ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB167

STATUS OF CONDUCTION COOLED SRF PHOTOGUN FOR UEM/UED*

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Abstract

Benefiting from the rapid progress on RF photogun technologies in the past two decades, the development of MeV range Ultrafast Electron Diffraction/Microscopy (UED and UEM) has been identified as an enabling instrumentation. UEM or UED use low power electron beams with modest energies of a few MeV to study ultrafast phenomena in a variety of novel and exotic materials. SRF photoguns become a promising candidate to produce highly stable electrons for UEM/UED applications because of 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]. The use of Nb_3Sn allows to operate SRF cavities at higher temperatures (4 K) with low power dissipation which is within the reach of commercially available closed-cycle cryocoolers.

Euclid is developing a continuous wave (CW), 1.5-cell, MeV-scale SRF conduction cooled photogun operating at 1.3 GHz. In this paper, the technical details of the design and a conduction cooling cryomodule commissioning results are presented.

INTRODUCTION

The use of SRF photogun brings certain benefits compared to normal conducting guns such as: unprecedented repetition rates and reduced almost to zero RF losses. As long as beam current is very low for UED/UEM applications, MW-level RF power source is not required and can be as low as several Watts. However, SRF was not user-friendly because it requires sophisticated cryomodules, experienced personnel and expensive cryogenics until recent proof of principle of conduction cooling at Fermilab [2], in which Euclid participated and Jlab [3].

Euclid is developing a CW, 1.5-cell SRF photogun operating at 1.3 GHz for UED/UEM applications. The design of the gun was based on an existing Euclid's cavity with an "on-axis" coaxial coupler [4], with an additional half-cell, the back wall of which is used for photo-emission. The half-cell geometry was optimized using CST, which was bench marked by ASTRA code [5]. The beam parameters can be found in Table 1 and are suitable for UED/UEM. Beam energy out of the gun is 1.65 MeV which requires field on the cathode of 20 MV/m. This field corresponds to accelerating gradient in a regular cell of 10 MV/m.

* Work supported by US DOE SBIR grant DE-SC0018621
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Table 1: Beam Parameters Simulated by ASTRA

Parameter	Value	Value
Application	UED	UEM
Beam energy, MeV	1.655	1.655
Charge, fC	5	500
Laser pulse length rms, fs	6.4	6.4
Laser spot size rms, um	36	180
Bunch length rms, fs	167	741
Beam emittance, nm	6.6	39.0
Energy spread (relative)	1.3e-5	6.4e-5

SRF GUN

The coaxial "on-axis" coupler has been changed to the conventional side coupler, which can be found in Fig. 1.

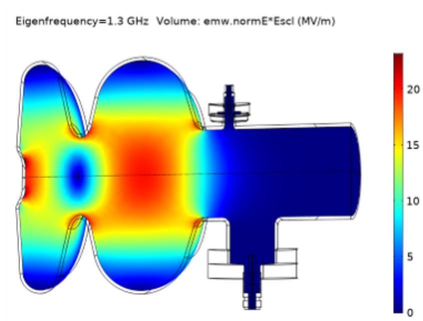

Figure 1: E-field distribution in the gun at E_{acc}=10MV/m.

An additional SMA pick-up feedthrough has also been added. No beam quality degradation has been found in simulations. The gun RF parameters can be found in Table 2 below.

Table 2: SRF Gun RF Parameters

Parameter	Value
Frequency, MHz	1300
Effective length, mm	160 (1.45 cell)
Q_0 at 4 K (Rs = 20 nΩ)	1.1E10
G, Ω	232
R/Q, Ω	176.9
Wall Power dissipation, W	0.9
E_{acc}, MV/m	10
Cathode field, MV/m	20
E_{max} on surface, MV/m	23.5
B_{max} on surface, mT	43.3
Beam energy, MeV	1.6

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The RF dissipated power is below 1 W at quality factor of Q_0 = 1.1E10 and accelerating gradient of 10 MV/m. This field level and quality factor is achievable nowadays even for 9-cell Tesla cavity [1]. The design of the gun has been optimized and finalized for fabrication. The gun was manufactured (see Fig. 2), the resonant frequency was 1 MHz higher the target value, which was tuned after receiving of the cavity. The gun is under routine chemical processing and will be tested in liquid helium first to benchmark the performance of the bare cavity. After that the cavity will be covered with Nb_3Sn and tested in liquid helium again to ensure a good coating is obtained. The covered gun will be tested in Euclid's conduction cooled cryomodule to demonstrate 10 MV/m of accelerating gradient.

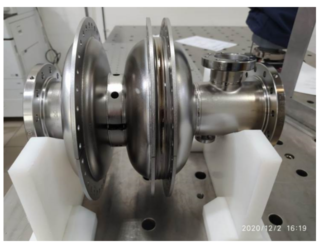

Figure 2: 1.5 cell Nb SRF gun with cooling rings welded.

CRYOMODULE DESIGN

A compact cryomodule has been developed by Euclid to accommodate the SRF photogun. The gun has an extremely low current requirement for UED/UEM, and is excited through RF cables. The cavity is cooled by a commercially available Sumitomo cryocooler though a high-purity AL bus that is connected to Nb rings welded to the cavity equators. For that project, there were no existing cryomodules available for conduction-cooling, and Euclid started the development of its own cryomodule to host a 1.3 GHz, 1.5-cell gun. The cryomodule with the gun is shown in Fig. 3.

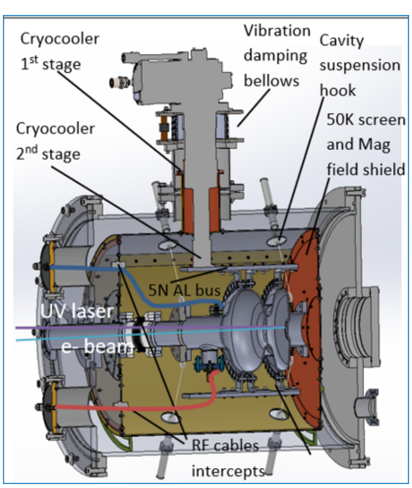

Figure 3: Solidworks models of Euclid-developed UED/UEM system based on a SRF photogun.

It has a cylindrical shape, in order to provide increased rigidity compared to a rectangular shape, which would have required additional stiffening ribs. The outer diameter of the vacuum vessel is 24 inches, and is large enough to host a 1.3-GHz cavity with its cooling links. The cooling links are made from 5N aluminum (k = 3–5 kW/m/K), and connect the 2nd stage (4 K) of the cryocooler to the cavity, which has welded Nb rings on the equators of the cells. A comprehensive thermal analysis with temperature-dependent material properties and contact resistance was performed to estimate the stable operating regimes. The results are presented in Fig. 4. As one can see the cryocooler capacity is higher than the dissipated RF power in the cavity at 10 MV/m of accelerating gradient for the case of surface resistance equals to BCS surface resistance of Nb_3Sn as a function of cavity frequency (1300 MHz) and residual resistance of 10 nΩ and 20 nΩ.The cavity will be stabilized at the left point of these two curves intercetion.

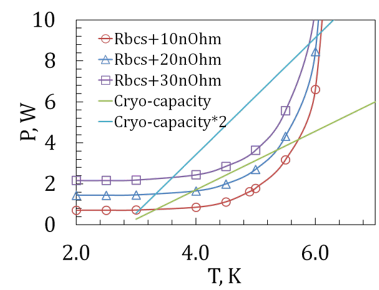

Figure 4: RF Power dissipation in the cavity at 10 MV/m and different temperatures together with the cryocooler capacity curve.

It was found that for the Q-factor $Q_0 = 10^{10}$ at 10 MV/m, the cavity can be stabilized at around 4 K, having less than 1 W of dissipated power. This Q-factor value is a bit ambitious, but is achievable (see [2]). One cryocooler should be enough to cover this dissipated power and the additional heat leak into the 4 K zone. The Sumitomo SRDK-418 Gifford-McMahon (GM) cryocooler was chosen because it has 2 W of cooling power available at 4.2 K with only 8 kW of wall-plug power consumption.

The cryocooler is placed on a standard 8-inch-OD CF sleeve through a bellows to reduce vibrations and to compensate for thermal shrinkage during the cool-down. A 30-K thermal screen is connected to the 1st stage of the cryocooler to intercept heat radiation and conduction through different sources. The total heat flux to the intercepting shield and 4 K zone are summarized in Table 3. The static heat flux to the 4 K zone is below 0.2 W, and to the intercept zone is around 20 W. The intercept temperature for a 20 W heat load can be found from the capacity map and is equal to 30 K.

Another important parameter of this cryomodule is the magnetic field shielding. The Earth's magnetic field (500 mG) can destroy the quality factor of SRF cavities because of the high sensitivity of their surface resistance to magnetic fields, which is equal to 0.8 nΩ/mG for Nb_3Sn.

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Table 3: Cryomodule Static Heat Loads

Source	30 K Zone	4 K Zone
Radiation, W	2	0.01
Beam pipe, W	17	0.03
Suspension, W	NA	0.05
RF cables, W	0.8	0.05
Total, W	20	0.14

Magnetic shielding was added on top of the intercepting copper screen (see Fig. 3 for details, magnetic screen - yellow). The cryogenically rated magnetic shielding material amuneal-4K^{TM} was used, since it is applied on the radiation screen that has a temperature of 30 K.

CRYOMODULE COMMISSIONING

Magnetic Field

The field inside the screen was measured at room temperature with a high sensitivity Bartington^{TM} fluxgate is presented in Fig. 5. The inset represent the gun longitudinal position relative to the measured field. Magnetic field was measured along the screen axis at different vertical positions. Magnetic field leakage was discovered closer to the OD of the screen (Y = 220 mm) but taking into account the gun radius is close to 100 mm, the magnetic field seen by the gun is less than 10 mG at room temperature. Nevertheless, shunting magnetic strips were applied and the leakage field of 220 mG was reduced below 10 mG at Y = 220 mm. The measured magnetic field is in good agreement with Comsol simulations. The difference in the amplitude between the measurements and the simulation is caused by the expected degradation of the properties of amuneal-4K^{TM} at room temperature. The shielding should be more efficient at cryogenic temperatures which will be measured in the near future.

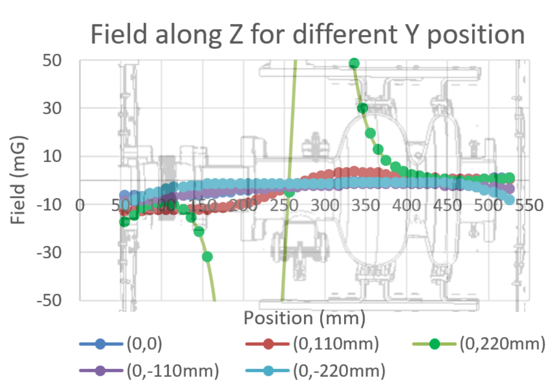

Figure 5: Magnetic field measured inside the screen at room temperature (the inset represents the gun longitudinal position).

1st Cool Down

The cryomodule was manufactured, assembled and tested with no gun installed. The cooldown curves are presented on Fig. 6. The 2nd stage, which did not have anything connected to it, reached 2.5 K (see C2), while the 1st stage, which is responsible for thermal shielding reached 28 K (see C1), a temperature that is very close to the value estimated during the developmental stage. The second stage reached its equilibrium temperature much faster, as it did not have any mass to cool (see the red curve in Fig. 6), while the 1st stage had the thermal screen connected to it (see the white curve in Fig. 6).The temperature drop discovered between C1 (1st stage) and C3 (side cap of the radiation screen) indicates a poor thermal contact which will be improved in future.

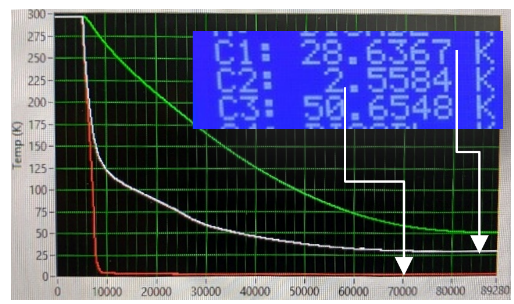

Figure 6: Measured temperature during cool-down (in seconds), with an inset of the final temperatures detected.

FUTURE PLANS

The final goal of this project is the development of UED/UEM user facility in Brookhaven national laboratory in ATF-II bunker. The initial agreement is already obtained. 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.

CONCLUSION

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

- The gun power coupler and pick-up has been redesigned, followed by beam tracking simulations.
- The conduction cooled cryomodule has been designed and commissioned: low magnetic field (below 10 mG at room temperature) was obtained; the cryomodule has been cooled down to 2.5 K.
- SRF gun drawings have been produced. The gun was manufactured (and delivered to Fermilab for routine chemical treatment and cryogenic high power test in liquid helium.

ACKNOWLEDGMENTS

We would like to thank the Department of Energy Small Business Innovation Research office for their support provided to conduct the research: grant #DE-SC0018621.

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