Characteristics of the First H-Mode Discharges in the National Spherical Torus Experiment

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We report observations of the first low-to-high (L-H) confinement mode transitions in the National Spherical Torus Experiment. The H-mode energy confinement time increased over reference discharges transiently by 100–200%, as high as ~100 ms. This confinement time is ~2 times higher than predicted by a multimachine scaling. Thus the confinement time of spherical tori has been extended to a record high value, leading to an eventual revision of confinement scalings. Finally, the power threshold for H-mode access is >10× higher than predicted by an international scaling from conventional aspect-ratio tokamaks, which could lead to new understanding of H-mode transition dynamics.

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Introduction.—Spontaneous transitions from a low confinement (L mode) to a high confinement regime (H mode) have been observed [1] in fusion experiments for many years. H modes offer an improved confinement time for both energy (τ_E) and particles (τ_p) in fusion plasmas, and are potentially attractive reactor operational scenarios because they can lead to self-sustained fusion burn in relatively small, low cost devices.

The concept of a low aspect-ratio toroidally symmetric device (spherical torus or ST) was proposed [2] many years ago, and test facilities were constructed in the mid-1990s. The first ST to demonstrate [3] H-mode operation was the START device in Culham, England. The heating power requirement for accessing the H-mode regime (power threshold) in START was significantly higher than predicted by a multimachine database [4] compiled from conventional aspect-ratio tokamaks. Recently H-mode transitions were reported [5] from the MAST device in Culham also; both START and MAST have $R/a \sim 1.3$–1.4. We report in this paper the observation of H-mode transitions in the National Spherical Torus Experiment (NSTX), extending the START/MAST results to record high-energy confinement ~100 ms. This achievement challenges the existing international power threshold and energy confinement time scalings [6] based on conventional aspect-ratio tokamaks. The remainder of this paper discusses characteristics of the H modes in NSTX.

NSTX is a relatively new fusion research facility [7,8] ($R = 0.85$ m, $a = 0.67$ m, $R/a \geq 1.26$, $B_t \leq 0.6$ T), which commenced physics operation [9] in July 1999. NSTX was designed for operation at 1 MA of plasma current (I_p) 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 [10], which includes center stack resistive bakeout up to 300 °C, glow discharge cleaning, and boronization [11,12].

H-mode discharge signatures.—H modes in NSTX have characteristics similar to conventional aspect-ratio tokamak H modes. Figure 1 compares the characteristics of the longest H-mode duration obtained to date in NSTX with an L-mode reference discharge. These discharges had $I_p = 1$ MA and neutral beam injection power (P_{NBI}) = 1.5 MW (Figs. 1a and 1b). Edge visible light, measured by filtered visible spectroscopy (e.g., D_α in Fig. 1c) and a fast visible camera, was reduced on a 1 ms time scale after the H-mode transition at $t \sim 191$ ms in No. 104312. NSTX had 3 separate spectroscopic views with 12 total channels, measuring deuterium, carbon, boron, oxygen, and helium line radiation; light emission was reduced simultaneously on all these channels. Visible light is emitted from the edge plasma and increases with the local electron density (n_e). These simultaneous drops indicate a drop in the edge n_e, as often observed during H-mode transitions in tokamaks. While the scrape-off layer n_e decreases, the n_e just inside the magnetic separatrix increases during NSTX H-mode discharges, i.e., a steep n_e gradient is observed. Figure 2 compares the electron density, electron temperature (T_e), and electron pressure (P_e) profiles from Thomson scattering for the discharges in Fig. 1. Evidence of an increase in the edge n_e gradient relative to the L-mode reference was shown in the first Thomson pulse at $t = 197$ ms, following the transition at $t \sim 191$ ms. The n_e profile continued to evolve and actually developed a hump at the edge by $t = 230$ ms in the H-mode discharge,

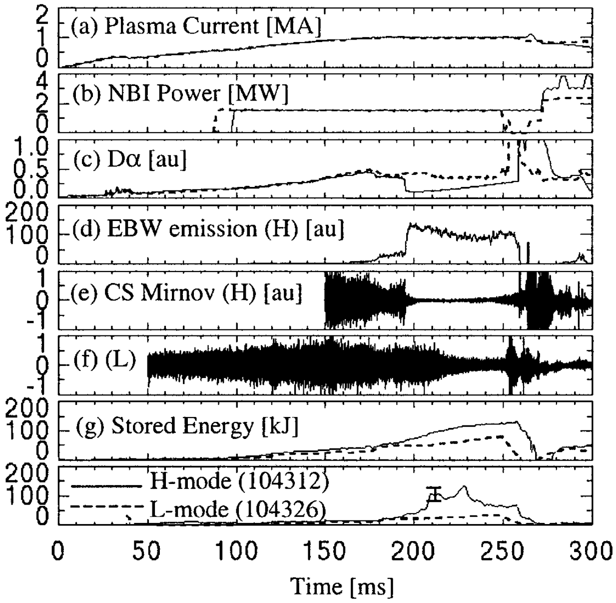

FIG. 1. Comparison of L-mode (dashed lines in panels) and H-mode (solid lines) discharges in (a) I_p, (b) NBI power, (c) divertor D_α emission, (d) electron Bernstein wave (EBW) emission at $R = 0.85$ m, (e) center stack Mirnov signal (H mode), (f) center stack Mirnov signal (L mode), (g) stored energy, and (h) τ_E. Panels (g) and (h) are obtained from EFIT reconstruction and include fast ion content. The H-mode phase lasts from $t \sim 191$ ms to $t \sim 260$ ms in No. 104312.

similar to the "ears" observed [5] on MAST. The T_e profile responded to the improved H-mode confinement on a longer time scale, and evidence of a weak T_e pedestal was observed at $t = 230$ ms in the H-mode case. The broader n_e and T_e profiles in the H mode lead to a decrease in the pressure peaking factor ($P_{\mathrm{peak}} \equiv P_0/P_{\mathrm{av}}$, with $P_0 =$ central pressure and $P_{\mathrm{av}} =$ 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 ($P_{\mathrm{peak},e} \equiv P_{0,e}/P_{\mathrm{av},e}$, obtained 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 $t = 230$ ms, 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 [13]. Mode conversion of electrostatic electron Bernstein waves to electromagnetic, X-mode radiation becomes more efficient [5] 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 identification of H-mode phases.

The energy confinement in H modes in conventional aspect-ratio tokamaks increases typically by 60–80% over L-mode levels. This increase in τ_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 Mirnov signals in Fig. 1e. Figure 1f shows

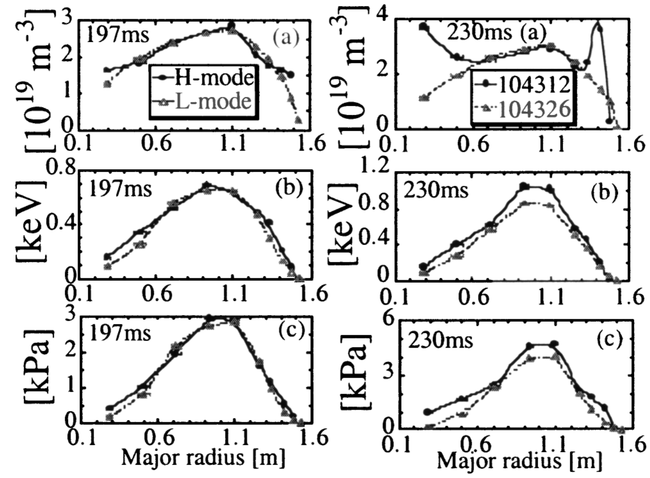

FIG. 2. Comparison of (a) n_e, (b) T_e, and (c) P_e profiles for L mode and H mode after time of the H-mode transition (left panels) and 33 ms later (right panels), during the ELM-free phase. The outer midplane separatrix lies between 1.45 and 1.50 m, and the inner midplane separatrix between 0.19 and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

the L-mode reference case. Note that the envelope of the oscillations was gradually reduced as the plasma X point was formed at 170 ms 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 245 ms, indicating the onset of new magnetohydrodynamic (MHD) activity (discussed later).

The peak stored energy, obtained by magnetic equilibrium reconstruction with the EFIT code [14], increased by 60% in the H-mode phase compared with the L-mode reference discharge (Fig. 1g). These values correspond to toroidal beta ($\beta_t \equiv 2\mu_0 P_{\mathrm{av}}/B_t^2$) 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 2.3×10^{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 apparently reduced τ_E to $\leq$35 ms in the reference discharge. In comparison, lower density L modes in NSTX achieved peak $\tau_E \leq 50$ ms and stored energy $\sim$100 kJ.

The estimated τ_E during the H-mode phase (Fig. 1h) varied between 70 and 120 ms, and was up to 3 times higher than the L-mode reference discharge shown, and also 4 times higher than the 28 ms value reported [5] from MAST. In computing the loss power for the τ_E estimate, the dW/dt term and time derivative of the poloidal field energy were subtracted off, but the core radiation, NBI shine-through and first-orbit loss components were not subtracted. In addition, the stored energy computed by EFIT contains the fast ion component, which is estimated (from the TRANSP code) to be between 15% and 20% of total stored energy. A useful normalization is the confinement time predicted by an international edge-localized-mode(ELM)-free H-mode scaling [6], which is based on neutral-beam heated, high-β, conventional aspect-ratio tokamaks with $(R/a) > 2.5$. The confinement time from this scaling is given by $\tau_E^{\text{ELM-free}} = 0.0314 I_p^{0.94} B_t^{0.27} \times n^{0.34} P_{\text{loss}}{}^{-0.68} R^{1.98} \kappa^{0.68} (a/R)^{0.10} M^{0.43}$, 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^{-3}, MW, m, atomic mass units, respectively, and κ and a/R are dimensionless. The discharge in Fig. 1 achieved up to 1.4–2.4 times the 50 ms $\tau_E{}^{\text{ELM-free}}$ predicted for NSTX parameters. A second commonly used H-mode scaling IBP98(y,2), based [6] on ELMy H-mode discharges, predicted a τ_E of ~80 ms 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 of achieving H-mode, which will lead to an extension of the databases and scalings to low aspect ratio.

Finally, a pronounced signature of the H-mode phase is the formation of a peripherally peaked shell in the ultrasoft x-ray (USXR) spectral region from 10–100 Å [15]. Figure 3 shows the USXR emission from another H-mode discharge (No. 104316), which had an L-H transition at $t = 202$ ms. Before the L-H transition (i.e., $t_1 = 194$ ms), the USXR profile was quite broad. The edge peaking began soon after the transition (i.e., $t_2 = 214$ ms) and continued to become more peaked prior to termination (i.e., $t_3 = 250$ ms). After the H-mode termination, the USXR profile resumed a broad shape, i.e., for $t > 260$ ms in the H-mode case. A similar H-mode discharge was modeled with the MIST code [16]. This analysis showed that the H-mode phase had a strong impurity transport barrier, evidenced by a 10× reduction in cross-field carbon particle flux compared to the L-mode phase. In addition, total radiated power (not shown) typically dropped just after the L-H transition as well, but then increased during the ELM-free phases of the longer duration H modes.

H-mode operating window.—H-mode access for NSTX has been observed in the following range of conditions: $0.7 \leq I_p \leq 1$ MA, $B_t = 0.45$ T, 0.85 MW $\leq P_{\text{NBI}} \leq 1.6$ MW, 0.8 MW $\leq P_{\text{OH}} \leq 1.1$ MW (Ohmic heating power), $1.7 \times 10^{19} \leq \overline{n_e} \leq 2.5 \times 10^{19}$ m^{-3}, inner-wall gap $\geq 1-2$ cm, and only in lower-single null diverted shape. In this configuration, the ion-Grad B drift direction was toward the X point. To date, no center-stack limiter H modes have been observed, even though 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 multimachine scaling [4]. Although START's high-power threshold was attributed [17] to high neutral content and edge convective loss, that explanation is questionable for NSTX which has much lower neutral content due to its closer fitting wall and smaller vacuum vessel. Alternately, ST's are predicted to have higher trapped particle fractions owing to the large magnetic field variation [2] on flux surfaces. This should lead to a higher neoclassical viscosity and poloidal flow damping rate, which could lead to an intrinsically higher-power threshold than conventional aspect-ratio devices. Detailed calculations are in progress.

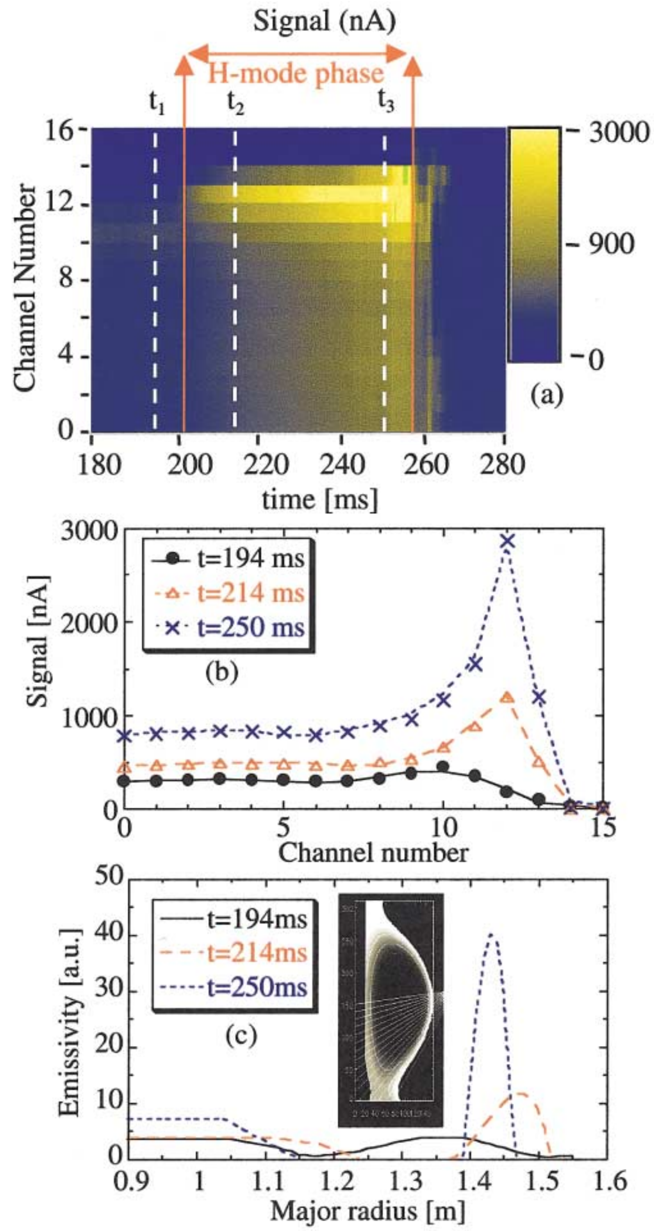

FIG. 3 (color). USXR profiles showing peaking of the emission at the edge during the H-mode phase: (a) Signal vs time and channel, (b) signal vs channel number, and (c) Abel-inverted emissivity for No. 104316, a single source H-mode discharge. The three time slices are $t_1 = 194$ ms—L-mode phase; $t_2 = 214$ ms—just after L-H transition; and $t_3 = 250$ ms—just before H-mode termination. The geometry of the USXR is an inset in panel (c), with the chord zero nearest the midplane and chord 15 through the divertor.

It should be noted that H mode was observed in NSTX only after the third boronization. While it is probable that wall conditions affect H-mode access in NSTX, the precise role is unclear at present.

H-mode evolution and termination.—H-mode duration in NSTX has ranged from 0.6 to 65 ms, all shorter than the

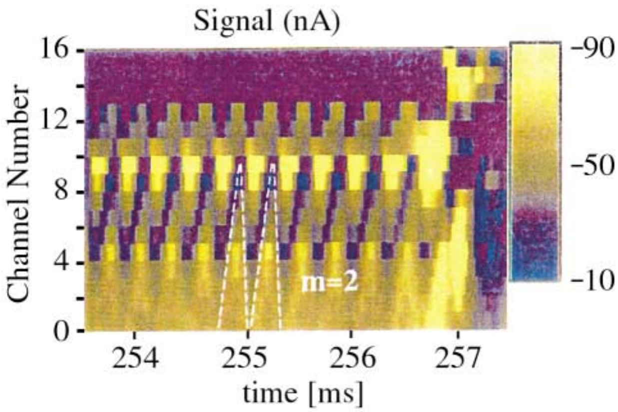

FIG. 4 (color). USXR spatial and time emission pattern, showing MHD activity onset during ELM-free phase in H mode and cold-island precursor before termination in No. 104316. The mode has $m = 2$ and is an emission "hole," i.e., a cold island.

estimated τ_E which are of the order of 100 ms. The first H modes on NSTX lasted about 8 ms and were terminated by a localized magnetic reconnection at the periphery, as determined by the USXR data. This MHD event looked very similar to an ELM [18]. There were no low or medium-m precursors 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 [3] 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 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 a cold, radiative island with poloidal mode number $m = 2$ which began to grow at that time (Fig. 4). 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 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 [19] 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, then, is to understand and prevent the ELMs from returning the discharge to L mode, as well as avoiding any β-related instabilities which may be destabilized due to the increase in heating power used to trigger the H modes.

Summary.—In summary, we have induced H-mode discharges in NSTX, in which the energy confinement time increased transiently by between 100%–200%. 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 β limits in tokamaks due to improved low-n kink stability, e.g., TFTR [20] and DIII-D [21]. Thus achievement of H modes is a potential path for achieving higher β in NSTX.

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