A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR -86-1810

CONF-860510 --5

RECEIVED BY POST JUN 06 1986
MASTER

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--86-1810

DE86 011243

TITLE CHARGE AND CURRENT NEUTRALIZATION PHYSICS OF HEAVY ION BEAM
DURING FINAL TRANSPORT

AUTHOR(S) G. R. Magelssen and D. W. Forslund, Los Alamos National Laboratory

SUBMITTED TO To be published in the American Institute of Physics
Proceedings on Heavy Ion Fusion. Will be presented at 1986
HIF Symposium in Washington D.C., May 27 - 29, 1986.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

CHARGE AND CURRENT NEUTRALIZATION PHYSICS OF A HEAVY ION BEAM DURING FINAL TRANSPORT

G. R. Magelssen and D. W. Forslund
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

Heavy ion fusion requires high power to be focussed onto a small pellet. If the reactor chamber pressure is below 10^{-4} - 10^{-5} Torr, beam compression will be limited by space charge unless neutralized by co-moving electrons. If higher chamber pressures are used, the heavy ion beam will create a significant number of background electrons during its propagation and will undergo stripping. The background electrons could provide the neutralization required for high beam intensities. In this paper we will focus on the physics associated with propagation through a fully ionized hydrogen plasma, so background electron generation is not included. One-dimensional electrostatic and two-dimensional fully electromagnetic particle-in-cell simulations are presented.

If a background plasma is present, we find that coinjected electrons whose purpose is to charge and current neutralize the ion beam become two-stream unstable and no longer provide the thermally cool neutralization required. Further, we find that the ion induced background electron temperature is very sensitive to the ion beam to background electron charge density ratio.

INTRODUCTION

Heavy ion fusion requires high beam power to be focussed onto a small pellet - intensities of 100 - 1000 TW/cm² may be required. If the reactor chamber pressure is below 10^{-4} - 10^{-5} Torr, beam compression will be limited by space charge unless neutralized by comoving electrons.¹ If higher chamber pressures are to be used, the heavy ion beam will create a significant number of background electrons during its propagation²⁻³ and will undergo stripping.⁴ The background electrons could provide the neutralization for high beam intensities.

Previous studies have avoided the background pressure region from about 10^{-4} - 10^{-1} Torr because the ion beam will become two-stream unstable.^{5,7} However, recent analytical estimates that included ion beam stripping, ion space charge, beam convergence, and electron generation suggest that the two stream instability

growth is too small - the electric field is too weak - to cause a significant change in the beam's waist size.⁸ Charge and current neutralization physics were not included.

In the past the neutralization problem was studied at pressures on the order of or greater than 1 Torr. As a result, the ion beam charge density was always significantly smaller than the background electron density except possibly at the front of the beam.⁹⁻¹¹

At background densities of 10^{-4} - 10^{-2} Torr, the beam charge density can become greater than and possibly significantly greater than the background electron density as the beam approaches the target. In this paper our primary purpose is to present results for this low pressure region of the heating of reactor chamber electrons by a heavy ion beam during its propagation to a target. We will not address the question of the amount of ion beam energy loss or the effect of the beam-generated electric and magnetic fields on the beam's waist. We focus on the electron temperatures generated. If the background electrons are to provide the neutralization required for a small focus at high ion currents,

high electron temperatures must be avoided.¹

Our approach was to first study the propagation problem in the electrostatic case to understand whether electron heating was significant and under what conditions. Our results suggested that heating could be important; so, two-dimensional fully electromagnetic simulations were done to determine whether the added dimension had a significant impact on the one-dimensional results. Two approximations were made to simplify the calculations. Neither the background electron generation nor the ion beam stripping were included in our simulations. The possible effects of these approximations are discussed in the summary.

The orientation of this paper is the following. First we present one-dimensional electrostatic simulation results that suggest significant electron heating can occur where the heating is examined as a function of the ion beam to electron charge density ratio. Results with a background plasma density gradient and with a comoving electron beam are also presented. This is followed by fully relativistic and electromagnetic two-dimensional simulation results that confirm the sensitivity of the background electron heating to the ion beam to background electron charge density ratio.

ONE DIMENSIONAL SIMULATIONS

We present one dimensional electrostatic simulations of electron heating by an ion beam under four different conditions. The simulation results were obtained using the Los Alamos code Wave, a two dimensional, fully relativistic and electromagnetic code that self consistently solves the Newton-Lorentz equations of

motion and Maxwell's equations for ions and electrons with the particle-in-cell technique.¹² The presentation of results will be brief emphasizing qualitative aspects of the simulations. Details have been left for a later paper.

The first simulation is ion propagation through a dense plasma into vacuum. The electron and ion density were an order of magnitude greater than the beam's peak charge density. This high density plasma that is located at the left boundary exists in all of our simulations. Thermal electrons are continuously injected from the left boundary to maintain charge neutrality. The plasma represents a grid placed in the ion beam's path near the entrance port to the reactor chamber. In all simulations the heavy ion beam is injected from the left boundary, propagates in the x direction, and is absorbed at the right boundary. Electrons are absorbed at the right boundary while background ions are reflected at all boundaries. The boundary condition for the electric field was aperiodic, metallic-like. In all simulations the mass-to-charge ratio was 20.000 for the heavy ions and 1836 for the background ions; the injected ion charge density profile was

$$A \{ \exp(-t/t_2) - \exp(-t/t_1) \}^3 \quad (1)$$

where A , t_1 , and t_2 are constants. For all simulations the ion drift velocity was $v_d = c/3$ and the momentum spread 0.003 - a value of 0.001 gave similar results. There were 20 cells per wavelength assumed to be $2\pi v_d / \omega_{pe}$. This is the value associated with the maximum growth rate for the ion electron two stream instability. In all simulations, the t_1 and t_2 coefficients were 20 and 300, respectively. Figures 1 and 2 illustrate the electron heating at time 200. The front of the beam was located at the position 60.

Fig. 1 Electron density F versus momentum P at $t = 200$ (vacuum).

In all figures time is normalized to ω_{pe}^{-1} , length to c/ω_{pe} , and the relativistic particle momentum P to $m_e c$. The ω_{pe} , c , and m_e are the electron plasma frequency, the speed of light, and the electron mass, respectively. Substantial heating of electrons occurs at early times creating a high energy tail in the momentum distribution. The electron distribution (arbitrary units) versus momentum is given in Fig. 1.

This shows the electron return current with an average velocity about equal to and a thermal velocity greater than v_d . Figure 2 is a plot of the electron momentum in the x direction as a function of the distance x. A virtual cathode-like structure is evident as was seen and described by S. Humphries et al.¹³ However, the cathode structure exists only near the dense plasma; so, a different description of the downstream electrons is needed. Filling the vacuum region with a plasma with a density equal to 1/10th the peak ion beam charge density had little effect on the cathode structure, or the return current average and thermal velocity. Figure 3 is a plot analogous to Fig. 2 and illustrates the similarity in the cathode structure and heating for these two plasma conditions.

Fig. 2 Momentum P versus distance X at $t = 200$ (vacuum).

Fig. 3 Momentum P versus distance X at $t = 200$ (plasma one-tenth beam's peak density).

In the second simulation the vacuum region was replaced with a uniform plasma that was twice the beam's peak density. Figures 4 and 5 illustrate the dramatic change in the electron temperature. These plots are snapshots at 200 the time of Figs. 1 and 2. The electron charge density versus momentum is shown in Fig. 4. The return current and background distributions have merged making it difficult to determine an average momentum associated with the return current. Figure 5 displays the momentum versus distance. The cathode structure is no longer evident and the number of high energy electrons greatly reduced.

Fig. 4 Electron density F versus momentum P at $t = 200$ (plasma twice beam's peak density).

Fig. 5 Momentum P versus distance X at $t = 200$ (plasma twice beam's peak density).

In the third simulation the vacuum region was replaced with a plasma with a linear density gradient. The density was twice the beam's peak charge density at the interface with the dense plasma and a tenth this peak density at the right boundary. The density

Fig. 6 Momentum P versus distance X at $t = 400$ (density gradient).

gradient was used to gain some understanding of beam convergence in one dimension. Initially the background electron heating was similar to that of the previous simulation - fairly low temperatures prevailed. However, when the beam charge density became greater than the electron density, the electron temperature rose. By the time the beam reached the right boundary, significant temperatures were generated. This heating is illustrated in Fig. 6 which is a plot of momentum versus distance at the time 400.

In the final simulation, the vacuum region was again replaced with a plasma with a density gradient. The gradient was the same as the previous calculation. Both ions and electrons were injected from the left boundary and they both had the profile given by Eq. (1). The temperature of the electron beam was chosen to be 2 KeV to minimize the electron-electron two-stream instability. If the injected electrons remain trapped in the ion beam, higher initial temperatures will not provide charge neutralization of a converging ion beam.¹ The electron and ion drift velocities were the same.

Fig. 7 Momentum P versus distance X at $t = 120$ (ions and electrons injected).

The gradient was used to provide some understanding of the effects of beam convergence. For example, both the electron-electron and the ion-electron two-stream instability are resonant processes and can be modified by density gradients in either the beam or background plasma. Figure 7 illustrates what happens to the comoving electrons. The injected electrons became two-stream unstable, lost a substantial amount of energy, and no longer provided a thermally cool neutralizing current required for ion beam compression.

TWO DIMENSIONAL SIMULATIONS

The two-dimensional simulations had the same boundary conditions in the x-direction as the one-dimensional calculations. The fields and particles had periodic boundary conditions in the y spatial dimension. The injected ion beam had a gaussian density profile in y and the density profile of Eq. (1) in time. The t_1 and t_2 were 20 and 300, respectively. The beam propagated in the x-direction with a speed of $c/3$ and a momentum spread of 0.003. For the simulations presented significant electric fields existed in the x and y directions as well as a magnetic field in the z direction. The results from two different plasma conditions are presented. As in the one-dimensional calculations, a dense plasma was placed at the left boundary in the x dimension.

Fig. 8 Momentum P versus distance X at $t = 200$ for 2-D simulation (plasma one-tenth beam's peak density).

Fig. 9 Electron density F versus momentum P at $t = 200$ for 2-D simulation (plasma one-tenth beam's peak density).

In the first simulation a uniform plasma one-tenth the beam's peak density was located to the right of the dense plasma. Figure 8 shows the plasma condition analogous to Fig. 3. The cathode structure is again evident as well as significant electron heating although somewhat reduced from the one-dimensional result. The electron density as a function of momentum is given in Fig. 9. The thermal velocity associated with the return current is the order of or greater than v_d . In the second

Fig. 10 Electron density F versus momentum P at $t = 200$ for 2-D simulation (plasma twice beam's peak density).

simulation the uniform plasma density was increased to twice the

beam's peak charge density. As in the one-dimensional calculation, a dramatic reduction in the electron temperature occurs. A plot analogous to Fig. 4 is depicted in Fig. 10.

SUMMARY

Our results suggest that if a plasma is present, coinjected electrons whose purpose is to charge and current neutralize the ion beam become two-stream unstable, become hot, and no longer provide the thermally cool electrons required. We also find that the ion beam induced background electron temperature is very sensitive to the ion beam charge density (n_b) to background electron density (n_e) ratio reaching a temperature on the order of or greater than the ion's drift speed for $n_b/n_e = 10$. At a ratio of 1/2, the temperature is greatly reduced as is illustrated in Fig. 10. Our results suggest that the background plasma may not provide the current and charge neutralization required if n_b/n_e is greater than 1 for a significant distance. The initial heating and subsequent beam compression could create electrons too hot to provide charge neutralization at the beam's waist.¹ Many unanswered questions remain, however. Neither the background electron generation nor the ion beam stripping have been included in our simulations. Because these processes determine n_b/n_e , without them accurate predictions of the electron temperatures will not be possible. A time and spatial variation of n_b/n_e could also modify the streaming instability growth rates. Finally, a simulation of a two-dimensional converging beam needs to be done to determine if electrons initially trapped remain trapped as the beam compresses.

REFERENCES

1. D. S. Lemons and M. E. Jones, IEEE Trans. Nuc. Sci. NS-32, 2474 (1985).
2. S. S. Yu, H. L. Buchanan, E. P. Lee, and F. W. Chambers, "Beam Propagation Through a Gaseous Reactor - Classical Transport," in Proceedings of Heavy Ion Fusion Workshop, Argonne National Laboratory report ANL-79-41, p. 403 (1979).
3. W. A. Barletta, W. M. Fawley, E. P. Lee, and S. S. Yu, "Final Transport of Heavy Ion Beams for Inertial Confinement Fusion," Lawrence Livermore Laboratory report UCRL-85089 (1981).
4. W. A. Barletta, "Heavy Ion Beam Degradation from Stripping in Near Vacuum Reactor Chambers," Lawrence Livermore Laboratory report UCRL 85651 (1981).
5. S. Jorna and J. B. Thompson, J. Plasma Phys. 19, 97 (1978).
6. R. F. Hubbard and D. A. Tidman, Phys. Rev. Lett. 41, 866 (1978).

7. Y. K. Kim and G. R. Magelssen (editors), Report on the Workshop on Atomic and Plasma Physics Requirements for Heavy Ion Fusion, Argonne National Laboratory report ANL-80-17 (1980).
8. P. Stroud, Laser and Particle Beams 4, 230 (1986).
9. D. A. Tidman, ERDA Summer Study of Heavy Ions for Inertial Fusion, Lawrence Livermore Laboratory report LBL-5543, p. 52 (1976).
10. D. Mosher, Ref. 9 p. 59.
11. P. F. Ottinger, D. Mosher and Shyke A. Goldstein, Phys. Fluids 24, 164 (1981).
12. R. L. Morse and C. W. Nielson, Phys. Fluids 14, 830 (1971).
13. S. Humphries Jr., T. P. Lockner, J. W. Poukey, and J. P. Quintenz, Phys. Rev. Lett. 46, 995 (1981).