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FUNDAMENTAL STUDIES ON TURBULENT HEATING OF A FUSION PLASMA

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FUNDAMENTAL STUDIES ON TURBULENT HEATING OF A FUSION PLASMA†

Annual Summary Report for Period

July 1, 1972 - June 30, 1973

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CONTENTS

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 there 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); the ion-energy isotropy and distribution, and how it scales with machine parameters. We have reported the results of these undertakings.[1-9]

During the past year we have continued our investigation of the scaling laws of turbulent heating and on optimizing the experiment as a pulsed 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. The ions have a small drift in one direction, and a high energy tail in the opposite (electron drift) direction; (3) The turbulent heating often limits itself before the peak of the current is reached. These results are discussed below in Sec. 2.3 and more fully in Ref. 9.

During the summer of 1972 we collaborated with the University of Texas experimenters on the third and final phase of joint experiments on r.f. ion heating of the preheated (collisionless) THM plasma. Up to 75 kw at 6 MHz in millisecond pulses was impressed, yielding resonant heating at ω_{ci} and 2 ω_{ci}, with final plasma energies of $100 < (T_e + T_i) < 250$ eV in a 4 liter volume at 3×10^{12} cm^{-3}. Results are reported in the literature

4,5.

In March, 1973 the THM was modified by removing the plasma injectron system from one end, and installing a relativistic electron beam system in its place.(Parameters are given in Sec. 2.8). Several exploratory experiments have been made, and results are published in the literature[12,13,14]. The major finding was that plasma heating similar to turbulent heating occured, with a average ion energies reaching 2-5 keV in densities of 5 x 10^{13}. A summary of important results if given in Sec. 2.9.

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

All of the objectives discussed in the proposal were accomplished, except for the fluctuation correlation studies. We were not sucessful in making probe measurements in the high voltage environment, and gave up that experiment in favor of others reported here.

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* Support for this program has been from AEC Contract AT(30-1)3958 (superceaded 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.

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 at 35GHz;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, $\tau \approx 50 \mu$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. $n_e \approx 10^{14}$ $W_\perp \approx$ 20 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 of turbulent heating 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	Thrid joint experiment with Texas team: 75 kw ion cyclotron wave heating. Found ion heating at w_{ci} and $2w_{ci}$.
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.
Jan., 1973	Installed relativistic electron beam system (REBS) on end of THM in place of one plasma source.
Mar., 1973	Testing of REBS begun. Beam injection in vacuum and single-ended THM plasma.
Apr., 1973	Experiments begun on plasma heating by interaction of REB with THM plasma.

2. NEW RESULTS AND DEVELOPMENTS

The following summary is abstracted largely from publications listed in Sec. 4.

2.1 Plasma Resistivity during Turbulent Heating

A sudden discontinuity in plasma resistance was found as the current exceeded 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 up to 25,000 amperes. At the end of the turbulent condition the resistance drops to a fraction of an ohm. The effective turbulent collision frequency calculated from this data is $10^9 < \nu_{eff} < 10^{10}$, which is about the same as the ion plasma frequency w_{pi}. Further details are given in Sec. C. of Ref. 9.

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 field[3] and thus contribute also to $W_\perp$.

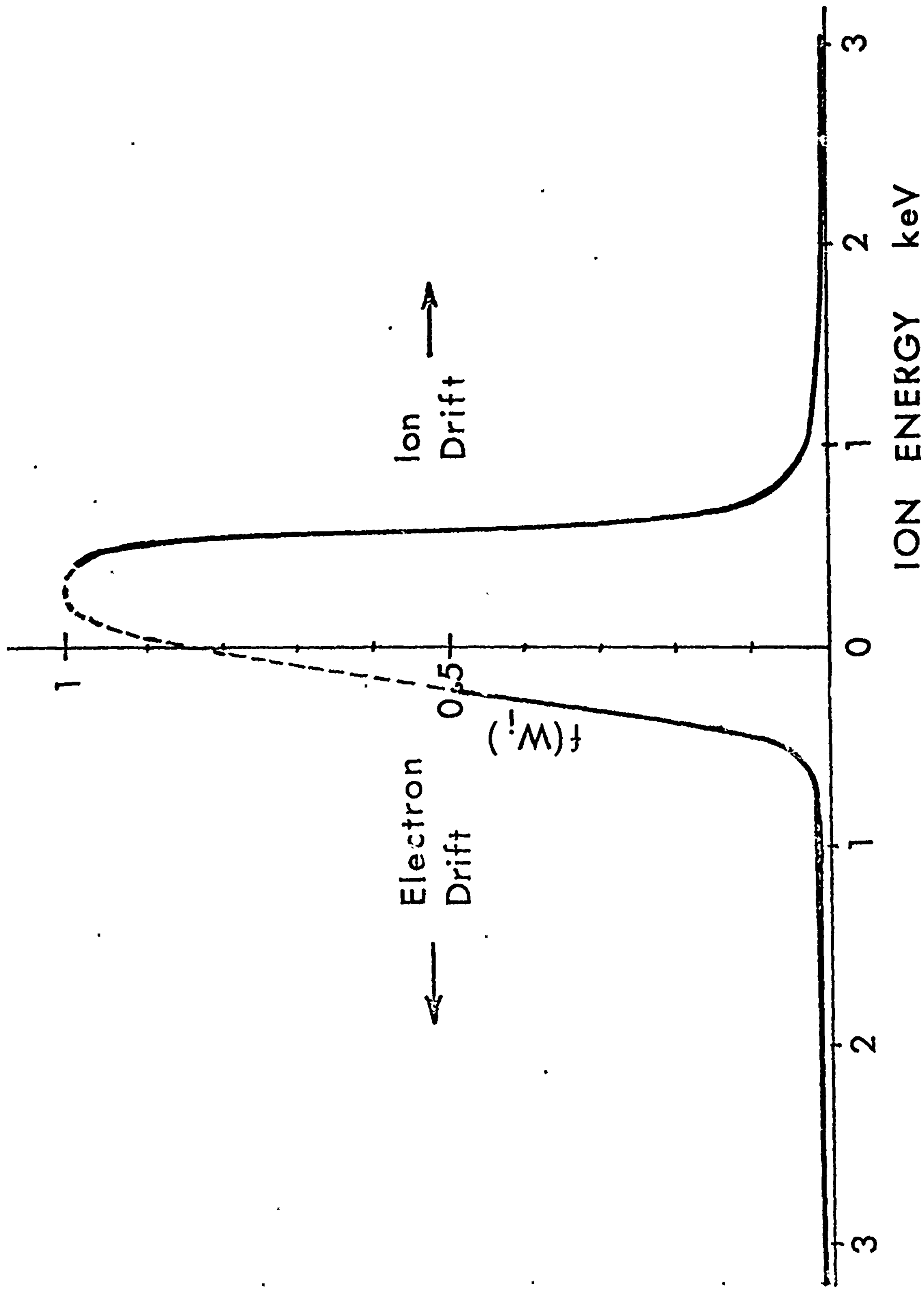

Fig. 1. Qualitative ion energy distribution function, showing the drift at low energies, and the enhanced high energy tail in the direction of electron momentum.

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 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 asymmetrics found in recent computer calculations[10] 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 for turbulent heating was made with a 2-channel electrostatic analyzer [2,9]. We have recently developed a 4-channel instrument, which has been tested, calibrated, and put in service. That instrument is now 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 obtain a fair approximation of the ion distribution function with each shot. Results using this instrument are given in Refs. 12, 13, and in Sec. 2.9 below.

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 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 6.8×10^{13} 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 did 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 Ref. 15.

2.8 Machine Modifications: Installation of REB.

We have installed a 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 Ref. 9, 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; $I_b \sim 5{,}000$ to 83,300 amps,

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

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

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

Beam power $P_b < 4 \cdot x\ 10^{10}$ Watts

Beam energy $W_e < 2500$ joules.

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

Plasma diameter = beam diameter = 5 cm.

2.9 Preliminary Results of REB-Plasma Heating

Our objective for the coming year is to study various aspects of the plasma heating due to interaction of the relativistic electron beam with the THM plasma. Some exploratory experiments have been performed and the results are published[12,13,14]. We summarize some of the noteworthy and significant results in this section.

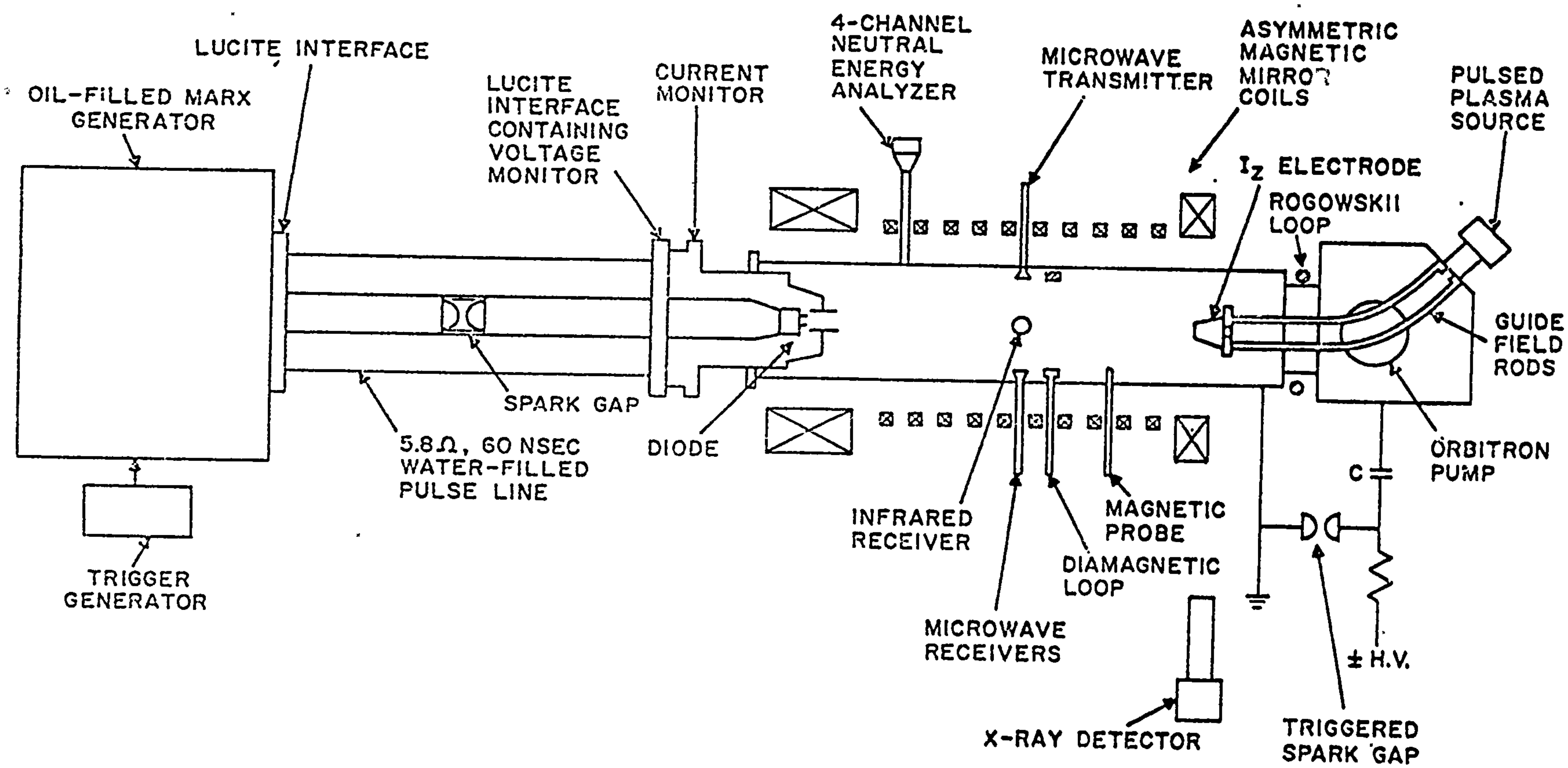

Figure 2. The Cornell turbulent heating - relativistic electron beam experiment.

(a) Diode and Beam Characteristics

Two types of diode structures were used, one with a 2.54×10^{-3} cm thick titanium anode foil, and one without. The plasma heating indicated by the diamagnetic loop and charge-exchange-neutral spectrum analyzer was similar for both configurations as long as plasma was allowed to enter the anode region. The main disadvantage of the foil anode was that the foil ruptured after 5 to 20 firings requiring that the experiments be opened for anode replacement. That procedure causes delays and unavoidable vacuum contamination, leading us to adopt the foil-less diode for most experiments. The beam diameter was matched to that of the plasma column, with the diode immersed in the magnetic field at the peak of the mirror.

The foil-less diode impedance was found to depend on several features, but was most sensitive to the presence of magnetized plasma in the anode region. Without magnetized plasma (to neutralize spacecharge) the impedance was high, and very little current could be extracted. The current that was extracted did not propagate very far in the vacuum magnetic field.

Without magnetic field the impedance was low due to direct electron transit to the anode ring, followed by "gap closure" from metal vapors filling the anode-cathode space. Considerable anode and cathode erosion occurred unless the proper geometry and conditions were found. With plasma present, in a strong magnetic field ($B \gtrsim 6000$ gauss), a brass tubular anode and a carbon ring (sharp-edged) cathode were useful for ~500 firings.

(b) Plasma Heating

For direct turbulent heating we found that the onset-threshold was at a plasma current of ~8000 amperes[9]. The same value of threshold was found for the relativistic electron beam current in these preliminary experiments. This evidence suggests the possibility that the reverse current induced by passage of the primary beam through the plasma is responsible for the heating,[11], since other mechanisms would not have the same threshold. Fig. 3 shows the sudden onset of heating and the steep dependence of total perpendicular energy $W_\perp$ on current.

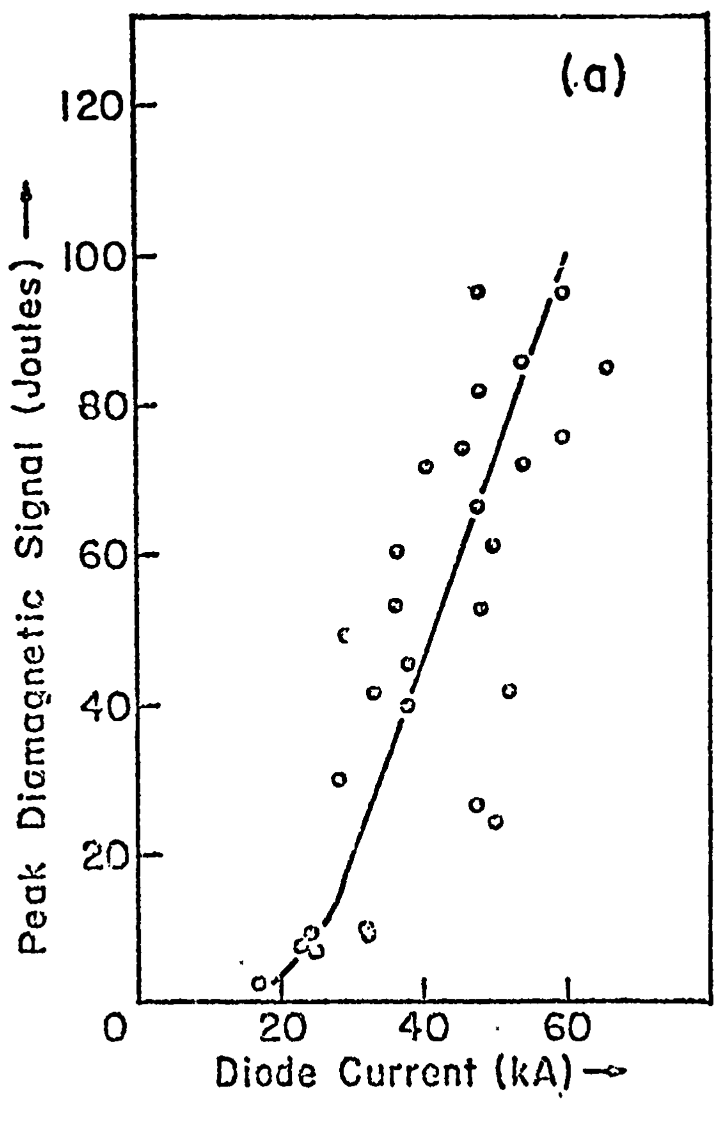

Fig. 3 Dependence of total perpendicular energy $W_\perp$ on diode current. Carbon cathode and foil-less anode used in diode. Magnetic field 3000 gauss at the diode.

$W_\perp$ was obtained with a diamagnetic loop. The values shown were read just after the heating pulse, before the decay due to confinement losses. The time-dependence of the diamagnetic signal was very similar to that for direct turbulent heating. At the end of heating the maximum $W_\perp$ was about 100 joules, corresponding to an energy of ≥ 15 keV per electron-ion pair. A rapid drop, with $\tau \sim 6$ μsec, was followed by a slower decay with $\tau \sim 50$ to 100 μsec. We associate the initial decay with loss of electron energy (e.g. by thermal conductivity to electrodes) and the slower decay with loss of energetic ions by scattering and charge exchange. The decay time of the electron density, as read by a 4 mm λ microwave interferometer, is longer than either of the above. Occasionally, at high heating levels, there are rapid decay steps in the diamagnetic signal [13], followed by the usual slower decay. We have not yet determined the cause of these steps, but we presume that they are associated with some kind of micro-instability, for example and electron velocity-space or cyclotron instability, expected for our co..'itions as the density falls.

(c) Ion Energy Spectrum

The 4-channel analyzer for energetic neutral atoms was placed 42 cm from the diode to receive atoms escaping perpendicular to the magnetic field. Spectrum were obtained for conventional turbulent heating and for heating with the beam. From Fig. 4 we see that the average ion energy is approximately 3 times as large for "moderate" beam heating as for "moderate" turbulent heating. Both types of heating had to enhanced high energy components, with the beam heating having slightly higher efficiency.

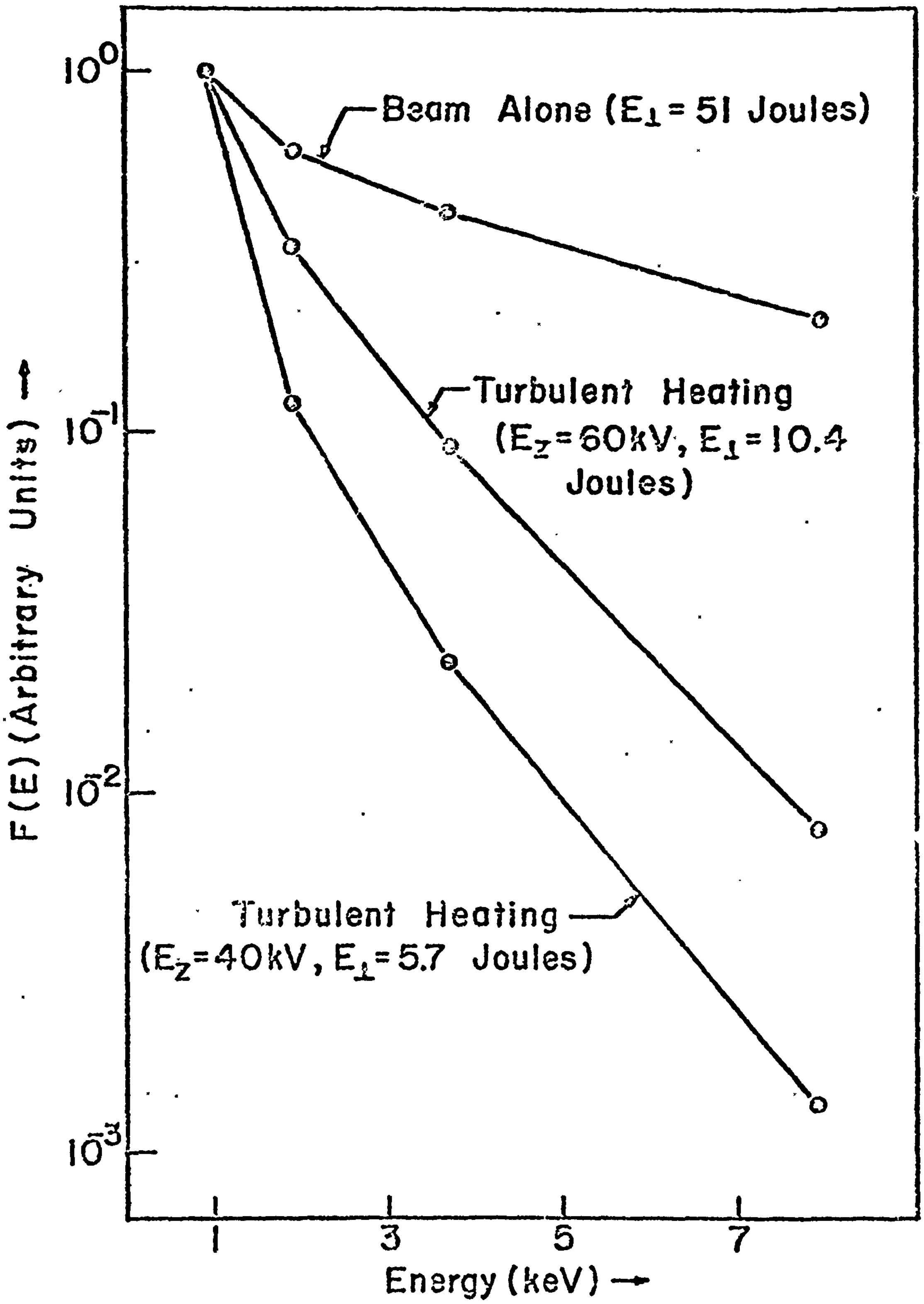

Figure 4. Ion distribution function vs. energy for beam plasma heating compared to plasma turbulent heating.

(d) Beam Interaction with Turbulent Plasma

We expected an enhanced interaction when the electron beam was injected into the already-turbulent plasma, as discussed in our proposal. We observed this enhancement. In the experiment it is possible to inject the beam into three completely different plasma conditions by simply changing the time of firing the sparkgap. Condition one is the unheated plasma column, condition two is the turbulent plasma column and condition three is the quiescent, heated plasma column. Fig. 5 shows $W_{\perp}$ due to the diamagnetic, signal as a function of this time variation. The large heating during the time of anomalous resistance is evident.

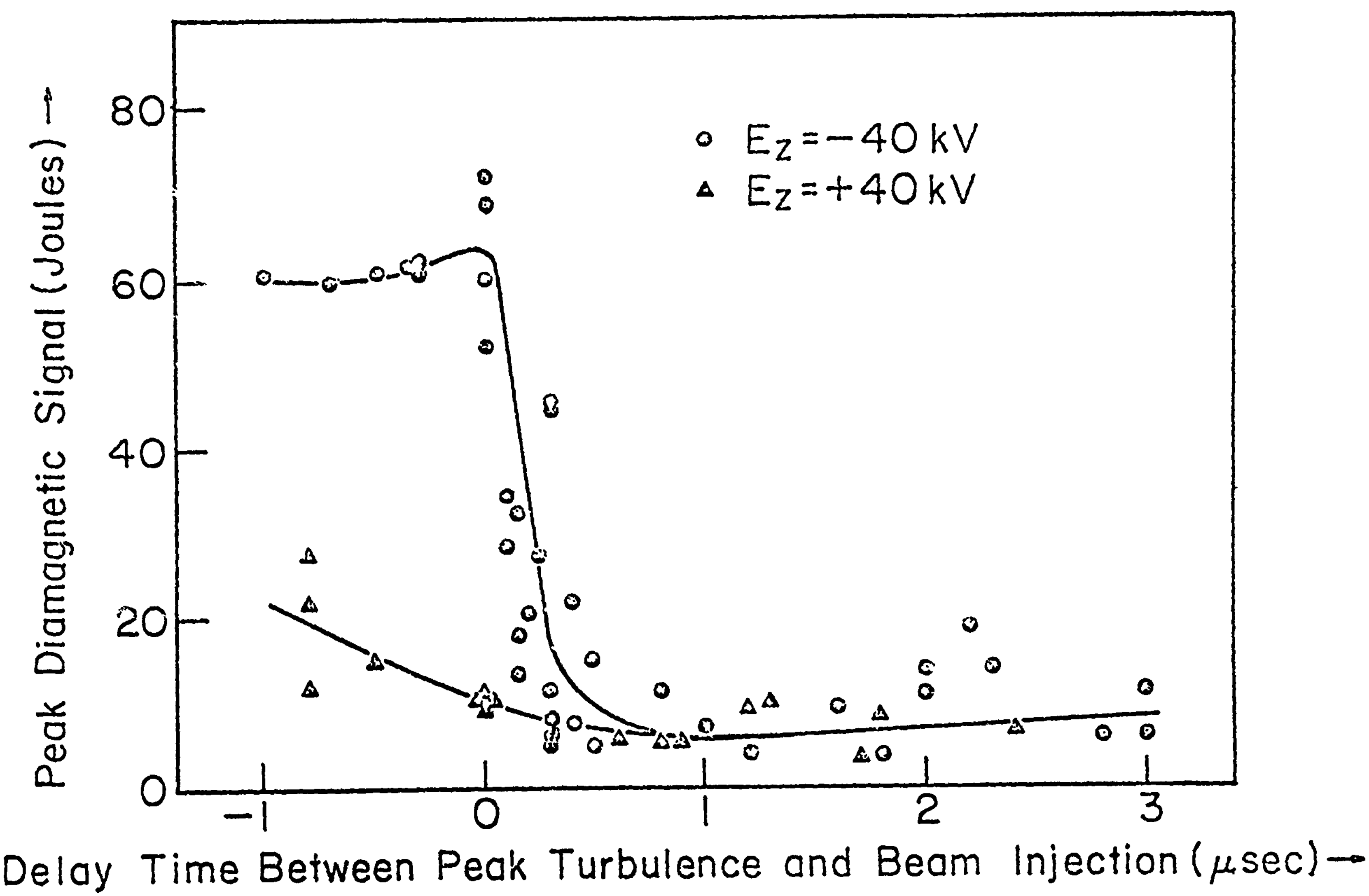

Figure 5 Peak plasma diamagnetism vs. delay time between peak turbulence and electron beam injection for a 2.5 cm aperture foil-less diode.

(18)

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5. ABSTRACTS OF PAPERS PRESENTED AT DPP MEETING, MONTEREY, CALIF., NOV., 1972

7C1 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 180° to the axial current direction indicated there were slightly more high energy ions traveling along the electron flow, which is also th direction of the 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 larmour 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 $\lambda \sim 4$mm microwaves are cutoff.

*Supported by the U.S. Atomic Energy Commission and the Office of Naval Research.

8C7 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 dependency 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 6×10^{13} 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 $T_e + T_i \sim 300$-400 ev.

*Supported by the U.S. Atomic Energy Commission.