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FIELD-EMISSION ELECTRON SOURCE EMBEDDED IN A FIELD-ENHANCED CONDUCTION-COOLED SUPERCONDUCTING RF CAVITY*

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Abstract

We present simulations and experimental progress toward the development of a high-current electron source with the potential to deliver high charge electron bunches at GHz-level repetition rates. To achieve these goals electrons are generated through field-emission and the cathode is immersed in a conduction-cooled superconducting 650-MHz RF cavity. The field-emitters consist of microscopic silicon pyramids and have a typical enhancement factor of about 500. To trigger field-emission, the peak field inside the RF cavity of about 6 MV/m is further enhanced by placing the field-emitters on the top of a superconducting Nb rod inserted in the RF cavity. So far, we cannot control the duration of the electron bunches which is of the order of RF period. Also, the present cryocooler power of about 2 W limits the beam current to microamp level.

INTRODUCTION

There is an increasing demand for high power electron injectors for a large variety of applications that range from building new radiation sources to medical applications and treatment of wastewater in large metropolitan areas [1]. To achieve multi-megawatt power the injectors should generate a beam average current in ampere range assuming a typical energy gain of a few MeV's. Such a large beam current requires that the injector operates at a repetition rate comparable with the RF frequency and the electron pulses charge is at nanocoulomb level.

The repetition rate of the high power normal conducting electron guns is constrained by the efficiency of heat dissipation through the walls of the RF cavity. Superconducting technology is increasingly a more appealing solution to avoid this limitation despite the relatively higher cost of the cryogenic systems [2]. Typically, the superconduction of RF cavities is achieved by immersion into a liquid helium reservoir. A different approach, that we follow in the research presented here, is to lower the temperature of the RF cavity to superconduction domain through heat conduction to a cryocooler [3, 4]. This technique eliminates the need for cooling fluids, greatly simplifies the cryogenic system and it could beneficiate from the fast growing technological developments in cryo cooling.

Photoemission is the most used process to extract electron bunches from the cathode with thermal emittance in the sub-micron range. The laser systems used to generate photoemission are expensive and repetition rate is relatively low (several kilohertz) in high power regime. Therefore, our option is to use a cathode consisting of an array of field-emitters [5]. In this case the repetition rate is the RF frequency and the total electron beam power is very close to the input RF power when the heat loses are substantially reduced by operating the RF gun in superconducting regime.

In this contribution we present a 650 MHz RF cavity operated in superconducting regime. The cavity temperature is lowered by a cryocooler through direct heat conduction. We present electromagnetic (EM) analysis of the RF cavity and the status of the experiment.

SETUP OVERVIEW

The electron source we use for this project is based on a 650 MHz SRF cavity designed and tested at Fermilab [6]. The elliptically shaped resonator, depicted in Fig. 1, is made of superconducting niobium with critical temperature $T_c = 9.2$ K and optimized to accelerate particles with $\beta = 0.9$. The RF power is supplied into the cavity through a 32 mm long copper antenna attached to the input flange. A bi-directional coupler connected to power supply and to input antenna allows the determination of input and reflected powers P_{in} and P_r. The input flange is also thermally connected to the cryocooler (Cryomech PT420) through conduction aluminum links. A similar probe antenna is attached to the pickup flange on the opposite side of the resonator to determine the transmitted power P_t. The pickup flange also incorporates an 40 mm-radius copper disc to measure the electron beam current. Both flanges are made of stainless steel. The overall length of the cavity, including the two 50 mm-radius pipes that flank the resonator is 560 mm.

In this design the amplitudes of the fields reach their maxima at the center of the resonator and they rapidly decay toward the two flanges. Therefore, a 2 mm-radius circular

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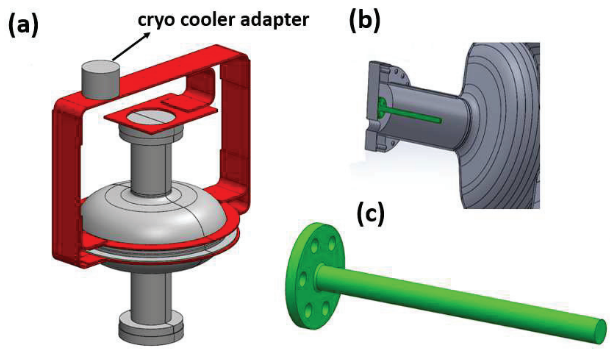

Figure 1: (a) View of the RF cavity connected to the cryocooler through aluminum conduction links shown in red. (b) Sectional view of the cavity in the region of the input flange. The rod, shown in green, is attached to the input flange. (c) Enlarged view of the rod. The field-emitters (cathode) are deposited at the free end of the rod.

cathode consisting of an array of field-emitters is deposited at the end of a superconducting niobium rod inserted into the resonator and attached to the input flange. The length and the radius of the rod 220 mm and 5 mm respectively were determined from EM and thermal simulations [7].

The input RF power of about 5 W is provided by a solid-state low-level rf-frequency (LLRF) which operates in CW mode at central frequency $f_0 = 650$ MHz and full-width bandwidth $\Delta f = 5$ MHz. The low temperature of the cryocooler thermal cycle is determined by the power load. To exemplify, the power load is about 2 W when temperature at cryocooler adapter (see Fig. 1) is 4.2 K. The power load is the sum of the power dissipated as heat in the RF cavity and transmitted through conduction to the cryocooler and the power loss P_{loss} due to additional heat dissipation in some equipment components. Previous studies [3] showed that the power loses (heat leak through RF cables,thermometer, heater wires) account for about 0.4 W.

At this stage of the experiment the input RF power is low (5 W) and expected beam current is at microamp level. Therefore, throughout this paper beam loading effects are ignored.

EM ANALYSIS

The average of the accelerating field along beam axis E_{av} is completely determined by the dissipated power P_d and the surface resistance R_s when the RF cavity is operated at resonance frequency of 650 MHz:

$$P_d = \frac{V_{acc}^2}{(R/Q)Q} = \frac{(E_{acc} \cdot L_{cav})^2 \cdot R_s}{(R/Q) \cdot G} \qquad (1)$$

where V_{acc} is accelerating voltage ($= E_{av} \cdot L_{cav}$), R/Q and $G \equiv Q \cdot R_s$ are geometrical factors that can be evaluated numerically and Q is the quality factor which can be determined experimentally from power decay time. The average

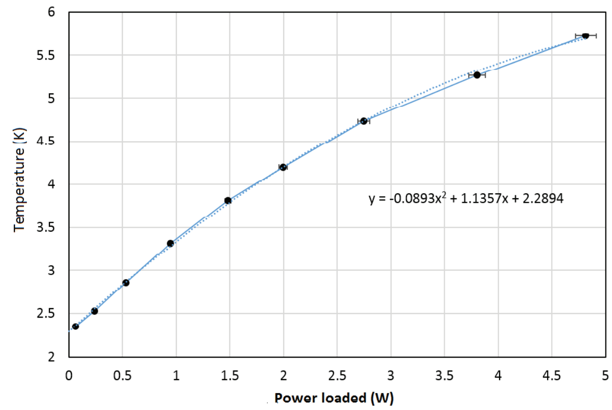

Figure 2: Experimental results of cryocooler adapter temperature as a function power loaded. The results of the fit with a second degree polynomial are also shown.

longitudinal electric field E_{av} scales as $\propto \sqrt{\frac{P_d}{R_s}}$ and quality factor $Q \propto R_s$. In practice dissipated power is set by adjusting the input power P_{in}. The coupling between RF power supply and the cavity is optimized by minimizing reflected and transmitted powers P_r and P_t. The power dissipated in the RF cavity is $P_d \approx P_{in} - P_r - P_t$ if beam loading is ignored.

RF Cavity Without Cathode Holder

In the first stage of the experiment the studies focus on RF cavity without the niobium rod inserted operated in superconducting regime when heat transfer to the cryocooler reaches steady state. The power dissipated in the RF cavity depends on surface resistance which is very sensitive to RF cavity operating temperature. The cryocooler has its own operating low temperature which is determined by the power load ($P_{load} = P_d + P_{loss}$) as shown in Fig. 2. The temperature difference between the cryocooler and the RF cavity is related to power load P_{load} and the thermal conductance κ_{link} of the aluminum conduction link: $\Delta T = \frac{P_{load}}{\kappa_{link}}$. Previous estimate $\kappa_{link} \approx 4$ W/K is expected to be about the same for our newly designed conduction link.

The average accelerating voltage of the RF cavity can determined from EM simulations or experimentally by measuring P_d and Q (see Eqn. 1) Simulations presented in this paper were performed with code Superfish [8]. Although the EM simulations are highly reliable the Superfish estimates for the superconducting surface resistance are significantly lower than those obtained with BCS formula when $T > \frac{T_c}{2}$. The values of the temperature dependent surface resistance were determined with code SRIMP [9] which solves numerically the BCS equation and takes into account material properties.

The dissipated power and quality factor evaluated with Superfish were recalculated to account for the correct evaluation of the surface resistance. The average longitudinal electric field obtained with Superfish is: $E_{av}^{SF} \times \sqrt{\frac{P_d}{P_d^{SF}}}$

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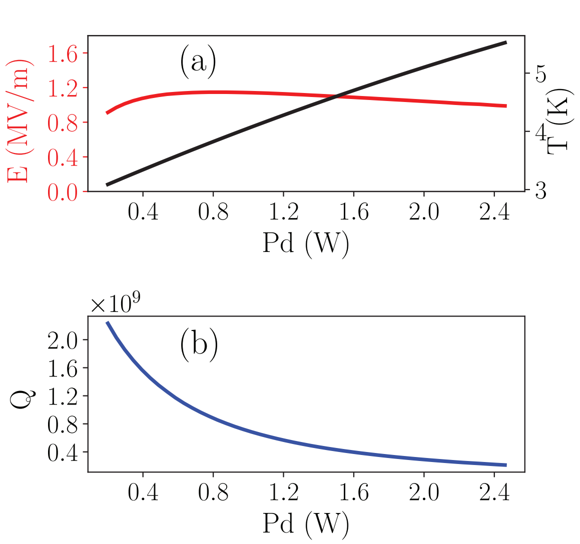

Figure 3: (a) Average longitudinal electric (red) and operating temperature (black) as functions of dissipation power. (b) RF cavity quality factor.

where P_d^{SF} is the corrected dissipated power reported by Superfish when average longitudinal electric field is E_{av}^{SF}. Figure 3 shows the expected average electric field, temperature and cavity quality factor as functions of the dissipated power P_d. The longitudinal electric field reaches a maximum when operating cavity temperature is about 3.5 K and then decreases slowly because surface resistance increases with temperature slightly faster than dissipation power.

Cathode Holder

The main purpose of the superconducting niobium rod inserted into the cavity is to position the cathode in a high longitudinal electric region. The array of field-emitters is deposited on the rod tip on a 2 mm-radius circular surface perpendicular to the RF cavity axis.

The amplitudes of the EM fields, shown in Fig. 4 were obtained through simulations when niobium rod length is 220 mm, dissipation power is 1.6 W and temperature at cryocooler adapter is 4.2 K. The expected peak field at cathode is about 8.4 MV/m large enough to trigger field-emission [10]. The EM field map is also used to determine the distribution of heat dissipated through the surface of the RF cavity and the rod [7]. This distribution is nonuniform and peaks at the rod tip. Although a rod length of about 283 mm is ideal to maximize the longitudinal electric field at cathode we had to compromize for a shorter rod length and lower fields to make sure that temperature is below $T_c = 9.2$ K at any position.

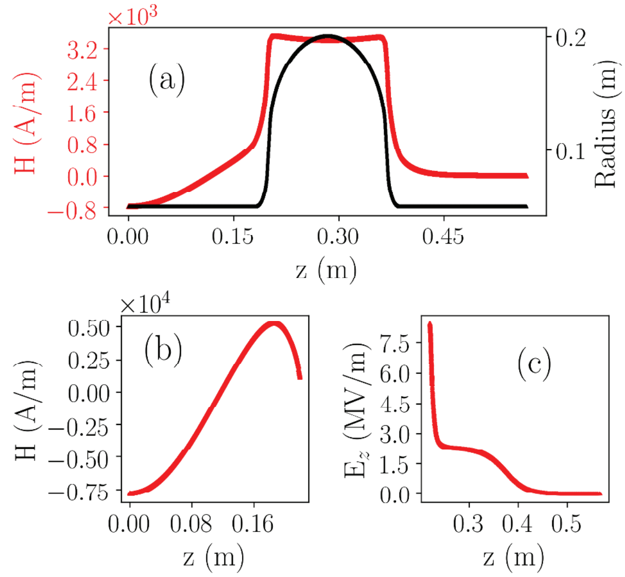

Figure 4: (a) Magnetic field (red) and cavity wall contour (black) (b) Magnetic field on the surface of a 220 mm-long and 5 mm-radius superconducting rod (c) Longitudinal electric field from the end of the rod to the pickup flange (c). The fields are evaluated when total dissipated power is 1.6 W.

EXPERIMENT STATUS & CONCLUSIONS

Manufacturing and installation of input and output flanges, antennas, copper disc, aluminum conduction links and RF cavity support structure was completed. At this stage we are ready to start cooling and performing electric field and quality factor measurements without niobium cathode holder. Then we intend to attach the niobium rod to the input flange and perform a second set of measurements mainly focused on EM and thermal analysis.

During the final step of this experiment a field-emission cathode will be deposited on the niobium rod tip. The expected beam current is in the range 1 to 10 μA and electron kinetic energy 30 to 40 keV. Very high repetition rate of 650 MHz can be obtained but electron pulse duration is very hard to control. Therefore, we also take under consideration generating electron pulses through standard photoemission process and keep the advantages offered by operating in superconducting regime obtained with heat conduction technique.

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REFERENCES

[1] P. Piot *et al.*, "Final Report: Conceptual Design of an Electron Aceelerator for Bio-Solid Waste Treatement", Fermilab-FN-1055-DI, 2017.

[2] R. Kephart, *et al.*, "SRF Compact Accelerator for Industry and Society" in *Proceedings of the SRF 2015 Conference*, Whistler, Canada, 2015, pp. 1467-1469.

[3] R. Dhuley, M. Geelhoed, and J. C. T. Thangaraj, "Thermal resistance of pressed contacts of aluminum and niobium at liquid helium temperatures", *Cryogenics*, vol. 93, p. 86-93, 2018.

[4] R. Dhuley, R. Kostin, O. Prokofiev, M. Geelhoed, T. H. Nicol, S. Posen, J. C. T. Thangaraj, T. Kroc, and R. Kephart, "Thermal Link Design for Conduction Cooling of SRF Cavities Using Cryo-Coolers", *IEEE Transactions on Applied Superconductivity*, 2019.

[5] C. A. Brau and J. L. Davidson, *ANL TAWG presentation*, 2008.

[6] I. Gonin and T. Khabiboulline, "650 MHz Cavity EM and mechanical design status", *Fermilab PIP II meeting*, 2015.

[7] O. Mohsen, *et al.*,"Simulations and Experimental Plans for a High-Repetition-Rate Field-Enhanced Conduction-Cooled Superconducting RF Electron Source", in *Proceedings of the IPAC19 Conference*, Melbourne, Australia, 2019.

[8] https://laacg.lanl.gov/laacg/services/serv_codes.phtml

[9] J. Halbritter, *Zeitschrift für Physik*, vol. 238, p. 466, 1970. https://www.classe.cornell.edu/ liepe/webpage/ researchsrimp.html

[10] O. Mohsen, *et al.*,"Performances of Silicon-Based Field-Emission Cathodes Coated with Ultranano Crystalline Diamond", in *Proceedings of the IPAC19 Conference*, Melbourne, Australia, 2019.