RAPID PLASMA HEATING BY COLLECTIVE INTERACTIONS,
USING STRONG TURBULENCE AND RELATIVISTIC ELECTRON BEAMS

Charles B. Wharton

Laboratory of Plasma Studies
Cornell University
Ithaca, NY 14853

MASTER

ABSTRACT

A multi-kilovolt, moderate density plasma was generated in a magnetic mirror confinement system by two methods: turbulent heating and relativistic electron beam. Extensive diagnostic development permitted the measurement of important plasma characteristics, leading to interesting and novel conclusions regarding heating and loss mechanisms.

The efficiency of turbulent heating was increased from 6-8% to above 20% by pulse tailoring; concurrently a method was found to eliminate a destructive instability that led to copious impurities. This "clean turbulent heating" experiment produced an efficient, hot, stable, large-nr plasma.

Relativistic electron beam diodes were made with and without foil anodes, and characteristics of both types were explored. Foilless diodes having good plasma contact gave high-level turbulent heating and not much relativistic beam. Thin-foil diodes gave heating results that agreed with theory and computer simulation, but ruptured at high currents. A foil-changer permitted up to 50 shots between machine openings.

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Electron and ion heating mechanisms were categorized, and parameter studies made to establish ranges of importance. Non-thermal ion and electron energy distributions were measured. Beam propagation and energy deposition studies yielded the spatial dependence of plasma heating.

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C. B. Wharton

Cornell University
Ithaca, N.Y. 14853

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I. INTRODUCTION

The Cornell Plasma Heating Laboratory, under the direction of Professor Charles Wharton, was founded in 1967 by a grant from the New York State Science and Technology Foundation. Subsequently, funding by the U.S.A.E.C. and by the O.N.R. supported research and student training through January, 1976. The objectives of the program have been:

1. To create a dense, heated plasma in a clean magnetic confinement geometry using collective interactions.
2. To develop and apply plasma diagnostic techniques.
3. To explore new heating mechanisms and to improve our understanding of rapid heating.

A specific application was in the use of turbulent heating to prepare a dense, warm, collisionless plasma column for use by a University of Texas team in ion cyclotron resonance heating (ICRH) experiments. The joint experiment clearly indicated superior heating at the second harmonic at r.f. power levels up to 1 MW in a plasma having a temperature well above that currently obtainable in tokamaks.

A further application of either turbulent heating or REB plasma interactions is the rapid heating of a large-volume, dense, fully-ionized plasma to multi-kilovolt temperatures for subsequent containment studies in magnetic traps, or as a target plasma for neutral beam injection. This method of preparing a dense, hot plasma is in competition with, and in many respects far superior to laser-pellet plasma production, because of the advantageously large $n\tau$ value, and the relative simplicity and low cost.

A continuing impact on the CTR community has been the piece-by-piece advancement in the understanding of strong collective interactions in plasmas, including the verification that such interactions lead to highly non-thermal distributions of both ions and electrons. Parameter ranges were established in which the various heating mechanisms are effective, and the final heating levels and efficiencies were pushed to new maxima. Our results have verified theories and have been used to check computer codes.

A potential application that we have just begun to address is the use of very intense relativistic electron beams to heat a dense DT plasma in a long solenoidal column to ignition. Such a repetatively-pulsed, steady-state reactor would constitute a very interesting alternative concept to the lower density magnetic confinement schemes. Our present activity is in developing a rep-rate diode, and in assessing the various conditions to design an optimum reactor.

The following report is divided into roughly four parts: the earlier turbulent heating experiments, the relativistic electron beam-plasma experiments, diagnostic developments, and student training.

Some of the most recent publications are included in the Appendix, and a full Bibliography is given in Sec. 9.

2. BRIEF CHRONOLOGY

- 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 and electron oscillations as heating agents. Electron density $\sim 10^{13}$, $W_{\perp} \sim 1$ joule, $\tau_c \sim 50$ μ sec.
- Oct., 1969 Refined measurements of anomalous resistance and turbulence frequency spectrum. Experiments using conductivity probe.
- Jan., 1970 Modified plasma guns: $n_e = 5 \times 10^{13}$. Began measurement of energy distribution of charge-exchange neutrals. Increased turbulent heating voltage from ± 18 KV to ± 30 KV.
 $W_{\perp} \sim 3.5$ joules.
- May, 1970 Installed fast turbulent heating bank: New capacitors, new pressurized spark gaps, new d.c. supply, ± 100 KV.
- Sept., 1970 Obtained consistent operation at ± 100 KV. $n_e \sim 10^{14}$
 $W_{\perp} \sim 20$ Joules, $\tau_c \sim 150$ microseconds. Comparison to theory 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_d 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 $2\omega_{ci}$ resonances.

Sept., 1972 Ion energy measurement for turbulent heating at 10-20 kA 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 the electron drift velocity.

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 Recorded plasma heating by interaction of REB with THM plasma.

June, 1973 Four-channel charge-exchange energy analyzer showed that ion energy spectrum has inverse power-law dependence on energy, rather than Maxwell-Boltzmann distribution. Heating enhanced when E-beam was injected during time of turbulent-heating current pulse.

Aug., 1973 Diamagnetic signal of REB-plasma interaction at low v/γ shows energy proportional to the ratio of beam-to-plasma density, n_b/n_p , at currents up to 40 kA.

Dec., 1973 Developed and applied a remote-controlled variable-impedance diode. Anode-cathode spacing can be changed from 3 mm to 1.3 cm.

Feb., 1974 Observed rapid plasma expansion after heating with REB, followed by radial oscillations of plasma column at frequencies proportional to Alfvén velocity.

Apr., 1974 Anisotropic ion velocity distribution observed immediately after REB heating, correlated with radial plasma acceleration. Ion velocities randomized as radial oscillations damped out.

June, 1974 High voltage turbulent heating observed by applying 400 kV output voltage of pulse line directly to plasma column. Higher heating levels observed than in previous turbulent heating experiments (up to ± 100 kV).

July, 1974 Received laser amplifier from University of Texas. Began development of laser scattering system to measure electron distribution function and time-dependence of electron heating.

Oct., 1974 Preliminary foil-scattering experiment: plasma heating inversely proportional to angle of electron beam scattering by anode foils of different thickness.

June, 1975 Laser scattering system functional and calibrated. Returned amplifier to Texas, borrowed another from LLL.

Aug., 1975 First measurement of electron temperature by 90° Thomson scattering of laser light in REB-heated plasma gave $T_e \sim 800$ eV.

Jan., 1976 Dependence of plasma heating on beam scattering in anode foil. Heating efficiency increased from $\sim 6\%$ to 23% . Related results to theory.

March 1976 Measured loss of energy of beam as it propagates in plasma (x-ray bremsstrahlung and miniature Faraday cup), and related this to gain in plasma nkT (Spatially resolved measurements).

April 1976 Experiments on Thomson scattering of laser light completed. High energy tail of electron distribution thermalizes in $\lesssim 1 \mu\text{sec}$. Electron temperature drops in $10 \mu\text{sec}$. to $\lesssim 100 \text{ eV}$. Ion energy-density has $\sim 100 \mu\text{sec}$. time constant.

May 1976 Beam electron angular distribution measured in space and time. Large angular scattering by plasma interaction observed. 20% of beam electrons trapped in mirrors.

May 1976 Determined heating mechanisms over wide parameter range.

May 1976 Remote-operated foil changer installed. Permits up to 50 foil changes without opening vacuum chamber.

Aug., 1976 "Clean turbulent heating" experiment. Column disruption prevented, reducing generation of contaminants (from walls) by factor of 6.

3. SUMMARY OF EXPERIMENTS BEFORE 1973

Turbulent heating in our laboratory was first achieved in June, 1968, using the apparatus sketched in Fig. 1. The first results, including the time-dependence of the anomalous resistivity and the frequency spectrum obtained by microwave scattering, were published in 1969¹. Subsequently, the following specific contributions in turbulent heating have been made and reported by our group:

1. Turbulent spectrum measured by microwave scattering¹.
2. Spatially-resolved anomalous resistivity measured by conductivity probe².
3. X-ray measurements showed no runaway electrons even for $E \geq 2 E_{crit}$.³
4. Skin effect measured with magnetic probes⁴.
5. Determined that final ion temperature is proportional to electron drift velocity³.
6. Ion energy distribution and anisotropy measured, using charge-exchange analyzer: ions are non-Maxwellian, with a high energy tail, but are isotropic, except for a small drift^{3,5,6}.
7. Dense hot plasma prepared by turbulent heating was found to be flute-stable because of line tying at the ends by cold plasma^{5,6}.
8. Used turbulent heating to prepare a collisionless plasma for ion-cyclotron heating and as a target for relativistic electron beam heating^{7,8}.
9. Demonstrated that skin effect does not impede heating rate at very high voltage⁹.

10. Developed "clean" turbulent heating by crowbarring the bank before the current channel explodes: Minimized impurities, raised heating efficiency from 6% to $> 20\%$ ¹⁰ (App. 1).
11. Showed that anomalous resistivity is associated with ion-acoustic turbulence at high density, but approaches the Buneman resistivity at $n_e \lesssim 10^{13} \text{ cm}^{-3}$ ¹⁰.
12. Developed microwave and corpuscular diagnostics that have wide application (see Sec. 5 of this report).

Let us now discuss some of these items a little more fully. Reprints of all papers covering the above topics except Ref. 10 have been included in Annual Reports CU-3958-4 and CU-3165-1, and will not be included again here. Ref. 10 is enclosed as Appendix 1.

3.1 Machine Description

A schematic drawing of the Turbulent Heating Machine (THM) is given in Fig. 1, showing the double-ended configuration used until 1973. Two conical Z-pinch guns inject plasma along hexapole guidefields into a 40 cm. diameter evacuated stainless steel chamber. A crowbarred 2:1 magnetic mirror field, rising to 3000 gauss in 8 ms and falling in 20 ms, is produced by the coils. A plasma column 5 to 8 cm in diameter, 180 cm long with a maximum density $n_e \sim 10^{14} \text{ cm}^{-3}$ and electron temperature 5 to 20 eV is produced.

Turbulent heating is accomplished by applying up to ± 100 KV through a small inductance to each hollow electrode through which the plasma is injected, driving a current of up to 25,000 amperes along the magnetic field. These electrodes make intimate contact with the plasma. Because of the combination of external and internal inductance the initial current is zero and the voltage is less than the full capacitive charge. As the current

Fig. 1 Schematic sketch of THM, showing diagnostic attachments. Plasma column length is 160 cm between electrodes. Inset shows a cross section through the microwave scattering horn antennas.

risers the electron drift velocity $v_d = J/ne$ eventually exceeds certain instability-thresholds, as discussed in the next sections.

The diagnostic attachments shown in Fig. 1 are described in Sec. 5 and in the references.

3.2 Plasma Resistivity

At densities above about 10^{13} cm^{-3} , there is a sudden discontinuity in plasma resistance as the heating current exceeds a certain threshold (for "standard conditions"* this is 8000 amperes). This current provides an electron drift velocity v_d about three times 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. In Ref. 3 the voltage and current relations are shown in Fig. 2, and the plasma conductivity as a function of time in Fig. 3. Voltage and current for "clean turbulent heating" are shown in Fig. 2 of Appendix 1. The column resistance during the turbulent phase is nearly constant at 4 to 6 ohms for currents up to 25,000 amperes, at which current a column instability often develops (see Sec. A.1). At the end of the turbulent condition the resistance drops in about 8 μs to a fraction of an ohm², and the plasma becomes quiescent and stably confined. Plasma conductivity was measured with a special r.f. probe described in Sec. 5.6. The effective turbulent collision frequency calculated from this data is $10^9 < \nu_{\text{eff}} < 10^{10}$, which is of the order of the ion plasma frequency ω_{pi} . Ion heating was shown to occur during the period of anomalous resistance.

*"Standard Conditions": $n_e = n_i = 5 \times 10^{13} \text{ cm}^{-3}$, $T_e = 1 \text{ keV}$, $T_i = 1 \text{ keV}$ with a high energy tail, plasma radius $a = 3 \text{ to } 4 \text{ cm}$, $B_z = 3000 \text{ gauss}$.

At densities below 10^{13} cm^{-3} the delayed voltage spike is not as obvious, since the drift velocity exceeds the ion acoustic speed very early in the pulse, while the voltage is still high. At sufficiently low densities the drift velocity can also exceed the electron thermal speed, in which case the plasma resistivity approaches the Buneman value. In research reported in Refs. 10 and 11 we found that ion heating began very soon after the initial voltage was applied at low densities, but occurred during the second voltage spike at high densities. This is clear evidence that there is a change in heating mechanisms at $n_e \sim 10^{13}$ in our machine, switching from an electron-electron interaction (with subsequent coupling to ion heating), to an electron-ion interaction as the density is raised above the electron thermal speed threshold.

By programming the applied pulse shape we were able to increase the heating efficiency from the previous 6% to greater than 20%.

3.3. Ion Energy Distribution for Turbulent Heating

The charge-exchange technique and the required equipment are discussed in Sec. 5.2, and a complete analysis of typical THM data is included in Ref. 12. Some of the highlights are reviewed in this section.

The first detailed ion energy-distribution measurements of a plasma heated by turbulent heating were reported by us at the IAEA meeting in Madison, Wisconsin in June, 1971.³ These measurements, showing that the distributions were very non-Maxwellian, were continued in 1971 and 1972 to establish that the shape of the distribution could be fit to an inverse power law. A parameter study was made to determine what conditions influenced the heating, and the results were published in 1973.⁶ Anisotropies were measured by varying the angle in respect to the magnetic field.

Energetic neutral atoms, arising from charge exchange of plasma ions with a background "target" gas of krypton or oxygen, escape across the magnetic field, some entering the analyzer where they are reionized and analyzed. Our present 4-channel analyzer uses magnetic deflection following the stripping cell, and contains grids that can be biased to exclude low energy, high-Z impurities, giving momentum analysis, with energy discrimination. With this instrument we obtain a fair approximation of the ion distribution function with each shot. The channels were set to receive protons having energies of 1, 2, 4 and 8 keV.

Fig. 2 presents a pair of energy spectra taken to show the heating variations due to changing the applied voltage, at $n_e \sim 6 \times 10^{13}$. Corroborative data obtained with a diamagnetic loop give the indicated total plasma energy $\int n(kT_e + W_i)dV$, and from these two measurements we infer the electron temperature $T_e^\dagger$. In earlier analyses we characterized the ion distribution (out to ~ 4 keV) as a 2-temperature Maxwellian that was approximately isotropic.³ But that approximation fails when the analysis is carried to higher energies and is done with precision at several angles. A better fit to the distribution is an inverse power law $F(W) \propto W^{-A}$, where $A \sim 2.2$, with a slight drift superimposed. It is the high energy part of the spectrum that is affected most by varying the applied voltage. Our conclusion is that this component arises because damping of current-driven ion acoustic waves, whose velocities are well above average ion thermal speeds, heat preferentially those ions having higher initial velocities. These waves, which propagate at angles up to 85° to the magnetic field,³ populate the tail that we see, contributing to both longitudinal and transverse energies.

[†] Our present laser Thomson scattering equipment was not available at the time turbulent heating was being studied.

Fig. 2 Comparative Ion Energy Distributions
Obtained from Charge-exchange Measurements.
Turbulent Heating at ± 40 and 60 kV.
 W_1 Obtained from Diamagnetic Loop.

3.4 Frequency spectrum of Turbulence

Four methods were used to obtain frequency information: electrostatic probes, magnetic probes, microwave radiation and microwave scattering.

The electrostatic probes had high voltage insulation and a 10,000:1 voltage division. They were used to measure large changes in potential along the plasma column to determine if there were large sheaths at the electrodes (there were not), and to look for displacements of the plasma column due to expansion or gross instabilities (occasional discontinuities were observed). The sensitivity and frequency response were too poor to detect fine-scale fluctuations.

Magnetic probes were able to follow fluctuations up to the ion cyclotron frequency, and some activity was seen in that vicinity. Care had to be exercised to prevent puncture of the glass insulation by the high potentials applied to the plasma, a precaution that limited their sensitivity. The main use of these probes was in documenting the skin effect of the pulse current⁴ and also to observe the progression of MHz noise inward at the same rate. At high heating rates the noise ran ahead of the current sheet. These probes also showed noise developing in the outer regions of the plasma just before the current channel exploded.¹⁰

Microwave radiation at $2\omega_p$ and scattering at ω_p indicated the presence of strong electron oscillations, just at the beginning of the applied voltage pulse. The scattering spectrum showed considerable activity, in general falling off in intensity as about $(\text{frequency})^{-1}$. A number of sporadic peaks were seen at tens of MHz, usually appearing in bursts like relaxation oscillations. On some occasions there was enhanced plasma loss associated with these bursts. The scattering equipment and theory are discussed in Sec. 5.5. A typical scattering spectrum is shown in Fig. 3, for the

conditions: $n_e = 10^{13} \text{ cm}^{-3}$, $V = \pm 40 \text{ keV}$, $B_z = 2200 \text{ gauss}$, $\theta = 120^\circ$.

Several shots were taken, using different frequency filters to fill in details of the histogram. Our scattering system had two shortcomings that prevented it's use over wide parameter ranges: wave cutoff (or at least severe refraction problems) limited the maximum useable plasma density to about 4×10^{13} , and the minimum turbulence scale-size, determined by the incident wavelength, was about .25 cm (see Sec. 5.5), which is much bigger than the Debye length. Our attempts to develop a scattering system at $337 \mu\text{m}$, using an HCN laser and Putley detector (which would have fulfilled both of the above shortcomings) was not successful. The final gap between scattered signal strength and detector sensitivity was about a factor of 10, even for ~ 1 kilowatt of laser output in the far-infrared,¹² because of the large signal bandwidth required in the detecting system. The liquid-helium-cooled detector was also used in later E-beam experiments to receive radiation signals in the far-infrared.

Figure 3. Frequency spectrum of 4 mm wave scattered at 120° from turbulent plasma. Amplitudes are averages of several shots. Frequency widths were determined by band-pass filters.

3.5 ICRH Experiments Using Turbulent-Heated Plasma Column

The THM was used to provide a collisionless pre-heated plasma column for rf heating experiments at the ion cyclotron frequency, and its second and third harmonics. The experiments were performed in collaboration with a team from the University of Texas, who fabricated the rf equipment in Austin and brought it to Ithaca. The reason for this procedure was that the THM provided a nearly ideal facility unavailable elsewhere for the experiments: low collisional damping of the 6 MHz wave, convenient access, and all of the necessary diagnostic instruments already in operation.

Three runs were made during the year, with the scheduling shown in Sec. 2. The first run, using an oscillatory capacitive discharge ringing at ω_{Ci} , produced some heating, but the wave absorption damped the ringing so fast that the integrated power was small. Nevertheless the coupling structures were studied and improved, and the resonance was observed.

The second run, using up to 75 kW in a 600 μ -sec. rf pulse, gave very encouraging results,⁷ showing that the rf power input at a plasma density $n_e \approx 10^{13} \text{ cm}^{-3}$ could maintain the ion temperature at $T_i > 100 \text{ eV}$ during the pulse. Distinct resonances in ion heating were found at the second and third harmonics, and wave propagation along the magnetic field lines was detected at these frequencies.

The third run employed rf powers up to 1 MW in 700 μ sec. pulses, giving plasma heating that scaled up linearly from that achieved previously.¹⁴ The contribution of turbulent heating was very obvious in these experiments: without it even the 1 MW of power produced

little ion heating, and resonances at ω_{Ci} and its harmonics were not seen, presumably because of heavy collisional damping. With modest turbulent preheating to $T_e > 50$ eV and $T_i \sim 100$ eV the r.f. heating was then able to carry the ion temperature on up to > 300 eV, with a tail at 1 to 2 keV. Fig. 4 shows a schematic sketch of the installation.

Figure 4 Schematic drawing of the Cornell University THM-2 turbulent heating machine and rf heating experiment.

The heating was measured with a diamagnetic loop (electron + ion energies) and the charge-exchange neutral atom energy analyzer (ion energy distribution). The ion energy distributions at two rf power levels for $\omega = 2 \omega_{Ci}$ are shown in Fig. 5. Both distributions

Figure 5: Results of neutral energy analyzer measurements with the rf resonant with the second harmonic of the ion cyclotron frequency.

Figure 6: Perpendicular plasma energy plotted as a function of net rf power transferred to the plasma.

are seen to be slightly non-Maxwellian, the departure increasing at higher powers. The departure from Maxwellian is even more marked for the fundamental frequency $\omega = \omega_{Ci}$, apparently because the higher phase velocity couples better to the high energy tail. The dependence of the diamagnetic signal on the incident rf power is shown to be roughly linear in Fig. 6.

Resonance effects were observed with microwave scattering and with rf electrostatic probes. The more consistent and reliable measurements were made with the microwave system described in Sec. 5.5. Special narrow band filters were used to get sufficient resolution. The results for $f = 2f_{Ci}$ are plotted in Fig. 7, along with data from the charge-exchange analyzer, set to detect 1550 eV protons (data points with error bars). The solid line (triangles) shows the

Fig. 7 Data for microwave scattering at $f = 2f_{Ci}$ and for ion heating at 1550 eV. Circles are for scattering at 120° , triangles for 20° . Error bars represent the variations of peak signals from the charge exchange analyzer.

signal intensity scattered at 20° (fluctuation scale-size 11.5 mm), while the dashed line (circles) shows that for 120° (fluctuation scale size 2.3 mm). Thus the longer wavelength, fast-wave data matches that of the ion heating better than the slow wave data. Further conclusions are discussed in Refs. 7, 14 and 15.

4. SUMMARY OF EXPERIMENTS BEGINNING IN 1973

The Cornell THM installation was modified in 1973 to include the option of plasma heating by a relativistic electron beam (REB) or by the previous method of current-pulse turbulent heating, or both simultaneously. The chronology of developments is found in Sec. 2.

4.1 The REB-THM Apparatus

The REB-modified system, shown schematically in Fig. 8, became operational in early 1973, and rapid heating of a collisionless plasma column by injection of the intense relativistic electron beam was observed on the first run. The experiments were performed in the same chamber, with the same plasma column and the same diagnostics as for turbulent heating, to permit an unambiguous comparison of results with those of previous THM experiments. The fully-ionized plasma column, magnetically-confined, is surrounded by high vacuum. This was an important difference from other beam-plasma experiments of that time, all of which had neutral gas surrounding the plasma column.

The relativistic electron beam system (REBS) was installed on one end of the THM vacuum chamber, in place of one plasma source, as shown in Fig. 8. During part of the turbulent heating parameter study reported in Ref. 6, we had operated the machine single-ended, and established that, aside from a 30% decrease in density, the operation gave results comparable to double-ended conditions. Machine characteristics are given in Table 1. Refer to Sec. 3.1 for further machine descriptions, and to Sec. 5 for details on the diagnostic attachments.

Fig. 8. The Relativistic Beam and Turbulent Heating Machine.

V_b up to 500 keV, I_b : 5,000 to 83,300 amps

$\beta = 0.86$; $\gamma = 1.96$; $\tau = 60$ nsec, 10 nsec rise, 40 nsec jitter.

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

$$\frac{v}{\gamma} = \frac{I_b}{I_L} < \frac{83,000}{28,500} (=2.9)$$

B_z : 3 kG in mid-plane, 2:1 mirror

Beam power $P_b \leq 4 \times 10^{10}$ Watts

Plasma density $n_e = 10^{12}$ to 6×10^{13}

Beam energy $W_e \leq 2500$ joules

Plasma diameter 5 to 8 cm

Table 1. Parameters of the modified REBS-THM machine

Vertical Scales
Voltage: V → (275 kV/div)
Current: I → (20.8 kA/div)

Fig.9. Typical voltage and current waveforms for Cornell REB-THM System when diode impedance $R_d \sim 8 \Omega$.

Two general types of diode structures were used, one with a titanium or aluminized mylar anode foil, and one without, as shown in Fig. 10. The plasma heating indicated by the diamagnetic loop and charge-exchange-neutral spectrum analyzer was similar for both configurations at high v/γ as long as some plasma was allowed to enter the right-hand side of the anode region. Differences are discussed in Secs. 4.2 and 4.3. In general higher beam currents are possible with the foil-less diodes before closure occurs; however, the influence of the plasma on the diode performance

FIGURE 10. Summary of Diode Structures.

greatly complicates data interpretation,⁸ and may decrease the energy of the electron beams. For example, when the beam was made to strike a target, the emission of hard x-rays using diode (c) was less intense by two orders of magnitude than with diodes (a) or (d), although there was significantly more damage to plastic rods from the foil-less diode. The similarity of foil-less diode results to those obtained with high voltage turbulent heating indicates that for some operating conditions the cathode of the diode serves simply as an electrode in contact with the plasma and the heating observed is current driven turbulence.⁹

The main disadvantage of the foil anode was that it ruptured after 1 to 5 firings at currents above 40,000 amperes, requiring that the experiment be opened for anode replacement. That procedure caused delays and unavoidable vacuum contamination, leading us to develop a foil-changing system that is now in use. Up to 50 foil changes are possible before the machine must be opened to clean interface insulators and replace the roll of foil. Gap spacing can also be changed under vacuum. The beam diameter usually is matched to that of the plasma column, with the diode immersed in the magnetic field near the peak of the mirror.

4.2. Heating Experiments at Moderate v/v_e

Plasma heating results were spectacular, from the very first run, with plasma energy-densities reaching 5 to 10 times the levels previously achieved with turbulent heating. The beam and plasma conditions initially chosen put us in a parameter range in which the E-beam head induced a large return current in the plasma column. The electron drift velocity associated with this current was high enough to strongly excite ion-acoustic turbulence, but not electron-electron 2-stream instabilities. This

return-current heating produces results similar to direct turbulent heating, but extending to much higher levels. Data from the diamagnetic loop and the charge-exchange analyzer are shown in Figs. 11 and 12. Different

FIGURE 11. Peak Plasma Diamagnetic Signal vs. Diode Current (Foil Diodes).

FIGURE 12. Ion Energy Distributions for Increasing Levels of Plasma Diamagnetism.

heating levels are obtained by varying the charging voltage on the Marx bank, which changes the diode voltage in a linear relationship. In Fig. 12, Curve 1 is the 40 kV turbulent heating data of Fig. 2. Curve 2 is for E-beam heating to $W_1 = 13J$, Curve 3 for 30 J, and Curve 4 for 40 J. The threshold at about 8 kA is evident, further suggesting a similarity to turbulent heating. The plasma energy-density nkT reached $1.5 \times 10^{17} \text{ eV/cm}^3$, about 10 times as large as for turbulent heating, and efficiencies of 10 to 15% were obtained, at least twice the previous value.

When the relativistic beam was injected during the turbulent heating pulse the interaction was greatly enhanced, especially when the polarity of the voltage pulse produced a drift velocity in the same direction as

the return current drift velocity.^{16,17} The enhancement is shown in the diamagnetic data plotted in Fig. 13, for an applied voltage pulse of 40 kV and various electron beam currents. About 20 shots were possible before the run was terminated by anode foil rupture. It appears that beam heating conditions revert to normal after the turbulent heating pulse has ended (squares), but that is only true for low levels of preheat ($\lesssim 60$ kV). When the turbulent preheat is large, the electron temperature is sufficiently large that the return current drift velocity cannot exceed the ion acoustic speed and little return-current heating occurs. In this case the direct E-beam-plasma electron interaction occurs, producing intense electron heating, but not as much ion heating. When the sense of drift currents is opposing and roughly equal there is very little ion heating.

Radiation at microwave and far-infrared wavelengths was very large during the time of the beam pulse, masking all but the strongest microwave scattering signals. Thus no scattering spectrum analogous to Fig. 3 was obtained for the E-beam heating. The intensity of microwave emission,

FIGURE 13. Peak Diamagnetic Signal as a Function of Diode Current for the Electron Beam-Turbulent Heating Interaction.

detected by a receiver having a passband of 60 to 100 GHz and a response time of 2 nS, was linearly related to the peak diamagnetic signal. The power density, integrated over the plasma, corresponds to 15 kW of radiated power. This power is too large by at least a factor of 50 to be explained by plasma bremsstrahlung or cyclotron emission, but it is of the correct magnitude to come from synchrotron radiation from the perpendicular component of beam electrons (See Sec. 4.3), or from collective interactions. Far-infrared radiation in the range 150-500 μ m was received by a Putley detector have a rise rate of 2×10^{-8} sec. These signals also occurred at the time of beam injection, but the fluctuation details were not well correlated with those of microwave radiation, and in some cases the signals were anti-correlated, as if the frequency of radiation were fluctuating up and down.

Beam propagation studies¹⁶ showed that plasma was required up against the anode in order to extract the beam and induce it to flow in the plasma column. Slender plexiglass rods, protruding in front of the beam, gave a qualitative assessment of the beam energy-density and spatial dependence by the damage patterns. A small floating sphere of wolfram (and more recently a foil of titanium) provided a target whose x-rays could be viewed to get particle energies, current density and spatial dependence. The beam was found to propagate with little loss of energy after the first 20 to 30 cm, where most of the interaction seemed to occur. (See Secs. 4.3 and 5.3).

Plasma heating at high current and high v/γ as discussed here has applications in CTR to magnetic containment devices at modest electron and energy-densities, such as tokamaks and mirror machines. Appreciable

heating in a tokamak, in which the beam penetrated into the plasma interior, has been reported,¹⁸ and several successful mirror machine heating experiments are in progress, including the one reported here, in which energies of 5 to 15 keV per electron-ion pair at densities in the 10^{14} range is reported.^{8,9}

4.3 Experiments at Small n_b/n_p

The long solenoidal reactor¹⁹ constitutes an interesting alternative to the more conventional, medium-density (10^{14} to 10^{15} cm⁻³) magnetic confinement systems. The moderate size (100 MW_e output), modular construction, and steady-state output are attractive features. The major loss rate of such machines is out the ends, and thus they must be long. To achieve thermonuclear breakeven the optimum plasma density is calculated¹⁹ to be $n_e = 10^{17}$ cm⁻³, and the electron beam is required to have an energy of 8 to 10 MeV and a current of 150 to 200 kA, in a plasma diameter of 2 to 5 cm; thus the ratio of beam-to-plasma density is about 10^{-4} . There should be an energy loss of a few percent per meter of beam propagation.

During the contract year we have performed several experiments in the appropriate n_b/n_p range, with results that have direct bearing on the E-beam long-solenoid reactor. We have had encouraging experimental success in substantiating theories²⁰ and in verifying computer simulations with our laboratory results.^{21,22}

4.3.1 Beam Interaction Mechanisms

At least four types of interactions leading to ion heating were identified in our experiments. (a) One type already discussed in the previous section, is due to the return current induced by passage of the

beam head, exciting ion acoustic waves that damp into the ions. This effect predominates at plasma densities of $10^{13} < n_e < 10^{14} \text{ cm}^{-3}$, and $.01 < (n_b/n_p) < .1$, a range that pertains to tokamaks, but not long solenoids. At these densities it was possible to perform laser scattering measurements and charge-exchange neutral atom emission measurements; thus the time histories of the electron and ion energy distributions are known.²³ The electrons were heated first, giving T_e/T_i large enough that the ion acoustic waves become unstable and ion heating begins. From the measured plasma resistivity²⁴, we calculate the electron-ion equilibration time to be about 20 n-sec.

At the end of the beam pulse the resistivity drops quickly, and the heated electrons and ions become uncoupled, each category decaying with its own time constant. Electrons scatter rapidly, the higher energy ones escaping fastest out the mirrors, the lower energy ones retarded by the ambipolar potential. The measured electron energy decay time constant is from 5 to 15 μsec . for the conditions stated, the electron temperature dropping from several keV to about 100 eV in that time.

Ions scatter more slowly (calculated 45°-scattering time is 300 to 500 $\mu\text{-sec.}$), but the combination of ambipolar loss, charge-exchange loss, and possibly drift-loss-cone instabilities reduces their containment time to about 150 $\mu\text{-sec.}$ (b) A second type of interaction occurs at lower densities ($n_e \sim 10^{12}$) when the return-current-induced drift velocity exceeds the electron thermal speed during the entire pulse (not just initially, as above). Intense electron heating then occurs by the 2-stream instability, driving the electron temperature up to 10 or 15 keV and strongly populating the tail of the ion energy distribution. The electron

oscillations do not impede the ion acoustic interaction, which also proceeds. The efficiency for heating in this mode is 5 to 6%, which is not as high as for the previous case. This also is not of solenoidal reactor interest.

(c) The third type of interaction is through the generation and damping of MHD waves. Theoretical developments and computer simulation have indicated that rapid local heating of plasma electrons, producing an acceleration of ions in a time short compared with an Alfvén period, should generate MHD waves.²² This effect is roughly the expanding-analog of fast Θ -pinch compression. The damping of these waves should produce ion heating.²⁵

We searched for and found the effects experimentally, verifying several aspects of the theory, for $\omega_{Ci} \ll \omega_{Pi} \ll \omega_{Ce} \ll \omega_{Pe}$. A high-current beam, having a diameter smaller than the plasma diameter was shot into a plasma of density $n_e \lesssim 5 \times 10^{12} \text{ cm}^{-3}$, and the region outside the beam radius was probed with a fast magnetic probe. Regular, damped oscillations in B_z were detected with this probe, and also

with a fast diamagnetic loop²⁶, as shown in Fig. 14. The frequency, amplitude and damping rate of these oscillations depend on the magnetic field and the plasma density. The frequency always was between the ion cyclotron frequency ω_{Ci} and the ion plasma frequency ω_{Pi} . The frequency dependence, shown in Figs. 4(a) and (b) of Ref. 26 (Appendix 2), is pro-

portional to the magnetic field B , and inversely proportional to the square

FIG. 14 Typical diamagnetic loop signal. Sweep speed is 200 nsec/(large) div.

root of ion density $\sqrt{n_i}$. In other words $\omega = G V_A$, where the Alfvén velocity $V_A = B/(\mu n_i M_i)^{1/2}$, and G depends on the relative magnitudes of the parallel and perpendicular wavenumbers $k_{\parallel}$ and $k_{\perp}$. The observed oscillations damp out in a few cycles (1 to 3 μ -sec) due to collisions, phase mixing, or nonlinear decay modes²⁵, indicating that the radial ion motion is being randomized on that time scale. The charge-exchange analyzer data confirms this effect, showing that initially the ions possess only perpendicular energy, but begin to gain longitudinal energy with the same time constant as the decay rate of the B_z oscillations.

The electron heating was found to be localized to about the first 30 cm of beam penetration along the plasma column, for reasons to be explained in (d) below. Thus the magnetic disturbance propagated along the plasma column and could be picked up 100 cm away with a magnetic probe. From phase shift we determined the propagation velocity to be V_A . Charge-exchange measurements also confirmed that the heating was localized. When the analyzer viewed a region of plasma downstream from the entrance region, the presence of hot ions was delayed in proportion to the distance from the beam anode foil.

Our conclusion is that there is ion heating by the damping of the MHD waves, but it is somewhat slower than that due to other effects, and for most plasma heating applications is probably less important. The method has the potential advantage that the MHD waves can propagate into regions where the beam cannot penetrate, depositing their energy in ions there.

(d) The fourth type of interaction is between beam electrons and plasma electrons, with ions heated subsequently by nonlinear effects. This relativistic 2-stream instability generates high-level turbulence that simultaneously acts as a pump for parametric instabilities (eg the oscillating 2-stream, mode-coupling etc.), and accelerates plasma electrons to add a tail to the energy distribution. Fig. 15 presents data of our laser Thomson scattering experiment in which a tail is observed early in time following the beam passage.²³ Roughly 30% of the plasma electrons have non-thermal velocities, and when integration over the distribution is carried out this translates to 50-60% of the energy. Computer simulation results in Ref. 20 had predicted this effect; thus our experiments tend to confirm the theoretical developments.

The parameter range in which ion heating by the above mechanism predominates is $n_b/n_p \ll 1$; that is, it is important for the long solenoid case, as well as for tokamak or mirror machine heating.

Figure 15
Parametric Study of The Electron Velocity Distribution with Time After Electron Beam Injection.

$$I = 14 \text{ kA}, \quad \gamma = 1.68, \quad n_p = 3.5 \times 10^{13} \text{ electrons/cm}^3$$

The fastest growing mode is that for a cold beam having purely axial velocity $V_{||} > \omega_0/k_0$, and any increase in perpendicular beam temperature decreases the growth rate of the electron streaming instabilities.²⁰ The theory shows that the loss of beam energy into plasma heating at saturation of the 2-stream instability is proportional to the fraction of beam electrons $\Delta n/n_b$ not scattered, that is the cold component:

$$\frac{\Delta W}{W_0} = \left(\frac{\Delta n}{n_b}\right) F$$

where W_0 is the initial electron beam energy $n_b \gamma_0 m c^2$,
 $F = (\gamma_w/\gamma_0)^3 s(s+1)^{-p}$, $\gamma_w = [1 - (\omega_0/k_0 c)^2]^{-1/2}$, $s = \beta_0^2 \gamma_0 (n_b/2n_e)^{1/3}$,
the cold-beam strength-parameter ($S \gg 1$ for strong interaction),
and p is a factor between 1 and 5/2. Scattering in angle is not necessarily accompanied by an appreciable change in electron energy:

$$\theta^2 \gg \frac{\delta W}{\gamma^2}$$

4.3.2 Beam Scattering by Anode Foil and Turbulence

In our experiments scattering of the beam electrons is due to two causes, deflection by atoms in the anode foil, and scattering by the fluctuations caused by the interaction itself. Results discussed in this section show that the two causes may produce effects of the same magnitude. The angular spread of beam electrons is taken in Ref. 20 to be gaussian; however the scattering of electrons by a foil is complicated, and does not produce a strictly gaussian shape. We have evaluated by numerical methods the angular dependence, and from this the fraction $\Delta n/n_b$ for various foil thicknesses and beam energies.

The results are plotted in Fig. 16. It is clear that the theory predicts an improvement in heating efficiency as the anode foil is made thinner, and also as the beam energy is increased. Thus for the relativistic 2-stream interaction a high γ beam is desired, rather than a high v/γ beam, as one might intuitively expect. In our experiments the heating efficiencies were increased from about 5% with a 2 mil foil, up to 25% at $n_b/n_p = 0.003$, with a 350 keV beam injected through a 1/2 mil titanium anode foil. For a beam energy of 750 keV (which we cannot achieve with our present machine) an efficiency of 41% would be expected.

Fig. 16 Calculation of Fraction of Beam Electrons in the Forward Resonance Cone.

The beam-driven instability generates large radial fluctuating electrostatic fields. These fields can scatter the beam electrons. In the experiments discussed in this section we see that effect, with the result that $\Delta n/n_b$ decreases with distance, creating a self-limiting of instability-growth, and a localization of plasma heating to the region near the beam entry.

In Figs. 11 and 12, in Sec. 4.2, we showed the variations of diamagnetic signal and charge exchange signal as the beam current was varied within the range where return-current heating was important. Let us now investigate the transition range where the 2-stream heating becomes more important as n_b/n_p is decreased.

In Ref. 9 we stated that the plasma heating was found to be roughly linear with the ratio n_b/n_p , in agreement with the warm 2-stream theory.^{20,27} The ratio was varied in two ways: by holding the beam current constant and varying the plasma density, and by holding the plasma density constant and varying the beam.

Both methods of varying n_b/n_p gave roughly the same heating efficiencies. The data plotted in Fig. 17 was obtained²⁴ by holding the diode characteristics constant (350 keV, 14 KA, 2 mil Ti foil) and varying the plasma density over two decades. The diamagnetic loop signal, which pertains to both electron and ion heating, is seen to follow the theoretical predictions for the 2-stream interactions rather well. The charge-exchange analyzer signal (ions) has a much slower dependence on n_b/n_p than the electron signal, indicating

that some of the electron energy gets lost without being transferred to the ions. $\bar{\theta}$ is the mean scattering angle of beam electrons.

The analytical theory and computer simulation models are necessarily incomplete and somewhat inaccurate, in order to make the solutions tractable.

FIG.17 The increase in net perpendicular energy per electron-ion pair (curve a) and perpendicular ion energy (curve b) versus the beam-to-plasma density ratio n_b/n_p . These data obtained by varying the plasma density with the beam parameters held fixed.

For example, in the experiment there is a magnetic field present; the upper hybrid instability then competes with the 2-stream, and the angles of wave propagation also have slightly different dependences on beam $v_{\perp}$. Also the theories do not include the various electron loss or ion heating mechanisms explicitly, subjects that need further work. Nevertheless the experimental agreement is found to be rather good, as shown in both Fig. 17, for an anode foil of 2 mils, and in Fig. 18, where the electron temperature is shown to increase as the foil

thickness is decreased. The solid curve of Fig. 18 is derived from the lower curve of Fig. 16 (theory). These data points were obtained from laser scattering, but they correspond almost exactly to diamagnetic loop data taken early in time, since most of the signal is then due to electron energy. The conclusion drawn in Ref. 27 was that our data tended to substantiate the warm-beam theory (see their Figs. 13 and 14), which they considered a valuable contribution.

The beam scattering was measured directly with a miniature Faraday-cup probe that could be rotated to vary the angle, and pushed in or out to change

Figure 18

Scaling of T_{e1} (eV) and W_{te1} (Joules) With Anode Foil Thickness

$$n_b/n_p = .012; \gamma = 1.68; n_p = 3.5 \times 10^{13} \text{ electrons/cm}^3$$

Solid Curve: Calculation of $\Delta n/n_b$ vs. anode foil thickness.

Data Points: Plasma Perpendicular Electron Temperature, measured 600 nsec after electron beam injection, for varying anode foil thickness. Data normalized to mean of 25.4 micron foil T_{e1} . Also shown is W_{te1} .

radial positions. A description of the probe and its application are given in Sec. 5.3, and its construction is shown in Fig. 19. The beam electrons are

initially scattered as they pass through the anode foil, losing some 15 to 40 keV of energy. Then within the next 30 cm of beam-plasma interaction they may be scattered further by an amount equal to the foil-

scattering. The second kind of

scattering removes beam electrons from the loss cone of the 2:1 magnetic mirror, leading to trapping of as much as 20% of the beam. This effect is seen in Fig. 19 as a reflected-beam hump at 120° , and a less-distinct one at about 60° corresponding to a second reflection. The mean scattering angle is seen to increase by 10° to 15° during the first 15 cm and another 15° during the next 10 cm. Then little further spreading occurs for the full length of the machine. Thus the beam scattering measurements bear out the previous conclusions, derived from spatial diamagnetic and charge-exchange measurements, that the plasma heating is localized, at the end of the machine near the beam entrance.

Fig. 19 Angular dependence of beam electrons following scattering in foil and by electrostatic fluctuations in the plasma.

Additional data is shown in Fig. 20, compiled from several plots like Fig. 19, at various distances from the anode foil where the beam enters the plasma. The thinnest foil scatters least, allowing initially the strongest beam-plasma interaction, whose turbulence spreads the beam angle to about the same asymptote as for the thickest foil. Thus the ultimate scattering angle, for a particular γ and current, seems to be somewhat independent of the foil thickness, even though the plasma heating depends strongly on the thickness.

Fig. 20. Mean-square-scattering of beam electrons. Points x are calculated values for each foil thickness. Data points were obtained from plots such as Fig. 19. Conditions same as for Fig. 18.

The beam probe was also used to measure the radial spreading of the beam at various positions along the axis.²⁴ The current density profiles at positions of 15, 52 and 129 cm from the anode foil are shown in Fig. 21. Very little spreading in radius is seen, and little attenuation in current occurs until the mirror region is reached; then about 10 to 20% of the beam gets reflected, accounting for the low level of the dotted curve.

Fig. 21. Beam current density profile made with miniature Faraday probe, at three distances from anode foil. Plasma density $1.2 \times 10^{13} \text{ cm}^{-3}$.

One final set of data shows that the loss of energy by the beam in passing the length of the plasma column is less than 30 keV out of the initial 350 keV. The energy spectrum of X-rays emitted by a small titanium foil patch, placed at various positions in the machine, yielded the data shown in Fig. 22. The apparatus and the calibration procedure are described in Sec. 5.3.

In conclusion, it seems clear that for conditions in which the heating is due to the relativistic 2-stream instability, the interaction strength (and thus the heating rate) is strongly dependent on the temperature of the electron beam, a cold beam giving large heating. The heating rate, which determines the energy deposition length, can thus be controlled by the experimenter, an important feature in experiments on the long E-beam plasma solenoid for application.

Fig. 22 . X-ray absorption data. Apparatus of Fig. 23 used to view a small $\frac{1}{2}$ μ m titanium foil at 15 and 100 cm from anode foil. Curves calculated as explained in Sec. 5.3 .

5. DIAGNOSTIC DEVELOPMENTS

Several useful diagnostics instruments were developed during the contract period. These instruments and techniques are mentioned throughout the report, but a few merit further discussion in this special section. In our experiments we have relied mostly upon the 4-channel charge-exchange analyzer, voltage and current monitors, magnetic probes, fast and slow diamagnetic loops, microwave interferometer measurements of plasma density, microwave scattering from fluctuations, x-ray target probes, a miniature Faraday cup beam probe, and very recently 90° Thomson scattering of light from a 10 joule ruby laser. Some of these techniques are discussed below.

5.1 Neutral Atom Beam Experiments

Beam attenuation experiments have been made using argon and hydrogen atoms, at high energies. The source used is a duoplasmatron, from which ions are extracted and accelerated to the desired energy, mass-analyzed, and 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, as shown in Fig. . The same source is used to calibrate the energy analyzer described in Sec. 5.2. The attenuation is due to ionization of the neutrals by the plasma, either by electron impact ionization (e.g. 8 keV argon atomic beam in a $T_e \lesssim 5$ keV plasma) or by charge exchange (e.g. 5 keV H atomic beam in a hydrogen plasma having $T_i \gtrsim 2$ keV.). Attenuations of 5 to 15% were observed in an 8 cm diameter plasma having $n_e \gtrsim 5 \times 10^{13}$, with attenuation directly proportional to $\int n dl$, making a straightforward density measurement possible. The measured attenuation values give peak plasma densities in agreement with microwave measurements, with the advantage that it would be possible to measure densities up to about 10^{15} cm^{-3} with the atomic beam, while our 4 mm microwaves are cut off about $6.8 \times 10^{13} \text{ cm}^{-3}$.

Fig. 22. Experimental arrangement for measurement of neutral beam attenuation.

5.2 Ion Energy Diagnostics

Very important in a plasma heating experiment are reliable diagnostics for ion and electron energy analyses. "Standard" techniques have evolved in many laboratories, including diamagnetic loops, energy analyzers for fast charge-exchange neutrals, doppler-broadening of optical lines, 90° laser scattering, soft x-ray energy analysis and numerous others. Each method has advantages and disadvantages, depending on experiment conditions, corroborative measurements and the ingenuity of the researcher. During the contract research period we made several important improvements to some of the techniques listed above, and in addition, developed some new diagnostic instruments that were useful for our research tasks.

An important diagnostics experiment completed was the first detailed ion energy-distribution measurements of a plasma heated by collective interactions, with the results on turbulent heating reported by us at the IAEA meeting in Madison, Wisconsin in June, 1971.³ These measurements, showing that the distributions were very non-Maxwellian, were continued in 1971 and 1972 to establish that the shape of the distribution could be fit to an inverse power law. A parameter study was made to determine what conditions influenced the heating, and the results were published in 1973.⁴ Anisotropies were measured by varying the angle in respect to the magnetic field, as shown in Fig.1 .

The method of charge-exchange diagnostics is straight-forward in principle but the application requires great care and attention to all pertinent features if meaningful results are to be achieved. A detailed calculation and analysis for our experiment is included in Ref. 12 .

Energetic neutral atoms, arising from charge-exchange of the THM plasma ions with a background "target" gas (e.g. krypton, nitrogen, hydrogen, or oxygen) escape across the magnetic field, some entering the analyzer where they are reionized and analyzed. Our earliest instrument was a 2-channel, electrostatic-deflection analyzer which measured only energy and could not discriminate between H^+ and several impurity ions at late times.²² Two improved versions were made and finally our present 4-channel instrument, having both magnetic and electric field deflection (both momentum and energy discrimination) was installed.²³ 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. A five-channel, self-calibrating instrument has been designed as an M.S. project for use with the installation. It is to be mounted on a curved track and attached to the plasma experiment with a flexible connection that permits the angle to be varied readily, in order to observe energy anisotropies.

A static background gas becomes burned out at the time of plasma heating, leaving practically no target atoms in the hot plasma region. The fast neutral atoms emitted thus arise only from the fringes of the plasma, not the interior, especially if a target gas having a large charge-exchange cross section is used (e.g. O_2 , K_r , X_e). If an H_2 background is used,

there is the possibility of a reflux of H atoms arising from the Franck Condon effect - dissociation of H_2 by electron impact releasing atoms having about 2.5 eV of energy. That is sufficient energy that these atoms have a mean free path of several centimeters in our plasma and are thus able to penetrate to the interior. Because H has a resonance with protons the cross section is large even at low energies. By choosing various target gases for a series of experiments it is possible to view either the interior of the plasma or the outer fringes. Careful analysis is required, and a computer program has been written for the experiment to assist in data reduction.

A great improvement to the system would be a source of energetic neutral target atoms ($W \lesssim 50$ eV) that could pass through the plasma column without being completely burned out. A neutral current density of $\Gamma = 1 \text{ amp/cm}^2$ of 2.5 eV Franck-Condon H atoms would give an H target density of $10^{13}/\text{cm}^3$ inside the plasma, which is 100 times the static background density outside the plasma and 10^5 times the burned-out neutral density on-axis in the plasma. We have undertaken the development of such a pulsed neutral atom source, in collaboration with another Cornell group.

Another method tried in our laboratory that is an improvement on the static background method is to introduce the gas locally with a fast-pulsed valve. A fast pressure manometer (e.g. a nude ionization gauge) records the pressure outside the plasma, but the pressure inside is reduced as the gas becomes ionized. This method is valid for relative measurements or for checking qualitative performance. A variant of this method, which in general causes too much perturbation to be useful in containment experiments, is to inject the gas through a "hypodermic needle" immersed in the plasma, in the solid angle viewed by the analyzer. All of these pulsed methods have

advantages over static fills in that the gas load on vacuum pumps is reduced, and impurity radiation and charge-exchange energy losses are decreased.

5.3 Electron Beam Energy Diagnostics

Spatial and angular current distributions of beam electrons were measured with a miniature collimated Faraday cup probe, developed in a Ph.D. project.²⁴ Approximate electron energy distributions were obtained by varying the thickness of foil absorbers in the throat of the collimator, and corroborated by x-ray measurements described below. The construction is shown in Fig. .

Although the presence of the probe in the plasma produced a slight perturbation, the results obtained were extremely interesting, and the development of this diagnostic instrument has permitted direct measurement for the first time of the angular velocity distribution of relativistic beam electrons. The spread in angle, discussed at length in Ref. 23 , was caused by two effects: first by the scattering of beam electrons as they passed through the metal anode foil, and second by the scattering of the beam electrons from high levels of turbulence generated by the beam-plasma interaction. The effective collision frequency due to the second mechanism was so great that for some conditions as many as 20% of the beam electrons were deflected to large enough angles to be trapped in the 2:1 magnetic mirror. As pointed out in Sec. 4.3.1 and explained in Refs. 10, 24 and 26, this rapid scattering of the beam reduces the interaction strength, so that the collective-interaction plasma heating occurs only in the first 20 to 50 cm. of beam penetration along the plasma column. This effect was measured with diamagnetic loops (Ref. 23), the charge-exchange analyzer placed at various axial positions and angles (Sec. 5.2),

magnetic loop B_z probes, and the miniature Faraday cup probe just described. All of these measurements gave a consistent picture of a self-limiting beam interaction.

To provide a second method of electron energy analysis, a pair of collimated x-ray detectors were constructed as an M.S. project²¹, and applied to measuring the spatial dependence and the energy of beam electrons. The detectors are built to view side-on, as shown in Fig. so that x-rays penetrate only the scintillator crystal and not also the photomultiplier. Each shield is a solid lead casting, carefully poured to avoid bubbles and thin spots. The detectors are completely blind to light and to 500 keV x-rays when the collimator hole is plugged, and in addition there is sufficient magnetic and electromagnetic shielding to eliminate stray pickup. A permanent tin absorber rejects radiation at energies below 75 keV, and a package of eight interchangeable lead absorbers in one collimator permits analysis over the range 150-500 keV. The second detector system is used as a monitor against which shots are normalized.

A "thin target" of 12.5 μm titanium was used to permit data analysis using a computer program written by Logan¹⁹ employing the Elwert-Haug theory²⁰ for x-ray bremsstrahlung from low-Z targets. Great care was taken in the calibration of all components, from target to scintillator, and the results are believed to be accurate within 20% even at the largest absorber thickness (4.45 mm). Because an anode foil had a life expectancy of only 40 to 50 shots, we took 3 shots with each absorber to get good statistics. We concluded that the "thin-target" method, which unfortunately yields small signals, has far fewer uncertainties than the "thick-target" method for the kind of measurements undertaken, in which we were looking

Figure 23. The X-ray target emission experimental set-up, drawn to scale.

for energy variations of a few percent. The results, reported in Sec. and in Ref. , show that 350 keV beam electrons lose 37 keV in the 2 mil anode foil and an additional 20 to 50 keV in the passage through the length of the plasma column, as shown in Fig. . The radial variation of energy is too small to resolve, indicating that not only is the current profile nearly uniform (Sec.), but^{so} also is the energy profile.

5.4 Ruby Laser Thomson Scattering Diagnostics

The time history of the electron temperature T_e in this experiment is of vital importance for the interpretation of results. For the electron temperatures of 0.1 to 5 keV expected at densities of $10^{13} < n_e < 8 \times 10^{13} \text{ cm}^{-3}$, the Salpeter parameter $\alpha \equiv (2k_o \lambda_D \sin \theta/2)^{-1}$ is less than 5×10^{-3} for 90° scattering of ruby laser light, assuring that we are observing the spectrum of incoherently scattered light. With careful calibration we can also measure the absolute intensity of the total scattered light, making possible a determination of both the electron density and the temperature as a function of time.

The ruby laser Thomson scattering system used for this measurement is shown in Fig. and Fig. . The optical efficiency of this system, ϵ , is greater than 13% after accounting for losses by reflection, scattering, grating efficiency, and losses in the fibre optics. A 10 Joule laser amplifier for this system was borrowed from the University of Texas for one year, then a replacement was obtained from Lawrence Livermore Laboratory.

We can estimate the minimum density, n_e , from which we can scatter and still have a conservative signal-to-noise ratio from the following considerations. The total number of scattered photons N_T from each laser pulse is

$$N_T = N_o n_e \sigma d\Omega L$$

Fig. 24. Cornell REB-THM Facility, Showing
Laser Thomson-Scattering and other Diagnostics.

Figure 25 : The Input System

I. THE SOURCE SYSTEM

1. 99.4% REFLECTING MIRROR
2. BREWSTER STACK POLARIZER
3. POCKEL CELL Q - SWITCH (HALF WAVE MODE)
4. OSCILLATOR RUBY ROD, 15.2×1.6 cm.
5. 86% TRANSMITTING QUARTZ ETALON
6. AMPLIFIER RUBY ROD, 20.3×1.9 cm
7. FLAT GLASS BEAM SPLITTER &
PIN DIODE POWER MONITOR
(SOURCE SYSTEM MOUNTED ON RIGID FRAME)

II. THE INPUT SYSTEM

1. FIRST INPUT LENS
(IMAGES AMPLIFIER ON SECOND INPUT LENS)
2. STEERING PRISM
3. DIVERGENCE STOP
4. SECOND INPUT LENS
(IMAGES DIV. STOP INTO SCATTERING VOLUME)

III. THE STRAY LIGHT ELIMINATION SYSTEM

1. INPUT BAFFLES
2. CS 4-72 BLUE GLASS BEAM DUMP

Figure 26. The Output System

III. THE STRAY LIGHT ELIMINATION SYSTEM

1. VIEWING DUMP

2. VIEWING BAFFLES

IV. THE COLLECTION SYSTEM

3. ACHROMATIC VIEWING LENSES, ZWILLINGER EYEPIECE ARRANGEMENT
(IMAGES SCATTERING VOLUME ONTO MASKED FIELD LENS)

4. MASKED FIELD LENS (IMAGES LAST VIEWING LENS ON FOCUSING LENS)

5. ACHROMATIC FOCUSING LENS (IMAGES SCATTERING VOLUME IMAGE ON 4. ONTO ENTRANCE SLIT)

6. CORNING CS 0 - 51 LOW PASS FILTER

7. FIELD LENS (IMAGES FOCUSING LENS ON COLLIMATING MIRROR)

V. THE DISPERSION SYSTEM

8. 1 mm x 1 cm POLYCHROMATOR ENTRANCE SLIT

9. JARREL - ASH 1/4 m, f/3.5 POLYCHROMATOR WITH 1180 1/mm & 295 1/mm GRATINGS

10. 6 FIBRE OPTICS BUNDLES (TRANSFORMS 1 mm x 1 cm EXIT SLIT TO 2 mm x 5 mm)

11. FINAL FOCUSING OPTICS (IMAGE FIBRE OPTICS ONTO Ga-As PHOTOCATHODES)

VI. THE DETECTION SYSTEM

12. 6 R.C.A. C-31034 PHOTOMULTIPLIERS IN SOFT IRON AND CONETIC FOIL MAGNETIC SHIELDING

13. LEAD ENCLOSURE FOR X - RAY SHIELDING

14. PHOTOMULTIPLIER HIGH VOLTAGE AND SIGNAL LEADS

where N_0 , the number of incident photons per 6J pulse, is 2.1×10^{19} ; the length of the scattering volume $L = 2$ cm; n_e is the plasma density; σ is the differential cross section for 90° scattering, $\sigma = (e^2/mc^2)^2 = 7.94 \times 10^{-26} \text{ cm}^2$; and $d\Omega = 0.0485$ steradian for F/4 optics. The number of photons collected in each channel, N_c , is approximately given by:

$$N_c = 0.9 \epsilon N_T \frac{\delta\lambda}{\Delta\lambda} F$$

where $\delta\lambda$ is the channel width ($\sim 160\text{\AA}$); $\Delta\lambda = 33(T_e/\text{lev})^{1/2} = 2333\text{\AA}$ is the FWHM of the spectral distribution for $T_e = 5$ keV; and at the center wavelength of the channel the spectral distribution is a fraction F of its maximum value. An estimate of the signal-to-noise ratio may be obtained from the variance σ_e in the number of photoelectrons emitted from the photocathode. We assume a steady flux of photons with an average number of photo electrons emitted per unit time

$$\langle N_{pe} \rangle = \eta N$$

where η is the quantum efficiency, and N is the number of photons incident in unit time. The variance is

$$\sigma_e^2 = \eta(1-\eta)N$$

An estimate of the signal-to-noise ratio is then

$$S = \frac{\langle N_{pe} \rangle}{\sigma_e} = \left(\frac{\eta N}{1-\eta} \right)^{1/2}$$

The quantum efficiency of the RCA C31034 Ga-As photocathode tubes we are using exceeds 10% for wavelengths less than $8000\text{\AA}$. The above equations can be combined to yield the minimum electron density for which a given signal-to-noise ratio is achievable:

$$n_e \geq S^2 (1-\eta) \Delta\lambda (0.9 N_0 L \sigma d\Omega \epsilon \eta F \delta\lambda)^{-1}$$

A plasma density in excess of $n_e = 6.8 \times 10^{12} \text{ cm}^{-3}$ gives a signal-to-noise ratio $S \geq 10$ for channels in the wings of the distribution ($F = 0.1$). Thus we are able to obtain a time history of the electron temperature with an excellent signal-to-noise ratio at least until the plasma density decays by an order of magnitude from its initial value.

To investigate the extent to which plasma radiation levels might interfere with this measurement, we may compare the expected free-free radiation with the scattered laser power. The emission per unit wavelength ϵ_λ for a hydrogen plasma is

$$\epsilon_\lambda = 1.9 \times 10^{-28} n_e^2 T_e^{-1/2} \lambda^{-2} \exp(-12395 \lambda^{-1} T_e^{-1}) \text{ watts cm}^{-3} \text{ \AA}^{-1}.$$

The power radiated into one of our polychromator channels may be approximated

by
$$P_{ff} = \epsilon_\lambda \delta\lambda V \frac{d\Omega}{4\pi}$$

where $\delta\lambda \approx 160 \text{ \AA}$ is the channel width. For the geometry of this experiment, the effective emission volume is $V \sim 5 \text{ cm}^3$, and the solid angle for the F/4 optics is 0.0485 steradian. This yields $P_{ff} = 5.8 \times 10^{-10} \text{ watt}$ for a channel centered at $6,000 \text{ \AA}$. The laser pulse width τ is less than 40 nsec, so the ruby light power scattered into this channel is

$$P_s \approx 0.9 (E_o \tau^{-1} n_e \sigma d\Omega) \frac{\delta\lambda}{\Delta\lambda} F$$

where E_o is the laser pulse energy. Again, for a channel in the distribution wings ($F = 0.1$), we obtain $P_s = 3.6 \times 10^{-7} \text{ watt}$. According to this conservative estimate the scattered light is at least 600 times greater than continuous radiation into each channel. Free-bound radiation intensities are harder to estimate, however this experiment is designed with the intent of keeping impurities and neutrals to minimal levels, and free-bound radiation does not interfere with the measurement, as long as background pressure does not rise above $\sim 10^{-5} \text{ torr}$.

Results using this equipment are given in Sec. 4.3 and in Refs.

5.5 Microwave Scattering

Electromagnetic wave scattering techniques are non-perturbing, have large intrinsic bandwidth, and yield information about turbulent fluctuations. A number of meaningful scattering experiments have been performed in the last several years from turbulent plasmas at very low densities, at medium densities, and at high densities. The frequency used for the incident wave depends upon the plasma density and upon the frequency and wavenumber of the plasma waves to be studied. In our experiments, in the density range 10^{12} to 5×10^{13} we have used microwaves, at wavelengths of 8mm and 4 mm.

Microwave scattering is a well-known but difficult technique,^{27,29} requiring considerable care in application to pulsed plasma experiments. Stray pickup and radiation are often very difficult to eliminate, and accurate calibration is very time consuming. But the results can tell much about the physical processes in the plasma.

Scattering from a single monochromatic wave occurs at a discrete angle and with a frequency shift given by

$$\omega_s = \omega_I \pm \omega_w$$

$$\vec{k}_s = \vec{k}_I + \vec{k}_w$$

where I denotes the incident wave, s the scattered wave, w the plasma wave, and $\vec{k}$ is the wave vector. The resonance condition for wavevectors gives the angle for maximum scattering

$$\sin \frac{\theta}{2} = \frac{|\vec{k}_w|}{2|\vec{k}_I|},$$

where the geometry is shown in Fig. 27.

Ion acoustic turbulence has the dispersion

$$\omega_w = \omega_{pi} k \lambda_D$$

Fig. 27. Geometry of microwave scattering experiment.

Our "standard" plasma conditions for turbulent heating during and slightly after the turbulent phase were:

$$a = 3 \text{ to } 4 \text{ cm (plasma radius)}$$

$$n_e = n_i = 5 \times 10^{13} \text{ cm}^{-3}$$

$$T_e = 1 \text{ keV}$$

$$T_i = 1 \text{ keV (with a high energy tail)}$$

Thus the Debye length $\lambda_D = 0.011 \text{ cm}$, the ion thermal speed $v_i = 4.2 \times 10^5 \text{ m/sec}$, the electron plasma frequency $f_{pe} = 6.35 \times 10^{10}$, the ion plasma frequency $f_{pi} = 1.48 \times 10^9$ and the ion sound speed $C_s = 9.4 \times 10^5 \text{ m/sec}$.

The maximum growth rate of unstable waves is expected for

$$(k_w \lambda_D)^2 \approx 0.28 - T_i/T_e = 0.08$$

$$k_w \lambda_D \approx 0.28$$

$$k_w \approx 2500 \text{ m}^{-1}$$

$$d_T = \text{turbulence scale-size} = 0.25 \text{ cm}$$

$$f_w = f_{pi} k \lambda_D = 400 \text{ MHz}.$$

Maximum scattering of the 75 GHz wave ($\lambda_I = 0.4 \text{ cm}$) will be at $\theta \approx 100^\circ$, and frequency components of $75,000 \pm 400 \text{ MHz}$ will be present in the received signal. For other conditions the maximum signal will be at

$$\omega_s \approx \omega_I \left[1 \pm 2 \frac{\omega_{pi}}{c} \lambda_D \sin \frac{\theta}{2} \right].$$

The differential cross section for scattering from turbulent density fluctuations is usually given in terms of the Thomson cross section multiplied by the spectral power density of fluctuations²⁸

$$q(\omega, \theta) = q_T(\theta) S(k, \omega)$$

$$= r_o^2 (1 - \sin^2 \theta) S(k, \omega) \text{ in the E-plane}$$

$$= r_o^2 S(k, \omega) \text{ in the H-plane}$$

where $r_o = \frac{e^2}{4\pi\epsilon_o mc^2} = 2.82 \times 10^{-15} \text{ m}$, the classical electron radius; $S(k, \omega)$ is

the spectral function, the Fourier transform of the density correlation function $C(r, \tau)$.

$$S(k, \omega) \equiv \int_{-\infty}^{\infty} d^3r d\tau C(r, \tau) e^{i(k \cdot r - \omega \tau)}$$

$$C(r, \tau) = \langle \delta n(R, t) \delta n(R+r, t+\tau) \rangle / \langle (\delta n(R, t))^2 \rangle.$$

The enhancement over the Thomson cross section is seen to depend on the spectral width, becoming large as the spectrum shrinks. Enhancement factors from $\sim 10^2$ to 10^6 have been reported in the literature.²⁹

In a turbulent plasma the refractive index fluctuations may lead to multiple scattering which can cause scintillation and/or angular broadening of the transmitted wave. These effects are small and the 1st Born approximation is valid if

$$\phi_o \equiv \frac{1}{\sqrt{2}} k_I \frac{\omega_{pe}^2}{\omega_I^2} \frac{\langle (\delta n)^2 \rangle^{1/2}}{\langle n \rangle} (ad_T)^{1/2} \ll 1,$$

for $\omega_{pe}^2 / \omega_I^2 < 1$. That is, the r.m.s. phase fluctuations ϕ_o must be less than unity. In our experiment the maximum r.m.s. level $\langle (\delta n)^2 \rangle^{1/2}$ reaches $\sim 1\%$ of the density. The corresponding phase fluctuations are ~ 0.08 radian. Although these phase fluctuations are small, they may cause observable effects. For example, there may be detectable fluctuations in the intensity of the transmitted wave. For ϕ_o much less than unity (which is expected), the mean-square fractional fluctuation of the

transmitted intensity, $\langle (\Delta I)^2 \rangle / \langle I \rangle^2$ is related to the spectral function $S(k, \omega)$ thusly:

$$\langle (\Delta I)^2 \rangle / \langle I \rangle^2 = 4\pi r_0^2 a \lambda_I^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dk_x dk_y \int_{-\infty}^{\infty} d\omega S(k_x, k_y, k_z = 0, \omega) \sin^2 \left| \frac{k_I}{2z} (k_x^2 + k_y^2) \right|$$

where z is the distance of the detector from the plasma center along the direction of the transmitted wave. Thus observations of the intensity fluctuations could provide useful information about the overall level of plasma fluctuations. This idea has not been tested experimentally, but we intend to develop it as a technique in another project in the laboratory. The method is potentially useful to detect (and measure) incipient fine-scale fluctuations in experiments having limited access, such as toroidal devices with liners and closely-packed field coils.

The microwave hardware is composed of a 1 watt cw klystron transmitter at 75 GHz. ($\lambda = 4$ mm), coupled to the horn antenna shown in Fig. , and two identical superhet receivers, each coupled to a receiving antenna at a different angle. A block diagram of the system is shown in Fig. . Each receiver consists of a bandpass waveguide filter, followed by a balanced mixer and a wideband IF preamplifier. The 450 MHz bandwidth signal is then split up by band-pass filters into four amplifier-detectors, each going to one channel of a 50 MHz. oscilloscope. A box full of various band-pass filters permits us to select any four slots of the frequency spectrum from 1 to 450 MHz. In homodyne operation that means we are receiving signals from fluctuations in just that frequency range. In superheterodyne operation we have a local oscillator klystron that tunes from 69 to 75 GHz, so that the received signals represent fluctuation frequencies in a 449 MHz band (or less, depending on the filters used) tunable from 0 to 6000 MHz.

Fig. 28. Block diagram of the microwave scattering system.

A typical spectrum obtained at $\theta = 120^\circ$, $V = \pm 40$ kV, $n_e = 10^{13} \text{ cm}^{-3}$ and $B_z = 2200$ gauss is given in Fig. 3. Several shots were made, using different filters to get the details shown. The widths of the various shoulders represent the filter pass bands, and not necessarily the real spectra.

5.6 R.F. Conductivity Probe

This small probe, developed to measure the anomalous resistivity during and following turbulent heating,² consists of a small coil of copper wire, well shielded against electrostatic pickup, and insulated inside a thin-wall glass tube. The coil is driven at its resonant frequency of 40 MHz by a stable oscillator, and the r.f. voltage across it is detected by a diode, whose d.c. (pulse) output is displayed on an oscilloscope. When plasma surrounds the coil its resonant frequency is shifted by reactive currents induced in the plasma, and power is extracted by dissipative currents. A sketch of the instrument is shown in Fig.

Two configurations were made, one with its axis oriented along the machine magnetic field, and one perpendicular. When the effective electron collision frequency was high (during turbulent conditions) both probes gave the same results: there was no shift of resonant frequency, only a lowering of the Q (Fig. b). After the heating pulse the plasma conductivity became very high and the reactive effect became extreme, effectively short-circuiting the probe. Thus quantitative data was obtained only before, during, and for about 10 μs following the turbulent heating pulse.

Calibration was made by immersing the probes in salt and acid solutions having known conductivity. This method also tested the effectiveness of the Faraday shield in isolating the coil from capacitive electrostatic pickup.

Fig.29. Tuned conductivity probe, mounted in insulating quartz tube for insertion into plasma. Driven by 40 MHz. signal generator. High impedance detector has .5 μsec response.

Fig.30. Resonance curves for tuned conductivity probe, showing three types of responses, depending upon relative reactive and resistive effects of the plasma in which the probe penetrates.

6. References

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7. EDUCATION AND TRAINING

Under AEC-ERDA support, this program has provided training for the graduate students and post-docs listed below. Eleven master's degrees and six Ph.D. degrees have resulted from the research in the Plasma Heating Laboratory. Of the students listed 7 have obtained positions in CTR research or management, 3 are in DOD laboratories, one is teaching and 2 are still students.

7.1 Postdoctorals receiving support from this Project:

Leslie Sharp	1967-1968
Moshe Friedman	1968
Peter Korn	1969-1973
Al Mondelli	1972
Carl Ekdahl	1973-1975

7.2 Graduate Students receiving training in the Project:

<u>Student</u>	<u>Thesis Title</u>	<u>Degree</u>	<u>Date</u>
Patricia A. Carrol	Microwave Antennas for Plasma Research	M.S.	June 1968
Daniel S. Prono	Ion Energy Distribution due to Turbulent Heating	Ph.D.	June 1970
Roy Benson	Lecher-wire Transmission Line for Plasma Diagnostics	M.S.	June 1972
Frederick L. Sandel	Far-Infrared Laser System	M.S.	Aug. 1972
Ethan R. Wilson	Optical Polychromator	M.S.	Aug. 1972
Scott Robertson	Neutral Atom Diagnostics	M.S.-Ph.D.	Aug. 1972
Gerrald Ferrentino	Diffusion in Fluids	M. Eng.	June 1973
Michael A. Greenspan	4-Channel Energy Analyzer	M.S.	Aug. 1973
Frederick L. Sandel	Relativistic Electron Beam-Plasma Interaction	Ph.D.	Aug. 1973

7.2 (Continued)

<u>Student</u>	<u>Thesis Title</u>	<u>Degree</u>	<u>Date</u>
Thomas R. Lockner	Drifts of Relativistic Electron Beams in a Torus	M.S.	June 1974
Milton D. Johnson	Whistler Wave Propagation in a Plasma Column	Ph.D.	June 1975
Raymond Seraydarian	X-Ray Diagnostics System	M. Eng.	June 1976
Bradley Patch	Clean Turbulent Heating	M.S.	Aug. 1976
John D. Sethian	Thomson Scattering and Diamagnetic Loop Studies of Plasma	M.S.-Ph.D.	Aug. 1976
Michael A. Greenspan	Experimental Study of Plasma Heating by Relativistic Electron Beam	Ph.D.	Jan. 1977

8. FUNDING HISTORY

Summary of AEC/ERDA Support for Project

Contract	Dates	Amount
AT(30-1)3958	1 Apr. 1968-31 Mar. 1969	\$ 62,117
AT(30-1)3958	1 Apr. 1969-31 Mar. 1970	65,528
AT(30-1)3958	1 Apr. 1970-31 Mar. 1971	65,000
AT(30-1)3958	1 Apr. 1971-31 Mar. 1972	65,000
Equipment supplement:	1 July 1971	15,340
AT(11-1)2194	1 Jan. 1972-31 Dec. 1972	13,500
AT(11-1)3165	1 Apr. 1972-31 Mar. 1973	70,461
Equipment supplement:	1 July 1972	20,130
AT(11-1)3165	1 Apr. 1973-31 Mar. 1974	75,000
AT(11-1)3165	1 Apr. 1974-31 Aug. 1974	40,000
AT(11-1)3165	1 Oct. 1974-30 Sep. 1975	70,000
AT(11-1)3165	1 Oct. 1975-31 Jan. 1976	21,670
Total AEC/ERDA funding		\$ 583,746

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APPENDIX 1

CLEAN TURBULENT HEATING

Final Report, LLL Order 1876813

"Study of Plasma Heating for
Application to Deep-Well Mirror Machine"

Charles B. Wharton

Cornell University
Ithaca, NY 14853
August, 1976

CLEAN TURBULENT HEATING

Introduction

Plasma heating by collective interactions has several noteworthy advantages as well as some distinct disadvantages, whose relative importances must be weighed when one attempts to apply the concept to practical plasma experiments. Turbulent heating, for example, has been shown to have a high efficiency, a low investment cost and great simplicity in heating large volume, high density plasmas to high temperatures, in both toroidal^{1,2} and lineal^{3,4,5,6} geometry. The heating time is very short, so that in spite of the high levels of turbulence attained, a well-designed experiment can avoid loss of plasma due to diffusion. At the end of heating, the turbulence levels quickly relax, permitting the plasma to be retained stably in a confinement geometry⁷.

The large currents (tens of kiloamperes) however may drive macro-instabilities, such as the firehose and various current-convective modes. The instability-onset not only terminates the effective plasma heating event, but often dashes the outer portions of the plasma against the vacuum wall or other objects, releasing copious impurities that quickly drain the plasma energy that has been gained. In extreme cases the entire plasma confinement is lost, as has been observed in a Stellarator experiment².

Heating by a burst of very short pulses, each having a duration less than the instability growth time and a separation longer than the turbulence relaxation time may avoid the destructive action, still allowing appreciable heating over microseconds, milliseconds or even

seconds of time. The optimum duration of a pulse must be long enough to achieve the desired heating, but short enough to inhibit the disruption. The compatibility of these requirements has been found possible in the Cornell THM experiment.

This report describes carefully performed experiments in which the duration of the heating pulse was varied, while observations were made of the current channel, the plasma diamagnetism, the ion energy distribution and the plasma density. From these⁸ and other observations it is possible to conclude that current disruption, with the attendant impurity generation, could be prevented, while the ion heating was not degraded by more than $\sim 10\%$, and the energy-confinement time was even increased, due to the curtailment of the impurity liberation. The energy efficiency was increased from 6% to $> 20\%$.

The liberation of impurities due to outgassing of the current-carrying electrodes was found to diminish during the first ten shots of a run to a level that was not detectable. The main contaminant was carbon from the diffusion pump oil. A small level of titanium contaminant (from the orbitron pump) was also detected in the spectroscopic analysis. The estimated concentration was a fraction of a percent of the ion density.

1. Characteristics of Normal Operation

The Cornell THM installation described in Refs. 4 and 7 was double-ended, one end pulsed positive, the other negative. The configuration used for the present experiments, and shown in Fig. 1 is single ended however, with only the plasma source-end pulsed. The opposite electrode (also serving in other experiments as the relativistic electron beam anode) is grounded. The hydrogen or deuterium plasma, generated in a conical-pinch discharge source, is guided through a titanium-pumped chamber by a hexapole magnetic field and injected with a velocity of 8 cm/ μ sec into the highly-evacuated main chamber along the magnetic lines of a 2:1 mirror field. Thus a fully-ionized 10-20 eV plasma column, 5 to 8 cm in diameter, is supported by the magnetic field along the axis of the 40 cm diameter vacuum chamber. The operating results of this THM-REB are quite similar to those of the older configuration, but the plasma density is lower (only one source) and also there is a greater tendency for the current column to disrupt. The diagnostic instruments used in these investigations are described in Sec. 4.

Typical voltage and current waveforms with $n_e \gtrsim 2 \times 10^{13} \text{ cm}^{-3}$ are shown in Fig. 2, for a 0.2 μ Fd. capacitor bank charged to -80 kV. The positive voltage spike at $t \approx 1.4 \mu$ sec is due to the large plasma resistance accompanying turbulence. The "normal" method of firing the machine is without the shorting sparkgap (shown closest to the machine in Fig. 1). The solid curves of Fig. 2 then represent the response. (The significance of the dashed curves will be discussed in Sec. 3.) At densities below 10^{13} cm^{-3} the initial voltage rise is

Fig. 1 THM, modified for the "Clean Turbulent Heating" experiment. Short-circuiting sparkgap, additional glass insulation, and three magnetic probes are shown.

larger than in Fig. 2 and the later spike is not as distinct. The current pulse is not as large, and there is not an appreciable notch present.

The plasma resistivity measured at the time of arrow No. 2 in Fig. 2 (peak of the voltage spike) is plotted in Fig. 3 as a function of plasma density. At low densities the values are seen to compare (within 50%) to the Buneman resistivity

$$\rho \approx .5 \left(\frac{m_e}{m_p} \right)^{1/3} \frac{1}{\epsilon \omega_p},$$

represented by the dashed line in Fig. 3. As densities are increased above 10^{13} cm^{-3} the ion acoustic instability begins to predominate, imposing a current threshold at a value such that the electron drift velocity exceeds the ion sound speed by about a factor of 3

$$v_D \gtrsim 3 C_s.$$

$$\text{where } v_D = \frac{J}{ne}.$$

Results reported in Refs. 4, 5, and 7 were for the high-density case, while those of Refs. 1, 2, and 10 apply mostly to the low-density case.

Several explanations of the heating processes can be found in the literature. At high densities it is clear how the electron-ion acoustic instability can develop, and the results on ion and electron heating by this process match the theory reasonably well^{3,4,5}. It is less clear how the electron-electron 2-stream instability develops, unless some electrons are able to run away under low-density conditions. The electron-ion instability heats electrons strongly when $v_D \gtrsim v_{eth}$.

Fig. 2 Measured plasma current and applied voltage as a function of time (solid curves: normal operation; dashed curves: operation with shorting gap triggered at peak of resistive period). Significance of numbers is explained in Sec. 3.

Fig. 3 Measured plasma resistivity as a function of peak density.

We have established that runaway did not occur at high densities, an observation recently substantiated at Nagoya⁶. But the presence of a resistivity-threshold, reported in Refs. 1 and 2, at the critical electric field strengths associated with electron runaway lends some support to the possibility at lower plasma densities.

2. Macroscopic Instability of the Current Channel

A small magnetic probe inserted into the plasma column 20 cm from one end (at position No. 2 in Fig. 1) indicates that for a large percentage of shots the current does not continue to flow in an axial channel for the full duration of the current pulse that is measured by the Rogowskii loop. This effect is shown in Fig. 4a, for conditions of plasma density $n \gtrsim 2 \times 10^{13} \text{ cm}^{-3}$ and $I_{\text{max}} \approx 10 \text{ kA}$. Current flows from the electrode into the plasma column and along it to the opposite end only up until and during the time of the resistive voltage spike. Then it is diverted to large radii. A portion flows back along the surface of the glass insulating cylinder to the near-end of the machine causing flashover, but most of the current seems to end up on the laser dump, the conducting object that protrudes the farthest into the chamber. The mode number of the anomalous current flow was not determined specifically, since we had only two functioning magnetic probes available. From the data typical to that shown in Fig. 4 it appears that the current was confined to the channel for 0.5 to 0.6 μsec and then switched to a large radius in about the same length of time. Data such as in Fig. 4d did not indicate an appreciable θ -component, but the available data is as yet inconclusive in establishing this fact.

MAGNETIC PROBE

AT R = 2 CM

(a)

MAGNETIC PROBE

AT R = 12 CM (NORTH)

(b)

MAGNETIC PROBE

AT R = 12 CM (SOUTH)

(c)

MAGNETIC PROBE

AT R = 12 CM (NORTH)

(d)

Fig. 4 Plasma current, 5 kA/cm, measured with a Rogowski loop around the electrode feed (top traces). Local magnetic field due to plasma currents, measured with a moveable magnetic loop probe, signal integrated with a 50 μ sec RC (bottom traces). Time scale 1 μ sec/cm.

Accompanying the current diversion is a flash of optical line-radiation and a large increase in electron density, indicative of copious impurity release from surfaces. The top trace of Fig. 5 is a typical response of the 4 mm λ microwave interferometer when the current transfer occurs. The average density about doubles. The newly generated plasma consists mainly of contaminants knocked off surfaces--carbon, oxygen, silicon, fluorine and molecular hydrogen ions. This cold, high-z plasma surrounds the heated plasma column (which surprisingly loses only a portion of its energy during the current diversion), causing a rapid drain of heat by increased charge exchange and scattering losses.

Fig. 5. Electron density as a function of time, as measured by a 4mm λ microwave interferometer. Zebra-stripe data presentation shown for each corresponding graph. The times indicated refer to those shown in Fig. 2.

3. Time-Dependent Current Shunt Experiment

We have supposed for some time that the premature termination of axial plasma current also terminates the heating event. To substantiate this conclusion a time-dependent experiment was performed, similar to that described in Ref. 6, indicating from the R.F. noise that there were two turbulent phases at low densities, one appearing immediately on application of the voltage, and the second one beginning at Time 1 of Fig. 2. As the density was increased above $\sim 10^{13} \text{ cm}^{-3}$ the second turbulence began to predominate. The time-resolution of the data from the diamagnetic loop and the charge-exchange-neutral energy analyzer was not sufficiently good to determine the exact time of heating. Also, the liberation of surface contaminants, delayed by a microsecond or so after the current-interruption, continued to influence conditions in the heated plasma during the subsequent confinement phase.

A second kind of time-dependent experiment was next performed, one in which a short circuit was applied across the input voltage at programmable times. The triggerable sparkgap shown in Fig. 1 shunts the plasma current externally at a preset time, and the diagnostics instruments record what has occurred up to that time. Some instants of time that were found to have particular significance are indicated in Fig. 2. Time 1 signifies the onset of the high resistivity phase, signalled by a voltage spike; Time 2 is the peak of the voltage spike; Time 3 is the end of the voltage spike and the onset of disruption; and Time 4 signifies the internal short-circuiting of the current channel to some place on the chamber walls, usually accompanied by

flashover along the main electrode insulator. The flashover occurs when ionization at large radius is generated, allowing charge build-up on insulating surfaces that are parallel to the magnetic field lines (refer to the geometry of Fig. 1). Disruption and flashover occur in more than 50% of the shots at voltages above 60 kV, if the voltage is permitted to remain on the electrode past Time 3.

When the shorting gap is fired at Time 2 or earlier there is no insulator flashover, no current transfer and no anomalous liberation of contaminants. The dashed lines in Fig. 2 indicate the plasma current and the electrode voltage for this case, and the bottom trace of Fig. 5 shows that no increase in plasma density results from application of the heating pulse (the interferometer response for the gun-plasma alone looks very similar to this trace, except that the density decays in about one fourth the time). When the dump-gap is fired at Time 3 there is usually already some current transfer and some contaminant liberation, as shown in Fig. 5(b).

It might be suspected that there would be a degradation of the heating when the current pulse is terminated prematurely. But Fig. 6 shows only a slight decrease in the total diamagnetism at early times, and in fact an increase at late times, indicating an improvement in energy containment time. The bottom trace in Fig. 6 shows the lack of containment when the downstream mirror was disconnected, evidence that the heated ions make up much of the late-time diamagnetic signal.

The results from the 4-channel charge-exchange energy analyzer, shown in Fig. 7, bear out the conclusion that the ion heating was only slightly inferior when the heating pulse was shorted out at the

Fig. 6 Signal from compensated diamagnetic loop for the two cases: "normal", and with the shorting gap fired at Time 2. The third trace is for "normal" operation, but with one of the magnetic mirrors disconnected.

peak of the resistance spike. At densities of $\lesssim 3 \times 10^{12} \text{ cm}^{-3}$ the short circuit could be advanced as early as $\sim 1/4 \text{ } \mu\text{sec}$ after voltage was applied, indicating that most of the heating occurred during the first turbulent phase. At densities above $\approx 3 \times 10^{13} \text{ cm}^{-3}$ the optimum instant to short the voltage was between Times 2 and 3, resulting in some release of contaminants if too much delay was allowed. In Fig. 7 a plot of data from Ref. 4 is reproduced for comparison. That data was from the double-ended configuration, using the same bank energy as used for the present investigation. The slopes and relative features are quite similar. The Ref. 4 data is displaced upward by a factor of 5 in plotting to reduce clutter in the figure.

The total perpendicular energy $W_{\perp} = nk(T_e + T_i)$ recorded at 10

Fig. 7 Ion energy distribution resulting from turbulent heating, derived from analysis of charge-exchange neutrals.

μsec after the heating pulse, is plotted in Fig. 8 as a function of plasma density, with the shorting at Time 2. The dependence is roughly inversely proportional to density, in agreement with theories of heating by electron-ion instabilities. The exact mechanism for the coupling of energy from current to electron thermal energy to ion thermal energy is not in general known for each specific situation, but it is safe to conclude that there are many possibilities.

FIGURE 8 Perpendicular energy per electron-ion pair as a function of axial line density, recorded at 10 μsec after turbulent heating (60 kV).

Some of these were discussed in Ref. 4. For the operating conditions of the experiments described here the two most likely ion heating modes are the ion acoustic instability, and the electron-ion (Buneman) streaming instability with coupling from electrons to ions by decay modes or nonlinear Landau damping.

Our measurements, made 10 μsec after the heating pulse show $T_e/T_i < 1$, with T_e decreasing rapidly for 50 μsec and then decreasing more slowly. Thus there is evidently a large drain of electron energy during the turbulent phase, either by scattering across field lines (improbable) or by scattering out the ends of the machine. The necessary high levels of turbulence could be achieved by either turbulence mode. This rapid drain may limit the ultimate electron temperature achievable (and thus also the ion temperature), if the electrons see turbulent fields long enough to scatter out or make collisions with the electrodes. A suggested remedy (which we hope to try in further applications) is to apply short enough pulses, which in this case must be 100 nsec or less, that the heated electrons do not have time to scatter out of the plasma column. To obtain large energy input, a train of pulses would be applied, a remedy for the macroscopic instability that was proposed in the Introduction.

The heating efficiency of the Clean Turbulent Heating Experiment has been increased to more than 20%, as shown in Fig. 9. The increased efficiency is due to the decreased time that current flows, decreasing the input power, while the heating remains nearly constant.

FIGURE 9. Heating efficiency as a function of the time of firing the shorting gap, recorded 10 μsec after turbulent heating.

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