H Mode of the W 7-AS Stellarator

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In W 7-AS the *H* mode has been observed for the first time in a currentless stellarator plasma. *H* modes are achieved with 0.4 MW electron cyclotron resonance heating at 140 GHz at high density. The *H* phases display all characteristics known from tokamak *H* modes including edge localized modes (ELMs). The achievement of the *H* mode in a shear-free stellarator without toroidal current has consequences on *H*-mode transition and ELM theories.

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The *H* mode (high confinement) is an operational regime of tokamaks with improved confinement properties [1]. The energy confinement time τ_E^H in the *H* mode surpasses that in the *L* mode (low confinement), which is the typical regime under auxiliary heating conditions, by about a factor of 2. The relevance of the *H* mode was clearly indicated within the framework of the ITER (International Thermonuclear Experimental Reactor) design activity. For ITER a confinement time of 3.8 s is required for ignition. This can be achieved in the *H* mode [2] whereas *L*-mode scalings predict 2.2 s [3].

The *H*-mode studies on tokamaks have shown that its main feature is the development of a transport barrier at the very edge of but inside the last closed flux surface (LCFS) [4]. In this region, fluctuations disappear within 100 μs [5] and both the temperature and density profiles develop steep gradients. Correlated with the reduction of the fluctuation level, strong poloidal rotation develops within the transport barrier [6]. Theory addresses various aspects of the *L*-*H* transition like the induction of poloidal flow at the plasma edge, the impact of differential flow on turbulence, and the self-consistent relation between poloidal flow and radially propagating fluctuations. A summary is given in Ref. [7]. Beyond the programatic importance, the *H* mode has inspired new interest in anomalous confinement of tokamaks, in particular in mechanisms which can reduce the level of turbulence.

Unlike the tokamak, stellarators operate without net current, are therefore free from disruptions, and have the potential of steady state operation. After the rigorous concept optimization of the last decade, stellarator theory has removed the concerns of high neoclassical losses, low α-particle confinement, and a low equilibrium β limit [8]. Present stellarators operate, however, at the *L*-mode confinement level [9]. Therefore, it is also important for stellarators to reach enhanced confinement. It is the main purpose of this paper to clearly demonstrate that the *H* mode is possible in stellarators. Emphasis is placed on a detailed presentation and discussion of those *H*-mode characteristics which are known from tokamak studies as being crucial.

W 7-AS [10] is a partially optimized, modular stellarator ($R=2$ m, $a_{\rm eff}=0.18$ m, five field periods) with extremely low vacuum field shear ($\Delta\iota/\iota \approx \pm 6\%$). Electron cyclotron resonance heating (ECRH: 70 GHz, 0.8 MW, 3 s and 140 GHz, 0.5 MW, 0.5 s) produces a net-current-free, high-temperature plasma. The low shear topology exhibits a strong sensitivity of the energy content on the boundary rotational transform $\iota\!\!\!-_a = \iota_a/2\pi$ [10]. The total rotational transform $\iota\!\!\!-_a$ is kept constant by a small induced Ohmic current which compensates the bootstrap current. Even at fixed $\iota\!\!\!-_a$, the confinement can still be influenced through local changes in the ι and ι' profiles [11]. Spontaneous transitions to higher or lower confinement have been observed at low density under limiter conditions ($n_{e0} \approx 3\times10^{13}$ cm^{-3}, $\iota\!\!\!-_a \approx 0.32$) [11] which were attributed to configurational effects and could be controlled by small changes in the gas-puff rate; they lead to a transient increase in electron temperature and a reduction in χ_e deuterium and D by up to 50%.

H-mode transitions in W 7-AS, as reported here, were obtained in an $\iota\!\!\!-$ range ($0.51 \le \iota\!\!\!- \le 0.53$) where the above-mentioned configuration effects do not play a role and maximum confinement prevails. The τ_E values obtained in the *H* mode are the highest (≈ 30 ms) obtained so far in W 7-AS at a heating power level of ≈ 0.4 MW and a density of 8×10^{13} cm^{-3}. Also χ_e ($\approx 3\times10^3$ cm^2/s) is lowest in the *H* mode.

The *H* mode develops in W 7-AS during ECRH with 140 GHz at elevated densities, under boronized wall conditions and in deuterium. The importance of the 140 GHz ECRH seems to be the accessibility to high density operation. There is a lower density limit for H-mode operation of about $\bar{n}_e \approx (4\text{–}5)\times10^{13}$ cm^{-3} which is about a factor of 2 above that in tokamaks. H-mode transitions with 70 GHz are also possible. Routine operation is obstructed, however, by the proximity to the cutoff density (6×10^{13} cm^{-3}).

The small ι range where H modes appeared up to now represents the border between limiter and separatrix operation of W 7-AS. At low ι, the plasma surface is determined by two rail limiters, one on the top and the other on the bottom of two adjacent elliptical cross sections. At high ι, the plasma surface is determined by a rather corrugated separatrix defined by a chain of natural $5/m$ magnetic islands. In the ι range of the H mode, the magnetic separatrix is close to the limiters. As discussed later, the H mode does not develop when the limiter determines the plasma edge.

Figure 1 shows the development of an H-mode discharge. The plasma was initially produced with a 70 GHz ECRH pulse. After the transition to 140 GHz ECRH of 0.4 MW, the density could be increased further owing to the higher cutoff density (1.2×10^{14} cm^{-3}). In the plateau phase of the second density level (8×10^{13} cm^{-3}), the transition occurs spontaneously at $t\approx0.5$ s out of a degraded phase. The transition is characterized by a sudden drop in H_α radiation associated with the recycling at the bottom limiter. All H_α monitors (viewing the wall or the limiters) display a drop in signal at the transition. Along with H_α the fall-off length of the ion saturation current, as measured with a Langmuir probe, decreases in the scrape-off layer. The transition seems to be somewhat slower than in tokamaks. This has been predicted [12].

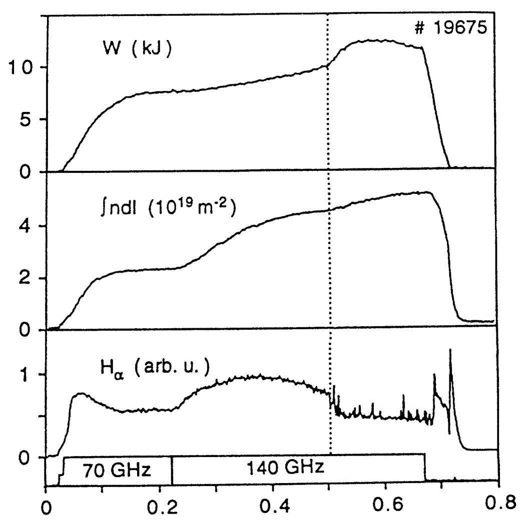

FIG. 1. Temporal development of energy content, line density, and H_α from the lower limiter during an H-mode discharge of W 7-AS.

The H_α trace is modulated during the H phase by bursts corresponding to edge localized modes (ELMs) in tokamak H modes [1].

As in tokamaks, a back transition occurs about 20 ms after the heating pulse has terminated. This transition leads again to a regime of degraded confinement, indicated by an increase in H_α back to the pre-H-mode level and a rapid decay of the particle content. A back transition occurring during the ECRH pulse provokes a rapid drop of the energy content. (The final spike in H_α in Fig. 1 is due to the afterglow of the discharge.) Like the existence of a prephase with degraded confinement, the back transition confirms the threshold nature of the H-mode development as known from tokamaks. H-mode transitions as shown in Fig. 1 could be reproduced whenever the required external parameters were set.

The H-mode transition is accompanied by an augmentation in energy and particle content. The maximal rise in energy confinement time is 30%. This is less than normally observed in divertor tokamaks; possible reasons will be addressed below. Also the density increase is smaller than typically observed in tokamak H modes with neutral beam injection. With ECRH, however, there is no particle fueling. As a consequence of the density rise, the density feedback system turns off the external gas supply. Along with energy and particle confinement, the confinement of impurities also improves. This is obvious from the rise in impurity radiation and $Z_{\rm eff}$ after a short transitory phase where impurity radiation decreases owing to the reduced plasma-wall interaction. The improvement in particle confinement has specifically been demonstrated in laser-blowoff (LBO) experiments using aluminum. Figure 2 shows the result from LBO when aluminum has been injected into the phase before the transition, after it, and for a case when the transition occurs amid the decay.

The essence of the confinement improvement in the tokamak H mode is the development of an edge transport barrier [4], indicated by the development of steep edge

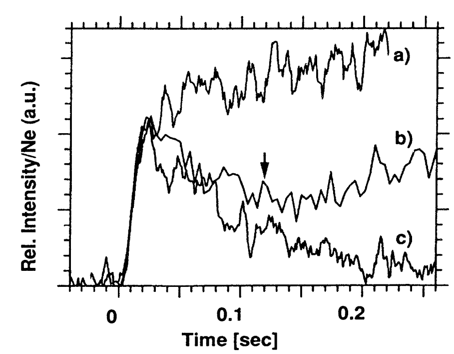

FIG. 2. Decay of Al XII spectral line (7.76 Å) after laser blowoff curve a into the phase after the H transition, curve b when the transition occurs amid the decay phase as indicated by an arrow, and curve c prior to the H transition (at lower plasma density).

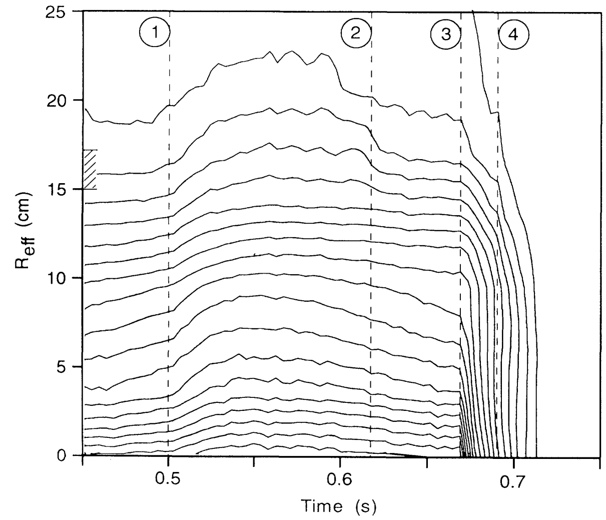

FIG. 3. Contour plot of the T_e- profile development; the H transition (1), the onset of ELMs (2), the end of the heating phase (3), and the $L \rightarrow H$ back transition (4) are marked. The approximate separatrix position is indicated by the hatched interval.

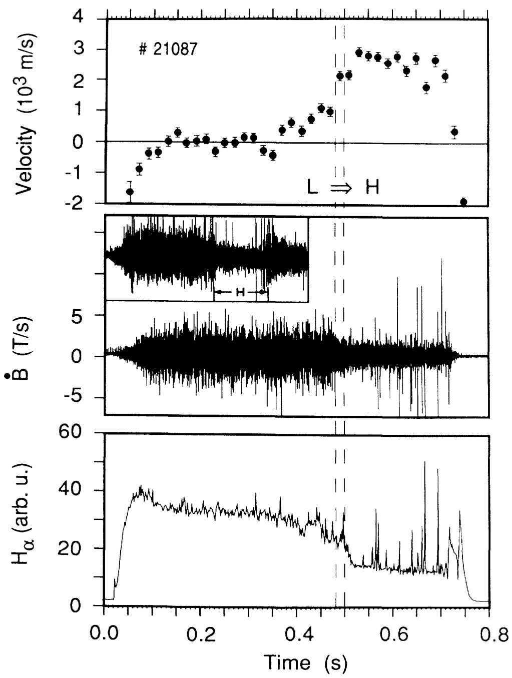

FIG. 4. Poloidal flow velocity of B IV at the plasma edge and magnetic fluctuations $\dot{B}$ as measured by a Mirnov loop. The inset shows the increase of $\dot{B}$ at the $H \rightarrow L$ back transition for another discharge. The H_α trace is shown for reference.

gradients in density, electron, and ion temperature. This development is also present in W 7-AS after the transition: The density profile (measured with Thomson scattering) shows steep gradients; the edge ion temperature deduced from the width of the B IV line rises typically from 80 to 120 eV. Also the charge-exchange flux spectra measured by a time-of-flight technique indicate a rise in mean particle energy after the transition [13].

Figure 3 shows in a contour plot the electron temperature profile measured by electron cyclotron emission. The overall rise and in particular the development of an edge pedestal after the H-mode transition can clearly be seen (1). As in tokamaks, the edge electron temperature is about 200 eV. The drop in edge T_e later in the H phase at 0.6 s is due to the onset of ELMs (2). The termination of the ECRH pulse (3) leads to a rapid collapse of the discharge; nevertheless, the $L \rightarrow H$ back transition (4) can be seen.

The presently most convincing theoretical ansatz to explain the development of the edge transport barrier is the decorrelation of turbulence in the velocity field of strongly sheared $\mathbf{E} \times \mathbf{B}$ flow [14]. The theory is guided by corresponding experimental observations of strong poloidal impurity rotation at the plasma edge [6]. The studies on W 7-AS also clearly indicate a strong rise in the edge poloidal flow of B IV. Results from passive line-of-sight integrated measurements are shown in Fig. 4 along with the H_α transition trace. No determination of the zero point of the poloidal velocity is available at present. Therefore, we can only conclude that after the transition the poloidal impurity rotation velocity increases in the electron drift direction by up to 4 km/s. The corresponding radial E field is about 100 V/cm. Rotation speeds comparable to those reported here were typical for ASDEX in ELM H modes [15].

It is theoretically expected that the sheared edge flow reduces the level of edge turbulence. Too little yet is known about the structure of the edge turbulence in W 7-AS to test the predicted threshold condition for $\mathbf{E} \times \mathbf{B}$ sheared flow induced turbulence decorrelation [14]. Incoherent fluctuations are, however, reduced in W 7-AS during the H phase. Figure 4 shows the level of magnetic turbulence $\dot{B}$, its drop after the transition, and its recovery at the back transition after the termination of the ECRH pulse. The inset shows another discharge where the increase of $\dot{B}$ at the $H \rightarrow L$ back transition is more pronounced.

Another important aspect of the H mode is its sensitivity with respect to recycling. This is one of the reasons why the H mode readily develops in tokamaks with a divertor but requires extensive conditioning in the case of a limiter. This may explain the present restriction for the H mode on W 7-AS, requiring the above-mentioned ι conditions. Even with $\iota \approx 0.5$ no H-mode transition develops when the limiter is positioned further in by 3 cm. A corresponding observation was made on ASDEX [5].

The existence of a power threshold is indicated by the appearance of a back transition. The exact boundary could not yet be determined. The H mode was accessible with 400 kW at 140 GHz and about 200 kW at somewhat lower density at 70 GHz. These values correspond to a power flux across the plasma surface of ≈ 3 to 1.5 W/cm^2, respectively. For comparison, the threshold power flux in the case of ASDEX and ASDEX-Upgrade is about 4 W/cm^2.

ELMs, as observed in the H mode of W 7-AS, give rise to losses of energy and particles. Similar to those in tokamak H modes, ELMs in W 7-AS are accompanied by short phases of enhanced turbulence (with frequencies ranging up to 300 kHz) of about 300 μs duration. A clear coherent precursor is usually not observed. The ELM appearance is rather erratic. ELMs transiently increase the density and the fall-off length within the scrape-off layer. As in ASDEX, the pivot point of ELMs resides about 3 cm inside the LCFS [5].

The improvement in confinement achieved by the H mode is less in W 7-AS than in divertor tokamaks. This may have many reasons which must be explored in detail in the future. A simple reason could be presence of the limiter at the plasma edge. It is known, e.g., from limiter H-mode studies on the Tokamak Fusion Test Reactor that even if H-mode characteristics are well developed, the gain in τ_E can nevertheless be small [16]. It is not clear yet whether this is, for example, due to a frictional reduction of the edge flow and/or a short circuiting of the edge transport barrier by charge-exchange losses. Based on the experience from ASDEX with large confinement improvements with divertor and small ones with limiter operation [5], there remains the hope that the margin of confinement improvement the H mode provides can be fully utilized as soon as stellarators are operated under proper divertor conditions.

The development of the H mode in stellarators is not in contradiction with the present line of H-mode understanding: sheared flow decorrelation of edge turbulence in conjunction with the development of a negative radial E field at the plasma edge [14]. Because of the lack of intrinsic ambipolarity of the electron and ion fluxes under the three-dimensional conditions of W 7-AS the development of a radial E field is rather natural. In the past the beneficial impact of a radial E field on the neoclassical ion transport in W 7-A has been noted [17]. Also a reduced damping of the poloidal flow at the large aspect ratio of 10 of W 7-AS may play a role and may ease the H-mode transition.

Some theoretical attempts to understand the H-mode transition in tokamaks can be discarded since the H mode is possible under stellarator conditions. Of little relevance are models based on specific current profiles in the H mode [18] or those based on the large shear at the edge of divertor tokamaks [19,20]. The importance of magnetic shear for the H transition was still under consideration because of the observation that limiter H modes have been possible at high $\beta_{\rm pol}$ with a confinement time which improves with ellipticity [21] and that H-mode transitions can be triggered by rapid current ramp down [22]. The magnetic shear at the edge of W 7-AS, however, is small, being at least a factor of 10 below that of a circular limiter tokamak.

With respect to ELMs, models based on current-gradient-driven kink modes may not be relevant; the potential role of the bootstrap current is still unresolved. The ELM observation on W 7-AS is consistent, however, with the concept of a pressure-gradient-driven instability.

The H mode in stellarators will contribute to the understanding of transport and confinement of toroidal systems, in particular of H mode plasmas. The development of the H mode in both configurations highlights the similarities in anomalous transport between tokamaks and stellarators. This kinship is not expected *a priori* because toroidal current governs tokamak confinement whereas stellarators operate net-current free. Improved confinement will add to the intrinsic merits of stellarators—no need for current drive and no disruptions.

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[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] J. P. Christiansen *et al.*, Nucl. Fusion **32**, 291 (1992).
[3] P. N. Yushmanov *et al.*, Nucl. Fusion **30**, 1999 (1990).
[4] F. Wagner *et al.*, Phys. Rev. Lett. **53**, 1453 (1984).
[5] ASDEX Team, Nucl. Fusion **29**, 1959 (1989).
[6] E. J. Doyle *et al.*, Phys. Fluids B **3**, 2300 (1990).
[7] K. H. Burrell *et al.*, Plasma Phys. Controlled Fusion **34**, 1859 (1992).
[8] G. Grieger *et al.*, Phys. Fluids B **4**, 2081 (1992).
[9] F. Wagner and U. Stroth (to be published).
[10] H. Renner, W 7-AS Team, NBI Group, ICF Group, and ECRH Group, Plasma Phys. Controlled Fusion **31**, 1579 (1989).
[11] H. Ringler *et al.*, Plasma Phys. Controlled Fusion **32**, 933 (1990).
[12] K. Itoh *et al.*, Comments Plasma Phys. Controlled Fusion **14**, 343 (1992).
[13] R. Schneider *et al.*, in *Proceedings of the Eighteenth European Conference on Controlled Fusion and Plasma Physics, Berlin, 1991*, Vol. 15C, Pt. III, p. 117.
[14] H. Biglari *et al.*, Phys. Fluids B **2**, 1 (1990).
[15] A. R. Field *et al.*, Nucl. Fusion **32**, 1191 (1992).
[16] C. E. Bush *et al.*, Phys. Rev. Lett. **65**, 424 (1990).
[17] U. Gasparino *et al.*, in *Proceedings of the Nineteenth European Conference on Controlled Fusion and Plasma Physics, Innsbruck, 1992*, Vol. 16C, Pt. I, p. 505, and references therein.
[18] N. Ohyabu *et al.*, Nucl. Fusion **26**, 593 (1986).
[19] C. H. Bishop *et al.*, Nucl. Fusion **24**, 1579 (1984).
[20] C. H. Bishop, Nucl. Fusion **26**, 1063 (1986).
[21] S. Sengoku *et al.*, Phys. Rev. Lett. **59**, 450 (1987).
[22] K. Toi *et al.*, Phys. Rev. Lett. **64**, 1895 (1990).