2
5-12-78
LA-7233-MS

Informal Report

Special Distribution

Issued: April 1978

MASTER

**Design Considerations for the
Air Force Weapons Laboratory
FX25 Plasma Heating Experiment**

Lester E. Thode

**los alamos
scientific laboratory**

of the University of California

LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

**UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36**

DESIGN CONSIDERATIONS FOR THE AIR FORCE WEAPONS LABORATORY
FX25 PLASMA HEATING EXPERIMENT

by

Lester E. Thode

ABSTRACT

The potential of using the FX25 relativistic electron beam generator to produce a multikilovolt, $10^{15} - 10^{17} \text{ cm}^{-3}$ density plasma is discussed. An initial design of an experiment to investigate the effects of ionization gradients, hydrodynamic gradients, anode foil scattering, external magnetic field strength, and beam self-magnetic field strength on the collective interaction is provided. It is concluded that a plasma energy density of $10^{20} - 10^{21} \text{ eV/cm}^3$ may be achievable with the FX25 generator.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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 represents that its use would not infringe privately owned rights.

I. INTRODUCTION

During early 1977, a seminar on the concept of high-density plasma heating using an intense, high-voltage relativistic electron beam was presented at the Applied Physics Branch of the Air Force Weapons Laboratory (AFWL). In addition to myself, W. P. Gula and K. Boyer represented the Los Alamos Scientific Laboratory (LASL) during this initial presentation. Essentially, the material presented can be found documented in Refs. 1 and 2. Following this initial presentation, a number of informal discussions occurred with C. Clark, D. Straw, and R. Miller of AFWL. As a result, on May 9, 1977, I provided the Applied Physics Branch³ with an informal document outlining design considerations for a plasma heating experiment using the FX25 electron beam generator. The present report contains the information transmitted in the previous informal document.

II. MOTIVATION

The concept of using an intense relativistic electron beam to heat a plasma has been investigated for a number of years.⁴⁻¹² Recent theory, which agrees

with the plasma heating experiments in the $10^{12} - 10^{14} \text{ cm}^{-3}$ density range, predicts that the plasma energy density W_p scales as

$$W_p \propto \gamma^{1/2} [n_b(\gamma)M(\gamma)]^{3/2} \tau, \quad ,$$

where γ is the beam relativistic factor, $n_b(\gamma)$ is the beam particle density, $M(\gamma)$ is the beam adiabatic compression ratio, and τ is the beam pulse length. This scaling is correct for a fixed beam coupling efficiency and indicates the potential of significantly increasing W_p by increasing the diode voltage of the beam generator. This conclusion follows from the fact that $n_b(\gamma)$ and $M(\gamma)$ are both increasing functions of the diode voltage.

Based upon recent theoretical¹⁰⁻¹¹ and experimental¹² agreement in the $10^{12} - 10^{14} \text{ cm}^{-3}$ regime, the potential of using a 10-30 MeV electron beam to heat a $10^{17} - 10^{20} \text{ cm}^{-3}$ plasma has been investigated.¹ The analysis has taken into account anode foil scattering, beam self-magnetic field larmor radius effect, electron-ion collision rate, external magnetic field strength, finite geometry effects, and radial beam or plasma density gradients. It is concluded that a coupling efficiency of 15-50% is achievable for such a high-density plasma.

A series of experiments are proposed to investigate the heating of a $10^{15} - 10^{19} \text{ cm}^{-3}$ plasma using an intense relativistic electron beam. Taken to completion, these experiments would greatly exceed previous heating experiments in plasma density, diode voltage, and coupling efficiency. More importantly, the beam energy is deposited into a relatively small volume plasma, with a possible final energy density in the 10^{22} to 10^{23} eV/cm^3 range.

The Air Force Weapons Laboratory has three relativistic electron beam generators which, with some modification, could be used for high-density plasma heating experiments:

- i) FX25 with $\gamma = 5$ and $\tau \approx 2 \times 10^{-8} \text{ s}$,
- ii) FX100 with $\gamma = 9$ and $\tau = 7 \times 10^{-8} \text{ s}$,
- iii) 1590 with $\gamma = 15$ and $\tau = 7 \times 10^{-8} \text{ s}$,

In Fig. 1 the expected plasma energy density $W_p (\text{eV/cm}^3)$, or equivalently plasma pressure $P(\text{atm})$, is plotted as a function of the above generators. It has been assumed that $n_b(\gamma) \propto \gamma$ with $M = 1$ for the FX25, $M = 2$ for the FX100, and $M = 4$ for the 1590. Although these assumptions appear reasonable, the actual dependence of W_p with increased relativistic factor can only be determined after

redesign and testing of the generators. Thus, Fig. 1 is only provided to indicate the potential for the follow-up experiments using the FX100 and 1500 generators. The characteristic plasma density range for each generator is given in brackets.

To put the potential of such a plasma into context, high explosives develop pressures of approximately 10^4 atm. However, the time scale to develop such a pressure is 10-50 times slower than the relativistic electron beam pulse length. Thus, the power associated with high-density, kilovolt plasmas significantly exceeds that of high explosives.

Two effects that could reduce the plasma heating have not been taken into account in the preceeding estimates:

- i) time dependent longitudinal plasma density gradients produced as a result of the target gas not being fully ionized, and
- ii) longitudinal plasma density gradients produced by the hydrodynamic motion of the plasma.

The reduction in coupling efficiency due to the time-dependent production of these gradients is difficult to estimate theoretically. However, the initial experiments have been designed to investigate these aspects of the deposition.

With carefully designed experiments, directed towards investigation of the basic physics of the deposition, both short-term payoff and probability of success of the proposed experiments appear to be high.

III. EXPERIMENTAL PROGRAM

The basic experimental setup is illustrated in Fig. 2. Initial diagnostics would include diamagnetic loops, magnetic probes, Faraday cup, calorimeter, and Rogowski loops. Time resolved and integrated x-ray measurements, time resolved neutron diagnostics, Thompson scattering measurements, time resolved Faraday

Fig. 1. Potential plasma energy density W_p (eV/cm³), or equivalently plasma pressure P (atm), attainable for the FX25, FX100, and 1590 electron beam accelerators.

rotation measurements, interferometer measurements, and time resolved beam profile measurements would also be desirable.

Two preliminary experiments should be carried out: i) characterization of the initial plasma state using interferometry and diamagnetic loops, and ii) characterization of the relativistic electron beam. Following these experiments, investigation of five basic aspects of the deposition are proposed. For example, the expected dependence of the calorimeter output for each experiment is depicted in Figs. 3 through 7.

A. Investigation of Ionization Gradient

Determine the coupling efficiency as a function of the initial fractional ionization level, from weakly to fully ionized plasma. It can be shown that for a given beam pulse length and characteristic deposition rate, there exists an initial level of fractional ionization above which significant ionization gradients cannot be formed on the beam time scale. In addition, the change in both the deposition rate and length is less than 30% if the initial fractional ionization exceeds 0.25. Thus, the degrading effect of the ionization gradient can be studied in this experiment, as shown in Fig. 3.

B. Investigation of Deposition Length and Hydrodynamic Gradient

Determine the coupling coefficient as a function of the plasma target length. The initial fractional ionization level should be large enough to produce negligible ionization gradient on the beam time scale, as determined in experiment A. As the target length L is increased, the beam energy transmission will show a decrease when $L \approx L_N$, where L_N is the characteristic deposition length. A further increase in the target length will provide information on the hydrodynamic gradient. If, as the plasma length is increased past L_N , the beam energy transmission remains relatively constant, as depicted by the solid line in Fig. 4, then the energy is being predominately deposited in a distance L_N . It follows that the hydrodynamic plasma motion is not significantly degrading the interaction.

Fig. 2. Sketch of proposed experimental setup: 1) cathode, 2) anode foil, 3) weakly to fully preionized plasma, $n_p \approx 10^{15} - 10^{19} \text{ cm}^{-3}$, 4) sectionalized calorimeter/Faraday cup, 5) movable seal to vary plasma target length, 6) sole-noid windings, and 7) diamagnetic loops.

Fig. 3. Example for percentage of beam energy transmitted to a calorimeter as a function initial fractional ionization f .

Fig. 4. Example for percentage of beam energy transmitted to a calorimeter as a function of calorimeter distance from the anode foil.

Fig. 5. Example for percentage of beam energy transmitted to a calorimeter as a function of anode foil thickness in gm/cm^2 .

Fig. 6. Example for percentage of beam energy transmitted to a calorimeter as a function of external magnetic field strength B_z .

Fig. 7. Example for percentage of beam energy transmitted to a calorimeter as a function of anode foil thickness in gm/cm^2 for various values of external magnetic field strength B_z .

However, if the beam transmission shows a characteristic linear decrease over multiples of the deposition length L_N , as depicted by the dashed line in Fig. 4, then the hydrodynamic gradient would be limiting the local deposition. Under these conditions, the time scale of the formation of the hydrodynamic gradient can be estimated.

C. Investigation of Anode Foil Scattering

Determine the beam energy loss as a function of anode foil thickness and material, as depicted in Fig. 5. It can be shown that the characteristic change in the deposition length is small relative to the deposition rate.

This provides an identification of the relativistic streaming instability as the anomalous coupling mechanism.

D. Investigation of External Magnetic Field Strength

Determine the beam energy loss as a function of external magnetic field strength. Theory indicates that there exists an optimal value of the external magnetic field strength for a given interaction. This character is shown in Fig. 6. If Thompson scattering is available, the effect of the external magnetic field strength on the heated plasma electron distribution might be investigated. Theory indicates that the energy is deposited increasingly into the bulk of the electron distribution as the external magnetic field is increased.

E. Investigation of Beam Self-Field Effects

Determine the effect of the discontinuity of the beam self-magnetic field B_0 on the deposition. From experiment C, the dependence of the beam energy deposition on the anode foil is known for a strong external magnetic field $B_z \gg B_0$. If the external magnetic field strength is reduced to $B_z < B_0$ and the calorimeter output follows the solid curve as for the $B_z \gg B_0$ data, then the finite larmor radius effect due to B_0 is not affecting the deposition. However, if as B_z is reduced the data begins to proceed as depicted in Fig. 7 by the dashed line, it would be an indication that the finite larmor radius effect is

beginning to degrade the deposition. Reducing the magnitude of B_z further would then lead to substantial degradation of the interaction, as depicted by the dot-dash, and double dot-dash lines in Fig. 7. In this manner, the effect of B_θ discontinuity could be estimated.

IV. BASELINE EXPERIMENT

In this section, the basic design of a plasma heating experiment in the $10^{15} - 10^{17} \text{ cm}^{-3}$ regime for the FX25 generator is presented. The FX25 has been operated in an external magnetic field with the following parameters:

Diode Voltage	$V = 2 \text{ MeV}$
Diode Current	$I = 20 \text{ kA}$
Beam Radius	$a = 0.64 \text{ cm}$
Pulse Length	$\tau = 20 \times 10^{-9} \text{ s},$

From these parameters, the following estimates are obtained:

Beam Relativistic Factor	$\gamma = 5$
Beam Current Density	$J = 15.5 \text{ kA/cm}^2$
Beam Particle Density	$n_b = 3.2 \times 10^{12} \text{ cm}^{-3}$
Beam Self Magnetic Field	$B_\theta = 6.25 \text{ kG}$
Beam Energy	$\epsilon = 530\text{--}700 \text{ J}.$

A. Electron-Ion Collisions

The effect of electron-ion collisions is determined by the magnitude of the dimensionless parameter

$$\chi_o = \gamma \ln \Lambda / (n_b/n_p)^{1/3} \Lambda, \quad ,$$

where Λ is the plasma parameter and n_p is the plasma particle density. For $\chi_o \leq 4$, the effect of electron-ion collisions can be ignored. For the FX25 parameters, collisional effects do not enter for $n_p < 5 \times 10^{16} \text{ cm}^{-3}$.

B. Ionization Gradient Effects

At $n_p \approx 10^{15} \text{ cm}^{-3}$, the beam pulse length is sufficiently short to insure no significant ionization during the beam pulse. At higher plasma densities, however, ionization gradients can be produced during the beam pulse. Fig. 8 shows the plasma density as a function of time for a $n_p = 2 \times 10^{16} \text{ cm}^{-3}$ plasma, as obtained from the numerical solution of rate equations for a hydrogen-like plasma. Thus, the $10^{15} - 10^{17} \text{ cm}^{-3}$ range allows for investigation of the ionization gradient.

C. Anode Foil Scattering

The beam can pass through $12.7 \mu\text{m}$ Al foil and still remain cold for $n_p = 2 \times 10^{16} \text{ cm}^{-3}$. In addition, the deposition can be reduced an order of magnitude by using a $75 \mu\text{m}$ Ti foil at $n_p = 2 \times 10^{16} \text{ cm}^{-3}$. Thus, the entire hydrodynamic and quasi-hydrodynamic range can be investigated.

D. Deposition Length

The deposition length is determined by

$$L_N \approx \ln \Lambda \gamma (n_p/n_b)^{1/3} (c/\omega_p) ,$$

where ω_p is the plasma frequency. For the FX25 parameters, $L_N \approx 3$ to 5 cm for the $n_p = 10^{15} - 10^{17} \text{ cm}^{-3}$ regime. Thus, a maximum plasma length of $L \approx 30\text{--}50 \text{ cm}$ should be sufficient for this experiment.

E. External Magnetic Field Strength

There are three conditions on the external magnetic field. First, the larmor radius of the beam electrons must be small compared with the beam radius, where

$$v_l = (B_\theta/B_z)c$$

is the characteristic transverse beam velocity. Second, the finite larmor radius has a negligible effect on the interaction if

$$3.36 (B_\theta/B_z)^3 \gamma^2 / B_z (\text{kG}) a (\text{cm}) < (n_b/n_p)^{1/3} .$$

Finally, optimal deposition occurs for

$$\omega_c/\omega_p \approx (0.25\text{--}0.75) \gamma^{2/3} (n_b/2n_p)^{1/3} ,$$

Fig. 8. Plasma density $n_p (\text{cm}^{-3})$ as a function of time for given initial fractional ionization f . The fully ionized plasma density is $n_p = 2 \times 10^{16} \text{ cm}^{-3}$.

where $\omega_c = eB_z/mc$ is the plasma cyclotron frequency. These three conditions can be satisfied for an external magnetic field strength of $B_z = 30$ kG. For this experiment, a peak coupling efficiency in the range of 20-30% is expected for $n_p \approx 2 \times 10^{16} \text{ cm}^{-3}$, with an electron temperature in the 10-20 keV range.

ACKNOWLEDGMENTS

The author acknowledges enlightening discussions with C. Clark, D. Straw, and R. Miller.

REFERENCES

1. L. E. Thode, "Preliminary Investigation of Anomalous Relativistic Electron Beam Deposition into a 10^{17} to 10^{20} cm^{-3} Density Plasma," Los Alamos Scientific Laboratory report LA-7215-MS (April 1978).
2. B. B. Godfrey, R. J. Faehl, B. S. Newberger, W. R. Shanahan, and L. E. Thode, "Collective Ion Acceleration," Los Alamos Scientific Laboratory report LA-7148-PR (February 1978).
3. W. Baker, Air Force Weapons Laboratory, personal communication, May 1977.
4. L. E. Thode and R. N. Sudan, "Two-Stream Instability Heating of Plasmas by Relativistic Electron Beams," Phys. Rev. Lett. 30, 732 (1973).
5. L. E. Thode and R. N. Sudan, "Plasma Heating by Relativistic Electron Beams. I. Two-Stream Instability," Phys. Fluids 18, 1552 (1975).
6. L. E. Thode and R. N. Sudan, "Plasma Heating by Relativistic Electron Beams. II. Return Current Interaction," Phys. Fluids 18, 1564 (1975).
7. B. B. Godfrey, W. R. Shanahan, and L. E. Thode, "Linear Theory of a Cold Relativistic Beam Propagating Along an External Magnetic Field," Phys. Fluids 18, 346 (1975).
8. L. E. Thode, "Energy Lost by a Relativistic Electron Beam Due to Two-Stream Instability," Phys. Fluids 19, 305 (1976).
9. L. E. Thode and B. B. Godfrey, "Energy Lost by a Relativistic Electron Beam Propagating Along an External Magnetic Field," Phys. Fluids 19, 316 (1976).
10. L. E. Thode, "Plasma Heating by Scattered Relativistic Electron Beams: Correlations Among Experiment, Simulation, and Theory," Phys. Fluids 19, 831 (1976).
11. L. E. Thode, "Effect of Electron-Ion Collisions on the Nonlinear State of the Relativistic Two-Stream Instability," Phys. Fluids 20, 2121 (1977).
12. C. Ekdahl, M. Greenspan, J. Sethian, and C. B. Wharton, "Observation of Enhancement of Plasma Heating with Relativistic Electron Beams Resulting from a Reduction of Anode Foil Scattering," Bull. Am. Phys. Soc. 20, 1270 (1975).