EXPERIMENTAL PROGRESS ON VIRTUAL CATHODE, VERY HIGH POWER, MICROWAVE SOURCE DEVELOPMENT*

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Abstract

The evolution of rf accelerator technology toward high-power, high-current, low-emittance beams produces an ever-increasing demand for efficient, very high power microwave sources. The present klystron technology has performed very well but is not expected to produce reliable gigawatt peak-power units in the 1- to 10-GHz regime. Further major advancements must involve other types of sources. The reflexing electron sources can produce microwave powers at the gigawatt level and have demonstrated operation from 800 MHz to 40 GHz. Pulse length appears to be limited by electron-beam diode closure, and reflexing electron devices have been operated in a repetitively pulsed mode.

An experiment is under way to investigate concepts to stabilize the frequency of the virtual cathode source. If one can successfully frequency and phase lock this source to an external signal, then this source can operate as a very high power microwave amplifier making it practical for accelerator applications. The progress on an experiment to test these concepts will be discussed.

Background

Virtual cathode sources have been operated over the last few years by many laboratories around the world. These sources routinely have produced outputs above 1 GW; recently, 10-20 GW has been reported[1] at 1.3 GHz in a 100-ns pulse. Didenko's group in the Soviet Union has produced a 120-MW pulse for 1.3 µs at 3 GHz with a beam-to-microwave-power conversion efficiency of 37%.[2] Didenko has also reported 500 MW at 3 GHz for half a microsecond.[3]

Conventional virtual cathode oscillator sources have several serious inherent problems that make them unsuitable in many contemplated applications. The device is an unstable free-running oscillator whose frequency can shift as much as 35% during a single pulse. The microwave output has peaks in a number of modes that are typically transverse magnetic.

The performance of the virtual cathode source must improve dramatically before it can become viable as a microwave power source in the gigawatt class. This source must be able to operate reliably for a pulse length of several microseconds. The frequency and phase should be controllable. Finally, there must be an efficient means of coupling the source power to the load. In short, this source should be made to operate as an amplifier, in a manner analogous to a cavity klystron.

Frequency and Phase Locking

Designs have been discussed for building a frequency- and phase-locked high power microwave amplifier based on the virtual cathode source.[4,5] Frequency locking may be achieved by surrounding the oscillating virtual cathode with a resonant microwave structure. A microwave cavity resonator has several properties of particular use to us in this application. First, it is frequency selective. The cavity supports a number of well-defined modes of oscillation, and each mode occurs over a very narrow bandwidth. Secondly, microwave energy can be effectively coupled out of a cavity resonator. The cavity klystron and the magnetron are examples of microwave generation by passing an electron beam through a resonant structure. A series of microwave cavities is used first to bunch the dc electron beam and then to extract the power from it at the microwave frequency. The dynamics of the oscillating virtual cathode are much more complicated and less understood than the previous examples. However, from computer simulations[6] there is reason to believe that a resonant cavity surrounding the oscillating virtual cathode would affect its dynamics. An experiment performed at Physics International with a resonant cavity surrounding an oscillating virtual cathode resulted in a 50% increase in output power and a factor of 5 reduction in bandwidth.[7] One can tune the oscillating virtual cathode by varying the beam current density. If the dominant free-running oscillation frequency is near the passband of a microwave cavity resonator surrounding the oscillating virtual cathode, then one should be able to create a strong beam/cavity interaction. Because of this interaction, the cavity field induced by either the Fourier components at the cavity resonant frequency of the oscillating virtual cathode or from some other source can feed back on the oscillating virtual cathode, forcing oscillations to build up in the desired mode at the cavity resonant frequency f_0. The formation of the virtual cathode is a beam-bunching phenomenon; therefore, if one can affect the dynamics of the bunching process, then one should be able to influence the behavior of the oscillating virtual cathode. Using this feedback interaction, the oscillating virtual cathode and the cavity field should lock together in phase and in frequency, converting beam power to microwave power with improved efficiency.

Experiment

An experiment to produce a frequency- and phase-locked virtual-cathode source at 1.3 GHz is under way. The experiment uses the cylindrical geometry of Fig. 1. The 1-MeV, 20-kA, space-charge-limited electron beam is accelerated into a cylindrical resonator where the TM_{020} transverse magnetic mode is excited. The electric-field pattern for the TM_{020} is also shown (Fig 1).

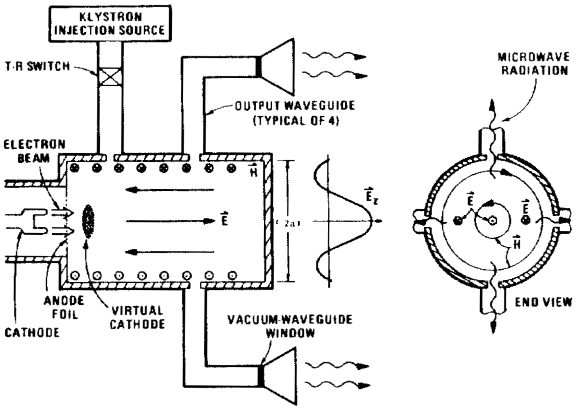

Fig. 1. Virtual Cathode cylindrical resonator configuration with klystron injection signal.

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The fields in the TM_{020} mode have the following form:

$$E_Z \propto J_0\left(\frac{5.520\,r}{a}\right),$$

and

$$H_\phi \propto J_0'\left(\frac{5.520\,r}{a}\right),$$

where J_0 and J_0' are the zero-order Bessel function and its derivative, a is the cavity radius, and r is the radial position. The radial dimension of the cylinder is selected to place the TM_{020} mode at 1.3 GHz. The electric field is axial in the z-direction, with maxima at the axis $r = 0$, and at $r = 0.7a$ (Fig. 1). The diameter of the electron beam will be chosen to be within the region of the central peak in the electric field centered at $r = 0$. This geometry will result in a strong coupling between the electric field from the oscillating virtual cathode and the cavity TM_{020} mode. Wall currents will be induced by the virtual cathode oscillations that set up the electric and magnetic fields characteristic of the TM_{020} mode. The TM_{020} mode resonant frequency depends only on diameter, not cavity length. Operating the cavity at a length longer than a half wavelength should be avoided because higher order modes such as the TM_{011}, TM_{012}, etc., could be excited. Because the TM_{020} mode cavity has more volume than the TM_{010} mode cavity for the same amount of stored energy, the voltage is lower, thereby reducing breakdown problems.

Power extraction from the cavity is completed by means of slot apertures around the circumference that allow the circumferential magnetic field of the TM_{020} cavity mode to couple into the TE_{10} magnetic field in the rectangular L-band waveguide.

An initial cavity design was completed by using the computer code SUPERFISH. Our cavity does not possess ideal cylindrical symmetry because of the waveguide and diagnostics penetrations; therefore, a cold (low-power) model was built to fine tune the SUPERFISH calculations. Measurements were then made on this cavity to determine the resonant frequencies of the TM_{020} mode and neighboring modes. This information was then folded into the design of the experimental cavity resonator. This cavity is a copper-plated stainless steel structure.

A cavity resonator possesses an infinite number of oscillation modes. The mode chart for a cylindrical resonator is shown in Fig. 2. For a given cavity geometry with a diameter D and length L, a vertical line can be drawn at $x = (D/L)^2$. The frequencies of the possible modes that can exist with this geometry are indicated wherever the vertical line crosses the line for each mode. One desires to operate in a mode with an electric field configuration suitable for coupling to the beam and a magnetic field suitable for coupling from the cavity to the output waveguide. Additionally, one would like the neighboring modes to be as far removed as possible from the operating mode to eliminate mode hopping and the corresponding frequency instability. The TM_{020} mode meets these requirements when $(D/L)^2$ is approximately 3 or 4. The actual mode spectrum can be shifted considerably from the ideal case in Fig. 2 because of the departure from the cylindrical geometry caused by output waveguide penetrations, vacuum ports, etc. These asymmetries load the different modes in various ways, causing the modes to move up or down in frequency. It is extremely difficult, if not impossible, to predict how far in frequency the various modes will move because of the asymmetries; there is no substitute for actual mode-spectra measurements.

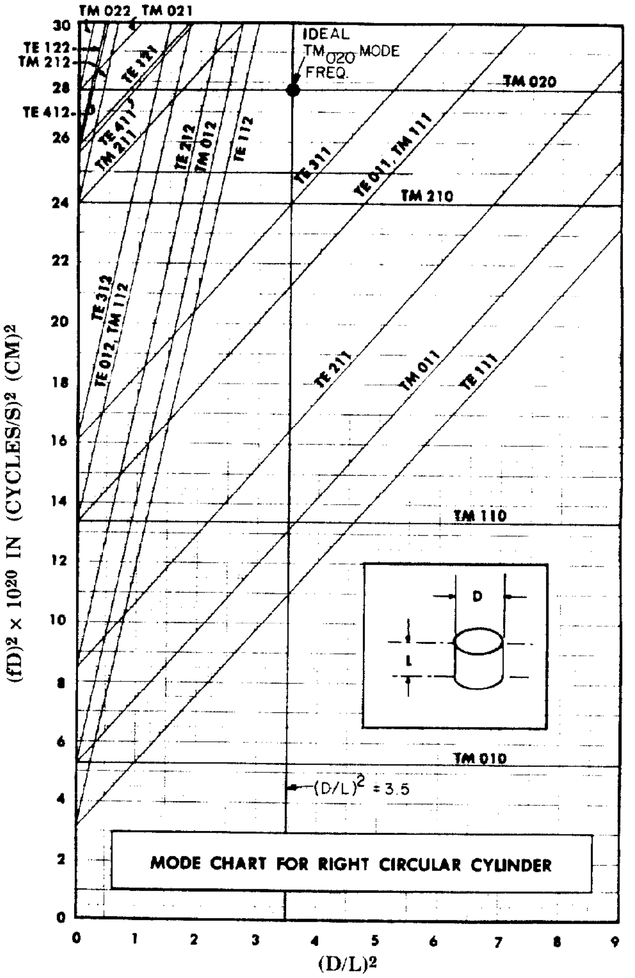

Fig. 2. Mode chart for ideal cylinder (from Saad, Microwave Engineers' Handbook, Vol. 1, p. 181, Artech House, Inc., Dedham, Massachusetts, 1971).

After final assembly of the cavity, Q measurements and mode-spectra measurements were performed. The unloaded Q of the TM_{020} mode at 1.3 GHz is 23 000. The mode spectra for this cavity is shown in Fig. 3. The nearest mode to the TM_{020} is 7 MHz away. Currently, the beamline is being prepared for cavity installation. In the coming experiments, electron-beam diode parameters such as anode-cathode gap spacing and diode voltage will be optimized to adjust the electron-beam current density so that the microwave radiation peaks in the 1.3-GHz regime. Because the cavity affects the dynamics of the

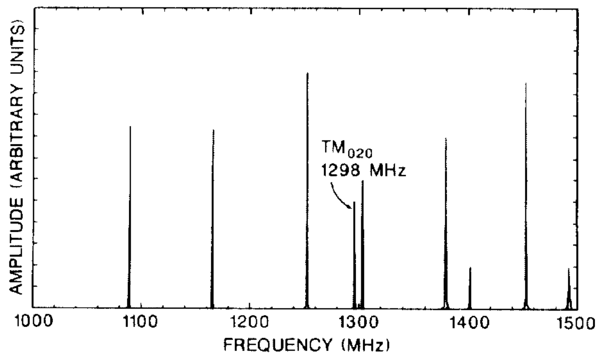

Fig. 3. Measured cavity mode spectra.

virtual cathode oscillation, we should observe an improvement in efficiency and a rise in microwave power output as we tune the oscillating virtual cathode frequency through the cavity resonant frequency. Also, the spectral output of the source should narrow considerably.

Injection-Locked Virtual Cathode Amplifier

A further refinement to the frequency-locking concept[5] involves exciting the cavity resonator with a microwave-pump signal at the cavity resonant frequency before injecting the electron beam into the cavity. The power level of this microwave pump would be a few percent of the microwave power produced by the electron beam. The role of the microwave pump is to establish the microwave field in the cavity so that, when the electron beam enters the cavity, the beam will interact with the desired existing cavity field. With this technique, the beam should be forced to oscillate at the same frequency as the microwave pump instead of waiting for the virtual-cathode oscillation to stochastically build up from noise voltage on the beam. Then, no longer would one have a free-running oscillator; instead, one would have an amplifier where the beam's virtual cathode must interact with a resonantly pumped cavity. The output of this virtual cathode device would be locked in frequency and in phase to the injection source that will be a high-power klystron, as shown in Fig. 1.

The microwave cavity enhances the effect of the klystron output power by storing the klystron-produced energy in the cavity electromagnetic field over a relatively long period of time compared to the electron-beam pulse length. The electric field in our cavity, assuming a loaded Q of 1000, is about 220 kV/cm at 10 MW of klystron output as compared with a field of around 500 kV/cm in the diode. It must be kept in mind that the rf voltage in the oscillating virtual cathode starts from near zero amplitude in the presence of the 220-kV/cm cavity field. Because our injected signal is comparable in amplitude to the diode field, it seems quite possible that we should be able to injection lock the oscillating virtual cathode with the klystron.

Conclusions

A frequency- and phase-locked virtual cathode source, should it prove possible, offers an exciting alternative to supplement conventional microwave sources in the very high power regime. With power outputs possible in the several hundred megawatt to multigigawatt range, one such device could replace many klystrons (and associated modulators and high-voltage power supplies) in certain applications. This could potentially result in less complex microwave power systems because of fewer components. The inherent simplicity of the virtual cathode source is also a desirable feature.

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