OBSERVATION OF TOKAMAK PLASMAS WITH AN ARRAY OF PIN DIODE DETECTORS

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OBSERVATION OF TOKAMAK PLASMAS WITH AN ARRAY OF PIN DIODE DETECTORS*

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Abstract

Soft x-ray emission from the Oak Ridge Tokamak (ORMAK) has been studied with an array of diode detectors. The thermal character of the plasma emission allows observation of phenomena associated with fluctuations in electron temperature. Measurements of internal disruption growth rates and repetition times corroborate a theoretical tearing-mode instability model. Heat pulses from the disruption evolve diffusively, but with a heat conduction coefficient larger than that inferred from the plasma equilibrium.

The Diagnostic System

The hot plasma of a tokamak discharge emits soft x rays as a result of electron-ion free-free and free-bound collisions. One method of extracting information from this flux of x rays is to use a crude pinhole camera arrangement such as shown in Figure 1. On ORMAK, the plasma is viewed by nine diffused-junction PIN diode detectors through a slit aperture along the chords shown in the figure. Because (1) the x-ray emission depends strongly on temperature and density and (2) temperature and density are usually highest at the center and decrease with radius, most of the signal to a given detector originates near the point along the chord which is closest to the plasma center. These points are indicated by crosses in the figure; the distance from a cross to the center is the "chord radius." The detectors are arranged so that the chord radii step in 2-cm intervals and are collimated so that the spatial resolution is about 1.7 cm.

The diodes are sensitive to photons with energies from 1 to 10 keV (the low-energy cutoff is adjustable by positioning different thicknesses of beryllium in the viewing path). The x rays create electron-hole pairs in the silicon diode, resulting in an electrical current proportional to the incident radiated power in this energy range. The current is amplified by an operational amplifier circuit. Because the signal falls off with chord radius, different conversion gains ranging from 6×10^{-7} A/V to 10^{-8} A/V are progressively used for different chords. Noise level in the diode is less than 1 nA, and signals from the central chord can be as large as a few microamperes. The diodes, op amp feedback resistors, and FET preamplifiers are located inside lead shielding in a vacuum where nearby magnet coils are cooled by liquid nitrogen. The detector assembly itself cools to about -70°C , with the advantage that the diode leakage current goes to zero.

The principal means of data acquisition was photography of oscilloscope signal displays, although it should be noted that recent improvements include high-speed analog tape recording of signals for analog-to-digital conversion and computer analysis. Band pass filtering was used to accentuate frequency components of interest.

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Fig. 1. The nine-detector array for soft x-ray measurements on ORMAK.

Observations of Plasma Oscillations

The bandwidth of the diagnostic allows the spatially resolved observation of fluctuations in the range of 0.2-20 kHz. Perhaps the most striking feature of the signal is that it often has the "sawtooth" oscillations⁽¹⁾ seen in Figure 2. These are typically a 10% amplitude fluctuation with a smaller, higher-frequency, growing sinusoidal oscillation superimposed.

Fig. 2. Composite oscillograms of soft x-ray signals for two discharges. For both cases, the top trace gives the signal from one detector over the full time of the discharge; the rest of the signals are on an expanded time-scale starting at 45 msec, which falls in the middle of the full-time trace. Amplification factors for each signal are different for purposes of display. The signals labeled B_0 are poloidal magnetic field fluctuations from pickup loops.

The significance of this observation can best be understood in the context of the tokamak equilibrium. Effective confinement of the plasma is achieved by a magnetic field with two components: the stronger externally applied toroidal field B_t and the weaker poloidal field resulting from an induced toroidal current I . The parameter q , proportional to B_t/I , describes the amount of "twist" in the field lines. Typically, $q \approx 1$ at the center and $q \approx 4$ or 5 at the edge of a tokamak discharge. Moreover, $q = m/n$ is the condition for the plasma to be unstable to a perturbation of the form $\cos(m\theta + n\tau)$ (where θ and τ are the poloidal and toroidal angle coordinates and m and n are integers). The perturbation above leads to "islands" of magnetic flux.

The internal disruption, which generates the observed sawtooth oscillation in the soft x-ray signal coming from the interior of the tokamak, was soon recognized as an instability at the $q = 1$ singular surface.⁽¹⁾ It was not clear, however, specifically what unstable mode was responsible. We find that a tearing-mode theoretical model compares favorably with data from a large representative set of ORMAK discharges.⁽²⁾

The model, consistent with observations and previous tearing-mode calculations,⁽³⁾ assumes that at the time a sawtooth begins to rise, the temperature and q profiles are nearly flat inside a radius r_0 . The electrons inside r_0 (where $q = 1$; $r_s < r_0$) begin to re-heat resistively, which increases the current density and thus drives q below unity at the center. The shear $\alpha \{=(dq/dr)\}$ at the singular surface drives the $m = 1$ tearing-mode island increasingly wider until it completely engulfs the center of the discharge and

rapidly flattens the T_e and q profiles. The sudden drop in temperature is manifested as the rapid-fall portion of the sawtooth in x-ray intensity. Then the cycle is repeated.

Experimentally, we find agreement to a factor of two between the heating rate observed as the slow rise of the x-ray signal and the rate estimated from an electron heat balance equation. Observed radial profile shapes of both the $m = 1$ oscillation (i.e., the growing sinusoidal signal) and the sawtooth are very similar to those resulting from a numerical code calculation of tearing-mode growth. To predict the growth rate, we estimate the shear at r_s to be of the form $a_0 + \bar{a}t^2$, based on the resistive heating in the central core. Because $\gamma \propto a^2$, this produces a rapidly accelerating growth of the x-ray $m = 1$ amplitude, $\ln A \sim a_0^2 t + (2/3)(a_0 \bar{a} t^3) + (1/5)(\bar{a}^2 t^5)$. We observe growth rates with time dependences ranging from t to t^5 ; their magnitudes agree with the model to a factor of two with no free parameters. We estimate the period of the sawtooth to be the time it takes the island width to become $2r_s$ and find that the model predicts the repetition time t_0 to better than a factor of two, as shown in Figure 3. We thus conclude that the tearing-mode model offers a viable description of the internal disruption process.

We have also carefully examined the space-time evolution of the pulse heat resulting from the internal disruption and have compared this evaluation with the electron energy transport in the bulk plasma.⁽⁴⁾ The basic observation is that the sawteeth outside the singular surface, which have an inverted shape, peak later and broaden with increasing radius. This behavior can be understood in terms of a simple diffusion equation for the electron temperature perturbation, ΔT_e , which has a solution

$$\Delta T_e = \frac{8r_s \Delta Q}{3n_e r^2} \frac{t_p}{t} e^{-(t_p/t)} \quad (1)$$

where $t_p \equiv (3r^2)/(8\chi_{ep})$ and χ_{ep} is the heat conduction coefficient for the pulse. Data shown in Figure 4 demonstrate:

(1) $t_p \propto r^2$ (from which we can determine χ_{ep}), (2) observed signal shapes agree with the model, and (3) the maximum ΔT_e (i.e., at t_p) is consistent with the predicted r^{-2} dependence (which is a consequence of energy conservation).

Thus the pulse transports diffusively. However, when χ_{ep} is compared with the conduction χ_e estimated from T_{ee} , the electron energy containment time characteristic of the observed plasma equilibrium, we find that χ_{ep} and χ_e appear uncorrelated, with $\chi_{ep} > \chi_e$ by factors of 3 to 15. Thus, the technique does not presently allow a straightforward local measurement of the transport that determines the plasma equilibrium.

We are investigating reasons for this. There is evidence that the anomaly arises from looking only at the x rays produced by high-energy electrons. Also, we have assumed that the influence of the internal disruption does not enter into the problem, which may not be correct. The rapid transport of the pulse may be indicative of a new phenomenon that remains to be satisfactorily explained.

Fig. 3. Experimental sawtooth repetition time t_0 compared with the theoretical prediction $t_0 = D\bar{t}$.

Fig. 4. Comparison of data with diffusive model: (a) Peak arrival time vs radial position. The slope of the asymptote is $3/(8\chi_{ep})$ and thus gives a measurement of χ_{ep} . (b) t_p vs r^2 in normalized units for a representative set of discharges. Each symbol corresponds to one discharge, for which χ_{ep} has been obtained from a plot such as Figure 2a. Solid symbols are discharges with neutral beam injection, and open symbols are for no injection. (c) Graphical reconstruction of one set of pulses (third from left in Figure 2, shot 11389) compared with normalized computer-generated pulse shapes. (d) Maximum ΔT_e (normalized) inferred from x-ray signal level as a function of radius.

Conclusion

The x-ray imaging technique described here provides only crude spatial resolution but very fast time resolution of a hot tokamak plasma. As such, it has proved valuable in examining the dynamics of thermal processes inside the discharge. Measurements of sawtooth oscillation parameters such as heating rates, $m = 1$ growth rates, and repetition times have led to a successful theoretical model of the internal disruption process based on the evolution of a tearing mode. Also, diffusive transport of heat was observed in the pulse propagation. In summary, this rather simple technique has provided information about tokamak plasmas that was previously unavailable.

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