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# Performance Measurements of Sealed-Tube Electron Beam Windows

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# PERFORMANCE MEASUREMENTS OF SEALED-TUBE ELECTRON BEAM WINDOWS[1]

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## ABSTRACT

**This paper describes the performance of the thin-film windows used in a new sealed-tube electron gun. Measurements include beam current, power, and power density along with window transmission, temperature, electron scattering and window life tests. A number of novel beam diagnostic tools were developed as part of this effort. Results are compared to Monte Carlo computer predictions and show good agreement. Transmitted beam powers in excess of 200 watts have been achieved, with current densities exceeding 30 milliamperes per square centimeter at sixty kilovolts beam energy. Predicted window wearout time exceeds several thousand hours at a current density of two milliamperes per square centimeter and a beam accelerating voltage of 60 kilovolts. This work was carried out under a Cooperative Research and Development Agreement (CRADA) between Lawrence Livermore National Laboratory and American International Technologies, Inc.**

## INTRODUCTION

Lawrence Livermore National Laboratory and American International Technologies are jointly developing a sealed-tube electron beam gun for material processing applications. Tubes have demonstrated power outputs of up to 150 watts at 60 kilovolts gun voltage (figure 1). This device obviously has great potential for reducing both the capital and operating costs for electron beam processing, by eliminating the need for a dedicated vacuum system, reducing x-ray shielding and facilitating maintenance. The key element of this device is the thin film window that is relatively transparent to electrons, and leak tight enough to maintain the sealed-tube's vacuum for extended periods of time. The window must also survive the elevated temperatures produced by the beam, be chemically inert and resistant to radiation. Our organizations, operating under a Cooperative Research and Development Agreement (or CRADA) have developed several electron beam window variants capable of meeting the above requirements. These are described briefly. The principal purpose of this paper is to document a series of tests to verify the performance of these thin-film windows.

As part of the tests to verify the performance of the e-beam windows we have developed a number of novel diagnostic devices. These include a unique beam current monitor for measuring electron beam current, devices for measuring the e-beam footprint at the tube window and outside the window, a calorimeter for beam power measurement, and an infrared imaging system for measuring window temperature while the beam is in operation. We describe these devices in some detail in this paper, along with the results of the tests. A window test-stand was constructed to carry out these tests, and is briefly described. Lifetime tests, along with projections of the window wearout lifetime are discussed at the end of the paper.

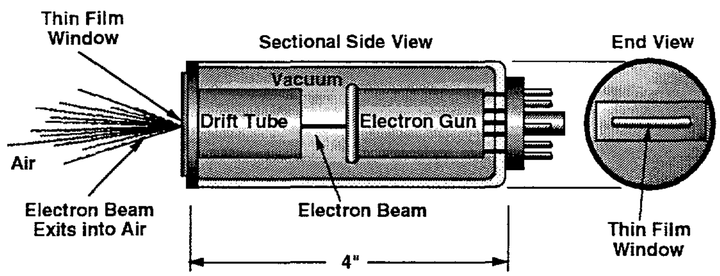



**Figure 1. Sealed-tube electron beam gun. Nominal operating parameters: beam voltage 30-75 kilovolts, beam current 1-2 milliamperes and beam power of up to 150 watts.**

## ELECTRON BEAM TUBE WINDOWS

Electron beam windows meeting the requirements for our sealed-tube electron gun were developed jointly by LLNL and AIT. Final refinement of the design and manufacturing process was carried out in special facilities at LLNL. A number of window types were developed with areal densities ($gm/cm^2$) ranging from $6 \times 10^{-5}$ to $6 \times 10^{-4}$ grams per square centimeter and open areas ranging from 1 to 50 square millimeters. Several highly successful window designs have been demonstrated. The windows, which are designed to withstand several atmospheres of pressure drop under operating conditions, are made of low Z (atomic number) materials for minimal electron scattering, are chemically inert to prevent reaction with oxygen, ozone and other reactive species produced by the electron beam interactions with the atmosphere outside the tube (air, helium, nitrogen, etc.) and will withstand temperatures of several hundred degrees centigrade for extended periods. In addition these windows are impermeable to gases, with measured helium leak rates less than $10^{-8}$ Torr-liters/second. Dimensions of the windows used in tests described in this paper measured 2 millimeters by 25 millimeters, with an area of 50 $mm^2$ (or 0.5 $cm^2$).

## WINDOW TEST-STAND

A test-stand (figure 2)was constructed for measuring electron gun and window performance, as well as life testing the guns and windows. The test-stand consists of a high speed turbomolecular pumping system (2000 liter/second pumping speed), a 0 - 75 kilovolt high voltage system, and a vacuum vessel which houses the electron gun and thin film windows. Typical pressure in the chamber during beam operation is 3-4 x $10^{-7}$ Torr. The system is shielded to limit operator x-ray exposure to less than 0.25 mrem/hr. After the electron beam passes through the window it enters a shielded enclosure outside the vacuum chamber with viewports for viewing the beam. This test-stand duplicates most of the conditions inside the sealed-tubes with the exception of the absence of the glass (dielectric) tube enclosure.

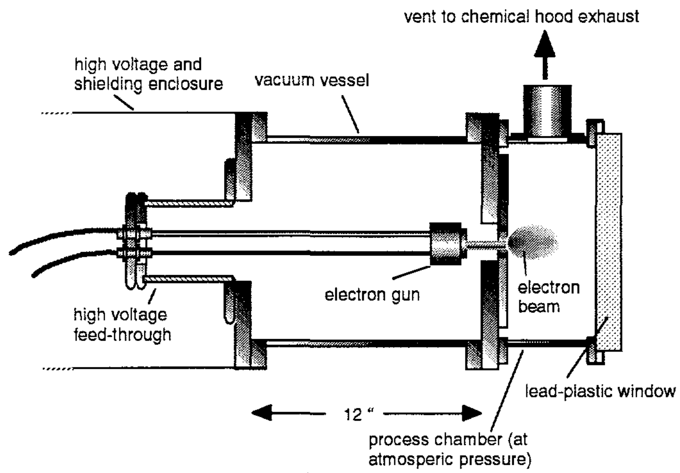



**Figure 2. Test-stand vacuum chamber showing the position of the electron gun, window and beam enclosure. Electron guns and windows in our tests were identical to those used in the sealed-tube guns.**

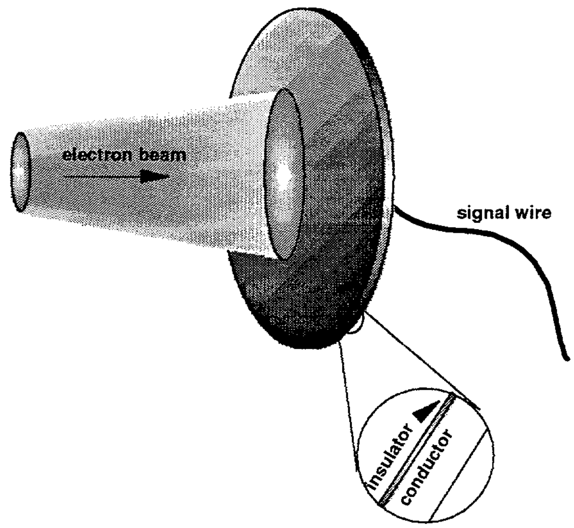
## BEAM CURRENT MEASUREMENTS

A key measurement for an electron beam system used for processing materials at atmospheric pressure is the beam current (and current distribution) at the point where the subject material will be exposed to the beam. Beam current measurement in the atmosphere is complicated by the ions and electrons (plasma) produced by the beam as it passes through the air (or helium, nitrogen or other gas used as a blanket). A conductor (metal) in the path of the beam will stop, and conduct away beam electrons as a measurable current. However, plasma ions and electrons, reflected beam electrons, secondary electrons and x-ray produced secondary electrons will also contribute to the measured current. These currents can be large compared to the beam electron current, making interpretation of the measurement difficult or impossible. A traditional solution to this is to use a faraday cup with a thin, grounded, metal foil in front of the faraday cup. This approach works for high energy electrons (hundreds of kilovolts) and at low power densities (tens of watts per $cm^2$). However, our effort is aimed at developing low energy electron beams (≤ 75 kilovolts) with power densities exceeding several hundred watts per $cm^2$. A new measurement technique was required for our tests.

We developed a current detector consisting of an electrically conducting plate covered with ~500 Å of non-conductive material (figure 3). The non-conductive surface material was selected for very low radiation-induced conductivity, high dielectric strength, and low atomic number. The insulating layer is thin enough to permit beam electrons to pass without significant attenuation, and thick enough to both stop secondary electrons from leaving and prevent low energy plasma electrons and ions from contributing to net current flow to the conducting base.

To assure that the device is working properly we performed two tests. The first of these was to accurately predict the monitor current for a known electron beam configuration, and compare that with the value measured in the laboratory. We employed a fully three dimensional Monte Carlo computer code[2] that includes the scattering of the electron beam by the window, structures surrounding the beam aperture, and air gap between the window and detector. The model also included the effects of the detector and its insulating front layer on the beam, namely reflection and absorption of beam electrons. Figure 4 shows a sample output from the code. The test case was run with the detector placed one inch (2.54 cm.) from the front surface of the electron beam window. Summary code results for runs with a 6 x $10^{-4}$ gm/cm$^2$ window are shown in table I. As can be seen in the table, less than half the beam electrons reach the detector, the remainder being scattered by the air in the gap between the window and detector, or lost to the structures surrounding the window. Those electrons stopped by the conducting substrate behind the insulating layer will contribute to the measured detector current.

**Figure 3 (right). Current monitor developed for measuring low energy electron beams. This device, developed and fabricated at Lawrence Livermore National Laboratory, consists of a conducting substrate covered with a thin layer of insulation. The insulating layer has a combination of high dielectric strength and maintains low conductivity under intense radiation. This device was used throughout our test series and proved to be a valuable tool for measuring the electron gun and window performance.**



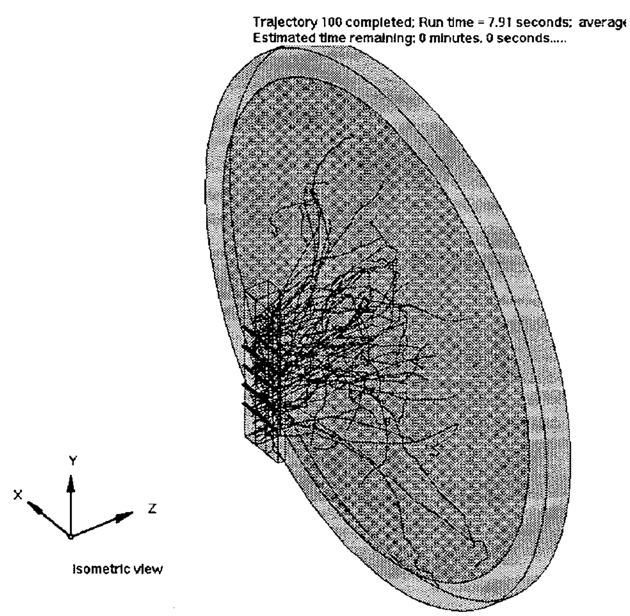



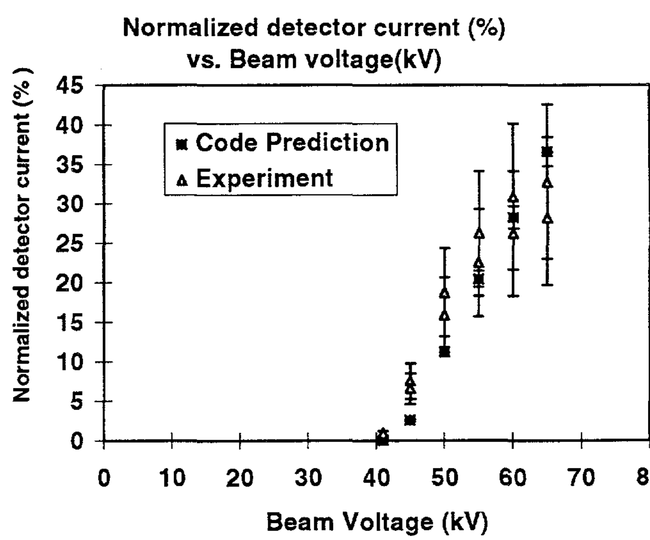

**Figure 4 (right). Code output showing electron trajectories for the beam and detector configuration used in the current detector tests. The beam is emitted from the window structure at the left, and passes through the thin film window into the air gap beyond. As can be seen in the plot. Most of the electrons are scattered and absorbed in the air gap between the window and the detector.**

The code predictions and parallel experiments show reasonable agreement. The experimental data were taken at an incident beam current of 0.3 milliamperes. The cutoff of detector current at about 40 kilovolts is due to electron scattering in both the window and air gap between the window and the detector. Near cutoff, the power dissipation in the window (and window heating) rises sharply, reaching several tens of watts per square centimeter. Operation at low current decreased the signal to noise ratio for the detector current measurements, and hence introduced relatively large error bars in the data. Nonetheless both the cutoff and overall scaling of the detector current are in reasonable agreement.

| Beam Energy (keV) | Theory (code prediction) | | | Experiment |
|---|---|---|---|---|
| | % Trans. | % Refl. | % Net | % Net |
| 35 | 0.00 | 0.00 | 0.00 | 0.00 |
| 40 | 0.0 | 0.0 | 0.0 | 0.00 |
| 45 | 3.64 | 1.09 | 2.55 | 7.0 ± 2.2 |
| 50 | 14.97 | 3.74 | 11.23 | 17.3 ± 5.2 |
| 55 | 27.83 | 7.40 | 20.43 | 24.4 ± 7.4 |
| 60 | 38.91 | 9.95 | 28.24 | 28.6 ± 8.6 |
| 65 | 46.17 | 11.53 | 36.64 | 30.5 ± 9.2 |
| 70 | 52.48 | 13.04 | 39.44 | n/a |
| 75 | 57.22 | 14.13 | 43.09 | n/a |

**Table I (above). Table showing Monte Carlo code predictions for beam electrons with a $6 \times 10^{-4}$ gm/cm$^2$ window and a one inch air gap. Shown are code predictions for percent of the electrons transmitted to the detector, percent reflected, and net percent relative to the initial number of electrons in the beam before entering the window. The net percent is that portion that will be detected as current. The window transmission for beam electrons is over 90%, but many electrons are absorbed in the one inch air gap between the window and the detector. Although the window is transparent to electrons at low energies, absorption in the air creates the "cutoff" at 40 keV. Also shown are experimental values for the same configuration. The relatively large errors in the experimental values are due to operation at low beam currents to avoid window damage near transmission cutoff at low beam voltages.**

**Figure 5 (right). Graph showing the data in Table I for beam electrons with a $6 \times 10^{-4}$ gm/cm$^2$ window and a one inch air gap, along with experimental data for the same configuration. As stated above, the relatively large errors in the experimental values are due to operation at low beam currents to avoid window damage near transmission cutoff at low beam voltages.**



The next test was to verify the linearity of the detector with beam current at constant voltage. This test is important to show that background plasma currents are not shunting the detector current to ground instead of passing through the current meter, which would result in a low measurement. As beam current increases the background plasma density(fractional ionization of the air) in the air gap between the window and detector increases. If a significant fraction of the detector current is flowing to ground through the ionized air instead of the current meter, the detector response would likely be nonlinear with respect to beam current (at constant beam voltage). Also the magnitude of the detected current would be lower than predicted. Neither effect was observed in our tests (as shown in figure 6) for currents up to and exceeding 3 milliamperes and power levels exceeding 200 watts. The experimental data shows linearity within the measurement errors, and the absolute magnitude of the measured detector current (slope) agrees within a few percent of code-predicted values (0.27 measured versus 0.28 predicted for the 6 x $10^{-4}$ gm/cm$^2$ window, for example).

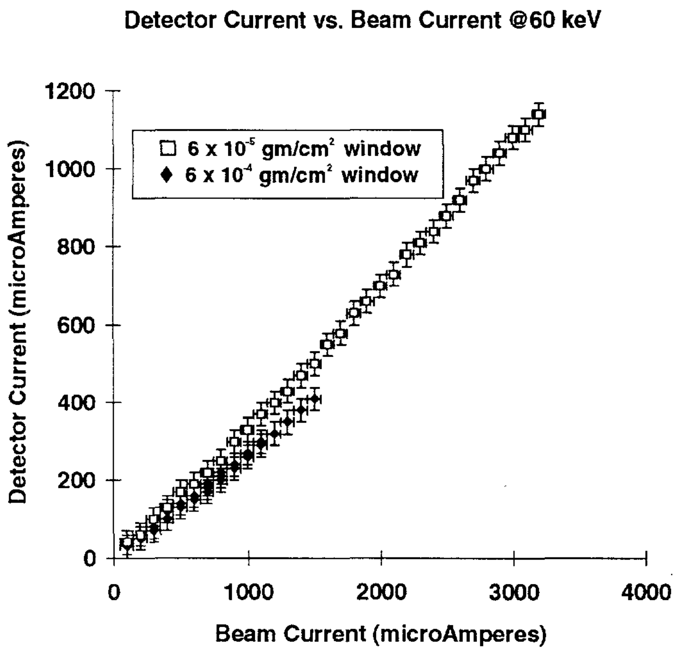



**Figure 6 (left). Graph showing the linearity of detector response with varying beam current. As can be seen from the graph, the detector is linear with respect to beam current. Data is shown for two different windows, with areal densities of 6 x $10^{-5}$ gm/cm$^2$ and 6 x $10^{-4}$ gm/cm$^2$ respectively.**

## BEAM POWER MEASUREMENTS

Beam power measurements were carried out with an LLNL developed calorimeter. This device consisted of a cylindrical copper block 2.0 inches in diameter by approximately 0.75 inches thick. The back and sides of the copper block were surrounded by insulating foam for thermal insulation (figure 7). Block temperature was monitored by a thermocouple embedded in a recess the back side of the copper block. In operation the calorimeter was placed 0.6 inches from the e-beam window with the exposed face of the copper block facing the e-beam window (figure 8). The beam was turned on for a predetermined period of time, nominally several seconds, and then turned off. The temperature rise of the calorimeter was noted after an equilibration time of a few seconds. The temperature rise, divided by the known thermal capacity of the copper block and the beam exposure time yields the e-beam power deposited in the calorimeter. The device was calibrated using a resistor embedded in the copper block (not shown in the drawing). The calibration was confirmed with a calculation of the copper block's thermal mass based on dimensions. As with the current detector, results from the calorimeter test were compared with three dimensional code predictions. Again, good agreement between prediction and measurement was achieved. For example, the e-beam was operated at 60 kilovolts and 1.5 milliamperes for 60 seconds. The predicted energy deposition was 3620 joules, compared with a measured value of 3762 ± 180 joules.

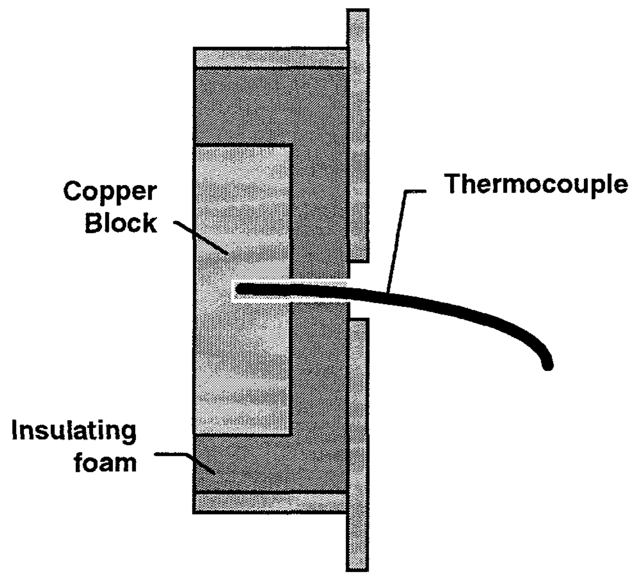



**Figure 7. Sectional view of the calorimeter showing the copper block, insulation and thermocouple.**

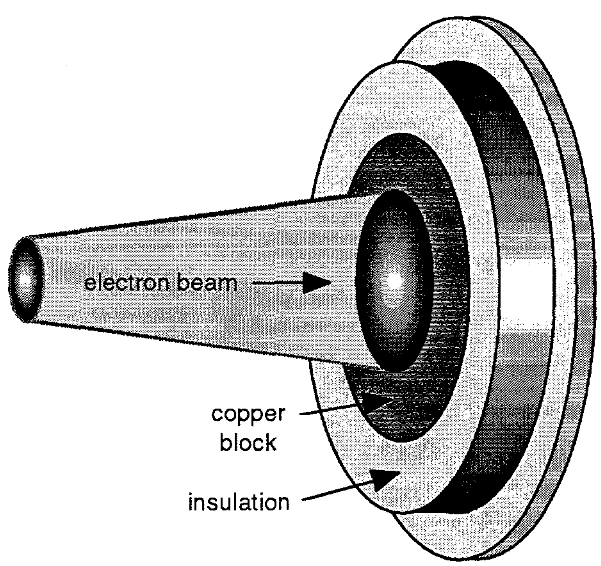



**Figure 8. View of the calorimeter showing the electron beam and copper block.**

## BEAM PROFILE MEASUREMENTS

The current and power measurements are useful for determining the overall characteristics of the e-beam, but provide no detail of the beam "footprint" or profile. To accurately determine the radiation exposure of parts or materials being processed, a detailed knowledge of the profile is required. To accomplish this we developed two devices (profilometers) for measuring the beam profile at the e-beam window and beyond, one useful for very high spatial resolution (≤ 30 microns) at beam powers of a few watts or less, and another with reduced spatial resolution(≤ 300 microns) capable of higher power operation. The first of these uses a glass plate coated with a thin layer of cathode ray tube phosphor (P-31, zinc sulfide, ~ 25 microns thick) with a thin layer (5000 angstroms) of evaporated aluminum to carry off any deposited electrical charge. The screen is placed in the path of the beam and the light emitted from the beam striking the phosphor recorded via a solid state image converter. Video output from the image converter is then digitized and plotted as a three dimension plot. Care was taken to assure that the phosphor or image converter was not saturated and that the intensity of emitted light is a linear function of beam current by taking several measurements at increasing beam current values and checking output data for linearity with current. The device has been operated both in vacuum and in air with no difficulty. The device produced data of good quality at beam currents as low as a few microamperes. Operation at higher currents was limited by temperature rise of the glass and phosphor, and another device was needed for measurements at high power.

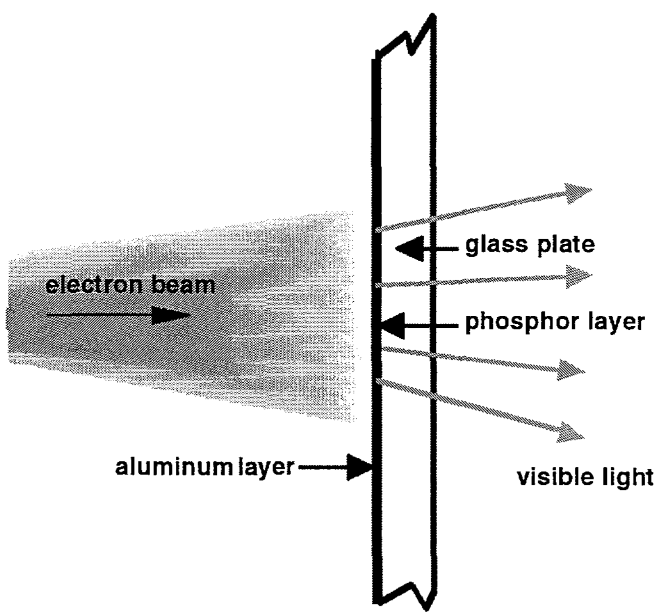



**Figure 9. Sectional view of the low-power beam profilometer showing the beam, aluminum and phosphor layers and glass substrate. Temperature rise of the glass and phosphor sets the upper limit of beam power for this device.**

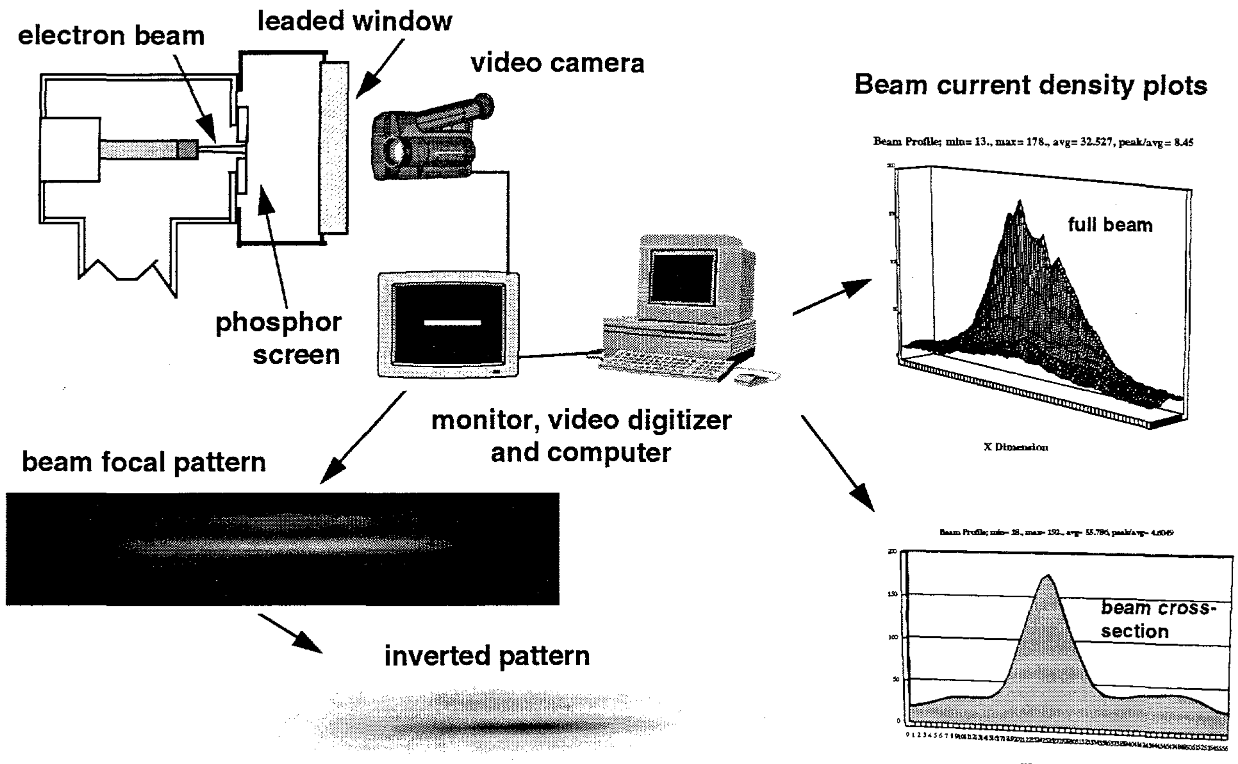



**Figure 10. Pictorial showing the steps for acquiring and digitizing beam profiles.**

Because of the power limits of the above device, a second device was designed for high power operation. This device takes advantage of the Bremstrahlung and characteristic x-rays generated by an electron beam striking a target. A conducting disk is used as the target. The back side of the disk (away from the beam) is coated with a thin layer of phosphor similar to the low power device. Beam electrons striking the front surface will generate x-rays, and the fractional beam energy converted to x-rays is approximately given by the equation

$$\text{Conversion eff.} \approx 2.8 \times 10^{-9}\, ZV \qquad (1)$$

where Z is the atomic number of the target material and V is the electron energy in electron volts. For the voltages and material employ this efficiency is of the order of 0.2 percent. A fraction of the x-rays will pass through the target material to the phosphor on the back side, and excitation of the phosphor will produce a visible image of the beam. The thickness of the conducting target must be made adequately thick to carry off deposited heat, yet thin enough to transmit a useful fraction of the x-rays. Also the spatial resolution of the image will be degraded with increasing target thickness. We used thickness ranging from approximately 0.010 to 0.020 inches, which was found adequate to carry off heat and thin enough to provide useful resolution at power densities up to approximately 5 watts per square centimeter. Higher powers could be achieved with water cooling, although we did not pursue this for the work described here. Both these beam profile-measuring devices have been used extensively in the development of both electron guns and electron beam windows.

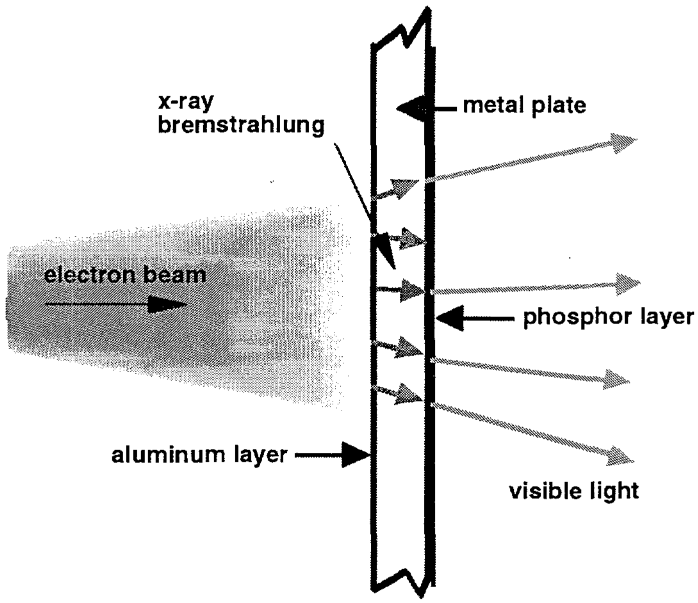



**Figure 11(left). Sectional view of the high-power beam profilometer showing the beam, aluminum, target, and phosphor layers. Power for this device is limited by the heat transfer through the target layer.**

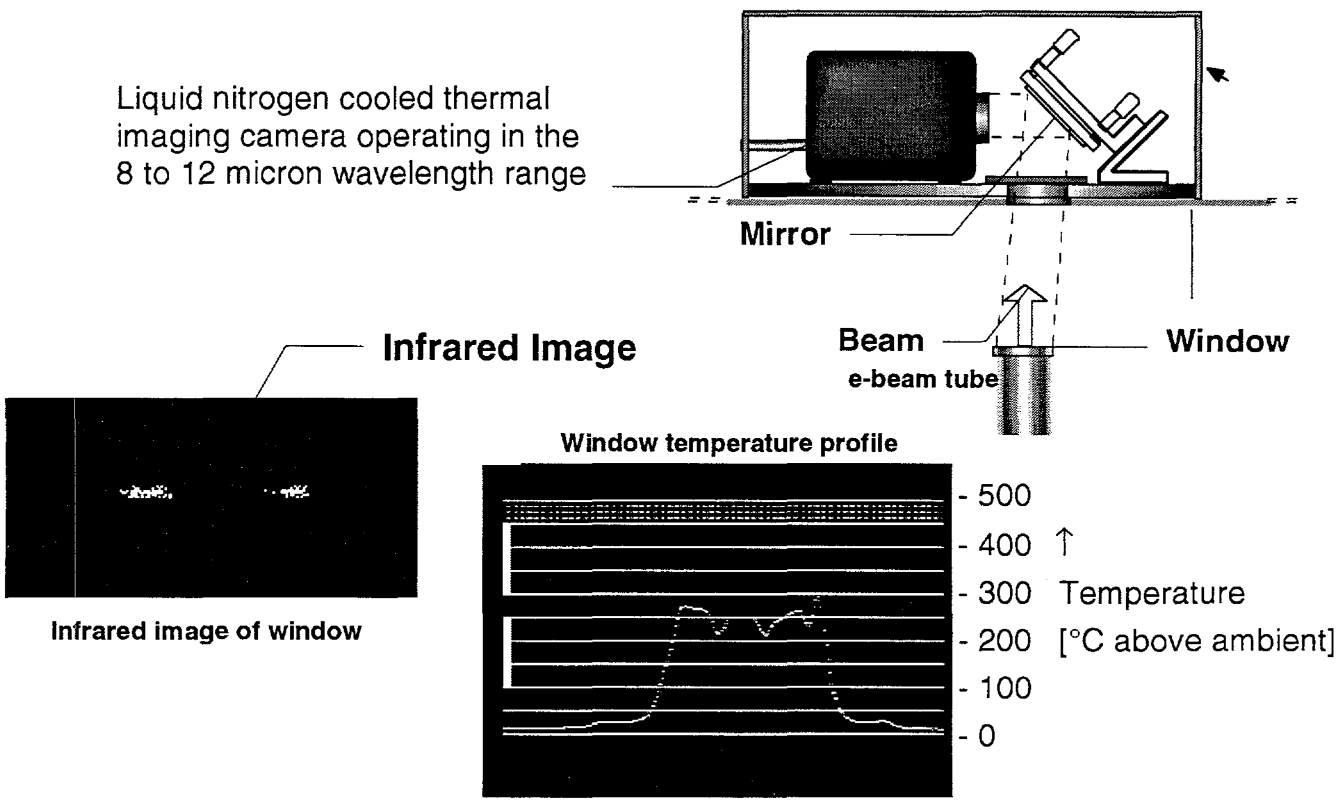



**Figure 12. Pictorial view of the diagnostic system used to measure electron beam window temperatures during beam operation. Theses tests verified the predicted performance of the window cooling system, a design which has proven itself at very high peak power densities.**

## WINDOW TEMPERATURE MEASUREMENTS

The thin film windows used in the sealed-tube electron guns absorb several percent of the electron beam energy that passes through. Because of high power densities of the beams, considerable heating of the window takes place. In order to successfully carry this heat away and maintain the window temperature within tolerable limits, we undertook a program to design an air cooling nozzle to convectively cool the tube windows. The full scope of this work, which included extensive thermal analysis, a laser diagnostic (Schlieren) system to measure air flow, and considerable experimentation, is beyond the scope of this paper. However we will describe a key element of our thermal management effort.

The final measure of success of the cooling system is in the measurement of the window temperature on sealed tubes operating at design power. We carried out this final measurement using a liquid nitrogen cooled thermal imaging camera, which viewed the e-beam window during operation. A front surface mirror was used to view the window, and remove the imager from the very high x-ray radiation environment present in the vicinity of the window. Initial tests were made to assure that the window was optically thick at the wavelength of measurement, a condition required for accurate measurement. The thermal imager was calibrated using a black body at several known temperatures. Measurements then were made on an operating tube at various power levels and air flow rates. These tests showed that we are able to maintain window temperatures below 500 degrees centigrade at beam power up to 100 watts (continuous) though a 2 mm. by 25 mm. window. Furthermore, we were able to accomplish this with low mach number laminar flow. Subsequent evolution of the design has achieved power levels of over 200 watts through window of the same size. Peak power densities of over 2000 watts per square centimeter of transmitted beam power have been sustained by advanced window designs.

## WINDOW ENDURANCE MEASUREMENTS

Initial endurance tests of the electron guns and windows have been carried out. While many more tests will be required for high statistical confidence in endurance data, these initial results are highly promising. There are a number of processes that can potentially degrade the e-beam windows with time. Many of these are temperature dependent, an important factor in projecting the useful lifetime of the windows, as discussed in the following paragraph. We have carried out a thorough study and literature search to determine all potential mechanisms that might cause window failure or wearout.

The principal wearout processes identified in this study were:

- radiation damage
- chemical erosion by active species (O, $O_3$, OH*, etc.)
- diffusion processes
- mechanical fatigue
- creep due to reduced strength at operating temperature

At constant beam voltage, the rates for these processes will scale linearly with current density **J** or faster than linearly with respect to **J**. Our initial endurance run, was carried out at 60 kilovolts with a peak beam current density of ~12 mA/cm$^2$ for 768 hr., or one month of continuous operation. Graphs of operating current and window transmission are shown in figures 13 and 14. Extensive laboratory analysis, including scanning electron and scanning Auger microscopy, over the highest current density region of the window revealed no changes in window thickness, composition, or structure[3]. Because any of the identified processes that might degrade the window scale linearly or faster than linearly with current density, we can place a lower bound on the number of operating hours expected as long as the current density does not exceed the peak value of ~ 12 mA/cm$^2$ (@ 60 keV). Unaffected window operation can be expected if the product of current density and operating time does not exceed the product of the demonstrated current density and time, or ~ $10^4$ ampere hours per square centimeter.

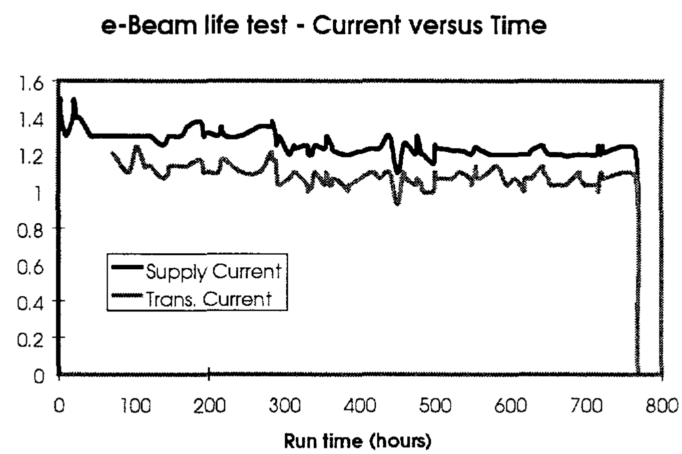



**Figure 13 (right). Graph of beam current and transmitted beam current during our initial endurance run.**

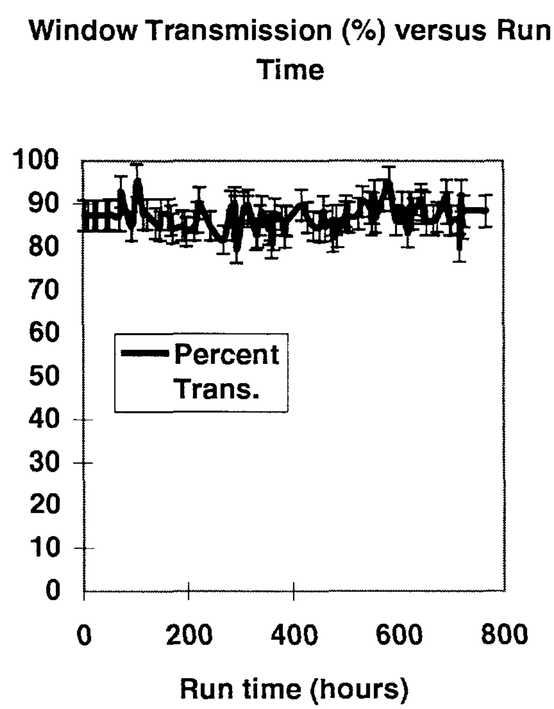



**Figure 14(right). Graph of window transmission beam during our initial endurance run.**

## SUMMARY

We have described a series of measurements to verify the performance of the thin-film windows and electron gun used in a new sealed-tube electron gun. Measurements include beam current, power, and power density, window transmission, temperature, and window endurance tests. A number of novel beam diagnostic tools were developed as part of this effort. Results show generally good agreement when compared to Monte Carlo computer predictions.Transmitted beam powers in excess of 200 watts were achieved, with current densities exceeding 30 milliamperes per square centimeter at sixty kilovolts beam energy. Projected window wearout time exceeds several thousand hours at a current density of two milliamperes per square centimeter and a beam voltage of 60 kilovolts. This work was carried out under a Cooperative Research and Development Agreement (CRADA) between Lawrence Livermore National Laboratory and American International Technologies, Inc.

## ACKNOWLEDGMENTS

The authors wish to thank William Biehl, who helped design many of the devices described here, and was essential in carrying out many of the tests. We also wish to thank James Davin, who was responsible for the design and initial tests on the window cooling system, as well as the staff at American International Technologies, Inc. who contributed to this work in ways too numerous to describe here.

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[1] Work performed under the auspices of the U.S. Department of Energy, DOE Contract Nos. W-7405-ENG-48, by LLNL.

[2] This code is a further development of the Monte Carlo code described at RadTech '94, "An Electron Beam Dose Program for Personal Computers", B. Myers, *RadTech 94 North America Proceedings*, 150-155 (May, 1994). This code, e-Beam3D, has the capability to model three dimensional objects of a variety of shapes and will calculate dose distributions from an electron beam over all the surfaces and volumes within a configuration.

[3] A very thin layer of silicon dioxide was found on the front surface of the window following the above run. This was later traced to a nearby silicone rubber gasket that had partially decomposed during the run.

Keywords: electron beam, electron gun, electron beam diagnostics, calorimeter, current measurement, electron beam profile