ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT005

FIELD ENHANCED, COMPACT S-BAND GUN EMPLOYING A PIN CATHODE

R. Bazrafshan[1,4], M. Fakhari[1], T. Rohwer[1], K. Flöttmann[2], N. H. Matlis[1] and F. X. Kärtner[1,3,4]
[1]Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[2]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[3]The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Germany
[4]Physics Department, Universität Hamburg, Germany

Abstract

S-band RF-guns are highly developed for production of low emittance relativistic electron bunches, but need powerful klystrons for driving. Here, we present the design and first experimental tests of a compact S-band gun, which can accelerate electrons up to 180 keV powered by only 10 kW from a compact rack-mountable solid-state amplifier. A pin-cathode is used to enhance the RF electric field on the cathode up to 100 MV/m as in large-scale S-band guns. An electron bunch is generated through photoemission from a flat copper surface on the pin excited by a UV laser pulse followed by a focussing solenoid producing a low emittance bunch with 0.1 mm mrad transverse emittance for up to 100 fC bunch charge. We are currently in the conditioning phase of the gun and first experiments show good agreement with simulations. The compact gun will serve three purposes: (i) it can be used directly for ultrafast electron diffraction; (ii) as an injector into a THz booster producing 0.3MeV to 2 MeV electron bunches for ultrafast electron diffraction; (iii) The system in (ii) serves as an injector into a THz linear accelerator producing a 20 MeV beam for the AXSIS X-ray source project.

INTRODUCTION

Photocathode rf guns have been proven to be an excellent electron source for very high-quality beams required for vacuum ultra-violet (VUV) and X-ray FELs [1]. In photocathode rf guns, electron beams are generated at the photocathode by the drive-laser pulses and accelerated immediately by the rf field. Since the electron bunches after emission from the photocathode are of very high intensity and have close to zero a velocity, high space charge forces quickly deteriorate beam quality. Thus, a high acceleration field at the cathode is of great importance for reaching a high electron beam quality. The beam quality can be further optimized by means of three-dimensionally (3D) shaped laser pulse with a well-defined profile [2]. The expansion and non-linearity of the electron bunch in the phase space can be minimized with the optimized initial electron distribution. The initial profile of the beam after extraction from the cathode undergoes a modification under the rf and the solenoid fields as well as the space charge force. Due to the strong accelerating field in the cavity, electrons can be field-emitted from the copper cavity surface and the photocathode. Any dusts on the front surface of the cathode may be a strong field emitter as well causing increased dark current. Dark current at the gun can be accelerated together with the electron bunch, thus the dark current dynamics must be investigated. During gun operation, multipacting peaks are found at the beginning and/or at the end of the rf pulse. The multipacting depends on the solenoid field profile. The amount of dark current and multipacting can be reduced by careful conditioning of the gun.

The concept of the AXSIS project at the Deutsches Elektronen-Synchrotron (DESY) is the development of a compact X-ray light source using terahertz acceleration [3]. Although the final AXSIS machine is expected to be powered exclusively by THz radiation, intermediate phases may resort to a radio-frequencies (RF), i.e. 3 GHz. S-band RF-guns are highly developed for production of low emittance relativistic electron bunches, normally need powerful klystrons which are bulky and expensive. Here, we present the design and first experimental tests of a compact electron source which can accelerate electrons up to 180 keV by only 10 kW from a compact rack mountable amplifier.

RF GUN DESIGN

The AXSIS RF gun is an S-band compact RF gun with a frequency of 2.998 GHz, combining both acceleration and compression of the electron bunch in a single device. By implementing a pin-shaped photocathode with a flat 0.8 mm tip [4,5], strong enhancement of the RF-field strength in the vicinity of the cathode is achieved which substantially reduces the power requirements, and hence the cost and complexity of the device. A solenoid is also used just after the gun to focus the electron beam transversely.

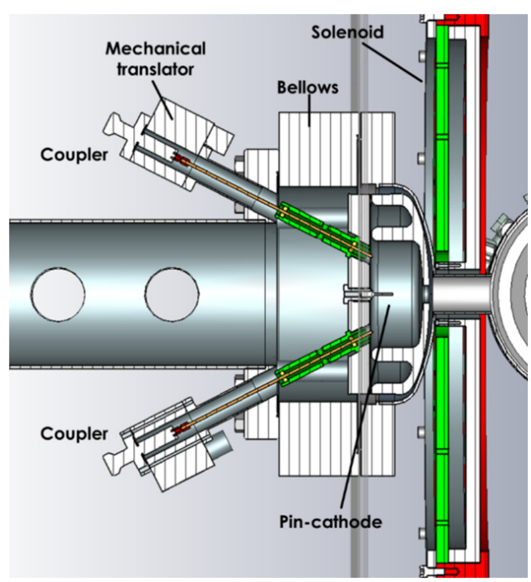

Figure 1: Sectional view of AXSIS RF gun (first prototype).

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT005

Figure 1 shows the designed structure. The electrons are generated via photoemission from a circular area with a diameter of 0.8 mm at the top of the stud. The 10 kW input power is injected into the cavity with an input antenna via a coaxial feedthrough shown in Figure 1. A second antenna is used as the pick-up for measuring the electric field inside the cavity. For tuning the cavity, this gun consists of two parts: the anode part is fixed, while the cathode part can be moved by a mechanical translator giving us also the possibility of tuning the cavity by adjusting the distance between the cathode and anode. In addition, the cavity design employs a choke filter which confines the field, and also facilitating access to the interior of the cavity and tuning the cavity for optimal coupling.

BEAM DYNAMICS

A half-cell pillbox cavity employing a metallic pin-cathode is designed to be used as the electron injector. The electric field distribution in the cavity is computed with CST Microwave Studio Eigen-mode solver [6] and is shown in Fig. 2. The electrons are injected in the negative phase of the RF signal. Therefore, a negative energy chirp is introduced to the bunch which leads to longitudinal compression. The ASTRA particle tracking solver is used to investigate the beam dynamics in the gun [7].

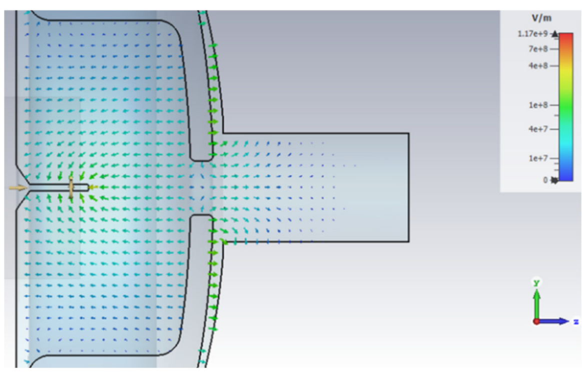

Figure 2: Electric field distribution.

The simulation results are shown in Fig. 3. The cavity field, reaches over 110 MV/m using only a 10 kW peak power solid-state amplifier, to both accelerate the electrons from rest up to 180 keV kinetic energy and impart an approximately linear velocity chirp onto the bunches with 0.1 mm length at the beginning near the cathode, allowing them to compress via velocity bunching to 10 μm corresponding to 30 fs rms durations at a distance 8 cm after the cathode. In order to focus the beam transversely to provide the required spatial resolution we designed a solenoid to be installed directly after the cavity. According to Fig. 3(c) this solenoid focuses the beam to 100 µm rms spot size.

RF GUN PERFORMANCE

The first prototype of the RF gun based on the above design was constructed and is currently being commissioned. In the initial design, in order to access the cavity from behind, a chamber connected to the cathode part. Using a vector network analyzer, the frequency response of the cavity was determined and a loaded quality factor of 6,000 was measured with a reflection (S_{11}) reaching below -50 dB. Although the RF Gun demonstrated a satisfactory frequency response in agreement with the design, RF leakage into the back chamber resulted in arcing when power above 8 kW was applied. In addition, high levels of secondary electron emission from multipacting was observed. To address these issues, a second prototype was designed and fabricated with shorter couplers surrounded by RF fingers (Fig. 4). The revised prototype demonstrated excellent performance, in good agreement with simulation, as well as near complete suppression of multipacting.

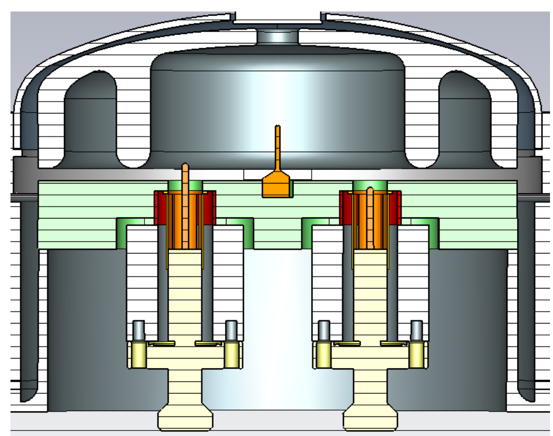

Figure 4: Second prototype design of developed compact RF Gun.

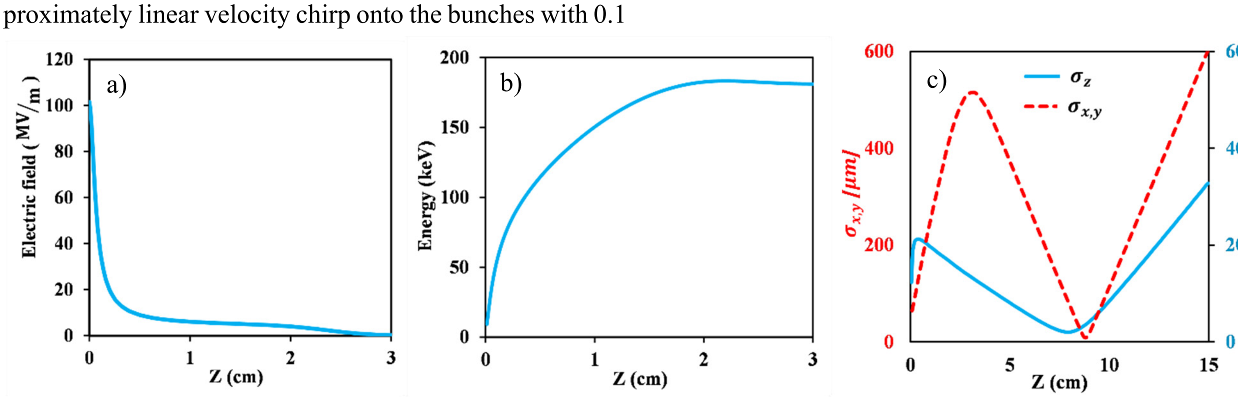

Figure 3: Respectively from left to right, a) Field enhancement at the cathode vs propagation distance (Z), b) Acceleration dynamics of the electron bunch vs Z, c) Focusing and compression of the bunch vs Z.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT005

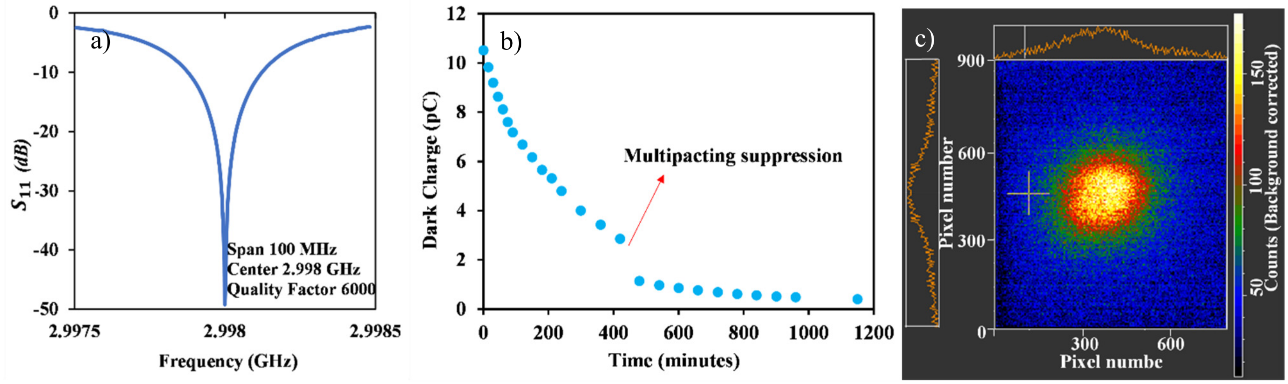

Figure 5: Respectively from left to right, a) Frequency response of the RF Cavity. b) Reduction of dark charge and multipacting during conditioning measured with a Faraday-cup. c) Field-emitted beam detected with a YAG scintillator.

Figure 5a shows the frequency response of the cavity with a resonance at 2.998 GHz. Conditioning of the gun using the 10 kW amplifier enabled strong suppression of multipacting and reduction of dark charge to below 400 fC per RF pulse of 5.5 µs (Fig. 5b) at a repetition rate of 12.5 Hz, it can be reduced by increasing the repetition rate and continuing conditioning. A combination of a Faraday Cup and a YAG scintillator (30 cm away from the cathode) were used to measure the charge and field-emitted beam shape (Fig. 5c). The resulting transmitted power (P_{21}) of 10 kW signal and negligible reflected power (P_{11}) were measured using the probe and feed antenna respectively (Fig. 6).

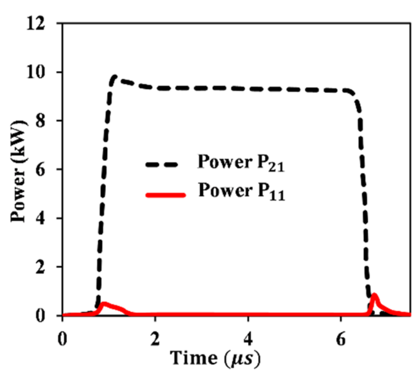

Figure 6: Coupled and reflected RF power.

CONCLUSION

A compact RF gun has been designed and fabricated (Fig. 7) and has undergone initial testing demonstrating a high cavity quality factor of 6,000 and low levels of multipacting and dark charge (400 fC). Based on simulation, this performance, which matches or slightly exceeds expectation, will allow operation of the gun at an energy of up to 180 keV low emittance electron bunches, powered by only 10 kW solid-state amplifier as the power source. A solenoid is used to focus the beam transversely. The rms longitudinal and transverse sizes of the electron bunch at the sample interaction point would be 10 mm and 100 mm respectively, which fit excellent for the purposes of the UED and AXSIS applications. Following completion of the conditioning phase, photo-triggered electron generation using a UV laser on the photocathode will follow, with first results expected in the next couple of months. The next round of testing will target characterization of the energy, energy spread and emittance of the beam.

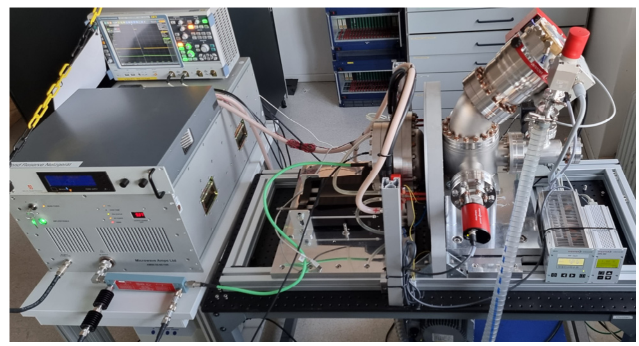

Figure 7: Compact RF gun setup with a compact amplifier.

ACKNOWLEDGEMENTS

The authors are very grateful for the help and support in electron beam conditioning and diagnostic from Dr. Hossein Delsim-Hashemi and Dr. Matthias Hoffmann.

REFERENCES

[1] V. Ayvazyan *et al.*, "Generation of GW radiation pulses from a VUV free-electron laser operating in the femtosecond regime," Physical review letters 88.10 (2002): 104802.

[2] LiHua Yu *et al.*, "First ultraviolet high-gain harmonic-generation free-electron laser," Physical review letters 91.7 (2003): 074801.

[3] Franz X. Kaertner *et al.*, "AXSIS: Exploring the frontiers in attosecond X-ray science, imaging and spectroscopy," Nuclear Instruments and Methods in Physics Research Section A, 829 (2016): 24-29.

[4] Hazem Daoud, Klaus Floettmann, and R. J. Dwayne Miller. "Compression of high-density 0.16 pC electron bunches through high field gradients for ultrafast single shot electron diffraction: The Compact RF Gun," Structural Dynamics 4.4 (2017): 044016.

[5] German patent application DE 10 2016 105 443.7. 23. March 2016.

[6] CST, Computer Simulation Technology, `https://www.cst.com/`

[7] Klaus Flöttmann, ASTRA, "A Space Charge Tracking Algorithm," March 2017.