A new method of ELM control using lower hybrid waves on EAST

Y. Liang[1,2,a], J.G. Li[2], B.N. Wan[2], X.Z. Gong[2], G.S. Xu[2], H.Y. Guo[2,3], M. Rack[1], P. Denner[1], L. Zeng[2], Y. Sun[2], K.F. Gan[2], E. Gauthier[4], L. Wang[2], ,Y.M. Wang[2], B. Lv[2], B.J. Ding[2], R. Chen[2], L.Q. Hu[2], J.S. Hu[2], F.K. Liu[2], Y.X. Jie[2], J.P. Qian[2], J.F. Shan[2], B. Shen[2], T.H. Shi[2], F.D. Wang[2], H.Q. Wang[2], M. Wang[2], Z.W. Wu[2], S.B. Zhang[2], T. Zhang[2], X.L. Zou[4], X.J. Zhang[2], N. Yan[2], U. Samm[1], and the EAST team

[1] Institut für Energie- und Klimaforschung - Plasmaphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

[2] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

[3]Tri Alpha Energy, Inc., P.O. Box 7010, Rancho Santa Margarita, California 92688, USA

[4] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

[a] Email address: y.liang@fz-juelich.de

Next-generation fusion machines, like ITER and DEMO, will need a reliable method for mitigating or suppressing large Edge localized Modes (ELMs). To date, in all existing ELM mitigation or suppression experiments using resonant magnetic perturbations (RMPs), these magnetic perturbations are induced by either in-vessel [1] or external [2] coil systems. In-vessel perturbation coils have been considered and designed for ELM control in ITER. However, in future fusion reactors, like DEMO, in-vessel perturbation coils may not be feasible. Thus, ELM control through actively changing the magnetic topology by other mechanisms offers an attractive solution for next-generation tokamaks beyond ITER.

Experimental Advanced Superconducting Tokamak (EAST) was built for demonstrating long-pulse stable high-performance H-mode plasmas with ITER-like configuration and heating schemes, i.e., with a flexible selection of double null, lower single null (SN), or upper SN poloidal divertor configurations and dominant radio frequency heating [3]. The lower hybrid wave (LHW) system [4], operating at 2.45 GHz with an array of 20 (4 columns and 5 rows) waveguide antennas, was installed at the low field side midplane. The maximum output power of the LHW system is 2 MW. It was originally designed for a core plasma current drive by transferring momentum to the plasma via electron Landau damping with a peak parallel wave refractive index of ~2.1, and can achieve long-pulse H-mode operations with or without additional ion cyclotron resonance heating (ICRH). However, similar to other experiments [5 , 6], significant LHW power can be lost at the plasma edge, especially in a high-density plasma, due to a complex problem of coupling between fast waves and plasma particles.

Recently, ELM mitigation has been observed on the EAST when lower hybrid waves (LHWs) are applied to H-mode plasmas sustained mainly with ion cyclotron resonant heating (ICRH) [7]. This has been demonstrated to be due to the formation of helical current filaments (HCFs) flowing along field lines in the scrape-off layer induced by LHWs. Because of the geometric effect of the LHW antenna, the perturbation fields induced by the HCFs are dominated by the n=1 components, where n is the toroidal mode number.

In comparison to previous RMP ELM mitigation experiments, using a set of fixed in-vessel coils, ELM mitigation with LHWs on EAST is achieved with a wider range of q_{95} as shown in Fig.1. In this experiment, a long ELMy H-mode phase is established mainly by ICRH with an input power of 1 MW in a relatively high-density regime (the Greenwald fraction is about 0.9) after a fresh Lithium wall coating [8]. The plasma currents in the three discharges were 0.4, 0.45 and 0.5 MA, which correspond to a q_{95} of 4.7, 4.2 and 3.8, respectively. A 10 Hz modulation of LHWs with a power of 1.3 MW has a 50% duty cycle in all three discharges, thus the duration of the LHW-off phase is 50 ms, which is about half of the energy

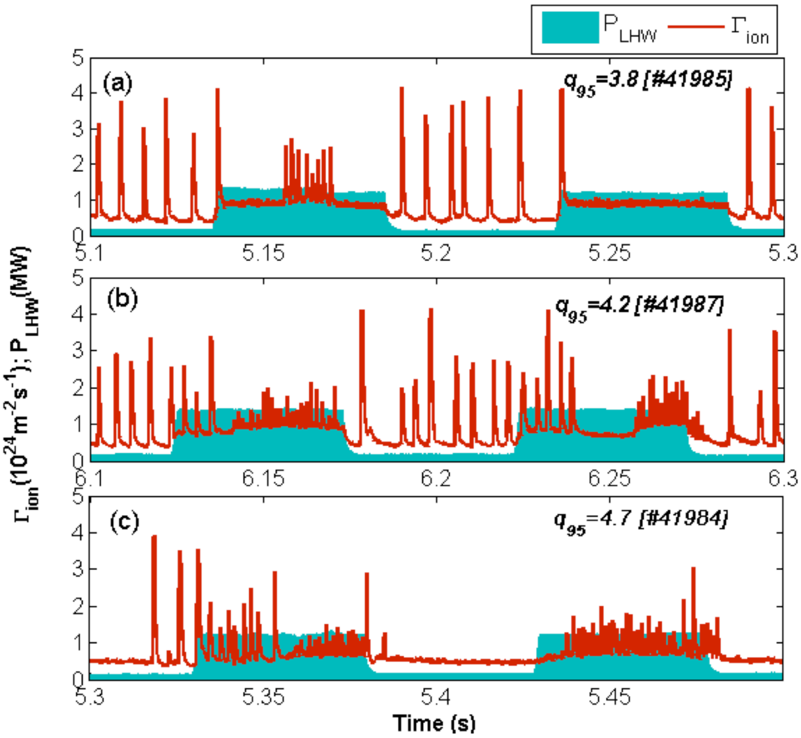

Figure 1: Effect of LHWs on ELMs by modulating LHW power in a series of target H-mode plasmas sustained by ICRH with a different edge safety factor, q95 of 3.8, 4.2 and 4.7. The time traces are the peak ion-flux in the outer divertor (red), and injected LHW power.

confinement time. Without LHWs, the ELM frequency is fairly regular at ~150 Hz. When the LHWs were switched on, both a significant increase in ELM frequency (up to ~1 kHz) and reduction in ELM peak particle flux (up to a factor of 4) were observed. For the low q_{95} discharge, the influence of LHWs on ELMs can be rather quick in time, and ELMs can even be completely suppressed. However, a longer delay time before the appearance of large ELMs was observed in the high q_{95} discharge after fast switching-off of LHW, sometimes longer than 50 ms, as seen in Fig. 1 c).

Splitting of the outer divertor strike point during LHWs has been observed similar to previous observations with RMPs [5] (see Fig. 2). The change in edge magnetic topology has been qualitatively modelled by including the HCFs in a field line tracing

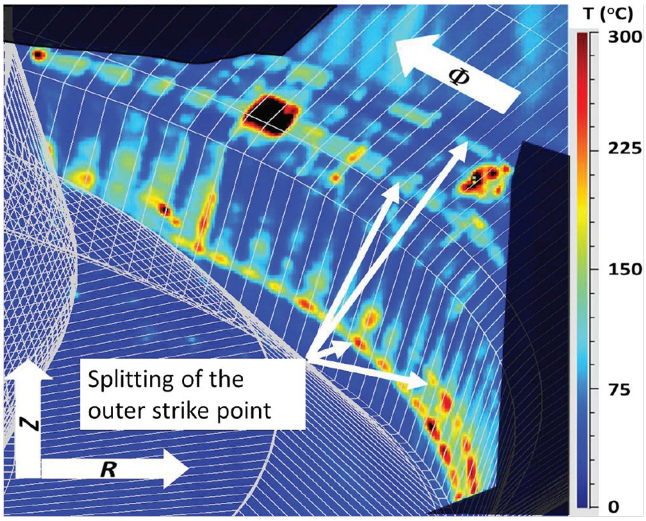

Figure 2: IR image of the outer lower divertor plate in a toroidal range of ϕ=1.3π –1.5π rad during the application of LHWs. Splitting of the original outer SP is shown as a multiply striated heat pattern on the divertor plate. The toroidal asymmetry of the SP splitting can be observed.

code (see Fig. 3). The connection lengths of the magnetic field lines are calculated using an experimental equilibrium superimposed with a vacuum field from the HCFs with a total measured filament current of a few hundred A. The results show a strong modification of the plasma edge topology dependent on the edge safety factor as well as the amplitude of currents flowing in these filaments. The fields produced by the

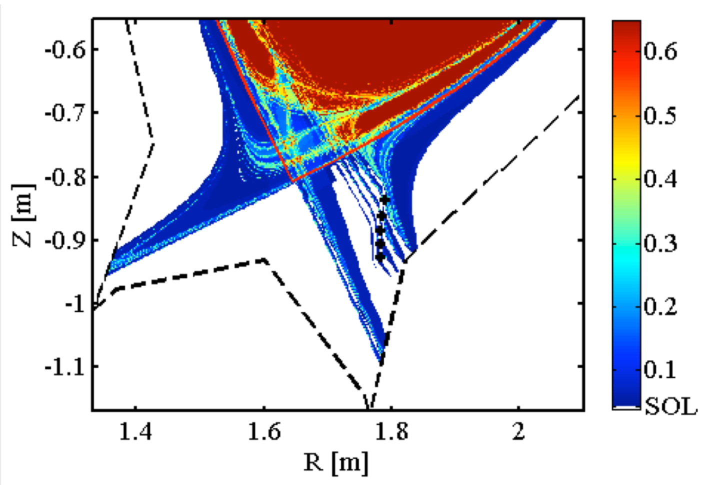

Figure 3: Connection length plots of the lower X-point region for a HCF current of 1.5 kA. The solid line gives the LCFS of the unperturbed case. The colour scale represents the connection length.

HCFs form several lobes with long connection length field lines near the X-point which can hit the outer divertor plate, resulting in splitting of the SP. This can qualitatively explain the experimental observations of SP splitting.

When the LHW power is switched on, a reduction in edge density (so called density pump-out) has been observed in the H-mode phase, while the edge density increases slightly in the L-mode phase. This can be explained by the HCF-induced edge stochastization layer, where both the particle diffusion transport and the neutral particle distribution are affected, but the dominant changes are different in L-mode and H-mode plasmas.

It is to be mentioned that the currents in the SOL induced by LHW have been observed on several devices [6，7], however, the physical mechanism is still unclear. A simulation using the GENRAY-CQL3D code package with a two-dimensional SOL model including the effects of collisional damping shows that about 10% of LHW power can be deposited in the SOL in the high-density plasmas on EAST. However, the experimentally observed currents (~7 kA) in the SOL are far too large to be explained by direct current drive via collisional absorption of the LHW [7]. Note, however, that the absorption of LHW in the SOL could contribute to an increase in the ionization rate for neutrals in the divertor region, thus enhancing the thermoelectric current flowing along the SOL field lines from the hotter, less dense divertor plate to the colder, denser divertor plate.

It is worth noting that ELM control with RMPs induced by in-vessel coils is normally limited by a narrow resonant q_{95} window [1, 6] due to the fixed coil geometry. However, the HCFs induced by the LHWs flow along the magnetic field lines in the SOL, thus the helicity of the HCFs always closely fits the pitch of the edge field lines whatever the value of the plasma edge safety factor. In addition, the HCF-induced magnetic perturbations are localized at the plasma edge, without significantly affecting the plasma core. Therefore, this may provide a better method for ELM control on ITER. |\

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