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Transient transport studies and MHD activity in the RFP

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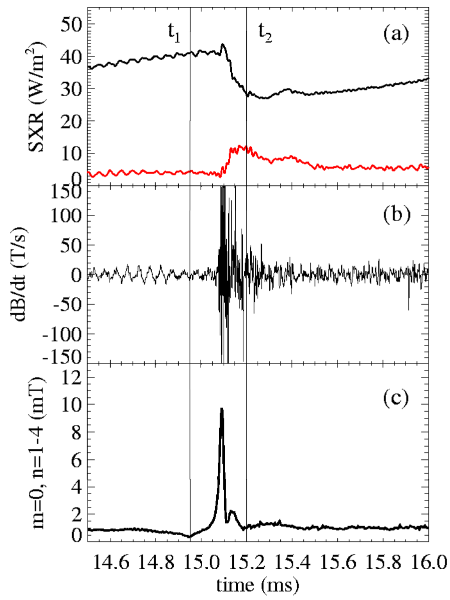

Figure 1:

The investigation of transient transport phenomena has allowed in the last years to obtain important information on basic transport mechanisms in tokamak and stellarator plasmas [1]. We report here a similar phenomenology occurring in Reversed Field Pinch (RFP) plasmas. Using a high time resolution soft-X ray (SXR) diagnostic [2], we have observed evidences of fast SXR profile relaxation in the Madison Symmetric Torus (MST) device [3]. Line integrated measurements of SXR emissivity are available in MST along 24 lines of sight. SXR signals are filtered through a $16\mu m$ thick Beryllium foil. Four high bandwidth magnetic pick-up probes have been used to monitor high frequency ($f < 1500kHz$) magnetic activity, in order to complement the standard low frequency mode resolved measurements obtained by a toroidal array of probes.

Profile relaxation phenomena have been observed for the first time in MST during enhanced confinement regimes obtained through Pulsed Poloidal Current Drive (PPCD) operation [4]. These plasmas are characterized by record low levels of magnetic fluctuations and related thermal transport in a RFP [5]. Fast thermal relaxations originate from an edge resonant instability related to $m = 0$ modes and produce as a result transient transport of heat from the plasma core to the edge.

SXR profile relaxation. In several PPCD discharges in MST, rapid losses of energy confinement associated with magnetic activity starting with $m = 0$ modes are observed (Fig. 1-c). An example of such an event is shown in Fig. 1 at approximately $15ms$. During these events, a sudden variation in the SXR brightness profiles occurs: while central chords (black line) display a rapid decrease in the SXR signal, outer chords (red line) show a transient increase (see

Fig. 1-a). This can be interpreted as a propagation of heat from the plasma core towards the edge. Core electron density (measured by a one-chord interferometer) shows a slight $\simeq 5\%$ variation during these events, while the decrease in the core electron temperature (measured with a double-filter SXR technique) amounts to $\simeq 10-20\%$. Considering the strong dependence of the SXR emissivity on electron temperature in these plasmas ($SXR \propto n_e^2 T_e^3$), it can be concluded to a first approximation that the SXR variations correspond to temperature perturbations. This assumption has been used in a thermal transport model, which will be described in the following. The SXR brightness profiles shown in Fig. 2 correspond to two time instants marked by vertical lines in Fig. 1, respectively before ($t_1 = 14.95ms$, black) and during ($t_2 = 15.2ms$, red) heat propagation: the transient increase in SXR signals is detected by 4 edge chords marked by dashed lines.

By analyzing in more detail the time evolution of these 4 edge SXR signals, it appears that the peaks in these signals don't occur at the same time, but are time delayed for chords nearer to the edge, as shown in Fig. 3-a. The time at which the peaks occur t_p is a function of the chord impact parameter squared p^2 (Fig. 3-b), a feature which turns out to be consistent with a diffusive heat propagation.

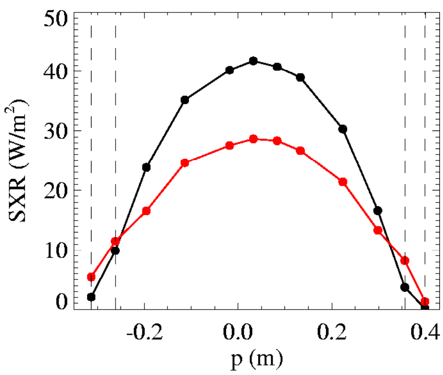

Figure 2:

Magnetic measurements. A rich magnetic dynamics is observed just before and during the profile relaxation events. In a RFP the magnetic shear has opposite sign compared to a tokamak: the safety factor profile $q(r)$ is positive in the core and changes its sign near the edge. Therefore $m = 0$ modes are resonant in the edge region. A bursty increase in $m = 0, n = 1$ to 4 mode amplitudes precedes the SXR emissivity crash, but also $m = 1$ modes do show an interesting time evolution. As far as $m = 1$ modes are concerned, their growth dynamics depends on the position of their resonant surface. The external $m = 1, -15 < n < -10$ modes are usually not resonant in standard discharges, due to the shallow reversal of the q profile. They become resonant during PPCD due to the induced variation in the current profile and the consequent increase in reversal. These edge modes are indeed observed to transiently grow almost simultaneously with $m = 0$ modes, while core resonant $m = 1$ (positive n) modes are observed to be destabilized only after the edge resonant ones. High frequency magnetic fluctuations ($100kHz < f < 1500kHz$, not mode resolved) are observed either before and after the thermal relaxation (Fig. 1-b). Two-point spectral estimates indicate that these high frequency ($f > 300kHz$) bursts are due to a broadband turbulence of modes resonant outside the reversal surface and with relatively high toroidal mode numbers, $n \simeq -40$ to -10.

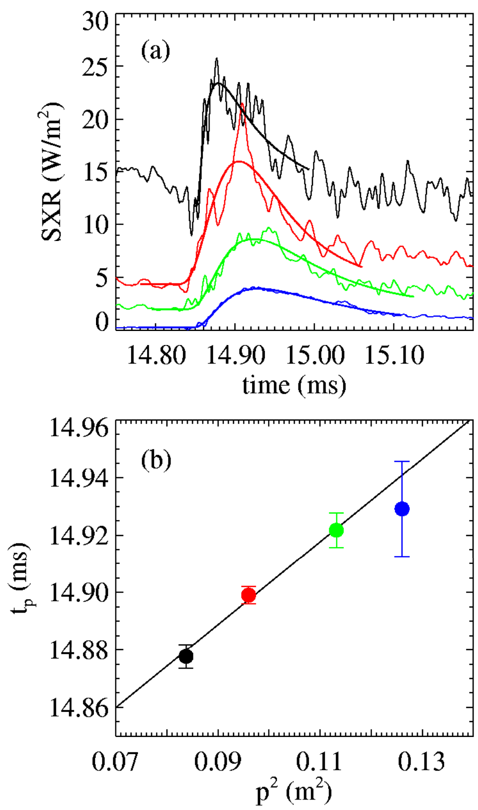

Figure 3:

Modeling of the heat pulse. The ordered sequence of SXR peaks in edge chords closely resembles that of heat pulses observed in tokamaks after sawtooth crashes [6], though with some differences. In tokamaks the heat pulse phenomenon can be described assuming a localized electron temperature perturbation propagating over an essentially unperturbed electron thermal conductivity χ_e profile. The profile relaxation we observe in MST is less localized and is likely to be due to a sudden change in the thermal conductivity profile. The profile relaxation phenomenology can be described by a time dependent cylindrical thermal transport model, which has been also used to give an estimate of the perturbative thermal conductivity χ_e. The equation governing diffusive radial heat transport in a cylindrical plasma is given by the following expression:

$$\partial_t \left(\frac{3}{2} n_e(r) T_e(r) \right) = \frac{1}{r} \partial_r \left[r n_e(r) \chi_e(r) \partial_r T_e(r) \right] + \sum Q \qquad (1)$$

where the term $\sum Q$ summarizes all of the sources and sinks of heat in the system. Before the burst the electron temperature is evolving on a slow time scale: we therefore assume that the system is in equilibrium and we use the ensemble averaged estimates of the electron temperature profile as an initial condition. In these conditions a power balance estimates of $\chi_{e,0}(r)$ is obtained and shown in [7]. By assuming a stepwise increase in χ_e throughout the radius, we numerically integrate Eq. (1) in order to simulate the behavior of the profile relaxation. A direct comparison with experimental data is obtained by simulating the line integrated SXR measurements. This is required because SXR emissivity is a strong non linear function of the temperature in these plasmas. We find that the line-integration procedure slightly alters the time of the peaks(t_p) with respect to the local T_e ones, but a diffusive linear relation among t_p and the square of the impact parameter p^2 is still predicted, as shown in Fig. 4 for two values of the perturbed χ_e, 50 and $150 m^2 s^{-1}$. In accordance with previous computations of heat pulse propagation, the relation between the peak of the temperature pulses and its positions is $r^2/t_p \simeq 1/(9\chi_e)$. For line integrated SXR measurements, the relation becomes $p^2/t_p \simeq 1/(14\chi_e)$.

The above relation has been used to compute χ_e for a database of $\simeq$ 20 relaxation events in reproducible PPCD shots. During these events, characterized by a transiently enhanced magnetic fluctuation level compared to the best PPCD plasmas, we estimate that $\chi_e \simeq 40 - 300 m^2 s^{-1}$: these value are higher than those obtained with the power balance technique ($\chi_e \simeq 10 m^2 s^{-1}$) in the best PPCD plasmas without $m = 0$ events [4, 5], but lower than those measured with the same technique in standard discharges ($\chi_e \simeq 400 m^2 s^{-1}$). The concurrent increase in MHD activity during heat pulse propagation suggests that the discrepancy among the power balance and the perturbative estimates of χ_e may be ascribed to a increased level of magnetic fluctuations during heat propagation. Further experimental and numerical investigations will aim at understanding more deeply the transport mechanisms responsible for heat propagation during these events.

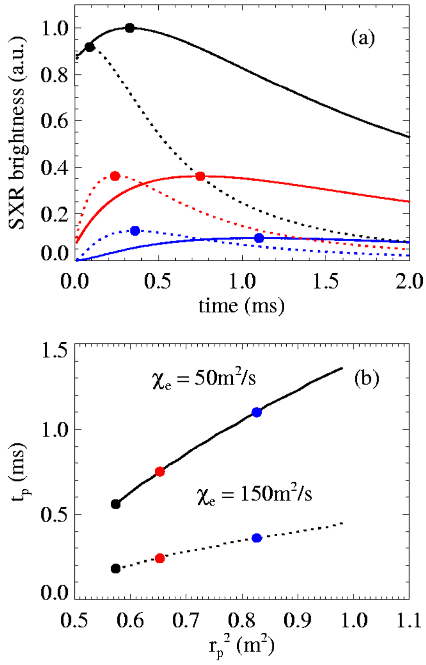

Figure 4:

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