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Optimizing beam dynamics in the EuPRAXIA@_SPARCLAB RF injector

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Summary. — The EuPRAXIA@SPARC_LAB RF injector provides high-brightness electron beams accelerated and longitudinally manipulated in the velocity bunching regime (VB). The RF injector works in the so-called comb configuration. It foresees a 30 pC witness and a 200 pC driver longitudinally compressed in the first two accelerating structures both operated in the VB regime. The beam stability can be improved by adding a High Harmonic Cavity (HHC), interposed between the Gun and the first accelerating structure, to shorten and flatter the charge distribution and manipulate the beams to reach proper transverse and longitudinal parameters. The paper reports on beam dynamics studies performed with the insertion of the X-band RF cavity that is proposed to shape the beam current distribution, linearize the longitudinal phase space, and stabilize it with respect to RF jitters.

1. – Introduction

At EuPRAXIA@SPARC_LAB [1, 2] 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 main challenge of EuPRAXIA@SPARC_LAB is producing a high-brightness plasma accelerated beam to induce self amplified spontaneous emission in an FEL undulator. The electron bunches are generated in an RF injector [3] that consists of a 1.6-cell S-band gun followed by four S-band TW accelerating structures, where the first two exploit the VB regime [4, 5] and are embedded with long solenoids.

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2. – Beam dynamics optimization, ASTRA, and GIOTTO simulation tools

Injector dynamics have been optimized starting from the EuPRAXIA@SPARC_LAB comb working point (table I). The RF phases, gradients, magnetic fields, and cathode distribution are adjusted to reach the final injector beam parameters (table II). The first step of the work consists of a benchmark between the ASTRA [6] simulation tool and the Tstep [7] code. This benchmark aims to compare and validate the results already presented in the EuPRAXIA@SPARC_LAB conceptual design report with another simulation tool. The two codes are different in the statistical approach setting the reference particle of the distribution so of a unique RF phase. In the VB regime, sensitive to 0.1-degree order of magnitude those differences made necessary the use of a genetic algorithm, GIOTTO. The advantage of using the ASTRA simulation tool is to have a further simulation tool for implementing beam dynamics studies and since ASTRA works in tandem with the GIOTTO [8] genetic algorithm also beam dynamics optimizations. The results obtained using GIOTTO to optimize the dynamics are in table III and fig. 1.

TABLE I. – *Beam parameters at the cathode.*

Bunches	Witness	Driver
spot size (mm)	0.175	0.35
bunch length (fs)	290	290
charge (pC)	30	200
bunch separation (ps)	4.67	

TABLE II. – *Injector exit parameters.*

Bunches	Witness	Driver
spot size (mm)	0.118	0.127
bunch length (um)	5	62
emittance (mm-mrad)	0.55	1.5
energy (MeV)	124	126
energy spread (%)	0.18	0.55
bunch separation (ps)	0.5	
peak current (kA)	1.8	

TABLE III. – *Injector exit parameters optimized with GIOTTO.*

Bunches	Witness	Driver
spot size (mm)	0.123	0.174
bunch length (um)	3.2	67.5
emittance (mm-mrad)	0.49	1.69
energy (MeV)	125	127
energy spread (%)	0.33	0.61
bunch separation (ps)	0.46	
peak current (kA)	1.6	

3. – Beam dynamics with *X*-band linearizer cavity

The challenge of the RF photo injector is to generate an ultra-short and high-quality beam. The stability and reproducibility of the beam greatly depend on the RF generation. The beam's stability can be improved by adding an HHC, an X-band SW RF structure that is interposed between the RF Gun and the first accelerating structure [9-11]. A sensitivity jitter study for all RF injector components has been done comparing the

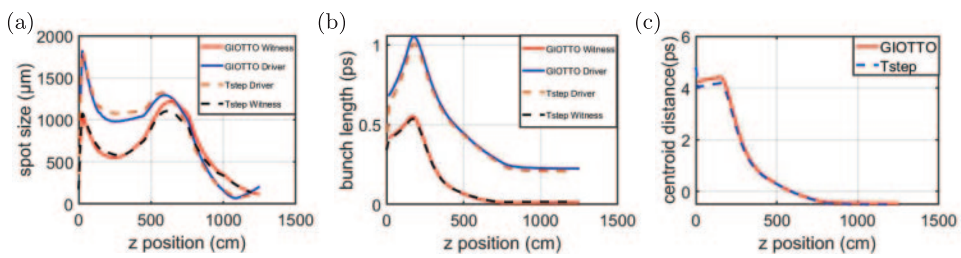

Fig. 1. – RMS envelopes, bunch length, and centroid distance optimized with GIOTTO. (a) Emittance, (b) bunch length, (c) centroid distance.

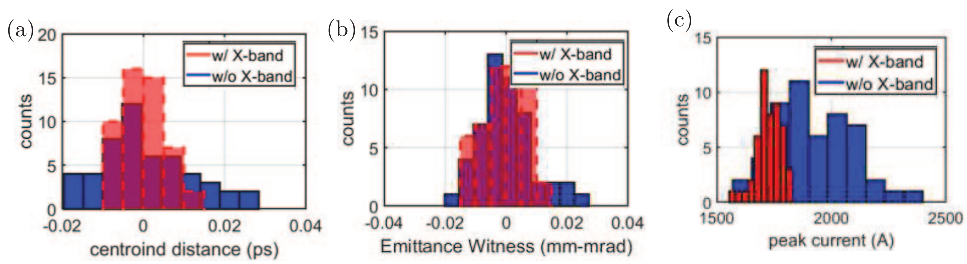

Fig. 2. – Bunch separation, witness emittance and peak current with 30 fs of RF jitter. (a) Bunch separation jitter, (b) witness emittance jitter, (c) witness peak current.

TABLE IV. – *Jitters value.*

total charge	spot size	time of arrival @cathode	rf phase	voltage
2% of the total	1% of the total	30 fs rms	30 fs rms	0.1% of the total

TABLE V. – *Jitter analysis results.*

beam parameters	w/ X-band all jitter	w/ X-band Rf jitter	w/o X-band all jitter
emittance (mm-mrad)	0.672 ± 0.031	0.676 ± 0.013	0.5710 ± 0.091
witness bunch length (ps)	$0.0137 \pm$ 7e-4	$0.0140 \pm$ 2e-4	$0.0180 \pm$ 7e-4
witness peak current (kA)	1733 ± 230	1728 ± 56	1923 ± 173
bunch separation (ps)	0.5337 ± 0.0117	0.5337 ± 0.0117	0.5011 ± 0.0115

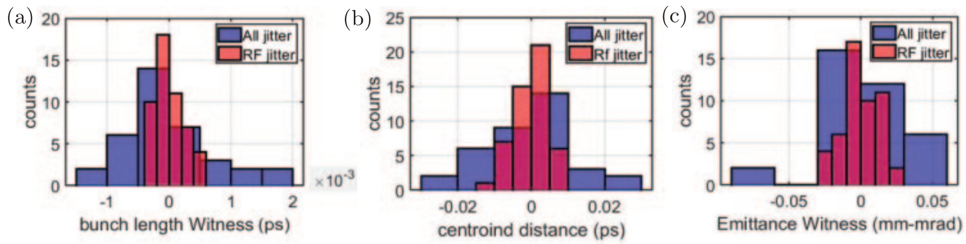

Fig. 3. – Bunch separation, witness emittance and bunch length with table IV jitters. (a) Witness bunch length all jitter, (b) bunch separation all jitter, (c) witness emittance all jitter.

stability results w/ and w/o an X-band cavity. Since the VB regime is strongly dependence on the RF phases, the aim is that this cavity stabilizes the beam with respect to the RF jitters. The RF jitters simulated are 30 fs RMS for both the S-band and X-band phases. Simulations of RF jitter show that emittance and bunch separation jitters are mitigated with the X-band cavity as well as the witness peak current (fig. 2). Adding other jitters (table IV), the results of stability analyses w/ and w/o the X-band cavity are presented in table V. In fig. 3 there is a comparison between RF and table IV jitters.

4. – Conclusion

The paper reports on beam dynamics simulations with ASTRA and GIOTTO codes to implement the EuPRAXIA@SPAR_LAB working point studies with new simulation tools. The stability of the beam has been studied with a deep investigation of jitters including the RF systems and the cathode's generation. Other jitter simulations are ongoing to find the best configuration for the EuPRAXIA@SPARC_LAB user facility.

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