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CYBORG BEAMLINE DEVELOPMENT UPDATES

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Abstract

Xray free electron laser (XFEL) facilities in their current form are large, costly to maintain, and inaccessible due to their minimal supply and high demand. It is then advantageous to consider miniaturizing XFELs through a variety of means. We hope to increase beam brightness from the photoinjector via high gradient operation (>120 MV/m) and cryogenic temperature operation at the cathode (<77K). To this end we have designed and fabricated our new CrYogenic Brightness-Optimized Radiofrequency Gun (CYBORG). The photogun is 0.5 cell so much less complicated than our eventual 1.6-cell photoinjector. It will serve as a prototype and test bed for cathode studies in a new cryogenic and very high gradient regime. We present here the fabricated structure, progress towards commissioning, and beamline simulations.

INTRODUCTION

Beam brightness improvements at the cathode is one of the main goals of the next generation of linear accelerators. The methods by which we would like to achieve these improvements are typified by the scaling law shown in Eq. (1).

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

We note that this implies strong beam brightness increases with increasing launch field E_0 and decreasing cathode temperature T_c at or near the photoemission threshold [1]. The advantage of cryogenic operation of a photogun is further strengthened by fundamental physics research showing the increased accelerating gradient able to be sustained in a normal conducting cavity at low temperatures [2]. These effects should be able to be harnessed in variety of photogun designs. Of particular interest is the conceptual ultracompact xray free electron laser (UCXFEL) photoinjector [3, 4]. The device in question is complicated and in many ways a new paradigm in photoinjector design. As a result, we are constructed a new beamline to study a new CrYogenic Brightness-Optimized Radiofrequency Gun (CYBORG) [5].

We then take this opportunity to highlight some of the significant engineering challenges associated with the construction and operation of the CYBORG beamline.

GUN DESIGN

As previously presented, the gun is a 1/2 cell C-band reentrant cavity with single RF feed through and symmetrized dummy load port. It is a modified test geometry of the Tantawi-style distributed coupling optimization [6]. It was designed to operate at the frequency of 5.712 GHz at 77K when considering thermal contraction. The cavity was fabricated in 2 pieces and brazed in order to permit higher tolerance machining of the transverse coupling ports [5]. Furthermore, inspired by the FERMI photoinjector at Elettra, the back plane including the cathode is entirely demountable by hand [7]. This is especially useful in providing versatility to modify the gun where necessary.

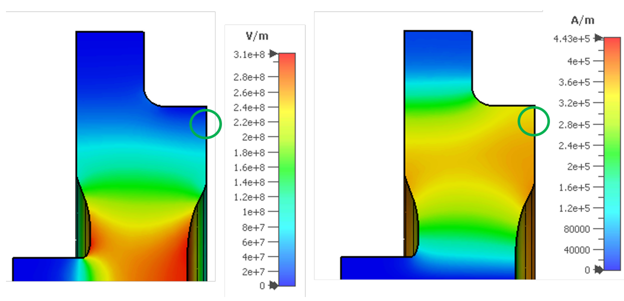

Figure 1: CYBORG RF simulations showing electric (left) and magnetic (fields). Circled is a low electric high magnetic field area ideal for tuning modifications.

Cavity Tuning

The first modification we have in mind is the introduction of a tuning groove. During fabrication excess braze material built up around the circumference of the cavity. As presented previously, low level RF tests have been performed showing a slightly higher frequency then design specifications by 5–6 MHz. We can use an LC circuit model of the cavity to understand this:

$$\omega = \sqrt{\frac{1}{LC}} \ . \qquad (2)$$

The presence of braze material removes a small vacuum volume in high magnetic field region we decrease inductance increasing resonant frequency. To return to our design frequency of 5.695 GHz at room temperature we can add a small vacuum volume in high magnetic field region to increase inductance (i.e. adding smooth groove or dimples in surface by removing material in the back plane). The ideal location for this is shown in Fig. 1. We are especially careful not to place this groove in an area with high electric field since the added discontinuity in surface smoothness could increase the chance of electric breakdown by increasing the surface field beyond potentially manageable levels.

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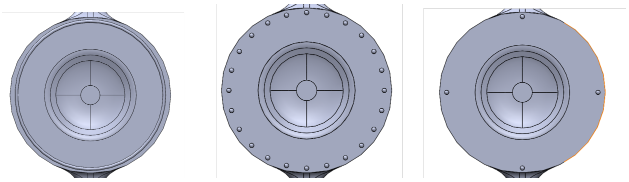

Figure 2: Different perturbations examined for retuning the cavity. (Left) cylindrically symmetric groove with elliptic profile most ideal when compared to (middle) many shallow dimples and (right) a few deep dimples.

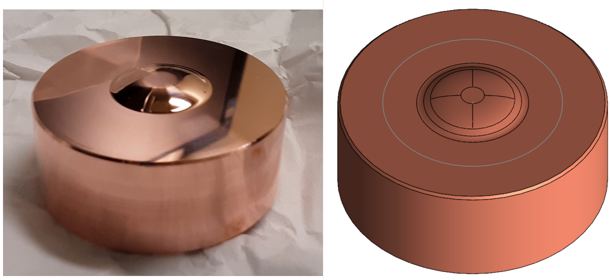

Figure 3: (Left) Unmodified demountable cathode backplane (Right) Location of elliptical tuning groove.

We consider multiple different perturbations in the pursuit of an ideal geometry to allow the appropriate tuning. Three of these geometries are shown in Fig. 3. We consider fully cylindrically symmetric grooves with circular and elliptical profiles, multiple shallow dimples, and a few deep dimples. The most advantageous of these modifications is the fully cylindrically symmetric grooves with elliptical profiles. The circular profile creates a sharp ridge which increases electric fields locally. The dimples do not remove sufficient material to increase the frequency by the desired 5–6 MHz. To give a visual illustration of what this modification will look like we include Fig. 3.

Vacuum Considerations

As an additional nuance we note that the deep divots did not significantly impact the resonant frequency and field from a tuning perspective but they may be able to aid in another design challenge; that of achieving sufficient UHV performance in the cathode cavity. For forward compatibility with air sensitive semiconductor cathodes, the gun and cathode cavities must achieve at minimum ultra high vacuum below 10^{-10} torr. This is especially difficult in our first phase of development where we will only be testing copper cathodes and have no direct pumping of the cathode antechamber. More about the phases of development is explained here [5]. The complex UHV geometry is shown in Fig. 4 in the context of a UHV molecular dynamics simulation using MOLFLOW+ [8]. We can see the downstream beam pipe to the left and the waveguide coming on from above are the nearest locations for pumping. The small central cylinders is the 1/2 cell cavity and the much larger chamber to the right is the cathode backplane antechamber.

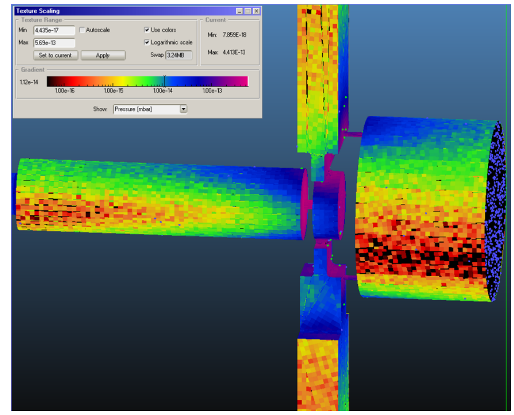

Figure 4: MOLFLOW+ [8] simulation of the CYBORG cavity including the large cathode antechamber which is inaccessible to direct pumping in our initial phase of experiments.

We can see that two venting ports have been added in the waveguide away from the cavity in the waveguide.

We may be able to add additional through holes for pumping in the cavity based on the idea of changing the dimples in Fig. 2 into through holes since they do not seem to significantly change the eigenmodes and electric field. However, further examination is necessary.

RF POWER

Progress in the production of sufficient RF power is ongoing. As previously mentioned, the intention is to operate at Cband frequencies to limit the power needed to power the cavity [9].

The Thales Cband klystron was activated to produce sufficient output to run the photogun, potentially up to 1 MW. However, a custom modulator was used that was originally designed for S-band XK5 SLAC style klystrons. Development of a Cband designated miniaturized version of this modulator is ongoing. A schematic of this minimodulator is shown in Fig. 5 with the 6-cell pulse-forming network using GE capacitors visible in the center. We further are pursuing a design for a Cband SLED system for eventual increased power in collaboration with SLAC.

CRYOGENICS

The final significant sub system under examination is the integration of a usable photogun within a fully realized cryogenic setup. For cost reduction and in order to avoid the complicated liquification and liquid cryogen infrastructure, we opt for conduction cooling via cryocoolers. The use of cryocoolers fits well within the paradigm of cost reduction and miniaturization implicit in a UCXFEL type machine.

Thermal isolation of the gun from its surrounding room temperature environment is challenging due in no small part to the many cryostat penetrations necessary. Particularly notable are the waveguide, downstream beam pipe, and eventual upstream cathode exchange load lock. Both of the

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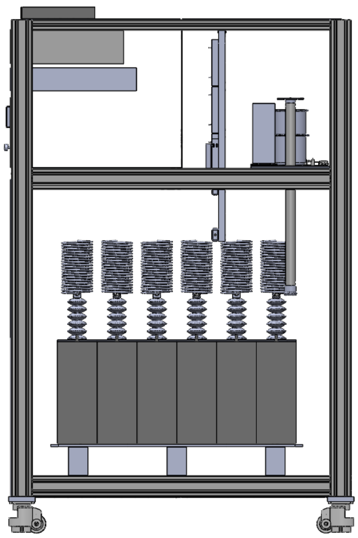

Figure 5: Cband minimodulator with visible 6 cell pulse forming network (PFN).

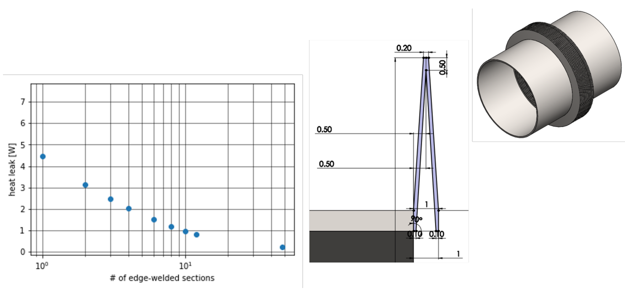

Figure 6: Equivalent heat heat leak for 2-3/4" edge welded bellows as a a function of number of welded discs. Relevant as this will help with thermal isolation.

later penetrations can take advantage of edge welded bellows potentially reduce the heat leaks. A thermal simulation demonstrating this idea is shown in Fig. 6. Here we show that 20 edge welded bellow sections for a 2-3/4" flange reducing the heat leak of an equivalent pipe from 4.5 W down to less than 0.5 W.

We can also account for all the significant heat leaks present in the setup to perform transient cooldown simulation given capacity curves of our cryocoolers. We show this in Fig. 7. Here achieving a gun temperature of 77K should take about 70 hours. This is not unreasonable given the existing infrastructure. The number is also not final as a number of additional considerations were not included here, such as the addition of extra cryo cooled thermal shielding and improved thermally isolated connection currently in development.

Optics & Alignment

The simplicity in using conduction cooled cryocoolers does not come for free. In exchange for cost reduction we are given a nontrivial source of vibration which may be visible

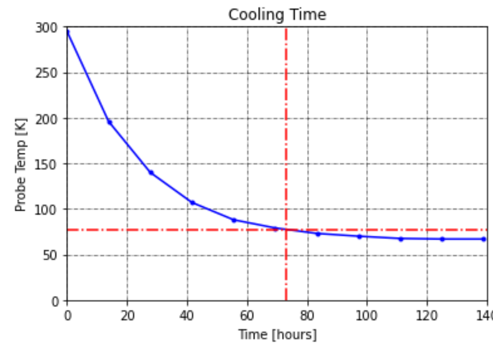

Figure 7: Thermal simulations of gun using the capacity curve of the CH-110LT cryocooler and estimated heat loads including beampipe and waveguide section.

downstream and affect the guns alignment capabilities. The edge welded bellows in various locations will be used to isolate as much of the CYBORG cryostat as possible. In addition, we have begun to consider numerically assess the affects of small gun perturbation on downstream beam dynamics and measurements.

CONCLUSION

Development of the CYBORG beamline and preparation for cryogenic photocathode testing are progressing in good time. We have outlined here the main technical hurdles and provided updates on their status. The main considerations of gun performance (RF and alignment), vacuum pumping, RF power, and cooling integration present unique challenges and possibilities. Continued progress is expected within our projected timeline.

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