CONF-9006179--3
UCRL- JC-103714
PREPRINT

Received by OSTI
JUL 13 1990

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This Paper was Prepared for Submittal to
Fifth National Conference on High Power
Microwave Technology
West Point, NY
June 10-15, 1990

May 31, 1990

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UCRL-JC--103714

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ABSTRACT

The progress toward high efficiency, long pulse operation of virtual cathode oscillators is described. The conditions for the resonance at which high efficiency is obtained are that the beam frequency equals the reflex frequency to within two percent. This implies that cathode closure in the anode-cathode gap is not acceptable. We have therefore developed and tested a cathode that will operate at 300 amps/cm^2 without significant closure for times in excess of one microsecond.

1. OVERVIEW OF THE BALBOA PROGRAM

It is the purpose of the Balboa program to develop a compact source of high energy microwaves at a frequency near 3 gHz. The source, including the explosive generator of electrical energy, is small and will fit into a missile; its primary mission is to disable enemy electronics. In the following, we will describe the state of development of the microwave generating device, the Side Shooting Virtual Cathode Oscillator (SSVCO). Other components of the Balboa program, such as the explosive flux compression generator, have been described elsewhere [1]. We have found that microwave power can be generated with good (5 - 10%) efficiency under very specific operating conditions. The maximum energy output obtained in a single pulse has been 105 Joules. The RF energy output appears to be limited by our ability to maintain the high efficiency operating conditions for the duration of the pulse. At present, the efficiency of the device varies widely throughout the pulse, with the high power output limited to durations less than 100 ns. As a consequence, the thrust of our development has been to develop a power supply and a cathode/anode stucture that allow the high efficiency conditions to be maintained in steady state. We first describe the experimental device, the principles for high efficiency operation, and the results obtained. These point toward the necessity of eliminating the plasma closure of the anode/cathode (AK) gap. We have successfully reduced the closure rate and improved the uniformity of lighting with a new type of explosive emission cathode and developed two other cathode types capable of operating without gap closure for times in excess of one microsecond. One of them will operate at a current density greater than 300 A/cm^2 without gap closure. We are in the process of installing this type of cathode in the high energy microwave source. We expect that the constant condition operation at high efficiency will substantially advance the energy output form the present maximum of 100 joule/shot toward the one kJoule level which is the goal for the experimental device.

2.THE MICROWAVE DEVICE

Virtual cathode oscillators are capable of generating large levels of RF power in the 1 - 10 GHz range. The have been operated in a variety of configurations and with and without cavities [2,3,4]. The virtual cathode oscillator employed for the Balboa program is capable of being tuned to operate at the high efficiency resonance conditions where the beam frequency equals the reflex frequency. Short pulse and high power operation of the SSVCO has been reported previously [5,6]. The device operates in an axial magnetic field to minimize radial beam transport, and the power flows out radially from the generating region within the electron beam. The power is generated in a low Q environment, so cavity breakdown does not limit the power output of the device. A recent set of experiments at AFWL has illustrated the difficulty of employing high Q cavities for high power operation [4].

A cut-away drawing of the SSVCO is shown in figure 1. The beam is generated at the cathode (discussed more fully below), and is accelerated through the AK gap. The virtual cathode is formed between the anode and the collector, and is located downstream of the anode at a distance approximately equal to the AK gap. The anode consists of two screens, one downstream of the other, so the transit time of the electrons through the drift space (the AA gap) can be adjusted by varying the distance between the screens. The device is brought into the high efficiency resonance conditions by proper settings of the AK gap and the AA gap at a given beam voltage. The magnets shown in figure 2 can impose a near-axial magnetic field of up to 6.6 kGauss. The microwave power leaves the vacuum enclosure through an azimuthally symmetric Lexan window (whence the name of the Side Shooter). In a weapon confuguration, the magnetic field will be produced by coils imbedded in the cathode stem and the anode structure, and the microwave power will be directed axially by a reflecting antenna after passing through the window. We have found that a good vacuum is essential for long duration pulses of microwaves; in particular, it is important to pump the water vapor with a large surface cooled by liquid nitrogen. The effects of pumping and electrode cleaning on pulse length has been described previously [7].

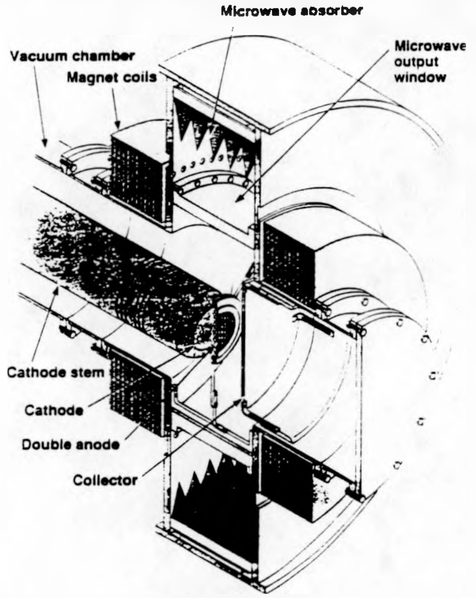

Fig. 1 Cut-away drawing of the SSVCO illustrating the electrode geometry, the low Q environment of the electron beam, and the radial RF extraction geometry.

In the laboratory, the electrical pulse is provided by a Marx generator modified by a series switch and an array of peaking capacitors. The latter allows a good impedance match between 15 and 100 ohms for a corresponding value of the capacitance and the switching time. The maximum output voltage is approximately 800 kV. The maximum pulse duration into a matched load is one microsecond.

The microwave power and the frequency is measured by antennas located in the anechoic chamber exterior to the windows. The antenna array consists of 7 "cluster" antennas, where each cluster consists of a set of three orthogonal dipoles. The use of "cluster" antennas minimizes measurement errors due to the direction of the polarization and the power flow.

For much of the past operation, the cathode surface was velvet which was caused to explosively emit by the field applied across the AK gap. We have found, however, that the rate of plasma closure of the AK gap was excessive with this arrangement. In addition, the lighting of the cathode plasma was not as uniform and as fast as desired. The beam would apparently tend to be annular. We have developed new cathodes to solve these problems. One consists of graphite pins which are covered by a layer of graphite followed by a layer of velvet. This arrangement decreased the plasma closure velocity from 2.5 cm/microsecond to 1.5 cm/microsecond; it also increased the uniformity, reproducibility, and the speed of lighting. This improvement was still not sufficient to produce long duration pulses at high efficiency. A further improvement is expected from the use of the T/F cathode as discussed below.

We have employed a number of anode materials in the past, though we have mostly used stainless steel screens with a variety of transparencies, typically on the order of 80 % for a single screen. We now use graphite screens with 80 % or greater transparency, lined up so the two screens gave the same transparency as a single screen. The anodes are machined to have square holes with a web thickness of $4.3 * 10^{-4}$ m and a mesh of 9.

We have found that certain conditions exist where the efficiency of microwave production is in the range of 5 - 10%; high efficiency operation occurs when the measurement frequency equals the reflex frequency f_r and the beam frequency f_b. The relations we employ for these frequencies are

$$f_b = 2.4 \times 10^{8} \{j/(\gamma^2 - 1)^{1/2}\}^{1/2}$$

$$f_r = 1.46 \times 10^{10} \beta / (2 d_{ak} + d_{aa}) \quad \text{(cgs)},$$

where j is the current density, d_{ak} the anode-cathode gap, and d_{aa} the anode-anode gap.

A recent set of data from shot 6626 illustrates these observations. Figure 2 shows the temporal behavior of the RF efficiency for a shot that passes through resonance, i. e. when f_r equals f_b at a particular time.The ratio of f_r to f_b is shown in figure 3. Figure 4 shows that the region of high efficiency operation is narrow indeed when measured in terms of the frequency ratio. In the data, we use the computed frequency ratio to illustrate the point since the accuracy of the measured frequency is limited by the bin width. We have conducted other experiments where the emitted frequency has been measured with a mixer. Changing the AK gap slightly to change the rate of measured to reflex frequency showed that the band width of high efficiency operation was approximately 50 MHz. The device is so sensitive to geometry that variations of 10^{-4} m in the AK gap significantly affect the RF output. Variations of 10^{-3} m are excessive for accurate tuning. The maximum RF output power has been 105 joules and is limited by the geometry variations due to plasma closure and, of course, by the power input.

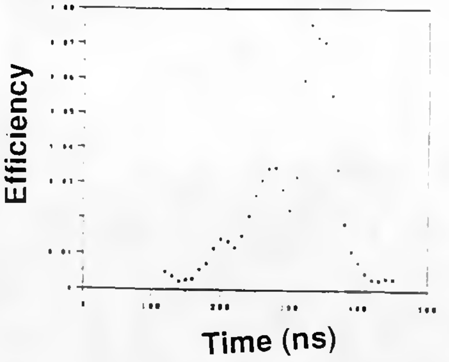

Fig. 2 The RF efficiency varies strongly with time and peaks when $f_b = f_r$.

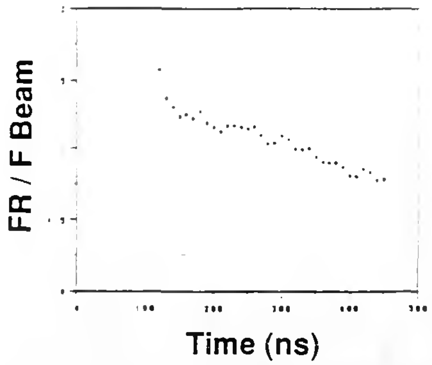

Fig. 3 The reflex-to-beam frequency ratio passes through unity during the shot

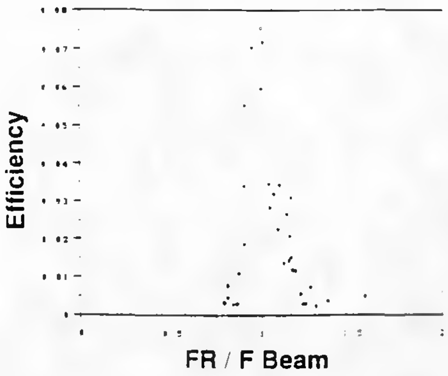

Fig. 4 The conditions of resonance occur when the beam frequency is within 2% of the reflex frequency.

A related observation is that the width of the emitted frequency spectrum generally narrows greatly as the device goes into resonance and emits greater power with greater efficiency. As the AK gap continues to close and the beam parameters change, the resonance condition is lost, the width of the emitted spectrum increases, and the emitted power decreases. Figure 5 shows the standard deviation of the frequency for shot 6907 as measured by the array of filter bins. This behavior was first reported by Burkhart, et. al. who observed it in a particle simulation code [2].

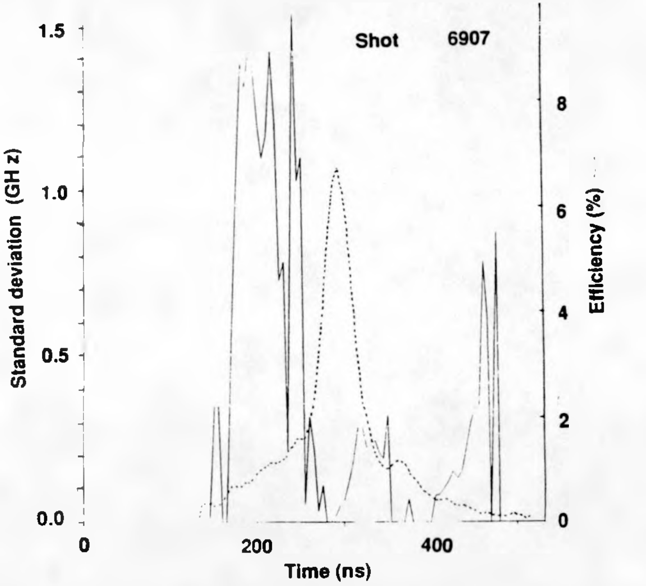

Fig. 5 The standard deviation of the frequency distribution is minimum when the power is maximum (typical binwidth is 0.3 GHz)

It is apparent from an analysis of the data that the region of resonance is narrow. To operate at the high efficiency resonance conditions, the power supply must provide a voltage that is constant in time, and the impedance of the diode must be constant. The current extracted is approximately one half the Child-Langmuir current corresponding to the voltage, the cathode area, and the gap. It is the closure of the AK gap due to plasma formation that must be eliminated if operating conditions are to be held constant. This, in turn, demands that explosive emission cathodes not be used, or that the plasma expansion be controlled.

To estimate the degree of control that must be imposed upon the operation of the device to remain in resonance, we have plotted the frequency ratio f_r/f_b versus the voltage or the current, using the AK and AA gaps as parameters. Figure 6 shows a typical relation for a space charge limited cathode and for a temperature limited T/F cathode. For no change in the AK and AA gaps during the shot, i.e. without plasma formation, the tolerances on frequency ratio, voltage, and current are

$\Delta f_r/f_b = 0.02$

$\Delta V/V = 0.09$ $\Delta I/I = 0.13$ space charge limited
$\Delta V/V = 0.10$ $\Delta I/I = 0.05$ temperature limited

For an explosive emission cathode, plasma closure causes voltage and current variations outside the stated limits. Given an adequate power supply we expect to satisfy the voltage and current regulation requirements with the T/F cathode. We note that the sensitivity of the emitted RF power to the voltage and current for a given geometry does have a possible application: It is relatively easy to modulate the voltage outside the above range and thus modulate the emitted RF power at a frequency of 10 - 100 MHz.

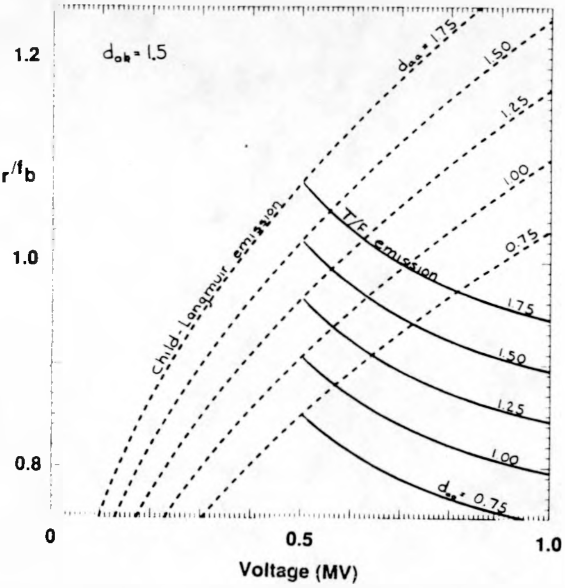

Fig. 6 Frequency ratio a function of voltage and AA gap for Child-Langmuir operation (---) and T/F operation.

3. CATHODE DEVELOPMENT

We have worked on several different types of cathodes to reduce or eliminate the gap closure and to assure uniform and speedy lighting over the entire cathode surface. The cathode types are explosive cathodes with ballasted graphite pins covered with a layer of graphite and a layer of velvet, cathodes where electrons are extracted from a stationary plasma, and the T/F cathode. The cathode development is described in detail in a companion paper, so only a brief description of the cathode types and the results will be given here [8].

The first type is a combination of resistively ballasted pins and velvet. Graphite pins alone will generate beamlets and also produce enough plasma at the current densities employed here (_ 250 A/cm^2) to close the AK gap as fast as velvet alone (_ 2.5 cm/microsecond). However, if a .38 cm layer of graphite is inserted between the pins and the velvet, the closure speed is reduced to 1.5 cm/microsecond. We were able to extend the pulse duration somewhat using this method, but the reduction in closure velocity was insufficient to keep the diode in resonance for a sufficient duration. An order of magnitude decrease in closure velocity was required

The second cathode under development is one which controls the expansion of plasma into the AK gap. It is a variant of a cathode developed by Rocca and others [9]. For our purposes we needed to develop the source plasma in a few microseconds to eliminate the presence of neutrals in the beamline. If the plasma is formed in the steady state, the background pressure in the beamline is typically 10^{-2} to 10^{-3} Torr, and other problems result. We were able to develop the source plasma in a few microseconds in the 3 mm gap between a pin/graphite/velvet cathode and a fine mesh screen. We were able to extract a beam from the source plasma at a current density of 5-10 A/cm^2 without closure and breakdown for one microsecond. Further advances requires a more stable extraction supply and careful grading of the electric field around the cathode screen. The work on this cathode was postponed indefinitely due to the success of the T/F cathode. However, the confined plasma cathode has many advantages such as unlimited current density and the small energy storage required to form the source plasma.

The T/F cathode turned out to be the most successful for the present application. It consists of a array of heated tungsten wires. The thermionic emission alone is insufficient to supply the required current density; however, the wire spacing creates an enhancement of the field at the wire surface, and that additional effect can boost the extracted current density to values in excess of 300 A/cm^2 averaged over the beam cross-sectional area. The array is a spiral wound set of equal length, equal diameter tungsten wires. The layout is shown in figure 7. The wires are connected in parallel so each passes the same current and operates at the same temperature. The heating time is a few seconds with the lower limit set by the forces on the wires due to the current traversing the imposed magnetic field. We are in the process of installing this type of cathode in the high power microwave device; we expect that once it becomes operational, the diode will be able to stay in resonance for a large fraction of a microsecond, with a consequent advance in emitted microwave energy toward the one kJoule experimental goal.

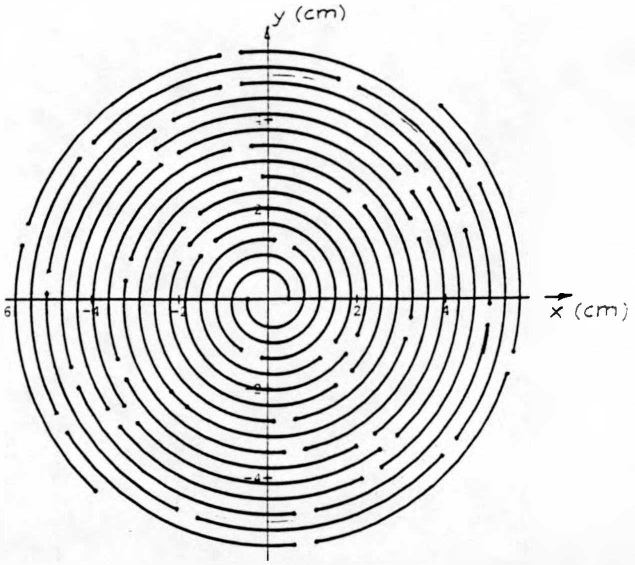

Fig. 7 Lay-out of the T/F cathode filaments

REFERENCES

[1] P.A. Pincosy, D.K. Abe, and J.B. Chase, "High Gain Flux Compression Design," Proceedings of the 5th International Conference on Megagauss Magnetic Field Generation, 1989.

[2] S.C. Burkhart, R.D. Scarpetti, and R.L. Lundberg, "A Virtual Cathode Reflex Triode for High Power Microwave Generation," J. Appl. Phys. 58 (1), July 1985

[3] H. Sze, J. Benford, W. Woo, and B. Harteneck, "Dynamics of a Virtual Cathode Oscillator Driven by a Pinched Diode," Phys. Fluids 29 (11), November 1986

[4] D.E. Voss, et. al., "Novel High Power Microwave Source Development," AFWL report WL-TR-89-95

[5] P. Poulsen, et. al., "Design and Performance of the SSVCO," Proceedings of the Fourth National High Power Microwave Conference, 1988

[6] P. Poulsen, J.J. Morrison, and D.W. Greenwood, "Results of the AFWL/LLNL SSVCO Experiments," Proceedings of the 7th Pulsed Power Conference, 1989

[7] P. Poulsen and J.J. Morrison, "Extension of the RF Pulse of a Virtual Cathode Oscillator," Proceedings of the Fourth National High Power Microwave Conference, 1988

[8] P.A. Pincosy, et. al., "Cathode Applications to High Current Diodes," this conference.

[9] C.S. Murray, J.J. Rocca, and B. Szapiro, "A Reflex Electron Beam Discharge as a Plasma Source for Electron Beam Generation," IEEE Transactions on Plasma Science, Vol. 16, No. 5, October 1988.

Acknowledgements: Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.