Ion Heating at the Disruptive Instability in the LT-3 Tokamak

by

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Abstract. Measurements of the ion temperature and the toroidal current density and electric field during the disruptive instability in LT-3 are presented. Rapid ion heating and strong current inhibition have been observed. Fluctuation measurements suggest that these effects may be attributable to the excitation of ion cyclotron drift waves in the plasma.

Introduction. The LT-3 tokamak[1,2] (major radius 40 cm, minor radius 10cm, radius of magnetic aperture 9 cm) normally operates in an unstable mode in which the plasma undergoes successive disruptive instabilities which are marked by large negative spikes in the loop voltage V_ϕ (at the instability $V_\phi \lesssim -100$ V/turn). The instabilities are separated by intervals of 200 to 800μs depending on the value of q_a, the safety factor at the aperture. Rapid ion heating has been observed to occur at the disruptive instability[3], provided that the toroidal magnetic field, B_ϕ, and the plasma current, I_ϕ, exceed ∿0.6T and ∿15kA respectively. We believe that the ion heating is the result of strong plasma turbulence induced by the high electric field inside the plasma column which accompanies the rapid expansion of the current channel at the instability.

Measurements. The ion temperature in LT-3 has been deduced from measurements of the Doppler broadening of oxygen impurity emission from the hydrogen plasma and from the energy spectrum of charge exchange neutrals escaping the plasma.

A typical result obtained from measurements of the line OV 2781Å is shown in figure 1 for a time interval including the first disruptive instability. In this diagram, time is measured from the initiation of the discharge; at the time of the disruptive instability, B_ϕ = 0.9T and I_ϕ = 15kA. Since OV emission is localised to a region near the centre of the discharge, these results should be representative of the central impurity ion temperature in the discharge. It is not possible to follow the rise in the ion temperature during the period of the instability (∿10μs) as rapid minor radial motion of the plasma produces an additional

Doppler broadening contribution. Following the rapid rise, the OV temperature relaxes to the level observed prior to the instability with a time constant of about 100μs, which is somewhat shorter than the estimated ion energy confinement time before the disruption.

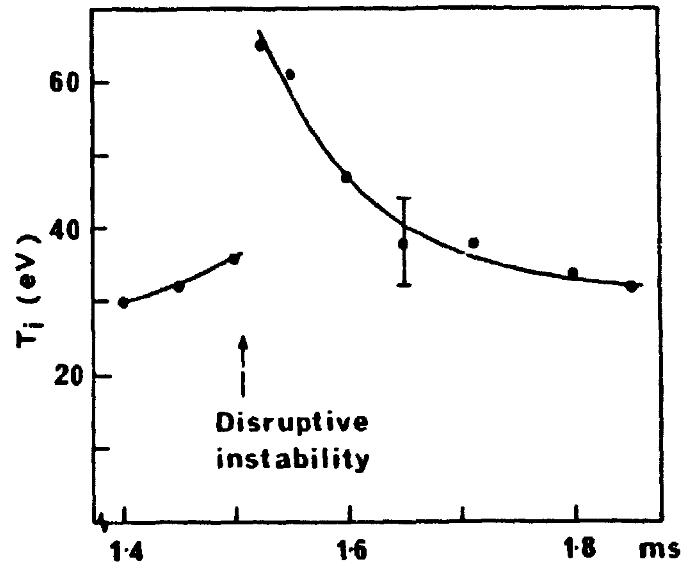

Figure 1. OV ion temperature

Results from the neutral particle analysis are shown in figure 2, where time is measured from the onset of the instability. Following a disruption, the neutral particle spectrum in the energy range 0.2-5keV contains a high energy tail corresponding to a substantially higher temperature than that indicated by the spectroscopic measurements. The temperature decays with a time constant of about 50μs. Prior to an instability, the ion temperature is too low to be measured with the neutral particle spectrometer, which is sensitive only above ∿150eV in energy. The high energy neutral signals have a risetime of about 2μs, indicating very rapid heating during the instability.

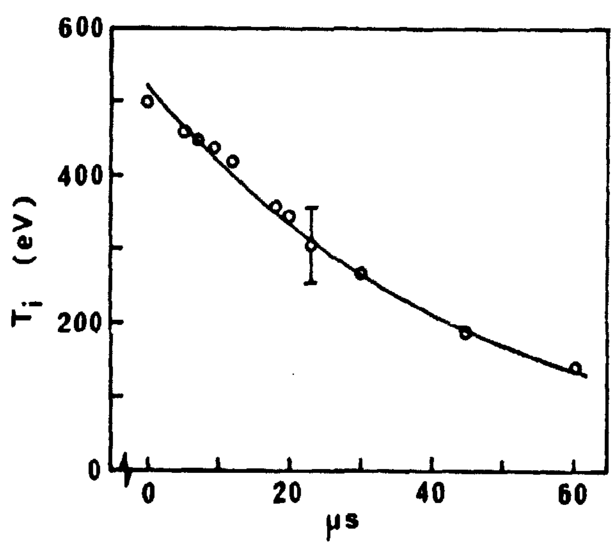

Figure 2. Neutral spectrum ion temperature

Measurements[4] have indicated that the total poloidal-beta of the plasma, β_θ, increases slightly following a disruptive instability, provided that q_a is less than 4.0 approximately. The increase in β_θ is generally less than 20%, however.

The source of energy for the ion heating at the disruptive instability is, ultimately, the energy stored in the poloidal magnetic field of the system, which is reduced by the expansion of the current channel at the instability. The redistribution of the current has been measured with a multi-coil magnetic probe which simultaneously records the evolution of the poloidal field at up to eighteen points, separated by 5mm. The probe was inserted along a minor radius parallel to the major axis (z-axis) of the torus. To avoid excessive perturbation of the plasma, the tip of the probe was not inserted beyond a point 3cm from the minor axis. In the analysis of the results, the poloidal field is assumed to be zero on the minor axis; shifts of the magnetic axis of the plasma may introduce errors up to 15% in the derived current density on axis, which is of the same order as the uncertainty in the measurements. A typical result for the toroidal current density $J_\phi(r)$ is shown in figure 3, where the time is measured arbitrarily from the oscilloscope

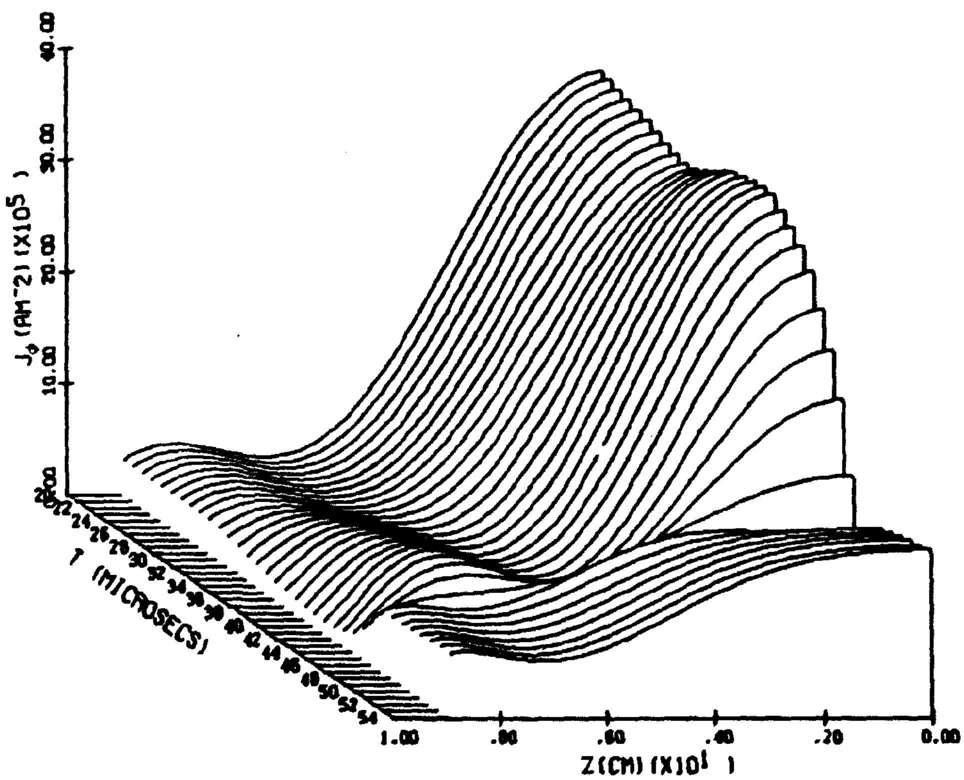

Figure 3. Evolution of toroidal current density

trigger and the point $z = 0$ coincides with the torus minor axis. The overall flattening of the current profile is clearly visible.

The relaxation of the current profile during the instability induces a large toroidal electric field gradient in the plasma, which is manifested externally as the negative spike in the loop voltage. The electric field within the plasma column was measured with a probe consisting of a rectangular loop of wire, 3mm wide by 100mm long. When inserted into the plasma column with the loop lying in the local ϕ-z plane, the voltage induced in this loop is simply proportional to the difference between the toroidal electric field E_ϕ at the inner and outer ends of the loop, provided that the plasma expansion is locally independent of the toroidal (ϕ) coordinate. The external field deduced from the measured toroidal loop voltage V_ϕ, provides a reference to obtain the absolute field at different radii inside the plasma. The toroidal electric field at the V_ϕ loop and that measured with the field probe at the point z = 4cm are shown in figure 4 during a disruptive instability. The induced electric field was also calculated from the measured evolution of the poloidal magnetic field by applying Faraday's law:

$$E_\phi(z_2)-E_\phi(z_1)=-\int_{z_1}^{z_2} \frac{\partial B_\theta}{\partial t}\, dz \ .$$

By integrating this equation numerically, the results of the magnetic probe measurements could be extrapolated towards the minor axis, into the region where directly inserting the probes would have caused significant perturbation of the plasma.

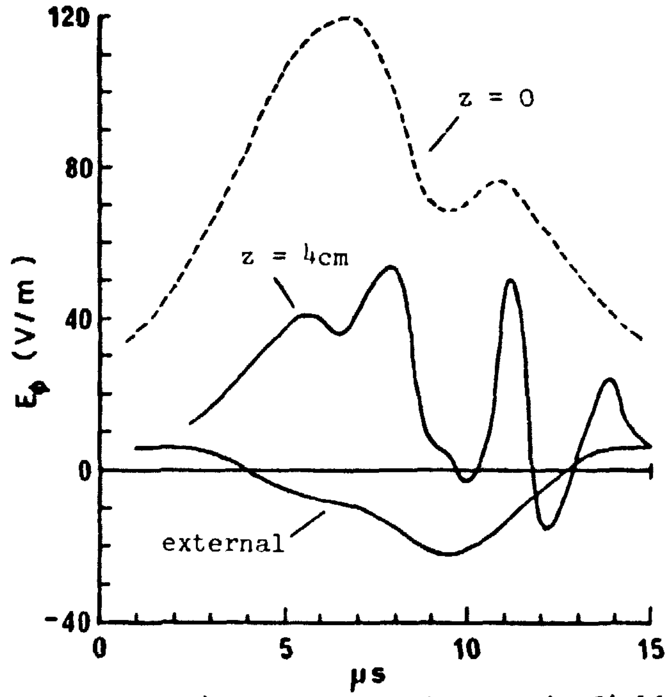

Figure 4. Evolution of electric field

An example of the calculated electric field at the minor axis is shown dashed in figure 4. The time resolution of this calculated value was limited to ∿2μs and the high frequency structure visible on the E_ϕ-probe trace was therefore not reproduced.

In figure 5, the radial profile of the induced electric field at the time of its peak value on axis is shown. The curve represents the profile calculated from the magnetic probe measurements, the experimental points were measured directly with the E_ϕ-probe. The agreement between the data, which were recorded on different shots, is extremely good.

Discussion. The probe results indicate that the direction of the induced electric field changes from positive (in the direction of the toroidal current) on the minor axis to negative at the outside of the plasma column.

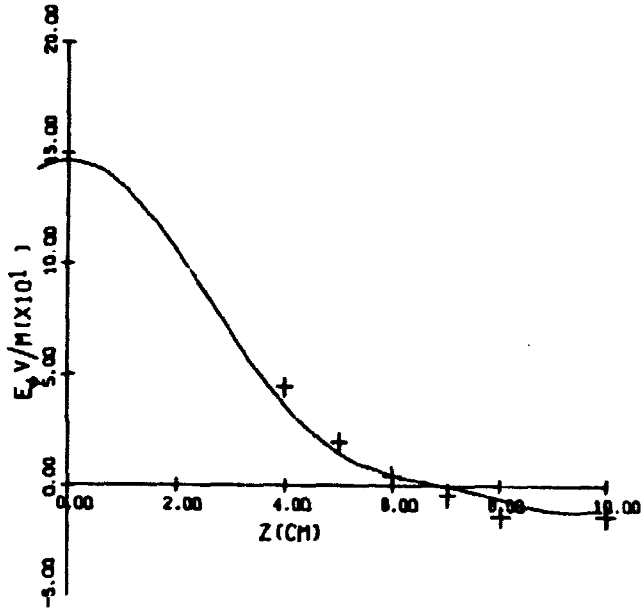

Figure 5. Profile of electric field

However, by considering the form of Ohm's law appropriate to a moving plasma

$\underline{\eta}\cdot\mathbf{J} = \mathbf{E}_{eff} = \mathbf{E} + \mathbf{v}\times\mathbf{B}$

it may be deduced that, as a result of the rapid minor radial plasma motion at the disruption ($v_r \sim 10^3 ms^{-1}$), the effective electric field is actually positive throughout the plasma column. The oscillations in the E_ϕ-probe signals with a period of approximately 2μs (figure 4) probably arise from MHD perturbations of the plasma column which are present during the disruption.

Clearly, a situation of current inhibition is occurring in the plasma at the instability: an increased electric field is being accompanied by a reduction in the current density. It is likely that turbulent wave excitation in the plasma is responsible for both the current inhibition and the ion heating which occur at the disruption. Although current driven ion-acoustic instabilities[5] have very large growth rates for $T_i \ll T_e$ ($\gamma \sim \omega_{pi} \approx 7$GHz in LT-3), it is unlikely that such turbulence alone could account for the observed plasma behaviour. Ion acoustic instabilities become strongly ion Landau damped when $T_i \sim T_e$, whereas the neutral particle analysis has shown that the temperature of at least a fraction of the ions rises well above the electron temperature occurring just prior to the instability ($T_e \lesssim 100$eV).

An alternative mechanism for the current inhibition and ion heating is the excitation of current-driven ion cyclotron drift waves (ICDWs). Such waves have previously been observed in a Q-machine[6] for values of the ratio of electron drift to thermal velocity of order 0.2 and were accompanied by strong current inhibition and ion heating to temperatures well above the electron temperature. The ICDWs are longitudinal, have a continuous frequency spectrum in the range $\omega_{ci} < \omega_{ICDW} < \omega_{pi}$, peaking near $\omega_{pi}/4$, exhibit wavelengths $\sim$0.3-3 times the ion Larmor radius and propagate azimuthally.

In an attempt to identify the nature of the plasma turbulence at the disruptive instability, measurements with a double Langmuir fluctuation probe have been made in LT-3. The electrode separation of the probe was 2.5 mm which is comparable with the expected wavelength of the ICDWs. With the probe inserted to minor radii between 6 and 8cm, brief bursts (∿1μs) of high frequency oscillation, 30-120MHz, superimposed on irregular, slower (2-10MHz) oscillations, were observed during the instabilities. The proton ion cyclotron frequency is typically 15MHz in LT-3. A typical oscilloscope trace obtained with the probe at 7cm is shown in figure 6. Owing to the difficulty experienced in matching the probe to the signal line and the uncertainty in the high frequency sheath impedance of the probe, a meaningful frequency spectrum of the fluctuations has not yet been obtained. We estimate that the observed signals correspond to a potential fluctuation level in the plasma of at least 50V between the electrodes. Between the instabilities, only the much slower (<10MHz) oscillations were observed.

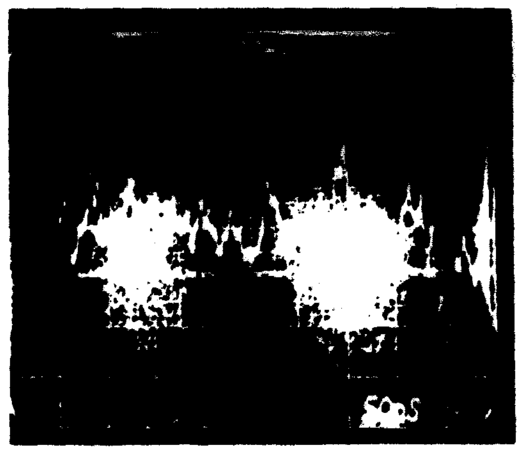

Figure 6. Plasma fluctuations during a disruptive instability

Interaction with ICDWs will tend to increase the transverse energy of the ions. In the small LT-3 device, ions with a large transverse energy will be rapidly lost due to their large trapped orbits. This may account for the apparently low efficiency of the heating process, as evidenced by the very modest rise in β_θ following the disruption. The dependence of the heating on the cyclotron frequency of individual ion species could explain the apparent discrepancy between the neutral particle and the impurity ion temperatures. The impurity ions would be less efficiently heated by the waves and would probably gain energy mainly by Coulomb interaction with heated protons.

Conclusion. We have observed ion heating and current inhibition at the disruptive instability in a tokamak, which fluctuation measurements suggest are attributable to the excitation of ion cyclotron drift waves. The spatial profile of the induced electric field exciting this turbulence differs from that of the externally applied field in normal turbulent heating experiments, in that it is peaked at the centre of the plasma column and therefore provides favourable conditions for heating the plasma throughout its cross-section. The indentification of the turbulence with ion cyclotron drift waves would create the possibility of raising the ion temperature in a tokamak above that of the electrons.

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