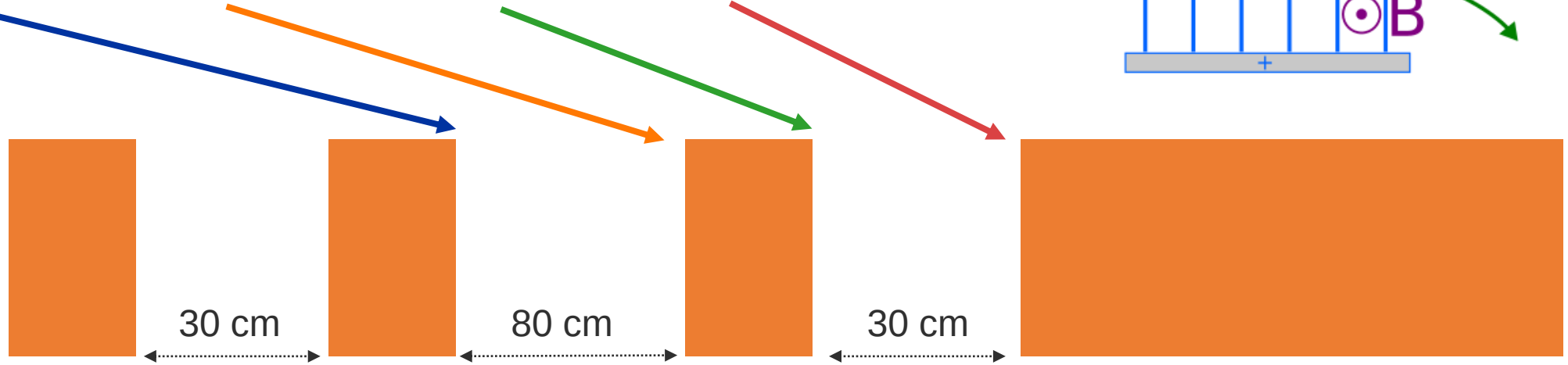
Polarized electron source

Longitudinal trace space snapshots (relativistic velocity | longitudinal positions)



Wien filter





Thermionic gun
300 kV
1 ns emission, 5 nC

250 MHz buncher
1 MV/m

500 MHz buncher
1 MV/m

TWS
20 MV/m

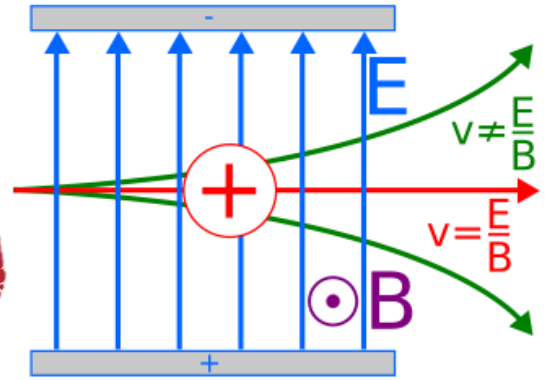
Polarized electron source

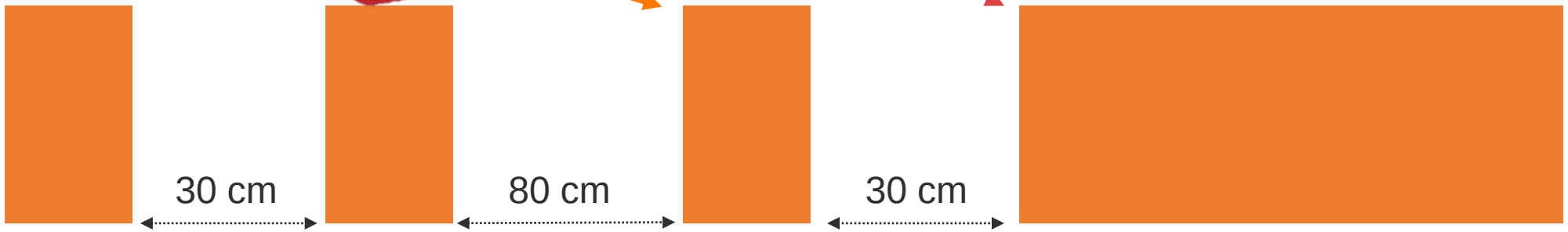
Longitudinal trace space snapshots (relativistic velocity | longitudinal positions)



WORK IN PROGRESS

Wien filter





Thermionic gun
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1 MV/m

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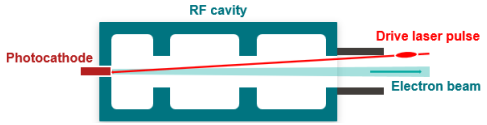
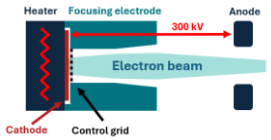
So, to conclude…

Photoemission RF gun 	Design baseline complete Test stand being built at PSI Charge variation scheme & photocathode lifetime to be tested
Thermionic DC gun 	First preliminary design developed Discussion about compatibility with linacs and positron source Investigations of feasibility of the charge variation
Polarized electron source	Photoemission DC gun – building on existing simulations Exploration of spin rotator Exact input parameters to be specified

CERN EPFL PSI CHART Swiss Accelerator Research and Technology

Thank you :)



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