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Demonstration of a cryocooler conduction-cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients

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We demonstrate practical accelerating gradients on a superconducting radiofrequency (SRF) accelerator cavity with cryocooler conduction cooling, a cooling technique that does not involve the complexities of the conventional liquid helium bath. A single cell 650 MHz Nb_3Sn cavity coupled using high purity aluminum thermal links to a 4 K pulse tube cryocooler, generated accelerating gradients up to 6.6 MV/m at 100% duty cycle. The operation was carried out with the cavity-cryocooler assembly in a simple vacuum vessel, completely free of circulating liquid cryogens. We anticipate that this simple cryocooling technique will make the SRF technology accessible to accelerator researchers with no access to full-stack helium cryogenic systems. Furthermore, the technique can lead to SRF based compact sources of high average power electron beams for environmental and industrial applications.

Electron irradiation is a proven technique for environmental protection applications such as the treatment of industrial/municipal wastewater, flue gases, sewage sludge, etc. and has been demonstrated on several pilot scale projects[1]. For electron irradiation to be competitive on the large scale with existing treatment methods, electron beam (e-beam) sources capable of providing beam energy of $1-10$ MeV, megawatt-class average beam power, and high wall-plug efficiency ($>$50%) are needed[2]. The sources must also be robust, reliable, and have turn-key operation to be viable in the harsh environment expected around these applications[2]. Compact sources requiring smaller footprints that lower the infrastructure cost may also be preferred.

E-beam sources using superconducting radiofrequency (SRF) cavities as the beam accelerator can meet several of the above requirements. A meter-long or even a shorter structure of standard niobium cavities[3] or of low-dissipation Nb_3Sn cavities[4], both of which easily generate accelerating gradients $>$10 MV/m, can be an electron source with the desired beam energy. The low surface resistance of SRF cavities reduces their surface losses and provides high efficiency transfer of the input RF power to the beam, which can help to achieve the wall-plug efficiency target. The low surface resistance also facilitates constructing cavities with a larger aperture and allows RF operation with 100% duty cycle (continuous wave or cw mode), both of which are favorable for generating and efficiently transporting beams of very high average power. SRF cavities, however, need operation at cryogenic temperatures and are conventionally cooled by immersion in baths of liquid helium held near $2-4.5$ K. The cryogenic infrastructure[5] needed for compressing, liquefying, distributing, recovering, and storing helium as well as expert cryogenic operators[6] needed for oversight run counter to the robustness, high reliability, compactness, and turn-key operation desired in industrial settings.

An approach to simplify the helium cryogenic infrastructure and reduce its footprint is to integrate a closed-cycle 4 K cryocooler into an SRF cryomodule and recondense in-situ the boil-off helium gas produced by the cavity dynamic heat dissipation. Although this compact and operationally simpler cooling scheme, as implemented at the JAERI FEL[7], was shown to work reliably over year-long periods, it still relies on a liquid helium bath, leading to some undesirable requirements: (1) a separate helium cryosystem/liquid inventory for initially filling the cryomodule, (2) rigorous pressure vessel and relief design of the cryomodule as it contains a bath of liquid helium, and (3) fairly large helium gas compressors and a storage system to recover the helium during warm-up.

Conduction cooling an SRF cavity by directly connecting to a closed-cycle cryocooler with a thermally conductive link will eliminate the need for the conventional helium bath. This elimination leads to dramatic simplification of the accelerator: (1) a liquid helium inventory, a helium recovery/storage system, and a helium pressure vessel and relief design is no longer needed, (2) the cryogenics becomes very reliable (commercial 4 K cryocoolers have mean time between maintenance of $>$20000 hrs (2.3 years)[8]), safe (no liquid helium safety and oxygen deficiency hazards), and simple to operate (cryocoolers turn on/off with push of a button), and (3) significantly reduced footprint as well as added option of portability because all of the cryogenics is integrated into the cryomodule. Following its conceptualization[9] in 2015, conduction cooling of SRF cavities has been studied albeit only by means of computer simulations. Previous work is limited to understanding its feasibility based on multiphysics (electromagnetic and thermal) simulations[10,11] and a design of an e-beam accelerator using a conduction cooled SRF cavity[12]. A program to demonstrate practical accelerating gradients on conduction cooled SRF cavities began at Fermilab in 2016. In this letter we present experimental results from this program, demonstrating a cw accelerating gradients up to 6.6 MV/m on a single cell SRF cavity.

The elliptical single-cell niobium cavity used for the present work has the following parameters: resonance frequency 650 MHz, accelerating length, L_{acc} = 0.23 m, shape factor, G = 270 Ω, and normalized shunt impedance, r/Q = 156 Ω. For conduction cooling, niobium rings (SRF grade, RRR$>$300) were welded to the two elliptical half-cells as illustrated in Fig. 1. The cavity surface was prepared by removing 120 μm via electropolishing (EP), 3 hour 800 °C vac-

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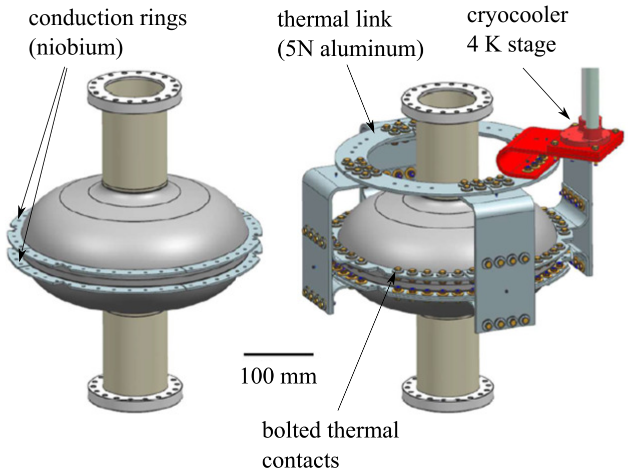

FIG. 1. Preparation of a single cell 650 MHz niobium cavity for conduction-cooling: niobium conduction rings electron-beam welded to the cavity near its equator (left) and a 5N aluminum thermal link[14] connecting the cavity to the 4 K stage of a cryocooler (right). All the bolted thermal contacts were prepared as described in our prior report[15]. The cavity was coated with Nb_3Sn on the RF surface before cryogenic testing.

uum furnace treatment, 20 μm light EP, and high pressure rinse with ultra-pure water. After initial performance evaluation, the cavity inner surface was coated with a thin layer of Nb_3Sn, grown via vapor diffusion[13], to enable low dissipation operation[4] at temperatures near 4.5 K. The cavity was then cooled in 4.4 K liquid helium in the Fermilab Vertical Test Stand (VTS) to obtain a baseline of quality factor, Q_0 *vs*. cw accelerating gradient, E_{acc}. The cavity was then warmed, removed from the VTS, and prepared for conduction cooling without disturbing the inner vacuum.

A thermal conduction link of 5N aluminum (purity >99.999%) was designed[14] and machined out of stock plates, chemically cleaned to remove surface oxide, and bolted to the cavity niobium rings following the procedure developed in our prior work[15]. The procedure involves interposing a 4 mil thick foil of indium between the niobium and aluminum plates and pressing the contact with 2 kN force applied by a silicon bronze screw, a brass nut, and stainless steel Belleville disc springs. The other termination of the thermal link was bolted to the 4 K stage of a pulse tube cryocooler. The cavity-thermal link assembly was then installed on a test setup[16] (conduction-cooled test setup or CCTS) recently developed at Fermilab. This setup is comprised of a vacuum vessel, a magnetic shield (an enclosure with <10 mG background), a thermal radiation shield, and a Cryomech PT420 two-stage pulse tube cryocooler (rated to provide cooling of 2 W @ 4.2 K with 55 W @ 45 K). A new RF power source was also developed that is capable of feeding up to 10 W @ 650 MHz of cw power to the cavity, measuring the forward, reflected and transmitted powers, and locking the source frequency to the instantaneous resonance frequency of the cavity during cryogenic RF operation. For recording temperature of the cavity-cryocooler assembly, the cavity carried four cryogenic thermometers affixed to the niobium rings and the cryocooler carried one cryogenic thermometer on its 4 K stage. The cavity temperature referred to in this letter is the average of the four cavity thermometer readings.

Three RF tests were performed including one with liquid helium (baseline) and two with cryocooler conduction cooling. Fig. 2 shows the cavity quality factor, Q_0 *vs*. cw accelerating gradient, E_{acc} (both accurate to within 10%), determined using standard cavity measurement procedure[17]. Test 1 was carried out in the Fermilab VTS with liquid helium and witnessed carefully controlled conditions *viz*. a background magnetic field of $\sim$2 mG and slow/uniform cooldown with rate of 0.1 K/min through the Nb_3Sn superconducting transition temperature[18] of 18 K. Both these factors reduce the residual surface resistance of Nb_3Sn, which enhances the Q_0 of the cavity[13]. During the RF measurements, the cooling power of the helium bath was regulated using a vapor pumping system so that the cavity remained isothermal at $\sim$4.4 K over the range of E_{acc}. Test 1 recorded Q_0 of 3x10^{10} at E_{acc} of 1 MV/m and Q_0 of 4x10^9 at E_{acc} of 10 MV/m. The highest gradient of $\sim$12 MV/m recorded in Test 1 was limited by RF power.

For Test 2, the cavity was cooled conductively using the cryocooler to below 4 K, with a slow cooldown rate of 0.03 K/min through the Nb_3Sn transition temperature. Although the magnetic shield of the CCTS provided a background of $\sim$10 mG, we later found that some stainless-steel disc springs on the thermal link had residual field as high as 30 G. The slow cooldown in such high magnetic field is expected to trap the flux in the Nb_3Sn layer, causing the cavity Q_0 to degrade significantly. A Q_0 of 6x10^9 at E_{acc} of 1 MV/m was recorded in Test 2, which is five times smaller than in Test 1. Limited by the power output of the RF source, the cavity sustained maximum E_{acc} of $\sim$5.5 MV/m during Test 2. For Test 3, magnetically cleaner disc springs with resid-

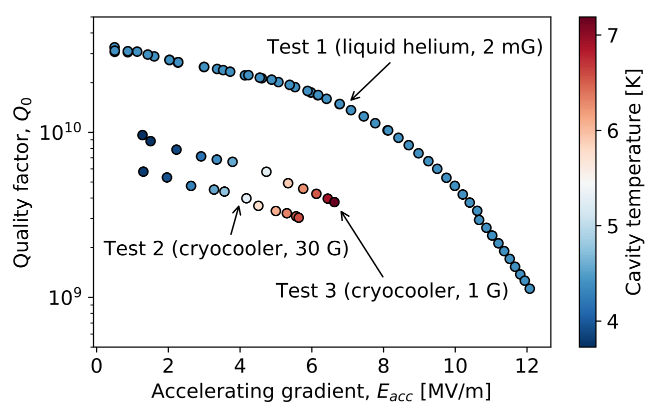

FIG. 2. Cavity quality factor, Q_0 *vs*. accelerating gradient, E_{acc} measured on a single cell, Nb_3Sn coated, 650 MHz niobium SRF cavity. The data uncertainty is <10%. Test 1 used a helium bath cooled cavity at 4.4 K, in Fermilab Vertical Test Stand with background magnetic field of 2 mG. In Tests 2 and 3, the cavity was conduction-cooled with a 2 W @ 4.2 K pulse tube cryocooler. The improvement in Test 3 resulted from the reduction of magnetic field around the cavity when magnetic disc springs (residual $\sim$30 G) were replaced with relatively cleaner disc springs (residual <1 G).

ual of <1 G were installed on the thermal link. The cavity showed noticeable improvement: Q_0 of 10^{10} was measured at E_{acc} of 1 MV/m and the cavity sustained maximum E_{acc} of $\sim$6.6 MV/m, limited again by the RF power source.

We note in Fig. 2, a distinction between the Q_0 *vs*. E_{acc} data measured with liquid helium and cryocooler conduction cooling. As previously mentioned, the helium bath temperature control system in the VTS (Test 1) held the cavity isothermal over the range of E_{acc}, yielding a Q_0 *vs*. E_{acc} curve at the near-constant temperature of $\sim$4.4 K. In the CCTS, however, there was no temperature regulation system on the cryocooler. So as heat dissipation in the cavity increased with the increase in E_{acc}, the steady state temperature of the cavity increased as well. The color gradient in the data for Test 2 and Test 3 reflects this effect. Thus, unlike Test 1, the Q_0 *vs*. E_{acc} data from Test 2 and Test 3 do not correspond to a fixed cavity temperature but rather have the cavity temperature vary from $\sim$4 K to $\sim$7 K depending on the E_{acc}.

Fig. 3 presents a graphical summary of the present findings in terms of the cavity temperature, dissipated power, and the corresponding cw accelerating gradient. The plot is divided into two regions by the cryocooler load curve, accounted for the 0.8 W heat leak prevailing during the measurements. cw operation is not possible with the cryocooler in the shaded region because here the dissipated power exceeds the cryocooler capacity at a given temperature. For instance, the operation at 10 MV/m cw at 4.4 K with $\sim$7.2 W of dissipation lies in this region. The unshaded region allows cw operation with the cryocooler. At 4.4 K, conduction cooling produced a modest E_{acc} of $\sim$3.4 MV/m, limited by the cryocooling capacity at this temperature as well as due to the degraded Q_0 from flux trapping. However, with the increase in the cryocooling capacity with temperature, the cavity at $\sim$7.2 K generated an E_{acc} of $\sim$6.6 MV/m. This suggests that the attainable E_{acc} is not limited by the cryocooler cooling capacity at $\sim$4.4 K and a significantly larger E_{acc} can be generated by letting the system operate warmer than $\sim$4.4 K.

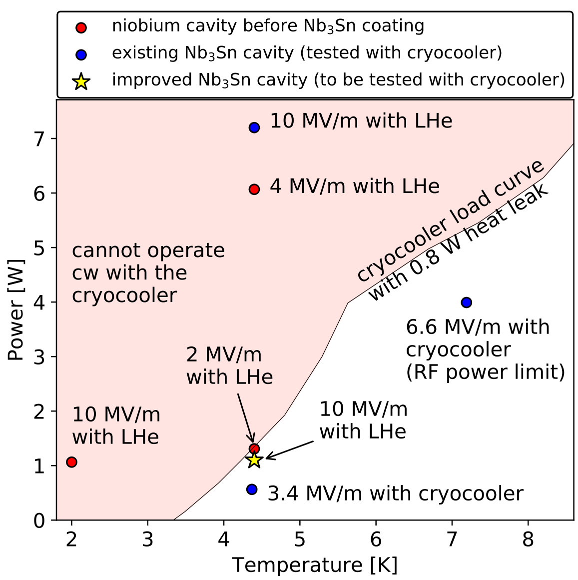

FIG. 3. Dissipated power *vs*. temperature for the 650 MHz Nb_3Sn single cell cavity under study compared with the PT420 cryocooler load curve. The load curve accounts for the 0.8 W heat leak prevailing during measurements. Observed notable cw gradients with conduction cooling (with their current limits) marked on the graph are: 3.4 MV/m at $\sim$4.4 K (cooling capacity) and 6.6 MV/m at $\sim$7.2 K (RF power). A Q_0 of $\sim 3\times10^{10}$ at 4.4 K is needed to achieve 10 MV/m with conduction cooling. An improved Nb_3Sn coating has already attained this Q_0 in a recent test[19] in the Fermilab VTS. For comparison, the niobium cavity before Nb_3Sn coating produced 2 MV/m cw in 4.4 K liquid helium (VTS), which is the limit achievable with the cryocooler at this temperature. Producing higher E_{acc} required more cooling power (6 W at 4.4 K to get to 4 MV/m cw) or a higher Q_0 operation (at 2 K to produce 10 MV/m cw), both not attainable with the cryocooler.

Fig. 3 also highlights that reaching practical cw gradients with a pure niobium cavity may not be feasible with the cryocooler. We show representative gradients obtained in the VTS on the cavity before coating with Nb_3Sn. An E_{acc} only up to 2 MV/m at 4.4 K lies within the range of the cryocooler capacity at this temperature. Achieving higher gradients either needed more cooling capacity ($\sim$6 W at 4.4 K to reach 4 MV/m) or higher Q_0 operation at colder temperature (2 K to produce 10 MV/m cw), both of which are out of the cryocooler cooling range.

The E_{acc} of $\sim$6.6 MV/m over L_{acc} = 0.23 m equals an energy gain of $\sim$1.5 MeV. This clearly makes our existing configuration of one-cell cavity with one-cryocooler practicable for treatment of industrial flue gas[12]. The attainable E_{acc} with one cryocooler can be pushed up by improving the Q_0 of our cavity. The ongoing efforts for Nb_3Sn coating optimization have already produced a Q_0 of $\sim 3\times10^{10}$ at 10 MV/m cw on a similar 650 MHz single-cell cavity[19] in the Fermilab VTS. The corresponding dissipation of $\sim$1.1 W at 4.4 K is now in the regime of cryocooler conduction cooling as marked in Fig. 3. Replicating this performance with conduction cooling requires improvements to the magnetic hygiene of our CCTS. These improvements are currently underway including complete replacement of stainless steel disc springs with those made of non-magnetic beryllium copper.

Large SRF accelerators for basic research (for example, LCLS-II[20]) that use hundreds of cavities require kilowatt-level refrigeration at liquid helium temperatures. We emphasize that cryocooler conduction cooling may not be economical for such large-scale cooling demand simply due to the lower efficiency of the cryocoolers: a large helium cryoplant requires $\sim$0.4–0.8 kW(electrical)/W(cooling) while a cryocooler typically requires $>$10 kW(electrical)/W(cooling). However, it can be an enabler for a new class of compact, small-scale SRF accelerators, a concept of which is illustrated in Fig. 4. Here we envision a 10 MeV e-beam source comprising of a meter-long 5-cell[21] 650 MHz SRF cavity generating 10 MV/m cw. With $\sim$6–7 W of dissipation at 4.4 K, the cavity can be conduction-cooled using four two-stage cryocoolers each of 2 W capacity. The thermal radiation shield can be maintained near 40–50 K, by conduction cooling to the warmer stages of the cryocoolers, resulting into a completely liquid cryogen-free, standalone SRF machine. Design efforts

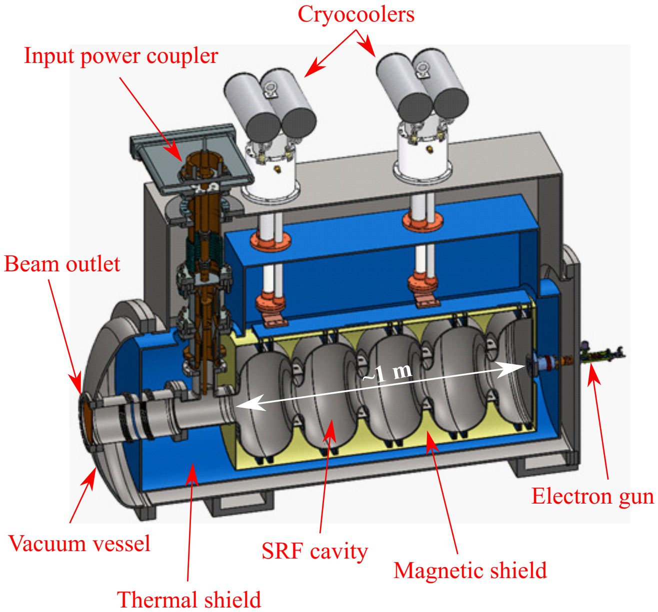

FIG. 4. CAD rendering of a compact, meter-long e-beam accelerator showing the components.

for a suitable components for such a machine *viz.* an input RF power coupler[22] and an electron source[23] are currently underway.

In this letter we introduced the method to cool an SRF cavity to cryogenic temperatures by conductively coupling to a closed-cycle 4 K cryocooler. The method when adopted in an SRF accelerator will eliminate the conventional cavity liquid helium bath and offer compactness, robustness, reliability, and turn-key cryogenic operation, making the accelerator attractive for industrial settings. A 650 MHz Nb_3Sn single-cell cavity generated cw accelerating gradient of ~6.6 MV/m (electron energy gain of 1.5 MeV) with Q_0 of 4x10^9 when cooled using a 2 W @ 4.2 K pulse tube cryocooler. Continued work targets to further improve Q_0 to push the E_{acc} beyond 10 MV/m, develop conduction-cooling for multi-cell SRF cavities, study potential cavity microphonics resulting from cryocooler vibration, and subsequently develop a compact SRF accelerator as a source for $1-10$ MeV energy, high average power e-beams for industrial and environmental applications.

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