DEVELOPMENT OF THE RESONANT-CAVITY VIRTUAL-CATHODE AND LARGE-ORBIT GYROTRON HIGH-POWER MICROWAVE SOURCES*

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Abstract

At Los Alamos National Laboratory, research is continuing on the development of both the resonant-cavity virtual-cathode source and the large-orbit gyrotron high-power microwave source. The resonant-cavity virtual-cathode development effort has succeeded in demonstrating narrow-band, single-mode operation of this typically wide-band source. This is accomplished by supplying feedback to the oscillating virtual cathode with a resonant-cavity structure. The large-orbit gyrotron effort is developing a method for efficiently coupling the microwave power from the device so that it can be easily used as a high-power microwave generator for accelerator applications. A repetitive pulse capability is also being developed for both microwave sources. Experimental results are presented in this paper.

Background

There is a continuing demand for ever more powerful and efficient RF power sources to drive the RF accelerating structures used to accelerate particle beams. The need for very high power, far exceeding the capability of commerically available microwave tubes, becomes quite evident as one reviews the proposed designs for future linear colliders. The RF power requirement for these machines is in the terawatt regime and the required frequency is in the 10- to 30-GHz range.

A wide range of alternative high-power microwave sources is being investigated at various laboratories. These include the (1) relativistic klystron, (2) lasertron, (3) magnetically insulated line oscillator (MILO), (4) gyroklystron and gyrotron, (5) virtual-cathode-based sources, and (6) the large-orbit gyrotron. At present, no candidate has emerged as the clear source of choice, and the related technologies are very immature when compared with the klystron technology that has matured over the last 40 years. This paper will describe the progress at Los Alamos on two of these sources: (1) the large-orbit gyrotron (LOG) and (2) the resonant-cavity virtual-cathode source.

Large-Orbit Gyrotron

Los Alamos has been engaged in a collaboration with the University of Maryland to develop large-orbit gyrotron microwave sources in the 2- to 8-GHz frequency band. The LOG is a microwave device that converts the kinetic energy of an axis-encircling, rotating electron ring into high-power microwaves by a resonant interaction between a magnetron-like resonator and the negative mass instability on the beam. The axis-encircling beam is produced by injecting the hollow linear beam, accelerated from a circular knife-edge field-emission cathode, through a magnetic cusp. This rotating beam is then injected into the microwave resonator, which has a dc solenoidal magnetic field imposed along the longitudinal axis. The electron beam executes cyclotron motion around these magnetic field lines as it propagates downstream. The resonator is designed to operate at a harmonic of the fundamental cyclotron frequency of the rotating beam.

The large-orbit gyrotron is a microwave source well suited for driving future linear-colliding beam accelerators because of its high-power output and narrow bandwidth. The LOG has also demonstrated the capacity (to date, at the kilowatt level) for repetitively pulsed operation at a pulse length of 5 μs. This source, in experiments done by the University of Maryland, has demonstrated a microwave output as high as 500 MW with a very narrow bandwidth and has operated at frequencies in the 7- to 15-GHz range with an overall electronic efficiency of 10%.[1] These experiments, performed at Maryland by Destler et al., used an electron beam having a pulse width of 30 ns FWHM. The electron energy was 2 to 3 MeV and the current 20 to 30 kA. The 15-GHz experiment demonstrated an output of 500 MW. A 9-GHz device was also tested that achieved an output of 250 MW. In these cases, the microwave radiation was extracted axially through a large diameter vacuum window located in a plane perpendicular to the longitudinal axis of the cylindrical resonant structure. Another experiment has been done at the other extreme of electron energy and current (25 to 30 kV, 1 to 2 A, 5 μs FWHM, 60 Hz) using conventional thermionic cathode technology instead of field emission cathodes. This device demonstrated efficiencies as high as 42% at 7 GHz.

An initial experiment was done at Los Alamos on a 2-GHz LOG device with a 70-ns FWHM electron beam at an energy of 550 keV. Microwave power was estimated at 10 to 50 MW with the power extraction handled in a similar manner to the experiments at the University of Maryland. This device operated with a modest magnetic field of about 600 gauss. Before the Los Alamos experiment, the large-orbit gyrotron had been operated in two very different energy and current regimes. At one end of the spectrum was a beam with an energy of 25 keV and several amperes whose behavior could be described by single particle dynamics. At the other end was a beam of 2 to 3 MeV and a current of 10 to 20 kA. The space-charge effects in this high-current beam are mitigated by the fact that the beam is much stiffer, having a γ of about 6. The Los Alamos experiment used a 550-keV beam at 10 to 15 kA. Some concern exists about the deleterious effects of the space charge because the beam's γ is only 2, while the current is about the same as that in the 2- to 3-MeV experiments.

Efforts are currently underway to develop techniques for coupling microwave power from the device into rectangular waveguide. This is essential if the LOG source is to be used for any realistic application. In the initial waveguide-output-coupling experiment, the power is iris-coupled from the bottom of one of the three resonator slots into a rectangular waveguide. Data are shown in Figs. 1 to 3. The output power was 2 to 10 MW. The downstream end of the resonator was open, and a lucite window had been placed on the downstream end of the vacuum envelope. This allowed most of the power to radiate out the window instead of out of the waveguide. Waveguide stub measurements in the far field indicated a power level of 20 to 100 MW. The

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resonator used in this experiment had an unloaded Q of several hundred. The waveguide-coupling iris consequently provided relatively weak coupling to the resonator. Attention is now focused on optimizing the waveguide coupling by careful selection of (1) iris position along the slot, (2) the appropriate conducting boundary at the downstream end of the resonator to raise the Q, and (3) multiple waveguide outputs.

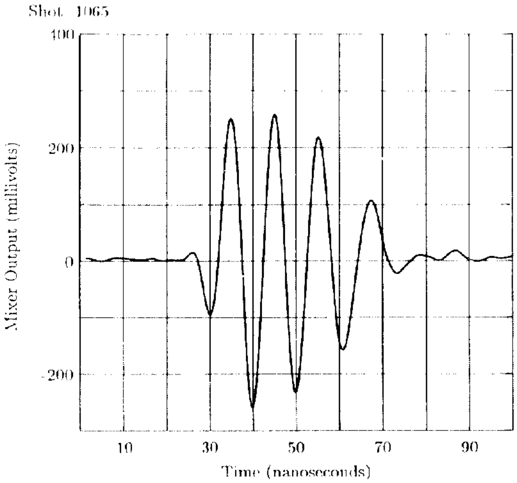

Fig. 1. Downconverted (IF) signal from frequency detector (LO = 2.00 GHz).

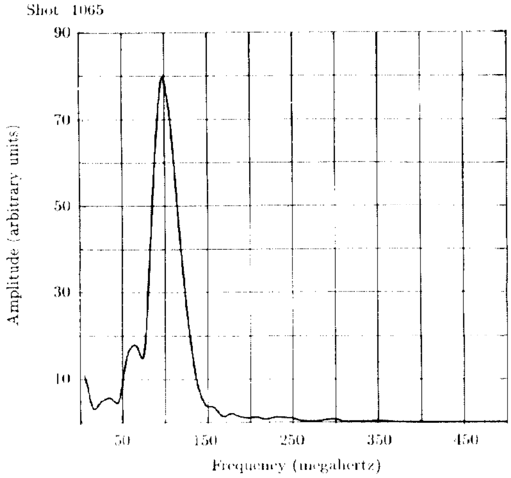

Fig. 2. FFT of IF signal.

Figure 1 shows the downconverted intermediate frequency (IF) output signal from a mixer used as a heterodyne frequency detector. This signal has been digitized and the FFT of this time domain signal is shown in Fig. 2. The RF center frequency is 1.900 GHz with a bandwidth of 25 MHz. Beam voltage and current waveforms are shown in Figs. 3 and 4.

Resonant-Cavity Virtual-Cathode Source

The virtual-cathode oscillator, unlike the large-orbit gyrotron, operates only at electron-beam current levels above the space-charge-limiting current; therefore, it is intrinsically a high-power source. The frequency of the free-running virtual-cathode oscillator is roughly the beam plasma frequency ω_p, with

$$\omega_p = \left(\frac{4\pi n e^2}{\gamma m}\right)^{1/2}$$

where

n = electron density,
γ = Lorentz factor, and
m = electron rest mass.

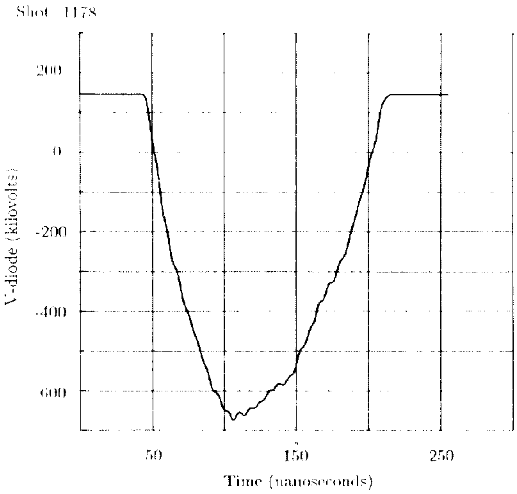

Fig. 3. Diode voltage.

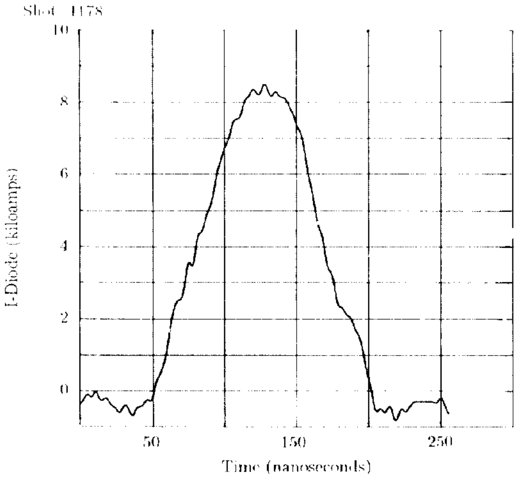

Fig. 4. Diode current.

The free-running virtual-cathode oscillator is a source that has demonstrated multigigawatt power output at several laboratories, at pulse lengths on the order of 100 ns in a single-shot mode. Although the output power levels have been very high, the devices have exhibited considerable frequency instability with chirping during the pulse that can be as high as 40%. This characteristic makes the free-running virtual-cathode oscillator unsuitable for accelerator and most other applications.

Our work has been directed toward making the virtual-cathode source operate in a well-behaved mode at a single frequency. To accomplish this, we surround the oscillating virtual cathode with a resonant cavity and take advantage of the feedback interaction between the induced and cavity fields and the oscillating virtual cathode to make the source operate at the resonant frequency of the cavity mode. The resonant cavity structure is a cylindrical resonator that operates in one of several higher order TM modes, the TM_{012} and the TM_{020}. The experiment and the results have been described in detail elsewhere,[2] but will be briefly summarized here.

The experimental configuration is shown in Fig. 5. The electron beam is produced by a diode with a field emission cathode. Microwave power is extracted through three L-band waveguide ports located around the cavity at 90° intervals. The basic approach is to tune the frequency of the oscillating virtual cathode by varying the beam current density so that its free-running oscillation frequency is near the passband of a suitable mode in the microwave cavity resonator. The TM modes are ideal because the electric dipole field associated with the virtual cathode couples well to the axial electric field, while the output waveguide couples well to the azimuthal magnetic field for power extraction in the dominant TE_{10} waveguide mode.

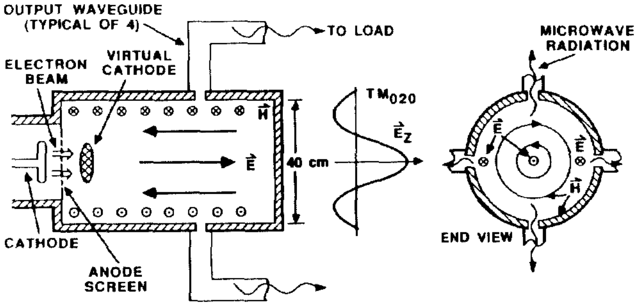

Fig. 5. Resonant-cavity virtual-cathode source experimental configuration.

Figure 6 shows the microwave output frequency as a function of peak injected beam current. For comparison, the free-running virtual-cathode oscillation frequency is also plotted. The cold-cavity mode spectrum is shown along the right axis. Nominal diode voltage was 300 to 400 kV. The data are taken on a single-shot basis because the pulse power source is a Marx/Blumlein system. The FWHM of the beam pulse was about 90 ns. Each data point on the graph corresponds to the output frequency of a single pulse. These data clearly indicate that the virtual cathode will oscillate at a single frequency when feedback is provided by a resonant structure.

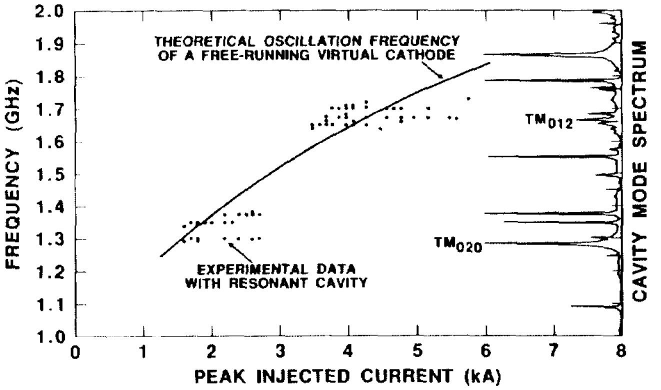

Fig. 6. Measured microwave frequency as a function of peak injected current.

The oscillation frequency of the virtual cathode locks to the TM_{012} and the TM_{020} modes over as much as a 70% change in electron-beam current. This virtual-cathode resonant-cavity configuration results in a 3-dB bandwidth of less than 1% (approximately 17 MHz at 1.66 GHz). The bandwidth appears to be limited by the finite temporal width of the microwave pulse, which is approximately 100 ns.

Future Work and Pulsed-Power Technology Development

The development of both the large-orbit gyrotron and the resonant-cavity virtual-cathode source will enter a new performance regime with the availability of two new high-voltage pulsers for driving these microwave sources. The first of these is BANSHEE, which is designed to deliver 1-MV pulses at 10 kA of 1-μs duration (flat top). The pulse rise time is ~1.0 μs and the repetition rate is 5 Hz. The unit is currently being commissioned and is operating at 300 kV and 6 kA. Figure 7 shows the output waveform into a 50-Ω resistive load. With this pulser, thyratron-switched line-type modulator technology is being extended to the megavolt level. The details of this pulser are described elsewhere.[3] These performance parameters are made possible by recent advances in thyratron technology resulting in a tube that can hold off 100 kV and conduct currents up to 200 kA with a di/dt approaching 10^{12} A/s total. This is almost a factor of 2 in voltage and a factor of 4 in peak current over the best demonstrated performance of a single thyratron.

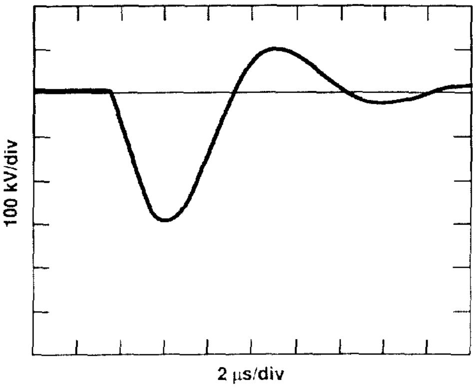

Fig. 7. Banshee output into 50-Ω resistive load.

A second high-voltage pulser producing 600 kV, 3 kA, for 100 ns, at 10 Hz is under construction. This pulser, also a thyratron-switched, line-type modulator, will be used to drive a repetitively pulsed, 8-GHz, large-orbit gyrotron.

References

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