Beam Dynamics Simulation of a High Brightness RF C-band Photoinjector for Future EuPRAXIA@SPARC_LAB Upgrade*

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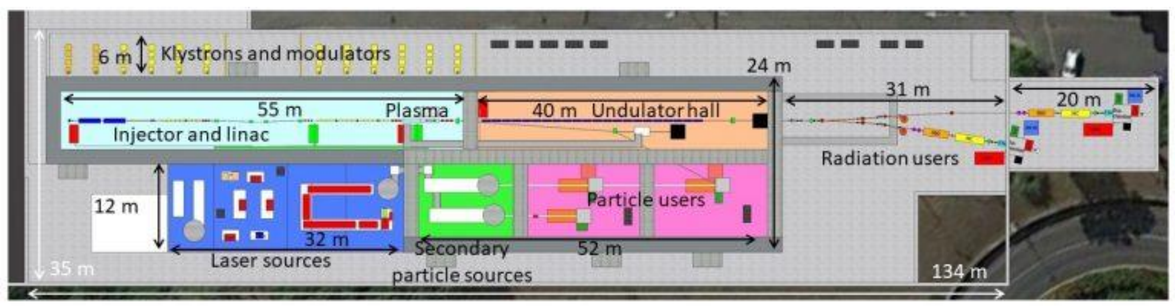
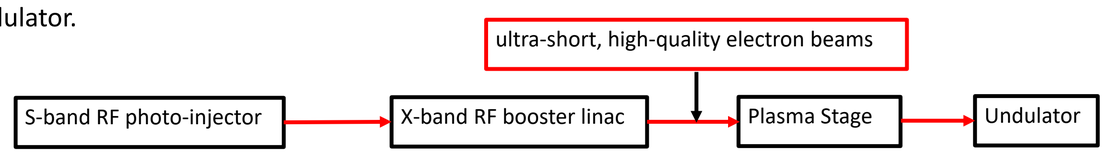
Abstract:

High-brightness RF photo-injectors are crucial for generating high peak current and low transverse emittance electron beams, which are necessary for driving plasma Wake-field acceleration in advanced accelerator concepts and novel radiation sources. To enhance the EuPRAXIA@SPARC_LAB photo-injector for future upgrades, it is essential to investigate and assess the feasibility of achieving higher charge and multi-bunch working points, commonly referred to as the "comb configuration" for particle-driven Wake-field acceleration. A solution to reduce the photo-injector's footprint while preserving beam quality and brightness is to implement a C-band injector operating at 5.712 GHz. Evaluating the possibility of achieving a working point within the velocity bunching acceleration scheme is critical, as this will determine the degree of compression achievable with a full C-band injector. Start-to-end beam dynamics simulations will be conducted to identify the optimum configuration for the C-band photo-injector dedicated to particle-driven plasma-based acceleration.

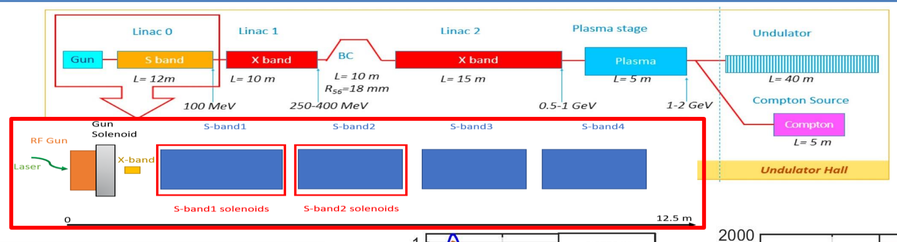
EuPRAXIA@SPARC_LAB



EuPRAXIA@SPARC_LAB is the first European research infrastructure to demonstrate the usability of a plasma accelerator combining a high-brightness GeV–range electron beam generated in a state-of-the-art linac, and a 0.5 PW–class laser system. The main challenge of EuPRAXIA@SPARC_LAB LAB is producing a high-brightness plasma accelerated beam to induce Self Amplified Spontaneous Emission (SASE) in an FEL undulator.



EuPRAXIA@SPARC_LAB full S-band RF injector

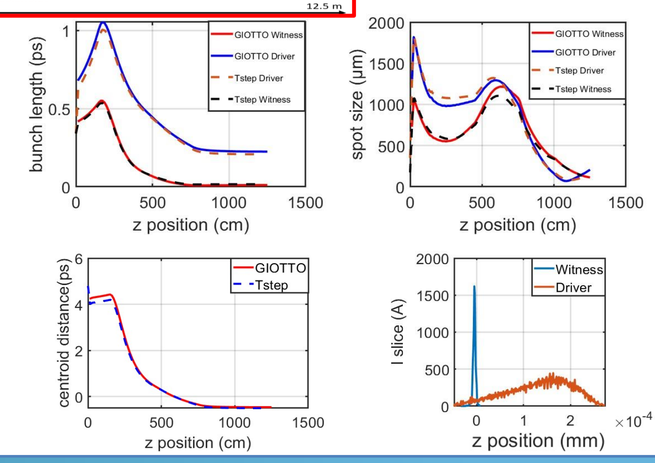


Injector exit parameters	Witness	Driver
Spot Size	0.123 mm	0.174 mm
Bunch Length	3.2 μm	67.5 μm
Emittance	0.49 μm	1.69 μm
Energy	125.54 MeV	127.52 MeV
Energy spread	0.33 %	0.61 %
Bunch separation	0.46 ps	- -
Peak current	1.6 kA	- -

Injector parameters optimized with GIOTTO

Injector exit parameters	Witness	Driver
Spot Size	0.118 mm	0.127 mm
Bunch Length	5 μm	62 μm
Emittance	0.55 μm	1.5 μm
Energy	124 MeV	126 MeV
Energy spread	0.18 %	0.55 %
Bunch separation	0.5 ps	- -
Peak current	1.8 kA	- -

Reference Injector parameters



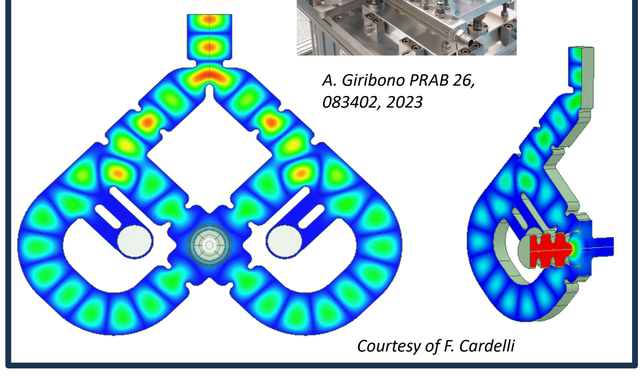
EuPRAXIA@SPARC_LAB C-band RF Gun and single bunch simulations

The proposal of the RF injector consists of a C-band RF Gun (5,712 GHz) followed by four C-band TW accelerating structures 2 m long. The first and second accelerating structures exploit the velocity bunching regime both with the "comb" and single bunch configuration.

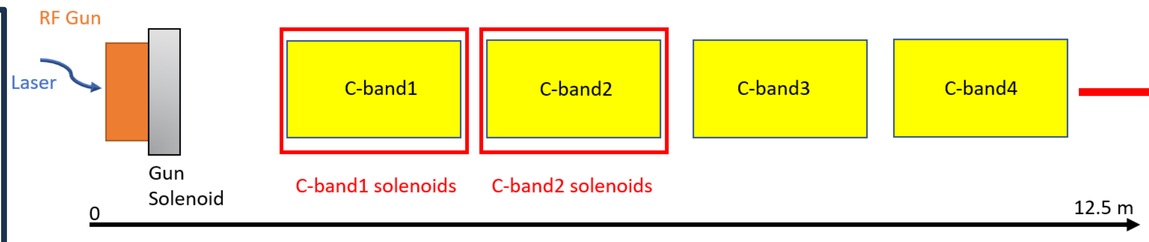
C BAND (I.FAST/TUAREG)

Ready to be tested !!!

A. Giribono PRAB 26, 083402, 2023



Courtesy of F. Cardelli



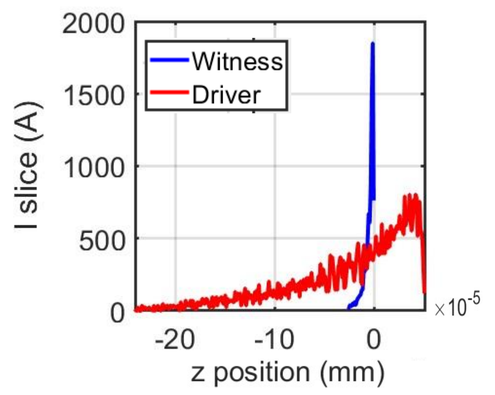
C-band RF gun:

- **Higher achievable cathode peak field as high as 160-180 MV/m.**
- **Higher efficiency**, so it is suitable for **applications requiring repetition rates in the 200 Hz÷1 kHz range.**

The maximum achievable field strength of the RF gun is 180 MV/m; however, in the simulation, we have set the field strength to 140 MV/m in order to exploit the velocity bunching compression scheme in the comb case and in the single beam. If the energy at the gun exit is too high, the velocity bunching effect may not provide sufficient compression of the bunches at the photo injector exitΔ.

C-band Injector exit parameters	Witness	Driver
Spot Size	0.42 mm	0.67 mm
Bunch Length	5 μm	62 μm
Emittance	0.58 μm	1.29 μm
Energy	156 MeV	157 MeV
Peak current	1.8 kA	0.8 kA

Beam parameters @ injector exit for single bunch simulations

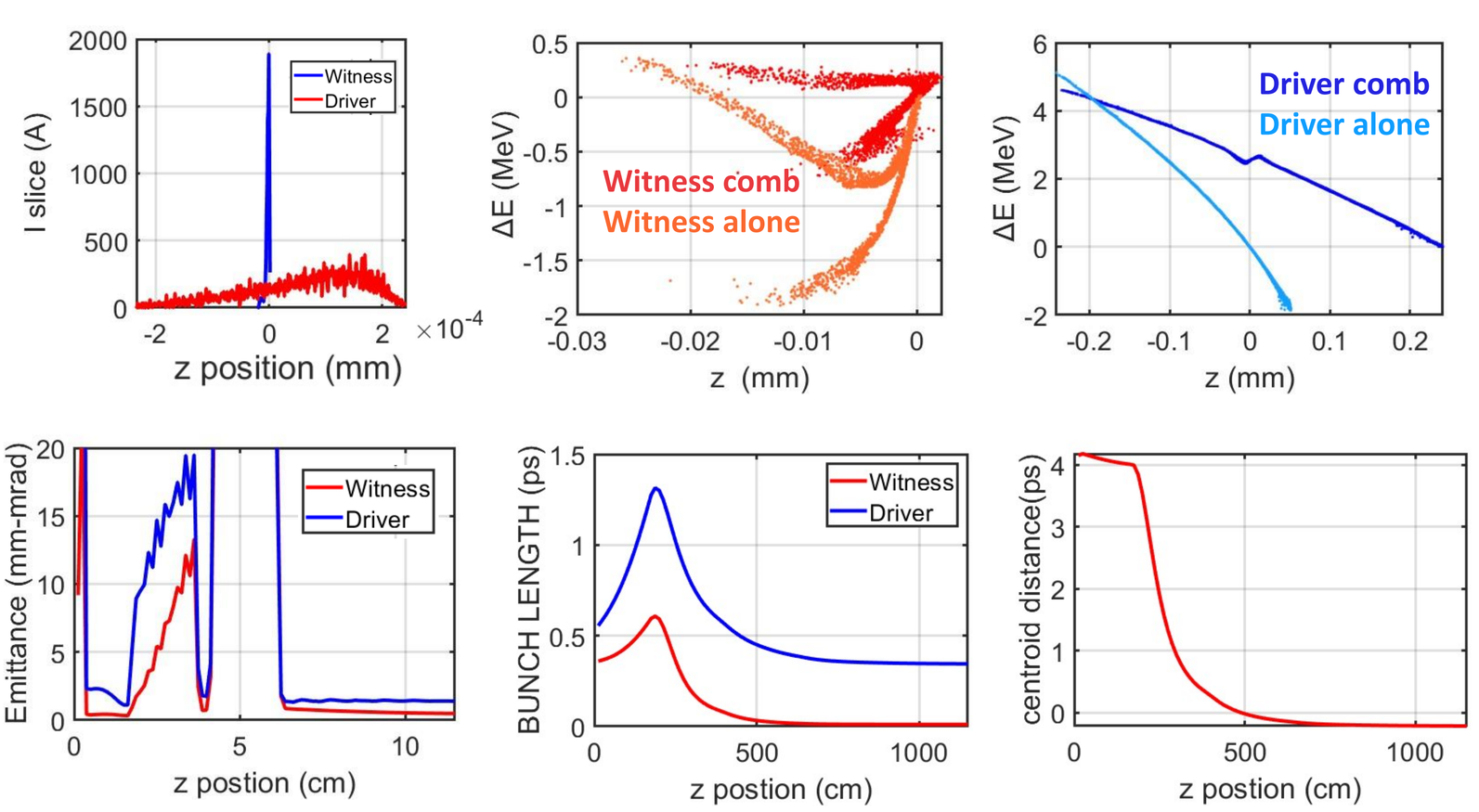


EuPRAXIA@SPARC_LAB full C-band RF injector comb simulations

Beam parameters @ cathode	Witness	Driver
Spot Size	0.175 mm	0.35 mm
Bunch Length	220 fs	220 fs
Charge	30 pC	200 pC
Bunch separation	6.3 ps	- -

C-band Injector exit parameters	Witness	Driver
Bunch Length	3.4 μm	100 μm
Emittance	0.48 μm	1.40 μm
Energy spread	0.2 %	1.1 %
Bunch separation	0.22 ps	
Peak current	1.9 kA	0.3 kA

The witness dynamic is completely reproduced, comparing the results with the full S-band case. The driver bunch shows a different longitudinal dynamic and needs to be optimized to achieve the correct length and reduce the energy spread.



Conclusion

The bunch parameters in terms of emittance, bunch length, and peak current have been achieved by comparing the single bunch working point with the comb configurations. Further beam dynamics simulations should be done to investigate the possibility of obtaining the separation needed before the booster linac section.