IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

PROTON INJECTION INTO A LARGE AMPLITUDE SPACE CHARGE WAVE†

Richard J. Adler, George Gammel*, John A. Nation, James D. Ivers, George Providakes, Victor Serlin

Abstract

An account is presented of some aspects of recent progress in the Collective Ion Space Charge Accelerator (CISCA) program at Cornell University. The object of this program is to explore the potential of the slow space charge wave on an electron beam for use in an ion accelerator. We describe in this paper the results of a study of a Luce diode as an ion source and outline initial results obtained when the proton beam is injected into a space charge wave growth section. We find that it is possible to inject a beam of protons through a vacuum diode, used to generate the beam for wave growth, and for the conditions achieved to date to maintain the growth of a coherent wave.

Introduction

Previous reports[1-4] have described aspects of the use of a slow space charge wave for collective ion acceleration. Because the space charge wave can only propagate with zero phase velocity when the beam current is equal to the space charge limiting current, it is difficult to obtain and control the propagation of a wave capable of picking up an ion having a velocity of much less than 0.15 c. We have, therefore, chosen to study the Luce diode as a source of protons for injection into a demonstration wave accelerator. This device produces a continuous spectrum of protons up to an energy of about twenty times the energy of the electrons in the accelerating beam. For the purposes of demonstrating the space charge wave accelerator only the high energy protons in the tail of the ion distribution are relevant and we shall attempt to further accelerate them in the slow space charge wave.

It has proved convenient to generate the space charge wave by coupling the slow wave on a pencil electron beam to the TM modes of a periodic slow wave structure. In this configuration we have achieved wave growth and extracted waves with electric field strengths of 60 kV/cm without evidence of saturation. We have also observed wave coherence over lengths of more than one meter. Under the conditions used, the lowest phase velocity observed for the space charge wave has been about 0.25 c, a value in agreement with calculations using the measured beam operating conditions.

A central problem in the use of any wave accelerator is the injection of the protons into the wave for acceleration. The main purpose of the work described in this paper is to examine an experimental technique which will permit the nonadiabatic injection of a proton beam into the wave acceleration section. The results reported in this paper are preliminary and no effort has been made to achieve the conditions necessary for ion trapping. Rather we simply report on the technique used and on the results obtained with easily achievable ion fluxes.

Before discussing the results in the body of the paper it should be noted that we do not view the Luce diode system as a practical injector for a space charge wave accelerator. This device yields a proton flux which is restricted in its time duration and in the flux of useful ions that it yields. It does, however, serve the very useful purpose of providing an adequate source of high energy protons for injection into the wave accelerator for testing the principles involved in both the injection, loading, and acceleration. We presently believe that the most suitable wave accelerator injector system will probably be a proton Induction Linac. In this context we note that Induction Linacs have not yet been used for the acceleration of ions, although the acceleration of Cesium ions has been proposed as part of the Heavy Ion Fusion Program.[5] We are currently carrying out a design study of an ion injector system for use in a wave accelerator. The principle problem appears to be the control of the ion beam expansion, especially at low beam energies, by a combination of a partial space charge neutralization, and by magnetic guide fields. We conclude this section by noting that the injector problems, and the effects on the wave growth and wave acceleration can be adequately tested with the Luce diode as the ion injector.

Ion Source Developments

We now describe the results of our recent studies on the Luce diode as a source of high velocity protons for injection into the wave accelerator. The configuration used in these studies is shown in Fig. 1. In the results reported, which are representative of recent experiments, we have succeeded in obtaining protons with energies of more than twenty times the injection energy of the electron beam. The electron beam is generated from a Blumlein transmission line feeding a vacuum diode. The diode uses a conical

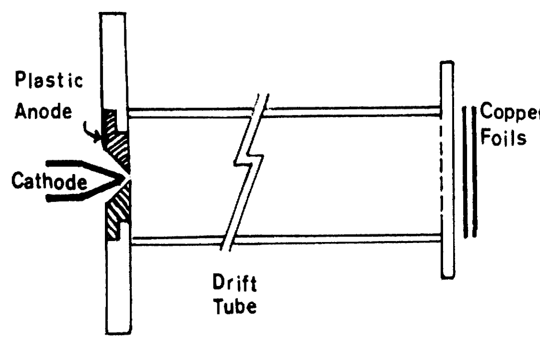

Figure 1. Experimental configuration used in the ion injector development.

aluminum or graphite cathode with a rounded tip having a radius of curvature of about 2.5 mm. The anode consists of a polyethylene disc with a thickness of 12.5 mm. It has a 45° full angle conical hole tapering at the drift tube side to 12.5 mm in diameter. A prepulse switch limits the prepulse, during the approximately 700 nsec duration charging of the line, to less than 15 kV. On a second pulse line, having a prepulse level of about 80 kV, it was not possible to obtain satisfactory diode operation. The experimental results for the ion energy spectrum, obtained using a nine ohm diode at 570 kV, less an inductive correction of order 100 kV, are shown in Fig. 2. Similar results have been obtained with higher electron beam injection energies.

To obtain this high multiple of the proton to electron energy it was necessary to operate at the impedance level stated. This occurred when the cathode tip penetrated about 6 mm into the polyethylene anode plate. The drift tube used had a 7.5 cm interior diameter and was about 1.3 m long. The ion energy spectrum was determined from copper activation of 25 micron foils located outside the drift tube. The drift

---

The authors are affiliated with the Laboratory of Plasma Studies and School of Electrical Engineering, Cornell University, Ithaca, New York 14853.
*Present address: Brookhaven National Laboratory, Upton, Long Island, New York 11973

0018-9499/79/0600-4223$00.75 © 1979 IEEE

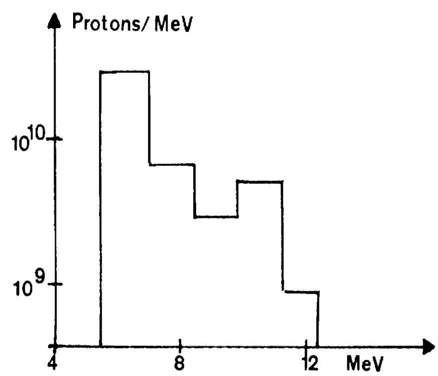

Figure 2. Proton energy spectrum from a 570 kV electron beam, obtained using a 'Luce' diode. Only that part of the spectrum above 5.3 MeV is shown.

tube was evacuated to a base pressure of approximately 10^{-4} Torr and the proton beam extracted, into the stacked copper foil system for activation analysis, through a 25 micron stainless steel foil. The results presented show an analysis of the ion spectrum taking the foils two at a time. Similar results were obtained (to within a factor of less than two) with the single foil analysis. In all cases where substantial acceleration of the protons occurred there was magnetic neutralization of the electron beam and substantially greater net currents than allowed in vacuum were monitored. The acceleration length for this experimental data was not measured, but based on previous data, was probably less than 10 cm. Autoradiographs,[6] obtained from the activated copper foils, showed that the high energy proton flux had a very low beam divergence. The spot size, after propagation of 1.3 m, was approximately 0.6 cm. This result, which is very encouraging for ion injection into wave experiments, is in contrast to the results obtained elsewhere, where a strong divergence of the high energy component of the ion beam was reported.[7] Part of this difference, as is the enhanced multiple of the proton to electron energy, is probably due to the relatively low beam diode impedance. The characteristic long high energy part of the distribution was enhanced as the beam impedance was decreased. The experiments reported here use lower beam impedances, and greater multiples of available electron current to the vacuum space charge limit,[8,9] than those reported elsewhere.

Ion Injection Into a Space Charge Wave

To test the concepts of the wave accelerator it is necessary to devise a scheme whereby the protons emitted from the Luce diode assembly can be injected into a wave growth and acceleration region. Since the injection must be nonadiabatic, we inject the proton beam into a second electron beam prior to growing the wave. Ions with the appropriate energies will be trapped in the wells of the space charge wave as it grows. In addition, since we have used for this demonstration experiment scheme one collective accelerator to produce the protons for injection into the second stage, we need to dump the hot electrons, generated in the Luce diode assembly, prior to their injection through the second diode. The dumping of the primary electron beam must be accomplished close to the second diode so that we do not lose the preaccelerated protons, prior to the space charge, re-neutralization in the second electron beam. These conditions are more severe than one might expect to encounter if an Induction Linac can be satisfactorily used as the ion source. The dumping of the remnants of the hot electrons in the first primary beam is required so that wave growth can be achieved with a second low energy, cool electron beam.

The above mentioned criteria have been satisfactorily met using the double diode configuration shown in Fig. 3.

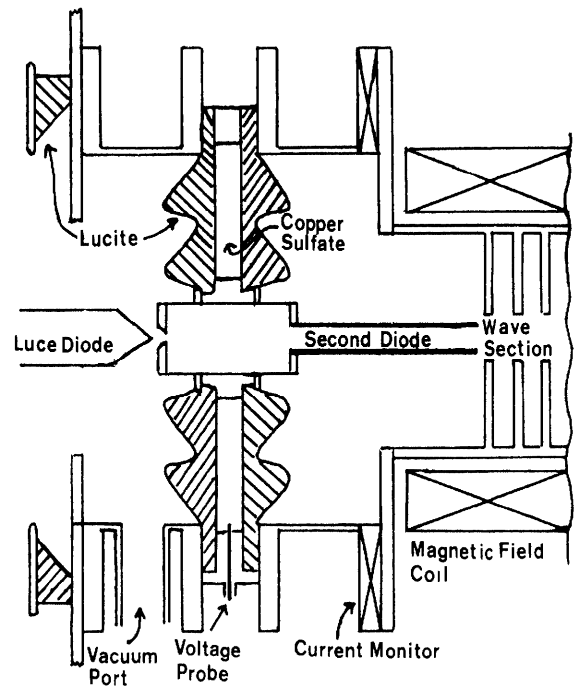

Figure 3. Schematic showing the double diode used for the injection of the proton beam into a wave growth section.

The dual diode assembly consists of a Luce diode, fed from a pulse line system, operated in series with a radial resistor. The potential drop across this ~4 Ohm $CuSO_4$ resistor is used to feed the cathode of the second, low voltage diode. A pulsed magnetic field of up to about 12 kGauss is used to confine the low energy annular electron beam. The field spreads out radially close to the second cathode and does not extend into the proton acceleration region. The proton beam is accelerated from the first diode through a section of 7.5 cm diameter drift tube. The length of this section was about 10 cm in these experiments. Following the acceleration section, the three inch diameter tube changes discontinously to a 2.5 cm diameter stainless steel tube, in which is mounted the carbon cathode for the second beam. The carbon cathode is annular having a central hole of approximately 0.6 cm, through which the protons are injected into the wave growth region.

Experimental observations show that the primary electron beam current is reduced to less than 500 A, prior to exiting through the second cathode. This reduction is not due to the applied magnetic field. In fact, in the absence of the field the primary current drops to less than 50 Amps.

The protons, which are detected by the activation of Copper foils, or by time resolved Faraday cups, indicate that there are approximately 5 x 10^9 protons with energies between 5 and 7 MeV traversing the 1.7 meter length from the first diode to the end of the drift region. The current associated with this part of proton flux is approximately 0.1% of the electron current injected into the wave growth region. In addition to the higher energy ions there are also a number of ions with energies below the approximate 5.5 MeV energy threshold for activation of the Copper foils, external to the drift tube (approximately 1 MeV is lost in traversing the 25 micron stainless steel vacuum seal). Figure 4 shows traces of various waveforms from the double diode system and the Faraday cup detector. The arrival of the higher energy ions follows the rise of the diode voltage pulse by about 60 nsec. There is also a comparable electron current reaching the cup. This precedes the positive ions so that the arrival time of the fastest ions may be over estimated. In addition, the time taken for the neutralized electron beam to detach from the anode of the Luce diode is of order 10 nsec. We, therefore, find that the Faraday cup observations are consistent with the observed activation data. The ion signal recorded by the Faraday cup lasts about 100 nsec corresponding to a range of proton velocities from 0.12 c to 0.03 c (energy range of 7 to about 0.25 MeV).

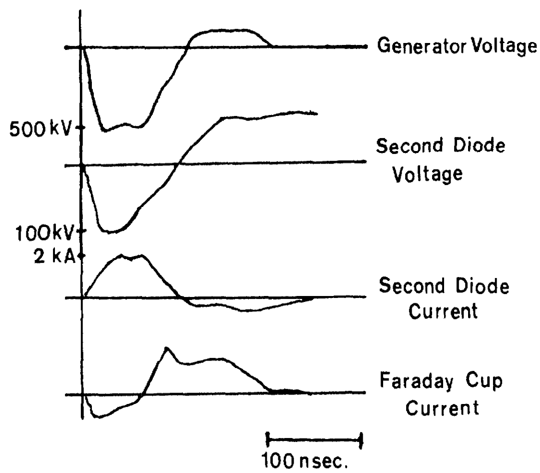

Figure 4. Double diode, and Faraday cup waveforms. The upper trace shows the generator output voltage and the second gives the lower energy diode voltage (also the primary diode current). The lower traces show the low voltage diode current and the response of the Faraday cup detector, 1.7 m from the 'Luce' diode.

Wavegrowth was recorded by a magnetic pick up loop located in the fifth of the six r.f. cavities used in the slow wave structure. This cavity was located approximately 65 cm from the Luce diode. Consequently, the proton flux traversed the measurement cavity at a time starting 20 to 30 nsec after the initiation of the diode pulse and continued throughout the remainder of the electron beam duration. r.f. emission was detected during the time interval when protons were present. There was no detectable degradation of the r.f. emission when the protons flux was present over that with no ions present. The r.f. emission was, in part, associated with the electron beam current from the first diode as evidenced by a reduction in the emission level when the hole through the second cathode was blocked. It is not clear, however, whether the contribution to the electron current arising from the primary beam has the full generator energy or only that of the low voltage diode. In these experiments the total line voltage was in the range 350-600 kV with a Luce diode current of about 25 kA. The second (low voltage) beam was therefore operated in the energy range 80-100 keV, and at a diode current level of 600-900 A.

In summary, we find that we can propagate high energy ions through a low voltage diode and maintain growth of a coherent wave. The operating conditions have not yet been optimized and it is possible to increase the ion and electron energies and the electron beam current. It is now possible to study, at interesting ion loading levels, the effects of resonant and nonresonant neutralizing background protons on wave growth and ion acceleration.[10] These measurements will be carried out in the near future. The present measurements have confirmed the viability of the injection technique and give favorable first indications of the effects of ion loading on wave generation.

†This work supported by AFOSR, BMDATC, and NSF.

References

1. R. Adler, G. Gammel, J. A. Nation, M. E. Read, R. Williams, P. Sprangle, and A. Drobot, "A Wave Accelerator for Collective Ion Acceleration", Proc. 2nd Int. Conf. on High Power Electron and Ion Beam Research and Technology, Vol. II, 509-220, (Oct. 1977).

2. R. Adler, G. Gammel, J. A. Nation, G. Providakes, and R. Williams, "Space Charge Waves and Collective Ion Acceleration", to be published in Proc. 3rd Int. Conf. on Collective Methods of Acceleration, (June 1978). See also, Cornell University Laboratory of Plasma Studies Report 248 (July 1978).

3. R. Adler and J. A. Nation, "Ion Acceleration Mechanisms in Vacuum Diodes", Cornell University Laboratory of Plasma Studies Report 255 (Aug. 1978). To be published.

4. G. Gammel, J. A. Nation, and M. E. Read, "Slow Space Charge Wave Propagation on a Relativistic Electron Beam", Cornell University Laboratory of Plasma Studies Report 262 (Jan. 1979). To be published.

5. A. Faltens and D. Keefe, "Applications of Induction Linac Technology to Heavy Ion Fusion", Lawrence Berkeley Laboratory Report 6453 (July 1977).

6. R. Miller and D. Straw, "Scaling Studies of Collective Ion Acceleration with Intense Relativistic Electron Beams", IEEE Trans. Nucl. Sci. NS-22(3), 1022-1024, (June 1975).

7. J. Adamski, P. Wei, J. Beymer, R. L. Guay, and R. L. Copeland, "Collective Ion Acceleration in a Vacuum Diode", Proc. 2nd Int. Conf. on High Power Electron and Ion Beam Research and Technology, Vol. II, 497-507, (Oct. 1977).

8. J. S. Luce, "Neutrons and Radio Isotopes Produced by Collective Effect Acceleration", Annals of the N.Y. Acad. of Science 25, 217-233 (1975).

9. C. N. Boyer, W. W. Destler, and H. Kim, "Controlled Collective Field Propagation for Ion Acceleration Using a Slow Wave Structure", IEEE Trans. Nucl. Science NS-24, 1625-1628, (June 1977).

10. P. Sprangle, A. Drobot, and W. Manheimer, "Collective Ion Acceleration in a Converging Waveguide", Phys. Rev. Lett. 36, 1180-1183 (1976).