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An Aspect of Discrete Dynamo Event in a Reversed-Field Pinch Plasma as Self-Organized Criticality

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Abstract

A detailed look at a discrete dynamo event in a reversed-field pinch plasma (RFP), TPE-1RM20, is given. Dynamics of the magnetic signals are especially shown for a typical case with an analytic scenario to understand the phenomena. An alternative, synthetic aspect is tried by checking the similarities to the Self Organized Criticality.

Keywords:

reversed field pinch, TPE-1RM20, discrete dynamo event, self organized criticality

1. Introduction

In reversed-field pinch (RFP) plasmas, we often observe sawtooth-like repetitive oscillations in soft X-ray signals. They are sometimes accompanied by sawteeth in the global parameters as I_p, F and Θ, where I_p, F and Θ are plasma current, reversal ratio and pinch parameter, respectively. Amplitude of the sawtooth crashes becomes prominent especially when Θ increases. We call these large sawtooth crash events as discrete 'dynamo' events since the toroidal flux generation is often accompanied with the large sawtooth crash events. These discrete dynamo events occur after a gradual change of the current profile (peaking) in resistive time scale and appears as a rapid release of the stored energy as well as a rapid change of the current profile (flattening). Soft X-ray signals are observed to crash with $n = 0$ structure, i.e., the crash is almost instantaneous along the torus, where n is the toroidal mode number. These natures of the discrete dynamo events in RFP could be normally explained by a MHD picture as is tried in the first half of this paper. It is also tried in this paper if these events have any similarities to the self-organized criticality (SOC) [1] which is a state of complex systems. Sand pile crashes, earthquakes and many other natural phenomena accompanied with some sort of crash events might be understood by SOC.

In this paper, we give a close look at an example of the discrete dynamo event from a middle Θ discharges in TPE-1RM20 device [2] featuring wave number (or n-spectrum) and frequency spectra. Then we discuss about similarities of the discrete dynamo event to SOC.

2. Experimental Device and Operation

TPE-1RM20 is a medium sized RFP (R/a = 0.75/0.192m) which was operated in 1992–1996, where R and a are major and minor radii, respectively. General features of the coherent oscillations and discrete dynamo events are reported in [3]. The n-spectrum is obtained from the toroidal pick-up coil array for B_t component

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placed on the outboard and inboard side of the equatorial plane. There are 32 pairs of in- and outboard pick-up coils so that we can resolve from n = 0 to n = 15. To have much higher band width than the B_t-array outside the vacuum vessel, frequency spectrum (f-spectrum) is obtained from an insertable B_t probe placed at 2 cm away from the plasma surface. Note that the typical cut-off frequency of the vacuum vessel for the $m = 1/n = 0$ component is 5kHz while the in-situ magnetic probe has 250kHz band width limited by the sampling frequency.

To have a typical discrete dynamo event in TPE-1RM20, we operated the machine with a deeper reversal at I_p = 130kA. The typical waveforms of a discharge in a middle Θ region (~1.7–1.8) is shown in Fig. 1. It exhibits a couple of discrete dynamo events during the discharge. We show an enlarged dynamics of the n- and f-spectra for the narrow box in Fig. 1.

3. Dynamics of a Discrete Dynamo Event

Soft X-ray signal enlarged for one of the typical discrete dynamo events in Fig. 1 is shown in Fig. 2 (a).

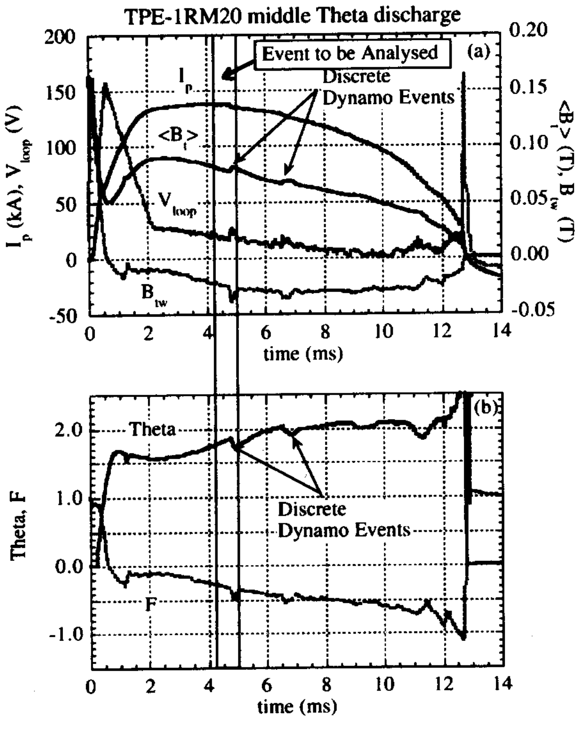

Fig. 1 Typical waveforms of a middle Θ discharge in TPE-1RM20 are shown for I_p, $<B_t>$ (average toroidal field), V_{loop} (one turn loop voltage) and $B_{tw\,in}$ (toroidal magnetic field at the limiter surface) in (a) and F and Θ in (b).

It clearly shows a relatively long current diffusion phase, where plasma is heated, and a crash event in much shorter time scale. Difference between in- and outboard side B_t signals is raveled as m = 1 (odd) component and plotted in Fig. 2 (b) for the same time-

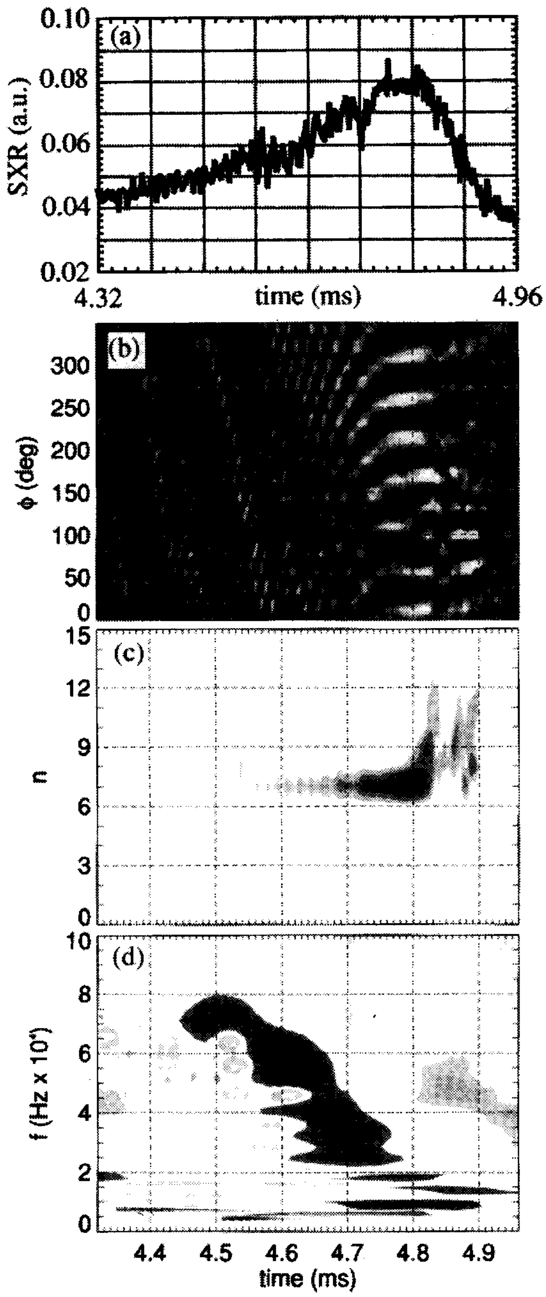

Fig. 2 Enlarged dynamics of the discrete dynamo event is shown in SXR signal (a), toroidal distribution of m = 1 magnetic signals (b), n-spectrum (c) and f-spectrum (d).

interval as Fig. 1 (a). The rotation and wall-locking of the $m = 1$ mode is clearly seen. Figures 2 (c) and (d) show the n- and f-spectra for the same discrete event. To have the well time-resolved spectrum, we used a Wavelet technique for the f-spectrum [4]. Time resolution of this technique is about ten sampling points so that it is about 20μs for the data shown here. It is sufficiently small compared with the typical time of change in the f-spectrum of about 200μs. Note that a normal FFT would not be appropriate for this fast dynamics. In Fig. 2 (d), the rotation of the mode at 70 kHz and its slowing down toward the wall-locking is seen. If there is no poloidal mode rotation, toroidal rotation of the single mode ($m = 1/n = 7$) is 10kHz at $t =$ 4.5ms.

The discrete dynamo event shown here is a typical example of those in the middle Θ discharges in TPE-1RM20. The discrete dynamo event in Fig. 2 is understood by the following scenario. In the current diffusion phase, as current profile is being peaked, single unstable mode (plausibly, near-axis resonant tearing mode) starts to grow at $t = 4.60$ms in a time scale of 200μs. The mode is initially rotating toroidally but is slowing down and finally locks to the wall at $t =$ 4.75ms. Then the n-spectrum becomes broader to the higher n side in $t = 4.80$–4.82ms. This may be either due to the non-linear coupling of the modes or due to the change of the current profile so that the higher n-modes become unstable. The magnetic islands overlap to all over the plasma cross-section and an expulsion of the stored energy occurs corresponding to a crash of the soft X-ray at $t = 4.82$ms. A relaxation phase follows in $t =$ 4.82–5.0ms with an enhancement of $m = 0$ with low-n numbers. Then the current diffusion process resumes. During the relaxation phase, the toroidal flux is enhanced showing the 'dynamo activity'.

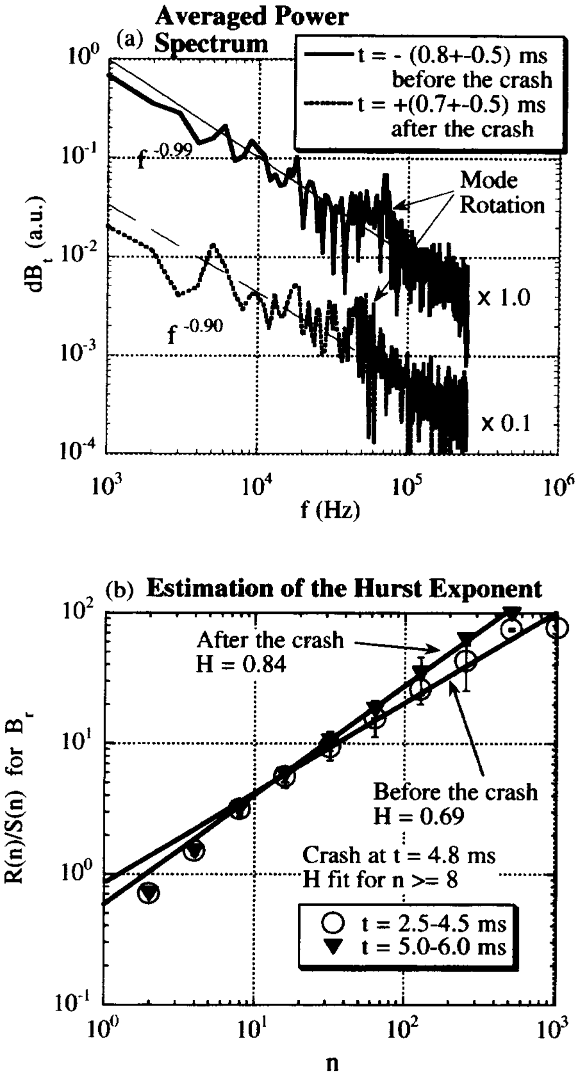

Fig. 3 The magnetic signals of the insertable probe are analyzed. Power spectrum of the B_t signal in (a) and R/S versus sampled data for the B_r signal to estimate the Hurst exponent [5] in (b).

4. Self Organized Criticality (SOC)

Alternatively, the slow change ending with a rapid crash might be understood by SOC. Mathematical method to show that the system is SOC, is not well defined. There are, however, some indicators which the SOC state should exhibit. Checking the k- or f-spectrum if they show a geometrical function; k^{-x} or f^{-y} is one way. FFT is used for the averaged f-spectrum of the B_t signal of the insertable probe in 1 ms (Fig. 3(a)). It is interesting to note that the obtained power spectrum has almost linear trend in log-log plot and approximately shows a f^{-1} decay in 1kHz $< f <$ 250kHz both before and after the crash event. A hump appears at 70kHz (before) and 40kHz (after) corresponding to the rotation of the mode. This is one of the characteristics of the SOC, though other causes may be possible. To check long-range or long-time correlation in fluctuations is another way. This method is usually done by calculating the Hurst exponent, H [5]. The system is said to have a long-time correlation when $0.5 < H < 1.0$. Figure 3 shows the R/S values (see [5]) versus sampled number of data for well before and after the crash event in Fig. 2 for B_r of the insertable probe. Obtained H exponent is 0.64 before the crash and increases to 0.82 after the crash. Both values show a long-range time correlation which is also one of the characteristics of the SOC. Especially, the value before the crash (H = 0.64) agrees quite well with those values in various types of plasma confinement systems summarized in Ref. [5]. The increase of H after the crash means that the system becomes more distant from the random state (H = 0.5). Then a reduction of transport might be expected. It is of interest to note that the SXR increases to a larger level in the next heating cycle than the peak before the crash. It indicates that the electron stored energy increases, which may have a relation to the increase of H value. Finally, a caution needs to be noted for interpretation of H obtained here in a sense that the situation is not necessary be stationary, the sampled points (1000 and 500 points before and after the crash, respectively) may not be large enough and the mode rotation might be affecting the result. In fact, R/S profile is greatly modified if B_t is used probably because of an effect by the mode rotation.

5. Discussion and Summary

A typical example of the discrete dynamo event in RFP plasma is shown in the real space signal, n- (k-) and f- spectrum. A scenario for the discrete event is given from an experimental observation. Alternatively to this analytic approach to the phenomenon, a synthetic way of understanding is also tried. A discrete dynamo event with a fast crash followed by a longer driven phase reminds us of a similarity of the phenomena to the SOC. A preliminary trial to obtain characteristics related to the SOC state is tried by using a magnetic signal in the scrape off region. It shows a $1/f$ spectrum regardless of the crash event. The H exponent is in the range from 0.64 before the crash to 0.82 after the crash. They are in fact part of the features of the SOC, though not necessarily proving it. They may be one of the various aspects of the complex natures of the plasma.

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