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HIGH GRADIENT OPERATION OF CRYOGENIC C-BAND RF PHOTOGUN AT UCLA

G. E. Lawler*, F. Bosco, A. Fukasawa, P. Manwani, S. O'Tool,
Y. Sakai, A. Smith, O. Williams, M. Yadav, J. B. Rosenzweig
UCLA, Los Angeles, CA, USA

Abstract

Future electron accelerator applications such as x-ray free electron lasers (XFELs) and ultra-fast electron diffraction (UED) are dependent on significantly increasing beam brightness. We have designed and produced a new CrYogenic Brightness-Optimized Radiofrequency Gun (CYBORG) for use in a new beamline at UCLA to study the brightness improvements achievable in this novel low temperature high gradient accelerating environment. We are currently in the process of commissioning the photogun for operation with peak cathode fields in excess of 120 MV/m. We report here highest achieved peak cathode field and the lowest gun temperature: 93 MV/m and 82 K respectively.

INTRODUCTION

High brightness electron beams are of interest to the development of many future linear accelerators including xray free electron laser (XFELs), ultrafast electron diffraction (UED), linear colliders, and medical applications such as Flash radiotherapy [1–4].

As part of the continuing studies at UCLA towards the realization of higher gradient accelerating cavities and consequent increased electron beam brightness, we have designed, commissioned, and are iteratevly improving upon a novel compact beamline utilizing using a normal conducting CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG) [5, 6]. In addition, to serving as a designated test bed for studying electron emission at cryogenic temperatures, it also acts as a template for the next generation photoinjector for the ultra-compact xray free electron laser (UCXFEL) concept [7].

In these proceedings, we present an overview of the commissioning status of the cryogenic RF beamline including the current achieved gun performance and the directions for future improvement.

CYBORG PHASE 1

The development of the CYBORG bemaline as a complicated novel system is being commissioned in multiple phases. We are currently in the first phase of development, where infrastructure integration and cryogenic cavity physics are the focus. Hardware integration between the RF, cryogenics, and downstream beamline were especially important during this phase of development.

In Figure 1, we can see a diagram of the so-called phase1 CYBORG bemaline configuration. In the diagram we show the large cryostat cube vacuum chamber with the door open to show the internal geometry. We can see one of the two cryocoolers on the top of the chamber, a Sumitomo CH110LT (there is an additional Cryomech Al125 behind the gun and obscured in the photo). The cryocoolers are connected to the photogun via thermal braids. The gun itself is mounted solely to a stainless steel straight wave section also dropping down into the cryostat from above. Edge-welded bellows connect the gun cavity to the downstream beam pipe which includes a focusing solenoid, two steering magnets (not shown in the photo), a pop-in YAG screen and placement for optional Faraday cup or radiation monitor.

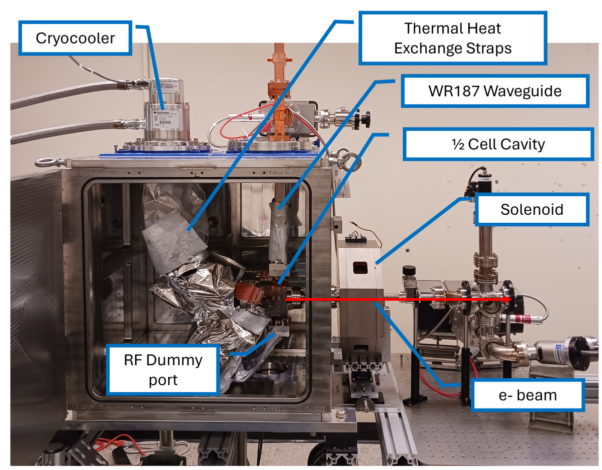

Figure 1: Existing state of CYBORG beamline currently being used for high power commissioning and cryogenic dark current measurements. The setup includes the high gradient photogun, focusing solenoid, steering magnets, YAG screen, and optional placement for radiation detector and/or Faraday cup.

Every piece within the cryostat is then covered with 14 layers of mylar radiation shielding insulation (the gun section is partially covered in the included photo). Additional features depicted in the current configuration include several temperature sensors for measuring thermal stability of the gun, the location of the dummy port with could allow for additional RF diagnostics, and the placement of two ion pumps, one in the waveguide section and the other downstream after the YAG screen but none close to the gun. The outer cryostat is pumped to 10^{-5} during operation and the gun cavity itself is pumped to $< 10^{-8}$ torr, the current limit of measurement at the ion pumps combined with molecular dynamics simulation.

* gelawler@physics.ucla.edu

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C-band RF Power

The RF power into the gun comes from resurrected legacy equipment namely a Thales C-band tube and electromagnetic coupled to a scavenged but usable XK5 pulse tank inherited from SLAC. Figure 2(a) shows the waveguide run from the klystron into the gun from within the radiation bunker. Most of the waveguide is filled with 25 PSI of nitrogen during operation and the UHV window marking the transition to the vacuum section waveguide is located immediately before waveguide T visible in the lower right of the photo.

RF measurements are taking with picoscope measurements from two couplers one located immediately after the klystron outside the bunker (used for the forward pulses) and the second before the horizontal bend towards the cryostat [visible in the photo in Fig. 2(a)]. The reason for this horizontal bend is for future compatibility with C-band experiments, including the ongoing development of a novel SLED power amplifier.

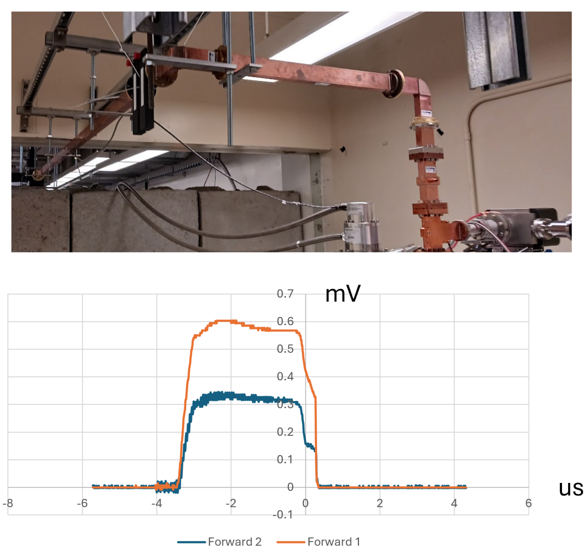

Figure 2: C-band waveguide used to feed CYBORG (above) and maximum pulse length of 4 µs produced from klystron and showing slight breakdown in the waveguide before the gun (below).

To characterise fully the behavior of the klystron, we first, before putting power into the gun, went fully off resonance such that the full RF power was reflected into the 5 MW isolator which is also located outside the bunker in the high pressure nitrogen waveguide section. We then output the maximum klystron pulse length and highest operational power yet achieved, 4 µs and 450 kW, respectively. The pulse structure is shown in Fig. 2(b) with the forward pulse in orange and reflected in blue, note the difference in scaling is only a question of calibration as the figure shown is raw voltage measurement. This is included in for accurate analysis.

Going to the maximum specification in the above case was also interesting as likely small klystron tube breakdowns were observed, thus establishing a maximum pulse length around 3.5 µs.

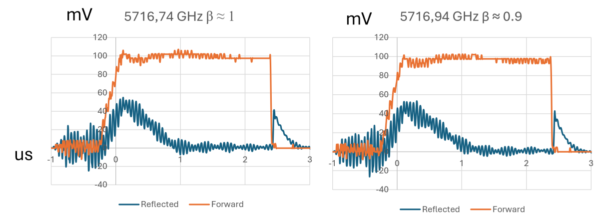

Figure 3: Forward pulse from C-band klystron into CYBORG at cryogenic temperature showing detuning from room temperature resonance of 5.695 GHz to around 5.712 GHz. Slight change in coupling for close frequencies shown to illustrate slight change in filling time visible in the reflected pulse.

HIGH GRADIENT OPERATION

The procedure of conditioning taken began as somewhat standard but additional modifications were made for low temperature operation. Several factors such as our desire to minimize the stress on the klystron during the initial stages of commissioning and experiments led us to limit the power extracted from the klystron to 450 kW. The high shunt impedance optimized geometry of the gun cell cavity still means that this allows room temperature peak fields $>$ 70 MV/m.

The general cryogenic conditioning procedure is the following: beginning with a 500 ns pulse, the power was ramped to the 450 kW level slowly pausing enough to limit breakdown. Instead, vacuum fluctuations on the ion were used. At each increase of power the vacuum spikes were allowed to settle back to their initial pre-input levels. This is useful for a number of reasons, not the least of which is that the 1 Hz rep rate required for temperature stability mean that accumulating breakdown statistics becomes increasingly difficult. After reaching 450 kW input with no ion pump vacuum fluctuations the power would be dropped back down to zero and the pulse length increased by 500 ns. This process was continued to the current value of 2.5 µs with no significant vacuum rises.

The process was then repeated at cryogenic temperatures, first at a temperature of around 100 − 105 K and then again between 80 − 82 K, with the ranges corresponding to the heating increase from averaged RF heating during gun operation.

Example RF forward and reflected pulses are shown in Fig. 3. Both are RF pulses input into the gun cavity at cryogenic temperatures, which can be seen in the coupling and detuning with great improvement from room temperature value. As a complementary study to existing low power RF antenna measurements, we can use the emptying side of the reflected curve to measure measure the loaded quality factor Q_L and the coupling measured from the height of the reflected pulse after full filling of the cavity along with Eq. (1) to measure the unloaded quality factor Q_0 [8]

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_E} = \frac{1+\beta}{Q_0}. \tag{1}$$

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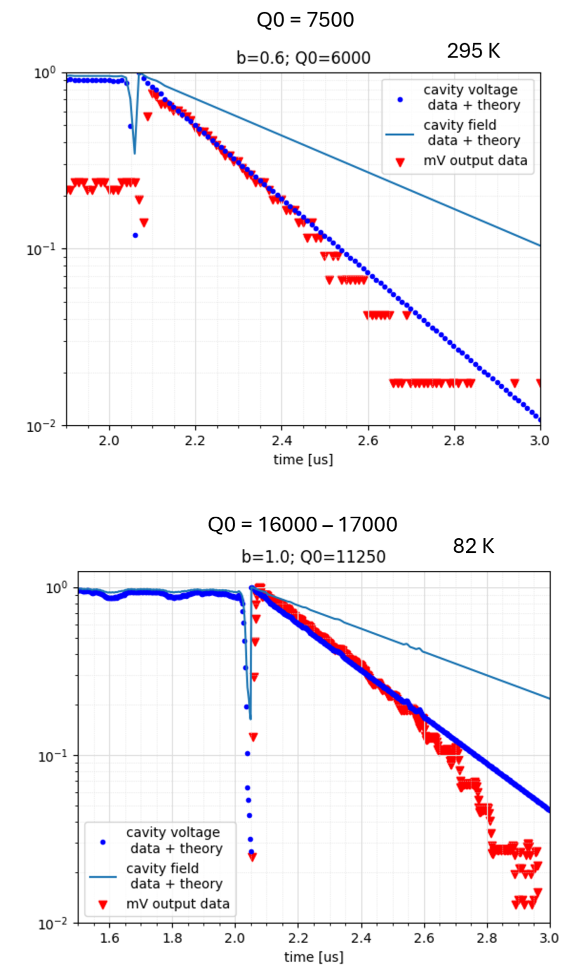

Figure 4: Two RF pulses at room temperature (above) and 82 K (below). Each is used to evaluate the experimental Q0 calculated from QL measured from the decay of the voltage as the cavity empties. Both show a reduction in Q0 which we attribute to beam loading from the dark current.

Using Eq. (1) and intentionally tuning the cavity filling such that $\beta = 1$ we can compute Q_0 at both room temperature and cryogenic temperatures to obtain the results shown in Fig. 4.

At room temperature the $Q_0 \approx 7500$ based on RF power measurements, but as seen in Fig. 4(a) the high power value shows Q_0 closer to 6000. In addition, as seen in Fig. 4(b) the cryogenic Q_0 expected based on ASE theory and low power RF measurements is around 16000 – 17000 but measurements again shows a reduction to 11250. In terms of relative Q_0 enhancement, the theory predicted a factor of 2.1 – 2.3 but 1.875 was measured. Similar input power was here used to generate 66 MV/m fields at room temperature and 93 MV/m at cryogenic.

Dark Current

During operation of CYBORG while conditioning, the downstream YAG screen was used to verify the peak accelerating field based on the deflection via the steering magnets. The dark current YAG screen signals corresponding to Fig. 4 are shown in Fig. 5.

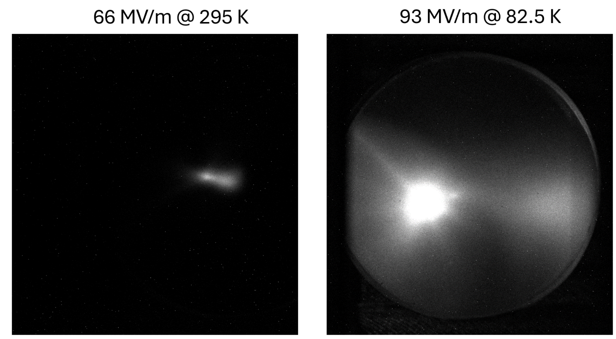

Figure 5: YAG screen images of dark current produced by CYBORG measured for the same input power of 450 kW. The increase in dark current in the cryogenic measurement is caused by the significant increase in copper conductivity at 82K leading to an increased shunt impedance and allowing access to >90 MV/m cathode fields.

CONCLUSIONS AND FUTURE DIRECTIONS

The commissioning of CYBORG has so far seen cryogenic temperatures of 82 K and high gradients > 90 MV/m at the cathode thus opening up a new regime for the study of RF physics and electron emission at UCLA. Future iterative development will push the accelerating gradient above 120 MV/m and down to liquid nitrogen temperatures, around 77 K. Existing experiment plans include investigation electron field and photoemission at cryogenic temperatures uses copper cathodes. Phase 2 of the CYBORG beamline will introduce a load lock for semiconductor physics studies and optimization for a compact cryogenic RF based UED application is planned using the higher RF fields planned.

ACKNOWLEDGMENTS

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