PULSELAC PROGRAM

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I. Introduction

The Pulselac Program at Sandia Laboratories is a recent addition to the Heavy Ion Fusion Program. The purpose of this paper is to give a brief introduction to the work performed to date and future plans for the development of high current accelerators. The basis of the program is the investigation of practical methods of neutralizing the space charge of intense ion beams both in accelerating and transport regions. Alleviation of space charge constraints on ion beam transport would open up a broad range of new options for accelerator fusion drivers.[1,2,3] The method to be employed is the introduction of electrons from external sources into the volume of the ion beam, allowing the relaxation towards a state of lower potential energy. Both the spatial location and velocity distribution of the electrons must be controlled. Our approach is to utilize weak magnetic fields, which have negligible effect on the ion orbits, to accomplish this. The physics of the electron control and magnetic field geometry requires an ion beam with annular geometry.

The program has two major goals. The first is to gain an understanding of the general phenomenon of beam neutralization. The second is to demonstrate the technological feasibility of the utilization of these principles to produce multi-kiloampere ion beams in a controlled and reproducible manner. It should be emphasized that we are investigating new methods of beam transport; actual beam acceleration is conventional. In particular, the inductive linear accelerator technology under development at LBL would be ideally matched to the high current beam transport systems.

The physical basis of neutralized beam transport has been discussed in the proceedings of the Argonne National Laboratory Workshop, 1978 (3) as well as in a number of other references.[4,5,6] In this paper, progress since the Argonne Workshop will be reviewed, and plans for a fusion demonstration accelerator, Pulselac C, to be built over the next 2.5 years, will be discussed.

II. Theoretical Work

Neutralized beam propagation presents a number of novel research areas, both for the plasma physicist and accelerator theorist. The microscopic problems of gap behavior and local neutralization must be combined with systems considerations. A wide diversity of new phenomena can occur because of the two-particle nature of the problem. The electron dynamics is of equal importance to that of the ions in determining the behavior of the system. Familiar techniques in accelerator theory, such as the treatment of space charge as a perturbation and the approximation of focusing forces as linear away from the axis of symmetry, must be completely discarded. We have made initial efforts to construct a theory of neutralized beams; results are summarized in this section.

A. Ion Beam Neutralization

One-dimensional computer simulations have confirmed that space charge in ion beams can be almost completely cancelled by electrons introduced from sources external to the beam.[7] Basic scaling laws for the time-dependence of the neutralization process have been verified.

B. Two-Dimensional Particle Simulations

A two-dimensional particle simulation model has successfully demonstrated a number of the physical aspects of the Pulselac gap. The code follows individual, self-consistent particle orbits to look for quasi-steady-state solutions. Virtual cathode formation and drift tube neutralization are clearly demonstrated. The computer results also indicate two important constraints on the time response of neutralization; the access of the electrons to the beam volume (which may be affected by magnetic field line contours), and the rate of relaxation of the electron velocity distribution.

C. Neutralized Beam Propagation

The problem of the propagation of neutralized ion beams in free space (plasmoids) is not trivial when the beam changes dimension, as in a transverse or longitudinal focus. Possible problems arising from the transfer of energy from the ions to electrons by adiabatic compression were mentioned in an earlier reference.[8] Recent two-dimensional computer simulations of focused neutralized beams in vacuum have verified that the beam focus can be limited by thermoelectric effects in the electron cloud. This disturbance can grow unstably if the beam pulselength is too long. These considerations set requirements on the quality of the neutralizing electron distribution and the beam pulselength.

D. Transport of Beams in Non-linear Focusing Systems

Analytic studies have been published[6] which describe methods for treating the transverse confinement of beams in focusing systems that vary non-linearly with distance from the symmetry axis. The most important results of these studies are that beams can be transported in highly non-linear systems without emittance growth once the beam has reached an equilibrium distribution appropriate to the system, and that non-linear systems may have advantages from the point of view of beam stability because of the large spread in transverse oscillation frequencies.

E. Longitudinal Instabilities

Velocity bunching in accelerators of neutralized ion beams can be a serious problem. The ions are generally non-relativistic, the individual gaps are strongly loaded by the beam and longitudinal space charge effects (which impede bunching) have been greatly reduced. A particle simulation model has been used to investigate such instabilities in the case where space charge effects are absent. A longitudinal velocity spread (which can be simply related to the impedance of the gap driving circuits) can provide stability. The required spread does not preclude a macroscopic beam bunching for power compression to the target. The non-linear development of the instability can be followed. Since the instability increases the longitudinal velocity spread, it is self-stabilizing.

III. Experimental Work

Experimental work on neutralized beam propagation has been carried out for the past two years at Sandia Laboratories. The purpose of these experiments was to investigate a wide diversity of problems associated with neutralized beams in order to form a basis for the design of practical systems. Considerable work has been carried out on injector gaps and on a two-gap system with independently applied voltage. These results are reported in Ref. 8.

Recently, a five gap accelerator has been operated with encouraging results. Peripheral work has been performed on the development of large area electron sources and pulsed guns for intermediate ion mass plasmas.

A. Injector Development

A novel injector has been developed which holds great promise for technological development. It is the first intense ion gun to use plasma injection into the anode plane from independent plasma sources. Initial operation was with carbon plasmas. Extracted carbon ion beams in the range 100-200 keV and 3-4 kA have been obtained. The injectors can be fired repetitively, limited mainly by the performance of the plasma guns. They operate at 20-30 A/sq. cm, roughly 10 times the Child-Langmuir limit. This current density enhancement is due to electrons trapped in the magnetic fields of the acceleration gap. The beams can be aimed by shaping the electron distributions through magnetic field curvature. Parallelism better than three degrees has recently been obtained.

B. Post-Acceleration

Experiments have been performed to post-accelerate beams in a number of gaps. These are the first such experiments with intense ion beams. Most recently, a five gap system has been operated. The final energy of the beam agrees closely with the sum of voltages on the acceleration gaps. Carbon beams at over 600 keV, 3 kA have been measured at the output. Pulselength is about 0.5 microseconds. Of greatest importance, the divergence angle of beams emerging from the five gap injector have been measured to be about 0.7 degrees, better than any results with single gap, intense ion beam injectors.

C. Beam Neutralization

It has been difficult to perform controlled measurements on beam neutralization phenomena in the close confines of the accelerator. Nonetheless, measurements of current density as a function of longitudinal position are useful since the ion orbits are sensitive to any imbalance in the space charge. These measurements imply an average upper limit of 0.2% in the imbalance of space charge during the propagation of the ion beams in the downstream drift regions. Roughly 2/3 of the beam current is measured 30 cm downstream from the injector. Without neutralization, the beam would be expected to blow up within 2 mm of the extractor.

D. Electrostatic Focusing

By purposely introducing curvature into the magnetic fields of post-acceleration gaps, the acceleration fields can be used to apply transverse electrostatic focusing forces to the ions because of the curved virtual electrode surfaces. Such experiments were performed using scintillation image detectors and probe arrays to measure the convergence of the ion beam. Tight azimuthal line foci were obtained (when the post-acceleration gap voltage was applied), in good agreement with calculations of the field line curvature. These tests provided a dramatic demonstration of virtual electrode effects.

E. Electron Sources

A critical requirement for the success of beam neutralization methods is the development of large area sources of electrons that can supply multi-kiloampere pulsed current. Steady state sources (such as thermionic sources) are clearly impractical in an application with a duty cycle 1/1,000,000. Secondary emission electrons from the walls produced by a blow-up of the head of the beam have provided neutralization in first generation experiments. This is not extrapolatable to multi-gap systems. We have been investigating the use of surface sparks to produce dense plasmas localized at the drift tube walls to act as a zero work function source of electrons. These require only a small energy investment (a few joules per sq. m). We have recently had success towards development of a practical source. It uses a unique method of capacitive ballasting to produce many sparks (possibly thousands) with one voltage input. The plasma is in good contact with a grounded metal screen. The unit can be shaped and is only 2 mm thick, so it can be easily mounted inside the accelerator drift tubes.

IV. Pulselac C

It has recently been decided that we should proceed with the construction of a demonstration fusion accelerator based on neutralization principles. This device, Pulselac C, will be a 4 MeV linear induction accelerator designed to accelerate 5 kA of ions in a 50 ns pulselength. Total beam output energy will be 1 kJ. Design parameters of the accelerator are listed in Table 1. The goal is to build an accelerator with technology within the range of existing devices. It will have enough gaps to study system problems of intense ion beam transport. The curvature of the gap magnetic field lines will be externally adjustable to allow investigation of transverse focusing. The pulselines will store four times the energy required by the gaps. This will allow investigation of the stabilization of longitudinal velocity space instabilities and permit the application of time-ramped voltages using passive shunt circuits for beam bunching experiments. The Pulselac C accelerator will be a test bed for neutralized transport; it will be built on a scale that will allow it to either succeed or fail unambiguously. A scale drawing of an acceleration gap and core module is shown in Fig. 1 to demonstrate the compatibility of the neutralized transport system and inductive LINAC technology.

References

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TABLE I. Pulselac C Parameters

Accelerator length	6 m
Number of gaps	16
Voltage per gap	250 kV
Beam current	5 kA
Pulseline impedance	12.5 ohm
Pulselength	50 ns
Gap efficiency	25%
Drift tube cross sectional area	200 cm sq.
Average gap magnetic field	4 kG
Longitudinal potential gradient	0.67 MV/m
Injector voltage	100 kV
Injector pulselength	1 microsecond
Ion species	C+
Beam bunched pulselength	20 ns
Beam output power (bunched)	50 GW
Beam output divergence	Less than 0.5 degree
Focused beam area	1 cm sq.
Total beam energy	1 kJ
Repetition rate	1 ppm

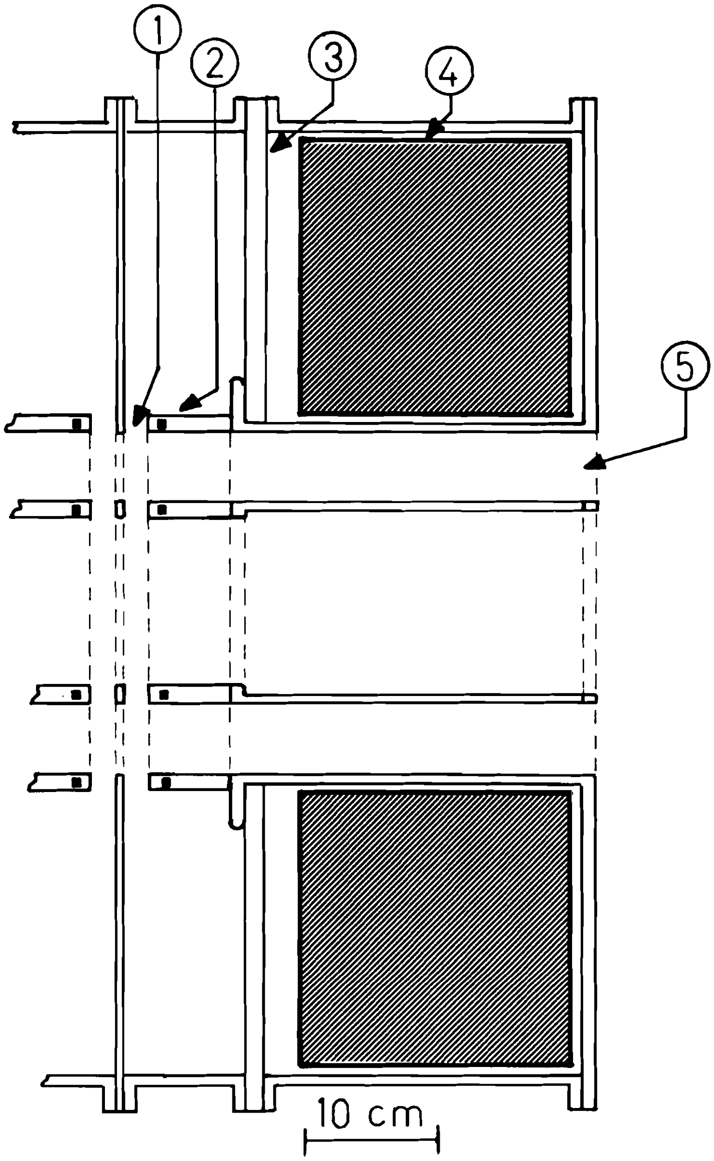

Figure 1. Pulselac C Acceleration Module. 1) Magnetically insulated acceleration gap. 2) Coaxial drift tube structure with magnetic coils. 3) Vacuum insulator. 4) Ferrite core (250 kV, 50 nsec). 5) Annular drift region.