ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPC06

CHARACTERISATION AND OPTIMISATION OF A C-BAND PHOTO-INJECTOR FOR COMPACT LIGHT SOURCES

G. Campri*, La Sapienza University of Rome, Italy
S. Di Mitri, ELETTRA Sincrotrone Trieste, Italy
A. Giribono, D. Alesini, F. Demurtas, INFN-LNF, Frascati, Italy
M. Placidi, Lawrence Berkeley National Laboratory, Berkeley, California, USA
A. Bazzani, G. Turchetti, University of Bologna, Italy

Abstract

We performed an optimisation study of a C-band photo-injector for high-charge electron beams. Such a device is capable of producing high brightness electron beams, with low energy spread and small transverse emittance, which are properties required by Inverse Compton Scattering radiation sources and compact light sources in general. This work aimed to carry out, via numerical simulations, optimisation and benchmark results of the beam generated by such photo-injector, in the pursuit of its real application in the context of current projects, namely EuPRAXIA@SPARC_LAB, and proposals such as BoCXS at the University of Bologna.

INTRODUCTION

High gradient RF photo-injectors represent a pivotal element for high brightness electron beam development. This technology enables the creation of electron beams with high peak currents, low transverse emittance and low energy spread. These qualities are crucial for meeting the rigorous demands of applications like free-electron lasers, Compton sources, and high-energy linear colliders. The high resonant frequencies of a C-band gun can provide a high cathode peak field, which is proportional to the achievable beam brightness [1], while reducing the breakdown rate probability. Moreover, the compactness of such device makes it a desirable option for future compact light source applications. This work is part of the collaboration between the University of Bologna, involved in the BoCXS proposal [2], a Compton source, and the LNF, site of the EuPRAXIA@SPARC_LAB project [3]. We make use of the simulation tools provided by ASTRA code [4] to show the performance of a C-band photo-injector in view of the forthcoming application of a similar instance for EuPRAXIA@SPARC_LAB, where the use of a C-band photo-injector has been proposed [5, 6].

MATERIALS AND METHODS

Preliminary Studies and Scaling

We started by considering a well known case of S-band photo-injector composed by a 1.6 cell RF-gun, a solenoid magnet for the emittance compensation, followed by a drift space and two TW cavities. The peak field of the RF-gun and the cavities fixed at 120 MV/m and 28 MV/m respectively. The bunch charge was set at 0.1 nC and the laser pulse had a length (FWHM) of 8.5 ps with a longitudinal flat-top distribution and a rise time of 1.0 ps, while the the transversal distribution was uniform radial with $\sigma_r = 0.25$ mm. According to the emittance compensation theory [7], we performed a beam dynamics simulation, matching the beam to the linac and we found a first working point. From that we

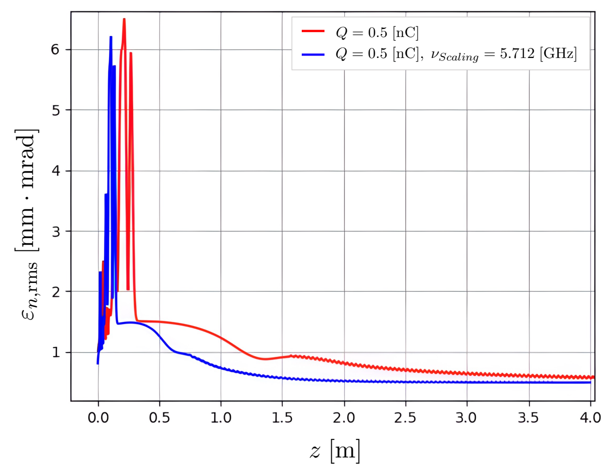

Figure 1: Normalised transverse emittance evolution inside the photo-injector for an S-band (red) and a scaled C-band (blue) structure.

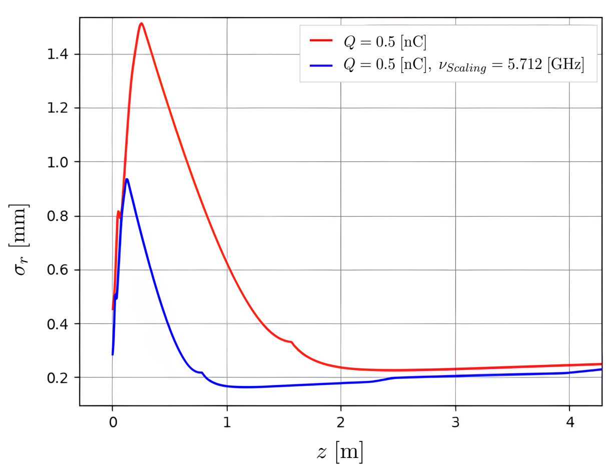

Figure 2: Transverse beam size evolution inside the photo-injector for an S-band (red) and a scaled C-band (blue) structure.

proceeded with the scaling process, paying attention to the scaling laws in order to preserve the beam dynamics [8]. We

* giovanni.campri@uniroma1.it

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considered the case of a high-charge electron beam (0.5 nC), as set out in the BoCXS design. Thus, we scaled up the bunch charge to 0.5 nC and the resonance frequencies to the C-band, doubling their values. This also meant doubling the field values and halving the length of the entire photo-injector. Figures 1 and 2, show a beam dynamics study for such scaling procedure. This first part of the work was done to gain confidence with the scaling laws and the beam dynamics, while also having an understanding of the order of magnitude of the beam parameters to work with.

Photo-Injector Layout

The goal of this work is to carry out an optimisation study revolving around a realistic case of a C-band photo-injector, and obtain a set of high quality beam parameters at the end of the accelerating structure. A straight scaling from the S-band case does not represent a proper realistic scenario. Indeed, a simple halving of the length of the whole structure leads to a drift section, after the solenoid, too short for the housing of the whole pumping and diagnostic systems. Beside that, doubling the peak field of the gun and accelerating cavities is also not so straightforward due to various technical limitations, such as the power dissipation in the structure and the power available to the klystron, which affect the maximum accelerating field and the repetition rate of the machine. In our study we considered a repetition rate of 0.1 kHz which allows for a peak field of 180 MV/m for the gun and 40 MV/m for the TW cavities. Having this value of the field gradient inside the gun, rather than the 240 MV/m obtained with a straightforward scaling, implies that, to maintain a similar beam dynamics, one needs to modify the structure by adding a cell and making it a 2.6 cell RF-gun. In the end, in our simulations, the C-band photo-injector made use of such RF-gun, followed by three C-band TW structures, as shown in Fig. 3.

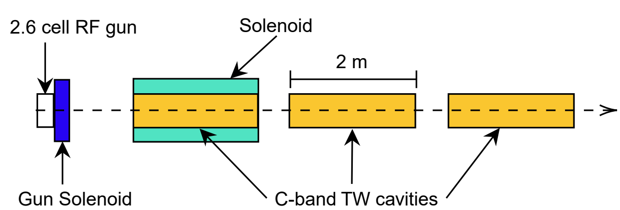

Figure 3: Layout of the C-band photo-injector. The 2.6 cell RF-gun provides a peak field of 180 MV/m, the TW structures work with a peak field up to 40 MV/m and a $2\pi/3$ phase advance per cell. All the structures operate at 5.712 GHz.

Both on-crest and velocity bunching case were tested using 50k macroparticles. In the on-crest operation, we set the first two cavities to 40 MV/m (peak field) while the last one was used to minimise the relative energy spread with the proper field phase and was set to 23.65 MV/m. In the velocity bunching case all the TW structure were set to 40 MV/m, and the first cavity was used to obtain a longitudinal compression by changing the injection phase to -84 deg.

RESULTS

We started by considering the previously used beam distribution at the cathode (uniform transverse distribution and flat-top longitudinal distribution), with an improved rise time of 0.5 ps and we aimed for a final energy of 165 MeV. We observed a final emittance < 0.5 mm·mrad and energy spread < 0.3 %, giving a peak brightness of ~ 10^{17} A/m^2.

In the end we also performed a simulation for the velocity bunching regime, in order to reach higher peak current. In this case, the first cavity phase and the solenoid magnetic field around it had to be correctly tuned to reach a compression ratio of 3 while keeping the spot size and emittance under control. Figure 4 shows the beam dynamics studies of the two regimes for a bunch with the characteristics expressed in Table 1, where we show a set of optimised beam parameters.

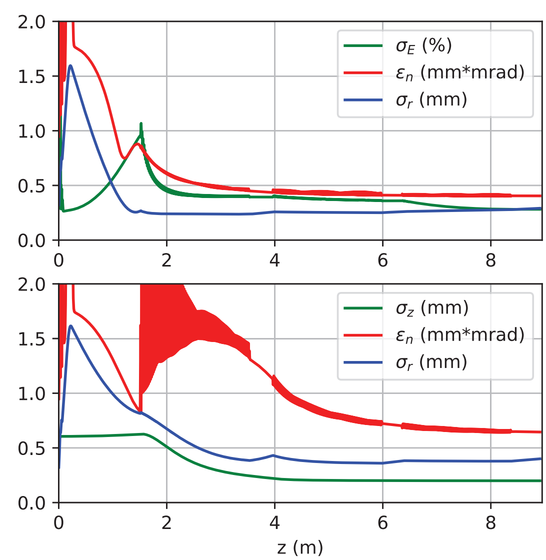

Figure 4: Simulation of beam evolution along the C-band photo-injector. Top: beam envelope, emittance and energy spread evolution for the on-crest operation. Bottom: beam envelope, emittance and bunch length evolution for the velocity bunching operation.

From Fig. 5 one can observe the behavior of the slice emittance and beam current at the end of the photo-injector. The slice analysis shows a consistent low value of the emittance within the FWHM of the beam current.

DISCUSSION

To have a sample of the operative capabilities of the photo-injector, we aimed to minimise both the final beam normalised transverse emittance and final relative energy spread, regardless of what would be installed further down the line, after the photo-injector. More in detail, such optimisation

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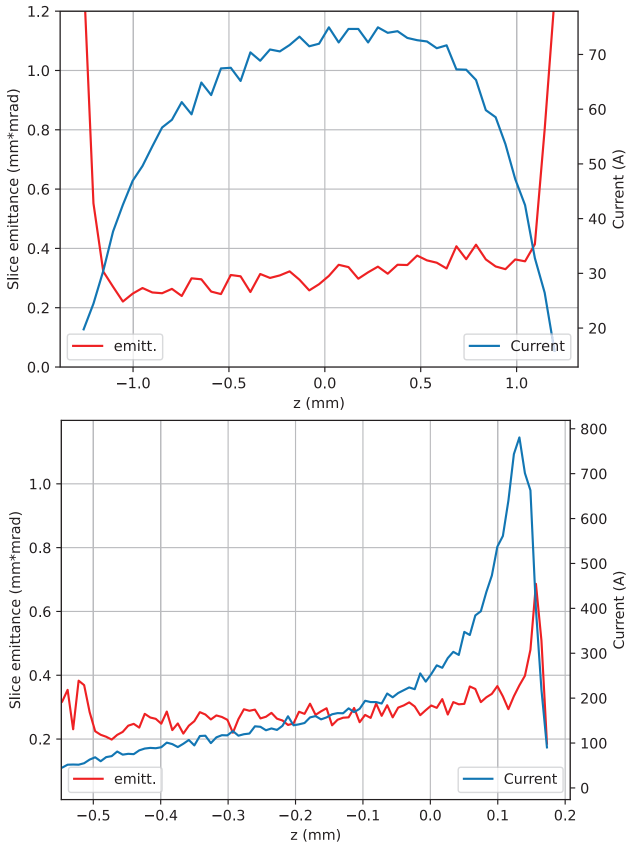

Figure 5: Slice analysis of the bunch at the end of the photo-injector for the on-crest operation (top) and velocity bunching (bottom).

involved a fine tuning of many parameters of the machine. To minimise the emittance, the parameters we scanned included the gun solenoid's magnetic field, the length of the drift space and the RF-gun injection phase; while for the optimisation of the energy spread the main parameter was the field phase inside the accelerating cavities. Beyond that, another important aspect affecting both final emittance and energy spread is represented by the laser parameters, which

Table 1: Set of Optimised Beam Parameters for the C-band Photo-Injector, with and w/o Bunch Compression

Parameter	**w/o BC**	**with BC**
Bunch charge [nC]	0.5	
Rep. rate [kHz]	0.1	
Laser rms spot size (Uniform)[mm]	0.3	
FWHM length pulse [ps]	8.5	
Rise time [ps]	0.5	
e-Beam final energy [MeV]	165	145
Norm. proj. emittance [mm mrad]	0.41	0.65
Bunch length, σ_t [ps]	2.1	0.7
Transverse beam size, σ_r [mm]	0.3	0.4
Relative energy spread, σ_E[%]	0.28	1.77
Slice peak current [A]	75	750

define the initial bunch distribution and dimensions at the cathode [9]. This is even more relevant when considering the use of the photo-injector without any mechanism of bunch compression, especially with a high-charge beam. In such cases, the energy spread is mainly due to the RF curvature, and a longer bunch results in a higher energy spread at the end of the linac, while a shorter one could increase the space-charge forces within the bunch, leading to an increase in the transverse emittance at the cathode. Thus, the initial transverse and longitudinal bunch dimensions have a large impact on the final beam characteristics, and must be chosen carefully. The velocity bunching operation allowed us to obtain a slice peak current of 750 A but it is worth to note that a magnetic bunch compression system in the beam-line could enable to reach a peak current of several kA, with proper preservation of the transverse emittance. Indeed, this is the case for the forthcoming application of such photo-injector to the EuPRAXIA@SPARC_LAB project, where a much higher peak current is required for various applications such as plasma-wakefield acceleration and FEL experiments [10].

CONCLUSIONS

We have carried out a characterisation of the performance of a C-band photo-injector, for a high-charge beam (0.5 nC) using the tracking code ASTRA. Starting by a scaling of the S-band scenario, we optimised the parameters that have largest impact on the beam brightness. We provided benchmark results for the on-crest operation, obtaining a final emittance < 0.5 mm·mrad and relative energy spread < 0.3 %. Velocity bunching was also tested, with a compression factor of 3 and proper emittance compensation.

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