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Bunch Beam Production and Mircrowave Generation in Reditrons

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ABSTRACT

We have discovered in our two-dimensonal particle-in-cell simulations that the oscillation of virtual cathodes in reditrons can produce a highly modulated electron beam. Full (100%) current modulation of the leakage electron beam was observed in our simulations. The modulation is at the frequency of the oscillating virtual cathode and the transverse magnetic mode generated by the reditron. We had further incorporated an inverse diode in the reditron and showed that the kinetic energy of the modulated electron beam was efficiently converted into transverse electromagnetic waves. Our simulations showed an efficiency of 26% and the time averaged microwave power was about 6 GW.

I. INTRODUCTION

The reditron[1-5] (reflected electron discrimination microwave generator) is a new type of virtual cathode device which uses an electron range thick anode to prevent reflected electrons from re-entering the diode region. As a result, the microwave generation is purely due to oscillation of the virtual cathode in a reditron. It has been shown in our computational and experimental study that reditrons can produce microwaves with a much better spectral purity and with much higher efficiency in comparison with other virtual cathode devices. It has been demonstrated experimentally that the reditron can produce 2.3 to 3.3 GW of microwave radiation at 7.5 to 10.0 % efficiency with a very narrow spectrum centered at 2.15 GHz[6,7]. The spectral width was predominantly limited by the number of cycles of microwaves produced in the pulse (about 100 cycles). This is roughly a factor of 2.5 to 3.3 increase in efficiency and about 3 in bandwidth narrowing over conventional vircators.

In our recent simulation study, we discovered another important aspect of the reditron that the transmitted electron beam current can be highly modulated by the oscillatory characteristics of the virtual cathode. Furthermore, we showed in our computer simulations that through the use of an inverse diode that a modulated electron beam can be effectively converted into coherent transverse electromagnetic waves. The result is very encouraging that an overall efficiency of TEM wave production reached 26%. The use of an inverted diode to extract power from a modulated electron beam is only one of the many methods available to us. For example, the use of a slow wave structure can lead to strong excitation of transverse magnetic modes. Incorporation of such an efficient device into the reditron design can greatly enhance the operating power level and its efficiency.

II. PRODUCTION OF HIGHLY MODULATED ELECTRON BEAMS IN REDITRONS

The reditron configuration has a number of parameters which can be varied to optimize output power. Among them are the anode-cathode gap, the anode slot width, and the applied magnetic field. In previous work[6], 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. We used the optimal configuration to investigate the modulation of the leakage electron beam and the extraction of coherent electromagnetic radiation in a inverse diode configuration.

We 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, Δ_{ak} = 3.7 cm, δ = 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 field of the external coil in the diode region. The magnetic field profile of field coil was calculated according to various experimental situations by the time independent code, BFIELD. The external magnetic field in a particle-in-cell simulation of reditrons was initialized according to the result from the code BFIELD. The space charge limiting current in the waveguide section is calculated to be approximately 12 kA according to the formula for infinitesimally thin annular electron beam. 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 diagrams of the electron beam at an instant of time are shown in Fig. 1. The formation of a strong oscillating virtual cathode is evident. 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 the waveguide mode TM_{01} was observed. The time history of the electric component of the TM_{01} mode and its Fourier spectrum are shown in Fig. 2. The frequency was 1.9 GHz. The bandwidth was basically limited by the pulse length of the microwave radiation in the simulation. The radiation power in the TM_{01} mode in the waveguide was monitored during the course of the simulation. Figure 3 shows the time evolution of the axial Poynting vector associated with the TM_{01} mode and its energy. The high-power and high-efficiency characteristics of the reditron were clearly demonstrated. Note that the simulation was only run out to 9.45 ns to illustrate the trend in the operation of the reditron.

We have also discovered in the computer simulation that the leakage electron beam was highly modulated due to the oscillatory characteristics of the virtual cathode. The virtual cathode behaved as a gate controlling the transmitted electrons at the oscillating frequency. 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. 4. 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 is significant that further extraction of radiation power from the modulated electron beam can greatly enhance the power level and efficiency of reditrons. The frequency of modulation is that of the TM_{01} mode, which is the oscillating frequency of the virtual cathode. Unlike other schemes producing modulated electron beams, the leakage electron beam does not need any drift region to achieve full modulation. This discovery in the reditron suggests the incorporation of an inverse diode or any suitably chosen slow wave structures to further increase the microwave power and production efficiency.

III. MICROWAVE GENERATION IN REDITRONS

One of the more straight forward ways to extract coherent radiation from a modulated electron beam is the use of an inverse diode. The center conductor in the coaxial configuration serves as the electron beam dump and the voltage developed between the inner and outer conductors is transmitted along the coaxial line in the form of a TEM wave. Figure 5 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 simulation parameters are the same as the optimal case for the reditron described in the previous section. The leakage electron beam was found to be highly modulated. In Fig. 6, the time evolution of the leakage electron beam obtained by a probe at an axial position before the center conductor showed strong and coherent modulation. The frequency was the characteristic oscillation frequency of the virtual cathode and the strongly excited TM_{01} mode. The amplitude of the TEM waves as a function of time is shown in Fig. 7 indicating strong excitation of TEM waves at the frequency of 1.91 GHz in the coaxial transmission line. 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. The axial power flow of the TEM waves in the coaxial transmission line at three axial positions from the simulation is shown in Fig. 8.

Interaction of a modulation electron beam with slow wave structures leading to generation of high-power microwaves is a reasonably well established subject. Usually, the slow wave structure causes bunching of the electron beam and electromagnetic waves are generated through an instability involving a negative energy space charge beam mode. A highly pre-modulated electron beam would have the advantage of inducing the instability at a pre-selected frequency and therefore the bandwidth of the unstable waves becomes much narrower. The reditron has already been shown to generate microwaves with narrow bandwidth and it would be natural to integrate it with the interaction between a suitably chosen slow wave structure and the highly modulated leakage electron beam. This could lead to greatly enhanced operating power level and overall efficiency.

IV. CONCLUSIONS

We have shown that the reditron can produce a highly modulated electron beam in addition to high-power microwaves. It is further demonstrated the possibility of the conversion of the modulated electron beam into electromagnetic energy, in particular, through the use of an inverse diode. By properly integrating the two mechanisms, one might realize a modified reditron which can be operated at even higher power level and efficiency.

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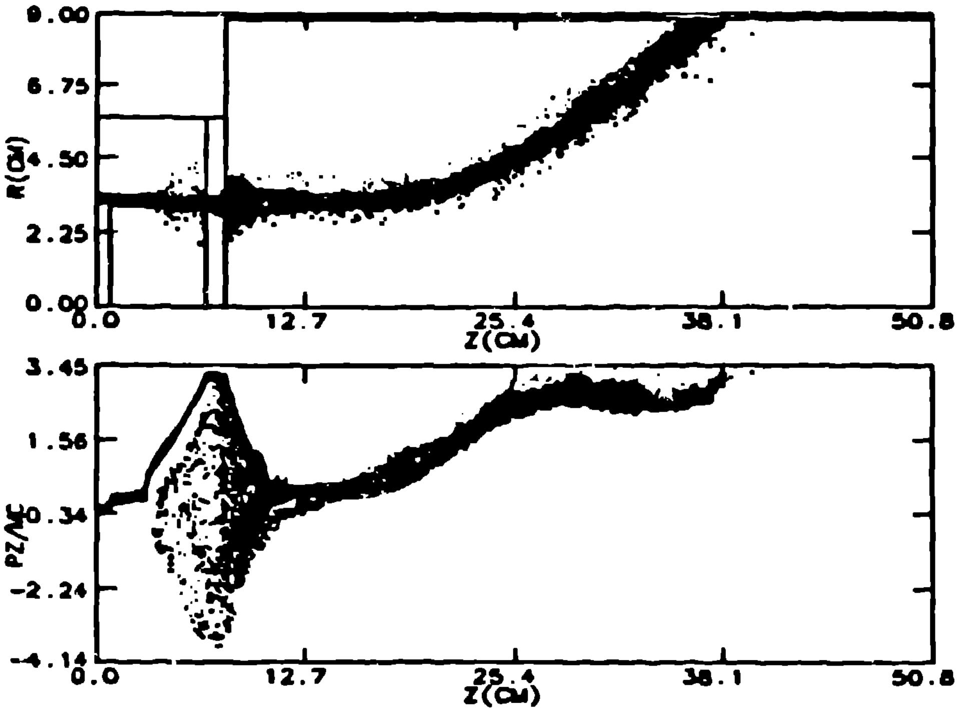

Fig. 1 Real and phase space diagrams of the optimized redtron.

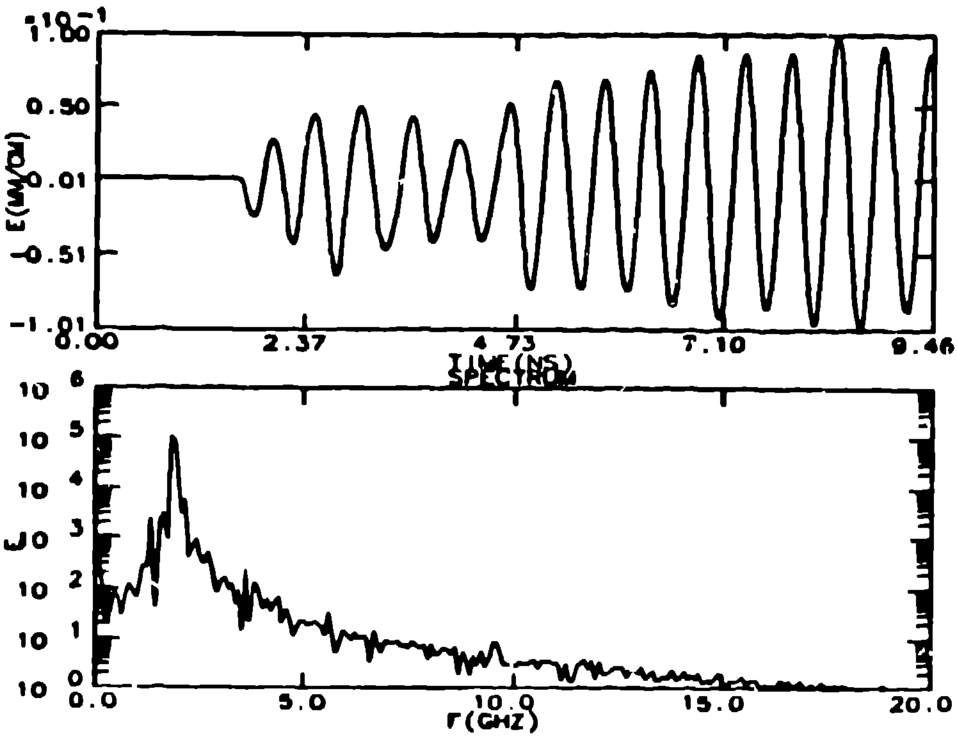

Fig. 2 Time history and Fourier spectrun of TM_{01} from the simulation.

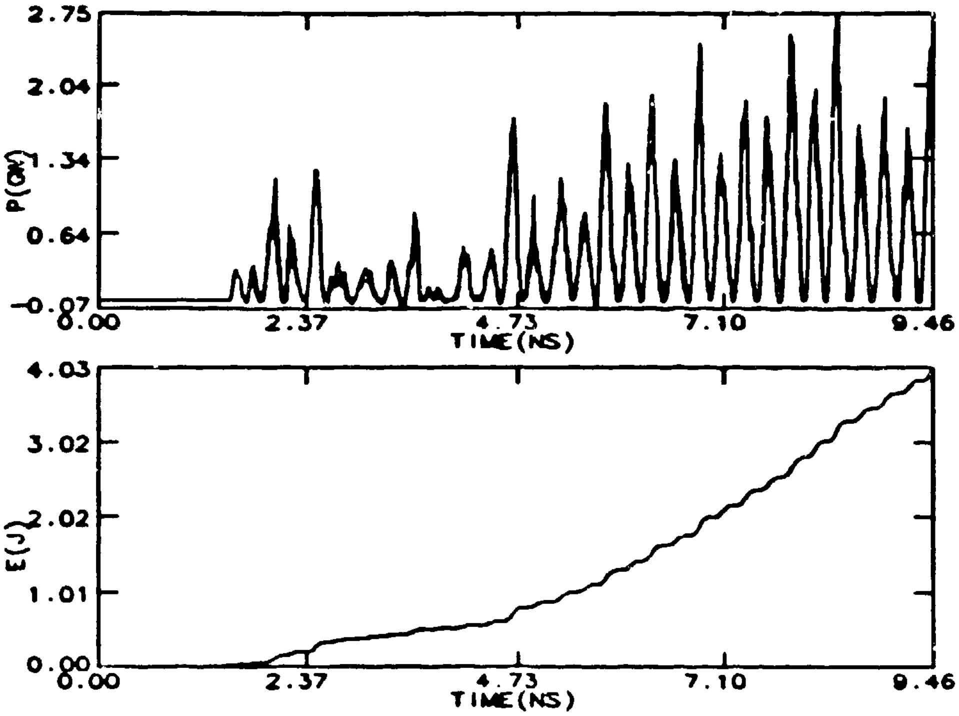

Fig. 3 Time histories of microwave power and energy produced in the optimized reditron.

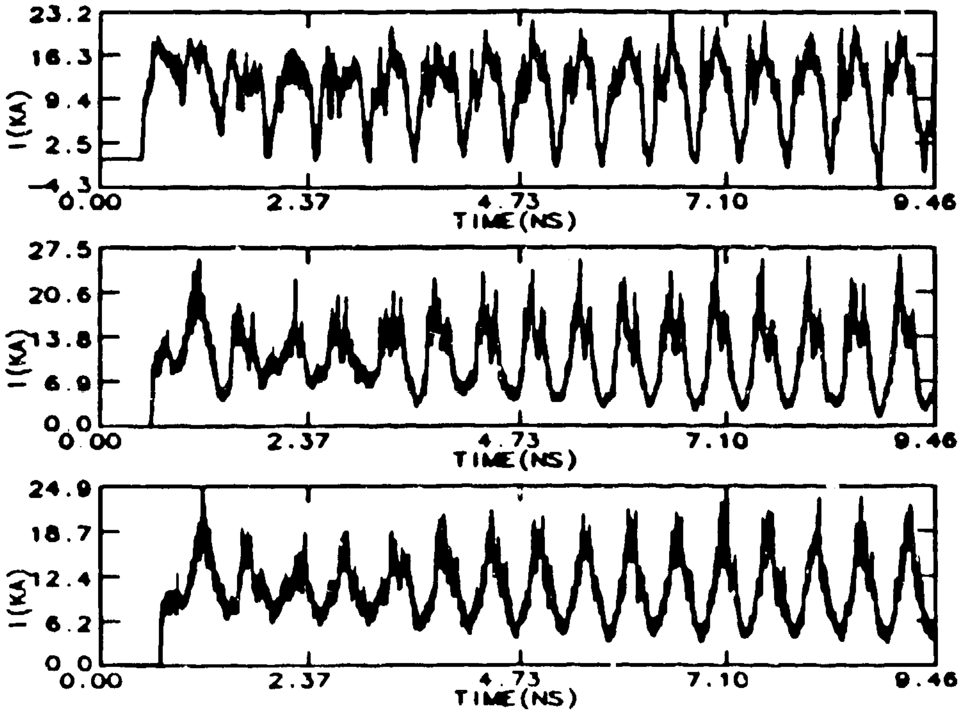

Fig. 4 Modulated electron beam produced by the reditron.

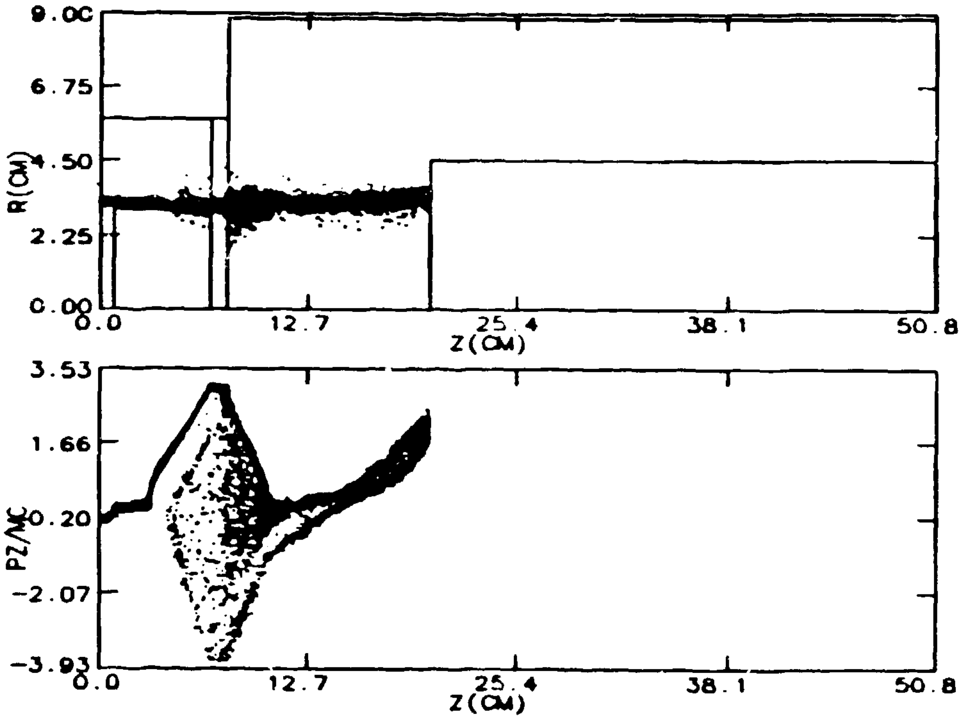

Fig.5 Incorporation of an inverse diode in the reditron.

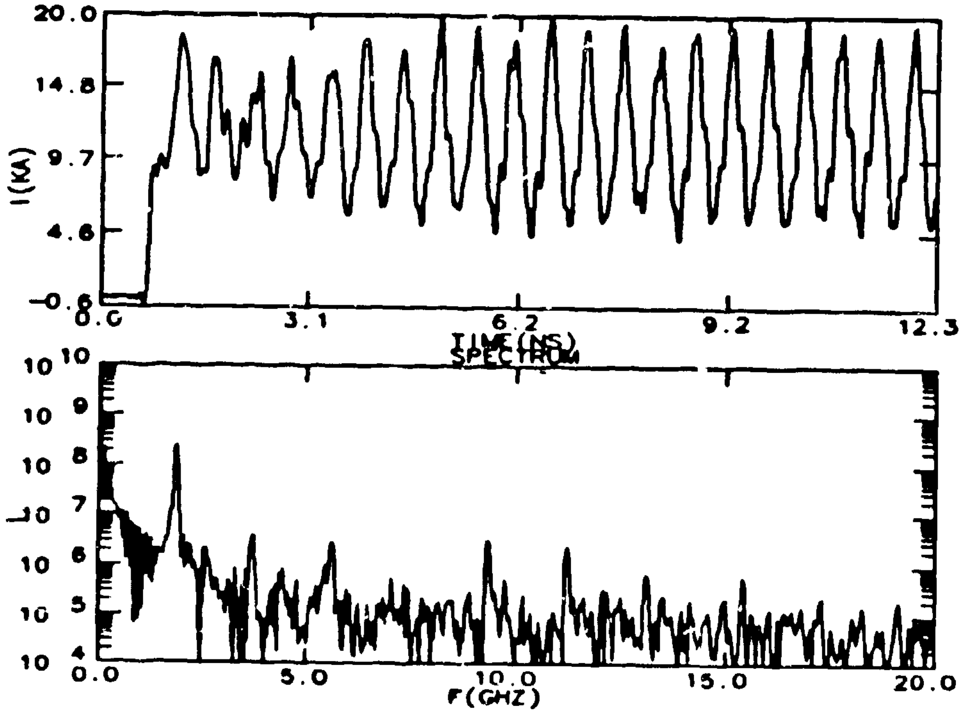

Fig. 6 Current modulation of the transmitted beam is not affected by the center conductor.

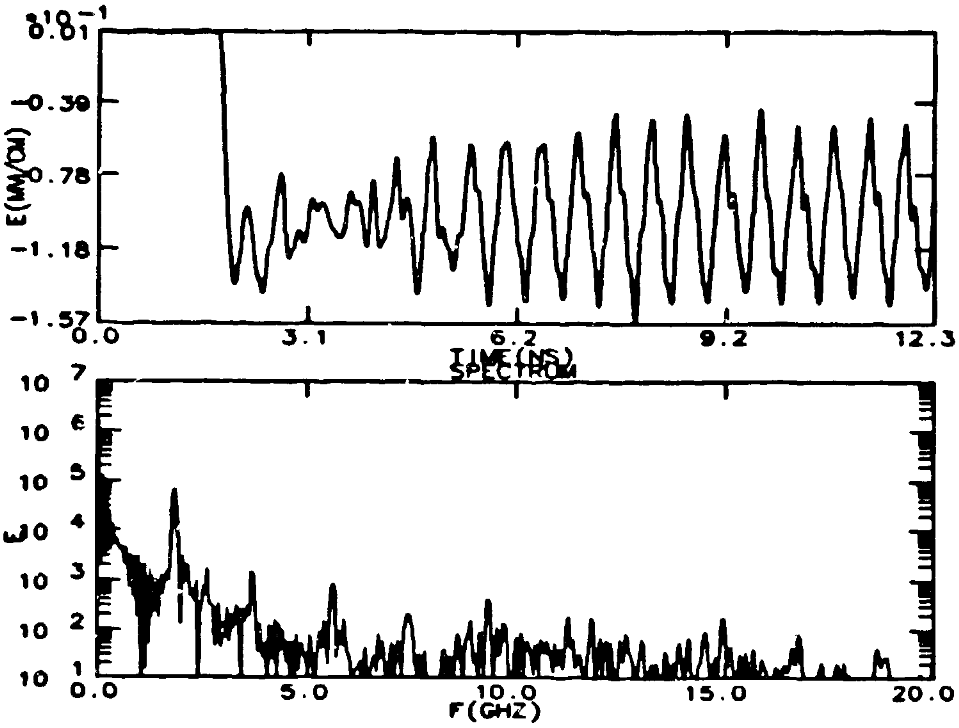

Fig. 7 Strong excitation of TEM wave in the reditron with an inverse diode.

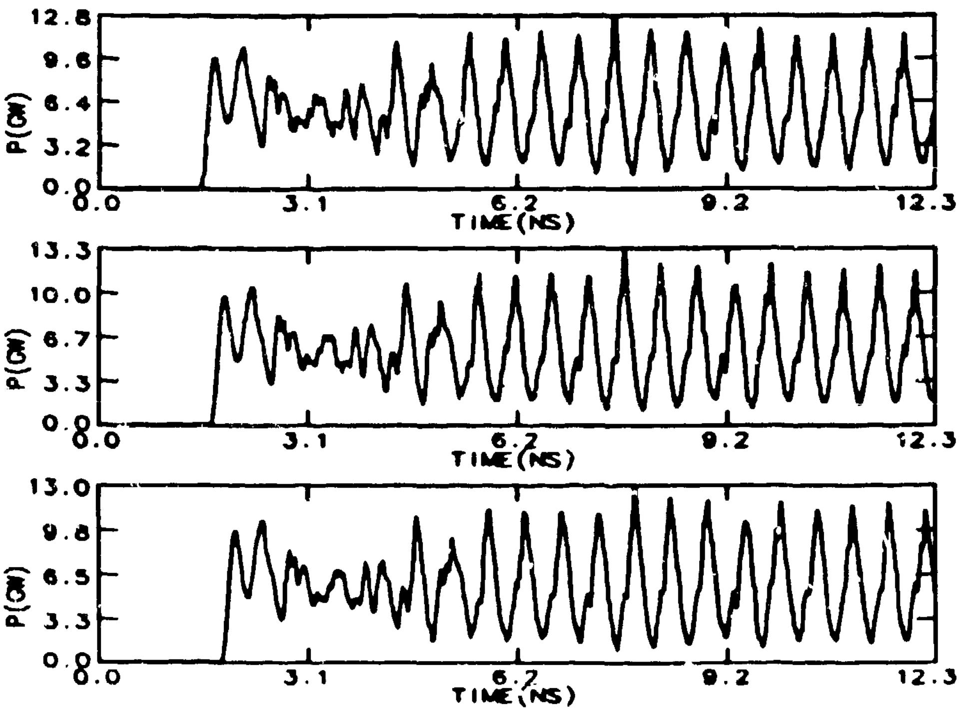

Fig. 8 Power flow of the TEM waves at three different axial positions in the coaxial transmission line.