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RECENT PROGRESS TOWARD A CONDUCTION-COOLED SUPERCONDUCTING RADIOFREQUENCY ELECTRON GUN

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Abstract

High-repetition-rate electron sources have widespread applications. This contribution discusses the progress toward a proof-of-principle demonstration for a conduction-cooled electron source. The source consists of a simple modification of an elliptical cavity that enhances the field electric field at the photocathode surface. The source was cooled to cryogenic temperatures and preliminary measurements for the quality factor and accelerating field were performed. Additionally, we present future plans to improve the source along with simulated beam-dynamics performances.

INTRODUCTION

Superconducting radiofrequency (SRF) electron sources can produce high repetition rate beams with continuous-wave (CW) operation with a wide scope of industrial and societal applications. However, their employment in such applications is hindered by the complex infrastructure associated with the required cryogenic system [1].

Conduction cooling offers a path towards simpler infrastructure for SRF technologies through cryogen-free cooling. Cryogen-free systems generally employ compact closed-cycle cryocoolers contacted to the cavity via thermal-conduction links; see Fig. 1. This approach eliminates some of the complex infrastructure associated with the required cryogenic system (e.g. liquefaction and storing of Helium). Subsequently, this type of cooling can enable a footprint class of accelerators for different applications [2].

In this paper, we report the experimental results of testing a conduction-cooled SRF gun at Fermi national accelerator Laboratory (FermiLab).

DESIGN

The overall design is based on a 650-MHz SRF resonator fabricated by PAVAC [3]. The niobium (Nb) resonator consists of a single elliptically-shaped cell optimized for the acceleration of $\beta = 0.9$ relativistic particle. The Nb cell is flanked with 50-mm radius Nb pipes with end flanges located $\simeq$ 284 mm on both sides of the cavity center. The flanges incorporate auxiliary instrumentation including an excitation antenna and an electromagnetic field probe. Such a cavity is non-ideal for the emission of an electron beam as the field in the pipes region is principally a decaying fringe field. The approach we adopt to circumvent such a limitation

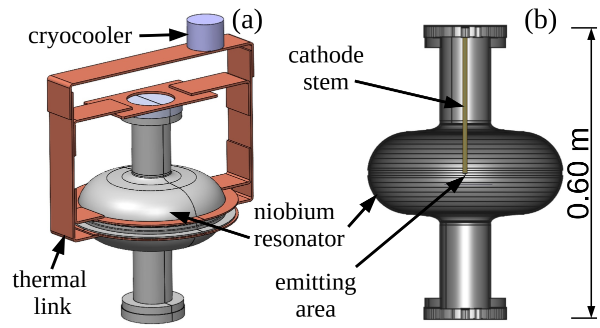

Figure 1: A 3D rendition of the modified single-cell 650-MHz cavity (b) and associated sectional view (b).

is to introduce a cylindrical rod with its extremity located in the high-field region (ideally in the cavity center) as shown in Fig. 1(b). Such a setup produces an enhanced field at the cathode surface but presents challenges in terms of thermal cooling.

A key aspect of this design is the use of direct heat conduction to achieve cryogenic temperatures using a *cryocooler*; see Fig. 1(a). Thermally, the cavity acts as a heat source in which the electromagnetic fields dissipate power into the cavity wall which results in ohmic losses. The cryocooler act as a heat sink and the thermal links are the heat conduction medium. The performance of the cryocooler depends on its temperature which depends on the heat dissipation in the cavity. The cavity temperature depends on the thermal conductance of the thermal links the temperature at the cryocooler and the system is at equilibrium if the power dissipated by the cavity (source) is equal to the power absorbed by the cryocooler (sink) through the conduction link [3].

Earlier electromagnetic and thermal studies were performed on the design to proves its feasibility. The reader is referred to [4] for more information about the design and [5] for possible applications of it and its performance in thermal and beam-dynamics simulations. Subsequently, the radius and the length of the stem inserted in the cavity were chosen to be 0.5 cm and 22 cm, respectively. Electromagnetic simulations indicate that such a configuration can produce ~ 8 MV/m with quality factor $Q_o \sim 10^8$.

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EXPERIMENTAL SETUP

To investigate the thermal and electromagnetic potentials of the simulated cavity-stem assembly, several thermal and RF tests were performed on the cavity. A similar setup to the one illustrated earlier in Fig. 1 was assembled at Fermilab; see Fig. 2. The main goals of the tests were to prove the feasibility of the conceptual design by cooling the cavity-stem assembly, store electromagnetic power inside the cavity, and attain appreciable accelerating gradients that agree with the simulations.

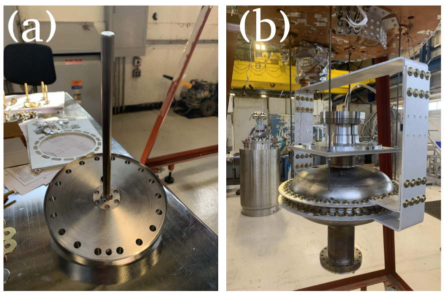

Figure 2: Photo of the Nb rod and the flange (a) and cavity and thermal links (b) during assembly.

The experimental setup consists of the 650 MHz Nb cavity, Nb rod, and flange. The cryocooler is connected to the cavity with the high purity Aluminium (AL) thermal links; see Fig. 3. The Nb rod and flange were machined at the FermiLab workshop from high purity Nb bulks. Afterward, the Nb rod was welded on a Nb plate which is bolted into the flange; see Fig 2 (a). The thermal links Al links were machined from Al plates and bolted into the cavity; see Fig 2 (b) [6]. To help with heat conduction, 100 µm thick foils of indium were interposed between the Nb and Al plates. The modified cavity and the Al links assembly are housed in a thermally shielded vacuum vessel. The vacuum level in the vessel can reach up to 10^{-6} – 10^{-7} Torr which is achieved by a turbo-pump. The temperature in the setup is measured by placing cryogenic temperature [7] thermometers at different locations in the cavity. The thermometers have a temperature range 1.4 K to 300 K and typically have error ΔT of 20 mK around 4K.

The RF measurements were performed using an in-house low-level radio-frequency (LLRF) system. The already-available system operates in CW mode at a central frequency of 650 MHz with a full-width bandwidth $\Delta f = 10$ MHz and able to provide up to 10 W of RF power. Subsequently, the cryocooler available for the setup can provide 1 W at 4.2 K with a heat leak of about 0.67 W. The system can measure the forward and reflected powers from the input coupler and the transmitted power through the pickup coupler; see Fig. 3. The powers are measured using RF diodes that use the RF power as a signal and produce a voltage as output. The output, recorded on an oscilloscope, is converted back to RF power using the diodes calibration curves [8]. Prior to the test, the cables of the RF systems are calibrated to minimize any RF losses. Furthermore, we assume a 10% error in the measured quantities during the RF test. We propagate these uncertainties into the calculated quantities (e.g. Quality factor) using python-based UNCERTAINTIES error-propagation package [9]. The RF measurement took place into 2 parts; a decay measurement and a continuous-wave (CW) measurement [10]. In the decay measurement, the loaded quality factor Q_L is determined by observing the energy decay which is given by $U \equiv U_o \exp\left(-\frac{\omega_o t}{Q_L}\right)$, while the coupling strength of the input $\beta_1 \equiv \frac{P_r}{P_d}$ and pickup couplers $\beta_2 \equiv \frac{P_t}{P_d}$ are determined from the dissipated power, which is inferred to from power balance:

$$P_d = P_f - P_r - P_t \, , \tag{1}$$

where P_f,P_r, and P_t are the forwrad, reflected P_r, transmitted powers, respectively. The intrinsic quality factor of the cavity only is then:

$$\frac{1}{Q_o} = \frac{1}{Q_L} - \frac{1}{Q_1} - \frac{1}{Q_2} \tag{2}$$

where Q_1 and Q_2 are the quality factors of the input and pick up couplers, respectively. The CW measurement is then performed measuring the intrinsic quality factor Q_o and the average accelerating gradient E_{acc} by increasing the input power P_i where:

$$Q_o = \frac{Q_2 P_t}{P_d} \, , \tag{3}$$

$$E_{acc} = \sqrt{Q_2 P_t \, (R/Q)}/L \, . \tag{4}$$

where R/Q is the geometrical shunt impedance determined from simulations and L is the effective length of the cavity.

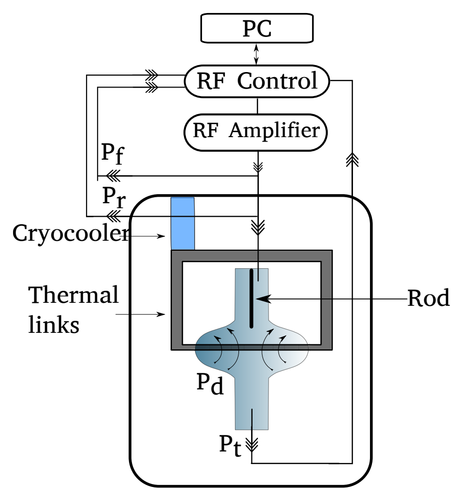

Figure 3: Illustration of the RF measurement preformed at FermiLab.

Thermal and RF Measurements

The cavity-stem assembly is cooled down in 2 stages of the cryocooler. The first stage brings the temperature of the cavity down to ~ 30 K while the second brings it down to

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~ 4.2 K. Earlier results with the current cryocooler indicate that at 4.25 K there is a heat leak of about 0.67 W. The overall cool-down process took about 4 days and resulted in an average temperature ~ 4.5 K. After the cool-down was confirmed the RF measurements were performed.

The decay measurement confirmed the expected resonant frequency f_o^{exp} = 646.2 MHz [from simulation f_o^{sim} = 646.8]. However, the quality factor of the cavity was lower than expected [$Q_o \sim 7.5 \times 10^6$]. The CW measurement was performed after calculating the coupling parameters $\beta_1 = 0.4 \pm 0.03$ and $\beta_2 = 0.0067 \pm 0.001$ and by increasing the forward power P_f while recording the P_t, P_r and P_d. During the CW measurement, the dissipated power P_d increased as the forward power increased P_f indicating that power was stored in the cavity; see Fig. 4.

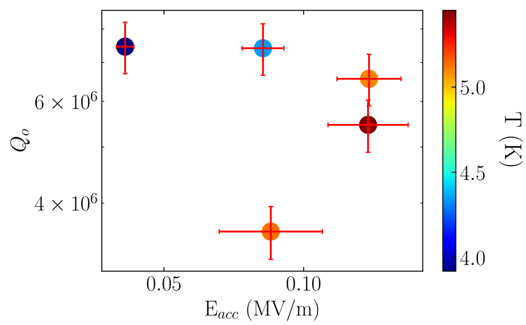

Figure 4: Average accelerating gradient E_{acc} verses the quality factor of the cavity-rod assembly Q_o. The color represent the operating temperature of the cryocooler.

During the period of the RF test, the recorded temperature at different locations at the cavity outer surface remained below the critical temperature T_c = 7.2 of Nb; see Fig. 5(a). The performance of the cryocooler was recorded by measuring the dissipated power P_d and the temperature T_c at the cryocooler. The performance curve is shown in Fig. 5(b) and agrees very well with the expected performance.

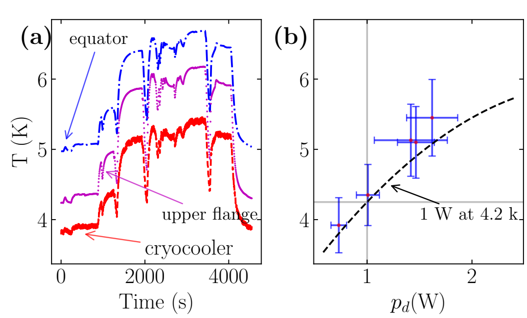

Figure 5: Thermometers reading at 3 different locations during the test (a), and performance curve of the cryocooler (b).

DISCUSSION

In terms of the temperature, the cavity showed good agreement between simulated (T_{avg} ~ 5.1 K) and measured (T_{avg} ~ 5.9 K). The reason behind the unpredicted low-quality factor of the cavity is not well understood. Simulation indicate that $Q_o = 3 \times 10^8$ while the highest recorded was $Q_o^{exp} \sim 7.5 \times 10^6$. However, it should be noted that no additional chemical-based cleaning treatment was performed on the Nb rod and the Nb flange after machining. The coupling between the cavity-rod assembly and the input coupler was $\beta_1 \sim 0.4$ which meant that the system was slightly under-coupled. The measured accelerating field E_{acc} versus Q_o is shown in 4 and indicate that maximum $E_{acc} \sim 0.12 \pm 0.01$ MV/m corresponding to $E_{cathode} \sim 0.88$ MV/m. Such values are lower than the expected from simulations $E_{acc}^{sim} \sim 1$ MV/m. The attempt to furher increase the forward power P_f so to attain higher E_{acc} value resulted in a temperature increase at the cavity with a lower accelerating gradient; see Fig. 4. Such behavior indicates that the temperature at the rod might be exceeding the critical temperature T_c. A summary of the measured RF quantities is tabulated in Table 1.

Table 1: Summary of the Calculated and Measured RF Parameters During the Test with Comparison with Simulation when Applicable

Decay measurement		
	Experiment	Simulation
f_o (MHz)	646.2 ± 6.4	646.8
$Q_o \times 10^6$	7.5 ± 0.76	3×10^8
$Q_{ext} \times 10^7$	1.8 ± 0.2	3.1

CW measurement	
P_d **(W)**	E_{acc} **(MV/m)**
0.73 ± 0.07	0.04 ± 0.003
1.01 ± 0.08	0.09 ±0.007
1.47 ± 0.13	0.12 ± 0.01
1.62± 0.19	0.123 ± 0.014
1.42 ± 0.29	0.09 ± 0.02

CONCLUSION

Thermal and RF testing was conducted on the modified cavity and confirmed the validity of earlier simulations by measuring the resonant frequency f_o and by cooling the cavity below 5 K. So far, the measured quality factor is lower than expected possibly due to contamination on the stem and the flange. In the near future, the stem flange will be chemically cleaned and tested in an available Nb_3Sn coated cavity.

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