

DARK CURRENT STUDIES FOR A HIGH GRADIENT SW C-BAND RF GUN*

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Abstract

It is now well-established that for the generation of very high brightness beams, required for fourth generation light sources, it is highly advantageous to use injectors based on Radiofrequency photo-guns with very high peak electric fields on the cathode (>120 MV/m). This very high surface electric field leads to the generation of undesirable electrons due to the field emission effect. The emitted electrons can be captured and propagate along the Linac forming a dark current beam, leading to background radiation that can damage the instrumentation and radio-activate components. Consequently, it is important that the emission of these electrons, and their subsequent transportation, is carefully evaluated. Recently, in the framework of the I-FAST project, a high gradient, standing wave, C-band (5712 MHz) RF photogun has been designed and will be realized soon. In this paper, the results of dark current studies and simulations are illustrated. The transport efficiency and the spectrum of the dark current have been evaluated by Particle-In-Cell simulations for different cathode peak field values considering also the effect of the focusing solenoid on the dark current beam.

INTRODUCTION

A few years ago, an R&D activity on C-band (5712 MHz) Radio-Frequency (RF) Gun and a full C-band Injector [1, 2] has been started at INFN-LNF. Such a system is very promising in terms of achievable beam parameters, compactness and possibility to reach very high repetition rates (up to 1kHz). Recently, this activity received new impetus with its inclusion in the European IFAST project. IFAST is an initiative from the European Union Horizon 2020 Research program to develop the next generation of accelerator technologies. Crucial for future light sources is the continued development of electron sources to improve beam quality, in particular higher beam brightness, while also offering more compact and cost effective solutions. As part of this project, INFN is involved in the design, realization, and low and high power RF testing of a high gradient C-band RF photo-cathode gun. It is a Standing Wave (SW) RF normal conducting Gun which aims to achieve peak cathode gradients greater than 160 MV/m (Fig. 1). The final RF test of this SW prototype will be performed at PSI. Working at very high peak fields and gradients lead to the increase of 'field emitted' electrons from the metal surfaces exposed

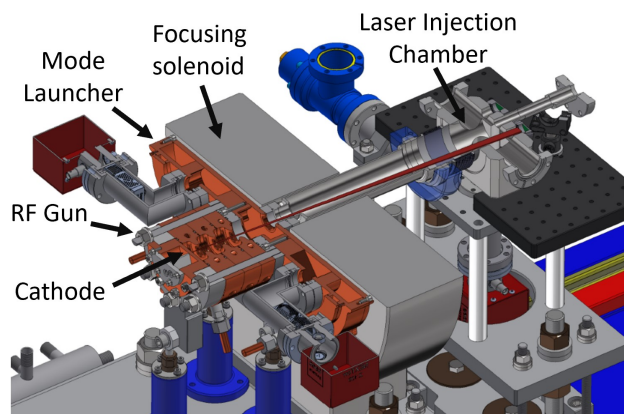


Figure 1: Section of the mechanical model of the C-band photo-injector with main components.

to the field. This so called Dark Current (DC) beam can lead to transverse kicks on bunches and can damage instrumentation and produce background radiation [3]. For this reasons it has to be carefully evaluated in order to properly design radiation protection systems for instrumentation and personnel. Below the design and layout of the C-band SW Gun will briefly presented and then the preliminary dark current studies performed on this new high gradient gun are reported.

THE SW C-BAND GUN

To reach very high gradient fields, while keeping under control and reducing the breakdown rate (BDR), the C-band RF Gun has been designed to work with very short RF pulses (300 ns). For this purpose, the coupling coefficient β of the Gun coupling cavity has been increased and consequently also the required RF input power, taking into account the maximum sustainable reflected power. An industry-made RF isolator will be used to protect the source from the power reflected at the Gun input.

Working with such high field means that standard couplers cannot be used so a 4-port mode launcher has been integrated to lower the pulsed heating and to compensate the quadrupole field components due to the aperture in the gun cell. Design and beam dynamics simulations of this mode launcher are reported in [4,5]. In the last years many RF Gun, like the new SPARC_LAB RF Gun [6], have been fabricated with the clamping technique developed at the Frascati Laboratory of INFN demonstrating excellent performances, so the same technology has been chosen also for the realization of this gun. The clamping technology allows one to avoid

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the brazing procedure by using special gaskets and keeping the Copper "hard". The use of non-annealed hard copper for high gradient structure has shown to reduce both BDR and time required for conditioning procedure [7]. A detailed description of the electromagnetic and mechanical design of the Gun can be found in Ref. [8].

The solenoid has been designed with the goal to reach at least the same focal length of the LCLS and SPARC_LAB one (about 50 cm for an electron beam energy of 6 MeV) but with a smaller overall length (126 mm with respect to 200 mm). The solenoid consists of one coil with 280 turns, surrounded by iron shield to increase the peak field and to limit the stray field around the magnet. It is powered with a current of 184 A who corresponds to a peak field of 6708 G. The combination between the gun layout and the solenoid's field allows one to keep a very low magnetic field on cathode (less than 20G on the solenoid axis). The main parameters of the gun are summarized in Table 1.

Table 1: SW C-Band RF Gun Main Parameters

Parameter	Unit	Value
Frequency	MHz	5712
Number of cells		2.5
Cathode type		OFHC Cu
$E_{cath}/\sqrt{P_{diss}}$	MV/(m MW ^{0.5})	51.4
Peak input power	MW	18
Cathode field	MV/m	160
Quality factor		11 900
Rep. Rate	Hz	100
Filling time	ns	166
Coupling coefficient β		3
RF pulse length	ns	300
E_{surf}/E_{cath}		0.96
Mod. Poynt. Vector	W/ μm^2	2.5
Pulsed heating	°C	<16
Avg dissipated power	W	300

DARK CURRENT SIMULATIONS

To evaluate the dark current a theoretical approach based on the well known Fowler-Nordheim (FN) model has been considered to evaluate the emitted current from the cathode in an RF pulse (Fig. 2).

A numerical approach using the 3D CST Particle-in-Cell code [9] and the simulation technique described in [10], has been used to evaluate the cathode emission, the transport along the gun structure and energy spectrum at the gun end of DC beam. With the 3D simulations the effect on the beam by the magnetic field generated by the solenoid at the nominal current of 184A has been evaluated. As source of particle, both in the theoretical and numerical approach, the entire cathode area $A_{cathode}$ has been considered. To scale it to the effective area of the emitters ($A_{emitters} = 0.01\mu m^2$) we define an emitter density factor and applied it to the FN model model:

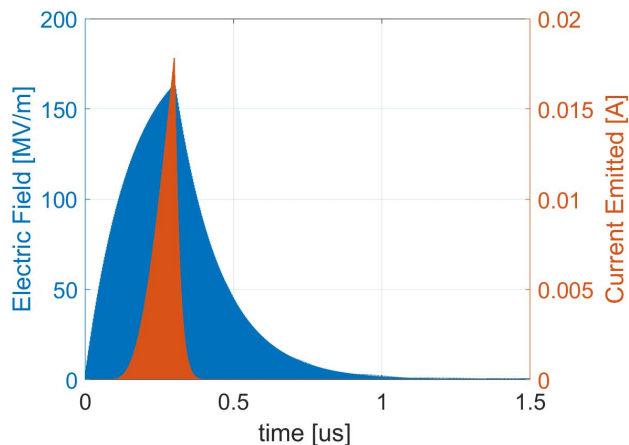


Figure 2: Current emitted by the cathode (red) and Peak Cathode field (blue) during an RF pulse.

$$j'_F(x, y, t) = \frac{A_{emitter}}{A_{cathode}} = j_F(x, y, t) \quad (1)$$

Modelling dark current is difficult due to unpredictability of the emitter area A_e and the field enhancement factor β [11]. The latter depend not only on the material but also on the details of the cleaning and roughness of the emitting surface, and can be estimated from DC measurements on the device by varying the peak field on the cathode. In our case to have a preliminary DC estimation, the values that have been considered in the simulations are those evaluated at the PSI for the SwissFEL Gun [12]. For the 3D numerical calculation the geometry of the Gun from the cathode up to the UV laser injection chamber has been considered. The gun RF field and the magnetic field of the solenoid have been previously simulated on this geometry and then imported in the PIC simulation. An example of the fields along the Gun axis, calculated by CST for a cathode peak field of 160 MV/m are reported in Fig. 3. The simulations have been carried out for two different values of the cathode peak field 160 MV/m and 180 MV/m, and with and without the solenoid

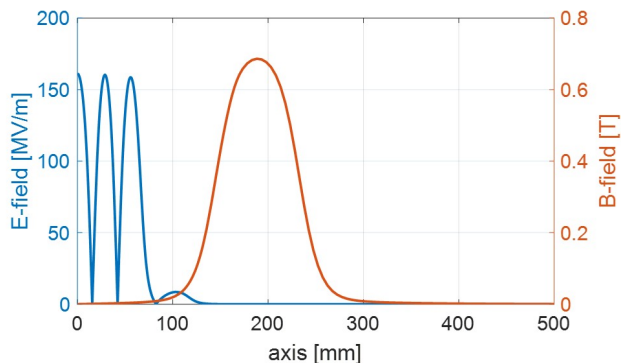


Figure 3: RF longitudinal Electric field and solenoid magnetic field along the Gun axis.

field generated at the nominal current of 182 A. Figure 4 demonstrates, as an example, the DC beam emitted only by the cathode propagating up to the laser injection chamber obtained as result of the PIC simulation.

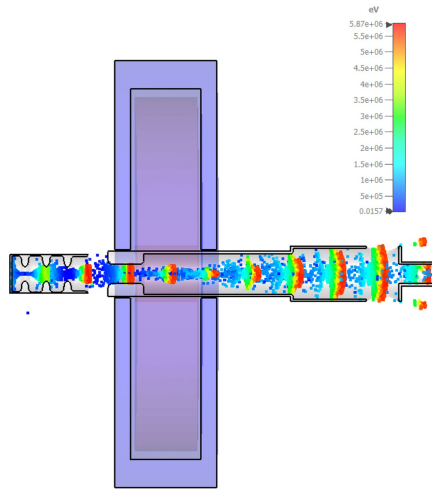


Figure 4: Snapshot of DC beam emitted by the cathode and propagating up to the laser injection chamber obtained as result of the PIC simulation for 160 MV/m of cathode peak field and with the solenoid turned on.

As well as the field emitted electron from the cathode, electrons emitted from the Gun irises have also been evaluated, but they are negligible compared to that emitted from the cathode, for this reason they were not taken into account in the results. In Table 2 the results obtained from the simulations are summarized for both the two working points and turning off and on the solenoid. The field emitted electron evaluated with the theoretical approach have been compared with those of the numerical simulation giving the same results. Finally in Fig. 5 the spectra of the DC beam reaching the end of the gun chamber are plotted.

Table 2: Simulations Parameters and Main Results

Parameter	Unit	Value			
Field factor β		70			
$A_{emitter}$	μm^2	0.01			
Peak Cathode Field	MV/m	160	180		
Solenoid Current	A	0	184	0	184
$Q_{emitted}$	fC	360		950	
$Q_{transported}$	fC	33	15	78	35
Transport ratio	%	9.1	4.2	8.2	3.7
Maximum Energy	MeV	5.7		6.4	

Turning on the solenoid at the nominal working point the ratio of captured DC decreases by about half. From beam dynamics simulations, the calculated spectra are compatible with those of a long beam injected across the crest of the RF signal. The emitted and transported charge is the one corresponding to a single period which occurs for the maximum value of the cathode field, starting from these results it

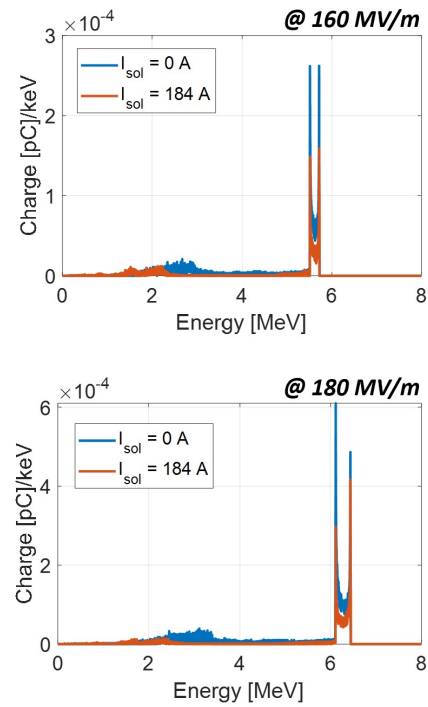


Figure 5: Spectra of the DC beam detected at the end of the gun chamber for the two working points (160MV/m and 180MV/m) with and without the solenoid field.

will be possible to subsequently obtain the total transported charge relative to a whole RF pulse.

CONCLUSION

A new SW C-band RF Gun with cathode peak field $\geq 160\text{MV/m}$ is currently under construction at INFN-LNF in the framework of the I.FAST project, and once realized it will be tested with high power at PSI. The preliminary results regarding dark current evaluation on this gun have been presented but further work is needed to characterize completely the transported beam. Once the gun is built, the dark current beam will be measured and fully characterized during the high power test. The comparison between the measured values and the simulated ones will allow to evaluate the effective enhancement factor β to use for the Fowler-Nordheim field emission model.

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REFERENCES

- [1] D. Alesini *et al.*, "Design of a full C-band Injector for ultra high brightness electron beam", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019. doi:10.18429/JACoW-IPAC2019-TUPTS

- [2] M. Croia *et al.*, "High gradient ultra-high brightness C-band photoinjector optimization", *J. Phys.: Conf. Ser.*, vol. 1596, p. 012031, 2020.
doi:10.1088/1742-6596/1596/1/012031
- [3] Karl L. F. Bane *et al.*, "Dark currents and their effect on the primary beam in an X-band linac", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 064401, 2005.
doi:10.1103/PhysRevSTAB.8.064401
- [4] A. Giribono *et al.*, "Effects of mode launcher on beam dynamics in next generation high brightness C-band Guns", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 813-816.
doi:10.18429/JACoW-IPAC2021-MOPAB257
- [5] G. Pedrocchi *et al.*, "A C-band RF mode launcher with quadrupole field components cancellation for high brightness applications" in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 3638-3641.
doi:10.18429/JACoW-IPAC2021-WEPAB398
- [6] D. Alesini *et al.*, "The new SPARC_LAB RF photo-injector" in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, paper MOPOMS019, this conference.
- [7] A. D. Cahill *et al.*, "High gradient experiments with X-band cryogenic copper accelerating cavities" *Phys. Rev. Accel. Beams*, vol. 21, p. 102002, 2018.
doi:10.1103/PhysRevAccelBeams.21.102002
- [8] D. Alesini *et al.*, "The new C-band Gun for the next generation RF photo-injectors" in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, paper MOPOMS021, this conference.
- [9] SIMULIA,
<https://www.3ds.com/products-services/simulia/>
- [10] T. G. Lucas *et al.*, "Dependency of the capture of field emitted electron on the phase velocity of a high-frequency accelerating structure", *Nucl. Instrum. Meth. A*, vol. 914, pp. 46-52, 2019. doi:10.1016/j.nima.2018.10.166
- [11] L. Zhou *et al.*, "Development of a high-gradient X-band RF gun with replaceable field emission cathodes for RF breakdown studies" *Nucl. Instrum. Meth. A*, vol. 1027, p. 166206, 2022. doi:10.1016/j.nima.2021.166206
- [12] S. Bettoni *et al.*, "Low energy dark current collimation system in single-pass linacs", *Phys. Rev. Accel. Beams*, vol. 21, p. 023401, 2018.
doi:10.1103/PhysRevAccelBeams.21.023401