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CRYOGENIC COMPONENT AND MATERIAL TESTING FOR COMPACT ELECTRON BEAMLINES

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Abstract

Cryogenic regimes of operation are, for various reasons, highly advantageous for normal conducting accelerator structures. Liquid cryogen-based systems are costly to implement and maintain. As a result, developing cryogenic test facilities at a smaller more cost effective scale using cryo-coolers is attractive. Before real implementations of a cryo-cooler based beamline, a significant amount of information is necessary regarding the behavior and properties of various components and materials at cryogenic temperatures. Finding this information lacking for our particular beamline case and by extension similar electron beamlines, in the near term we endeavour to generate a thorough more through library of relevant material and component properties down to the range of a liquid nitrogen temperatures (77 K) and the nominal operating temperature of a modest Gifford-McMahon cryocooler (45 K).

INTRODUCTION AND MOTIVATION

Cryogenic operation, that is temperatures below 100 K, of linear accelerator components promises a number of intriguing advantages from improved electron beam brightness to significant reductions in length and cost. As a next generation light source, we have proposed a 40 meter long ultra-compact x-ray free-electron laser (UC-XFEL) [1]. Several of the essential subsystems including the photoinjector, accelerating sections, and magnet systems such as the undulators and focusing solenoids are reliant on cold temperature operation. There is also significant interest in linear colliders based on cryogenically cooled copper accelerating cavities [2, 3]. A valuable resource for low temperature material properties are monographs from the National Institutes of Standards and Technologies (NIST). These are useful but do not always contain information about the new alloys and novel materials and components we are interested in. We then find a strong need to develop the ability to perform low temperature testing of components and various material characterizations. We are currently building up this infrastructure so will highlight here some of the initial motivational experiments.

Cryogenic C-band RF

Accelerating structures such as those found in photoinjectors use radiofrequency (RF) electromagnetic waves to accelerate electrons. High gradients are especially desirable as they can improve electron beam brightness at the cathode and reduce the total required length of accelerating structures and in doing so significantly reduce the costs for both the UC-XFEL and collider cases.

RF breakdown in accelerating structures is a complicated phenomenon and fully understanding it from on a first principles basis poses a complicated theoretical problem. A number of theories have been proposed to explain the exact mechanisms [4–6]. From an experimental perspective, high power RF breakdown experiments at SLAC show significant benefits to operating normal conducting accelerating cavities at low temperatures [7–9]. High gradients in accelerating structures are primarily limited by RF breakdown rates (BDR). In the regime of cryogenic temperatures, the BDR is dramatically reduced, in part due to increased material hardness, reduced coefficient of thermal expansion, and reduced surface dissipation which limits pulse heating. These effects are which make the planned 240 MV/m required by the UC-XFEL photoinjector possible [1].

Further, we have an incentive to operate at a higher RF frequency to reduce cooling power requirements. We are interested in the C-band, at 5.712 GHz, twice the frequency of the S-band 2.856 GHz that is, for example, used at the LCLS. RF pulse lengths using the same input power can be shorter leading to less pulse heating. Filling time is reduced by over a factor of 3 going from S-band to C-band. As a result, RF pulse lengths using the same power can be shorter leading to less pulse heating. The power needed to drive a scaled geometry at constant gradient scales inversely with the square of the frequency so we would also see a factor of four reduction in the power required to drive the structure by doubling the frequency [10].

Cryogenic Photocathode Test Bed

The Natural Science Foundation Center for Bright Beams is currently examining the limits of electron beam brightness. As part of these studies in high brightness photocathode behavior at cryogenic temperatures, at UCLA we are designing a compact electron beamline for characterizing the temperature dependence of novel cathodes in a high gradient photogun [11]. Several material engineering question are opened for consideration by this prompt.

LOWER POWER Q-FACTOR MEASUREMENT

Analytic Pillbox

Having considered these motivations, a first experiment is a lower power RF test of quality factor for a pillbox geometry. To begin we can derive the quality factor and cavity detuning analytically for the ideal pillbox resonator and use NIST measured material properties for the coefficient of thermal expansion and conductivity of the closest available copper to predict the results. We can then obtain the surface

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resistivity based on the Reuter and Sondheimer theory for the anomolous skin effect (ASE) [12].

We can first examine the temperature detuning expected and see the results in both Fig. 1 and Table 1. We can see based on the inflection point in the thermal expansion curve for cryogenic copper, that the detuning per Kelvin is much smaller at cryogenic temperature and so our cryogun designs will be more stable.

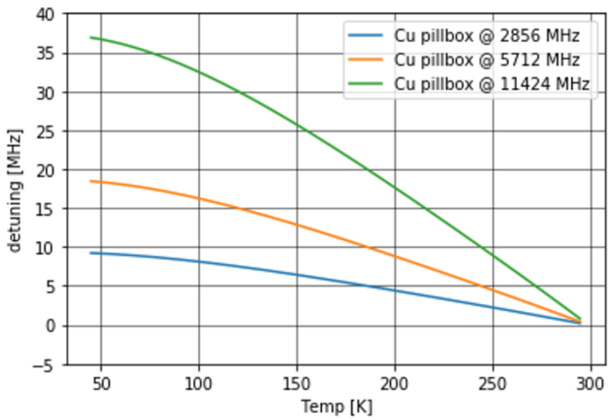

Figure 1: Cavity detuning due to temperature changes at different frequencies of operation.

Table 1: Cavity Detuning Using NIST Data

Frequency	293 → 77 K	293 → 40 K
S-Band	8.58 MHz	9.23 MHz
C-Band	17.17 MHz	18.46 MHz
X-Band	34.34 MHz	36.93 MHz

We can further consider how the residual resistance ratio (RRR) changes the expected quality factor and predict the effects on quality factor based on NIST data (Fig. 2). This quantity is the ratio of the resistance at room temperature and the value approaching 0 K often using liquid helium temperatures as a close approximation and is a useful characterization of material purity. Using our analytic pillbox model we find the quality factor scales as the square root of the conductivity

$$Q_{\text{pillbox}} \propto \sqrt{\sigma}. \quad (1)$$

These results are shown in Fig. 2. We find that RRR only slightly affects the quality factor at our designed operational temperatures. However, me must note that previous tests performed for X and S-band frequencies showed deviation from the exact Reuter and Sondheimer theory of ASE [7]. We have begun work on modifications to the theory which incorporates a more realistic scattering model at the copper-vacuum interface taking into account electron-phonon interactions based on implications of the Gurzhi effect [13]. This addition would be sensitive to material purity and so we are working on incorporating RRR explicitly into this theory. We have also begun considering testing this with our cryogenic infrastructure.

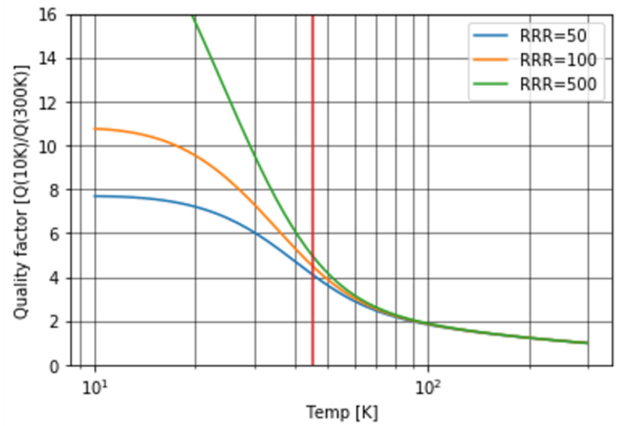

Figure 2: Quality factor predictions for an analytic cavity based on NIST material data. The red vertical line indicates the 45 K operating point intended for our first cryostat.

Brazed Pillbox for Low Power Tests

The cavity geometry and design for the real pillbox to be used in the low power test is shown here. We are using a brazed lid geometry with a smooth surface finish on the bottom as the location for a press fit coupling to thermal braids that will attach to the cryocooler cold head that is based on the previous S-band and X-band designs [8]. An exploded diagram of the brazed pillbox cell is shown in Fig. 3 along with a cross section of the cavity showing the resonant TM_{010} eigenmode.

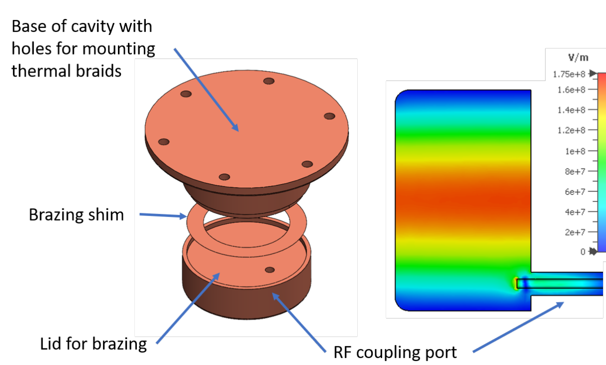

Figure 3: Brazed pillbox assembly.

RF PHOTOGUN-CATHODE INTEGRATION

One major question in the development of the cryocathode test bed is how to obtain the best thermal interface between the cathode substrate, photogun copper cavity and thermal braids coupling to the cryocooler cold head [14]. Cornell has developed a cryogenic test bed for high brightness cathodes in a DC gun environment so there is significant experience to

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draw upon in terms of what additional thermal information is needed [15]. In our RF environment a good RF seal is also necessary in addition to the good thermal contact. One idea we would like to test involves the measuring the quality and usefulness of the thermal interface we can obtain from different materials with different coefficients of thermal expansion. The idea is to use a *shrink fit* of the copper cavity backplane around the photocathode molybdenum substrate. The stress of this seal, a copper annulus around a molybdenum cylinder from 300 to 45 K, is shown in Fig. 4. The outer annulus is 10 cm in diameter and the inner Mo cylinder is 1.676 cm in diameter in order to approximate the 1/2 cell backplane and cathode plug. The cryostat tests will involve thermal cycling of the components in order to verify the reusability of the seal.

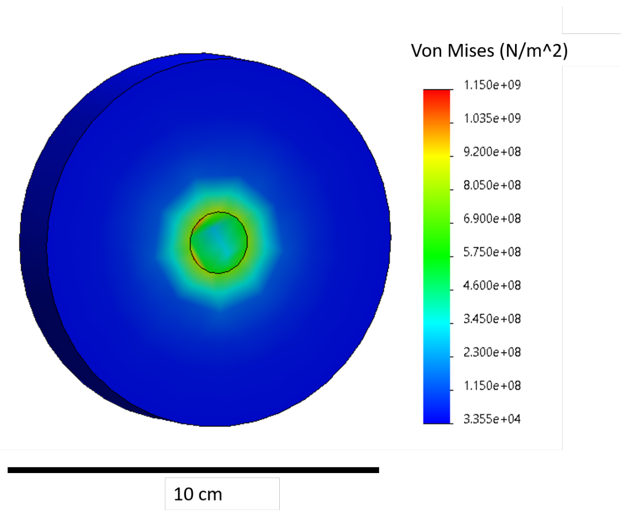

Figure 4: Stress calculations for annulus of copper with molybdenum cylinder within when cooled from 300 to 45 K. The outer annulus is 10 cm in diameter and the inner Mo cylinder is 1.676 cm in diameter in order to approximate the 1/2 cell backplane and cathode plug.

CRYOSTAT IMPLEMENTATION

The implementation of our simple vacuum cryostat with an example pillbox contained within can be see in Fig. 5. The significant vibrations from the Gifford McMahon cryocooler will be decoupled from the cavity with edge-welded bellows and an external support structure. Contained within the vacuum is a rigid aluminum frame for mounting multi layer insulation (MLI) to reduce radiative heating. We expect that 10–15 layers will be sufficient to shield a small sample. Cernox® temperature sensors for measurement will be mounted to removable jigs for reusability with different samples. The AL125-CP830 cryocompressor package has been commissioned and is now operational.

CONCLUSIONS AND FUTURE WORK

UCLA Particle Beam Physics Laboratory is building up infrastructure for testing cryogenic material and component

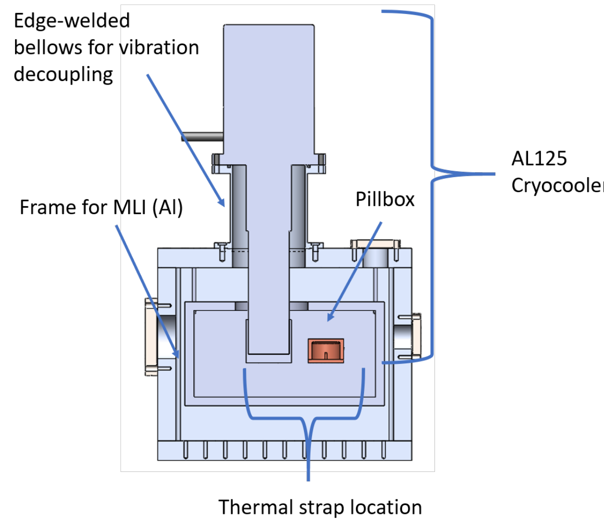

Figure 5: Simple cube shaped vacuum cryostat for initial tests including lower power RF and cathode thermal stress measurements.

properties. We will use it to validate results and perform new material tests that are applicable to cryogenic beamlines in general and UC-XFEL specifically. The cryostat will remain active for the foreseeable future for testing various other materials and components: including the equivalent thermal resistance of edge-welded bellows which will be needed for cryogenic beamline alignment, novel waveguide thermal interfaces that are needed to feed the 1/2-cell photogun [11], radiative shielding geometries, and components for a novel foil-wound solenoid [16]. To modify the Retuer-Sondheimer theory for the cryogenic resistivity, we have identified several ways forward which we will present in future work.

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