FIRST EDGE-LOCALIZED MODE SUPPRESSION WITH LOWER HYBRID WAVES ON THE EAST TOKAMAK

Shaocheng Liu[1,2], Yunfeng Liang[3,4*], Rui Ding[3*], Manni Jia[3], Fuqiong Wang[1,2], Ning Yan[3], Miaohui Li[3], Yifeng Wang[3], Xiaohe Wu[3], Li Li[1,2], Mengze Xu[1,2], Tonghui Shi[3], Liang Liao[3], Wenyin Wei[3,4], Genfan Ding[3], Shuai Xu[4], Yifei Jin[3], Qing Zang[3], Lingyi Meng[3], Gongshun Li[3], Tao Zhang[3], Ran Chen[3], Hailin Zhao[3], Youwen Sun[3], Long Zeng[5], Huiqian Wang[6], Tengfei Tang[6], Rong Yan[3], Liang Wang[3], Guoqiang Li[3], Guosheng Xu[3], Jinping Qian[3], Xianzu Gong[3], Xiang Gao[3], Fangchuan Zhong[1,2] and EAST Team

[1] College of Physics, Donghua University, Shanghai, China.
[2]Member of Magnetic Confinement Fusion Research Centre, Ministry of Education, China.
[3] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China.
[4] Forschungszentrum Jülich GmbH, Jülich, Germany.
[5] Department of Engineering Physics, Tsinghua University, Beijing, China.
[6] General Atomics, San Diego, California, United States of America

Email: scliu@dhu.edu.cn

We report the first successful suppression of edge-localized modes (ELMs) achieved through lower hybrid wave (LHW) on the EAST tokamak, accompanied by the identification of the edge magnetic topology changes via the sheared turbulence structure. First, the spatial structure of the LHW-induced helical current filaments (HCFs) is measured by a newly developed directional electron probe, covering a radial region of about 25 mm and a maximum current density above 20 A/cm^2. A density threshold is discovered to generate considerable HCFs in experiment, which is the key dependence of the HCFs on plasma parameters. Based on these experimental results, a fine 3D HCFs model is reconstructed by the field line tracing, and the magnetic topology induced by HCFs is analyzed by the MAPS code. The radial magnetic field perturbation calculated by the HCFs model matches that measured by the magnetic coils, and the divertor heat flux footprint estimated by the field-line diffusion model is consistent with that measured by the Langmuir probe, demonstrating the validity and accuracy of the HCFs model. With an optimized experimental scenario, stable ELM suppression is achieved in a series of experiments with line-averaged density $n_e =$ 3.5-4.5×10^{19} m^{-3}, LHW heating power 1-1.5 MW and modulation frequency 5-10 kHz. The normalized radial magnetic field perturbation has very good resonant features with the resonant surfaces at the plasma edge, with a predominant perturbation mode $n = 1$ and an amplitude B^ρ/B^ζ in the order of 10^{-3}. As calculated by the MAPS simulation, edge magnetic islands are created by the HCFs, and a stochastic region is formed in the pedestal region. During ELM suppression, the pedestal density decreases significantly, leading to a slightly smaller electron pressure gradient, which shifts the pedestal plasma from the stability boundary of the peeling-ballooning (P-B) mode to a stable operational regime, i.e., from ELMy plasma to ELM-free plasma. In addition, the SOL electron density and temperature, as well as divertor particle deposition increase significantly in the ELM suppression phase compared to the ELMy phase, indicating enhanced cross-field transport in the edge plasma, which is crucial for maintaining the lower pedestal plasma density in the ELM-free phase. Edge broadband turbulence is enhanced greatly and an ECM is observed in the pedestal region during ELM suppression, which could drive outward cross-field transport. Furthermore, the spatial structure of the ECM measured by GPI is intensively sheared in the radial range of $\rho =$ 0.96-0.97, and the turbulence radial velocity also decreases strongly in this region, which agrees with the poloidal structure of local magnetic topology, indicating the existence of magnetic islands and stochastic region, which is a key feature of the physical theory of ELM control with resonant magnetic perturbations.

This work systematically investigates the interplay between LHW-driven HCFs, magnetic topology, and edge turbulence dynamics, providing novel insights into ELM control mechanisms. In summary, LHWs could drive the SOL HCFs, generate magnetic field perturbations and create magnetic islands or stochastic region in the edge plasma, then enhance the cross-field transport, lower the plasma density and pressure in the pedestal, finally move the plasma from unstable region of the P-B mode to stable region and maintain the ELM-free H-mode. This mechanism is demonstrated by our experiment and modelling. Compared to external coils, LHWs-induced HCFs are located much closer to the pedestal region, facilitating efficient modulation of the magnetic topology and transport in the pedestal while preserving the core plasma confinement. In addition, the magnetic perturbations of the HCFs have good resonance features. The steady-state scenario of ITER is operated with $q_{95}\sim$ 5 and lower hybrid current drive, which is similar to the experimental condition on EAST. Since the higher plasma density amplifies the SOL current in ITER, LHW offers a promising avenue for ELM control without complex external coils. This study not only advances the understanding of ELM control mechanisms, but also paves the way for practical, economical solutions for controlling ELMs in ITER and next generation fusion reactors.

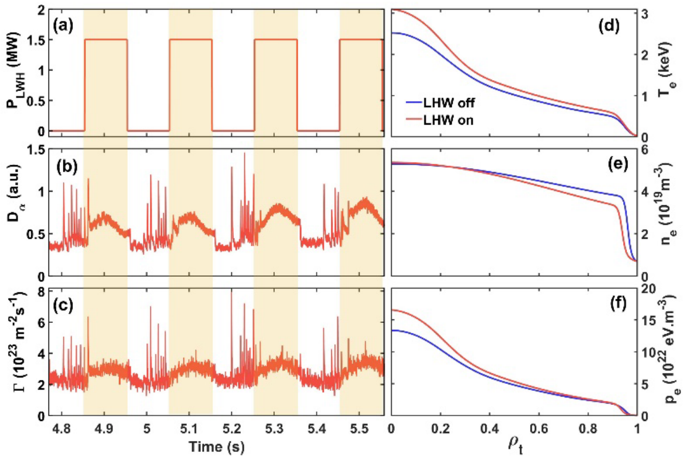

Figure. 1. Plasma parameters of the ELM control experiment with LHW, including (a) LHW heating power, (b) D_α emission intensity, and (c) particle flux measured by DLPs. Radial profiles of the fitted electron temperature (d), electron density (e), and electron pressure (f), with the horizontal axis ρ_t as the normalized toroidal flux.

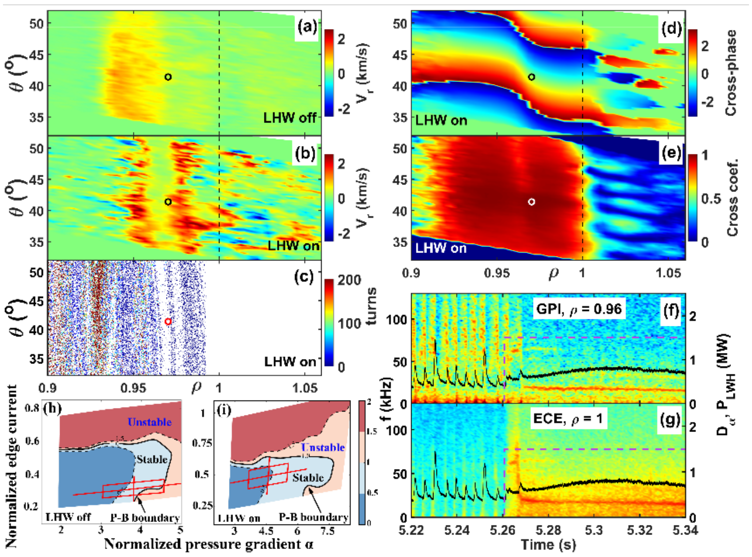

Figure. 2. Radial turbulence velocity derived from GPI diagnostic in LHW-off (a) and LHW-on (b) phases, with the black dashed line as the LCFS. (c) Poincaré plot at the toroidal position of the GPI in ELM suppression. Cross-phase (d) and cross-coefficient (e) between GPI fluctuations within 16-19 kHz and that of a reference pixel marked by a circle for the LHW-on phase. Spectrogram for GPI signal (f) and ECE signal (g), D_α emission intensity (black line) and LHW heating power (purple dashed line). Pedestal stability diagrams for LHW-off (h) and LHW-on phases (i).

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