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Investigation of the hydrogen fluxes in the plasma edge of W7-AS during H-mode discharges

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Abstract

In the stellarator W7-AS the H-mode is characterized by an edge transport barrier which is localized within a few centimeters inside the separatrix. The corresponding L–H transition shows well-known features such as the steepening of the temperature and density profiles in the region of the separatrix. With a so-called sniffer probe the temporal development of the hydrogen and deuterium fluxes has been studied in the plasma edge during different H-mode discharges with deuterium gas puffing. Prior to the transition a significant reduction of the deuterium and also the hydrogen fluxes can be observed. This fact confirms the assumption that the steepening of the density profiles starts at the outermost edge of the plasma. Moreover, sniffer probe measurements in the plasma edge could therefore identify a precursor for the L–H transition. The analysis of the hydrogen neutral gases shows a distinct change of the hydrogen isotope ratio during the transition. This observation is in agreement with the change in the particle fluxes onto the targets and can also be seen in the reduced H_α signals from the limiters. It is further demonstrated that significant improvement in the time resolution of the measured data can be obtained by deconvolution of the data with the apparatus function using Bayesian probability theory and the Maximum Entropy method with adaptive kernels. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: W7-AS; H-mode; Wall pumping; Mass spectrometry; Data analysis

1. Introduction

Wendelstein 7-AS is an advanced, partially optimized modular stellarator with low magnetic shear, five field periods, a major radius of $R = 2$ m and an effective plasma radius of $a_p < 0.18$ m [1]. The appearance of the H-mode in W7-AS is restricted to rather small ranges of the rotational transformation [2,3]. The quiescent H-mode (H^*) and the corresponding L–H^* transition show specific signatures: improved confinement, formation of a transport barrier in the plasma edge, reduction of edge turbulences, reduction of the H_α signals from the limiters and steepening of the gradients of electron and ion temperatures and densities in the region of the separatrix (the pivot point lying slightly inside the separatrix). Due to these properties it can be expected that the H-mode also significantly influences the plasma edge region. Here we present mass spectrometric measurements of the hydrogen isotope fluxes and their spatial and temporal changes during the L–H^* transition in W7-AS. Remarkable changes are detected in this context, showing that the profile steepening starts from the outer parts of the plasma edge and particle fluxes to and from the vessel walls are modified. Finally, the application of advanced concepts of data analysis is discussed with the aim to improve the effective time resolution of the so-called sniffer probe used for these measurements.

2. The sniffer probe

Sniffer probes have been used successfully for spatially resolved mass spectrometric measurements in various fusion devices [4–7]. They proved to be very useful for monitoring e.g., the hydrogen isotope ratio in

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the plasma edge for various discharge parameters and wall conditions. Here we used a recently installed new sniffer probe at W7-AS [8] that has already been applied for analyzing the hydrogen isotope ratio during neutral beam injection (NBI) heating [9].

The probe has a graphite probe head with an oval opening of 12 mm width and 8 mm height that can be oriented perpendicular (for monitoring ions) or parallel (for monitoring neutrals) to the magnetic field lines. Particles entering the orifice are detected at the end of a tube system of about 160 cm length with a quadrupole mass spectrometer (Balzers QMG 511). For recording the mass range of interest with hydrogen isotopes, i.e., $m/e = 1$–4, the mass spectrometer has a time resolution of 40 ms. The response time of the entire probe including the tube system is about 120 ms. The probe is positioned at port 8' in Section 4 of W7-AS. There the plasma is nearly elliptically shaped, the longer axis being slightly tilted away from the vertical direction and the probe is located outwards in the direction of greater plasma radii. The distance between probe and plasma can be varied by moving the probe along its vertical axis, its position is always outside the magnetic separatrix. The spatial resolution is of the order of 1 cm.

3. Results and discussion

3.1. Hydrogen fluxes in the plasma edge

To demonstrate the effect of the different discharge types on the deuterium ion fluxes in the plasma edge, we compare two similar deuterium discharges with ECRH (electron cyclotron resonance heating): discharge #47059 with and #47057 without H-mode. The results are shown in Fig. 1, giving the stored energy, the line averaged density and heating power, the H_α signal, and the D^+ flux as a function of discharge time in the respective panels (from top to bottom). The time evolution of the plasma parameters is in fact quite similar for both discharges. Without H-mode (#47057) the D^+ flux in the plasma edge roughly follows the evolution of the line integrated electron density. However, a significant reduction of the D^+ flux is observed for the case of the L–H* transition, the flux being reduced by more than a factor of 3 at the end of the discharge. This result is an evident indication of the improved confinement and constitutes a very clear signature of the L–H* transition for sniffer probe measurements. It can also be noted that the maximum in the D^+ flux and therefore the beginning of the flux decrease occurs distinctly before the L–H* transition takes place ($t < t^*$). This observation is obviously of interest for the time evolution of the H-mode and is further discussed in the following.

Fig. 2 shows a comparison of two plasma discharges in deuterium with hydrogen neutral injection (NI), both discharges turning into the H* regime. The D^+ as well as the H^+ fluxes show the decrease due to the H-mode transition as mentioned before. It is, however, interesting to note that while for discharge #47108 the reduction starts before the L–H* transition ($t_{\max} < t^*$), this occurs after the transition for #47111 ($t_{\max} > t^*$). It was supposed that this difference originates from the different positions of the probe relative to the plasma edge. Therefore this effect was studied more systematically as shown in the next section.

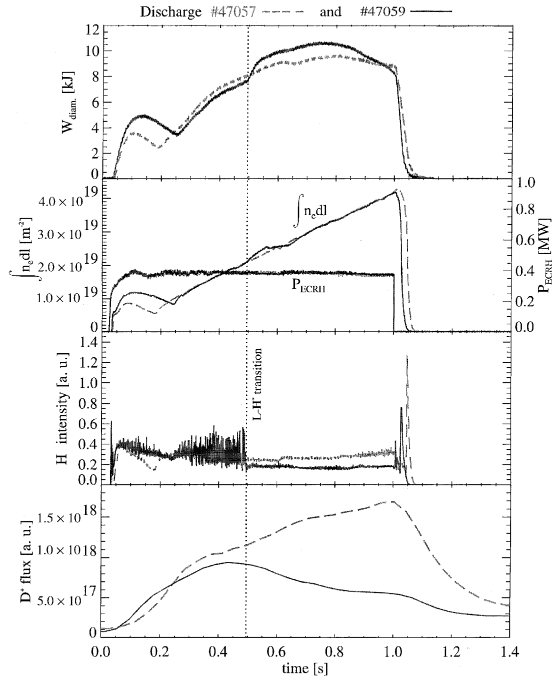

Fig. 1. Comparison of two similar discharges in D_2 with ECRH and with (#47059)and without (#47057) H-mode. In both cases the probe position was $z_{sp} = 26.5$ cm from the plasma centre.

3.2. Radial dependence of the H-mode transition

For a number of discharges with neutral injection (NI) or ECR heating the H-mode transition was studied using varying positions of the sniffer probe. For NI with H the H/D ratio increases for smaller distances to the plasma (data contained in Fig. 3), for ECRH no full probe scans are available. Results are shown in Fig. 3 where the time difference between the maximum in the measured D^+ flux and the H-mode transition time determined from the H_α signal, $t_{\max} - t^*$, is plotted as a function of the distance of the sniffer probe from the plasma, $z_{sp} - a_p$. It can be clearly seen that the hydrogen fluxes decrease earlier for larger distances from the plasma. This result supports the conclusion that the steepening of the density profile in the region of the

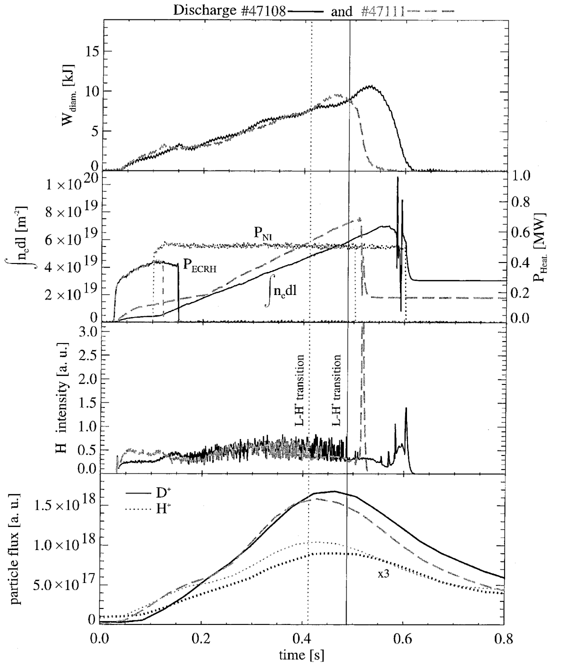

Fig. 2. Comparison of two discharges in D_2 with NI (H) and H-mode regime. $z_{sp} = 21.5$ cm.

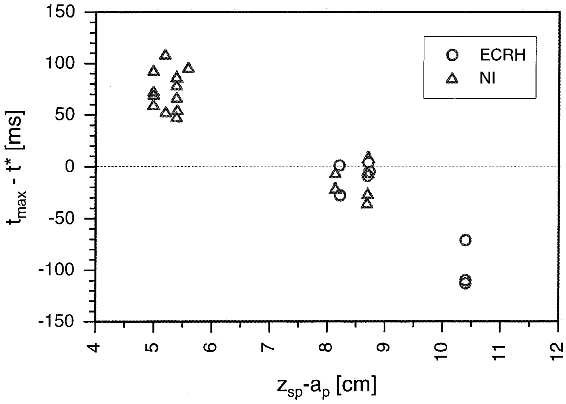

Fig. 3. Time difference between D^+ flux maximum and H-mode transition, $t_{max} - t^*$, as a function of the distance of the sniffer probe from the plasma, $z_{sp} - a_p$.

separatrix during the H-mode transition starts from the outermost parts of the plasma edge [10]. With suitable probe positioning and sufficient time resolution this can be studied in detail by sniffer probe measurements. Equally, the identification of possible precursors for the L–H* transition appears possible. Promising efforts in this direction are presented in the last section but first we complete the investigated H-mode effects by considering the wall fluxes.

3.3. Wall fluxes

The particle fluxes to and from the vessel walls and their variations can be analysed by using the sniffer probe for partial pressure measurements in the region between plasma and vessel wall and by applying a simple particle balance model [11]. Within this scheme the particle balance is written as

$$V_{\text{Plasma}}(t)\frac{\mathrm{d}n(t)}{\mathrm{d}t} + (V_{\text{Torus}} - V_{\text{Plasma}}(t))\frac{\mathrm{d}n'(t)}{\mathrm{d}t} = \Gamma_{\text{fuel}}(t) - \Gamma_{\text{wall}}(t) - \Gamma_{\text{pump}}(t), \qquad (1)$$

where V and Γ refer to the respective volumes and fluxes, and Γ_{fuel} describes the total influx of one species, i.e., gas puffing and NI, if applicable. In the discharges considered here always D puffing and H NI were applied. The particle influx due to NI is of the order of 10^{20} s^{-1} and about a factor of 10 below the gas puffing rate. n denotes the particle density of a species in the plasma and n' denotes such a density in the region between plasma and wall. Fig. 4 shows results for a deuterium discharge, #48147. It can be seen that the deuterium flux to the walls decreases steeply at the onset of the L–H* transition, thus indicating the increase in the particle confinement. In contrast, the H-flux from the vessel walls is not strongly influenced by the H transition and shows only a small modification.

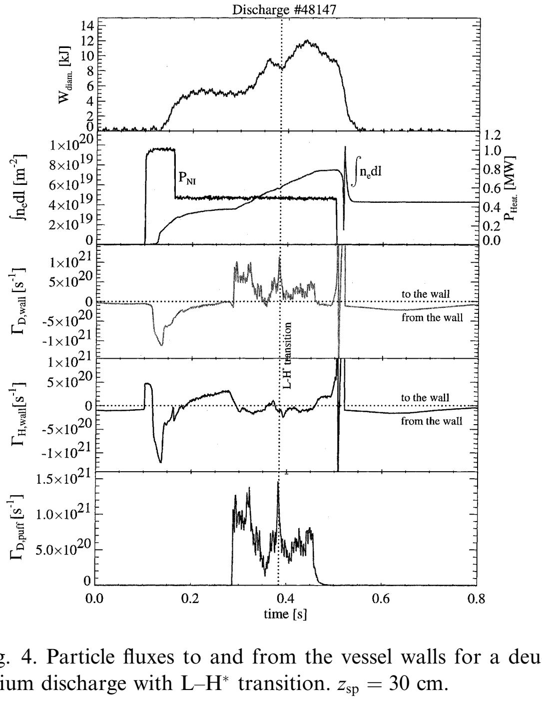

Fig. 4. Particle fluxes to and from the vessel walls for a deuterium discharge with L–H* transition. $z_{sp} = 30$ cm.

4. Time resolution

For analyzing details of the L–H* transition an improved time resolution is desirable as has been shown in Section 3. The response function of the sniffer probe is determined by the gas dynamic properties of the device and cannot be essentially changed owing to the boundary conditions given by the W7-AS vessel. However, the time resolution in the data can be improved by deconvolution with respect to the gas dynamic response function of the sniffer probe, the so-called apparatus function. The deconvolution can be performed with advantage by using the Bayesian probability theory and the Maximum Entropy method with adaptive kernels [12] as demonstrated in the following.

We are interested in obtaining the original flux distribution f from the measured data D. Bayes theorem relates the unknown posterior probability density $p(f|D)$ to the likelihood $p(D|f)$ and the prior probability density $p(f)$:

$$p(f|D) = \frac{p(D|f)p(f)}{p(D)}. \tag{2}$$

Here we use an entropic prior, $p(f) \propto e^{\alpha S}$, with the entropy function $S(f) = \int dx f(x) \ln f(x)$. The desired distribution $f(x)$ is obtained by a multi-resolution technique with an adaptive kernel B [12],

$$f(x) = \int dy B\left(\frac{x-y}{b(y)}\right) h(y). \tag{3}$$

Fig. 5 demonstrates the potential of the method. First we have to find the apparatus broadening function of the sniffer probe. This is done by deconvolution of the time distribution of the hydrogen pressure measured with the sniffer probe with a pressure spectrum measured outside the probe. Here we assume that the pressure spectrum measured outside the sniffer probe is not broadened by any apparatus function and therefore represents the time development of the torus pressure at the entrance of the probe. The result is shown in Fig. 5(a), yielding the required apparatus function. Next we give a test example of the possibility to gain the improved time resolution by taking the known apparatus function into account. To test this method of deblurring a sniffer probe measurement we generate a mock data set. A measured time development of the torus pressure is convoluted with the apparatus function of Fig. 5(a) to simulate the broadening effect of the sniffer probe measurement and then the data are deteriorated with Gaussian noise with a standard distribution of 10^{-4} of the maximum in the data. For de-blurring these noisy data are now deconvoluted with the apparatus function. The de-blurred distribution is shown together with the confidence interval in Fig. 5(b) and has to be compared with the true distribution. The match of the two curves is indeed remarkable, as is the enormous gain in time resolution. It is intended to apply this method in the future for further investigating in detail the L–H* transition in the plasma edge region of W7-AS.

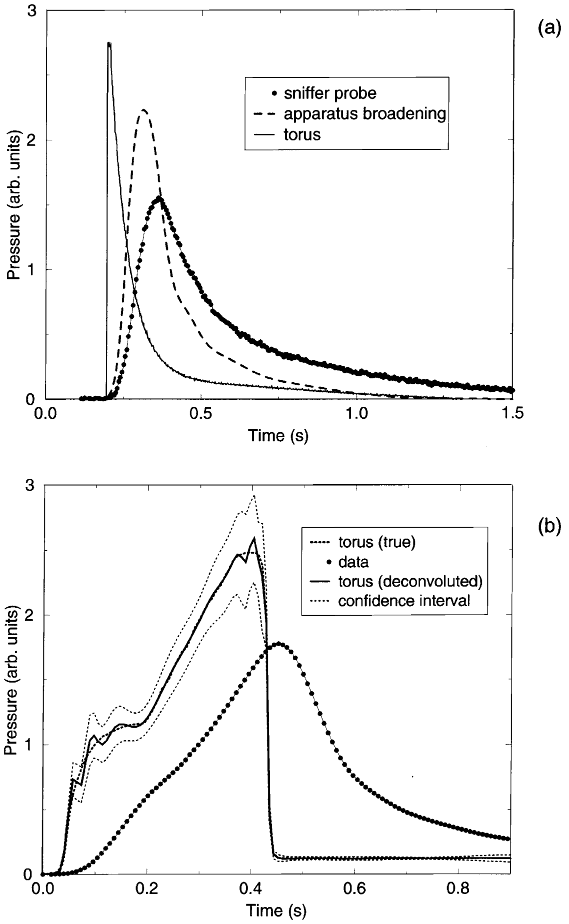

Fig. 5. (a) Time distribution of the hydrogen pressure measured with the sniffer probe and in the torus vessel and the apparatus function obtained by deconvolution of these distributions. (b) Time distribution of the hydrogen pressure in the torus, mock data obtained from this distribution by convolution with the apparatus function and simulated noise, and deconvoluted torus pressure with confidence intervals. This last distribution very closely matches the 'true' torus pressure, showing the improved time resolution obtained by this method.

5. Summary

1. Measurements with the sniffer probe show a drastic reduction of the hydrogen (H^+ and D^+) fluxes in the plasma edge of W7-AS in correlation with the H* mode.

2. The results support the assumption that the steepening of the density profiles starts during the L–H* transition in the outermost parts of the plasma edge.
3. Possible identification of a precursor for the H-mode transition requires the improvement of the overall time resolution of the sniffer probe.
4. Deconvolution of the sniffer probe data with the Maximum Entropy method allows the best possible utilization of the experimental time resolution and thus provides the required improvement.

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References

[1] H. Renner, W7-AS Team, NBI Group, ICF Group, ECRH Group, Plasma Phys. Control. Fus. 31 (1989) 1579.

[2] R. Brakel, W7-AS Team, Stellarator News 61 (1999) 13.

[3] M. Hirsch, M. Kick, H. Maaßberg, U. Stroth, W7-AS Team, Stellarator News 61 (1999) 16.

[4] W. Poschenrieder, G. Venus, Y.G. Wang et al., in: Proceedings of the 12th EPS Conference on Controlled Fusion and Plasma Physics, Budapest, Abstract 9F, 1985, p. II-587.

[5] V. Philipps, E. Vietzke, M. Erdweg, J. Nucl. Mater. 162–164 (1989) 550.

[6] H. Wolff, P. Grigull, W. Poschenrieder, J. Roth, P. Pech, W7-AS-Team, in: Proceedings of the 19th EPS Conference on Controlled Fusion and Plasma Physics, Innsbruck, Abstract CII, 1992, p. 827.

[7] P. Zebisch, P. Grigull, V. Dose, E. Taglauer, W7-AS Team, J. Nucl. Mater. 241–243 (1997) 919.

[8] P. Zebisch, E. Taglauer, W7-AS Team, Rev. Sci. Instr. 70 (1999) 3007.

[9] P. Zebisch, E. Taglauer, W7-AS Team, NBI team, Nucl. Fus. 39 (1999) 451.

[10] P. Grigull, M. Hirsch, K. McCormick, J. Baldzuhn, R. Brakel, S. Fiedler, Ch. Fuchs, L. Giannoe, H.-J. Hartfuss, D. Hildebrandt, J. Kisslinger, R. König, G. Kuehner, F. Wagner, H. Wobig, W7-AS Team, in: A New H-Mode Operational Range in W7-AS. Proceedings of the International Stellarator Workshop, IAEA Technical Meeting, Madison, WI, USA, 1999.

[11] U. Langer, E. Taglauer, W-AS Team, Mass-spectrocopic analysis of the hydrogen inventory of the W7-AS stellarator, to be published.

[12] R. Fischer, M. Mayer, W. von der Linden, V. Dose, Phys. Rev. E 55 (1997) 6667.