ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN1

DESIGN, REALIZATION AND HIGH POWER RF TEST OF THE NEW BRAZED FREE C BAND PHOTO-GUN

D. Alesini*, F. Cardelli, G. Di Raddo, L. Faillace, M. Ferrario, A. Gallo, A. Giribono, A. Gizzi, S. Lauciani, A. Liedl, V. Lollo, L. Pellegrino, L. Piersanti, C. Vaccarezza, A. Vannozzi, L. Spallino
Istituto Nazionale di Fisica Nucleare, Frascati, Italy
T.G. Lucas, C. Beard, L.J.F. Hol, P. Craievich, Paul Scherrer Institute, Villigen, Switzerland
L. Ficcadenti, Sapienza University of Rome, Rome, Italy

Abstract

RF photoguns are the most common electron sources for FELs and Compton facilities. They are key in such accelerator facility and, presently, primarily operated in the S band regime (3 GHz). Such S band RF photoguns typical achieve cathode peak fields of 80-120 MV/m and repetition rates lower than 120 Hz. An innovative C Band (5.712 GHz) RF gun aiming at reaching cathode peak field larger than 160 MV/m, with repetition rates exceeding the 400 Hz, has been designed, realized and high power tested in the context of the European I.FAST and INFN Commission V projects. It is a 2.5 cell standing wave cavity with a four-port mode launcher, designed to operate with short RF pulses (300 ns). Its realization is based on the new brazing-free technology developed and successfully tested at INFN. In the paper, after a short overview of the design and RF gun capabilities, we illustrate the realization procedure and the results of the high power RF tests that have been performed at the high power C-band test facility at PSI (Switzerland).

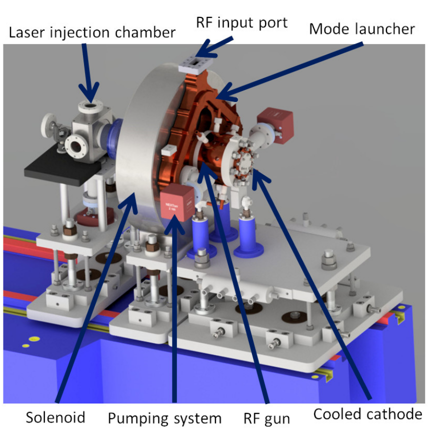

Figure 1: Mechanical drawing of the gun assembly.

INTRODUCTION

The achievable beam brightness in rf photo-injectors is strongly dependent on the cathode peak field [1]. For this reason, in the last generation rf guns, a great effort has been put to increase the field amplitude keeping under control the breakdown rate probability (BDR) [2]. In this context, the possibility to implement a full C band injector is strongly attractive for both the reachable beam parameters [3] and compactness than for the possibility to operate at high repetition rate (up to 1 kHz) using short RF pulses, as proposed for the X-band linacs of the EuPRAXIA@SPARCLAB project [4] and XLS design study [5]. The gun is also extremely attractive for its possible applications in upgrades of existing photo-injectors for FEL. The electromagnetic and thermo-mechanical analysis have been already illustrated in previous papers [6, 7] and the main rf parameters are reported in Table 1. The gun is a 2.5 cell structure and its design has been optimized to minimize the peak E field, the modified Poynting vector [8], the rf pulse length and pulsed heating [9]. For this reason the gun has been designed with a coupling coefficient equal to 3 to allow operation with short rf pulses (300 ns) thus reducing the BDR, pulsed heating and the power dissipation. An elliptical profile of the iris with large aperture has been also implemented to reduce the peak electric field, to increase the frequency separation with the nearest $\pi/2$-mode thus avoiding excitation of this mode with short rf pulses and to have a better pumping on the cathode cell. A four-port mode launcher [10, 11] with an on-axis coupling has been also adopted to reduce the pulsed heating on the coupler and to have a perfect compensation of the dipole and quadrupole field components. The mode launcher has been also designed to integrate two pumping ports.

Table 1: Main Parameters of the C-band Gun

Parameter	Value
Resonant frequency [GHz]	5.712
E_{cath}/P_{diss} [MV/(mMW$^{0.5}$)]	51.4
rf input power [MW]	18 (19)
Cathode peak field [MV/m]	160
Rep. rate [Hz]	100-400
Quality factor	11900
Filling time [ns]	166 (147)
Coupling coefficient	3 (3.5)
rf pulse length [ns]	300
Mode sep. $\pi - \pi/2$ [MHz]	47 (48.3)
E_{surf}/E_{cath}	0.96
Mod. Poy. vector [W/m^2]	2.5
Pulsed heating [°C]	16
Average diss. Power [W]	250-1000

* alesini@lnf.infn.it

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN1

The realization and test of the C-Band gun has been funded by the EU in the framework of the I.FAST project [12] and by INFN Commission V. The gun has been realized without brazing, with the new technology developed at INFN [13] and already adopted for the realization of RF photoguns in S band [14–16]. The technology allows one to assemble the device using special gaskets in a clean room and to proceed, after the vacuum test, directly to the rf characterization. The main advantage is the possibility to use forged, not annealed, copper that, according to X-band high gradient tests [17] and our tests on S band gun [14–16] has been verified to exhibit extremely good performances in term of conditioning time and BDR. The gun realization procedure and the low power rf measurements results are illustrated in [7].

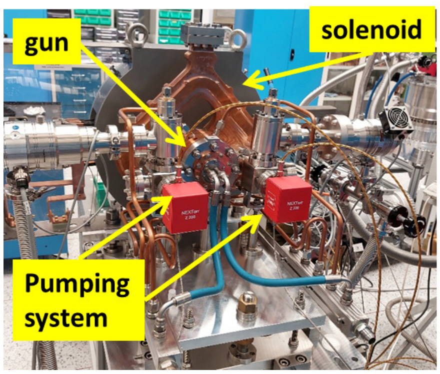

Figure 2: Picture of the assembled gun with solenoid, vacuum system, support and vacuum chambers.

After its realization, the gun has been assembled with all vacuum components and is now under test at PSI in Switzerland. In the present paper we illustrate the final assembly procedure, its installation in the high power test station and the results of the high power test that shown extremely good performances of such a device capable to reach cathode peak field above the 147 MV/m.

C BAND GUN LAYOUT AND FINAL ASSEMBLY

The 3D mechanical layout of the whole injector is given in Fig. 1. The gun is followed by an emittance compensating solenoid and the laser injection chamber that allows a laser injection with the last mirror in air. Two pumping ports are integrated in the mode launcher and allow to reach a vacuum level of the order of 10^{-10} mbar/l sec without any bakeout. The gun integrates several different components: the standing wave (SW) cells, the four port mode launcher and the copper cathode. The mode launcher has been machined using the five axis milling machine Micron UCP600 Vario with precision on the internal dimensions of $\pm$ 8 µm and roughness below 200 nm. It has then been brazed in a vacuum furnace using palcusil 5 alloy. The SW cells and cathode have been machined using, for the final finishing of the surfaces the lathe Schaublin 225 TM-CNC. The internal dimensions of the cells have been machined with a precision of $\pm$ 2 µm and a surface roughness below 30 nm. After the machining, the cells have been cleaned and assembled with the gun as illustrated in [7]. The gun, after the final assembly and vacuum test has been assembled in its final configuration with the solenoid and vacuum chambers as displayed in Fig. 2.

HIGH POWER RF TEST SETUP

The whole system has then been transported to PSI and installed in the High Power Test Stand [18]. The picture of the gun connected to the C-band waveguide system and ready for the high power test is illustrated in Fig. 3. The original gun feeding scheme foresaw the use of a new in-vacuum isolator that experienced some delays due to the difficulties that have been encountered during its realization. For this reason we have developed an alternative scheme using power dividers and a BOC-type pulse compressor already available at PSI as illustrated in [7]. A four-port power splitter outputs the RF power fed in with a power ratio of 1 to 9 at the two output ports. The power from the 10 % port is then compressed with the pulse compressor in order to increase the peak power. With this scheme, the reflected power from the cavity is split again with the same ratio allowing the reflected power to the klystron to be reduced to ≈ 500 kW. In the setup there are eight NEG-ion pumps and four directional couplers. The vacuum is also monitored through four vacuum gauges; one in the laser injection chamber, two near the BOC and one near the klystron window. These have been used to monitor the local vacuum in the regions expected to suffer the most from high power operation.

HIGH POWER RF TEST RESULTS

After the first tests of the system and controls at high power in December of 2023, the RF conditioning began in February 2024 once the water system for the BOC was completed. The conditioning was done in a semi-automatic way, monitoring the vacuum at the different vacuum pumps and progressively increasing the power from the klystron and pulse length keeping the repetition rate at 100 Hz. In case of a vacuum discharge event, identified with a vacuum spike exceeding 3×10^{-8} mbar, the algorithm automatically interlocks the system. In the case of a reflected power to the klystron exceeding a 1 MW, the system also interlocks. During the interlock, the power is set to zero and the power ramped back to the level at which the system previously interlocked. The history of the input power, converted into a the peak cathode field generated in the gun is shown in Fig. 4. In the same plot we have also reported the vacuum behaviour as measured by the vacuum gauges distribute in the waveguide transport line and laser injection chamber. In the first phase of the conditioning, the pulse compressor has been detuned by changing its temperature thus reducing the maximum input power into the gun. It is important to note that the conditioning has been dominated by the vacuum activity in the waveguide system and that the final maximum input power from the klystron has been limited

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN1

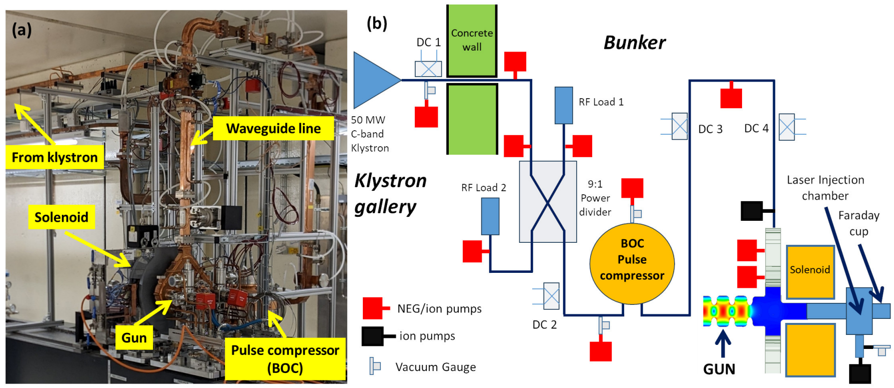

Figure 3: (a) The realised waveguide network and installed gun. (b) A diagram of the waveguide network.

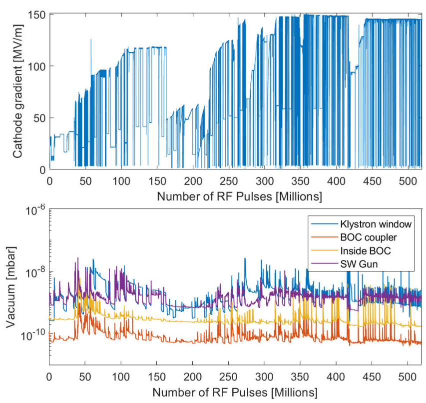

Figure 4: History of the input power, converted into a the peak cathode field (top) and vacuum pressure (bottom).

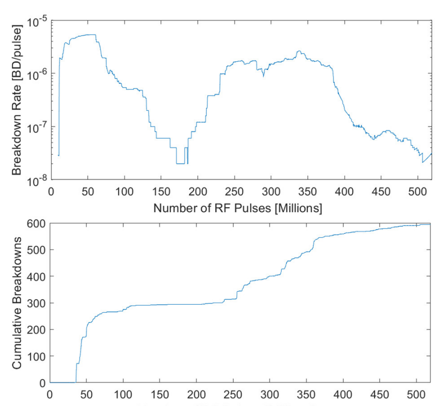

Figure 5: Break down rates as a function of the number of RF pulses (top) and cumulative breakdown events (bottom).

by a vacuum activity in the ceramic of the klystron probably due to the reflected power from the system. In Fig. 5 we have reported the vacuum breakdown events in the gun and in the waveguide system. At the maximum input power we reached so far the calculated cathode peak field is about 150 MV/m with no limitation due to the gun. In the same figure we have also reported the cumulative number of breakdown events. Examples of the input signal into the gun and from

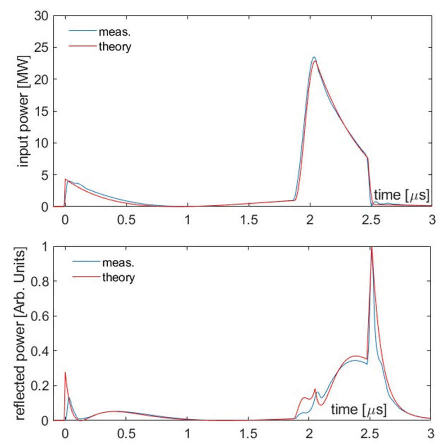

Figure 6: Gun input (top) and reflected (bottom) power compared with expectation.

the gun are given in Fig. 6. They have been compared with the calculated ones [7] showing a very good agreement.

CONCLUSIONS AND FUTURE PLANS

A new Standing wave C band gun has been designed, fabricated and high power tested reaching so far cathode peak field at the level of 150 MV/m without limitations due to the gun itself. This device is both extremely promising for the achievable beam performances than for the possibility to operate at repetition rates above 400 Hz. After the conclusion of this test the gun will be installed in the INFN TEX Facility [19] where a 400 Hz C band power station is being implemented allowing to fully explore the C band gun capabilities also in term of repetition rate.

ACKNOWLEDGEMENTS

We would like to acknowledge the COMEB Company [20] for the technical support in gun realization. This project has received funding from the European Union's Horizon 2020 Research and Innovation program under GA No101004730 and from the INFN Commission V.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN1

REFERENCES

[1] J.B. Rosenzweig and E. Colby, "Charge and Wavelength Scaling of RF Photoinjector Design", Rep. TESLA-95-04, 1995.

[2] V. A. Dolgashev, Y. Higashi, T. Higo, C. D. Nantista, and S. G. Tantawi, "RF Breakdown in Normal Conducting Single-cell Structures", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper ROAC007, pp. 595–599.

[3] A. Giribono *et al.*, "Dynamics studies of high brightness electron beams in a normal conducting, high repetition rate C-band injector", *Phys. Rev. Accel. Beams*, vol. 26, p. 083402, 2023.

[4] D. Alesini et al., ""EuPRAXIA@SPARC_LAB Conceptual Design Report", INFN-18-03/LNF.

[5] `http://www.compactlight.eu/Main/HomePage`

[6] D. Alesini *et al.*, "The New C Band Gun for the Next Generation RF Photo-Injectors", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 679–682. `doi:10.18429/JACoW-IPAC2022-MOPOMS021`

[7] D. Alesini *et al.*, "Progress on the new high gradient C Band standing wave RF photo-gun", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1374–1377. `doi:10.18429/JACoW-IPAC2023-TUPA009`

[8] A. Grudiev, S. Calatroni, and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures,"*Phys. Rev. Spec. Top. Accel Beams*, vol. 12, no. 10, Oct. 2009. `doi:10.1103/physrevstab.12.102001`

[9] V. A. Dolgashev, "High magnetic fields in couplers of X-band accelerating structures,"in *PAC-03*. IEEE, 2003. `doi:10.1109/pac.2003.1289674.`

[10] G. Castorina *et al.*, "A TM01 mode launcher with quadrupole field components cancellation for high brightness applications,"*J. Phys. Conf. Ser.*, vol. 1067, p. 082025, Sep. 2018. `doi:10.1088/1742-6596/1067/8/082025`

[11] G. Pedrocchi *et al.*, "A C-Band RF Mode Launcher with Quadrupole Field Components Cancellation for High Brightness Applications", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3638–3641. `doi:10.18429/JACoW-IPAC2021-WEPAB398`

[12] `https://ifast-project.eu/home`

[13] D. Alesini *et al.*, International Patent Publication No. WO 2016/147118 A1, assigned to INFN.

[14] D. Alesini *et al.*, "New technology based on clamping for high gradient radio frequency photogun,"*Phys. Rev. Spec. Top. Accel Beams*, vol. 18, no. 9, Sep. 2015. `doi:10.1103/physrevstab.18.092001`

[15] D. Alesini *et al.*, "Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun,"*Phys. Rev. Accel. Beams*, vol. 21, no. 11, Nov. 2018. `doi:10.1103/physrevaccelbeams.21.112001`

[16] V. Shpakov *et al.*, "Design, optimization and experimental characterization of RF injectors for high brightness electron beams and plasma acceleration,"*IEEE Open J. Instrum. Meas.*, vol. 17, no. 12, p. P12022, Dec. 2022. `doi:10.1088/1748-0221/17/12/p12022`

[17] E. I. Simakov, V. A. Dolgashev, and S. G. Tantawi, "Advances in high gradient normal conducting accelerator structures,"*Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 907, pp. 221–230, Nov. 2018. `doi:10.1016/j.nima.2018.02.085`

[18] T. Lucas *et al.*, "Developments and first results from a test stand for high brightness C-band photoguns at PSI", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper WEPC69, this conference.

[19] F. Cardelli *et al.*, "Advancements in X-band technology at the TEX facility at INFN-LNF", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper TUPR02, this conference.

[20] `http://www.comeb.it/`