ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL115

DEVELOPMENT OF A COMPACT HALF-CELL RF PHOTOCATHODE GUN FOR SINGLE-SHOT KEV ULTRAFAST ELECTRON DIFFRACTION WITH FEMTOSECOND RESOLUTION

R. Bazrafshan[1,4], G.H. Kassier[1], M. Fakhari[1], H. Delsim-Hashemi[2], T. Rohwer[1]
K. Flöttmann[2], N.H. Matlis[1] and F. X. Kärtner[1,3,4]
[1]Center for Free-Electron Laser Science (CFEL), Deutsches Elektronen-Synchrotron, 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

Ultrafast electron diffraction (UED) is a powerful tool for the direct visualization of structural dynamic processes in matter on atomic length and time scales. Observations on a femtosecond time scale with atomic resolution spatially have long been a goal in science and are currently achieved with large photo injectors developed for FEL frontends. Here we demonstrate a compact 180 keV photocathode S-band electron gun, which employs field-enhancement at a pin-shaped cathode to produce an extraction field strength of 102 MV/m driven by a rack-mountable solid state 10 kW peak power supply. Simulations predict that high-brightness electron bunches with RMS duration of 10 fs, a radius of 135 μm, and spatial emittance of 0.1 mm-mrad are possible for a bunch charge of 10 fC. The impact of laser spot size and duration, as well as their spatial distribution, on the temporal bunch length of electrons on the specimen was investigated. Following the successful completion of the conditioning phase of the RF gun and multipacting suppression, photo-triggered electrons using a UV laser on the photocathode were observed.

INTRODUCTION

Ultrafast electron diffraction (UED) also known as femtosecond electron diffraction (FED) has become an important tool for probing atomic-scale structure due to the orders-of-magnitude higher interaction cross sections and orders-of-magnitude lower damage per scattering event relative to X-ray diffraction [1]. In addition, electron probes provide increased sensitivity to hydrogen atoms, which are of fundamental importance for understanding biological systems [2]. These properties, in conjunction with a significantly lower fabrication cost than comparable X-ray sources, make electron sources highly attractive for ultrafast atomic-scale research.

Traditionally, UED sources are inexpensive, static voltage DC photoelectron guns capable of delivering high-coherence electron bunches with energies typically in the range of 50 – 100 keV. The space charge, however, causes a rapid spatial and temporal expansion of the electron beam in this range of energy, resulting in a decrease in the brightness and temporal resolution of the UED system [3]. An alternative to DC fields for the purpose of rapid acceleration of charged particles to high energies is the application of rf-fields in normal or superconducting cavities which are commonly used for the acceleration of electrons to energies ranging up to the MeV. The propagation speed of rf waves within these constrained dimensions leads to the fast alternating character of the fields, with frequencies typically ranging in the GHz range.

However, multi-MeV RF guns, typically driven by klystrons, require a level of cost and infrastructure not accessible to the majority of small, university-scale labs. Here, we propose an intermediate solution between the DC-gun and RF-gun technologies which is still low cost and requires low levels of infrastructure, but significantly increases electron energies beyond what is typically feasible with DC guns: a compact RF gun driven by a low-average-power solid-state amplifier which harnesses field-enhancement at a pin-shaped photocathode to increase field strengths, electron energies and hence bunch quality [4].

RF GUN DESIGN AND BEAM DYNAMICS

The RF cavity, designed particularly with UED applications in mind, is based on a half-cell pillbox with a frequency of 2.998 GHz, incorporating a pin shaped photocathode with a flat 0.8 mm diameter tip which results in strong fields even at modest driving power. A solenoid lens is placed directly in front of the anode for beam collimation. The electric field distribution in the cavity is computed with CST Microwave Studio Eigen-mode solver [5] and is shown in Fig. 1.

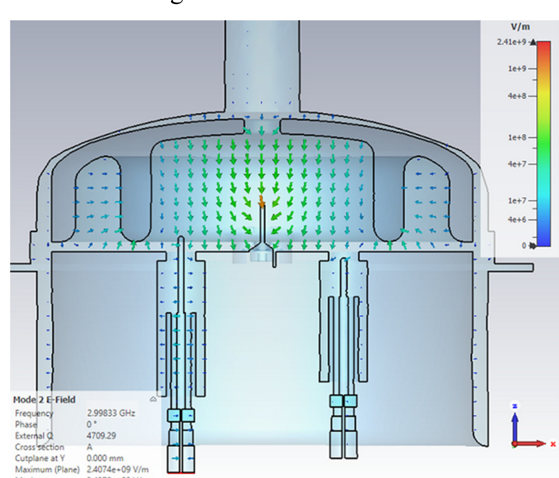

Figure 1: The distribution of the electric field in the eigenmode simulation with 1 Joule feeding power.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL115

Using only a 10 kW peak power solid-state amplifier, the electric field enhancement at the cathode (Fig. 2) can exceed 102 MV/m and accelerate electrons up to 180 keV.

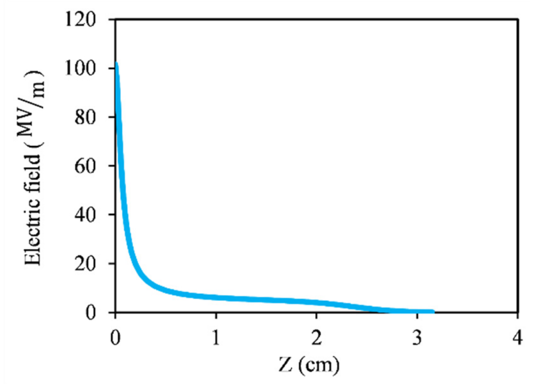

Figure 2: Field enhancement at the cathode vs propagation distance, Z.

In preparation of the electron beam for UED, it is necessary to focus the electron beam temporally on the specimen (8 cm away from the cathode), while simultaneously collimating the electrons in the transverse direction by the solenoid magnetic field. Knowledge of the final energy and energy spread of electrons is also beneficial.

It is important to note that how these conditions are achieved depends on the laser pulse duration ($T_{l,rms}$), laser spot size ($XY_{l,rms}$), and electron bunch charge. Additionally, for a specific $T_{l,rms}$ and $XY_{l,rms}$, it must be identified under which phase of the electric field (φ_E) and magnetic field of solenoid (B_s) these conditions will be established. Consequently, for a wide range of $T_{l,rms}$ and $XY_{l,rms}$, the minimum possible bunch length σ_z in fs for a bunch charge of 10 fC is simulated and illustrated in Fig. 3. The ASTRA particle tracking solver is used to investigate the beam dynamics in the gun [6]. Also, in Fig. 4, the energy of electrons on the specimen is shown in terms of $T_{l,rms}$ and $XY_{l,rms}$. Moreover, the simulation indicates that for the above $T_{l,rms}$ and $XY_{l,rms}$ values, the maximum relative energy spread of electrons on the specimen will be 0.92%.

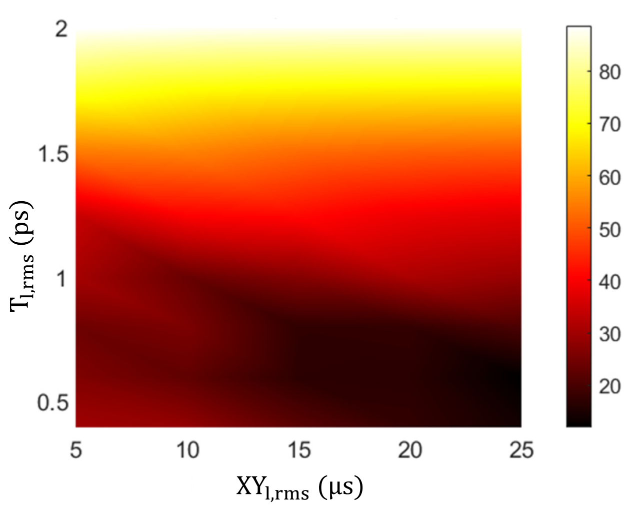

Figure 3: Minimum rms bunch length (σ_z) in fs in terms of $T_{l,rms}$ and $XY_{l,rms}$ for electron bunch charge of 10 fC.

Furthermore, the effect of the longitudinal and transverse distribution of electrons in an electron bunch on the temporal bunch length was investigated. In the simulations above, gaussian distributions of electrons were considered both longitudinally and transversely. Based on Fig. 5, which shows the bunch length in fs in terms of $T_{l,rms}$ when $XY_{l,rms} = 20\mu m$, the bunch length will decrease by approximately 40% if the electrons are distributed uniformly in both the transverse and longitudinal directions. According to the figure, the uniform distribution in the z direction has a greater impact on reducing σ_z, and the space charge effect is quite evident at lower $T_{l,rms}$.

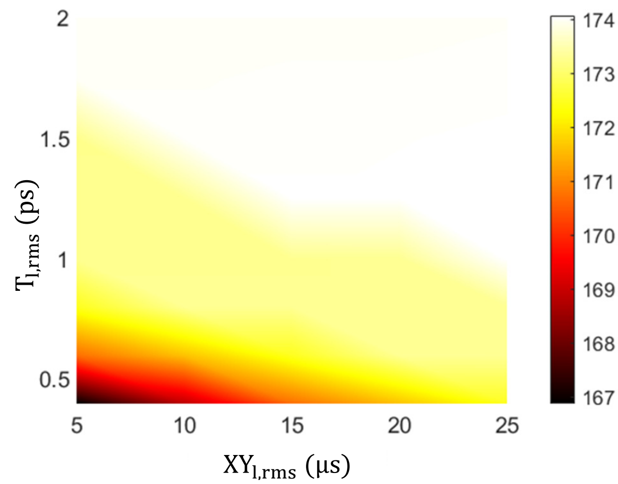

Figure 4: The energy of electrons on the specimen expressed in terms of $T_{l,rms}$ and $XY_{l,rms}$.

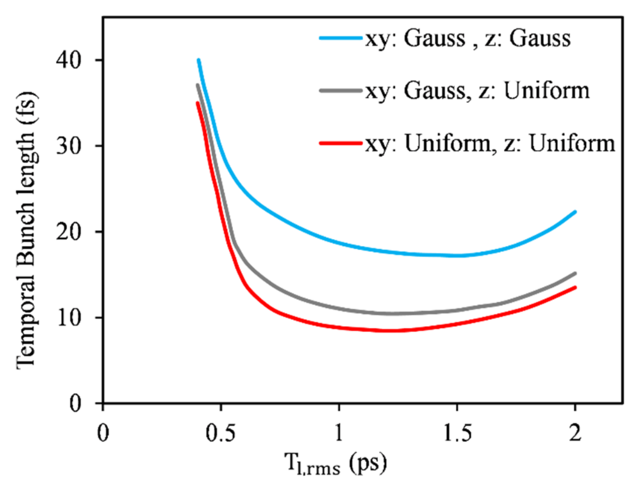

Figure 5: Bunch length vs laser pulse duration for different distributions of electrons in a bunch length.

PHOTOEMISSION SETUP

The laser beamline required for photoemission generation is powered by a Coherent Legend Elite Duo amplifier operating at 800 nm center wavelength and delivering 5 mJ pulses with a pulse duration of 35 fs. For photoemission from the copper pin cathode the 800 nm fundamental is tripled to 267 nm followed by spatial and temporal shaping.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL115

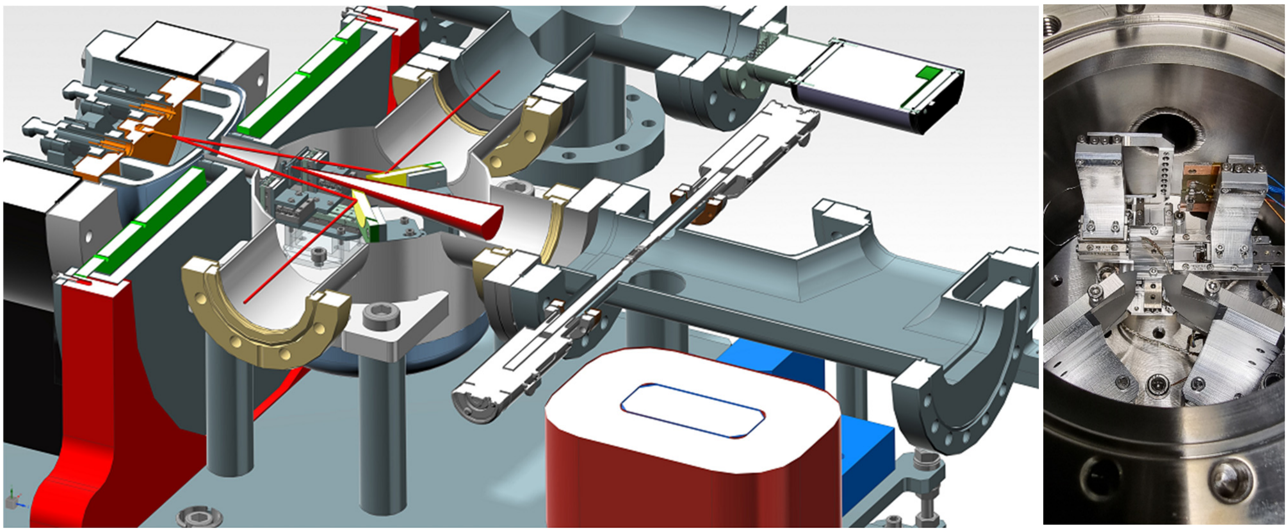

Figure 6: left: Sectional view of Compact RF gun including the cavity structure, solenoid, and energy spectrometer, right: interior of the test chamber, showing electron beam aperture, specimen and streak camera assemblies.

The former is accomplished by imaging an illuminated pinhole onto the photocathode, and we have demonstrated a one sigma truncated Gaussian beam profile of 30 µm diameter, approximating the ideal 'half circle' radial profile desired for linear space charge expansion dynamics. Temporal shaping to the required picosecond timescale for effective RF cavity compression is accomplished by a four-prism stretcher. Beam characterization features of the setup include a MCP imaging detector, Faraday cup for charge measurement and a streak camera featuring a gallium arsenide photoconductive semiconductor switch (GaAs PCSS) for sub-100 fs resolution electron bunch profiling and arrival time jitter measurement. Figure 6 shows a sectional view of the RF gun test setup used in UED.

The frequency response of the cavity at 2.998 GHz was determined using a vector network analyzer, and the loaded quality factor of 4860 was measured with a reflection (S_{11}) reaching below -50 dB. An initial challenge during operation was multipacting, which is further exacerbated by the solenoid magnetic field. Through a better understanding of this phenomenon using simulations and development of a careful conditioning protocol, elimination of multipacting was achieved. The dark charge was reduced to below 200 fC by conditioning the gun with a 10 kW amplifier power for 5.5 µs at a repetition rate of 50 Hz. Upon aligning the UV beam on the cathode and injecting 10 kW of RF into the cavity, it was observed that the electrons generated by photoemission were focused on the MCP about 60 cm away from the cathode. In Fig. 7, the dark charge in the center of the MCP (4 cm diameter) is shown, while photoelectrons can be easily relocated on the MCP by transversely shifting the solenoid.

CONCLUSION

A compact electron source was presented that can accelerate electrons up to 180 keV with only 10 kW power from a rack-mountable amplifier. Simulations predict that very bright electron bunches with an rms duration of 10 fs, a radius of 135 µm, and a spatial emission of 0.1 mm-mrad are achievable for a bunch charge of 10 fC. Following completion of the conditioning phase, photo-triggered electrons using a UV laser on the photocathode were observed. The next round of testing will target characterization of the energy, energy spread, and emittance of the beam. A successful beam characterization will then lead to development of a dedicated UED instrument based on this platform.

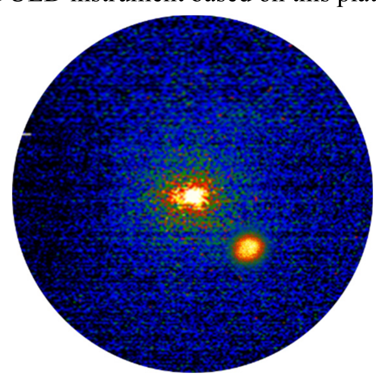

Figure 7: Dark charge and photoelectrons on MCP.

REFERENCES

[1] R. Miller, "Femtosecond crystallography with ultrabright electrons and X-rays: Capturing chemistry in action," *Science* 343, 1108 (2014). doi:10.1126/science.1248488

[2] King, Wayne E., *et al*. "Ultrafast electron microscopy in materials science, biology, and chemistry." *J. Appl. Phys*. 97.11 (2005): 8. doi:10.1063/1.1927699

[3] Tao, Zhensheng, *et al*. "Space charge effects in ultrafast electron diffraction and imaging." *J. Appl. Phys*. 111.4 (2012): 044316. doi:10.1063/1.3685747

[4] Bazrafshan, R., *et al*. "Field enhanced compact S-band gun employing a pin cathode." *J. Phys.*: Conference Series. Vol. 2420. No. 1. IOP Publishing, 2023. doi:10.1088/1742-6596/2420/1/012013

[5] CST, Computer Simulation Technology, URL:https://www.cst.com/

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