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2012 Plasma Phys. Control. Fusion 54 085005

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ELMy H-mode confinement and threshold power by low hybrid wave on the EAST tokamak

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Received 2 September 2011, in final form 30 April 2012
Published 30 May 2012
Online at stacks.iop.org/PPCF/54/085005

Abstract
Stationary type-III ELMy H-mode plasmas were achieved on Experimental Advanced Superconducting Tokamak (EAST) by low hybrid wave in 2010. The threshold power increases with plasma density, and a significant reduction in the H-mode occurs by decreasing the distance between the X-point and the strike point at the outside lower divertor on EAST. A series of statistics for the H-mode confinement such as the dependence of energy confinement time ($\tau_E$) on plasma density and loss power is experimentally studied in detail.

1. Introduction
H-mode produced by low hybrid current drive (LHCD) alone has been observed on JT-60 [1] and JET [2]. Low hybrid wave (LHW) alone produced H-modes in the limiter tokamak discharges on JT-60U and in single null X-point plasmas with strongly off-axis power deposition on JET. Experimental Advanced Superconducting Tokamak (EAST) is a non-circular advanced steady-state experimental device [3–6]. In this campaign, with the auxiliary heating of LHW, a stationary H-mode plasma discharge with a duration longer than 6 s was obtained with $I_p = 0.4 \sim 0.8$ MA, $B_T = 1.3 \sim 2$ T, $n_e$ (target) $= 1.5$–$2.5 \times 10^{19} \text{ m}^{-3}$, $P_{LHW}$ (injection) $= 0.5 \sim 1$ MW, double null or near double null and single null ($\nabla B$ drift towards X-point) divertor configurations [7]. The problem of prediction of the threshold power of L–H transition in fusion devices has raised considerable interest for a long time and there is no established theory for the prediction. The transition may be affected by many factors—zonal flow [8], $Er$ [9], neutral density [10, 11], X-point geometry [12–18] and so on. The dependence of the H-mode threshold on X-point height was first noticed in JET [13, 14]. About 30% reduction in threshold power was observed by decreasing the X-point height from 26 to 10 cm on DIII-D [16, 17]. In this campaign, a similar result was observed on EAST. The confinement was studied on almost all the tokamaks including EAST, but the H-mode confinement on EAST by LHW has not been discussed. The experimental progress of LHW experiments including threshold power and confinement is presented in this paper.

2. Experimental set-up
EAST, as a full of superconducting tokamak, is aimed at long pulse (60–1000 s) high-performance operation. A water-cooled graphite wall was installed in EAST from 2008 to 2011, as shown in figure 1. The device parameters include a major radius of $R_0 = 1.75$ m, minor radius of $a = 0.4$ m, aspect ratio of 4.25, an elongation range 1.2–2, and multi-configurations of single null divertor, double-null divertor and circular configurations with a limiter. The main operational parameters used for EAST experiments are an ohmic-heated hydrogen discharge with plasma current $I_p = 100$–500 kA, a toroidal field of 2 T at $R_0 = 1.75$ m, a line-averaged density of $(0.5$–$4) \times 10^{19} \text{ m}^{-3}$, an edge value of safety factor of 2–10 [19]. In this campaign, all the ELMy (ELM = edge localised mode) discharges are operated with deuterium.

A lower hybrid wave frequency range at 2.45 GHz is available for heating and current drive. It consists of 20 klystron amplifiers, which can each deliver 100 kW with CW capacity at 2.45 GHz. A multijunction coupler consists of 5 column $\times$ 4 row main waveguides. Each main waveguide
is split into eight sub-waveguides and powered by individual klystron amplifiers. The coupler can launch the LHCD power with a parallel refractive index $N_\parallel$ of 1.6–2.6 and a typical FWHM of 0.2 at $N_\parallel$ peak $= 2.3$. The spectra of $N_\parallel$ can be changed within a fast response time of 0.1 ms during one discharge, which provides a possible tool for the control of the plasma current density profile.

3. Threshold power study

It is well known that the H-Mode can be achieved above a certain threshold power ($P_{\text{thr,cal08}}$) which is, in particular, studied using the ITPA multi-machine threshold power database [20–22]. The $P_{\text{thr,cal08}}$ is as follows:

$$P_{\text{thr,cal08}} = 0.0488 e^{0.057} n_{e20}^{0.717} B_T^{0.403} S^{0.941}$$

where $B_T$, $n_{e20}$ and $S$ are, respectively, the magnetic field, line-averaged density and plasma surface area, with the following units: T, $10^{20}$ m$^{-3}$ and m$^2$. H-mode experimental threshold power is characterized by the total power loss to the plasma boundary, which is defined according to $P_{\text{loss}} = P_{\text{oh}} + P_{\text{aux}} - dW/dt$ where $P_{\text{oh}}$ is the ohmic power, $P_{\text{aux}}$ is the absorbed power contributed by LHW or ICRH on EAST and $dW/dt$ is the time variation of the total plasma energy.

Most devices have observed the presence of a minimum in the threshold power as a function of the plasma density [23–28]. In EAST, the threshold power increases with either the plasma density or the toroidal field, as shown in figure 2, but separating the two dependences is not possible with the present data set. The L–H transition is observed only at higher densities, and this may be due to the fact that in our case the heating power is just close to the threshold. Compared with the L-mode discharge, the threshold power should be higher than the scaling law at lower densities (below $2 \times 10^{19}$ m$^{-3}$), and the minimum threshold power is 0.9 MW using LHW alone on EAST at 1.6 T in this campaign.

In addition to the magnetic field, line-averaged density and plasma surface area, changing the distance between the X-point and the strike point at the outside lower divertor can also influence the threshold power. In our case, this effect was subsequently investigated in deuterium plasmas to determine whether the effect could be reproduced, and use LHW as the auxiliary heating. Figure 3(a) shows the change in the plasma shape in going from the standard shape which had the X-point at 34.3 cm (shot number: 33162) to the shape with a lowered X-point of 28.8 cm (shot number: 34816). Figure 3(b) shows how the H-mode threshold power changed with the X-point. The significant reduction ($\sim 25\%$) in H-mode threshold power with the lowered X-point was investigated. The reason for these large changes in the threshold power is as yet unknown, but further experiments studying the changes in recycling, scrape-off layer (SOL) flows or atomic processes would give us more and more details and help us to determine the physics behind the effect.

4. Confinement study

Figure 4 illustrates a typical H-mode discharge with LHW alone at the plasma parameters $I_P = 480$ kA, $B_T = 1.8$ T,
Figure 3. Power required to induce the L–H transition as a function of the distance between the X-point and the strike point at the outside lower divertor. (a) Plasma shape for the high X-point (solid red) and low X-point (dashed black). The green line is the divertor. (b) The threshold power as a function of the X-point.

Figure 4. Typical H-mode discharge with LHW alone with the plasma parameters from top to down: plasma current, plasma density, stored energy, total power and Hα. The red dashed line is the power of LHW and blue solid line is the lithium dropping. $P_{\text{LHW}} = 1\,\text{MW}$. During the current ramp-up phase, about 50 mg lithium powder is dropped in 1 s (from 500 to 1500 ms). Lithium is dropped to reduce the radiation, and to achieve the L–H transition at a low power threshold [11]. The stored energy increases by 40 kJ, and remains constant for about 1 s after the L–H transition. Typical ELM frequency is 100–800 Hz. The collisionality of the pedestal plasma can be defined as $v^\ast_{\text{pol}} = R_{q95}e^{-3/2}(\lambda_{e,c})^{-1}$, where $\lambda_{e,c}$ is the electron–electron Coulomb collision mean free path [29]. The collisionality on EAST, which is calculated by using the data from Thomson scattering and microwave reflectometry, is at a high level from 1 to 8, as shown in figure 5. MHD precursor of the ELM has been found, and energy loss of an ELM on divertor is below 2.1% which has been presented in the 20th ITPA Pedestal TG Meeting. All these phenomena have proved that most of the ELMy on EAST is type-III ELMy.

Figure 6 shows that the energy confinement time ($\tau_E = E/(P - dE/dt)$, where $E$ is the plasma energy and $P$ is the total injected power) decreases with increasing loss power both in H-mode and L-mode, and energy confinement time for the
L-mode is much lower than the H-mode. The dashed line shows $\tau_{\text{th, ITER89}} \sim P_{L}^{0.15}$ and $\tau_{\text{th, 98y2}} \sim P_{L}^{0.69}$, consistent with the experimental trends. Figure 7 shows the dependence of the energy confinement time on different line-averaged densities from the hydrogen cyanide (HCN) laser interferometer. The energy confinement time increases with plasma density, as shown in figure 7. The scaling for the L-mode thermal energy confinement time ($\tau_{\text{th}}$) is called the ITER89-P scaling,

$$\tau_{\text{th, ITER89}} = 0.048 I_{p}^{0.85} B_{T}^{0.2} n_{20}^{-0.1} P_{L}^{-0.5} R^{1.2} \epsilon^{0.3} \kappa_{a}^{0.5} M^{0.5},$$  

(2)

(in s, MA, T, $10^{20}$ m$^{-3}$, MW, m). The effective elongation is defined as $\kappa_{a} = S_{c}/\pi a^{2}$, where $S_{c}$ is the plasma cross-sectional area. The most reliable scaling expressions since 1998 for the ELMy H-mode thermal energy confinement time ($\tau_{\text{th}}$) is the so-called IPB98(γ,2) scaling [30];

$$\tau_{\text{th, 98y2}} = 0.0562 I_{p}^{0.93} B_{T}^{0.15} n_{19}^{0.41} P_{L}^{-0.69} R^{1.97} \epsilon^{0.58} \kappa_{a}^{0.78} M^{0.19},$$  

(3)

5. Summary

Typical type-III ELMy H-modes have been achieved in EAST by LHW. Typical ELM frequency is from 100 to 800 Hz. The minimum threshold power is about 0.9 MW at $2 \times 10^{19}$ m$^{-3}$. There is a dwell time of L–H transition in the range 40–1360 ms, which tends to decrease with power increase. The energy confinement time of H-mode discharges increases with plasma density, and decreases with $P_{\text{loss}}$. The distance between the X-point and the strike point at the outside lower divertor may also influence the threshold power. A significant reduction (~25%) in the H-mode threshold power is achieved by decreasing the X-point by 5.5 cm. These results are in agreement with those of JET and DIII-D.

Acknowledgments

The authors are grateful to Dr Kensaku Kamiya and Dr Changxuan Yu for discussions on this work. This work was supported by the National Magnetic Confinement
Figure 8. Dependence of experimental energy confinement time in L-mode and H-mode discharges on (a) ITER89 and (b) IPB98(y2) scaling laws.

Figure 9. Dependence of dwell time on total power.

References