Study on Stabilization of Tearing mode with ECRH and its resultant transport properties on HL-2A tokamak

Yi Liu, Wei Deng, X.Q. Ji, Yunbo Dong, J.Zhou, Y. Zhou, Q.W. Yang

South Western Institute of Physics, Chengdu, China

Corresponding Authors's e-mail address: yiliu@swip.ac.cn

Abstract. Electron cyclotron resonance heating (ECRH) has been used successfully to suppress MHD activity on the HL-2A tokamak. This was achieved in the discharges of relatively low current where large m/n=2/1 radiation induced tearing mode instabilities were suppressed by continuous or successive ECRH. The effective suppression was observed when the EC resonance was located in the narrow region that is associated with the position of the q=2 surface. Especially, it is manifested that the suppression of m/n=2/1 tearing mode instability can be sustained by successive ECRH modulated with low frequency, leading to a continuous density rise because of the steady improvement of the particle confinement. The continuous rise in central plasma density and temperature as well as the confinement improvements sustained by the successive ECRH power, can be attributed to the additive effect of internal transport barrier (ITBs) formed after each ECRH switch-off or non-local response to the removing of ECRH. This provides a low-cost, effective means of controlling m/n=2/1 tearing modes and extending the beneficial effects of MHD suppression on particle and energy confinement.

1. Introduction

Magnetohydrodynamics (MHD) instabilities, by which the plasma is deformed macroscopically, are commonly observed in tokamaks. In particular, the magnetic islands associated with the tearing modes, which exist at resonant surfaces with the rational values of the safety factor q, can grow to a relatively large amplitude. In high-density regime, it is generally observed [1] that the high radiation loss at the edge will induce the formation of MHD tearing mode which is called radiation induced tearing mode (RTM). The presence of RTM modes leads to degradation of plasma confinement or even leads to disruptive termination of a discharge. So it is of great importance to control the evolution of RTMs as soon as they develop in a tokamak discharge. This can be achieved by cancelling the mode helical current perturbation either by raising the temperature in island interior and reducing the resistivity with off-axis ECRH or by localized current drive with electron cyclotron current drive (ECCD) [2]. The avoidance of density-limit disruptions by suppression of the tearing modes with ECRH that develop during the radiative precursor of these disruptions was reported from T-10 [3]. Moreover, active control of MHD modes was achieved in ASDEX Upgrade and RTP through modulated ECRH in phase with the O-point of the island.

The stabilization of tearing modes by off-axis ECRH is through the modification of helical current distribution, which also leads to the change of magnetic shear near rational surface. Many of the experimental results from different tokamaks demonstrate that the q profile with low or negative shear in the core region is the most auspicious condition for eITB triggering, and that even a small decrease in magnetic shear leads to obvious ITB formation. Furthermore, it has been observed that immediately after off-axis ECRH switch-off the core electron temperature stays constant for some time [4], which suggests that the low shear magnetic configuration continues to exist until the current profile is rearranged in a new manner. This provides the possibility to apply off-axis ECRH in an integrated way for making combined effects on both the stabilization of tearing modes and transport reduction through ITB formation.

On HL-2A, the controlling of the MHD activities and tailoring of current profile can be realized either by localized off-axis ECRH or ECCD. In the present paper, we report the experimental observations on stabilization of tearing mode with continued or modulated ECRH and its resultant transport properties.

2. Experimental Arrangement

HL-2A is a medium-sized tokamak (major radius R=1.65m, minor radius a=0.40m) with a double null closed divertor. The operating conditions in this experiment were varied in the range of Ip=130-200kA, Bt=1.1-1.45T, qa=2.1-4.3 and $<n_e>=(1-4)\times 10^{13}cm^{-3}$. ECRH is one of the main auxiliary heating schemes for the HL-2A plasma. An ECRH system at 68 GHz, delivering up to 2MW by 4 gyrotrons, has been brought into operation in the HL-2A tokamak. The power of each gyrotron is 500 kW, and pulse duration is about 1 second. In the present experiments, the ECRH/ECCD system with total power of 2 MW is realized. The ECRH power with O-mode (selected harmonic number n=1) or X-mode (n=2) is injected from the low field side, and propagates along the equatorial plane nearly perpendicularly. A sinusoidal grooved polarizer has been developed. With the low power test results, the X-mode purity of the polarizer reaches 85% and almost 100% when the toroidal angle is 15^o. The high power EC wave of 340kW can be transmitted through the line with the polarizer. With the polarizer, ECRH/ECCD in second-harmonic X-mode experiments has been carried out in HL-2A tokamak with two gyrotrons. By changing toroidal field, the location of ECR power deposition can be adjusted for the tearing mode stabilization.

The electron density profile is measured by a five-channel FIR HCN laser interferometer, so that the distance between the channels is 4cm and the temporal resolution about 1ms. The electron temperature is measured by Thomson scattering system (TS) as well as using the soft x-ray spectra diagnostics. A set of 24 magnetic field coils located in one toridal cross-section is used to analyse MHD activity with low m (m<5) poloidal wave numbers. The evolution of MHD instabilities in the plasmas is followed by a 100 channel soft X-ray(SXR) multi-camera system (5 arrays, 20 channels for each array) being able to detect the energy range of 1eV-10keV. The spatial and temporal resolution of the system is 2.5cm and 10us, respectively. The diamagnetic energy, Edia, is measured by the diamagnetic loops on HL-2A.

3. Experimental observation of m=2/n=1 tearing mode

Tearing modes are frequently observed on HL-2A when the total current is lower than 200 kA, due to the weakening of field line curvature stabilization. This usually causes the discharge entering a regime with permanent MHD activity, the so-called MHD regime. These regimes exhibit intensive m=2, n=1mode activity during density limit discharges or in discharges even with low and moderate plasma density. This results in the formation of quasi-stationary, rotating islands as shown in figure 1. The large m = 2 islands cause local flattening of the SXR profile near the O point of the island. From the SXR profile, it can be seen that the q=2 surface lies at about r = 24cm (r/a = 0.65) which agrees with the EFIT simulation calculation. The saturated magnetic island can remain in a quasi-steady state for up to several hundred milliseconds with an island width about 5cm, which approximately equal to 18% of the plasma radius in HL-2A. Figure 2 shows the time evolution of the plasma current, gas puffing, central line-average density, stored energy, and the fluctuating magnetic field for a typical shot with high-MHD activity. Also plotted (with a red line) are the corresponding signals for a MHD-free shot. MHD activity starts increasing at 200 ms, then saturates for 150 milliseconds and leads to a disruption at 380 ms. The MHD activity observed in the present experiment may be associated with RTMs, a non-linear instability with low m/n modes which are resonant near the rational surface with q=m/n(see Sec.5).

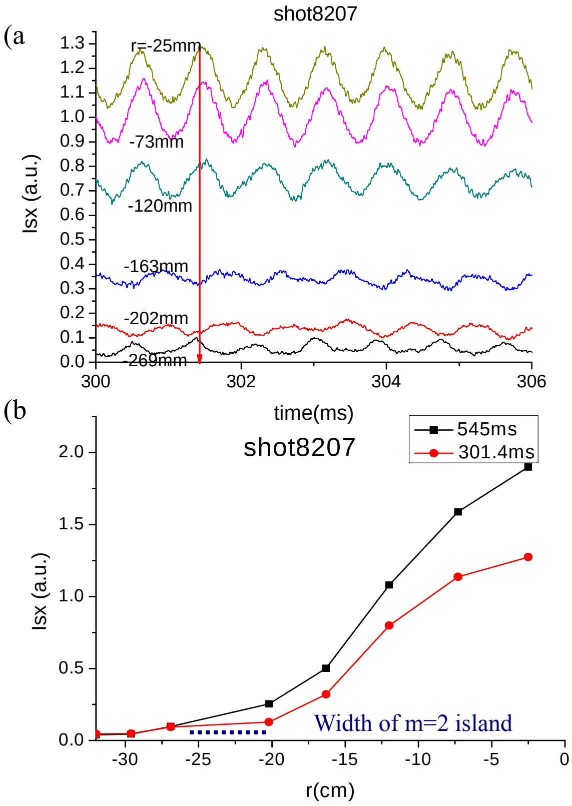


Figure 1 (a) Time evolution of soft X-ray emission showing a large m = 2 perturbation; (b) Radial profile of x-ray emission measured during m = 2 perturbation compared with the profile after its disappearence.

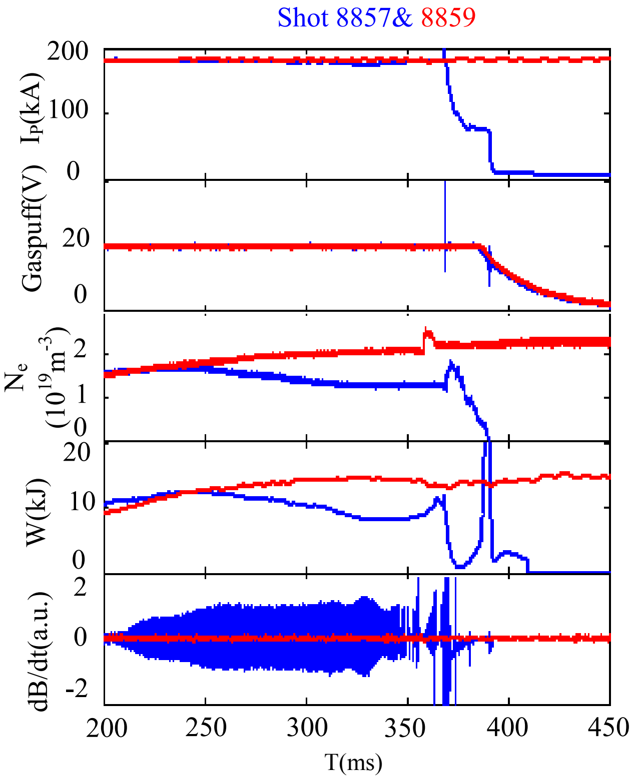


Figure 2 Effect of a growing (m,n)=(2,1) island on the stored energy. The red curves are from a MHD-free discharge. The blue curve is from a shot which developed a large island.

4. Effects of ECRH on MHD activity

4.1. *The stabilization of the $m = 2$, $n = 1$ tearing mode with continuous ECRH*

In HL-2A, the investigation on 2/1 mode suppression by ECRH has been performed. A location scan of EC power deposition has been realized on HL-2A. For a plasma with Ip=150kA, the the resonance location of 68 GHz ECRH was varied across the plasma minor radius, by changing the toroidal magnetic field B_t, from shot to shot. The toroidal magnetic field was adjusted so that EC resonance occurres at different positions with respect to the q=2 surface on the low magnetic field side of the torus. Experiments show that the behavior of 2/1 modes is very sensitive to the position of EC power deposition. The 2/1 tearing modes can be suppressed by ECRH when the power is absorbed near the island position. Figure 3 (a) shows the cross-section of the HL-2A plasma equilibrium marked with the ECRH power deposition. ECRH power trace, and the fluctuating magnetic field amplitude and its spectrogram from an m=2 pickup coil are shown in figure 3 (b).

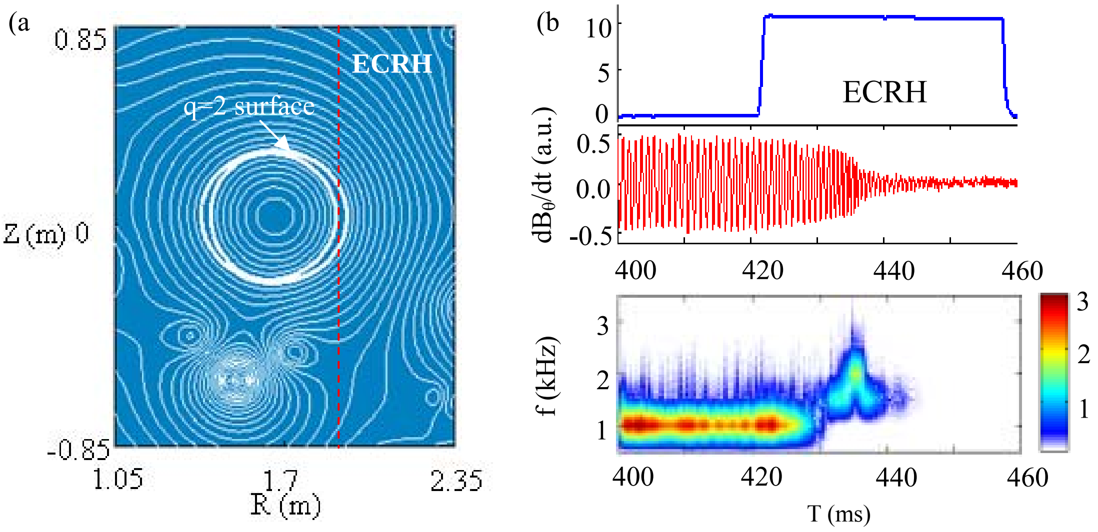
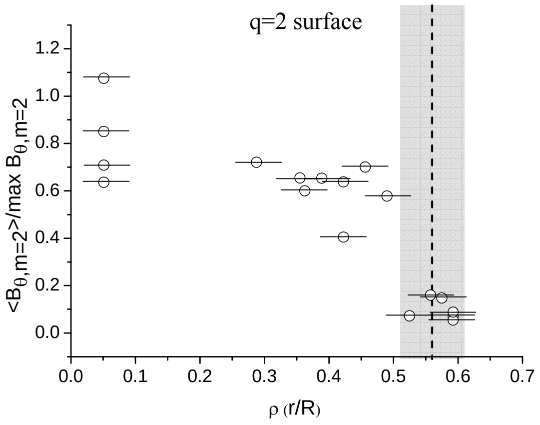


Figure.3 (a) Cross-section of the plasma equilibrium, marked with the ECRH power deposition and the q=2 surface; (b) Time traces of magnetic fluctuation and its spectrogram for a discharge in which ECRH is applied far off-axis.

Controlled experiments regarding the stabilization of tearing modes by ECRH were carried out, varying parameters like the density, the magnetic field, the ECRH power and its pulse length. It was found that when the location of the EC resonance is close to the q = 2 surface, the tearing mode can be suppressed. Such effect is very position dependent. The sensitivity of stabilization to the position of ECRH power is shown in figure 4 which shows that only heating near q=2 surface can lead to stabilization. With the suppression, the enhancements in the plasma density and stored energy have been observed, as shown in figure 5. The suppression of the m=2/n=1 tearing mode is perfectly reproducible, and one of the interesting features of some of these discharges is that the m=2 activity does not resume even after the ECH pulse is turned off, an example is shown in figure6 (a).



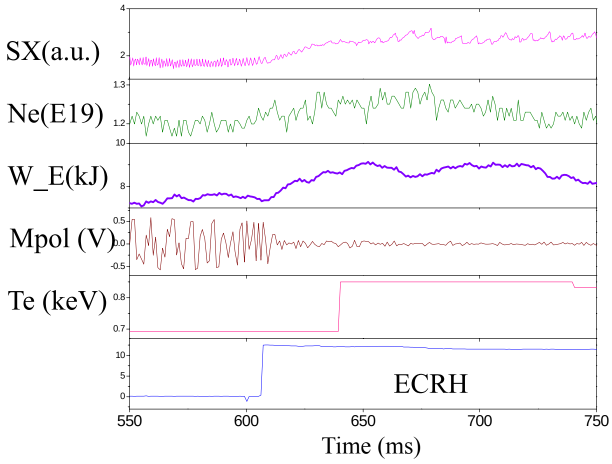


Figure.4 Variation of the perturbation field change with the location scan of ECR power deposition.

Figure.5 Time traces of magnetic fluctuation, stored energy When ECRH is applied off-axis.

Furthermore, another important feature is that the subsequent gyrotron switch-off can induce a reversed polarity in SXR intensity: the central intensity increase promptly rather than decrease in response to the removing of ECRH (figure 6). It was noted that the density increases continuously while the core SXR intensity first increases for several tens of milliseconds then it starts to decrease. Taking into account that the difference between the evolution of SXR intensity and density is due to the change of Te, we can follow SXR intensity to study the evolution of plasma temperature. Thus, we can use SXR intensity to follow the evolution of electron temperature. The steep profile in SXR intensity near q=1 surface in figure 6(b) reflects a change in the central electron temperature. Before it decays, the steep gradient can last for about 30ms, in which the central plasma transits to an enhance confinement. Heat wave propagation analysis also suggests that the thermal transport coefficients are reduced in the gradient zone. These interesting features and the fact that such kind of effect can be additive[4], motivated us to apply another ECRH pulse before the decay of the steep gradient, i.e., using successive low frequency modulated ECRH for sustaining MHD-free phase and obtaining a continuous confinement improvement.

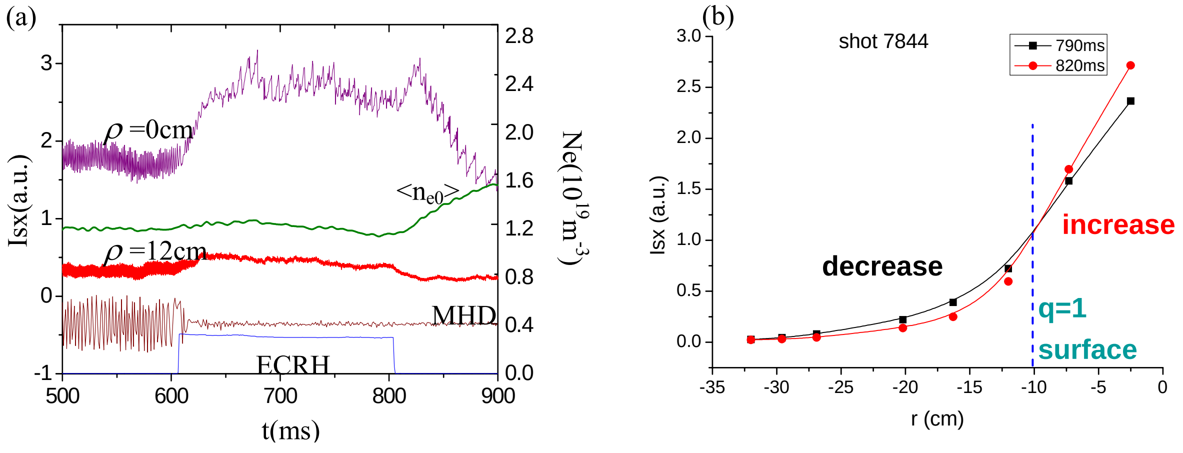


Figure.6 (a) Time traces of magnetic fluctuation, central density, SXR intensity at the central and near q=1 surface for a discharge in which ECRH is applied far off-axis, showing the effects of ECRH on both MHD stabilization and on ITB formation; (b) I_{sx} profiles before and after ECRH switch off.

4.2. The stabilization of the tearing mode with successive ECRH

Further advance in plasma confinement improvement has been made by taking the advantage of above mentioned features of plasma response after far-off axis ECRH switch-off in the present experiments, i.e. the changes caused by ECRH are not reversible after the pulse is turned off. We applied ECRH power modulated with a frequency of about 10Hz to explore a more favorable regime taking advantage of the enhance confinement after each switch-off, i.e. a steady increase in plasma temperature and density, and a continuous confinement improvement. In order to study the effect of modulated ECRH on island stability P_{ECRH} was deposited just around the magnetic island. The power depth modulation was 100%, with a duty cycle of 50%. In this operation mode the maximum power that the gyrotron could deliver was limited to 250kW.

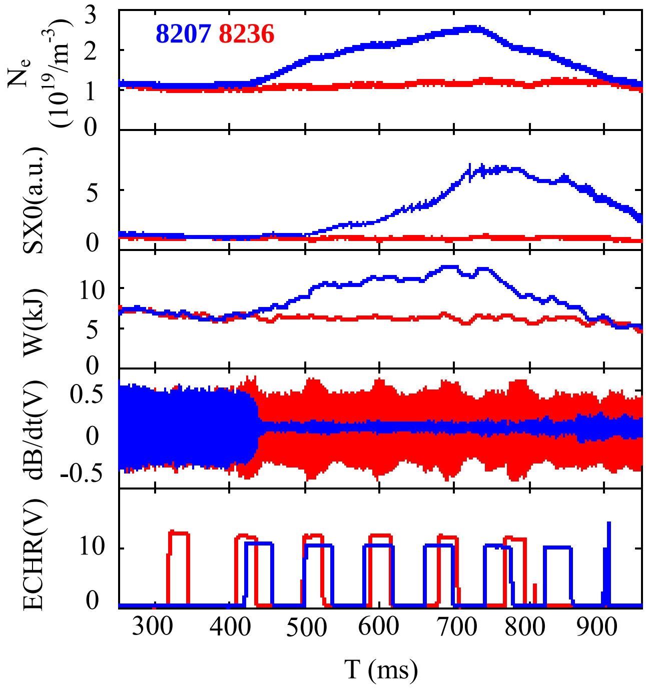


Figure.7 Time traces for discharge 8207 in which the 2/1 mode is suppressed by successive ECRH pulses and a case with 2/1 tearing mode (8236).

The beneficial effect of mode suppression on energy confinement is shown in figure 7 where two discharges are compared. They are almost identical apart from the ECRH absorption layer, which in one case (#8207) is correctly positioned to achieve stabilization while in the other case (#8236) is 3 cm inside the q = 2 surface, so that the stabilization fails. The behaviour of central temperature, density and stored energy is the same in the two shots until the stabilization occurs in shot #8207. The amplitude of the m=2/n=1 begins to decrease after the injection of modulated ECRH at 425ms in discharge #8207. From this time on a better energy and particle confinement is achievedas well as a stored energy twice higher. Concurrently with the suppression of m=2/n=1 tearing mode the plasma density, stored energy, and energy confinement time increase ~ 80%, ~ 50%, and ~ 40%, respectively, indicating that a much better confinement occurs. Thus, the experimental results show that indeed a better effect of the suppression can be achieved with such lower frequency modulated ECRH in the vicinity of the q = 2 surface. The suppression event is characterized by a feature of the continuous improvement of confinement, i.e. the plasma density, temperature, stored energy and energy confinement time increase steadily throughout the modulated ECRH period. This provide an alternative way to control m=2/n=1 tearing mode in addition to continuous ECRH or modulated ECRH with a high frequency in phase with the O-point of the island [4].

5. Discussion and Summary

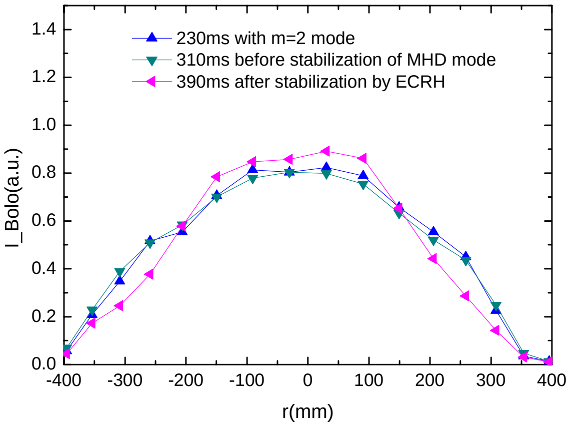


Figure.8 Radiation profiles at different times with and without m=2 MHD mode.

An important clue to the mechanism for suppression of the magnetic island can be found by comparing the changes in the radiation profile before and after stabilization of MHD mode. In figure 8, the radiation profiles are peaked around the q=2 surface from 230ms to 310ms when the m=2 mode are presented. After the onset of ECRH power, the m=2 mode was stabilized at 390ms while the locally peaked radiation around q=2 surface was removed. Thus, destabilization of the MHD mode can be induced by strong radiation power emitted from the m=2 island, as indicated by the island evolution equation $\frac{dW}{dt} = \eta\,(\Delta' - C\,\frac{p}{\kappa T_e}W\,)$ Where W, η, Δ' are the island width, the plasma resistivity, the parameter of the tearing mode instability, the net total power density absorbed in the island, and the cross-field heat conduction coefficient, respectively[5]. So, the main effect of the ECRH power is to off-set the radiation lost via localized heating in the island interior, leading to stabilization of MHD mode, which is corresponding to the experimental results that only localized heating around the q=2 surface can cause effective stabilization.

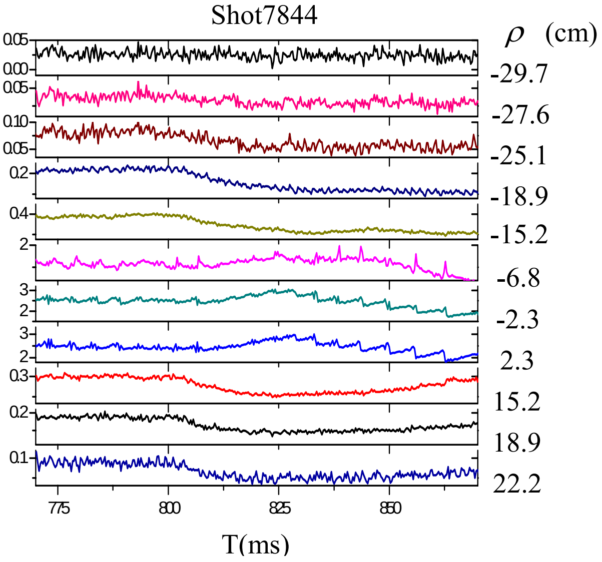


Figure.9 Transient SXR responses to an ECRH switch-off at about 810ms.

We have mentioned earlier that there are two important features of the suppression of m=2/n=1 tearing mode with ECRH in the range of $0.6<P_{ECRH}/P_{ohm}<1$ on HL-2A, which are related to the removing of ECRH. Both the features of no resuming of the m=2 activity and the delayed Te decrease or even increase after ECRH switch-off indicate that the change in current distribution caused by ECRH is not reversible after the pulse is turned off [8]. An understanding of the physics therein can be gained by looking at the time evolution of line-integrated SXR emission in figure 9 in more detail. There, we see that the removing of ECRH induces a Te drop in the edge region. Simultaneously, we see that over the inner region of the plasma($\rho < 6.8cm$), the electron temperature begion to rise. There are two possibe mechanismes for this. One is related to the formation of transient ITB characterizing by a

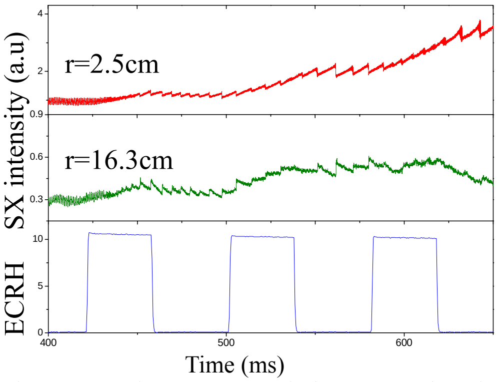


Figure.10 Time traces of the SXR showing that three successive ECRH pluses produce an additive increase in SXR emissivity.

delayed Te decrease after the off-axis ECRH switch-off as reported on T-10 and TEXTOR[6], HL-2A[7]. Another is the non-local phenomenon[4], but response to removing of ECRH, which plays a similar effect as edge cooling. Both mechanismes are in favor of the continuous improvement of confinement with successive ECRH. In figure 10, three successive ECRH pulses produce an additive increase in SXR emissivity, indicating a series of increase in central Te. Thus, the continuous rise in central plasma density and temperature as well as the confinement improvement sustained by the ECRH power modulated with a frequency of about 10Hz, can be attributed to the ITBs created after each switch-off or non-local response to ECRH removing. Therefore, successive ECRH power modulated with a low frequency can be applied to explore a more favorable regime taking advantage of the enhanced confinement due to a series of ITB formation or non-local response.

In summary, the experimental results on HL-2A directly confirm the effectiveness of off-axis ECRH on stabilisation of m=2 tearing mode. Successful MHD mode suppression was achieved when the EC resonance was located in the narrow region near the q=2 surface. In addition to continuous EC heating, and most importantly, successive ECRH has been used to suppress MHD activity and sustain the beneficial effects from MHD stabilization. It is manifested as a new result that the suppression of m/n=2/1 tearing mode instability can be sustained by successive ECRH, leading to a continuous density rise as the particle confinement improves steadily. The continuous rise in central plasma density and temperature as well as the confinement improvements sustained by the successive ECRH power, can be attributed to the ITBs or non-local response after each ECRH switch-off. This provides a low-cost, effective means of controlling m/n=2/1 tearing modes and extending the beneficial effects of MHD suppression on particle and energy confinement.

Acknowledgments

This work is supported by National Science Foundation of China under the Grant No.10775045 and also partially supported by the China-Japan CUP Agreement.

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