Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Beam dynamics optimization of EuPRAXIA@SPARC_LAB RF injector

To cite this article: G J Silvi *et al* 2024 *J. Phys.: Conf. Ser.* **2687** 062024

Beam dynamics optimization of EuPRAXIA@SPARC_LAB RF injector

G J Silvi[12],A L Bacci[3], M Carillo[12],E Chiadroni[14],L Faillace[4],D Francescone[12],A Giribono[4],P Iovine[5],A Mostacci[12],M Ferrario[4],R Pompili[4],C Vaccarezza[4]

[1]Sapienza University of Rome, 00161 Rome, Italy
[2] INFN-Sez. Roma 1, Rome, Italy
[3] INFN-Sez Milano, 20133 Milano, Italy
[4] Frascati National Laboratories INFN-LNF, 00044 Frascati (RM), Italy
[5] INFN-Sez Napoli, 80126 Naples, Italy

E-mail: gillesjacopo.silvi@uniroma1.it

Abstract. At EuPRAXIA@SPARC_LAB an X-ray FEL user facility is driven by a plasma accelerator in the particle-driven configuration where an ultra-relativistic beam, the driver, through a plasma generates a wake of charge density useful for accelerating a witness beam. The electron bunches are generated through the so-called comb technique in an RF injector that consists of a 1.6-cell S-band gun followed by four S-band TW accelerating structures. The main working point foresees a 30pC witness and a 200pC driver longitudinally compressed in the first accelerating structure operated in the velocity-bunching regime, which allows to accelerate and manipulate the beam to reach proper transverse and longitudinal parameters. The optimization of the witness emittance is performed with additional magnetic field around the gun and the velocity bunching S-band structures and by shaping the laser pulse at the cathode. The paper reports on beam dynamics studies performed also with the insertion of an X-band RF cavity after the gun that is proposed to shape the beam current distribution and stabilize it with respect to RF jitters.

1. Introduction

1.1. EuPRAXIA@SPARC_LAB

EuPRAXIA@SPARC_LAB, Fig.1 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 [1][2]. The RF accelerator of EuPRAXIA@SPARC_LAB consists mainly of two parts:

- an S-band RF photo-injector made up of an RF gun equipped with a photocathode and followed by an S-band linac booster for a maximum final energy of 170 MeV. The four S-band accelerating structures are set to exploit the velocity bunching compression technique [3];
- an X-band RF linac to raise the electron beam energy up to a maximum final value of 500MeV by means of X-band RF sections providing accelerating gradients of the order of Eacc $> 50 MV/m$. The RF system is designed to produce ultra-short, high-quality electron beams.

The main challenge of EuPRAXIA@SPARC_LAB is producing a high-brightness plasma accelerated beam to induce Self Amplified Spontaneous Emission (SASE) in a FEL undulator. To achieve it, EuPRAXIA@SPARC_LAB will be designed to have a high brightness beam at the plasma injection, the beam quality preservation during the plasma acceleration, including the control of energy spread which is quite difficult in plasma accelerated beams.

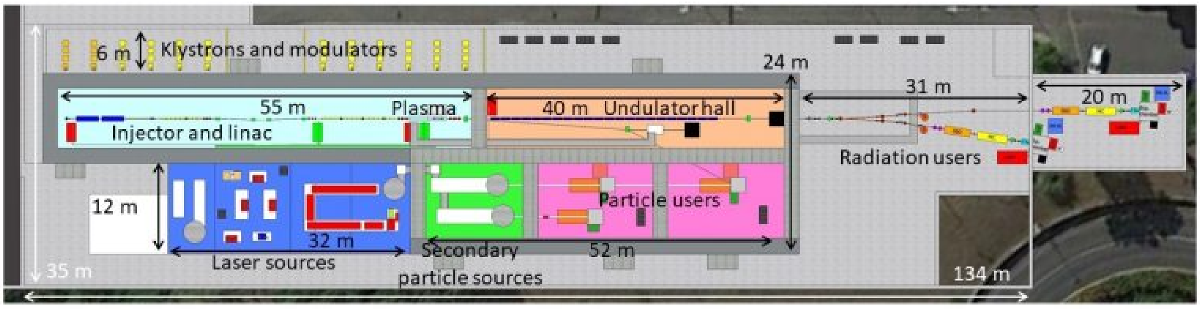


Figure 1: EuPRAXIA@SPARC_LAB layout [2].

1.2. *EuPRAXIA@SPARC_LAB RF injector layout*

The RF injector [4] consists of an RF SPARC_LAB -like S-band gun (2.856 GHz) followed by four S-band TW accelerating structures with an overall length of 12.3 m, Fig. 2. The Gun rises beam energy up to 5.7 MeV and a gun solenoid performs emittance compensation and focusing in the low-energy region [5]. The first and second S-band structures are dedicated to the velocity bunching compression scheme, a longitudinal phase space rotation based on a correlated time-velocity chirp of the electron bunch. The beam quality in terms of emittance and spot size is preserved with long solenoids around those two sections. The last S-band structures are used to adjust the beam shape and to reach a final energy of around 130 MeV. In addition, an X-band cavity is located between the RF gun and the first S-band structure to shape the current distribution and compress the beams.

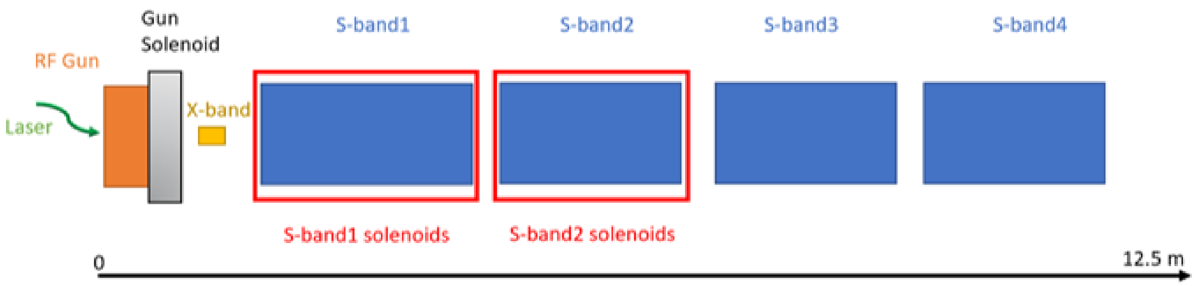


Figure 2: EuPRAXIA@SPARC_LAB RF injector layout, the first S-band structure is 3 m while the others are 2 m long.

2. Beam Dynamics Simulations

Beam dynamics studies were performed with a comb-like electron beam Tab.1. Comb beams are composed of two or more high brightness electron bunches, of 10s of fs duration separated by ps scale time distance. Such a longitudinally modulated beam is used to drive plasma-based accelerating modules. In Particle-driven plasma Wakefield Acceleration the high-gradient

Table 1: Reference EuPRAXIA@SPARC_LAB working point.

Cathode's beam parameters	Witness	Driver
Spot Size	0.175mm	0.35mm
Bunch Length	290fs	290fs
Charge	30pC	200pC
Bunch separation	4.67ps	- -

Table 2: Reference injector exit parameters.

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

WakeField is driven by an intense, high-energy charged particle beam (driver) as it passes through the plasma. A second, properly phased accelerating beam (witness), with less charge than the drive beam, is then accelerated by the wake. The witness dynamics control is fundamental to achieving the optimum transverse and longitudinal matching needed at the plasma entrance to prevent emittance growth during the acceleration in the plasma module. Intense beam dynamics studies have been performed to set the reference working point for the EuPRAXIA@SPARC_LAB photo-injector [6]. Up to now, the TStep [7] code has been used as the main simulation tool. Besides further optimization studies, the paper reports on the tentative of adding the ASTRA [8] code in our tool-set so to take advantage of its interaction with the GIOTTO algorithm.

2.1. ASTRA VS TStep SIMULATIONS

The beam parameters at the injector exit are resumed in Tab 2. In this section, we will describe the benchmark simulation to align ASTRA and TStep codes. Starting from the cathode distribution of Tab.1, ASTRA input file is tuned in terms of phases, gradients and magnetic fields of all beam-line components to reproduce the TStep working point. The results of the benchmark are shown in the following plots.

Simulations show a different behavior of the comb beam, Fig. 3 and Fig. 4, in the two codes coming from the treatment of the charge extraction from the cathode, space charge, and the set of the reference particle of the comb. In detail, the main difference lies in the fact that ASTRA foresees an adaptive longitudinal grid mesh along the photo-injector while TStep does not. Because of that, a slightly different beam length at the cathode has been set in the two codes in order to reproduce the same final results, shorter in ASTRA of the order of 20%. Another issue regarding the definition of a unique RF phase of the elements in the two codes is due to the fact that they set the reference particle of the distribution with different

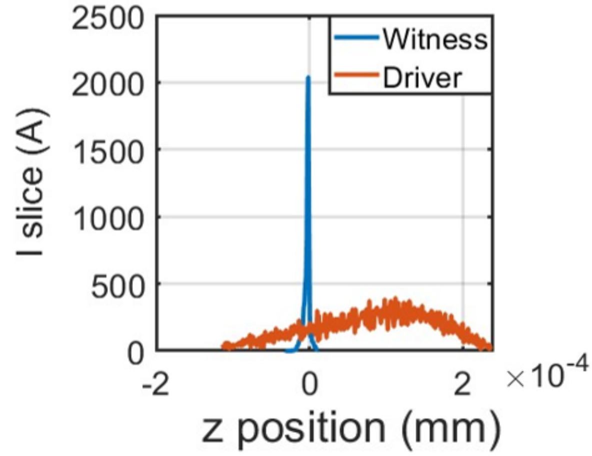
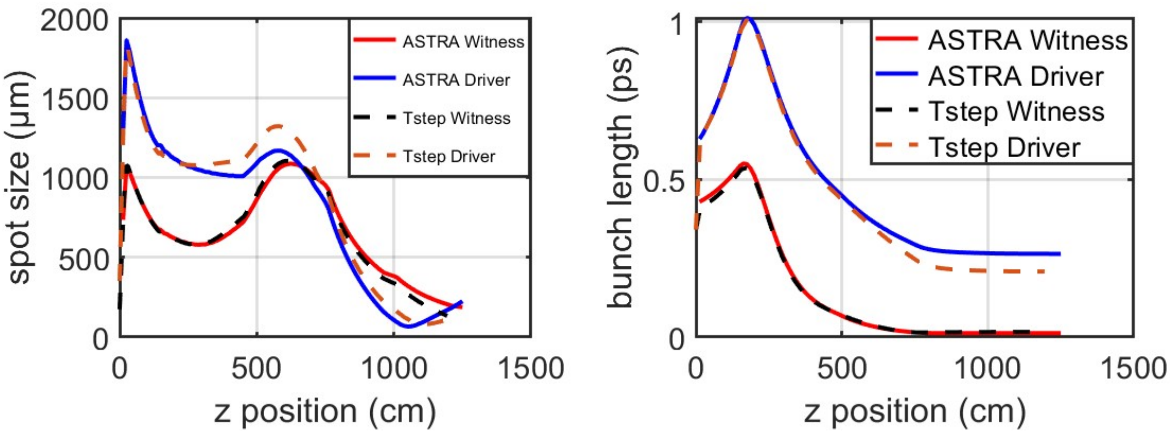


Figure 3: ASTRA peak current is higher (2kA) than reference ones.



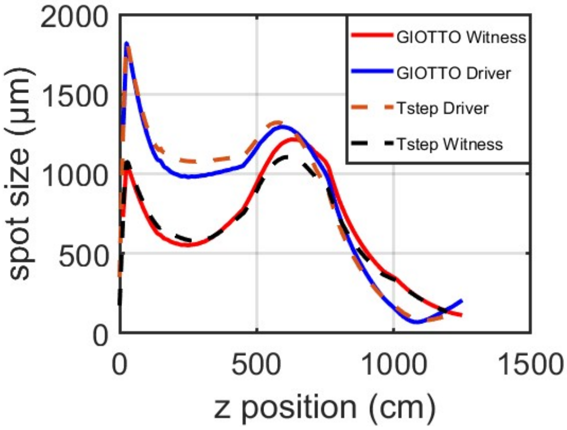
(a) Rms envelope (b) Bunch length

Figure 4: ASTRA and TStep comparison; (a)ASTRA vs TStep Beams rms envelope, in this configuration the witness transverse dynamics is at list the same for the two codes. The driver is over-focused in the second velocity bunching structure. (b) ASTRA vs TStep bunch length, witness longitudinal dynamics is the same, the driver shows a different behavior after the second velocity bunching structure.

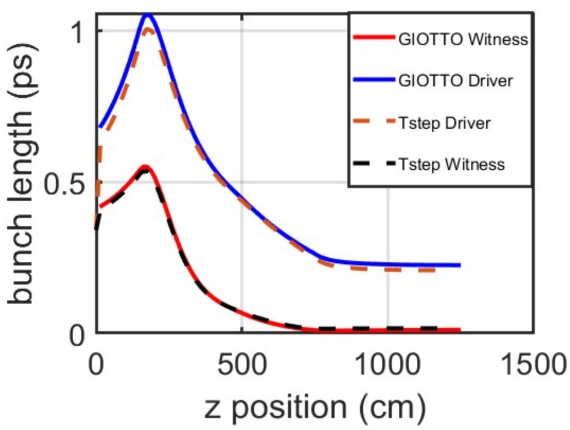
statistical approach with the beam dynamics in the velocity bunching regime sensitive to 0.1 degree order of magnitude. After some iterations, the following parameters have been achieved: beam emittances are respectively 1 mm-mrad and 1.46 mm-mrad for witness and driver; energy and energy spread are 128 MeV, 0.12% and 130 MeV, 0.47 % for witness and driver. The worst result is related to the bunch separation of 0.27 ps, instead of 0.5 ps. This machine setup has been used as starting point for optimization with the GIOTTO algorithm.

2.2. GIOTTO optimization
GIOTTO is a software based on a Genetic Algorithm (GA). When the parameters, defining an acceleration machine beam line, are strongly correlated in nonlinear way, the GAs are a powerful tool to cope with these difficulties [9]. These conditions are typically generated by

space-charge, as in the high brightness e-beam photo-injectors or when the Velocity Bunching compression technique is used. GIOTTO works in tandem with ASTRA input so the above described configuration achieved with ASTRA was sent to GIOTTO to perform a fine parametric scan of beam line elements and pulse shaping at the cathode. The optimization stops when the goal values defined in the GIOTTO input are reached. Those parameters are resumed in Tab.2. The GIOTTO output file contains the results of the optimization Tab.3 in which the final beam parameters are now comparable with the ones in Tab.2. Longitudinal and transverse bunch dynamics are also reproduced along all the injector, Fig. 5 and Fig. 6. Optimization works on the bunch distribution and on space charge routine, also parameters of the beam-line are adjusted starting from the ones defined in the benchmark simulations.

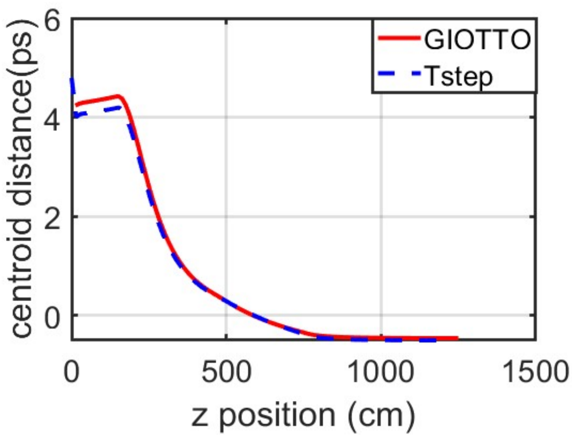


(a) Rms envelope

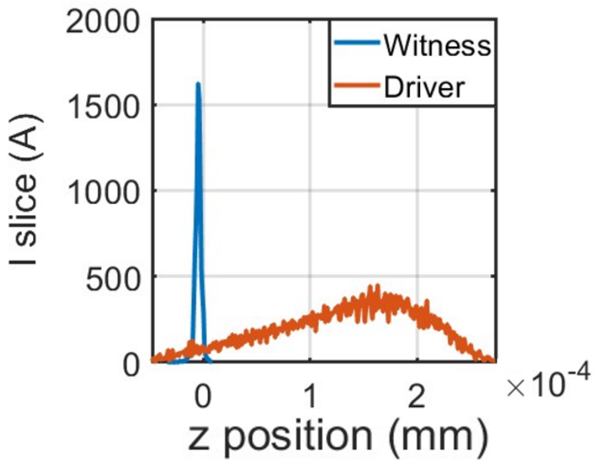


(b) Bunch length

Figure 5: Beams parameters after GIOTTO optimization; (a) rms envelopes are now comparable with reference ones (b) bunch length achieves the desired value at injector exit.



(a) centroid distance

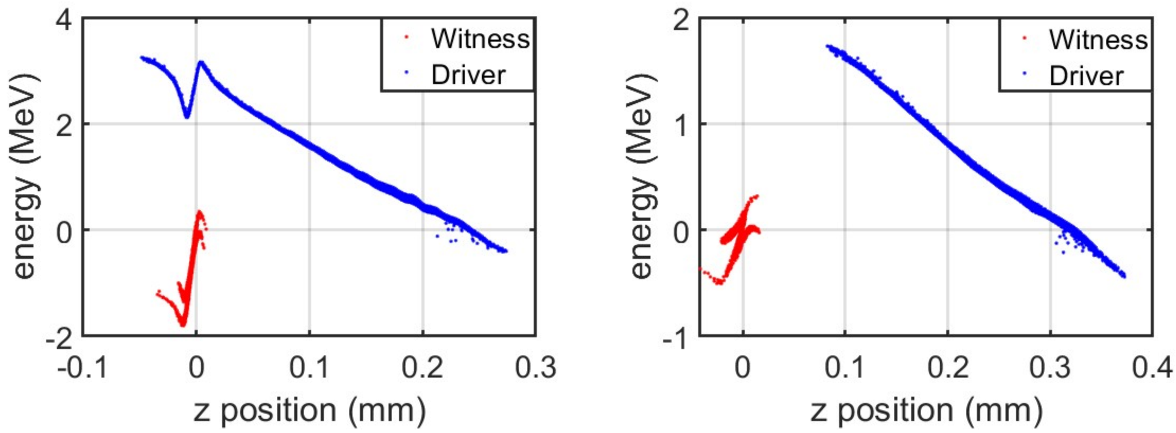


(b) peak current

Figure 6: Beams parameters after GIOTTO optimization;(a) witness peak current is of the order of kA to satisfy the high brightness condition (b) centroid distance is $\sim 0.5ps$.

Table 3: Injector exit parameters optimized with GIOTTO.

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

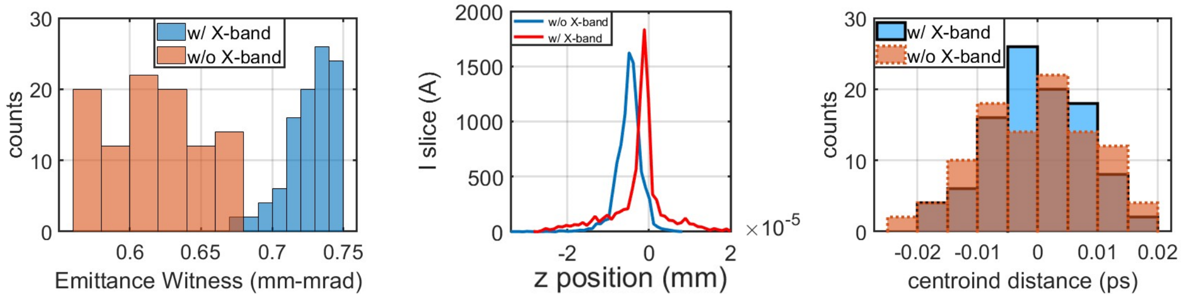


(a) Longitudinal phase space w/o X-band (b) Longitudinal phase space w/ X-band

Figure 7: The figure shows the effect of the X-band RF cavity on the longitudinal phase space at the injector end which is linearized and energy spread reduced.

2.3. X-band RF cavity

The X-band RF cavity (11.424 GHz) is a 7-cell standing wave structure, 4 mm radius and 11 cm long, positioned between the gun and the first S-band section (Figure 2)[10]. This cavity works with an RF phase of $-\pi$, at the decelerating crest, the peak field in ASTRA is 27 MeV/m with an energy gain of 1.26 MeV. The beam is decelerated and compressed [11], the longitudinal phase space is linearized Fig. 7, and the current profile is shaped [12]. Beam dynamics simulations show that the longitudinal parameters of the comb bunches in terms of bunch length, peak current, and also the witness emittance could be achieved with only one velocity bunching structure, with a higher compression phase, while the second is switched on crest like the other S-band cavities. The bunch separation is higher, 0.67 ps compared to the reference parameter. Simulations of RF jitter show that emittance jitters are mitigated with the X-band cavity Fig. 8a, the current profile is stabilized, velocity bunching moves peak current while the X-band center it Fig. 8b. Looking at centroid distance there isn't an evident effect of RF jitter in these simulations Fig. 8c, the RF jitters simulated are 30 fs both for S-band and X-band phase.



(a) Emittance (b) peak current (c) bunches distance

Figure 8: Witness jitter analysis w/ and w/o X-band.

3. CONCLUSION

The beam dynamics studies reported in this paper show that ASTRA and TStep give comparable results for the EuPRAXIA@SPARC_LAB RF injector layout. The beam dynamics optimization performed with GIOTTO adjust the injector parameters and the pulse shaping at the cathode to achieve the injector reference parameters. The comb beam dynamics with the insertion of an X-band cavity has been investigated to understand the impact of this element on bunch dynamics, the jitter studies are still ongoing.

References

[1] Assmann R W *et al.* 2020 *The European Physical Journal Special Topics* **229** 3675–4284

[2] Alesini D *et al.* 2018 Eupraxia@sparc_lab conceptual design report National Institute of Nuclear Physics Frascati National Laboratory Report INFN-18-03/LNF

[3] Serafini L and Ferrario M 2001 *AIP Conference Proceedings* **581** 87–106

[4] Giribono A *et al.* 2018 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **909**

[5] Ferrario M *et al.* 2010 *Phys. Rev. Lett.* **104**(5) 054801

[6] Giribono A *et al.* Electron beam analysis and sensitivity studies for the EuPRAXIA@SPARC_LAB RF injector IPAC'23 TUPL130

[7] Young L M and J B 2003 The particle tracking code parmela *Proceedings of the 2003 Particle Accelerator Conference*

[8] Floettmann K A space charge tracking code `https://www.desy.de/ mpyflo/`

[9] Bacci A, Rossetti Conti M and Petrillo V 2016 Giotto: A genetic code for demanding beam-dynamics optimizations

[10] Bacci A, Faillace L and Rossetti Conti M 2018 Extreme high brightness electron beam generation in a space charge regime

[11] Alesini D *et al.* 2015 Study of a C-band harmonic RF system to optimize the RF bunch compression process of the SPARC beam *6th International Particle Accelerator Conference* p TUPWA058

[12] Emma P 2001 X-Band RF harmonic compensation for linear bunch compression in the LCLS SLAC Nation Accelerator Laboratory Technical Note SLAC-TN-05-004, LCLS-TN-01-1