Progress Report: Dependence of the H-mode Pedestal Structure on Aspect Ratio

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Abstract. We report on the progress of a set of experiments between DIII-D, MAST, and NSTX to determine the aspect ratio dependence of the pedestal. The pedestal-top electron collisionality $\nu_e^* \sim 1$ was matched in all three devices, and the pedestal-top normalized ion gyroradius $\rho_i^* \sim 0.015$ was matched between NSTX and DIII-D. The goal of this set of experiments is to assess the pedestal widths and gradients, as well as the edge stability of each set of discharges. The status of experiments and analysis on each machine is described.

I. Introduction

An accurate prediction of the ITER H-mode pedestal parameters is key in performance projections, e.g. high pedestal temperature is linked to sufficient core energy confinement, while ideal MHD stability appears to set the maximum edge pressure gradient in the pedestal before large edge-localized modes (ELMs) are encountered[1]. Explicit determination of the dependence of the pedestal heights, widths, and gradients on the device inverse aspect ratio ($\varepsilon = a/R$) has recently received attention, because many of the machines in the international database used for scaling to ITER have different aspect ratios. In this regard, a strong dependence of the pedestal on aspect ratio

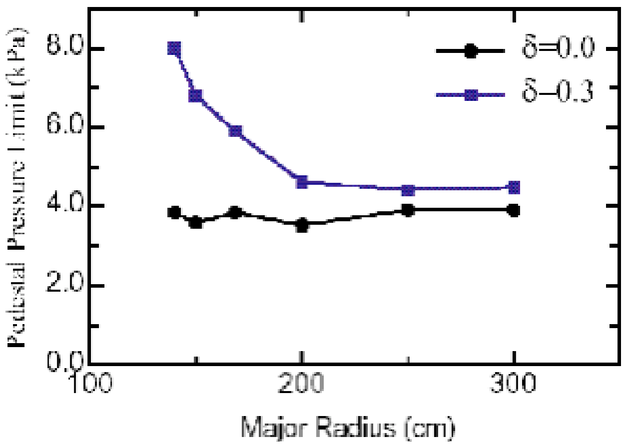

Fig. 1. Dependence of pedestal pressure limit in major radius at a fixed minor radius of 0.603m, i.e. an aspect ratio scan[6].

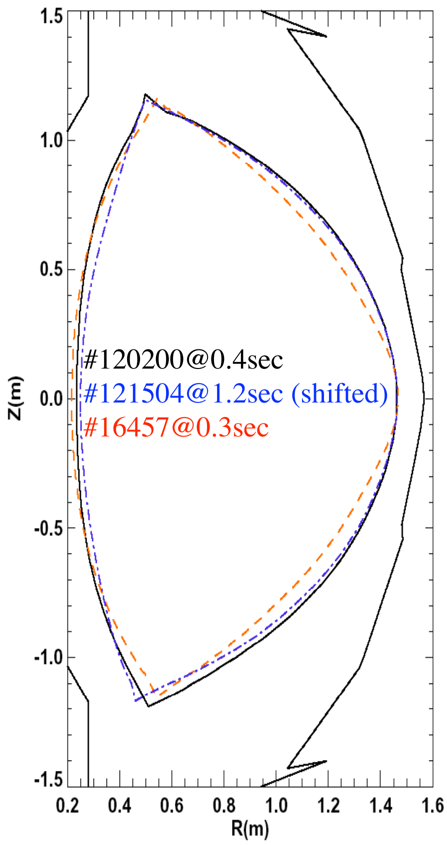

Fig. 2. Common double-null shape developed for aspect ratio scan. Color code: NSTX (black), MAST (red: dashed), and DIII-D (blue: dash-dot). The DIII-D shape was shifted inward by 0.82m.

would not be surprising, because variation of the aspect ratio primarily affects the edge magnetic topology. Determination of the effect of aspect ratio can take the form of an explicit aspect ratio term in the pedestal scaling[2], or a multi-machine comparison as discussed here.

Previous studies have confirmed the possibility of a strong aspect ratio dependence of the pedestal. For example, a scaling study of the H-mode T_e pedestal width (Δ_{Te}) between DIII-D and JT-60U showed clear differences in the pedestals; specifically $\Delta_{Te} \sim \varepsilon^{0.5}$ if solely attributed to the aspect ratio difference[3]. More recently, stability calculations with the ELITE code[4, 5] rather robustly showed that the pedestal pressure was expected to increase with decreasing major radius at moderate shaping, i.e. triangularity $\delta \sim 0.3$-0.4 (Figure 1)[6]. Note that this calculation was done assuming a fixed pedestal width, so that the prediction is effectively of the critical pedestal gradient. Also, the minor radius was held constant, such that the aspect ratio decreased with decreasing major radius. Thus the prediction equates to an increase of the pedestal pressure gradient with inverse aspect ratio. Other fixed quantities in this calculation were plasma current I_p, toroidal field B_t, and density; the pedestal T_e (P_e) and gradient were varied until the onset of the peeling/ballooning instability. Note that this prescription of locating the peeling/ballooning boundary results in a decreasing ν_e^* along the x-axis of Figure 1 because[7] $\nu_e^* \sim T_e^{-2}\, \varepsilon^{-1.5}$.

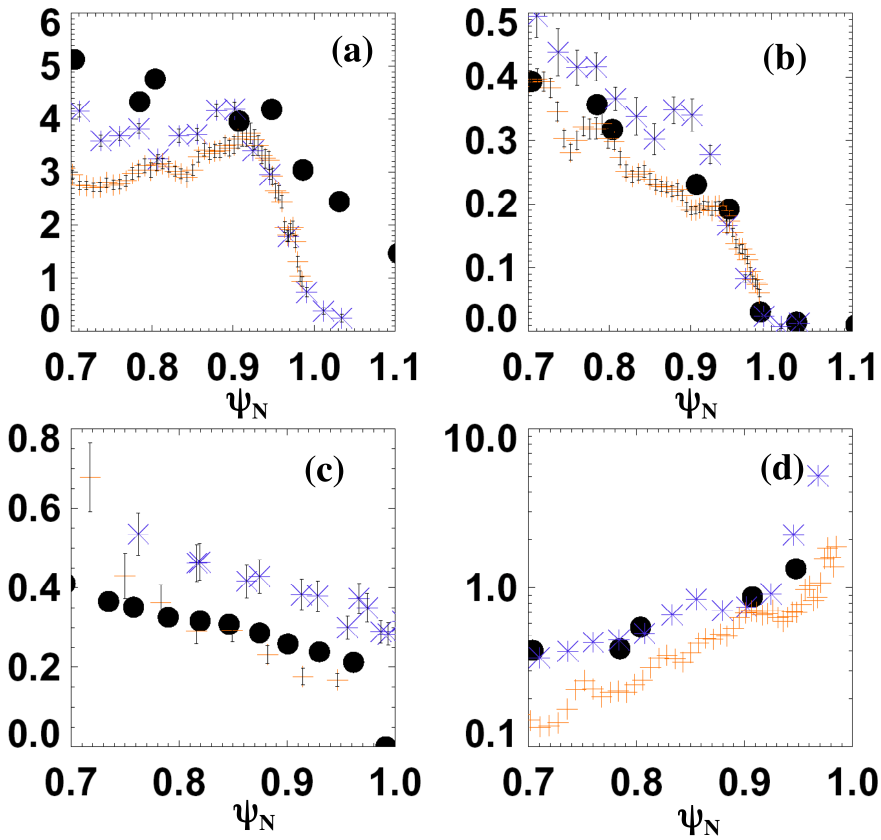

Fig. 3. Profiles from DIII-D (blue stars - #121504), MAST (red crosses - #16457), and NSTX (black circles - #120200) for: (a) n_e, (b) T_e, (c) T_i, (d) ν_e^*. Note that panels (a) and (b) extend radially further than panels (c) and (d). Error bars for NSTX data are smaller than the symbols.

MAST, NSTX and DIII-D are ideal aspect ratio scan candidates, with the first two machines providing a low aspect ratio comparison with $\varepsilon \sim 0.7$, as compared with the DIII-D $\varepsilon \sim 0.35$. We note that the actual NSTX and MAST major radii lie to the left of the x-axis in Figure 1, leading to the prospect of a measurably large difference in the pressure gradient limit before the onset of intermediate-n peeling/ballooning modes.

II. Status of experiments

To test the ELITE code prediction discussed above, a common double-null shape was developed for these experiments within each machine. This shape had minor radius ~ 0.61m, triangularity $\delta\sim0.5$, and elongation $\kappa\sim1.9$, and is shown in Figure 2. There are some minor, residual differences in the shapes between the three devices. In particular, the squareness[8] varied from about 0.0 to 0.2 between MAST and NSTX, with MAST having the lower squareness value. This difference in squareness was concluded to have little impact on the edge stability for this set of experiments: the shape flexibility of DIII-D was used to verify that a squareness variation from 0 to 0.2 had no substantial impact on the plasma profiles within that device in this regime. The toroidal fields and plasma currents used were 0.45-0.55 T and 0.6–0.8 MA in all three machines.

Generally speaking, the plasma profiles obtained in all three machines were similar (Figure 3), although the edge temperature in MAST was somewhat lower, owing to the maximum amount of NBI power available at the time of the experiment. The dimensionless parameter $\nu^*\sim1$ was nonetheless well-matched at the top of the outboard pedestal by variation of the target density while maintaining ELMy H-mode (panel 3d). The normalized ion gyro-radius $\rho_i^*\sim0.015$ was also matched between DIII-D and NSTX, whereas MAST was ~ 50% lower, owing to a lower edge T_i. The outboard pedestal values were chosen as the quantities to be matched because ballooning stability imposes the most stringent limits on the local gradients at the low-field side, i.e. the outer midplane.

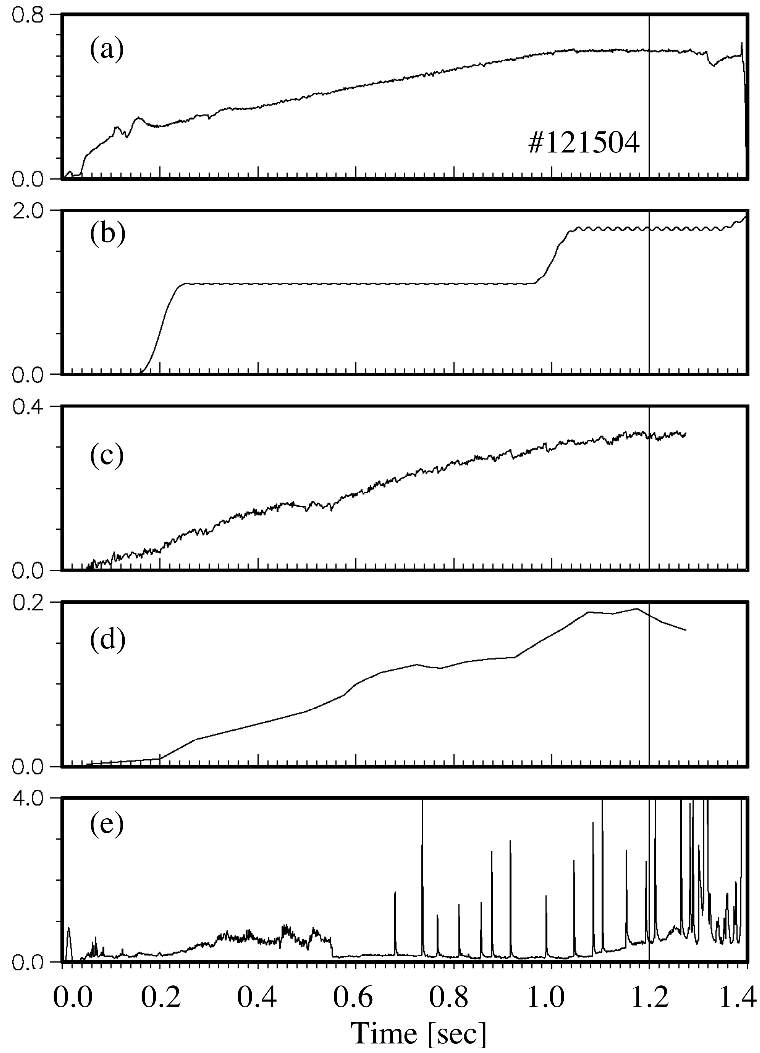

Fig. 4. Characteristics of DIII-D discharge: (a) I_p [MA], (b) neutral beam power P_{NBI}, [MW], (c) line average density n_e [10^{20} m^{-3}], (d) stored energy W_{MHD} [MJ], and (e) divertor D_α [au].

IIa. DIII-D results

In order to keep the ion gyro-radius approximately constant across machines, the DIII-D discharges were run at a reduced B_t level of 0.5 T; this was the lowest B_t value that allowed reproducible discharges. The I_p value of 0.6 MA was selected to yield a comparable |B| across machines at the outer midplane, as preliminary experiments indicated that the actual values for the pedestal ion temperature T_i would be comparable at the edge stability limit.

Time traces of the main characteristics of a DIII-D discharge from this experiment are show in Figure 4. The L-H transition was observed at t=0.55sec, resulting in an ELMy H-mode discharge. At t=1.0 sec., the neutral beam power P_{NBI} was increased to ~ 1.8 MW to push toward the stability limit. The shape was matched reasonably well, and the discharge was quasi-steady during the analysis window of t=1.15-1.25 sec.

Table I: Pedestal characteristics in DIII-D, obtained from the hyperbolic tangent fits

Profile	Height	Width (% of ψ_N)	Peak Gradient
n_e	0.36 (10^{20} m^{-3})	6.3	5.2 (10^{20} m^{-3}/ψ_N)
T_e	0.33 (keV)	8.5	4.2 (keV/ψ_N)
P_e	1.9 (kPa)	6.6	29 (kPa/ψ_N)

The procedure to analyze the edge stability has been described elsewhere[9] and is summarized here. This procedure consists of three parts: step 1 consists of equilibrium reconstruction using the kinetic profiles for constraints within the EFIT reconstruction code[10]. Here n_e, T_e, and P_e profiles are available from a 200 Hz, 40-channel Thomson Scattering system, and T_i profiles from a 100 Hz charge exchange recombination spectroscopy system. Only the kinetic profiles occurring over the last 20% of the ELM cycles in the analysis window are used as the basis for the equilibrium fits. These profiles were fit with a modified hyperbolic tangent procedure[11], and the bootstrap current was obtained from a neoclassical calculation. We note that the pedestal n_e, T_e and P_e widths measured for these discharges were between 6-8% in ψ_N (normalized poloidal flux), i.e. almost twice as large as the normal range of widths at the normal B_t=2.1 T (see Table I). Step 2 consists of a variation of the edge pressure gradient (at fixed current density) and the edge current density (at fixed pressure gradient) in a

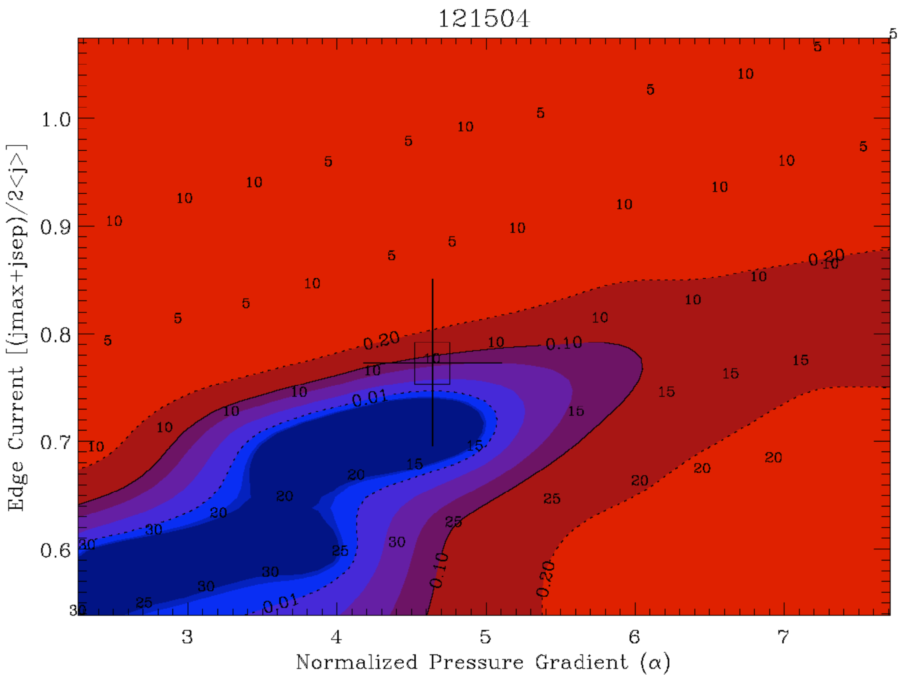

Fig. 5. Results of edge stability calculations for the DIII-D discharge, showing that the edge bootstrap current lies close to the peeling mode boundary. DIII-D discharges from this experiment with slightly higher collisionality lie closer to the ballooning mode boundary than the peeling mode boundary.

fixed-boundary calculation starting from step #1. Finally step 3 involves evaluation of the edge stability of the equilibria from step #2 with the ELITE code.

Figure 4 shows that the discharge experimental edge current density and normalized pressure gradient are rather close to the peeling mode instability boundary for the discharge in Figure 3. More specifically Figure 4 shows a contour plot of the normalized growth rate (γ/ω_A) for toroidal mode numbers n=5,10,15,20,25,30 computed with the ELITE code, and the reference point is given by the symbol with 10% error bars. The solid line marks the contour of γ/ω_A =0.1, which is a reasonable estimate of the effective stability boundary where $\gamma > \omega_*/2$. Roughly speaking, the blue region is stable, and the shades of purple are the transition region to instability. The small numbers on the plot indicate most unstable mode. This result is consistent with other DIII-D analysis which shows that the edge plasma is near either the peeling or ballooning boundary shortly before a Type I ELM[6].

IIb. MAST results

Time traces of the main characteristics of a MAST discharge from this experiment are show in Figure 6. The L-H transition was observed at t=0.265sec, resulting in an ELMy H-mode discharge which subsequently became ELM-free past ~ 0.31 sec. Heating power of 1.9 MW was provided both by the old ORNL beam as well as the new JET-based neutral beam injectors.

On MAST, two Thomson scattering systems are installed: a Ruby laser system with 300 channels at a single time slice[12], and a YaG laser system at 200 Hz which was recently upgraded to 35 channels. The pedestal widths in MAST are obtained from a fit to a hyperbolic tangent function as described above[11], with the extra consideration of the spatial resolution of the diagnostic. This high resolution system has enabled the investigation of various issues, such as the inboard/outboard mapping of pedestal widths[13]. For the subsequent pedestal analysis, we use the 300 channel system (at t=0.33 sec) for optimum spatial resolution, with the pedestal widths

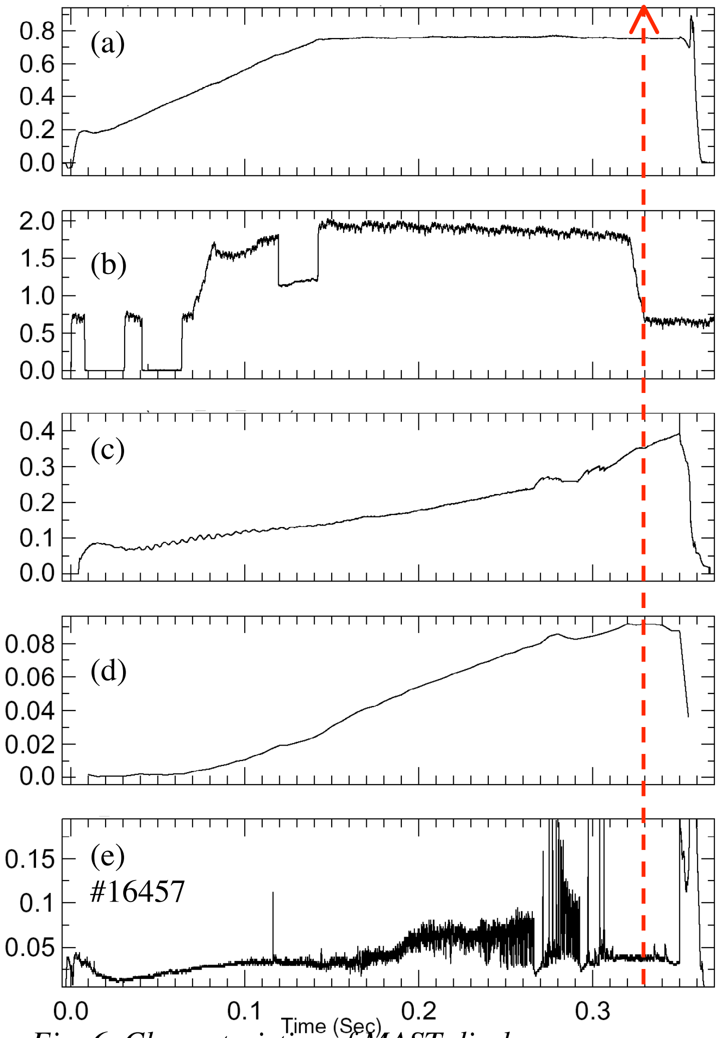

Fig. 6. Characteristics of MAST discharge: (a) I_p [MA], (b) neutral beam power P_{NBI}, [MW], (c) line average density n_e [10^{20} m^{-3}], (d) stored energy W_{MHD} [MJ], and (e) divertor D_α [au].

obtained from fits of the high-field side data for technical reasons.

In contrast to the broad pedestal widths measured in the DIII-D discharges, the pedestal widths in MAST were measured at between 3.6-4.4% in ψ_N space; the n_e, T_e, and P_e widths were all comparable (Table II).

Table II: Pedestal characteristics in MAST, obtained from the hyperbolic tangent fits

Profile	Height	Width (% of ψ_N)	Peak Gradient
n_e	0.39 +/- 0.11 (10^{20} m^{-3})	4.6 +/- 0.4	8.8 +/- 0.3 (10^{20} m^{-3}/ψ_N)
T_e	0.16 +/- .006 (keV)	3.6 +/- 0.7	3.8 +/- 1.1 (keV/ψ_N)
P_e	1.1 +/- .05 (kPa)	4.2 +/- 0.4	27 +/- 2.0 (kPa/ψ_N)

The edge stability analysis procedure is similar to that described above for DIII-D, with the ELITE code being the common element. An adjustment is required to the profiles because the time of the Ruby laser firing is almost 20ms before the large ELM that terminates the discharge. The more frequent YaG system profiles show that the n_e and P_e pedestal heights continue to increase by about 25% before the large event near t=0.35 sec; both the n_e and P_e widths, as well as the T_e pedestal height and width, remain relatively constant during that time. Hence the Ruby profiles are n_e and P_e heights and gradients were increased by 25% to account for the pedestal evolution. Figure 7 shows that the discharge was rather close to the ballooning mode boundary, and well away from the peeling mode stability boundary, i.e. the edge current density would have to increase by at least 100% to destabilize peeling modes.

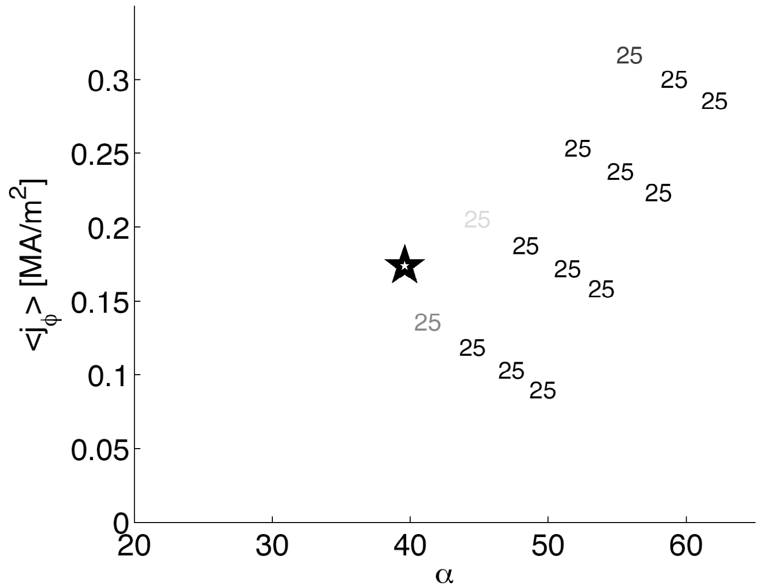

Fig. 7. Results of edge stability calculations for the MAST discharge. The datapoint is close to the ballooning boundary.

IIc. NSTX results

Time traces of the main characteristics of an NSTX discharge from this experiment are show in Figure 8. The L-H transition was observed at t=0.165sec, resulting in a Type I ELMy H-mode discharge. A secular density rise is observed in panel (c), a common characteristic of H-mode discharges in NSTX, which originates mainly from the absence of active divertor pumping. This rapid density rise necessitates a higher NBI power of 4 MW to achieve the target ν_e^*.

Evaluation of the profile heights and widths is accomplished with a modified hyperbolic tangent procedure[11] similar to that mentioned above for DIII-D and MAST. The pedestal heights typically obtained in NSTX H-modes are 2-5 x 10^{19} m^{-3}, 100-300 eV, and 1-3 kPa for n_e, T_e, and P_e respectively[14]. Analysis of these heights and widths from this experiment are still in progress, which will be followed by stability analysis with the ELITE code.

III. Summary

We have obtained data in the target shapes in devices in ELMy H-mode discharges. In DIII-D, the pedestal width corresponds to 6-8% of ψ_N, which is ~ 50-100% larger than typical pedestal widths at higher field. The edge stability analysis indicates the plasma is at the peeling/ballooning boundary just before a Type I ELM. In MAST, the pedestal widths measured on the inboard side correspond to 3-4% of ψ_N, which is comparable to typically observed widths. The peak pressure gradients are comparable from these two devices. The pedestal T_e and T_i values are lower in MAST than the other devices, and additional NBI heating is required to increase these values. This additional heating will be available in 2007. However, recent work suggests that this additional heating will increase the T_e pedestal height and width, while maintaining the same gradients[15]. The stability analysis in MAST indicates proximity to the ballooning boundary, but several issues relating the differences between pedestal widths measured on inboard and outboard sides need to be resolved for a firmer conclusion. Finally in NSTX, data from additional Thomson scattering channels is being calibrated at presented, which will allow for an assessment of the pedestal characteristics and edge stability in early 2007.

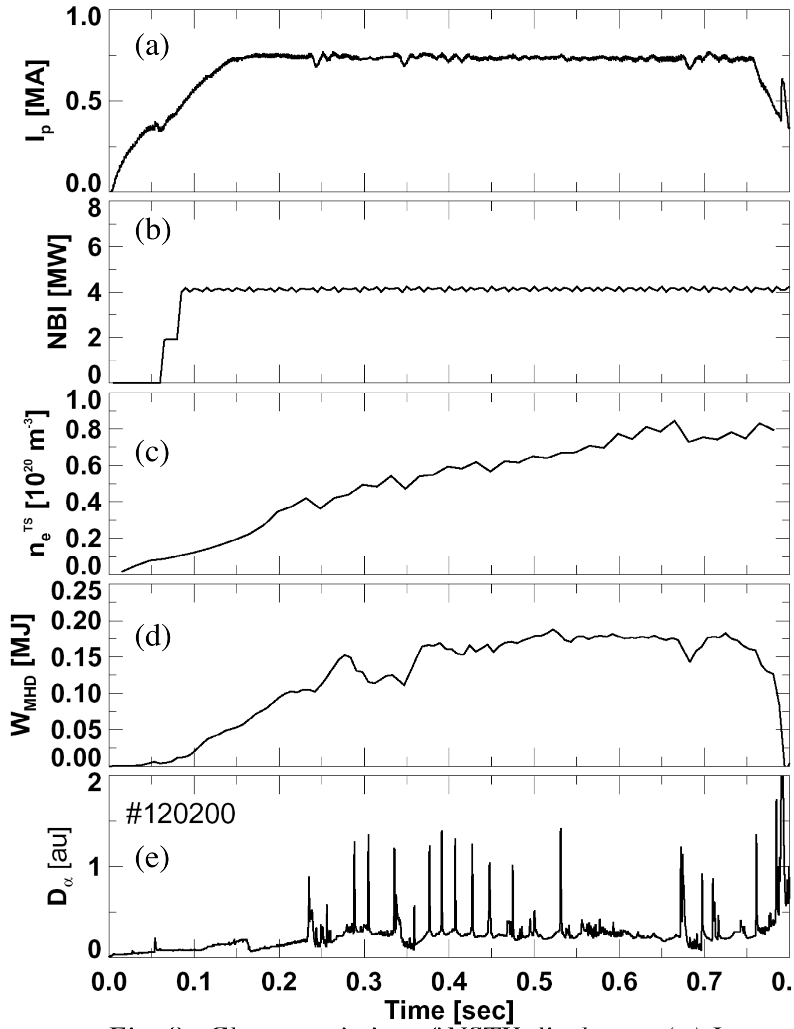

Fig. 8. Characteristics of NSTX discharge:(a) I_p [MA], (b) neutral beam power P_{NBI}, [MW], (c) line average density n_e [10^{20} m^{-3}], (d) stored energy W_{MHD} [MJ], and (e) divertor D_α [au].

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