Link of Internal Transport Barriers and the Low Rational q Surface on HL-2A

Yunbo Dong [1], Yi Liu [1], Dick Hogeweij[2], Roger Jaspers[2], Jun Zhou [1], Yuan Huang [1], Chunhua Liu [1], Min Liao [1], Wei Deng [1]

[1]Southwestern Institute of Physics, Chengdu, China, www.swip.ac.cn;

[2]FOM Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, Nieuwegein, the Netherlands, www.rijnhuizen.nl.

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

ABSTRACT. Recent experiments in the HL-2A tokamak have shown that the soft X-ray and electron temperature profile in ECRH discharges can have only a small number of distinct profile shapes, depending on the location of the additional heating. The sharp transitions between the profile shapes are associated with lower rational q surfaces. These observations suggest that electron heat transport in a tokamak plasma is governed by a sequence of narrow transport barriers separated by regions that act as thermal bridges, and the electron thermal diffusivity χe is a direct function of the safety factor q. In addition, after the off-axis ECRH switch off, the core soft x-ray intensity keeps constant or even an increase for several tens of milliseconds before it starts to decrease, while the edge soft x-ray intensity decreases just after the ECRH switch off. The delay only can be observed on off-axis heating with low shear and reversed shear. From the statistic analysis of dependence of the change of the central soft x-ray intensity (ΔIsx) on the central magnetic shear dq/dr after ECRH switch off, we found that there are three domains related to the formation of ITBs in the central part of the plasma, which links with the different dq/dr near the rational magnetic surface.

1. Introduction

At present time on many large and small tokamaks the phenomenon of internal transport barriers (ITBs) has been studied. By 'the barrier' we mean the zone with locally reduced transport, i.e. the zone with the enhanced pressure gradient ∇P, temperature gradient ∇T or density gradient ∇n, which can be deduced from profiles of electron and ion temperatures T_e, T_i and density n_e. It is very important for the ITER project to understand what factors are responsible for transport barriers formation, what is the scaling for the threshold power (if such a threshold does exist).

Numerous experiments were performed on various tokamaks to clarify the link between rational q, magnetic shear and internal transport barriers (ITBs) by varying the q-profile from a monotonic one to the profile with a central negative shear [1-6]. A common observation has shown that q(r) profile has the effect on the transport barrier formation. However, it is still not very clear about the link between the formation of the barrier and the location of the low rational q surface. To be able to make more accurate extrapolation, it is important to understand the 'necessary' conditions for ITB formation.

An advantage of the Electron Cyclotron Resonance Heating (ECRH) is its excellent localization. Thus a wide range of actual physical problems can be studied by applying ECRH.

The pure electron heating allows us to perform confinement studies in the conditions of a hot electron component. The required discharges for ITB formation study can be achieved and controlled using ECRH. So we can study ITB formation by changing the deposited power location to vary the local q(r) profile near the rational q.

Experiments in the RTP tokamak suggest that electron heat transport in a tokamak plasma is governed by a sequence of narrow transport barriers separated by regions that act as thermal bridges[7]. A scan of ECRH power deposition along plasma minor radius was performed and the result is quite similar with that of the RTP.

This paper is also to investigate the phenomenon of delayed Te decrease after the off-axis ECRH switch-off and study whether there is a connection between the transport barrier and the local value of dq/dr near the rational q.

The paper is organized as follows. In section 2, we describe the experimental set-up and used diagnostics. In section 3, we describe the result of ECRH power deposition scan along plasma minor radius. Section 4 describes the experimental results of transient ITB after ECRH switch-off on four investigated regimes. Section 5 contains discussion and conclusions.

2. Experimental set-up

HL-2A is a divertor tokamak device with a major radius of 1.65m and a minor radius of 0.4m. The experiment was performed with line-averaged electron density n_e=1-4×$10^{19}$$m^{-3}$, central electron temperature $T_e(0)$=1-5keV, central ion temperature $T_i(0)$=0.2-0.6keV, plasma current Ip in the range 130–480 kA, toroidal magnetic field in the range 2.2–2.8 T [8]. ECRH is one of the main auxiliary heating schemes for the HL-2A plasma.

Electron cyclotron resonance heating is one of the main auxiliary heating schemes for the HL-2A plasma. The ECRH system consists of two 68 GHz gyrotrons for fundamental resonance heating. 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 heating wave starts from the weak field side, and propagates along the equatorial plane nearly perpendicularly. In 2007, 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. 340kW high power EC wave 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.

The typical parameters on the HL-2A of these experiments are: electron density measured by a five-channel FIR HCN laser interferometer, n_e=1.3×$10^{19}$$m^{-3}$; central electron temperature, Te ~ 1keV, measured by the soft x-ray spectra diagnostics. Electron temperature profiles are measured by Thomson scattering system(TS): the multi-point Thomson scattering system measured 5 spatial points. Five points can be scanned by moving the fiber bundles on the fiber holder. Thus the measured plasma region is z = -3 ~ -35 cm. The spatial resolution is about 2.2 cm along vertical direction, and the time interval is 100ms.

3. Heat convection and transport barriers

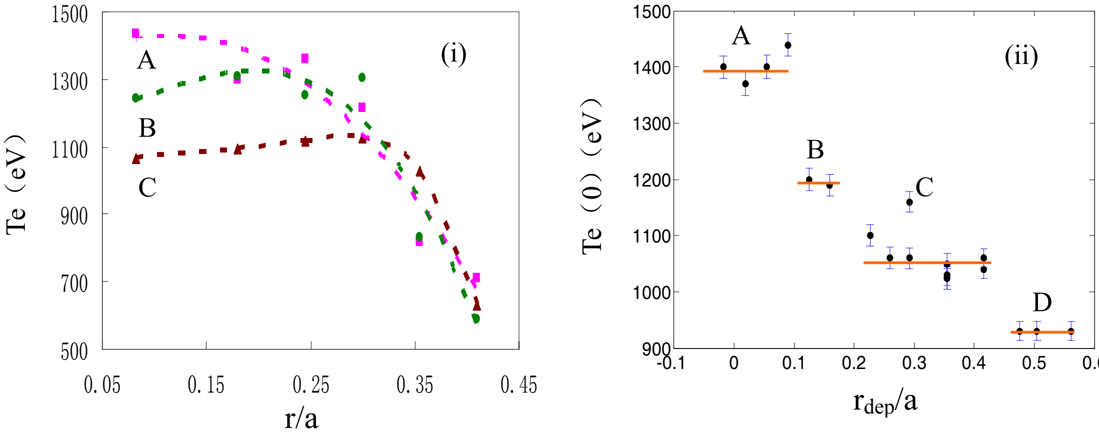

FIGURE 1. Shot-to-shot scan results for I_p=133kA, P_{ECRH}=300kW, $\bar{n}_e \approx 1.3\text{x}10^{19}\text{m}^{-3}$, $q_a^{max} \approx 5$. The central electron temperature $T_e(0)$ for one scan of the normalized ECRH power deposition radius. (i) T_e profile corresponding to the three plateaus measured by Thomson scattering system; (ii) the central electron temperature $T_e(0)$ for one scan of the normalized ECRH power deposition radius.

To find the link between the ITBs and the low rational values of the safty factor q, a shot-to-shot scan of the central Te(0), was performed with variation of the power deposition radius(r_{dep}) by changing the toroidal magnetic field B_t in ECRH discharges on HL-2A tokamak.

Using a 300kW ECRH (P_{ECRH} ~ $2P_{OH}$, where P_{OH} is the Ohmic power), the hot electrons were effectively decoupled from the ions. The ECRH power was deposited in a very localized region, within a width of ~0.15a. All plasma parameters are kept fixed except for B_t; the toroidal magnetic field is varied between 1.22T and 1.39T to change the location of the power deposition. The r_{dep} is varied in small steps between discharges. All data presented here have been taken 5–10 current diffusion times after switch-on of ECRH, i.e. when the q profile had relaxed to steady state. All Te(0) data used are from the TS system. Though there are some uncertainties in the temperature measurements from the TS, the collective action of the barriers at low rational q-surfaces describes the peakness very well.

The scan results have indicated that the Te profile does not change smoothly from central to far off-axis heating. Rather, it jumps in discrete steps through a series of distinct profile shapes, changing abruptly from one profile to the next. The Te profiles of the individual shots comprising each plateau are shown in figure1(i). The electron temperature profile in ECRH discharges can have a small number of distinct profile shapes.

To show clearly the abrupt transitions of the Te profile, it is illustrative to plot the steady state central electron temperature, Te(0), against r_{dep}. It is observed that Te(0) does not continuously adapt to the change of heating location; instead, sudden transitions occur between the discrete plateaus，labeled A-D in the figure 1(ii), in which a variation of r_{dep} has very little effect on the Te profile.

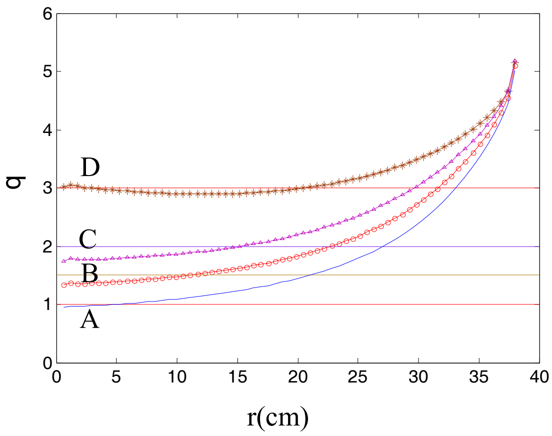

FIGURE 2. Various q profiles for typical shots correspond to different regimes of figure 1.

From the Te profiles of the discharges in this scan q profiles were calculated (figure 2), by using the EFIT code. Comparing the q profiles of the discharges of one level to the next, we discovered that a discrete jump of the Te profiles was accompanied by the loss of a (half-) integer q surface: e.g. for the discharges of the class denoted by B in figure 2, q reaches just over 1; the discharges of class C have q just over 1.5 everywhere. The transition from B to C is thus directly linked to the loss of a transport barrier near q = 1.5. Similarly, we can link the other transitions to rational q surfaces.

In conclusion, we have found barriers linked to q = 1, 3/2, 2 and 5/2. We have obtained confirmation of these values of q from the observation of sawtooth inversion surface, and the occurrence of magnetic islands and MHD modes.

These experimental observations suggest that electron heat transport in the tokamak plasma is governed by a sequence of narrow transport barriers separated by regions that act as thermal bridges. The results highlight the decisive role of the safety factor q for the presence and position of the transport barriers. To explain these results, the so-called q-comb model for electron heat conductivity, χ_e, has been developed in which χ_e is supposed to be a function of q only with a constant high value interspersed with narrow regions of low conductivity located near the low rational values of q: 1, 4/3 , 3/2 , 2, 5/2 , . . .[9]. The empirical transport model featuring barriers near the half-integer q surfaces successfully reproduced the observations.

4. ITB Triggered during ECRH

Reduced core transport or ITB has been observed with off-axis deposited ECRH around rational surfaces (q=1, 2 or 2.5 surface) in subsequent experiments at HL-2A. It was shown that a low value of dq/dr near the rational magnetic surface leads to an ITB formation. This is inferred from the experimental observations in some HL-2A regimes with off-axis ECRH. After the off-axis ECRH switch-off, the core soft x-ray intensity, does not decrease immediately and continuously in time towards the Ohmic value. Instead, the core I_{sx} first stays constant or even a slight increase for several tens of milliseconds before it starts to decrease in the timescale of energy confinement time, while the edge I_{sx} decreases just after the ECRH switch off (Figure 3(a)). Meanwhile, the n_e increase continuously after the ECRH. The difference between the evolution of I_{sx} and n_e is due to the change of T_e, so we can use I_{sx} to study the evolution of electron temperature. Besides the similarities with the experiments on other tokamaks [10], the results in HL-2A sometime show an obvious increase in the central soft x-ray intensity, indicating a much steeper temperature profile. Moreover, the delay can appear not only with sawteeth stabilization, but also can appear with sawteeth, or with m=1 mode in our experiments:

1. Delay with sawteeth stabilization: this case always happened when the q_a is bigger, the $q_0>1$ and with slight magnetic shear $dq/dr\approx0$ or reversed shear $dq/dr<0$.
2. Delay with sawteeth: this case, $q_0<1$. sometimes there is a slight shear $dq/dr\approx0$.
3. Delay with m=1: $q_0=1$, $dq/dr\approx0$.

The shot in figure 3(a) is shown the case with sawteeth, and the periods of sawteeth become larger because of the central ne increases during that phase. Figure 3(b) is the T_e profiles before ECRH switch-off, just after ECRH switch off and 50ms after, which shows that the central I_{sx} increases obviously just after the ECRH and the core region becomes peaked and narrower than that during ECRH. Thus a steep I_{sx} profile is formed (Figure 4(a)). The central electron temperature remains constant for some time after ECRH switch-off, while the off-axis temperature decreases at the same time. Hence the ∇T_e increased near the inverse surface confirmed from I_{sx} profile during this phase (Figure 4(b)), while ∇n_e measured by microwave reflectometer increases slightly.

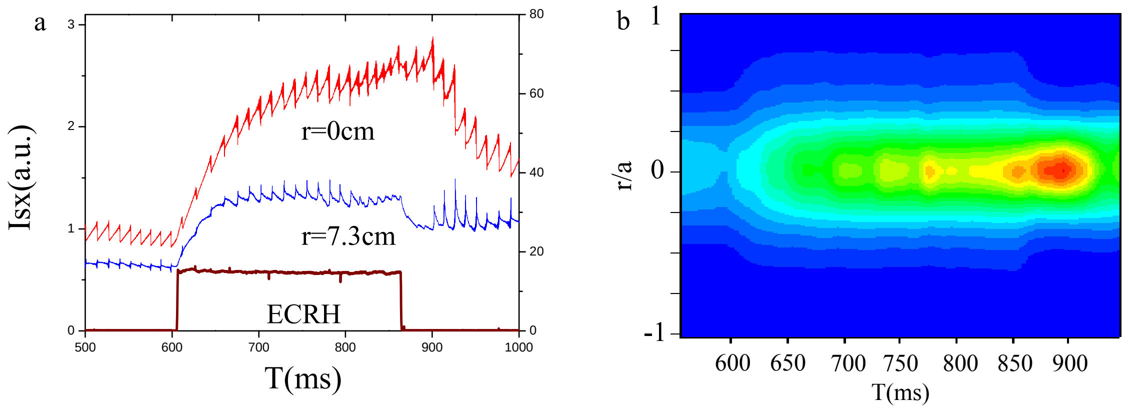

FIGURE 3. (a) Delayed decrease in the core I_{sx} after ECRH switch-off; B_t = 2.16 T, I_p = 300 kA, $n_e=2.6\times10^{19}$ m^{-3}, P_{ECRH} = 1100kW; (b) Contour plot of SXR signals from camera reflecting.

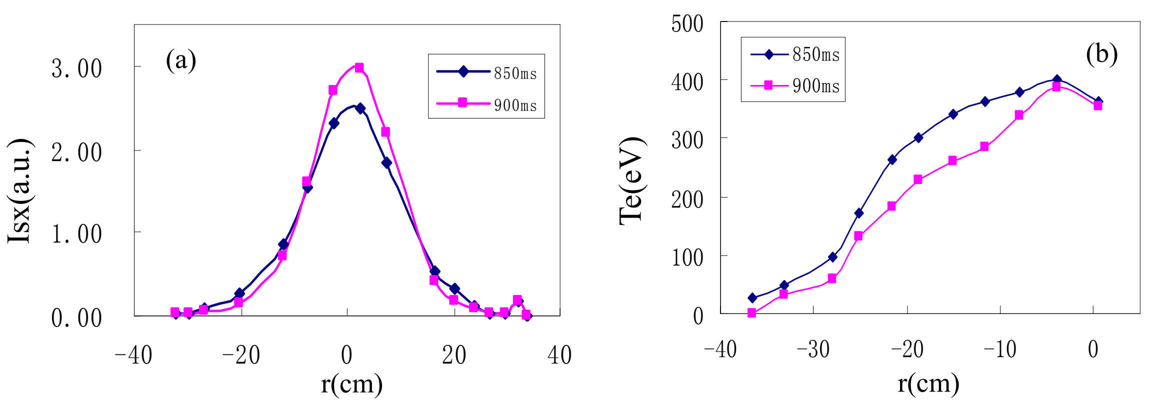

FIGURE 4. (a) I_{sx} profile during ECRH and after ECRH switch off; (b) T_e profiles before ECRH switch-off , just after ECRH swtich off.

The fact leads to the conclusion that the heat-diffusivity coefficient, χ_e, must be reduced. Figure 5 shows the electron heat diffusivity in three phases calculated by using the heat pulse propagation in response to sawtooth crash: in the OH phase, at the end of the ECRH phase and just after the ECRH switch off. The value of χ_e is larger during ECRH than OH discharge, and the maximum is observed near the heating deposition location. The transport coefficient reduces at all radii just after the off-axis ECRH switch off, especially near the heating deposition location.

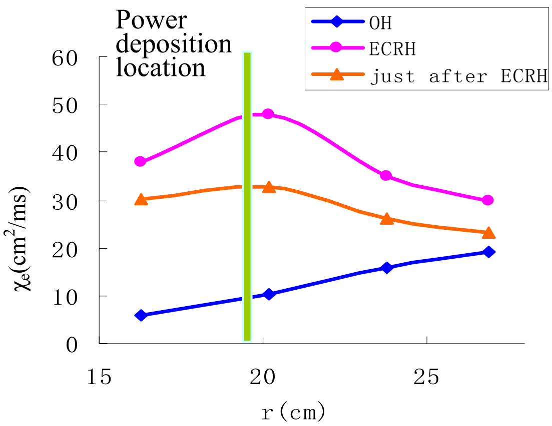

FIGURE 5. Electron heat diffusivity in the OH phase, at the end of the ECRH phase and just after the ECRH switch off.

It was found that such phenomenon is closely linked to the change in the central magnetic shear causing by the off–axis ECRH heating. The delay of Te（0）decay only can be observed on off-axis heating with low shear and reversed shear. The possible explanation is that off-axis ECRH switch off leads to current density redistribution and transiently low magnetic shear near the rational magnetic surface causing the internal transport barrier (ITB) formation. To investigate whether low dq/dr near the rational magnetic surface is an important condition for the observed confinement improvement, the following experiments were done:

1. Ip=133kA, P_{ECRH}=270kW, Bt=1.26T, $\bar{n}_e \approx 1.38\times10^{19}m^{-3}$, r(deposition location)=6cm, qa=4.0. During ECRH, q<1, and after ECRH switch off, central q still small than 1, q=1 surface became smaller, and dq/dr > 0**.** In this case, the transient ITB did not appear. (figure 6)

2. Ip=158kA, P_{ECRH}=220kW, Bt=1.26T, $\bar{n}_e \approx 1.38\times10^{19}m^{-3}$, r(deposition location)=6cm, qa=3.5. This regime has the same n_e and Bt with the first one, and just increase the Ip to get smaller q_a and bigger q_0. During ECRH, q>1, but after ECRH switch off, dq/dr≈0 near the q=1 surface. The transient ITB has been observed just after ECRH switch off. (figure 7)

3. Ip=133kA, P_{ECRH}=280kW, Bt=1.34T, $\bar{n}_e \approx 1.1\times10^{19}m^{-3}$, r(deposition location)=15cm, qa=4.6, r2.5=14.5cm, ECRH power deposited just at the radius of the q=2.5 surface. After ECRH switch off, q_{min} passed the q=2.5 surface, and dq/dr < 0 near the inner q=2.5 surface in the barrier region. An obvious increase in the central soft x-ray intensity was observed, and most notably, a response of opposite polarity (the core Isx increasing but the edge Isx decreasing), indicating a much steeper temperature profile. Meanwhile, the electron density significantly increases after the ECRH. The inverse surface of the responses is near the q=2.5 surface. It seems that the transport barriers formed during these responses are also associated with low rational q surface. (figure 8)

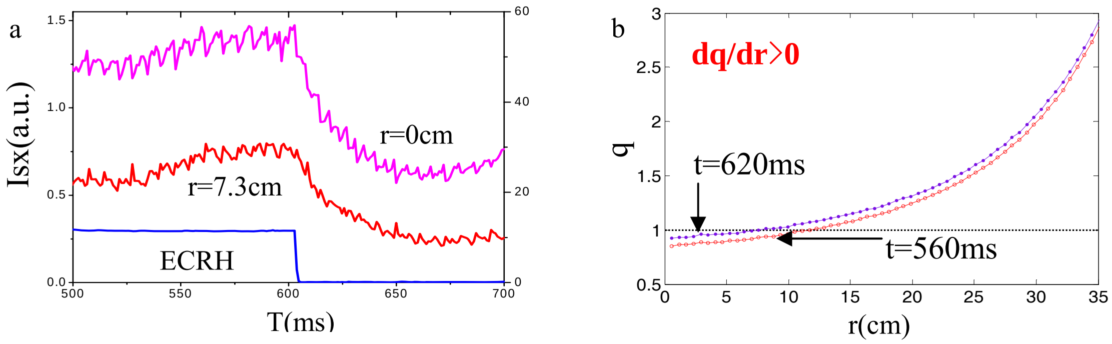

FIGURE 6. The shot in regime 1, with dq/dr>0 near q=1 surface. (a) no delayed decrease in the core Isx after ECRH switch-off; (b) q profile before and just after ECRH.

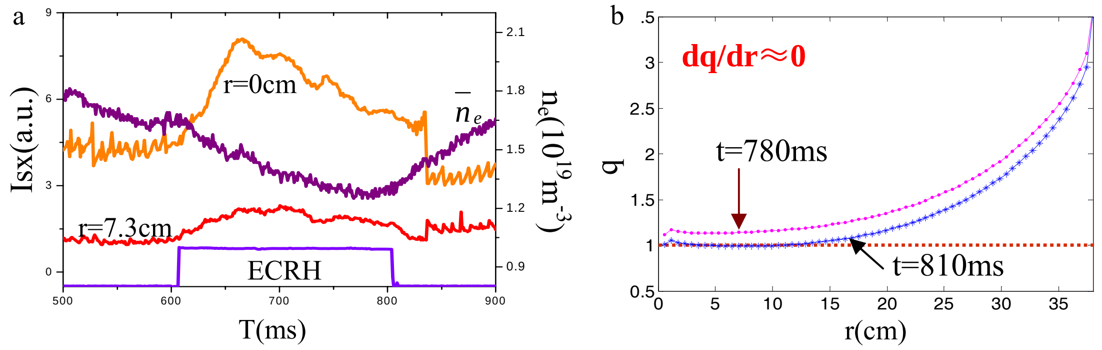

FIGURE 7. The shot in regime 2, with dq/dr≈0 near q=1 surface. (a) delayed decrease in the core Isx after ECRH switch-off; (b) q profile before and just after ECRH.

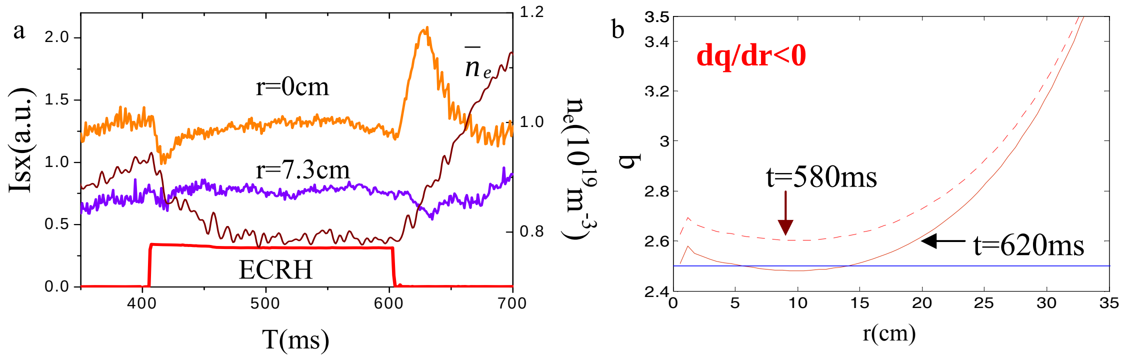

FIGURE 8. The shot in regime 3, with dq/dr<0 near inner q=2.5 surface. (a) the core Isx non-local responses after ECRH switch-off; (b) q profile before and just after ECRH.

From the statistic analysis of dependence of the change of the central soft x-ray intensity (ΔI_{sx}) on the central magnetic shear dq/dr after ECRH switch off, we found that there are three domains related to the formation of ITBs in the central part of the plasma (figure 9), which links with the different dq/dr near the rational magnetic surface inside the barrier region. Firstly, in the case of dq/dr ≈ 0, the change of central I_{sx} is nearly equal to 0. Secondly, in the case of dq/dr < 0 with ECRH power deposited in the inner side of rational surfaces, the core I_{sx} also stayed constant just after ECRH switch off. In last case, although dq/dr < 0 is same as the second case, the ECRH power was deposited in the vicinity of rational surfaces. The central I_{sx} increase sharply, and forms a steep soft x-ray profile. It can be concluded that a low or negative dq/dr near the rational magnetic surface induced by localized off-axis ECRH is crucial to the formation of internal transport barrier, and optimum effect can be realized by depositing ECRH power around the low rational q surfaces.

It was shown that typically the barriers formed in the region where dq/dr ≈ 0 and near the rational q. The lower m and n, the easier the barrier formation, and the local reduction of transport is more effective. It was shown that the characteristics of the formed ITB are influenced by the presence or absence of the negative magnetic shear S in the plasma core.

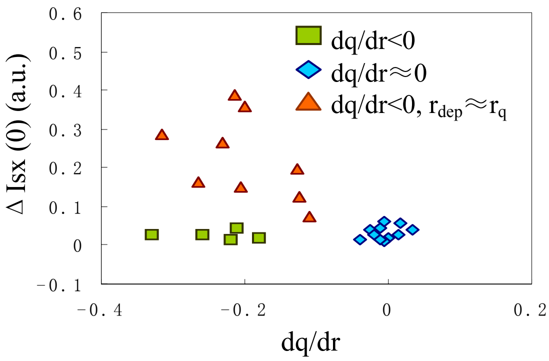

FIGURE 9. Statistics about ΔI_{sx} as a function of the dq/dr after ECRH switch off.

5. Discussion

Two consequences of the observations presented here:

I. Deposition scan performed from axis to LFS for Te(0). The scan results show that Te profile in ECRH discharges can have only a small number of distinct profile shapes, depending on the location of the additional heating. The results highlight the decisive role of the safety factor q for the presence and position of the transport barriers.

II. Delayed central Te decay after off-axis ECRH switch-off are observed on HL-2A. The difference of the q profiles and dq/dr near the rational magnetic surface in the barrier region might be attributed to the existence of eITBs in the central part of the plasma.

The experimental results strongly point towards the conclusion that a low value of dq/dr leads to a confinement enhancement only if the local value of q is near a rational value. We still do not understand the physical processes at the rational surfaces, which determine the confinement changes. As were observed in the fact that the strongest effect in TEXTOR is seen after the shortest ECRH pulses [10] and the simulations done for the successful steady state [11], a possible explanation about the transitions can be constructed: the q-profile evolves to a favourable shape in～50ms, and then (when ECRH is still on) it further evolves to a less favourable shape; just after the ECRH, the q profile also reacts to form a low shear region around the rational surface, the chain curves give the profiles to the new equilibrium finally.

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