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THE GENERATION OF GIGAWATT POWER LEVELS OF MICROWAVE RADIATION

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Introduction

Recent dramatic increases in the ability to produce ultrahigh power bursts of microwave radiation[1] both in the United States and in the Soviet Union are causing a complete reevaluation of our use of electronic systems on the battlefield and the susceptibility of current devices to new forms of electronic warfare. At the Harry Diamond Laboratories, a reflex triode has been used to produce peak powers as high as 3 GW in the X-band. Although this device was originally developed as an ion source,[2,3] the oscillating dipole motion of the electrons makes it an obvious candidate for a source of electromagnetic radiation. A fully relativistic, time-dependent, one-dimensional simulation code was written to investigate these collective oscillations and to predict the microwave energy spectral density.

The Experiment

The basic geometry of the triode is shown in figure 1. When connected to the FX-45 Flash X-Ray machine at the Harry Diamond Laboratories,[4] the carbon cathode delivers 20 kA average current during a 25 ns wide pulsed accelerating potential of 1 MV peak. The anode is a 6.4 m thick aluminized Mylar film located 1 cm from the emission cathode. To keep the random energy and self-fields of the electrons from blowing up the beam (radially), a slow pulsed magnetic field of variable (0 to 4 kG) peak amplitude was applied along the axis of the triode. The final section of the vacuum coaxial line and

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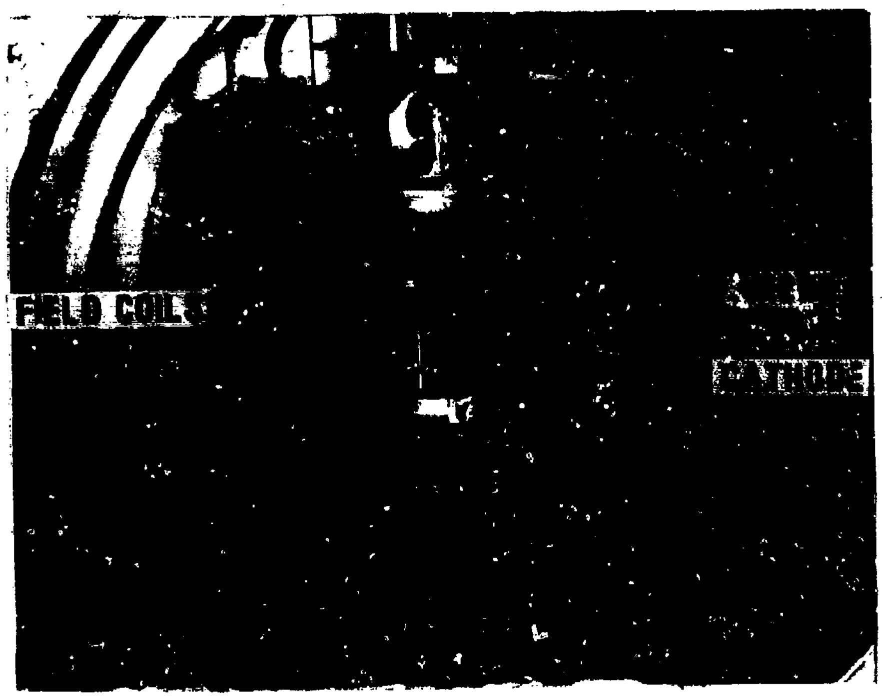

Figure 1. Reflex Triode Attached to FX-45 Pulse Time.

the cathode support structure were fabricated from copper clad G10 circuit board to maximize the intensity of the applied magnetic field and minimize the eddy current losses. The cathode diameter was 5 cm, the cathode-ground plane gap was 10.5 cm, and the anode-cathode gap was 1 cm.

The placement of the microwave diagnostics is shown in figure 2. X-band and Ku-band waveguides were used to carry signals to the detection apparatus. For radiation perpendicular to the triode axis, both horizontal and vertical polarizations were recorded by inserting and removing twists in the waveguide. Radiation parallel to the triode axis also was measured. Crystal detectors were used to determine power magnitudes, and long dispersive waveguides were used to examine the frequency content of the radiation.

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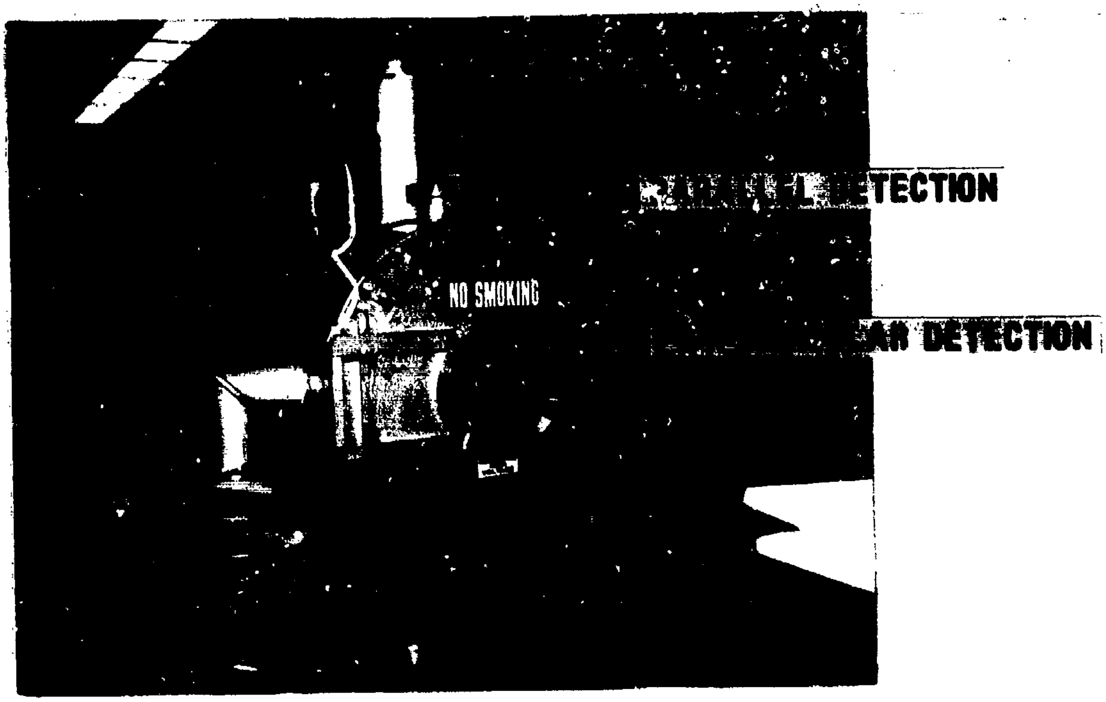

Figure 2. The Reflex Triode Vacuum Chamber with Microwave Diagnostics in Place.

Theory of Operation

The actual operation of the reflex triode is demonstrated by the particle trajectory shown in figure 3. As current from the cathode flows through the anode, space charge effects lead to the formation of charge bunches. These charge bunches reflect the electrons, and give rise to multiple modes of oscillation about the anode. The resultant space charge oscillations are similar to the Barkhausen oscillations that were observed in the early radio tubes of the 1920's.[5] These waves have a rich frequency content in which the dominant modes are determined by gap spacing, gap voltage, and applied magnetic field.

To gain insight into the parameters that affect microwave radiation from a reflex triode, a computer simulation of the electron motion was undertaken.[6] Based on a relativistic extension of the techniques used by Birdsall and Bridges,[7] the code used superparticle

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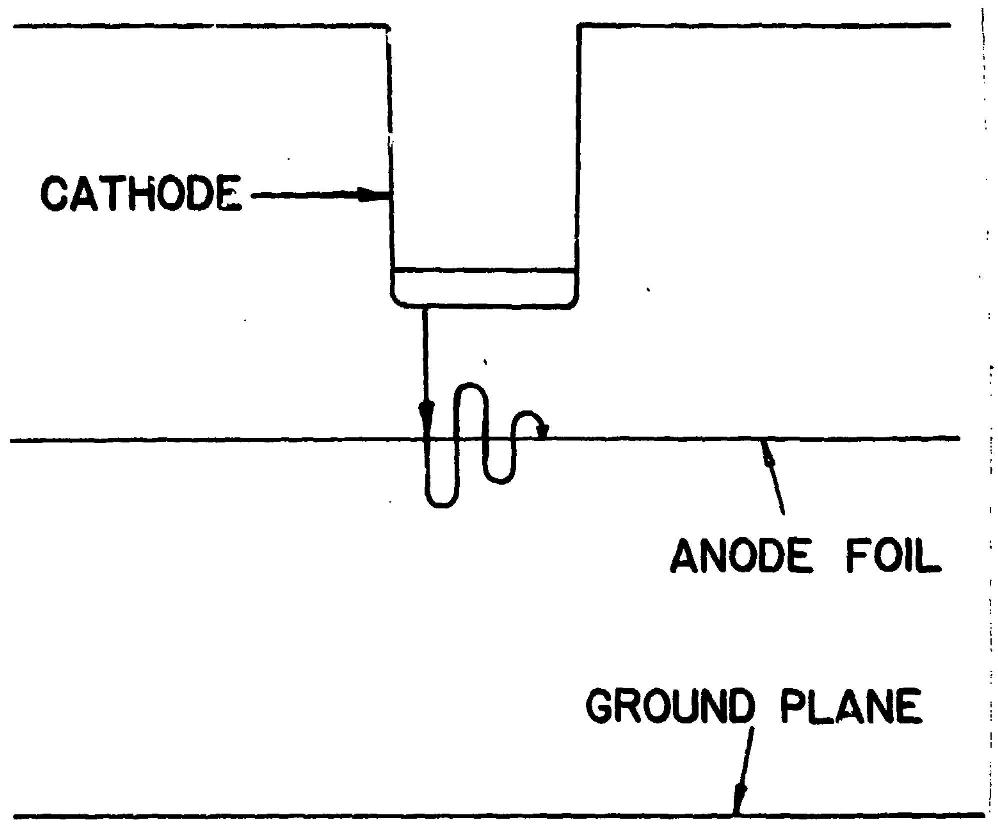

Figure 3. A Particle Trajectory in the Reflex Triode.

space charge sheets to represent the flow of charge in the triode. It was found that seven parameters completely define the electron dynamics of a reflex triode simulation run. The three geometric parameters are the distances from the anode to the near and far cathodes (shown as a ground plane in figure 3) and the area of the emitting cathode. The machine parameter is the waveform of the voltage applied to the anode-cathode gap as a function of time. The material parameter is the stopping power of the anode foil as a function of electron energy. The two internal code simulation parameters are the time step between electric field calculations and particle pushes and the available current for injection into the anode-cathode region. Time steps are chosen to be a small fraction of an anode-cathode light transit time. Typically, a time step of 0.26 ps is used, giving a Nyquist cutoff frequency of 2000 GHz.

The simulation results show that, at the onset of the voltage pulse across the anode-cathode gap, electrons are explosively pulled out of the cathode plasma and fill the triode region. The total space charge, however, does not monotonically increase but oscillates in time while rising to a saturated time averaged total charge. Electrons entering the gap with favorable phase relative to the given frequency component of the resultant space charge fields give up energy to the fields and remain in the triode region, while those with unfavorable phase will gain energy from the fields and are ejected from the triode region. Favorably phased electrons tend to be grouped together spatially since they enter at nearly the same time. Also, space charge periodically limits the subsequent entrance of electrons at the emission cathode. These mechanisms give rise to electron space charge bunching. While the electron bunches oscillate back and forth about the anode, they also interact with one another ejecting and capturing electrons from one another and thereby depleting and growing in size. This behavior is similar to strong Langmuir turbulence in a relativistic electron plasma.

Once the triode has been saturated, the total charge oscillates about the mean value. A spatially fluctuating virtual cathode forms on the far side of the anode at a time averaged distance approximately equal to the anode-cathode gap. Transient bunching mechanisms lead to high frequency oscillations about the anode. Spectral analysis of these space charge oscillations reveals a broad spectrum of peaks in the gigahertz regime separated by 0.2 to 0.4 GHz and peaking at 10 GHz.

The actual spectral density of the emitted radiation was computed in the far field dipole approximation by using the calculated current density of the space charge cloud. An important

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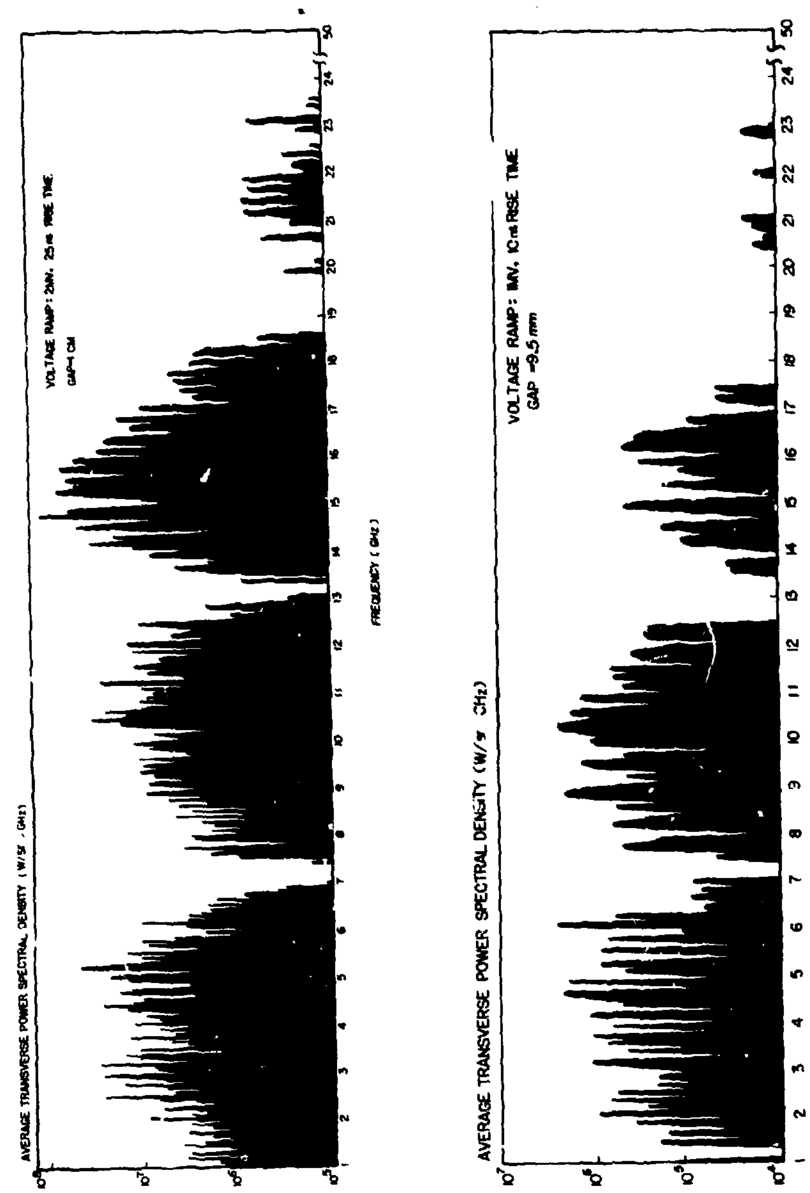

Figure 4. Calculated Microwave Spectra from a One-Dimensional Reflex Triode Computer Simulation

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consequence of this treatment is an interference form factor for the oscillating space charge cloud geometry with zeroes in the region of interest (7.2 and 13.2 GHz).

Discussion

Figure 4 shows two calculated average power spectra for typical experimental parameters. On the upper plot, the predicted average power in the X-band is approximately 50 MW. This prediction compares favorably with experimental shots during which a high (several kilogauss) magnetic field was applied along the axis of the triode and confirms the validity of the model in that parameter regime. The high magnetic field confines particle movement to the one-dimensional motion seen in the computer simulations. The lower plot shows the computed radiation spectrum that would be expected if a larger (higher peak and longer rise time) pulse were applied across the anode-cathode gap. The power output is seen to be sensitive to changes in the size of the applied voltage pulse, which (in our machine) typically varies by 5 to 10%. Such variations can at most account for power outputs of 100 to 150 MW, while peaks as high as 3 GW have been recorded experimentally.

For all shots on which more than 200 MW of peak power was measured, the applied field was less than 500G. At these low magnetic field levels, the electron motion is no longer constrained to one dimension and the system may allow multi-dimensional motion and bunching effects which would influence the production of gigawatt peak power microwave pulses. To better understand and exploit these effects, a fully relativistic, time dependent, 2 $\frac{1}{2}$- dimensional superparticle simulation code is being prepared and should be operational by mid 1980. It is hoped that a more sophisticated model of triode operation will be constructed that will predict the production of higher peak and average output powers with a substantial increase in efficiency (presently 5%). Already, 30% efficiency at gigawatt power levels in S-band has been achieved with a triode at the Tomsk Polytechnical Institute in the Soviet Union.[8]

Near term experiments will attempt to operate without a physical anode foil, to match the impedance of the triode to the electron beam generator, and to carefully map the dependence of the microwave radiation on the applied magnetic field. Long term goals will concentrate on using the results of our simulation effort to improve our understanding of the reflex triode and to increase its radiation output.

Microwave Devices and Applications

Table I lists the values of various parameters associated with the reflex triode and allows comparison with values from two other experimental devices that have produced gigawatt power levels of microwave radiation. The magnetron is an attractive device, but the small size required for microwave operation limits the voltage and the current that can be applied and therefore the power that can be extracted. The pulsed Gyrotron is a large, inefficient experiment that requires (in its present form) a huge electron beam generator which would prohibit practical use on the battlefield. However, the reflex triode requires only a modest electron beam source, and optimization should be able to increase both its output and its efficiency.

Table I
Parameters for Ultrahigh Power Microwave Generating Experiments

Parameter	Magnetron[9,10]	Gyrotron[11]	Reflex Triode[6]
Accelerating potential	360 kV	3.3 MV	1 MV
Beam current	12 kA	80 kA	20 kA
Pulse length	30 nsec	70 nsec	20 ns
Axial field	8 kG	10 kG	75 G
Power out	1 GW	1 GW	1 GW
Frequency	S-band	X-band	X-band
Efficiency	35%	0.4%	5%

To place a device like the reflex triode experiment in a proper practical perspective, it is necessary to consider its actual use on the battlefield. Historically, one of the weakest links preventing exploitation of these ultrahigh power microwave sources has been the electron beam generators. However, capabilities for producing intense relativistic electron beams have also increased dramatically over the last several years.[12,13] Although most of the industry's attention has been devoted to the superhigh power generators like the (10 MV, 1 MA) AURORA and the (1.5 MV, 4.5 MA) Proto II facilities, a great deal of work has been done on improving reliability, reproducibility, and the repetition rate of the smaller (0.25 MV, 5 to 30 kA) machines.

At the Sandia Laboratories, an electron beam machine has been designed[14] to deliver 350 kV, 30 kA, 30 nsec pulses at a continuous rate of 100 per second. The machine has actually operated in this

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mode for several minutes without suffering any type of breakdown. Improved versions of this machine have delivered voltages as high as 1 MV to diodes on a sustained repetition rate basis. Any of the Sandia repetition rate machines would easily fit on a flatbed trailer, and with some minor component redesign, they could probably be squeezed onto a pickup truck. In short, these machines are on the verge of becoming exceptionally transportable. With such electron beam generators already being developed, practical use of the ultrahigh power microwave generation schemes is already becoming possible.

There are four major areas where microwaves find use on the battlefield: communications, radars, electronic warfare, and directed energy weapons.

In communications applications, high power means longer ranges, better signal to noise ratios, and immunity to jamming and interference. Practical monopulse radars could be developed to cover problem-situations in which the transmitter must remain hidden or the target must be acquired rapidly and there is no time to process multiple pulses. These sources are useful not only as jammers, but also as simulators of enemy jamming equipment. Finally, the outputs of these devices are reaching levels where they can be considered as directed energy weapons.

Conclusion

Although several laboratory experiments have demonstrated the capability of generating gigawatt power levels of microwave radiation, the Army's work on the reflex triode has established it as the clear front-runner in the race to put practical ultrahigh power microwave sources on the battlefield in the 1980's. We should be ready to incorporate these new sources into our defense technology, and we should be prepared for the problems that these devices can cause when they are used against us.

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