6. TESTING OF THE 6.5" CATHODE AT LBNL

6.1 The Motivation

The Relativistic Two-Beam Accelerator (RTA) test stand at LBNL was modified to accept the full-size (6.5") DARHT-II cathode in an effort to assist the cathode development and commissioning for DARHT-II. The original idea was that by testing the cathode off-line from DARHT-II, we can save time and money for the project. The cost of running the RTA test stand was many times less than running DARHT-II. Furthermore, the RTA test stand may provide better controls and diagnostics in testing the cathode than what can be done on DARHT-II.

The dispenser type cathodes usually require an "activation" process before they can emit full current density. The process involves slowly bringing up the cathode temperature while keeping the vacuum in check. Chemical reactions occur during this phase and eventually the cathode surface will reach an equilibrium condition with the proper work function for electron emission. It was thought that the RTA test stand can be used to pre-activate the cathode before shipping it to mount on the DARHT-II injector, thus minimizing DARHT-II's down-time.

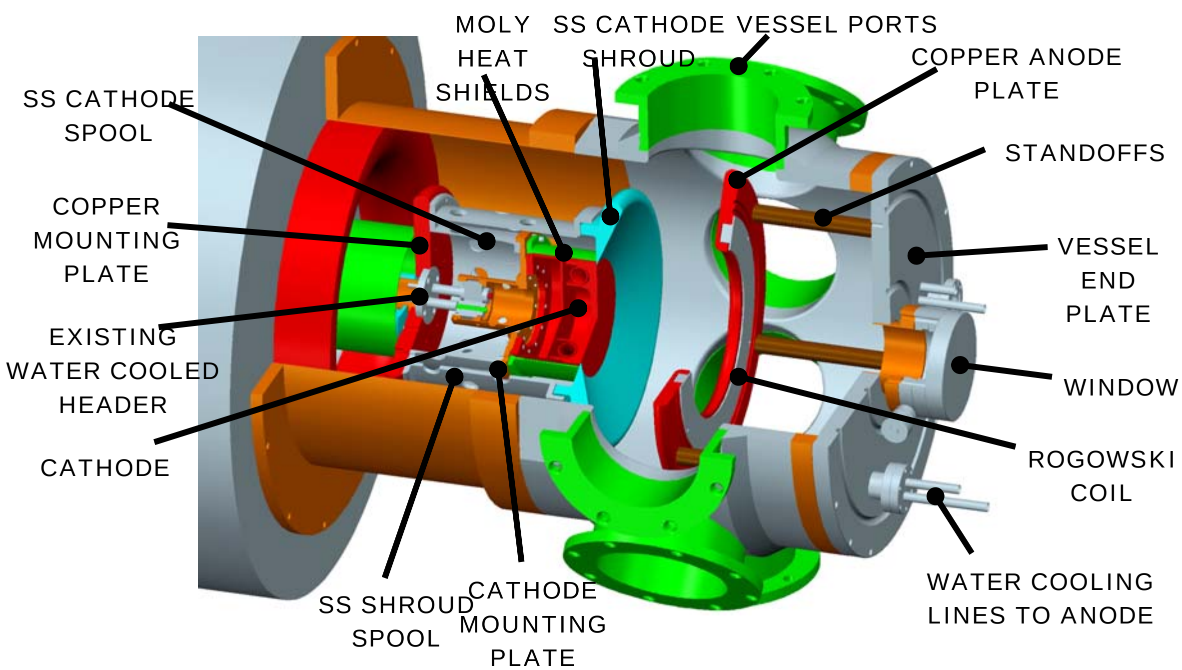


Fig. 6.1. Exploded view of the RTA test stand with a 6.5" cathode.

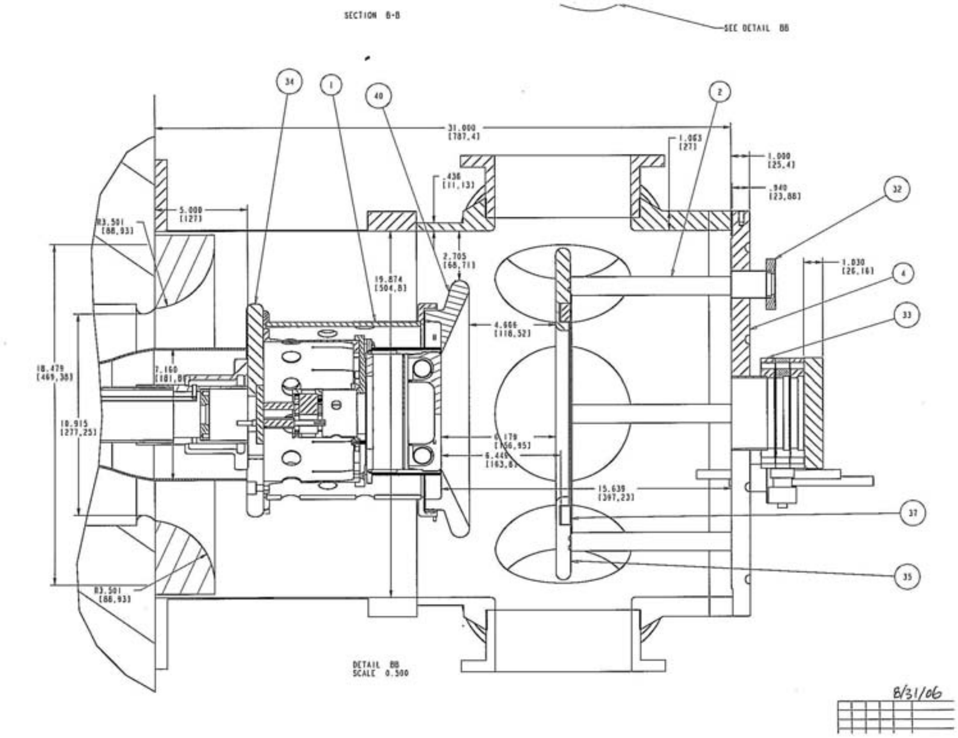


Fig. 6.2. Schematic diagram of the 6.5” cathode mounted in RTA.

6.2 Experimental Set Up

Figure 6.1 is an exploded view of the RTA test stand with a 6.5” cathode and Fig 6.2 is a schematic diagram of the set up. The window downstream provided access for optical pyrometry to measure the cathode surface temperature. Figure 6.3 (a, b, c, d) are photographs of the components.

In planning this experiment, we assumed that once the cathode was activated, the work function could be measured and that the value of the measured work function would remain constant during operation in DARHT-II. Furthermore, it was assumed that the work function (ϕ) remains a constant independent of the operating temperature. The electron emission would be described by the Richardson-Dushman equation:

$$J_s = A_0 T^2 \exp(-\phi / kT) \tag{6.1}$$

where J_s = saturated emission current density, and A_0 = Richardson’s constant.

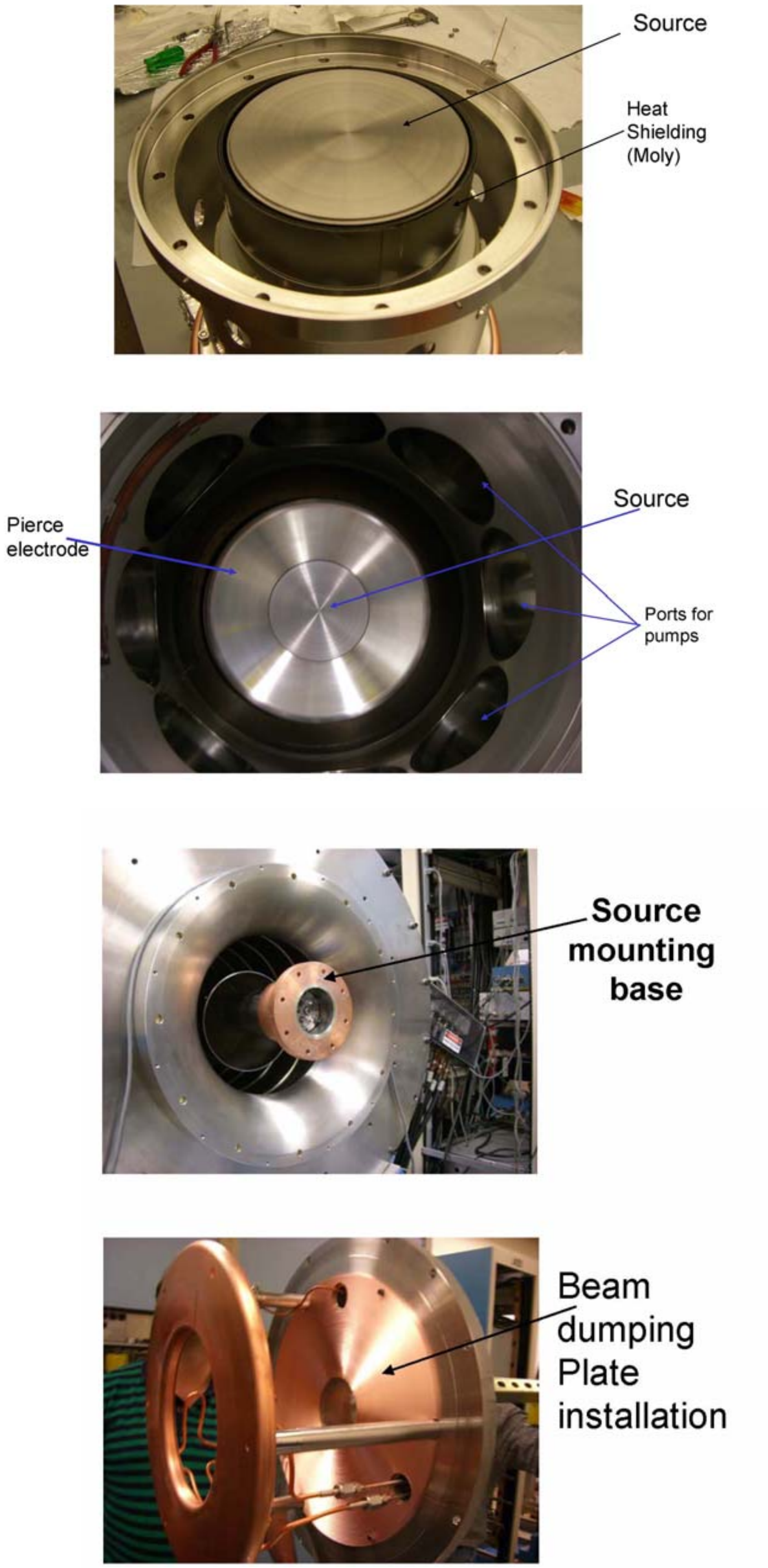


Fig. 6.3. Photographs of the RTA test stand with a 6.5” cathode.

From equation (6.1), the effective work function can be determined by measuring the current density and the temperature. In the emission limited regime, the beam current will be determined by the temperature, not by the voltage applied across the extraction diode (between the cathode and the anode). Computer simulation indicated that a beam current of 16A can be extracted when 50 kV diode gap voltage was applied. Beam optics was not essential in this case as long as all the beam current was collected (without losing secondary electrons). Our task was to measure the required temperature in order to reach 16A of beam current. The setting of 50 kV, with a pulse width of 200 ns, was chosen in order to limit the x-ray radiation hazard (to get approval for radiation safety). The test stand was capable of much higher voltage and we could revise the administrative limit, if necessary, after we have done initial survey of the radiation level. We initially started with a DC supply (Lambda EMI TCR100T120-4, 100V, 120A) for the heater filament, but it was later replaced by a 60Hz AC power supply (variac, Superior Electric Powerstat 60MB1156D-2P, 120VAC, 100A) to avoid reactions which may deposit conductive material on the Alumina potting (see SpectraMat bulletin).

6.3 Activation Procedures and Handling Guideline

The guidelines for activation of dispenser cathodes from SpectraMat can be found in their company technical bulletin TB-147–C 12/04. These guidelines were written mainly for small cathodes in vacuum tubes that can be baked-out to achieve good vacuum down to below 10^{-8} Torr range. But DARHT-II can not be baked and the 6.5” cathode is massive, so it is necessary to modify the activation procedure accordingly. Furthermore, the vacuum gauges in DARHT-II are at a considerable distance from the cathode, therefore one has to make an educated guess of the true pressure in front of the cathode surface.

The ETA-II has a 12.5 cm diameter cathode and their system is also not baked. Therefore the ETA-II experience may be more relevant to DARHT-II than that prescribed in the SpectraMat bulletin. The main difference is in the length of time used in accordance with the size of the cathode. For ETA-II, after installation of the cathode, they allow their system to pump overnight without heating the cathode to establish a baseline vacuum condition. If the weather has been moist or the injector has been open for several days, the pumping may take as long as a few days. After an initial heating to about 1/5 of nominal operating power (1750 watts at 70 amps and 25 volts), the cathode is soaked at this medium temperature overnight (i.e. minimum twelve hours). Then in the next step, the cathode is slowly brought to the nominal operating temperature (1061 °C) and is soaked again overnight at that temperature. Finally, the cathode temperature is raised to the "red-line" level and held there for 8 hours before returning to the standby power level (1/5 nominal power).

Based on the SpectraMat bulletin and the ETA-II experience, we have written the following procedure to be used for activating a new cathode in the DARHT-II injector. The complete technical note can be found in the attachment section at the end of this report.

- Before starting, make sure that the vacuum is good. Lower vacuum is always better and it should be at least in the low 10^{-7} Torr range.
- Increase the Cathode Heater Power in small increments (typically 0.05 kW per step) while keeping the injector vacuum stabilized below 3×10^{-7} Torr.
- When the Cathode Heater Power set point reaches 0.4 kW, hold this Power setting for 12 hours (overnight). The vacuum must be stabilized before resuming Heater Power ramp and pressure control.
- Ensure the FAR Pyrometer is on when Heater Power reaches 1 kW.
- When the Far Pyrometer reads a stable temperature of 875 ± 25^{o}C, hold the Cathode Heater Power constant for 8 hours. The vacuum must be stabilized before resuming Heater Power ramp and pressure control.
- When Far Pyrometer temperature reaches 1025^{o}C (nominal operating temperature) hold this power setting and temperature for 8 hours (overnight). The vacuum must be stabilized before resuming Heater Power ramp and pressure control.
- When Far Pyrometer temperature reaches 1050^{o}C hold this power setting and temperature for 2-4 hours or more until the temperature stabilized.
- The activation is done when the vacuum is also stabilized.
- Either lower temperature to nominal operating temperature for beam extraction, or turn down to standby mode at 875 ± 25^{o}C.

Another issue is related to the handling of the cathode during storage and transportation. There was uncertainty regarding what kind of gas (or vacuum) should the cathode be stored inside a canister. Another question is when the cathode is removed from the canister, how long can it stay in air before pumping down. To be sure, moisture can be damaging to a BaO dispenser cathode. In the end, we have decided to store the cathode in nitrogen, and limit the exposure to 8 hours. That means the cathode should be installed within a working shift and not left in air overnight. One must follow normal clean room procedure during handling. Good record keeping is essential to track the life history of a cathode. We wrote a note to provide guidelines for the handling and storage (see attachment section).

6.4 Experimental Results

As mentioned in sections 6.1 and 6.2, our main goal was to activate (or re-activate in the case of a used cathode sent back from DARHT-II) a 6.5" cathode and to measure its work function. The first problem we found was that even though the base pressure in room temperature was in the low 10^{-8} Torr range, the vacuum pumping (using 2 turbo pumps and 2 cryo-pumps) was not good enough to keep the system below the mid 10^{-8} Torr range when the cathode was hot. Test data later found in the quarter-inch cathode test stand (see chapter 7) confirmed that our cathode should operate in the low 10^{-8} torr or below in order to have good emission. Thus we were not able to activate the cathodes in the desired fashion. It took up to 7 days of continuously monitored heating and pumping to reach the activation temperature of 1050°C. The situation was complicated by the fact that we were trying to recycle used cathodes that were taken from the DARHT-II injector. One of these cathodes had experienced vacuum accident (exposed to air while hot) and the others were stored in air under uncontrolled environment. Thus it was possible that these cathodes can not be revived at all regardless of the vacuum condition during activation in the RTA test stand.

In the activation run for the Os-W coated 311-XW cathode, the filament power was 43.86V, 66.81A, (2930W, 0.66 ohm) and pressure at $2.114E^{-7}$ Torr. Temperature measured with a 2-color pyrometer indicated the cathode surface at 1050°C. The temp vs. power was closely repeating the result previously obtained at DARHT-II, see Fig. 6.4. After raised the temperature to 1071°C (3084W, 45.5V, 67.7A, 3.0E-7 Torr), the heater power suddenly dropped to 27.34V, 67.7A and we saw the left half of cathode significantly darker than the right half. All things indicated that the heater filament (bifilar winding) failed and was shorted near the mid point, thus stopping power flow to the left side. Since both Os-W coated 311X cathodes (one at DARHT-II and one at LBNL) failed before reaching the desirable operating temperature, we concluded that this was not the suitable type of cathode for DARHT-II (under the existing 6.5” diameter design). The 311-XW was acceptable for ETA-II because that cathode was smaller and consequently required less heating power, so the filament temperature was lower. In chapter 7, we showed that the Os-W coating has a higher emissivity and therefore higher heat loss. Changing to a Os-Ru coating (M coating) can reduce the heat loss and the 311-XM type cathode was later proved to be successful in producing 2 kA of emission at DARHT-II.

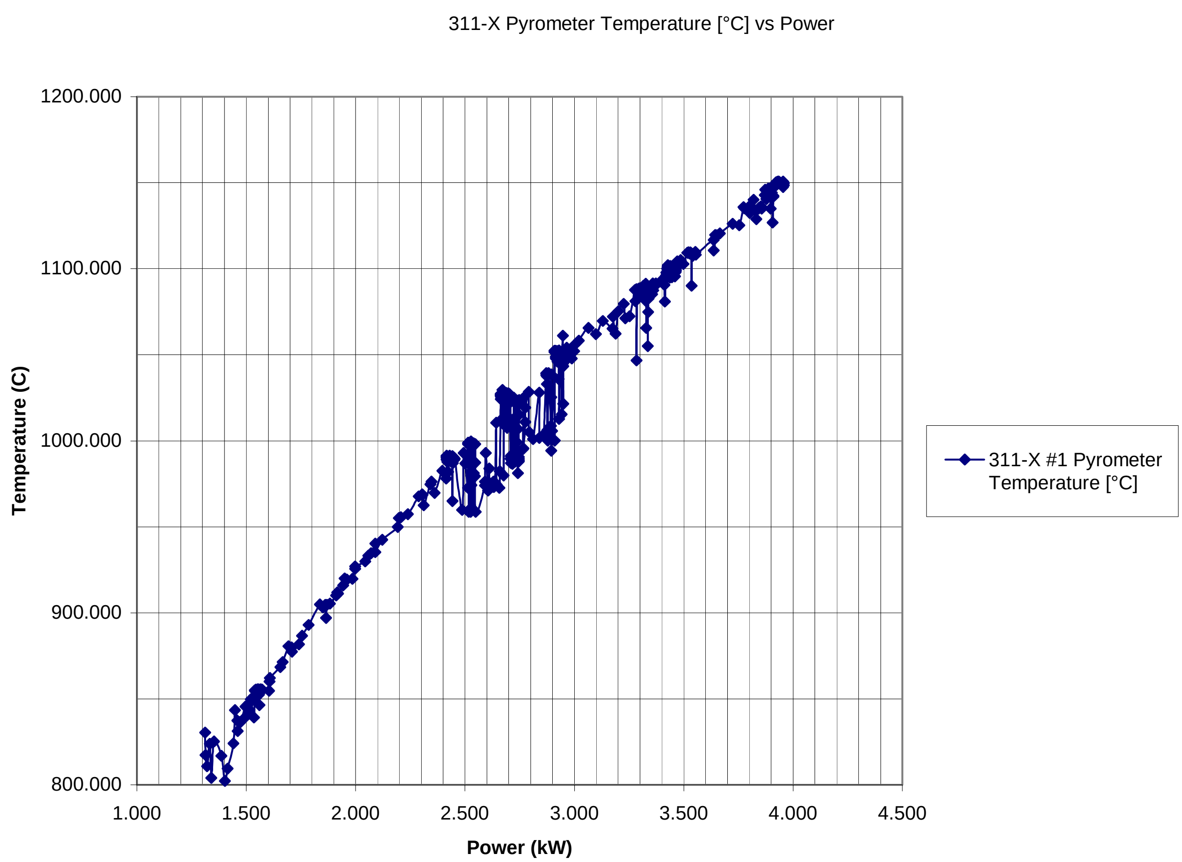


Fig. 6.4. Heating characteristic of the Os-W coated 311-X cathode (data obtained at DARHT-II).

We encountered another issue due to the long cooling time of the cathode. As we shall see in the quarter-inch size cathode test results, discussed in chapter 7, the work function did not stay constant when the system has less than ideal vacuum condition. In other words, the work function was a result of the surface condition that was dynamically balanced between the diffusion rate of the impregnated material (BaO), and the poisoning effect from impurities in the vacuum. Thus measuring the work function at a lower temperature when the cathode is only emitting 16A will not reveal the work function that we are interested to know when the cathode is required to emit 2 kA at a higher temperature. Furthermore, we measured J and T to derive the work function according to Richardson's equation (Eq. 6.1). The measurement must be done rapidly in order to prevent the work function from changing over time. Usually the heater power was turn down to allow the cathode to cool, thus giving simultaneously the readings for J and T. Unfortunately, this condition could not be achieve because the cooling time of the cathode was very long. Figure 6.5 shows the cooling characteristic after the heater power was turned off. More useful data was eventually obtained from the quarter-inch size cathode, which cools much more rapidly to allow a valid work function measurement.

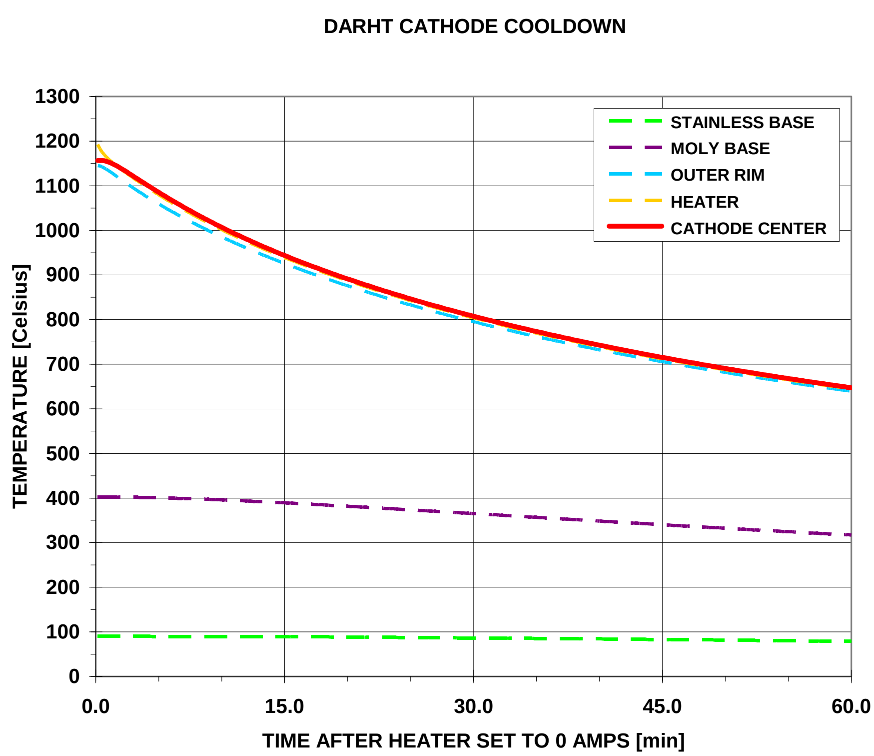


Fig. 6.5. Cooling characteristic of the Os-W coated 311-X cathode (data obtained at LBNL).

7. TESTING OF THE QUARTER-INCH CATHODE AT LBNL

7.1 Experimental Set Up (need to revise Fig 7.7 and Fig 7.10b)

In order to measure the performance of cathodes with various combinations of impregnation and coating, and also run the experiments under controlled environment, we modified an existing ion source test stand to test quarter-inch size cathodes. The HV power supply polarity was inverted to provide up to 27 kV to extract electrons. The Faraday cup geometry was modified and the gap distance between the cathode and the anode was adjusted. According to EGUN simulation, the new set up allows 10A/cm^2 maximum current density of electron emission. A schematic diagram of the set up is shown in Fig. 7.1, and the computer simulation results are shown in Fig. 7.2. Some photographs of the test stand are shown in Fig. 7.3.

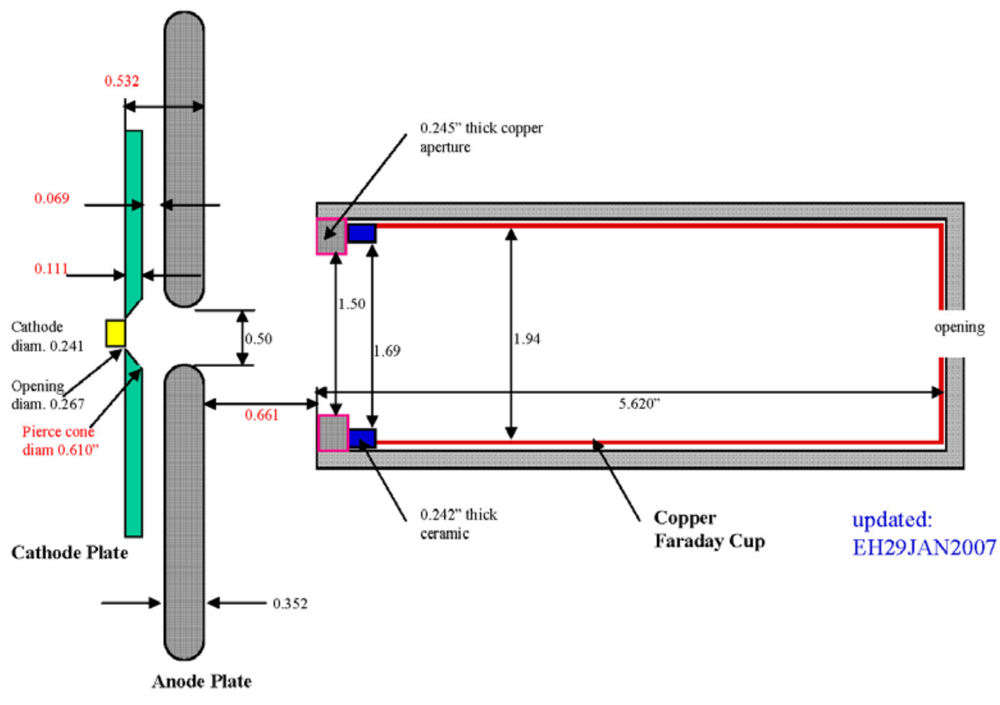


Fig. 7.1. The ¼“ cathode test set up with up to 26 kV extraction voltage.

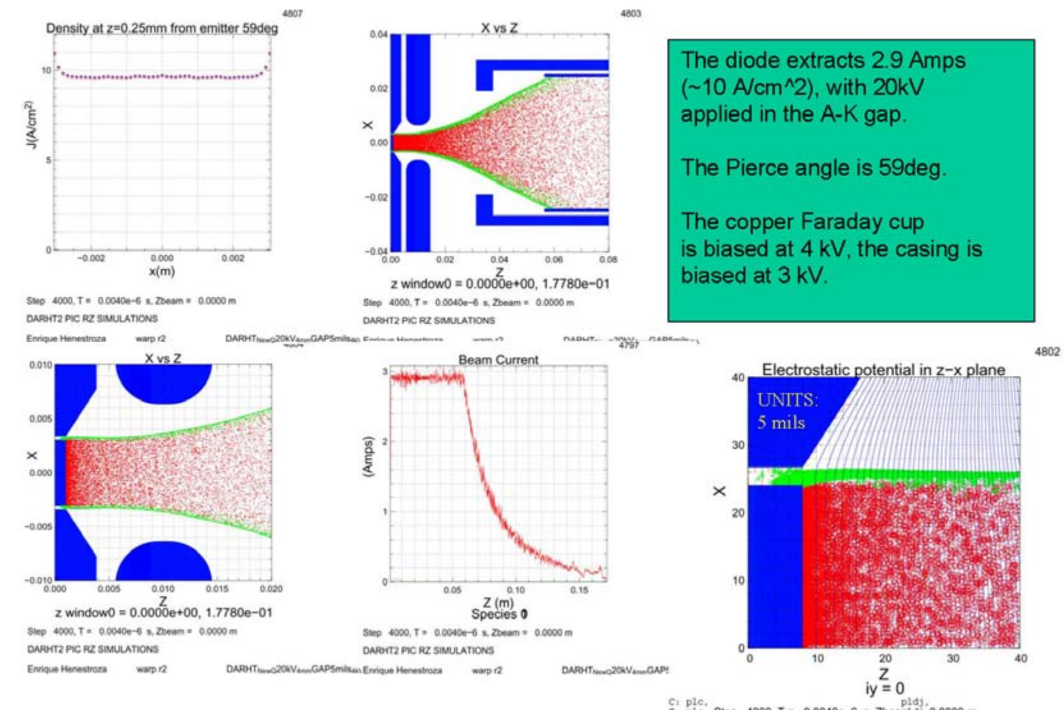
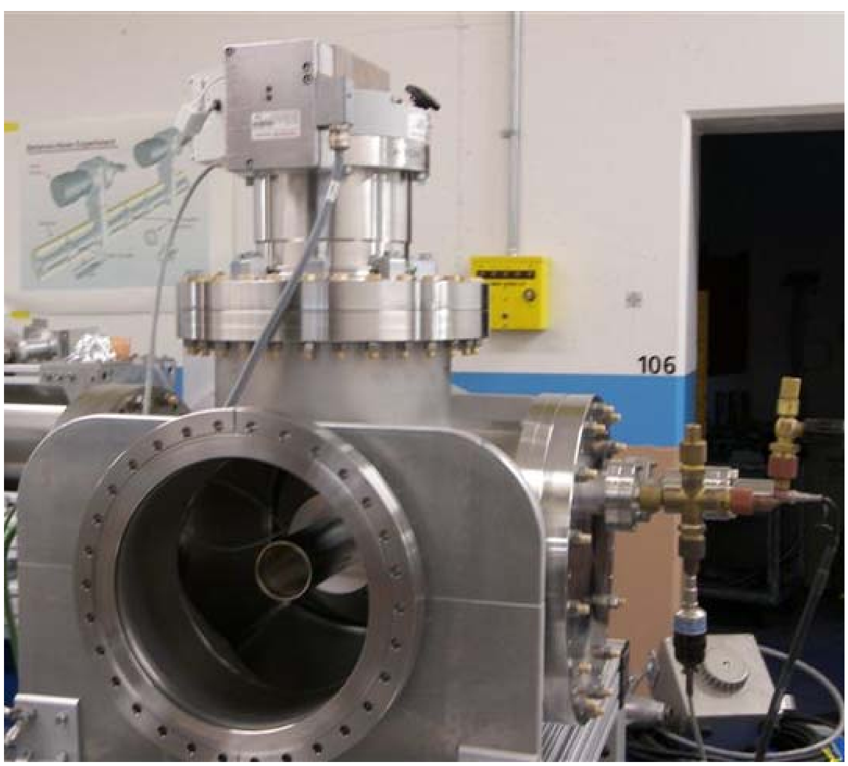


Fig. 7.2. EGUN simulation of the ¼" size cathode testing.



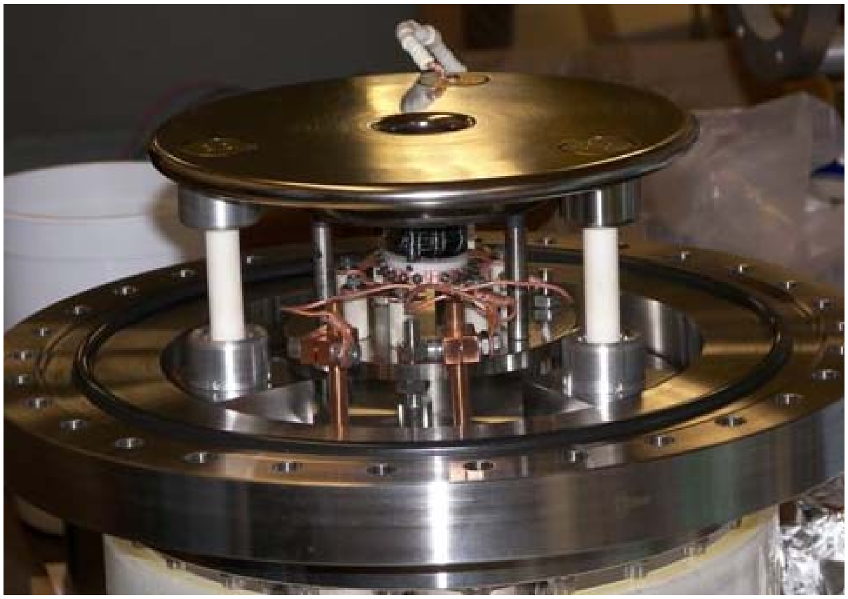


Fig. 7.3. Photographs of the “26 kV” test stand with ¼“ size cathode testing.

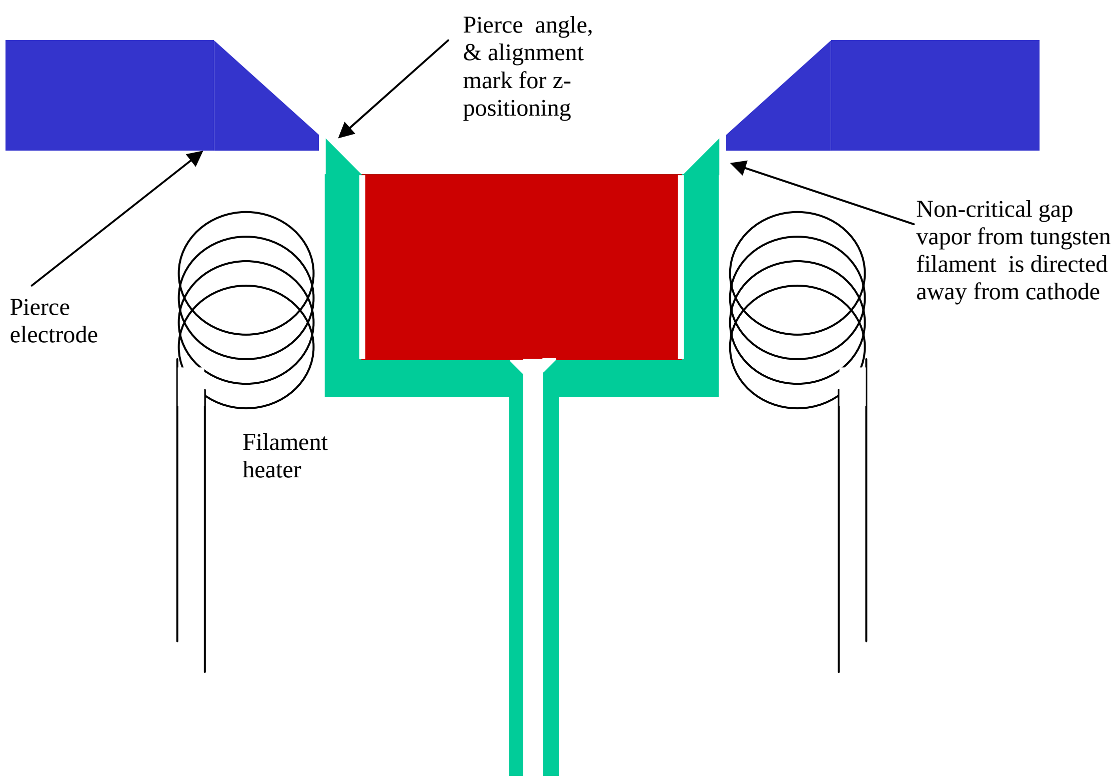


Fig. 7.4 Cathode and heater assembly.

The "electron gun" was designed to mount vertically, and the ¼" cathode was simply a "button" with no built-in heater. The button could be dropped into a cup holder. Heating was done by a set of 4 filaments surrounding the cup holder, connected in series. Figure 7.4 depicts the cathode and heater assembly. The filament was powered by a DC power supply in current control mode with the voltage limit set just above operating voltage (Sorenson DCS50-20E, 50V, 20A). While the cathode assembly was at ground potential, electrons were extracted when high voltage was applied to the extraction electrode. The HV Pulser was a solid-state modulator feeding into a step-up transformer with a negative bias voltage to suppress DC electron emission when the pulser was not on, see Fig. 7.5. After extraction, the electrons would decelerate as they approach the Faraday cup which was normally biased at about +3.5 kV. The housing of the Faraday cup was at a slightly lower potential (about +2.5 kV) but still positive w.r.t. ground potential in order to keep the electrons from stalling before entering the cup.

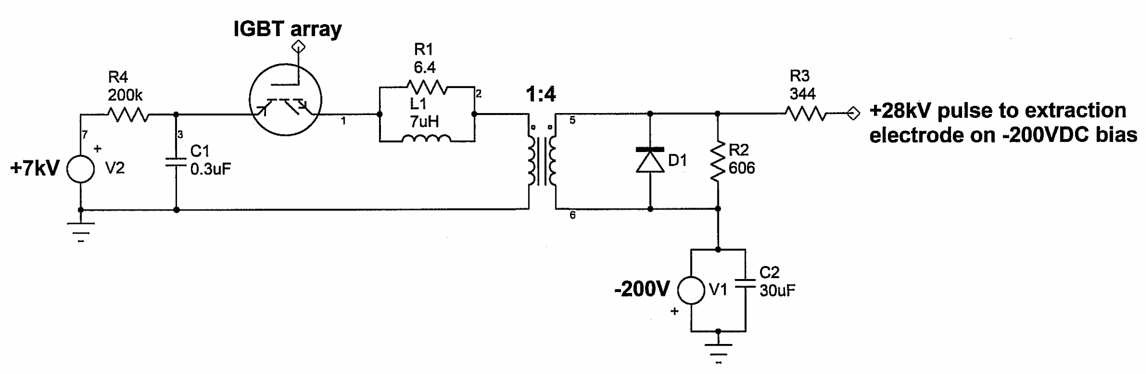


Fig.7.5. Circuit diagram of the biased HV pulser for extraction electrode.

The experiment required continuous 24/7 operation, therefore it was necessary to upgrade our control system, using LabView and VNC to remotely monitor and (partially) control the operating parameters during night time and over the weekend. It was essential to have this capability in order to make the testing possible.

The vacuum tank was thoroughly cleaned, and we use metal seal for the flanges in order to be able to do baking. Typical vacuum base pressure is in the 10^{-9} Torr range when the cathode heater was turned off. Given the small cathode size, the system was able to maintain in the high 10^{-9} Torr range even when the cathode was hot.

The Faraday cup was designed with an opening at the rear end such that the cathode temperature can be measured by using an optical pyrometer. According to the computer simulation, this small opening at the rear would not significantly affect the beam current measurement. Since it usually took more than 2 seconds to obtain a good reading from the manually operated optical pyrometer, it was not always possible to obtain the cathode temperature simultaneously with the current measurement. This was actually a problem during the experiment when we measured the work function verse temperature. In the end we had to rely on the cathode being cooled in a reproducible way to derive the cathode temperature from a calibration curve.

A number of cathode buttons were purchased from SpectaMat. Table 7.1 shows the combination of impregnation and coating material. Due to the availability of time, only the 612M, 311XW and 311XM were tested (X stands for having Scandate in the cathode, "M" is the Os-Ru coating and "W" is the Os-W coating).

Table 7.1. ¼" size button made by SpectraMat

Run	Block	Factor 1 A:Impregnant	Factor 2 B:Scandate	Factor 3 C:Coating
1	Block 1	612	w/Scandate	Os-W
2	Block 1	612	w/Scandate	Os-Ru
3	Block 1	612	w/Scandate	None
4	Block 1	612	w/Scandate	Os-Ru
5	Block 1	311	w/Scandate	Os-W
6	Block 1	311	w/Scandate	Os-Ru
7	Block 1	311	w/Scandate	None
8	Block 1	311	w/Scandate	Os-W
9	Block 1	612	None	Os-Ru
10	Block 1	612	None	None
11	Block 1	612	None	Os-W
12	Block 1	612	None	Os-W
13	Block 1	311	None	Os-Ru
14	Block 1	311	None	None
15	Block 1	311	None	Os-W
16	Block 1	311	None	Os-Ru

7.2 Cathode Temperature vs. Heating Power

An important issue with the 6.5" cathode operation was the heating power required to reach the operating temperature of ~ 1050 ºC. The equilibrium temperature was governed by the filament power and the radiation heat loss as a function of the emissivity of a hot surface. In running the 311XW cathode, it was found that more heating power was required for that cathode to reach the same temperature as the 612M cathode.

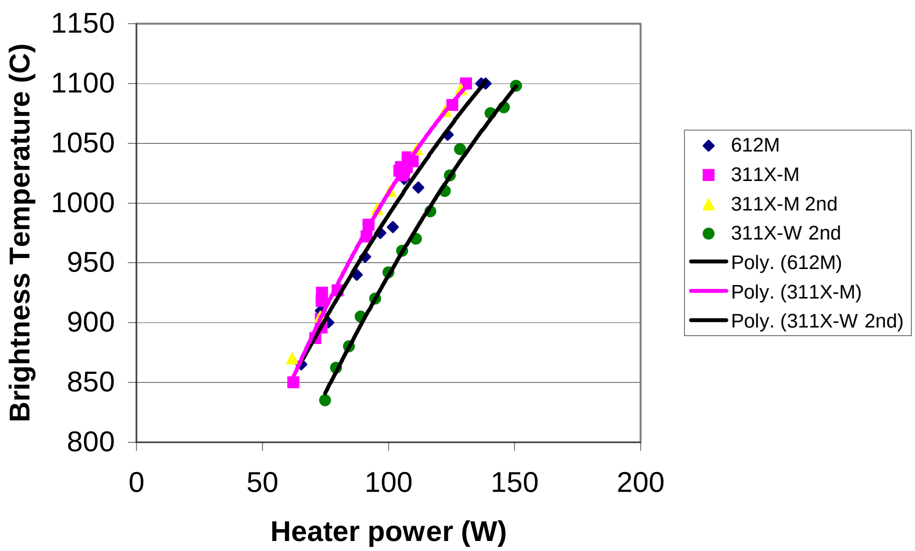


Fig. 7.6 Temperature of a ¼" cathode as a function of heater power. (Temperature was measured by an L&M disappearing filament type optical pyrometer.)

After finding out that the 6.5" 311XW cathode could not reach the desired activation temperature of 1100 ºC before damaging the heater filament, we decided to try the 311XM and hope that, with the scandate, it would have a low function like the 311XW while the heating characteristics could be similar to 612M based on their similar coating material. If both assumptions were true, then the combination of these 2 properties would provide the proper condition for reaching 2 kA within the filament power supply and temperature limits of the 6.5" cathode. We ran an experiment with quarter-inch size buttons to confirm the temperature behavior before procuring a 311XM cathode from SpectraMat.   That result is shown in Fig. 7.6. As expected, the 311XW ¼" buttons had the lowest temperature whereas the temperatures for the 612M and 311XM buttons were similar to each other and at a higher level.

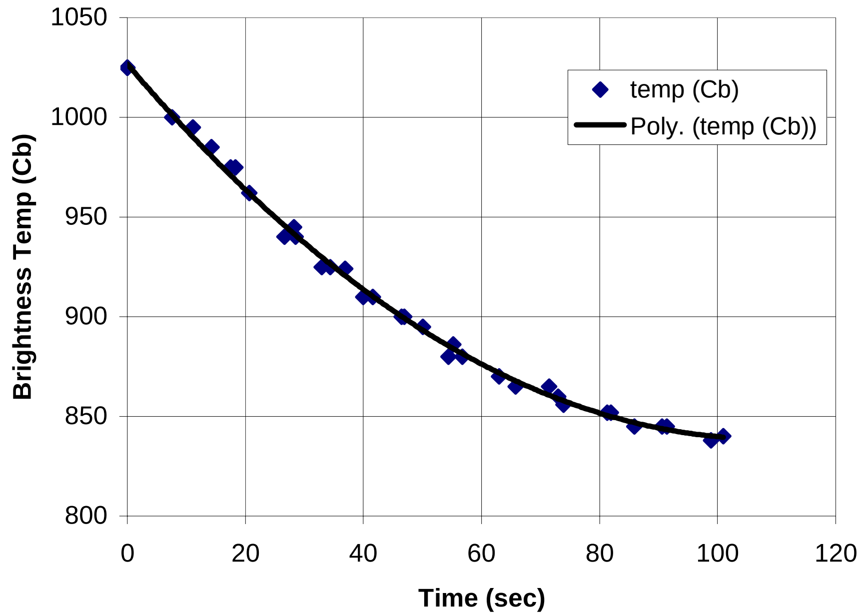


Fig. 7.7 Cathode temperature ramping down after heater power reduced from 14.8V, 7A to 10V, 5.5A. Solid line is a polynomial fit of the data points.

Figure 7.7 shows how a ¼" button typically cooled down when the heater power was suddenly reduced to a lower level. This kind of temperature calibration curve was used to correlate the cathode temperature when it was necessary to measure the beam current as a function of temperature rapidly. Taking the measurement quickly, e.g. within 1-2 minutes, will minimize the chemical change on the surface, thus allowing the work function to stay constant.

7.3 Measuring Current as a Function of Temperature Under Good Vacuum

As a precaution step in making beam current measurement, we checked the gun perveance by plotting beam current as a function of extraction voltage like that shown in Fig. 7.8.   The data displayed a $V^{3/2}$ scaling according to space charge limit beam extraction. The perveance was found to be in generally agreement with the designed value therefore gave us the confidence that the measured beam current was not contaminated by secondary electrons.

The plot of current density vs. temperature, as shown in Fig. 7.9, provided the best evidence showing the 311XM cathode reached 10 A/cm^2 (i.e. 2 kA for the 6.5" cathode) with the cathode temperature at < 1075 ºC. The different data series corresponded to extraction voltage settings at 8, 12, 16, 20 and 24.6 kV. Each data series would reach saturation according to the space charge limit for the applied extraction voltage. By comparing the experimental results with the Richardson equation curves (lines without dots), using various values of work function, we concluded that the effective work function of this cathode was between 1.85 eV to 1.95 eV.

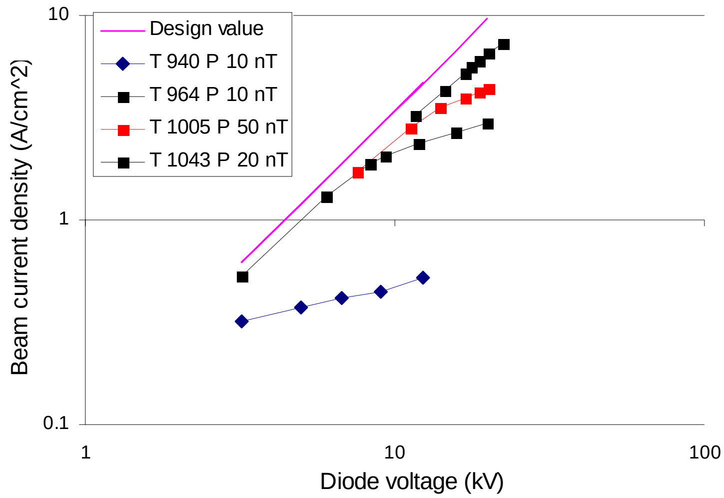


Fig. 7.8 Beam current reaching space charge limit according to gun perveance.

As mentioned before, the data for each data series was taken within 1-2 minutes immediately after dropping the heater power from 109W to 54W while the cathode cooled from 1100 ºC to 900 ºC. In order to provide a convenient comparison between this testing and those obtained from DARHT-II, we plotted the "true" temperature in Fig. 7.9. Here the true temperature was calculated from the measured brightness temperature (as provided by the L&M pyrometer) by assuming that the emissivity = 0.4. The conversion from brightness temperature [in absolute unit] to true temperature can be done by using the following equation[1]:

[1] Temperature, Its Measurement and control in Science and Industry", Reinhold Publishing Corp, NY, 1941

$$\frac{1}{T_{true}} = \frac{1}{T_{br}} + \lambda \frac{\ln(\varepsilon)}{14320}$$

where λ is the optical wave length [in unit of mirrons] used in the measurement and ε is the emissivity at that wavelength. At the DARHT-II injector, the true temperature was measured directly from using a 4-color optical pyrometer.

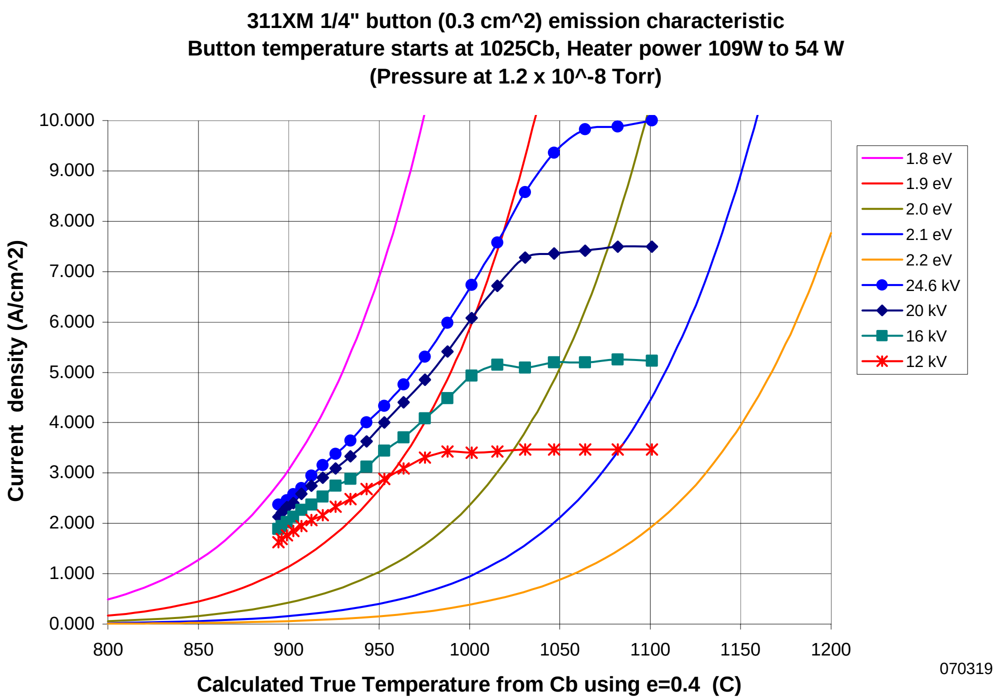
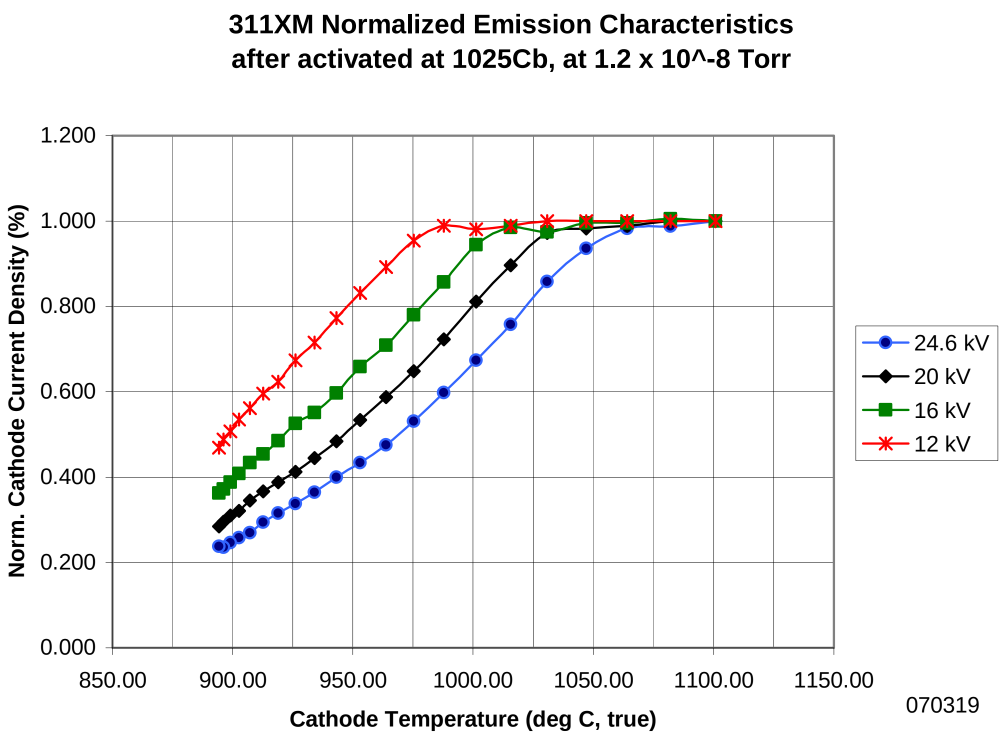


Fig. 7.9 Beam current density vs. temperature for 311XM.

The data in Fig. 7.9 can be plotted in different ways to produce either the “cathode loading curves” as shown in Fig. 7.10a or the “Miram Curves” in Fig. 7.10b. According to George Miram, these normalized plots are often used in the cathode industry to evaluate the performance of individual cathodes. For example, the Miram curve of a good cathode will peak at a low work function value and have a narrow profile.



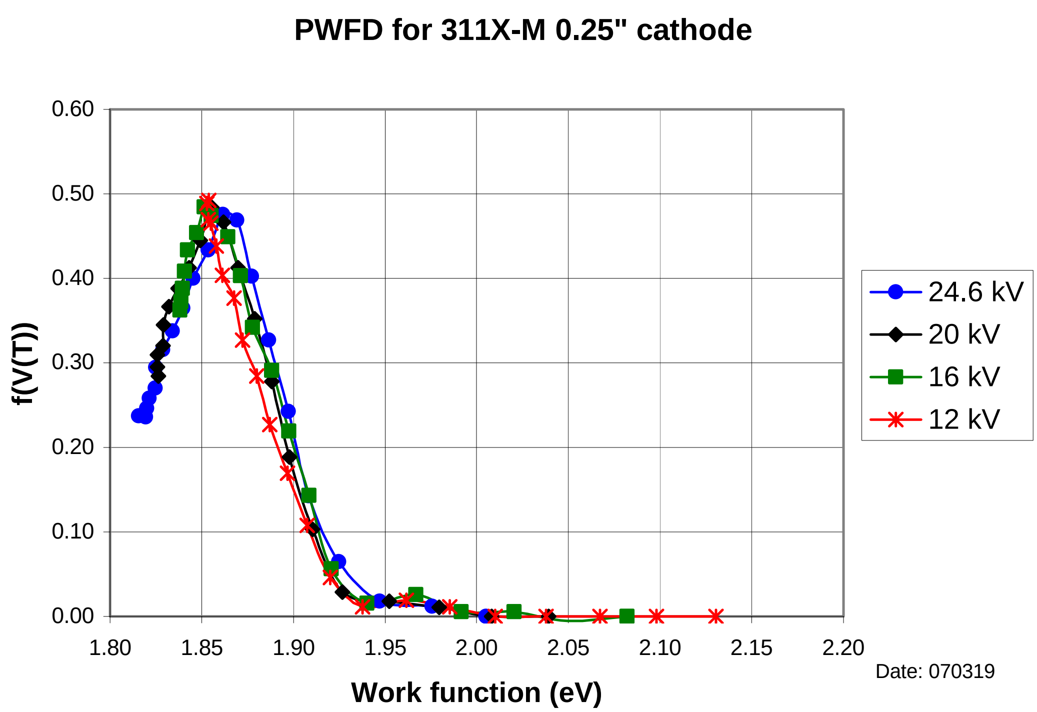


Fig. 7.10 (a) Cathode loading curves, and (b) Miram (pwfd) Curves.

7.4 Transient Effect Due to Cathode Poisoning

Figure 7.11 shows how the beam current evolved as a function of time after the heating power was suddenly dropped from 109W to 54W, and then later raised back to 109W. We observed that there were two distinct periods. In the first period, which lasted only a couple of minutes, the cathode temperature dropped to reach a steady state, the current also dropped rapidly as governed by the Richardson equation. Within this short period, we expected minimal change to the surface condition of the cathode and therefore the work function would be relatively constant. In the second period the cathode temperature remained constant, but the there was a gradual reduction in beam current probably due to the slowly changing surface condition.

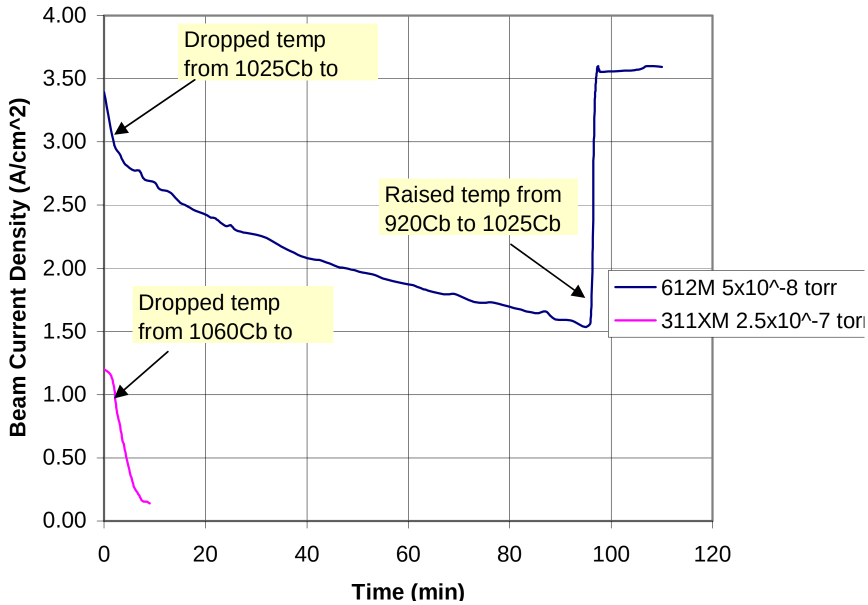


Fig. 7.11 Beam current reduction after dropping the heating power.

The slow degradation during the second period can be explained by a gradual increase in the work function due to poisoning of the cathode under the influence of poor vacuum. This model was further confirmed by the fact that the time constant of degradation depended on the partial pressure in the vacuum. Higher pressure corresponded to higher reaction rate and therefore shorter time to reach equilibrium. At high pressure (poor vacuum) of mid-10^{-7} Torr, the emission was poor and it usually took less than an hour to reach a new equilibrium after dropping the heater power. On the other hand at low pressure (good vacuum) of below 1 x 10^{-8} Torr, the emission was good and it could take many hours, some times overnight, to reach new equilibrium. In fact taking data was very time consuming and one had to be very patience when working with good vacuum condition. Automation in data acquisition and remote control became a necessity in order to collect trustworthy data.

In the situation when the cathode is subjected to poisoning, the surface condition of the cathode is in a dynamic equilibrium between the contamination rate and the diffusion rate of the BaO which helps to overcome the poisoning. Besides the issue of long time constant, we also observed minor hysteresis effect making it possible to see the same beam current emission under multiple temperature readings.

These issues of poisoning and transient behavior generally do not occur in cathodes that are manufactured in sealed tube with baking to attain good vacuum. However, for open systems like the one in DARHT, where Viton O-rings are used in many places, and baking is not allowed, the issue of poisoning can dictate the cathode performance. In this case, the best strategy is to choose the type of cathode that has the most resistance against poisoning.

7.5 Measuring Temperature vs. Pressure of Various Gases at 10A/cm^2

Our goal was to develop a DARHT cathode that could produce 2 kA of electron beam. With a cathode size of 6.5 inch diameter, the corresponding current density was 10A/cm^2. The required cathode temperature that could produce such current density varied depending on the types of background gas and its partial pressure. We have carried out a series of measurement to compare the effects of argon, carbon dioxide, nitrogen, air, dry air, and water vapor for the 612M and 311XM cathodes. The extraction voltage was set at 25 kV with a corresponding space charge limited current density of 10A/cm^2; this is the similar space charge limited condition that DARHT will operate. Figure 7.12 shows the data taken with normal air and a 311XM quarter-inch button cathode. As expected, the current density increased with temperature until it reached the space charge limited saturation level. Higher temperature was needed (to produce the same beam current) for higher pressure.

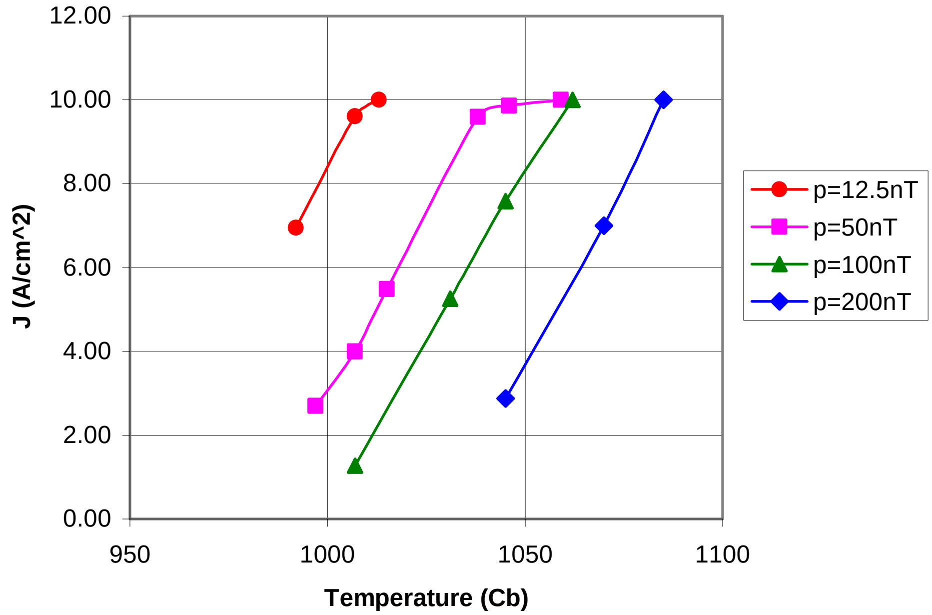
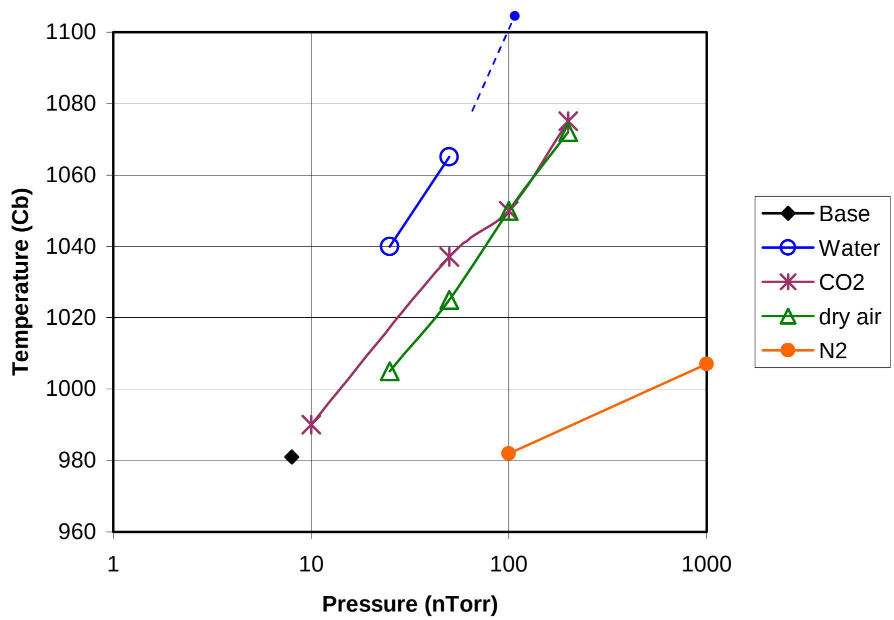


Fig. 7.12 Cathode performance at various levels of partial pressure of normal air. Extraction at 25kV such that the space charge limit is at 10A/cm^2.

The knee points (at 10 A/cm^2) can be plotted as a function of "critical temperature" vs. pressure. The experiment was repeated for different types of gas (a very time consuming process). Figure 7.13 compares the effect of various types of gas for the 612M cathode. All the data in the graph were taken with the same quarter-inch button cathode. We were able to verify that the cathode was not permanently contaminated in each run (thus no accumulated poisoning effect) except the very last run when using water vapor. The data suggested that nitrogen was most friendly to the cathode, while carbon dioxide and dry air (presumably due to the oxygen) were similar in effect, and water vapor was the worse contaminant.

A similar effort was done to measure the 311XM performance and the results are shown in Fig. 7.14. Again the trend was the same with argon and nitrogen being the most friendly gases, carbon dioxide was not as good, and the worse was water vapor and normal air (presumably due to water moisture in the air). By comparing Fig. 7.13 with Fig. 7.14, we found that the critical temperature for 10 A/cm^2 at very good vacuum, e.g.

below 10 nTorr, was nearly the same for both 612M and 311XM cathodes. However, at 100 nTorr, the critical temperature was higher for the 612M cathode than the 311XM cathode. In other words the 612M and 311XM were equally good under good vacuum (e.g. below 10 nTorr) , but if the vacuum is poor then the 311XM is preferred because it is less affected by gas poisoning.



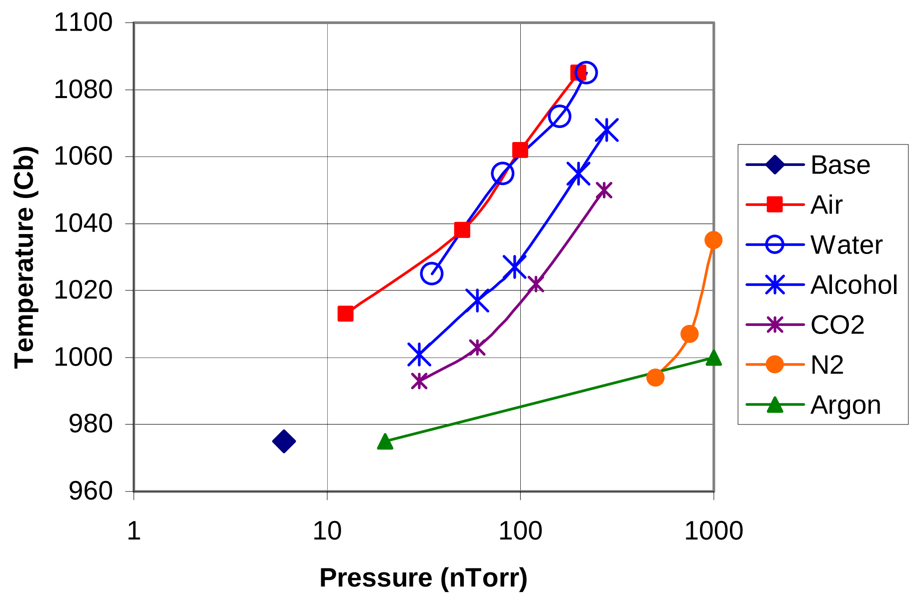


Fig 7.13 Critical temperature for 10A/cm^2 emission as a function of gas pressure. (a) for the 612M and, (b) for the 311XM.