SPACE CHARGE WAVE ACCELERATORS

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INTRODUCTION

Various novel schemes have been described to produce very high field gradient accelerators. In this report we briefly summarize some of the features associated with one proposal, the space charge wave accelerator. In this device we grow space charge waves on a weakly relativistic electron beam; the beam to be accelerated is then injected into the electron beam supported wave, and the wave phase velocity changed at a rate commensurate with the ion acceleration obtained in the electric field in the wave. Changes in the wave phase velocity may be achieved, either by expanding the beam or by converging the waveguide. In either case the effective plasma frequency is reduced and the wave phase velocity increased.

In the following sections we present an account of experimental observations showing control of the wave phase velocity for a slow wave, measurements of the wave electric field, and indicate how these results might apply to an ion accelerator. An interesting and new possibility is also indicated, namely the use of fast waves for electron accelerators. In this case preliminary estimates indicate that comparable field gradients to those already obtained in the slow wave scheme should be obtainable in fast waves and that these field gradients can be maintained at phase velocities close to the speed of light. The most likely wave for this application would appear to be the upper hybrid mode of the low energy, high current electron beam.

EXPERIMENTAL RESULTS

Space charge waves have been grown on weakly relativistic electron beams (200-400 keV, 500-2000 A, 50-500 nsec) by propagating the magnetically confined electron beam through a slow wave structure consisting of a series of disk loaded, coupled cavities excited in the TM010 mode. The slow space charge wave couples to either a forward or to a backward wave of the disk loaded structure depending on the experimental parameters used. Following wave growth the beam is extracted into a waveguide which is beyond cut off for the wave frequency chosen. In the experiments reported here the wave frequency was 1.067 GHz and the guide dimension was varied from 10 to 5 cm over relatively short distances, i.e. over distances comparable to or slightly greater than a guide wavelength$^{1)}$. The object of the experiments was to compare the measurements of the wave phase velocity with linear theory predictions. The linear theory utilized describes slow space charge wave propagation on a pencil electron beam in a uniform guide. The converging guide was modelled in these calculations by using the results for different diameter guides and assuming that the changes in the guide dimensions were adiabatic at the wave frequency. This is obviously a poor approximation but nonetheless forms a convenient reference. A second goal was the measurement of the time resolved electric field. The electric field was inferred from measurements of the wave radial electric and azimuthal magnetic fields. From these measured values, and using the experimentally determined value of the wave phase velocity, we calculate the axial electric field of the wave at the beam edge. This measurement requires an accurate determination of the wave phase velocity with an estimated accuracy in the normalized phase velocity of 0.02 c resulting in a 10% accuracy for the axial electric field strength.

Results for the wave phase velocity (determined by measuring the phase shift of the wave between two adjacent ports) and the axial electric field are shown for a typical shot in Fig. 1. At a phase velocity of 0.2 c the electric field approaches 300 kV/cm. This field strength is typical of the results found in these experiments. Figure 2 shows a summary of the experimental results for the variation of the phase velocity with the drift tube size for various values of the electron beam current. The solid line represents the results of the linear theory calculation of the wave phase velocity. As can be seen from the figure we can control the wave phase velocity over a range of values up to the electron velocity.

It is interesting to note that we have on some occasions observed fast waves propagating on the beam. The mechanism leading to the fast waves generation is not completely clear but is believed to be associated with mismatches in the wave impedance in the structure at the boundary between the wavegrowth region and the uniform guide section.

DISCUSSION OF RESULTS

The wave electric fields measured are very competitive with those achievable using standard accelerator technology. They have certain other features which make them more attractive, namely:

(i) The field is a maximum at the beam location and becomes weaker close to the conducting walls and,

(ii) The fields measured are low estimates of the actual field since they are calculated on the basis of linear theory.

In practice the waves are non-linear[2,3] and the actual field strength may be larger by an order of magnitude. Simulations demonstrating this phenomenon have been reported elsewhere. Note that the non-linear wave steepening occurs after growth so that the fields at the walls of the wave-growth structure may be significantly lower than those in the accelerating structure.

The available electric fields are limited by self trapping of the primary beam electrons in the space charge wave. The onset field for self trapping is of order[4]

$$E_t = \frac{\alpha k_z}{\gamma_\phi} (\gamma_r - 1) \frac{m_0 c^2}{e}$$

where γ_r is the electron relativistic factor measured in the wave frame of reference, and α is a numerical factor of order 3 reflecting the fact that one can operate above the self trapping onset level in at least short accelerator sections. Estimates indicate that one can obtain acceleration field gradients of 200 MV/m with a 2.0 MeV electron beam and a wave frequency of 7.5 GHz.

The results shown in Fig. 2 show deviations from the linear theory results, especially at low phase velocities. The difference is outside the experimental error in the measurement and is associated with the non-linear reduction in the wave phase velocity. Non-linear effects have been confirmed, although not quantitatively determined, by observations of strong signals at the second harmonic of the wave frequency. The deviations from the linear theory at the small tube diameters are probably associated with inaccuracies in the modelling, especially the errors associated with ignoring the axial component of the wave electric field at the tube wall.

APPLICATION TO ACCELERATORS

The space charge wave accelerator scheme is applicable to ion acceleration and is in principle applicable for ion acceleration up to an energy equal to the mass ratio (accelerated particle to electron) times the electron beam energy. Perhaps a more severe limitation is the decrease in the self trapping field strength as one approaches the electron drift velocity. It appears at present that it is possible to grow waves at sufficiently high field strengths and to control the wave phase velocity sufficiently well that one could build a test section of an accelerator based on this principle. For ease of testing the injector should have an energy of at least 50 MeV.

A variation on the converging guide accelerator has been proposed and tried at Cornell University[5]. In this device we grow a large amplitude space charge wave on the beam using the techniques described earlier. The slow space charge wave supported by the electron beam is then propagated through a quasi-periodic rippled magnetic field. If the local wavenumber of the field ripple is K and that of the wave k then beat waves are generated with phase velocities of

$$v_B = \frac{v_\phi k}{k + K}$$

where v_ϕ is the phase velocity of the space charge wave. The velocity of these waves is unbounded and hence this configuration can be used for acceleration of particles to velocities up to the speed of light. This principle has been demonstrated on a statistical basis by accelerating protons through 2 MeV at an average gradient of about 4 MeV/m. The proton injection energy was 5 MeV. This configuration may also be used, in principle at least, for electron acceleration.

Finally we reiterate our earlier comments regarding fast waves. These waves do not grow naturally on beams and require that external work be done on the system to grow the waves. We have observed fast space charge waves on beams and have recently initiated experiments to deliberately excite this mode. There appear to be a number of ways of exciting this mode, and the upper hybrid mode, which seem feasible. These modes appear to be especially attractive for possible electron accelerators.

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REFERENCES

1) A. Anselmo, G. Kerslick, J.A. Nation and G. Providakes, "Space Charge Wave Propagation in Inhomogeneous Waveguides", accepted for publication in Physics of Fluids.

2) T.P. Hughes and E.E. Ott, Physics of Fluids, Vol. 23, pp. 2265 (1980).

3) D.L. Fenstermacher and C.E. Seyler, Physics of Fluids, 27 (4) (1984).

4) P. Sprangle, A.T. Drobot and W.W. Manheimer, Phys. Rev. Letters 31, pp. 1234 (1973).

5) Electron Beam Wave Accelerators. A. Anselno et al. Proc. 5th International Topical Conference on High Power Electron and Ion Beam Research and Technology (San Francisco 1983).