LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR-88-2189

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--88-2189

DE88 014317

TITLE: EFFECTS OF MODULATED ELECTRON BEAMS AND CAVITIES ON REDITRONS

AUTHOR(S): T. J. T. Kwan, H. A. Davis, R. D. Fulton, and E. G. Sherwood

SUBMITTED TO: BEAMS - '88, Karlsruhe, Germany, July 4-8, 1988

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

EFFECTS OF MODULATED ELECTRON BEAMS AND CAVITIES ON REDITRONS

T. J. T. Kwan, H. A. Davis, R. D. Fulton, and E. G. Sherwood
Los Alamos National Laboratory
Los Alamos, New Mexico
U. S. A. 87545

ABSTRACT

The virtual cathode, when formed in a cavity, can generate microwaves at different cavity modes depending on the geometry of the cavity. We found that the formation and the oscillation frequency of the virtual cathode in a reditron can be significantly influenced by cavity designs. The length of a cavity can play a role in frequency and mode selection. Our simualtions showed that TM_{012} and TM_{033} were excited for cavity lengths of 15.0 cm and 22.5 cm, respectively. In addition to the cavity effects on reditrons, we discovered that highly modulated electron beams can be produced in reditrons. Full modulation (100%) of the transmitted electron beam current has been confirmed in our simulations. We further showed that incorporation of an inverse diode configuration can achieve microwave production efficiency of 26%.

INTRODUCTION

Virtual cathode oscillators are among the most promising high-power microwave sources.[1-9] The reditron[10] is a virtual cathode microwave generator where an intense inject an intense electron beam is injected into a circular waveguide through a slot in a range-thick anode. An axial magnetic field guides the electrons through the slot. The injected beam current is above the space-charge limit in the circular waveguide causing the formation of a virtual cathode. Computer calculations[10] have shown this approach potentially leads to enhanced efficiency, more monochromatic output, and better mode control than conventional unmagnetized or magnetized systems because of the elimination of reflexing electrons. An efficiency of 12% with bandwidths of less than a few percent were predicted. Subsequently, we demonstrated experimentally[11] inhibition of electron reflexing into the diode region, and reported on gigawatt level microwave radiation. In recent experiments, 7-10% efficiency has been achieved in reditrons. (See the paper by H. Davis et al., in this volume.)

The reditron configuration has a number of parameters which can be varied to optimize produced power. Among these are the anode-cathode gap, the anode slot width, and the applied magnetic field. In previous work[11], the optimum anode-cathode gap was determined to be 3.7 cm. Of course, the optimum values change with respect to electron beam voltage and current and the geometric dimension of the device.

PRODUCTION OF HIGHLY MODULATED ELECTRON BEAM IN REDITRONS

We have used the two dimensional fully electromagnetic and relativistic particle simulation code, ISIS, to study an optimized operation of the reditron. The parameters of the case simulated were: $V_0 = 1.2$ MV, $I_0 = 19$ kA, $R_w = 9.0$ cm, $R_b = 3.0$ cm, $B_0 = 6.1$ kG, $\Delta_{ak} = 3.7$ cm, $\delta = 0.35$ cm. V_0 is the beam voltage. I_0 is the beam current. R_w is the waveguide radius. R_b is the radius of the annular electron beam. Δ_{ak} is the anode-cathode gap. δ is the slot size of the anode. B_0 is the magnetic of the external coil in the diode region. The magnetic field profile of field coil was calculated according to various experimental situations by a time independent code, BFIELD. The external magnetic field in a particle-in-cell simulation of reditrons was initialized according to the result of BFIELD. A TEM wave was launched from the left side into the coaxial line formed by the cathode and the anode as depicted in Fig. 1. Electron emission from the cathode was modelled according to the space charge limited field emission process. The phase space diagram in Fig. 1 shows the formation of a strong oscillating virtual cathode. The reflexing electrons were virtually eleminated by the thick slotted anode since the chance for an electron to go through the slot several times was negligibly small. The diverging electron beam in the waveguide was a result of the magnetic field lines of the external coil. In the simulation, the voltage had a linear rise and was then kept constant thereafter. Strong and coherent excitation of waveguide mode TM_{01} was observed. The time history of the electric component of TM_{01} and its Fourier spectrum are shown in Fig. 2.

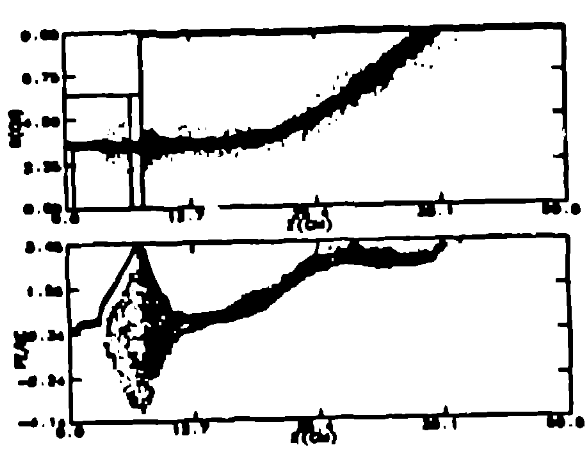

Fig. 1 Real and phase space diagrams of the optimized reditron.

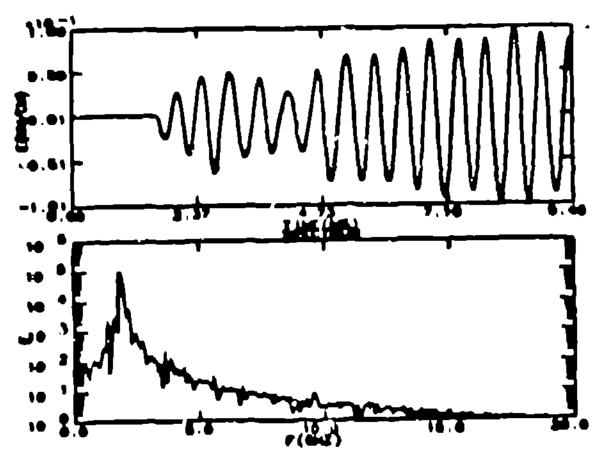

Fig. 2 Time history and Fourier spectrun of TM_{01} from the simulation.

The bandwidth was basically limited by the pulse length of the microwave radiation in the simulation. We have also discovered that the leakage electron beam was highly modulated due to the oscillatory characteristics of the virtual cathode. The current of the leakage electron beam was monitored in time in the simulation at three different axial positions and the results are shown in Fig. 3. Almost full modulation (100%) of the electron beam was achieved immediately beyond the virtual cathode. The strong and coherent modulation of the leakage current in reditrons suggests the incorporation of an inverse diode to further increase the microwave power and production efficiency.

Figure 4 shows a computer simulation where a center conductor was inserted in the waveguide to intercept the modulated electron beam so that the its kinetic energy would be converted to a transverse electromagnetic (TEM) wave in the coaxial transmission line. The amplitude of the TEM waves as a function of time is shown in Fig. 5 indicating strong excitation of TEM waves at the frequency of 1.91 GHz. This frequency corresponded to the electron beam modulation and the TM_{01} mode excited by the reditron. The time averaged power of the TEM wave was about 6 GW which was 26% of the electron beam power in the diode.

EFFECTS OF CAVITIES IN REDITRONS

The importance of the use cavities in reditrons are bandwidth narrowing and frequency and mode selectivity. We have numerically simulated the operation of the reditron with cavities of different lengths. The cavity was placed immediately after the thick anode and its radius was chosen to be 9.0 cm. The cavity length was varied in different simulations. The reditron diode was modelled to produce an electron beam of 1.2 MeV and 14.0 kA. In the first case, the cavity length was 10.0 cm. The external magnetic field was 11.9 kG on axis in the diode region. The space

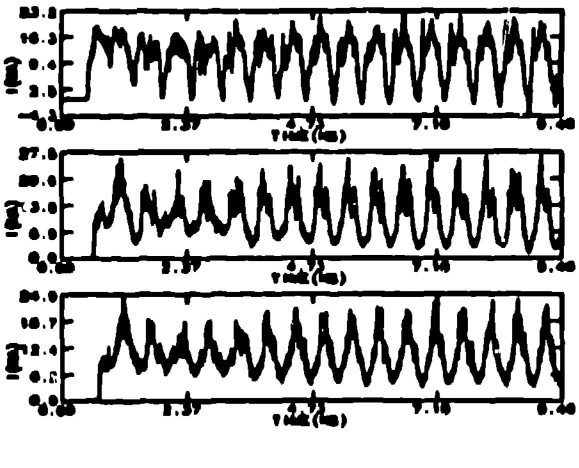

Fig. 3 Modulated electron beam produced by the reditron.

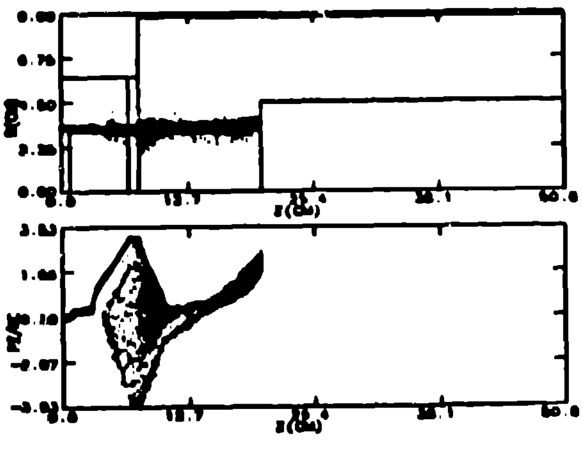

Fig. 4 Incorporation of an inverse diode in the reditron.

charge limiting current as calculated from $I_{scl} = I_0(\gamma^{2/3} - 1)^{3/2}/2\ln(r_w/r_b)$ was 10.6 kA. However, the cavity was found to significantly change the space charge limiting current from the infinite waveguide approximation because the cavity length was about the same as its radius. In the simulation, a virtual cathode did form and oscillate initially but it was only a transient phenomenon. The level of electromagnetic radiation in the cavity was found to be very low and experimental data also confirmed this. (See the paper by H. Davis et al., in this volume.)

The next case which we studied had a cavity length of 15.0 cm. The diode was identical to the previous case. The real space (r vs z) and phase space (p_z vs z) diagrams of the electron beam from the simulation are shown in Fig. 6. The formation of an oscillating virtual cathode is clearly illustrated and most of the reflexing electrons were intercepted and subsequently absorbed by the thick anode. It should be pointed out that Monte Carlo electron transport method was used in the particle simulation to determine the interaction of the electrons with the anode material. Strong microwave emission from the oscillating virtual cathode was observed in the simulation. The dominant mode was found to be TM_{021} and the other modes had much smaller amplitudes (at least an order of magnitude smaller). The time history of TM_{021} and its Fourier transform were illustrated in Fig. 7. The frequency spectrum shows a narrow peak at 3.09 GHz which corresponds to TM_{021}.

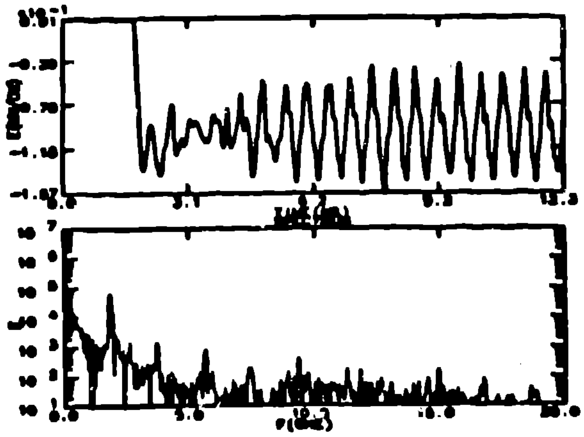

Fig. 5 Strong excitation of TEM wave in the reditron with an inverse diode.

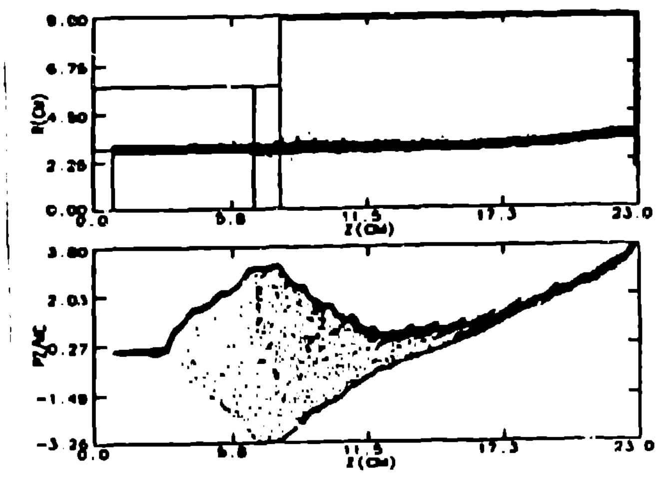

Fig. 6 Real space and phase space diagrams of the electron beam of the reditron in the 15.0 cm long cavity.

charge limiting current as calculated from $I_{scl} = I_0(\gamma^{2/3} - 1)^{3/2}/2\ln(r_w/r_b)$ was 10.6 kA. However, the cavity was found to significantly change the space charge limiting current from the infinite waveguide approximation because the cavity length was about the same as its radius. In the simulation, a virtual cathode did form and oscillate initially but it was only a transient phenomenon. The level of electromagnetic radiation in the cavity was found to be very low and experimental data also confirmed this. (See the paper by H. Davis et al., in this volume.)

The next case which we studied had a cavity length of 15.0 cm. The diode was identical to the previous case. The real space (r vs z) and phase space (p_z vs z) diagrams of the electron beam from the simulation are shown in Fig. 6. The formation of an oscillating virtual cathode is clearly illustrated and most of the reflexing electrons were intercepted and subsequently absorbed by the thick anode. It should be pointed out that Monte Carlo electron transport method was used in the particle simulation to determine the interaction of the electrons with the anode material. Strong microwave emission from the oscillating virtual cathode was observed in the simulation. The dominant mode was found to be TM_{021} and the other modes had much smaller amplitudes (at least an order of magnitude smaller). The time history of TM_{021} and its Fourier transform were illustrated in Fig. 7. The frequency spectrum shows a narrow peak at 3.09 GHz which corresponds to TM_{021}.

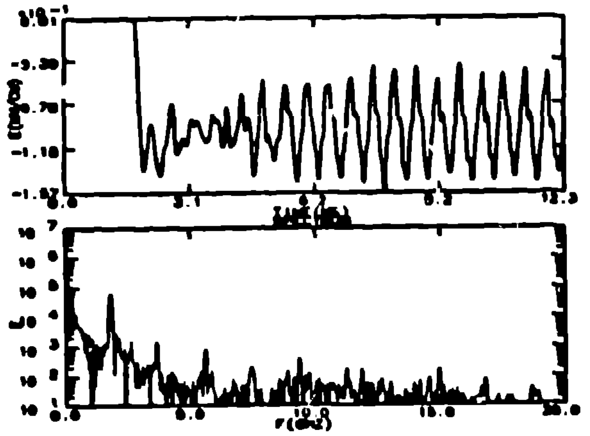

Fig. 5 Strong excitation of TEM wave in the reditron with an inverse diode.

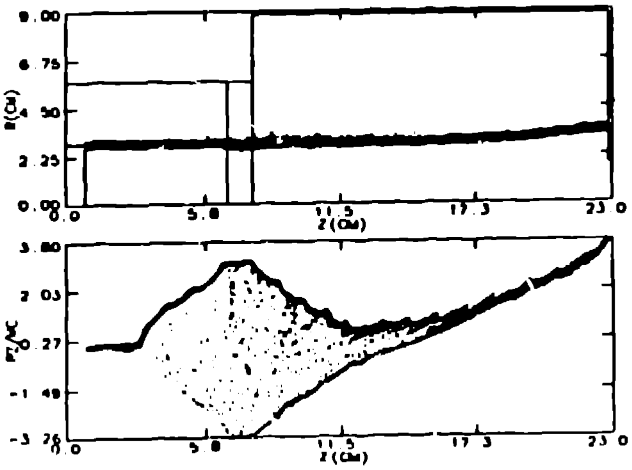

Fig. 6 Real space and phase space diagrams of the electron beam of the reditron in the 15.0 cm long cavity.

The third series of simulation was carried out with a cavity length of 22.5 cm. We observed from the simulation that the dominant mode was not TM_{021} but TM_{033} with a frequency of 4.9 GHz. There were other competing mode in the simulation but their amplitudes were relatively small. The time evolution of the TM_{033} and its Fourier transform are shown in Fig. 8. The beating phenonemon observed in the time histroy of the mode is an indication of mode competition. This is confirmed by its Fourier transform which shows a relatively broad peak at 5.0 GHz. Careful optimization with respect to magnetic field strength might yield a narrower bandwidth and this is under current investigation. The fact that the excited cavity mode and its frequency depend on the cavity length can render the reditron frequency and mode selectivity.

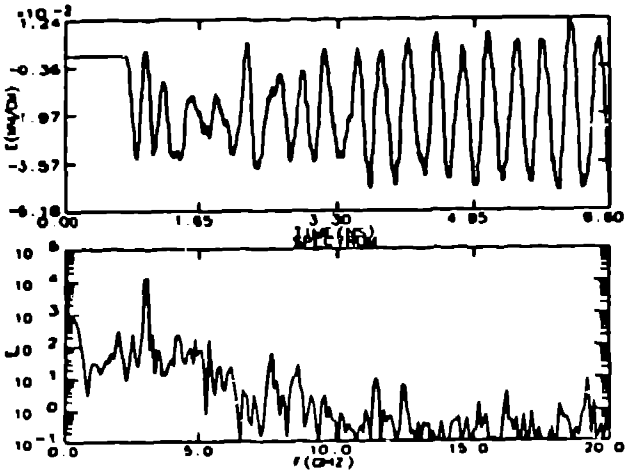

Fig. 7 Time evolution of the cavity mode TM_{021} showing coherent oscillations and very narrow bandwidth.

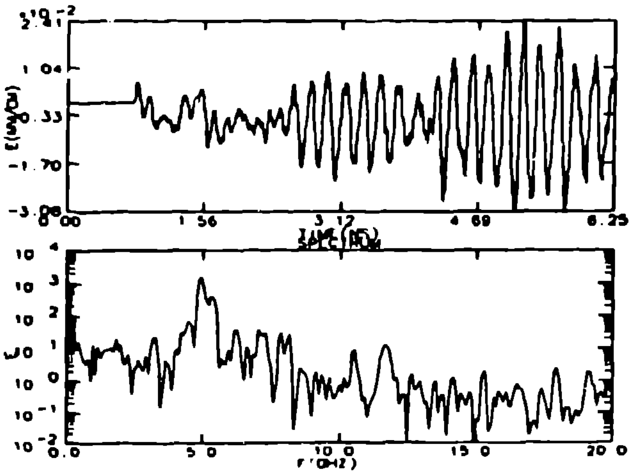

Fig. 8 Excitation of a different cavity mode, TM_{033}, using a 22.5 cm long cavity in the reditron.

CONCLUSIONS

Our investigation showed that the incorporation of a inverse diode in the reditron can generate very high-power monochromatic microwaves with an efficiency of 26% which is an order of magnitude higher than conventional vircators. Furthermore, we domonstrated through computer simulations and it was verified by experiments that the use of cavities in reditrons can effectively select the output microwave frequency and its mode structure.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy and by the U. S. Strategic Defense Organization, Office of Innovative Science and Technology, under a contract managed by Department of the Army, Harry Diamond Laboratory.

REFERENCES

1. R.A. Mahaffey, P. Sprangle, J. Golden, and C.A. Kapetanakos, Phys. Rev. Lett., 39, 843 (1977).
2. H.E. Brandt, A. Bromborsky, H.B. Bruns, and R.A. Kehs, Proc. Second International Topical Conference on High Power Electron and Ion Beam Research and Technology,Cornell University, 1977, p. 649.
3. J.M. Buzzi, H.J. Doucet, B. Etlicher, P. Haldenwang, A. Huetz, H. Lamain, C. Rouille, J. Cabe, J. Delvaux, J.C. Jouys, and C. Peugnet, ibid, Ref. 3, p.663.
4. A.N. Didenko, A.G. Zherlitsyn, A.S. Sulakshin, G.P. Formenko, V.I. Tsvetkov, and Yu.G Shtein, Pis'ma V Zhurnal Tekh. Fiz. 9, 1510, (1983).
5. D.J. Sullivan, IEEE Trans. on Nucl. Sci. 30, 3426 (1983).
6. T.J.T. Kwan and L.E. Thode, Phys. Fluids 27, 1570 (1984).
7. H.A. Davis, R.R. Bartsch, L.E. Thode, E.G. Sherwood, and R.M. Stringfield, Phys. Rev. Lett. 55, 2293 (1985).
8. H. Sze, J. Benford, T. Young, D. Bromley, and B. Harteneck, IEEE Trans. on Plasma Sci. PS-13, 492 (1985).
9. R.D. Scarpetti and S.C. Burkhardt, in ibid, Ref. 9, p. 506.
10. T.J.T. Kwan, Phys. Rev. Lett. 57 1895 (1986).
11. H.A. Davis, R.R. Bartsch, T.J.T. Kwan, R.M. Stringfield, and E.G. Sherwood, Phys. Rev. Lett. 59, 288 (1987).