

THE FIRST BEAM PRODUCED BY A CONDUCTION COOLED SRF PHOTOGUN*

C. Jing[†], R. Kostin[‡], Y. Zhao, E. Knight, Euclid Beamlabs LLC, Bolingbrook, USA
S. Posen, G. Ereemeev, T. Khabiboulline, D. Bice, A. Netepenko, Fermilab, Batavia, USA
G. Chen, W. Liu, E. Wisniewski, S. Doran, A. Ody, J. Power, M. Kelly
Argonne National Laboratory, Lemont, USA

Abstract

We report on the first beam produced by the world's first conduction cooled SRF photogun. Over the past five years, Euclid, working in collaboration with Fermilab and Argonne National Laboratory, has been developing a continuous-wave (CW), 1.5-cell, MeV-scale, conduction-cooled SRF photogun operating at 1.3 GHz. The primary objective of this effort is to demonstrate ultra-stable electron beams for UEM/UED applications, enabled by the exceptional shot-to-shot stability achievable with SRF technology compared to room-temperature RF photoguns. Although SRF systems were historically too costly for industrial deployment, two recent advancements: Nb₃Sn coatings and conduction cooling, have dramatically reduced system complexity and operating costs. This SRF photogun can deliver true CW operation while dissipating only ~2 W of RF power, eliminating the need for a high-power RF system and significantly reducing facility footprint. This SRF photogun is also featured with a raised Nb₃Sn backwall serving as the photocathode, removing the need for an external cathode insert. In this paper, we present the first beam results from this system along with its cooldown performance, Q-slope behavior, synchronization characteristics, and initial beam parameters.

INTRODUCTION

Ultrafast electron diffraction and microscopy place stringent demands on electron source stability, beam throughput, bunch length, and energy spread. Superconducting RF (SRF) photoinjectors operating in continuous-wave (CW) mode offer orders-of-magnitude improvements in bunch repetition rate (laser-limited), as well as superior amplitude and phase stability compared to normal-conducting RF photoguns. However, conventional SRF implementations rely on liquid-helium cryogenic systems, which constrain their deployment to large-scale accelerator facilities only.

Over the past seven years, Euclid has led the development of the world's first conduction-cooled Nb₃Sn SRF photogun, targeting applications in MeV ultrafast electron microscopy. Owing to the significant technical challenges associated with this novel concept, multiple cavity tests were conducted at different stages of development to identify and mitigate unforeseen issues. A record-high gradient of 22 MV/m (equivalent to 44 MV/m at the cathode) was achieved (single opening cavity) during the second vertical test of the Nb cavity (prior to Sn coating), along with a peak

quality factor of $Q_0 = 1.2 \times 10^{10}$ at 2 K [1]. In contrast, the second vertical test of the Nb₃Sn-coated cavity reached only 7 MV/m. The low-field quality factor was also reduced, with $Q_0 = 7 \times 10^9$ and noticeable degradation beyond 6 MV/m. Due to resource constraints, a third Nb₃Sn coating iteration was deferred, and the effort proceeded directly to conduction-cooled cryomodule testing. These results were reported in Proc. IPAC2024 [2].

Although the achieved gradient of the Nb₃Sn cavity fell short of the design target, primarily due to the later identified Sn contamination in the coating furnace, the prior work established the feasibility of operating a photogun-class SRF cavity using a commercial cryocooler without liquid helium. Figure 1 presents the integrated cryomodule and its control system.

In this paper, we report subsequent progress, focusing on continued system development, beamline preparation, and the first beam generation experiment.

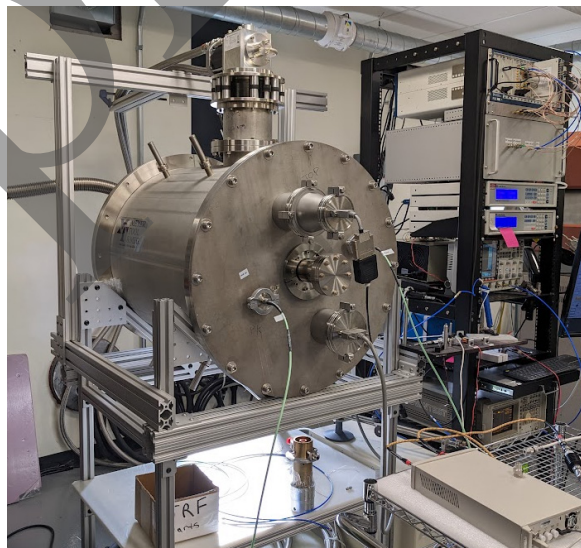


Figure 1: The cavity loaded conduction cooled cryomodule along with LLRF control rack and electronics at Euclid.

BEAMLINE PREPARATION

The beam generation experiment for the conduction-cooled Nb₃Sn SRF photogun was ultimately carried out at the Argonne Wakefield Accelerator (AWA) facility, selected for its proximity to the development site and availability of a 300 fs high-power UV laser. A dedicated beamline was designed (see Fig. 2) and installed in the AWA bunker, with supporting infrastructure prepared in advance. Beam dynamics simulations indicated reduced

* Work supported by DoE SBIR Grant # DE-SC0018621.

[†] c.jing@euclidtechlabs.com

[‡] Now with Lam Research Co.

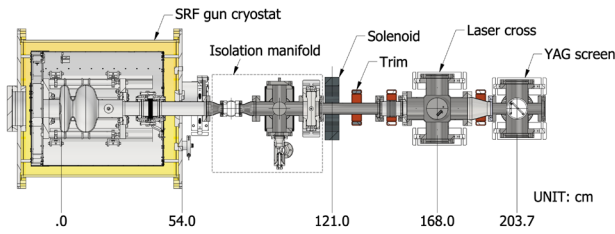


Figure 2: The beamline layout of the conduction cooled SRF photogun at AWA.

beam energy compared to the design expectation due to Nb₃Sn coating degradation, limiting the achievable accelerating gradient to approximately 45% of the nominal value.

The SRF photogun cryomodule and control systems were delivered to AWA in April 2024. Critical assembly steps, including integration of the valve system and beam pipe, were performed in a cleanroom environment to minimize particulate contamination prior to installation. Following installation, an initial standalone cooldown test of the cryostat (without the cavity) confirmed proper operation of the cryocooler and thermal system after transport.

During subsequent photogun integration, a mechanical imbalance was identified due to added mass from the valve and beam pipe assembly, resulting in a shifted center of gravity and insufficient load capacity of the original support structure. A redesigned support system using aluminum rails mounted to the cryostat wall and thermally anchored to the radiation shield was implemented (Fig. 3). Follow-up cooldown tests verified that the new structure maintained acceptable thermal performance while ensuring mechanical stability.

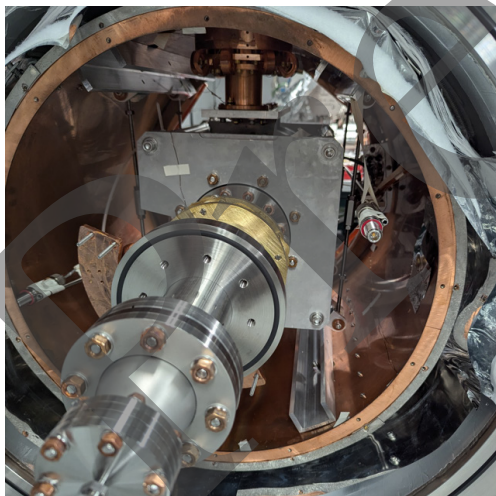


Figure 3: Installation process with improvement measures to effectively reduce residual magnetic fields and thermal leakage.

Thermal optimization and vacuum integrity were critical challenges during commissioning. Initial cooldown of the fully integrated system revealed excessive thermal gradients (~2.2 K) between the cryocooler cold head and the cavity, traced to thermal shorts associated with titanium fasteners. Replacing these with brass hardware reduced the gradient to below 0.8 K. Additional instabilities were

linked to inadequate vacuum conditions in the sealed cavity, prompting re-pumping and further diagnostics. Persistent limitations in cavity quality factor (~10⁹ range) led to the identification of significant residual magnetic fields in multiple components. Mitigation measures, including degaussing RF cables, replacing magnetic fasteners, removing magnetic connectors, improving thermal contacting surfaces, and relocating DC blocks, substantially reduced magnetic contamination (4~8mG being measured at cavity region) and improved system performance.

In the final controlled cooldowns, the system achieved stable cryogenic operation with a cold head temperature of 3.3 K and cavity temperature below 3.7 K, with minimal thermal gradients. RF testing yielded a quality factor of ~3×10⁹ at low field and supported operation at 4 MV/m with 10 W RF input (refer to Fig.4), corresponding to an expected peak beam energy of approximately 400 keV.

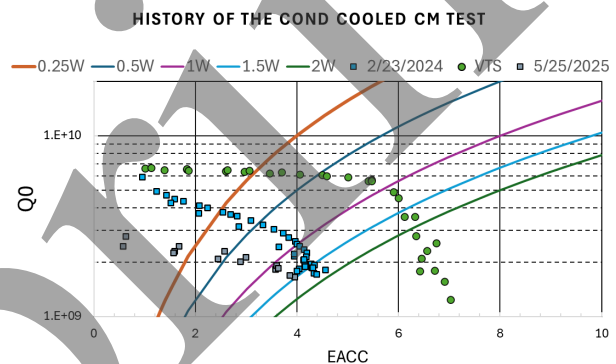


Figure 4: Measured Q slopes summarizing three RF tests of Nb₃Sn SRF photogun: VTS and two conduction cooled tests (2/23/2024 and 5/25/2025).

Final beamline assembly required controlled exposure of the cavity to atmosphere. A localized clean environment was established in the AWA bunker using a custom Class 10k clean hood (Fig. 5), while critical subassemblies such as the gate valve system were prepared in a Class 10 cleanroom. The gate valve assembly, incorporating a pumped intermediate chamber, enabled staged vacuum commissioning: the SRF cavity was brought to ultra-high vacuum while maintaining isolation from downstream beamline construction. This approach ensured cleanliness and vacuum integrity throughout integration.

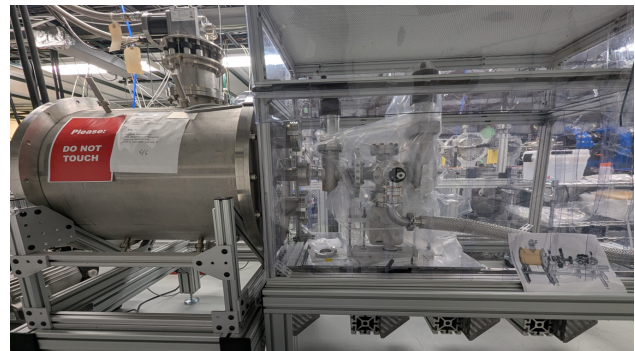


Figure 5: The gate valve assembly was connected to the SRF cryomodule in the customized clean hood.

Overall, beamline preparation established a stable and contamination-controlled platform for beam generation, while addressing key engineering challenges in mechanical support, thermal management, vacuum performance, and magnetic shielding, that are essential for conduction-cooled SRF photogun operation.

BEAM GENERATION

The first beam experiment was conducted in December 2025. A 262 nm UV laser was aligned to the center of the cathode region. Notably, this SRF photogun employs a raised Nb₃Sn back wall as the photocathode, eliminating the need for an external cathode insert [3]. The quantum efficiency (QE) of Nb₃Sn was previously measured at room temperature to be on the order of 10⁻⁷ at 255 nm, approximately one order of magnitude lower than that of pure Nb under the same conditions. During the beam test, the laser pulse energy was about 3.7 μJ, with a spot size of approximately 10 mm in diameter on the cathode. 3.5 W of CW RF power was delivered to the cavity, resulting in a temperature rise to 4.8 K. After a brief tuning period, the first photoemitted beam was successfully observed on the downstream YAG screen (Fig. 6).

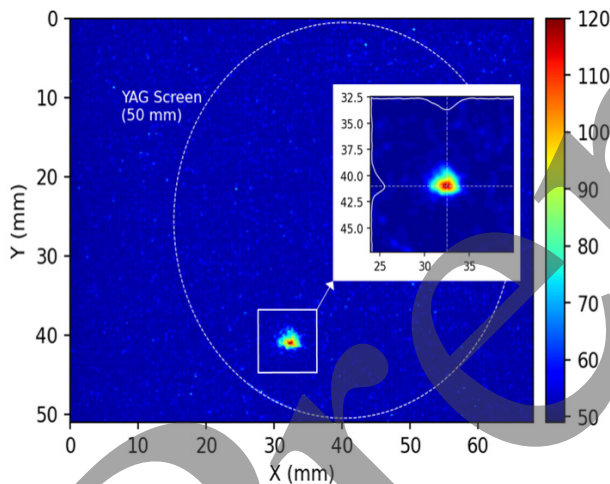


Figure 6: The first photoemission beam captured at the downstream YAG screen.

Phase scans were attempted; however, synchronization issues in the control system prevented stable locking between the drive laser and the RF signal. As a result, a clean phase scan dataset could not be obtained. In addition, because the beam energy was significantly lower than the design value, no dedicated energy spectrometer was available in the relevant range. Instead, the beam energy was inferred using a calibrated trim magnet (Fig. 7), with its field profile and strength carefully characterized in advance. The measured beam energy was approximately 190 keV, corresponding to an effective accelerating gradient of ~7 MV/m at the cathode surface.

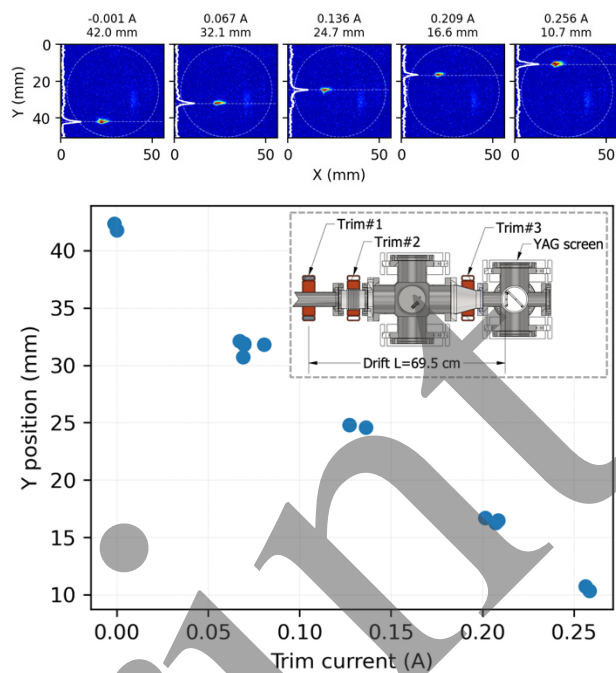


Figure 7: Energy measurement using a trim magnet. Top: selected beam images at different trim current settings. Bottom: beam centroid position as a function of trim current. Inset: experimental layout

FUTURE WORK

Future work will focus on recovering cavity performance and advancing toward fully characterized beam operation. Priority will be given to improving Nb₃Sn coating quality and restore the designed accelerating gradient. In parallel, the laser–RF synchronization system will be upgraded to enable stable phase locking and systematic beam dynamics measurements. These efforts will support subsequent high repetition rate beam studies and move the system closer to practical application in MeV ultrafast electron microscopy.

REFERENCES

- [1] R. Kostin, *et al.*, “Nb₃Sn SRF photogun high power test at cryogenic temperatures”, in *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-4, Aug. 2023. doi: 10.1109/TASC.2023.3253066.
- [2] R. Kostin *et al.*, “First conduction cooled photoinjector status”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2747-2750. doi:10.18429/JACoW-IPAC2024-WEPS23
- [3] A. Liu, P. V. Avrakhov, C. Jing, and R. A. Kostin, “Optimization of an SRF gun design for UEM applications”, in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 305-308. doi:10.18429/JACoW-NAPAC2019-TUYBA4