High gradient ultra-high brightness C-band photoinjector:

BD results and comparison for different cathode peak fields

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Introduction

- The photoinjector is a key device to reach the high brightness ($B = \frac{2I}{\epsilon_r^2}$).

- The first contribution to the beam emittance is the thermal one ϵ_{th}, while to reduce the emittance growth due to space charge forces, after the emission an RF structure pushes quickly the beam up to relativistic energy.

- To reduce the beam emittance some efforts are done increasing the cathode peak field, reducing the laser spot on the cathode [1] and pushing the beam faster up to relativistic energies. [2,3]

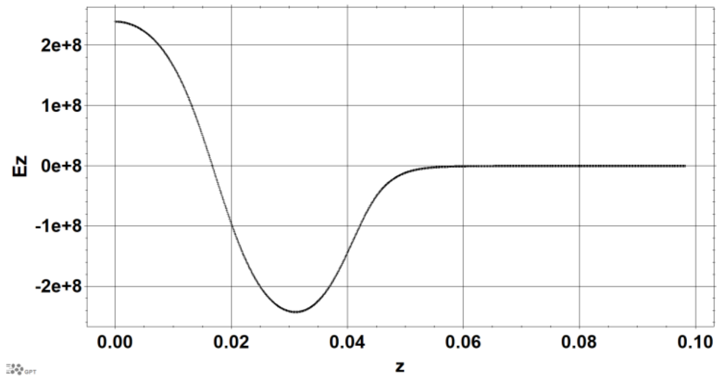
$$\epsilon_{th} \propto \sigma_x \qquad \epsilon_{sc} \propto 1/E_{cath}$$

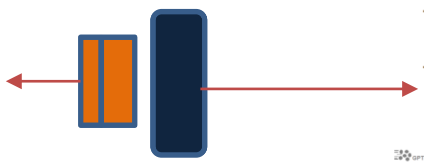
- Maintaining the same $\mathrm{f_{RF}}$, the same RF structure lenght and increasing the peak field, the disadvantage could be an higher energy at the entrance of the first accelerating structure. In that case an RF compression is not possible.

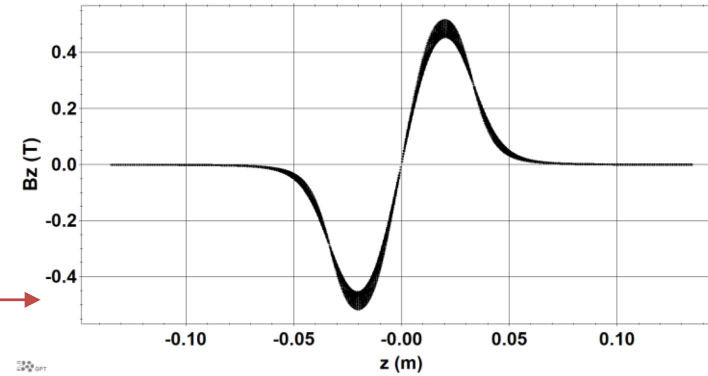
1. Rosenzweig, J.B., Colby, E. TESLA-95-04.
2. Rosenzweig, J. B., et al. *Physical Review Accelerators and Beams* 22.2 (2019): 023403.
3. Rosenzweig, J. B., et al. *Nucl. Inst. and Meth in A:* 909 (2018): 224-228.

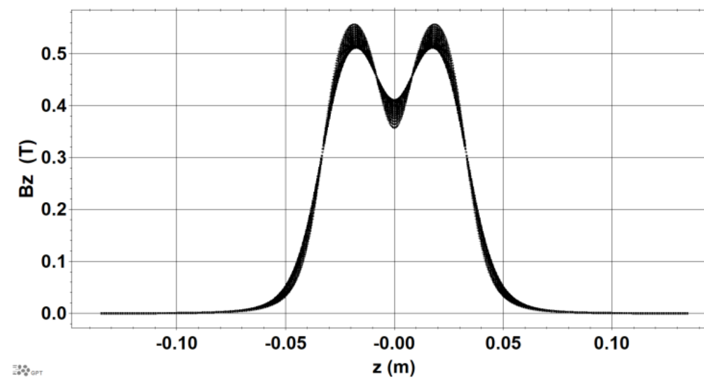
C-band gun layout

- In order to maintain the main features of the well established S-band working points, a 1.6 cells C-Band gun was used with 240 MV/m. In this way $E_{final} \approx 6\ MeV$ as in the S-band 120 MV/m case.









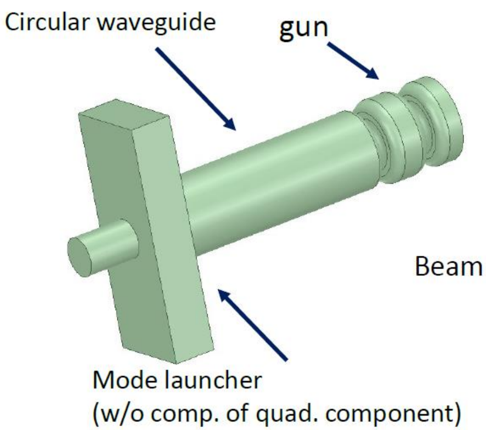
- Each device lenght was scaled by a factor 2 and each field was doubled respect to the S-Band scenario.

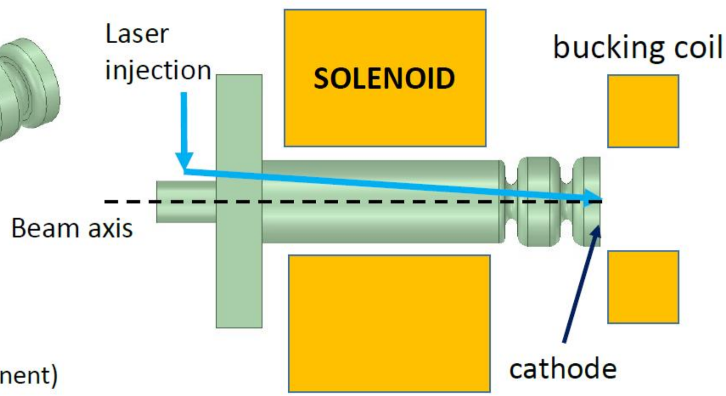
C-BAND GUN POWERING SCHEMES

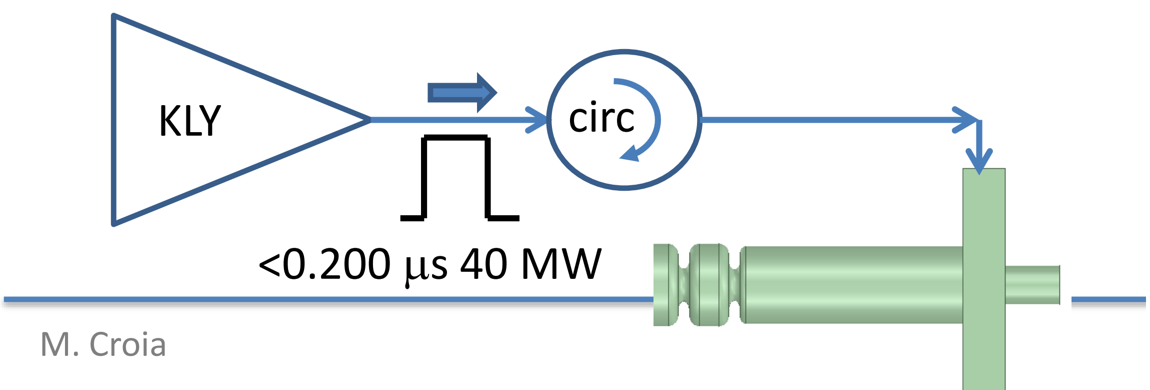
The **design and fabrication** of the new gun will be driven by the s**ame criteria used in the design of high gradient X band structures** developed in in the framework of linear collider projects (NLC, JLC and CLIC). There are four main quantities that play a crucial role in the BDR control: the **peak electric field**, the **modified Poynting vector** (S_c), the **RF pulse length** (t_p) and the **pulsed heating** (ΔT). The gun will be designed and fabricated keeping under control these quantities.

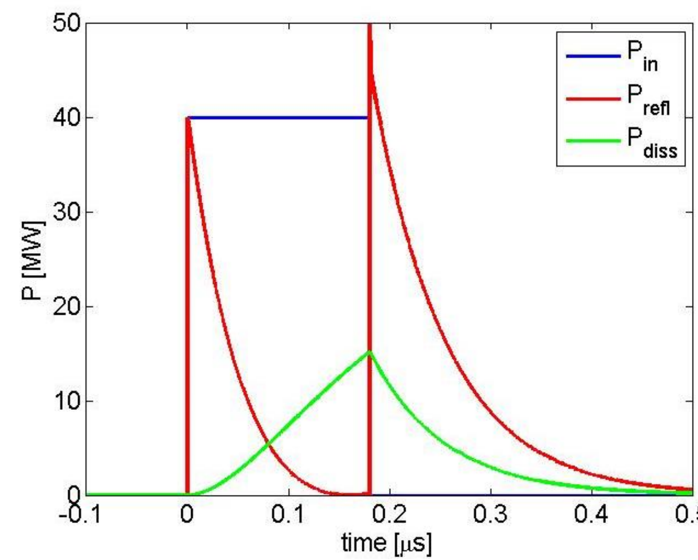
Alesini, D., et al. JACOW Publishing, Geneva, Switzerland, 2019.

E_{cath}	240 MV/m
$\Delta f_{0-\pi}$	≈ 100 MHz
Q_0	11000
β	3
P_{diss} @240MV/m	12 MW
$E_{CAT}/\sqrt{P_{diss}}$	67 [MV/mMW$^{0.5}$]
P_{IN} @240MV/m	31 MW
ΔT @ 200 ns	<30 °C
RF pulse length	<200 ns
Av diss power	2000-200 W
Rep. Rate	1000-100 Hz









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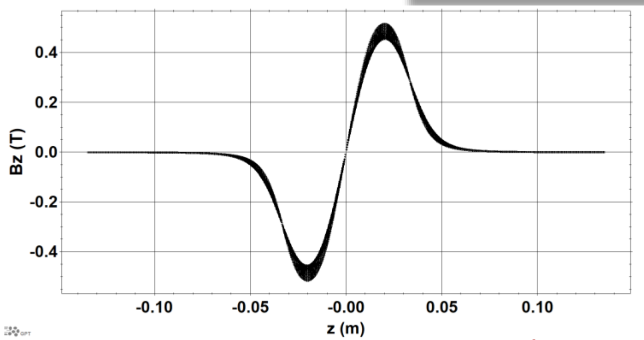
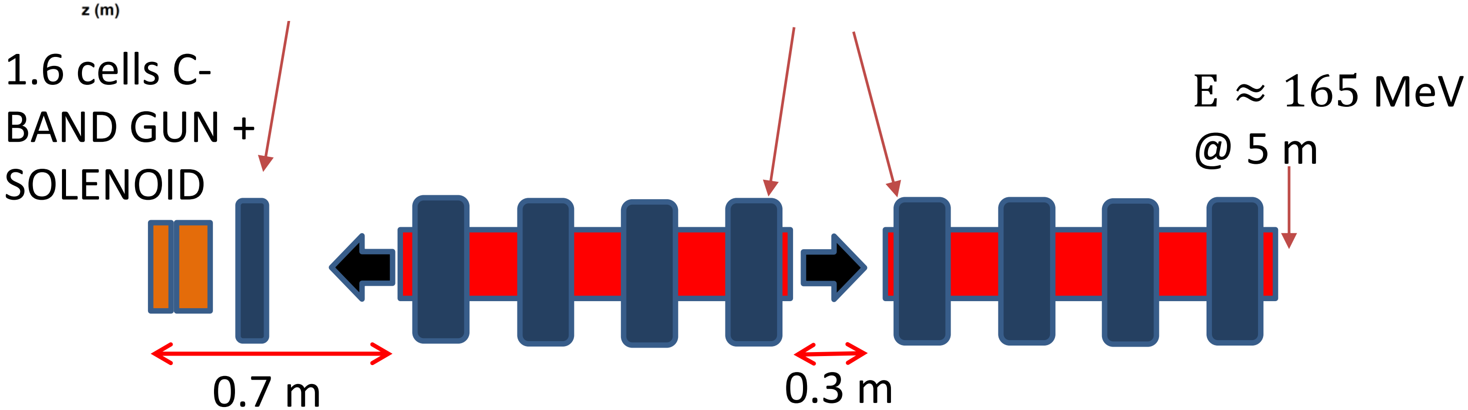
FULL C-band photoinjector layout

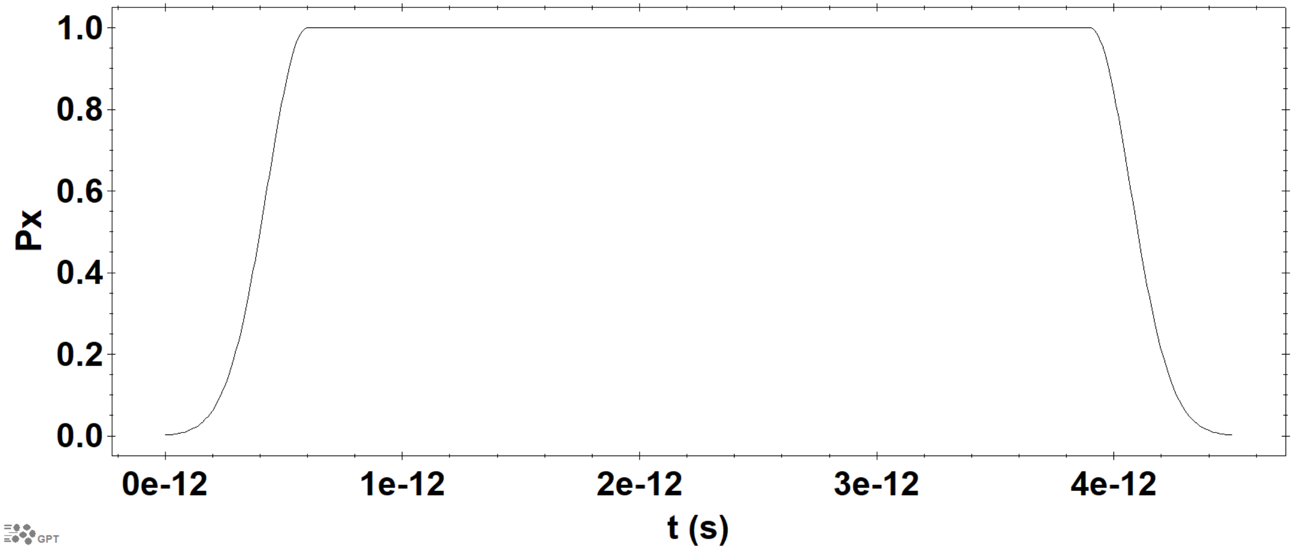


During the RF compression solenoids on the firsts two sections are used to keep under control the beam spot size and the emittance



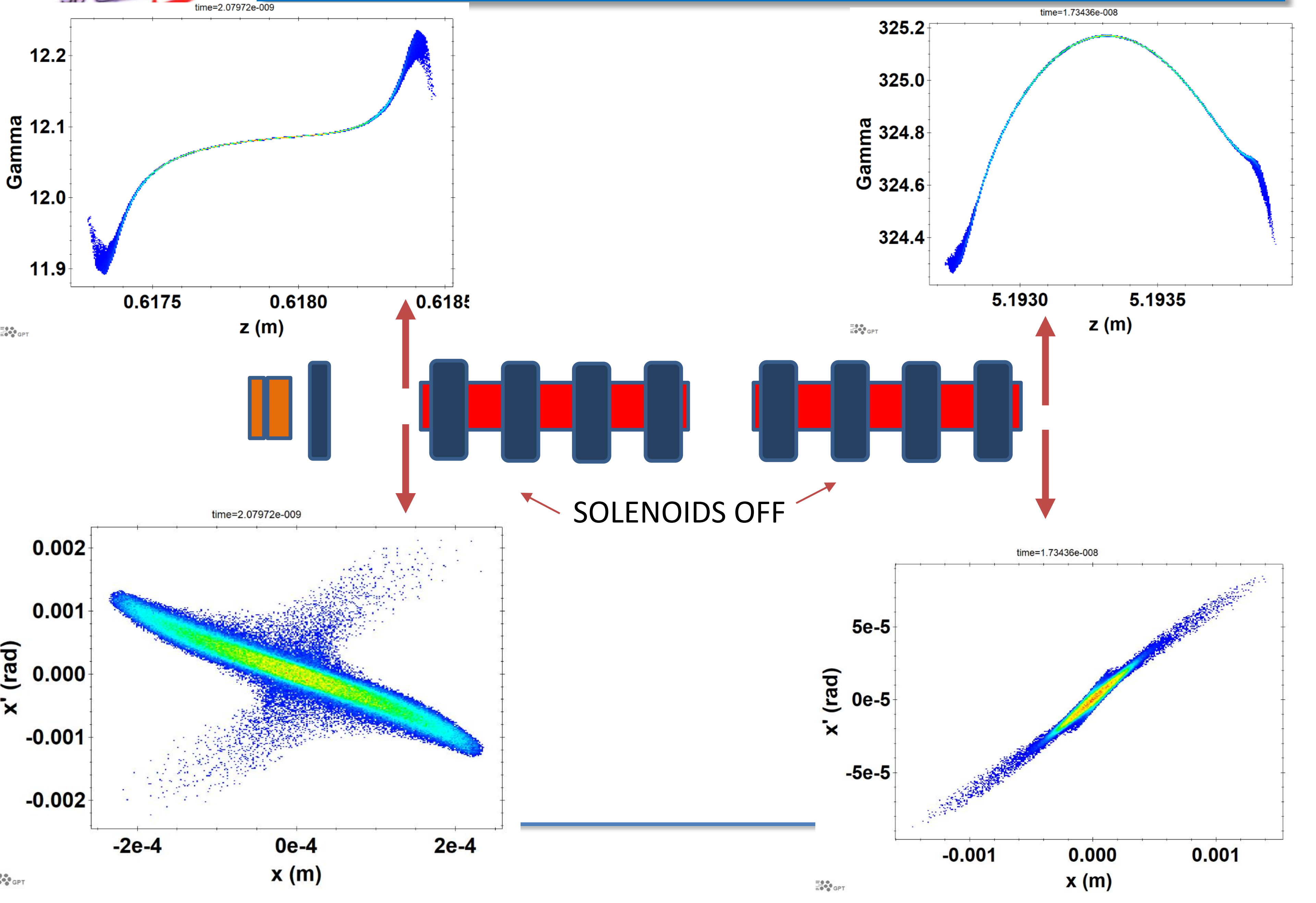
- C-BAND SECTIONS ($l = 2m$) operating at 40 MV/m average accelerating gradient (as example, PSI-like structures with 1 klystron every 2 sections)

- Using the GPT code the section positions and the integrated magnetic fields were optimized. The first section RF phase was setted to perform an RF compression (velocity bunching).

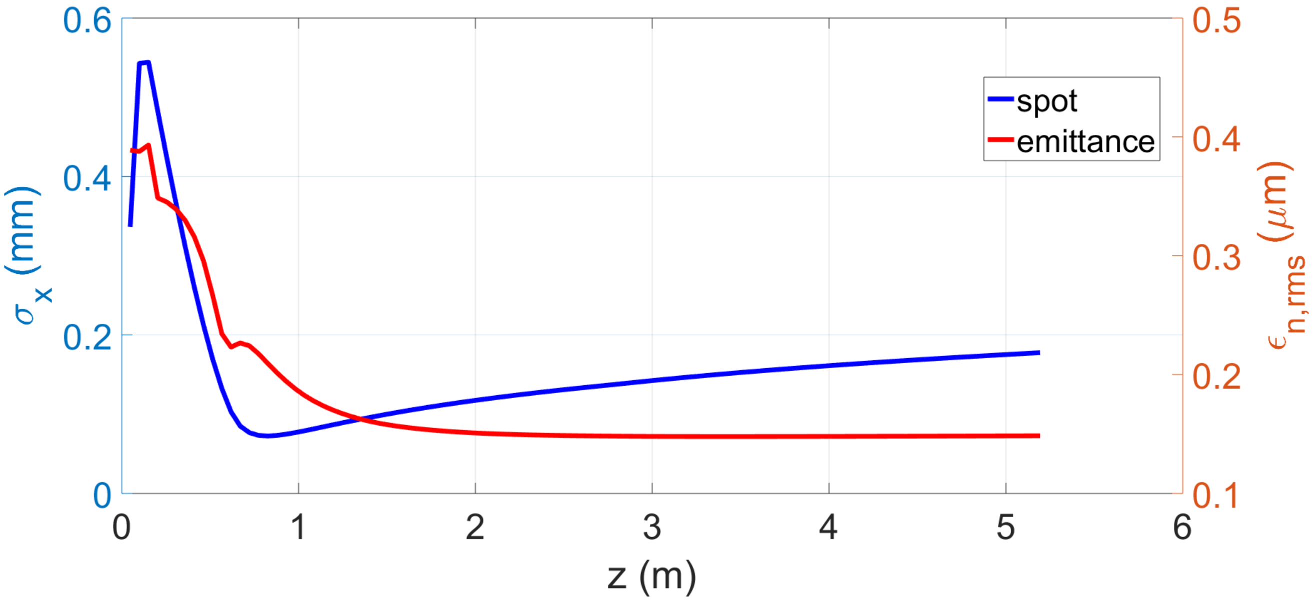


- $Q = \mathbf{75\ pC}$
- **GPT** 500k particles
- Laser on cathode : $\begin{cases} radius = 294\ \mu m\ (uniform) \\ E = 4.66\ eV\ \text{(corresponding to } \lambda = 266.7\ nm) \end{cases}$
- The field on the cathode is: $E_z = E_0 sin\phi_{launch}$. In this case $E_0 = 240 MV/m$ and $\phi_{launch} = 35°$ $\rightarrow$ $\boldsymbol{E_z \approx 137 MV/m}$
- The starting intrinsic emittance was analitically re-calculated for an ideal high gradient case and setted to: $\varepsilon_{int} = 118\ nm$.

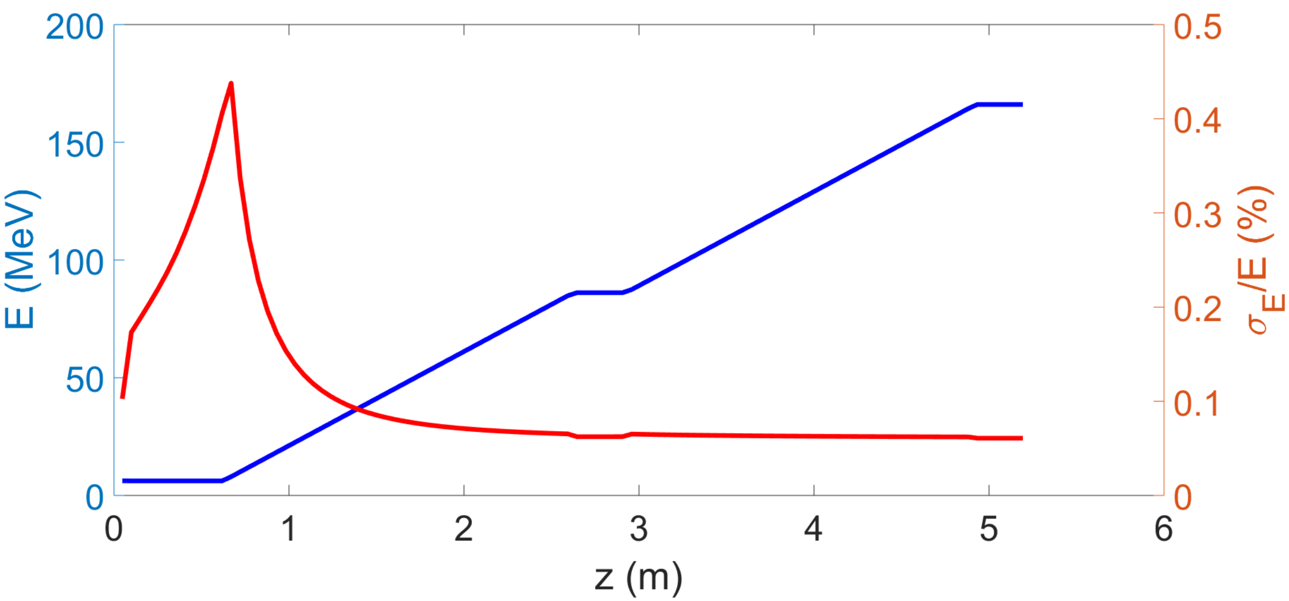
ON CREST BEAM



Main beam parameters trend



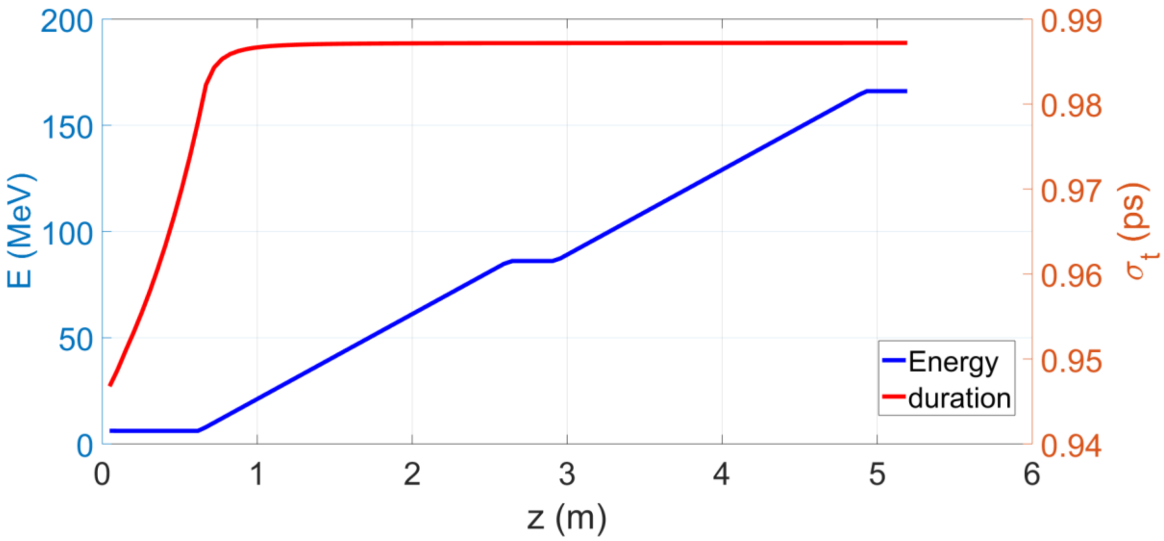
$\epsilon_{n,rms,final} \approx \mathbf{0.15}\ \mu m$



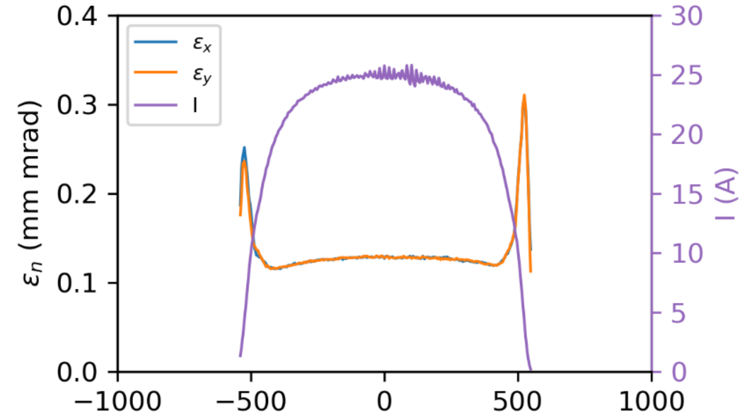
$E_{gun,exit} \approx 6\ MeV$

$\boldsymbol{E_{final} \approx 165 MeV}$

$\boldsymbol{E_{spread} \approx 0.06\ \%}$

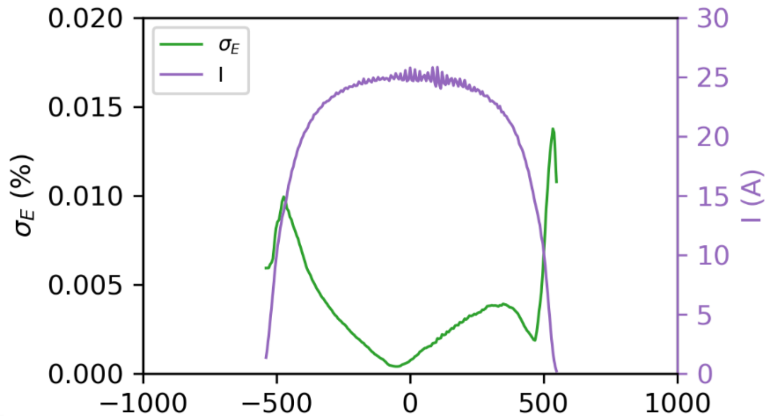


$\boldsymbol{\sigma_{z,final} \approx 296\ \mu m}$



"Rolling" slice analysis

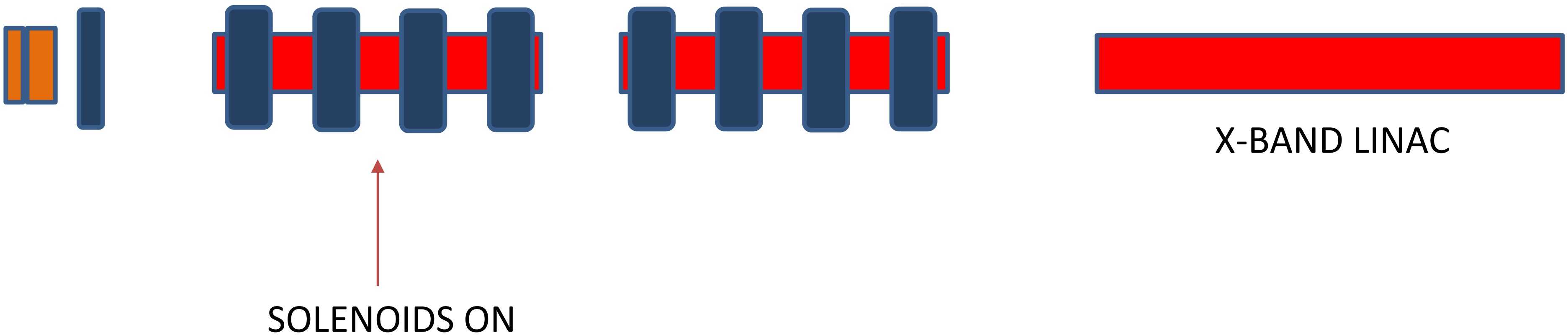
$L_{slice} = 30\ \mu m$



$\boldsymbol{I_{slice} \approx 25\ A}$

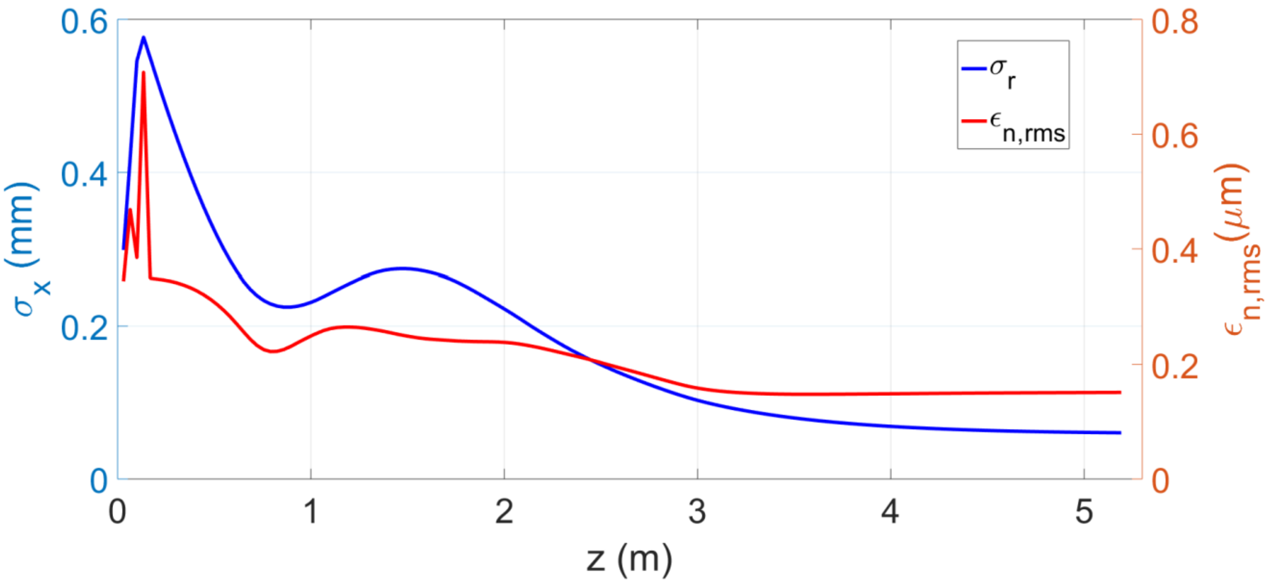
Courtesy of
A.R.Rossi and S. Romeo

SOFT RF COMPRESSION FOR COMPACT LIGHT [1]



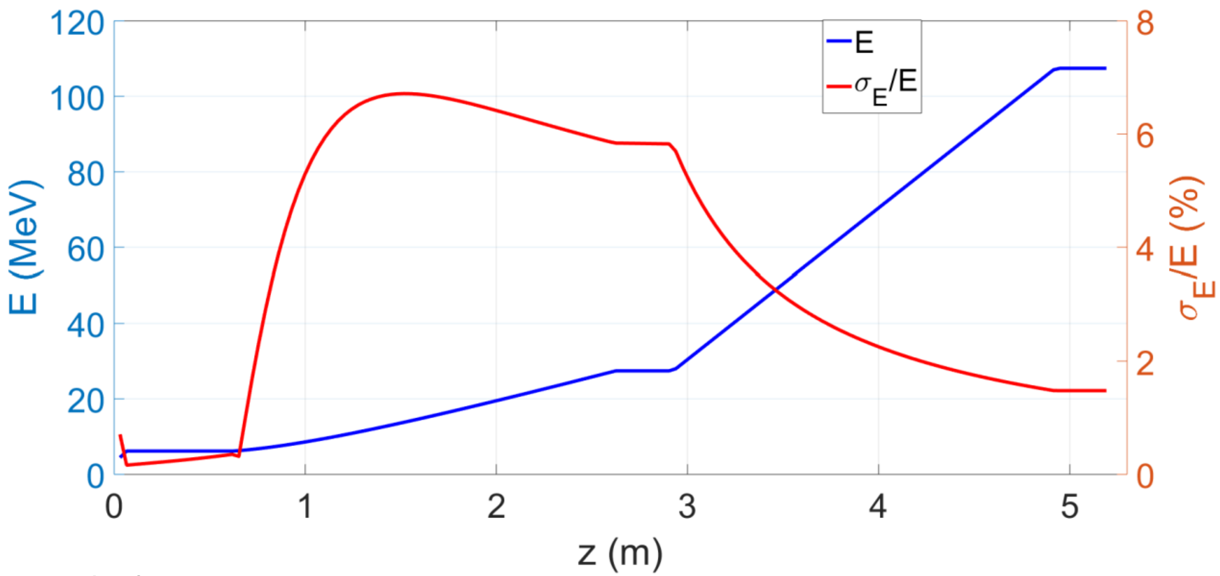
1. D'Auria, G., et al. "The CompactLight Design Study Project." *May 2019*. JACOW Publishing, Geneva, Switzerland, 2019.
2. Compact Light, www.compactlight.eu

Spot and emittance



$\epsilon_{r,final} \approx 0.15\ \mu m$

$\sigma_r \approx 60\ \mu m$

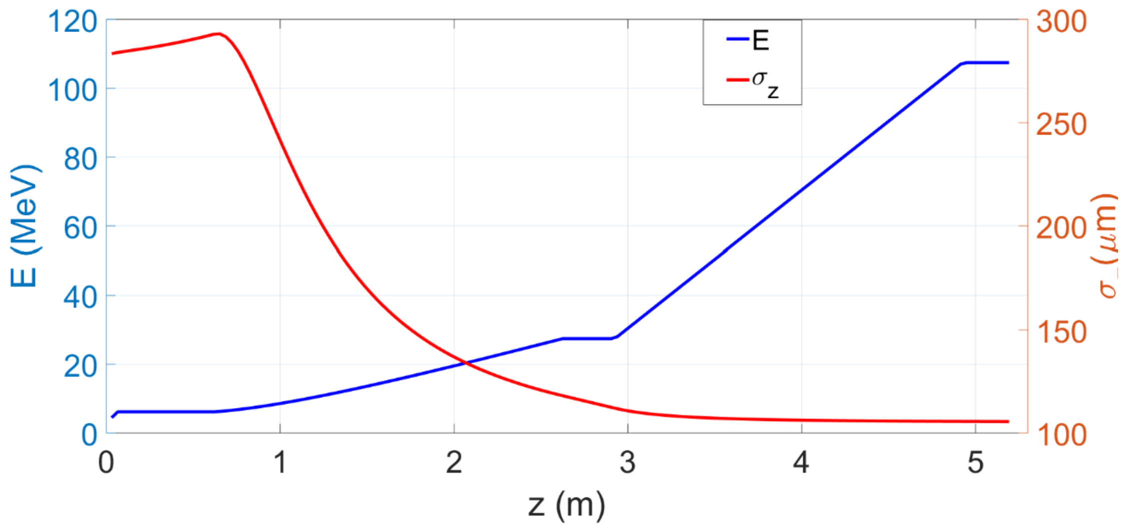


$E_{final} \approx 108\ MeV$

$E_{spread} \approx 1.4\%$

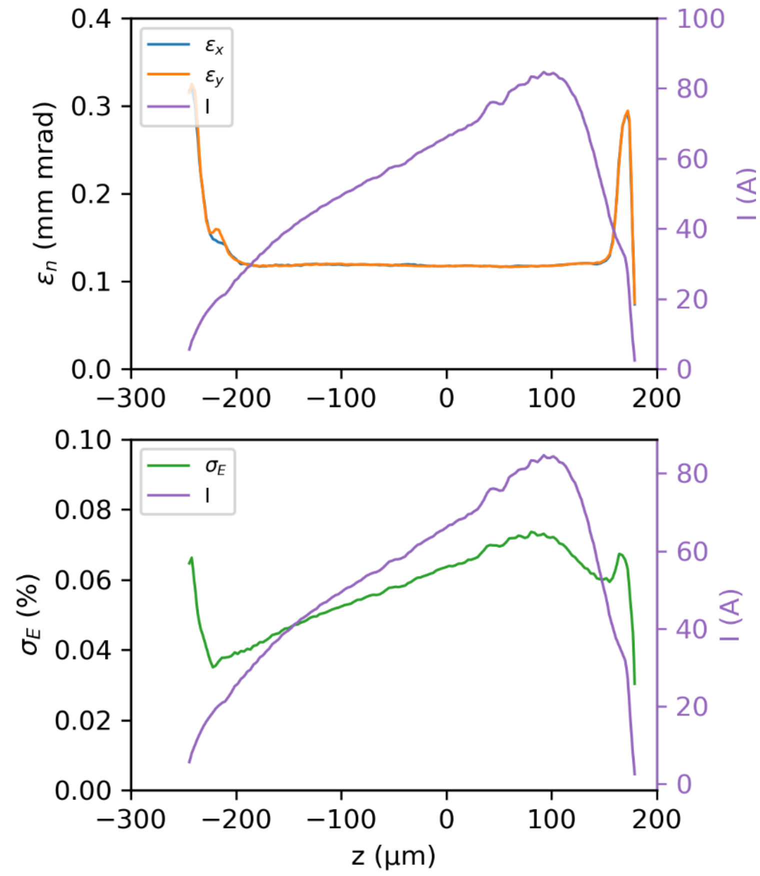
Beam compression and slice analysis

$\sigma_{z,final} \approx 105\ \mu m$



Compression factor ≈ 3

SLICE ANALYSIS



$L_{slice} = 15\ \mu m$

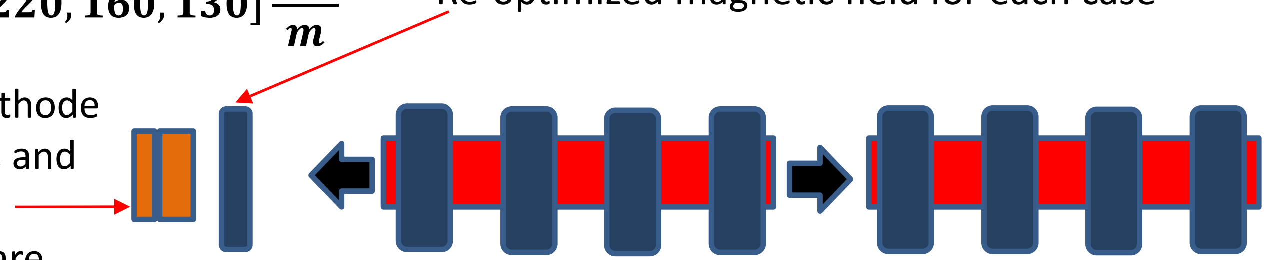
FINAL PHOTO-INJECTOR PARAMETERS

	units	ON CREST	SOFT RF COMPRESSION	COMPACT LIGHT
Q	pC	75	75	75
E	MeV	165	107	300
$\boldsymbol{\sigma_E/E}$	%	0.06	1.4	0.5
$\boldsymbol{\epsilon_{n,rms}}$	μm	0.15	0.15	0.2
$\boldsymbol{\sigma_z}$	μm	296	105	-
$\boldsymbol{I_{peak}}$	A	22 (25slice)	62 (80 slice)	60

Comparison for different cathode peak fields

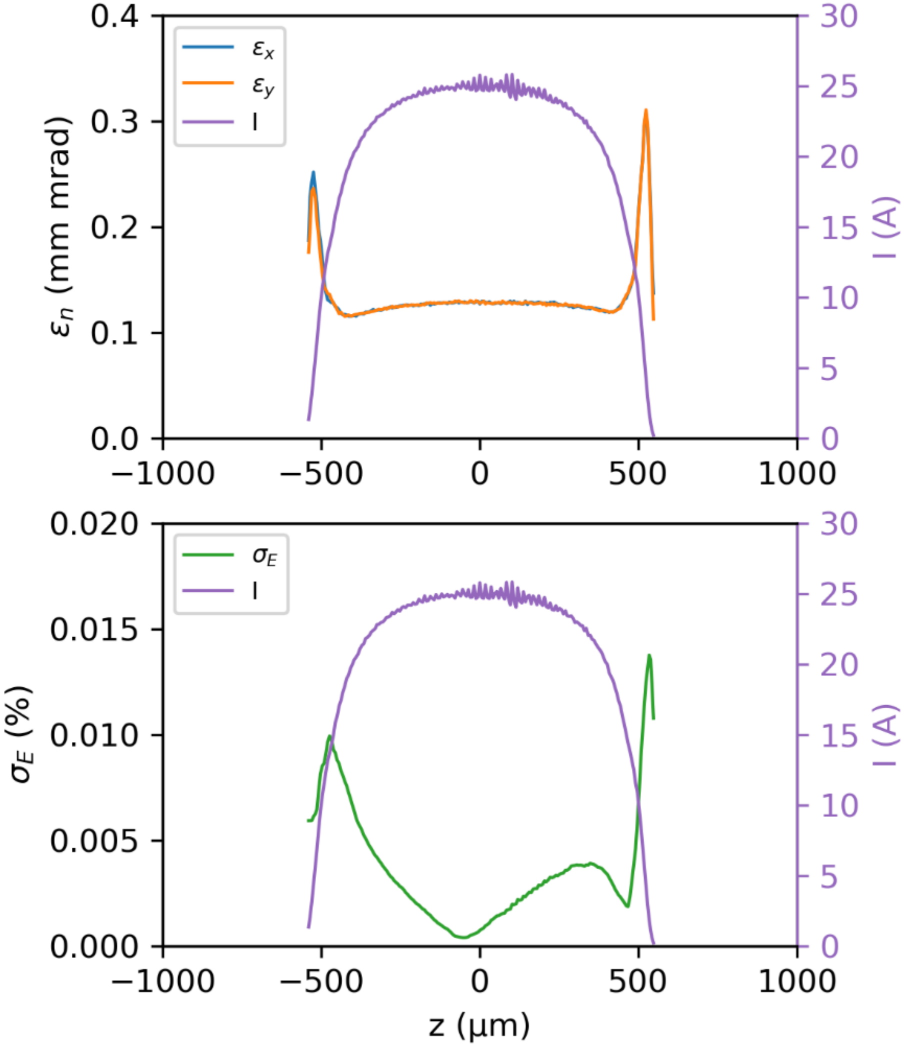
- To explore beam final parameters for lower gradients we optimized different layouts decreasing the cathode peak field.
- The scan was performed re-optimizing the entire line (magnetic fields, launch phases and structure positions).

$$E_{cath}[240, 220, 160, 130]\frac{MV}{m}$$



- This study can be useful in the case we will reduce the cathode peak field (160 MV/m), to increase the bunch repetition rate toward the KHz.

C-band 240 MV/m

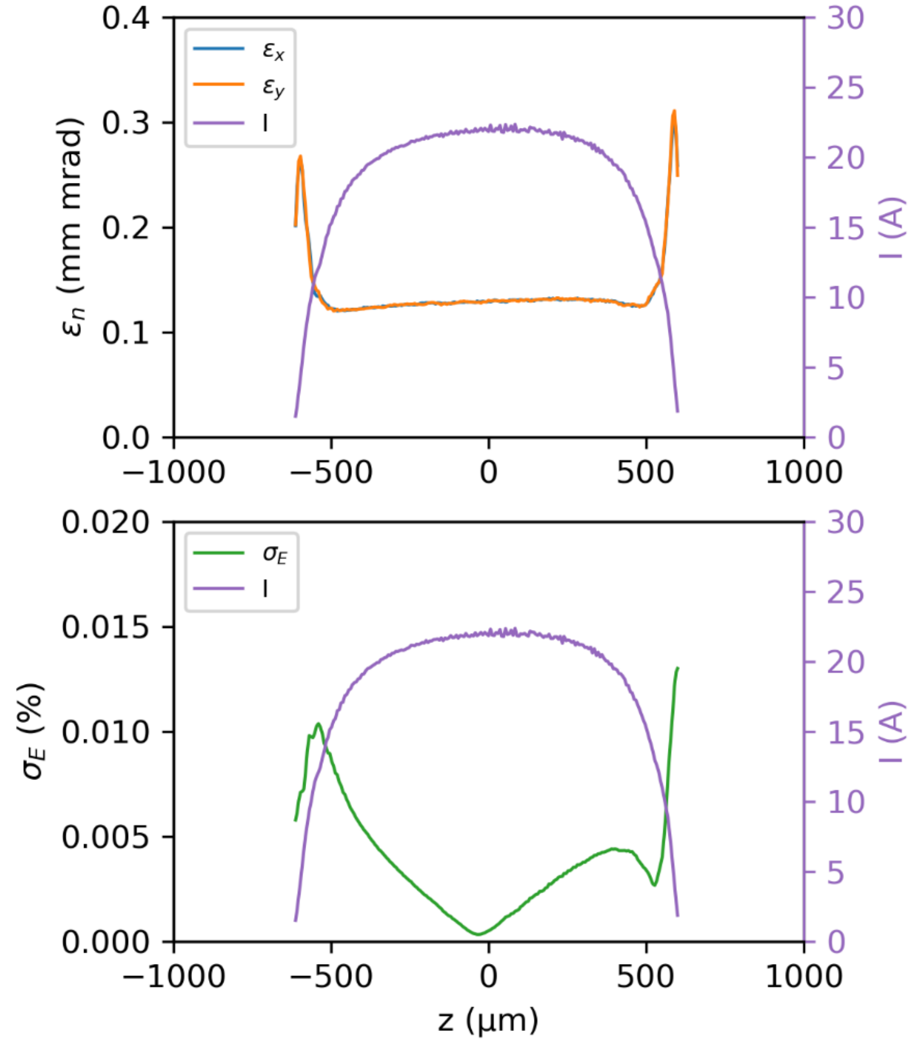


$\epsilon_{n,rms,final} \approx \mathbf{0.15}\ \mu m$

$\sigma_{t,gun\_exit} \approx \mathbf{0.99}\ ps$

$E_{spread} \approx \mathbf{0.06}\ \%$

C-band 220 MV/m

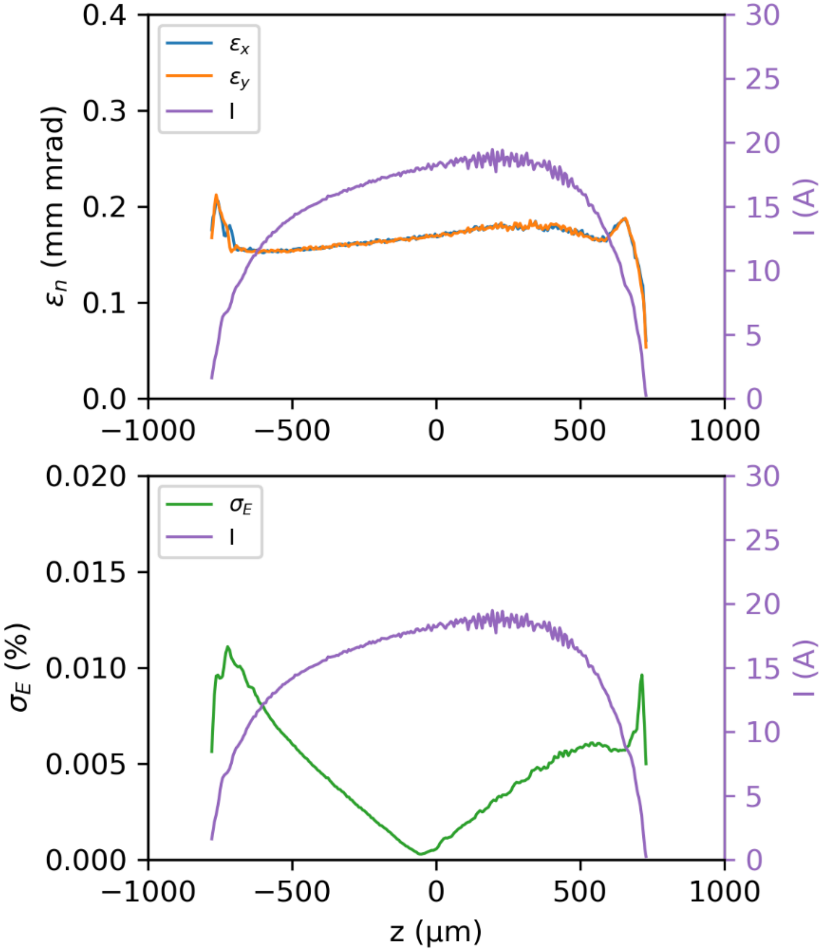


$\epsilon_{n,rms,final} \approx \mathbf{0.15}\ \mu m$

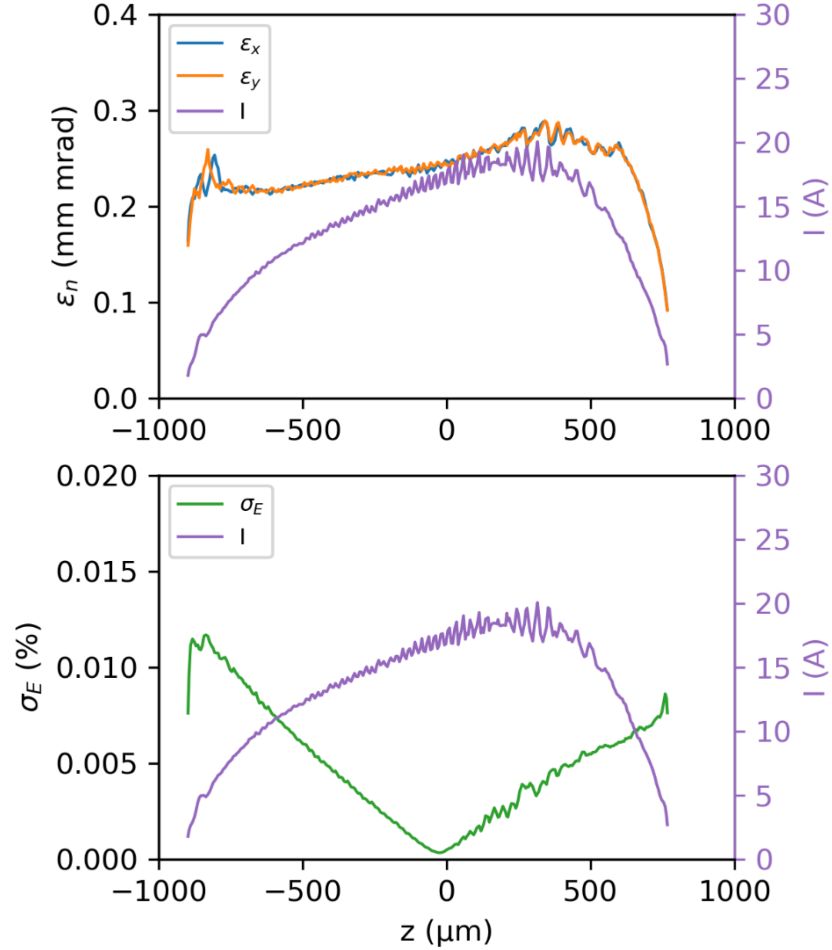
$\sigma_{t,gun\_exit} \approx \mathbf{1.05}\ ps$

$E_{spread} \approx \mathbf{0.07}\ \%$

C-band 160 MV/m



C-band 130 MV/m



$\boldsymbol{\epsilon_{n,rms,final} \approx 0.18\ \mu m}$

$\boldsymbol{\sigma_{t,gun\_exit} \approx 1.28\ ps}$

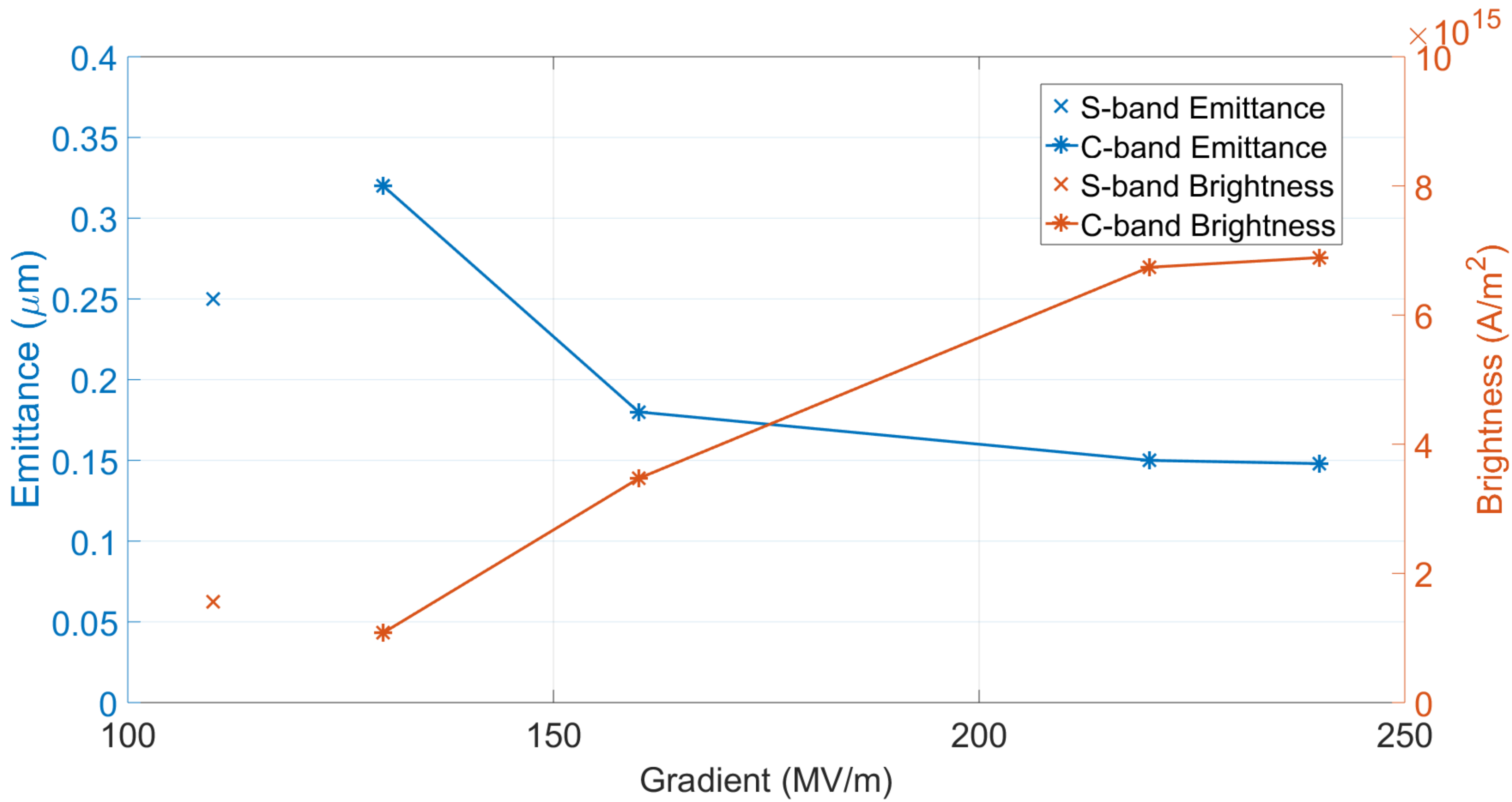
$\boldsymbol{E_{spread} \approx 0.1\ \%}$

$\boldsymbol{\epsilon_{n,rms,final} \approx 0.32\ nm}$

$\boldsymbol{\sigma_{t,gun\_exit} \approx 1.39\ ps}$

$\boldsymbol{E_{spread} \approx 0.12\ \%}$

Comparison for different cases (ON CREST)



Using $160MV/m$ it is possible to improve the beam Brightness and increase the repetition rate toward kHz

CONCLUSIONS

- We started to study and simulate an ultra-high gradient C-band photoinjector. An ultrafast RF approach and a preliminary new design of the cells was made.

- This device was optimized also to guide the X-band linac for the COMPACT LIGHT design study, and the simulation results completely match the requests.

- It can represents also a good option for EUPRAXIA.

- To increase the repetition rate we explored which gradient improve the beam brightness compared to an S-band gun (110 MV/m). A gradient of 160 MV/M seems to be a good compromise.

- A lot of work needs to be done: RF tests, dark current, proper cathode material…