H-Mode Operation in the START Spherical Tokamak

A. Sykes,[1] R. J. Akers,[1] L. C. Appel,[1] P. G. Carolan,[1] J. W. Connor,[1] N. J. Conway,[1] G. F. Counsell,[1] A. Dnestrovskij,[1,2] Yu. N. Dnestrovskij,[1,2] M. Gryaznevich,[1] P. Helander,[1] M. P. S. Nightingale,[1] C. Ribeiro,[1] C. M. Roach,[1] M. Tournianski,[1] M. J. Walsh,[1,3] H. R. Wilson,[1] The START Team,[1] and The NBI Team[1]

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*
[2]*Kurchatov Institute, Institute of Nuclear Fusion, Moscow, Russia*
[3]*Walsh Scientific Ltd., Abingdon, Oxon OX14 3DB, United Kingdom*

(Received 23 August 1999)

H-mode operation has been achieved in high current ($I_p > 200$ kA) plasmas in the START spherical tokamak for both neutral-beam-injection-heated and Ohmic discharges. The transition to H mode features the development of well-defined edge pedestals in density and temperature, which signifies the formation of an edge-transport barrier, and associated edge-localized modes. Recent operation at plasma currents exceeding 250 kA shows that these features are accompanied by increases in energy confinement time. This is the first clear demonstration of the H-mode regime in a spherical tokamak.

PACS numbers: 52.55.Fa

The tight aspect ratio, or "spherical" tokamak (ST) [1], has some features in common with the spheromak (namely, geometry) and the reversed field pinch (i.e., high β, where β is the ratio of thermal to magnetic energy). At the time that START was designed, both of these types of devices were considered to have poor confinement compared to the conventional aspect-ratio tokamak; moreover, predictions of confinement time in START from early forms of Ohmic tokamak scalings (e.g., neo-Alcator scaling given in [2]) were pessimistic. Measurement of the energy confinement in START has therefore always been of great interest. Early estimates [3], confirmed by later studies [4] using advanced diagnostics (30-point Thomson scattering, 20-chord charge exchange spectroscopy, and EFIT magnetic reconstruction [5]), found that energy confinement was up to 8 times better than predicted by early forms of the neo-Alcator scaling. Indeed, confinement was comparable to the ITER97 scaling law derived for H-mode conventional tokamak plasmas, although the relevance of these scalings, so far from the parameters of the relevant database, is uncertain. Coupled with the observation that the power per surface area could be some 40 times larger than that required for L-H transition, as estimated from conventional aspect ratio tokamak databases, this led to the suggestion that START plasmas were always in an ST analog of H mode, in which case no further improvement in confinement could be expected.

However, during a series of neutral-beam-injection (NBI)-heated discharges, which combined good vacuum conditions with high density and plasma currents of over 200 kA, features new to START plasmas appeared: a sharply defined plasma edge, steepening of edge profiles (especially of density), and infrequent H_α spikes, similar in nature to the edge-localized mode (ELM) seen in H-mode operation in conventional tokamaks [6,7]. Some of these discharges, which employed neutral beam injection of hydrogen into a deuterium plasma in a double null divertor configuration, showed confinement better than ITER97H scaling [4]—a key factor in the achievement of record β values of $\beta_T \sim 40\%$, $\beta_N \sim 5.5$ [8]. The same features were observed in high-β Ohmic discharges, which obtained a β value of $\beta_T \sim 24\%$, some 10 times greater than achieved in Ohmically heated conventional tokamaks and indicative of both the good energy confinement and the enhanced self-heating inherent in the ST. These features were subsequently documented [9], but it was not clear whether the good confinement was due to access to a H-mode regime, or due to some high-β turbulence-suppression mechanism.

Clear, regular ELMs coupled with a well-defined increase in confinement time have now been identified during operation at still higher plasma currents. This follows improvements to power supplies and vacuum conditions, which have enabled operation of START at plasma currents up to 310 kA. Regular ELMs can appear in shots within the region of density and plasma current operating space shown in Fig. 1, when $I_p > 190$ kA and for a range of line averaged density $3.8 < \overline{n}_e < 6.2 \times 10^{19}$ m^{-3}. The absence of ELM onset at high density may be because increasing density by gas puff leads to high neutral densities in both the plasma edge (10^{17}–10^{18} m^{-3}) and tank (up

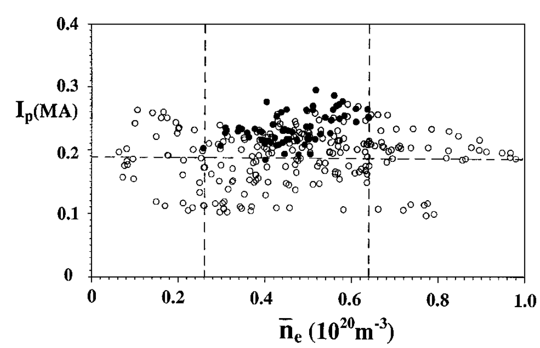

FIG. 1. Occurrence of regular ELMs in START discharges. The onset of regular ELMs (denoted by solid symbols) occurs for $I_p > 190$ kA and in a certain density range.

to 10^{19} m^{-3}). These values are large because the START plasma occupies only around 7% of the tank volume and has a low visibility to recycled neutrals as a result of the open divertor configuration. This can lead to ionization losses in the NBI beam duct, charge exchange with beam ions at the plasma edge, and losses due to collisional ionization of beam neutrals in the tank. Special gas feed and tank gettering mechanisms are proposed for the successor MAST experiment [4] in order to reduce the cold neutral population.

A typical discharge exhibiting regular formation of ELMs is shot 36 078 (Fig. 2), which has neutral beam injection (injected power $\sim$ 800 kW, energy $\sim$ 30 keV) applied throughout the discharge. A plasma current of $\sim$120 kA is first produced by the "induction compression" scheme [10], the current then being ramped up to $\sim$220 kA by flux swing from the central solenoid (current drive from the beam is predicted to be small for these START plasmas). The plasma density is increased mainly by conventional gas puff valves and recycling from the walls; beam fuelling is calculated to be 2×10^{20} atoms/s for this shot which is less than 10% of the refuelling rate assuming a particle confinement time of 5 ms. The puff valves are switched off at time 8.5 ms, which is approximately the time at which the plasma forms a double null divertor configuration with well-defined magnetic separatrix, with major and minor radii 0.30 and 0.21 m, and elongation $\sim$1.7. Fast ion gauge measurements indicate a relatively constant molecular density in the tank after this time. However, as indicated in Fig. 2, plasma density is then observed to increase spontaneously at a rate of $\sim 10^{21}$ atoms/s. This feature is not observed in discharges without ELMs and indicates an improvement in particle confinement. We shall use these features (presence of ELMs combined with improved particle confinement) to classify START discharges as H or L mode, as we shall show that an improvement in energy confinement is a less reliable indicator. A common feature of H-mode discharges in START is the presence of sawteeth (as indicated by the soft-x-ray trace in Fig. 2). Although a sawtooth crash often triggers an ELM, the ELM frequency is considerably higher than that of sawteeth.

The energy confinement time is evaluated using EFIT equilibrium reconstruction. The fast ion component is estimated and subtracted from the total plasma energy to determine the plasma thermal energy. The input power is taken as the sum of the Ohmic input and the NBI power absorbed; i.e., the shine-through and first orbit losses (which together can be as high as 50% in START) are subtracted. The confinement time in discharge 36 078 reaches $\sim$3 ms but it is convenient to normalize it to the ITER97H ELM-containing scaling, as this normalized confinement (denoted H_{97}) more clearly shows changes in the nature of confinement. As shown in Fig. 2, H_{97} increases before the ELMs begin and then levels off. This is a common feature in START H-mode discharges, and suggests a gradual transition leading to increased edge pressure gradients, which then destabilize ELMs. The electron temperature and density profiles shown in Fig. 2 were obtained (at the time indicated by the arrow in the inset) just before an ELM.

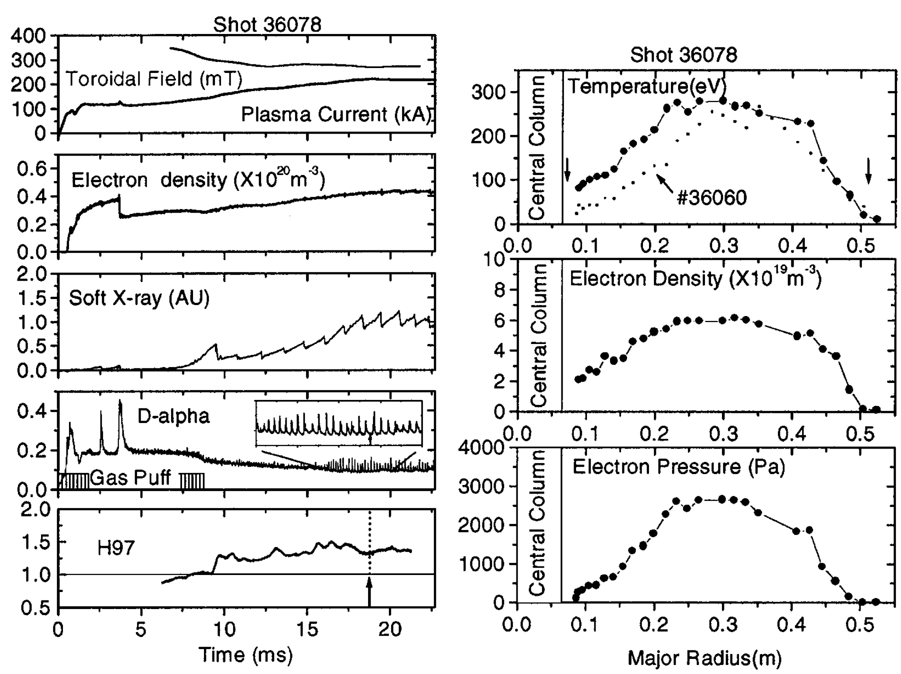

FIG. 2. Development of ELMs and improved confinement in a typical NBI heated discharge. The electron profiles are obtained from the Thomson scattering diagnostic at the time indicated; the beta and q values at this time are $\beta_T = 13\%$, $q_{95} = 5.2$, and the Troyon limit, using the conventional form $\beta_T = 3.5\mathrm{I/aB}$, is also 13%. The inboard and outboard separatrix positions (as determined by EFIT) are indicated by arrows on the electron temperature trace, and the trace for a typical L-mode shot of similar parameters is indicated by dots.

A scatter plot comparing the energy confinement time of NBI heated discharges in START with the predictions of the ITERH97 scaling was shown in Ref. [4]; over the totality of discharges, those having ELMs show no clear enhancement in confinement compared to other auxiliary heated shots. However, selecting all discharges having plasma currents >250 kA shows (Fig. 3) that, for these high current discharges, those in H mode exhibit an increase in confinement of approximately 50% over the corresponding L-mode shots.

The transition to H mode usually occurs during NBI additional heating, and usually persists if the beam is then turned off. Indeed, the onset of ELMs and typical H-mode behavior can occur some time after beam turn-off, provided that the improvement in confinement (evidenced by spontaneous density increase) has begun during NBI and that plasma current and density are in the range shown in Fig. 1. Since the beam thermalization time is $\sim 1-2$ ms, some 5 ms after the beam cutoff, plasma forming ELMs can be regarded as in Ohmic H mode and these discharges have yielded the highest confinement on START ($\sim$5 ms). The persistence of the H mode following beam cutoff in these discharges may be because the radial electric field generated by the beam is then maintained by the pressure gradient produced by the pedestal.

The power input to START easily exceeds the predicted threshold power P_{thr} required for L-H transition in conventional tokamaks. For the START parameters of the shot shown in Fig. 2, namely, $n_e = 5 \times 10^{19}$ m^{-3}, $B_T = 0.28$ T, $R = 0.3$ m, the ITER-EPS97 scaling [11] $P_{\mathrm{thr}} = 0.65 n_e^{0.93} B_T^{0.86} R^{2.15}$ [MW, 10^{20} m^{-3}, T, m] yields $P_{\mathrm{thr}} \sim 9$ kW, which is almost 2 orders of magnitude lower than the total input power (i.e., including Ohmic) of $\sim$800 kW for these auxiliary heated discharges. Even Ohmic discharges, with typical Joule heating of 400 kW, greatly exceed this threshold. In the ITER scaling the L-H transition is controlled by a critical value of the heat flux P_{tot}/S. However, the H-mode transition should be considered in terms of local edge conditions, for which a number of theoretical models exist. In the canonical profiles transport model (CPTM) [12], the transition is defined by the critical value of the dimensionless relative pressure gradient ap'/p at the plasma edge, yielding an estimate for P_{thr} which successfully predicts transition in conventional tokamaks. For START parameters relevant to Fig. 2, this model gives an estimate of $P_{\mathrm{thr}} \sim 150$ kW which is significantly larger than the values obtained from the ITER scaling but is still below that required in START.

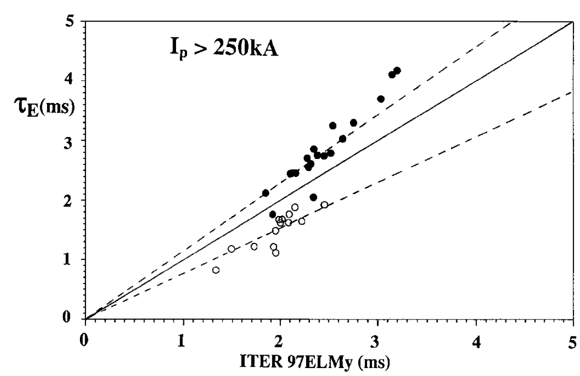

FIG. 3. Energy confinement vs ITERH97 prediction for all H-mode (solid symbols) and L-mode (open symbols) discharges having $I_p > 250$ kA.

This remaining difference may be explained by the presence of the high neutral density in START discussed previously, which will introduce additional convective heat losses P_{con} at the plasma edge. Recent studies [13] indicate that the appropriate transition criterion is then $P_{\mathrm{tot}} - P_{\mathrm{con}} > P_{\mathrm{thr}}$; P_{con} becomes large (typically 250 kW) for H-mode plasmas due to the combination of their high edge density and temperature with the high edge neutral density in START. This large convective heat loss will both degrade confinement and impede the L-H transition. Since it is greater for H-mode plasmas, it will counteract any improvement in confinement and may explain why improvement was not generally obvious for the first L-H transitions in START. However, both Ohmic power and the fraction of NBI power absorbed increase approximately linearly with plasma current, and estimates of the total power input to a typical START plasma at density 5×10^{19} m^{-3} with injected power of 800 kW increase from 816 kW at 200 kA (where only 52% of the NBI power is absorbed) to 1175 kW at 300 kA (72% absorbed). The convective heat loss is therefore less significant at higher plasma current, and this may explain the clear improvement in confinement for H-mode discharges at high plasma current shown in Fig. 3. (Note that this improvement in confinement is not due to the increase in NBI absorption efficiency, as the absorbed power is used in evaluating the confinement time.)

The temperature pedestals present in START H-mode plasmas show an unexpected feature when measured by the Thomson scattering diagnostic, namely, that the pedestal is higher and more clearly defined on the inboard side, as seen in Fig. 2, where the profile is obtained just before an ELM. This may arise because the Ohmic heating peaks on the inside of a small aspect ratio torus since the parallel current is proportional to the magnetic field strength, typically 3–4 times greater on the inboard in START. The Ohmic heating is therefore an order of magnitude greater on the inside of an ST than at the outer edge. In addition, losses due to plasma turbulence and ionization of cold neutrals should be greater on the outboard side. This result implies that T_e is not constant along the outer flux surfaces, whereas conduction along a flux surface is usually extremely rapid so that the temperature is equalized. However, analytical and numerical estimates suggest that parallel heat conduction is not able to distribute the heat evenly over the flux surface for electron temperatures of several tens of eV, the conditions relevant to the edge of these START plasmas.

Edge pedestal scalings derived from conventional tokamak data, for example, the scaling $T_{e(\mathrm{ped})} = 0.07 B_t^{2.26} n_{\mathrm{ped}}^{-0.23} M^{-0.6}$ [14] can be applied to the electron profiles shown in Fig. 2, but results depend crucially on where B_t is evaluated. At the inboard pedestal $B_t \sim 1$ T; at the outboard pedestal $B_t \sim 0.17$ T. These choices give $T_{e(\mathrm{ped})} \sim 65$ and 1 eV, respectively, consistent with the profiles shown in Fig. 2 and suggesting that the temperature pedestal scaling may be a local phenomenon.

The combination of tight aspect ratio and low magnetic field in the START tokamak gives added interest to the role of rotation and edge electric fields in accessing H-mode conditions. On START this information was available from Doppler spectrometry with toroidal viewing of the C^{5+} ion, primarily from charge exchange of C^{6+}, and with vertically viewing of the C^{2+} ion, whose emissivity profile peaks at, typically, ~2 cm in from the separatrix. In START, no significant changes are seen in the toroidal velocity during the H-mode phase, either from the central or edge regions. During the early phase of the ELM-containing H mode the vertical velocity shows only small changes, but during ELM-free periods, rapid poloidal acceleration is seen in the edge C^{2+}, reaching $\sim 9\ \mathrm{km \cdot s^{-1}}$ in ~3 ms. (The calculated C^{2+} diamagnetic velocity is typically $\sim 2\ \mathrm{km \cdot s^{-1}}$, and its contribution is ignored here.) This acceleration is fairly reproducible as shown in Fig. 4, here obtained from the poloidal velocity at the end of an ELM-free period from a series of H-mode discharges. The vertical line-of-sight collected light from the periphery inwards to about 0.05 m, i.e., to $R_{\mathrm{major}} = 0.43$ m. In determining the radial electric field E_r from Doppler observations of impurity velocity and temperature, a simple radial force balance model is used. The dominant contribution to E_r is from the $v_\theta B_\phi$ term where $B_\phi \sim 0.12$ T at $R = 0.43$ m for the discharges shown in Fig. 4. The corresponding radial electric field is approximately -1 kV/m (pointing inwards). This behavior can be compared to that of the similarly sized, but conventional, COMPASS-D tokamak [15], where the poloidal acceleration begins at the L to H transition (within ~0.14 ms), and is most clearly observed in a direct transition to ELM-free. The acceleration, $\sim 7\ \mathrm{km \cdot s^{-1}\, ms^{-1}}$ in COMPASS-D ELM-free, is approximately double that in START. The reduced rotation observed in START may be a consequence of viscous damping produced by the high neutral density; however, these observations suggest that the buildup of the observed poloidal velocity is a relatively gradual affair and is not a prerequisite for the L- to H-mode transition in all tokamaks.

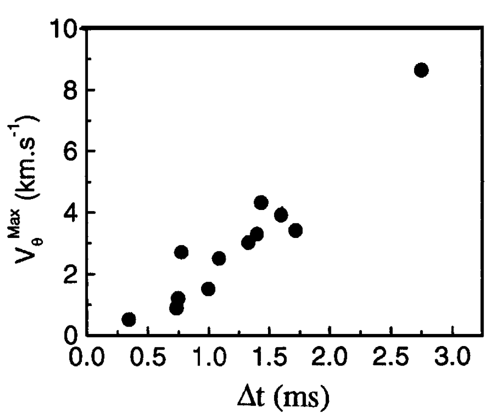

FIG. 4. Maximum poloidal velocity (C^{2+}) obtained from a series of H-mode discharges with a range of inter-ELM periods, Δt.

In summary, it has been shown that H-mode operation is accessible in START. For discharges with plasma currents in excess of 250 kA, H-mode confinement clearly exceeds that in equivalent L-mode shots, and also exceeds the prediction of ITER H-mode scalings such as ITER97H (ELMs present). Edge pedestals in density and temperature develop, indicating the appearance of an edge-transport barrier. Although the threshold power for L-H transition in START greatly exceeds that predicted by ITER global scalings it may be more reasonably represented by local edge models, such as the canonical profiles transport model, and, moreover, modeling indicates that the transition will be significantly impeded by convective heat losses due to the high neutral density on START.

The achievement of H-mode confinement in the spherical tokamak is an important result for possible long-term applications of the ST as a materials test facility, a burning plasma experiment, or a fusion power plant. Studies of H-mode behavior in the larger spherical tokamaks now being commissioned will also provide additional insight into the underlying physical processes present in the H-mode regime, relevant to all tokamaks.

The work is jointly funded by Euratom and the United Kingdom Department of Trade and Industry. The NBI equipment on START is loaned by the U.S. DOE, and the EFIT reconstruction code is supplied by General Atomics.

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