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Thermal load distribution on the ALT-II limiter of TEXTOR-94 during disruptions

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Abstract

Disruptions investigated on TEXTOR-94 are initiated by unstably growing modes. The island width of these modes corresponds to 5–10 cm resulting in a perturbation field amplitude of the order of 100 Gauss. The energy stored in the plasma is released in short and intense power fluxes towards the limiter; the power decay length is practically unchanged with respect to the normal power *e*-folding length. These observations can be interpreted in the following way: The perturbation fields associated with the modes create an ergodization of the full plasma cross-section creating a laminar zone with convective fluxes at the plasma edge. The energy transport inside the plasma is determined by the ergodic transport while the power flux to the limiter is convective. The assumption of the ergodization has important consequences for runaway electron level created during disruptions. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Disruptions remain a major concern for tokamak devices, in particular, for large machines [1–6]. The critical issues are the induced currents (halo currents) in the structural materials and the resulting forces, the excessive heating of exposed surfaces by the instantaneous power release, and the possible occurrence of high energetic runaway electrons in the decay phase of the plasma current where consequently the induced loop voltage is rather high.

In previous papers [7,8], the power release and heat deposition during disruptions have been analysed. It has been observed that disruptions start with internal modes; then the confinement begins to deteriorate first in the plasma core. The plasma energy is transported from the core to the edge of the plasma where an intermediate temperature rise just prior to the observation of the power quench takes place. The proper power quench can be a single heat pulse or a series of heat pulses. The time duration of the individual power deposition pulses is very short, it is only a few 10 μs long. Even though the instantaneous power density is extremely high, the spatial pattern of the disruptive power deposition resembles in many aspects the ‘normal convective’ power deposition on the limiter surface; the power *e*-folding length which has the same structure as in a normal discharge with the ‘short’ and ‘long’ decay fractions as described in [8,9] is not noticeably enlarged.

These observations have shown that the power flux to the wall during a disruption cannot be described by a diffusive process. In a purely diffusive process occurring on the short time scale observed for the disruptive power flux to the walls, the power *e*-folding length should be very large which is inconsistent with the experimental data. On the other hand, the ergodic–diffusive model [10] is an often assumed picture for the internal plasma transport in the pre-disruptive and disruptive phases. This picture bases also on the presence and overlapping of internal modes observed as precursors for disruptions [11–16].

In order to unify the picture of the enhanced diffusive power flow of the ergodized core with the observed high

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power flow at normal power *e*-folding length, we have made the hypothesis in the previous paper that the strong ergodization creates a laminar zone [17,18] which can be understood as the open boundary of the ergodic structure. The laminar zone is formed by those magnetic field lines which intersect material objects. In contrast to an ergodic zone, the magnetic field line topology in the laminar zone is well ordered and the plasma particles flowing convectively along those field lines should behave to a large degree as those of the conventional SOL.

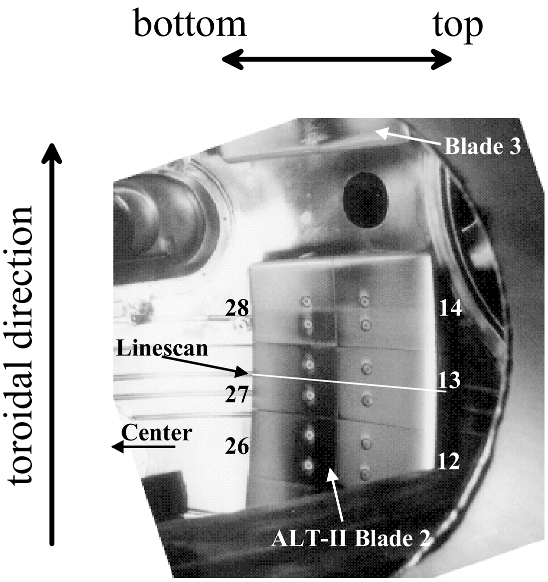
2. Experimental conditions and diagnostics

In order to investigate the development of disruptions, the recording of several diagnostics has been set to high time resolution. For this purpose an experimental day has been selected on which the density limit was the aim of the investigations. The main diagnostics for the recording of the disruptions are ECE for the electron temperature, magnetic coils to determine the mode structure and an IR-scanner to determine the power flux to the limiter blades [8].

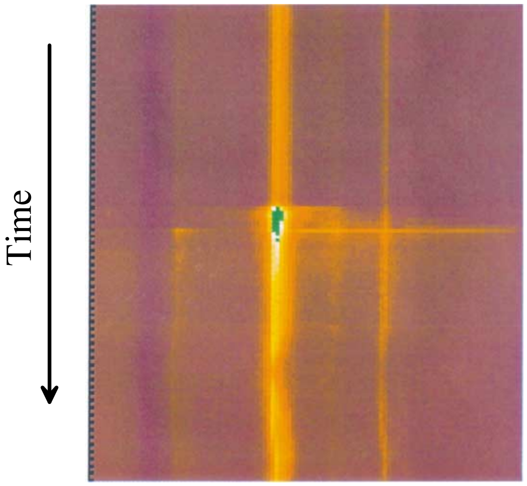
TEXTOR-94 is equipped with a set of ECE channels providing a spatial resolution of 4–5 cm in the gradient zone (i.e., near the $q = 3$ surface). At the very edge, ECE cannot be applied due to the lack of optical thickness of the low temperature plasma there.

An IR-scanner (Inframetrix model 760) has been installed in order to measure the heat fluxes to the ALT-II pump limiter. To understand the measurements on disruptions, some details of the IR-scanner have to be discussed. The basic elements of the scanner are a horizontally sweeping mirror, a vertically sweeping mirror and the IR-detector. The detector itself provides only time information. The spatial information of the system is obtained by the scanning mirrors. The vertical mirror moves in a sawtooth-like manner and sweeps over the picture within 20 ms. The horizontal movement of the mirror operates at 8 kHz. A line scan mode is obtained by switching off the vertical mirror motion. This option allows for a time resolution of less than 100 μs.

The IR-scanner views the pair of tiles next to the end tiles of the pump limiter ALT-II. The tile shape is in particular suited to determine the radial profile of the incoming power near the last closed flux surface, i.e., the fraction of deposited power with the small decay length. Fig. 1(a) shows a photograph through the port with the viewing port with the pump limiter ALT-II and an example of an IR picture (Fig. 1(b)) taken in the line scan mode with the sudden temperature rise during a disruption (the sudden colour change). The camera has been oriented such that the poloidal direction of the limiter blade is horizontal allowing for the line scan orientation as indicated in Fig. 1(a).



a) View thru IR-Fenster



b) Fast Line Scan Mode of disruption (one frame correnponds to 20 ms)

Fig. 1. (a) Photograph through the IR viewing port. The camera orientation is chosen such that the toroidal direction is from top to bottom and the poloidal one is horizontal. The selected location of the line scan is indicated. (b) IR-image taken in the line scan mode with a disruption. The false colours indicate the temperature. The time progresses from top to bottom.

3. Observations during disruptions

In the following, the disruption shown in Fig. 1(b) is described in more detail. In Fig. 2, the electron temperature of four ECE channels near the $q = 3$ surface is

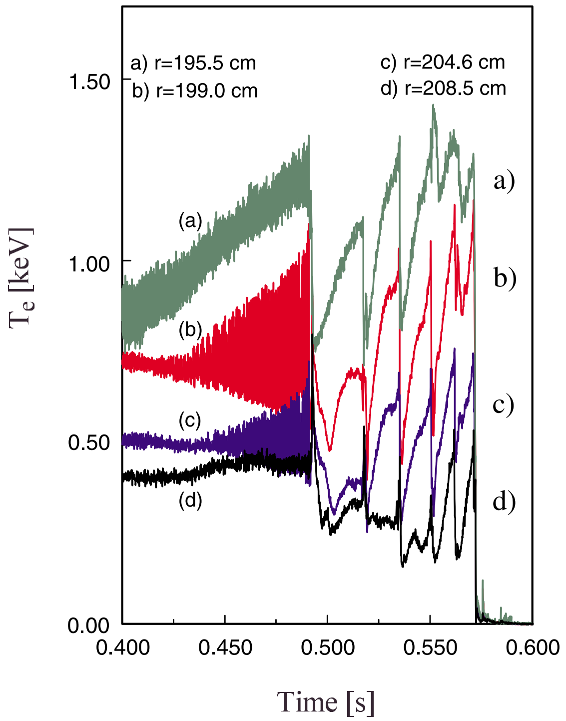


Fig. 2. T_e measurements (from ECE) taken at four locations near the $q = 2$ surface. The location of the individual channels is indicated.

presented; the radial separation of the channels amounts to 4–5 cm. One finds that about 50 ms before the first minor disruption a quickly rotating mode starts to grow. This mode is located at $r/a = 0.5$. This first minor disruption is connected with a sharp reduction in the rotation speed of the mode such that it either rotates very slowly or that it even locks. The mode may even be stabilized for some time in between the minor disruptions. The sudden loss of stored energy is coincident with the spikes in D_α or the released power.

The development of the individual ECE channels is explained by the presence of an island at $r = 25$ cm with a width of about 7 cm. From the width of the magnetic island and the shear of the equilibrium field, a perturbation field strength near the $q = 3$ surface is of the order of 100 Gauss. Magnetic probe measurements indicate a similar perturbation field strength also for those modes located closer to the plasma edge. In the analysis, it is assumed that the mode number m/n has a low rational value, i.e., the mode is rather coarse.

The temperature development on the pump limiter blade is plotted as top trace of Fig. 3 for the time around the disruption. The temperature increases at a low rate until the sudden jumps during the minor and finally, the major disruptions. Here the surface temperature reaches a value of 475 C and drops very quickly again. The temperature given here is taken from the centre (poloidally) of the blade and corresponds to the highest temperature along the poloidal cord. The trace shows several straight line sections connecting the signal sections which exhibit small noise contributions. These straight sections correspond to those times where the vertical mirror of the scanner swings back and where therefore no data are displayed.

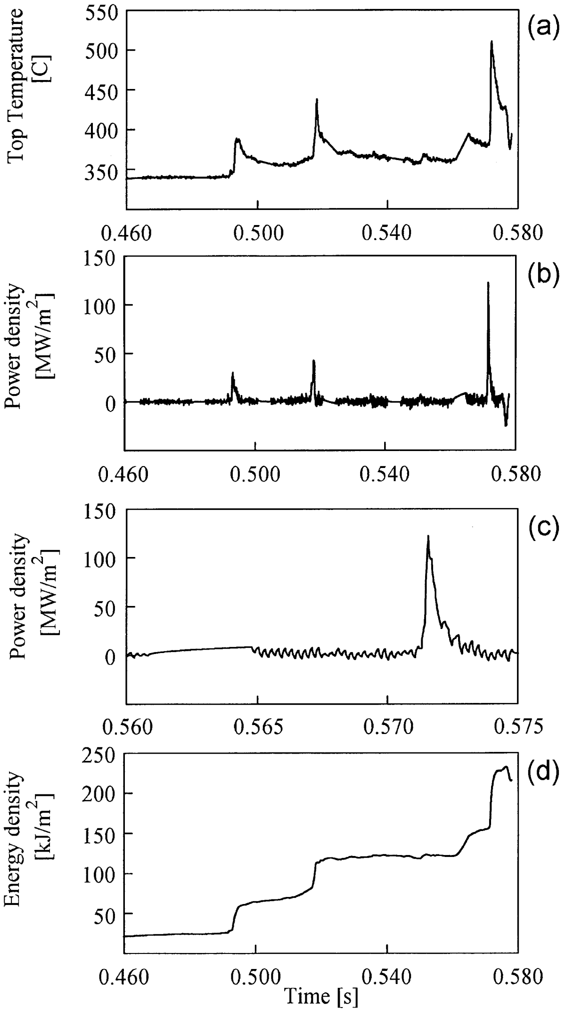


Fig. 3. Temperature, power flux density and deposited energy density during the disruption.

From the temperature development the power to the limiter surface is calculated by solving the heat diffusion equation of the graphite tiles and using the surface temperature as the boundary condition. This power density to the limiter surface is displayed in Fig. 3(b). As expected from the temperature trace, the average power density is rather low and only the sharp peaks during the minor and major disruptions are remarkable. The peak power reaches a value of more then 100 MW. Fig. 3(c) shows the power flux density of the major disruption with enhanced time resolution. It is obvious that the heat pulse rises within about 100 μs and has a half width of less than 1 ms. Within this millisecond there seems to be even a modulation. The integration of the power flux with respect to time yields the deposited energy density which is displayed as bottom trace (Fig. 1(d)). During the disruptive power release, the power density amounts to about 50 kJ/m^2. Since the temperature is recorded at the most exposed location, the values are the peak values of the blade.

4. Discussion

The disruptions of TEXTOR-94 analysed so far show mode activity before the power release phase. If the mode amplitude exceeds a value of few hundred Gauss, the thermal quench is observed. This cycle with mode excitation, power release and partial recovery can repeat several times before the discharge ends in the final disruption. At the moment of power release, several internal rearrangements of the plasma column are taking place: the plasma rotation may stop suddenly and the perturbation currents generating the islands are changing leading to a transient stop of power outflow during the minor disruptions. The observed size of the islands, the temporal structure of the power outflow together with their spatial deposition characteristics [8] make it plausible to assume that the disruption is linked with a growth of island chains inside the plasma until they overlap and ergodize the magnetic field. In this picture, the power loss pulses are attributed to a sufficient growth of laminar layer which is formed by the open ergodic structure.

The laminar layer belongs to the class of 'open chaotic systems'. An intuitive example of these systems is a billiard game where part of the cushion is removed. The orbits of the ball on a racetrack-shaped table are an often used example for ergodic movement (the orbit of the ball will cover finally the whole table if the losses are neglected). By removing part of the cushion, it is obvious that the orbits are divided into two classes: the first are the 'long' orbits of the former ergodic part; the second are the 'short' orbits – the ball can leave quickly through the open section. This class is equivalent to the laminar layer of the edge ergodized magnetic field. It is intuitively obvious that the open laminar structure increases with the degree of edge ergodization.

A generic model was set up in order to investigate the ergodization level and the resulting transport. This model is based on the magnetic field line mapping method. It is assumed that perturbation currents are flowing at the different low rational q-surfaces which create the observed magnetic islands there. The magnetic field amplitude of the modes decays from the resonant surfaces with the power $B_{r,mn}(r) = B_{r,mn}\ (r/r_{mn})^{\pm m-1}$ (cylindrical approximation; the + sign for $r < r_{mn}$, the − sign for $r > r_{mn}$, r_{mn} is the resonant surface of the mode $m/n = q(r_{\mathrm{res}})$). A Poincaré plot of the resulting magnetic field line structure is shown in Fig. 4 for field amplitudes of $B_{r,m,n} = 100$ Gauss ($m/n = 2/1$, 3/1, 3/2, 5/2, 4/3, 5/3) and a toroidal magnetic field of 2.25 T; the abscissa is the poloidal angle and the ordinate represents the minor radius. One sees that at these perturbation levels the magnetic field of the tokamak is strong enough to fully ergodize the plasma and that the laminar zone (white area on the top) reaches 2–3 cm into the plasma connecting the ergodic sea with the wall.

The assumption about the role of ergodization is not only important for the disruptive power loss but also for runaway electrons which sometimes are reported to occur in the current decay phase of disruptions [19]; these runaway electrons are regarded as a severe danger for ITER. Our view on the disruption development is as follows: The disruption is initiated by unstable growing modes which create the stochastization of the magnetic field. As soon as the full toroidal cross-section is ergodized, the power is lost towards the edge and flows then convectively along magnetic field lines of the laminar

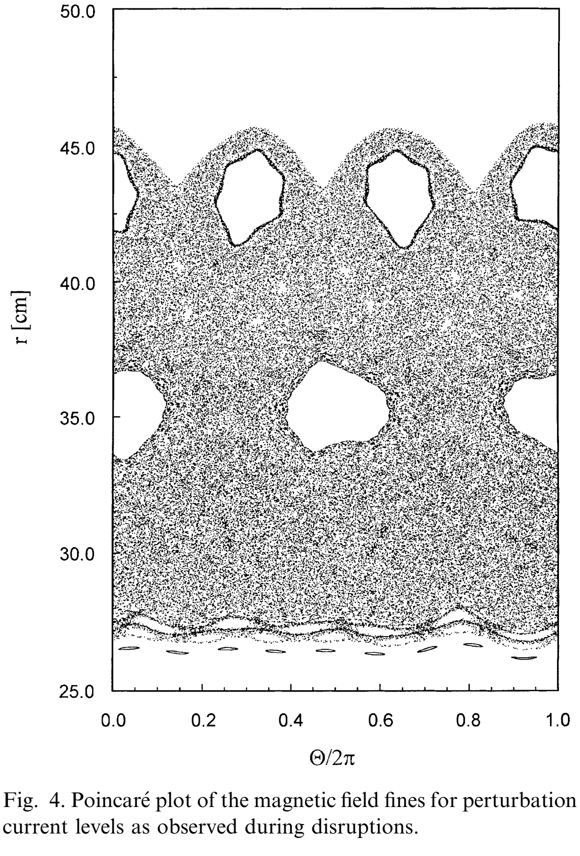


Fig. 4. Poincaré plot of the magnetic field fines for perturbation current levels as observed during disruptions.

zone. The width of the laminar zone grows with the increase of the edge ergodization.

After this power loss phase the current decay phase starts. During this phase the magnetic surfaces may heal partially again such that runaway electrons can be confined in the tokamak (in TEXTOR it was shown that an internal ergodization leads to a fast loss of the runaway electrons [20]) and be accelerated by the high loop voltage. The dangerous effect of the runaways can therefore be mitigated either by reducing the generation rate (e.g. density increase) or by reducing the loss rate e.g. by the ergodization.

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