DESIGN, REALISATION, AND HIGH-POWER OPERATION OF THE FIRST TRAVELLING-WAVE PHOTO-EMISSION ELECTRON GUN

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Abstract

A novel travelling-wave (TW) RF photogun driven by ultra-short RF pulses has been successfully tested, stably reaching cathode fields of 170 MV/m for 100 ns pulses and 190 MV/m for a 10 ns pulse. This cathode surface electric field gradient far surpasses current S-band photoguns and represents a significant step toward increasing the brightness of future XFELs. Here we present an overview of the RF design, its unique tuning-free implementation, and high-power performance, highlighting how TW RF Photogun technology opens new opportunities for advanced electron sources.

INTRODUCTION

Radio-frequency (RF) photoemission electron guns (RF photoguns) are key sources of high-brightness electron beams. High cathode electric fields rapidly accelerate electrons to relativistic energies, reducing space-charge effects and improving beam brightness [1]. The highest brightness electron beams are produced using pulsed S-band room-temperature RF photoguns, which routinely operate at peak cathode fields of 100–120 MV/m, are widely used in X-ray free-electron lasers (XFELs) [2]. Achieving higher cathode fields requires new approaches. Ultra-short RF pulses are promising route to higher gradients because they reduce RF breakdown rates at a given surface electric field, enabling improved high gradient performance [3]. Here, we report the first travelling-wave (TW) RF photogun with a 100 ns filling time. The design supports operation with RF pulses an order of magnitude shorter than typical S-band RF photoguns [2], aiming to extend achievable cathode gradient beyond the current state-of-the-art for next-generation high-brightness electron sources.

REVIEW OF ELECTROMAGNETIC AND MECHANICAL DESIGN

The electromagnetic design of the TW RF photogun is described in detail in [4]; here we provide a brief overview. The design is an 11.5-cell C-band TW RF photogun with coaxially fed input and output couplers. The input coupler uses magnetic coupling slots to feed the cathode cell. This improved mechanical robustness near the region allowing an exchangeable cathode. A long coaxial input line enables integration of the main solenoid and bucking coil around the full structure. The highest electric field within the TW RF photogun occurs at the cathode to support photoemission and subsequent rapid acceleration, while the peak magnetic field is located on the coupling slots of the input coupler.

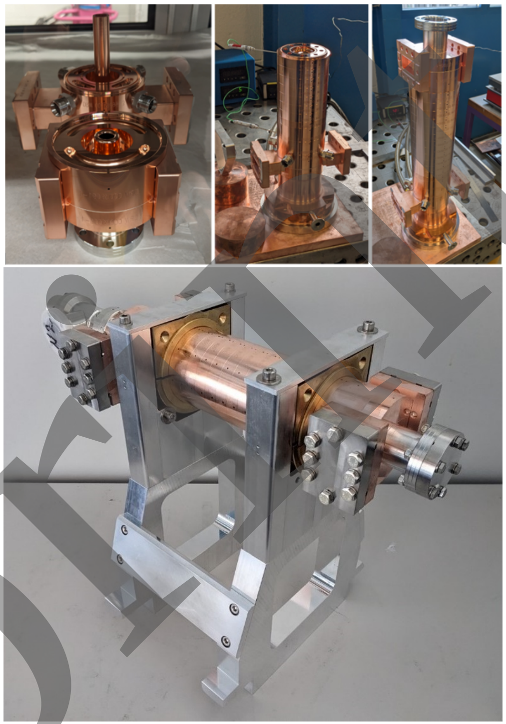

Figure 1: The brazed couplers (top-left); stacking of the cells and couplers (top-middle,top-right); and final realisation of the TW RF photogun (bottom).

REALISATION USING TUNING-FREE TECHNOLOGY

For realisation of the device, the components were machined from oxygen-free high-conductivity (OFHC) copper by VDL ETG Precision with pre-machining followed by high-precision single-point diamond turning and ultra-precision milling. All components were measured with a coordinate measuring machine, cleaned, and inspected before shipment to the Paul Scherrer Institute (PSI) where they underwent assembly and a multi-stage brazing to realise the final device (Figure 1). Final quality assurance of the device included a vacuum leak test, yielding a leak rate of 3.9×10^{-11} mbar·L/s.

LOW-POWER TESTING

Low-power testing of the TW RF photogun was performed in a clean-room environment to minimise contamination.

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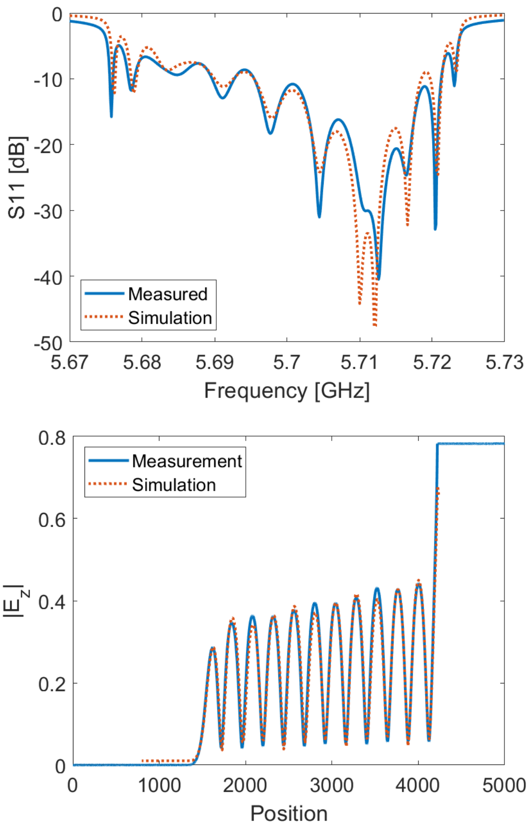

Figure 2: Low power measurements of the TW RF photogun compared to simulations including an S-parameter and bead-pull measurement.

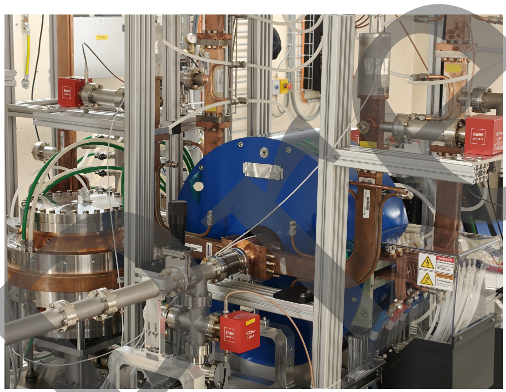

Figure 3: Installed TW RF photogun.

The measurement programme included S-parameter and bead-pull measurements to validate the electromagnetic design [5]. Only the cathode position required adjustment, avoiding the need for additional cell tuning. All low-power measurements were carried out using a dummy cathode with a central aperture, allowing the bead-pull wire to pass through the full structure.

After optimization of the cathode position, the measured reflection coefficient showed good agreement with simulations, achieving $S_{11} < -35$ dB (Figure 2). Bead-pull measurements further confirmed the field profile. These results validate the tuning-free fabrication approach and demonstrated good agreement between the fabricated structure and the electromagnetic design, after which the photogun was prepared for high-power testing.

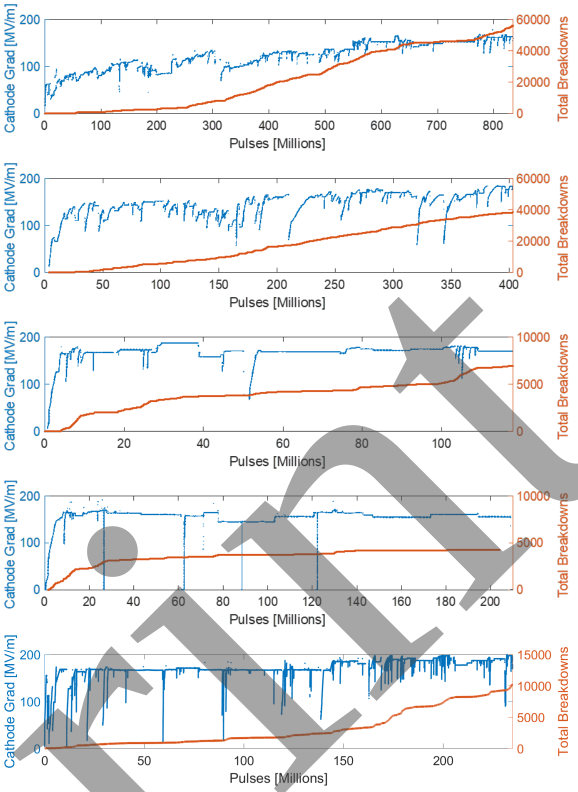

Figure 4: RF conditioning history of the TW RF photogun cathodes which includes the conditioning of cathode 1 (top), conditioning of cathode 2 (second from top), stable operation with cathode 2 (middle), operation with flattened BOC pulse (second from bottom), and operation with high field solenoid and final high gradient tests (bottom).

COMMISSIONING OF THE HIGH-POWER TEST STAND

A dedicated high-power test stand was constructed at PSI for commissioning and testing C-band RF devices [6]. The RF source comprised a 50 MW C-band Canon klystron driven by a Scandinova solid-state modulator delivering pulses up to 3 µs at repetition rates up to 100 Hz. A barrel open cavity (BOC) RF pulse compressor was used to maximise peak RF power, with tuning provided by a temperature control unit. The TW photogun was installed in an adjacent bunker for high-power operation (Figure 3). Directional couplers and interlock systems enabled real-time RF monitoring and klystron protection, providing a flexible platform for conditioning and high gradient studies.

HIGH-POWER OPERATION

High-power conditioning of the TW RF photogun aimed to:

1. investigate the maximum achievable cathode gradient with RF pulse length exceeding the filling time,

2. determine the repeatability of achieve high gradients with exchangeable cathodes,
3. investigate the impact of the high-field solenoid around the device, and
4. trial short-pulse operation below the filling time.

All phases of the conditioning are demonstrated in Figure 4 which included the equivalent of 200 days of operation and below summarises the operational history during this time.

Cathode 1

Conditioning of the first cathode began in February 2025 using 50 ns RF pulses with the BOC detuned by 2 MHz to allow operation with a short rectangular pulse directly from the klystron, bypassing the pulse compressor. The power initially increased gradually and in a logarithmic-like fashion, reaching 125 MV/m after ~150 million pulses while maintaining breakdown rates below 10^{-4} breakdowns per pulse (bpp). The RF pulse length was then increased to 100 ns, corresponding to 10 % more than the filling time of the TW RF photogun, and conditioning resumed after initially reducing the gradient by ~ 20 %. A gradient of 140 MV/m was achieved after ~300 million RF pulses.

At this point the pulse compression was enabled, a 100 ns compressed RF pulse produced gradients up to 165 MV/m after ~650 million pulses with some lengths of stable operation in between. Stable operation at 160 MV/m yielded a breakdown rate of ~ 10^{-5} bpp. After this, the pulse length was shortened to 30 and 50 ns aim to investigate whether higher gradients could be achieved. This ultimately reached a gradient of 185 MV/m but with a breakdown rate in excess of ~ 10^{-4} bpp. However, following a vacuum-system malfunction, we decided to exchange the first cathode and spring assembly.

Cathode 2

Conditioning of the second photocathode began on 30 October 2025 (Figure 4). Using 50 ns pulses generated with the BOC, gradients above 150 MV/m were reached within ~50 million RF pulses, significantly faster than for the first cathode, demonstrating that some conditioning was retained during the cathode exchange despite the cathode itself having the largest surface electric field in the device. The compressed pulse length was then increased to 100 ns. A gradient of 155 MV/m was achieved after 100 million pulses, though operation was temporarily affected by false interlocks caused by faulty hardware (100-150 million pulses). After a hardware replacement, normal conditioning resumed. At gradients above 150 MV/m, conditioning slowed and partial reconditioning was required following any scheduled operational shutdowns. During these scheduled shutdowns, the device and waveguide network remained under vacuum but RF power ceased for up to 2 weeks at a time. Ultimately, 180 MV/m was achieved with a 100 ns compressed decaying RF pulse but with a high breakdown rate up to ~ 10^{-4} bpp. With this gradient achieved, the device was left to condition further to achieve more stable operation and, subsequently, characterised over the following several months including with the gun solenoid. The characterisation studies found the following about the high power operation of the TW RF photogun:

- The structure could operate with a cathode gradient of 170 MV/m with the full pulse length and a breakdown rate ~ 10^{-5} bpp. When operating at 165 MV/m this value dropped to ~ 2×10^{-6} bpp.
- The addition of the gun magnet with the main solenoid and bucking coil set up to 0.55 T peak field, the TW RF photogun at first required conditioning for a few hours at 100 Hz with an increase in outgassing events at low power (few MW) but once this issue passed, the system re-established its high gradient operation without issue and the breakdown rate only marginally increased.
- The mean accelerating gradient over the structure for a cathode gradient of 165 MV/m was 75 MV/m. This makes the cell geometry and output coupler interesting for TW structure technology.
- Shifting to short pulses of ~ 10 ns on the second cathode, where the pulse length was measured at the 90 % of the peak field, allowed the instantaneous peak electric field to hit 200 MV/m with a breakdown rate of 2×10^{-4} bpp. Dropping to 190 MV/m allowed operation at 3×10^{-5} bpp.

CONCLUSION

The first TW RF photogun with a 100 ns filling time has been successfully designed, fabricated, and operated at high gradient. Low-power measurements showed excellent agreement with simulations, validating the tuning-free fabrication approach and requiring only cathode-position adjustment. High-power testing demonstrated stable operation at 170 MV/m with the full 100 ns pulse length and a breakdown rate ~ 10^{-5} bpp. Operation with the integrated solenoid system was also demonstrated successfully. These results establish short-filling-time TW RF photoguns as a promising route for achieving higher cathode gradients and advancing next-generation high-brightness electron sources.

REFERENCES

[1] J. Rosenzweig *et al.*, “Next generation high brightness electron beams from ultrahigh field cryogenic RF photocathode sources”, *Phys. Rev. Accel. Beams*, vol. 22, no. 2, p. 023403, 2019. doi:10.1103/PhysRevAccelBeams.22.023403

[2] T. Lucas, “A discussion of key concepts for the next generation of high brightness injectors”, in *Proc. LINAC’22*, Liverpool, UK, Aug.–Sep. 2022, pp. 324–329. doi:10.18429/JACoW-LINAC2022-TU1PA01

[3] 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, p. 102001, Oct. 2009. doi:10.1103/PhysRevSTAB.12.102001

[4] T. G. Lucas *et al.*, “Toward a brightness upgrade to the SwissFEL: a high-gradient traveling-wave RF photogun”, *Phys. Rev. Accel. Beams*, vol. 26, no. 10, p. 103401, 2023. doi:10.1103/PhysRevAccelBeams.26.103401

[5] C. W. Steele, “A nonresonant perturbation theory”, *IEEE Trans. Microw. Theory Tech.*, vol. 14, no. 2, pp. 70–74, 1966. doi:10.1109/TMTT.1966.1126168

[6] T. G. Lucas *et al.*, “Developments and first results from an RF test stand for high brightness C-band photoguns at PSI”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 2133–2136. doi:10.18429/JACoW-IPAC2024-WEPC69