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(***ref. C-Mod?***). 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 predominantly 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 suggests 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, dr_{sep}, which is the radial separation distance at the outboard mid-plane of two flux surfaces, which correspond to the upper and lower X-points. As such a "balanced" DN configuration has $dr_{sep}=0$. By convention $dr_{sep}<0$ corresponds to LSN plasmas, and $dr_{sep}>0$ corresponds to USN plasmas.

Table 1 summarizes the 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 $|dr_{sep}|$ 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 (***give number***). At higher plasma current, the plasmas spontaneously transitioned into H-mode without any auxiliary heating in DN and LSN configurations. This represents the first time that Ohmic H-mode discharges in LSN configuration have been seen in NSTX. As of yet, an USN Ohmic H-mode has not been observed in NSTX (***Check with Charles Bush on this***).

Pulse	Ip (kA)	Conf.	dr_{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 dr_{sep}, for NBI, rf, and Ohmically heated plasmas.

Previous experiments on NSTX (in 2004) 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 (***give numbers***). 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 cocurrent direction and exerts a significant amount of torque on the core of the plasma, leading to high measured toroidal rotation rates (***give number***). Moreover, NBI predominantly heats core ions, while (HHFW at 30 MHz) rf power as used on NSTX heats predominantly core electrons[4]. 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.

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. In particular, during NBI (RF) heated discharges prior to H-mode, the core ion and electron temperatures were T_{i0}~300 $(250)_{rf}$ eV and T_{e0}~450 $(350)_{rf}$ eV, respectively. After H-mode is established (50 ms post L-to-H), T_{i0}~700 $(500)_{rf}$ eV and T_{e0}~700 $(800)_{rf}$ eV. Similarly, the core toroidal rotation increases from v_{T0}~15 $(15)_{rf}$ km/s to 75 $(30)_{rf}$ km/s from L- to H-mode, respectively. 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, about 1 cm inside the LCFS, $(T_{i95})_{NBI}$~$(T_{i95})_{rf}$~50 eV, $(T_{e95})_{NBI}$~$(T_{e95})_{rf}$~50 eV, and $(n_{e95})_{NBI}$~$(n_{e95})_{rf}$~0.5×10^{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 both before and $(E_r)_{NBI}$~$(E_r)_{rf}$~-10 kV/m during H-mode, to within experimental errors. Likewise, 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 (***double check with SZ on this***) show any qualitative difference between NBI and rf heated plasmas[8]. Hence, it appears that edge parameters play a larger role in governing the L-to-H transition.

Discussion

Theory suggests that flow shear in the plasma destroys turbulent eddies, resulting in reduced radial transport of particles and energy, leading to H-mode formation(***cite Pat Diamond or T.S. Hahm***). These experiments 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. After the L-to-H transition occurs, the toroidal rotation of the NBI heated plasma increases significantly. This appears more consistent with H-mode triggering via zonal flows, rather than equilibrium flow shear(***cite Diamond and Kim***). After the zonal-flow-encouraged transition occurs, turbulent "drag" on the plasma is reduced, allowing equilibrium flow rates in NBI driven discharges to reach high levels. Thus high rotation rates are "allowed" in NBI plasmas, but rotation (and its inherent shear in the edge) does not necessarily lead to H-mode transition. Otherwise H-mode would not occur in rf heated plasmas, unless the amount of rotation required is very low, and can be supplied by SOL flows(***cite C-Mod***). Presumably, if a significant amount of angular momentum is able to reach the core plasma of rf heated discharges, higher rotation rates than in L-mode would also be observed, as is found here.

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