

## Characterization of H-mode Discharges in NSTX

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We report the observation of the first H-mode transitions in the National Spherical Torus Experiment (NSTX). Energy confinement time transiently increased by more than a factor of 2, to order 100ms. Our results are similar to other STs, such as the START and MAST machines<sup>1,2</sup>. As in START, the heating power requirement for accessing the H-mode regime (power threshold) was significantly higher than predicted by a multi-machine database<sup>3</sup> compiled from conventional aspect ratio tokamaks. These H-mode observations in STs challenge *and extend* the existing international power threshold and energy confinement time scalings<sup>4</sup> based on conventional aspect ratio tokamaks. The remainder of this paper discusses characteristics of the H-modes in NSTX. Additional details are given in ref. [5].

NSTX is a relatively new fusion research facility<sup>6,7</sup> (R=0.85m, a=0.67m, R/a = 1.26, B<sub>t</sub> 0.6 T), which commenced physics operation in July 1999. NSTX was designed for operation at 1 MA of plasma current (I<sub>p</sub>) and has achieved 1.4 MA to date. Auxiliary heating systems include a neutral beam injector (NBI), capable of delivering 5 MW to NSTX, and a radio-frequency system designed for 6 MW input power. All of the plasma facing components on the center stack and divertor are clad in graphite armor. NSTX employs a conventional wall conditioning program<sup>8</sup>, which includes center stack resistive bake-out up to 300 deg. C, glow discharge cleaning, and boronization<sup>9,10</sup>. An overview<sup>11</sup> of results is given at this conference.

H-modes in NSTX have characteristics similar to tokamak H-modes. Fig. 1 compares the characteristics of the longest H-mode duration obtained to date in NSTX with an L-mode reference discharge. These discharges had I<sub>p</sub>=1 MA and neutral beam injection power (P<sub>NBI</sub>) = 1.5 MW (Fig. 1a, 1b). Edge visible light, measured by filtered visible spectroscopy (e.g, D in Fig. 1c) and a fast visible camera, was reduced on a 1 ms time scale in the H-mode discharge. This drop indicated a drop in the edge n<sub>e</sub>, as often observed during H-mode transitions in tokamaks. While the scrape-off layer n<sub>e</sub> decreased, the n<sub>e</sub> just inside the magnetic separatrix increased during NSTX H-mode discharges, i.e. a steep n<sub>e</sub> gradient was observed. Fig. 2 compares the electron density, electron temperature (T<sub>e</sub>), and electron pressure (P<sub>e</sub>) profiles from Thomson scattering for the discharges in Fig. 1. The H-mode transition occurred at t=191ms in discharge #104312, and evidence of an increase in the edge n<sub>e</sub> gradient relative to the L-mode reference was shown by the first Thomson laser pulse following the transition at t=197ms. The n<sub>e</sub> profile continued to evolve and actually developed a hump at the edge by t=230ms in the H-mode discharge. The T<sub>e</sub> profile responded to the improved H-mode confinement on a longer time scale, and evidence of a weak T<sub>e</sub> pedestal was observed at t=230ms in the H-mode case. The broader n<sub>e</sub> and T<sub>e</sub> profiles in the H-mode lead to a decrease in the pressure peaking factor (P<sub>peak</sub> = P<sub>0</sub>/P<sub>av</sub>, with P<sub>0</sub>=central pressure and P<sub>av</sub> = volume average pressure) computed with EFIT, from 2.4 in the L-mode down to as low as 2.1. The electron kinetic pressure peaking factor (P<sub>peak,e</sub> = P<sub>0,e</sub>/P<sub>av,e</sub>, obtained

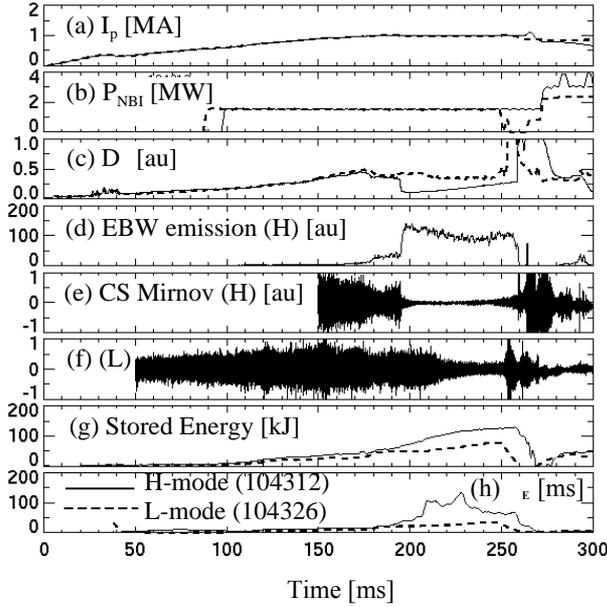


Fig. 1 - Comparison of L-mode (dashed lines in panels) and H-mode (solid lines) discharges in (a)  $I_p$ , (b) NBI power, (c) divertor D emission, (d) Electron Bernstein Wave (EBW) emission at  $R=0.85m$ , (e) Center stack Mirnov signal (H-mode), (f) Center stack Mirnov signal (L-mode), (g) stored energy, and (h)  $\tau_E$ . Panels (g) and (h) are obtained from EFIT reconstruction.

Mirnov signals in Fig. 1e. Fig. 1f shows the L-mode reference case. Note that the envelope of the oscillations was gradually reduced as the plasma X-point was formed at 170ms in both discharges, but that the H-mode discharge exhibited a rapid drop at the L-H transition. However the fluctuation level in the H-mode discharge began to increase slowly at 245ms, indicating the onset of new magneto-hydrodynamic (MHD) activity (discussed later).

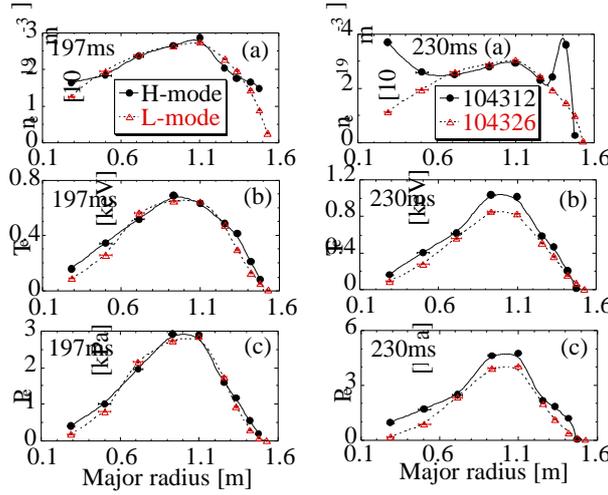
The peak stored energy, obtained by magnetic equilibrium reconstruction with the EFIT code<sup>13</sup>, increased by 60% in the H-mode phase compared with the L-mode reference discharge (fig. 1g). These values correspond to toroidal beta ( $\beta_t = 2\mu_0 P_{av}/B_t^2$ ) of 10% and 6% respectively. The peak rate of rise of both the plasma stored energy,  $dW/dt$ , and the plasma electron inventory,  $dN_e/dt$ , increased by more than 100% in the H-mode phase, up to 1.7 MW and  $2.3 \times 10^{20}$  electrons/s respectively. We mention that the L-mode reference discharge in figs. 1-2 had gas puffing to achieve comparable line-average density prior to the L-H transition in the H-mode discharge. This gas puffing during NBI apparently reduced  $\tau_E$  to 35ms in the reference discharge (fig. 1h). In comparison, lower density L-modes without gas puffing during NBI in NSTX achieved peak  $\tau_E$  50ms and stored energy  $\sim 100$  kJ.

The estimated  $\tau_E$  during the H-mode phase (fig. 1h) varied between 70ms and 120ms, and was up to 3 times higher than the L-mode reference discharge shown. In computing the loss power for the  $\tau_E$  estimate, the  $dW/dt$  term and time derivative of the poloidal field and toroidal field energy were subtracted off, but the NBI shine-through and first orbit loss components were not subtracted. In addition, the stored energy was not corrected for the fast ion component. A useful normalization is the confinement time predicted by an international

from the raw profiles in Fig. 2) also decreased, from 3.7 in the L-mode reference case to 3.1 in the H-mode discharge at  $t=230ms$ , due primarily to the flattening of the  $n_e$  profile.

During the H-mode phase, an enhanced signal was observed (fig. 1d) on the electron Bernstein wave (EBW) emission<sup>12</sup>. Mode conversion of electrostatic Electron Bernstein waves to electromagnetic, X-mode radiation becomes more efficient with the increased edge  $n_e$  gradient during the H-mode. Thus, the prompt increase on the radiometer signal following the L-H transition serves as a useful confirmation of H-mode phases.

The energy confinement in H-modes increases typically by 60-80% over L-mode levels. This increase in  $\tau_E$  has previously been correlated with reduced transport at the edge (and sometimes in the core), as manifested in steep edge  $n_e$  gradients, and the reduced transport is in turn caused by a reduction in the turbulence levels. A signature of the reduced edge turbulence in the NSTX H-modes was observed on the center stack



.Fig. 2 - Comparison of  $n_e$ ,  $T_e$ , and  $P_e$  profiles for L-mode and H-mode (a) 5ms after time of the H-mode transition, and (b) 33ms later, during the ELM-free phase. The outer midplane separatrix lies between 1.45 and 1.50m, and the inner midplane separatrix between 0.19 and 0.22m.

of achieving H-mode, which will lead to an extension of the databases and scalings to low aspect ratio. Other diagnostic signatures are discussed in reference [5].

H-mode access for NSTX has been observed in the following range of conditions:  $0.7 < I_p < 1$  MA,  $B_t = 0.45$  T,  $0.85$  MW  $< P_{NBI} < 1.6$  MW,  $0.6$  MW  $< P_{OH} < 1.5$  MW (ohmic heating power),  $1.7 \times 10^{19} < \bar{n}_e < 2.5 \times 10^{19}$  m<sup>-3</sup>, inner-wall gap 1-2 cm, and only in lower-single null diverted shape. In this configuration, the ion-Grad B drift direction was toward the X-point, and the X-point height was 18cm. To date, no center-stack limiter H-modes have been observed, despite that most high-power NSTX discharges were conducted in that configuration. Also, no ohmic H-mode discharges were obtained. As in the START device, H-modes were obtained well above the 60 kW power threshold predicted for NSTX from a multi-machine scaling<sup>3</sup>. For example, the reference discharge in fig. 1 had loss power ~900 kW. In addition, H-modes were observed only after the third boronization. While it is clear that wall conditions affect H-mode access in NSTX, the precise role is not yet quantified.

H-mode duration in NSTX has ranged from 500  $\mu$ s to 65ms, all shorter than the estimated  $\tau_E$  which are ~ 100ms. The first H-modes on NSTX lasted about 8ms and were terminated by a localized magnetic reconnection at the periphery, as determined by the ultra-soft X-ray (USXR) array<sup>14</sup> data. This MHD event looked very similar to an ELM<sup>15</sup>. Low or medium-m precursors were not observed<sup>5</sup> in the USXR emission, and the MHD activity (other than H-mode termination) was generally reduced in the H-mode phase compared with the L-mode phases. ELMs in tokamaks and also in the START device are usually transient outfluxes of particles and energy. Thus, it is unclear why NSTX did not recover an H-mode phase after the ELM-like event.

ELM-like termination in the short H-modes is contrasted with more global MHD termination in the longer H-modes, which showed a magnetic precursor. For example, the Mirnov activity is observed to increase at  $t=245$ ms during the H-mode in fig. 1(e). The USXR raw data showed<sup>5</sup> a cold, radiative island with poloidal mode number  $m=2$  which began to grow at that time. This mode had toroidal mode number  $n=1$ , determined by a toroidal Mirnov array. The growth of this cold island, coupled with the rapid increase of the

edge localized mode (ELM)-free H-mode scaling<sup>4</sup>, which is based on NBI heated, high- $\beta$ , conventional aspect ratio tokamaks with  $(R/a) > 2.5$ . The confinement time from this scaling is given by  $\tau_E^{ELM-free} = .0314 I_p^{0.94} B_t^{0.27} n^{0.34} P_{loss}^{-0.68} R^{1.98} (a/R)^{0.68} M^{0.43}$ , where  $I_p$ ,  $B_t$ ,  $n$  (plasma density),  $P_{loss}$  (power through separatrix),  $R$ , and  $M$  (working gas mass) have units of MA, T,  $10^{19}$  m<sup>-3</sup>, MW, m, atomic mass units respectively, and  $a/R$  are dimensionless. The discharge in fig. 1 achieved up to 1.4-2.4 times the

$50$ ms  $\tau_E^{ELM-free}$  predicted for NSTX parameters. A second commonly-used H-mode scaling IBP98(y,2), based<sup>4</sup> on ELMy H-mode discharges, predicted a  $\tau_E$  of ~80ms for NSTX, i.e. actually higher than the ELM-free scaling. The excellent performance of NSTX relative to either of these scalings underscores the significance

edge carbon emission in the USXR band, suggests that impurities accumulated due to the improvement in particle confinement during the H-mode, and induced a tearing mode due to enhanced radiation near rational mode surfaces, as also observed<sup>16</sup> in ASDEX-Upgrade. In future experiments, impurity accumulation could possibly be eliminated by inducement of regular ELMs, which typically purge the edge plasma of impurities. The fact that these discharges were ELM-free suggests (from tokamak experience) that NSTX was operated close to the L-H power threshold, and that further increase of heating power should induce regular ELMs. The operational challenge to extend the H-modes is to understand and prevent the ELMs from returning the discharge to L-mode, as well as avoiding any  $\alpha$ -related instabilities due to the increase in NBI power used to trigger ELMs.

In summary, we have induced H-mode discharges in NSTX, in which the energy confinement time increased transiently by between 100-300%. These H-modes had energy confinement well above ELM-free H-mode scaling laws, and had a significantly greater threshold power than predicted. Thus H-modes in NSTX will eventually help extend the confinement and threshold power scalings to low aspect ratio. Finally, H-modes have broader pressure profiles than L-modes (e.g. the pressure peaking factor was reduced by ~15% in NSTX), and broad profiles generally have higher  $\beta$  limits in tokamaks due to improved low-n kink stability, e.g. TFTR<sup>17</sup> and DIII-D<sup>18</sup>. Thus achievement of H-modes is a potential path for achieving higher  $\beta$  in NSTX.

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