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TURBULENT HEATING OF PLASMA IN A MIRROR*

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A plasma has been heated substantially by passing a current through it. The plasma was injected axially into a mirror field, and the current was passed through the plasma parallel to the magnetic field. We obtained a heating efficiency, insensitive to variations of the discharge-circuit parameters as well as the density of the initial plasma, of 3-4%.

The possibility of rapidly heating a plasma to high temperatures by means of turbulence generated when current is passed through a plasma has excited wide interest because of its importance to controlled thermonuclear-fusion research. Publications of work done by Babykin et al.[1] reporting very high heating efficiency in such an experiment has aroused considerable debate because of their method of measuring plasma temperature and heating efficiency.

Hydrogen plasma injected axially into a magnetic-mirror field from two plasma guns has been heated by passing a current through the plasma. The current was passed axially through the plasma from two electrodes placed just outside the mirrors. This configuration is similar to the one used by Babykin et al.,[1] and the experiment is related to the one by Hamberger et al.[2] A schematic of the experiment is shown in Fig. 1. Under "standard" conditions the field strength is 1600 G in the midplane of the mirror field, the mirror ratio is 2, and the distance between the mirrors is 180 cm. Electrostatic probe measurements show that the initial plasma has a maximum density of $\sim 5\times10^{13}$ cm^{-3} and a diameter of 2-3 cm, and that the electron temperature is of order 10 eV. From time-of-flight observations it is found that the mean ion directed energy is ~100 eV. The axial current results from the discharge of the two condensers in series. The circuit provides an open-circuit voltage of up to 80 kV between the electrodes and a ringing frequency of ~1 Mc/sec when shorted. The effective capacity of the circuit is 12 nF and thus the maximum current is ~5000 A.

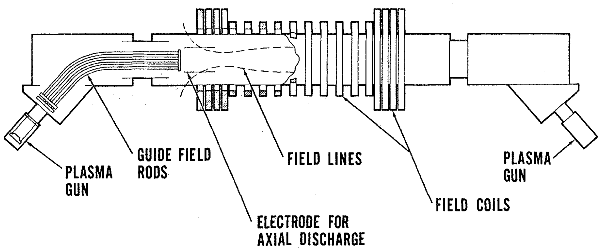

FIG. 1. Schematic of the experiment.

By means of a compensated flux loop, with a diameter of 35 cm, the perpendicular energy of the plasma column was measured. The passage of the axial current through the plasma gave rise to a considerable increase of the kinetic energy of the plasma. Figure 2 shows the time dependence of the axial current and the perpendicular plasma energy measured by the flux loop. The efficiency of energy transfer to the plasma, in terms of the ratio between the perpendicular plasma energy and the energy initially stored in the condensers, has been found to be nearly constant. The perpendicular energy was measured not at the peak but at 7 μsec after the axial discharge starts. Fig-

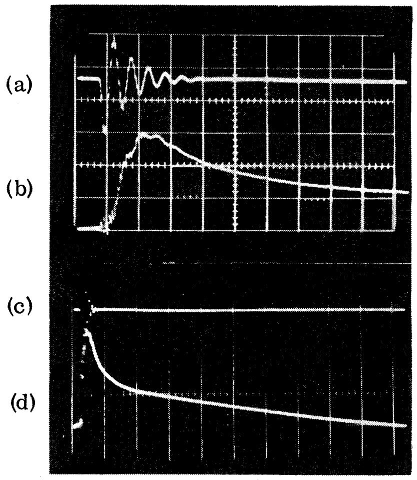

FIG. 2. Time dependence (a), (c) of axial current and (b), (d) of perpendicular plasma energy (b) and (d). Sweep speed: 2 μsec/large division for (a) and (b); 10 μsec/large division for (c) and (d).

ure 3 is a plot of the perpendicular plasma energy observed as a function of the energy available which was varied by changing both capacity and voltage. Furthermore the transfer efficiency is insensitive to a variation of the magnetic field strength. A change by less than a factor of two is found when the central field strength is varied from 400 to 2400 G. Finally, density variations of a factor of 5 in the initial plasma do not appreciably affect the transferred energy.

From the initial density and dimensions of the plasma and from the energy transferred, one finds that ~200 eV per electron-ion pair is transferred under "standard" conditions and ~1000 eV per electron-ion pair when the density is decreased by a factor of 5. This is based on the assumption that no influx or loss of particles takes place during the heating phase. This assumption is consistent with density measurements made with an 8-mm microwave interferometer. It should however be noted that some knowledge of the plasma density profile is necessary for the interpretation of the interferometer results. The knowledge of the plasma radius was based on measurements of the azimuthal magnetic field associated with the axial current. Since the characteristic diameter associated with the axial current density increases during the heating phase to ~8 cm, it is assumed that the plasma diameter increases to that value also. It should also be noted that the interferometer signals are uninterpretable under high-density ("standard") conditions for ~30 μsec after the heating.

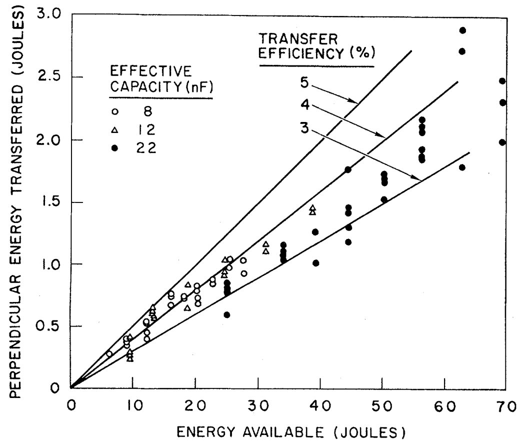

FIG. 3. Perpendicular plasma energy versus energy available.

Under "standard" conditions the value for the kinetic energy per electron-ion pair given above has been verified by flux-loop measurements when the magnetic field configuration was changed from a mirror field into a field which decreases towards the ends. The initial rise of the flux-loop signals under these conditions is very similar to the one seen with the mirror field, but a rapid decay, roughly exponential with an e-folding time of 3 μsec, follows the peak. If one assumes that this decay time can be approximated by the ratio between half the distance between the mirrors and the sound speed, one finds the energy per electron-ion pair to be 500 eV.

Under "standard" conditions measurements have also been made of the energy spectrum of neutrals emitted from the plasma due to charge-exchange reactions between the ions of the plasma and the neutral background gas. These measurements were performed with a stripping cell system described by Fleischmann and Tuckfield.[3] Easily measurable quantities of neutrals were found in the energy interval 100-1600 eV for 100-200 μsec after the heating phase, depending on the energy. No measurements were made at energies above 1600 eV since this is the upper limit for the analyzer system used. The efficiency of the analyzer has been measured[3] for energies up to 300 eV. Using an extrapolation of the efficiency it is estimated that the average energy of the neutrals emitted is several hundreds of electron volts. The conclusion that this is also the average energy of the ions of the plasma can however not be made since the nature of the background gas is not known. It was also found from these measurements by the use of a grid shutter and time-of-flight observations that most of the neutrals emitted are hydrogen atoms.

Since the aim of the experiment was to look for gross effects and scaling laws, no attempts have been made to investigate the nature and the type of the turbulence which causes the heating or the instability that limits containment. The possibility that counter-stream instabilities and the ion-sound instability are responsible for the turbulence and the heating has been pursued by a number of researchers.[4] The presence of energetic ions in this experiment and the scaling with voltage and density, as well as the radial expansion, may suggest that magnetohydradynamic instabilities cause the heating.

Thus, this experiment demonstrates that energy can be transferred from a condenser bank to a plasma by passage of current parallel to the confining field with efficiencies of 3-4%. Since classical Joule heating is completely negligible for the conditions of this experiment we have termed the heating mechanism "turbulent".

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EVIDENCE OF NUCLEAR SPIN ORDERING IN SOLID HELIUM-THREE*

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Measurements of the pressure versus temperature for constant-volume samples of solid He^3 to 20 mdeg K show the expected T^{-1} dependence due to spin ordering at low temperatures. A value for the exchange integral $|J|/k$ of about 0.7 mdeg K is obtained for a molar volume of 24 cm^3, with $\partial \ln|J|/\partial \ln V = 16.4$.

As absolute zero is approached, the properties of solid He^3, such as specific heat, susceptibility, expansion coefficient, and the melting curve, are largely determined by the ordering of the nuclear-spin system. In a rigid lattice the ordering would not take place until $T \sim 10^{-6}$ °K brought about by the dipole-dipole interaction.[1] It was pointed out by Bernardes and Primakoff[2] that, because of the large zero-point motion in solid He^3, there would be considerable overlap of the wave functions of neighboring atoms, resulting in an exchange interaction J which would cause ordering of the spins at a much higher temperature.

Theoretical calculations of Nosanow and others[3] have given $J/k \simeq -0.1$ mdeg K, indicating antiferromagnetic ordering. While susceptibility data[4] also indicate this type of ordering,

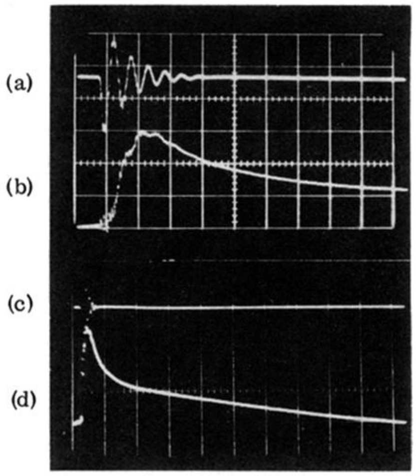

FIG. 2. Time dependence (a), (c) of axial current and (b), (d) of perpendicular plasma energy (b) and (d). Sweep speed: 2 μsec/large division for (a) and (b); 10 μsec/large division for (c) and (d).