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Nb_3Sn SRF Photogun High Power Test at Cryogenic Temperatures

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***Abstract*—Superconducting RF (SRF) photoguns are emerging as promising candidates to produce highly stable electrons for Ultra fast Electron Diffraction/Microscopy (EUD/UEM) applications due to the ultrahigh shot-to-shot stability compared to room temperature RF photoguns. SRF technology was prohibitively expensive for industrial use until two recent advancements: Nb_3Sn [1] and conduction cooling [2], [3]. SRF gun can provide a CW operation capability while consuming only several Watts of RF power which eliminates the need of an expensive high power RF system and saves a facility footprint. Euclid is developing a continuous wave (CW), 1.5-cell, MeV-scale SRF conduction cooled photogun operating at 1.3 GHz. In this paper, we present first high power results of the gun covered with Nb_3Sn.**

***Index Terms*—Accelerating cavities, cryocoolers, electron gun, Nb_3Sn, stand-alone cryomodule, superconductivity, UED/UEM.**

I. Introduction

THE use of SRF photoguns brings certain benefits compared to normal conducting guns such as: unprecedented repetition rates (CW-operation), reduced almost to zero RF losses, higher RF stability. In addition, normal conducting guns employ MW-class pulsed RF power sources such as klystrons to generate high RF fields and compensate RF losses. Klystrons require high voltage modulators which makes this duet quite expensive ($1M) and cumbersome. Some part of the RF power is consumed by the beam, but in UED/UEM application the beam current is minuscule. Contrary to that, an SRF gun requires only few Watts of RF power to compensate RF losses in the walls, thus only a 10 Watt solid state RF amplifier should provide enough power, which is three orders of magnitude cheaper and more compact than the klystron and the modulator.

The SRF gun requires a cryomodule to provide sufficient cooling of the gun to maintain its superconducting state. Currently, most of superconducting accelerator facilities employ cryomodules filled with liquid helium and nitrogen. Accelerating cavities from pure Niobium are immersed in liquid helium bath which cools them down to 2K. Liquid helium is provided through a distributed pipe system from a cryoplant which collects and liquefies the evaporated helium from the cryomodules. This complicated system requires highly skilled personnel for operation and maintenance and is efficient and cost effective for big facilities, however is not affordable for small scale machines. The SRF gun described in this paper relies on a different relatively new approach - conduction cooling and the use of Nb_3Sn superconducting material which is produced by Sn vapor condensation on pure Nb walls. Adoption of this superconductor for SRF cavities allows to operate them at higher temperatures. BCS surface resistance is still low enough even at 4.4 K, resulting in low RF losses on the order of several Watts at accelerating gradients of tens of MV/m [1] which is within the cooling capacity of modern closed-cycle cryocoolers. Closed-cycle cryocoolers are relatively inexpensive and easy to use self-contained system filled with helium gas and does not need any refills. They can be directly connected to the accelerating cavities through high thermal conducting links which eliminates the need to use liquid helium and drastically simplifies cryomodule design, maintenance and operation. This approach is called conduction cooling and is a relatively new method for SRF community, however, it was used for superconducting magnets cooling for a long time. Conduction cooling of SRF cavities have been demonstrated independently almost at the same time at Fermilab [2] and Jlab [3] where decent accelerating gradients have been achieved. This approach opens the opportunity for small scale SRF accelerators development like the one described in this paper.

Euclid is developing a CW, 1.5-cell L-band conduction-cooled SRF photogun operating at 1.3 GHz for MeV UED/UEM applications [4], [5]. Several MeV high energy electron beam significantly improves beam quality due to faster acceleration which helps to reduce space charge effects. The design of the gun was initially based on an existing cavity with an "on-axis" coaxial coupler developed by Euclid [6], however it was later changed to a standard Tesla end-cell with side couplers [7] to lower manufacturing costs and an additional half-cell for low energy beam section. Beam quality was not affected by the change of the coupling scheme from axially symmetrical coaxial on-axis coupler to the beam pipe coupler. The half-cell geometry was optimized to provide the best beam quality (low energy spread) with the highest possible beam energy. As long as quality factor usually degrades with higher accelerating gradients a conservative gradient of 10 MV/m was chosen for operation with the goal to achieve Q_0=1.1E10 for low RF losses. This field level and quality factor is achievable nowadays even for 9-cell Tesla cavity covered with Nb_3Sn [1].The half-cell design was optimized using CST software, which was bench marked by ASTRA code. The beam parameters were optimized and are suitable for UED/UEM [8]. Beam energy out of the gun is 1.65 MeV which requires field on the cathode (on axis) of 20

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MV/m (not to be confused with the accelerating gradient, which is the average gradient along the length of the gun). The electron beam is generated by the first cell metallic wall illumination by a short UV-laser beam. Despite the fact that the quantum efficiency of Nb_3Sn is an order of magnitude lower than copper, it still can provide enough electrons for UED/UEM applications with mW laser power. The Nb gun was manufactured by electron beam welding of die pressed sections and can be found in Fig. 1.

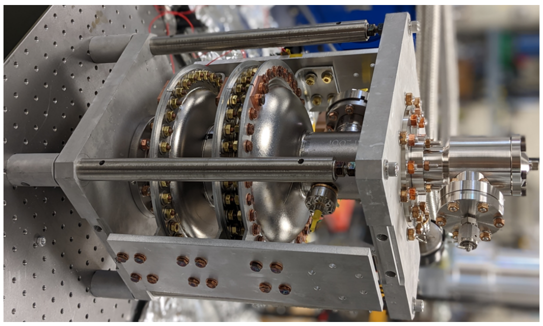

Fig. 1. 1.5-cell conduction cooled SRF gun for UED/UEM.

The gun has Nb rings welded on the equator regions of the cells for conduction cooling. High purity 5N aluminum busses connect the gun with a cryocooler for cooling - Fermilab's conduction cooling approach developed in collaboration with Euclid [9]. The RF dissipated power was simulated to be below 1 W at quality factor of Q_0=1.1E10 and accelerating gradient of 10 MV/m. The "dry" cryomodule has been developed and is ready to host the cavity (see details in [5]) once the gun performance covered with Nb_3Sn is demonstrated in liquid helium at 4 K. Longitudinal gun stiffeners (flange to flange) were designed to prevent the gun deformations under the differential pressure as Nb_3Sn deposition process happens at high temperatures which anneals the Nb and makes its yield stress several times lower (20 MPa). The pure Nb gun was tested in liquid helium Dewar at Fermilab before proceeding with Nb_3Sn deposition to benchmark its performance and make sure the gun was free of any defects. The test results can be found in Fig. 2.

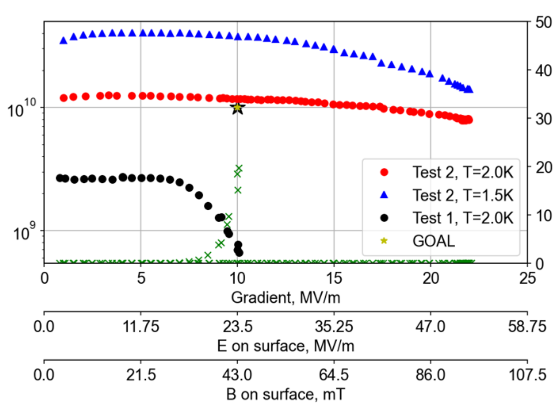

Fig. 2. Results of test 1 and 2 (pure Nb gun) in liquid helium Dewar.

Accelerating gradient of 10 MV/m was achieved during the very first test which is the target operating gradient at 4 K, however the quality factor at low fields was low quite low, equaled to Q_0=2.6E9 degrading after 7 MV/m because of increasing field emission. Multipactor was not present up to the operating gradient. One can conclude from the first test that the cavity surface required more thorough cleaning. In preparation for the next 2 K test, the gun received 10 um BCP and improved High Pressure Rinsing (HPR) which provided a better surface cleaning. Accelerating gradient of 22 MV/m was achieved during the second test and the quality factor was greatly improved up to Q_0=1.2E10 with no degradation at higher gradients. No multipactor or field emission were observed. Successful cleaning procedure has been established which eliminated field emission problems. The pure Nb gun demonstrated satisfactory performance and was ready for the next step - Nb_3Sn deposition. This paper presents the current test results of the Nb_3Sn gun in liquid helium Dewar.

II. The Gun Frequency

As long as Nb_3Sn is quite brittle and will not survive high deformations of the gun during frequency tuning it was done before the deposition. The gun frequency should be tuned to 1297.80 MHz (2.2 MHz lower) at room temperature and air inside the gun to obtain the required frequency of 1300.00 MHz during the cryogenic test. Table I below, demonstrates the frequency change due to 200 um Bulk Chemical Polishing (BCP) (which was done for initial gun processing of pure Nb), vacuum evacuation and temperature change.

TABLE I
GUN FREQUENCY CHANGE. F_s - SIMULATED, F_{mi} - MEASURED.

Case	F_s, MHz	F_{m1}, MHz	F_{m2}, MHz
300 K, air	1300.20	NA	NA
300 K, air, BCP	1297.80	1297.70	1297.70
300 K, vac, BCP	1298.20	1300.35	1298.09
002 K, vac, BCP	1300.00	1302.06	1300.09

Expected frequency change due to air evacuation is +0.40 MHz and cool down from 300 K to 2 K is +1.8 MHz taking into account Nb expansion coefficient CTE=0.143%. The gun frequency after the second test in liquid helium was 1300.78 MHz at room temperature with 20% higher field in the first cell and can be found in Fig. 3 (see F1 curve).

The first cell field closer to the metal wall is increased due to the image effect in the wall, so the real field level corresponds to the point where the field slope significantly increases. The field level and the resonant frequency were tuned by 14 consequent push-pull operations of the cell. At the end the frequency was tuned to 1297.70 MHz. Table I also contains resonant frequencies of the following two tests of the gun with Nb_3Sn deposition. The thickness of the deposition is too think to cause any noticeable frequency shift and can be ignored. It was found before the first Nb_3Sn test that the frequency of the gun was 2 MHz higher than expected. The support fixtures stressed the cavity which resulted in this frequency shift and possible cracking of the Nb_3Sn layer which resulted low performance of the cavity (see the following section). This issue was recognized and was solved in the following test by

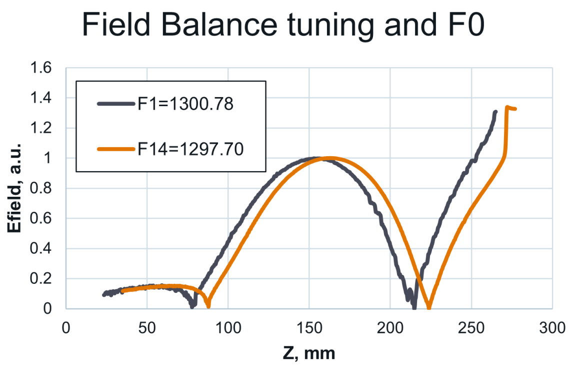

Fig. 3. 1.5 cell SRF gun field balance and frequency tuning results (F1 before tuning, F14 after the tuning).

frequency monitoring of the gun during the support fixture assembly.

III. Nb_3Sn Gun Test 1

The gun with the first deposition of Nb_3Sn was tested in a vertical cryostat at Fermilab at 4.4 K. One can find the "Q versus E" curve in Fig. 4.

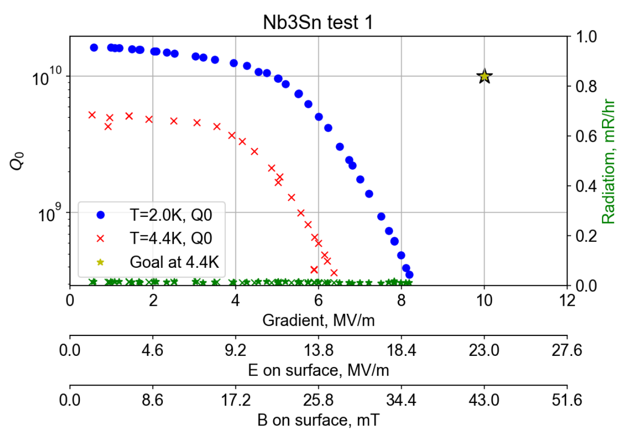

Fig. 4. QvsE curve of the gun covered with Nb_3Sn for the first time tested in liquid Helium Dewar.

Accelerating gradient of 6 MV/m was achieved during the test limited by the power source, however the quality factor at low fields was low, equaled to Q_0=5E9 degrading after 4 MV/m. Possible Nb_3Sn cracking caused underperformance of the gun as was discussed in the previous section. Multipactor and field emission were not observed, benefiting from the improved surface processing developed earlier. The gun was tested at 2.0 K as well resulting in improved "Q versus E" curve. It is important for Nb_3Sn to keep the cooling rate of the gun below 0.1 K/min and temperature across the gun below 15 mK during transition through the critical temperature in order to have minimal thermal currents which might lead to trapped flux during transition into the superconducting state. Ambient magnetic field should also be as low as possible for the same reason. Temperature of the gun and ambient magnetic field were recorded and can be found in Fig. 5. As one can see from this figure magnetic field was below 1 mG and controlled cool down temperatures were as expected leading to the conclusion that the damaged Nb_3Sn layer caused low quality factor obtained during the test.

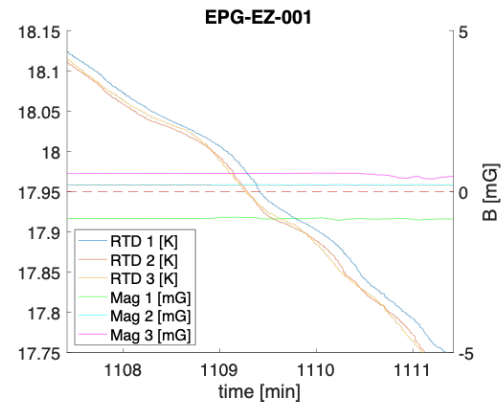

Fig. 5. Magnetic field (Mag_i) and cavity temperature (RTD_i) curves during transition through the critical temperature of Nb_3Sn show slow and uniform cool-down and low magnetic field.

IV. Nb_3Sn Gun Test 2

The damaged Nb_3Sn layer was removed from the gun, followed by the cavity frequency tuning and deposition of a new layer. This time, the gun frequency was monitored during assembly of the reinforcement fixtures to prevent the layer deformations. The frequency was measured and was close to the expected values (see Table I, F_m2=1298.09 MHz). The gun with the second deposition of Nb_3Sn was tested in a vertical cryostat at Fermilab at 4.4 K. One can find the "Q versus E" curve in Fig. 6.

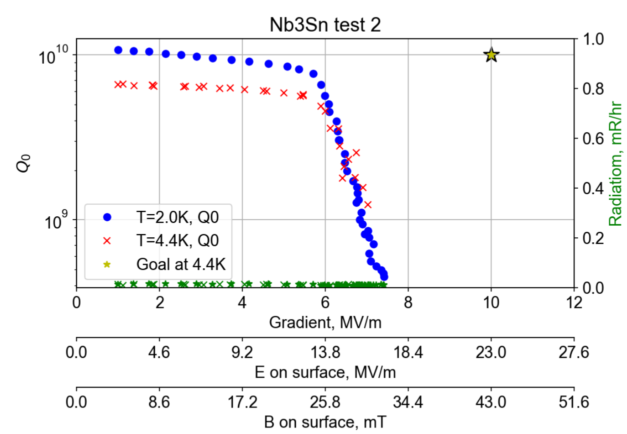

Fig. 6. QvsE curve of the gun covered with Nb_3Sn for the second time tested in liquid Helium Dewar.

The gun showed an improved but lower than expected performance. Accelerating gradient of 7 MV/m was achieved during the test limited by the power source. The quality factor at low fields was low, equaled to Q_0=7E9 degrading after 6 MV/m. No multipactor or field emission were observed. The test at 2.0 K resulted in a improved performance at low fields, however, similar Q factors were observed at high fields. The gun was controlled cool down with ambient magnetic field compensation similar to the previous test. As was found later, the gun was contaminated with Si during Nb_3Sn deposition which resulted in lower than expected quality factor. The deposition furnace is being decontaminated and prepared for the next deposition.

It is worth to mention, that the current gun performance should be able to provide 1 MeV beam at 6 MV/m of accelerating gradient. Power dissipation is around 1 W with the obtained quality factor and is presented in Fig. 7.

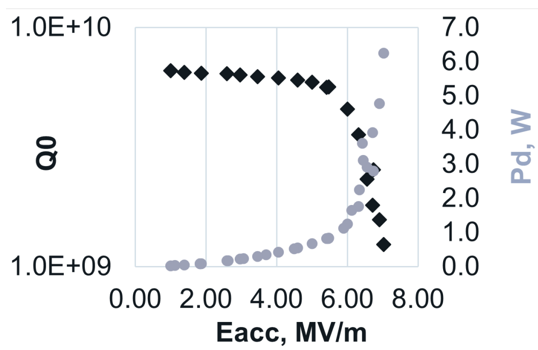

Fig. 7. The second Nb_3Sn test QvsE curve and power dissipation in the gun at 4.4 K

V. Future Plans

The gun will be integrated into the "dry" cryomodule and tested for the initial integration studies and cooling while the deposition furnace being decontaminated and prepared for a new run. Quality factor of the gun cooled by the cryocooler will be measured. The gun will be covered with a new layer of Nb_3Sn and tested in Fermilab's vertical cryostat with the goal to demonstrate high Q_0=1E10 at E_{acc}=10 MV/m and 4.4 K. The next stage will include the gun test at Euclid using conduction cooled cryomodule. The final goal of this project is the development of UED/UEM user facility in Brookhaven National Laboratory in ATF-II bunker. Once the gun performance is demonstrated the whole system will be delivered to BNL where a beam line will be assembled for beam generation and characterization.

VI. Conclusion

Several key milestones towards UED/UEM facility based on conduction cooled SRF photogun have been accomplished:

- Two tests of the gun with Nb_3Sn deposition were accomplished;
- The gun reached E_{acc}=6 MV/m and Q_0=5E9 at 4.4 K at low fields;
- The gun deformation was responsible for the first test underperformance which was recognized and improved with the following test;
- The second test showed a slightly improved performance compared to the first test, however contamination by Si of the deposition furnace resulted in the reduced quality factor;
- There are no visible problems towards achieving the target gradient and quality factor once the furnace contamination is resolved;
- There are four SRF gun cryogenic tests have been performed which can be found in Fig. 8, demonstrating steady improvement to the final goal.

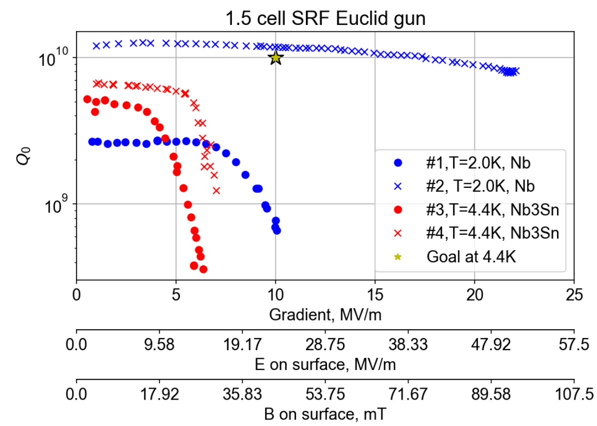

Fig. 8. All the gun test results summarized.

Acknowledgments

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