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CRYOGENIC BRIGHTNESS-OPTIMIZED RADIOFREQUENCY GUN (CYBORG)

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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 45 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 primary motivational concept for much of the work at UCLA regarding cryogenic operation of normal conducting cavities is the 40 meter, ultra compact x-ray free electron laser [1]. It is based on the use of a combination of several novel technologies including, most notably, high gradient cryogenic C-band linac sections and photoinjector. We note that the photoinjector is a complex, novel device and so would be difficult to realize without a stepping stone.

As a prototype, we have thus designed and fabricated a 1/2-cell CrYogenic Brightness-Optimized Radiofrequency Gun (CYBORG) to serve as this stepping stone. It thus has three main functions. The first is as a general fabrication and RF test. We have examined in detail the beam dynamics for reentrant cavities with high spatial harmonics in simulation [2] but this is our first high gradient, cryogenic gun experiment. The second function is to serve as a development platform for infrastructure, especially in C-band RF and cryogenics.

The third function primarily refers to our collaboration within the National Science Foundation's Center for Bright Beams (NSF CBB). We are particularly interested in improving the brightness of electron bunches at the cathode [3]. Referring to a useful scaling law for the 1D beam brightness from equation 1, we expect to see improvements in the electron brightness that scale as the square of with the launch field and inversely with the cathode temperature, provided that we are near the photoemission threshold. Cooling also

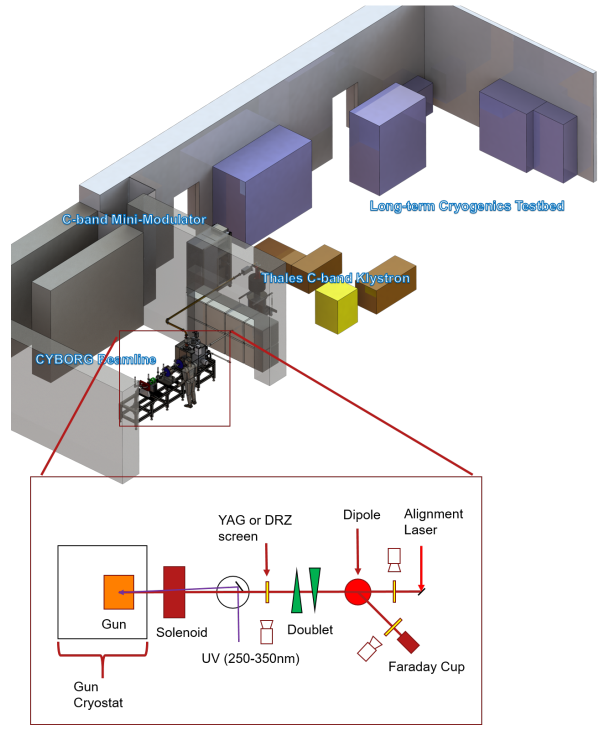

Figure 1: MOTHRA lab for developing CYBORG diagnostic beamline and general cryogenic and RF infrastructure.

lowers the quantum efficiency so we have an incentive to employ more novel, high QE cathodes such as semiconductors for our brightness needs [4].

$$B_{1d} \approx \frac{2ec\varepsilon_0}{k_B T_c} \left(E_0 \sin \varphi_0\right)^2 \tag{1}$$

Figure 1 shows a diagram of our lab space with an inset denoting the first phase of the CYBORG beamline. Our plan is to commission the beamline for eventual novel cathode testing but our first development phase will focus on the production and measurement of quantum efficiency (QE) and mean transverse energy (MTE) from a cryogenic copper cathode.

DESIGN

The device itself is composed of two half cavity pieces, brazed together, and a copper cathode backplane pressed into place. We initially considered a split in the y-z plane but the high machining tolerances in certain locations made it difficult to split. So the split for the braze joint was made in the x-y plane as shown. It is also worth noting that we use DESY/RIKEN UHV flanges on WR-187 waveguide.

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Table 1: RF Parameters at Different Temperatures

Parameter	295K	100K	77K	40K
Frequency	5.695 GHz	5.711 GHz	5.712 GHz	5.713 GHz
Q_0	8579	18668	24200	39812
β	0.7	1.53	1.98	3.26
Filling time	-	0.41 μs	0.45 μs	0.52 μs
RF power	-	1.19 MW	1.13 MW	1.04 MW
Energy deposition	-	0.191 J/pulse	0.15 J/pulse	0.097 J/pulse

RF Considerations

The RC cavity is a half cell using the reentrant style with an intended launch field of 120 MV/m. The surfaces are optimized, in collaboration with SLAC, to obtain high shunt impedance. For the most part, this keeps the expected energy deposition in the cavity walls manageable. We can see representative numbers in Table 1.

We include multiple temperature working points here since it is beneficial to operate at several temperatures for the sake of basic cathode physics research. RF parameters are not provided for the room temperature case because it is not an intended working point with the existing unmodified cavity geometry. One of the reasons why we do not have a working point at more ambitious temperatures below 45 K is due to the empirical observation of a local minimum in surface resistivity which we discuss more in related publication [5].

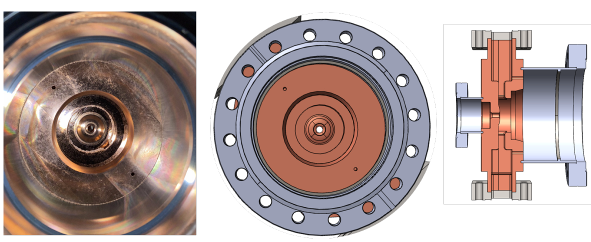

Figure 2: $\frac{1}{2}$−cell gun cavity surfaces without backplane shown.

With respect to the cavity's sensitivity to thermal contraction, we can note that under 77 K, the cavity should be relatively insensitive to temperature detuning which may enhance of RF stability. However, since our cavity will be within a cryostat and inaccessible most of the time for any mechanical tuning it is important to identify the most sensitive RF surfaces and respond accordingly by making their permissible machining tolerance tighter. Our algorithm for doing so is by setting as default each surface to a 10 micron tolerance. Slater's perturbation theorem is used to compare detuning and, for highly sensitive surfaces, we reduce the tolerance down to 5 micron [6].

For forward compatibility with our cathode tests we want to allow for a suite of insertable cathodes. The general template we can consider for the future is the INFN style mini puck [7]. This style is currently being used in a collaboration between UCLA's PEGASUS lab and Cornell University. We considered multiple topologies but ultimately decided for a fully removable back plane using the press fit in the style of the FERMI gun [8]. By using a fully demountable back plane we also have the ability to fine tune the RF cavity resonance where needed by modification of future back plane variants. In Fig. 2 we can see the front of the cavity without the back plane in place in order to see the cavity surfaces.

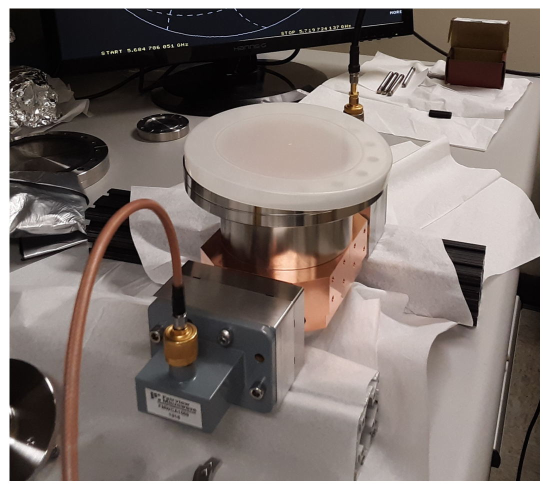

Figure 3: Photo of LLRF setup used for initial $\frac{1}{2}$-cell measurements.

Thermal Considerations

Also we note here for RF power delivery we considered a racetrack but this would be a large, un-needed thermal load and adds more UHV volume. Instead, we use only one RF feed with a dummy port to symmetrize the fields. We included a choke on the dummy port to attach an RF diagnostic probe closer to the gun.

Liquid cryogen cooling is challenging due to the large infrastructure required. Instead, we use a low temperature cryocooler cold head and compressor instead. The coupling between the gun and the cryocooler is made through pressed thermal contact connections and flexible copper thermal straps. The tapped holes on the sides of the gun where these connections will be made are visible in Figure 3.

Using this fully defined gun we can work on thermal simulations. In Fig. 4 we show a representative simulation using existing cryocooler specifications and other hardware specifications, including those of the thermally conduction, vibration isolating straps currently being manufactured by Tech Apps.

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Allowing for 15 W of cooling and 3 W unanticipated heat leak budget, the phase 1 setup is expected to reach 65 K. The main sources of heat leakage are the waveguide and downstream CF flange. To limit this leak, a 35 cm stainless steel waveguide plated with copper is used as a thermal break. In the future, heating may be further reduced with thinner walled steel waveguide and some novel geometries. The downstream flange is connected using edge welded bellows as a thermal break. Cooling is sufficient at low temperatures to achieve target operating temperatures, but alignment becomes an issue.

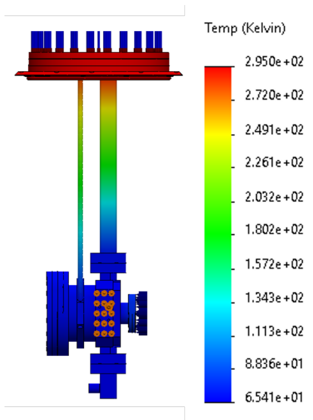

Figure 4: Thermal simulations of gun using the capacity curve of the CH-110LT cryocooler and estimated heat loads from beampipe and waveguide section.

LLRF MEASUREMENTS

Preliminary, low level RF (LLRF) measurements of the 0.5-cell have been performed. We found that the resonant frequency at room temperature is 6 MHz higher than simulation. We attribute this primarily to the presence of braze material in the edges of the cavity where magnetic field is high. The presence of this extra brazing material around the circumference decreases the inductance and increases the frequency slightly. We then use S_{11} to calculate Q_0 and loaded Q, Q_L. These results are consistent with expectations with Q_0 approaching its design value with clamping. The extra 6 MHz offset puts us slightly out of the bandwidth of our RF source below 77 K. We have worked out an additional working point of 100 K which should be in this bandwidth. The klystron bandwidth provided by the datasheet will be verified using a new mini-modulator, presently under construction.

Table 2: $\frac{1}{2}$-Cell Photogun LLRF Measurements

Parameter	Measurement	Design
f_0	5.701 GHz	5.695 GHz
β	0.52	0.7
Q_L	$\approx$ 5,000	5,167
Q_0 (partially clamped)	$\approx$ 4,600	-
Q_0 (fully clamped)	7,649	8,579

DISCUSSION

The versatile design of the 0.5-cell cavity will permit the correction of this 6 MHz detuning by modifying the backplane. We can remove a small bit of material in our next backplane in a high magnetic field, low electric field region to increase the inductance and lower the frequency again. Simulations shows this as a small divot, parametrized by radius, being scanned to obtain the design frequency of 5.695 GHz. The results of this study are shown in Figure 5. We can do this without changing the on-axis electric field notably.

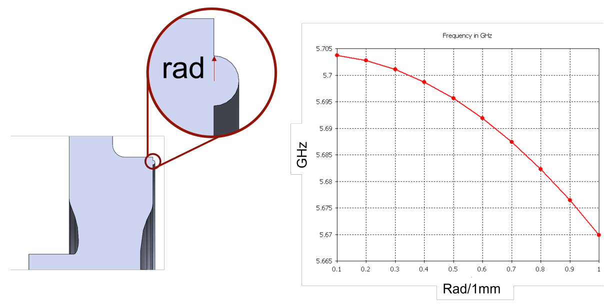

Figure 5: (Left) Divot added in next back plane variant in order to tune cavity back to design frequency. (Right) Parameter sweep of radius of divot.

Additional backplane variants include one with an on-axis hole to facilitate bead pull measurements and another with to interface with cathode plugs. Even without a modified backplane we can aim for 100 K operation. We will also continue commissioning tests including a bead drop LLRF tests; UHV pump down tests and RF and cooling optimization.

CONCLUSIONS

CYBORG is part of a planned high gradient cryogenic cathode test bed and also constitutes a stepping stone towards a high gradient, cryogenic photoinjector. Preliminary LLRF tests have begun and are ongoing. Next steps are finishing the infrastructure for high power tests and diagnostic beamline.

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