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Development of Multiple Beam Guns for High Power RF Sources for Accelerators and Colliders

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Abstract. There is a need for high power RF sources for the next generation of accelerators and colliders. Sources that operate at reduced beam voltage allow solid state power supplies with significant cost reduction over conventional pulse modulators. Multiple beam RF sources provide reduced beam voltage by using a multiplicity of beamlets that traverse the RF circuit through individual beam tunnels, reducing the space charge forces that drive the voltage requirement. The current generation of multiple beam devices typically use Brillouin focusing, which limits high power operation. The devices reported here utilize confined flow focusing which allows much tighter control of the electron beamlets and consequently, higher power operation. Progress in the development of a 100 MW multiple beam electron gun with confined flow focusing is reported.

INTRODUCTION

The next generation of high energy accelerators will require RF sources producing output power levels in the range of 50 - 150 MW at frequencies from 700 MHz to 11 GHz and higher. Traditional klystrons are being developed to provide this power; however, they typically operate with beam voltages of several hundred kV. The proposed 75 MW klystron for the Next Linear Collider (NLC), for example, will require a beam voltage of 490 kV with a beam current on the order of 250 A, assuming operating efficiency of 60%[1]. One of the major cost drivers for these devices is the high operating voltage. Not only are the power supply costs significant, but the high voltage leads to increased circuit length, higher radiation hazards, larger insulating ceramics, and increased problems with high voltage breakdown.

One way to avoid high operating voltages is to use a klystron with a multiple beam electron gun to raise the effective perveance. In the multiple beam gun (MBG), the cathode emits a number of ‘beamlets’ that traverse the tube in separate beam tunnels. This reduces space charge forces that drive the voltage requirement. The perveance of each

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beamlet can be lower than would otherwise be necessary, leading to increased efficiency and greater bandwidth.

Calabazas Creek Research, Inc. (CCR) embarked on an innovative approach to multiple beam gun design and developed a design methodology where the magnetic field strongly controls the electrons in a confined flow configuration. This allows determination of cathode placement based on area convergence, magnetic field compression, beam location, and cathode loading. This program was tasked with developing multiple beam electron guns applicable to RF sources producing more than 50 MW in X-Band for accelerator applications. Multiple beam RF sources would also have other applications, including radar, communications, and industrial heating an processing.

The current generation of multiple beam sources are restricted to lower powers due to the difficulty in designing multiple beam guns with confined flow magnetic focusing. Confined flow focusing is required to achieve acceptable beam transmission for high power and/or high duty applications. This program focused on developing a basic understanding of the magnetic configurations required for multiple beam sources and developing mechanical configurations to achieve the required field shape in practical devices.

Critical to the success of the program were 3D design tools and techniques capable of modeling the geometries of interest. Such tools and techniques were developed and provided the knowledge and insight required to achieve the basic goals of the program. In particular, a design was achieved that included 8 singly convergent electron beamlets operating at 175 kV, 55 A each. The gun is capable of powering a 50 MW multiple beam klystron. The predicted beam scallop is approximately 5% with a beam fill factor of approximately 65%. Predicted beam transmission is 100%. This is close to ideal for klystron circuit interaction. The design was achieved with a single magnetic coil around the body of the klystron with no additional gun coils.

GUN DESIGN

As expected, the principle challenge involves the magnetics design. The symmetry of the electric fields is easily maintained by retaining the configuration of the cathode, focus electrode, and anode with respect to the axis of each individual beam. The program developed effective techniques for obtaining the required magnetic field configuration and for eliminating beam spiraling about the device axis.

Strategically placed iron provided the required field configuration that produced perpendicular magnetic fields in the vicinity of the emission surface. The program focused on eliminating gun coils and based the design around a solenoid for the main magnetic field.

The task of the program was to determine the electron beam specifications for a gun applicable to a multiple beam klystron at the 50-75 MW RF power level. This was accomplished in a previous program (U.S. DOE SBIR Grant DE-FG03-97ER82341). In that program, Dr. Erling Lien, formerly the director of Varian Associates, Inc., Microwave Research and Development Department, Dr. D. M. Petroff of Torey Company, and Y.R. Besov of Svetlana in Russia independently arrived at the same design. The location of the various beams were the same, as was the beam tunnel size. The number of beams is not a function of the circuit design, but depends on physical and cathode current emission constraints. For this development, the singly convergent guns provide beams located 6.3 cm from the device axis propagating in beam tunnels with a 4 mm diameter.

Once the beam position and size constraints were determined, a single, convergent gun that would provide the required beam on axis was designed. The operating voltage was selected to be 185 kV with a gun perveance of approximately 0.9, producing a beam current of approximately 55 A. The size of the cathode was based on allowable emission current density and was limited to less than 20 A/cm^2. This is higher than typically employed, but cathodes with higher emission current densities have provided more than 20,000 hours of operation. Eight such cathodes would produce 102 MW of beam power which should provide more than 50 MW of RF power at 50% efficiency.

A simulation of the on-axis gun is shown in Figure 1. This geometry was modeled in 3D TOPAZ and 2D codes to verify the accuracy of the simulation. Once the on-axis gun achieved the performance required (beam size, scallop, field gradients, etc.), the gun was moved off-axis to the radius dictated by the circuit design and duplicated azimuthally to achieve 8 beams. The basic configuration is shown in Figure 2.

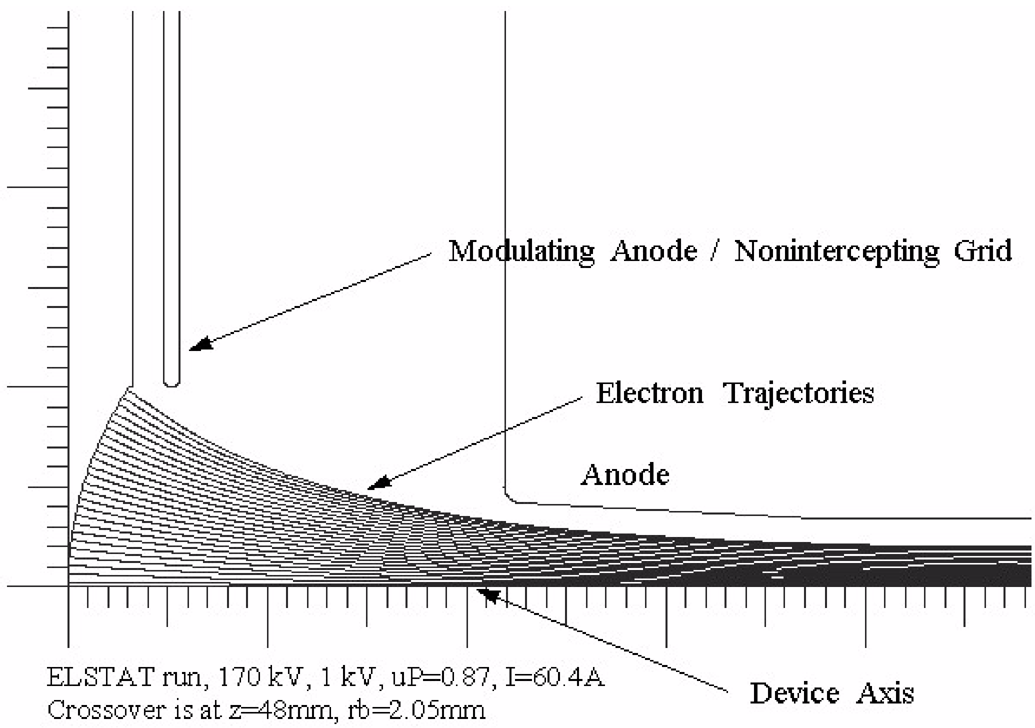

FIGURE 1. On-axis simulation of electron gun at 170 kV, 60 A.

The basic configuration consists of a solenoid around the circuit that is surrounded by iron. Iron polepieces are located on the ends of the solenoid with opening for the beams. The size of the polepiece openings is dictated by the flux required in the cathode - anode region for confined flow focusing. In all the simulations the main solenoid consisted of a single winding. Typically, multiple coils are employed to allow greater control of the magnetic field; however, excellent performance was predicted with a single coil.

FIGURE 2. Configuration of electron guns for eight beam multiple beam gun.

As previously mentioned the essential problem was modifying the magnetic field in the off-axis guns to achieve a configuration similar to that for the on-axis gun. Simulation of the magnetic field with and without modification is shown in Figure 3. The top image shows the uncorrected magnetic field, and the bottom image shows a preliminary result with an improved field. Notice that the flux lines in the top figure are not symmetric about the beam centerline in the Cathode - Anode Region. This will lead to unacceptable beam quality and failure to propagate the beam through the beam tunnel.

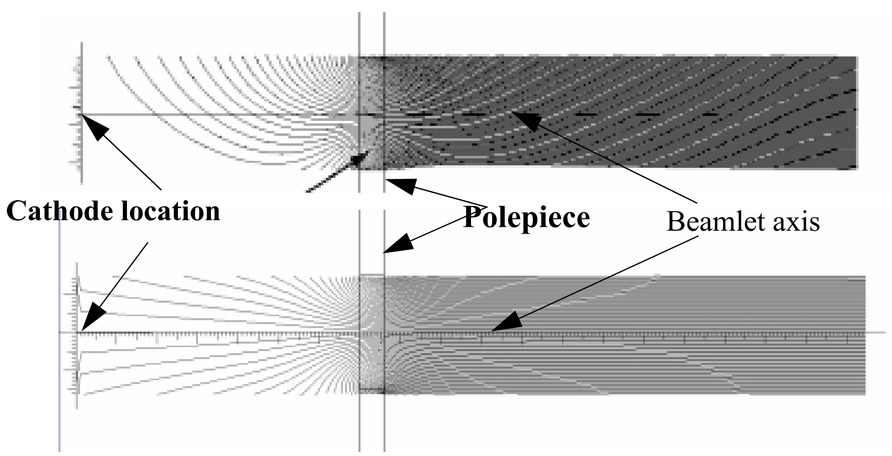

FIGURE 3. Uncorrected and corrected magnetic flux lines for off-axis electron guns.

A large number of different configurations were modeled in an attempt to correct the magnetic field structure. Many of these configurations successfully corrected the field but required mechanical configurations that would be difficult to implement in a practical device. Never the less, these configurations provided insight and understanding of how various structures influence the fields, and practical solutions emerged. The final design incorporates specially shaped iron structures around the cathodes to correct both the radial and azimuthal field profile. A solid model image and a photograph of this structure is shown in Figure 4.

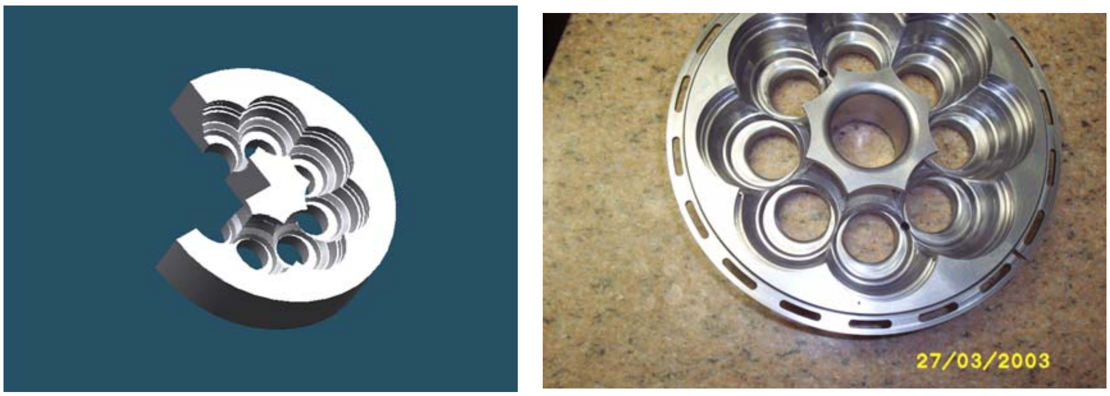

FIGURE 4. Solid model and photograph of magnetic field shaping iron **.**

Figure 5 shows a beam simulation for one of the eight electron beams. This is the result of a complete 3D simulation of all eight beams, so self magnetic field effects from other beams are included.

A solid model and layout drawing of one of the cathode stems is shown in Figure 6. The gun stem includes an isolated and separately energized focus electrode. This will allow adjustment of the beam focusing by adjusting the voltage difference between the focus electrode and the cathode. The ceramic insulator supports to 5 kV. For full voltage operation (185 kV), it is predicted that no potential difference will be required; however,

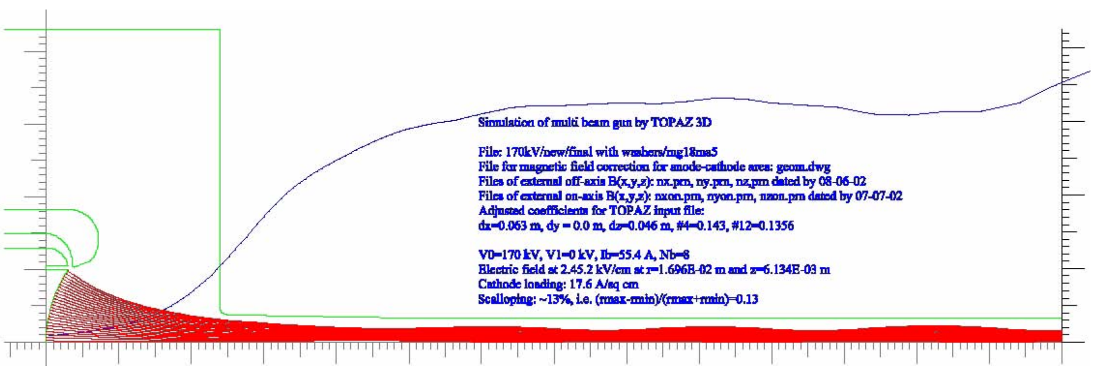

FIGURE 5. 3D beam simulation results for one beamlet of eight beam multiple beam gun.

it is anticipated that approximately 2 kV will be required for reduced voltage testing to achieve proper focusing.

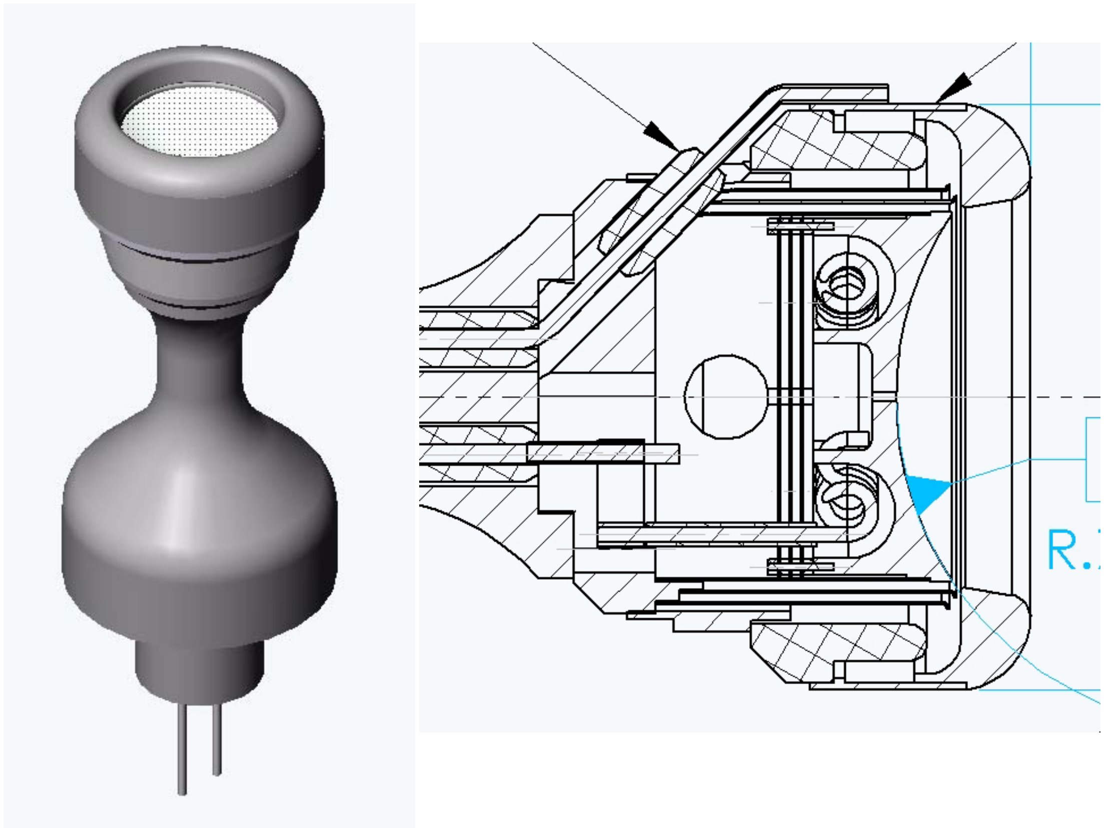

FIGURE 6. Model of gun stem and layout drawing of cathode stem assembly.

The gun is being designed for testing in a beam analyzer, which will be described later. The beam analyzer will allow detailed measurements of the current density in a single beamlet as a function of distance from the cathode. A complete transverse map of the current density profile will be measured. This analysis requires gun operation at reduced voltage to facilitate the measurement system and avoid destruction of the current probe. Consequently the gun ceramic and the vacuum envelope are designed for 20 kV operation. A solid model of this configuration is shown in Figure 7. The gun incorporates a reduced length ceramic insulator, an ‘O’-ring seal at the back to facilitate insertion and removal of the cathodes, and three pumping ports around the periphery.

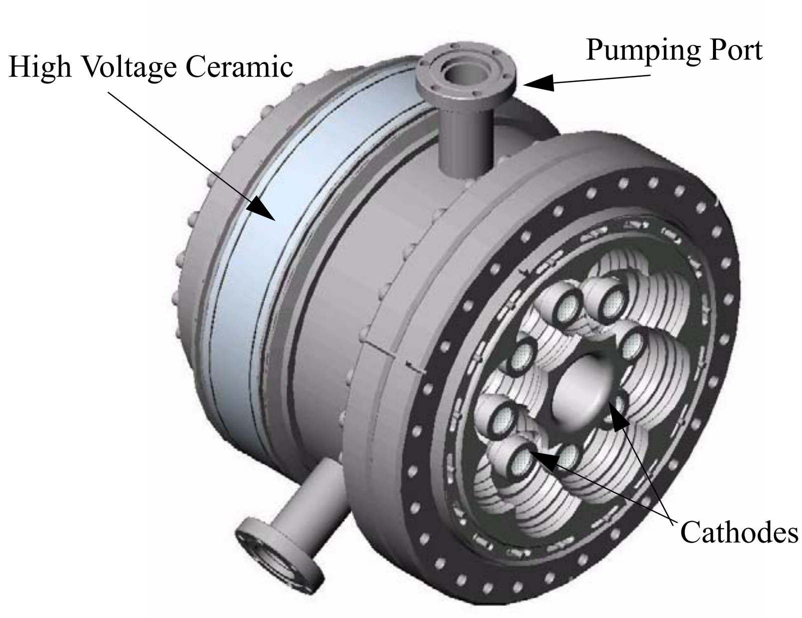

FIGURE 7. Solid model of complete electron gun for beam analyzer testing.

The gun is currently under construction, with completion scheduled for September 2003. A photograph of the gun stem assembly mounted in the vacuum envelope is shown in Figure 8.

FIGURE 8. Photograph of the cathode stem assembly mounted in the gun vacuum envelope.

BEAM ANALYZER

A major of task of the program is to develop a system for precise measurement of multiple beam gun performance. A beam analyzer is under construction that will allow precise measurement of transverse beam current profiles as a function of distance from the cathode. This will allow measurement of beam scallop, size, spiraling, and current uniformity.. A layout drawing of the analyzer with the multiple beam gun installed is shown in Figure 9. A close-up of the probe section of the analyzer is shown in Figure 10.

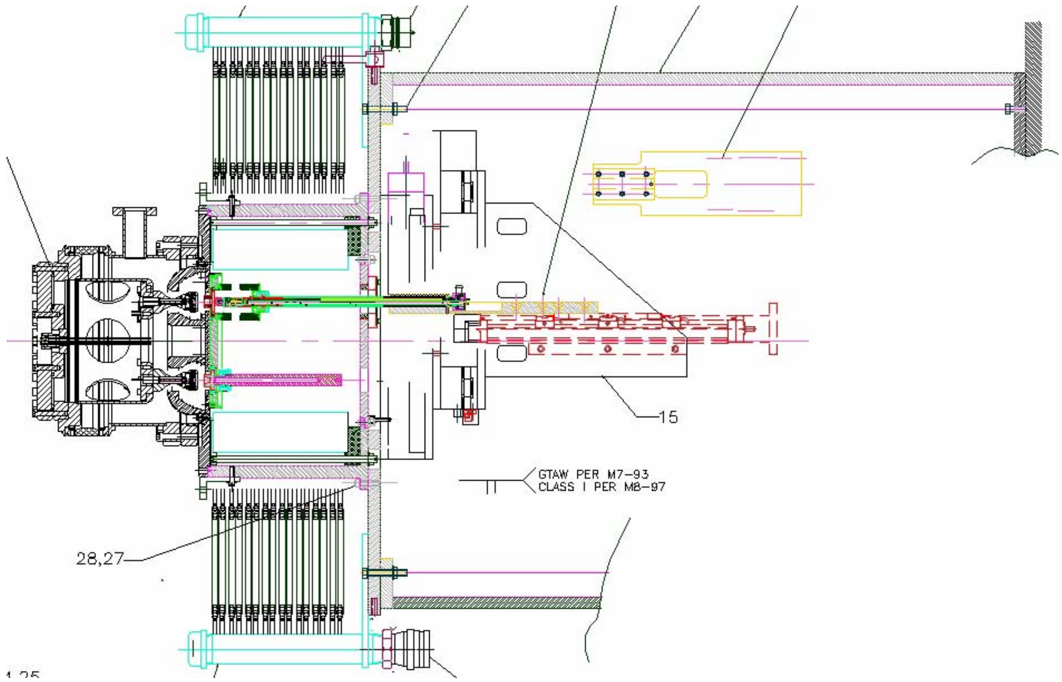

FIGURE 9. Layout of multiple beam gun analyzer.

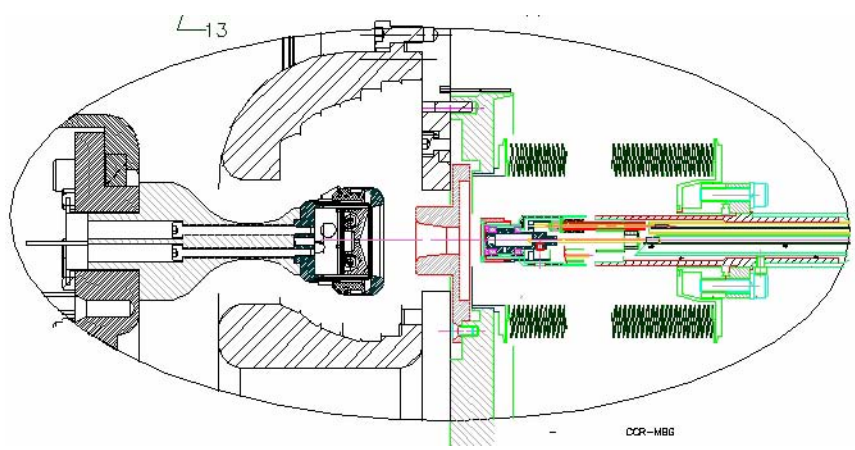

FIGURE 10. Probe section of beam analyzer.

The entire system will be controlled by a computer for pulsing the power supplies and synchronizing the probe measurements to the beam pulses. The system controls the location of the probe and incorporates a post processor for data reduction and presentation. The software is being developed by Communication and Power Industries, Inc. based on their existing beam analyzer system for single beam electron guns.

The current probe, shown in Figure 11, consists of a Faraday cage that is electrically isolated from the outer support structure, allowing voltage biasing of the probe. Electrons are collected through a small aperture at the end of the probe, providing high positional resolution of the current level in the beam. The probe is mounted on precision sliders

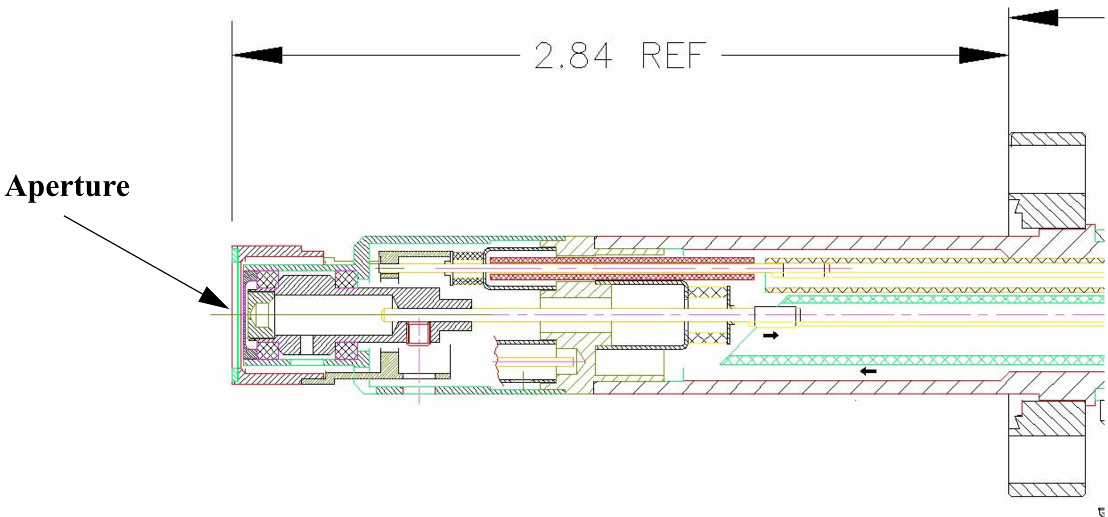

FIGURE 11. Cross section view of beam analyzer current probe.

driven by stepper motors, which are controlled by the analyzer computer. A photograph of the precision sliders mounted to the beam analyzer support structure is shown in Figure 12.

SUMMARY

Development of a multiple beam electron gun for high power RF applications is progressing. The computational design is complete, parts are fabricated, and the assembly is in progress. A beam analyzer is also under construction that will provide precision measurements of beam performance for off-axis electron beams. This facility will be available for testing the current multiple beam guns as well as those developed in the future. Successful completion of this program would demonstrate the high power capability of these devices and lead to a number of new applications.

ACKNOWLEDGEMENTS

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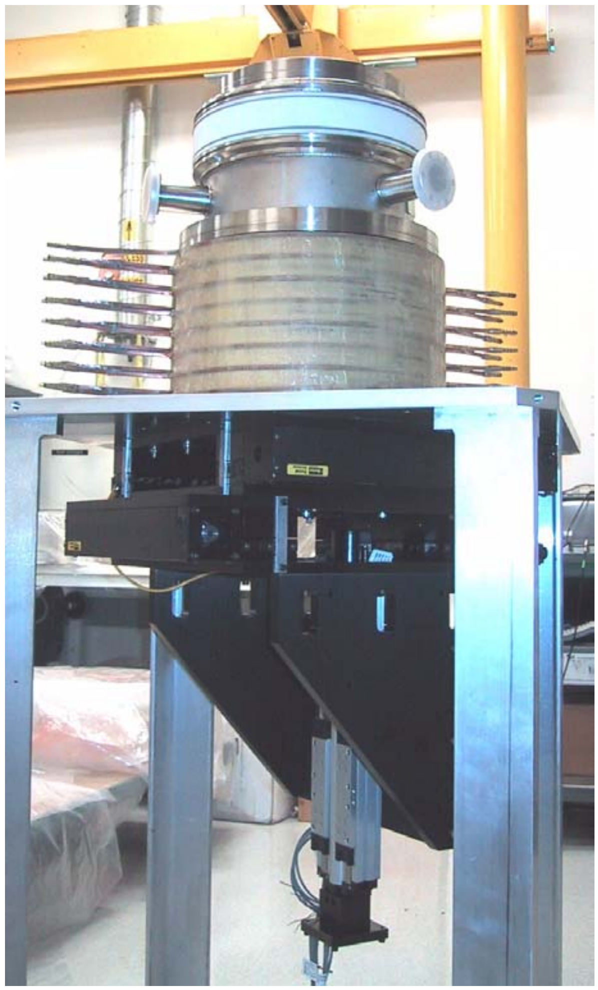

FIGURE 12. Precision support hardware for beam analyzer current probe

REFERENCES

1. Robert M. Phillips and Daryl W. Sprehn, "High-Power Klystrons for the Next Linear Collider," Proceed. of the IEEE, Vol. 87, No. 5, May 1999.