L-to-H power threshold comparisons between NBI and rf heated plasmas in the National Spherical Torus Experiment

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Recent experiments on the National Spherical Torus Experiment[1] (NSTX) have focused on investigating important dependencies of the power threshold for the L-to-H mode transition, P_{LH}. These experiments are motivated by recent results from MAST and ASDEX-Upgrade[2], which show a reduction of P_{LH} in double null configuration compared to single null configuration with the ion grad-B drift towards the lower X-point. The role of magnetic configuration (double null, lower single null, upper single null) on P_{LH} was investigated for both neutral beam injection (NBI) heated and high harmonic fast wave (HHFW) rf heated plasmas. Furthermore, the height of the X-point was found to be an important parameter in establishing H-mode in Ohmic, NBI, and rf heated plasmas, as investigated previously on JET[3]. At fixed configuration (e.g. balanced double null) it appears that P_{LH} is similar for discharges that are NBI heated and those that are rf heated. This is surprising since NBI heats partly the core plasma ions and imparts a large amount of toroidal rotation to the plasma, while rf heating predominantly heats core plasma electrons and imparts little toroidal rotation. This confirms that edge plasma conditions are more important in determining the L-to-H transition, and that in NSTX the transition is relatively insensitive to the two primary heating mechanisms available (since they impart energy and momentum largely in the core of the plasma.)

Observations

The magnetic configuration was scanned between lower single null (LSN), double null (DN), and upper single null (USN). The magnetic configuration can be quantified by defining the parameter $d_{r,sep}$, which is the radial separation distance at the outboard mid-plane of two flux surfaces, corresponding to the upper and lower X-points. As such, a “balanced” DN configuration has $d_{r,sep}$=0. By convention $d_{r,sep}$<0 corresponds to LSN plasmas, and $d_{r,sep}$>0 corresponds to USN plasmas.

Table 1 summarizes the injected P_{LH} values for the wide range of plasma conditions that were explored in this experiment. In both NBI heated and rf heated plasma the lowest P_{LH} occurred for a DN configuration, increasing in LSN plasmas, and was highest for USN plasmas. Moreover for rf heated plasmas in the LSN configuration, P_{LH} was observed to increase as $|d_{r,sep}|$ was increased. For rf heated plasmas it was not possible to reach H-mode in the USN configuration for the amount of heating power available (3.2 MW). At higher plasma current the plasmas spontaneously transitioned into H-mode without any auxiliary heating in DN and LSN configurations.

Pulse	Ip (kA)	Conf.	$d_{r,sep}$ (mm)	P_{NBI} (MW)	P_{rf} (MW)
117752	600	DN	0	0.6	--
117747	600	LSN	-20	1.1	--
117750	600	USN	14	4.0	--
117767	600	DN	0	--	0.6
117777	600	LSN	-5	--	1.7-2.2
117782	600	LSN	-17	--	2.7
117756	900	DN	0	--	--
117754	900	LSN	-24	--	--

Table 1: Summary of P_{LH} and magnetic configuration, quantified by $\mathbf{d_{r,sep}}$*, for NBI, rf, and Ohmically heated plasmas.*

Previous experiments[2] on NSTX have covered a similar scan of configuration and heating power. In those experiments it was not possible to achieve H-mode with the heating power available except in DN configuration, which has the lowest P_{LH} as shown here. Those prior experiments were performed with a significantly “higher” (i.e. closer to the mid-plane) X-point location. Though a detailed scan of P_{LH} versus X-point height was not the goal of these experiments, it does reinforce the importance of this parameter in attaining H-mode.

This set of experiments allows plasmas heated by NBI or rf power to be compared with similar wall conditions, in similar magnetic configurations. In particular, the role of plasma rotation in the L-to-H transition can be examined since NBI in NSTX is in the co-current direction and exerts a significant amount of torque on the core of the plasma, leading to high measured toroidal rotation rates. Moreover, while (HHFW at 30 MHz) rf power as used on NSTX heats predominantly core electrons[4], about 33% of NBI heating power goes directly to ions, leading to a larger T_i/T_e ratio. The role of ion versus electron heating in P_{LH} can thus be examined, in principle.

In NSTX the protective tiles surrounding the rf antenna act as the limiting surface on the outboard mid-plane. In the discharges presented here, the magnetic configuration was held approximately constant as NBI or rf power was applied, with one difference: the rf heated plasmas were shifted outward by ~5 cm at the mid-plane to provide better plasma-antenna coupling. In NBI heated plasmas the "outer gap" was 5 cm wider to prevent beam fast-ions from damaging the rf antenna. This represents one difference in comparing across heating schemes with nominally fixed configuration. Additionally, during HHFW rf heating approximately 20% of the launched power is absorbed through the parametric decay instability by edge ions[5]. However, to determine P_{LH} discreet input power levels were applied (in both NBI and rf heated plasmas) while looking for an L-to-H transition; the separation between these input power levels was greater than the known 20% uncertainty in the rf power deposition.

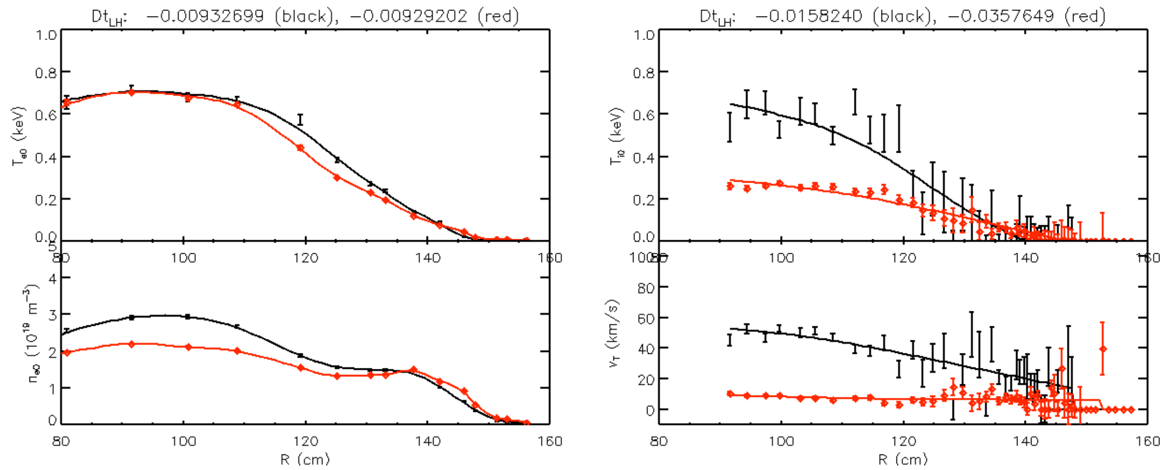

Figure 1: Comparison between NBI heated (black) and rf heated (red, diamonds) DN discharges prior to the L-to-H transition.

Nevertheless, P_{LH} was similar in NBI and rf heated plasmas for a given magnetic configuration, e.g in DN plasmas. This is true despite large difference in core plasma parameters, as shown in Fig. 1. Charge exchange measurements of ion parameters are accomplished in rf heated plasmas by momentarily (10 ms) pulsing the NBI. Since the beam-slowing-down time is about 30 ms in NSTX, this beam "blip" should not significantly perturb the plasma during the period of measurement. Though these numbers suggest different plasma behaviours in the core, inconsistent with the observed P_{LH} similarities, examination of the plasma edge suggest these plasmas (in the edge) are more similar than different. Before the L-to-H transition, $(T_{i95})_{NBI}$~$(T_{i95})_{rf}$~50 eV, $(T_{e95})_{NBI}$~$(T_{e95})_{rf}$~50 eV, and $(n_{e95})_{NBI}$~$(n_{e95})_{rf}$~$1x10^{19}$ m^{-3}, within experimental errors. Moreover the radial electric field in the same region, E_r, as measured by the Edge Rotation Diagnostic[6] (ERD), suggests that $(E_r)_{NBI}$~$(E_r)_{rf}$~-5 kV/m before H-mode, to within experimental errors. High time and spatial resolution video images of the plasma edge from Gas Puff Imaging[7] (GPI) at the outboard mid-plane, which capture the L-to-H transition, do not show any qualitative difference in the size scale or speed of edge turbulence between L- and H-mode NBI heated plasmas[8].

Discussion

Theory suggests that perpendicular flow shear in the plasma edge destroys turbulent eddies, resulting in reduced radial transport of particles and energy, leading to H-mode formation[9]. Since the pitch angle of the magnetic field in a spherical torus like NSTX can be ~30^o, toroidally measured plasma flow has a significant perpendicular component. The experiments here indicate that toroidal rotation in the edge prior to H-mode is at a low level for both NBI (high core rotation input) and rf (small core rotation) heated plasmas. This suggests that the edge flows are set by some mechanism other than outward momentum transport from the core rotation, leading to similar P_{LH} values in NBI and rf heated plasmas.

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