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LOW-EMITTANCE SRF PHOTO-INJECTOR PROTOTYPE CRYOMODULE FOR THE LCLS-II HIGH-ENERGY UPGRADE: DESIGN AND FABRICATION*

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Abstract

The high-energy upgrade of the Linac Coherent Light Source II (LCLS-II-HE) will extend the X-ray energy range up to 20 keV. The goal is to produce low emittance (0.1 mm·mrad) electron bunches (100 pC/bunch) and accelerate 30 μA beams through the superconducting linac to 8 GeV. A low-frequency superconducting radio-frequency photo-injector (SRF-PI) will be a key aspect of the upgrade. An SRF-PI cryomodule with a 185.7 MHz Quarter-Wave Resonator (QWR) for operation at a cathode field of 30 MV/m and a cathode system compatible with high quantum efficiency photo-cathodes operating at 55-80 K or 300 K are currently being developed. We report on the design and fabrication status of the SRF-PI cryomodule and cathode system for LCLS-II-HE.

INTRODUCTION

The high-energy upgrade of LCLS-II is oriented toward increasing the electron beam energy to produce higher-energy, higher-brightness X-rays at the end of the superconducting linac [1, 2]. A new low-emittance injector is one of the key technologies to meet this goal. A low-frequency SRF-PI system is the solution of choice, as it allows for continuous wave (CW) operation with a high accelerating field and a low RF phase advance across the bunch. An SRF-PI cryomodule with a 185.7 MHz QWR and cathode system are currently being developed for the project. The scope of the collaborative project undertaken by FRIB, HZDR, ANL, and SLAC is to design and prototype a high-field SRF-PI cryomodule; develop a cathode system compatible with high-performance photocathodes operating at cryogenic (55-80 K) or warm (300 K) temperatures; and test the prototype cryomodule with a metal photocathode [3]. The LCLS-II-HE design requirements are technically challenging; operation of a QWR SRF-PI with a cathode field of 30 MV/m level has never been demonstrated.

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CHALLENGES AND DEVELOPMENT STRATEGY

Three QWR SRF-PI systems have been developed so far, for the Naval Postgraduate School [4], the Wisconsin Free Electron Laser (WiFE) [5], and the coherent electron cooling system at Brookhaven National Laboratory [6]. The existing systems have demonstrated (1) compatibility with semiconductor cathodes; (2) CW operation with a cathode field of 20 MV/m; and (3) up to 4 MeV beam energy. Challenges for our project include (1) a cathode field of 30 MV/m, which is much higher than existing SRF-PI systems have reached in operation; (2) avoidance of field emission and multipacting (MP), which have been problematic for existing systems; (3) prevention of cavity performance degradation with cathode exchange; and (4) cathode operation at different temperatures.

Figure 1 shows a drawing of the SRF-PI cryomodule. The cold mass consists of a cathode stalk to support the photocathode in the desired position, maintain it at the desired temperature, and interface with the cathode load lock system; the SRF-PI cavity with an off-axis fundamental power coupler (FPC) and an upstream mechanical tuner; and a superconducting (SC) solenoid package, including correctors (dipole and quadrupole windings) for emittance compensation. A local magnetic shield surrounds the cavity to shield it from the solenoid's field and ambient fields. The cryogenic circuit is designed to operate the cavity and solenoid package at 4 K; the thermal shield will be cooled to 55-80 K with helium gas. The cathode temperature is maintained by conduction to the cathode stalk. The stalk cooling circuit will operate with gas either from the thermal shield or from a room temperature source.

The overall design approach is as follows: (a) use past experience as the foundation—adapt the FRIB "bottom-up" cryomodule design [7] with a room-temperature strong-back for alignment, decoupling of the cryogenic circuit from the cavity to minimize cryogen-induced microphonics, and unique 3-D seal for full cold mass assembly in the clean room (including cathode stalk installation for the SRF-PI cryomodule); adapt the cathode insertion and

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load-lock system developed at HZDR for their 1.3 GHz SRF-PI system and make use of their proven operating experience with ELBE [8]. (b) Put a strong emphasis on SRF technology—using the lessons from existing QWR SRF-PI systems, the cavity design is oriented toward avoidance of MP and ease of access for surface preparation and cleaning; the vacuum system and FPC design were made compatible with in-situ plasma cleaning for reduction of FE and MP in operation. (c) Orient the design toward future operational needs—considering the cryogenic system, vacuum system, cathode system, utilities, and maintenance.

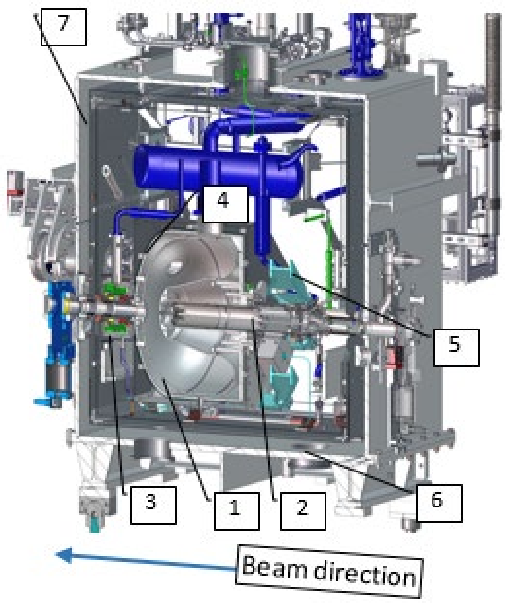

Figure 1: Sectional view of the SRF-PI cryomodule. 1: cavity; 2: cathode stalk; 3: solenoid; 4: FPC; 5: tuner; 6: baseplate; 7: thermal shield; 8: vacuum vessel.

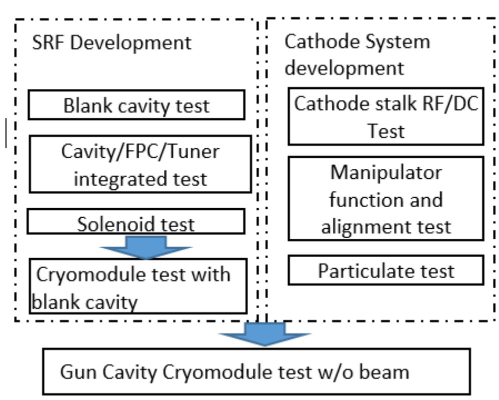

Figure 2: Technical validation steps.

Figure 2 outlines the technical validation path for this project, from individual components to the full system. The cathode system development and cryomodule development initially are undertaken in parallel tracks, merging into the full system at the end.

The cryomodule development scope includes the cavity, solenoid package, FPC, and tuner. Two cavities are being fabricated: a "blank" cavity and a full cavity; the only difference is that the blank cavity has no cathode port. The goal is to demonstrate SRF performance via a Dewar test, an integrated test with the FPC and tuner, and a cryomodule test using the blank cavity. The full cavity will be fabricated after validation of the blank cavity in the Dewar test. This approach allows us to address technical risks as early as possible.

The development scope for the cathode system includes validation of (1) the cathode stalk design via an "RF/DC test" without the cavity; (2) the cathode insertion system; and (3) particle-free cathode insertion.

After the cryomodule test with the blank cavity and completion of the cathode system development, the full cavity will be installed into the cryomodule and tested with a copper cathode and the load lock system.

PROJECT STATUS

The project started in October 2021; we expect to complete the final cryomodule tests in early 2025. The cryomodule design is mostly complete with the exception of the cathode system, for which the final design review will be held in June 2023. All major cryomodule components are in development or fabrication. The current focus is on blank cavity fabrication, SC solenoid fabrication, the RF/DC test, and the cathode insertion test.

Cavity

The detailed cavity design has been presented elsewhere [9]. It is based on the WiFEL cavity design, with optimization of the anode plane to suppress low-field MP. The cavity length was shortened to facilitate integration with the cathode stalk and tuner. A total of 4 access ports on the upstream and downstream walls were added to facilitate electropolishing and high-pressure water rinsing; 2 of these ports are used for the FPC and pickup antenna. The tuner is interfaced with the cathode stalk flange. The tuning sensitivity is about −435 kHz/mm. The cryomodule is designed for 4 K operation to avoid the complications of a 2 K cryogenic system. The maximum design pressure at 4 K is 3 bars for consistency with the rest of the LCLS-II-HE cryomodules.

Cavity fabrication is being done by FRIB with support from outside vendors. Figure 3 shows the completed cavity and FPC with cold and warm RF windows. Jacketing of the cavity into the titanium vessel is on-going. After jacketing, the cavity will be electropolished and rinsed at ANL and then cold tested at FRIB. After the Dewar test, the cavity, FPC, and tuner will undergo an integrated test (approximating the cryomodule environment for system validation) at ANL.

Superconducting Solenoid Package

The emittance compensation solenoid package contains 2 independently-energized, identical solenoids plus bucking coils to minimize the fringe field at the cavity [10]. The design is oriented toward low downstream emittance over a wide range of cathode field levels [1]. The distance between the cathode and solenoids' centroid is 187 mm, with

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40 mm spacing between the centroids of the 2 solenoid coils. Dipole and quadrupole coils are included to compensate for field errors from imperfect fabrication or alignment. The conductor is 0.3 mm NbTi wire to minimize winding errors and allow lower operating current. The main solenoid winding is complete, as shown in Fig 4. Room temperature mapping and corrector winding are ongoing. The magnet will be cold test and mapped at FRIB before installation onto the cold mass.

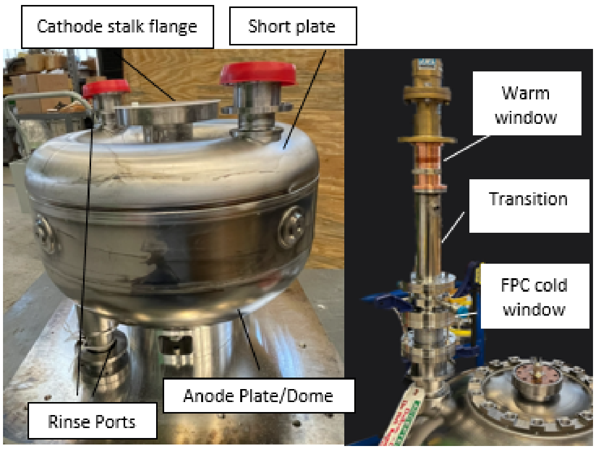

Figure 3: Left: Blank cavity. Right: FPC.

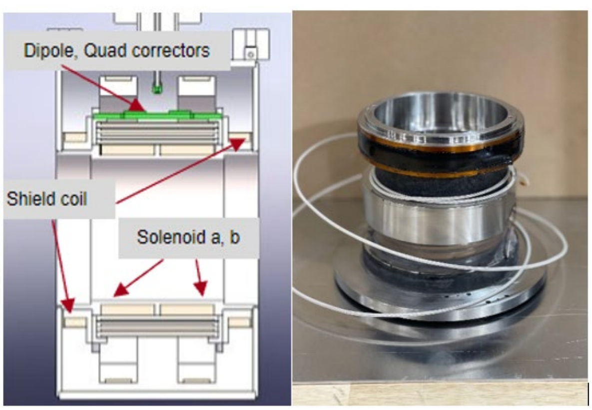

Figure 4 Left: Solenoid package design. Right: Solenoid with shield coils.

Cathode Stalk RF/DC Test

The cathode stalk is one of the most critical components of the SRF-PI system. The stalk must (1) provide mechanical support for the cathode and allow for cathode exchange, (2) cool the cathode to the desired temperature, (3) minimize RF leakage through the cathode port, and (4) provide DC bias for the cathode to suppress MP. The stalk design is challenging; its performance and SRF cleanliness directly impact the performance of the overall system. The stalk has been identified as a weak point in previous SRF-PI projects.

The design [11], shown in Fig. 5, is adapted from the HZDR cathode system [8]. The RF short and DC break close to a quarter wavelength serve as an RF choke and allow the DC bias to mitigate MP in the cathode and stalk. The tip of the stalk is cooled by helium gas (at the thermal shield temperature or room temperature). The cathode tip is cooled by conduction.

An RF/DC test setup was designed to match the RF load and magnetic field profile in the cavity, as shown in Figure 6. The RF/DC test is intended to validate (1) the RF joint between the cathode and the stalk, (2) the thermal performance of the cooling system, (3) thermal stability in the presence of RF heating, and (4) MP suppression. The thermal test has been completed, with thermal anchoring and cooling having performed as expected. One issue is excess stress in the ceramic DC break due to the differential thermal expansion coefficients, which caused cracks in the ceramic during cryogenic testing and necessitates a redesign. In the initial high-power RF test, we reached a field level equivalent to 34 MV/m; MP appeared above this power level. The stalk test is still ongoing.

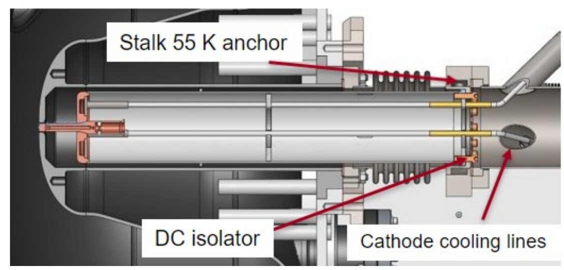

Figure 5: Cathode stalk sectional view.

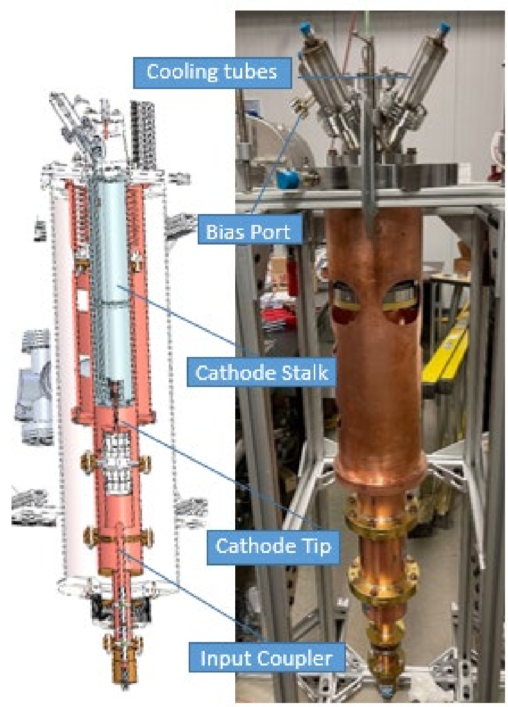

Figure 6: Setup for the RF/DC test of the cathode stalk.

SUMMARY

The low-emittance SRF photo-injector project for LCLS-II-HE is moving from design to development and construction. Validation of critical components is progressing. We anticipate cold testing the first cavity in autumn of 2023.

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