Doubly Convergent Fundamental Mode MBK Final Report

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Introduction

Calabazas Creek Research, Inc. (CCR) proposed to develop a compact, inexpensive, fundamental mode, multiple beam klystron (MBK) at 1.3 GHz for driving a superconducting accelerator. The goal was to incorporate at doubly convergent multiple beam gun and enable a new generation of distributed beam devices. The proposed klystron requirements for targeted toward the TESLA collider.

The differences between singly and doubly convergent multiple beam guns is illustrated in Figure 1. In the singly convergent gun the center position of the cathode is the same distance (radius) from the axis as the final beam in the circuit. There is only convergence of the electron beam about its local axis.

In the doubly convergent gun, the center of the cathode is at a larger radius from the klystron axis than the final electron beam. There is convergence of the electron beam about its local axis and convergence of the local beam axis toward the axis of the klystron. Consequently, the cathode can be larger with reduced cathode loading.

In both configurations, it is necessary that the electrons do not spiral about the klystron axis. This occurs more naturally for the singly convergent electron beam than for the doubly convergent beam. Canonical angular momentum must be conserved, and there is a more radical change in magnetic field in the doubly convergent gun. It is this issue that has prevented designers from attempting this development.

Figure 1. Schematic of a singly convergent electron gun (top) and doubly convergent electron gun (bottom)

CCR proposed to develop a fundamental mode, 1.3 GHz, 10 MW, multiple beam klystron with a doubly convergent electron gun. This would allow the simplest and least expensive RF circuit while still ensuring that cathode loading is consistent with long lifetime.

The proposed research built on recently completed SBIR programs at CCR to develop a confined flow multiple beam gun (MBG) for an X-Band klystron[1-4] and to implement computer optimization in gun design[5,6].

During Phase I, CCR employed its advanced computational tools for the design a 1.3 GHz, fundamental mode, 10 MW MBK with a doubly convergent electron gun. A solid model illustrating the design is shown in Figure 2. The design goals included the following:

- Six electron beams
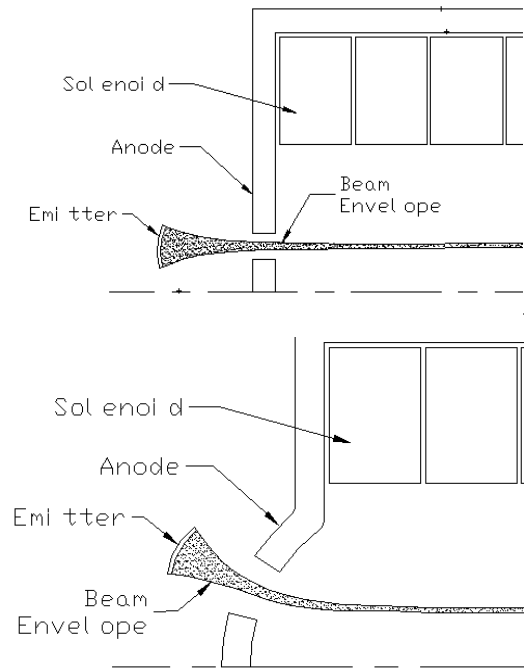- A magnetic circuit design, including one or more solenoids and field shaping iron

- An efficient, compact, fundamental, interaction circuit with discrete single gap cavities

- RF input and output coupler and vacuum window designs

- A preliminary spent beam collector design

The Phase I program was not successful in developing a doubly convergent multiple beam gun. As described below, the increase in parameter space that occurred with an off-axis shift of a simple Pierce gun exceeded the current design capabilities. While an MBK circuit design was achieved, without successful development of the electron gun, the program could not move forward. The program was successful in identifying

Figure 2. Illustrative model of a doubly convergent multiple beam electron gun

issues that prevented the gun development, and a subsequent program was funded to develop the necessary computational capabilities. If this program is successful, CCR will apply them to the doubly convergent gun design in a future program. Until those computational capabilities are in place, it does not appear that a doubly convergent multiple beam electron gun is feasible.
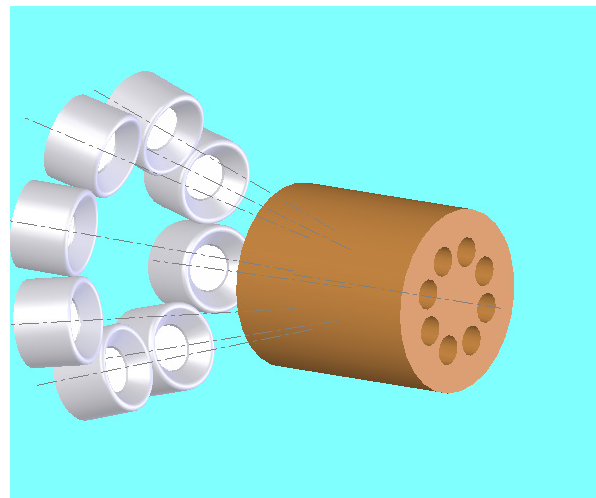
The Phase I Project

a. Technical Objectives

The technical objective of the Phase I program was to design a a doubly convergent electron gun and a fundamental mode, 10 MW, multiple beam klystron. Specific objectives included the following:

- Design a doubly convergent multiple beam electron gun with confined flow focusing

- Design a fundamental mode RF circuit meeting the performance specifications

- Design additional components, including the magnet, input and output windows and couplers, and the spent beam collector

- Develop a preliminary mechanical design for construction of the klystron.

b. Phase I Work Plan Results

Task 1. Electron Gun Design

The key to the program was development of the doubly convergent electron gun. Several organizations, including CCR, have designed multiple beam klystron circuits. The gun design was based

on the specifications indicated in Table 1. All specification are those for the TESLA requirement except for the cathode loading, which is derived based on the requested lifetime.

Table 1. Multiple beam klystron specifications

Parameter	Value
Output Power	10 MW
Maximum Beam Voltage	120 kV
Microperveance per beam	< 0.6
Efficiency goal	65%
Cathode loading	~ 3.0 A/cm^2

Given these parameters, one can derive the basic requirements for the electron gun. From the efficiency, one can derive the required beam power. As a worst case (or perhaps more realistic case), the beam power delivered was based on 60% efficiency. Both the Thales and CPI MBKs achieved this efficiency. Therefore, the total beam power requirement was 16.7 MW. For six beams, the beam voltage requirement was 117 kV. The total current requirement was approximately 140 A with approximately 24 A in each of the six beams. For a maximum cathode loading of 3 A/cm^2, the cathode radius was approximately 1.6 cm. For reference, the radius of the cathodes in CCR's X-Band gun is 1.0 cm.

For a fundamental mode klystron, it is recommended that the ensemble of beams be within a $\lambda_0/4$ diameter circle about the klystron axis, and the beam tunnel diameter should be approximately $\lambda_0/12$ [7]. For the proposed 1.3 GHz klystron, this means that all the beams should be within a circle of 5.76 cm diameter. For reference, the eight beams in the CCR's X-Band gun are located 6.3 cm from the klystron axis.

There are now two convergences to consider. The first is the convergence of each beam about its local axis and the other is the convergence of the ensemble of beams toward the klystron axis. In CCR's X-Band gun, the area convergence of each beam about its local axis is approximately 15. Because the TESLA requirement is lower frequency, a larger final beam diameter was acceptable, so the local convergence could be reduced. The required value was determined by the RF circuit. The required convergence of the ensemble of beams toward the device axis depends on the location of the cathodes in the electron gun. Each cathode must be a sufficient distance from its neighbor to avoid interactions.

Figure 3 shows the conceptual design of the X-Band gun. The key to its success was iron that forced the magnetic field contours to be parallel to the cathode surface. The figure actually shows artificial flux lines that are perpendicular to the magnetic field contours, so the flux lines should be perpendicular to the cathode surface. Flux lines are actually more useful in estimating the potential path for emitted electrons.

The principle concern with essentially all confined flow multiple beam devices is spiraling of the individual beams about the device axis. This results in beam interception on the tunnel walls and failure of the device.

The situation becomes very complex for a doubly convergent electron gun. In this case, there can be no azimuthal motion about the klystron axis added to the electrons in the beam tunnels. Otherwise, the beam will impact the walls, resulting in potential destruction. This can be achieved if the only changes seen in the value of the magnetic field are those about the local beam axis. In this case the canonical angular momentum seen at the cathode will be the same as that of the electrons about the local beam axis.

The field shaping structures successfully employed in the previous program should work equally well for the doubly convergent gun. It was anticipated that the task would be somewhat easier for the doubly convergent gun, since there is less modification required of the fields. The approach was to use the natural radial divergence of the magnetic field in the gun region to provide the convergence toward the klystron axis with local modifications at the cathode surface to achieve the required local symmetry and field magnitude.

If the conservation laws could be satisfied with no bulk azimuthal motion of electrons about the

Figure 3. Conceptual design of the X-Band multiple beam gun

klystron axis and the required azimuthal motion about the local axes was achieved for proper beam propagation, then the design goals would be achieved.

The task was to first analytically calculate the fields required at the cathode to balance the forces in the beam tunnels. This depended on the local beam convergence, beam voltage and current, beam current density profile, and the magnetic field in the drift region. This information was used to determine a goal magnetic field condition in the cathode-anode region. Maxwell 3D was used to generate the magnetic field for beam simulations.

3D beam simulations were performed using Beam Optics Analysis. It was anticipated that once initial simulations achieved a design close to the specifications, that optimization routines developed by CSRC would achieve the optimum design.

The program initially developed an acceptable design for a single electron gun on axis. This provided the required beam convergence and current for one of the multiple beam electron guns. The next step was to shift the gun slightly off axis and modify the geometrical parameters to achieve an acceptable beam. To simplify the problem, a flat cathode was used with the center trajectory used to determine the anticipated beam path. As anticipated, the electrons began spiraling about the main problem axis. Figure 4 shows a 3D simulation of this effect.
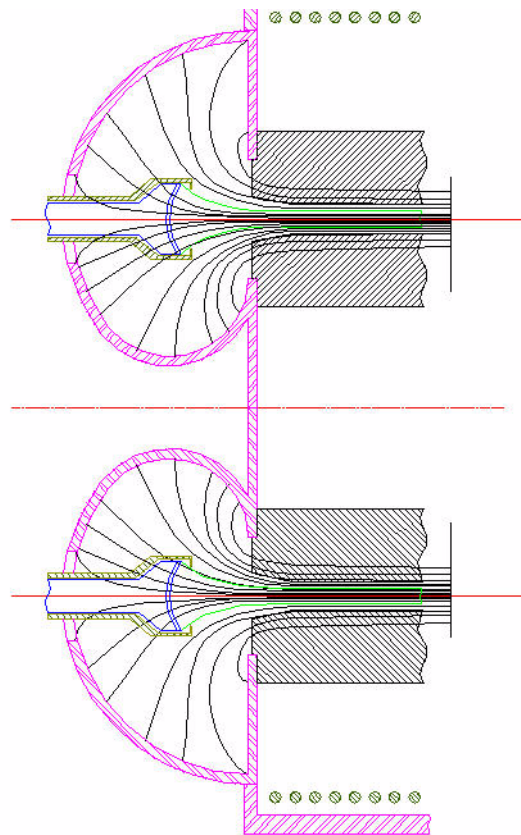
Attempts were made to manually modify the geometry to achieve the desired path for the center trajectory. Many simulations were executed with modifications to the geometrical parameters, including the cathode tilt, cathode-anode spacing, focus electrode shape, and anode shape. Figure 5 shows one of these simulation where the cathode and focus electrode were tilted with respect to the magnetic field axis and the cathode was shifted with respect
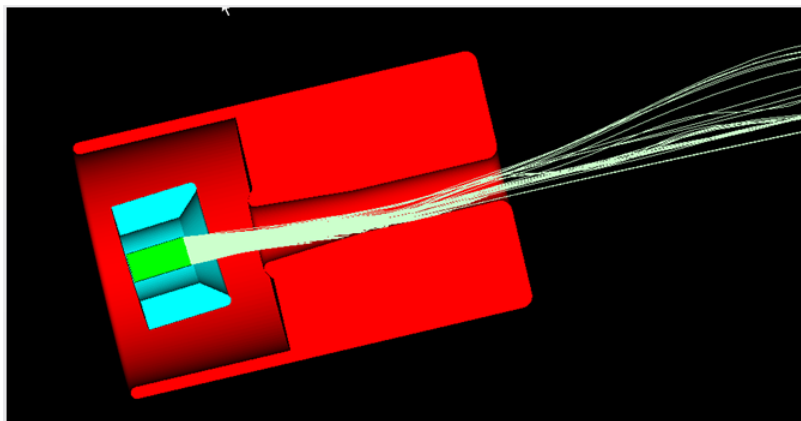

Figure 4. Simple confined flow electron gun shifted 1 cm radially from magnetic field axis.

to the beam tunnel axis. Figure 5 also illustrates the increased complexity necessary for this process to work. While the cathode tilt was successful in neutralizing the spiraling, somewhat, an axial shift was necessary to recenter the beam. This created asymmetries in the spacing between elements of the cathode, focus electrode, and anode. This would require complex solid modeling of these surfaces within the CAD program to correct these issues. It soon became apparent that manually searching parameter space for the correct shapes and spacing essentially increased the number of parameters far from what could be achieved manually.

At this point the program focused on investigating and developing computer optimization techniques to automate the design process. CCR successfully demonstrated feasibility of this approach in a DoD-funded SBIR using the 2D computer code EGUN. Efforts not focused on implementing this capability into CCR's 3D code Beam Optics Analysis (BOA). Unfortunately, it became apparent that complete integration of computer optimization into 3D design would require significantly more resources than available in this program. Still,

Figure 5. 3D beam simulation of off-axis cathode tilted with respect to the magnetic field axis and shifted from the beam tunnel axis.

significant progress was achieved that was used to justify award of a Phase I SBIR program focused specifically on developing this capability.

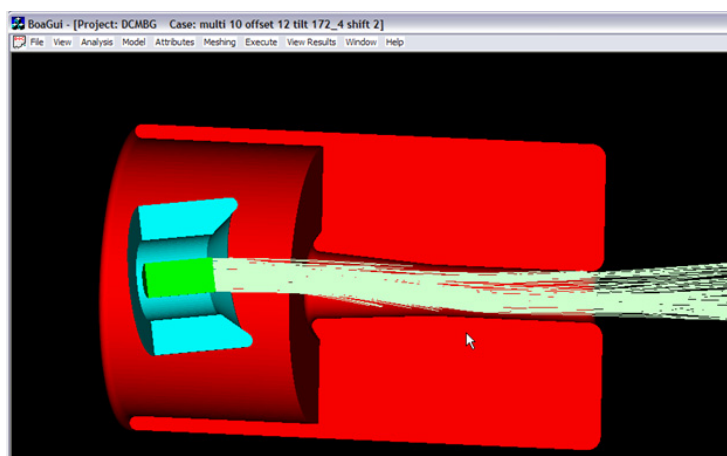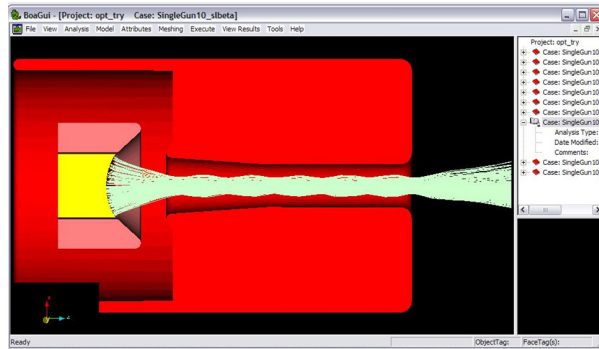The optimization effort focused on improving the design of a confined flow Pierce electron gun. Routines optimized the beam quality by modifying the cathode curvature, cathode anode spacing, and position of the magnetic field. The goal function was based on the required current, beam size, and beam ripple (scallop). This effort was highly successful. Figure 6 shows simulations
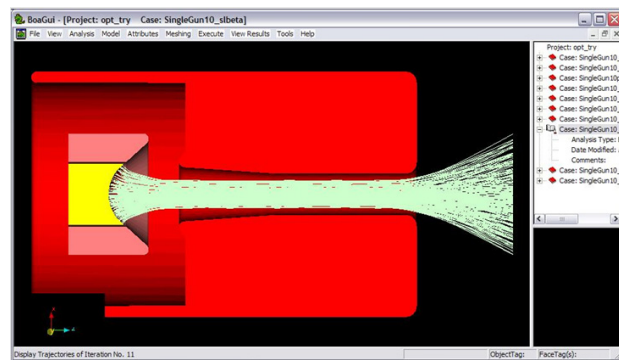
before and after the optimization routines modified the design. The goal was to achieve a 66% fill factor at 20 A with minimum beam scallop. This optimization process required 50 design iterations and approximately 7 hours on a Toshiba laptop computer running Windows XP.

Before   **After**

Beam Current 27.9 A
Beam Size 48.5%
Beam Scallop 17.5%

Beam Current 19.59
Beam Size 70%
Beam Scallop 3.1%

Figure 6. Results of optimization of a Pierce electron gun. Figure on left is before optimization and image on the right is after optimization

The current effort in the new program is using surfaces defined by spline curves to optimize the geometrical shape of objects. The optimization routines position points defining the splines to achieve improved performance. This program is making excellent progress and will be applied to a sheet beam cathode in the near future.

While this task was not successful in developing doubly convergent multiple beam gun, it more clearly defined the technical requirements and tools necessary for such a design. The foundation was established for the new program design to develop that technology and those tools. If the new project is successful, CCR will apply that technology toward future development of the doubly convergent gun.

Task 2. Design of a Fundamental Mode Cavity Without Parasitic Oscillations

In anticipation of a successful gun development, CCR designed a compatible fundamental mode circuit. The configuration is shown in Figure 7. The beam centers are on a 4.7 cm bolt circle with the cavity diameter equal to 12.18 cm and cavity length of 6.3 cm. This provided a resonant frequency of 1.299 GHz and R/Q of 59.6.
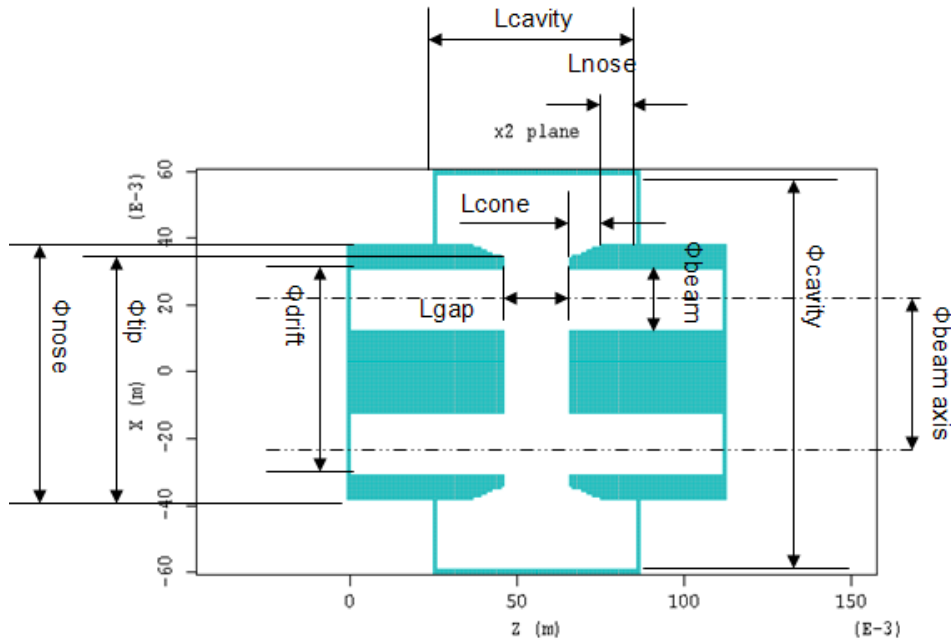
Figure 7. Configuration of 1.3 GHz fundamental mode cavity for doubly convergent multiple beam gun

A second harmonic cavity was designed by utilizing a pillbox cavity, rather than a reentrant cavity as in Figure 7. A MAGIC simulation of this cavity is shown in Figure 8. Japandsk was used to design and simulate a circuit consisting of 6 cavities. The Japandsk input is presented in Figure 9. The simulations predicted an efficiency of 65.4%. One should expect that these results will be slightly optimistic, based on experience with other devices.
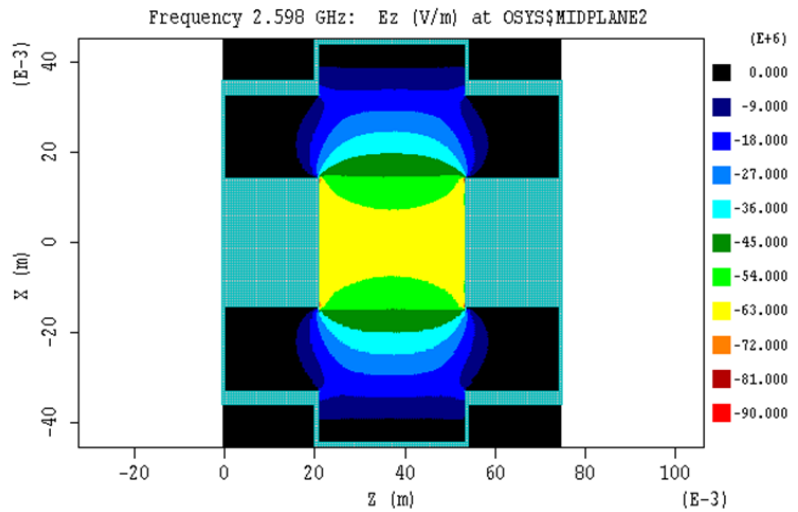

Figure 8. MAGIC simulation of second harmonic cavity for doubly convergent multiple beam klystron

Task 3. Analysis and Optimization of Electron Beam-RF Wave Interaction Circuit

Beam-RF simulations were performed using 3D MAGIC. Complete 3D simulations for the complete circuit would be extremely computationally demanding, so only the output cavity was analyzed in 3D assuming a prebunched beam at the input to the cavity. The prebunched beam was

simulated using 2D MAGIC and assuming only a single beam cavity, with the beam parameters appropriately scaled.

```
Lband
  Voltage =115.0 kv    Current=2.000A    freq=1300MHz    beam tunnel
radius =0.9398(cm)   beam radius =0.6108(cm)       Input drive
power=15.0watts
Cavity      1st     2nd     3rd     4th     5th     6th
Qext:       500.   3000.   3000.   3000.   3000.     90.
R/Q:        60.0    60.0    60.0    60.0    60.0    60.0
Lgap(m)     0.023   0.023   0.014   0.023   0.023   0.023
Spacing(m)*0.00     0.15    0.28    0.54    0.68    0.82
Detuned freq**0.    -0.2    1300.0  18.0    28.0     0.0
```

- spacing means: spacing from 2nd to 1st cavity is .15m, from 3rd to 2nd cavity is .14m, from 4th to 3rd cavity is .26m, from 5th to 4th cavity is .14m, from 6th to 5th cavity is .14m.
- detuned freq is equal to the cavity frequency – operation frequency (1.3GHz)

Figure 9. Input data for Japandsk

Figure 10 shows the prebunched beams and the output cavity. The beam voltage is 115 kV with 22A of current in each beam. The magnetic field is 915 G. The external Q of the cavity for the six beam geometry is 21, which is equivalent to 126 for a single beam cavity with the same beam voltage and 132 A of beam current. In place of an output coupler, loss conductance is added to simulate RF power extraction from the cavity. When the interaction of each electron beam with the RF in the cavity is stable, the voltage across the gap is 145 kV, equal to 1.26 times the beam voltage. The power absorbed by the lossy conductance is 10.92 MW, which yields 72% efficiency.

3D MAGIC. Beam-RF Interaction in 1.3GHz MBK Output Cavity
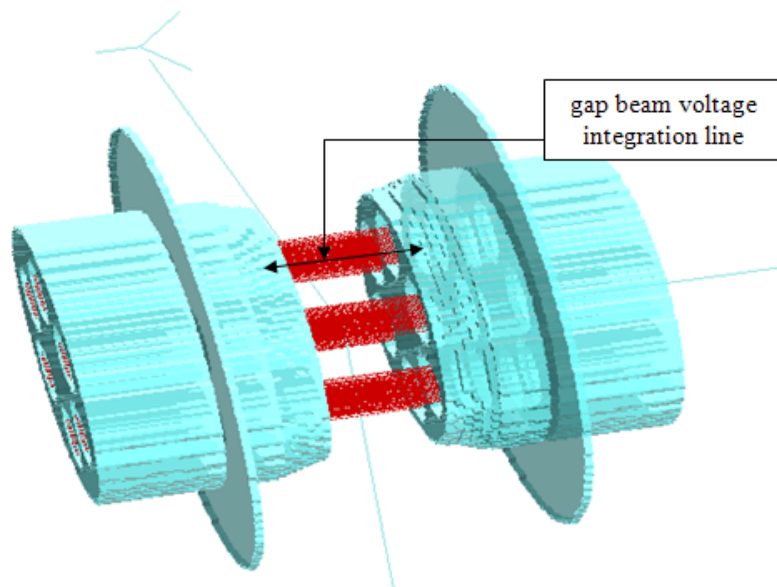

gap beam voltage integration line

Figure 10. Pre bunched beam through 1.3 GHz fundamental mode MBK output circuit (cavity outer shell is transparent).

Efforts to improve the circuit design were terminated once the gun design encountered problems. These results, however, indicate that a circuit for such an electron gun is feasible.

Task 4. Design of the RF Windows, Input and Output Coupler, and Spent Beam Collector

No work was performed on this task.

Task 5. Preliminary Mechanical Design

No work was performed on this task.

Summary

The Phase I program failed to develop a doubly convergent multiple beam gun for a fundamental mode klystron. It identified critical issues related to this development, and these issues are currently being addressed in another program. If the new program is successful in advancing the computational technology sufficiently for optimized design of 3D structures, including shape optimization, CCR will revisit the doubly convergent multiple beam gun. The Phase I program generated the preliminary design of a fundamental mode circuit for the doubly convergent MBG that achieved the goals of the program, demonstrating the potential advancement that can be achieved if the gun can be developed.

1. Development of Multiple Beam Guns for High Power RF Sources for Accelerators and Colliders, U.S. Department of Energy Small Business Innovation Research Program, DE-FG03-00ER82964, Sept. 2001-June 2004.

2. "Confined Flow Multiple Beam Guns for High Power RF Applications," L. Ives, M. Miram, A. Krasnykh, Valentin Ivanov, 13th IEEE Conf. Plasma Sci., Las Vegas, NM, June 2001.

3. "Development of Multiple Beam Guns for High Power RF Sources," Advanced Accelerator Concepts Ninth Workshop, AIP Conf. Proc. 569, Santa Fe, NM, October 2000.

4. Electron Gun for Multiple Beam Klystron Using Magnetic Focusing, U.S. Patent Number 6,768,265, July 27, 2004.

5. Development of a 3D, finite element Charged Particle Code with Adaptive Meshing, DOE SBIR contract number DE-FG03-00ER82966, September 2000 - June 2003.

6. Computer Optimized Design of High Performance Vacuum Electronic Devices, Funded by the Office of Naval Research under Contract Number N00014-04-M-0170, April 2004 - October 2004.

7. E. Wright, A. Balkum, H. Bohlen, M. Cattelino, L. Cox, M. Cusik, E. Eisen, K. Eppley, F. Friedlander, S. Lenci, J. Petillo, "The VKL-8301 Multiple Beam Klystron," Communications and Power Industries, Inc. presentation to DESY, April 2004.