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RF TESTBED FOR CRYOGENIC PHOTOEMISSION STUDIES

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Abstract

Producing higher brightness beams at the cathode is one of the main focuses for future electron beam applications. For photocathodes operating close to their emission threshold, the cathode lattice temperature begins to dominate the minimum achievable intrinsic emittance. At UCLA, we are designing a radiofrequency (RF) test bed for measuring the temperature dependence of the mean transverse energy (MTE) and quantum efficiency for a number of candidate cathode materials. We intend to quantify the attainable brightness improvements at the cathode from cryogenic operation and establish a proof-of-principle cryogenic RF gun for future studies of a 1.6 cell cryogenic photoinjector for the UCLA ultra compact XFEL concept (UC-XFEL). The test bed will use a C-band 0.5-cell RF gun designed to operate down to 40 K, producing an on-axis accelerating field of 120 MV/m. The cryogenic system uses conduction cooling and a load-lock system is being designed for transport and storage of air-sensitive high brightness cathodes.

INTRODUCTION

The broad context for this work is the development of accelerator based light sources. At this point they are ubiquitous in large scale science important to many fields as far ranging as chemistry, biology, and material science and engineering [1]. Light sources have evolved in several generations over the decades beyond their initial origins as parasitic applications of high energy physics machines to the enormous dedicated facilities that they are today. The most recent generation of light sources includes the X-ray free electron laser (XFEL). XFEL facilities, such as the LCLS at SLAC National Laboratory, are kilometers in scale and require a significant investment for real estate and infrastructure, upwards of hundreds of millions of US dollars. Reducing these costs to make XFELs more accessible to smaller laboratories then becomes a tempting goal.

As part of the National Science Foundation Center for Bright Beams, we are also interested in pushing the limits of achievable electron beam brightness, here roughly speaking defined as the density of the electrons within the beam's 6 dimensional phase space. For this work, we are then interested in the development of future, next generation accelerator based light sources based on reducing the scale of XFELs by utilizing high brightness electron beams. We have proposed an ultra-compact X-ray free-electron laser (UC-XFEL) concept totaling about 40 m in length [2]. Producing and manipulating the high brightness beam relies on combining several enabling novel technologies, many of which rely on cryogenic regimes of operation such as the normal conducting accelerating cavities, photoinjector, unduluator magnets, and solenoid magnets. We are here concerned primarily with the investigating the normal conducting cryogenic RF photoinjector. Specifically, we are most focused on the improvements to beam brightness that we can obtain with temperatures at or below liquid nitrogen temperatures (77 K) and above liquid helium (4 K).

One can derive an expression for the scaling of the expected electron beam brightness limit born from the photocathode using a simplified 1D model [3]:

$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c} \left(E_0 \sin\phi_0\right)^2 . \qquad (1)$$

Where e, c, k_B, and ε_0 are the usual fundamental constants, T_c is the temperature of the emitted electrons, E_0 is the launch field, and ϕ_0 is the phase of the accelerating field. We note that the brightness at the photocathode scales as the launch field squared so we have an strong incentive to increase the accelerating gradient as high as possible. We draw from the extensive research into high gradient RF structures. Gradients in copper cavities are generally limited to around 120 MV/m because electric breakdown rate becomes too significant above that. However, cooling copper to cryogenic temperatures increases material hardness, reduces coefficients of thermal expansion, and lowers surface dissipation. Experiments have shown that fields up to 250 MV/m could be supported at 45 K [4]. Equation (1) implies over a factor of 4 increase in brightness.

While there exist many open questions concerning the exact physics behind the complicated phenomena leading to electric breakdown, the practical implications operating at cryogenic temperatures to increase the accelerating gradients in acceleration structures has been well studied [5]. The proposed UC-XFEL photoinjector is a 1.6-cell RF photogun operating at the C-band frequency of 5.712 GHz at 45 K with a peak on axis accelerating gradient of 240 MV/m. The cavities are a reentrent design to increase shunt impedance. This also decouples the cells so each must be independently fed. One possibility is that each is fed with symmetric transverse waveguide coupling in a racetrack geometry. The complicated nature of this device and the optimization of many ancillary systems such as gun alignment and cooling necessitates the development of a simpler proof-of-concept before this is attempted.

Still to be understood in greater detail is the impact of cryogenic temperature on the photoemission process of the cathode and how this can effect photoinjector brightness.

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Studies of cryogenic cathodes have been done at Cornell for example in a DC gun environment successfully [6] and comprehensive studies of cathode optimization in different photoguns has been performed [7]. In order to extend this work and make it applicable to the UC-XFEL concept we further want to integrate cryogenic emission measurements into an RF environment. The solution is then to design and commission a compact cryogenic photoemission test bed using a 1/2 cell C-band normal conducting cavity photogun based on the UC-XFEL style reentrant cavity designs and operate it in conjunction with a specially designed cathode exchange system and electron beam diagnostic line.

HALF CELL PHOTOGUN

In our design for a simpler test gun for cathode tests, we note that for beams with very low emittance at room temperature, the thermal motion of the electrons from the cathode could be limiting factor. In the limit as the incident photon energy approaches the photoemission threshold, $h\nu \rightarrow \varphi_{\mathrm{eff}}$, the electron photoemission temperature approaches the thermodynamic cathode temperature. We can again refer to Eq. (1) to see that this implies brightness scales inversely with the cathode temperature in this case. Model predictions for copper have been performed and show that cooling a copper cathode from room temperature to below 30 K reduces the possible minimum T_c by an order of magnitude [3].

Cavity Design

The design of the 1/2-cell's particular geometry is based on a reentrent nosecone design. Field maps for the E and H field magnitudes can be found in Fig. 1. Various cavity specifications are listed in Table 1.

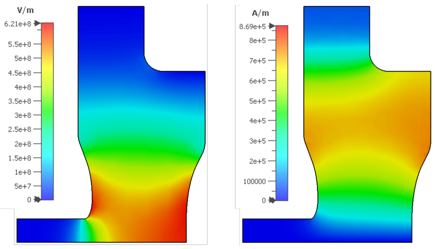

Figure 1: $\frac{1}{2}$−cell gun cavity fields: E on the right and H on the left. The backplane where the cathode is located is on the right and emitted electrons travel to left.

Table 1: 1/2-Cell Photogun Specifications

Paramater	**Values**	**Units**
Operating temp	45 – 77	K
Launch field	120 – 240	MV/m
Frequency @ 77 K	5.712	GHz
β @ 77 K	4	-
Q_0	24750	-
Q_{ext}	6056	-
Laser λ	250 – 350	nm

Our launch field will be in excess of 120 MV/m, well below the maximum possible gradients implied by the high power RF power breakdown tests [4]. In addition to testing the cathode properties at low temperature, the cryogenic temperature here is primarily useful for RF stability and reducing the heat load. Indeed there is expected to be a 2.9 factor of improvement of Q_0 from 300 K to 77 K. In addition, the coefficient of thermal expansion becomes smaller at cryogenic temperatures so the smaller C-band cavity becomes less sensitive to detuning due to temperature instabilities as we get colder. We have designed our cavity to have the target 5.712 GHz frequency at 77 K to allow a wide range of tuning temperatures since our minimum expected temperature is 45 K including our predicted heat leaks. We do not want meeting our resonance condition to be limited by unexpected heat leaks.

Cooling Considerations

The main development challenges remaining are the implementation of the 1/2-cell gun cryostat, especially in terms of thermal isolation and the cooling power our cryogenic infrastructure needs to provide. In order to reduce infrastructure needs and generalized cost, we are opting for conduction cooled coupling from the cavity and cathode to the cryocooler which extracts around 100 W at 45 K. Our current best estimate for thermal leaks includes those from cable feedthroughs, downstream beam pipes, upstream cathode exchange connection and RF pulse heating (which can be minimized by operating at low repetition rates). The expected leak rate is about 20 W, but this will increase as more tuning and alignment feedthroughs are added. Our cryostat is a large 2'x2' chamber manufactured by IdealVac with modular, removable face panels that custom feedthroughs can be added and replaced for a useful amount of versatility.

In order to reduce the load on the cryocooler, we have opted for a single port RF feed to the gun from a WR-187 waveguide rather than 2 symmetric racetrack style waveguide feeds. We accomplish this with a dummy load to symmetrize the field within the cavity. We also add a waist in the waveguide in order to attenuate the RF on the dummy port side for the installation of diagnostic probes. This can be seen on the bottom RF port of the cavity in Fig. 2.

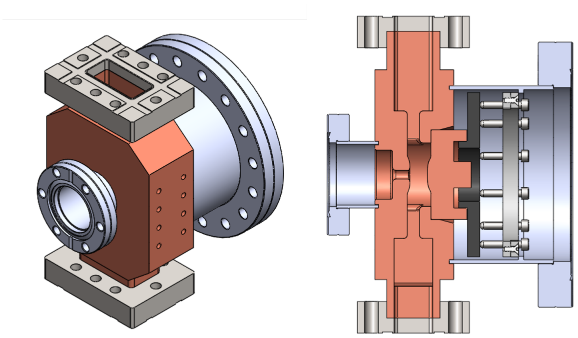

Figure 2: CAD design for fully fabricated 1/2 cell gun.

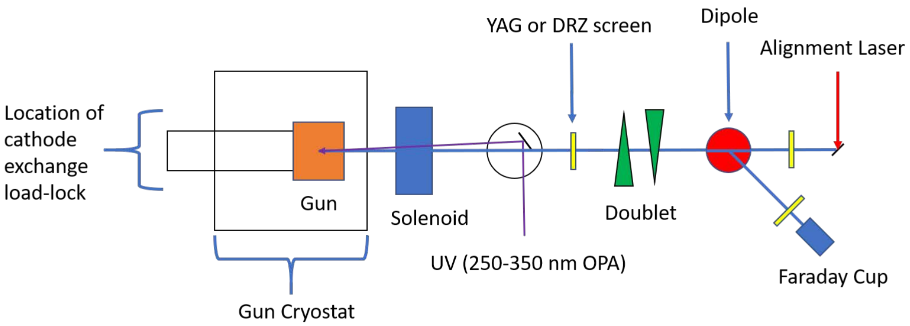

Figure 3: Schematic of the first iteration of the diagnostic beamline. The cryogenic load lock and possible TEM grid [8] will be added in the second iteration after initial copper cathode measurements.

Cryogenic Load Lock

We include a fully removable backplane for replacing cathodes via a press fit inspired by the FERMI II gun backplane which was designed to satisfy similar needs at the Sincrotrone Trieste (ST) facility [9].

The high brightness cathodes we intend to study are highly air sensitive. In order to test them once the cathode exchange back-plane is added to the gun, an ultra high vacuum (UHV) compatible transfer system that is compatible with cryogenic cooling is a requirement. This system is under development and combines features of the Cornell DC gun cathode exchange [6] and the load-lock cathode exchange setup used for the APEX project at LBNL [10]. We further introduce a novel method of cathode gun RF seal and coupling based on a thermal interference fit and will soon begin testing the robustness of the technique with respect to continued thermal cycling.

DIAGNOSTIC LINE

The diagnostic beamline will be used for making two relevant measurements as a function of temperature in the cryogenic range: quantum efficiency (QE) and mean transverse energy (MTE). QE refers to the ratio between the number of absorbed photons and emitted electrons and MTE is the well-established figure of merit used to measure intrinsic cathode emittance [7].

Due to the complicated nature of the setup, the two main diagnostics will be added in two iterations of the beamline. The first iteration is depicted schematic form in Fig. 3. It consists of a focusing solenoid as close to the gun as the cryostat envelope allows followed by the laser box where the tunable UV laser will be used to illuminate the cathode under test. A quadrupole doublet will be used for additional downstream focusing for scans for a coarse emittance measurement; downstream, a deflecting dipole and Faraday cup will be used to measure the charge at various energies, allowing a precise measurement of QE. The first iteration will only be used with the copper cathode backplane for initial commissioning and cryogenic emission tests of copper. The high brightness cathodes have MTEs lower than will be accurately measured with a coarse quad scan so the second beamline iteration will contain an additional, more precise MTE measurement setup for low charge beams based on a transmission electron miscroscopy (TEM) grid [8].

CONCLUSION AND FUTURE WORK

UCLA Particle Beam Physics Laboratory is developing a compact electron beamline for testing high brightness photocathodes at cryogenic temperatures to support the realization of the ultra-compact XFEL. The full gun design is currently under review at Comeb for manufacturing. We are currently in the process of planning the commissioning of existing large gun cryostat and high power Sumitomo cryocooler. With respect to the diagnostic line, a redesign of the pole faces of existing dipoles is necessary and the focusing solenoid's novel design is discussed in greater detail in [11]. Finishing the laser line which will illuminate the cathode also needs to be completed. The timeline for cathode tests will be as follows: cryogenic QE measurement of copper cathode with beamline iteration one, cryogenic precise MTE measurement of copper cathode with beamline iteration two, cryogenic QE and precise MTE measurement of high brightness cathode with beamline iteration two and functioning cryogenic load lock.

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