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The Relativistic Electron Beam Plasma Heating Experiment

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by

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ABSTRACT

An intense (5×10^5 Amp/cm^2), relativistic (5 MeV), electron beam will be used to investigate the heating of small volumes (~5-10 cm^3) of dense plasma (10^{17}—10^{18} electrons/cm^3) to kilovolt temperatures via the electrostatic two-stream instability

INTRODUCTION

This is one of a number of experiments being carried out by the New Initiatives Group in the Physics Division to investigate the properties of materials at very high temperatures and densities or in highly excited states characteristic of fusion energy sources.

The impetus for the present relativistic electron beam (REB) heating experiment can be traced to the results of a number of relativistic beam-plasma interaction experiments done in the early 1970's, first in the Soviet Union and later in the U.S. All of these investigations showed, in varying degrees, a much stronger absorption of beam energy by the plasma than could be explained by classical Coulomb interactions. However, the experiments were carried out at relatively low plasma densities (10^{12} - 10^{14} cm^{-3}) and beam energies (0.3 - 1 MeV). The main thrust of the present experiment is to investigate the beam-plasma interaction at much higher densities and energies, where meaningful weapon and fusion experiments become feasible.

The anomalous coupling of beam energy to a plasma observed in the earlier experiments has been ascribed to the excitation of one or both of two classes of plasma instabilities: (1) return-current-driven instabilities such as current-driven ion acoustic modes; and (2) relativistic streaming instabilities such as electron-electron two-stream-driven Langmuir modes. The former are relatively low-frequency, long-wavelength modes that increase the resistivity of the plasma and result in enhanced ohmic heating. These instabilities appear to dominate those experiments using very high current (>500 kA) and relatively low energy (≤0.5 MeV) beams.

On the other hand, streaming instabilities are characterized by high frequency ($\omega \approx \omega_p$, ω_p = the electron plasma frequency) and short wavelengths ($\lambda \sim c/\omega_p$, c = speed of light). This class of instabilities appears to be the major coupling mechanism for high-energy (>1 MeV), high-density, and well-collimated, i.e., only weakly scattered, beams. The shorter wavelengths and extremely fast growth rates are attractive for a plasma heating method, where it is desired to rapidly heat a small volume of plasma. Interest in streaming instabilities for plasma heating has been further stimulated by detailed theoretical investigations,[1,2] which predict that a significant fraction of the beam energy, e.g., 20-50%, can be absorbed by the plasma under optimal conditions.

Since the REB heating experiment at LASL is directed toward reaching the highest possible plasma temperatures, it has been designed to optimize beam-plasma interactions due to relativistic streaming instabilities. That is, within financial constraints, the beam energy (5-6 MeV) has been maximized consistent with a beam density ($\sim 10^{14}$ cm^{-3}) adequate to heat a moderately dense plasma (10^{17}-10^{18} electrons/cm^3). Under these conditions an electron temperature of several keV can be expected if 30% of the beam energy is absorbed, and losses from the target plasma during the very short time of energy deposition ($\sim$50 ns) are negligible.

The purpose of the experiment will first be to confirm quantitatively the predictions of the nonlinear theory regarding scaling with respect to parameters such as beam density, externally applied magnetic field, beam divergence, etc. The next objective will be to study the properties of the resulting hot, turbulent plasma, e.g., the kinds and energy density of waves present, the shapes of the electron and ion velocity distributions, and the transport properties such as thermal conduction.

THEORETICAL CONSIDERATIONS

Streaming instabilities arise because natural wave modes exist in the plasma that have phase velocities very near the electron beam velocity $v_p \cong c$. Thus, in the electron's frame of reference, the wave electric field changes only slowly and is able to exert considerable influence on the beam. This coupling from the wave electric field to the electron beam causes the beam electrons to tend to form bunches, which, when decelerated by the wave, feed energy to it. The wave amplitude thereby grows, causing an even stronger bunching of the electrons. This feedback process results in exponential growth of the wave amplitude until saturation occurs.

Saturation of wave growth is caused by nonlinear processes in the plasma such as wave mixing or parametric effects that cause energy to be removed from the growing resonant wave, and to appear in waves that do not interact with the beam but instead interact with either the background plasma electrons or ions. These secondary waves can thereby give up some of their energy to the plasma, resulting in considerable heating. A high saturation level is critical to efficient beam-plasma coupling over a relatively short interaction length. In order that the beam electrons be strongly decelerated, the wave's electric potential must reach a significant fraction of the beam's kinetic energy.

An estimate of the coupling efficiency and its dependence upon experimental parameters has been obtained by Thode.[1,2] The simplest model of energy coupling is based on simple linear considerations, assuming that all beam electrons remain synchronous with the wave during the bunching process. Notation for the equations describing the model is as follows:

c = speed of light,
β = v/c, v = the beam electron velocity,
γ = $(1 - \beta^2)^{-1/2}$, γmc^2 = the beam electron total energy,
n_b = beam electron density,
n_e = plasma electron density,
Δw = total energy removed from beam.

Noting that the change in energy of a relativistic beam ($\delta\gamma$) due to a given change in velocity $\delta\beta = \delta v/c$ is

$$\delta\gamma \cong \gamma^3 \beta\delta\beta \, , \qquad (1)$$

and that the change in velocity during bunching can be estimated by[2]

$$\delta\beta = (n_b/2n_e)^{1/3} \beta/\gamma, \qquad (2)$$

the fractional change in γ is found to be

$$S = \beta^2 \gamma (n_b/2n_e)^{1/3} \quad (n_b/n_e \leq 10^{-2}) \qquad (3)$$

where $S \equiv \delta\gamma/\gamma$.

From Eq. (3) the fractional energy removed from the beam can become of order unity if, for example, $\gamma > 10$ and $n_b/n_e > 10^{-3}$. However, not all the beam electrons remain in synchronism with the wave. Thode, employing a one-dimensional analysis,[2] has taken this into account to obtain a corrected energy transfer given by the relation:

$$\alpha = 1.5S\,(1 + 1.5S)^{-5/2} \qquad (4)$$

where the coupling coefficient α is the fractional energy removed from the beam defined by

$$\alpha = \Delta w/\gamma n_b mc^2 \qquad (5)$$

α is found to reach its maximum value of $\sim$0.2 at $S \cong 0.45$.

More accurate predictions of the coupling coefficient have been obtained by Thode using a fully relativistic, two-dimensional computer simulation. With optimized choices for beam collimation, n_b/n_e, plasma homogeneity, externally applied axial magnetic field, and beam γ, coupling coefficients as high as 0.6 have been calculated.[3]

For the experimental conditions of the present experiment (E_b = 5.5 MeV, γ = 11.7, $n_b = 10^{14}$, $n_e = 10^{17}$-10^{18}), coupling coefficients are expected to range from 0.2 to 0.4 if the beam is well collimated (beam divergence angle $\leq 0.5°$), if electron-neutral collisions can be neglected, and if the saturation level and evolution of the streaming instabilities are as predicted by the simulations.

The first experimental objectives will be measurement of the magnitude of α, and its dependence upon beam and plasma parameters. In later experiments, properties of the heated plasma, e.g., energy transport, infrared emission, soft x-ray emissions, will be of primary interest.

EXPERIMENT

In this section the apparatus required for the study of the beam-plasma coupling coefficient will be discussed, along with the necessary diagnostic instrumentation. Precise requirements for apparatus and diagnostic instruments for the energy transport, soft x-ray emission, and later applications experiments are still in the discussion stage.

Apparatus

The apparatus to carry out the beam-plasma experiment will comprise a pulsed-power generator, a field emission diode, a beam-plasma interaction chamber and, probably, a preionizer to generate the initial, unheated plasma. The pulsed-power generator is shown schematically in Fig. 1. The output specifications for this generator are:

Peak voltage : 5.5×10^6 volts
Peak current : 1.5×10^5 amps
Pulse duration : 65×10^{-9} sec (FWHM)
Output energy : 5.0×10^4 joules
Prepulse voltage : $<10^4$ volts

The last specification, prepulse voltage, requires that less than 10 kV may appear on the output terminal prior to the arrival of the output pulse. This specification, which is essential for proper operation of the field emission diode, represents a substantial improvement in the state of the art.

As indicated in Fig. 1, the high-voltage pulse is generated by a 54-stage Marx generator, which is initially charged to 100 kV/stage. Upon receipt of a trigger signal, the Marx generator erects and charges the 4-Ω (ohm) coaxial transmission line to 5.4 MV. When the 4-Ω line reaches peak voltage, the spark-gap switch between the 4-Ω and 10-Ω coaxial lines breaks down, launching a 2.7-MV pulse toward the output. The impedance mismatch between the 4-Ω and 10-Ω lines, and between the 10-Ω line and the 37-Ω output, causes the pulse voltage to rise from 2.7 MV up to 5.5 MV at the output. This technique of voltage multiplication by impedance mismatch, while wasteful of energy, is fundamental to the low prepulse voltage capability of this generator. The electrical energy still contained in the machine after generation of the output pulse is shorted to ground through 4-Ω resistors via two diverter spark gaps. The pulsed-power generator is being built by Maxwell Laboratories and is currently nearing the final test stages at LASL.

The field emission diode is shown schematically on the left-hand side of Fig. 2. The design of this diode is critical to the experiment since it controls two fundamental parameters of the interaction, beam density and collimation. The design of this diode is a joint effort of the New Initiatives Group and the Intense Particle Beam Theory Group at LASL. A fully electromagnetic, particle simulation code developed by members of the Particle Theory Group has been used to study the influence of diode geometry and applied axial magnetic field on the collimation of the beam electrons.

A design, which appears to satisfy the requirements of this experiment, is the so-called "foilless diode," with a cathode radius of 1 cm and an anode radius of 1.5 cm. By operating this diode in a magnetic field of 100 kilogauss, the sideways motion of the electrons is restricted, and beam divergence angles of 2 degrees or less are predicted. The beam, which will be generated by the diode, is a hollow annulus with a radius of 1 cm and a thickness of 0.5 mm or less. The beam density will exceed 3×10^{14} cm^{-3} at a current of 150 kA.

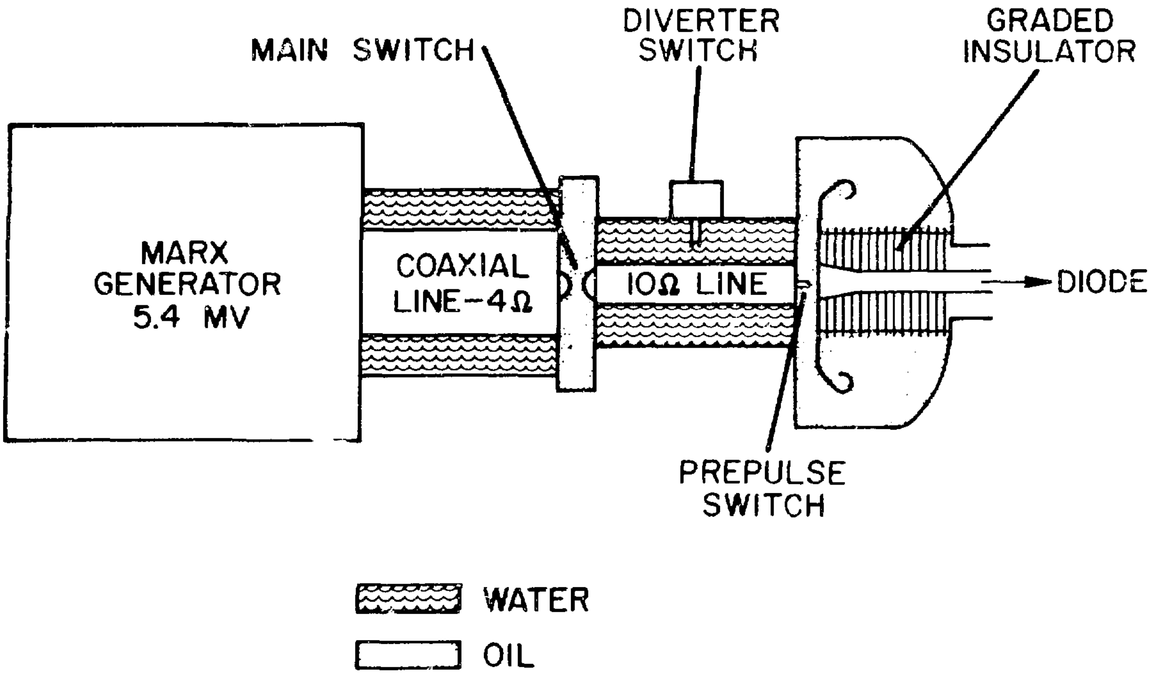

Fig. 1.
Schematic of the pulsed-power generator.

Power flow from the pulsed-power generator to the diode poses a problem not encountered in previous experiments. This problem arises in the interaction of the 100-kG axial field with the space charge currents surrounding the cathode conductor; the proposed solution involves careful control of the parallelism between axial magnetic field lines and the cathode conductor surfaces. Experimental verification of proper power flow into the diode will be one of the first steps in the experimental program.

The beam-plasma interaction chamber is a titanium alloy cylinder with a nominal length of 30 cm and an inner diameter of 6 cm. Titanium alloy is used because its high electrical resistivity permits the magnetic field generated by the external coils to fully penetrate into the plasma region during the 800-μs rise time of the field. The titanium cylinder is provided with 4 rows of 6 diagnostic ports, which are accessible through spaces between the external magnet coils. These ports can be equipped with various windows for visible or x-ray observation, or they can be used to make connection to electrical probes inside the titanium cylinder.

The apparatus on the right in Fig. 2 is a beam-dump region, which is separated from the experimental region so that the energy density of the beam can be reduced by expansion before it strikes the calorimeter. This configuration also permits more convenient installation of lead shielding around the calorimeter to reduce the 5.5-MeV x-ray spectrum generated by the beam electrons as they are stopped. The beam expansion also provides radial clearance for an on-axis diagnostic port for those instruments, which can be adequately shielded against hard x-rays.

The need for a preionizer to form the plasma has not been established. Calculations of beam-propagation physics suggest that, for H_2 at densities below $\sim 10^{16}$ cm^{-3}, the plasma can be created by ionization processes associated with the beam. At higher densities it will probably be necessary to completely ionize the gas with an external energy source. Techniques for accomplishing this are currently under investigation.

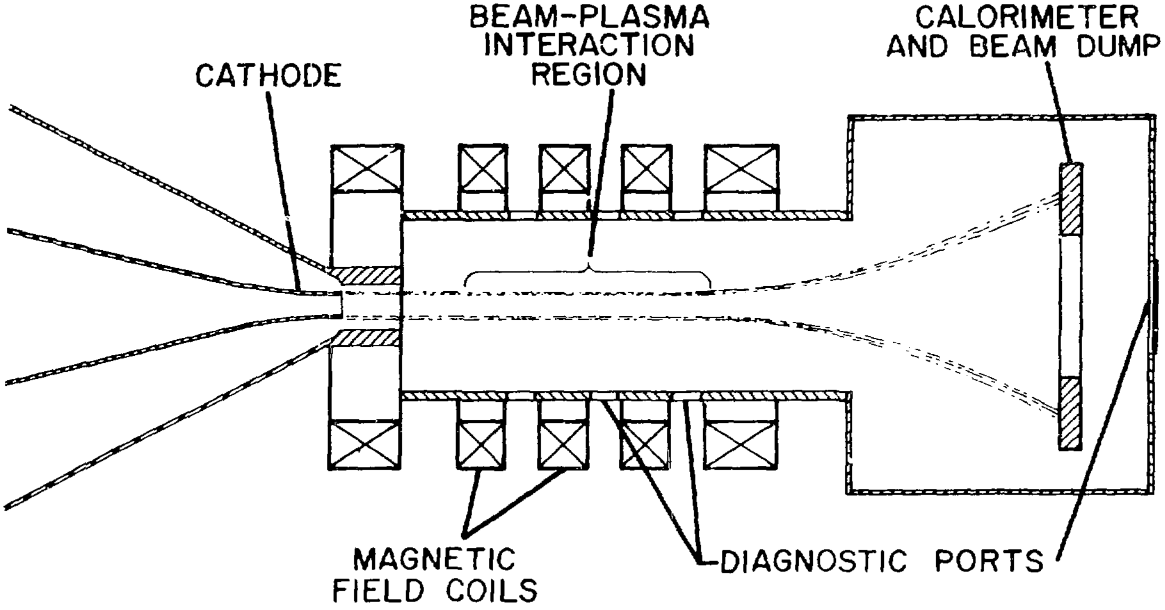

Fig. 2.
Experimental configuration of the relativistic electron beam-plasma interaction experiment.

Diagnostics

Diagnostic instruments can be conveniently divided into instruments for electron-beam diagnostics and those for plasma diagnostics. The primary function of the electron-beam diagnostics is to establish the state of the beam both before it enters and after it leaves the interaction region. Table I lists the instruments that will be used and the beam parameter, which each instrument measures.

The most difficult quantity to measure is the beam divergence angle. The diamagnetic effect is expected to be useful only for angles greater than ~5 degrees. A laser-scattering experiment is under discussion to provide greater sensitivity, but it is not yet clear that the potential results will justify its cost and complexity.

The magnetic spectrometer analyzes the beam energies over the energy range 2-6 MeV with ~100 keV resolution. The energy lost by the beam during the beam-plasma interaction is related to the saturation mechanisms and levels. While this instrument currently uses film to obtain a time-integrated spectrum, it will be converted in the near future to provide 6 to 10 time-resolved channels.

The plasma diagnostics, which will be used to characterize the heated plasma, are listed in Table II, together with the physical parameters they measure. The first few entries represent basic diagnostics to which the more specialized instruments listed later in the Table will be added for specific experiments.

The high temperature and density of the plasma under investigation preclude the use of diagnostics, which physically contact the plasma. This is reflected in Table II in the preponderance of diagnostics which utilize the electromagnetic radiation from the plasma.

EXPERIMENTAL PLAN

Currently, the REB generator is nearing completion. Following a performance verification test, which will last about one month, two principal issues must be resolved before beam-plasma interaction experiments can begin.

TABLE I

BEAM DIAGNOSTICS

Diagnostic	Measured Quantity
$\dot{B}$ probe	Current
$\dot{E}$ probe	Voltage
Calorimeter	Total energy
Stopping Power Calorimeter	Voltage, total energy
Hard x-ray pinhole camera	Current density
Diamagnetic loops	Beam divergence
Magnetic spectrometer	Energy spectrum

TABLE II

PLASMA DIAGNOSTICS

Diagnostic	Measured Parameter
Diamagnetic loops	Electron-ion temperature
Soft x-ray pinhole camera	Interaction region size
Laser interferometer	Plasma density, uniformity
Framing/streak camera	Interaction region size
Infrared spectrometer	Plasma wave strength, plasma turbulence
Soft x-ray spectrometer	Electron temperature, density
Thomson scattering	Electron velocity distribution, density fluctuations

The first issue is efficient power transfer from the pulsed-power generator to the diode region; this is dominated by the strong, externally applied magnetic field. It is anticipated that several months will be required to assemble the apparatus and perform the diagnostic tests needed to verify its proper operation.

The second is the actual generation of the electron beam. A beam, of the required charge density, energy, and collimation, represents substantial advances in the state-of-the-art technology. Although the diode design has been carefully checked using computer simulations, it is still expected to take several months to find the optimum operating conditions, and to measure the resulting beam parameters.

With these two issues resolved, preliminary beam-plasma experiments can commence using a neutral-gas target at low density ($\sim 10^{16}$ cm^{-3}). To reach the desired density (of 10^{18} cm^{-3}), a fully ionized plasma target will probably be required. The design and fabrication of a preionizer will be carried out in parallel with the tasks discussed above and should be completed by the spring of 1980.

Following installation of the preionizer, approximately one year of experimental effort will be devoted to measuring the beam-plasma coupling and its parametric dependence. The experimental program beyond 18 months is not well defined at this time. It will certainly incorporate both application experiments and more fundamental investigations into the physics of this unique plasma.

Over the three to four year lifetime of this experiment, significant knowledge will be gained about the physics of the beam-plasma interaction and the behavior of dense, hot, strongly turbulent plasmas. At the same time, more will be learned about the potential use of such a plasma for future weapon and other applications.

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