Soft X-Ray Pulses in the Reversed-Field Pinch

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***Abstract*—Data obtained in the Madison Symmetric Torus reversed-field pinch with a soft X-ray diagnostic will be presented. They have been used to study transient transport events in this device. Fast thermal relaxation events are associated to bursts of magnetohydrodynamic fluctuations.**

***Index Terms*—Magnetohydrodynamics, reversed-field pinch.**

IMAGING techniques based on the detection of soft X-ray (SXR) radiation constitute a powerful diagnostic of hot plasmas. These non-invasive methods can be used to investigate a large variety of phenomena both in laboratory plasmas, like those magnetically confined in thermonuclear fusion experiments [1], and in several natural plasma systems, like for example the sun and other astrophysical settings [2]. The SXR emissivity from a plasma is a function of the electron density n_e, electron temperature T_e, and impurity content. In the magnetohydrodynamic (MHD) framework, the SXR iso-emissive surfaces coincide with magnetic flux surfaces.

The SXR radiation flux can be measured by means of relatively low-cost detectors arranged in very compact pinhole photocameras, which makes these diagnostics very flexible and allows for high time and spatial resolution. These photocameras are schematically constituted of a pinhole and of a series of photodiode detectors, which define a fan of collimated lines of sight. Such systems thus provide line integrated SXR measurements.

Magnetized plasmas host magnetic self-organization processes. Self-organization processes in such highly nonlinear systems can produce very rapid events and/or localized structures [3]. These are usually driven by magnetic instabilities, and produce macroscopic rearrangements of the main plasma structure. All these seem to be very universal features of the plasma state. For example, events like edge localized modes (ELMs) in toroidal fusion plasmas have been shown to share many common features with other events occurring in the solar corona; for example, solar flares and coronal mass ejections [2].

In this paper, we illustrate SXR measurements during fast thermal relaxation events occurring in reversed-field pinch (RFP) plasmas [4]. These toroidal plasmas are confined by a magnetic field, which has a toroidal B_ϕ and a poloidal B_θ component. In RFPs, the B_ϕ changes its sign near the wall.

Transient transport phenomena are an important research subject in plasma physics since many years [5]. They provide a powerful technique to investigate basic transport mechanisms and, in some cases, have been used to directly probe the radial profiles of the thermal diffusivity coefficient. Such phenomena have been recently observed also in RFP plasmas and a detailed experimental and numerical study is underway [6], [7]. We will show that the imaging of perturbative phenomena can provide a good chance to study the relation between anomalous thermal transport and MHD turbulence in these plasmas.

Measurements have been taken in the Madison Symmetric Torus (MST) RFP device [8] (minor radius $a = 0.52$ m, major radius $R_0 = 1.5$ m, maximum plasma current $I_p \approx 500$ kA) by means of a recently installed SXR pinhole photocamera [9]. This diagnostic is composed of two fans with 12 lines each. They are mounted 90° apart in the same poloidal cross-section. This diagnostic can detect fluctuation phenomena as fast as $\sim$10 μs. The measurements reported in this paper refer to plasmas where the so-called pulsed poloidal current drive (PPCD) has been applied [10]. With PPCD, a poloidal electric field pulse is inductively driven at the edge of the plasma. This usually causes a drastic reduction of magnetic fluctuations, heating of the plasma and a significant improvement of confinement.

In Fig. 1(a), we report a contour plot of the SXR brightness as a function of the time and of the relative impact parameter p of the different lines of sight. The SXR brightness is the line integral of the SXR emissivity along a particular line of sight. It can be observed in fact that the SXR brightness increases during the discharge, reaching values up to $\sim$100 Wm^{-2}, whereas in typical standard conditions, it assumes values $\sim$10 Wm^{-2}. This emissivity increase is mainly due to an electron temperature increase, which rises from $T_e \sim 400$ eV in standard conditions to $T_e \sim 1000$ eV during PPCD. Electron density in these plasmas is $n_e \sim 1 \times 10^{19}$ m^{-3} and varies much less then electron temperature.

During very optimized high confinement PPCD periods, occasionally sudden bursts of magnetic turbulence are observed. They are mainly associated with $m = 0$ and $m = 1$ modes, and last for $\approx$0.5 ms. The origin of these MHD bursts is not completely understood at present, though it seems likely that they could be related to some MHD instability triggered by the current or pressure profile gradients. The transiently increased level of MHD turbulence during these events produces a certain deterioration of the energy confinement. The transport barrier in the plasma is broken and a heat pulse is induced, which propagates from the hot plasma core toward the colder edge. This is shown in Fig. 1(a) and highlighted in the zoom panel of Fig. 1(b). We observe that a fast drop in SXR brightness occurs in the central region of the plasma at $\mathrm{t} \approx 17.3$ ms. An increase is observed in the edge region. Independent measurements of the core electron temperature by means of the double-filter technique during these events show a decrease $\Delta T_e \approx -10/-30\%$, while the

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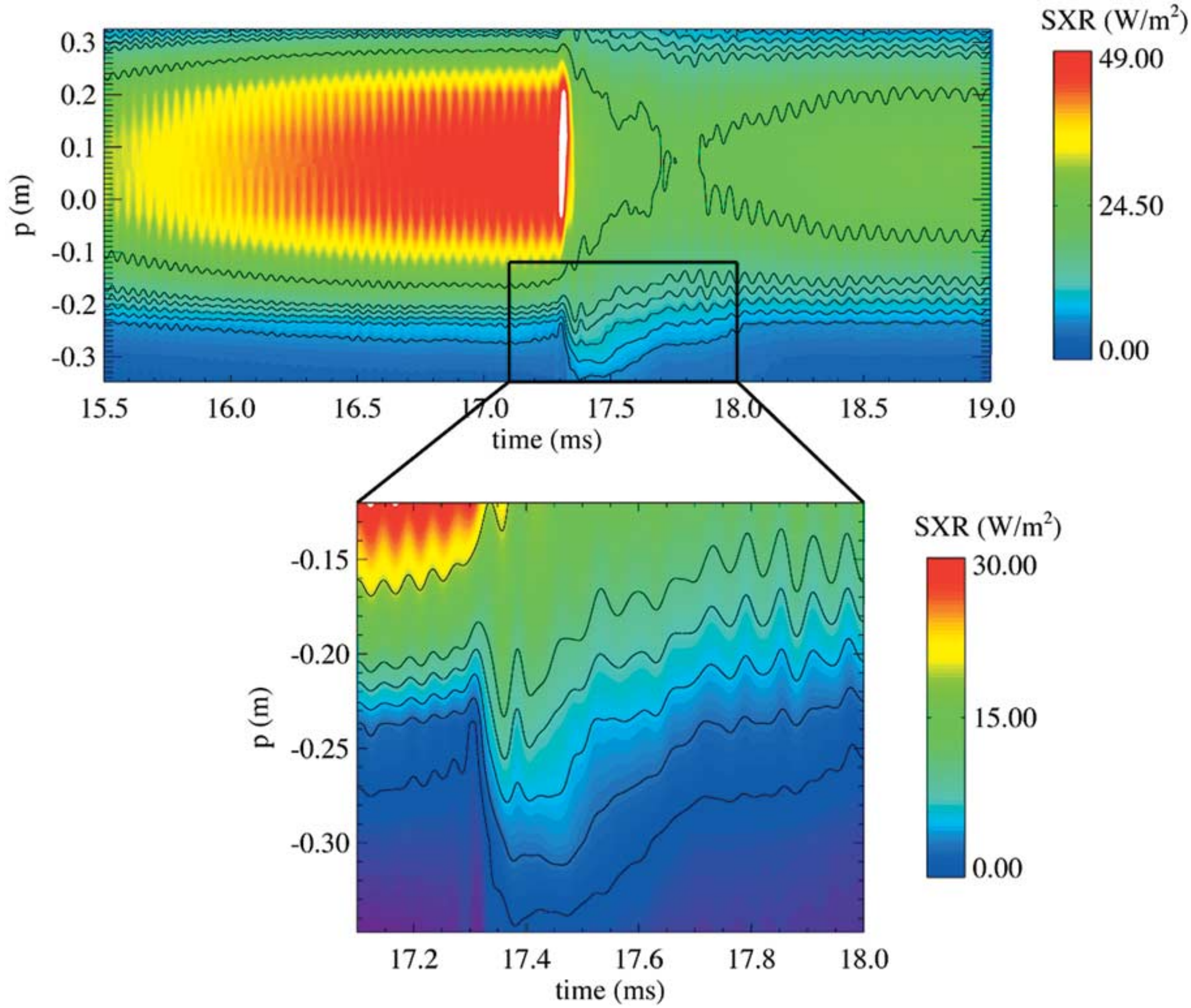

Fig. 1. (a) Contour plot of the SXR brightness measured as a function of the impact parameter p and of the time during a PPCD discharge in the MST experiment. (b) Zoom of the above plot, which shows in greater detail the propagation of a heat pulse from the hot plasma core toward the edge. Color bar indicates the values of the SXR brightness in the two cases.

electron density perturbation is much less $\Delta n_e \approx -3/-5\%$. Hence, the pulse observed in the SXR signal represents to a good approximation a heat pulse that propagates from the core toward the edge.

A more detailed analysis of the SXR signals measured by the edge lines of sights has shown that the heat pulses reach increasing radii with an increasing time delay. This could in principle offer a method to estimate the average electronic thermal diffusivity in the region of the plasma where the pulse propagates. A model of diffusive heat propagation in a cylinder is under development and preliminary results show good agreement with the data shown here.

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