SLAC-PUB-17102

Test of a BAC Klystron

R. Kowalczyk, A. Haase, E. Jongewaard, M. Kemp and J. Neilson
SLAC National Accelerator Laboratory
Menlo Park, CA

A. Jensen
Leidos
Billerica, MA

***Abstract*—Test results are reported on a 5045 klystron with a circuit modified using the BAC method to achieve more idealized bunching. An increase in efficiency from 45% to 55% is measured, at nearly the same perveance, without modification to the length of the device. Oscillations in the circuit preventing operation to the full pulse width are discussed.**

***Keywords*—Electon tubes, high-voltage techniques, klystrons**

I. Introduction

Klystrons are the RF source of choice for high power RF accelerators. The efficiency of a klystron is typically inversely correlated with perveance, since reduced space charge allows tighter bunches to be created at the output, allowing for more energy to be extracted from the beam. Improving upon a scaling with perveance requires improvements to the RF circuit. The last klystron breakthrough occurred in the 1970s, when Lien showed that a second harmonic cavity could be used to achieve efficiencies around 70% for low perveance designs [1]. A new approach which promises to further improve efficiency at a given perveance is the BAC (bunch – align – collect) technique [2]. The 5045 klystron, with 65 MW RF output power, has been in production at SLAC for 30 years. Its efficiency of 45% matches expectations for a perveance 2.0×10^{-6} klystron. In this work, the BAC method is applied to increase the efficiency [3].

II. BAC Klystron Design

In the BAC approach to high efficiency klystron design, a series of three cavities is used to phase focus all electrons, regardless of initial phase, towards the optimal time to pass through the output cavity. This approach can be contrasted with conventional klystron design in which a large fraction of the phase space is treated optimally, but some portion is neglected, resulting in some electrons passing through the output in the wrong phase, and reducing efficiency. Fig. 1 shows a 1D simulation of the 5045-BAC klystron phasespace at saturation, showing that almost all of the electron disks are consolidated into a single bunch at the output.

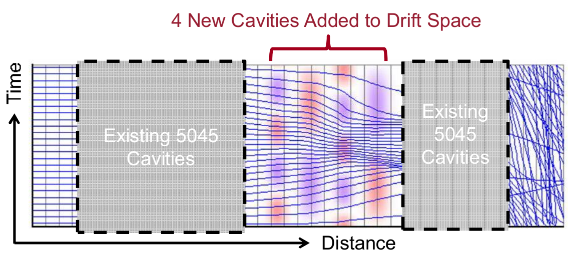

Fig. 1 - Modifications to the 5045 RF circuit.

Fig. 2 shows the geometry of the 5045 klystron, taken from 2D simulations in the MAGIC particle in cell (PIC) code [4], and the first version of the 5045-BAC. Note that the drift tube diameter in the second half of the BAC klystron was reduced to improve the beam-wave coupling. At 350 kV, 415 A, the standard 5045 produces 65 MW of output power, resulting in a circuit efficiency of 45%. The 5045-BAC klystron is predicted to produce 80 MW of output power, thus an efficiency of 55%.

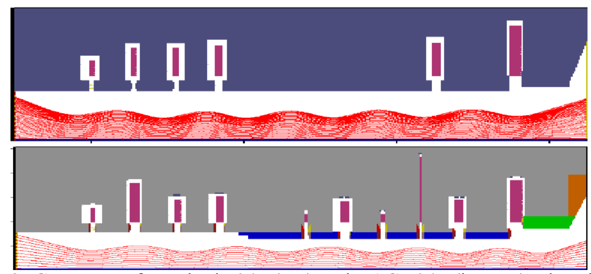

Fig. 2- Geometry of standard 5045 (top) and BAC 5045 (bottom) taken from MAGIC2D simulations.

III. Test Results

Upon initial test, the perveance of the diode electron gun was found to be 1.85×10^{-6}, significantly lower than the typical value of 2.0×10^{-6}. Unfortunately, the klystron oscillated at the standard pulse length of 3.5 microseconds, necessitating test of the RF circuit at substantially shortened pulse widths. At 100 ns, the measured RF output power is shown in Fig. 3. At saturation, this corresponds to an efficiency of 54%.

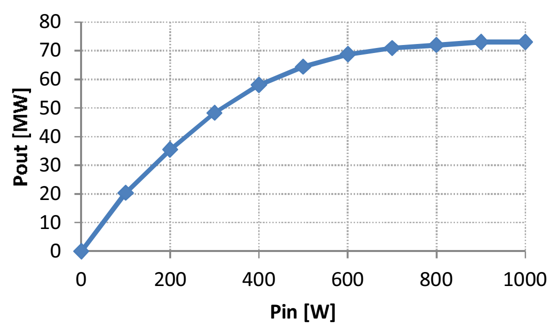

Fig. 3 - Measured RF output power for the 5045-BAC at 100 ns pulse width.

The measured spectrum at the output of the klystron, when no RF input power is applied, is shown in Fig. 4. Adjusting the solenoid settings changed the amplitude of the oscillation signal, but no conditions were found in which stable operation for 3.5 microseconds could be achieved.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-76SF00515.

is measured at the start and the end of the circuit, and if it has decreased, the mode is unstable in the presence of the beam.

This approach correctly identifies the 6.7 GHz mode described previously as unstable. However, the 4.2 GHz mode is found to be stable. Additional analysis has shown that the this 4.2 GHz is only identified in a model that includes the forward klystron gain in the non-axisymmetic mode at the unstable frequency.

Due to the difficulty in identifying the 4.2 GHz mode, it was used as a test of alternative PIC codes. A simplified version of the problem, including only the first four cavities, was solved in MAGIC3D and VSim from Tech-X [6]. Fig. 7 shows the beam behavior in both codes. For similar timestep and geometric resolution, both codes run on a single processor in a similar time. The parallel capability of the VSim code though allows the problem to be easily split over processors, resulting in a significant decrease in runtime.

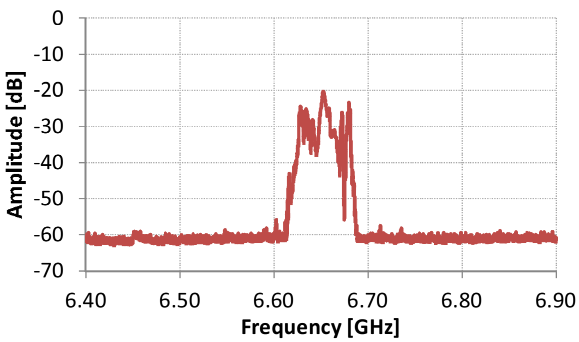

Fig. 4 - Observed spectrum at the RF output under no-drive conditions.

IV. CAUSE OF OSCILLATION

Three dimensional PIC simulations were used to determine the cause of the oscillation. These studies uncovered two possible unstable modes. The first mode, trapped in cavities 7 and 8, has resonant frequency of 6.7 GHz. A MAGIC simulation in which this mode is excited, causing beam instability, is shown in Fig. 5. The frequency is nearly identical to the tunnel cutoff frequency in this region of the klystron. The second identified unstable mode is trapped in cavities 2, 3, and 4, and has a resonant frequency of 4.2 GHz. Note that this mode is below the drift tube cutoff of 5.4 GHz.

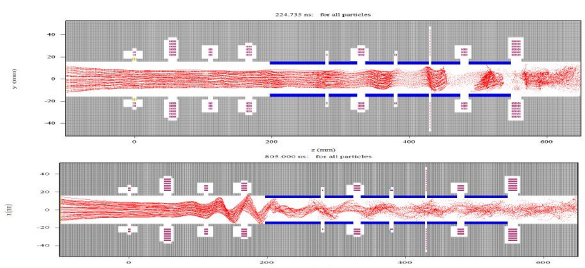
Fig. 5 - Simulation of beam breakup due to 6.7 GHz mode (top) and 4.2 GHz mode (bottom).

Both oscillations produce strong transverse electric fields in the tunnel, which causes the disruption seen in the MAGIC plots.

V. NEXT DESIGN AND OSCILLATION PREDICTION

A new design is being developed to allow operation at the full pulse width. As part of the design process, a methodology is being developed to predict oscillations prior to their manifestation in tested devices. Previous work at SLAC on this front has focused on analytic prediction of mode stability [5], and a ray tracing approach to supplement the analytical calculations.

To automate the ray tracing, an approach in which the entire circuit geometry is analyzed by the SLAC massively parallel computation tool ACE3P. In this approach, all of the eigenmodes of the structure are identified, up to the third harmonic of the drive frequency. For each mode, the amplitude is set to an arbitrary value, and ray tracing is used to transport the electron beam through the circuit. The energy in the beam

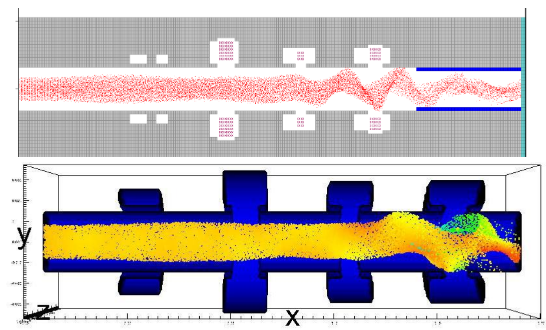
Fig. 6 - Comparison of MAGIC and VSim in model of the first four cavities.

VI. CONCLUSION

A BAC version of the 5045 klystron has been tested, demonstrating a 10% increase in efficiency. Instabilities which prevent operation at the full pulse length have been identified.

ACKNOWLEDGMENT

Work supported by the US DOE under contract DEAC03-76SF00515.

REFERENCES

[1] Lien, Erling L. "High efficiency klystron amplifier." In *Electron Devices Meeting, 1969 International*, vol. 15, pp. 98-98. IEEE, 1969.

[2] Guzilov, I. A. "BAC method of increasing the efficiency in klystrons." In *Vacuum Electron Sources Conference (IVESC), 2014 Tenth International*, pp. 1-2. IEEE, 2014.

[3] Jensen, Aaron, Andy Haase, Erik Jongewaard, Mark Kemp, and Jeff Neilson. *Increasing Klystron Efficiency Using COM and BAC Tuning and Application to the 5045 Klystron*. No. SLAC-PUB-16466. SLAC National Accelerator Laboratory (SLAC), 2016.

[4] Goplen, Bruce, Larry Ludeking, David Smith, and Gary Warren. "User-configurable MAGIC for electromagnetic PIC calculations." *Computer Physics Communications* 87, no. 1 (1995): 54-86.

[5] Bane, K. L. F., A. Jensen, Z. Li, G. Stupakov, and C. Adolphsen. "Sheet Beam Klystron Instability Analysis." In *Proc. Particle Accelerator Conf.(PAC09)*. 2009.

[6] Nieter, Chet, and John R. Cary. "VORPAL: a versatile plasma simulation code." *Journal of Computational Physics* 196, no. 2 (2004): 448-4