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FUNDAMENTAL STUDIES OF TURBULENT
HEATING OF A PLASMA

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SUMMARY

From the outset of the program in 1968 the emphasis has been on the fundamental aspects of turbulent heating: The identity of waves in the turbulent spectrum and how these waves grow and damp; the relationship between the turbulent spectrum and other observable phenomena, such as anomalous resistivity, transport across the magnetic field, and the diamagnetic signal (nkT_e); the ion-energy distribution and how it scales with machine parameters. We have reported the results of these undertakings¹⁻⁸.*

During the past year we have continued our investigation of scaling laws and on optimizing the experiment as a plasma heating device. We have reached three main conclusions from these investigations: (1) The plasma resistivity is anomalously large during turbulent heating, approaching the "Buneman" value normally associated with the electron 2-stream instability, yet the observed turbulent spectrum is more appropriate for ion acoustic waves; (2) The ion energy distribution is non-Maxwellian, but nearly isotropic. It has two kinds of small anisotropies, each in opposite directions; (3) The turbulent heating limits itself before the peak of the current is reached. These results are discussed below in Sec. 2.3 and more fully in Appendix C.

During the summer of 1972 we collaborated with the University of Texas experimenters on the third phase of joint experiments on r.f. ion heating of the preheated (collisionless) THM plasma. Up to 1 megawatt at 6 MHz. was impressed, yielding resonant heating at ω_{ci} and $2\omega_{ci}$, with final plasma energies of $310 < (T_e + T_i) < 380$ eV in a 4 liter volume at $3 \times 10^{13} \text{ cm}^{-3}$. Explicit results are given in Appendices A and B, and in the Final Report for that project C00-2194-1, Jan. 1973.

The brief Chronology below has been updated from that in last year's report, to reflect our present and future objectives. Experimental details and diagnostic developments are discussed in Section 2.

* Support for this program has been from AEC Contract AT(30-1)3958 (superceeded by AT(11-1)3165) and ONR Contract N00014-67-A-0077-0002, with the addition of ONR Contract N00014-67-A-0077-0022 in July, 1971, and AEC Contract AT(11-1)2194 in January, 1972.

1. BRIEF CHRONOLOGY OF CORNELL TURBULENT HEATING EXPERIMENT

Jan., 1968 Vacuum chamber and magnet coils installed

Mar., 1968 First plasma

June, 1968 Turbulent heating observed

Jan., 1969 Measured turbulence spectrum with microwave scattering; related spectral intensity to anomalous resistance and ion heating. Identified ion acoustic waves as heating agent. Electron density $\approx 10^{13}$, $W_{\perp} \approx 1$ joule, $\tau \approx 50\mu\text{sec}$.

Oct., 1969 Refined measurements of anomalous resistance and turbulence spectrum, using conductivity probe. Comparison with theory begun.

Jan., 1970 Modified plasma guns: $n_e \approx 5 \times 10^{13}$. Began measurement of spectrum of charge-exchange neutrals. Increased turbulent heating voltage from ± 18 KV to ± 30 KV. $W_{\perp} \approx 3.5$ joules.

May, 1970 Modified turbulent heating bank: new capacitors, new spark gaps, new d.c. supply, ± 100 KV.

Sept., 1970 Obtained consistent operation at ± 100 KV. $n_e \approx 10^{14}$, $W_{\perp} \approx$ joules, $\tau \approx 150$ microseconds. Comparison to theory developed under sponsorship of AT(30-1) 3782 progressing well.

Dec., 1970 Ion energy measurement, obtained by charge-exchange neutral analysis across and along the magnetic field. Results indicate non-Maxwellian ion energy distribution.

Aug., 1971 Completed first joint experiment with University of Texas team on ion heating at harmonics of ion cyclotron frequency. Found evidence that ICR heating also provided enhanced mirror containment, accompanied by a sloshing of plasma at the mirror bounce frequency.

Oct., 1971 Parameter study using ion energy analyzer showed that ion energy depends on maximum electron drift velocity. Increasing V increases ion temperature. Heating nearly independent of B_z .

Jan., 1972 Second joint experiment with Texas team: damped oscillations from LC switched circuit impressed.

Feb., 1972 Electromagnetic wave scattering from turbulence at 74 GHz.

- June, 1972 Third joint experiment with Texas team: 1 MW ion cyclotron wave heating. Found ion heating at ω_{ci} and $2\omega_{ci}$.
- Sept., 1972 Ion energy measurement, obtained by charge-exchange neutral analysis at five angles to the magnetic field. Results show Maxwellian distribution drifting in ion frame at low energies, and enhanced high energy tail in direction of ion acoustic wave propagation.
- Dec., 1972 Installed relativistic electron beam system (REBS) on end of THM in place of one plasma source.
- Jan., 1973* Testing of REBS begun. Beam injection in vacuum and single-ended THM plasma.
- Feb., 1973* Experiments on turbulent heating by interaction of REB with THM plasma.

*Experiments not yet completed.

2. NEW RESULTS AND DEVELOPMENTS

The following summary is abstracted largely from Appendix C. Fuller details are found there.

2.1 Plasma Resistivity

A sudden discontinuity in plasma resistance was found at a current of 8000 amperes. For our conditions this current provides a drift velocity v_D about twice the ion sound speed C_s of the unheated plasma, implying that the increase in resistance is due to the onset of ion acoustic instability. The column resistance during the turbulent phase is nearly constant at 4 ohms for currents on up to 25,000 amperes. At the end of the turbulent condition the resistance drops to a fraction of an ohm. The effective collision frequency calculated from this data is $10^9 < \nu_{\text{eff}} < 10^{10}$, which is about the same as the ion plasma frequency ω_{pi} . Further details are given in Section C. of Appendix C.

2.2 Non-Maxwellian Ion Energy Distribution

The composite spectrum of ion energies is given in Fig. 1. It is obviously non-Maxwellian and also slightly anisotropic. In earlier analyses we characterized the distribution (out to ~ 4 keV) as a 2-temperature Maxwellian that was approximately isotropic^{2,3}. But when the analysis is carried to higher energies and is done with great precision at several angles those approximations fail. A better fit to the distribution is an inverse power law $F(w) \propto W^{-A}$, where $A \approx 2.5$. It is the high energy part of the spectrum that is affected most by varying the applied voltage. Our conjecture is that this component arises from damping of ion acoustic waves (which have velocities well above average ion thermal speeds), driven by the electron-ion streaming instability. These waves propagate at angles up to 70° or 80° to the magnetic field³ and thus contribute also to $W_\perp$. In Fig. 1 we see that there is an accentuation of the high energy part of the distribution in the direction of the electron drift velocity. This evidence implies that electron momentum was transferred to that part of the ion distribution, presumably by way of collisions with ion acoustic waves.

The low energy part of the distribution also has an upstream-downstream asymmetry, which may be characterized as a drifting Maxwellian. The

Fig. 1. Qualitative ion energy distribution function, showing the drift at low energies, and the enhanced high energy tail in the direction of electron momentum.

drift velocity of 10^6 cm/sec is about 1/2 to 1/4 the average ion drift velocity in the applied electric field.

Similar asymmetries found in recent computer calculations⁹ were much more pronounced than our measured results.

2.3 Saturation of Turbulent Heating.

In most heating pulses of our experiment we observe that the heating ceases before the peak of current has been reached, sometimes at only 1/2 the maximum electron drift velocity v_D . We have advanced two possible explanations: (a) The instability threshold velocity rises up to v_D because the ratio T_e/T_i decreases near the end of heating; (b) The turbulent conditions cease because of nonlinear saturation and destruction of the instability. Effect (a) could have two possible causes in our experiment: either the electrons are cooled by rapid loss or thermal conductivity or the ion heating rate is larger than that of electrons. The test for this effect is to provide auxiliary heating for the electrons, eg. by microwaves or beam-plasma interaction. We intend to try electron beam heating during the coming year. Explanation (b) implies that there is a fundamental limit to the turbulent levels or the duration of turbulent conditions, imposed by nonlinear effects such as mode-coupling, particle trapping etc. We have no experimental evidence to show up any of these effects.

2.4 Four Channel Charge-Exchange-Neutral Energy Analyzer.

The ion energy analyses were made with a 2-channel analyzer^{2,8}. We have recently developed a 4-channel instrument, which has been tested and is being calibrated. If that instrument meets expectations it will be put in service as our standard ion energy analyzer. The 4-channel analyzer uses magnetic deflection following the stripping cell, and contains grids that can be biased to exclude low energy, high-Z impurities. After deflection, the ions that pass through each of the four analyzing slits are accelerated to surfaces that emit secondary electrons. These electrons are accelerated (at 90° to the ion direction) through a foil into a scintillator crystal that is cemented to a photomultiplier tube. With this instrument we will

obtain a fair approximation of the ion distribution function with each shot.

2.5 Neutral Atom Beam Experiments

Beam attenuation experiments were made using argon and hydrogen atoms, at energies of 8 keV. The same source as used to calibrate the analyzers was employed. The source is composed of a duoplasmatron, from which ions are accelerated to the desired energy and are then charge-exchanged in a gas cell to produce energetic neutral atoms. The resulting atomic beam passes through the machine plasma and is detected by the analyzer on the opposite side. Nearly all of the attenuation of the hydrogen beam is due to charge exchange with plasma ions, because of the large $H^+ \rightarrow H^0$ cross section. The attenuation is thus proportional to plasma density n_i . Attenuation of the argon beam is due mostly to electron impact ionization, and is thus dependent on both n_e and T_e .

The measured attenuation values give peak plasma densities in agreement with microwave measurements, with the advantage that densities up to about 10^{15} cm^{-3} can be measured with the atomic beam, while our 4 mm microwaves are cut off above $6.8 \times 10^{13} \text{ cm}^{-3}$.

2.6 Optical Line Broadening

An optical polychromator was developed and applied to look at the broadening of the H_α and H_β lines. Doppler broadening and anomalous Stark broadening (due to turbulent electric microfields) were the effects sought. Even with the best optical and electronic systems that we could employ, in conjunction with the available 1/4 meter spectrometer, we were not able to get enough light intensity when viewing perpendicular to the plasma column to make a measurement. When light was viewed along the axis we were able to see a signal, but it was not broadened. We conclude that the radiation came from colder plasma outside the central, heated plasma column. We have set aside this experiment temporarily, but will return to it in the future after we obtain a better dispersive instrument.

2.7 Far Infrared Diagnostics

The cyanide laser system has been improved to about the limit of our ability. It produces over 100 watts consistently and is quite reliable. The cryogenic detector has finally been made to perform according to the manufacturer's specifications on sensitivity and risetime. However, the fall time is still excessively long, due to the slow decay of I_{ν} at 1.9° K. (Pumped helium). Thus the system will not function for scattering from high frequency fluctuations. We still have hopes that we can develop a satisfactory point-contact or other diode that will perform as a superheterodyne detector for scattering. Full details of the far-infrared developments are given in Appendix D.

2.8 Machine Modifications: Installation of REB.

We have completed the installation of the relativistic electron beam system (REBS) on one end of the THM vacuum chamber, in place of one plasma source. A schematic sketch of the installation is shown in Fig. 2. As part of the parameter study reported in Appendix C, we operated the machine single-ended, in preparation for installation of the beam system. We established that, aside from a 40% decrease in density, the operation is comparable to double-ended conditions.

The parameters of the modified REBS-THM machine are:

V_b up to 500 keV; $I_b \sim 17,000$ to 83,300 amps,

$\beta = 0.86$; $\gamma = 1.96$; $\tau = 60$ n sec.

$I_{\text{LAWSON}} = 17,000$ $\beta\gamma = 28,500$ amps.

$$\frac{v}{\gamma} = \frac{I_b}{I_L} = \frac{83,300}{28,500} = 2.9$$

Beam power $P_b \approx 4 \times 10^{10}$ watts.

Beam energy $W_e \approx 2500$ joules.

Plasma density $n_e \approx 5 \times 10^{13} \text{ cm}^{-3}$.

Plasma diameter = beam diameter = 5 cm.

Our objective for the coming year is to achieve plasma heating by the interaction of the relativistic electron beam with the THM plasma¹⁰. Experiments are scheduled to begin in February, 1973.

Fig. 2. Cornell THM installation modified to include turbulent heating capability by an intense relativistic electron beam. Chamber diameter is 40 cm; distance between electrodes 180 cm.

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701 Neutral Particle Diagnostics of a Turbulently Heated Plasma. S. Robertson, P. Korn, and C. B. Wharton, Laboratory of Plasma Studies, Cornell University.-- Measurements of the neutral atom energy flux from the Cornell THM-3 device are reported for different observation angles to the axial turbulent heating current. A net ion drift from the anode to the cathode is observed in the 70°, 90°, and 110° observation angle data. Neutral spectra taken at 0° and 160° to the axial current direction indicated there were slightly more high energy ions traveling along the electron flow, which is also the direction of ion acoustic wave propagation. Off-axis measurements at 90° near the periphery of the plasma column yielded a different neutral atom energy spectrum resulting from finite lamour radius effects. The attenuation of a neutral Argon beam from electron impact ionization and that of a neutral Hydrogen beam from charge exchange ionization upon passage through the plasma column are compared and used to determine the temporal variation of plasma density when λ -4 mm microwaves are cutoff.

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807 High Power Ion Cyclotron Resonance Heating in a Mirror Machine. R. W. Clark, D. G. Swanson, Univ. of Texas at Austin, P. Korn, F. Sandel, S. Robertson, and C. B. Wharton, Laboratory of Plasma Studies, Cornell Univ.--Experiments with rf heating near the megawatt level on a turbulently preheated plasma show strong ion heating at both the fundamental and first few harmonics of the ion cyclotron frequency with a single loop antenna. In the 1.9:1 mirror a sharp resonance in the charge exchange neutral production was observed when the wave frequency matched the ion cyclotron frequency or one of its harmonics at the neutral energy analyzer port. The ion energy spectrum is approximated by a power law dependence but local slopes of the distribution function indicate ion temperatures in excess of 1 KeV in the range 2 KeV-8 KeV. Microwave interferometry implies peak densities up to $6 \times 10^{13} \text{ cm}^{-3}$ and microwave scattering from radial wavelengths between 3 mm and 1.8 cm suggest the presence of large amplitude electrostatic waves. From diamagnetic loop measurements energies up to 10 joules/m are observed which correspond to $T_e + T_i \sim 300\text{-}400 \text{ ev}$.

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