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REFURBISHMENT AND TESTING OF THE WiFEL E-GUN AT ARGONNE*

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Abstract

We report on the refurbishment and testing of the Wisconsin Free Electron Laser (WiFEL) superconducting radiofrequency electron gun with application as an electron injector for DOE accelerators and as a possible future stand-alone tool for electron microscopy. Initial testing at ANL showed the cavity had a very low quality factor, ~107, later determined to be due to contamination sometime since the initial assembly. Following ultrasonic cleaning, high-pressure water rinsing, reassembly, and cold testing, the e-gun has largely recovered with Q~109 and surface electric fields ~15 MV/m. We intend that WiFEL be available as a testbed for future high brightness sources and, in particular, for testing an SRF gun photocathode loader design; an essential, and as yet, not sufficiently proven technology. We report here on many operationally important properties of a quarter-wave SRF cavity for application as an e-gun, including microphonics, pressure sensitivity, and mechanical tuning. New electromagnetic simulations show that the WiFEL cavity shape and design can be optimized in several respects.

INTRODUCTION

The Wisconsin Free Electron Laser superconducting RF electron gun was designed to meet the specifications for a high brightness, high repetition rate electron source [1]. This includes sources such as the LCLS-II-HE upgrade, which requires an emittance of < 0.1 µm @ 100 pC. The gun was designed at the University of Wisconsin (UW), and the cavity was fabricated by Niowave, Inc. The gun was initially tested at UW, and was later shipped to SLAC for continued study. In December 2019 the gun was shipped to Argonne, in large part, due to the availability of a liquid helium refrigerator which had not been available for WiFEL testing at the previous locations. After full disassembly, re-cleaning by HPR, and re-testing (as highlighted in Fig. 3) the cavity achieved useful, stable operating field with Epeak = 14.3 MV/m and Vacc = 1.07 MV as shown in Fig. 1.

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COLD RF TESTING

Q Curves and Conditioning

Following the cleaning of the cavity and re-assembly of the cryostat, the e-gun was cooled down to 4.5 K. The cavity initially hit a multipacting barrier that was conditioned (about V_{acc} = 8 kV to 30 kV) over multiple days before recording a full Q curve. The coupler was manually adjustable, and allowed a range of Q_{ext} from ~1 x 10^9 to 5 x 10^7. This adjustability was used to over-couple while conditioning.

The cavity then underwent multiple rounds of high power, pulsed RF conditioning, which allowed the cavity to be operated at higher field gradients. During pulsed conditioning, a maximum field level of ~24 MV/m was reached for short durations before breakdown. The results of multiple rounds of conditioning are shown below, in Fig. 1. A maximum CW peak electric field was found to be 14.3 MV/m.

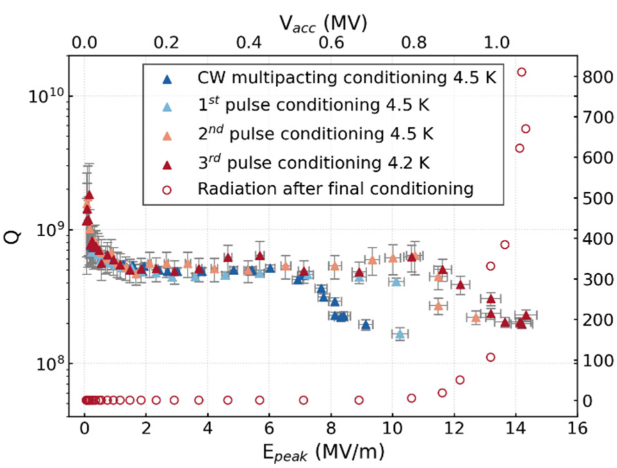

Figure 1: WiFEL cavity Q curves after multiple rounds of RF pulse conditioning.

The Q_0 measurement of the cavity at ANL, with low field Q ~10^9 and medium field Q ~5 x 10^8, are lower than made previously at Niowave and UW [1], however it should be noted these measurements were performed calorimetrically, a technique that is inherently more challenging than RF measurements at near critical coupling. Error bars in the ANL data are estimated systematic experimental errors associated with the measurement of RF decay time (ie. the Q), the forward and reflected power from the cavity, the field probe RF amplitude, and in the HP 437B power meter used as the absolute power reference.

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REFURBISHMENT PROCESS

Several modifications were made to the cryostat after relocation to Argonne. The most important was the installation of new supply/return liquid helium bayonets for connection of the cryomodule to the 4.5 K liquid helium cryoplant in the ANL test facility. Other hardware work included a repair of cavity string bellows that was damaged during shipment, adding ASME burst discs to the RF, helium, and insulating volumes in the cryostat, the removal of the cathode stalk assembly, installation of an RF pickup probe (replacing the cathode stalk assembly), and installation of silicon diode thermometry, the latter permitting temperature data readout down to liquid helium temperatures.

To confirm that the entire system was functional on arrival it was decided to test the WiFEL cryomodule without complete disassembly and cleaning of the cavity. However, initial cold testing showed that the cavity performance was much lower than anticipated, with $Q_0 = 4.8 \times 10^7$. Even given the likely particulate contamination from the bellows damage during shipment, this result pointed toward some other sort of cavity contamination.

Contamination Investigation

This led to investigation of possible causes, and simulations were performed to analyze the size of a dielectric or metallic contaminant that could cause this Q drop. It was determined that particles at least several millimeters in size would likely be needed, meaning that any contamination should be macroscopically visible. By inserting a small flexible borescope into the cavity, and the contaminant was clearly visible (Fig. 2).

Analytical chemistry using SEM/EDS analysis showed that this fine dust was principally niobium pentoxide. It is possible the source of this was the argon-oxygen based plasma cleaning performed shortly after initial delivery of the cavity from Niowave, but this is admittedly speculative.

Cryostat Disassembly and Cleaning

The cleaning process required removing the cavity from the cryostat. After disassembly and removal, the cavity was ultrasonically cleaned, and subsequently high pressure rinsed with de-ionized water for approximately three hours. Due to the difficult shape of the cavity and lack of access ports, the cavity was ultrasonically cleaned in multiple orientations to facilitate removal of the contaminant. The HPR was done with the only cavity port facing down, with the wand inserted into the port at approximately 45 degrees. During HPR the cavity was placed on a turntable and rotated manually about the wand (see Fig. 3).

After cleaning, re-assembly was done in a clean room until the cavity string was sealed. Selections of this process are shown in Fig. 3.

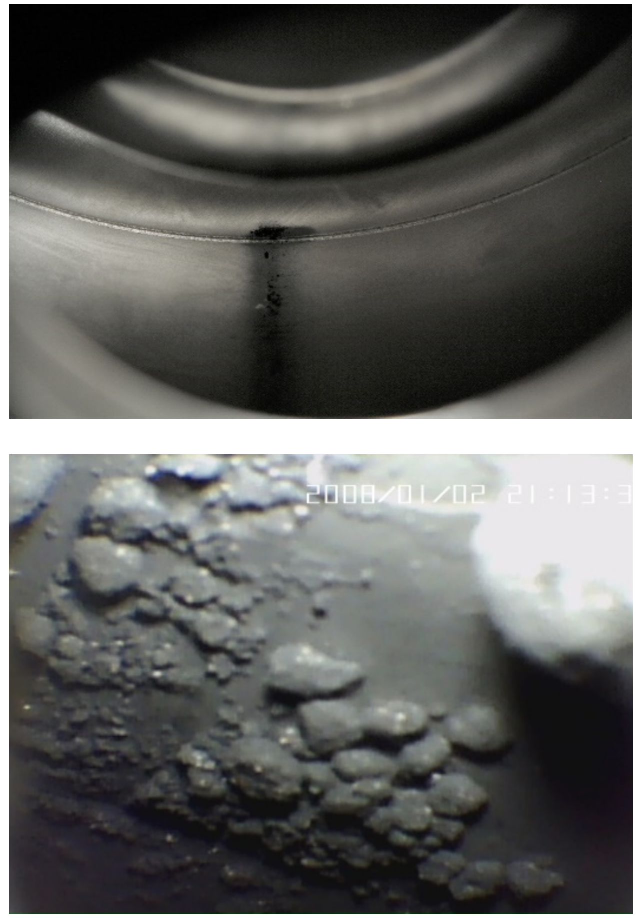

Figure 2: Niobium oxide dust at the bottom of the WiFEL cavity, as seen through the cavity port (top). A close up view of the contamination, seen through a flexible borescope inserted into the cavity prior to cleaning (bottom).

Figure 3: Photos of disassembly, cleaning, and reassembly of the WiFEL cryostat. Initial disassembly (left), high pressure rinsing the cavity (middle, top), cleanroom assembly (middle, bottom), and cryostat assembly (right).

Reassembly Note

The process of disassembly and reassembly provided opportunities for improvement of future designs. One example is the superconducting solenoid, which in order to preserve low beam emittance should be placed as close as pos-

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sible to the cavity exit. In the case of WiFEL the high temperature superconducting solenoid is physically separate from the floppy copper-plated stainless steel bellows inserted through the magnet bore. The bellows was exceedingly hard to clean and install, and likely contributed to field emission seen during testing.

Microphonics

Frequency deviations due to the effect of cavity microphonics are likely to be a critical issue for the e-gun applications, given the strict amplitude and phase stability requirements. Measurements of microphonics in the WiFEL cavity were taken at multiple times during the two week period of cold testing. Data were collected by digitizing the error signal in the cavity test system phase-locked loop. The Fourier spectrum and frequency probability density plots for eigenfrequency excursions for both the cryostat connected to and isolated from the helium refrigerator are shown in Figs. 4 and 5, respectively.

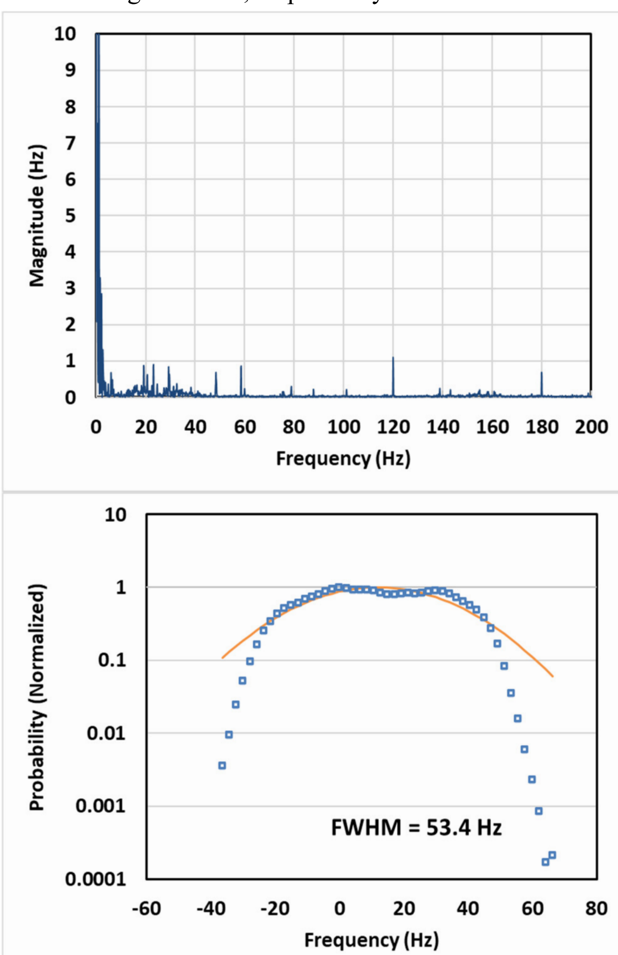

Figure 4: FFT and frequency probability density plots for measured microphonics on the helium refrigerator.

While connected to the refrigerator there is a large, low frequency, few Hertz microphonic signal present. This was believed to be due to an oscillation in the refrigeration system when connected to the system. This contrasts with the data collected with the cryomodule disconnected from the refrigerator, as shown in Fig. 5, where the microphonics below 10 Hz are small. Since future low frequency SRF guns are also likely to operate at 4 K, additional WiFEL testing may provide an early opportunity to identify and suppress these effects.

Interestingly there is a sizable signal around 20 Hz while disconnected from the refrigerator that is not present while on the refrigerator. There are also various harmonics of the 60 Hz line frequency present, with their signal sizes likely due to the data being taken at differing sampling rates, causing some aliasing.

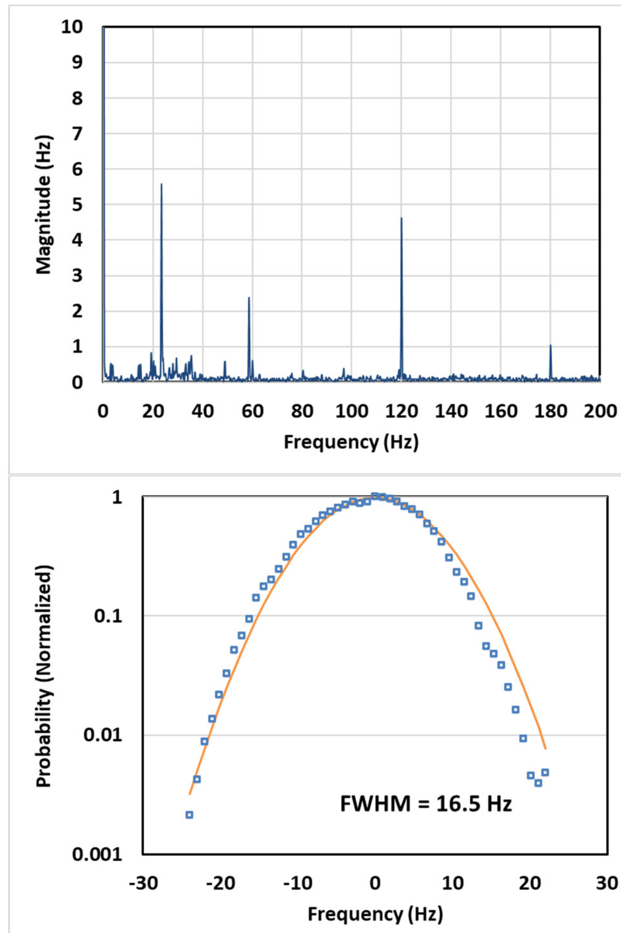

Figure 5: FFT and frequency probability density plots for measured microphonics off the helium refrigerator.

Pressure Sensitivity df/dp

A relatively simple measurements to make, but one of the most impactful for real operation, is the cavity eigenfrequency sensitivity to external pressure (variations in the helium system pressure). This measurement was taken as the helium space of the cryostat was vented to atmosphere, slowly bleeding down to atmospheric pressure from the operating pressure of approximately 1.3 bar. As seen in Fig. 6, the measured sensitivity was found to be -35 Hz/torr. It is thought that the small nonlinearities are due to imperfect tracking of the phase locked look near the edge of the control window. The measured value is fairly large by today's standards for a quarter-wave geometry at this frequency and is an area for improvement in future designs.

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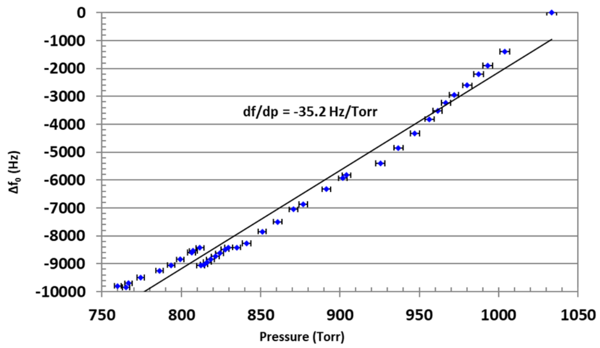

Figure 6: Frequency sensitivity to helium pressure.

Mechanical Tuner

The WiFEL cryostat was designed with a cold mechanical lever tuner system driven by an external motor connected to the cavity by a rigid half meter long shaft. This tuner was manually operated, with a load cell reading out the force on the tuner. The cavity frequency was then measured, as shown below in Fig. 7. The frequency response was found to be very linear, with a sensitivity of 21.64 Hz/N. We anticipate that the safe tuning range is much larger than the 25 kHz shown, but without detailed analysis at the time of testing, it was decided to limit the testing range for the present purposes.

We note that though the WiFEL design uses a warm motor with a long feedthrough to the cold tuner, the tuner itself is easily adaptable such that the motor could be inside the cryostat, or even inside the nitrogen shield. We further note that the tuning force could also easily be applied by a direct drive pneumatic bellows, such as those used extensively at ANL and FRIB, with the added benefit of little to no microphonics impact.

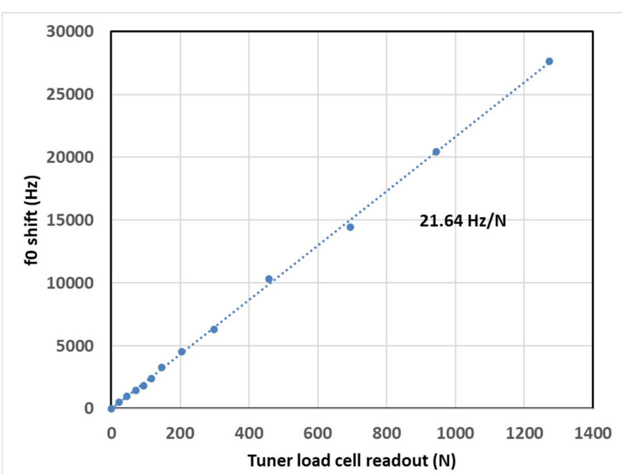

Figure 7: Frequency sensitivity to mechanical tuner force.

Lorentz Detuning

Another useful measurement on SRF cavities is that of the Lorentz detuning factor. This measures how much the cavity is detuned from its nominal frequency from mechanical deformation due to the Lorentz force at high electric fields.

The large scale oscillations in the pressure of the helium system of the cryostat, along with pressure increase from large cavity power, made direct measurements of the frequency shift difficult to detangle from df/dp effects. Ideally this would be done with the helium system vented to atmosphere to keep constant helium pressure during measurement. To make our measurement the pressure was noted before and after high power was applied in an effort to separate pressure and Lorentz detuning effects. Figure 8 shows the time profile of the frequency shift, with two data points taken for each of three field levels. Figure 9 shows the calculated frequency shift for given field levels.

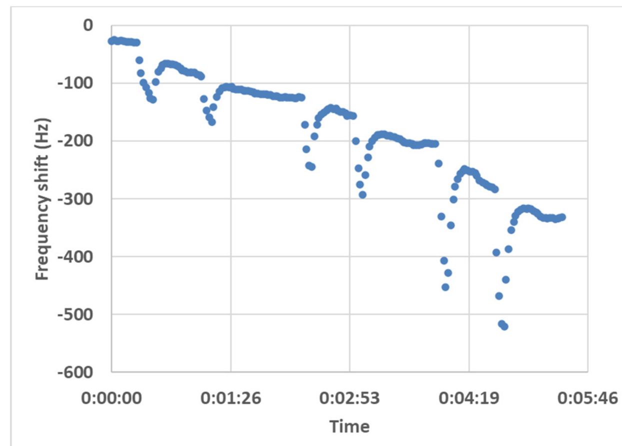

Figure 8: Lorentz detuning measurement data superposed on top of a relatively constant drop in pressure.

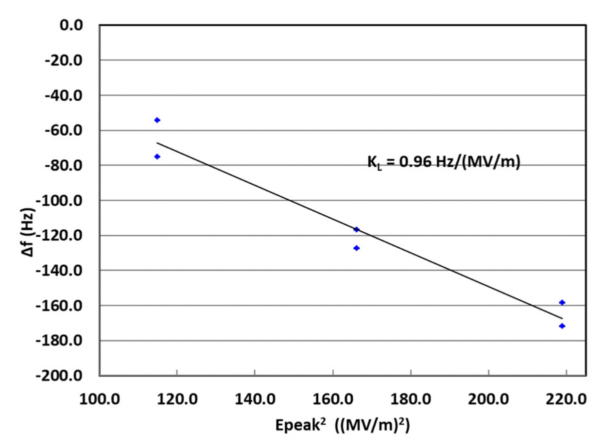

Figure 9: Lorentz detuning factor plot, detuning of 0.96 Hz/(MV/m).

Q Disease Testing

After initial RF testing, the shape of the Q curve led us to speculate that the cavity may be hydrogen contaminated and suffer from hydrogen Q disease. Since the effects of Q disease scale with how long the cavity stays within the hydride forming temperature region (approximately 70-150 K), we planned to test this by warming the cavity and holding it in this region.

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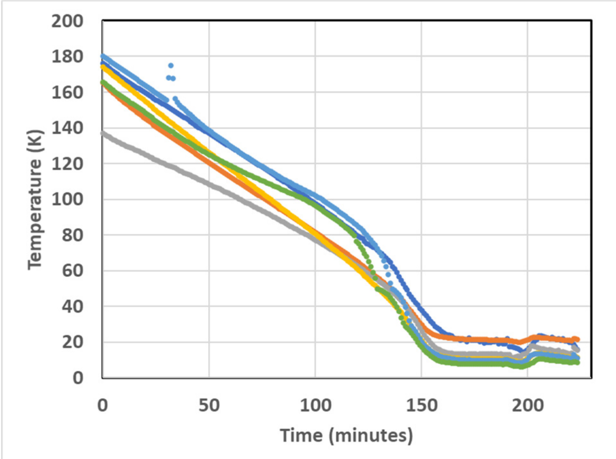

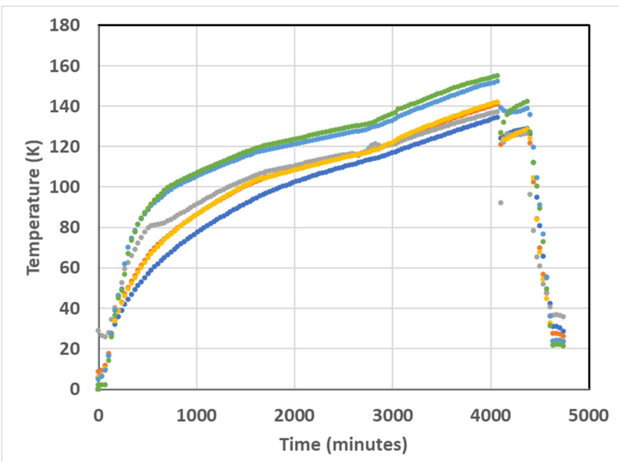

Figure 10: WiFEL thermometry data during the second (top) and final (bottom) cooldowns. The second cooldown stayed in the hydride forming temperature region for ~100 minutes while the final cooldown remained in that region for 2+ days.

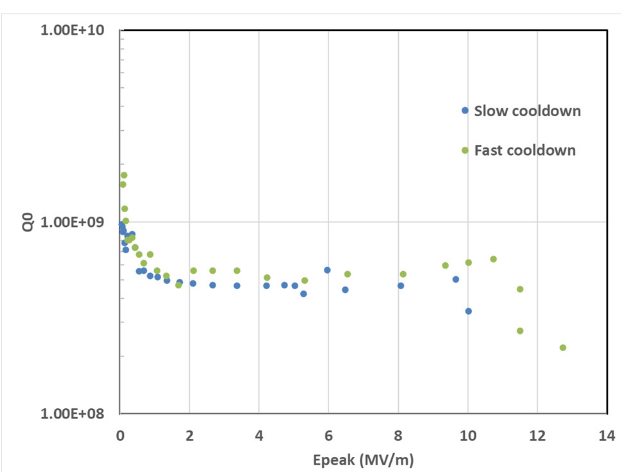

Figure 11: Q curve comparison between cooldowns.

If the cavity is indeed hydrogen contaminated, this would cause an order of magnitude change in the measured Q. The first two cooldowns were between 1-2 hours, so for a stark comparison we held the cavity in the hydride forming region for 2.5 days. The cooldown profiles are shown in Fig. 10.

A comparison of the measured Q curves for the two cases shows very little difference between the two, shown in Fig. 11. There is a measurable difference in the quality factor of the cavity, but significantly less change than would be expected from Q disease (greater than a factor of 2) [2]

FUTURE WORK

The WiFEL e-gun has the potential for utility in multiple possible projects. The main consideration is as a test bed for cathode insertion schemes, in order to test cathode loader designs in a high field cavity. The peak field requirements for a test bed such as this would be 20 MV/m. Additional cleaning of the cavity would likely allow for operation at this level, but without some additional gain in Q this may be too high a load for the helium refrigerator in the facility. It is possible some gain could be made in the Q of the cavity, but as previously noted, testing for hydrogen Q disease characteristics did not point toward hydrogen contamination of the SRF surface.

Other considerations are to use the gun as a source for ultrafast electron microscopy/diffraction experiments. The high repetition rate and high brightness are ideal for this sort of setup.

Cavity Shape Optimization

Another aspect of future work is that of optimizing the cavity shape, for various reasons. The cavity shape affects the multipacting seen by the cavity, and can be reduced to some degree. Additionally the spatial derivative of the accelerating field can be flattened (which is beneficial from a beam physics aspect) by changing the geometry, specifically flattening the cathode face of the center conductor.

SUMMARY

The WiFEL e-gun performed at the level of our expectations considering the initial RF testing results. Being able to successfully clean the cavity of contamination enough to recover a reasonable Q level (albeit with a large amount of field emission at higher gradients) proves that WiFEL can continue to be useful, and additional steps can be taken to optimize the cryomodule for re-purposing.

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