SLAC-PUB-15330

Sheet Beam Klystron for the Navy FEL

Aaron Jensen, Michael Fazio, Andy Haase, Erik Jongewaard, David Martin, Jeff Neilson, Daryl Sprehn, and Arnold Vlieks

SLAC National Accelerator Laboratory, RF Accelerator Research & Engineering Division, 2575 Sand Hill Road, Menlo Park, California 94025

The objective of this project is to build a 2.1GHz, 200kW CW, sheet beam klystron for the Office of Naval Research (ONR) and their free electron laser (FEL) program. A design point was chosen based on optimal efficiency at minimal voltage while maintaining a drift tube cutoff to the fundamental frequency (as is customary for round beam klystrons) to avoid beam instability.

Both solenoid and periodic permanent magnet (PPM) focusing schemes were evaluated for their ability to transport the beam and maintain beam stability. Final results from this study show beam stability in a solenoid field at all values above the Brillouin field (the minimum field required to transport the beam, i.e. to balance the electric field forces in the beam which would otherwise cause the beam to scallop or grow in size). However, the PPM focusing scheme was unstable at all achievable field strengths. For this reason the solenoid focusing scheme will be used as the baseline for the ONR sheet beam klystron. Given the weight and size advantages of a focusing scheme based on permanent magnets, further theoretical studies and simulations of the PPM design will be conducted to evaluate methods of stabilizing PPM transport of the beam in a future revision of the tube.

KEYWORDS: Klystron, Sheet Beam, Stability, Free Electron Laser (FEL)

1. Introduction

With respect to traditional round beam klystrons, sheet beam klystrons operate with decreased current density and increased surface area making them advantageous for high power and CW applications. By distributing the beam current over a greater area these devices have better power handling capability and are generally more compact, higher efficiency, and lower voltage than an equivalent round beam klystron. This technology is being used to develop a 200kW CW S-band klystron for the Office of Naval Research (ONR). The final operating specifications for the ONR sheet beam klystron are shown below in Table 1.

Presented at The 15th Anual Directed Energy Symposium
Albuquerque, New Mexico, November 26-30, 2012

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

Table 1. Design specifications for the ONR sheet beam klystron.

Parameter	Design Goal/Specification
Beam Voltage (kV)	**36**
Beam Current (A)	**10**
Frequency (GHz)	**2.1**
Output Power (kW)	**200+**
Beam Aspect Ratio	**12:1**
Beam Shape	**Semi-Elliptical**
Drift Tube Cutoff (GHz)	**2.50**
Gain	**> 40dB**
Efficiency (%)	**55+**

The ONR sheet beam klystron will use a 12:1 aspect ratio semi-elliptical beam. The shape of the beam is shown in detail in Figure 1. The fill factor of the beam in the drift tube is 50% which is the conventional fill factor for a CW klystron to minimize beam interception on the drift tube wall.

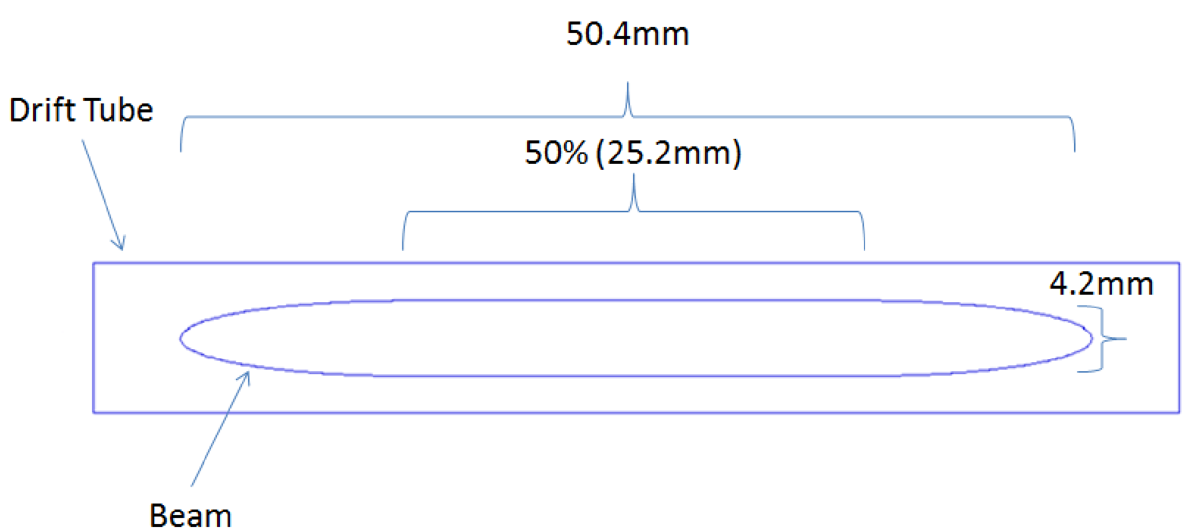

Fig. 1. 12:1 Aspect ratio beam for the ONR sheet beam klystron (pictured inside a rectangular drift tube).

2. Electron gun design

The electron gun is critical for generating a high quality electron beam that can be used in the RF portion of the klystron. The electron gun geometry can first be simulated in two dimensions and then extended to three dimensions by carefully optimizing the shape of the focus electrode. The ultimate design is three dimensional in nature and requires careful optimization to generate a laminar beam that also produces the proper cross sectional beam profile, beam current and beam voltage. Figure 2 shows the side view of the final 3D gun geometry.

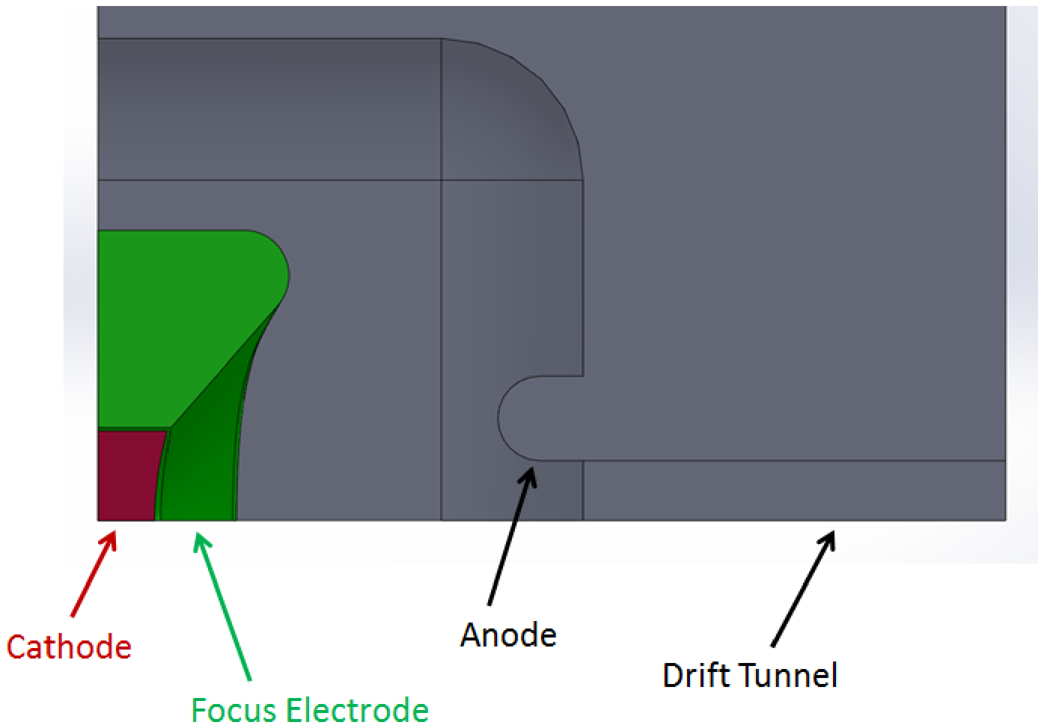

Fig. 2. Side view of the final 3D model of the ONR sheet beam gun.

Figure 3, the final MICHELLE 3D gun simulation, shows a laminar beam with a 50% fill factor at the beam minimum. Although particles emitted from the face of the cathode are laminar, particles emitted from the cathode stalk are not as laminar. However, the particles emitted from the cathode edge represent less than 1% of the beam current, and although not as well behaved, transport successfully to the collector with solenoid focusing. MICHELLE shows successful generation of a high quality 12:1 aspect ratio beam that will produce the desired RF interaction and 200kW of CW power.

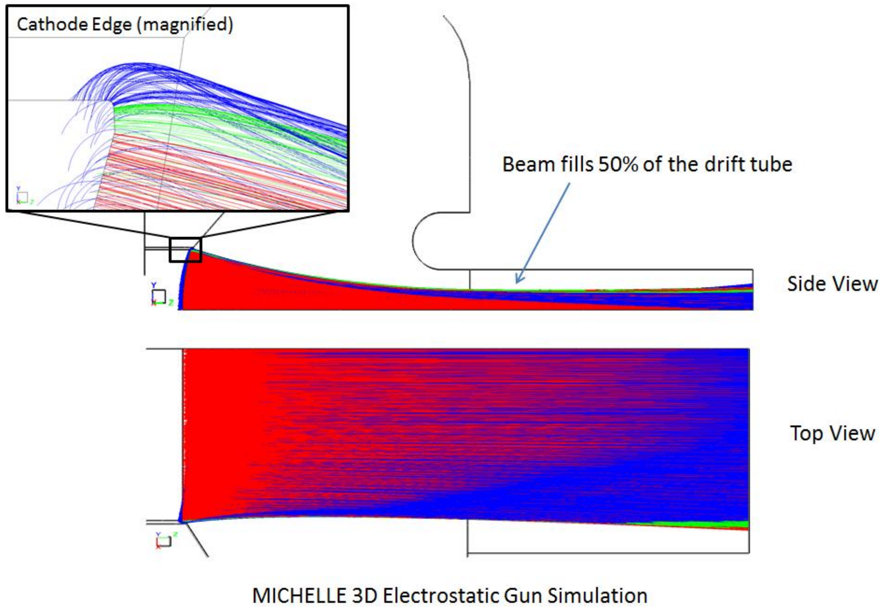

Fig. 3. MICHELLE 3D simulation of the sheet beam gun.

3. Cathode design

A thermal stress analysis of the cathode assembly was completed using ANSYS. A series of solid models were built using Solid Edge and imported into ANSYS, where thermal models were created to account for radiative and conductive heat transfer and to determine steady state thermal conditions. The cathode design was optimized to minimize thermal gradients across the face of the cathode (Figure 4), and balance differential thermal expansion between the cathode body and focus electrode support structure. Features such as the shape of the cathode heater, internal pockets in the cathode, perforations in the support structure, as well as the specific shapes of various support plates, were implemented to develop a cathode design that maximized performance with a minimum of manufacturing risk.

With only 1.9 degrees of temperature variation on the cathode face the beam will exhibit near uniform current density. This is important for predictable RF interaction and beam transport.

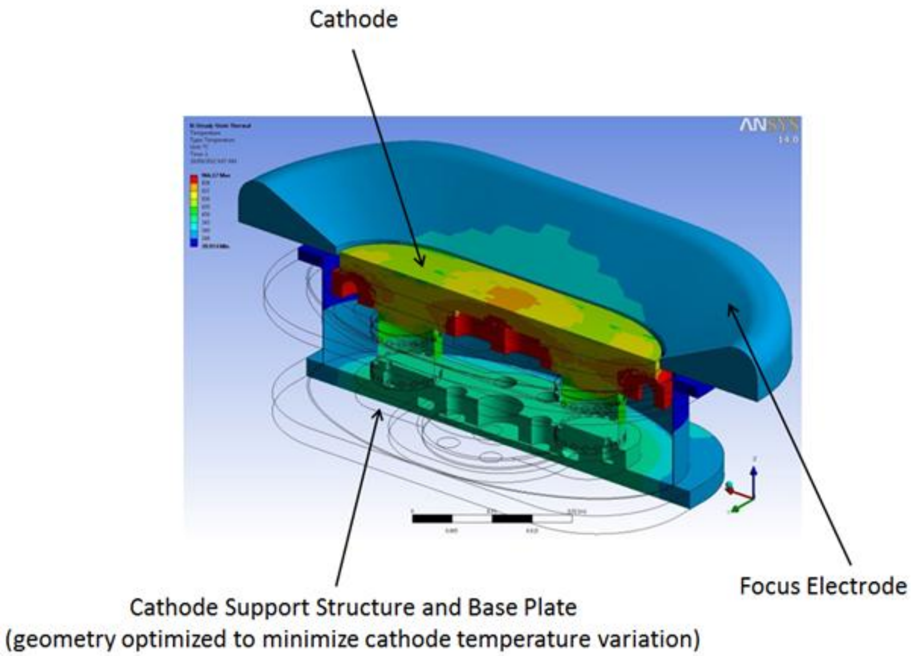

Fig. 4. 3D thermal model for the cathode showing uniform cathode heating for optimal beam quality and RF performance.

4. Window design

An electrical design for a traveling wave window has been completed. It was evaluated for ghost modes (a ghost mode is a mode trapped in the ceramic which could break the window if excited by the operating frequency) and none were found close to the operating frequency. The window is centered at 2.1 GHz as seen in Figure 5. A parametric study of the geometry was done to find dimensions that achieve both a good match and are tolerant of small mechanical changes and changes in permittivity. Simulations show about 20 Watts will be dissipated in each window which can easily be cooled with no risk of cracking the window due to thermal loading.

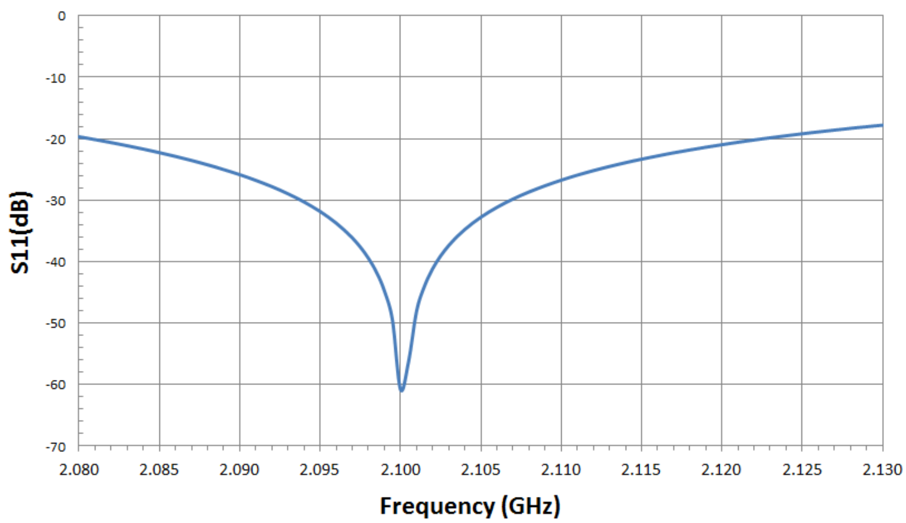

Fig. 5. Window reflection versus frequency showing the window is well matched (transparent) at the operating frequency.

5. Cavity design

Flat fields were achieved across the beam using a planar RF cavity with quarter wave matches on both ends (Figure 6). Having a flat field is important to ensure the RF cavity fields bunch the beam uniformly across the beam width. The electrical cavity design is complete for all cavities. However, some minor modifications for tooling may be required, such as rounding the corners.

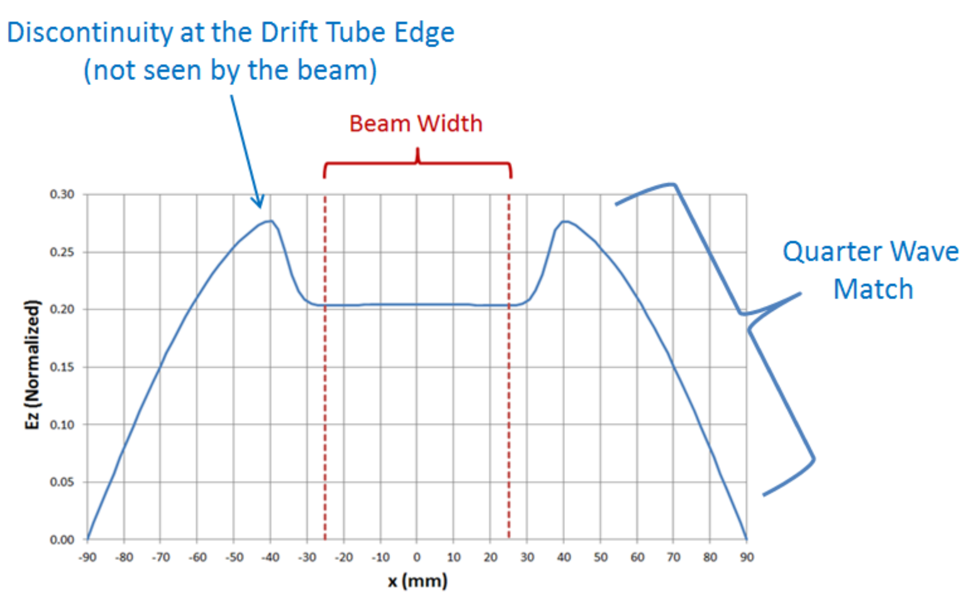

Fig. 6. Axial electric field versus beam width for the nominal sheet beam cavity. (quarter wave matches on either end of the cavity flatten the field over the beam so that the RF interaction will be constant with respect to beam width).

6. RF design

MAGIC2D particle in cell (PIC) simulations predicts greater than 200kW CW and more than 55% efficiency. MAGIC3D simulations without RF drive have been completed and show stable operation of the device when using solenoid focusing. 3D RF simulations that confirm the MAGIC2D results will be performed next.

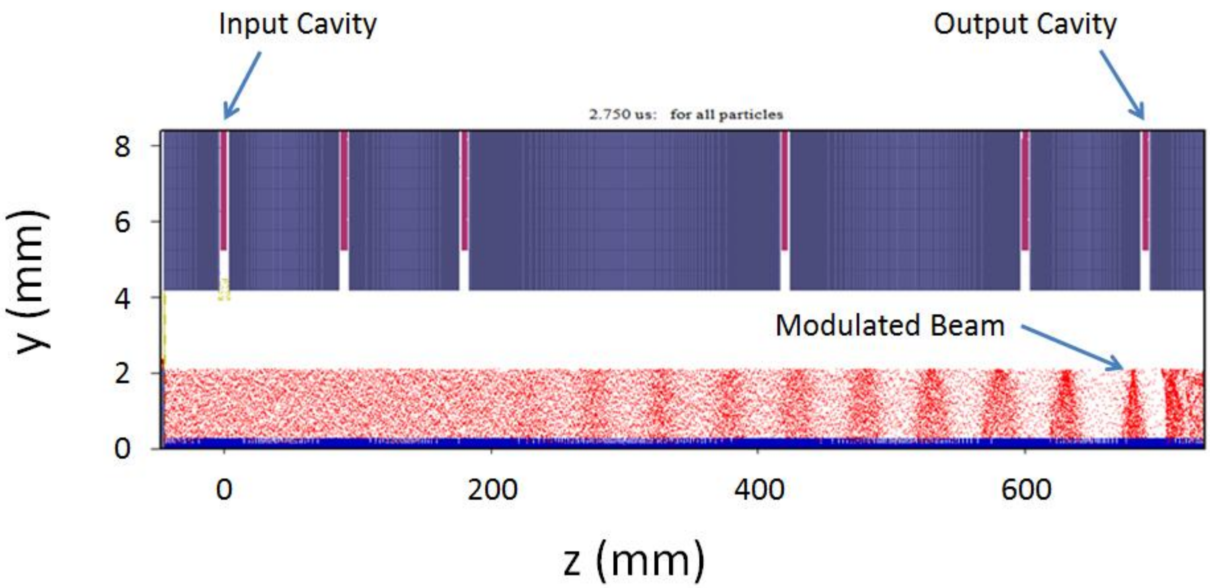

Fig. 7. MAGIC2D particle simulation of the 6 cavity ONR SBK showing 200kW of output power at greater than 55% efficiency.

7. Beam transport and stability analysis

A large percentage of design effort was dedicated to modeling PPM focusing and solenoid focusing and their relationship to beam stability. The solenoid provides a focusing force at all times resulting in a stiff beam that is not susceptible to transverse electric (TE) mode instabilities[1] (which would otherwise move the beam up and down in the drift tube and cause interception). Instabilities in the solenoid case were only observed at very low focusing fields where just enough field was applied to focus and transport the beam to the collector. The PPM design was unstable at all achievable field strengths. This was confirmed in MAGIC where Maxwell's equations are solved numerically and by an alternative method of calculating the growth rates of all the TE eigenmodes in the drift tube directly from the field profile of each trapped mode. Both methods predict the solenoid design is stable and the PPM design is not.

No rotation of the beam was observed when transporting the beam through the solenoid and the beam transmission was 100% in simulation. The transport of the beam is shown in Figure 8. Optimization of the beam entrance condition will be completed to minimize beam scalloping.

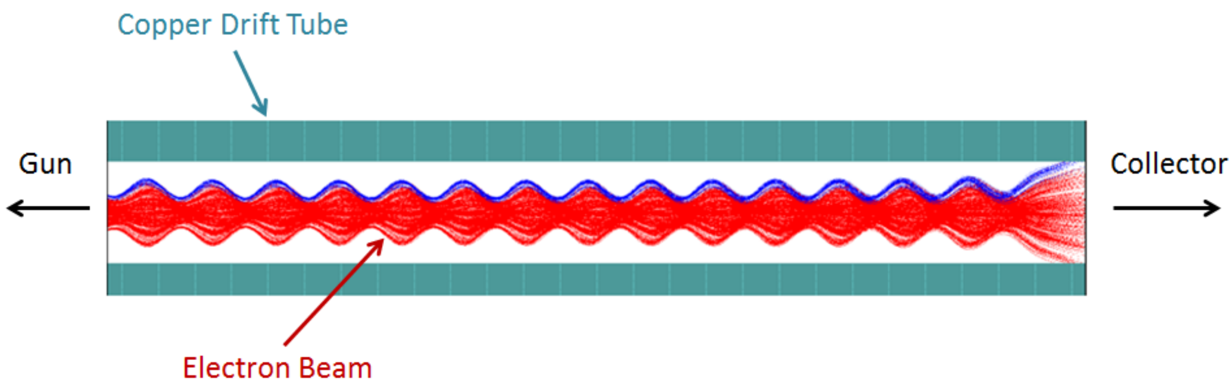

Fig. 8. Preliminary 3D beam transport through the solenoid showing 100% transmission and no beam rotation.

8. Conclusion

The final design parameters for the ONR sheet beam klystron have been established. This effort consisted of evaluating beam stability for PPM and solenoid focusing. The outcome of this study showed solenoid focusing must be used for stability. Further theoretical studies to identify stable PPM designs will be completed, but this project will focus on finalizing and constructing a sheet beam klystron using solenoid focusing.

Simulations confirm the sheet beam klystron will meet all expectations.

The thermal and mechanical designs of the gun and collector are scheduled for completion in December 2012 and drawings and fabrication of the klystron will begin in January.

Acknowledgements

The authors of this paper would like to especially thank Dr. Quentin Saulter and the Office of Naval Research for their support of this project.

References

[1]Bane, K., Jensen, A., Li, Z., Stupakov, G., and Adolphsen, C., Sheet Beam Klystron Instability Analysis, SLAC-PUB-13602 (May 2009).