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HIGH CURRENT LINEAR ION ACCELERATORS UTILIZING ELECTRON NEUTRALIZATION

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Abstract

The transport and post-acceleration of multikilo-ampere ion beams is being studied at Sandia Laboratories for application to inertial fusion. A number of projects have been carried out over the past year, including theoretical investigation of non-linear beam transport, rapid space charge neutralization of ion beams by electrons emitted from boundaries, and longitudinal instabilities of pulseline driven linear accelerators. In the experimental part of the program, injectors have been developed which can deliver 10 kA of protons and 2 kA of carbon ions (at 100-200 keV) for microsecond pulse durations. These beams have been post-accelerated in a magnetically insulated acceleration gap. By suitably shaping the electrostatic gap boundaries, focusing of the beams has been demonstrated.

Introduction

The purpose of the Pulselac Program at Sandia Laboratories is to investigate the feasibility of multiple stage accelerators for intense ion beams.[1] A multiple stage system is one method of alleviating the problems of high intensity ion diodes for inertial fusion applications.[2,3] Post-acceleration can reduce the divergence angle of a beam (and hence increase standoff from the fusion target) and significantly reduce the requirements for instantaneous power and energy flux to attain the necessary final beam power.[4,5] These are valuable qualities for high repetition rate devices. The Sandia approach differs from that envisualized for conventional accelerators[6] in that the beam will be neutralized by electrons within the accelerator volume. The resulting high currents, lower beam energy, and system simplicity give Pulselac significant cost advantages over conventional devices.

Many of the problems encountered in neutralized accelerators have their counterparts in conventional accelerator practice, although the resolution of these problems demands unique approaches dictated by the high current levels involved. Areas of particular interest for the Pulselac Program include the development of high brightness sources of intermediate mass ions, the transverse confinement and stability of high current beams, and the longitudinal stability of accelerators driven by loaded pulselines. In the past year, encouraging theoretical and experimental progress has been made in these areas. A brief review of the concepts of ion beam neutralization will be given, followed by a summary of work done to date to verify these concepts.

Physics of the Pulselac Acceleration Gap

The version of the Pulselac acceleration gap used in present experiments is shown in Fig. 1. A radial magnetic field is produced by four coils located around the annular propagation region. The magnetic fields provide insulation against electron flow along the longitudinal potential. This allows concentration of the field gradient in a small fraction of the accelerator length. (The longitudinal field gradient is limited by insulator properties as in all pulseline driven linear accelerators.) Short acceleration gap length is important since the beam must be un-neutralized in the gap. There is a limit to the accuracy with which the resulting transverse space charge fields can be balanced by applied fields.

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The magnetic field performs two other functions. It acts as a barrier against electron leakage from the drift tubes. There is thus no energy dissipation from electron backflow. Equally important, the trapped electrons can reach a high enough density to provide effective neutralization. The second property of the

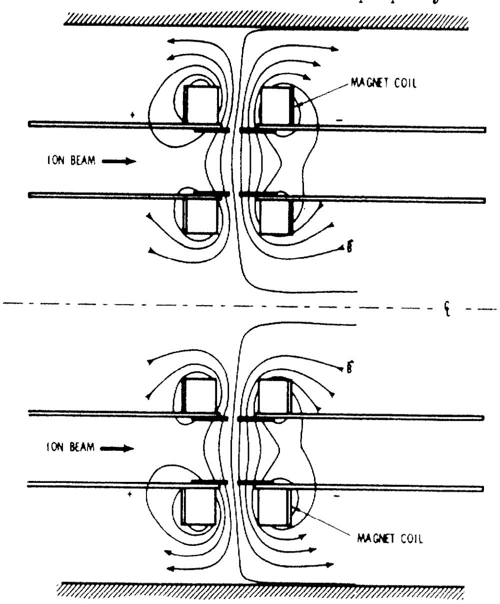

Fig. 1. Four coil Pulselac gap showing magnetic field geometry.

magnetic field is that it can be used to determine equipotential surfaces. Electrons can flow along the field lines interesecting the extreme physical protrusions into the acceleration gap. Since electric fields along the magnetic field line are reduced to zero, the surface defined by the magnetic field can act as a virtual conducting sheet.[7,8] By curving the virtual electrodes, the accelerating field can be used to provide strong focusing forces to maintain the annular beam. The dense neutralized beams cannot be affected by electric fields applied directly (the Debye length is shorter than the beam dimensions), but by combining electric fields with magnetic insulation, electrostatic focusing is possible.

It can be shown (through conservation of canonical angular momentum) that the magnetic fields give no net azimuthal velocity to the paraxial ions. Inside the drift tubes, sources on the boundaries provide free electrons. These can rush in along field lines (or follow the beam in field free regions) to neutralize the ion space charge. If the velocity distribution of the entering electrons can become randomized (a natural process in most systems with realistic asymmetries), then the light electron mass allows almost complete cancellation of space charge effects on nanosecond time scales. More detailed discussion on these subjects are given in References 1, 15 and 16.

Magnetic Insulation Experiments

The Pulselac gap of Fig. 1 has a magnetic field geometry that prevents electrons from crossing the gap (even under high field stress) and gives the electrons stable, closed orbits. Tests were performed to investigate the insulation properties of

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this gap, which forms the basis for the acceleration scheme. Initial experiments were performed with a short pulse generator (60 nsec) with no ion injection at field stress up to 0.5 MV/cm[9]. Application of the magnetic field reduced the electron leakage perveance by a factor of up to 600. This result indicated that the electron residence time in the gap was long, confirming the stability of the electron orbits. Similar results were obtained using a long pulse generator. Useful insulation times of over 2 μsec were observed with 0.16 MV across a 0.7 cm gap. Electron leakage and final breakdown occurred outside the gap, so that improved performance is expected with a redesign of the surrounding vacuum chamber and insulator.

Proton Injectors

Proton injection experiments were performed initially with the short voltage pulse generator. A standard surface flashover plasma source[7,10] was located in the anode plane of the gap of Fig. 1. The diode area was 150 cm^2. The pulseline produced a flat voltage pulse, and the injector had a steady impedance with fast initiation of the ion current. Probe measurements near the extraction cathode showed a well defined ion pulse, and a time of flight detector clearly showed the beam consisted mainly of protons. The ion current density ($\sim$20 A/cm^2) was close to the Child-Langmuir value. There were azimuthal non-uniformities caused by small errors in the electrode parallelism. The major problem with short pulse operation was the high beam divergence caused by plasma granularity and space charge effects in the gap. Attempts to alleviate the optics problem by shaping the anode failed because the flashboard produced plasma preferentially at the anode extrema.

The divergence problem was solved by the fortuitous observation that the injector would evolve into a different mode of operation if the voltage pulse was extended by direct connection to a Marx generator. Currents far in excess of the Child-Langmuir limit were observed with high uniformity and an acceptable divergence ($\sim$3°). Currents up to 30 kA were measured at a voltage of about 100 kV for microsecond pulselengths. The late time behavior is believed to be governed by a weak instability of the rotating cathode electron cloud.[11] The main drawbacks to this mode of operation were the rapidly falling gap impedance and the late time contamination of the beam by heavier elements from the flashboard surface. In addition, flashboards are not well suited to the production of pure beams of heavier ions (i.e., oxygen) that are of greatest interest for fusion applications.[5]

Carbon Injectors

A major breakthrough in the development of high brightness injectors was the operation of a carbon ion injector. An array of six carbon plasma guns was located 20 cm upstream from the extraction gap, as shown in Fig. 2. The pulsed guns were fired a few microseconds before the main voltage pulse. The gap was reconfigured with field excluders so that the magnetic field did not extend upstream of the gap; the plasma stagnated upon reaching the magnetic boundary. Currents of 3 kA at 160 kV were observed for pulselengths of 1.5 μsec. Typical ion current densities were 10-20 A/cm^2. Time of flight detectors and a Thompson parabola mass spectrometer indicated a beam composed primarily of C^+ and C^{++}, in agreement with measurements of the gun plasma. The ion current appeared to be source limited; the gap impedance was found to rise with time, an unusual circumstance for high powered beam work. These experiments represented two important milestones: the first intense injector of ions other than p^+ and d^+, and the first magnetically insulated diode using an active plasma source decoupled from the acceleration gap.[12]

Post-acceleration Experiments

The injectors were used with a second magnetically insulated gap to investigate post-acceleration at high current levels. With a carbon source and a gap separation of 25 cm, over 2 kA of ions were given an energy increment of 200 keV over a 300 nsec pulselength. The energy gain was confirmed by mass spectrometer data.

The observation of beam focusing by the gap was equally as important as the demonstration of electrostatic acceleration. Detector arrays and scintillator sheet image detectors showed a sharp annular line focus of the higher energy ions when the second gap voltage was applied. The effective focusing power of the gap could be varied by changing the location of the gap with respect to the curved magnetic field lines (see Fig. 1). No real electrodes were used, so the focusing effects confirmed the existence of virtual electrodes determined by the electron space charge.

Electron Sources

Large area boundary electron sources have been developed in conjunction with J. Ramirez[13]. These are thin sheets upon which a ballasted array of hundreds of surface sparks can be produced. The dense plasma centers allow extraction of average electron current densities approaching 1 kA/cm^2 for a few microseconds. Only a small energy investment is needed (a few J/m^2).

Theory of Ion Beam Neutralization

Two studies were undertaken to understand the time dependent process of neutralization by electrons emitted from boundaries. Computations on ion beam propagation in free space[14] showed a self-consistent sheath solution with electrons extracted from boundaries by the space charge fields of the ions. They followed the ions to provide both space charge and current neutralization. In the case where the beam was strongly focused, the electron distribution played an important part in determining the minimum focal spot.

In a second case, cold electrons were introduced perpendicular to the beam direction in the presence of a transverse magnetic field.[15] This is applicable to sections of magnetically insulated linear accelerators (as in Fig. 1) and in high current optical elements. Studies were made with a computer simulation code that followed the electron dynamics in the presence of a rising ion density. If the electron velocity distribution could become randomized, almost complete neutralization occurred within nanoseconds for typical cases.

Non-linear Beam Transport

A neutralized linear accelerator geometry using external coils only was treated theoretically.[16] In this study it was necessary to develope a description of transverse beam dynamics in highly non-linear focusing systems. Major results of this work were: a) particle orbits in a transport system composed of discrete, non-linear focusing elements could be approximated by those in a non-parabolic potential well, b) this approximation could be used for a first order optical system design, c) the non-linearities gave particles a spread in oscillation frequency that made them resistant to parametric instabilities, and d) the characteristics of the transport system and beam self-fields set a lower limit on the transverse beam temperature. This theory was an important first step since high current beams have strong self-field interactions that are far removed from the linear approximation used in treatments of conventional accelerators. The transverse beam temperature is significant for fusion applications since it determines the minimum focal spot.

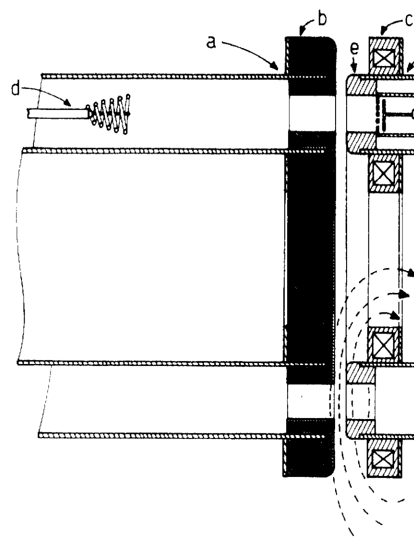

Fig. 2. Injector gap. a) Stainless steel support structure. b) Aluminum magnetic field excluder. c) Magnet coil. d) Carbon plasma gun. e) Electric field shaper. f) Diagnostic probe.

Longitudinal Beam Stability

A computer simulation was used to investigate the longitudinal stability of linear accelerators with gaps driven by loaded pulselines. The work is relevant to the Pulselac approach and also to heavy ion proposals based on inductive accelerator technology.[17] The major results were: a) voltage oscillations in a gap could be amplified by velocity bunching to produce a strong system instability which increased the longitudinal velocity spread, b) a sufficient velocity spread (determined by the properties of the gap driving circuit) provided stability, c) an unstable beam became self-stabilized when its velocity spread reached the required limit, d) it was necessary to maintain constant beam length during acceleration to avoid growth of the effective phase space area, and e) the velocity spread required for stability did not preclude beam containment and a temporal compression of the beam after acceleration. The model was not applicable to very high frequency disturbances in the gap. Finite gap width effects, the influence of space charge, and more complex gap driving circuits must be included. A model incorporating these additions is presently under development.

Computer Simulations of Acceleration Gaps

A complete computer simulation model of an azimuthally symmetric Pulselac gap was developed. The model includes self-consistent magnetic and electric fields of ions and electrons, ion dynamics, complete dynamics of electrons emitted from boundaries, the ability to inject neutralizing electrons with the entering ion beam, and the versatility to handle a wide variety of applied fields and boundary conditions. A number of runs were performed with the external coil gap geometry and have confirmed ideas on virtual electrodes, space charge effects on ion orbits through the gap, and neutralization in the drift tube regions.

The model is presently being adapted to the gap geometry of Fig. 1. Future studies include the optics of the gap under various circumstances, limits to the transportable beam current determined by the transverse beam temperature, and the optimization of beam transport in experimental multistage systems.

Pulselac B

A five stage, low β accelerator is presently under construction, and should be operational by the Summer of 1979. A number of problems that were observed in initial experiments will be remedied in the new design. The acceleration gaps (which also act as optical elements) will be located close together (7.5 cm spacing on the average) to control the low velocity beam with little beam loss. In present experiments, pulse termination is brought about by breakdown external to the gap, so the vacuum chamber and insulator designs will be considerably improved to obtain longer pulselengths. Success in areas such as magnetic insulation, long pulse ion injection with active plasma generation, electrostatic beam focusing, and simulation of beam optics has laid a good engineering base. We feel that Pulselac B performance can be projected with a much higher degree of confidence than the position of one year ago. (A drawing of Pulselac B is included in the article by G. Yonas, these proceedings.)

Predicted output parameters are 3 kA of ions at 1 MeV times the ion charge state. The applied voltage will be 200 kV/stage. Beam divergence should be less than 1°. The average accelerating gradient will be 2.5 MV/m. Present experience indicates that the accelerated ion species is completely dependent on the characteristics of the plasma source. Experiments will be performed with the present pulsed carbon plasma guns as well as others. A hydrated titanium washer stack gun has been supplied by Lawrence Livermore Laboratory for proton beam generation. Experimental investigations of sources of C^{4+} are underway at Sandia Laboratories.

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