# TEST RESULTS FOR A 10-MW, L-BAND MULTIPLE BEAM KLYSTRON FOR TESLA*

E. Wright, A. Balkcum, H. Bohlen, M. Cattelino, L. Cox, E. Eisen, K. Eppley, F. Friedlander,
S. Lenci, A. Staprans, B. Stockwell and L. Zitelli, Communications and Power Industries,
811 Hansen Way, Palo Alto, CA 94303-0750
K. Eppley#, Science Applications International Corporation, Burlington, MA, USA

## *Abstract*

The VKL-8301 high-efficiency, multiple-beam klystron (MBK), has been developed for the DESY Tera Electron volt Superconducting Linear Accelerator (TESLA) in Hamburg, Germany. The first prototype is built and will be tested in March of 2004. The prototype has been designed for long-life operation by utilizing the benefits inherent in higher-order mode (HM) MBKs. The primary benefit of HM-MBKs is their ability to widely separate individual cathodes. One of the major obstacles to the success of this approach is the design of the off-axis electron-beam-focusing system, particularly when confined-flow focusing is desired. We will show simulated and measured data that demonstrates a solution to this problem. High-power test results will also be shown.

## BACKGROUND

Other papers are available that discuss in significant detail the design process and trade-offs for those interested [1], [2]. In short, the VKL-8301 MBK has been designed to meet the performance characteristics shown in Table 1; italicized are those parameters we were free to choose. Six cavities were required to meet the gain and efficiency requirements. The input and output circuits use $TM_{020}$ cavities, while the remaining four are conventional $TM_{010}$ cavities; one of these is tuned near the second harmonic for improved efficiency. The HM-MBK uses six electron beams evenly distributed around a bolt circle of 267 mm.

The successful implementation of CPI's HM-MBK requires inventive solutions for a number of unique challenges. The most difficult of these are the design and performance of the beam focusing system and the rf performance of the $TM_{020}$ cavities.

There are two aspects of the beam-focusing system we needed to verify. First, how well would the computer codes agree with the measured fields, and second, with a given level of agreement between model and simulation, what impact would this have on measured performance? There were also two aspects of the rf performance that we needed to explore. First, would these circuits be unconditionally stable (oscillation free) as our analysis showed, and would we meet our goal of providing 10 MW? All of our questions were answered favorably, as can be seen below.

Table 1: MBK Design Parameters

| **Parameter** | **Value** | **Units** |
|---|---|---|
| Peak Output Power | 10 | MW |
| Average Output Power | 150 | kW |
| Beam Voltage | 114 | kV |
| Beam Current | 131 | A |
| Efficiency | 65–67 | % |
| Frequency | 1300 | MHz |
| Pulse Duration | 1.5 | ms |
| Saturated Gain | 47 | dB |
| Solenoid Power | 4000 | W |
| *Number of Electron Beams* | *6* | - - - |
| *Beam Bolt-Circle* | *267* | *mm* |
| *Number of Cavities* | *6* | - - - |
| *Cathode Loading* | *~2.0* | *A/cm$^2$* |

## TEST RESULTS

### *Cold Test – Magnetic Circuit Verification*

Successful transport of the electron beam depends on our ability to realize a magnetic lens system that provides the individual beams with their own magnetic centerlines. Each beam needs to see symmetric, convergent, and divergent magnetic fields in the gun and collector regions, respectively, and at the same time see minimal transverse magnetic fields over the entire circuit length; the target beam diameter and scalloping must also be achieved. The challenge is to do this when each of the six electron beams has its own centerline some 133 mm in radius from the geometric axis of klystron and solenoid.

To achieve this goal, extensive modeling of the magnet circuit was performed, first with MAFIA [3] followed by MAXWELL 3D [4]. Once a solution was found that met the criteria described above, the design was frozen and the parts ordered and fabricated. Tooling was developed to properly support the iron lens system when installed in the solenoid, which precisely centers a two-axis Hall-effect probe on one of the six beam tunnels. A computer-controlled stepper-motor system was developed to position and rotate the probe down the length of the

---

*Work supported by DESY

circuit so that both the longitudinal and transverse components of magnetic field were measured simultaneously.

The culmination of this process can be seen in Figure 1. Good agreement between the MAXWELL 3D model and measurement was achieved. The peak transverse field has a measured value of –6.8 Gauss (0.9% of $B_Z$) at Z=55.0 inches, which is near the output cavity gap. The center of the cathode is at Z=0.0 inches; the large transverse fields measured at Z<0.0 are behind the cathode and do not influence the beam. Three-dimensional modeling and simulation of the electron beam with the use of the computer code MICHELLE [5], combined with the 3D magnetic field array generated by MAXWELL 3D, showed good beam transport with an acceptable amount of beam wander. These results gave us confidence we would be successful transporting the beam through the circuit.

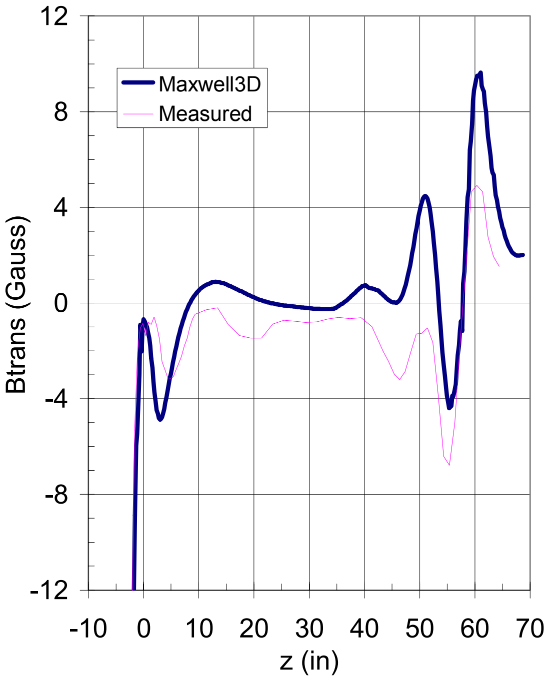

Figure 1. Measured and simulated transverse magnet fields for VKL-8301 focusing system.

## *Hot Test – Beam Transport*

The ultimate verification of the beam optics occurred when we tested the MBK and measured beam transmission, with and without rf applied. The prototype MBK was developed with six collectors, one per beam, that were isolated from the body with ceramics. This provides us with the capability of monitoring the six beam currents independent of one another, and monitoring the body-current contributions of each beam when rf is applied. A plot showing the measured collector currents for all six beams can be seen in Figure 2. Note that the plot is actually showing the output voltages of the six current transformers (CT) used to monitor these currents; a 1-volt reading on the CT represents 10 amperes of beam current. We have also vertically offset each of the traces to highlight the fact that the six electron beams emit equal current. Lastly, the body current was measured at 0.6 amperes with 139 amperes of beam current; our beam transmission is better than 99.5%.

Equally low levels of body current were measured with rf applied, as can be seen in Figure 3. We were curious to see how sensitive the focusing system is to changes in focus-coil current, so we ran an experiment where we carefully monitored body current, with and without rf, while varying the banks of coil currents by ±5% from nominal, Figure 3. Coil 1 (actually a number of independent coils connected in series) is near the electron gun, while Coil 2 is near the collector. We were pleased to see that the body current was relatively insensitive to changes in focus-coil current.

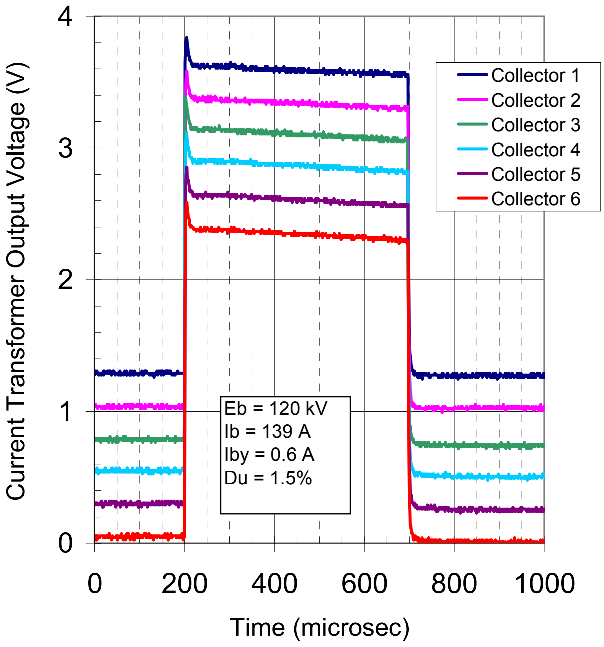

Figure 2. Measured collector currents, no RF.

## *Hot Test – RF Performance*

A spectrum analyzer was connected to the klystron and the spectrum monitored for signs of spurious oscillation. No oscillations were observed in any of the modes identified to have the potential for self-excitation. Stability analysis of the higher-order modes supported by the $TM_{020}$ resonator showed that approximately 175 amperes of beam current are necessary to set up an oscillation, and none were observed.

Considerable time was spent rf conditioning the klystron. We were quickly able to evaluate the rf circuit by pulsing the drive in the 10-microsecond range, where the average power is low. These early results showed us that our design was fundamentally sound; the transfer characteristics were the same as a single-beam klystron. Initial saturated gain was high, measured at 57 dB, which is not desirable for a high-efficiency klystron. The second cavities were tuned to reduce the gain; this also increased the bandwidth. After some additional fine tuning and processing, we were able to achieve the 10 MW of rf output power at 60% efficiency, as can be seen in Figure 4.

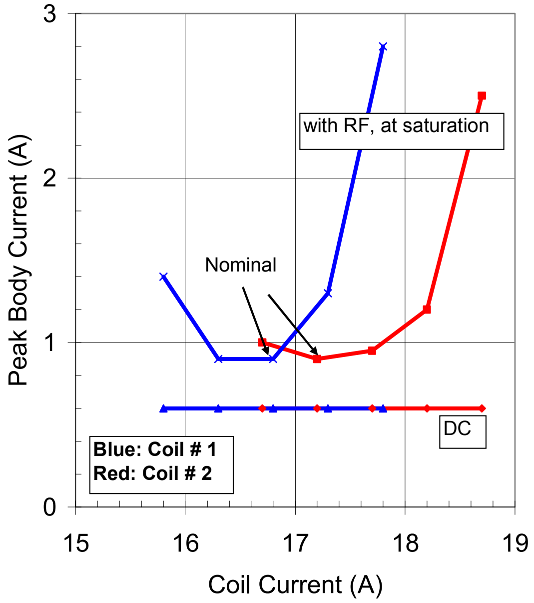

Figure 3.Body current, with and without RF, for various magnet supply currents.

Unfortunately our processing was cut short due to a problem with one of the two output windows. During long-pulse, high-average-power testing (at approximately 100 kW of average power), several substantial gas bursts were observed, along with severe rf pulse shortening. The average power handling capability of the output circuit degraded after these events. The problem with the window was identified, and attempts to correct the problem externally showed success; we were able recover and process the klystron to even higher average power levels. However, we later experienced similar rf pulse tearing and gas bursts. Concerned that we might break the window, which would force a costly repair (the gun would need to be rebuilt), the call was made to remove and replace the defective window. The klystron will be repaired in the coming months and shipped to DESY before the Christmas holiday.

## SUMMARY

CPI has significantly advanced the state-of-the-art of MBK technology with the TESLA MBK development effort. The performance of the focusing system exceeded all our expectations, and we were able to meet most of our rf performance objectives. As with any significant development, there is room for improvement. Refinements will be added to the second MBK to move the efficiency from 60% to 65%. A team of scientists and engineers is working on these refinements now.

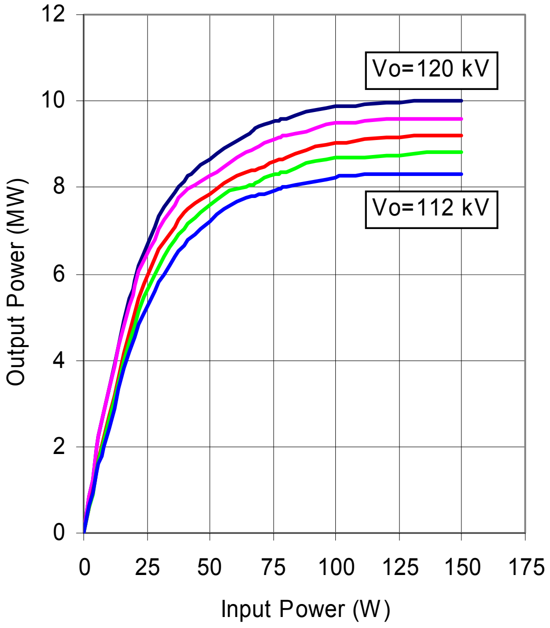

Figure 4. Transfer curves from 112 kV to 120 kV, in 2 kV increments.

## ACKNOWLEDGEMENTS

The authors would like to thank our sponsors at DESY for supporting this development effort, in particular Dr. Stefan Choroba and Dr. Alexander Gamp. We would like to acknowledge the contributions of Dr. Ken Eppley of SAIC for his work performing the 3D magnetic and beam optics simulations. Special thanks go to Mr. Lance Thompson of Stangenes Industries for his tireless effort designing, manufacturing, and optimizing the solenoid to the high degree of accuracy demanded by this application.

## REFERENCES

[1] E. Wright, et al., “Development of a 10-MW, L-band, multiple beam klystron for TESLA”, Proceedings of PAC’03, TPAE029, p. 1144-1146.

[2] E. Wright, et al., “Development of a 10-MW, L-band, multiple beam klystron for TESLA”, Proceedings of EPAC’02, TUPLE120, p. 2337-2339.

[3] T. Weiland et al., “MAFIA Version 4”, Computational Accelerator Physics, AIP Conference Proc. 391, 1996, pp.65-70.

[4] Maxwell 3D is a registered trademark of Ansoft Corporation, Pittsburg PA.

[5] J. Petillo et al. “The New 3D Electron Gun and Collector Modeling Tool: MICHELLE”, 2nd IEEE International Vacuum Electronics Conference 2001, 199-204.