

DEVELOPMENT OF A PARTICLE-FREE CATHODE LOADLOCK SYSTEM FOR SRF-GUN

R. Xiang[†], A. Arnold, S. Gatzmaga, A. Hoffmann, P. Murcek, R. Steinbrück, J. Teichert, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

C. Adolphsen, J. Maniscalco, J. Smedley, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

W. Hartung, T. Konomi, A. Taylor, B. Tousignant, T. Xu, Z. Yin, Facility for Rare Isotope Beams, East Lansing, MI, USA

J. Lewellen, Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract

A prototype of SRF Gun has been built and successfully tested at MSU for LCLS-II HE project. This gun uses an HZDR-type cathode and required the development and implementation of a special cathode transfer and insertion system to ensure reliable operation. The main objectives were to prevent particle contamination, achieve a transverse alignment accuracy of less than 100 μm over a transfer distance of 1.3 m under ultra-high vacuum conditions ($<10^{-9}$ Torr), and ensure the safe and repeatable insertion of the cathode into the cold cavity of the SRF gun. The cathode suitcase is used to transport a single cathode but can be upgraded in the future to accommodate high quantum efficiency (QE) semiconductor cathodes. To enable robust cathode exchanges, HZDR developed and built a special manipulation mechanism and an automated alignment system. The alignment concept was implemented using a translation rod equipped with contact electrodes and driven by precision stepper motors. Commissioning and final testing were successfully carried out at MSU to validate the transfer process. No change in RF performance was observed after the cathode exchange. The results confirmed that the system meets the design specifications and enables particle-free cathode exchange for the SRF gun at varying temperatures.

INTRODUCTION

Superconducting radio-frequency (SRF) guns are attractive electron sources for next-generation accelerator facilities because they can provide high-brightness electron beams with high repetition rate and low emittance. Compared with normal-conducting RF guns, SRF guns allow continuous-wave (CW) operation with significantly reduced RF power dissipation, making them highly suitable for applications such as energy recovery linacs, free-electron lasers, ultrafast electron diffraction, and compact accelerator-based light sources.

The Quarter-Wave Resonator (QWR) SRF gun developed within the collaboration between SLAC, MSU, HZDR, and ANL is designed as a low-emittance photoinjector capable of stable CW operation at

accelerating gradients of 30 MV/m [1]. The gun uses the HZDR-type photocathode concept, which enables cathode replacement without warming up the gun cavity.

One of the major technical challenges in SRF photoinjectors is the implementation of a reliable cathode load-lock system. Particle contamination generated during cathode transport or insertion can significantly degrade SRF cavity performance by increasing field emission or causing cavity quench. At the same time, semiconductor photocathodes require ultra high vacuum to preserve their quantum efficiency and operational lifetime. To address these challenges, a dedicated cathode load-lock system has been developed. The primary goals of the system are to avoid introducing particles into the SRF cavity, ensure accurate cathode positioning during insertion, maintain ultra-high-vacuum conditions during cathode handling, and enable reliable long-term operation.

This paper presents the design, development, and final test result of the particle-free cathode load-lock system developed for the QWR SRF gun project.

SYSTEM DESIGN AND REQUIREMENTS

The load-lock system was developed to support secure cathode exchange while preserving SRF cavity cleanliness. Several design requirements were identified at the beginning of the project. The cathode insertion system had to minimize mechanical contact and keep particle generation less than 10 counts/ft³ @ 0.3 μm , and maintain vacuum levels below 1×10^{-9} Torr during operation. In addition, the cathode position inside the stalk had to be reproducible with transverse alignment accuracy better than 100 μm .

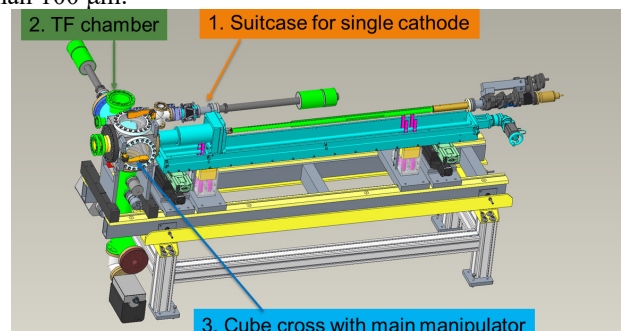


Figure 1: The designed cathode load-lock system with three main vacuum chamber groups.

[†]r.xiang@hzdr.de

The complete system consists of a cathode manipulation mechanism, a motorized main manipulator with long bellow, a dedicated alignment system with controller, vacuum system, and a cathode transport suitcase with load-lock unit (see Fig. 1). A bayonet-style cathode holder was adopted to ensure secure mechanical fixation while allowing efficient insertion and removal procedures. Special attention was given to minimizing particle generation during all stages of cathode handling. Only ultra-high-vacuum and bakable materials were used. Mechanical surfaces and contact regions were carefully optimized to reduce friction and abrasion. In addition, the cathode insertion trajectory was designed to avoid unnecessary contact between moving components [2].

MANIPULATION MECHANISM AND PARTICLE CONTROL

The cathode manipulation mechanism plays a central role in achieving reliable particle-free cathode exchange. The cathode is handled through a sequence of short linear and rotational movements. During insertion, the transfer rod with cathode first approaches the stalk, followed by rotation and locking operations that fix the cathode into the stalk (see Fig. 2). During manipulation, the gripper engages only the back of the cathode, which is located outside the cavity region.

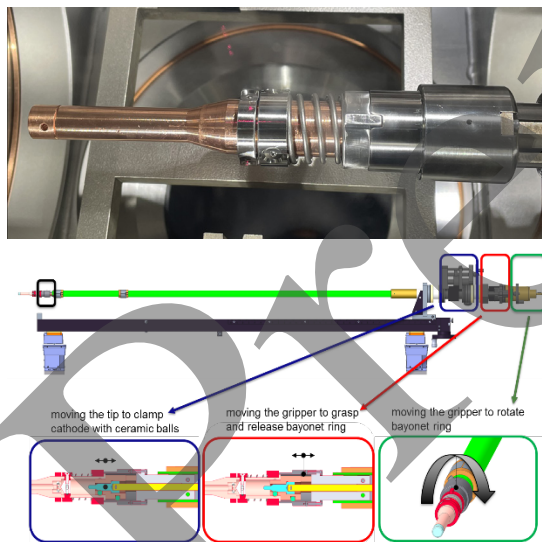


Figure 2: (top) A photo of the cathode grasped with rod from the backside. The bayonet structure with relaxed spring can be seen on the cathode. (bottom) Three motion to manipulate the bayonet of cathode.

Particle generation during cathode manipulation was systematically investigated using a particle-counter (Lighthouse Solair 3100) in the cleanroom. Repeated insertion and removal procedures were tested to identify the new particle generation. The parts were blown with 5 bar ionized filtered N_2 flow (Richmond AFC2), and the counter ran for 1 min, in volumn ft³. The results showed

that the total particles after one cathode exchange process was down to 5 counts @ 0.3 μm . The particle-counting studies demonstrated that smooth operation and contact geometry are essential for minimizing contamination risks.

AUTOMATIC CATHODE ALIGNMENT

Accurate cathode positioning inside the stalk is essential for ensuring SRF cavity as well as minimizing particle generation. Misalignment can lead to possible mechanical crash and friction during insertion. The gap between the cathode and cavity is 1 mm, thus the cathode must be inserted into the stalk with transverse accuracy on the order of 100 μm . To address this request, an automatic cathode alignment system was developed. The alignment concept uses two groups of precise contact electrodes integrated into both the stalk and the translator rod. During insertion, electrical signals from the contact electrodes are detected to determine the axis position (see Fig. 3).

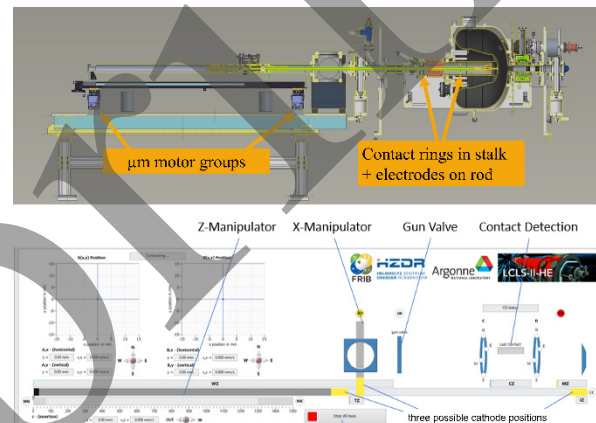


Figure 3: (a) Fine alignment concept with reference contact rings in cathode stalk and PC controlled μm motor stages. (b) Labview software for automatic alignment procedure.

A dedicated LabVIEW-based control program was developed to guide the cathode exchange procedure and execute the automatic alignment algorithm. The software applies eight touching motions, calculates the real axis of stalk, and adjusts the manipulator position to the stalk axis. The contact-based alignment method provides several advantages. It enables reliable position detection with minimum detectors under vacuum conditions, allows automated operation without direct visual access, and supports highly reproducible insertion procedures under different cryomodule temperatures. Repeated alignment measurements with dummy stalk demonstrated positioning errors below 100 μm , satisfying the operational requirements of the SRF gun.

INTEGRATION AND OPERATION WITH THE SRF GUN

The transfer system was tested using a dummy stalk assembly after delivered to MSU. These preliminary experiments allowed verification of the manipulation mechanism, vacuum performance, and alignment procedure before integration with the actual SRF gun

cryomodule. Last year the load-lock system was connected to the SRF gun cryomodule for integrated system testing (Fig. 4).

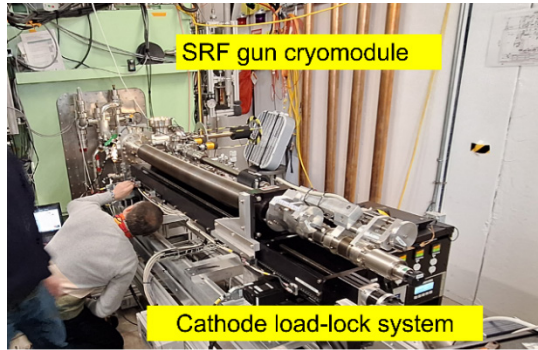


Figure 4: Cathode load-lock system connected to SRF gun cryomodule in MSU bunker.

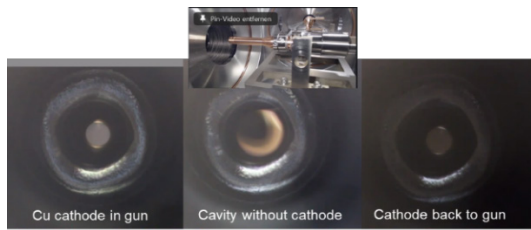


Figure 5: The copper cathode was removed from gun stalk to the cathode transfer system, and inserted into gun again.

One of the most important milestones was the successful cathode exchange performed when the cryostat was cooled down to 4 K. The cathode was removed and inserted while the SRF cavity remained cold (Fig. 5). The RF measurements demonstrated that cavity performance remained essentially unchanged after cathode exchange, indicating that no significant particle contamination or cavity degradation occurred during the procedure. Cavity resonant frequency shift and the stalk temperature change could be applied to confirm the cathode fixing in stalk during the cathode exchange. Vacuum measurements confirmed that the transfer system could reliably maintain pressures below 1×10^{-9} Torr during operation (Fig. 6), satisfying the stringent vacuum requirements for SRF applications.

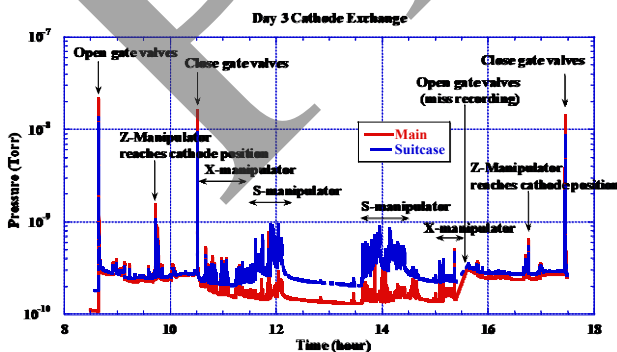


Figure 6: The vacuum in main chamber was 1.21×10^{-10} Torr and in suitcase chamber 1.93×10^{-10} Torr before experiments. Both remained below 1×10^{-9} Torr during the cathode exchange.

CONCLUSION AND OUTLOOK

A dedicated particle-free cathode load-lock system has been successfully developed for SRF gun applications. The system enables reliable cathode exchange while maintaining ultra-high-vacuum conditions and minimizing particle contamination risks. The strengthened main manipulator supports stable and reproducible cathode insertion procedures, while the automatic alignment system achieves positioning accuracy better than 100 μm . Systematic particle studies demonstrated that cathode manipulation mechanism can minimize particle generation during cathode exchange. Initial integration tests with the SRF gun cryomodule confirmed stable vacuum performance and successful cathode exchange at cryogenic temperature without measurable RF degradation of the cavity. These results represent an important step toward reliable operation of SRF photoinjector with advanced photocathodes.

The developed load-lock system provides a strong technological basis for future injector tests employing high-performance semiconductor photocathodes and demanding SRF cavity gradient [3]. Future work will focus on integrating semiconductor photocathodes into the gun through the exchange system. Compared with metallic cathodes, semiconductor cathodes are significantly more sensitive to contamination and vacuum conditions.

The experience gained from this project provides valuable input for future SRF photoinjectors requiring reliable cathode exchange under ultra-clean conditions. Further optimization of the manipulation mechanism might also be investigated to reduce mechanical complexity and to improve stability. For example, to select a main manipulator with dual guide rails. Advanced diagnostic tools, including high-resolution pressure transducer to measure the pressure applied from rod to cathode stalk, laser distance sensors to detect the real position of cathode, and automated vacuum interlock systems, may also be incorporated into future system versions. These developments will contribute to improved operational safety and reproducibility.

REFERENCES

- [1] T. Xu *et al.*, "Low-emittance SRF photo-injector prototype cryomodule for the LCLS-II high-energy upgrade: design and fabrication", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1396-1399. doi:10.18429/JACoW-IPAC2023-TUPA028
- [2] R. Xiang *et al.*, "Design of a Cathode Insertion and Transfer System for LCLS-II-HE SRF Gun", in *Proc. SRF'23*, Grand Rapids, MI, USA, Jun. 2023, pp. 267-270. doi:10.18429/JACoW-SRF2023-MOPMB067
- [3] J. Smedley *et al.*, "Status of the CW SRF gun development at FRIB for LCLS-II-HE", in *Proc. SRF'25*, Tokyo, Sep 2025, pp. 603-607. doi:10.18429/JACoW-SRF2025-THB04