H-6

SUPER-RELTRON ANALYSIS AND EXPERIMENTS

R. Bruce Miller, William F. McCullough
Kim T. Lancaster, Carl A. Muehlenweg

TITAN SPECTRON
Albuquerque, NM 87106

ABSTRACT

We have developed a highly efficient, high-power microwave tube called SUPER-RELTRON. We have achieved operation at >400 MW with ~50% efficiency at 1 GHz, and >300 MW with 50% efficiency at 3 GHz. The rf pulse durations are typically a few hundred nanoseconds. These lightweight, compact tubes do not require an external magnetic field. The rf output coupling is straightforward and power is delivered directly via the fundamental TE_{10} wave in rectangular waveguide without a mode converter. The key features of our tube include (1) generation of a well-modulated electron beam by periodic virtual cathode formation, (2) post-acceleration of the modulated beam to reduce the relative electron energy spread, and (3) a multi-cavity output section that efficiently extracts power without rf breakdown. In this paper, we discuss various aspects of our device and briefly summarize our experimental results.

1.0 INTRODUCTION

The essential elements of a high-efficiency, high-power microwave tube include (1) good electron bunching; (2) minimizing the relative energy spread of the electrons in the bunches; and (3) efficient energy extraction without rf breakdown. By paying close attention to these guidelines we have devised a new HPM tube that produces high power rf pulses with excellent power conversion efficiency (~50%).[1] A schematic diagram of our SUPER-RELTRON tube is given in Figure 1. The key elements are the injector, the modulating cavity structure, the accelerating gap region, and the output extraction cavities. The injector is usually a standard cold cathode field emitter that is well-described by known perveance relations. Also, the output cavities are well-described by conventional klystron theory. The other key elements, however, have novel features and we describe them in more detail.

The modulation cavity must produce a high current (few kA), well-bunched, electron beam for relativistic post-acceleration. As the result of research at the Naval Research Laboratory,[2] a collaborative effort by the Phillips Laboratory and Sandia National Laboratories,[3] and effort by ourselves, there are now at least three such sources of highly modulated, high current electron beams. The essential feature is that the beam current injected into a modulating cavity structure is a significant fraction of the space charge limiting current, and it is relatively easy to establish periodic virtual cathode formation.

While the virtual cathode mechanism is quite efficient in modulating the beam, the emerging electron bunches invariably have a large energy spread. We therefore insert a <u>relativistic accelerating gap</u> immediately after the the modulation cavity. This accelerating voltage causes all the electrons in the bunches to move at nearly the speed of light, thereby freezing the temporal bunch structure of the beam. It also supplies much more beam kinetic energy which can be converted into rf energy. We then use multiple output cavities to efficiently extract the available microwave power without rf breakdown.

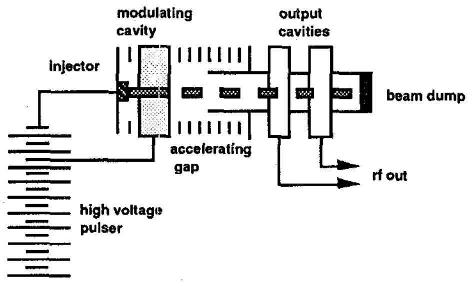


Figure 1. Schematic diagram of a SUPER-RELTRON tube.

2.0 MODULATING CAVITY ANALYSIS

H

As previously mentioned, there are now at least three sources of well-modulated, high current beams.[2,3] We will describe our 3-GHz modulating cavity structure because its behavior illustrates the beam-electromagnetic field interactions that are essential for good beam modulation. This structure is basically a three-cavity section of a side-coupled standing wave rf linac; it consists of two cylindrical pillbox cavities coupled to an intermediate cavity by magnetic coupling slots, as shown in Figure 2. The intermediate cavity is displaced to the side; the beam passes through the pillbox cavities only. The electric field structures of the three resonant modes are also illustrated in Figure 2.

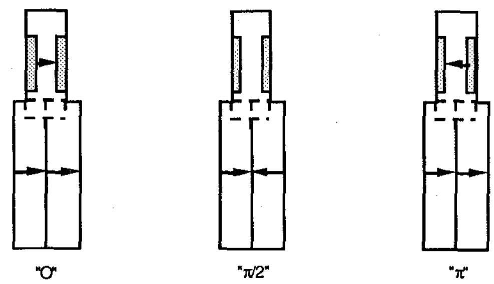


Figure 2. The electric field amplitudes of the three resonant modes of the beam modulation structure.

By properly adjusting the injector kinetic energy and pillbox cavity width the π/2 mode can be unstable. Consider an electron which enters the first pillbox at a time when the oscillating field in the pillbox will decelerate the electron. Then the cavity fields will grow by conservation of energy. Now, suppose that the transit time of the electron through the pillbox is about half the oscillation period. Then the electron will experience the same retarding field in the second pillbox, and the cavity fields will continue to grow. An electron injected a half-cycle later will be accelerated in both pillboxes. However, because the decelerated electrons spend more time in the cavities than the accelerated electrons, on average the net energy transfer is from the beam to the cavity fields. This is a classically unstable situation. For a 100 keV electron and a resonant frequency of 3 GHz, the instability will occur for a pillbox width of about 2 cm.

An initial linear growth phase follows shock excitation of the structure by the rising self-fields of the beam. Although the 0 and π modes are also excited, only the π/2 mode grows because it is unstable. If the beam current is a significant fraction of the space charge limiting current, however, the linear growth phase can evolve into a second nonlinear phase. The key point is that the rf field can become sufficiently high as to act as a gate, alternately stopping the beam, then accelerating the beam out of the cavity.

We have used both one- and two-dimensional simulation codes to verify this essential behavior. The results generally show that modulation coefficients of order unity can be obtained. Further, for a given pillbox width, higher modulation coefficients are obtained at lower kinetic energies, and, for a given kinetic energy, higher modulation coefficients are obtained with larger screen spacings. For the largest screen spacings and smallest kinetic energies some electrons are actually reflected out of the system backward toward the injector.

The steady-state field amplitude in the modulating cavity is established by energy conservation. For example, the injected beam carries energy into the system. As these particles exit, through either transmission or reflection, they carry energy out of the system. If the total energy of the exiting particles (over a cycle) is less than the total energy of the injected particles, then the rf fields in the system must grow. Under the opposite circumstance, the cavity fields must decrease. At the saturated field strength there is no net energy transfer from the beam to the system or vice versa.

While our modulating cavity can provide a highly bunched beam, the difficulty in efficiently extracting power without post-acceleration is suggested by the data in Figure 3, which show the spread in the electron beam kinetic energy as a function of the modulating cavity exit time. The energy spread in the electron bunch is almost 200%. The crucial feature which makes SUPER-RELTRON highly efficient is the large reduction in the relative kinetic energy spread of the electrons in the bunched beam that is provided by post-acceleration. For example, if 680 kV is added to the beam exiting the modulating cavity, the electron kinetic energy spread is reduced to < 30%.

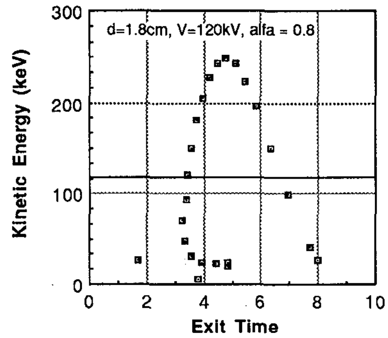


Figure 3. Variation in electron kinetic energy as a function of modulation cavity exit time.

3.0 EXPERIMENTAL RESULTS SUMMARY

We have conducted detailed experimental evaluations of our SUPER-RELTRON tube at both 1 and 3 GHz. Our initial feasibility experiments were performed using Sandia's PYRAMUS Marx generator operated in a run-down mode. For these first experiments the beam generated by the A-K gap was modulated by a split-cavity oscillator (SCO) at a frequency of about 1.08 GHz. The output extraction geometry for these experiments consisted of a single length of WR975 waveguide which contained two vanes, inductive irises, and shorting plungers. Using this very simple technique we were able to extract substantial rf power (>400 MW peak), with peak power conversion efficiencies of ≥50%. Sample diagnostic traces are reproduced in Figure 4. The total rf energy for this particular shot was 84 J, with a peak power of 375 MW. The variation of peak power with the Marx charging voltage is shown in Figure 5. As the charge voltage was increased, the peak output power increased from approximately 60 MW to the 400 MW level. The peak power extraction efficiency obtained during this series was ≥ 40% (400 MW at peak voltage and average current values of 800 kV and 1.2 kA).

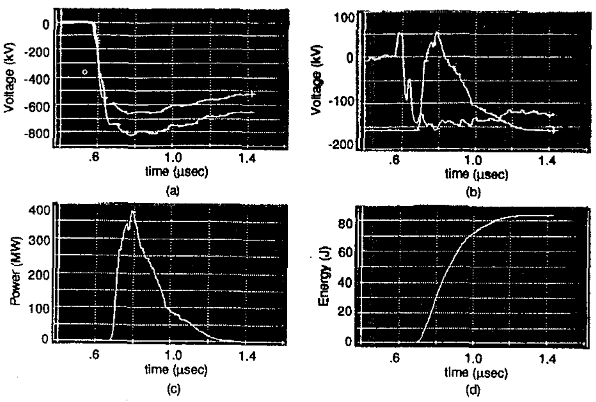


Figure 4. Representative SUPER-RELTRON diagnostic traces for a charge voltage of 40 kV. (a) Marx and accelerating gap voltage pulses; (b) Injector voltage pulse (150 kV peak) with the rf power pulse overlaid; (c) The RF power pulse (375 MW peak); and (d) the total pulse energy (84 J).

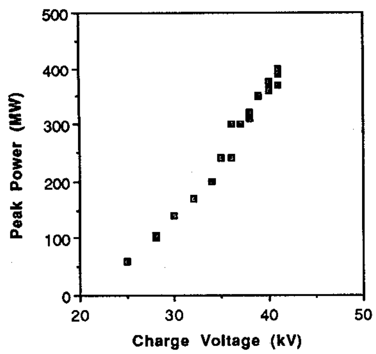


Figure 5. Variation of the peak rf power as a function of charge voltage.

For our 3-GHz experiments we used a Marx generator consisting of twenty-two 0.44-μF, 50-kV high voltage capacitors. A crowbar switch was used to terminate the high voltage pulse and eliminate late-time arcing (which was a problem in the 1-GHz experiments). We have typically used two extraction waveguides with two output cavities in each WR340 waveguide. Operating with an injector voltage of 200 kV, a beam current of 800 amperes, and an accelerating gap voltage of 700 kV, we have produced peak power pulses in excess of 300 MW.

The operating frequency of our tube can be varied both mechanically (by changing the modulating cavity dimensions) and electrically (by changing the injector voltage and/or the anode-cathode gap). For example, the mechanical tuning range of our 3-GHz tube is approximately ± 5% of the nominal center frequency, as exhibited by the cold-test data (i.e., without beam) of Figure 6. The required adjustments can be made outside the Marx tank and do not require tube disassembly or loss of vacuum. We find (for our 3-GHz tube) that the hot test frequency is usually lower (a few tens of MHz) than the cold test frequency, and that it varies slightly with injector voltage for a fixed anode-cathode gap. An example of this variation is shown as the bar in Figure 6. The center frequency for this case was 3.0725 GHz, and the beam modulation frequency could be varied over the range 3.060-3.085 by changing the injector voltage from 80-125 kV.

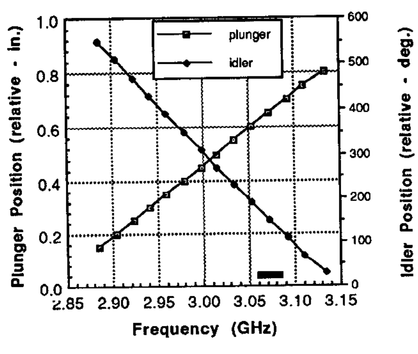


Figure 6. Variation of the cold-test frequency of our 3-GHz tube with changes in the modulating cavity dimensions. Also shown is the variation in the hot-test frequency with injector voltage for a nominal cold-test operating point. The voltage extremes were 80 kV and 125 kV.

Once a particular setup is chosen, the operating frequency is reasonably stable, both on a shot-to-shot basis and during the pulse. As an example, in Figure 7(a) we present the intermediate frequency obtained by mixing the rf power pulse with a local oscillator signal at 3.04 GHz. Also displayed is the high voltage pulse applied to the accelerating gap. (In Fig. 7(b) we present the rf power pulse as recorded by both a side-wall directional coupler and a B-dot probe in the anechoic chamber. Both signals were suitably attenuated and detected with a crystal.) The nominal frequency was 3.072 GHz, but it chirped to 3.08 GHz as the power began to decrease approximately 180 ns after the onset of beam modulation.

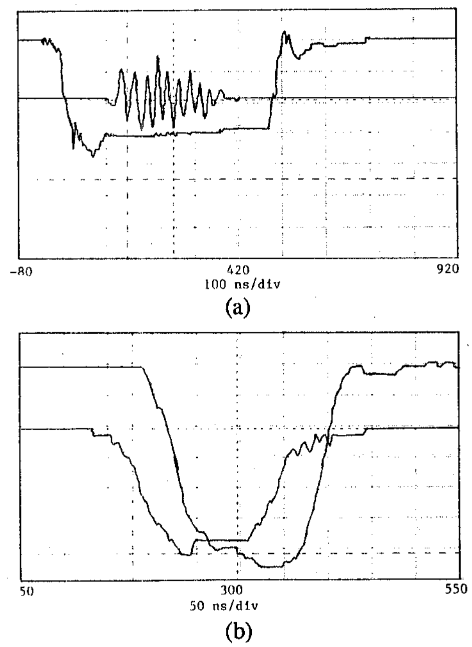


Figure 7. (a) Intermediate frequency signal from a mixer crystal with a local oscillator frequency of 3.04 GHz. Note that the frequency chirps upward at the end of the pulse. Also displayed is the high voltage pulse (approximately 600 kV) applied to the accelerating gap. (b) RF power pulses as measured by a directional coupler and a magnetic field probe in the anechoic chamber.

The power level and pulse shape are also reasonably repeatable. As an example, the peak power data from a 20-shot run, shown in Figure 8, are fairly typical. These data (at the nominal 100 MW level) were obtained from a single waveguide extractor with two embedded output cavities. Several pulses from this same run are shown in Figure 9 to give an example of the pulseshape variability that can be expected.

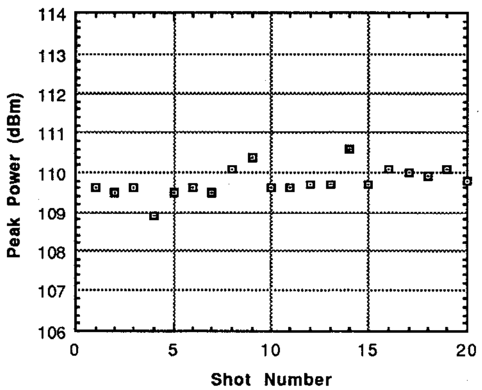
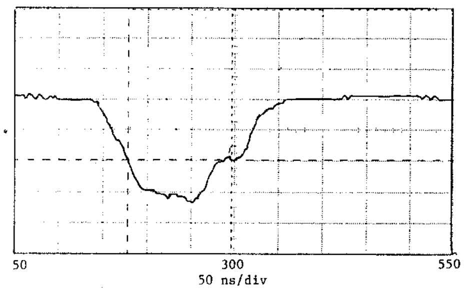
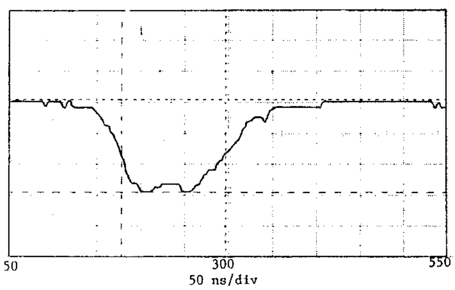


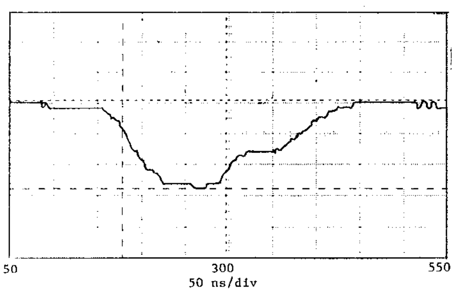
Figure 8. Variability of the peak power from our 3-GHz tube for a 20-shot run.



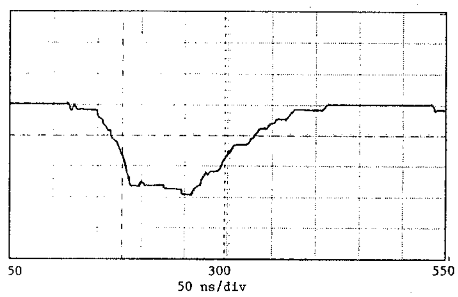
(a)



(b)



(c)



(d)

Figure 9. Typical pulse-to-pulse variability that can be expected with our 3-GHz tube. (Waveforms are from the data of Fig. 8.)

4.0 SUMMARY

In conclusion, we have developed a new high-power microwave tube called SUPER-RELTRON, which has already produced hundreds of megawatts of power in the few gigahertz range at efficiencies in excess of 40%. It does not require an external magnetic field, and is very compact and lightweight. (The 3-GHz tube is approximately 30 centimeters in length and weighs less than 15 kilograms.)

5.0 ACKNOWLEDGEMENTS

This work was funded in part by the U.S. Army Harry Diamond Laboratory, the USAF Phillips Laboratory, Sandia National Laboratories, TITAN/Spectron, and Martin Marietta/ADTO. We especially wish to thank M.C. Clark for arranging for our use of Sandia's PYRAMUS pulser, and S. Graybill (formerly of HDL and now at the Phillips Laboratory), and D. Furuno of MM/ADTO for their advice and support.

6.0 REFERENCES

1. R.B. Miller, TITAN/Spectron Invention Disclosure, SDL-88001, January 1988.

2. M. Friedman and V. Serlin, Phys. Rev. Lett. 54, 2018 (1985).

3. See the paper by B. Marder elsewhere in these proceedings.