UPPER HYBRID WAVE COLLECTIVE ACCELERATOR STUDIES

E. Chojnacki, T. J. Davis, J. D. Ivers and J. A. Nation,
Laboratory of Plasma Studies and School of Electrical Engineering,
Cornell University, Ithaca, N.Y. 14853

Introduction

The fast upper hybrid wave on an intense, weakly relativistic electron beam is being studied as a possible mode for use in a collective particle accelerator[1]. In linear theory the wave has a dispersion similar to that found for a cyclotron wave and differs from the cyclotron wave only in as much as the effects of space charge are important in the analysis[2,3]. A typical dispersion relation for the fast and slow hybrid modes is shown schematically in figure 1. The wave phase velocity can be tuned to the speed of light by control of the guide magnetic field strength. Thus ultrarelativistic particles can be accelerated in the wave without the need for sophisticated particle wave phase synchronization systems. In the following sections we report progress in the development of a low repetition rate modulator for use in this project and initial results on wave excitation on a 400 kV, 150-400 Amp. beam driven by a single shot Marx-Blumlein pulser. Waves are excited as the beam propagates through a cavity where an interaction develops between the rotating beam and electromagnetic waves in the cavity. The cavity is tapered into a uniform guide in which all electromagnetic modes are cut off for the frequencies of interest while the cyclotron body wave on the beam continues to propagate. We report on measurements of the body wave downstream of the cavity.

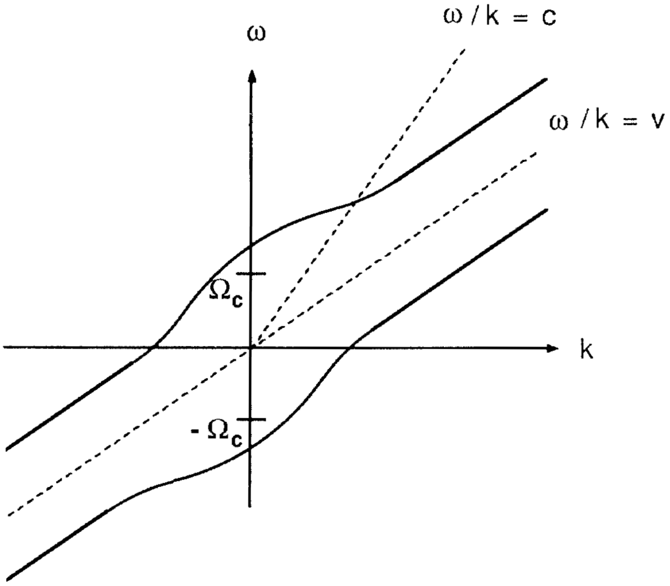

Fig. 1. Upper Hybrid Mode Dispersion Relation.

The accelerator concept is of interest for a variety of reasons, one of which is that it allows for the development of an accelerator in which we eliminate the need for coupling circuits between the rf source and the accelerated beam. A corollary of this is that the acceleration field is a maximum at the location of the beam being accelerated and not at the structure boundaries where breakdown may occur. A second important reason for the study is that the system is simple and eliminates the need for complex structures while retaining the essential features of an rf accelerator.

Experimental Configuration

In order to achieve the required degree of control on the beam and the wave it will be necessary to develop a low repetition rate system where we have digital control of the charging levels and can adjust parameters to match the experimentally determined optimum conditions. We outline progress in this area before describing current experiments which have been carried out on a single shot machine.

Figure 2 shows a schematic of a modified ETA accelerator module[4] with a newly added 2:1 step up output transformer. This brings the available output voltage from the single module up to a tested 500 kV at an impedance of 40 Ohms. To achieve this we have added a 5 ferrite core transformer section with a 13 mV. sec flux swing capability. The system has

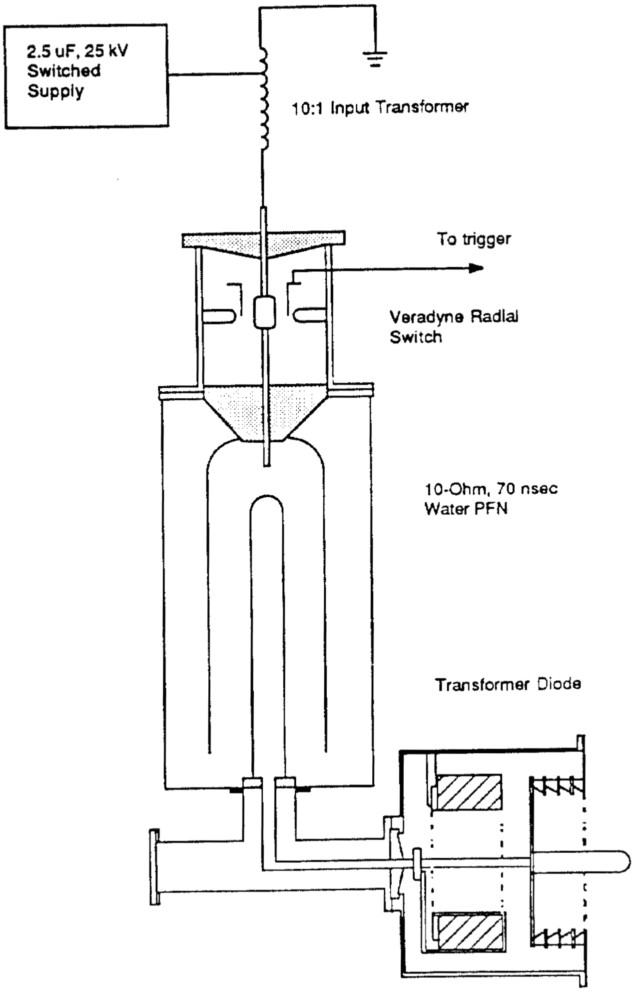

Fig. 2. Modified ETA Module

CH2669-0/89/0000-0734$01.00©1989 IEEE

been tested on a single shot basis with and without the transformer. Our present activities are focussed on installing additional smoothing in the output voltage with the transformer present.

In order that we can usefully drive the beam from the accelerator module described above at 1 pps we have had to develop a magnetic field capability commensurate with the pulse power system. Three electrolytic capacitors (450 V, 850 mF) are used to drive 7 or 8 coil modules with each coil having a 72 turn winding arranged in 12 layers on a 2 inch diameter form. The coils are driven in parallel and the timing control achieved with SCR circuits. Peak axial fields of 8 KG in a meter long system have been obtained in a repetition rate mode over extended periods. The system is digitally controlled to 0.5 % on the charging circuit so that we can ensure stable operation in experiments where the field profile and amplitude is critical. Note that each coil can draw a different current so that the field profile does not match that from a comparable length solenoid. The field strength is in fact more uniform along the solenoid length and falls off closer to the end of the coil.

The experiments performed to date have been carried out on a Marx Blumlein system operated at 400 kV, and at a beam current of 150-400 Amps. The pulse duration is 50 nsec although the flat top of the voltage pulse only extends over about a 20 nsec interval. The experimental configuration is shown in figure 3. A 5 mm diameter beam is generated in a field emission diode and injected into a 1.4 cm diameter guide. The beam is guided by a uniform axial magnetic field, typically about 5 kG. A four wavelength long, 4 cm. period, tapered bifilar helical magnetic field is used to impart rotational motion to the beam electrons. The taper extends over the first 12 cm of the helix while the final four cm. have a uniform winding. The transverse field reaches 800 Gauss in the uniform winding region. Following the helix the beam current is measured using a Rogowski coil. The bifilar helix has been operated in both the resonant mode, where

$$\kappa v = \Omega_c,$$

and κ and Ω_c represent the wiggler wavenumber and the electron cycloton frequency respectively, and at about 30-40% above resonance. At resonance the beam electrons acquire a substantial azimuthal velocity but many are lost to the guide walls. In most of our experiments we work away from resonance and increase the wiggler field strength to enhance the value of a, the ratio of the azimuthal to axial electron velocity. In these experiments we typically run with $\alpha \sim 0.2$. Figure 4 shows typical calculated single particle orbits in the wiggler from which the value of α was estimated. Following the wiggler and Rogowski the beam enters a 3.8 cm diameter cavity with tapered ends. The entrance wall makes an angle of 45° with the axis. The exit taper is 18 cm long to ensure a smooth transition between the cavity and the uniform guide. In some experiments the exit taper is lined with space cloth to absorb the electromagnetic wave while allowing the body wave to continue propagation into the uniform 1.4 cm guide. In the final guide section the rf wave is detected using magnetic pick up loops oriented to detect either the axial or azimuthal magnetic field of the body wave on the beam. The output from the loops is coupled to the screen room via X band waveguide and either crystal detected or heterodyned with the signal from a local oscillator. In some of the experiments the cavity section was omitted and in some cases there was an rf input signal provided at the cavity from an X band magnetron.

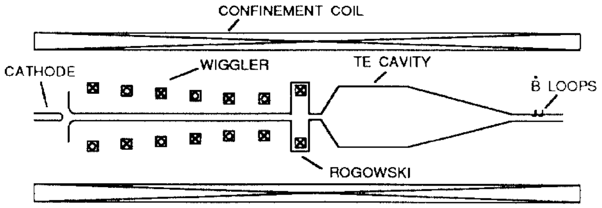

Fig.3. Experimental Configuration

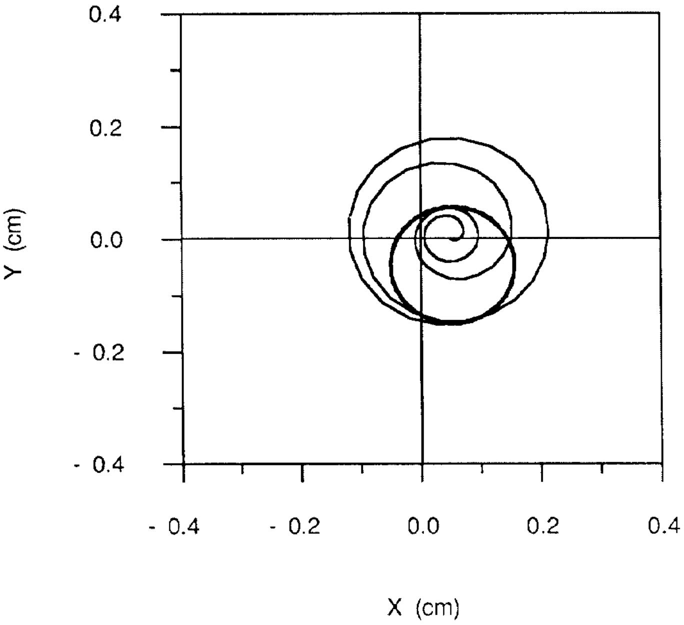

Fig.4. Single Particle Trajectories in Wiggler

Experimental Results

We report in the following observations on the characteristics of the interaction of the electron beam in the various systems described above. Briefly they may be summarized as follows:

(i) In the absence of the wiggler there was no wave excitation observed either in the presence or absence of the cavity,

(2) With the wiggler energized the beam current waveform, as measured in the drift tube after the wiggler, was perturbed. Close to the resonance condition indicated above there was a sharp dip in the transmitted current indicating that some of the beam electrons were lost to the guide walls. The actual loss varied substantially on a shot to shot basis depending on the details of the beam energy and current,

(3) With no cavity present wave growth was observed after the wiggler; wave growth was largest when we were close to the resonance condition for a strong wiggler interaction. The interaction frequency was close to 14 GHz as measured by filters and large signal levels were always accompanied by a

sharp dip in the transmitted beam current. Growth rates for the wave were estimated at 1.5 DB/cm by comparing the crystal detected wave amplitude at 10 cm downstream of the wiggler with that found 34 cm downstream.

(4) In the presence of the wiggler and the cavity, large amplitude waves were detected in the cavity at distances 20-50 cm downstream of the cavity. The wave frequency was found to be about 9.7 GHz, well below the cut off frequency for the lowest order electromagnetic wave in the 1.4 cm diameter guide. A typical crystal detected waveform downstream of the cavity is shown in figure 5,

(5) Priming the cavity in the TE$_{011}$ mode appeared to have some beneficial effects on the duration and coherence of a heterodyned output for the downstream wave, but did not affect its amplitude significantly. A heterodyned waveform for the downstream signal is shown in figure 5. The local oscillator was run at 9.7 GHz. Noise is often visible on the waveform, especially when the local oscillator frequency isis close to the wave frequency,

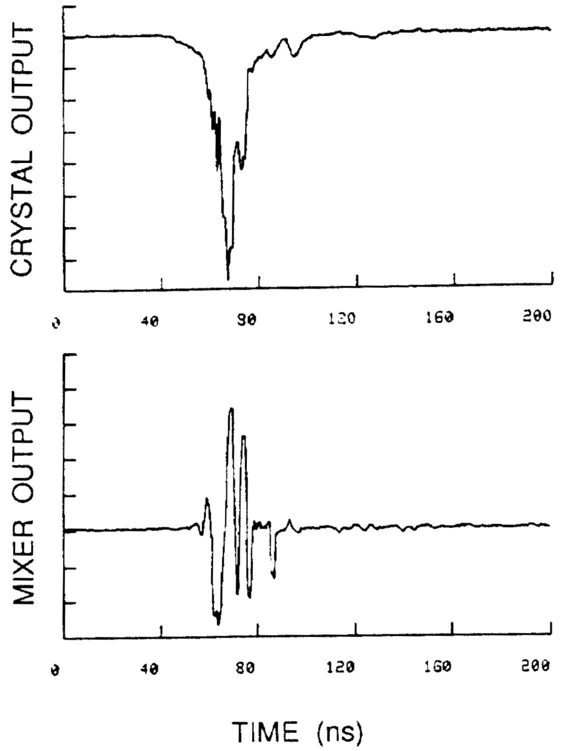

Fig.5. Crystal Detected and Mixer Outputs

(6) In the presence of the cavity the wavegrowth was restricted to the cavity region and no significant growth was observed in the uniform guide region,

(7) The observed oscillation frequency did not exactly match the magnetron drive frequency in the cavity; 9.71 GHz as opposed to 9.56 GHz,

(8) Energy drain was apparently observed as the beam passed through the cavity. The cavity excitation level was monitored by a crystal detector coupled to a loop antenna or through an iris coupling to waveguide. The signal level dropped substantially during the beam pulse.

Discussion of Results and Future Work

To date wave growth has been found under conditions when the beam electrons rotate about the axial guide magnetic field lines. The azimuthal rotation, which is provided by injecting the beam along a bifilar helical magnetic field, provides the free energy for the interaction. The rotational motion of the electrons couples to the azimuthal field of the TE wave mode. In the case of wave growth along the uniform pipe the most likely interaction is through the Cyclotron Auto-Resonance Maser. The TE$_{11}$ mode has a cut off frequency of about 12.5 GHz and no other mode propagates at the indicated wave frequency. Similar interactions have been reported by other workers[5]. In the case where the cavity was present the interaction can occur in a number of modes and was designed to occur with the TE$_{011}$ cavity mode at 9.56 GHz. The wave growth occurs in the cavity. As the beam/wave propagate into the uniform pipe the electromagnetic wave is cut-off whereas the body wave, a cyclotron mode, continues to propagate without further growth. As shown in figure 5 the wave frequency was monitored as 9.71 GHz and not at the cavity frequency, even though beam absorbtion of the rf energy was monitored. To date the mode for the interaction and the symmetry of the body wave have not been resolved. It is clear however that the approach to wave growth does permit the excitation of the cyclotron wave on the beam and that it propagates without serious loss in the drift tube.

Our earlier proposal called for wave growth using parametric excitation. This was not successful although we never attempted to use the parametric interaction with the spinning beam. Future investigations will explore this possibility and will also use axisymmetric wigglers to create the transverse motion of the beam electrons. We shall attempt to couple to a Gyrotron like mode. This type of interaction has been reported in many laboratories[6] and was investigated in our laboratory many years ago[7]. Through these steps we expect to ensure coupling to the required axisymmetric modes needed for the accelerator.

Further work must also be carried out to investigate limits on the accelerating fields achievable with these methods of wave excitation. Field limits may be set by the values of α achievable.

Acknowledgement

This work was supported by the U.S. Department of Energy.

References

1. J. A. Nation and A. P. Anselmo, Proc. I.E.E.E. 1987 Particle Accelerator Conference 1, 145, (1987)
2. V. Bevc and T.E. Everhart, J. of Electron Control 13, 185, (1962)
3. A. Trivelpiece and R. Gould, J. Appl. Phys., 30, 1784, (1959)
4. D. Birx et al. IEEE Trans. Nucl. Sci., NS-32, 2743, (1985)
5. G. Bekefi et al. Proc SPIE Conference of High Power Microwave Generation, Los Angeles, January 1989
6. See, for example K.R. Chu, V. L. Granatstein, P. Latham, W. Lawson, and C. Striffler, IEEE Trans Plasma Science PS-13,6, 424, 1985
7. Y. Carmel and J.A. Nation J. Appl. Phys. 44, 12, 5268, (1973)