L-H Mode Transitions in the NSTX Spherical Torus: Experiment/Theory Comparisons

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Abstract

Edge data from plasmas in the National Spherical Torus Experiment (NSTX) have been compared to theories of transport suppression that have been used to develop a framework for L- to H-mode transitions. The NSTX data were obtained in low aspect ratio ($R/a \simeq 1.3$) discharges taken from a variety of discharge phases, including L-modes, H-modes with and without ELMs and L-H transitions. The comparisons show that while the H-mode and L-mode groupings of points are clearly separated by the theories, indicative of the strong leverage by edge gradients, the transition grouping of points are well mixed with the purely L-mode grouping. These results are consistent with those from higher aspect ratio, and they indicate that the theories at present have not identified those parameters critical for 'predicting' that an L-H transition will take place. Additionally, there is no evidence for an edge temperature threshold necessary for transitioning into the H-mode.

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The discovery of the High-confinement (H-) mode[1] nearly two decades ago, as well as development of the "supershot"[2] operating scenarios, have indicated the critical role of the plasma edge in optimizing confinement throughout the entire plasma. In particular, the H-mode offers an operating scenario that can combine high energy confinement, greater plasma stability to magnetohydrodynamic (MHD) modes and steady-state operation. It is, therefore, important to understand those discharge conditions and parameters that could lead to the transition from the low confinement (L-) mode to the H-mode state. Since the H-mode transport barrier develops near the plasma edge, it is natural to study plasma edge parameters in this context.

There has been much work to develop theoretical models of transport suppression that both distinguish between the two confinement states, and, more importantly, that can lead to a predictive means of identifying conditions and parameter changes just prior to the transition between the two. The latter will help to identify the underlying physics mechanisms as well as facilitate device operation when H-mode states either are or are not desired. The theoretical developments have focused on drift-resistive ballooning modes,[3,4] peeling modes,[5] and the drift-Alfvén instability.[6] A description of the specific parameters of interest for each theory will come later.

The theory bases have enabled experimentalists to characterize the measured edge parameters by the important variables as predicted by the theory in an effort to identify the underlying change of transport processes. For instance, results from Alcator C-Mod indicated a threshold edge T_e for an L-H transition of approximately 200 to 250 eV, and clearly showed a distinction, within the framework of the drift-resistive ballooning mode theory, between discharges in well developed L- or H-mode plasmas.[7] That there is a temperature threshold was disputed by DIII-D results,[8,9] which, nevertheless, also showed a distinction between L- and H-mode phases for all three theories, but the results did not identify parameter changes as a precursor to an H-mode transition.[8] Furthermore, the H-mode edge parameters for pellet-fueled discharges in DIII-D fell significantly below those predicted

by the theories.[9] On the other hand, data from COMPASS-D appears to show some predictive capability of the drift-Alfv́en theory in that discharge characteristics near the time of the L-H transition clustered at or above the predicted transition threshold.[10]

In this paper, for the first time, data from L- and H-modes in a high power spherical torus (i.e., low aspect ratio tokamak) will be studied in the framework of the theories discussed above. The data were obtained from experiments on the National Spherical Torus Experiment (NSTX), which has the following operating parameters: Major/minor radius, R/a=0.85/0.68 m $\simeq$ 1.3; plasma current, $I_p \leq$ 1.4 MA; toroidal magnetic field, $B_T \leq$ 0.45 T; elongation, $\kappa \leq 2.2$; triangularity, $\delta \leq 0.4$; neutral beam heating power, $P_{NB} \leq$ 5 MW (80 keV D^0 neutral beams); High Harmonic Fast Wave RF heating power, $P_{HHFW} \leq 6$ MW, and D^+ plasmas. A complete description of the design and physics mission of the experiment can be found in Kaye et al.[11]

H-mode plasmas were created in NSTX with both NB and RF heating. In order to obtain an L-H transition with neutral beam heating, it was necessary to operate with plasmas in a lower single null configuration with a 1 to 3 cm inner wall gap, I_p from 0.7 to 1.0 MA, B_T from 0.4 to 0.45 T, and $P_{NB} > 0.85$ MW. For H-mode plasmas with RF heating only, I_p=0.35 to 0.5 MA. Densities at the transition were in the range from 1.5 to 2.0 $\times\ 10^{19}\ m^{-3}$. H-phases of up to 130 msec were produced, and the discharges tended to be ELM-free if the plasmas became diverted at the start of the current flattop phase but ELMy if the plasma became diverted during current ramp-up. Descriptions of the NSTX H-modes can be found in Maingi et al[12] and Bush et al.[13]

The critical data used for this study come from the multi-point Thomson scattering (MPTS) diagnostic, which measured instantaneous electron temperature and density profiles every 15 or 30 msec (a second laser was implemented during the last portion of the run allowing the halving of time between profile measurements). During the course of this run, the MPTS profiles consisted of 10 spatial points, with the channels separated by approximately 5 cm in the outer portion of the plasma. Because of the coarseness of the MPTS

spatial resolution, the density and temperature gradients may reflect more the height of the density and temperature "pedestals" respectively than local gradients existing over a spatial extent <5 cm. Temperature, density, and gradients of these quantities were taken from spline fits to the MPTS data for this study. Data were chosen at locations midway down the edge density gradient, similar to the location chosen for the DIII-D studies.[8] The edge reflectometer diagnostic, which could measure density profiles with much greater spatial resolution than MPTS, was just being brought on-line during this run, and data was not available for most of the discharges used for this study.

Figure 1 show sets of MPTS profiles in the outer portion of the plasma (R $\geq$ 1.1 m) for two discharges, one (Fig. 1a) just before the L-H transition (t_{LH}=207.6 msec), and one (Fig. 1b) in the midst of the H-phase (t_{LH}=158 msec). Also shown in each figure are the positions of the separatrix, as determined from EFIT magnetic reconstructions,[14] and the "mid-gradient" location at which the relevant plasma parameters are measured or calculated. Note that the mid-gradient location is determined from the positions of the knee and the separatrix. The red triangles in the figures represent the actual data points whose statistical (photon counting) errors are smaller than the triangle height. The blue lines are the spline fits to the data. For the L-H time shown in Fig. 1a, edge reflectometer data was available, and the density profile measured by this diagnostic is shown by the magenta line. As can be seen for this shot, the MPTS and the reflectometer data agree well to near the location of the density "knee" (R$\simeq$1.44 m). Beyond this radius the reflectometer data actually shows a slightly higher density and larger density gradient scale length than does the MPTS measurement. We cannot generalize this behavior to the other discharges for which the reflectometer data is not available, but at least for this discharge the density gradient is not being underestimated by the relative coarse spatial resolution of the MPTS diagnostic.

What is clearly seen in the Fig. 1b is the development of an "ear"[15] in the density profile, and the much larger region over which the edge density gradient exists, during the

ELM-free H-phase. In these cases, the density gradient, as determined from the spline fit, is about 55 to 60% larger during the H-phase than just prior to the transition. This result typically holds for all the points used in this analysis.

For the comparison with theory, 100 different time points from 81 different discharges were used. The 100 time points were grouped by the following discharge phases and conditions: L-mode - 33; Dithering transitions - 20; times just prior to the L-H transition - 18; ELM-free H-mode (NB heating) - 20; ELMy H-mode (NB heating) - 2; ELM-free H-mode (RF heating) - 5; ELMy H-mode (RF heating) - 2. For the L-H transition grouping, only times where the MPTS measurement was within 6 msec prior to the transition were used. For this grouping, the range of $\Delta t_{LH} = t_{LH} - t_{MPTS}$ was 0.0 to 6.0 msec, with an average value of 3.2 msec and a standard deviation of 2.0 msec. For the H-mode grouping, including both NB and RF heated, and ELM-free and ELMy points, the range of $\Delta t_H = t_{MPTS} - t_{LH}$ was 3.0 to 99.3 msec, with an average Δt_H=30.0 $\pm$ 21.4 msec. Dividing the data into these groupings is important for both determining any significant differences among the various phases as well as, particularly with the L-H grouping, determining whether there are any theory-based parameters that can be used as predictors for impending transitons.

The results of the comparisons are shown in Fig. 2. Data is plotted in terms of the relevant theoretical quantities for the drift-resistive ballooning mode (Fig. 2a), the peeling mode (Fig. 2b), the drift-Alfv́en mode (Fig. 2c), and, for completeness, the electron temperature is plotted versus the electron density at the mid-gradient location for all the groupings of points (Fig. 2d).

In the drift-resistive ballooning mode theory, the two controlling parameters are the MHD ballooning parameter, $\alpha_{MHD} = -Rq^2 d\beta/dr$ and the diamagnetic parameter, α_{DIA}, which reduces to $(\rho_s \Omega_e)^{1/2}/[2^{5/4}\pi(RL_n)^{1/4}(1+\tau)q\nu_{ei}^{1/2}]$ where $\rho_s = c_s/\Omega_{ci},\ \tau = T_i/T_e$, and L_n is the density scale length, with all quantities taken locally and τ taken to be one. The above expressions are valid for a shifted circle geometry, which is not entirely appropriate for NSTX; however, the difference in results from the above expressions and those

with general geometry and shaping corrections is small.[16] Also, for these comparisons, only the electron profiles were used to determine $L_n, L_p, d\beta/dr$, etc. Consequently, not as much attention should be paid to the absolute values of the parameters in Figs. 2a-c as as to the relative separations and boundaries among the groups of points.

In the drift-resistive ballooning theory, higher α_{DIA} causes enhanced poloidal flow shear which serves to suppress turbulence. In addition, and finite α_{DIA}, increased α_{MHD} also leads to transport suppression so that a reduced transport (H-mode) region forms at high values of α_{DIA} and α_{MHD}. The NSTX results shown in Fig. 2a show, in fact, a fairly clear separation between points in a developed H-phase and those points in either L-mode or the transition groupings consisting of dithering and L-H transitions. H-phase points occur for α_{MHD} values ≥ 1 at all α_{DIA}. Of particular interest is that little difference is seen among the L-mode and transition groupings. Some of the points in the L-H transition group appear to have slightly larger values of α_{MHD} than others; however, the majority of them do not.

In the peeling mode formulation, the key parameters are the electron collisionality, $\nu_e \propto n_e ln\Lambda Z_{eff} q R_0^{5/2}/(T_e^2 r^{3/2})$ and, once again α_{MHD}. The peeling mode is stabilized by edge pressure gradient, but destabilized by edge current. Therefore, high collisionality is needed to reduce the bootstrap current driven by large ∇p, thus forming a space of reduced transport at large α_{MHD} and ν_e. Fig. 2b also shows a clear separation between the H-phase points and the L-mode or transition groupings, with little evidence for pre-knowledge of an impending transition.

The same results are also seen in Fig. 2c, in which "β_n" $= (\frac{M_i}{m_e})^{1/2}\alpha_{MHD}/(sq(1+\nu_n^{2/3})$ where $s = rq'/q$, and $\nu_n = \nu_e(M_i L_p/sm_e qR)^{1/2}$), is plotted against ν_n. In this drift-Alfvén mode theory, transport is suppressed above a threshold in "β_n". The NSTX data do show that the H-phase points generally lie above "β_n" $\simeq 2$, consistent with the COMPASS-D and DIII-D results, but again the transition groupings appear to lie well within the L-phase grouping.

For completeness, the mid-gradient n_e and T_e values are shown in Fig. 2d, where there is no clear evidence for any temperature threshold separating the L-mode or transition points and the H-phase points. The fact that the H-phase generally occurs at higher densities is indicative of the development of the edge density transport barrier during this phase.

In summary, this paper presents the first attempt to relate edge measurements in a high power Spherical Torus to transport suppression theories in order to understand mechanisms that may lead to the transition from the L- to the H-mode. Data measured by the MPTS diagnostic were broken into different groupings, and for the three theories studied, clear differences between the H-phase points and L-mode and transition groupings are seen. These differences can be attributed primarily to the larger edge gradients during the H-phase, and the strong dependence of the respective theory parameters on these gradients and gradient scale lengths. Of significance is that, for the spatial resolution of the present diagnostic measurements, the transition groupings lie within the parameter range of the L-mode group, indicating that, as with higher aspect ratio results, these theories as yet have not identified those parameters key to predicting a transition, even within a few msec before this event, and, therefore, the theories indicate the effect of the H-mode, not the cause. Furthermore, the NSTX data show no temperature threshold for transitioning into the H-mode.

The present NSTX data set was admittedly limited by the relatively coarse spatial resolution of the MPTS diagnostic, and, therefore, large local gradients, those whose extent is <5 cm, cannot readily be resolved. This limitation will be obviated in future studies, which will take advantage of an upgraded MPTS system with 20 spatial points, having a spatial resolution near the edge of one to two cm. Additionally, density profile information will be obtained from an edge reflectometer, which has a spatial resolution between 0.5 and 1.0 cm and can complete a full profile measurement (i.e., frequency sweep) in 50 to 100 μsec. It is not inconceivable that the higher spatial resolution will yield data exhibiting finer scale structure than is reported here. Nevertheless, these first results from NSTX suggest that a

predictive tool for L-H transitions is still not at hand.

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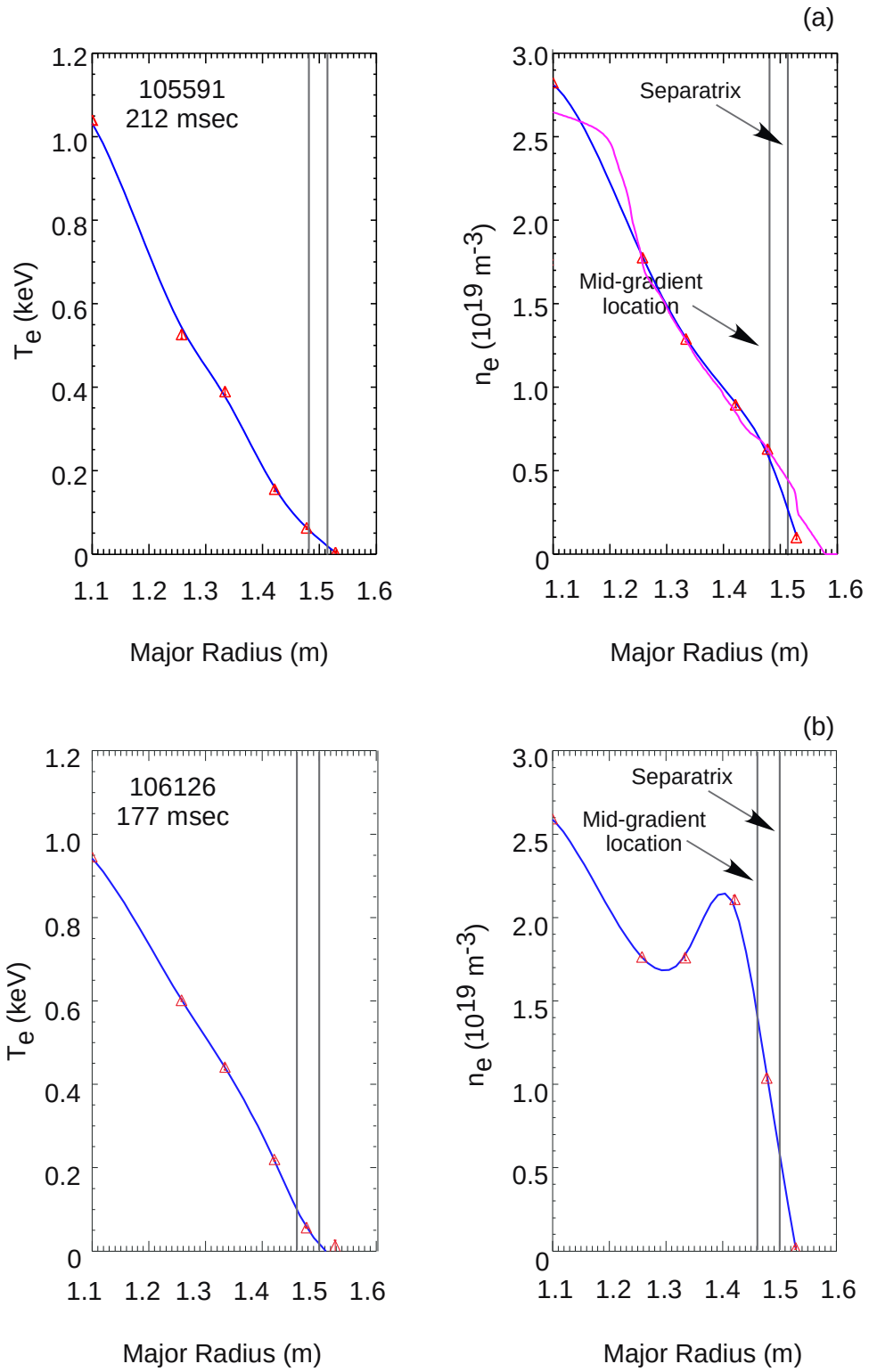

Figure 1: MPTS electron temperature and density profiles measured (a) just before an L-H transition and (b) during a well developed H-phase. The red triangles are data points, the blue curves are spline fits to the data, and the magenta curve is the density profile as measured by the reflectometer.

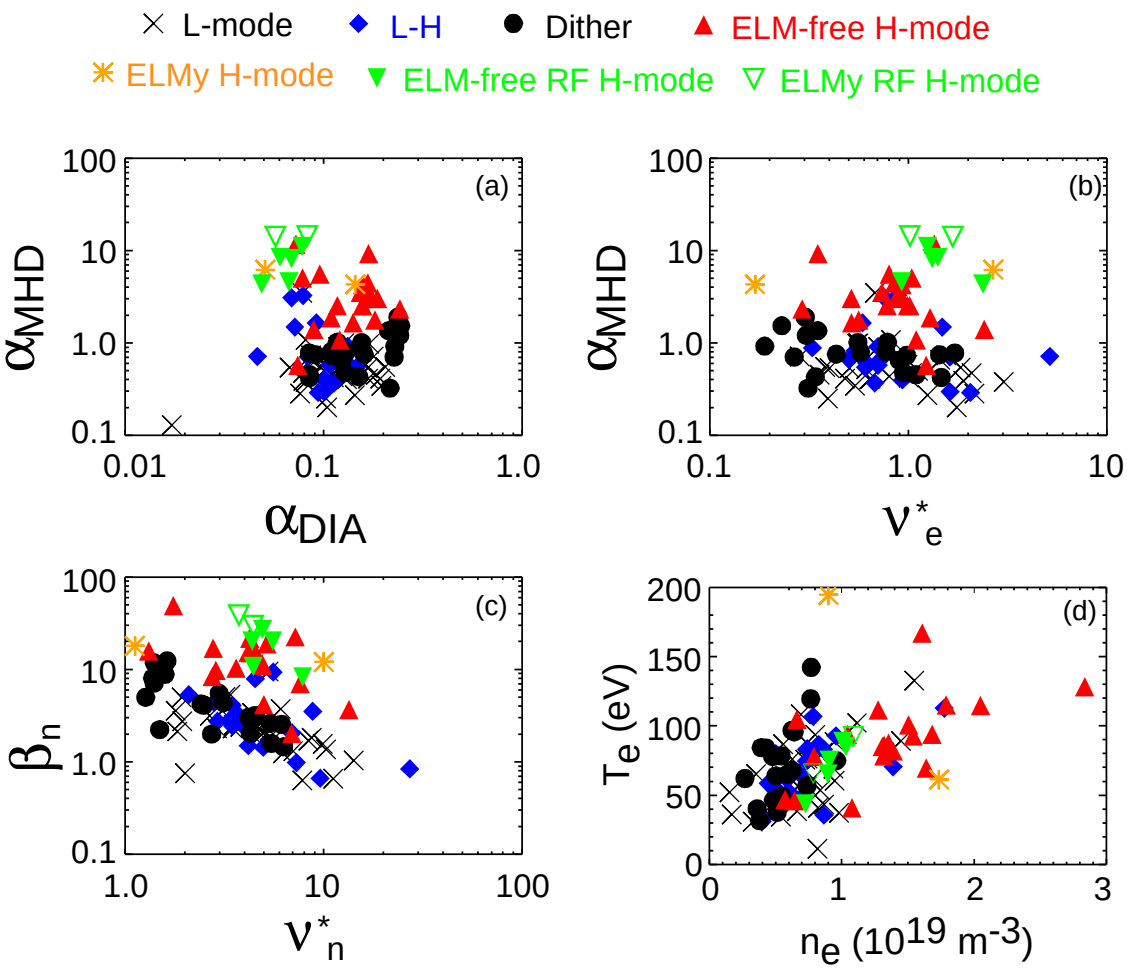

Figure 2: Comparisons between experimental data and theory for (a) drift-resistive ballooning modes, (b) peeling modes and (c) drift-Alfv́en modes. (d) gives the T_e plotted against n_e at the mid-gradient location.