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Edge Currents and Stability in DIII-D

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I. Introduction

Understanding the stability physics of the H-mode pedestal in tokamak devices requires an accurate measurement of plasma current in the pedestal region with good spatial resolution. Theoretically, the high pressure gradients achieved in the edge of H-mode plasmas should lead to generation of a significant edge current density peak through bootstrap and Pfirsh-Schlüter effects. This edge current is important for the achievement of second stability in the context of coupled magneto hydrodynamic (MHD) modes which are both pressure (ballooning) and current (peeling) driven [1]. Many aspects of edge localized mode (ELM) behavior can be accounted for in terms of an edge current density peak, with the identification of Type 1 ELMs as intermediate-n toroidal mode number MHD modes being a natural feature of this model [2]. The development of a edge localized instabilities in tokamak experiments code (ELITE) based on this model allows one to efficiently calculate the stability and growth of the relevant modes for a broad range of plasma parameters [3,4] and thus provides a framework for understanding the limits on pedestal height. This however requires an accurate assessment of the edge current. While estimates of j_{edge} can be made based on specific bootstrap models, their validity may be limited in the edge (gradient scalelengths comparable to orbit size, large changes in collisionality, etc.). Therefore it is highly desirable to have an actual measurement. Such measurements have been made on the DIII-D tokamak using combined polarimetry and spectroscopy of an injected lithium beam. [5,6]. By analyzing one of the Zeeman-split 2S-2P lithium resonance line components, one can obtain direct information on the local magnetic field components. These values allow one to infer details of the edge current density. Because of the negligible Stark mixing of the relevant atomic levels in lithium, this method of determining j(r) is insensitive to the large local electric fields typically found in enhanced confinement (H-mode) edges, and thus avoids an ambiguity common to MSE measurements of B_{pol}.

II. Diagnostic and Experimental Results

The system comprises a 30 keV, 10 mA neutral lithium injector, beam control system, and an optical system capable of collecting the beam fluorescence, spectrally filtering it

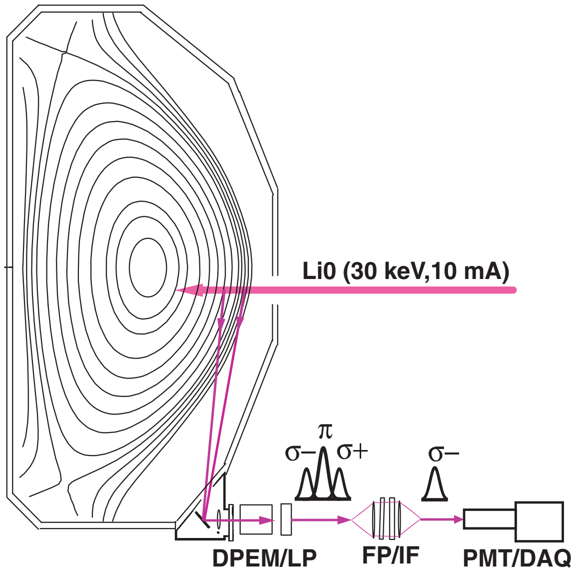

Fig. 1. Diagnostic layout. The 670 nm resonance fluorescence light from the collisionally excited beam is imaged at a series of closely spaced locations in the plasma edge. The polarization state of the σ-Zeeman sublevel is analysed by passing the light through dual photoelastic modulators (DPEM) and 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.

and analysing its polarization state with good temporal and spatial resolution. Figure 1 shows the layout of the diagnostic on the tokamak. The output measurement of the diagnostic results in an array of 32 finely spaced (δR ~ 0.5 cm) values of B_{VIEW}, the magnetic field component parallel to each of the 32 sightlines. Calibration constants for each of the individual channels are obtained using an Ohmic shot and the proper background subtraction for given discharge conditions. This allows us to account for systematic effects due to inadequate spectral filtering by some of the etalons and thus to obtain a more accurate profile. A spatial calibration allows us to decompose each measurement into {Br,Bz} combinations at the intersection of the sightlines and the injected beam. These values may be fed into the equilibrium solver EFIT in order to constrain the reconstruction of the plasma flux surfaces and current density profile.

Figure 2 shows a comparison of the diagnostic results on DIII-D L- and H-mode plasmas with a kinetic EFIT run using the existing magnetic coil and MSE inputs. The data is represented as the projection of the pitch angle $\gamma = B_{pol}/B_{tor}$ onto the sightlines. In the case of the lithium data γ is obtained by dividing B_{VIEW} by the known toroidal field; in the case of EFIT, by reconstructing the proper direction cosines from the known spatial calibration and the calculated $\{B_r,B_Z\}$ values. In the L-mode case the plasma pressure is quite low and very little edge current is predicted to exist. For the H-mode phase of the discharge the data was taken at a time immediately prior to the occurrence of a Type 1 ELM where the same total current exists but the edge pressure gradient has risen to a very high value. In this case, just inside the last closed flux surface there is a marked increase in the measured pitch angle in the H-mode, as compared to the L-mode data. The shear in the lithium beam pitch angle between 2.22 and 2.245 m is indicative of a substantial plasma current, exactly where the large pressure gradient exists; in contrast, the region inwards of 2.19 m shows little shear and is statistically indistinguishable from either the L-mode data or the EFIT data. Qualitatively, these results are exactly what are expected for the current density at the edge of this H-mode discharge. Ampere's law can be used to estimate the current density from the measured shear in BVIEW [7]. These estimates yield values in the range 1–2 MA/m^2 which are well in excess of those needed to affect MHD stability in the edge [8].

Next, the equilibrium reconstructions are rerun using the lithium beam polarimetry data as constraints on the internal magnetic field pitch. The EFIT response matrix was modified to include fitting of the lithium beam pitch angle measurements with full corrections of the viewing geometry. The equilibrium reconstruction results including the lithium beam data for the L-mode phase and the ELM-free H-mode phase of shot 115117 are shown in Fig. 3. The fit to the H-mode data shows a clear peak in the current density near the separatrix.

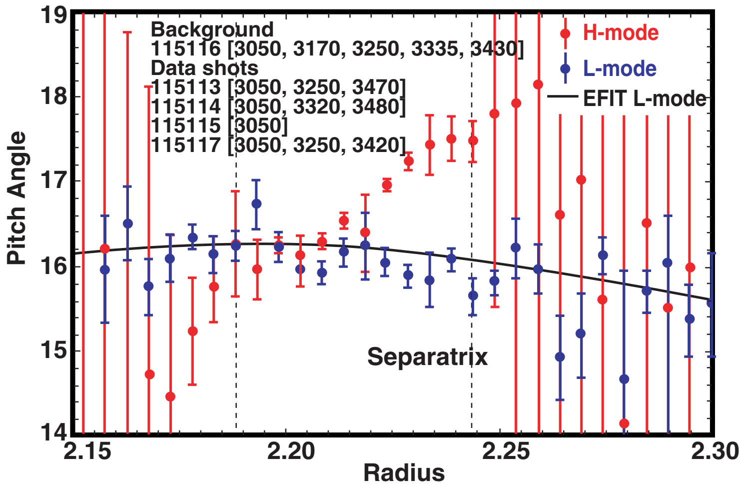

Fig. 2. Comparison of calculated magnetic pitch angle profile from EFIT (black) projected onto the LiBEAM viewchords with a measured profile from the diagnostic for Shot 115117 during L-mode phase (blue) and late H-mode phase (red) just before the collapse of the pedestal pressure. The large increase in the H-mode error bars at the two extremes of the array are due to low signals; on the outside due to the drop in plasma density and on the inside due to beam attenuation.

Next we compare the current density indicated by the lithium beam measurement to the calculated bootstrap current. The dashed curves in Fig. 4(a) are from two equilibrium reconstructions using the measured pressure profile and the current density near the edge (R > 2.22 m) constrained by the bootstrap current, which is calculated from the measured plasma pressure profile using the NCLASS [9] model. The two curves reflect slightly different boundary conditions on the pressure profile parameterization within the EFIT grid. The solid curve is the same as that in Fig. 3.

III. Discussion

Preliminary ELITE runs using the equilibria generated above indicate stability for modes having n below 15, marginal stability for modes of medium n (20-25) and instability for modes having n = 30–35 [10]. This behavior is consistent with the approach to ELM onset expected from the stability model. As seen in the curve, the current density from the lithium beam constrained fit agrees quite well with the calculated bootstrap current peak. This is somewhat surprising since, as mentioned previously, one might expect the neoclassical theory to break down in the edge region where ρ_i is comparable to the pressure gradient scale length L_p instead of being much smaller than L_p. In addition, the

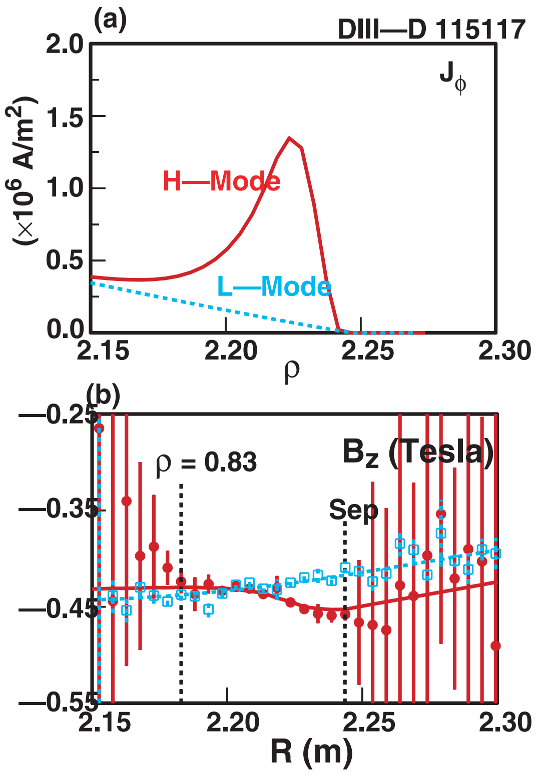

Fig. 3. (a) The toroidal current density as a function of the major radius from EFIT equilibrium reconstruction using magnetic data, motional stark effect data, and the lithium beam polarimetry data, comparing H-mode (solid curve) to L-mode (dashed curve); and (b) a comparison of the B_z from the reconstruction to the B_z profiles calculated directly from the lithium beam measurements.

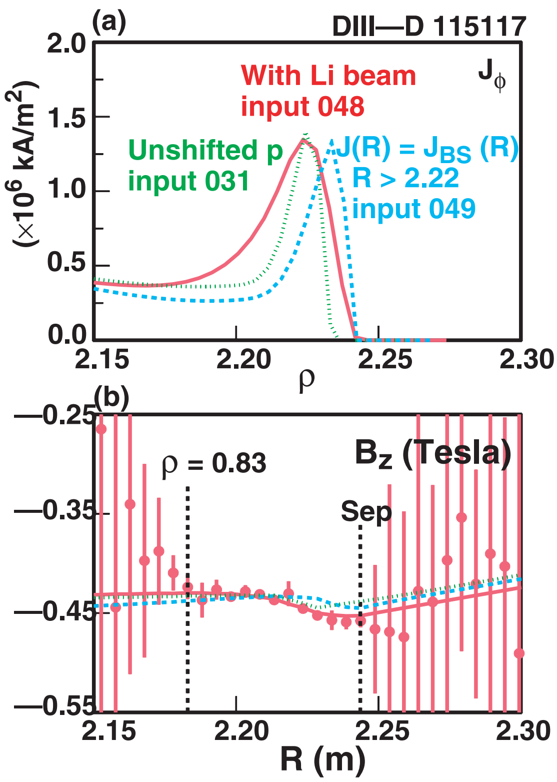

Fig. 4. (a) Comparison of the toroidal current density from bootstrap constrained fits (dashed curves) to current density from an equilibrium using the lithium beam data to constrain the fits (solid line), (b) comparison of the B_z from the bootstrap constrained (dashed lines) and lithium beam data constrained fits (solid line) to the measurements.

rapid change in collisionality and impurity content across the pedestal should also complicate the calculation. By varying such parameters as triangularity and edge density in future experiments, this new data should allow us to begin to evaluate and challenge the bootstrap current models in the edge, as well as further understand the stability limits.

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