HIGH-POWER MICROWAVE SOURCE DEVELOPMENT AT LOS ALAMOS*

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Abstract

Experimental research is under way at Los Alamos to develop the large-orbit gyrotron and the resonant-cavity virtual cathode oscillator as very high power microwave sources. These sources, though still in an early stage of development, have demonstrated power outputs from the several hundred megawatt to the gigawatt level at various Laboratories. These devices exhibit very narrow band output, making them candidates for future accelerator drivers. Our efforts are directed toward achieving repetitively pulsed operation at pulse lengths in the microsecond regime. To provide the pulsed power for these experiments, a 1-MV, 10-kA modulator with a 1-μs pulse length and a 5-Hz pulse-repetition frequency has been developed and is currently being assembled. The resonant-cavity virtual cathode source has achieved very narrow band output compared to the conventional free-running virtual cathode oscillator. Techniques are being developed for extracting the microwave power from both sources into the rectangular waveguide. The experimental effort is described and current experimental results are discussed.

Summary

The development of new types of high-microwave sources capable of generating power levels as high as 1 GW is being pursued at Los Alamos and a number of other Laboratories around the world. These very high power sources include the virtual cathode oscillator, relativistic klystron, gyrotron, large-orbit gyrotron, lasertron, and several others. At Los Alamos the source development effort is concentrated on the resonant-cavity virtual cathode source, the large-orbit gyrotron, and the lasertron. This paper will discuss the research effort on the first two.

For many applications, coupled with the desire for high power is the need for narrow bandwidth and repetitively pulsed operation at pulse widths ranging from 100 ns to several microseconds. Because of its characteristic single mode, very narrow band output, the large-orbit gyrotron may be particularly useful as the microwave driver for future linear colliders. Several Laboratories have demonstrated that the large-orbit gyrotron is capable of producing 200-500 MW of power and efficiencies of 40%.[1]

Researchers working on the virtual cathode oscillator (VCO) have routinely reported power levels in excess of 1 GW with the highest being ~ 30 GW (Ref. 2). Although its high power output and simplicity make the VCO attractive as a microwave source, it is inherently a wideband source, which makes it unsuitable as an accelerator power source in its simplest configuration. At Los Alamos, an approach has been developed that uses a resonant structure surrounding the oscillating virtual cathode to achieve a very narrow band output operating as a mode-locked oscillator. This concept has been further developed, and experiments are under way to operate the VCO as a source that is frequency and phase locked to a microwave signal injected from an external source.

These high-power sources have, in general, only been operated in a single-shot mode for pulse lengths of 100 ns or less. This is a limitation imposed primarily by the capabilities of the pulsed power sources that are used to drive these microwave devices. These devices require power sources capable of producing voltages as high as 1 MV and electron currents as high as tens of kiloamperes. In the past this power has been usually generated using Marx-Blumlein technology. To reach pulse lengths of a microsecond, and to achieve repetitively pulsed operation, Los Alamos is pushing conventional modulator technology into the megavolt-kiloampere-microsecond regime. These expanded capabilities are made possible by new improvements in thyratron technology.

Resonant Cavity Virtual Cathode

The free-running virtual cathode oscillator, which is produced by an electron beam whose current exceeds the space-charge limiting value, has an oscillation frequency that is roughly the beam plasma frequency ω_p, where

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

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

Virtual cathode devices operating in this free-running mode exhibit considerable frequency instability, which makes them unsuitable for most applications. Los Alamos has developed a technique for achieving frequency stabilization[3] that uses a cavity resonator surrounding the oscillating virtual cathode. 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. Creating a strong electron beam/cavity interaction allows the field induced in the cavity by the oscillating virtual cathode to feed back on the virtual cathode, forcing it to oscillate at the resonant frequency of the cavity mode.

Experiments were performed using a cylindrical cavity operating in the TM_{020} and TM_{012} modes. The electron beam was produced by a diode consisting of a field emission cathode and an aluminum-wire-screen anode located at the upstream end wall of the cavity. Microwave power was extracted through three L-band waveguide ports located around the cavity at 90° intervals. This configuration is shown in Fig. 1. The frequency of the microwave output was measured as a function of diode current. These data are plotted in Fig. 2, which shows the measured output frequency as a function of peak injected beam current. For comparison, the free-running virtual cathode oscillation frequency is also plotted. The mode spectrum for the cold

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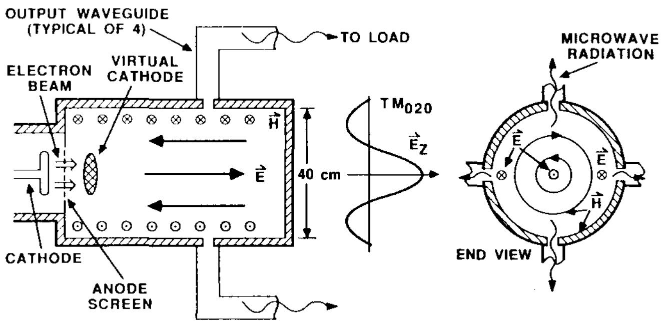

Fig. 1. Cylindrical resonator configuration.

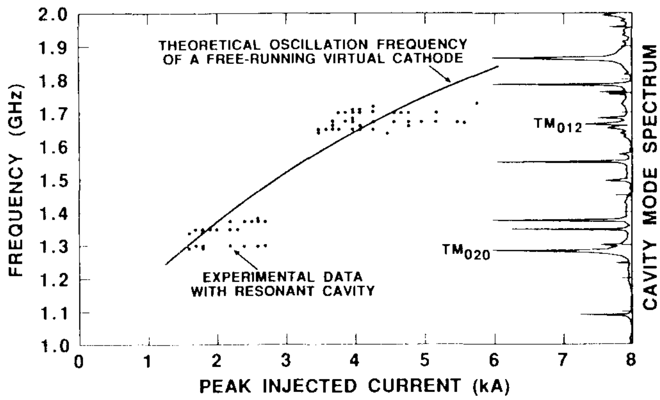

Fig. 2. Measured microwave frequency as a function of peak injected beam current.

cavity is plotted along the right axis. Nominal diode voltage was 300-400 kV. These data clearly indicate that the virtual cathode will oscillate at a single frequency when feedback is provided by a resonant structure.

The oscillation frequency of the virtual cathode locks to the TM_{020} and the TM_{012} 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% (~17 MHz at 1.66 GHz). The bandwidth appears to be limited by the finite temporal width of the microwave pulse, which is ~100 ns.

An experiment is currently under way to injection lock the frequency and phase of the injection signal from a high-power klystron. The basic idea is to excite the cavity with the klystron before firing the electron beam, which gives the cavity fields a chance to build up in the desired mode. Then when the electron beam is injected, the virtual cathode oscillations build up from the injected field in the cavity instead of building up in intensity from noise voltage present on the beam. In this way, the virtual cathode is locked in frequency and phase to the klystron injection signal.

Large-Orbit Gyrotron

The attractive features of the large-orbit gyrotron include high power and efficiency, as well as long-pulse (>1 μs) repetitive operation. The large-orbit gyrotron converts the kinetic energy from an axis-encircling rotating electron beam into microwave energy by a resonant interaction between the negative mass instability on the beam and a surrounding magnetron-like resonant structure. In the present experiment the electron beam is produced by a circular, knife-edged field-emission cathode. This hollow beam is accelerated toward the anode, which contains a circular slit through which the beam can pass. A magnetic cusp is provided at the anode plane that converts the linear beam into a rotating beam. The downstream solenoidal field then maintains the cyclotron motion of the beam as it travels downstream interacting with the resonant structure. The resonator has been designed for operation at 2 GHz, the third harmonic of the electron cyclotron frequency.

The Los Alamos program is focusing on three major areas: microwave source development including techniques for extracting the microwave energy into dominant mode waveguide, repetitively pulsed operation, and thermionic electron gun injection. All of these areas are being addressed in order to realize the goals of high-power, long-pulse, repetitive operation with reasonable reliability and lifetime.

The 2-GHz large-orbit gyrotron is currently operational using an existing single-shot pulser with a pulse length of 100 ns. The device operates at the third harmonic of the electron cyclotron frequency with a solenoidal magnetic field strength of 500 G. Typical operation is at 600-keV electron energy and a beam current of several kiloamperes. Power output is estimated at 100 MW for 50-100 ns. The current effort is focusing on coupling the power from the three-vane resonator into rectangular waveguide through longitudinal slots in the resonator wall. A second large-orbit gyrotron is being designed for operation at 8 GHz, 600 kV, 100 ns, with a 10-Hz pulse repetition frequency.

Pulsed-Power Technology Development

Crucial to the microwave source development is the availability of pulsed power sources with adequate performance characteristics compatible with the microwave source requirements. Thyratron-switched, line-type modulator technology is being extended to the megavolt level to power this new generation of high-power microwave sources. Los Alamos has two modulators under development. The first is a 1-MV, 10-kA, 1-μs flat-top, 5-Hz unit that is expected to be operational by December 1988. The second is a 600-kV, 3-kA, 100-ns, 10-Hz unit. The key technical issues are the thyratron tubes, minimizing system rise time and achieving reasonable component lifetimes. The microsecond pulser is described below.

The modulator is designed to supply up to 1-MV pulses of 1-μs duration (flat top) with a rise time of ~0.5 μs to diode impedances of ~100 Ω. The design uses two newly developed 100-kV hollow anode thyratrons to discharge four, parallel, lumped-constant Blumleins composed of 1- to 2-Ω PFNs. The Blumleins are command resonantly charged to 100 kV from a capacitor bank. The Blumleins are then discharged through a 10:1 step-up iron-core transformer to 1 MV.

A system block diagram is shown in Fig. 3. The primary switches in the modulator must be able to 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.

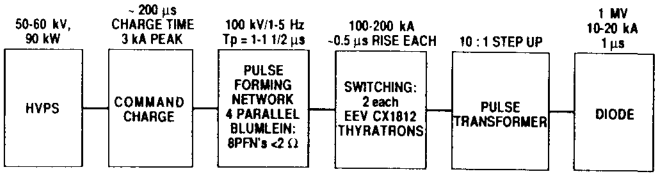

Fig. 3. System block diagram of 1-MV, 1-µs, 10-kA, 5-Hz pulser.

Initial tests have been conducted using one thyratron in conjunction with one or two Blumleins. A level of 50 kV across the tube has been attained with a resistive load instead of the pulse transformer.

The pulse transformer unit has a 10:1 step-up ratio, a pulse rise time of 0.5 µs, and tolerates an output level of 1 MV for 1 µs.

Conclusions

The resonant-cavity virtual cathode source has demonstrated narrow band single-mode operation. An experiment is currently under way to demonstrate frequency and phase locking of the oscillating virtual cathode to an injected klystron signal. The achievement of injection locking opens up the possibility of coherently operating several virtual cathode sources in parallel to reach very high microwave power levels because all the sources could be pumped by the same injection signal and would consequently be frequency and phase locked to each other.

Large-orbit gyrotron development is being pursued because of its single frequency, high efficiency, high power output that make it a candidate for future accelerator applications. To complement the microwave work, pulsed power sources are under construction to drive the microwave sources in a repetitive mode at useful pulse lengths.

References

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