which is less than 1% for a Nd-glass laser of 10^{14} W/cm^2 incident on a plasma with 1-keV temperature and $k_0L = 100$. This may account for the fact that there is no observable change in absorption of light when the $\frac{3}{2}\omega_0$ emission is enhanced by orders of magnitude.[4] We therefore conclude that the decay into two plasma waves is unlikely to contribute significantly to absorption of the laser light. Finally, from the saturation level given by Eq. (15), the scattered intensity at $\frac{3}{2}\omega_0$ can be expressed as[2]

$$|E_{3\omega_r/2}|^2/|E_0|^2 = (\sqrt{3}/4)(L\omega_p/c)(v_e/c)^2(\delta n_e/n)^2 \approx (3\pi/8\sqrt{2})(v_e^3 v_0^2/c^5)k_0^2 L\lambda_D, \tag{17}$$

which is about 10^{-5} to 10^{-6} for typical experimental parameters of Ref. 4. Furthermore, we may remark that the present theory is valid for relatively weak pumps, i.e., $\omega_{pi}t_s \gg 1$ or $v_0/c \ll 5(m/M)^{1/2}$. For strong pumps, computer simulations have also demonstrated that density-profile modification is important for the saturation.[10]

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Plasma Rotation during Implosion in a θ Pinch

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A differential rotation of a collisionless θ-pinch column during implosion has been observed and explained by a model in which the driving mechanism is the off-diagonal element $p_{r\theta}$ of the pressure tensor. Rotational motion was detected by directional probes and spectroscopic techniques. Experimental data were modeled by a one-dimensional hybrid code which included ionization and charge exchange of protons with neutral H atoms.

Rotation of the plasma in a θ pinch is a well-established phenomenon. Both experiment[1,2] and theory[3,4] have shown a rotation of the compressed-plasma column on time scales which are long compared to the implosion time or the ion–cyclotron-orbit period. In this Letter we show differential rotation of the plasma column which occurs during the implosion on a time scale less than the ion-cyclotron time.

Various mechanisms have been proposed to explain the origin of rotation in a θ pinch. Transfer of external angular momentum to the plasma by means of wall shorting,[4,5] end shorting,[6] collisions with the wall,[3] reaction on the external coil,[3] and transverse fields[7] all require a time longer than the observation time of the present experiment. However, such transfer is not necessary for the existence of rotation. Velikhov,[8] Haines,[3] and Bowers and Haines[9] have demonstrated in the context of a finite–Larmor-radius expansion that a nonuniform rotation may be driven by the off-diagonal element of the pressure tensor corresponding to $p_{r\theta}$. In the present work $(\Omega\tau)^{-1} > 1$ (τ is the characteristic cross-field time and Ω is the ion gyrofrequency), and the interpretation offered is an extension of these arguments.

One may show that a differential rotation of a plasma column conserving total angular momentum may result from the deviation of the ion distribution from a Maxwellian. The first moment of the Vlasov equation for a species yields a macroscopic momentum transfer equation, the θ component of which, when specialized to a cylindrically and axially symmetric θ-pinch geometry, is

$$nm\frac{d(rv_\theta)}{dt} - ner\left(E_\theta - \frac{v_r H_z}{c}\right) + \frac{1}{r}\frac{\partial}{\partial r}(r^2 p_{r\theta}) = r\pi_\theta, \qquad (1)$$

where $p_{r\theta}$ is the $r\theta$ component of the pressure tensor, π_θ is the momentum gained through binary encounters with other species, and $d/dt = \partial/\partial t + v_r\,\partial/\partial r$. Taking $\pi_\theta{}^i + \pi_\theta{}^e = 0$, and adding the ion and electron equations, one obtains

$$nr\frac{d}{dt}[r(m_i v_\theta{}^i + m_e v_\theta{}^e)] = -\frac{\partial}{\partial r}[r^2(p_{r\theta}{}^i + p_{r\theta}{}^e)]. \qquad (2)$$

An inviscid two-fluid model, which requires a diagonal pressure tensor, implies $m_i v_\theta{}^i + m_e v_\theta{}^e = 0$ locally provided it is so initially, whereas a model which allows kinetic ions, and thus $p_{r\theta}{}^i \neq 0$, does not. In fact, the distribution function arising from a resistive implosion and having a reflected ion beam may have $p_{r\theta}$ comparable in magnitude to p_{rr}. By integrating over space, defining the Lagrangian coordinate $N = \int_0^r rn(r)\,dr$, and taking $p_{r\theta} = 0$ at the outer plasma boundary ($r = R$), one may show that angular momentum is conserved globally even though it may not be conserved locally.

The plasma was created in a 10-cm-diam, 50-cm-long Pyrex tube by means of an oscillatory discharge between metal end electrodes. The initial filling pressure was typically 4 mTorr and the ringing discharge damped away in 30 μsec. The field-free plasma diffused to the walls in about 75 μsec during which time the turbulence and fields created by the initial discharge died out. The decay of the preheat plasma was monitored with a 4-mm microwave interferometer and the θ-pinch field was fired when a preselected electron density was reached. This density was typically 3×10^{12} cm^{-3}, which corresponded to about 1% ionization. Initially $T_e \approx 5$ eV, while during the implosion the electron temperature approached several hundred eV. The magnetic field had a peak amplitude of 550 G with a rise-time of 100 nsec. A static field of 25 G could be applied either parallel or antiparallel to the pulsed field.

Using magnetic probes of 1 mm diam inserted radially into the plasma, we measured the radial and temporal variation of the magnetic field. This work is described in more detail in earlier publications.[10,11] Two different modes of behavior were observed depending on the direction of the static field with respect to the driving magnetic field. In the parallel case (driving and bias fields in the same direction) the pulsed field appeared to penetrate rapidly into the plasma by diffusion and no well-defined magnetic piston was formed. In the antiparallel case, a magnetic piston was formed quickly and the penetration time was considerably longer. Other observers have obtained similar results.[12]

The rotation of the plasma column was detected with an asymmetric directional double probe. The probe tips were 0.5-mm-diam platinum wires extending 2 mm beyond glass supports. Half of one of the probe tips was insulated with glass as shown in Fig. 1, so the solid angle from which it collected particles was restricted. The probe tips were electrically connected through a Tektronix CT_2 current transformer. If the unshielded side of the insulated probe tip was pointed away from the rotation, an enhanced ion current

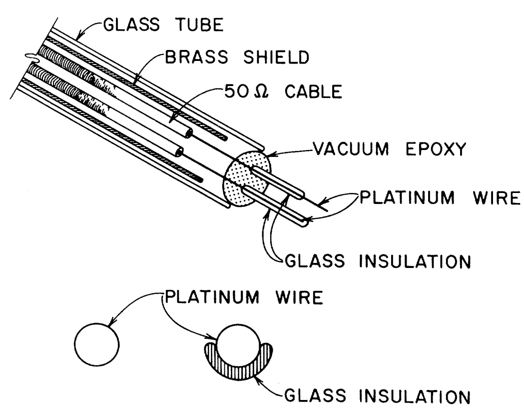

FIG. 1. Details of directional-probe construction.

proportional to the rotation flux nv_θ would reach only the uninsulated probe tip. That this signal indicated the presence of rotation was verified using an ordinary double probe which was identical to the directional probe except for the insulated tip. This ordinary probe gave no signal when positioned in the same way as the directional probe.

Using the directional probe we found no measurable rotation in the parallel bias case. In the antiparallel case rotation in the direction of an ion Larmor gyration in the driving B_z field was observed to begin at each radial position almost simultaneously with the start of field penetration and to reach a maximum a few nonoseconds after $\dot{B}$ reached a maximum. These results are similar to those obtained by Keilhacker *et al.*[1] Figure 2(a) shows the relative value of current flux, nv_θ, as a function of time, with the radial position as a parameter. The peak current in Fig. 2(a) is 10^{20} ions/sec.

Although it is evident that a rotation of the plasma column will produce a current in the probe, we can only approximately relate this current to the rotation velocity. To do this we use the fact that the directional probe is a floating probe, so the ion saturation current is balanced by an equal electron current. Since the rotation velocity is of the same order as the ion thermal velocity or the ion sound velocity, the ion saturation current to the uninsulated probe tip can be approximated by

$$I_i = 2en_i r_p l_p V ,$$

as Clayden[13] has shown. Here, r_p and l_p are the probe radius and length, respectively. Since the electron thermal velocity is greater than the rotation velocity, the collection of electrons is essentially unaffected by the rotation. Thus, the enhanced ion current to the uninsulated probe tip results in a slightly higher positive floating potential and more electron current. Approximately one-third of this electron current is collected by the insulated probe tip and measured by the current transformer.

For the conditions in this experiment, this is clearly an approximate analysis. All of the plasma parameters used in electric probe theory, such as T_e, T_i, n_e, and n_i, are changing rapidly. Hence, the quantitative results obtained with this probe are probably accurate only within a factor of 5. Another large source of error for quantitative interpretation is a possible misalignment of the probe along the plasma radius, or, equivalently, the plasma implosion could be slightly off center. The reason for this sensitivity is that $v_r > v_\theta$ during most of the implosion.

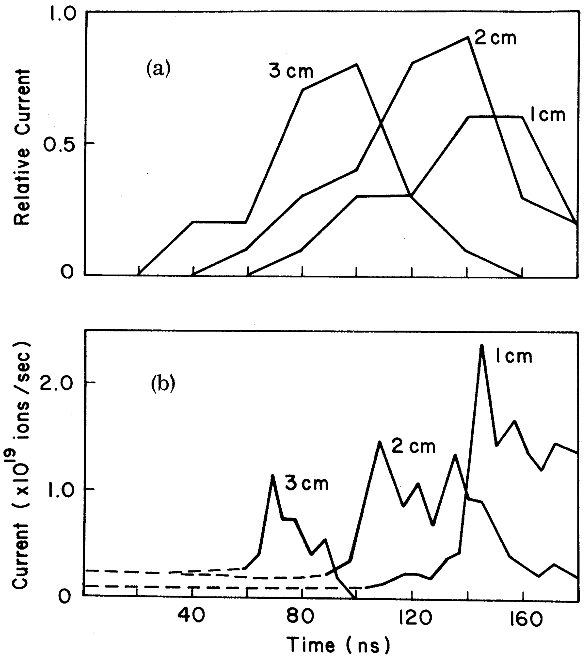

FIG. 2. (a) Experimentally determined ion current. (b) Calculated ion current.

In an attempt to confirm the probe measurements we observed the H_α line of neutral hydrogen with the assumption that asymmetry in the H_α profile could only result from single charge-exchange events of rotating ions with background neutrals, and thus would be indicative of rotation velocity. A monochrometer was set up to view the plasma along a chord at a perpendicular distance of 2 cm from the center. Rotating ions would be moving towards the monochrometer, so lines emitted by these ions are blue shifted. The light level was too low to measure an asymmetry of the line with narrow slits and thus give a quantitative estimate of rotation velocity. Using a wide slit ($\Delta\lambda_{1/2} \approx 3$ Å) we observed that the intensity on the blue wing always rose faster than the corresponding intensity on the red wing during the implosion. After the driving current had reversed, the line was symmetric and wavelengths on red and blue wings reached the same intensity. The low signal level observed was less than, but within an order of magnitude agreement with, calculations using known charge-exchange cross sections. This low signal level prevented any analysis of the ion-velocity distribution.

The experiment has been compared with a one-

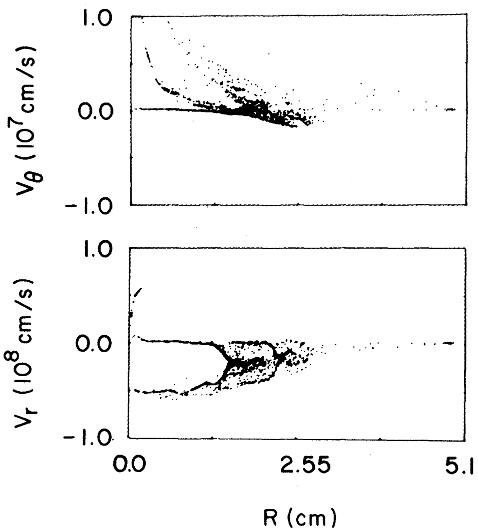

FIG. 3. Phase-space plots v_θ and v_r.

dimensional hybrid calculation[14] supplemented by the inclusion of charge exchange of protons with neutral H atoms. The resistivity was set to match the observed sheath thickness of the antiparallel case. The qualitative features are most easily demonstrated by a simulation in which the initial T_i is fictitiously set to zero. We find the typical features of a collisionless, resistive implosion: the ambient plasma, ions swept up by the sheath, and ions reflected from the sheath, as illustrated in Fig. 3. We also find from this figure that the reflected ion beam has a net positive θ velocity while the swept-up ions have a net negative θ velocity. Thus, because of the non-Maxwellian ion distribution, a rotation is generated during the implosion.

A qualitative demonstration that a resistive implosion would generate a rotation in the context of a hybrid model[14,15] is possible. In the reflected-ion region of Fig. 3 the average radial velocity satisfies $0<\bar{v}_r<-v_{rb}$, where v_{rb} is the reflected-beam velocity at a given point. Using Eqs. (1) and (2) of Ref. 14, one can show that

$$\dot{v}_\theta = (eH_z/m_i c)(\bar{v}_r - v_r).$$

As the calculated magnetic field penetrates the plasma, it falls from the maximum value at the boundary to zero near the tip of the reflected beam at $r=0$. Then for an ion in the reflected beam $\dot{v}_\theta>0$, while for an ambient ion $\dot{v}_\theta<0$, so that the reflected ions develop a positive θ velocity while the ambient ions develop a negative one. The swept-up ions acquire a negative velocity due to the negative velocity of the ambient plasma, the preferential inclusion of opposite-type particles in the reflected beam, and the requirement of global angular momentum conservation.

The simple beam-type distribution function in the reflected-ion region of Fig. 3 allows a calculation of the pressure tensor. Taking $f(v)=n_0 \times \delta(v_r)\delta(v_\theta)+n_b\delta(v_r+v_{rb})\delta(v_\theta-v_{\theta b})$, where n_0 is the ambient density and $n_b(=\alpha n_0)$ is the beam density, then $p_{rr}=\beta v_{rb}^2$, $p_{r\theta}=-\beta v_{rb}v_{\theta b}$, and $p_{\theta\theta}=\beta v_{\theta b}^2$, where $\beta=m_i n_0\alpha/(1+\alpha)$. Thus $p_{r\theta}$ may be comparable to p_{rr} and $p_{\theta\theta}$. Such an argument is more difficult in the swept-up–ion region, but for the reasons given above, one might expect a similar conclusion to be true.

For comparison with experiment, a numerical diagnostic which calculated $j_\theta=\int d^3v\, f(v)g(v_\theta)$ at positions 1, 2, and 3 cm was included in the model. Here $f(v)$ is the ion distribution function, and $g(v_\theta)=v_\theta$ if $v_\theta<0$; $g(v_\theta)=0$ if $v_\theta>0$. The results for swept-up ions are presented in Fig. 2(b). The agreement between the theory and experiment is good in the timing and widths of the curves, but discrepancies exist in the experimental existence and theoretical lack of the slowly rising precursor at early times. Similar comparisons for reflected ions were more difficult but showed qualitative agreement. A calculation which did not include charge exchange or ionization resulted in rotational velocity curves which were considerably narrower.

In conclusion, a differential rotation of a collisionless θ-pinch column during implosion has been observed and explained by a one-dimensional cylindrically and axially symmetric model in which the driving mechanism is the off-diagonal element $p_{r\theta}$ of the pressure tensor, which in turn is generated by the resistive nature of the implosion.[15]

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Turbulent Temperature Fluctuations in the Princeton Large Tokamak Plasma

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We present the first experimental evidence for the existence of turbulent temperature fluctuations in plasmas. These measurements were accomplished by a spectral analysis of blackbody electron cyclotron emission. The fractional fluctuation in the mean electron energy is up to 10% for typical Princeton Large Tokamak discharges. The spectrum of temperature turbulence extends well beyond the electron diamagnetic-drift frequency f_* and shows no resemblance to the simultaneously existing turbulent density fluctuations.

There have been extensive experimental studies of turbulent density fluctuations (such as those associated with drift waves, ion acoustic waves, electron plasma waves, etc.) in linear and toroidal plasma devices.[1] The purpose of these studies has been to identify the cause of turbulent density fluctuations and to examine the possible dependence of the observed apparent anomalous particle- and energy-confinement properties as well as the observed anomalous skin effect and the electrical resistivity of plasmas on the level of turbulence. These anomalous transport and resistive properties of plasmas can be caused not only by turbulent density fluctuations but also by turbulent temperature fluctuations. It is needless to say that a clear understanding of turbulence in toroidal plasmas is of vital importance to and is of considerable current interest in tokamak fusion research. To our knowledge no prior experimental study of turbulent temperature fluctuations in plasmas has been reported in the literature.

The apparent reason for the total lack of experimental information on temperature fluctuations in plasma is due to the fact that the conventional plasma diagnostic techniques (such as the scattering of electromagnetic waves from plasmas, Langmuir probes in low-density, low-temperature laboratory plasmas, etc.) are capable of measuring only the density fluctuations and are not at all sensitive to temperature fluctuations. In this Letter we wish to present the first experimental evidence for the existence of turbulent temperature fluctuations in plasmas. These measurements of temperature turbulence in the Princeton Large Tokamak (PLT) plasma were accomplished by a spectral analysis of blackbody emission near the second harmonic of the electron cyclotron frequency[2] (i.e., $f \approx 2f_{ce}$).

Figure 1 is a schematic block diagram of the

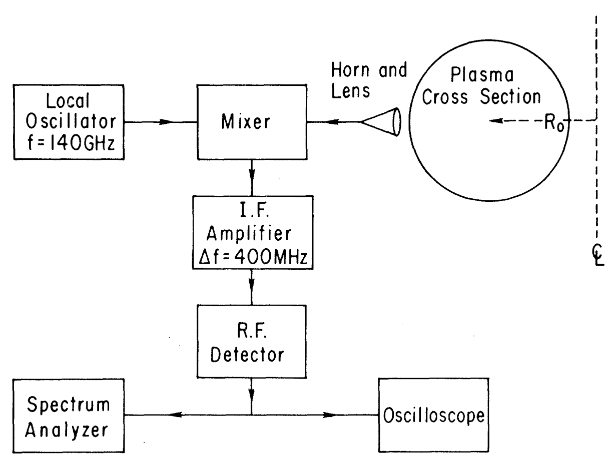

FIG. 1. Block diagram of the experimental arrangement.