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Edge Current Growth and Saturation During the Type I ELM Cycle

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Abstract. Initial studies have been made with the DIII-D LIBEAM system to examine the behavior of the edge current density j(r) during the Type 1 edge localized mode (ELM) cycle. J(r) is an important component of the pedestal in tokamaks and plays a major role in setting the magnetohydrodynamic (MHD) stability limits for this region, interacting with the pressure gradient ∇p through bootstrap and Pfirsch-Schluter effects. While the ion and electron pressure profiles have been extensively studied, the behavior of the edge current is less well known. To address this need, the LIBEAM system has been developed to provide a finely spaced profile of the edge poloidal magnetic field from which one can infer the current density. Previous work has shown a close correlation between the edge ∇p and the growth of large, localized currents for long ELM-free periods; however the j(r) measurement has significant signal-to noise and time resolution limitations. Conditional averaging of the signals for multiple ELMs improves the sensitivity and allows us to examine the dynamics of edge [j(r), ∇p] growth and decay as a fraction of ELM spacing, or fixed absolute time after an ELM. Initial analysis shows that the current peak can relax by about a factor of two within a few ms after an ELM, consistent with resistive decay times in the edge. The physics mechanism for the reduction of current has not yet been studied. The relative time behavior of the measured j(r) and the associated edge ∇p will also be discussed.

I. Introduction

The Type 1 edge localized mode (ELM) instability [1,2] manifests itself in toroidal magnetic confinement systems as a cyclic, rapid relaxation of the edge plasma pressure. The subsequent loss of energy and particles to open magnetic field lines is associated with large, cyclic thermal loads on the structures surrounding the plasma. In the case of the International Thermonuclear Engineering Reactor (ITER) [3] and other burning plasma devices, these instabilities are predicted to seriously erode or damage the divertor structure or other plasma facing components. In addition, the degradation of pedestal height due to the cyclic relaxation can significantly impair the core plasma performance and fusion performance. This instability appears to be a peeling-ballooning magnetohydrodynamic (MHD) limit [4] on the maximum achievable pedestal pressure, for a given magnetic configuration. While achieving a predictive understanding of the particle and energy losses will require progress on modeling the full, nonlinear evolution of the instability, the stability threshold for ELMs is already well explained by the (linear) theory of finite-*n* coupled peeling-ballooning modes. In this model, the specific threshold is strongly dependent on both the pressure gradient and current near the boundary. Hence, the question of what happens to the edge current during an ELM and afterward is critical to determining ELM dynamics and the ultimate pedestal performance. Important issues are whether or not the edge j(r) remains constant through an ELM and whether or not a close correlation is maintained between the edge ∇p and j(r). Such local measurements of current have been made on the DIII-D tokamak using combined polarimetry and spectroscopy of an injected lithium beam. Here we present some preliminary results on extending these measurements to very short timescales in order to examine the inter-ELM current behavior.

II. Diagnostic and Experimental Results

The poloidal field measurements are made on the DIII-D tokamak using the LIBEAM system (Fig. 1) which consists of a 30 keV, 10 mA neutral lithium injector, beam control system, and an optical system which collects the beam fluorescence, spectrally filtering it and analysing its polarization state with good temporal and spatial resolution [5,6]. The diagnostic provides 32 finely spaced ($\delta R \sim 0.5$ cm) values of B_{VIEW}, the magnetic field component parallel to each of the 32 sightlines. Because of the choice of sightline, B_{VIEW} is approximately equal to the poloidal field B_{POL}. Information on the edge electron pressure is obtained using the DIII-D multipulse Thomson scattering system [7]. The gradient and width are estimated using a hyperbolic tangent fit to the resulting electron temperature and density profiles [8].

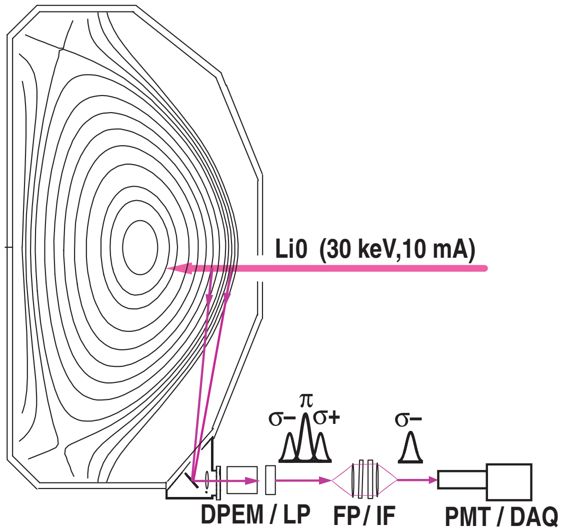

Fig. 1. Diagnostic layout. The 670 nm resonance fluorescence light from the collisionally excited beam is imaged at a series of closely spaced locations in the plasma edge. The polarization state of the σ-Zeeman sublevel is analyzed by passing the light through dual photoelastic modulators (DPEM) and a linear polarizer (LP) to amplitude modulate the emission, which is detected by a bank of 32 photomultiplier tubes (PMT). Individually tuned etalon pairs (FP) and an interference filter (IF) isolate the σ-component for each of the Doppler-shifted viewing locations. Lock-in analysis identifies the ratio of circular to linear polarization and, in conjunction with a spatial calibration, determines the value of the poloidal field at each measurement location.

III. Data and Method of Analysis

To investigate the dynamic behavior of the pressure and current during the ELM cycle, we examine a high triangularity DIII-D discharge having a very high edge pressure gradient and intermittent Type 1 ELMs. Details of the discharge are shown in Fig. 2. To improve the effective time resolution of the current measurement, we conditionally average the data obtained over approximately 23 ELM cycles. This is done by performing the poloidal field analysis over many short (0.5 to 2 ms) time periods and assigning each time slice two values: the phase or percentage of time through the particular ELM period in which the timeslice resides, and the absolute time after the ELM. The ensemble of values can then be sorted with respect to either ELM phase or absolute time and binned or averaged to reduce the statistical noise in B_{VIEW}. Because of problems with intense background light during the ELM itself, we reject the few timeslices that actually include an ELM. This represents a limitation on how close to an ELM event we can begin analyzing the current evolution. A similar sorting is done for the Thomson scattering timeslices to obtain corresponding values for the pressure gradient and pedestal width. To quickly assess the time behavior of the edge current, we examine the gradient in the poloidal field which is related to j(r) via Ampere's law [9]. In the present case we simply take the difference in three channels inside and outside of the pedestal region [B_{in}, B_{out}] as a proxy for this value, since we are chiefly interested in the relative time behavior of ∇p and j(r) for this initial study. A more comprehensive study will determine j(r) directly from Ampere's law and parametric fits to the full B_{VIEW} profiles in the future.

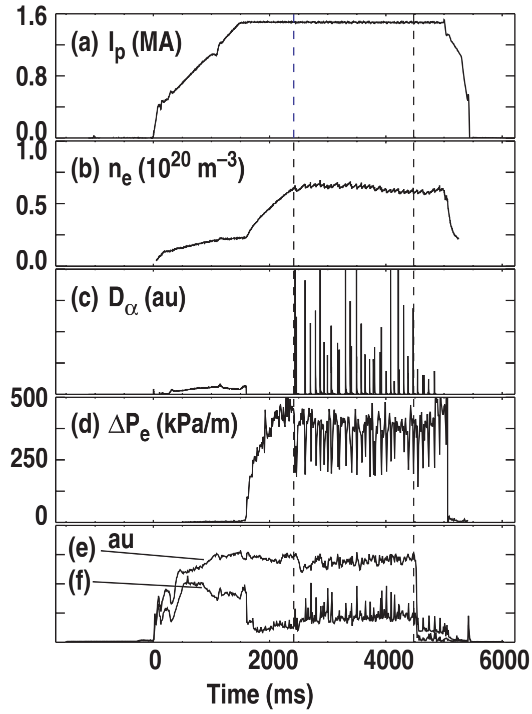

Fig. 2. Time traces for DIII-D shot 119089. (a) Plasma current I_p, (b) plasma density n_e, (c) divertor D_α, (d) edge pressure gradient ΔP_e from Thomson scattering, (e) lithium fluorescence at top of pedestal, (f) lithium fluorescence at foot of pedestal. ELMing period from 2400 to 4450 ms is used in subsequent analysis.

IV. Results and Discussion

Figure 3(a) shows the individual behavior of B_{out} and B_{in} as a function of phase in the ELM cycle. The poloidal field data represent approximately 3800 individual values with 5 ms averaging. The data are further smoothed over 20 points in phase (~0.6% of ELM cycle). In Fig. 3(b) we show the behavior of $\nabla B_{POL} = (B_{out}-B_{in})/(r_{out}-r_{in})$ and ∇P_e as a function of ELM phase. Because of the random firing times for the Thomson scattering lasers, the earliest pressure data occur after the pressure gradient has already relaxed — by a factor of 2 after the ELM crash. This drop in ∇P_e occurs within a ms, equivalent to about 1%-2% of the ELM cycle. The edge pressure gradient then recovers promptly and remains relatively stable for the last 75% of the cycle. The width of the steep gradient region exhibits roughly the same time evolution.

In terms of the poloidal field gradient behavior, while the averaging does set a limitation on the maximum achievable time resolution, and while we cannot examine the edges of the phase plot because of the background light problem mentioned previously, the data in Fig. 3(b) does

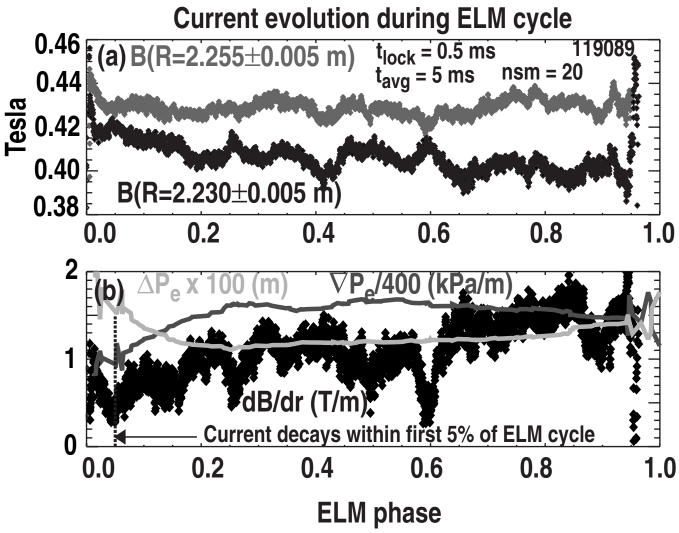

Fig. 3. (a) Plot of poloidal field B near top (black curve) and base (gray curve) of pedestal as a function of phase in the ELM cycle; (b) resultant poloidal field gradient dB/dr (black curve) and edge electron pressure gradient ∇P_e (dark gray curve) plotted as function of ELM phase. Also plotted is the width of the steep pressure gradient ΔP_e (light gray curve). Averaging time for poloidal field information is 5 ms. Data is smoothed over 20 adjacent points in phase.

show the general trend as a function of ELM phase. The two main characteristics are a rapid decrease in the poloidal field gradient (implying a rapid decay of the edge toroidal current j_ϕ within ~5% of the ELM cycle, and a slow recovery/increase of the current throughout the remainder of the cycle. While the rapid decrease is probably dominated by the change in the Pfirsch-Schlüter current due to the collapse of the pressure gradient after the ELM, the decoupling of ∇B_{pol} from ∇p at later times implies that the parallel current density is increasing during this time, since it is the toroidal component of both terms which combine to determine j_ϕ. The current appears to lag the pressure gradient evolution, both during the collapse and during the rest of the cycle, where the pressure has already returned to its pre-ELM value but the current continues to increase until the next ELM. This last observation leads to an interesting speculation: that it is the current rather than the pressure itself that serves as the ultimate trigger for the ELM. Much additional work remains to be done to confirm or disprove this possibility, and to further our understanding of the dynamics of the ELM cycle.

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