Dynamic behaviour of the H-mode edge transport barrier in the W7-AS stellarator

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Introduction

In the stellarator W7-AS the H-mode is characterized by an edge transport barrier which is associated with a strong reduction of magnetic and density turbulence and a sheared poloidal rotation in the electron diamagnetic direction [1,2,3]. A specific feature of W7-AS is the restriction of the H-mode operational range to narrow windows of the edge rotational transform where the H-mode is obtained even at the lowest available heating power. The quiescent ELM-free H-mode is always obtained through a phase with quasi periodic ELMs [3]. Once the quiescent state is reached, edge profile gradients and the spectroscopically measured poloidal plasma rotation develop on a timescale of about 20 ms while the energy confinement improves by $\Delta W/W \approx 30\%$.

Influence of edge parameters on the H-mode operational range

In the low-shear stellarator W7-AS H-mode operation is obtained within narrow windows of the edge rotational transform ι_a (e.g. at $\iota_a = 0.525 \pm 0.005$ and $\iota_a \approx 0.48$) at the lowest available heating power, 200 kW of ECRH (one gyrotron) or 340 kW of NBI (one source), respectively. The actual power threshold might even be lower. At the onset of an ELM-free quiescent H-mode the energy flux density across the separatrix is comparable or less to that found for the L-H transition in tokamaks [4].

The magnetic field topology within the operational windows is characterized by a comparatively large plasma minor radius and a plasma boundary determined by the inner separatrix of a natural island chain (e.g. 5/10 and 5/9). The limiter does not disturb this LCFS. Under these conditions two mechanisms are believed to contribute to the easy access into the H-mode: (1) outside the LCFS the connection lengths decrease to a value of some meters within a radial distance $\Delta r \approx 1$ cm. This allows for the development of a strong radial variation of the radial electric field and a corresponding velocity shear layer already before a fully developed H-mode is achieved [5]. (2) the poloidal viscosity is lower than for other values of ι_a, as the island structures which create strongly corrugated flux surfaces increasing the magnetic pumping are shifted out of the confinement region [2,6].

The quiescent H-mode is always reached through a phase with quasi periodic ELMs [2] with a typical repetition frequency $f_{ELM} > 1$kHz. Between the ELMs turbulence is strongly reduced and indistinguishable from the quiescent H-mode phase. Global confinement in this ELMy H-mode is close to the L-state which only exists outside the H-mode operational range. Within the H-mode operational windows no stationary turbulent L-mode is found to preceed the transition. Instead short (<1ms) quiescent phases and sequences of periodic ELMs are observed intermittently even in the early phase of the discharge. For the onset of an ELM-free quiescent H-mode a threshold density n_{th} is required which depends on the edge rotational transform as an important parameter. In Fig.1a the operational window around $\iota_a = 0.525$ is marked by the hatched area and the observed values of n_{th} are given by the squares. The numbers inserted in the Figure indicate the repetition frequencies f_{ELM} observed in ELMy H-modes. As the density approaches the threshold f_{ELM} decreases to a minimum of 1 kHz. Stationary ELMy H-modes have been obtained below the threshold for up to 700 ms if the line averaged density was kept constant. In Fig.1b the same range of the total edge rotational transform ι_a is scanned continuously within 130 ms in a single discharge by adding a small ohmic current (0 kA < I_{tor} < 5 kA). The average density is kept constant at <n>=4 10^{19} m^{-3}. ELMs appear as ι_a crosses the operational range and f_{ELM} approaches a minimum as the chosen density is close to the corresponding threshold density for a quiescent H-mode.

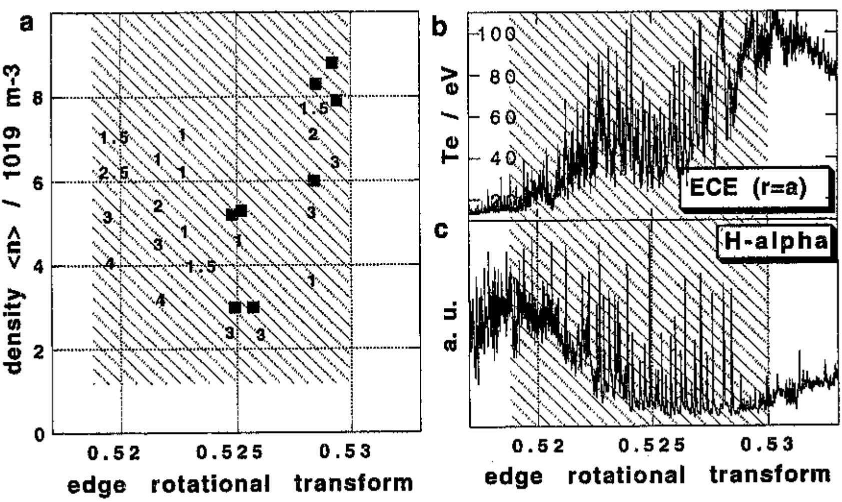

Fig. 1a: Operational range (hatched area) and threshold density (squares) for the quiescent H-mode in the ι_a window around ι_a=0.525. The numbers inserted indicate ELM repetition frequencies of ELMy H-modes in kHz.

Edge electron temperature from ECE (Fig. 1b) and H_α-signal (Fig. 1c) as the total edge rotational transform is tuned over the operational window shown in Fig 1a by adding an increasing ohmic current. <n> is kept constant at 4 10^{19} m^{-3}. The time window shown lasts 130 ms.

The influence of magnetic shear

The H-mode can also be achieved if positive or negative magnetic shear is induced in addition to the vacuum configuration by positive and negative ohmic currents. An improvement of the edge confinement can be obtained by magnetic shear even outside the H-mode operational windows [7]. With increased shear the fluctuation spectra observed with reflectometry are found to broaden and shift further into the electron diamagnetic drift direction.

Dynamic behaviour of edge parameters

The ELMs within the ELMy H-mode display characteristics similar to type III ELMs found in tokamaks [8]. They show up as bursts of magnetic and density turbulence with a repetition frequency >1kHz and a typical length of 200μs followed by an interval with strongly reduced turbulence identical to that in the quiescent H-mode phase. In most cases at the onset of the ELM magnetic coils measure a quasi coherent precursor activity with a frequency around 400 kHz. Edge profiles of T_e and n_e are obtained with high time resolution from EC- and SX-emission, reflectometry and a 10 channel mm-wave interferometer, respectively. As the broadband magnetic and density turbulence level starts to grow the edge profiles of T_e and n_e flatten over the first 3 cm inside the separatrix, emphasising the edge localized character of the phenomenon and the associated loss of confinement. As soon as the level of turbulence begins to decrease edge gradients again begin to steepen.

The *radial propagation* of the change of density perturbations is followed with reflectometry on a shot to shot basis using the onset of the H_α-burst as reference. Over a distance from 3 cm inside to 1 cm outside the separatrix the increase of the density fluctuation level occurs within a time interval as short as 20 μs.

The *poloidal propagation* of density perturbations can also be measured with the reflectometer system since the antenna beams are tilted with respect to the normal of the magnetic surfaces. The measured Doppler-shift of the reflected mm-wave results from the selected poloidal wavevector component and the poloidal propagation velocity of the density perturbation [9]. As an example Fig.2 shows a frequency power spectrum of the reflected wave during an ELMy H-mode. The spectrum is scanned over 20 ms, therefore about 30 ELMs and intermitted quiescent phases are covered. Selecting only time intervals during ELMs Fig.3 shows the radially resolved Doppler-shift on a shot to shot basis. The observed Doppler-shift towards negative frequencies is due to the poloidal propagation of the density perturbations in the electron diamagnetic drift direction. The poloidal propagation velocity of fluctuations derived from the Doppler-shift depends critically on the resulting tilt angle i.e. on the details of the complex edge topology. For positions inside the separatrix region a maximum poloidal velocity of about 20 km/s is estimated. Note that the observed velocity of the turbulence structures v_{pol} is the sum of poloidal plasma rotation and the intrinsic phase velocity of the turbulence itself.

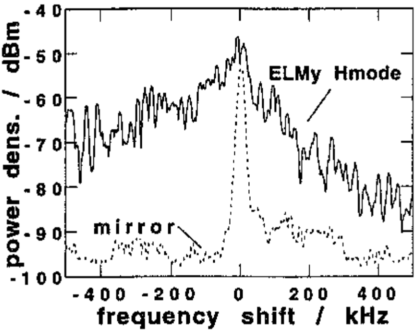

Fig 2 : Power spectrum of a reflected mm-wave measured over 20ms of an ELMy H-mode consisting of about 30 ELMs and intermittent quiescent intervals. The unshifted line reflected from the rear torus wall is given as a reference.

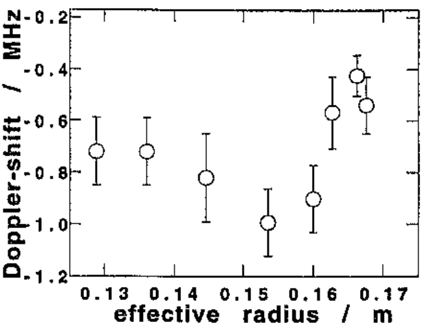

Fig 3 : Doppler-shift of the reflected signal ***during*** *ELMs. Each point is an average over 20 ELMs. Different radial positions have been probed on a shot to shot basis. The separatrix position estimated from an interpolation of equilibrium calculations is 16 cm. For the steep edge gradients observed the actual separatrix may be shifted more outward.*

Termination of the quiescent H-mode

After a quiescent H-mode of more than about 50 to 100 ms confinement tends to degrade which is accompanied by an increase of bolometry and SX radiation. During this phase strong *isolated* ELMs can appear as a distinct (duration less than 300μs) burst of magnetic and density turbulence associated with a huge spike in H_α-emission and a reduction of n_e and T_e gradients at the edge (i.e. less than 3 cm inside the separatrix). In contrast to the quasi periodic ELMs found in the ELMy H-mode the edge gradients do not recover immediately after the event but remain flat for a typical period of several ms. During that time the decrease of n_e and T_e propagates to the inner part of the plasma. In comparison to the quiescent H-phase the fluctuation level at the plasma edge in most cases remains significantly higher during this period.

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