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STATUS OF THE SLAC/MSU SRF GUN DEVELOPMENT PROJECT*

J. W. Lewellen†, C. Adolphsen, R. Coy, L. Ge, F. Ji, M. Murphy, L. Xiao
SLAC National Accelerator Laboratory, Menlo Park, CA, USA
M. Kelly, T. Peterson, Argonne National Laboratory, Lemont, IL, USA
Y. Choi, C. Compton, X. Du, D. Greene, W. Hartung, S-H. Kim, T. Konomi, S. J. Miller,
D. Morris, M. S. Patil, J. T. Popielarski, L. Popielarski, K. Saito, T. Xu
Facility for Rare Isotope Beams, East Lansing, MI, USA
A. Arnold, S. Gatzmaga, P. Murcek, R. Xiang
Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

Abstract

The LCLS-II-HE Project at SLAC seeks to increase the photon energy reach of the LCLS-II FEL to at least 20 keV. In addition to upgrading the undulator system, and increasing the electron beam energy to 8 GeV, the project will also construct a low-emittance injector (LEI) in a new tunnel. To achieve the LEI emittance goals, a low-MTE photocathode will be required, as will on-cathode electric fields up to 50% higher than those achievable in the current LCLS-II photoinjector.

The beam source for the LEI will be based around a superconducting quarter-wave cavity resonant at 185.7 MHz. A prototype gun is currently being designed and fabricated at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). This paper presents performance goals for the new gun design, an overview of the prototype development effort, status, and future plans including fabrication of a "production" gun for the LEI.

AN SRF GUN FOR LCLS-II-HE

The beam source for the LCLS-II-HE Project's Low-Emittance Injector will be a continuous-wave (CW) superconducting (SRF) quarterwave (QW) radiofrequency (RF) electron gun (hereafter referred to as the QW-SRF gun), resonant at 185.7 MHz.

Several alternatives to a superconducting QW RF gun were considered for the LEI, including normal-conducting RF guns evolved from the LCLS-II gun design [1]. However, compared to normal-conducting designs, the combination of an intrinsically outstanding vacuum environment (for cathode lifetime), and the potential for a larger ultimate performance envelope, led to the decision to pursue development of the QW-SRF gun.

DEVELOPMENT PROGRAM OVERVIEW

Overall Schedule

In late 2020, the HE Project issued a call for proposals for development of a quarterwave SRF gun. In April '21, the proposal from FRIB was selected, and the project formally commenced in October '21, with Argonne National Laboratory (ANL) and Helmholtz-Zentrum Dresden-Rossendorf (HZDR) joining as subcontractors to MSU. The program is expected to run through early 2025, concluding with a RF test of a prototype SRF gun in a standalone cryomodule at FRIB.

Performance Requirements

The performance requirements for the QW-SRF gun itself are given in a Technical Specification and Statement of Work [2], and, as part of the Low-Emittance Injector, in the Conceptual Design Report for the LEI [1]. Some key performance requirements for the QW-SRF gun include:

- Resonant at 185.7 MHz (7th subharmonic of 1.3 GHz);
- On-cathode electric field gradients of > 20 MV/m (target: > 30 MV/m);
- Beam energy > 1.6 MeV (kinetic);
- Capable of supporting a high-QE "green" photocathode with a mean transverse energy < 184 meV;
- Cathode lifetime > 1 week (target: > 1 month);
- Field emission / dark current @ 30 MV/m < 10 nA.

The target on-cathode gradient is approximately 50% higher than that in the normal-conducting LCLS-II gun. Experimental SRF guns are pushing to much higher fields on cathode [3], but achieving routine operation at 30 MV/m in a user-facility setting is expected to be challenging.

Design Approach

The SLAC/MSU program incorporates design and testing approaches intended to explicitly address areas of difficulty encountered in past SRF gun development efforts. These include the cathode system (RF joints, multipacting and RF power dissipation); field emission / dark current; multipacting in the SRF cavity; and, generally, late-stage problem emergence.

Two broad strategies have been adopted: parallel development tracks for the cavity/cryomodule and cathode systems, and a design/test/verify approach that extends throughout the project and to the subsystem level. Combined, these strategies allow early verification of critical component performance, and provide a "separation-of-problems" approach intended to facilitate troubleshooting and remediation. Throughout the design phase, beam physics modeling is used to confirm that the evolving design continues to meet program requirements.

Figure 1 shows a cross-section view of the cavity and cathode system concept.

* Work supported by the Department of Energy Contract DE-AC02-76SF00515
† lewellen@slac.stanford.edu

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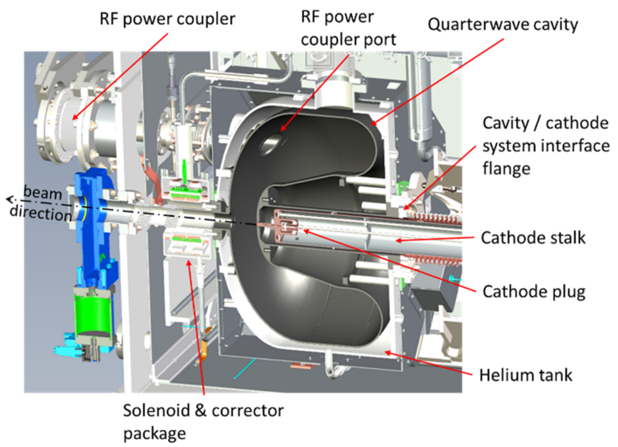

Figure 1: A cross-section view of the prototype cavity and cathode system design, within the cryomodule.

Beam Performance Modeling The SLAC and FRIB teams have complementary modeling and simulation capabilities for electromagnetic structures and beam physics. As the design of the QW-SRF gun evolves, for instance alterations of the cavity geometry to improve manufacturability, RF and beam physics models are updated to ensure that beam quality will not be adversely affected. The teams have also worked on optimizing the solenoid design to provide good performance across a range of gun gradients.

SRF Cavity Two cavities will be built during the R&D portion of the program. They are intended to be nearly identical, except that one will have provision for inserting a photocathode (the "gun" cavity), while the other (the "blank" or "dummy" cavity) will not. The "blank" cavity will be built first, to verify manufacturing processes, measure as-built cavity properties (e.g. Q0, stiffness, mode spectrum) and characterize performance as an SRF structure (multipacting, field emission, gradient limits) without the added complications of a photocathode system and without peak E-field enhancement from a vacant cathode aperture. The "blank" cavity tests will also commission the cavity tuner, power coupler, and cryomodule.

Following fabrication, the blank cavity will undergo a three-phase test sequence. First, vertical tests will be conducted at FRIB. Next, the dressed cavity will be fitted with its tuner and forward power coupler, and tested horizontally at ANL. Finally, the cavity will be integrated into the cryomodule for a bunker test at FRIB.

The "gun" cavity will incorporate design changes and improvements arising from the "blank" cavity fabrication and testing, and will be run through a similar test sequence as the "blank" but with a simplified photocathode plug installed.

More details of the cavity design may be found in [4].

Cathode System The cathode system for the QW-SRF gun, as in several other quarterwave SRF gun designs, keeps the photocathode mechanically and thermally isolated from the body of the gun, via a removable cathode plug locked into the end of an isolated "stalk," as opposed to integrating the cathode locking mechanism directly into the body of the gun. The concept is shown in Figure 2. While the cathode system must meet constraints for length, diameter, etc., its primary interface with the cavity is a single flange at the rear of the cavity, and in principle could be completely redesigned and replaced with no change to the cavity design.

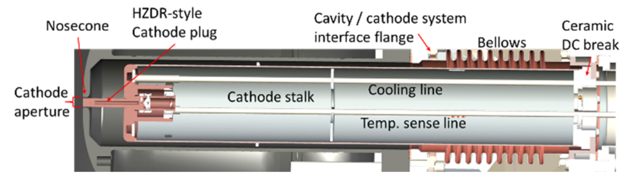

Figure 2: Close-up view of the cathode stalk concept.

A stalk-based approach offers several advantages, for instance the ability to operate the cathode at higher temperature than the gun body, and potentially reducing the probability of generating particles during cathode insertion and removal. However, the resulting cathode system resembles a coaxial line, or field probe, and RF fields will be excited along the cathode stalk proportional to the peak electric field on the cathode. The stalk design must therefore minimize the resulting RF power losses. The stalk must also have provision for DC biasing to suppress multipacting between the stalk and gun body. Finally, in addition to provisions for temperature stabilization and monitoring, the stalk must allow both transverse and longitudinal alignment of the photocathode plug to the gun cavity.

The design of the cathode stalk is being performed at MSU. HZDR is adapting their tapered-plug cathode design, in service for approximately a decade in the ELBE accelerator's SRF gun [5, 6], for use in the SLAC gun.

A series of bench tests will be conducted on the cathode stalk and plug system to verify key aspects of the performance. RF/DC bias testing at MSU will confirm the predicted losses on the cathode stalk vs. equivalent gradient on the cathode surface; verify the ability of the DC bias system to suppress multipacting; and confirm that RF isolation of the DC break is acceptable. Bench tests at HZDR will characterize particle generation during cathode insertion and removal, as well as confirm the performance of the cathode insertion alignment system.

Further details on the cathode stalk design may be found in [7].

Cryomodule, Tuner, Forward Power Coupler, Solenoid Other essential systems include the emittance compensation solenoid, cavity forward power coupler, tuner system, and cryomodule.

The cryomodule is based upon the FRIB "bottom-up" approach and is similar in design to those used in the FRIB accelerator [8]. The forward RF power coupler is based on the ANL 162-MHz design for PIP-II [9]; and the tuner is based on the design of the SSR1 tuner [10]. The stepper motor and piezo stacks are the same as those used in the LCLS-II 1.3-GHz cavity tuners.

Rather than use an iron return yoke, the MSU design for the emittance compensation solenoid includes guard coils, similar in concept to the design of high-field solenoids in the FRIB linac [11]. The solenoid is split into up- and downstream coils. This allows the effective magnetic

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center of the solenoid to be shifted along the beam axis, allowing better optimization of the emittance compensation process across a wider range of on-cathode field gradients. The solenoid magnet package will also include normal and skew quad windings, and horizontal and vertical dipole correctors.

Prototype Gun Testing

Once the "blank" cavity testing, cathode stalk bench testing, and "gun" cavity vertical testing are complete, all components will be integrated into the cryomodule for final testing at FRIB. These tests will be conducted with a photocathode plug inserted, but without a deposited photocathode, and beam will not be generated during this part of the testing.

CURRENT STATUS

As of this paper's submission, the cavity/cryomodule system has passed its preliminary design review (PDR). The final design review (FDR) for the cavity/cryomodule system is expected to be held mid-October '22; the PDR of the cathode system will be held concurrently with the cavity/cryomodule FDR.

In preparation for cavity fabrication, tests are currently underway to optimize forming dies for the major pieces of the SRF cavity; an example of a hydroformed copper test piece is shown in Figure 3. We anticipate testing the dressed "blank" cavity, with FPC and tuner, in 2023.

Figure 3: hydroformed copper test piece of the "short plate" (upstream end of the gun cavity). The outer diameter is approximately 0.6 m.

The RF/DC bias test stand design is nearly complete, and procurement has started on most components. Initial assembly is expected to roughly coincide with the cavity/CM FDR, and the first round of testing should conclude in late 2022.

CONCURRENT & FUTURE ACTIVITIES

Photocathode Characterization

Currently, CsK_2Sb and S20 (a Cs_3Sb layer deposited on an underlying Na_2KSb photocathode), illuminated at ~500 nm (green) are considered candidate cathodes for the LEI QW-SRF gun. However, there are concerns regarding operating the cathodes at 30 MV/m, both in terms of MTE performance and field emission behavior. More generally, one would prefer to make an informed choice of cathode material, laser wavelength and operating temperature, based on characterization of MTE and QE versus these properties, and measured behavior at relevant gradients.

To help facilitate a more informed choice for cathode selection, a collaboration has been formed to study the behavior of candidate materials in detail, at low and high gradients. Plans for this research are presented in these proceedings [12], and we anticipate commencing work shortly.

Beam Test

The current project concludes with an RF test of the prototype gun, in a standalone cryomodule at MSU. This will have the gun integrated with the cathode system, and a blank (uncoated) cathode plug installed; but there will be no photoelectrons generated, and no active photocathode deposited on the plug.

The project team is exploring options for performing a beam generation test following the prototype gun RF test, to address several key cathode-related concerns and questions in an operationally relevant environment. These include the evolution of cathode QE and MTE with time; field emission behavior; and, generally, cathode / gun compatibility. Such a test would also allow additional gun performance characterization, such as beam-based energy, energy spread, and jitter measurements.

Production Gun

The prototype gun developed in this project is intended to be able to serve as a beam source for the LEI, but the HE Project plan includes resources for the design and fabrication of a "production" gun. This will allow incorporation of "lessons-learned" directly from the prototype R&D process. Design of the production gun is scheduled to start at approximately the end of the prototype gun RF test.

CONCLUSIONS

The SLAC/MSU SRF Gun development effort began in October '21. At present, effort is transitioning from the initial design effort, to subsystem fabrication and testing. We anticipate initial results from the cathode stalk RF/DC bias bench tests in late 2022, "blank" cavity testing in 2023, and integrated testing of the prototype gun cavity starting in the second half of 2024.

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