UCRL-18423

FINAL REPORT
ON
CLEAN TURBULENT HEATING

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August, 1976

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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

1. Characteristics of Normal Operation

The Cornell TiB 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 TiB-RiB 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

Figure 1. The Relativistic Beam and Turbulent Heating Machine.

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

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

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 $n \geq 2 \times 10^{13} \text{ cm}^{-3}$ 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 $4\text{ mm } \lambda$ 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 $4\text{ mm } \lambda$ microwave interferometer. Zebra-stripe data presentation shown for each corresponding graph. The times indicated refer to those shown in Fig. 2.

5. Time-Dependent Current Short 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 5.

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 diagnostic loop for the two cases: "normal", and with the shorting gap closed at Time 2. The third trace is for "normal" operation, but with the shorting gap closed at Time 2.

peak of the resistance spike. At densities of $\leq 3 \times 10^{12} \text{ cm}^{-3}$ the short circuit could be advanced as early as $\sim 1/4 \text{ usec}$ 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 $W_L = nk(T_e + T_i)$ 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 μ sec after the heating pulse show $T_e/T_i < 1$, with T_e decreasing rapidly for 50 μ sec 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.

4. Diagnostic Developments

Several diagnostics instruments have been developed in the Plasma Heating Laboratory. These instruments and techniques are listed here, with a few singled out for expanded discussion. In our heating experiments we have relied mostly upon these instruments: the 4-channel charge-exchange analyzer, fast and slow diamagnetic loops, microwave interferometers for measurements of plasma density, magnetic probes (to show current channels), x-ray target probes (to find energy and spatial dependence of fast electrons) and very recently 90° scattering from a 10 joule ruby laser.

4.1 Neutral Atom Beam Experiments

Beam attenuation experiments have been made using argon and hydrogen atoms, at high energies. The source used was 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. 10. The same source is used to calibrate the energy analyzer described in Sec. 4.2. 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 $T_e \leq 1$ keV plasma) or by charge exchange (e.g. 5 keV H atomic beam in a hydrogen plasma having $T_i \geq 2$ keV.). Attenuations of 5 to 15% were observed in an 8 cm diameter plasma having $n_e \approx 5 \times 10^{13}$, with attenuation directly proportional to n_e , making a straightforward density measurement possible. The measured attenuation values give peak plasma densities in agreement with microwave measurements,

Fig. 10 Experimental arrangement for measurement of neutral beam attenuation.

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 microwave is cut off above $6.8 \times 10^{13} \text{ cm}^{-3}$.

4.2 Particle 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.

The first detailed ion energy-distribution measurements of a plasma heated by collective interactions were the results on turbulent heating reported by us at the IAEA meeting in Madison, Wisconsin in June, 1971.⁴ 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. Anisotropies were measured by varying the angle in respect to the magnetic field.

The method of charge-exchange diagnostics is straight-forward in principle but the application requires great care and attention to detail if meaningful results are to be achieved. Energetic neutral atoms, arising from charge exchange of 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^1 and several impurity ions at late times. 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. 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 is being designed for use with the installation. It will 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 from the fringes of the plasma, if a target gas having a large charge-exchange cross section is used (e.g. O_2 , Kr, Xe). 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 will be written for the experiment to assist in data reduction, with all known effects included.

A great improvement to the system would be a source of energetic neutral target atoms ($W \gtrsim 50$ eV) that could pass through the plasma column without being completely burned out. A neutral current density of $I = 1$ amp/cm² of 2.5 eV Franck-Condon H atoms would give an H target density of 10^{13} /cm³ 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 are presently considering 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 is not 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 the advantage over static fills in that the gas load on vacuum pumps is reduced, and impurity radiation and charge-exchange energy losses are decreased.

In very recent experiments we have measured the electron velocity distribution in TlI with 90° Thomson scattering of ruby laser light. The diagnostic system is described in Sec. 4.3.

A careful comparison of the laser-scattering data with the diamagnetic signal shows that the electron temperature falls rapidly after heating (from ≈ 1 keV down to ≤ 100 eV in a few microseconds), while the ion energy stays high for a hundred microseconds or so. At early times the charge-exchange, laser-scattering and diamagnetic data are consistent. At later times the charge-exchange data is not reliable, presumably because there is not adequate neutral target gas for charge-exchange reactions with the hot ions. The development of a copious source for low energy neutral atoms (in collaboration with another group at Cornell) is planned for the coming year. This source will permit charge-exchange diagnostics at late time.

A 5-channel, self-calibrating neutral particle analyzer has been designed and is being built in our laboratory. This analyzer has magnetic deflection followed by electrostatic deflection, to give both momentum and energy analysis. The deflection system was designed with a computer program to achieve focus in both planes. An ion source will be built into the stripping cell for calibration of sensitivity and energy spectrum of the system. The plan view is shown in Fig. 11.

Fig. 11 Plan view of the magnetic deflection system of the six-channel energy analyzer for charge-exchange spectroscopy

4.3 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 1 to 5 keV expected at a maximum density $n_e \approx 5 \times 10^{13}$, the Salpeter parameter $\alpha = (2k_0 \lambda_D \sin \theta/2)^{-1} \leq 2.4 \times 10^{-3}$ for 90° scattering of ruby laser light, assuring that we will be observing the spectrum of incoherently scattered light. With careful calibration we can also measure the total scattered intensity, making possible a determination of both the electron density and temperature as a function of time.

A ruby laser Thomson scattering system is available for this measurement. This system, shown in Fig. 12 and Fig. 13, is now in operation on the plasma heating experiment. The 6 Joule laser amplifier in this system is on loan from Lawrence Livermore Laboratory, and arrangements will have to be made to either extend this loan or replace this component to realize the full capabilities of the scattering system. The optical efficiency of this system, is greater than 13% after accounting for losses by reflection, scattering, grating efficiency, and losses in the fibre optics.

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

$$N_T \approx N_0 n_e \sigma \Omega l.$$

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_0 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:

$$N_c = 0.9 E N_0 \frac{\delta\lambda}{\lambda} F$$

where $\delta\lambda$ is the channel width ($\sim 160\text{\AA}$); $\lambda = 33(T_e/\text{eV})^{1/2} = 233\text{\AA}$ 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_c in the number of photoelectrons emitted from the photocathode. For a steady flux of photons with an average number of photoelectrons 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

$$\sigma_c^2 = \eta(1-\eta)N.$$

An estimate of the signal to noise ratio is then

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

The quantum efficiency of the RCA C31034 Ca-Ag 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:

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

Fig. 12 Block diagram of ruby laser and input optical system for Thomson scattering diagnostics on TIM.

1. Plasma scattering volume.
2. Aspheric viewing lenses (Zwillinger overcoat arrangement).
3. Flashed field lens (images last viewing lens on focusing lens).
4. Aspheric focusing lens (images scattering volume on entrance slit).
5. Corning CS-51 low pass glass filter.
6. 1 mm x 1 cm entrance slit and field lens (images focusing lens on collimator).
7. Jarrel-Ash 1/4 m, F/3.5 monochromator with 150 1/mm and 295 1/mm gratings.
8. 6 channel fibre optic transmission system (transforms 1 mm x 1 cm exit slits to 2 mm x 5 mm).
9. Converging lenses (image 2 mm x 5 mm fibre optics on 4 mm x 10 mm photocathodes).
10. RCA C-3103 Ga-Ag photocathode photomultipliers in soft iron and Gensic foil magnetic shields.
11. 2" lead X-ray shield.
12. High voltage and signal cables.

Steering mirrors have been omitted from this diagram for clarity.

Entire collection system is in a light-tight enclosure.

Fig. 13 Block diagram of collection optics and polychromator spectrum analyzer for Thomson scattering diagnostics on Iro.

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 will be 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

$$\epsilon_\lambda = 1.9 \times 10^{-28} n_e^2 T_e^{-1/2} \lambda^{-2} \exp(-1.2395\lambda^{-1} T_e^{-1}) \text{ watts cm}^{-3} \text{Å}^{-1}.$$

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 $\delta\lambda = 160\text{Å}$ 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 $6,000\text{Å}$. The laser pulse width τ is less than 40 nsec, so the ruby light power scattered into this channel is

$$P_s = 0.9 (E_0 \tau)^{-1} n_e \sigma d\Omega L \frac{\delta\lambda}{\Delta\lambda} F$$

where E_0 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 is unlikely to interfere with the measurement.

4.4 Microwave Scattering

Electromagnetic wave scattering techniques are non-perturbing, have large intrinsic bandwidth, and can 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. Thus in the ionosphere one scatters with short waves and in dense pinch and shock wave experiments one uses a ruby laser. In the density range 10^{12} to 5×10^{13} one uses millimeter wavelength microwaves.

Microwave scattering is a well-known but difficult technique,¹⁰ 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

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

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

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

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

where the geometry is shown in Fig. 1.

Ion acoustic turbulence has the dispersion

$$\omega_w = \omega_{pi} k_w \lambda_D.$$

Fig.14 . Geometry of microwave scattering experiment.

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

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

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

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

$$T_i = 2 \text{ keV (with a high energy tail)}$$

Thus the Debye length $\lambda_D = 0.011$ cm, the ion thermal speed $v_i = 4.2 \times 10^5$ 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 $C_s = 9.4 \times 10^5$ 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 ($\lambda_I = 0.4$ cm) will be at $\theta \approx 100^\circ$, and frequency components of $75,000 \pm 400$ 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 fluctuations¹⁷

$$\begin{aligned} q(\omega, \theta) &= q_T(0) S(k, \omega) \\ &= r_o^2 (1 - \sin^2 \theta) S(k, \omega) \text{ in the E-plane} \\ &= r_o^2 S(k, \omega) \text{ in the H-plane} \end{aligned}$$

where $r_o = \frac{e^2}{4\pi\epsilon_0 mc^2} = 2.82 \times 10^{-15}$ m, the classical electron radius; $S(k, \omega)$ is

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

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

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

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

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

$$\phi_0 \equiv \frac{1}{\sqrt{2}} k_I \frac{\omega_{pe}^2}{\omega_I^2} \frac{\langle (\delta n)^2 \rangle^{1/2}}{\langle n \rangle} (ad_p)^{1/2} \ll 1,$$

for $\omega_{pe}^2/\omega_I^2 < 1$. That is, the r.m.s phase fluctuations ϕ_0 must be less than unity. In our experiment the maximum r.m.s. level $\langle (\delta n)^2 \rangle^{1/2}$ reaches $\approx 1\%$ of the plasma 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_0 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:

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

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.

A 75 GHz scattering system is available for application to the proposed work if its use is needed.

References

1. B. A. Demidov and S. D. Fanchenko; "Turbulent Heating and Confinement of Plasma in Toroidal Multipole Trap". Atonnaya Energiya 50, 468 (May 1971) (In Russian).
2. S. M. Hammerger et al. "Experiments on Plasma Heating by Dissipation of Current-Driven Turbulence." IAEA 4th Conf. Plasma Phys. and Contr. Nucl. Fusion, Paper CN-28/E3. P. 37 (Madison, Wisc. 1971).
3. E. K. Zavoysskii et al.; "Progress in Turbulent Heating of a Plasma." IAEA 4th Conf. Plasma Phys. and Contr. Nucl. Fusion, Paper CN-28/E1. P. 3 (Madison, Wisc. 1971).
4. C. B. Wharton et al.; "New Results in Turbulent Heating." IAEA 4th Conf. Plasma Phys. and Contr. Nucl. Fusion, P. 25. Paper CN-28/E2 (Madison, Wisc. 1971).
5. V. A. Suprunenko et al. "Collective Interactions and Plasma Heating in a High Current Gas Discharge." Plasma Physics 12, 627 (1970).
6. Y. Nakagawa et al. "Dynamic Behaviour of Turbulent Heating of Plasma." EAEA 5th Conf. Plasma Phys. and Contr. Nucl. Fusion Vol. III P. 287 (1974). K. Adati et al. "Observation of Flat-Top Velocity Distributions of Electrons in Turbulently Heated Plasmas." Phys. Rev. Letters 35, 280 (1975).
7. P. Korn and C. Wharton; "Spatial Conductivity Measurements in Turbulent Plasmas." J. Appl. Phys. 42 (12) 4828 (1971).
8. B. Patch; "Time-Resolved Study of Turbulent Heating." Thesis, MSIE Cornell Univ. Aug. 1976.

9. H. W. Pickaar; "Turbulent Heating of Ions and Efficiencies in a Current-Carrying Plasma." Plasma Physics 15, 565 (1973).
H. Schrijver; "Time Dependence of Turbulent Resistivity in a Linear Plasma Column." Physica 70, 339 (1973).

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