High gradient ultra-high brightness RF photoinjector optimization

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On behalf of SPARC_LAB collaboration

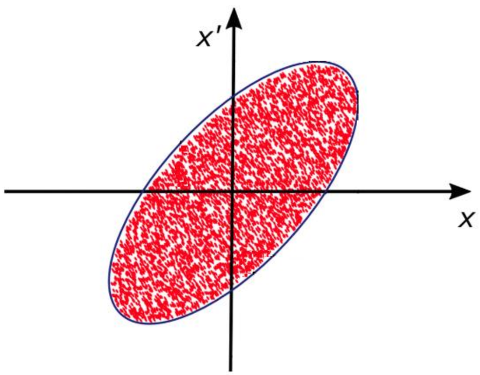
Introduction

- My work in the SPARC_LAB facility, that is able to produce high brightness electron beams.

- To optimize the present and future SPARC_LAB beam line I did:
  - To achieve higher beam brightness values, I optimized the BD for a completely new ultra high gradient 1.6 cells C-band (5.712 GHz) gun able to reach 240 MV/m as a peak field.
  - Layout design and simulations for the SPARC_LAB upgrade (EUPRAXIA) using the high gradient C-band gun.

Emittance and Brightness

- The emittance is a beam figure of merit, in general is proportional to the phase space occupied by the particles. It measures the possibility to produce a beam to small spot sizes, and the divergence of the beam during propagation.



Generally, there are five main contributions to the total projected emittance at the exit of a photo-emission gun, which can be summarized as

$$\varepsilon_{tot} = \sqrt{\varepsilon_{int}^2 + \varepsilon_{magn}^2 + \varepsilon_{sc}^2 + \varepsilon_{RF}^2 + \varepsilon_{optics}^2}$$

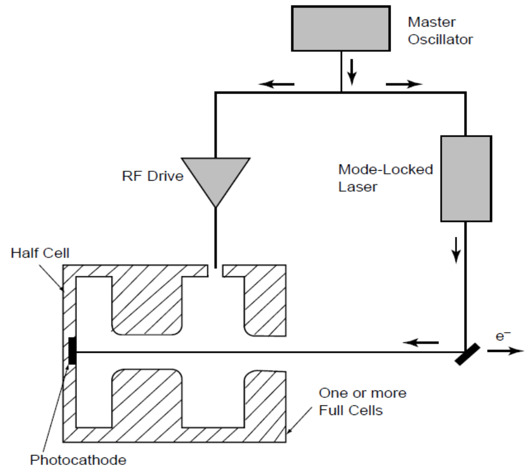
$$\varepsilon_{int} = \sigma_r \sqrt{\frac{2(\hbar\omega - \phi_{eff})}{3mc^2}} \quad \varepsilon_{sc} \ \alpha \ \frac{Q}{(2\sigma_r + \sigma_z)E} \quad \text{and} \quad \varepsilon_{RF} \ \alpha \ f_{RF}^2 \sigma_r^2 \sigma_z^2 E$$

- The beam brightness is defined by: $\boldsymbol{B} = \frac{\boldsymbol{2I}}{\boldsymbol{\varepsilon^2}}$, I(A) is the the beam current while the emittance is measured in m*rad.

- High gradient C-band gun to improve the ε_{tot}, new solenoid to improve ε_{magn}

RF photo-gun

- The idea of a laser driven electron gun was firstly studied and used at LANL (1986) and are currently under development new ideas to advance this device.

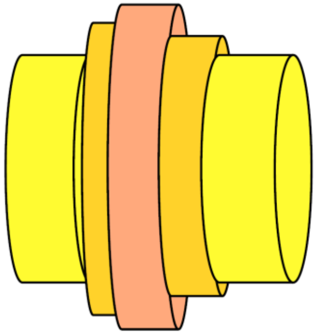


- The basic idea is to illuminate a surface (photocatode) with a time controlled laser, to extract electrons by photoelectric effect.
- Since $F_{sc} \propto \frac{1}{\gamma^2}$, to damp space charge forces the photocatode is embedded in an RF structure.
- Laminarity parameter: $\rho = \frac{I}{2 I_A \gamma} \frac{\sigma^2}{\varepsilon_n^2}$ ($\rho > 1$ the beam is SC dominated)

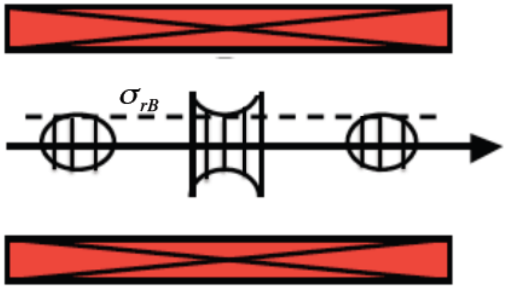
Emittance growth due to the SC forces

- One of the SC effects in the bunch evolution are longitudinal correlations inside the bunch that lead to consider a correlated emittance growth

- Considering a SC dominated beam in a focusing channel (e.g. solenoid)



Stationary solution $\sigma_{r,B}$: Brillouin flow



- Considering a transverse slice mismatching in the focusing channel, the slice oscilates around the stationary solution. This leads to a correlated emittance oscillation (reversible quantity).
- To compensate the emittance growth is used a solenoid after the gun. Furthermore the beam is matched in the first accelerating section to an invariant envelope $\sigma_{inv} = \frac{2}{\gamma'}\sqrt{\frac{I}{3I_A\gamma}}$ and to a proper phase of the emittance oscillation.

A new ultra high brightness scenario

- To improve the beam emittance and the beam brightness it is possible to increase the cathode peak field (reducing also the laser spot on cathode and ε_{int}).

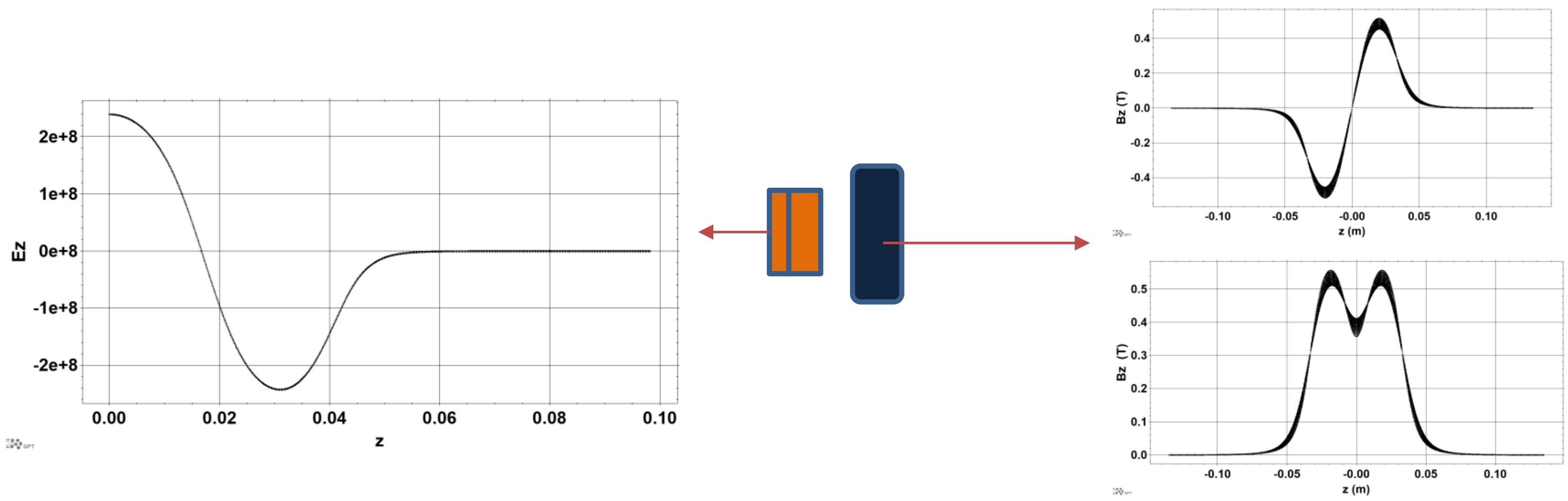
- At the very low emittance values can be also important to reduce the ε_{magn}, reducing the solenoid residual field on the cathode surface.

- In collaboration with UCLA-SLAC-LANL (MARIE X-FEL), at SPARC_LAB we are optimizing a **C-band gun** able to reach up to **240 MV/m** as a peak field.

- A new scenario has been opened, and I present the results for the emittance compensation using and properly scaling the design of the new SPARC_LAB gun solenoid, able to reduce the residual field on the cathode up to 3.6 G @ 150 A in the S-band scenario.

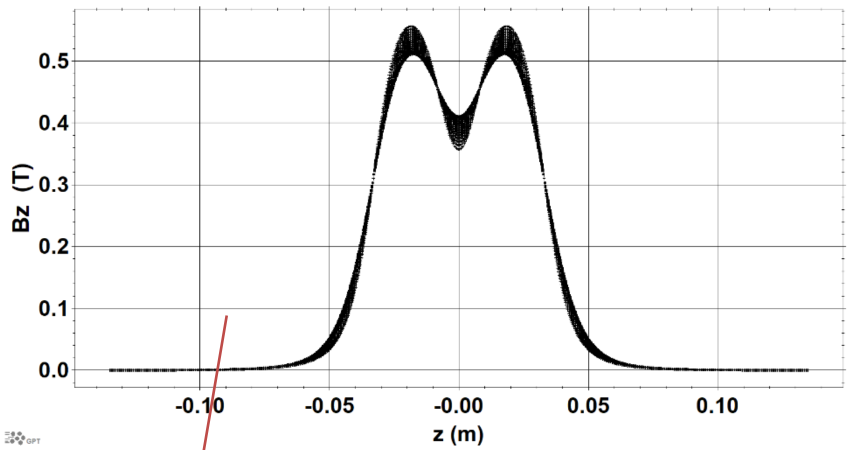
C-band gun layout

- In order to maintain the Ferrario WP a 1.6 cells C-Band gun was used with 240 MV/M. In this way $E_{final} \approx 5MeV$ as in the S-band 120MV/m case.

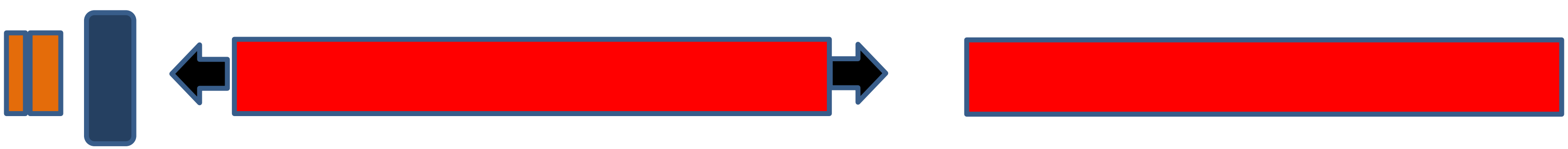


- Each lenght was scaled by a factor 2 and each field was double respect to the S-Band scenario: the lenght of the solenoid was scaled by a factor 2 and the integrated magnetic field was double.

Photoinjector layout



TW sections 57 MV/m



C-BAND GUN + SCALED SOLENOID

C-BAND (on crest)

C-BAND (on crest)

Using the GPT code the first linac position, the integrated magnetic field, bunch parameters, the residual magnetic field on the cathode were optimized.

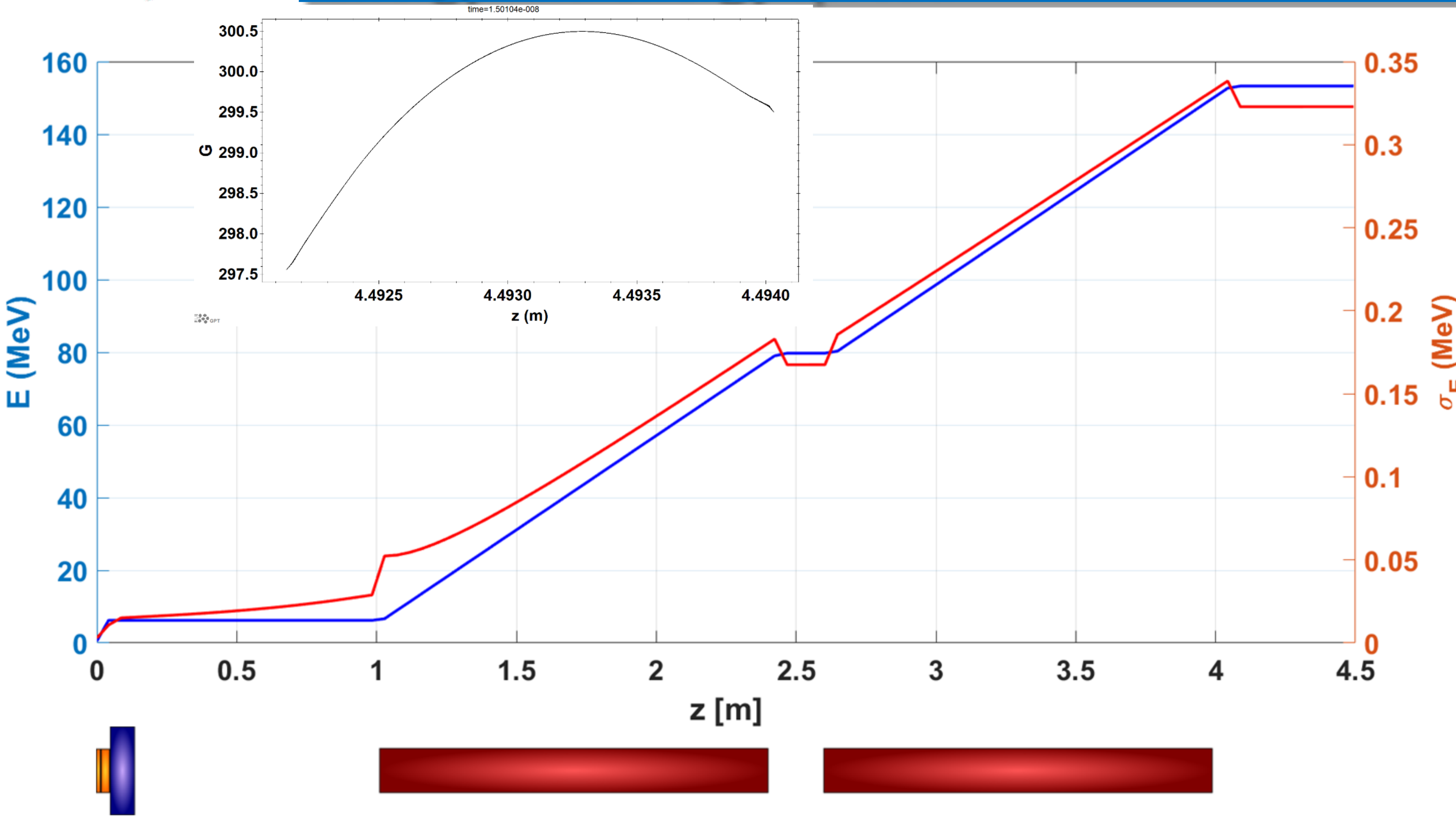
$$E_{final} \approx 150 MeV$$

$$E_{spread} \approx 0{,}2\%$$

GPT simulations – Starting parameters

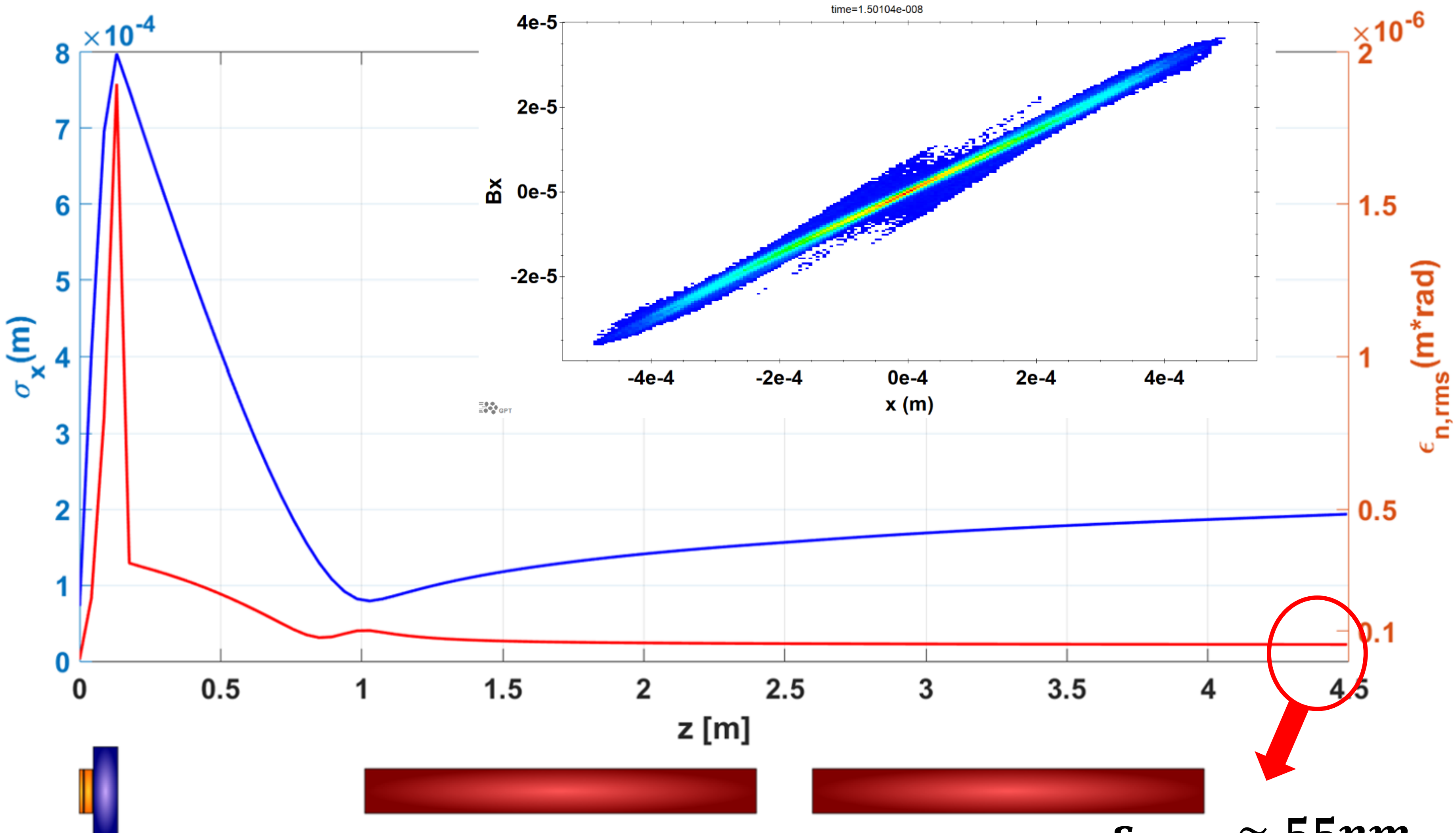
- $Q = \mathbf{100\,pC}$
- Laser on cathode : $\begin{cases} t_{length} = 5.8\,ps\ \ (uniform) \\ \sigma_x = 151\,\mu m\,(gaussian) \\ E = 4.66\,eV \text{ (corresponding to } \lambda = 266.7\,nm) \end{cases}$ (Cigar regime $\boldsymbol{\sigma_z} > \boldsymbol{\sigma_x}$)
- The field on the cathode is: $E_z = E_0 sin\phi_{launch}$. In this case $E_0 = 240MV/m$ and $\phi_{launch} = 38°$ $\rightarrow$ $\boldsymbol{E_z \approx 145MV/m}$
- The field map of the new SPARC_LAB gun solenoid (2 coils powered with the same current) was used dividing the lenght and doubling the field by a factor 2.
- The starting intrinsic emittance was setted to: $\varepsilon_{int} = 25nm$.

Energy and energy spread



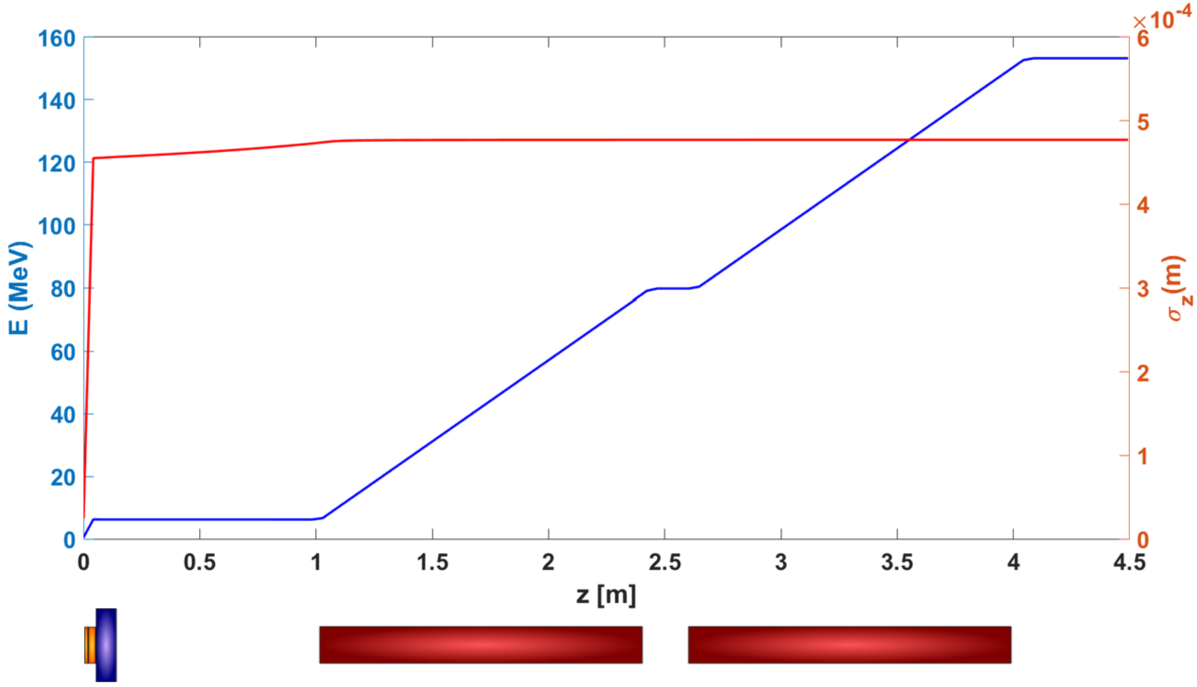
$E_{final} \approx 150 MeV$ $E_{spread} \approx 0,2\%$

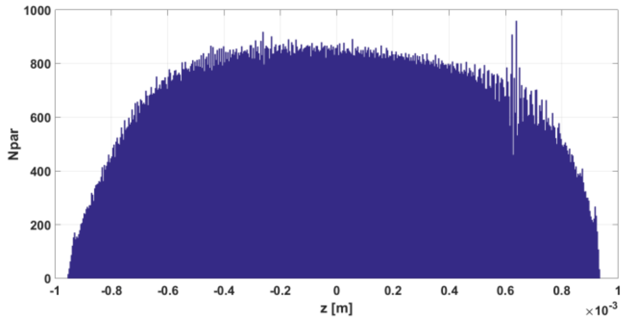
Spot and emittance



$\varepsilon_{final} \approx 55nm$

Bunch lenght





$$\sigma_{z,rms} \approx 4.7\ x\ 10^{-4} m$$

$I \approx 64.1$ A

$$\boldsymbol{B = \frac{2I}{\varepsilon_n^2} \approx 4.2\ \mathrm{x}\ 10^{16}\,\frac{A}{m^2}}$$

Magnetization emittance

- Busch's Theorem in order to estimate the magnetization emittance $\varepsilon_{n,mag}$

- When particles are emitted in a magnetic field they have a canonical angular momentum. This can be translated in an emittance contribution:

$$\varepsilon_{n,mag} \cong \frac{\sigma_{p\perp}}{m_0 c}\sigma_x \cong \frac{qB_0}{2m_0 c}\sigma_x^2 \quad \rightarrow \quad \varepsilon_{n,mag}(mm\ mrad) \cong 0.3B_0(mT)\sigma_x^2(mm^2)$$

- The scaled new SPARC_LAB solenoid has on the cathode a residual field $B_0 = 0.83\ mT$ @ 177A that leads to:

$$\varepsilon_{n,mag} = 5.7\ \text{nm}$$

- An optimization of the previous working point inserting a bucking coil in order to reduce the magnetization emittance was done leading to a final emittance value of $\boldsymbol{\varepsilon_{n,rms} \approx 54nm}$.

SPARC_LAB upgrade

- Recent proposal to upgrade SPARC_LAB with a new linear accelerator able to push the beam energy over the GeV scale and it will realized in the framework of two european projects. Both projects requires an high quality beam produced by a compact high gradient RF accelerator (X-band).

- Once extracted from the conventional accelerator the beam will be injected in a plasma channel, and after in a FEL.

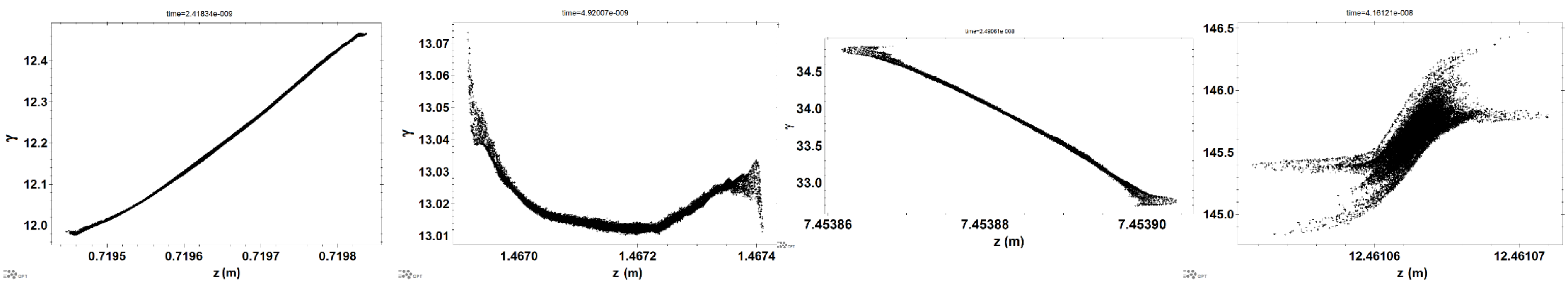
GOAL parameters:

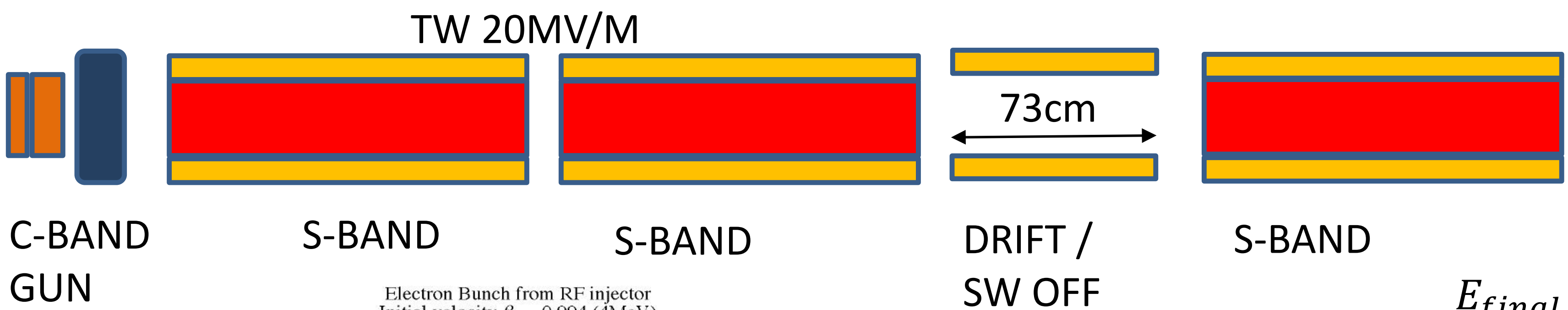
LINAC: X band (11.424 GHz) RF linac, accelerating gradient > 70MV/m, final energy $1 - 1.5$ GeV.

BEAM: $Q = 30pC$, peak current 3 kA (i.e. bunch lenght 3 μm), Espread $<\ 1\%$, $\varepsilon_{n,rms} < 1\ \mu m$

Photoinjector layout

- To optimize the beam quality during the longitudinal compression, I used an hybrid compression system. Velocity bunching + Ballistic bunching

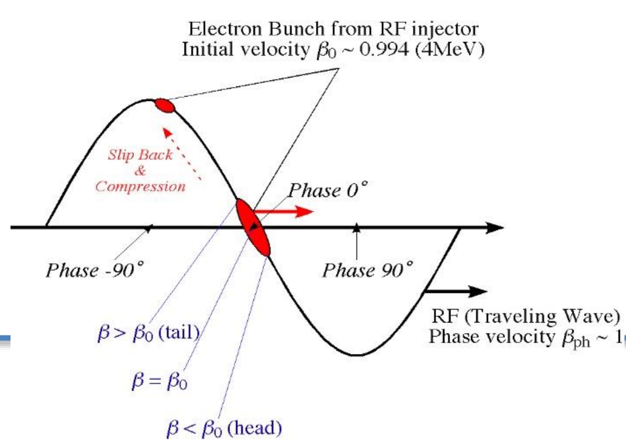




$E_{final} \approx 75MeV$

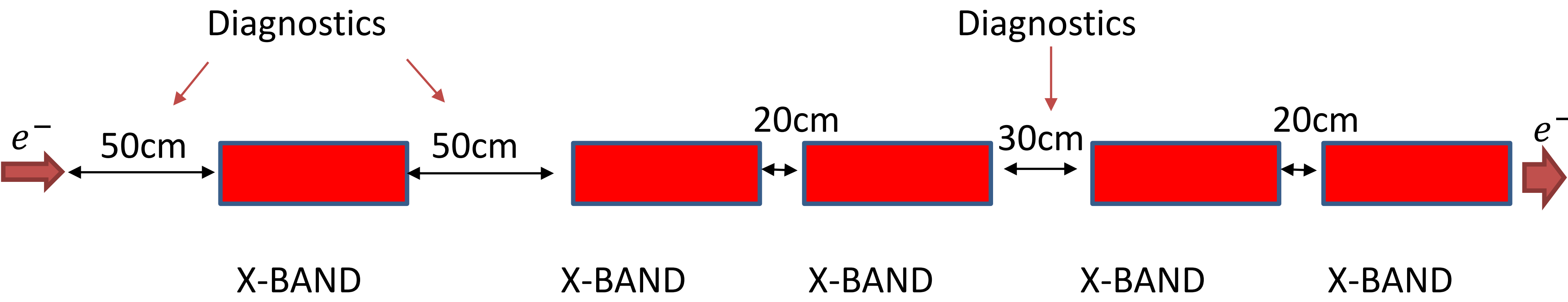
$E_{spread} \approx 0.1\%$

Longitudinal Ballistic Bunching



The X-band linac

X-BAND MODULE: 70cells, $E_{acc} = 70MV/m, L = 62\ cm$



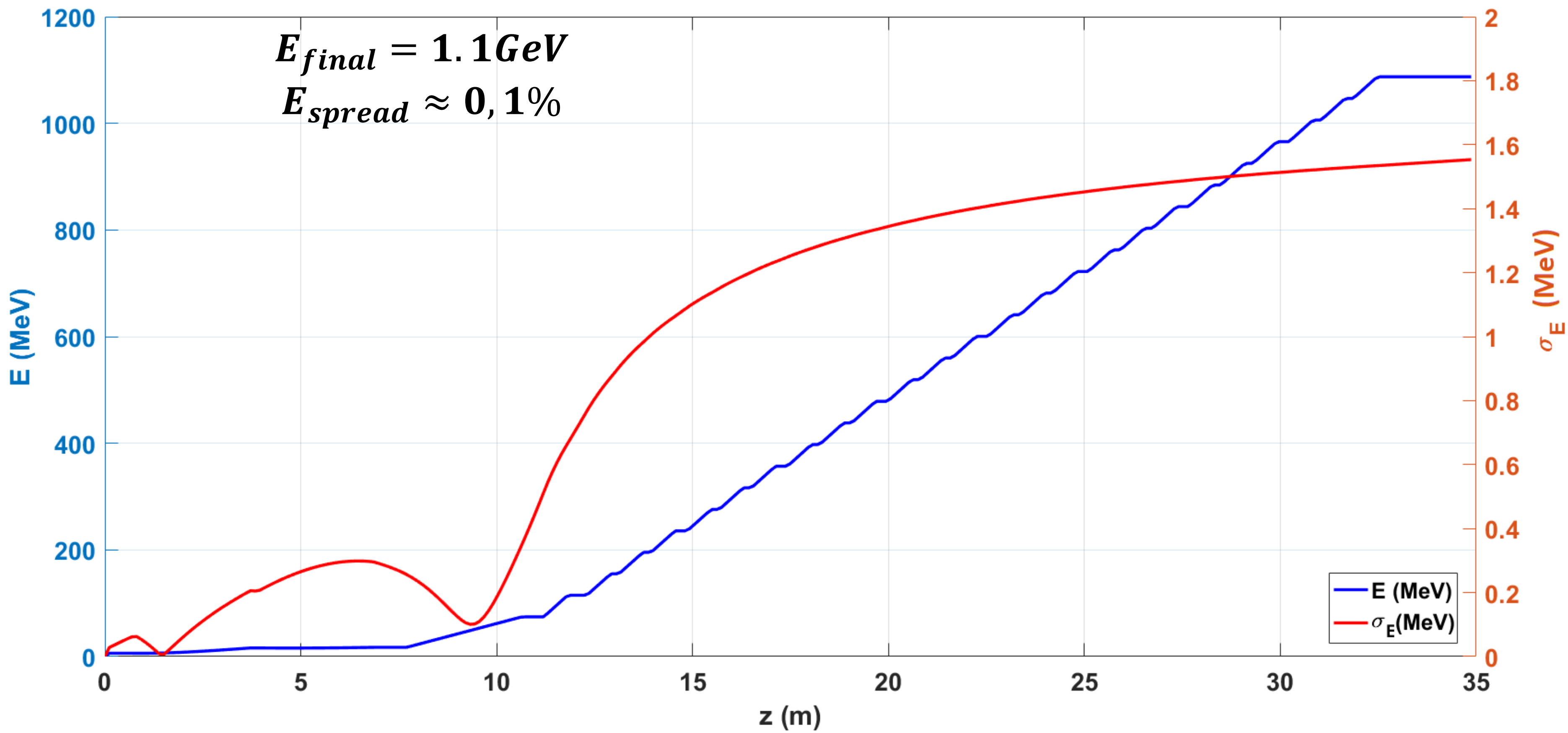
With 24 X-band modules $\boldsymbol{E_{final} = 1.1GeV}$, reaching a $\boldsymbol{Final\ lenght\ \approx\ 32m}$

GPT simulations – beam parameters

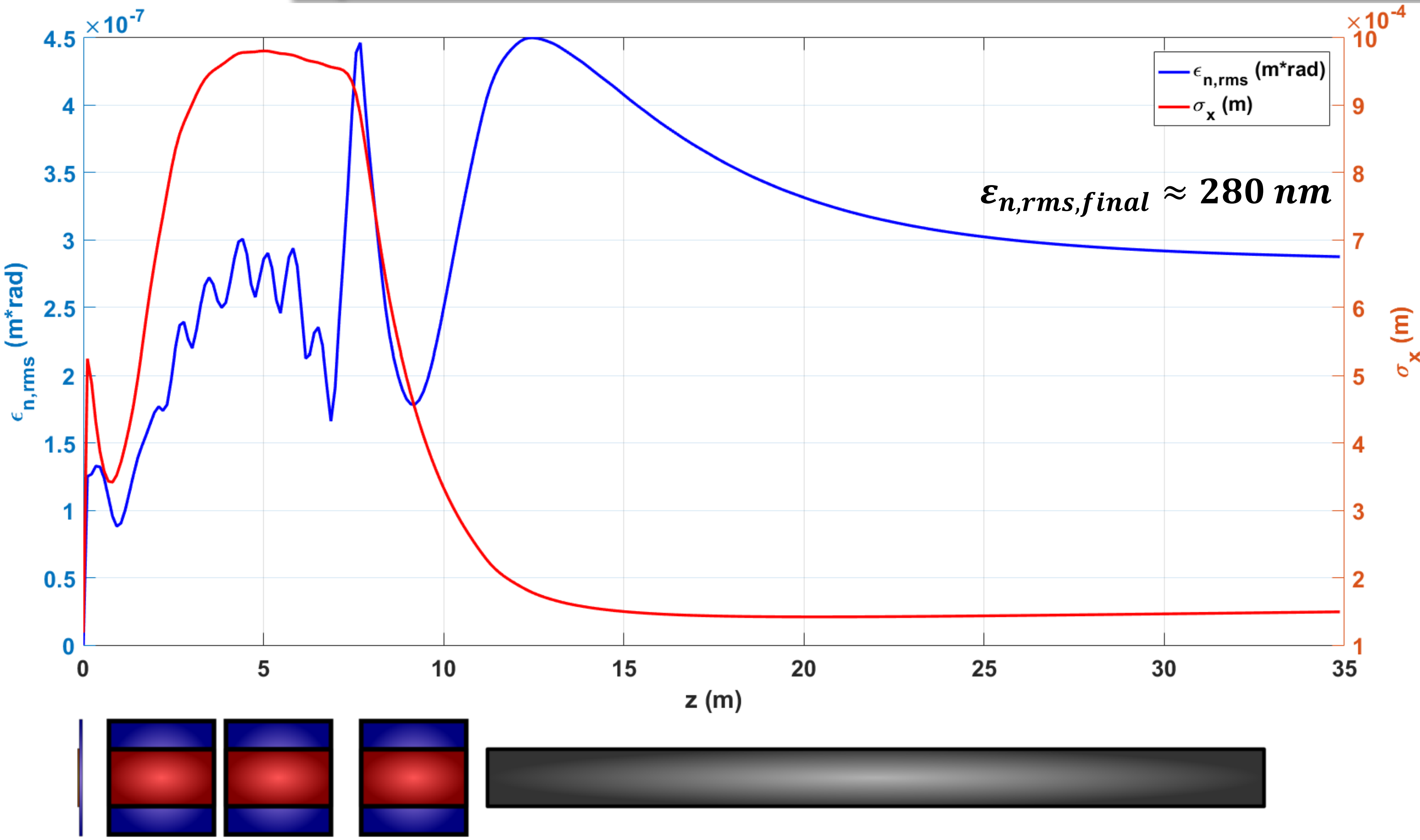
- $\boldsymbol{Q = 30\, pC}$
- Laser on cathode: $\begin{cases} \sigma_t = 21\, fs\ (rms) \\ \sigma_x = 175\, \mu m\ (rms) \\ E = 4.66\, eV \text{ (corresponding to } \lambda = 266.7\, nm) \end{cases}$ (Blow out regime $\boldsymbol{\sigma_x > \sigma_z}$)
- The field on the cathode is: $E_z = E_0 sin\phi_{launch}$. In this case:

$E_0 = 240 MV/m$ and $\phi_{launch} = 33°$ → $\boldsymbol{E_z \approx 130 MV/m}$

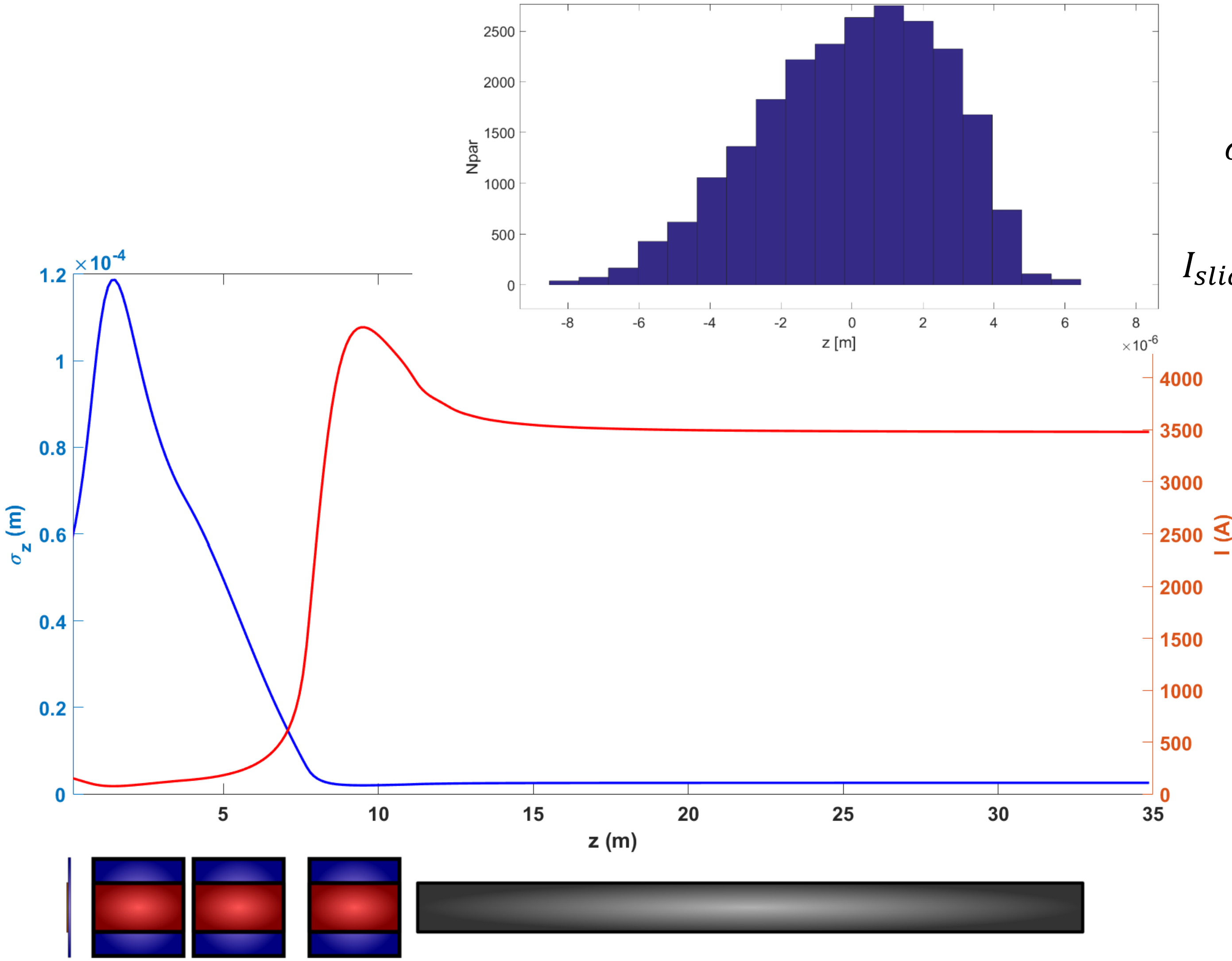
Energy and energy spread



Spot and emittance



Bunch length and beam current



$$\sigma_{z,slice} \approx \sigma_{z,bin} \approx 0.8\ \mu m$$

$$I_{slice} = \frac{Q_{slice}(3.3pC)}{\sigma_{t,bin}} \approx 1.3kA$$

$$\sigma_{z,rms} \approx 2.6\ \mu m$$

$$I_{peak,rms} = \frac{Q_{tot}}{\sigma_{t,rms}} \approx 3.5\ kA$$

Conclusions and perspectives

- To reach the impressive emittance value of $\boldsymbol{\varepsilon_{n,rms}} \approx \mathbf{55}\boldsymbol{nm}$ and a beam brightness of $\boldsymbol{B} \approx$ **4.2 x** $\mathbf{10^{16}}\,\boldsymbol{\frac{A}{m^2}}$, the layout and the beam dynamics of an high peak field C-band gun (240MV/m) have been optimized.

- A scan using cathode peak fields between 180-325 MV/m is starting. And a discussion on the RF technology able to reach these field has been opened.

- The performances of this gun were applied to design a complete layout for the SPARC_LAB upgrade (EUPRAXIA, XLS), reaching $\boldsymbol{E_{final}} = \mathbf{1.1}\boldsymbol{GeV}$ and $\boldsymbol{\varepsilon_{n,rms}} \approx \mathbf{280}\ \boldsymbol{nm}$.

- The possibility to reduce $\varepsilon_{n,rms,final}$ to $100\ nm$ using a cigar regime will be test.

- To have only one frequency and to save longitudinal space ($5 \approx m$), the study of a completely C-band injector is currently under test.