Only comparison of observations with and without applied axial field made the correspondence between fading of the plasma column and onset of intense neutron emission very obvious. In pinch discharges one usually assumes the visible light is plasma bremsstrahlung which has the following dependence on density and temperature ($T_e > 10$ eV): $P_b \propto n_e^2 T_e^{-1/2}$. Thus a sharp drop in luminosity implies a rapid decrease in density or a very large increase in the electron temperature. A sudden drop in plasma density is not consistent with various observations and analyses, particularly when the fading occurred between pinches. Therefore we attribute the rapid fading to electron heating. However, electron heating via the usual mechanisms of adiabatic heating, shock heating, or energy transfer from ions is not compatible with the observed behavior, especially with applied field, and thus we conclude that there is strong Ohmic heating. According to the well-known Spitzer expression, plasma resistivity decreases with a rise in temperature and this effect would tend to slow the heating process. But probe studies on slower z pinches have shown that the discharge current eventually diffuses to the axis[5] and for the small radius of a plasma focus column, the magnetic fields become enormous when a small fraction of the discharge current flows near the axis. Now when the electron-cyclotron frequency becomes greater than the electron-ion collision frequency, the plasma resistivity is greatly enhanced and so the rest of the discharge current can rapidly diffuse toward the axis. Such a rapid transition to a narrow, axially peaked current distribution is a key assumption in a recently developed model for deuteron acceleration to high energies.[6] This model explains the intense neutron production beginning when the plasma light fades. Apparently the diffusion of the current distribution is greatly retarded by the trapped flux in the case of applied magnetic field; consequently the intense neutron pulse is delayed.

These observations will be discussed more fully in a future paper and compared with other new neutron measurements. In the case with applied field, the nature of the early, low-intensity neutron production has not been established and indeed may be thermonuclear in origin.

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TEMPORAL AND SPATIAL ORIGIN OF HOT IONS IN TURBULENT HEATING OF A PLASMA*

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Plasma heating by turbulent current flow has been studied by means of particle analysis. The spatial and temporal origin of hot ions is determined and compared with the temporal change of the resistivity and the amplitudes of the high- and low-frequency fluctuations in the plasma.

Of the many ways to heat electrons and ions in a plasma, one of the more efficient and remarkable in performance is that of "turbulent heating."[1-4] Although the processes involved are not understood as yet, considerable documentation has established the impressive ion and electron energies that can be achieved, as well as something of the nature of the electromagnetic fields and their frequency spectra.

Since our interests lie along the lines of a preheater and injector for toroidal confinement devices, the geometry of the experiment is "single ended" in the sense that plasma readily flows through the heating region, and thus lacks the symmetry of many similar experiments. Furthermore, to minimize the injection of cold neutral gas, the plasma source is a pulsed gun and the experiment involves rapid heating of the plasma in transit. For these reasons, heating is accomplished by current flow between ring electrodes.[4] This geometry allows ready access for particle energy measurements and correlation

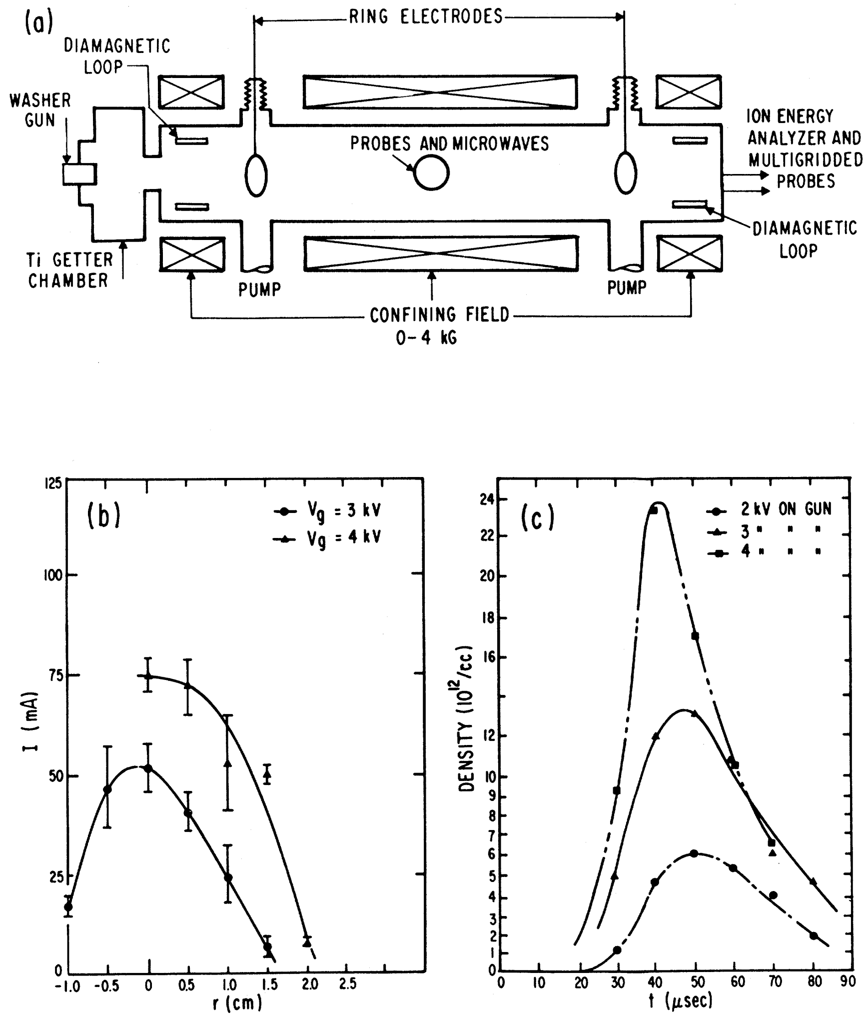

FIG. 1. (a) Schematic of the experimental apparatus. (b) Radial density profiles at the midplane of the machine, without turbulent current flow. (c) Temporal change of the plasma density at the midplane in the absence of turbulent current flow.

of energetic ion and electron production with the temporal behavior of the turbulent frequency spectrum. The work reported below deals primarily with these matters, and lends support to a picture which (although by no means novel in concept) has not hitherto been well documented.

The experiment is illustrated schematically in Fig. 1(a). The plasma source is an occluded hydrogen washer gun, which produces a plasma whose density at the region of the 4-mm microwave interferometer is variable from 10^{13} to $10^{14}/cm^3$. This ion composition is approximately 50% protons, the remainder consisting of various states of ionization of carbon, oxygen, and titanium. The electron temperature, as recorded by a double probe and a multigridded retarding potential probe, is 10 to 20 eV. This is also in agreement with the value evidenced by two diamagnetic loops when the electron density from the midplane measurement is corrected to account for the expansion at the diamagnetic loop position. The mean ion energy from the velocity along the field is ~200 eV, and the ion energy from the velocity perpendicular to the magnetic field is estimated to be 10 to 20 eV.

The magnetic field is uniform to within 5% over the region between the hollow electrodes, so that plasma flows freely from the heating region. At the magnetic field employed (1 to 4 kG), $\omega_{pe} > \omega_{ce}$ for the central density; ω_{pe} and ω_{ce} are the electron plasma frequency and the electron cyclotron frequency, respectively. Double-probe radial density profiles show a bell-shaped distribution [Fig. 1(b)], where at $r = 1.3$ cm (the inner radius of the ring electrode) the electron density is almost equal to a tenth of the central density. At this radius, where the heating current is initiated, the electron plasma frequency is almost equal to the electron cyclotron frequency. The electron density versus time is shown in Fig. 1(c). The density reaches a maximum at about 30 μsec, at which time the turbulent heating pulse is initiated.

Several electrode configurations have been tried, which include rings with 3-in. o.d. and 2-in., $1\frac{1}{2}$-in., or 1-in. i.d., as well as short sections of tubing ($\frac{5}{8}$-in. long) with an o.d. $1\frac{1}{8}$ in. and an i.d. $1\frac{1}{16}$ in. The gross behavior of current and voltage and of the turbulent heating is the same for all of the electrodes. The smaller inside diameters have better initial contact with the plasma, resulting in faster current initiation upon application of the voltage. The thick-ring electrodes (3-in. o.d., 1-in. i.d.) and the thin-ring electrodes (o.d. $1\frac{1}{8}$ in. and i.d. $1\frac{1}{16}$ in.) were quite similar in performance, which is reasonable in terms of the sharp density gradient near the electrode [Fig. 1(b)].

The electrode voltage and current for heating is obtained from two series-connected capacitors of 1.5 μF each, with charging voltages up to 20 kV to give 0.75 μF at 40 kV. The capacitors are isolated from the ground and the stainless-steel vacuum tube to minimize current flow through the vacuum tube rather than the plasma.

Ion energy distributions are measured by means of an electrostatic energy analyzer which is attached to the end of the machine opposite to the gun, and on the axis at the vacuum tube. From these measurements the origin (in position and time) of the hot ions can be determined, and from the shape of the ion energy distribution the ion temperatures are determined.

Fluctuations in the plasma are recorded by two methods: High-frequency oscillations, which cover the frequency range of ω_{pe} and ω_{ce}, are picked up by an X-band waveguide. Low-frequency oscillations in the plasma (10 to 2000 MHz) are picked up by a 50-Ω matched coaxial probe with a 3-mm tip, and analyzed through bandpass filters or a spectrum analyzer. The current distribution across the plasma column is measured by a magnetic probe.

If the charging voltage for the condenser bank exceeds a certain value, the voltage-current characteristics change, and a small mound appears on the voltage trace. This means that if the current exceeds a certain value (I_c), the plasma becomes very resistive.

The temporal change of the fluctuations in the plasma during the period of the current flow shows that high-frequency oscillations frequently appear earlier in time, followed by low-frequency oscillations, although the reverse is never observed. Figure 2(a) shows typical voltage and current characteristics for this case, as well as the ratio V/I. Here, at $t = 4.6$ μsec, the plasma has become strongly resistive. The resistivity at this time is several hundred times the Spitzer value, neglecting sheath drop at the electrode and taking into account the electron temperature measured by a gridded probe (200 to 600 eV). This anomalous resistance phase begins earlier for stronger magnetic fields.

An electrostatic ion energy analyzer is situated on axis at 4 m from the center of the vacuum tube. Since this device measures the energy per unit charge, only for protons does E/Z uniquely determine the velocity. In Fig. 2(b) the trajectories of the hot protons are shown, by drawing straight lines from the position of the analyzer and arriving times, with angles corresponding to their velocities. The measured energy range for protons is from 400 eV to 4 keV. As can be seen, most of the lines pass through a local region of space and time corresponding to their origin in position and time. Thus these hot protons, although they have different energies, are produced in a particular region and at a particular time; the spatial origin is between the electrodes, and the temporal origin is about 4.5 μsec —not at the time of voltage application, but rather during the period of high resistance. This is also the time when the low-frequency oscillations become strongest.

In Fig. 3 a typical ion energy distribution from the turbulent plasma is shown on a semilogarithmic plot against ion energy. Ion energies go to more than 4 keV and have a rather Maxwellian distribution. We estimated that about 10% of the total ions are heated up to the energy ranging from 1 to 4 keV. The slope of the distribution indicates that our ion temperature is about 900 eV. This temperature does not change appreciably with the strength of the magnetic field from 1 to 4 kG, but increases somewhat with the capacitor voltage.

Questions may arise as to whether the ions are heated by turbulent heating or by electrostatic acceleration. Two arguments lead us to say that turbulent heating effects predominate: (i) Time-of-flight measurements tell us that the hot ions are not formed at the time of placing the potential across the plasma, but rather several μsec

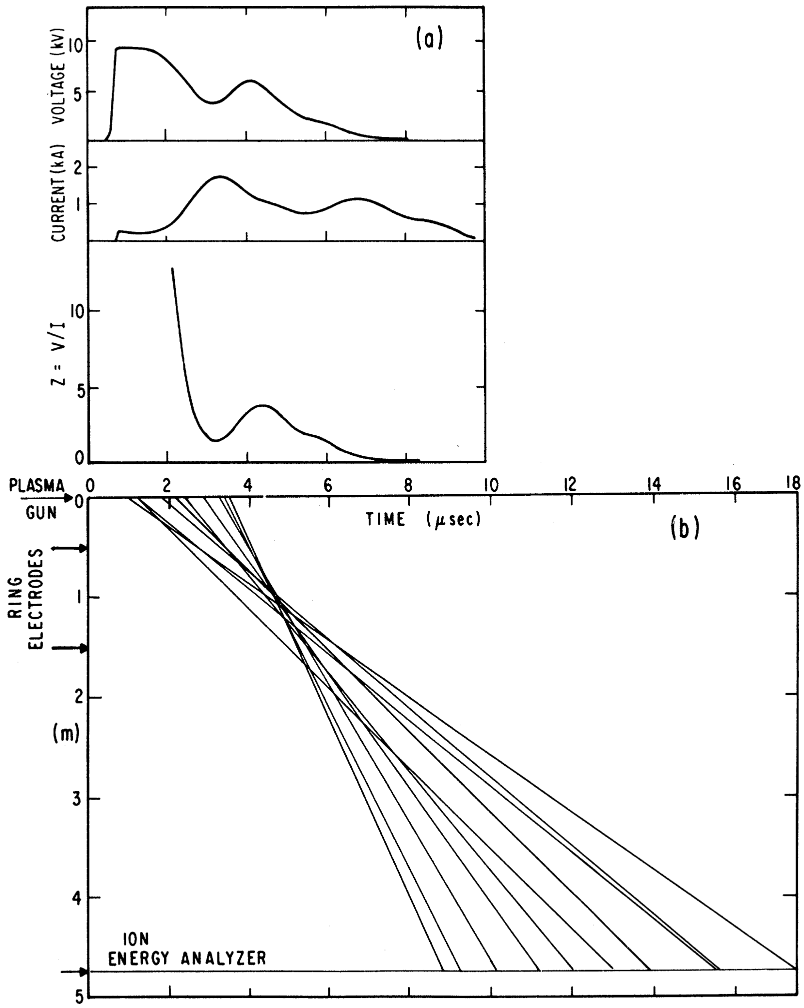

FIG. 2. (a) Typical temporal change of the voltage (V) and the current (I) and the ratio V/I. (b) Trajectories of turbulently heated protons of various energies. The time scales are the same for both (a) and (b).

later, during the current flow period. (ii) The axial electric field produced by the two ring electrodes is in the direction of accelerating the ions away from the ion energy analyzer, rather than toward it.

A 500-V plasma potential has been observed. The effect of this potential on ion temperature measurements is small. The greatest ambiguity in ion temperature occurs when the plasma potential is not constant along the length of the column. Even in this extreme case, the ion temperture ambiguity is only 20%.

The frequency spectrum of the low-frequency oscillation, shown to be correlated with the heating of the ions, is very broad, extending from the ion cyclotron frequency (6 MHz) to the ion plasma frequency (~800 MHz), indicating that this fluctuation is due to ion acoustic wave instability.[5] It seems clear, therefore, that the strong electron heating produces a situation where $T_e > T_i$, rendering the system unstable to the ion acoustic waves that heat the ions. The

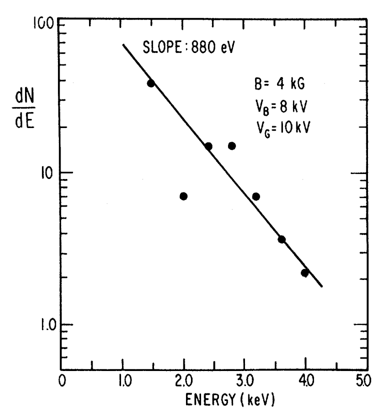

FIG. 3. Typical energy distribution of protons from the turbulent plasma.

ions are, indeed, heated during the period of low-frequency oscillation, leading us to think that the heating is caused by the ion acoustic wave, as mentioned by many authors.[6-9]

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COLLECTIVE EFFECTS IN THE OPTICAL PROPERTIES OF Cs ABOVE THE PLASMA FREQUENCY*

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Optical and dielectric constants of Cs have been obtained above the plasma frequency by measuring reflectance as a function of angle at a Cs-substrate interface. We find a strong, broad peak centered at 5 eV in the conductivity σ. The peak is attributed primarily to plasmon-assisted transitions, though direct transitions may contribute to the overall absorption in this energy region.

There has been much recent interest in the optical properties of the alkali metals. Much of the work, both theoretical[1-3] and experimental,[4-6] has been devoted to the lighter metals, Na and K, and to the energy region below the plasma frequency. Several recent theoretical studies suggest that excitation of collective modes makes an important contribution to the optical absorption above the plasma frequency.[1-3] Sutherland, Hamm, and Arakawa[7] reported structure in the optical constants of Na and K that is consistent with these predictions but does not distinguish between the absorption process suggested by Hopfield[1] as opposed to those of Lundqvist and Lydén[2] and Janow and Tzoar.[3]

We report here measurements of the optical and dielectric constants of Cs at photon energies above the plasma energy.

Experimental methods.—Reflectance measurements were made at the interface of Cs films evaporated onto quartz and CaF_2 substrates with light incident through the substrate. The techniques and equipment are described elsewhere.[7,8] Cesium (99.7% purity) was evaporated onto cooled substrates (10°C) in a 10^{-6} Torr vacuum, and thereafter maintained at 3×10^{-7} Torr. Films about 1 μm thick were evaporated in typical times of 10 sec. Since oxidation proceeds from the vacuum side of the cesium film, measuring times of many hours were available before oxidation of the film penetrated to the interface.

The reflectance was measured as a function of angle of incidence, and the optical constants derived from the behavior of the reflectance near