ELM-free and inter-ELM divertor heat flux broadening induced by Edge Harmonics Oscillation in NSTX

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Abstract. A new n=1 dominated Edge Harmonic Oscillation (EHO) has been found in NSTX. The new EHO, rotating toroidally in the counter-current direction and the opposite direction of the neutral beam, was observed during certain inter-ELM and ELM-free periods of H-mode operation. This EHO is observed to significantly broaden the integral heat flux width (λ_{int}) by up to 150%, decrease the divertor peak heat flux by >60% and induce strike point splitting. The λ_{int} is found to increase with the amplitude of EHO. An EHO induced filament was also observed by the gas puff imaging diagnostic. The filaments could change the edge magnetic topology resulting in strike point splitting and heat flux broadening.

1. Introduction

A recent multi-machine study of the midplane scrape-off layer (SOL) power fall-off length, λ_q in current tokamaks indicates that for ITER, λ_q is expected to be very narrow, ~1mm [1]. This result is consistent with the prediction from a heuristic drift-based theory [2]. However this theory does not consider the effects of edge magnetohydrodynamics (MHD). The narrow inter-ELM λ_q will result in a large peak heat flux, q_{peak} on the divertor in excess of the material limits of the plasma facing component (PFC). For ITER, the steady state heat flux limit is 10MW/m^2 [3]. However, edge MHD could be important in determining the divertor heat flux width. This paper describes experimental results that demonstrate that edge MHD activity, namely an Edge Harmonic Oscillation (EHO) broadens the divertor heat flux.

2. Background of EHO

An EHO is an edge localized, electromagnetic oscillation with multiple toroidal harmonics, which was first observed on DIII-D [4]. The EHO enhances the edge particle transport and is key to quiescent H-modes. It was found that the EHO can exist both for ELM-free phases and inter-ELM in standard type I ELM scenarios on DIII-D, and the EHO is not a saturated ELM precursor [5]. For the EHO in DIII-D, Infrared thermography (IRTV) shows a wide distribution of deposited heat flux in the divertor and on the baffle structure, in which the EHO increased the divertor peak heat flux, especially for the inner target plate, and an extra peak in the heat flux profile existed away from the outer strike point. It is believed that the EHO produced a perturbation on trapped ion orbits resulting in beam ion orbit losses that may contribute to the extra peak in the heat flux profile [6]. In DIII-D, EHO rotated in the direction of the neutral beam and was found to have no relationship with the plasma current direction [4].

The outer mode (OM) in JET may be related to the EHO [7]. By assuming a current filaments existed at q=4 rational surface and comparison with Mirnov signal, a spontaneously formed closed current ribbon has been observed for the OM. It is located at the pedestal top, it is long-lived, and it regulates transport across the plasma pedestal, significantly delaying the appearance of ELMs. Periodic bursts of heat arrive away from the maximum deposition location, and this is consistent with the effect of a rotating current structure at the top of the pedestal: it can break toroidal symmetry and produce partial ergodisation of field lines increasing overall particle and heat flux across the pedestal. Additionally, a flux tube can escape through the broken separatrix (a homoclinic tangle) and lead to the toroidally localized heat pulses. However, the peak heat flux caused by OM in JET is very large, on the order of 30 MW m^{-2} [7]. When the current rotates toroidally, the footprint of strike point splitting on the divertor will rotate toroidally, and the heat flux at a given toroidal angle will show a radial propagation, which can be observed from Figure 6 in [7]. The OM rotates toroidally along the co-current direction, and with the same direction as the main plasma toroidal rotation in JET [7].

EHO has also been previously found in NSTX when the ELMs were suppressed with lithium wall coating [8]. A number of diagnostics have confirmed n = 4–6 edge-localized and coherent oscillations in the 2–8 kHz frequency range, and they are not observed to provide significant particle or impurity transport [8]. This EHO was observed to rotate with both the co-current and neutral beam direction.

This paper describes the observation of a different type of EHO, which rotates at counter-current direction and in the opposite direction from the neutral beam, which is different from in DIII-D, JET and the previous EHO observation in NSTX.

3 Broadening divertor heat flux width induced by EHO

For the divertor heat flux measurements, a Santa Barbara Focal plane (SBF161) Infrared (IR) camera was used to measure the lower divertor temperature evolution with a spatial resolution of 6 mm/pixel and a frame rate of 6.3 kHz [9]. The heat flux is calculated by a 3D heat flux solver code, TACO [10]. In order to ensure a reliable heat flux calculation, TACO iterates on the heat transmission coefficient, α [11] until the total deposited energy on the divertor PFCs is constant after the end of discharge. The integral heat flux width is defined as $\lambda_{int} = (\int (q(R) - q(background))dR/q_{peak})/f_x$, where the q(R) is the heat flux distribution on the divertor target, q_{peak} is the peak heat flux and f_x is the magnetic flux expansion between the strike point and the outer middle plane separatrix [12]. The deposited power to the divertor surface is obtained by integrating the heat flux in both the radial and toroidal directions: $P_{div} = \int 2\pi R q(R) dR$; this equation assumes toroidal symmetry. Figure 1 shows the EHO effect on the divertor heat flux.

A characteristic signature of the EHO is displayed in the Mirnov signal: its harmonic structure, as shown in Fig. 1(a). The negative frequency indicates that the mode rotates in the counter-current direction and in the opposite direction from the neutral beam. In NSTX, the neutral beam involves a co-current injection. The shot 132405 is a lower single null, ELM-free H mode with ~4 MW of injected neutral beam power with a plasma current, I_p ~ 600 kA and toroidal magnetic field, B_T ~ 0.45 T. The data shown in Figure 1 is during the current flat-top. One can see clear harmonic oscillation with low frequency 2-4 kHz and low toroidal periodicity of n=1-2 from panel (a). The fundamental frequency is ~ 2 kHz and its toroidal mode number is n=1. The mode intensity in Fig. 1(b) shows the harmonic oscillation is n=1 dominated. The gas-puffing imaging (GPI) diagnostic [13] uses a fast visible camera to record the 2D Dα (656nm) line emission image near the seperatrix at a resolution of 64×64 pixels with a frame rate of ~110 kHz, the pixel resolution at the location of the gas puff is 3.8 mm × 3.8 mm, and the total viewable area is 24 cm × 24 cm. During shot 132405, the GPI diagnostic was operated passively, e.g. without active gas puffing. Figure 1(c) shows a spectrogram of Dα emission at the separatrix showing a ~ 2 kHz

oscillation. This is consistent with an n=1 mode, indicating that multiple harmonic oscillations exist in the edge plasma, so this harmonic oscillation could be considered as EHO. GPI does not observe the n=2 mode observed in the magnetic signals. The reason could be that the n=2 mode is too weak compared to the n=1 mode, such that the intensity of the n=1 mode is ~3 times stronger than the n=2 mode.

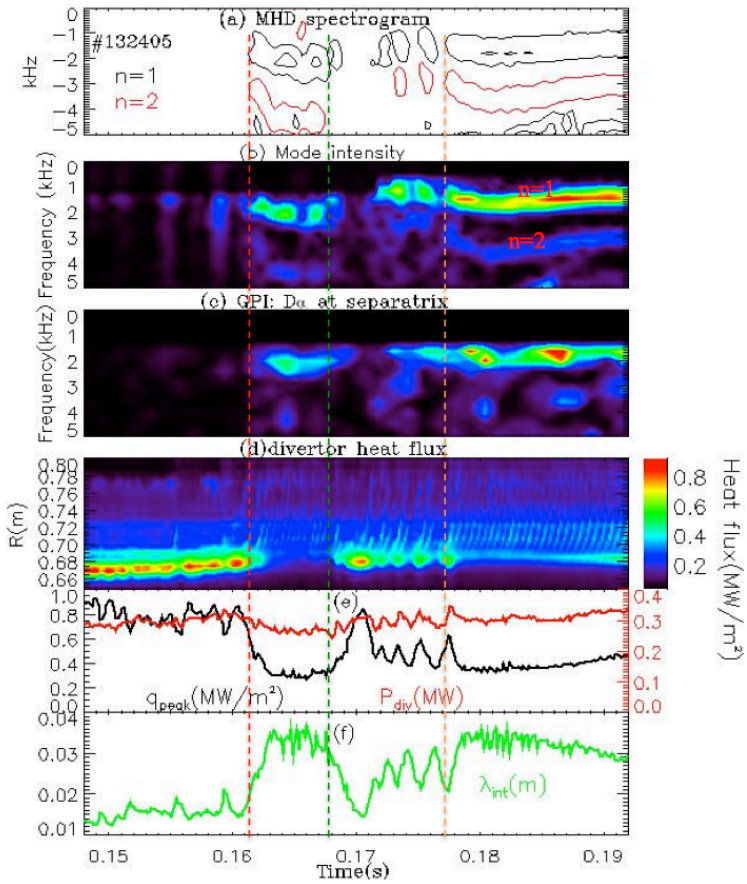

Figure 1. Broadening divertor heat flux measured during the EHO. The evolution of divertor heat flux on lower outer target plate (a), the divertor peak heat flux and deposited power on divertor (b), integral heat flux width (c), magnetic oscillation detected by Mirnov coil (d), relative mode intensity (e), Dα spectrogram at the separatrix measured by GPI diagnostic (f).

Fig. 1(d) shows the divertor heat flux evolution on the lower outer target plate. The red and yellow dashed lines in Figure 1 are marked for EHO appearance. We can see the λ_{int} (q_{peak}) significantly increases (decreases) with the appearance of the EHO. Before the EHO λ_{int} is ~1.4 cm and q_{peak} is ~ 0.9MW/m^2. When the EHO appears, λ_{int} increases to ~3.6 cm and q_{peak} decreases to ~0.35MW/m^2, as shown in Fig. 1(e) and 1(f). This is due to the broadening of the divertor heat flux during EHO as shown in Fig. 1(a). When the EHO disappears at ~0.167s

(green dash line), the λ_{int} decreases and q_{peak} increases. The EHO is intermittent between 0.172s and 0.177s (yellow dash line), as shown in Fig. 1(a) n=1 mode. This intermittent EHO is not considered to be an ELM since there is no burst for the P_{div}. The temporal evolution of λ_{int} and q_{peak} shows intermittent increasing and decreasing which is consistent with the intermittent nature of the EHO. However, the onset condition for this EHO is not yet understood. It is also clear that two λ_{int} peaks are observed just before 0.161s (red dash line) in Fig. 1(f), consistent with the perturbation of Mirnov signal in Fig. 1(e). There is a ~2 kHz oscillation that exists on the divertor heat flux during this EHO, which is especially clear after 0.177s, as shown in Fig. 1(d). Fig. 2(a) shows the detail of the EHO induced heat flux oscillation, but with a much more refined time scale from 0.1826s to 0.1863s. The stripe in divertor heat flux moves radially in time; beginning to deposit heat onto the near strike point and then further out to the far strike point at a later time. The divertor heat flux is consistent with an EHO n=1 mode in Fig. 2(b). The Mirnov signal were taken by data frequency filter (1.5 to 2.5 kHz) to get the magnetic signal from n=1 mode.

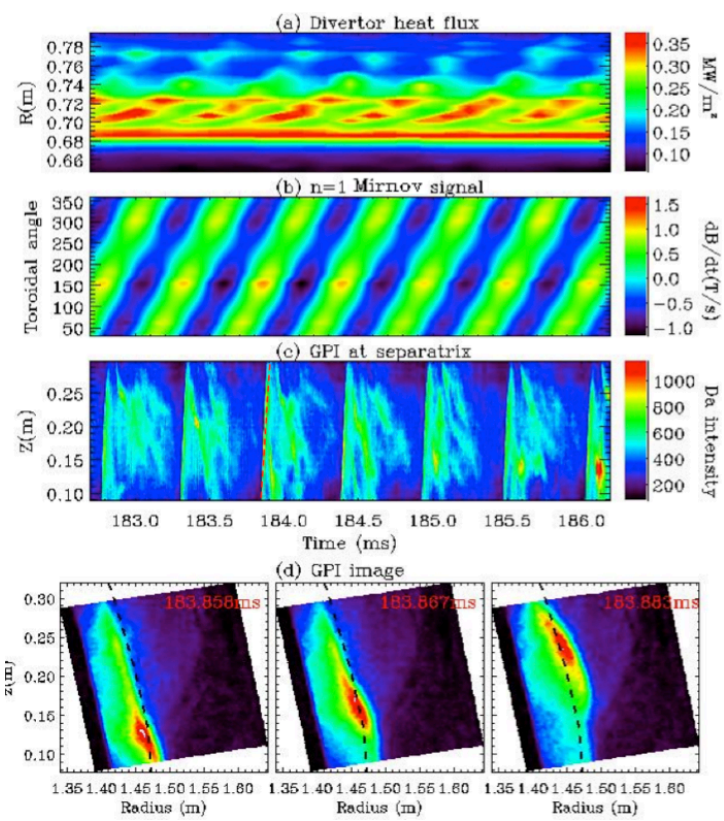

Figure 2. NSTX shot 132405: heat flux evolution on lower outer divertor target plate (a),

Mirnov signal of n=1 (b), temporal evolution of GPI data at separatrix (c) and 3 frames of GPI images, black line indicates the separatrix.

The GPI field of view can be seen in Fig. 2(d). The black line is the separatrix as obtained from EFIT. Figure 2(c) shows the time evolution of D_α emission at separatrix. The oscillation of D_α at separatrix is consistent with the EHO n=1 mode and the radial propagation heat flux. The 3 frames of GPI images in Fig. 2(d) were taken from the red dash line in Fig. 2(c). With the counter current EHO, a regular change can be observed from the GPI images: there is a fluctuation in GPI image, which moves in the positive z direction. The three frames at 183.858ms, 183.867ms and 183.883ms show an EHO induced fluctuation that moves from the bottom image to the top image, the next fluctuation movements in the GPI image as the Fig. 2(d) will appear in next EHO n=1 cycle.

In order to explain the movement shown in Fig. 2(d), along with the heat flux broadening, we define a hypothesis: a rotating filament is induced inside the separatrix by the EHO n=1 mode. NSTX could not measure the poloidal number by the Mirnov probe, so the rational surface of the EHO could not be located. The plasma current is counter-clockwise direction in top view. There is evidence for the rotated filaments on plasma edge induced by EHO. If filaments exist at the n=1 rational surface in Figure 3, then when the EHO n=1 mode rotates in counter current direction, the induced filament will also rotate in the counter current direction. This then would describe the observed movement of D_α emission propagating from the bottom to top as shown in Fig. 2(d). Fig. 2(d), it indicates that the EHO location could be really close to the seperatrix. However, the mode could not be located without poloidal mode number. The distance between the q=8 (15) rational surface and middle-plane separatrix is ~18 (3) mm, which is really close to the separatrix. Assume the EHO n=1 mode existed between q=8 and q=15 rational surface. From Figure 3, the toroidal angle which the n=1 field line should rotate to pass the GPI field of view can be calculated. Meanwhile, from the GPI movie as the Fig. 2(d), the time which the n=1 field line should rotate to pass the GPI field of view can be estimated. Then the toroidal rotation velocity of the EHO n=1 mode can be calculated. The calculated toroidal rotation velocity is 1.04-1.18 $\times 10^4$ rad/s from the q=8 to q=15, similar as the measured value (1.13×10^4 rad/s) by the Mirnov probes. It is more convinced that the GPI observation in Fig. 2(d) is induced by toroidal rotation of EHO n=1 field line. The EHO induced filament could be considered as a current

filament, since the Mirnov probe measured the magnetic fluctuation signal in Fig. 2(b). A current filament appears on the edge plasma: it may break toroidal symmetry and induce strike point splitting.

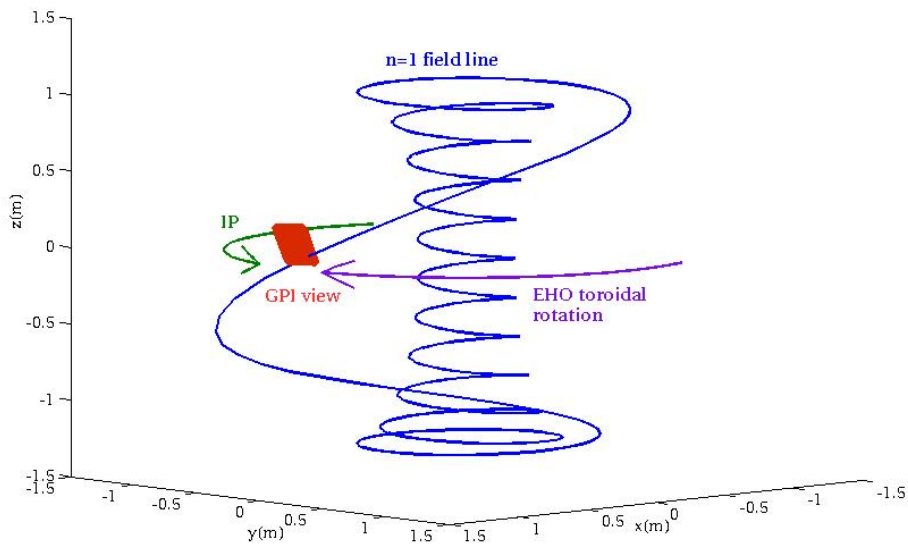

Fig. 3 n=1 field line and GPI field of view

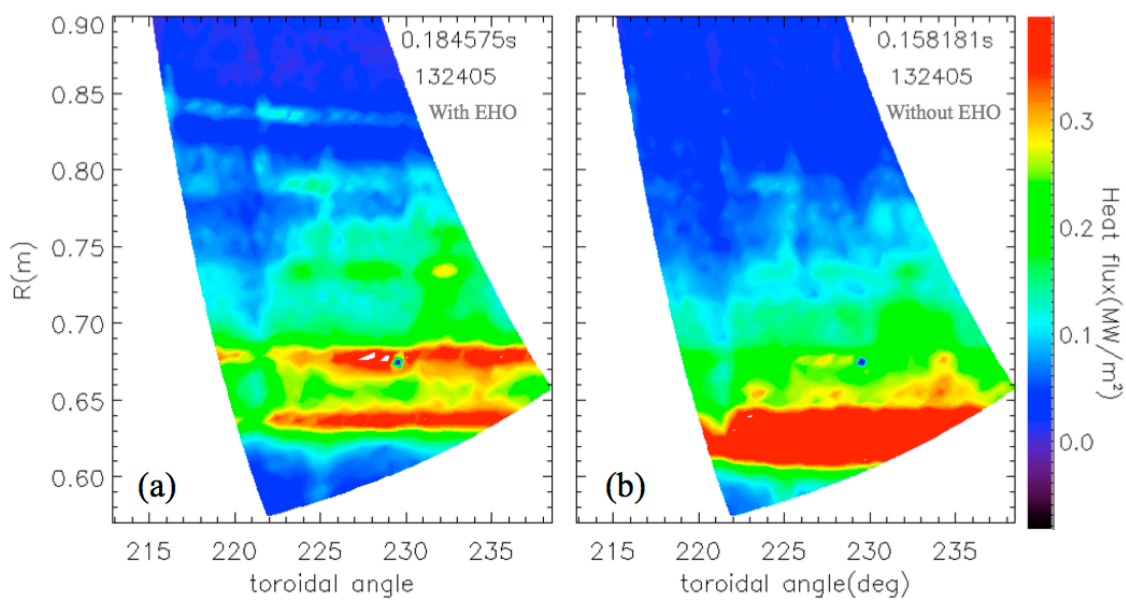

Fig. 4 strike points splitting induced by EHO, 2D heat flux distribution with EHO (a) and

without EHO (b).

Figure 4 shows a 2D divertor heat flux (a) during an EHO and (b) with no EHO for the shot 132405. While no strike point splitting is observed in the heat flux profile when the EHO is not present (Fig. 4(b), one can see several peaks in the heat flux distribution in Fig. 4(a), which is a clear indication of strike point splitting. Because of these multiple peaks, the Eich fitting method [12] could not be used to calculate λ_q. It is conjectured that the multiple heat flux peaks are induced by the EHO since the strike point splitting disappears without the EHO. The footprint of the strike point splitting on the divertor is non-axisymetric, the stripes location change with toroidal angle [14]. In Fig. 4(a), a heat flux strip which is located at R~0.84m shows a smaller radial location of the heat flux stripe with the larger toroidal angle. It is suspected that the strike point spliting will change in time due to the toroidal rotation of the n=1 mode. In Fig. 2(b), one can see the EHO n=1 mode rotate from smaller to larger toroidal angle. Thus the observed strike point splitting of the heat flux footprint should also rotate in the same direction as the n=1 mode, and then the heat flux at a given toroidal angle will propagate radially as shown in Fig. 2(a).

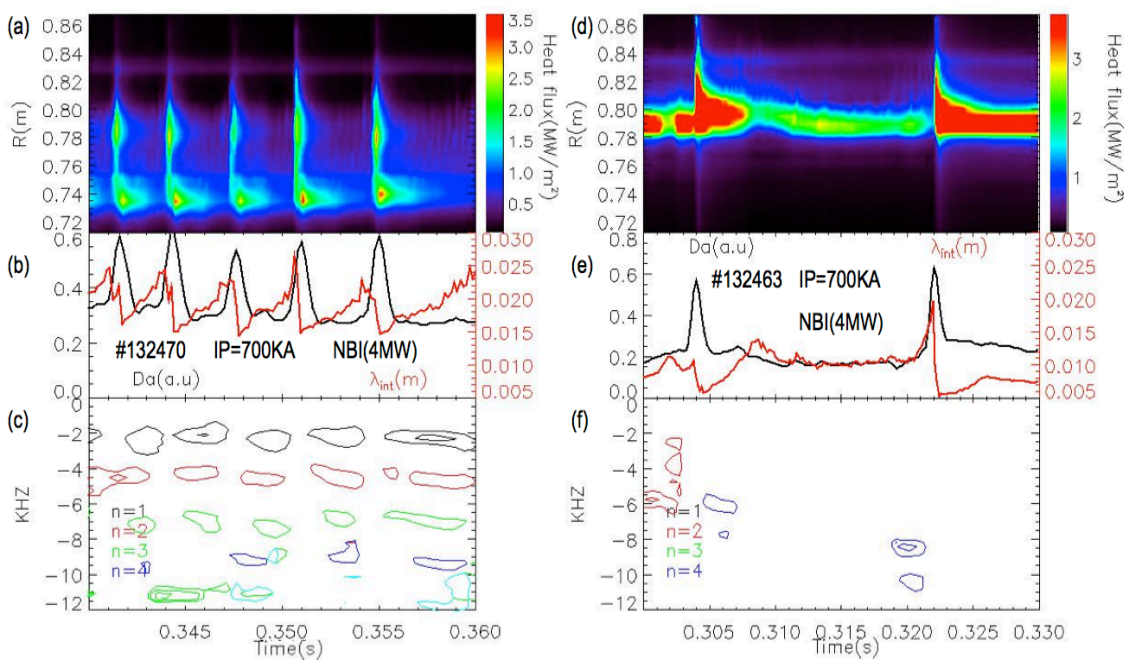

Fig. 5 Comparison of the during inter-ELM between with and without EHO: shot 132470 divertor heat flux (a), Da and λ_{int} (b), MHD spectrogram(c), shot 132470 divertor heat flux (d), Da and λ_{int} (e), MHD spectrogram(f).

The counter current EHO also appears during inter-ELM periods. Figure 5 shows inter-ELM heat flux data for two shots: shot 132470 with an EHO and shot 132463 without an EHO. Both of these shots have the same plasma current, injected neutral beam power and similar f_x~4. A clear, low frequency oscillation of between 2 - 10 kHz with low toroidal periodicity of n = 1 – 4 can be seen in Fig. 5(b). In this shot, the EHO is still an n=1 dominated EHO, and the heat flux oscillation is 2kHz as the EHO n=1 mode. q_{peak} is ~2.5MW/m^2 during the inter-ELM period for shot 132463 without an EHO. However, a reduced q_{peak} of ~ 1MW/m^2 is observed with the EHO in shot 132470. Likewise, it can be seen that λ_{int} is ~0.02 m with EHO from Fig. 5(b); while λ_{int} is ~0.01 m without EHO as shown in Fig. 5(e). This data supports the conclusion that the EHO acts to broaden the inter-ELM divertor heat flux.

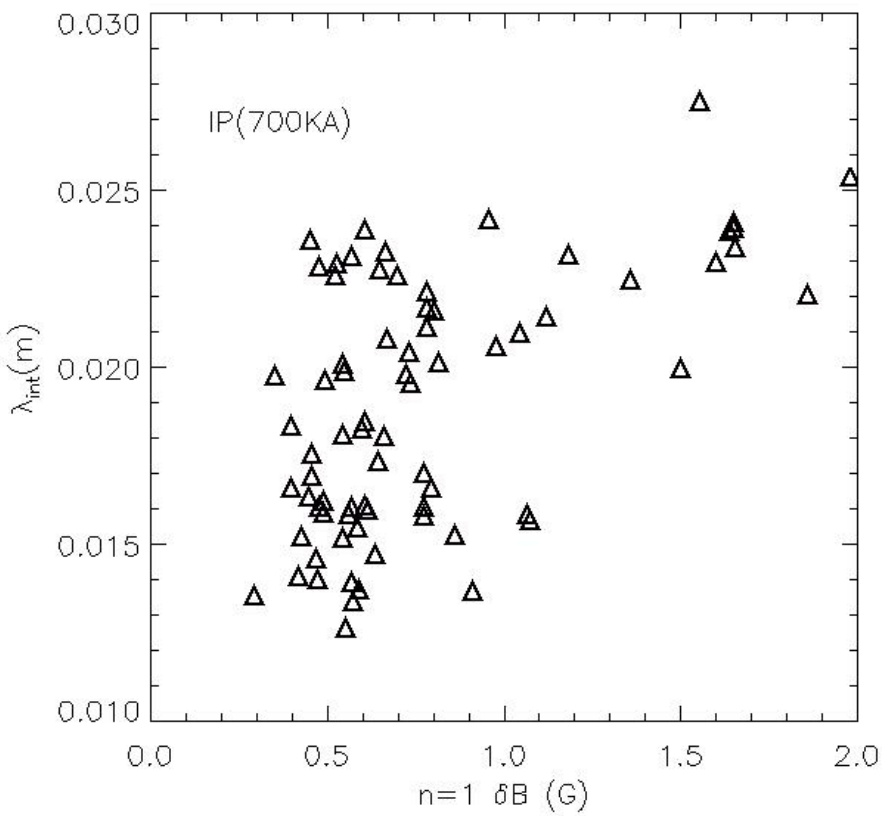

Fig. 6 Increasing λ_{int} with the amplitude of EHO n=1 mode

The amplitude of the EHO can significantly affect the divertor heat flux. Figure 6 shows that λ_{int}

increases with the amplitude of EHO n=1 mode as measured by Mirnov probe. Figure 6 includes ELM-free and inter-ELM heat flux data which were taken from low single-null shot with ~4 MW of injected neutral beam power, I_p ~ 700 kA and f_x ~ 4. A simple explanation is that the increasing magnetic amplitude indicates a larger current filament exists. This then leads to stronger strike point splitting which broadens the divertor heat flux profile and acts to reduce the peak heat flux. The counter-current EHO amplitudes are quite similar to the previous observation of the co-current EHO in NSTX [8], the co-current EHO in NSTX was not found to enhance particle transport [8]. However, there is no IR data for the co-current EHO for comparison. A larger λ_{int} was also observed during inter-ELM with a ~5kHz n=2 single mode in NSTX, although we can not fully analyze that result since the 6.3kHz IR data can not distinguish the heat flux oscillation because of the 5kHz mode.

4 Summary and discussion

A new n=1 dominated EHO rotating toroidally in the counter-current (and counter neutral beam) direction was observed during certain inter-ELM and ELM-free periods of H-mode operation in NSTX. This EHO is observed to significantly broaden the integral heat flux width (λ_{int}) by up to 150%, and decrease the divertor peak heat flux by >60%. λ_{int} is shown to increase with the amplitude of EHO. Multiple peaks appear in the heat flux profile in the presence of an EHO. This is believed to be due to an EHO-induced filament rotating around the separatrix in the counter-current direction due to measurements from the GPI diagnostic. The toroidally rotating filaments could change the edge magnetic topology and broaden the heat flux profile via strike point splitting, which was clearly observed in the divertor heat flux footprint. Because of the EHO toroidal rotation, the strike point splitting will also rotate toroidally. The toroidal rotation of footprint of strike points splitting due to a MHD mode was also observed in DIII-D [15,16]. Experimental observation of stripe movements in heat flux profile shows a consistent trend with the toroidal rotation of EHO n=1 mode.

The mechanism for the counter current EHO appearance is not yet understood in NSTX. The EHO is located near the separatrix. It might easily affect the edge magnetic topology and spread the heat flux distribution even with small amplitude EHO due to the size of the relative

perturbation of the edge magnetic field. Although both current theory [2], and experimental results [1] predict a very small λ_q for ITER, current measurements are dominated by neoclassical affects and the heuristic-drift model does not include any contribution from turbulence or edge MHD modes. Here we show that an edge MHD mode, namely the EHO, can increase λ_{int} at the outer strike point. The EHO may not change λ_q at the outer midplane, but may change the magnetic structure around the X point and broaden divertor heat flux by strike point splitting. The increased divertor heat flux width and decreased q_{peak} has also been observed by applying external magnetic perturbations in DIII-D [15]. It is thus suspected that edge MHD, not only EHO, could affect the divertor heat flux distribution. In particular, if the counter current EHO in NSTX, or other edge MHD, occur in future fusion tokamaks, this could reduce the PFC heat load through divertor heat flux spreading and q_{peak} reducing. However, these counter current EHO require further research to fully identify the underlying mechanism.

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