SPACE-CHARGE WAVEGROWTH AND PROPAGATION ON A RELATIVISTIC ELECTRON BEAM

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Abstract

A study into the growth and propagation of space charge waves on relativistic electron beams is currently in progress. The waves are grown by transporting an annular beam (180-200 kV, 0.8-1 kA, 300-400 ns) through a disc loaded cavity system. Measurements of the R.F. signal inside the slow wave structure and at both ends of this region show the presence of backward as well as forward space charge waves. In addition measurements of the average drift velocity of the beam electrons show high energy losses to the cavity system. Interactions between the beam, the cavity system, and at the discontinuity between the cavities and the uniform drift tube produce both fast and slow waves. Results showing this aspect of the wavegrowth processes and their effect on beam propagation are reported. The relevance of the results to collective acceleration are discussed.

Introduction

To explore the possibility of increasing the achievable field gradients in conventional r.f. linacs we are investigating the use of slow space charge waves for ion acceleration. The waves are grown on relativistic electron beams by the interaction of beam waves with the TM modes of slow wave structures. This scheme provides maximum electric fields at the beam location rather than at the guide tube boundaries. Successful ion acceleration depends on the growth of negative energy slow space charge waves, their extraction from the slow wave structure into a smooth guide and the trapping of ions in the wave throughout the acceleration region.

Previous experiments [1] have shown that it is possible to grow the desired mode in short pulse length systems and that the wave propagation can be adequately controlled. However, a useful accelerator will require coherent waves of longer pulse duration than have been achieved to date.

Initial measurements [2] indicate that wavegrowth can be degraded either when the wave pulse length is longer than the cavity transit time (cavity length/group velocity) or when energy loss from the beam to the cavities is large. With long pulses wave reflections at the cavity-drift tube impedance mismatch are detected. Large energy transfer to the cavities can result in changes in the oscillation modes of the structure.

Experiment

A schematic of the experiment is shown in Figure 1. The foilless diode produces an annular relativistic electron beam (180-200 kV, 0.8-1 kA, 300 ns) with a 1 cm. radius; the beam thickness is 3 mm. An axial magnetic guide field (8-10 kG) confines the beam within a metal guide tube (radius 2.2 cm.). The wavegrowth section consists of nine disc loaded, dielectric filled cavities with a periodic length of 3.7 cm.

Diagnostics include Rogowski coils to measure beam current at the input and the output of the cavity system. Capacitive probes are used to measure electric fields between the beam and the wall. By selective filtering it is possible to measure

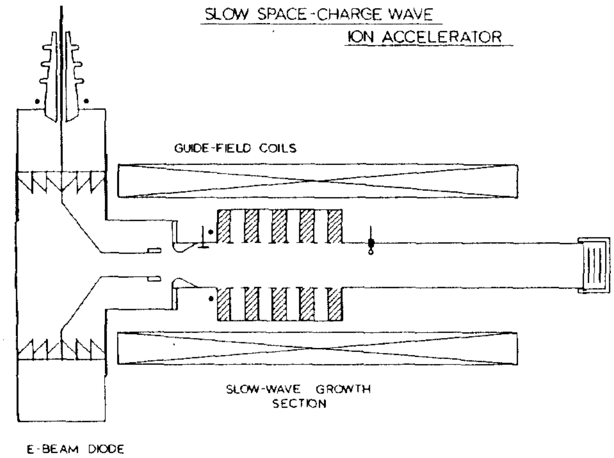

Figure 1. Experimental arrangement.

either the dc or the ac radial fields. Single turn magnetic pick-up loops are located along the drift tube wall and within the cavity system. These loops measure the B_θ fields of the waves present within the system. The signals from these loops (typically between 1-2 GHz) are down-shifted by microwave mixers for recording on oscilloscopes or transient digitizers. When used in pairs these loops also allow the measurement of wave phase velocity.

Experimental Results

To examine beam propagation in the absence of space charge waves, the electron drift velocity was measured in a smooth drift tube system. The results are shown in Figure 2. The measured values are compared with those calculated from the beam equilibrium. During the first 300 ns the agreement is good, however at later times agreement can only be obtained by assuming that the beam radius is increasing with time. This implies that the cathode plasma is expanding radially as well as axially.

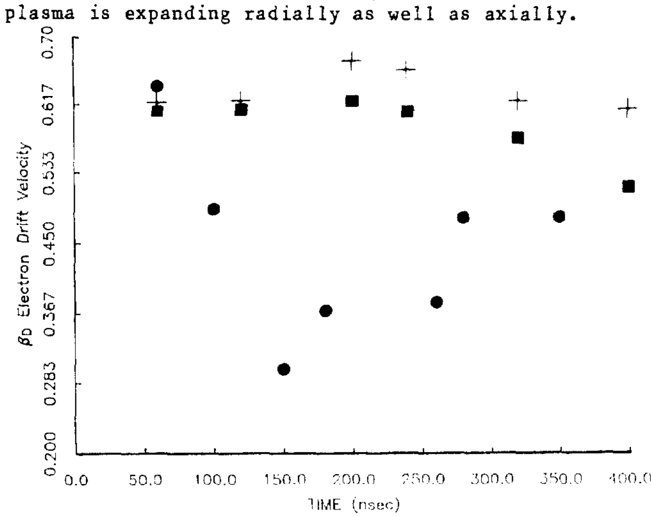

Figure 2. Electron drift velocity. (■) Calculated from beam equilibrium. (+) Measured in smooth drift tube. (●) Measured with cavity system present.

0018-9499/85/1000-3497$01.00

Figure 2 also shows that during the wavegrowth process the average electron drift velocity decreases significantly when compared to the smooth guide case. The drift velocity is obtained from the measured beam current (see Figure 6) and the dc radial electric field between the beam and the wall (see Figure 3). The measured value is compared to a calculated drift velocity based on a thin annular beam in a straight drift tube. Initially the measured drift velocity agrees with the calculated value. Following the risetime the drift velocity drops from 0.64 to 0.45c (±0.05c). During this time coherent wavegrowth occurs in the cavities, with an amplitude corresponding to a beam modulation of 10-30%. The IF signals from pick-up loops in the last cavity (#9) and the middle cavity (#5) are shown on Figure 3. From time delay measurements in the cavities this wave is identified as a forward wave with group velocity 0.015-0.018c. This low value is indicative of the narrow bandwidth of the system. As the drift velocity drops the intersection point between the slow-wave and the TM01 cavity mode moves towards the π-point. At this point the drift velocity is approximately 0.45c. The dispersion relation for the TM01 and TM02 modes is shown in Figure 4. Oscillations are observed in both modes at 1.23 GHz and 2.45 GHz respectively.

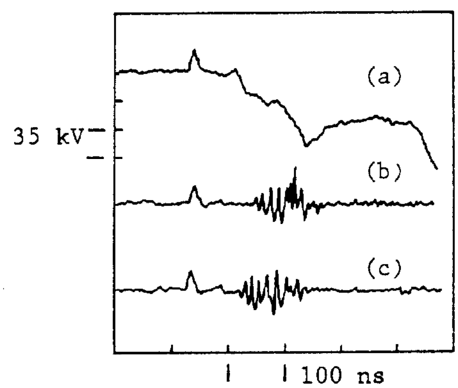

Figure 3. Oscilloscope traces showing: (a) capacitive probe signal, (b) IF signal in cavity #9 and (c) IF signal in cavity #5.

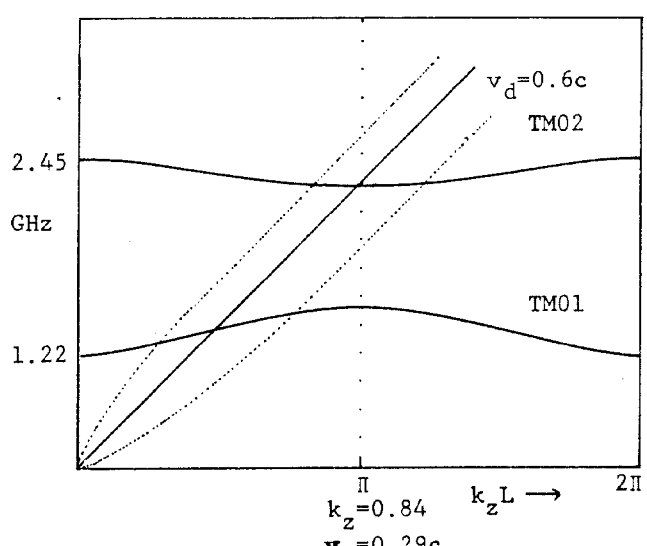

Figure 4. Schematic dispersion relation for TM01 and TM02 modes.

During the next 50 ns the drift velocity drops further to 0.30c (±0.03c). At this time approx. 40% of the injected beam energy has been transfered to electromagnetic energy in the cavities. Beam modulation in this large amplitude wave is 50-70%. Figure 5 shows this cavity energy compared to both the injected beam energy (W_{inj}) and the drift beam energy (W_d). The electromagnetic energy in the cavities, W_{em} is calculated from,

$$W_{em} = W_{inj} - W_{ba} - W_d$$

where W_{ba} is the potential energy stored between the beam and the wall, as measured by the capacitive probes.

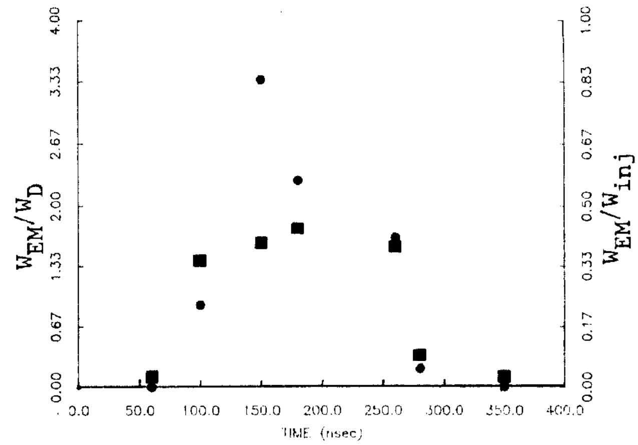

Figure 5. Electromagnetic energy stored in the cavities. (■) relative to the injected beam energy and (•) relative to the beam drift energy.

At the drift velocity of 0.3c the slow-wave interaction point is on the backward wave side of the cavity dispersion relation.

For the next 100 ns the electron drift velocity remains practically constant, as does the beam current The electromagnetic energy in the cavities is reduced from 44% to 39% of the injected beam energy. In the next 20 ns the cavity energy drops to 10%. This is accompanied by an increase in drift velocity from 0.37 to 0.47c. This increase is not driven by the diode voltage, as this is falling at this time, but rather by the electromagnetic energy transfer from the cavities to the beam. The drift velocity remains at 0.47c for a further 60 ns before dropping to zero. On some shots the drift velocity stays constant during this entire 180-200 ns period, at 0.38c.

Previous measurements on the same slow wave structure, but with lower beam voltage and current have shown coherent waves propagating in the system throughout the constant drift velocity stage. This is shown in Figure 7. Phase velocity measurements show this wave to be a fast space charge wave, with a phase velocity of 0.55-0.65c. During this time the beam current exceeds the limiting current, being driven by energy previously stored in the cavities.

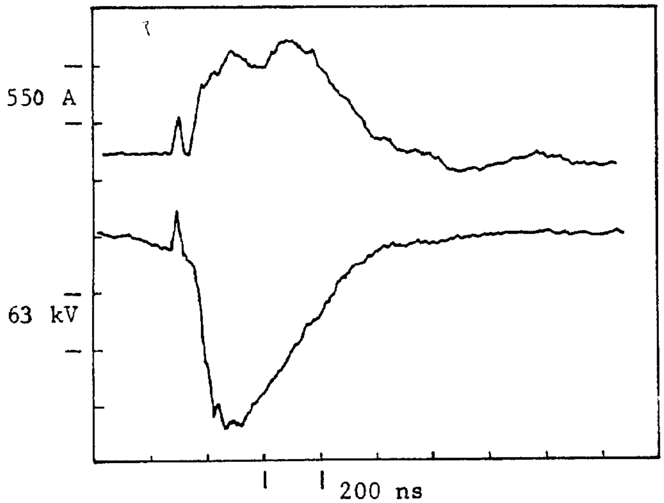

Figure 6. Oscilloscope traces of beam current (upper trace) and diode voltage (lower trace).

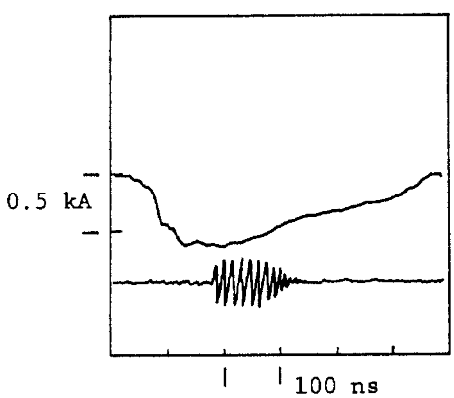

Figure 7. Oscilloscope trace of the fast wave IF signal measured in the drift tube.

Discussion

The measurements on the TM modes show that with beam loading in this cavity system the TM02 mode is at almost twice the frequency of the TM01 mode. The bandwidths of both modes are greatly reduced when an e-beam is present. This means that the slow and fast space-charge waves can exist with almost the same frequency. The observed fast wave is a positive energy wave, this can only grow as a result of mode coupling or energy transfer from an external source such as the cavities. Mode coupling is possible through the slow TM02 and TM01 modes (negative energy) and the fast TM01 mode. An indication for this coupling comes from measurements showing an abrupt increase in the amplitude of the TM01, TM02 and fast wave that occurs at the same time.

Conclusion

Use of passive structures as described in this paper for collective acceleration may be limited by several considerations. During long pulses reflections from impedance mismatches can inhibit further wavegrowth. In addition excessive energy losses from the beam can drive the system as a backward wave oscillator. Results presented in another paper [3] may suggest solutions to these problems. Energy lost from the electron beam is recovered from the cavities at later times, and drives an enhanced beam current. The measured fast wave can be grown by mode coupling or from energy stored in the cavity system.

Work supported by the United States Department of Energy.

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