Phase II Final Report
Development of a Multiple Beam Klystron

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1. Introduction

During the Phase II program Calabazas Creek Research, Inc. (CCR) designed and constructed an eight-beam, multi-beam klystron (MBK) amplifier at 11.424 GHz capable of generating 50 MW at a pulse width of 1.0 microseconds (μs) at a pulse repetition rate of 120 Hz. The klystron is designed to operate at a beam voltage of 190 kV with a current of 66 A for each beam; the total beam current for the eight beams is 528 A. This operating voltage and current are compatible with newly developed "solid-state modulators." The inherent advantages of operating at these parameters are the dramatic reduction in power supply and system cost, the large decrease in x-ray generation, and a more compact installation of the modulator-klystron system at the linear collider with added safety for the system operators. In addition, reducing the beam voltage from typically 400 kV for a 50-MW single-beam klystron reduces the total length of the klystron, reducing tube and magnet costs. An extensive review was published describing the advantages of MBKs over single-beam klystrons[1]. CCR's results agree very well with the issues discussed in this review. A photograph of the stacked MBK is shown in Figure 1. Several vacuum leaks are currently being addressed before the final seal can be achieved.

Figure 1. Stacked multiple beam klystron. The tube is not sealed.

The klystron uses an eight-beam electron gun constructed through another SBIR Phase II program (Grant Number DE-FG03-00ER82964). The gun design was complete and tested in a bean analyzer in that program.

The klystron was designed as a potential RF source for the Next Linear Collider (NLC). Unfortunately, the decision to abandon the NLC and dedicate resources to the International Linear Collider (ILC) program essentially eliminated demand and interest in high power X-Band sources. Consequently, resources are no longer readily available for testing the tube. In particular, the testing would require a high power modulator and X-Band driver. Though interest in the klystron seems to have dropped, CCR will continue to pursue potential resources for testing, and eventually, deploying the klystron.

The MBK design parameters are provided in Table 1.

Table 1: Parameters for Multiple Beam Klystron

Parameter	**Value**
Beam Voltage	190 kV
Total Beam Current	528 A
Number of electron beams	8
Current per beam	66 A
Microperveance per beam	0.8
Total gun microperveance	6.4
Total number of cavities per beam	7
Operating Frequency	11.424 GHz
Simulated efficiency	54%
Predicted Gain	55 dB
Input power for saturation	22 W
Total output power	54 MW
Magnetic field strength	3.6 kG (2.5 Br)
Total tube length	36 inches
Estimated klystron weight	75 lbs

Anticipated Public Benefits

Development of a high power MBK represents a major advance in RF technology. The reduction in beam voltage reduces the cost of future accelerator systems from reduced power supply costs, reduce shielding requirements, and lower risk components. Development of this device could have significant implications for other applications, including RADAR, electronic countermeasures, and communications, due to the reduced voltage, higher efficiency, and greater bandwidth of multiple beam devices. Although development of this particular klystron will not lead to additional X-Band sources, it does demonstrate capability to design and build RF sources of this complexity. Successful operation of the klystron would represent a significant accomplishment for high power RF sources for pulsed accelerators.

2. Multiple Beam Klystron Design

2.1. Electron Gun

CCR developed the electron gun on a previous DOE funded SBIR program (DE-FG03-00ER82964). The gun design was completed and successfully tested in a beam analyzer Beam simulations were performed using three different trajectory codes, and all results predicted the same performance.

A solid model of the gun is shown in Figure 2. The gun consists of eight cathodes producing beams that are 6.3 cm from the device axis. Each beam traverses through the klystron in its own beam tunnel, thereby reducing space charge forces and allowing significant reduction in beam voltage. The gun is designed to produce 100 MW of beam power at approximately 190 kV. This is equivalent to a microperveance of more than 6.4, much more than would be practical in a single-beam device.

Figure 2. Configuration of the multiple beam electron gun currently under construction

The gun is also operates with confined flow focusing. This is a significant advance over existing technology, because multiple beam guns using Brillouin focusing are typically restricted to power levels less than 1-2 MW. The inability to confine the bunched electron beam with a strong magnetic field results in unallowable beam interception at higher power levels.

Designing confined flow multiple beam electron guns requires careful analysis and control of the magnetic field in the cathode-anode region. There is a natural tendency for the flux lines to diverge away from the axis after exiting through the magnetic polepiece between cathode and magnet. This divergence causes a shear in the magnetic field at the cathode that disrupts beam propagation unless corrected. The principal goal of the gun program was to determine the proper placement of magnetic materials around the individual cathodes to duplicate the field configuration appropriate for the cathode if it were on axis of the solenoid. Figure 3 shows the uncorrected and corrected magnetic flux lines for the multiple-beam gun. The horizontal line represents the axis of an off-axis cathode. This axis is displace radially 6.3 cm from the device/solenoid axis. The lower figure includes the impact of magnetic material placed around each cathode to reshape the field to be symmetric about the local cathode axis.

Several codes were used in the design of the electron gun. 2D codes available included EGUN, TRAK, and X-Gun. These codes were used to perform initial design of an individual cathode without consideration for the magnetic field (electrostatic simulation). When the correct beam size and perveance were obtained, the structure was displaced 6.3 cm from the device radius and duplicated eight times around the circumference. 3D simulations involved a combination of advanced codes to properly model the electric and magnetic fields and model electron beam propagation. The electrostatic and magnetostatic fields are calculated using the commercial code MAFIA. These fields are reformatted and used as input to the 3D beam propagation code TOPAZ. TOPAZ propagated the electron trajectories through the problem domain, including the effects from space charge, self-magnetic fields, and relativity.

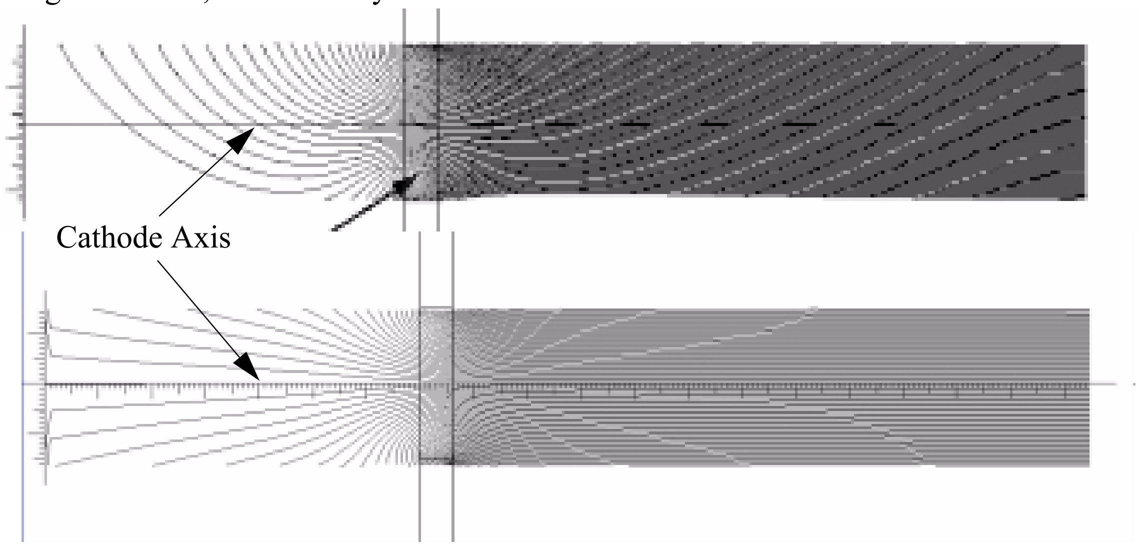


Figure 3. Uncorrected (top) and corrected magnetic field for multiple-beam electron gun for 50-MW klystron

A considerable effort was devoted to verifying the accuracy of TOPAZ. This effort included comparison with 2D simulations from other codes and with beam analyzer measurements of other guns. Results were also compared with other 3D simulation codes, specifically MICHELLE, for an S-Band multiple beam gun.

Figure 4 shows a TOPAZ simulation of an off-axis electron beam. This simulation included the effects of the other seven electron guns and their respective self magnetic and space charge fields. The simulation predicts complete propagation through the klystron with negligible beam spiraling.

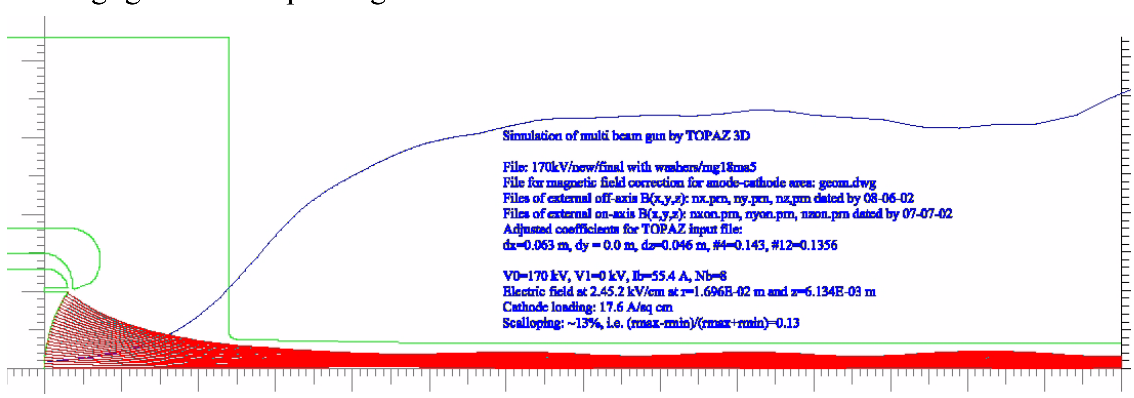


Figure 4. TOPAZ simulation of off-axis electron beam

The design provides for beam area convergence of approximately 10. Space limitations at the axial location of the cathodes requires a fairly high cathode emission current density, on the order of 15 A/cm^2. This is higher than would be appropriate for a long-life device; however, it is adequate for the development of the multiple beam klystron and demonstration of the design capability.

A photograph of the multiple beam gun is shown in Figure 5. This photograph shows the eight cathodes and guns stems.

More information on this gun can be found in the final report for the gun development program, which was submitted to DOE in June 2004.

Figure 5. Photograph of prototype multiple-beam gun

2.2. RF Circuit Design

There are few circuit design codes for modeling multiple beam devices, so a contract was provided to Los Alamos National Laboratory (LANL) to modify a suite of codes to couple multiple electron beams to multiple beam interaction circuits.

Most of the circuit design was achieved using a computer code called KLSC. KLSC is a 2 1/2D, fully relativistic, large signal code developed to simulate high-power klystrons. This code utilizes an electron beam composed of four deformable circular rings. No analytical gap modulation equations are used; rather, the electric fields generated by the LANL cavity code SUPERFISH are accessed as the electron beam propagates through the klystron. The accuracy of this code was documented against experimental results[2]. TRAK6, a conformal 2 1/2D electron beam code developed by Field Precision, Albuquerque, NM, was modified to provide an electron trajectory preprocessor data file for input to KLSC, in lieu of the deformable circular ring beam. Dr. Stan Humphries, developer of TRAK6, formulated this preprocessor. In addition, TRAK6 was converted to a full-beam simulation in 3D.

In support of the Phase I program, Los Alamos National Laboratory developed an interactive, graphical user interface (GUI) for KLSC simulations and improved the accuracy of data transfer from TRAK. The original plan was to generate the electron beam using results from a TRAK simulation; however, inspection of KLSC indicated that it contained two incompatible beam propagation algorithms, one for solenoid focusing and one for PPM focusing. It was decided to implement an interface that supported both solenoid and PPM focusing schemes. Results of this effort were provided in the Phase I report.

A photograph of the Body and Collector assembly is shown in Figure 6. The circuit consists of a ring resonator input cavity, eight stacks of five buncher cavities, and a ring resonator output cavity. The ring resonator input cavity allows all circuit stacks to be driven from a single cavity fed by a coax input for the drive signal. The ring resonator output cavity couples power from the eight circuit stacks into four output waveguides.

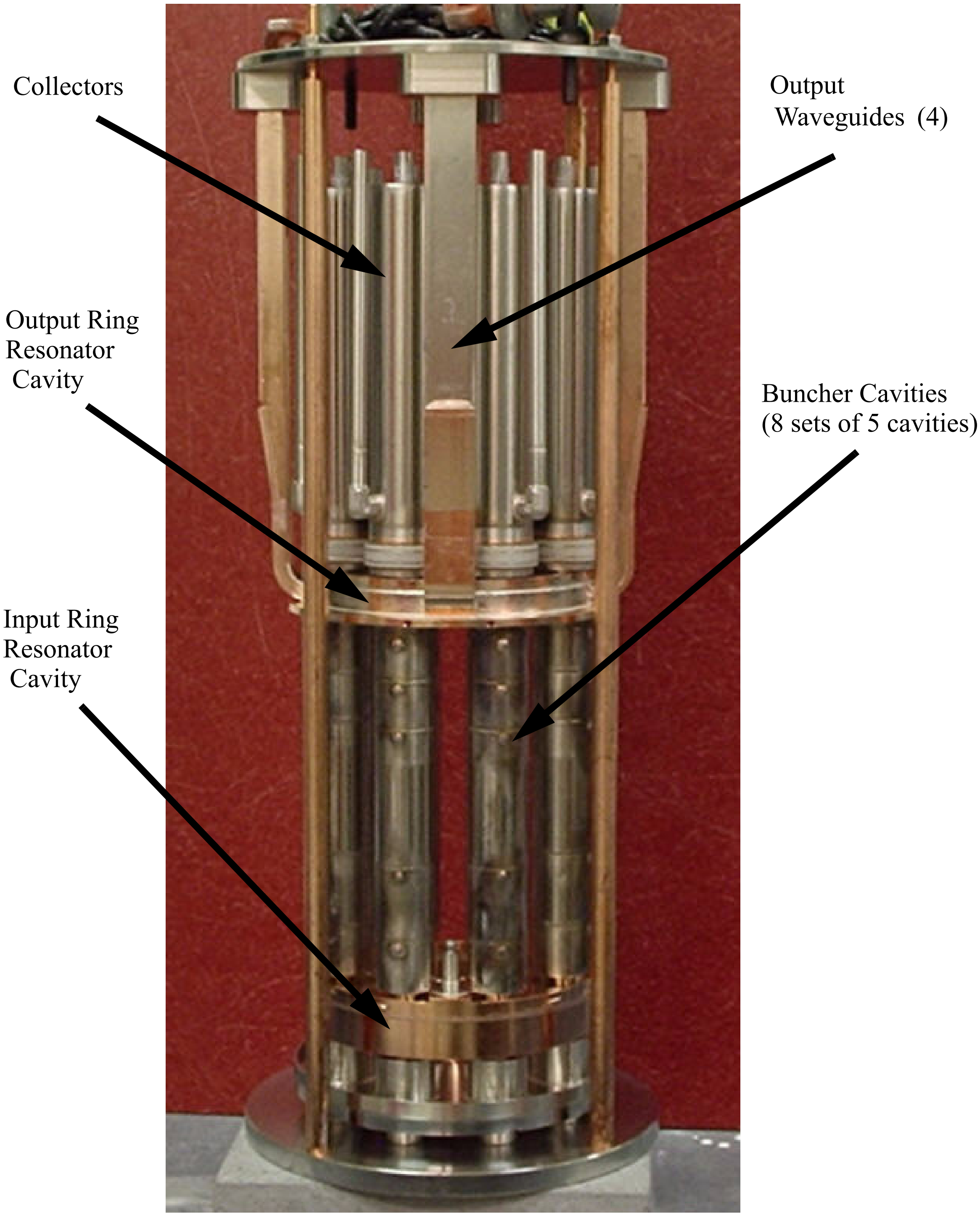


Figure 6. Photograph of cavity and collector assembly, including the output waveguides

The input ring resonator cavity uses pill box cavities to couple to the eight electron beams. Figure 7 shows an HFSS simulation of the input cavity at one beam location. The beam traverses through the cavity from left to right. Simulations indicate an R/Q of 12.28 at 11.432 GHz and a Q_0 of 3993.

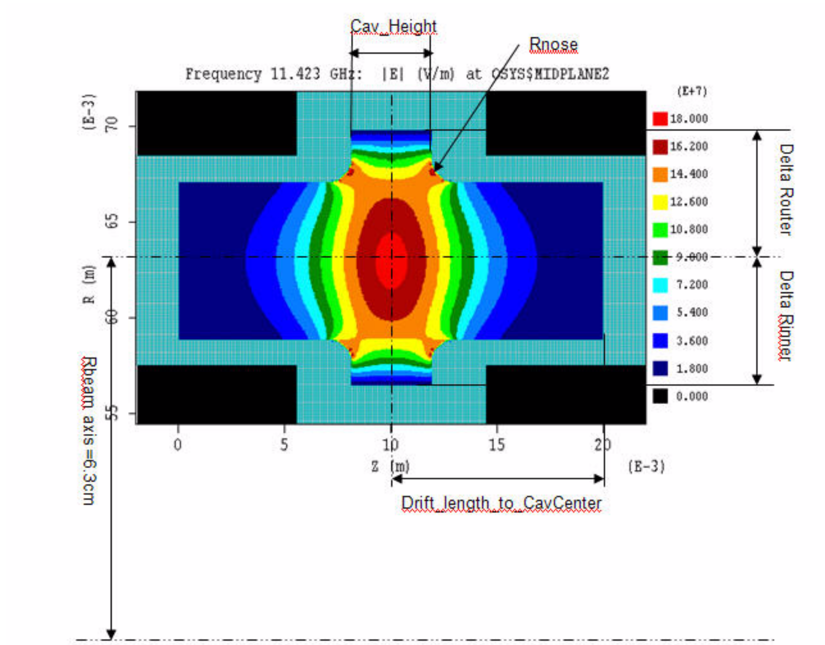


Figure 7. HFSS simulation of final MBK input cavity design - pillbox ring resonator cavity

Figure 8 shows the layout of the five cavities in the buncher stacks. The stacks use hybrid cavities tuned with a pin that is brazed in place following cold testing.

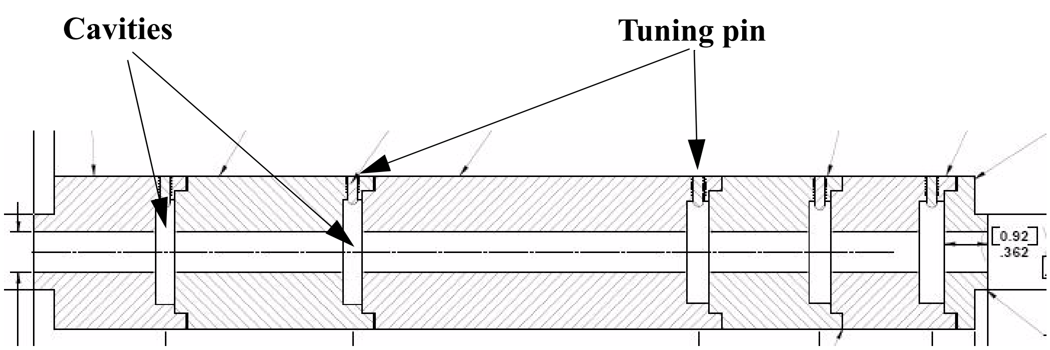
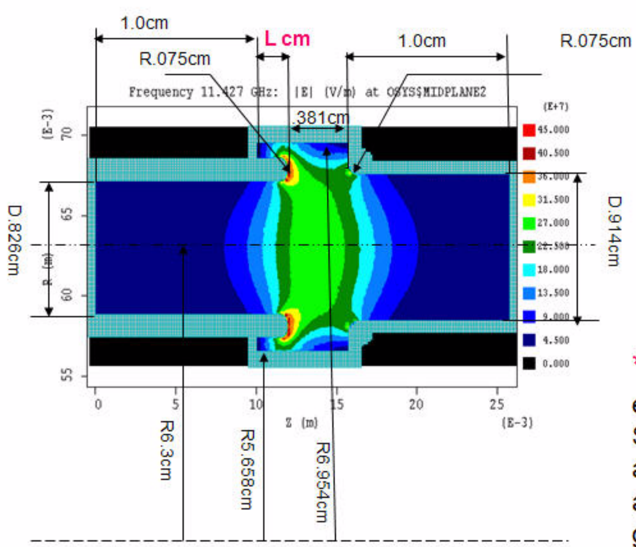


Figure 8. Layout of MBK buncher cavity stack

The output cavity was designed using Ansoft's High Frequency Structure Simulator (HFSS) with simulations verified by Communications & Power Industries, Inc. Figure 9 shows the determination of cavity frequency and Q with dimensions in centimeters. The design goal was a cavity Q of 330 and a resonant frequency of 11.424 GHz.



L	Iris gap	Freq	Q
.154	.740	11.44	380*
.159	.754	11.42	345

*Above calculation obtain using eigenmode/PML method. Using S11 calculation gave F=11.45 and Q of 300. Rasheda Begum at CPI used Kroll method and got F=11.44GHz and Q=340

Figure 9. Determination of output cavity frequency and Q using HFSS

The design had to carefully consider competing modes in the ring resonator cavity. Figure10 shows a comparison between the desired mode and the next higher mode, which resonates at approximately 13 GHz.

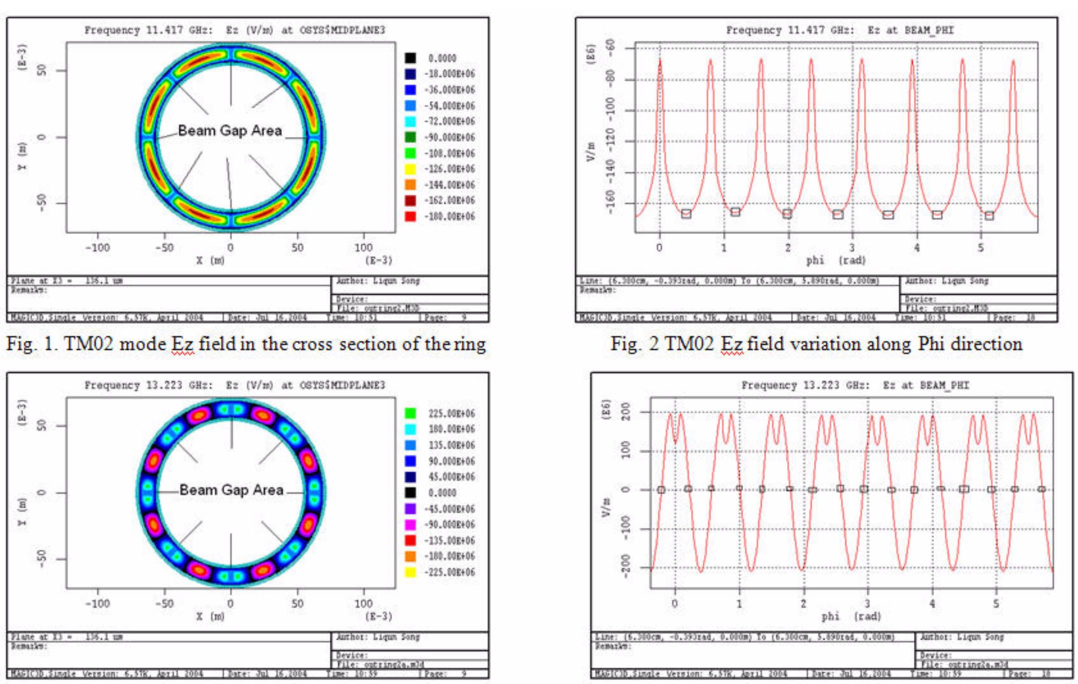


Fig. 1. TM02 mode Ez field in the cross section of the ring

Fig. 2 TM02 Ez field variation along Phi direction

Fig. 3. TM82 mode Ez field in the cross section of the ring

Fig. 4 TM82 Ez field variation along Phi direction

Figure 10. Comparison of desired ring resonator mode with nearest competing mode

The images in Figure 11 show the geometry and coupling from the output cavity to the output waveguide.

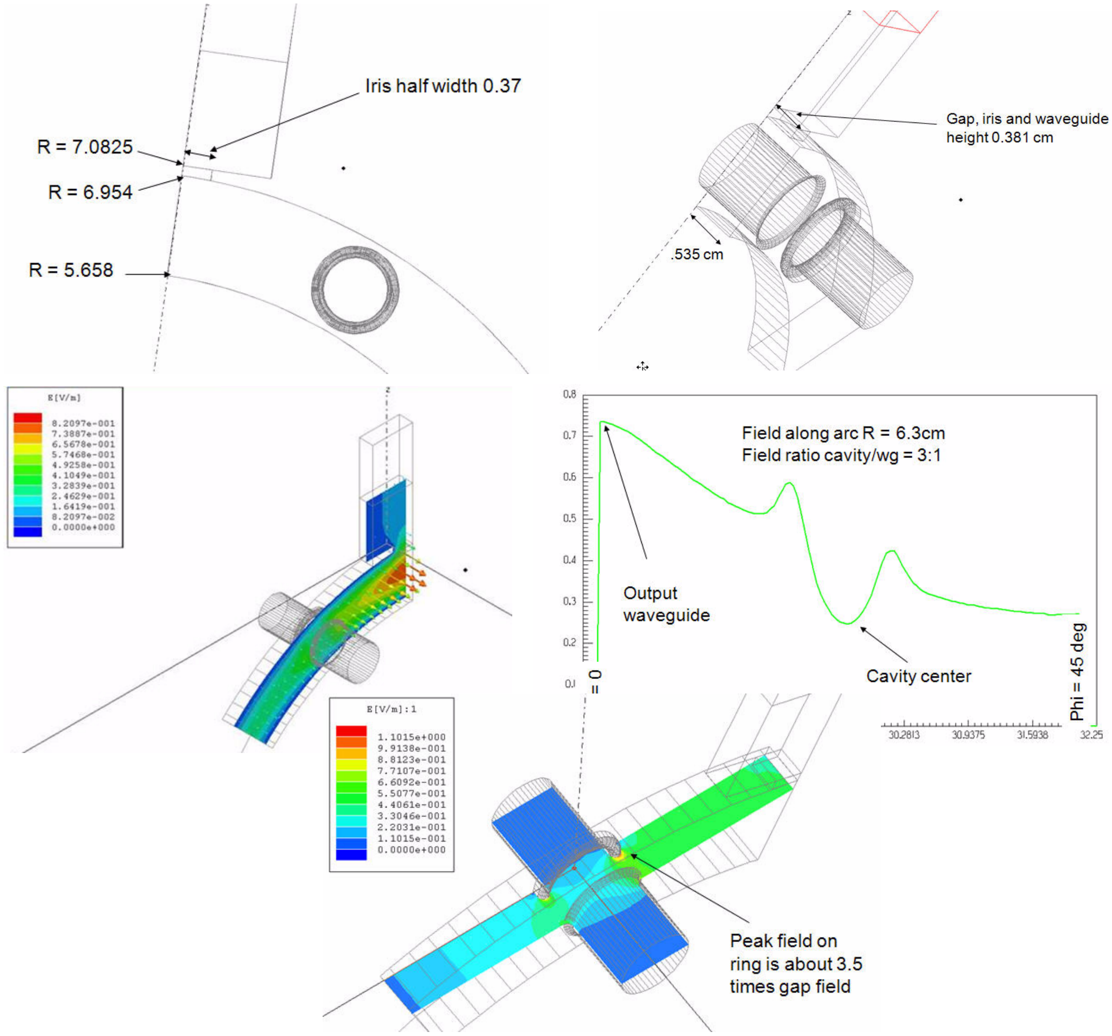


Figure 11. Simulations of output coupler

Simulations and cold test measurements before and during assembly indicate that the circuit should achieve the performance goals of the program. The predicted gain is 55 dB with an efficiency of approximately 50%. Predicted output power is 54 MW.

2.3. Collector Design

It was decided during the initial stages of the Phase II program to employ eight individual collectors for the eight electron beams. The principle challenge, as with all klystron collectors, is to insure that the electron beam traverses from the output cavity into the collectors without reflection or impact on the copper surfaces. Figure 12 shows the output cavity simulation with the transition to the collector sketched in. Spent beam data from MAGIC was used as input to the 3D trajectory code to design the collector and output polepiece configuration.

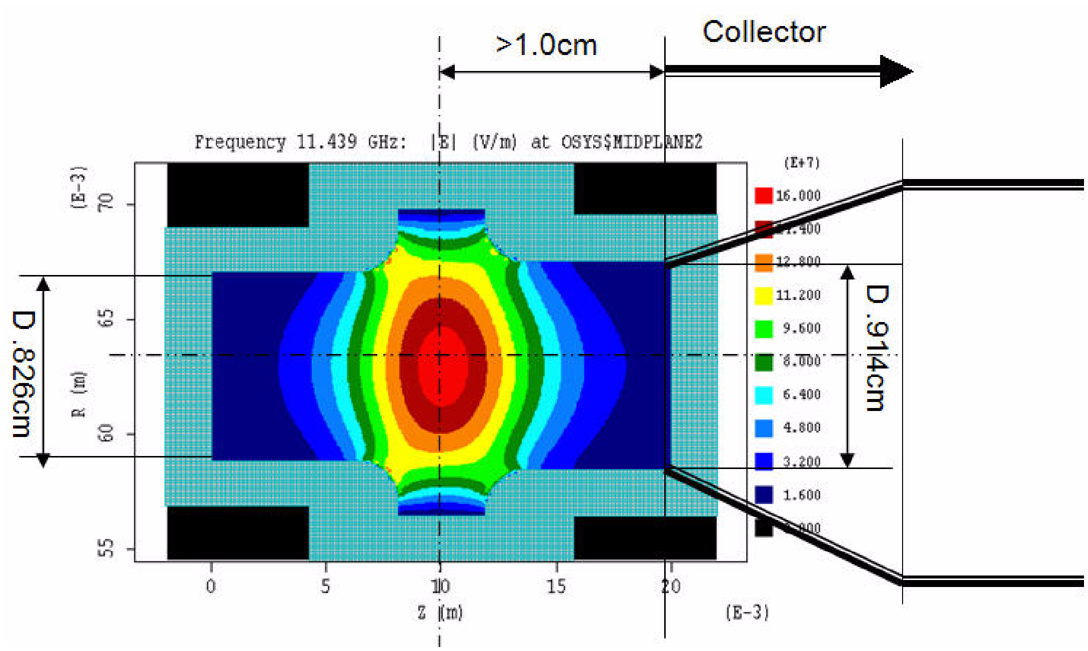


Figure 12. Schematic diagram showing transition from output cavity to collector

Figure 13 shows a photograph of the interface region between the collectors and the output ring resonator cavity. In particular, note the close spacing between the collectors. In order to insure that the beam propagates cleanly into the collector, it was necessary to install iron between the collectors in this region. Design of the collectors, collector ceramics, and output polepiece to achieve this goal required considerable effort.

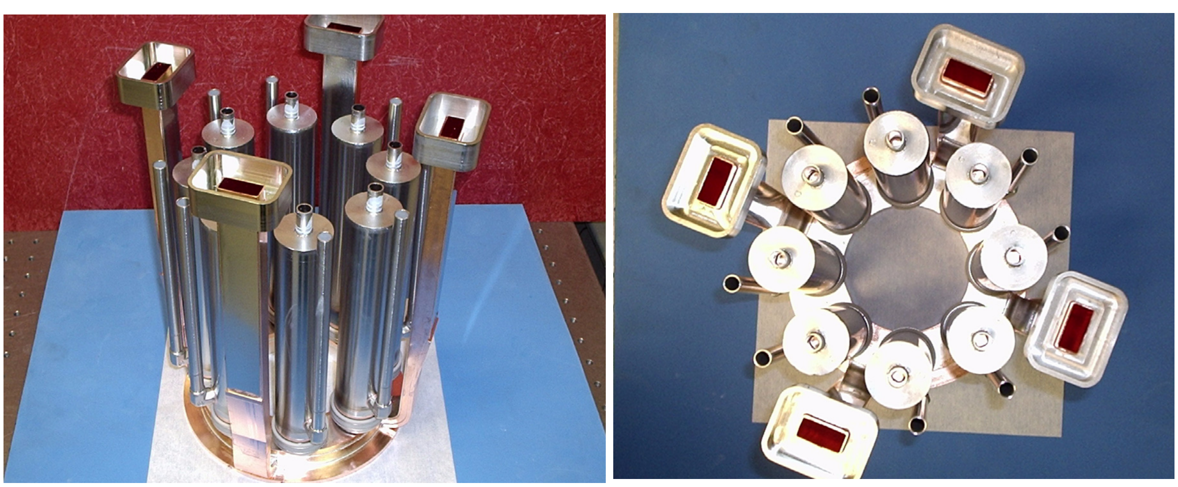


Figure 13. Photographs of collectors, waveguides and ring resonator cavity

The basic simulation geometry is shown in Figure 14. The outer cylinder represents the outer diameter of the solenoid and the red cylinder represents the inner diameter. The blue circles indicate the location of the beam tunnels and the blue rectangles represent the four output waveguides. The iron polepiece extends over the top of the solenoid and around the beam tunnels and waveguides.

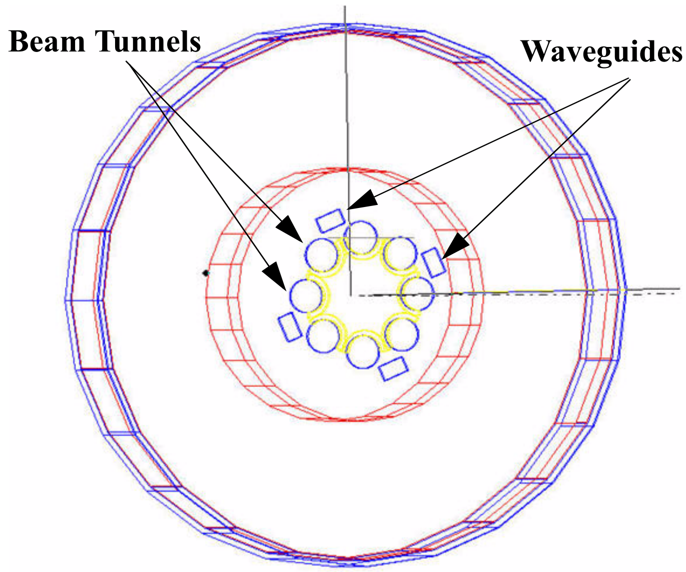


Figure 14. Solenoid geometry (magnet, polepiece, and return)

Since the beams propagate into individual collectors, it is only necessary to simulate one electron beam; however, this beam is located away from the axis of the magnetic field. Consequently, 3D simulations are required. These simulations were performed using CCR's 3D code Beam Optics Analysis.

Figure 15 shows views of the collector simulation results, including a plot of the incident power density on the collector wall. These results indicate that the power density at one location in the collector is near the limit for one microsecond pulse operation.

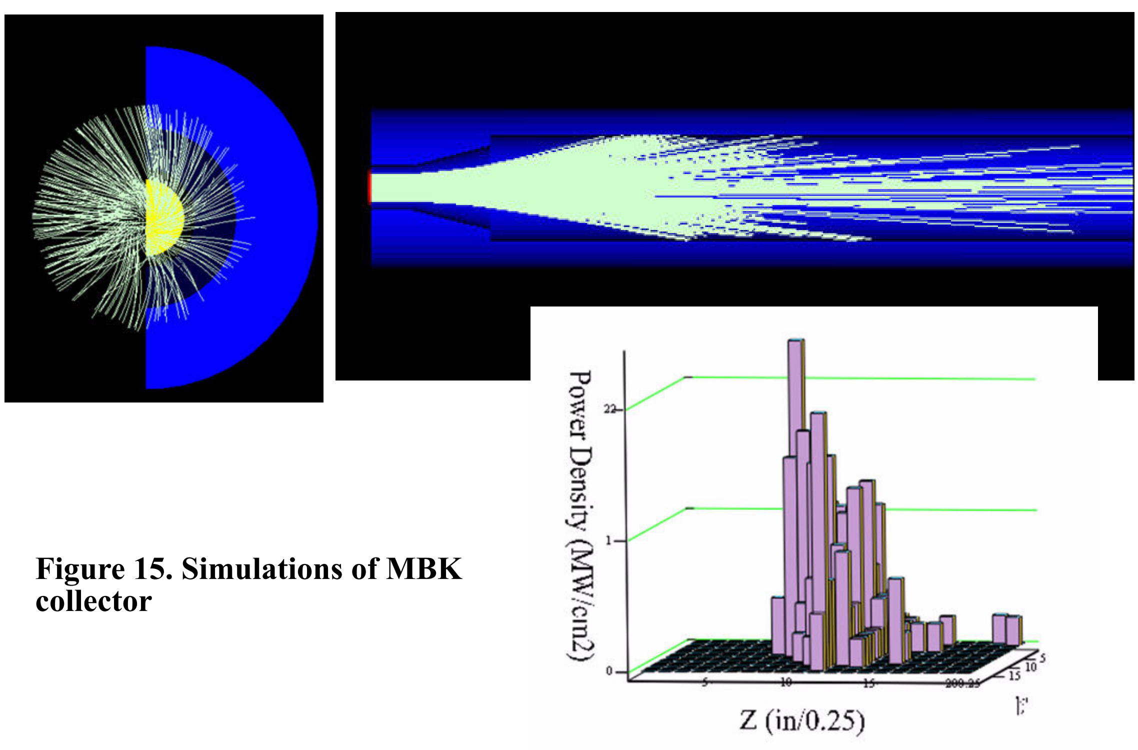


Figure 15. Simulations of MBK collector

2.4. Output Coupling

The Phase I report described the plan to extract the RF power toward the center of the klystron and transport it through a singe vacuum window. A solid model of this configuration is shown in Figure 16. During the Phase II program, considerable effort was

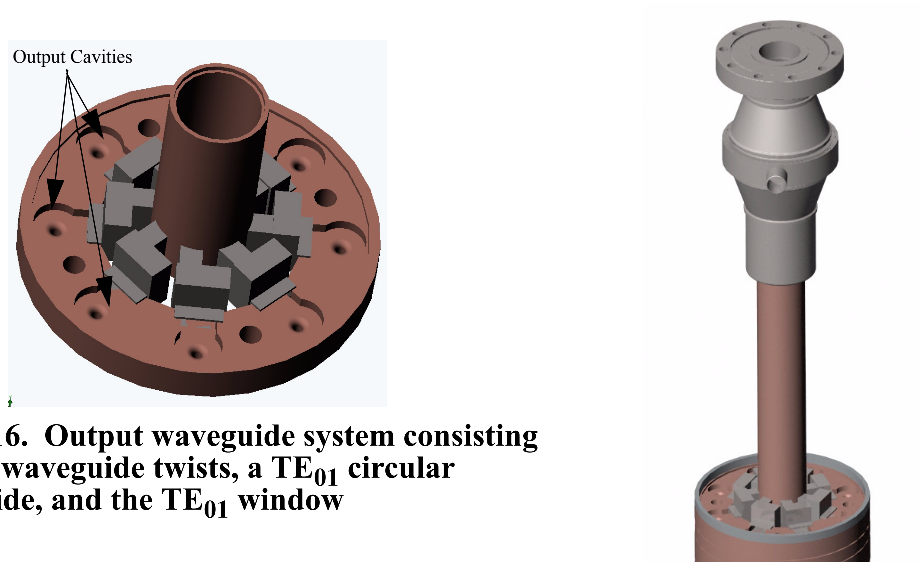


Figure 16. Output waveguide system consisting of eight waveguide twists, a TE_{01} circular waveguide, and the TE_{01} window

devoted to modeling and designing this configuration. While the simulations indicated that an electrical design could be achieved, the mechanical issues proved insurmountable. Differential expansions encountered during braze operations and constraints on both the outer and inner diameters prevented development of a realistic design. A particular concern was the inability to address any leaks or failed brazes in the interior of the structure.

Consequently, the design was modified to extract the RF power through four rectangular waveguides on the outside of the final cavity and use four, standard, pillbox windows. Since the windows are only required to propagate one fourth of the total output power, or approximately 13 MW, these were relatively simple, low risk designs. Section 2.2 described the simulations to properly design the coupling of the output waveguides to the output cavity. A photograph of one of the output windows is shown in Figure 17.

Figure 17. Output window for X-Band MBK

2.5. Magnet Design

CCR generated the specifications for the magnet and provided that information to Stanganese Industries, Inc. for construction of the magnet. The specified field profile is shown in Figure 18. CCR simulated the proposed mechanical design to insure that the iron

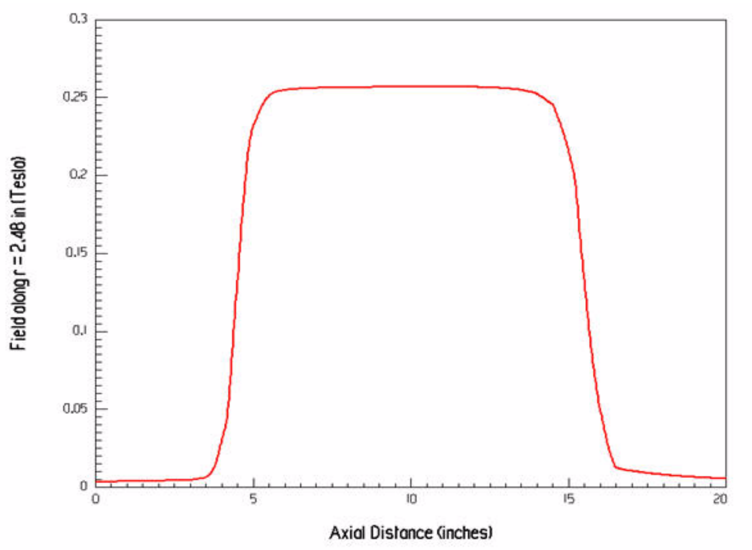


Figure 18. Specified magnetic field profile

polepieces and support structure would not saturate. This simulation is shown in Figure 19.

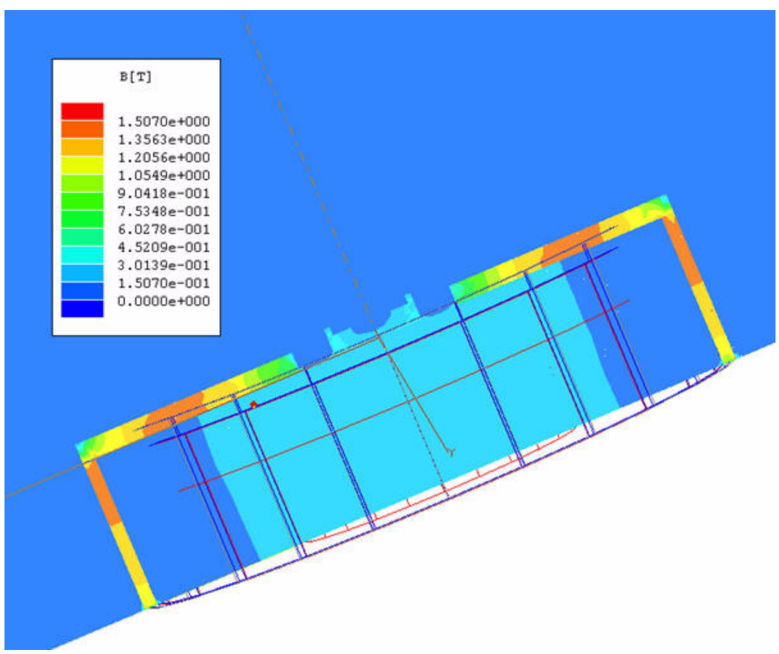


Figure 19. Plot of magnetic field showing values below saturation

2.6. Mechanical Design and Assembly

As can be seen from photos of klystron components, the mechanical design and assembly was quite complex and difficult. This required modification of the approach and design throughout the program. The experience with design modifications during the assembly process was similar to that for the multiple beam gun, where any change in the beam optics, circuit, or collector design often required modification of eight sets of parts. Not only was this time consuming, but often quite expensive. Unfortunately, the 3D design tools available during the program were not perfected to the accuracy level to allow single pass design. Often it was necessary to build and test components at low power to obtain accurate performance information.

The number of braze and weld joints is approximately eight times that in a single beam klystron. Consequently, the risk and number of braze and welding failures increased by the same factor. This proved especially troublesome because of the close proximity of the beam lines. Fortunately, most all brazes were successful with a single furnace operation. Unfortunately, a number of electron beam welds in sub assemblies began to leak following subsequent furnace operations. In most cases, it was not possible to access these regions for rewelding, requiring more creative, expensive, and time consuming operations.

Cold testing of the ring resonator structures also proved difficult, principally because of the increased number of components that were clamped together. It was difficult to get adequate electrical bonds between these components to prevent spurious RF losses. This was particularly true for the output cavity, which included four output waveguides, eight input drift tunnels, and eight output drift tunnels. Finally, it was decided to proceed with brazing these components, then cold testing the assembly to determine the expected performance. Fortunately, the final result was close to the design goals.

The assembly of the klystron is not complete, and CCR is proceeding with the program using its own funds. Currently, the program is addressing a number of electron beam weld leaks between the input ring resonator cavity and the eight buncher circuits. It is hope that these can be sealed by a low temperature braze operation. This is the last subassembly that requires brazing. All other assemblies are complete and only low risk welding operations remain. Assuming the leaks can be successfully repaired, the final assembly of the klystron should only require a few days. At that time, the tube will be baked and prepared for testing. Figure 20 shows the tube stacked with all required subassemblies in place. This will be the final configuration once the leaks are repaired and the welding completed. For reference, the klystron is approximately 40 inches in length. As can be seen, this is a significantly more compact 50 MW X-Band klystron then a single beam klystron at the same power level.

2.7. Future Testing

The magnet is complete, but CCR has not located a suitable driver or test set. When the program was initiated, the plan was to test the tube at Stanganese Industries, Inc.; however, this is no longer an option. Once the tube is complete and available for testing, CCR personnel will investigate potential testing facilities, including Stanford Linear Accelerator Center. Unfortunately, the lack of any potential market for this klystron makes significant additional investment difficult to justify from a business perspective. Still, successful demonstration of a confined flow multiple beam klystron would represent a significant achievement, so CCR will continue this program until the klystron can be tested.

3. Program Summary

CCR successfully designed a klystron suitable for supporting an X-Band linear accelerator or collider. Assembly of the magnet was completed, and the klystron should be fully assembled in a few weeks. At that point, testing could begin. The lack of a test set and driver, and the lack of interest in high power X-Band sources following cancellation of the NLC, make continued investment in this program problematic from a business perspective. Never the less, the gain from demonstration of capability, would be significant. Consequently, CCR will continue to pursue access to test facilities.

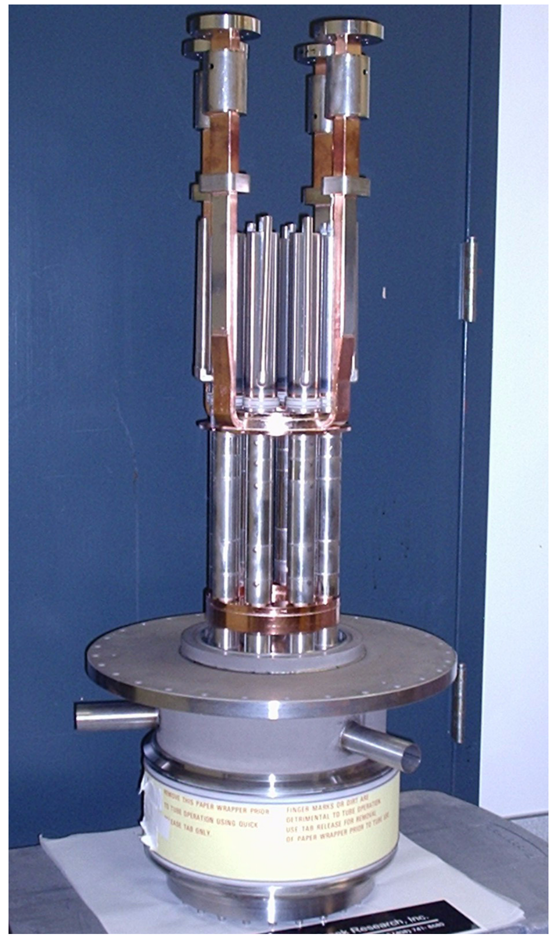


Figure 20. Stacked X-Band multiple beam klystron.

As was clearly demonstrated in this program and the proceeding gun program, the cost of multiple beam RF sources is significant. In addition to requiring 3D computer simulations, it is also caused by the high number of parts and the significantly increased risk from the larger number of joints and joining operations. For simpler sources, braze failures are typically addressed by adding additional braze material and rebrazing; however, the lack of access involved with multiple beam sources often makes this quite difficult.

On the other hand, the reduced voltage that can be achieved with multiple beam sources probably exceeds that available with other devices. Sheet beam devices can approach the voltage reduction; however the use of over moded cavities and non symmetrical structures and magnetic configurations make these sources quite expensive and high risk, also. One advantage of multiple beam sources over sheet beam sources is that most all components can be fabricated using lathes and milling machines. Sheet beam sources require significant operations with CNC machines with expensive material requirements. CCR recently completed a sheet beam electron gun program where a single gun part was quoted at approximately $30,000 (DE-FG03-01ER84350). This was in addition to the cathode, which cost approximately $20,000. In contrast, the multiple beam gun consists of eight relatively inexpensive cathodes. The iron shaping structure in the existing gun did cost $19,000; however, that cost can be significantly reduced using computer optimization techniques developed by CCR in a current, DOE-funded, SBIR program (DE-FG02-06ER86267).

Future high power accelerators and colliders will require advanced, distributed beam RF sources. This program demonstrated that complex multiple beam devices can be designed and built. The challenge now will be to demonstrate that they can be cost effective as well.

4. References

[1] G. Nusinovich, Baruch Levush, "A Review of the Development of Multiple-Beam Klystrons and TWTs", Naval Research Laboratory Memo NRL/MR/6840--03-8673, March 2003.

[2] B. Carlsten, P. Ferguson, D. Sprehn, "Accuracy of the Equivalent Circuit Model Using a Fixed Beam Impedance for Klystron Gain Cavities," IEEE Trans. Plasma Sci. Vol 26, No. 6, Dec. 1998.