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APPLICATION OF SLOW SPACE CHARGE WAVES ON AN IREB TO COLLECTIVE ION ACCELERATION†

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Abstract

Single shot time resolved techniques have been developed and applied to the measurement of the phase velocity, frequency, and coherence of space charge waves on an IREB. We report results for the time evolution of the wave phase velocity as a function of the beam and wave parameters. The application of slow space charge waves to collective ion acceleration will be summarized and a description presented of an experiment to demonstrate the viability of the use of space charge waves for ion acceleration.

Introduction

Efforts at Cornell University have been directed to the demonstration of collective ion acceleration using a slow space charge wave on a weakly relativistic electron beam.[1,2,3] To use this in an accelerator we require a source of energetic protons having sufficient energy that the protons can be successfully injected and trapped in the slow space charge wave. This paper focuses on the time evolution of the slow space charge wave and on the experimental techniques utilized to measure the wave parameters. Previous work[4] used the interference pattern, obtained by comparing the signals on a fixed probe with those on a second probe, moved along the axis of the experiment to determine the wave phase velocity on a shot-to-shot basis. Due to shot-to-shot variations and the rapid variation of the phase velocity with beam currents, at current levels close to the vacuum limit, this resulted in poor accuracy. It also was not possible to obtain temporal resolution of any of the parameters during the beam pulse. In this article we describe hetrodyne techniques to down-shift the wave frequency, to the domain where direct observation of the wave can be made, followed by a double balanced mixer used as a phase detector. By use of these techniques, we have been able to obtain time resolved (±2.5 nsec) measurements of the wave and correlate them with the beam parameters. Interpretation of the results shows wave phase velocities as low as 0.1 c. There is an excellent correlation between the measured wave parameters and the trends expected based on theory. Detailed numerical agreement, between the low phase velocities measured and theory, requires that nonlinear effects are important.

We also report on the initial efforts to incorporate the slow wave system outlined into a wave accelerator for protons. A description of this system including a novel pulse line system (300 kV, 3 kA, 400 nsec) for use in wave generator is presented.

Slow Wave Experiments

Figure 1 shows the experimental configuration used in these experiments. The beam is extracted from the vacuum diode using a foilless diode. Only the central portion of the beam is used to ensure radial uniformity and a low beam temperature. An axial magnetic field of 11 kG is used to confine the beam radially. A large amplitude 1 GHz wave is grown on the beam as it traverses the iris coupled cavities. Following wave growth the large amplitude wave passes through a 15 cm long, 2.5 cm diameter drift tube before entering the transition region to the 10 cm diameter experimental region. The beam current approaches the limiting current in this region. Although the return conductor is at a radius of 5 cm, it is physically separated from the beam by a 2.5 cm diameter quartz tube. This permits the surrounding region to be filled with a dielectric. The purpose

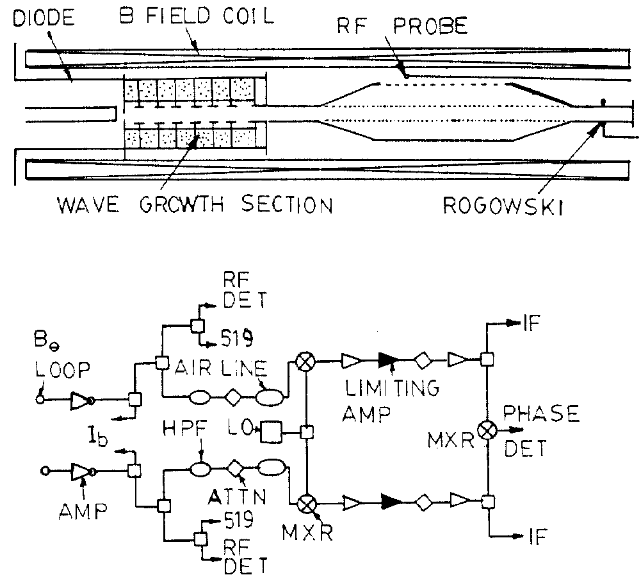

Figure 1(a) Simplified cross section of slow wave experiment.
(b) Simplified schematic of space charge wave diagnostics.

of the dielectric region is to allow adequate control over the beam to limiting current ratio. The wall of the drift region has three 1.5 mm wide, 30 cm long slots running parallel to the beam. Magnetic field probes are mounted in rectangular channels exterior to the tube and are coupled to the beam via the slots. The channels act as high pass (10 GHz) guides and, therefore, permit measurement of the local (axial) beam-wave fields. At the far end of the tube the beam current is measured using a calibrated Rogowski coil. The whole system is aligned to ensure that the beam and system axes are the same to better than 1.5 mm over the 2 meter experimental length.

The second half of Fig. 1 shows the wave diagnostics package used. Two magnetic pickup loops are employed as signal sources. Signals are downshifted in frequency to about 300 MHz using the signal from a local oscillator at 1.3 GHz. The IF is amplified using limiting amplifiers and then divided for direct display on 7912 digitizers (Fig. 2), with the second half of the signals fed to a double balanced mixer used as a phase detector.[5] Detailed calibrations to confirm the operation of the system have been carried out.

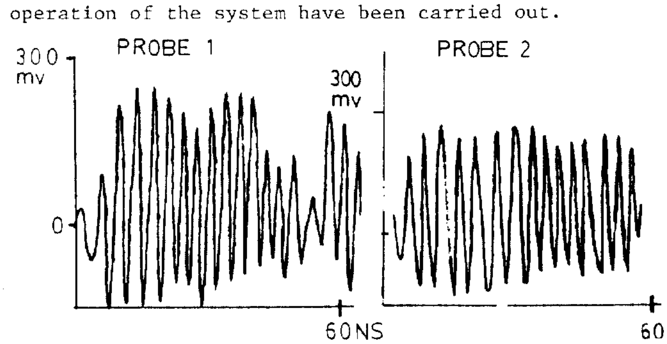

Figure 2 Downshifted signal detected by the two pickup loops.

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Figure 3 shows the phase difference between the detected signals as a function of their separation. This data was, of course, obtained on a shot-to-shot basis with currents and beam voltages having several

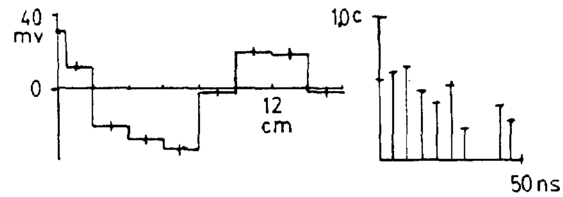

Figure 3(a) Phase detector response versus probe separation, 20 ns after start of beam.
(b) Computed phase velocity of the space charge wave as a function of time.

percent variation from shot-to-shot. Data was obtained every 2 cm. The use of data such as this, taken at different times into the beam pulse, allowed us to construct the phase velocity information shown in the same figure. Data was obtained at 5 nsec intervals and was referenced from digitizer to digitizer with a fiducial time mark. The data at 35 nsec showed too large a variation on the shot-to-shot basis to be included in the figure. It is clear, however, that the basic trend is to have a reduction in phase velocity as the beam current increases, followed by a speeding up of the wave. The estimated errors in this measurement are about 30%, mainly due to the shot-to-shot variations. In Fig. 4 we show the experimentally observed diode waveform, corrected for inductive effects, and the calculated limiting current, where we have assumed a beam size approximately equal to that of the hole in

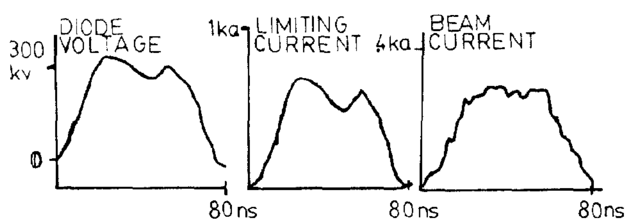

Figure 4(a) Electron beam diode voltage,
(b) Computed space charge limited current,
(c) Measured beam current.

the anode plate. Damage patterns suggest that the beam may have a smaller diameter. The final part of the figure shows the experimentally monitored beam current at a location 60 cm downstream of the wave measurement region. A comparison of the calculated limiting current waveform with that observed shows that the ratio of beam to limiting current starts at a low value and increases as time advances, reaching its maximum value at the dip shown in the calculated waveform. Following this the ratio decreases again. The ratio of observed to calculated limiting current reaches a peak value of greater than 0.8 before dropping late in the pulse. This behavior is in qualitative agreement with the data shown in Fig. 3 and provides the basis for accepting the single shot time resolved data presented next. Figure 5 shows the output of the phase detector for a particular shot in which the probes were 3 cm apart. The output should vary as $V = V_o \cos(k_z L)$, where V_o is the peak phase detector output and L the probe separation. This, of course, assumes sinusoidal signals (no clipping from the limiting amplifiers) and a constant signal on each of the probes. The latter is clearly not true, due in part at least to the expected rapid reduction in detected signal with decreasing phase velocity. This effect results in an overestimate of the phase velocity. The phase velocity is then calculated from the measured variation in k_z, the axial wavenumber. The results are shown in the second half

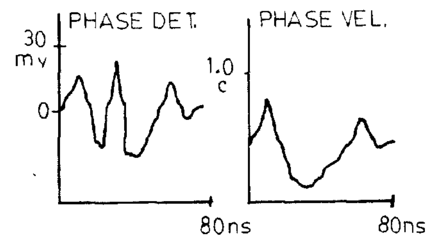

Figure 5(a) Phase detector response from a single shot.
(b) Computed instantaneous phase velocity.

of Fig. 5. Note that the output becomes ambiguous at a time corresponding to first minimum of the phase detector signal. We have resolved this using the known variation in the ratio of the current to limiting current, and also the corresponding data on phase velocity given in Fig. 3. The low value detected in this way is 0.1 c at a time corresponding to the second positive peak in the phase detector output. The observed phase velocity is lower than expected on the basis of linear theory and can only be accounted for by nonlinear slowing down of the wave. An analysis of this phenomenom has previously been given by Hughes and Ott.[6] We do not have good measurements at present of the wave electric field.

Finally, we observe that a fast Fourier transform of the IF signals shows that the bandwidth of the signals is a factor of between two and three larger than estimated using the natural bandwidth appropriate to the pulse duration of the signal. At present we do not have detailed analysis of the time evolution of the frequency, although it is apparent that there is a ~5% increase in the wave frequency during the pulse duration.

Proton Wave Accelerator

The results presented in the previous section are important in as much as they suggest that the requirement on the proton injection energy can be substantially relaxed over that predicted by the linear theory of wave propagation. With the 0.1 c phase velocity, the proton injection energy requirement drops to less than 5 MeV. This figure has not yet been optimized and could be lower still with large amplitude waves. In fact, calculations show that it is possible to have negative phase velocities with large amplitude waves on beams in bounded systems.

Figure 6 shows a schematic of the overall system to be used in the proof-of-principle experiment for the space charge wave accelerator. For the purpose of this experiment we intend to use a second collective accelerator as the proton source. This device, which has been described elsewhere,[7] gives an ample flux of protons having energies greater than 5 MeV. The protons will be injected through a hollow cathode into a second electron beam system for the wavegrowth and acceleration. As in the present experiments, the beam

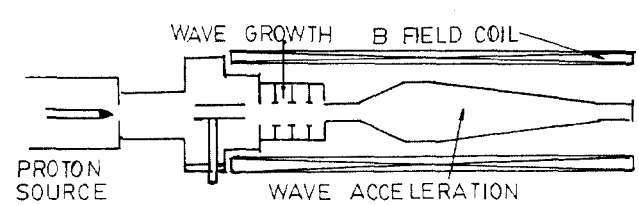

Figure 6 Proton wave accelerator schematic.

region will be surrounded by a thin quartz tube to permit a dielectric liner to be present. Essentially this liner allows a fine control of the wave velocity through the control of the beam to limiting current ratio. The change in tube diameter, to produce a given change in the effective plasma frequency, is enhanced over that with a vacuum surrounded by an amount of order of the dielectric constant of the liner. We have carried out tests with alcohol as the dielectric and observed satisfactory wave propagation. Sprangle[8] has suggested that such dielectrics, which have different dielectric constants at the wave and beam frequencies, might also be used to reduce the wave phase velocity.

In order to generate the electron beam for the wave growth part of the accelerator, we have developed a novel pulse power source. The system will generate a 400 nsec pulse of 300 kV at a source impedance of 100 ohms. The slow rise time (~100 nsec) and the relatively high impedance of the source make this suitable for relatively good control of the injected electron current. The source is sketched in simplified form in Fig. 7, where details of the triggering and charging assemblies have been omitted for the sake

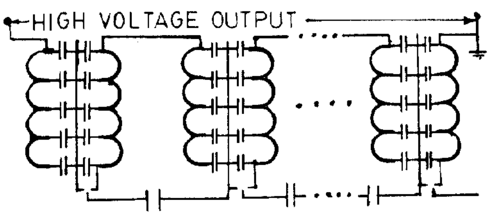

Figure 7 Simplified schematic of stacked, seven stage artificial Blumlein pulse source.

of clarity. It consists of seven artificial Blumlein lines which are charged in parallel and discharged in series. The system is triggered at the first gap and then self-erects using 300 pF coupling capacitors between the stages in a Marx configuration. These capacitors have only to erect as the switch current is provided by the main line 3.5 nF, 50 kV capacitors. This system has been tested at the required working voltage and found to operate satisfactorily electrically. The stacking achieved is approximately 20% less than one would expect under ideal conditions.

Conclusions

We have developed diagnostic techniques capable of providing nanosecond time resolution of the wave properties of a slow space charge wave on a relativistic electron beam. Based on a comparison of the time resolved observations with those obtained on a shot-to-shot basis we believe that we have developed a viable diagnostic. Temporal resolution of the wave, using these techniques, shows that the phase velocity decreases during the beam pulse, reaching an estimated low value of 0.1 c. This value can only be obtained if nonlinear effects decrease the wave velocity below the values calculated using linear analysis.

We have, in addition, indicated the configuration we have partially developed for using the slow space charge wave in a wave accelerator. Tests of proton injection into a wave growth section have been reported previously.

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