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Observation of Current in SOL Plasma and Possible Roles Played by Associated Error Field in AT Discharges in DIII-D Tokamak

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1. Introduction

Among the important challenges [1] facing the Advanced Tokamak (AT) as a viable reactor are control of resistive wall modes (RWMs), edge localized modes (ELMs), neoclassical tearing modes (NTMs), and locked modes (LMs).

The divertor wall in DIII-D is lined with rings of either 48 or 72 tiles each, depending on their radius. Up to 10% of the tiles in some rings have a resistive-element current transducer [2] to measure the SOL current. Earlier investigations [2,3] showed that a current flows in the scrape-off layer (SOL) plasma. Extending these results, this paper describes the SOL current observed concurrently with the low-frequency magnetic phenomena in AT and other discharge regimes. The discussion section at the end offers a hypothesis on the relationships between the SOL current and these magnetic phenomena.

2. SOL Current during Oscillating and Stationary Magnetic Perturbations

In the discharge in Fig. 1, normalized beta, β_N, was above a "rule of thumb" stability limit (2.4 times the internal inductance, ℓ_i) for the external kink mode in the absence of a conducting wall. This is an AT regime that is thought to lead to RWMs. The discharge went through several cycles of a thermal collapse followed by a recovery. Signals from three SOL current sensors, out of five in a toroidal array, are shown in Fig. 1 (ac) over one such cycle, together with other parameters in (d-f).

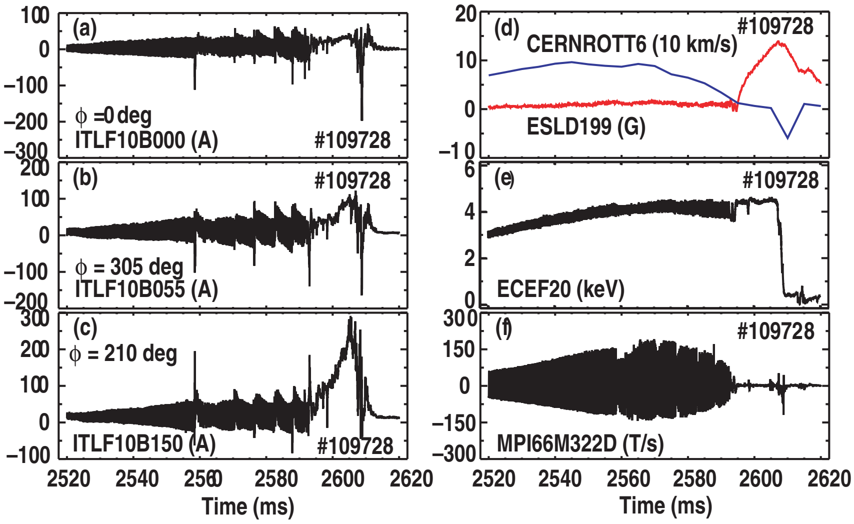

Fig. 1. (a-c) SOL current at three toroidal locations; (d) locked-mode detector (ESLD) and toroidal rotation charge exchange recombination (CER) signals; (e) T_e (ρ=0.44); (f) Mirnov signal (outer mid-plane).

Dark areas in the traces of SOL current (ITL), Mirnov signal (MPI), and the electron temperature, T_e, measured by the electron cyclotron emission (ECE) diagnostic, represent oscillatory signals in a several kHz range that cannot be resolved on this time scale. Several ELM-like spikes also punctuated this period. A classic LM-like sequence of events followed the cessation of oscillations in these signals at 2595 ms. The plasma toroidal rotation measured by the CER diagnostic also stopped about this time. The n=1 radial magnetic field measured by a ESLD rose about 13 G, and T_e collapsed a few ms afterward. The SOL current also increased in this quasi-stationary phase, strongly at some toroidal locations (at 210 deg) while barely changing at the others (at 0 deg). The helical current flowing along open field lines was thus not toroidally symmetric.

Mirnov, ECE, and SOL current signals are overlaid together in the top panel (Fig. 2) to show their relative evolution. The signals (in arbitrary units) are vertically scaled and displaced. The bottom panel is on an expanded time scale to reveal coherent oscillations on all three signals at the same frequency (current signal inverted). Magnetic perturbations and SOL current had a predominantly n=1 toroidal structure.

Oscillating magnetic perturbations with interior T_e fluctuations, similar to those in Fig. 2, are commonly thought to originate from an MHD instability, usually a tearing mode. Calculations by the PRIME code [4] indicate the tearing mode to be nonlinearly unstable in this discharge when NTM effects are included. These oscillations might appear to be NTMs at first glance, but a fast Fourier transform (FFT) analysis showed that the T_e fluctuations exhibited no clear phase reversals that would have indicated the presence of magnetic islands. The interior fluctuation structure was predominantly kink-like, without flux surface tearing, during the oscillating phase.

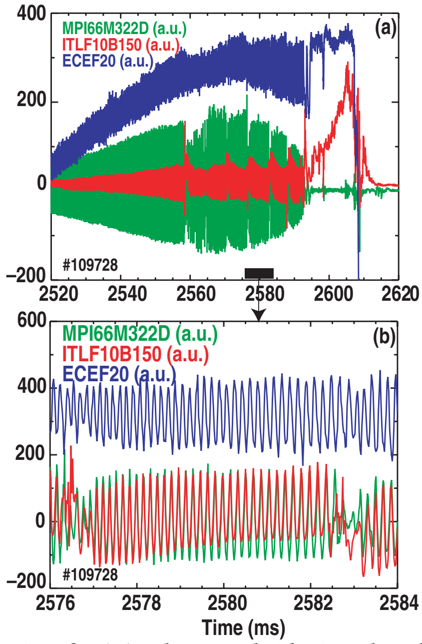

Fig. 2. (a) The overlaid signals of SOL current, Mirnov, and ECE showing their mutual relationships; (b) expanded view reveals oscillations.

The SOL current in Fig. 2 reached nearly 300 A/tile toward the end of the quasi-stationary phase. Assuming some neighboring tiles carried a similar amount, the total current involved has reached several kA, flowing in the immediate proximity of the plasma surface, large enough to be a concern in MHD stability physics. To place this current in perspective, the in-vessel, one-turn, RWM feedback coil system (“I-coils”) in DIII-D would apply <5 kA of current at a much greater distance from the plasma in an effort to control the MHD stability.

3. SOL Current During ELMs

An SOL current was observed to flow during the ELM in DIII-D, sometimes in bipolar directions [2,3] and in a non-axisymmetric manner [3]. The use of extensive sensor arrays and a higher bandwidth system allows an in-depth study. The current flow is found to be different [5], depending on the types of ELMs.

A standard way of identifying ELMs has been to look for “spiky” features in the trace of a D_α light signal. The blue curve in Fig. 3 represents a D_α light signal in an H-mode discharge. The red curve is the trace of an SOL current signal. Each curve has spiky features that are coincident with those of the other. The correspondence is essentially complete. The SOL current is as reliable an indicator of the occurrence of an ELM as the D_α light.

The SOL current rises rapidly during a single ELM event, reaching an ultimate value that varies widely, from a 100 A/tile range for a modest event to over 1 kA/tile for a large ELM. The total SOL current involved in the event may range from a few kA to tens of kA.

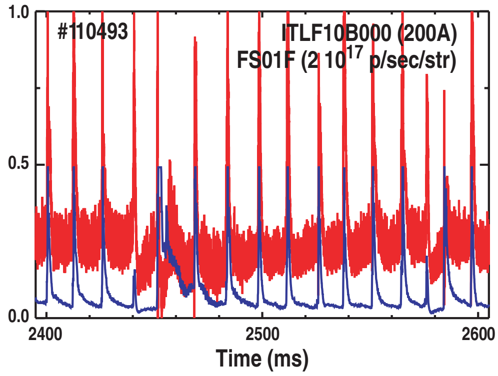

Fig. 3. Correspondence of spiky features in the D_α light (blue) and SOL current (red) is essentially complete. The SOL current is a reliable indicator of an ELM occurrence.

A single ELM event of a modest amplitude is presented in Fig. 4. The SOL current evolution during the event has two notable features. First is coherent oscillations with a steady amplitude before and after the ELM spike, and probably during the spike itself, and second is rapidly growing, less coherent oscillations prior to the spike, suggestive of a current flow instability.

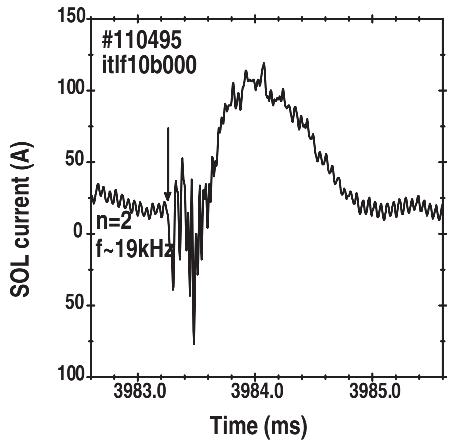

Fig. 4. SOL current in a single ELM. Coherent oscillations (19 kHz) may persist through the ELM event. A rapidly growing instability-like phase precedes the main ELM spike.

In the ELM event in Fig. 4, the SOL current flows in one direction (measured positive by this sensor) over most of its duration. The current reverses direction momentarily during the instability-like phase. Generally, the current flow reversal is found to occur in some ELMs and only during the instability-like period. The observation that the SOL current can actually reverse its direction, and do so quickly, places conditions on the kind of physical processes that can be identified as a driving mechanism of the current.

Figure 5 shows the result of a singular value decomposition (SVD) analysis for determining the toroidal structure of the SOL current during an ELM event in Fig. 3. It used six SOL current signals to calculate the modulus and the argument of toroidal harmonics, n=1-3. The n=0 component was computed separately as the toroidal average of the current.

The axisymmetric harmonic is dominant throughout the ELM event. Its peak value is about twice as large as peak values of the non-axisymmetric harmonics. The latter have comparable peak values among them. This suggests the existence of higher harmonics of significant amplitude that were not included in the SVD analysis. It is likely that the SOL current during this ELM had a profile broad in the Fourier space and possibly narrow or spiky in physical space. The non-axisymmetric SOL current quickly reached a peak and fell back to a pre-spike level. The axisymmetric component varied more gradually and smoothly.

Details of the harmonic evolution may vary from one ELM to another, but the basic feature described here appears to hold for other ELM events in that the non-axisymmetric components occur largely in the first half of the ELM spike.

4. Discussion

SOL current was observed to flow concurrently with low-frequency magnetic phenomena in an AT regime (DIII-D) with thermal collapses, low-n coherent saturated oscillations, quasi-stationary LM-like sequence, and ELMs). The current is generally non-axisymmetric, and will generate a non-axisymmetric magnetic field, presumably with resonant and non-resonant components.

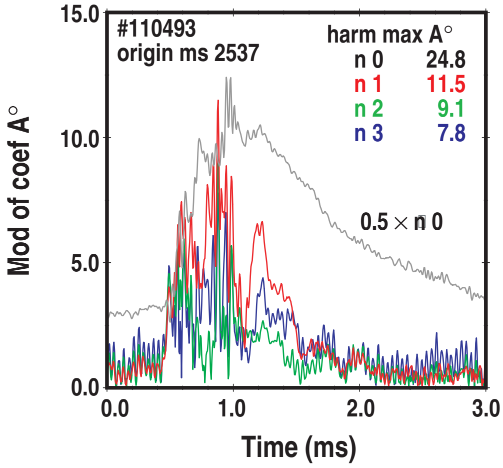

Fig. 5. The evolution of the toroidal harmonics of the SOL current during an ELM event. The non-axisymmetric components rise and fall largely within the first half of the ELM spike. The symmetric component, shown in half-scale, changes more gradually and smoothly.

In earlier work [6] oscillating magnetic perturbations were found in TFTR that were difficult to explain as a MHD instability. It was conjectured that a current flowed in the SOL, and created the observed perturbations. The low-n coherent oscillations reported here are similar to magnetic perturbations in TFTR, and were actually accompanied by an oscillating SOL current, lending credence to the TFTR observations.

It is hypothesized here that the SOL current is a common thread in a wide variety of magnetic phenomena, and plays a role in the MHD stability in AT and other discharge regimes through its associated non-axisymmetric error field. Resonant components of the error field may provide a destabilizing influence on the growth of tearing modes in LMs or NTMs, and of kink-modes in RWMs. In an ELM event, an instability in the SOL current flow participates in the MHD process at the plasma edge through its error field during the first half of the event, and is quenched during the second half, perhaps under the symmetrizing influence of heat and particles transported into the SOL from the main plasma resulting from MHD instability. According to this model, some low-n coherent perturbations in DIII-D are forced oscillations of a stable plasma column caused by the SOL current-generated *dynamic* error field through a mechanism analogous to the error field amplification [7] of *static* structural error field.

Further work is needed to examine the veracity of this hypothesis, and progress will be reported in future publications [8]. A useful experiment would be to investigate whether or not eliminating or reducing the SOL current by greatly increasing its circuit impedance will ameliorate some of the deleterious AT plasma phenomena.

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