Measurement of Edge Localized Mode using Fast Camera in NSTX

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This paper describes the ELMs measurement by a fast camera in NSTX. The images obtained by the fast camera reveals the ELMs behavior near the divertor region, and the X-point movement can be seen clearly at a first time. The X-point moves inner and down during large ELM. On the other hand the X-point moves up and down during tiny ELM. The difference of these ELMs behavior is also briefly discussed.

Key words: edge localized mode, H-mode, fast camera, peripheral phenomena, divertor plasma, NSTX

1. Introduction

Edge localized modes (ELMs) are essentially related to realize the steady state H-mode discharge, which is expected to use the operation scenario of the fusion reactor, because ELMs usually transport the heat/particle flux to the divertor region from the plasma core. Moreover H-mode would disappear due to large ELMs activity sometimes. In the National Spherical Torus Experiment (NSTX) ⁽¹⁾, ELMs of several types have been observed: 1) large ELMs (often called “giant ELM”), 2) medium ELMs, and 3) tiny ELMs. Large ELM drives a loss of a few to a few tens percents of the stored energy in plasma to the divertor region. On the other hand high performance lower single null discharges in NSTX have the tiny ELMs⁽²⁻⁴⁾ frequently, which seem to have some differences as compared with small-magnitude ELM types in the published literature. Moreover recently in double null configuration discharges another tiny ELMs were observed. To investigate the structure of these ELMs in NSTX and to clarify the relationship between peripheral fluctuations and ELMs, the fast camera (visible region) was installed to measure the peripheral phenomena in the divertor region⁽⁵⁾.

In this paper the recent results of ELM measurement using fast

camera are reported and the difference between these ELMs behavior is discussed. Also, the explanation of ELMs behavior is made an attempt.

2. Experimental Device

2.1 NSTX NSTX is a medium-size, mega-ampere class spherical torus (ST) machine to improve the proof of principle for the attractive nuclear fusion reactor. The main parameters of NSTX are $A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{\text{edge}} \sim 10$, and $I_p \leq 1.5$ MA, $P_{\text{NBI}} \leq 7.4$ MW (at 100 keV), $P_{\text{RF}} \leq 6$ MW. The physics of ST

Fig. 1. Fast camera location of NSTX

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plasma is tokamak based, and ST has the advantage of MHD characteristic (strong toroidicity and high safety factor) over conventional tokamaks. Therefore, the wide research for high performance plasma operation is possible in NSTX.

2.2 Fast Camera Installation NSTX has twelve-port sections toroidally (BAY-A to L) shown in Fig.1.

Two cameras (FASTCAM Ultima-SE and APX, Photron Inc.) were installed for ELMs measurement. To look down the divertor region of BAY-B&C Ultima-SE was located at the horizontal port of BAY-G, and to look the lower divertor region horizontally Ultima-SE was relocated at the divertor tangential port of BAY-F. APX was located at BAY-B to look near the center stack region to measure the fluctuation and ELMs in the high field side. Ultima-SE has the capability of up to 40500 frames per second (FPS) with 64x64 pixels and APX 160000FPS with 128x32 pixels.

Fig. 2. Typical field of view with tangential fast camera

Fig. 3. Divertor camera images during large ELM (LSN)

3. Results and Discussion

3.1 Large ELMs Large ELMs were shown in both lower single null (LSN) configuration and double null (DN) configuration. Fig.2 shows the field of view from tangential port using Ultima-SE; the left side of the trapezoidal box is limited by the passive plate and the right side is limited by the center stack. The field of view can be adjusted by re-entrant mirror system.

Figure.3 shows large ELM in LSN configuration obtained with almost the same view from the same camera. In these views there are almost tangential images near the X-point. the measurement speed is 13500 FPS. The time is shown below each frame. Before large ELM the X-point is clearly seen in the first picture (upper left in Fig.3). Then large ELM occurs, the X-point moves slowly down and inward (see the second picture) and the outer strike point brightened due to the particle loss simultaneously. ELM lasts around 8-9ms, and apparently we lost the X-point during 4-5ms. The multi-channel ultra soft X-ray signals (USXR)⁽⁶⁾ show that the increase of USXR in the peripheral region originates from near the outer mid-plane shown in Fig.4, and it goes towards the downward (the outer strike point) and the leftovers towards the inner region.

The decrease of USXR rapidly spread within the time resolution of USXR system. If the pedestal plasma moves out due to MHD activity within a magnetic dissipation time, the $J \times B$ force due to the residual plasma current of the outer pedestal region pushes the plasma to the center direction. Also plasma would be shrunk due to the major loss. Therefore, the X-point moves inner and downward.

After that the current will decrease with the time scale of the magnetic dissipation time. Then the plasma could have new equilibrium. This picture does not conflict with the divertor camera images.

Figure. 5 shows the divertor camera images with 13500 FPS

Fig. 4. EFIT reconstruction result of #111877

Fig. 5. Divertor camera images during large ELM (DN)

Fig. 6. Divertor camera images during medium ELM (LSN) Light signal is enhanced by a factor of 5

during the large ELM in DN configuration. The field of view is almost the same in Fig.2. In Fig.6 the similar phenomena obtained in LSN configuration are also seen. In Fig.5 the time intervals between each frame are not the same as that of Fig.3, because the time duration of the X-point extinction is around 2ms in DN configuration and it is shorter than that of LSN configuration.

In the second and third frames (time is 0.35296sec) the multi-leg are seen very clearly. In DN configuration it is not clearly seen that the X-point moves downward, because the bend of the light region in the right side is seen only in the fifth frame. However, it is also seen that the inner separatrix X-point moves inward; that means the X-point moves inward such as in LSN configuration.

Since EFIT can calculate only the time and spatial averaged magnetic surfaces, EFIT does not show these rapid changes of the X-point position. Even so if we can believe what we saw, the X-point would move towards the inner divertor plate during large

Fig. 7. Divertor camera images during tiny ELM (LSN)

Fig. 8. Tiny ELM near the divertor plasma (DN #112464)

ELMs.

3.2 Medium and Tiny ELMs

Figure 6 shows the camera images with the speed of 13500FPS during medium ELMs in LSN configuration. The X-point is clearly seen in the first frame in Fig. 6, also the bending outline of bright region at the lower right in the first frame is very similar to the magnetic surface obtained by EFIT. When ELM occurred, the bending outline would be near strait (second frame), and multi-curtain and multi-leg are seen frequently (second and fourth frame). One possibility of these multi-curtain and multi-leg phenomena is the drag of the magnetic flux due to fast plasma movement. If the dense and hot plasma run away from the pedestal region within the magnetic dissipation time, they would drag the magnetic fluxes.

During medium ELM the magnetic field line at the inner region and at the outer leg are always seen even though the X-point position is not clear from second frame to fifth frame.

The X-point movement during one tiny ELM in LSN configuration is shown in Fig.7. The time interval from the beginning to the end of this ELM is about 2ms.

Even though there is almost saturated area, it can be seen that the X-point moves up and down during one tiny ELM. The outline of the bright region, which seems to indicate the magnetic surface of the outer separatrix region, also moves up and down.

Figure 8 shows tiny ELM behavior near the divertor region (13500FPS, #112464) in DN configuration. In Fig.8 the X-point is not seen clearly, however, the outline of the twilight region indicated by an arrow in the first frame is similar with that of the inner separatrix region by EFIT results. Therefore, this outline should be the inner and outer separatrix.

During tiny ELM the bright region is seen near the X-point in the second frame, and this phenomena ends within 100 μ s (one frame) in this region. To search what is happened during this ELM in the upper of the divertor region, tiny ELM behavior near the center stack in DN configuration were observed by APX. Fig.9 shows tiny ELM behavior (40500FPS, #113650) near the center stack. The left side image in Fig.9 is the view of the fast camera at

Fig. 9. Tiny ELMs near the center stack (DN #113650)

full frame (256×256 pixels). The field of view is limited by port, however, the center stack can be seen clearly. The field of view is narrower when the frame speed is highest (40500FPS, 64×64 pixels) as shown in the middle of the left side image in Fig.9. The time intervals between each shot are about $98.8 \mu\text{s}$.

During tiny ELMs in LSN configurations the increase of USXR sometimes rise the outer mid-plane and toward the inner region, and sometimes the increase of USXR rise both direction of the inner mid-plane and the outer mid-plane. On the other hand, during tiny ELMs in DN configuration the increases of USXR signals are observed frequently near the outer separatrix region, and simultaneously the decrease of USXR signals at the inner separatrix regions. Then the decrease of USXR signals goes up to the inner mid-plane and occasionally would disappear at near inner mid-plane or towards the upper divertor region. USXR system does not have the line of sights to look up the plasma from the bottom port. Therefore, it is rarely observed that the decrease of USXR signals goes down from the inner mid-plane to the lower divertor region. Using the fast camera measurement the bright region should be high density or high recycling region because the light emission process in typical edge plasma parameter range is proportional to the product of the electron density, the excitation ratio and neutral density or incompletely ionized ions density. USXR is proportional to the square of the electron density and root of the electron temperature. In DN configuration USXR dropped at tiny ELMs position obtained by the fast camera. Therefore, tiny ELMs in DN configuration is thought to be relatively low temperature regions and is thought to associate with high recycling region.

3.3 Explanation of these ELMs Behavior Large, medium and tiny ELMs behaviors are shown qualitatively in the above section. The question arise what the key physics determine these ELMs behavior. It is not fully understood, and it should be research in the near future. However, it is widely believed that large ELMs are due to the ballooning or kink mode ($n=1$) near the outer mid-plane⁽⁷⁾, and as already shown above section the birth location of large ELMs are near the outer mid-plane of NSTX plasma in LSN and DN configurations. On the contrast tiny ELMs are originated from near X-point in both configurations. It suggests that one possible explanation for these ELMs behavior is due to the magnetic configuration.

For example Fig.10 shows the comparison of the magnetic

Fig. 10. Comparison of magnetic configurations

configurations of large ELMs and tiny ELMs plasmas in LSN configuration. Large ELMs occur at #111877, and tiny ELMs occur at #109069. The magnetic configuration of #111877 has a larger curvature than that of #109069, in particular the lower triangularity is very difference. Also the lower triangularity of #112171 (Fig.6) is in the middle value between #111877 and #109069. In these three shots plasma current I_p , toroidal magnetic field B_t , and NBI power is almost the same value. In DN configuration the similar results are gotten by EFIT (not shown in the figure). Also, in DN configuration #112464 (Fig.8) has both large ELMs and tiny ELMs, and it has observed only tiny ELMs in #113650 (Fig.9). Both shots have almost the same magnetic configuration; however, NBI power was 3.7 MW at #113650 and 6.8 MW at #112464. Using TS analysis the electron pressure gradients in edge of #112464 is higher than that of #113650. It is natural conclusion that this pressure gradient triggered the MHD instability near the outer mid-plane at #112464.

Therefore, the small curvature of the magnetic surfaces can afford to suppress the MHD instability near the outer mid-plane; however, the pressure gradient would be larger than the critical value, then large ELM should occur. While large ELM can be suppressed, the pressure gradient will become larger everywhere including near the X-point. There are weak or no poloidal magnetic field near the X-point, kink/tearing or interchange MHD activity seems to occur easily⁽⁸⁾. Before ELMs the equilibrium of

plasma is expressed as $\nabla p = \mathbf{j} \times \mathbf{B}$. When the dense and hot plasma in the pedestal near the X-point moves outward due to MHD activity, the cold region should be generated in the inner side of the X-point. The magnetic dissipation time is about hundred μsec at the plasma edge parameter ($\tau=86 \mu\text{sec}$, 10cm at 100eV). Therefore, within the magnetic dissipation time the $\mathbf{j} \times \mathbf{B}$ force would overcome the pressure gradient in this low temperature plasma region, the X-point should move inward. Also the current density near the X-point should decrease because of the poloidal magnetic flux conservation law. Thus, the X-point

moves up. When the cold plasma blob would be in the inner side from the X-point, it goes up toward the inner mid-plane due to the direction of JXB force. If MHD activity near the X-point is large enough, the JXB force will induce the cold region to go beyond the inner mid-plane. What is the difference of tiny ELM between LSN and DN configurations? In DN configuration the plasma position is to be fixed by two divertor (poloidal field) coils, as if the plasma is stretched by up and down sides. Thus, it is not so easy to move the X-point freely. On the other hand in LSN configuration the plasma is stretched by only one direction (up or down). Therefore, it is thought that the X-point easily moves in LSN configuration. At tiny ELM in LSN configuration a part of the dense and hot plasma goes up towards mid-plane sometimes. This guess does not conflict the results of the fast camera measurement.

To summarize this section, it is made a brave try at the explanation of ELMs behavior in NSTX. The balance between MHD activity at the outer mid-plane (kink or ballooning mode) and MHD activity near the X-point (kink/tearing or interchange mode) is one possibility for reasonable physical mechanics to change the types of ELMs. Behavior of the dense and hot plasma after run away from pedestal region is determined by the birth location of ELM. This scenario should be verified in the near future.

4. Conclusion

Many ELMs are observed in NSTX, in particular, new ELMs are found very recently. It was introduced that a fast camera and other diagnostics observed them, and the behavior and characteristics of these ELMs were discussed. The X-point can be seen to move up and down during ELMs and most likely this behavior of the X-point is the key issue to solve MHD activity, which determine the ELMs characteristics.

It is also shown that the fast camera is very useful tool for two-dimensional plasma diagnostics. It is expected that usage of the fast camera will be progressed more widely.

The physics of ELMs is very important to realize the steady state H-mode, and this research in NSTX is developing now.

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