Calabazas Creek Research, Inc.

Final Report

DOE SBIR Contract # DE-SC0006213

10 MW Annular Beam Klystron for Accelerators

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March 7, 2016

Introduction

The goal of the program was to develop a 10 MW, 1.3 GHz, Annular Beam Klystron (ABK) for accelerator applications. The ABK, shown in Figure 1, is a simpler, lower cost alternative to the Multiple Beam Klystron (MBK) as a high perveance source of high power microwaves. After extensive modeling and simulation in two Phase I programs, the ABK was projected to meet the requirements originally given for the International Linear Collider (ILC). Those parameters are shown in Table 1. While the requirements for the actual “next” linear collider continue to evolve, the parameters of the CCR ABK are expected to be relevant for many applications and are appropriate for a test of the concept.

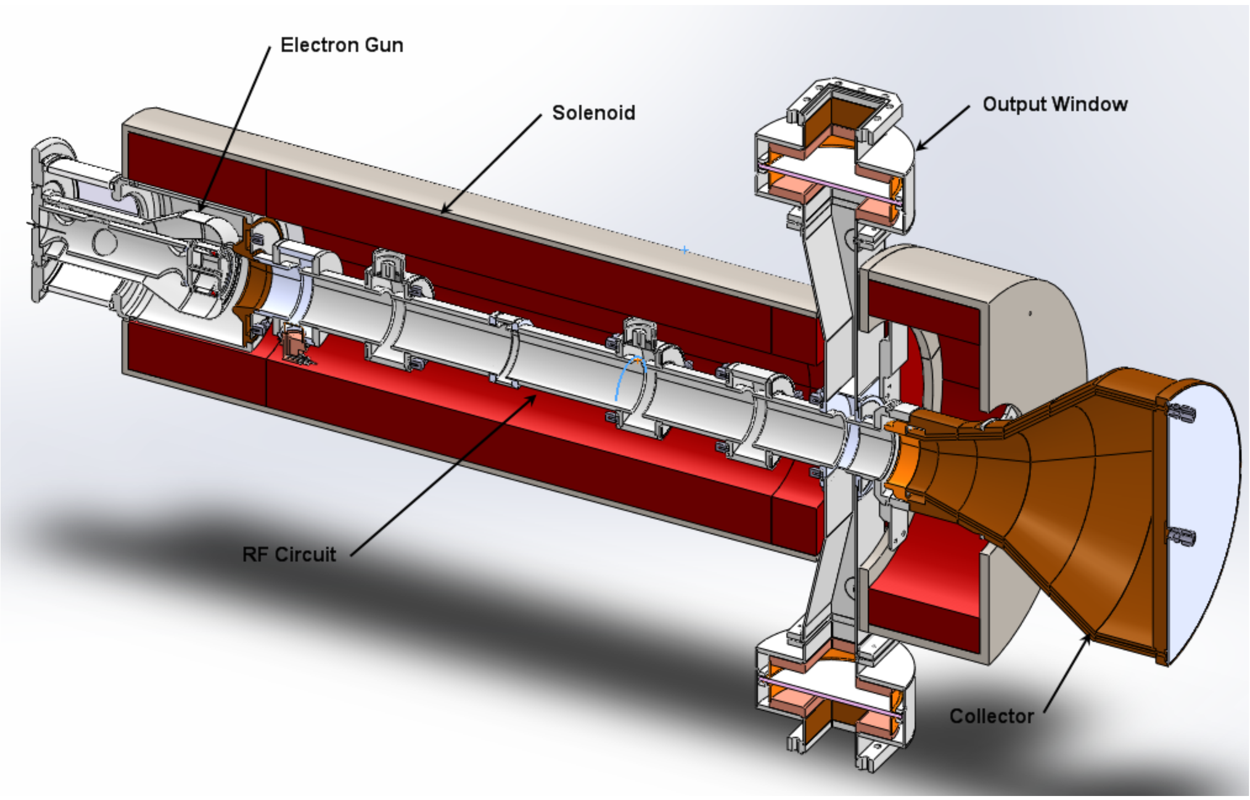

Figure 1. CCR 10 MW, 1.3 GHz Annular Beam Klystron (ABK).

Table 1. Calculated operating parameters of the CCR ABK.

Parameter	Value	Parameter	Value
Frequency	1.3 GHz	Perveance	3.4 micropervs
Power	11 MW	Pulse Width	10 ms
Efficiency	66%	Pulse Repetition Rate	10 Hz
Voltage	120 kV	Cathode lifetime	100,000 Hrs
Current	140 A	Magnetic Field	0.15 Tesla

Activity

The design of the ABK was relatively mature at the end of Phase I, and, in particular, the circuit was ready for detailed mechanical design. Phase I designs of the electron gun, collector and solenoid were improved in Phase II. The design of the electron gun was modified significantly. An evolving technology, CCR's Controlled Porosity Reservoir (CPR) cathodes, was incorporated into the ABK. CPR cathodes can operate at high emission current densities and still provide the long lifetimes required for accelerators. For the ABK application, the beam could be formed without compression. This reduced the diameter of the cathode dramatically, simplified the beam optics, and improved beam quality. The beam current density of 16 A/cm^2 is far below the 50 A/cm^2 demonstrated with CPR cathodes, and the cathode lifetime is expected to exceed 100,000 hours [1].

The original design of the gun, shown in Figure 2, used an emitter that was 18 cm in diameter. The new design, shown in Figure 3, uses an emitter diameter of 6.8 cm. This reduces the overall diameter of the gun and the diameter of the solenoid, significantly decreasing the cost of fabrication. With a magnetic field of 0.15 Tesla, the predicted beam ripple is +/- 0.35 mm peak-

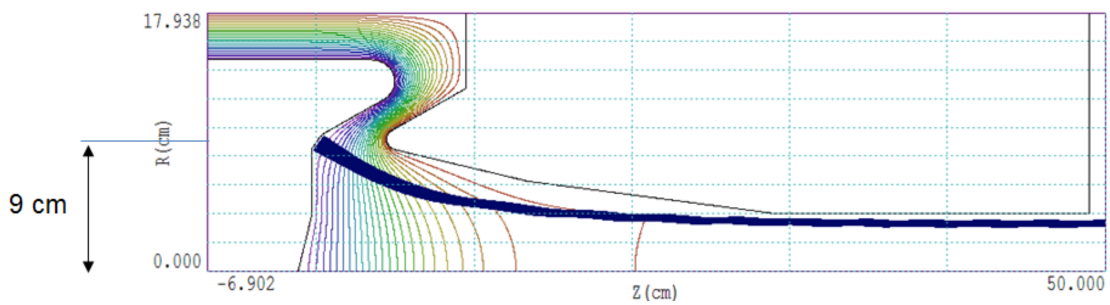

Figure 2. Original gun design using a conventional cathode.

peak, significantly less than the +/- 1.3 mm achieved with the conventional cathode.

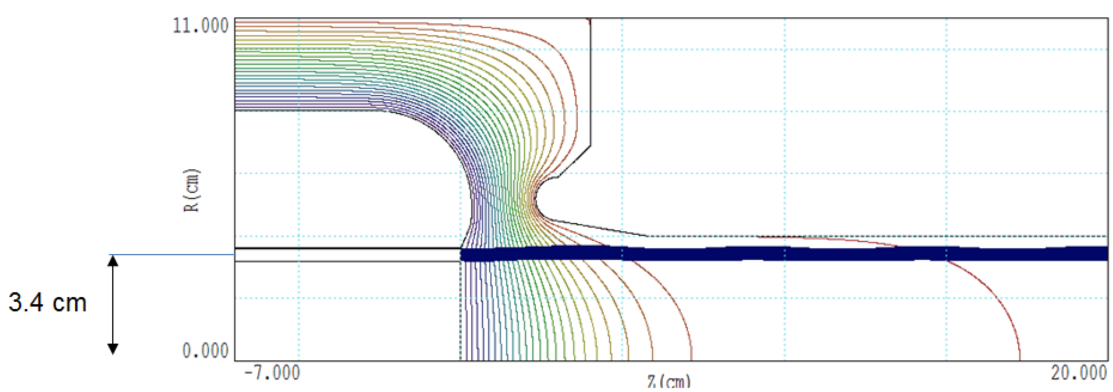

Figure 3. New gun design using the CCR Controlled Porosity Cathode, and without compression.

One of the issues with high current density cathode emission is the electric fields in the diode. As shown in Figure 4, the peak field on the focus electron is 63 kV/cm. Optimization of the electrode shape kept this field below that in the original diode, which was less than the 76 kV/cm limit for the operating voltage.

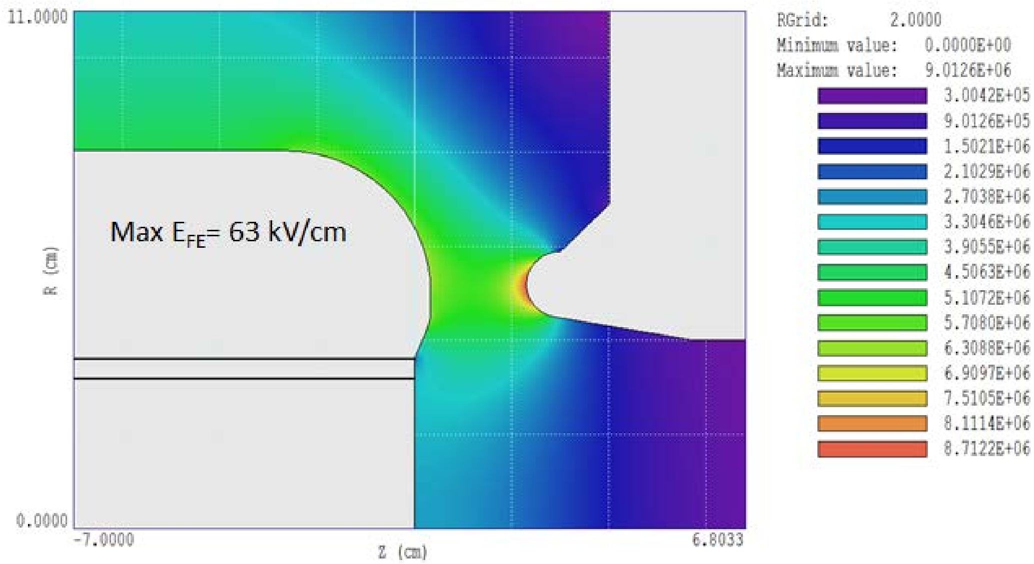

Figure 4. Electric field magnitude in the ABK gun diode.

The fabrication process for CPR cathodes made it impractical to fabricate the emitter in a single piece [2]. The emitter was made in twenty four segments, as shown in Figure 5. These segments were brazed to form a cap over a reservoir of barium calcium aluminate. To reduce the risk of braze failure, the emitters were brazed into six subassemblies each containing four emitters. The subassemblies were combined to form a complete annulus.

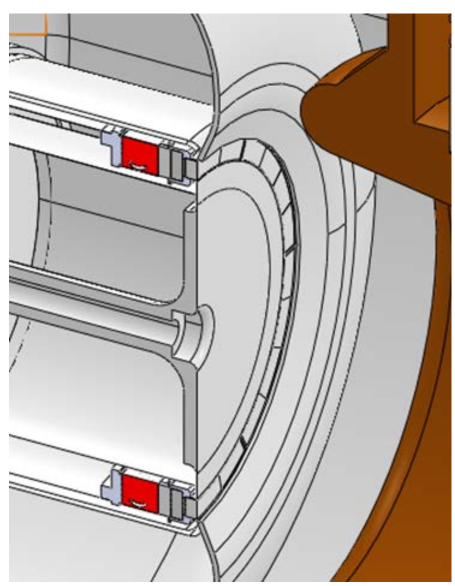

Figure 5. CPR cathode with segmented emitters.

There are small regions between the six subassemblies with no electron emission, and there was concern that this would degrade the beam optics. To check this, a simulation was made using the 3D trajectory code Beam Optics Analyser (BOA). The results shown in Figure 6 indicate that the gaps do not impact the beam performance. In fact, even the deletion of an entire emitter did not noticeably impact the performance.

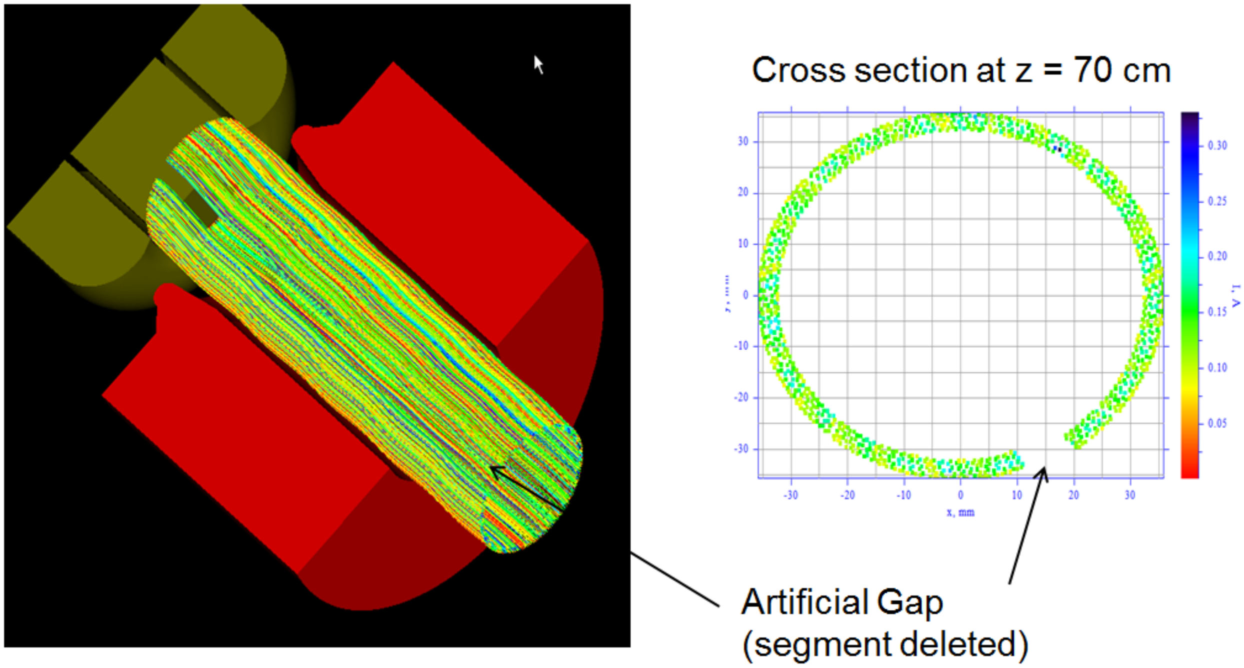

Figure 6. Results of a BOA simulation of the cathode with segmented emitters. One entire emitter was omitted. Left: beam trajectories; Right: beam cross section 70 cm downstream of the cathode.

Collector

The collector was re-designed to minimize the size while avoiding high power densities. Results of thermomechanical analysis are shown in Figure 7, indicating the peak power densities are well below levels of concern.

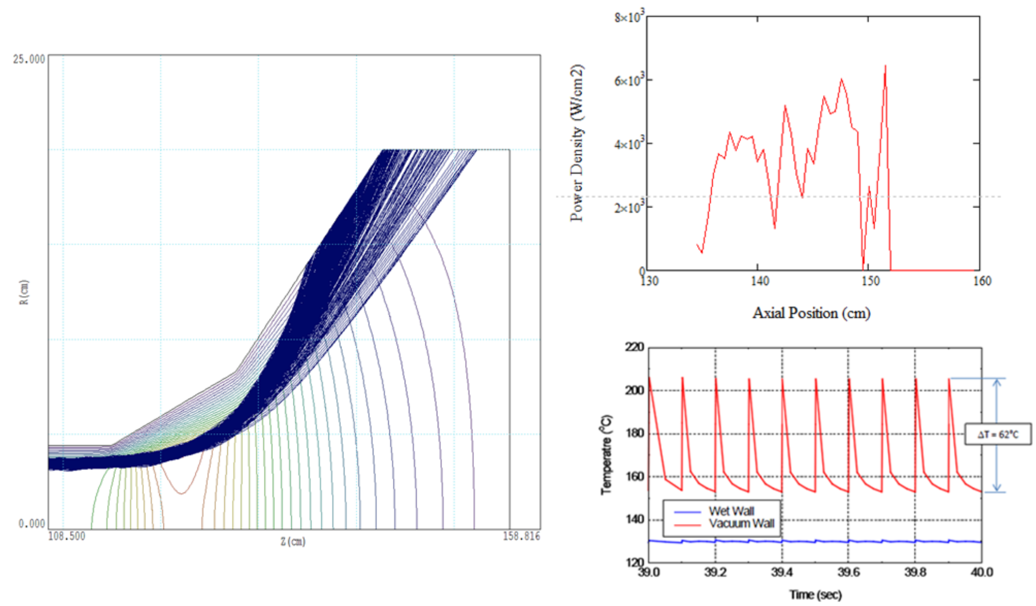

Figure 7. Left: trajectories of the spent beam in the collector. Right, top: power density as a function of axial position; Right, bottom: temperature excursion during 1.5 ms, 10 pps pulses.

Solenoid

The solenoid design, shown in Figure 1, consists of two sections to allow integration with the output waveguides. It was originally planned to remove a section of one of the coils to accommodate the output waveguides; however, the resulting asymmetric magnetic field caused the beam to become elliptical. Consequently, the last coil in the first section was shortened to provide a symmetrical gap for the waveguides.

Fabrication

The assembled klystron is shown in Figure 8 and Figure 9

Figure 8. Annular beam klystron prior to bakeout.

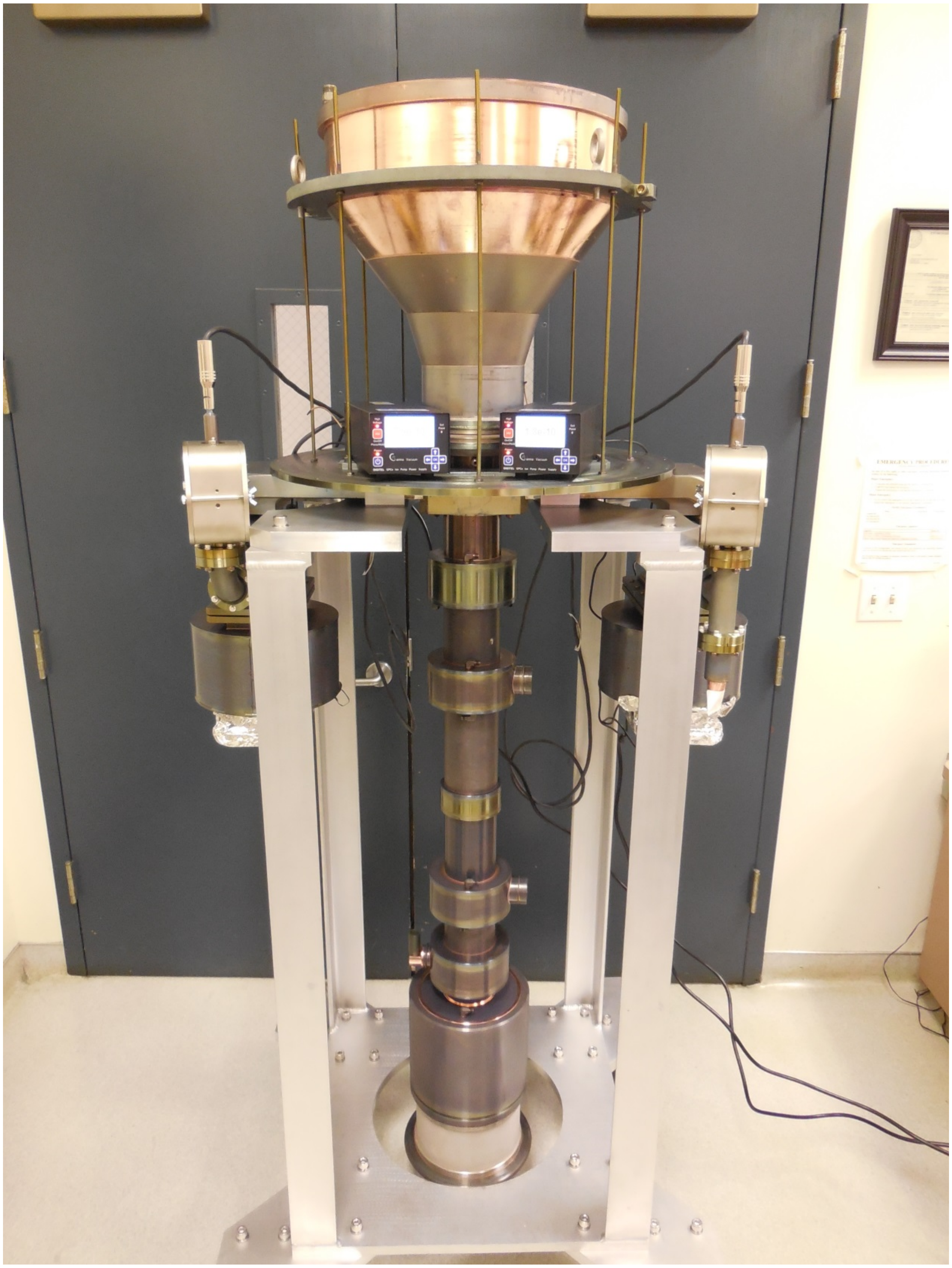

Figure 9. ABK after bakeout with ion pumps attached.

Figure 10. Photograph of electron gun emitter in a vacuum bell jar for initial testing

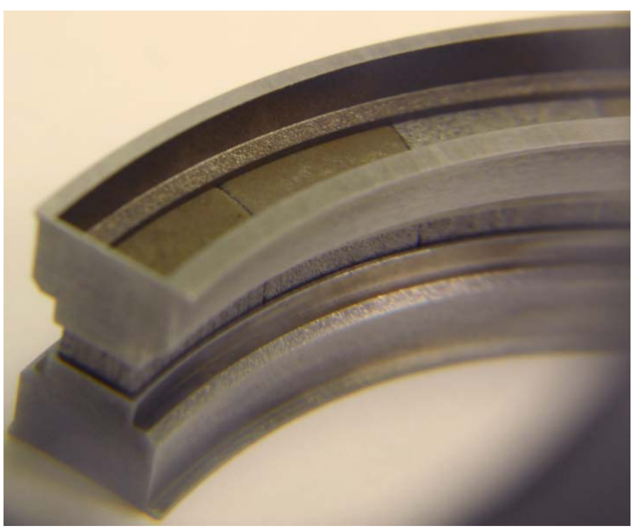

Figure 11. Photograph of emitter segments in an electron gun subassembly

Figure 12. ABK mounted in the magnet, in the test set.

Testing

Cavity cold test

The output cavity is shown in Figure 13. Machining errors initially caused the output cavity Q output cavity to exceed an acceptable value. Further machining reduced the Q to 22.9, adequately close to the design value of 19. The resonant frequency is very close to the design value of 1.3 GHz, as shown in Figure 14.

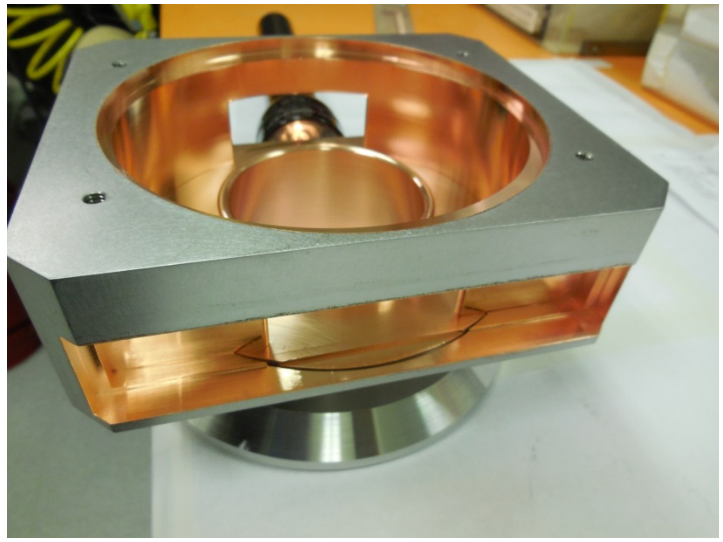

Figure 13. Output cavity.

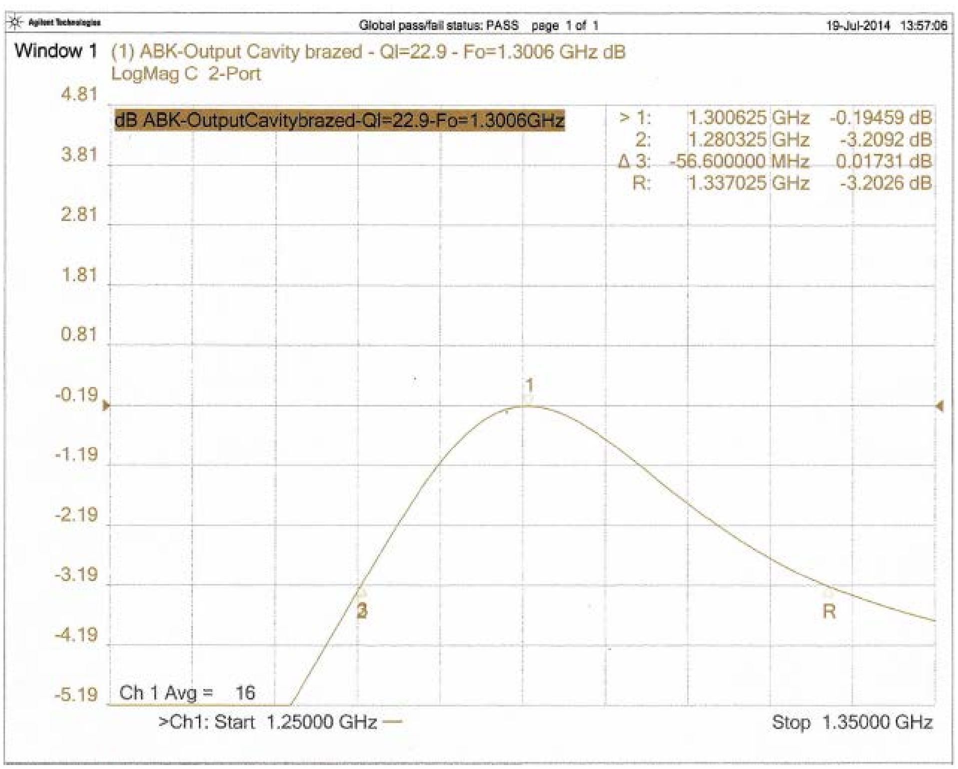

Figure 14. S11 plot of the output cavity.

High voltage hold off

The tube was "hi-potted" and found to hold off 10% above the 120 kV design voltage without difficulty.

Cathode

The temperature of the cathode was measured while it was operating in a bell jar, as shown in Figure 15 and Figure 16. The cathode at operating temperature (1000 °C) is shown in Figure 16. The heater power and temperature measurements from the test are shown in Figure 17.

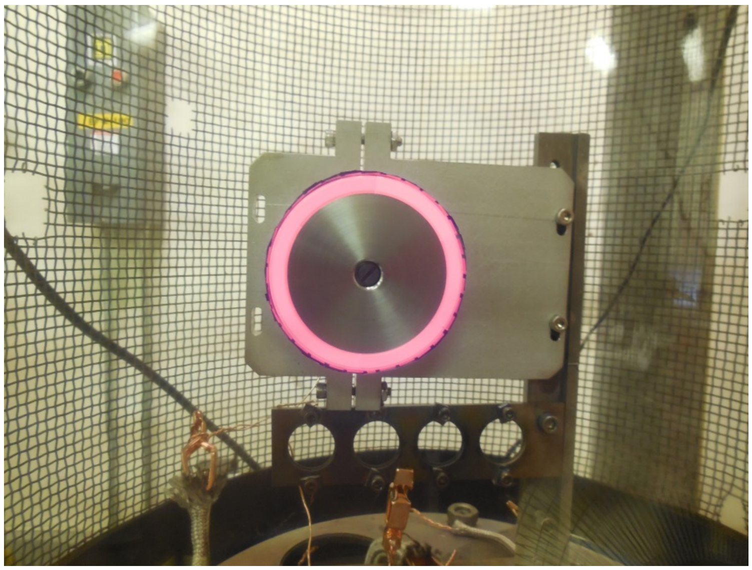

Figure 15. Cathode assembly in bell jar.

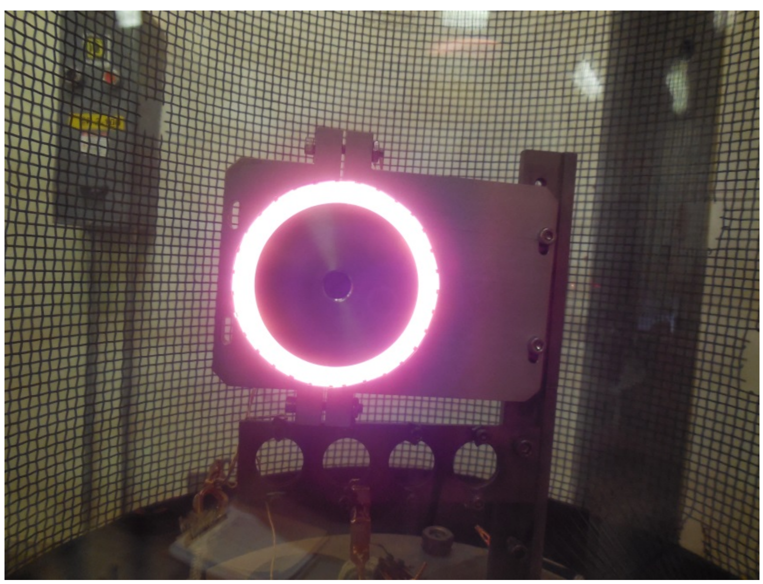

Figure 16. Cathode at operating temperature (1000 °C)

The temperature was measured using a disappearing wire optical pyrometer. The vacuum pressure was maintained below 10^{-6} Torr during testing.

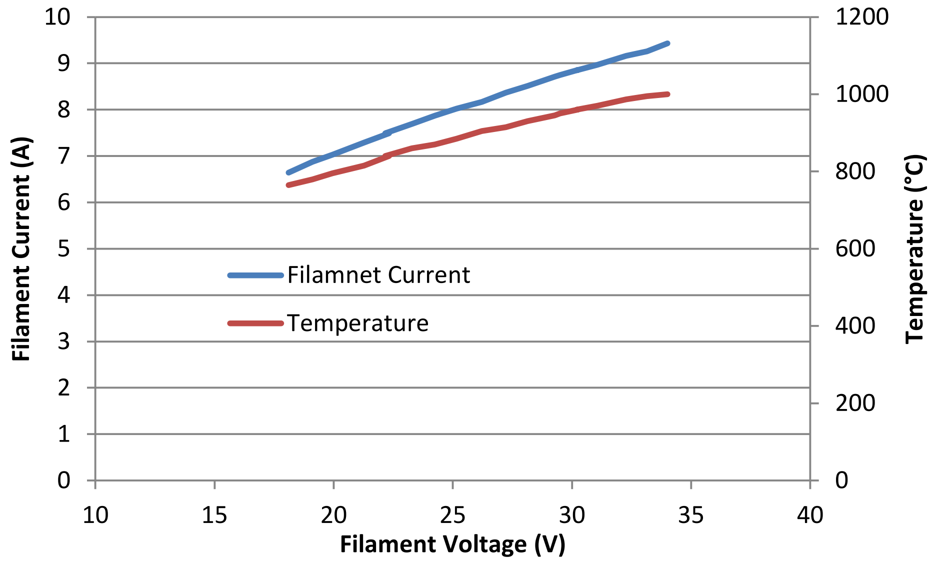

Figure 17. Measurements of the emitter temperature in a bell jar.

High Voltage Tests

After bakeout, the ABK was installed for high power testing at Communications & Power Industries, LLC, as shown in Figure 18.

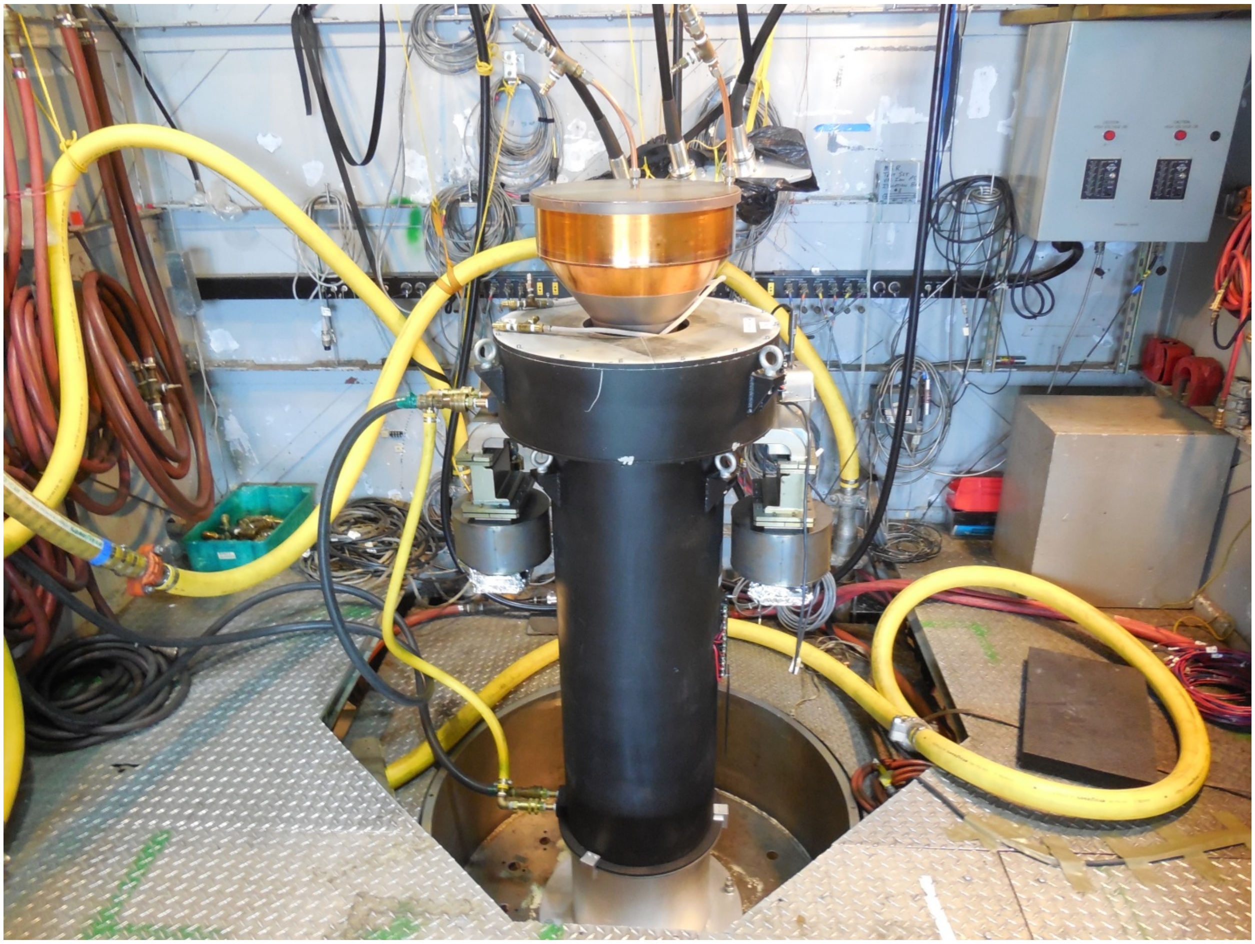

Figure 18. ABK in the CPI superpower test set.

The tube was operated briefly with microsecond pulses at low duty and low voltage (less than 10 kV). The current was significantly below the required level and appeared to be temperature limited. Attempts to increase cathode temperature resulted in excessive gas levels inside the klystron.

The tube was removed from the test set to a conditioning station where a low DC voltage could be applied. Attempts were made to get Miram curves to determine the health of the cathode. The results are shown in Figure 19. The pressure at the pumps was about 8 10^{-7} Torr, which indicates the pressure at the cathode probably exceeded 10^{-6} Torr. This is a pressure where cathode poisoning is expected. Not the current versus filament voltage shifted to higher voltages on the second day of testing. This indicates that the emission is degrading, as would be expected with high gas pressures.

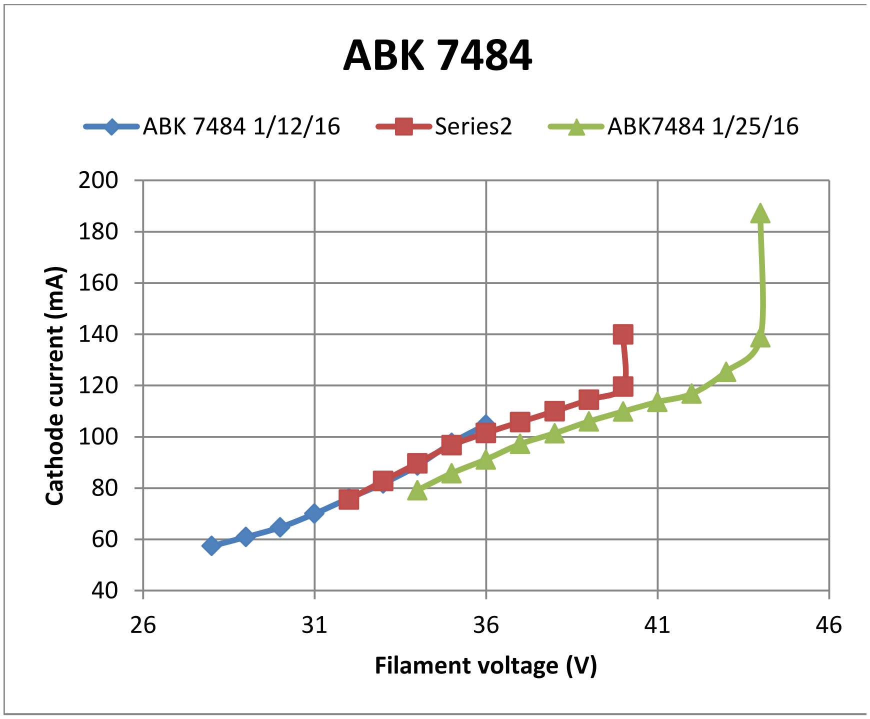

Figure 19. Cathode emission tests run with a cathode-anode voltage of 1000 V.

The perveance as a function of filament voltage is plotted in Figure 20. As expected, the perveance is below the design value of 3.4 micropervs for low filament voltages. But, the perveance, rather than plateauing with increasing voltage, rises above the design value. The cause for this is not known. It may be due to the cathode being operated at too low a temperature. The maximum filament voltage was 29% higher than in the bell jar tests, but this still may not be sufficient to outgas and activate the cathode. The maximum filament power was 455 W,

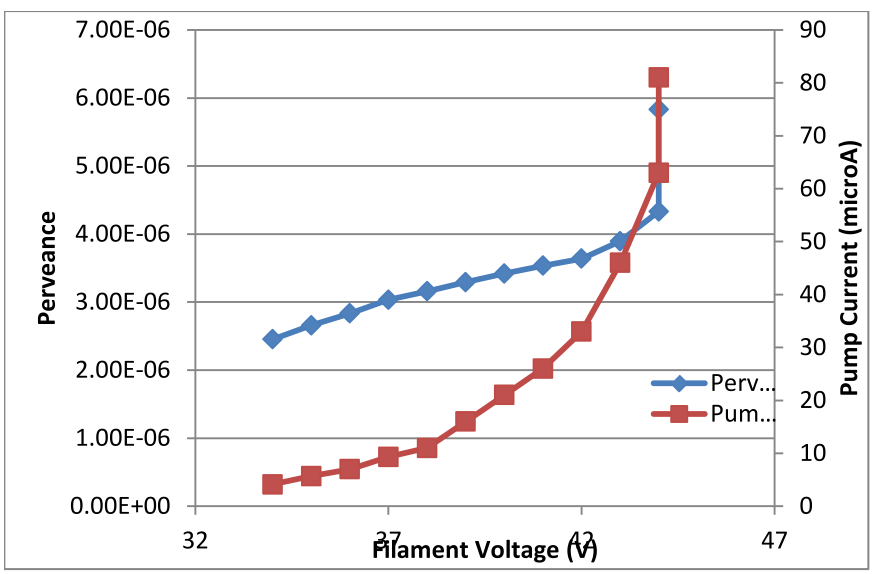

Figure 20. Perveance and pressure for the data from Figure 16 for 1/25/2016.

significantly below the maximum power rating of 600 W. The heater power is being increased, as allowed by the vacuum pressure, to achieve space charge limited operation.

Summary and Conclusions

The ABK was fabricated and initial testing performed. The cathode emission was much lower than expected, and steps are being taken to correct the problem. As soon as this issue is resolved, the ABK will be reinstalled in the test set for high power testing. The test set is scheduled to be available in June 2016.

References

1. R. Lawrence Ives, Senior Member, IEEE, Louis R. Falce, George Miram, George Collins, "Controlled Porosity Cathodes for High Current Density Applications," IEEE Trans. Plasma Sci., Special Edition on High Power Microwave Sources, Vol. 38, No. 6, pp. 1345-1353, June 2010
2. R.L. Ives, L.R. Falce, S. Schwartzkopf, and R. Witherspoon, "Controlled Porosity Cathodes from Sintered Tungsten Wires, IEEE Trans. On Electron Devices, Vol. 52, No. 12, pp. 2800-2805, December 2005.