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Publication date:
2012

Citation (APA):
Yan, N., Naulin, V., Xu, G. S., Juul Rasmussen, J., Wang, H., Liu, S. C., ... Wan, B. N. (2012). Observation of current structures during edge localized modes on EAST. Abstract from 24th IAEA Fusion Energy Conference, San Diego, CA, United States.

Observation of current structures during edge localized modes on EAST

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Abstract: Measurements of current carrying filaments associated with edge localized modes (ELMs) have recently been made in the Experimental Advanced Superconducting tokamak (EAST) by direct probing the edge plasma using magnetic probes. Prior to type-III ELMs, magnetic precursor develop with decreasing frequency until the phase delay between radial and poloidal magnetic components reach $\pi/2$， which seems to behave as the trigger condition for the type-III ELM crash. In addition, there is no remarkable current structure to be observed releasing from the pedestal during type-III ELMs. On the contrary, the pronounced magnetic perturbation associated with current filaments has been detected commonly in type-I like ELMs without magnetic precursor. In the scrape off-layer (SOL), type-I like ELMs manifest themselves as filamentary, field aligned structures, rotating toroidally/poloidally and moving radially on EAST. Further more, a strong SOL current is found to arise just prior to the transport phase of ELM indicted by the burst in Dα emmision. The direction of SOL current shows a strong dependence on the direction of toroidal magnetic field. These observation provide key insights into the understanding the generation mechanism of ELM, and will help to develop a predictive mode for the dynamics of filaments in ELM.

1. Introduction

In present day high-confinement (H-mode) divertor tokamak operation, a significant part of plasma–wall interaction is due to edge localized modes (ELMs), releasing a substantial amount of particles and energy to the first wall and divertor in a burst-like fashion. Thus, ELMs have been universally recognized as one of the greatest threats to the viability of ITER and future [1]. For decades, a variety of models emerge, in which different parts of the ELM phenomenon are treated, from onset and non-linear development of the magnetohydrodynamic (MHD) instability in the H-mode pedestal region, to propagation of the resulting transient heat pulse in the scrape-off layer (SOL), both parallel and perpendicular to open magnetic field lines [2 and its reference].

The MHD instability develops flute-like ripples (e.g. n ∼ 5–20) in the pedestal quantities during ELM cycle, which later grow in magnitude and evolve into distinct plasma filaments. Such filaments have been observed in most tokamaks propagating outwards with radial velocities in the range 0.5–5 km s^{-1} [3]. However，the electromagnetic feature of these filamentary structures are still missing as a significant information. In addition to a complex spatial–temporal structure of ELM, no convincing comprehensive ELM model yet exists, allowing observations of ELM formation, size, propagation, etc. on today's tokamaks to be extrapolated to ITER. Recently, direct experimental evidence of a parallel current associated with coherent structures has been obtained on RFX-mod reversed field pinch device [4].They revealed that coherent structures (blobs in L mode) are vortices in the perpendicular plane across the magnetic field, with a pressure peak associated with current density filament aligned along the local magnetic field and traveling according to the mean E×B flow. These experimental observations support the theory reported in [5, 6], which interprets electromagnetic feature of coherent structures in boundary plasma. In Type I ELM H-mode on ASDEX Upgrade, it has been observed that the ELM filaments may carry considerable current during the propagation through the SOL. The current flow along the magnetic filed lines and has a uni-directional nature [7]. Additionally, burst in the scrape-off layer Current (SOLC) has been observed concurrently with ELMs [8]. The possible connection between ELMs and SOLC bursting was pointed out [9]. They proposed that the SOLC can potentially play an important role to trigger the ELMs through SOLC generated field which can affect the MHD modes at the boundary.

The main objective of this work is to study the ELM fine structures contributing to a better understanding of the ELM phenomena and the associated filaments transport. The ELM time evolution and the radial propagation in the far SOL of EAST are studied in detail. Data obtained with a magnetic probe system allowing the measurements of electromagnetic nature associated with ELM structure.

2. Experimental set-up

Since ELMs are highly non-linear electromagnetic events originating mainly from the transport barrier region, magnetic pick-up coil arrays are prime candidates for ELM structure analysis. However, the radial location of the responsible perturbations remains uncertain from such a non-local diagnostic. To complement this weak point, the probe head equipped with a multi-pin Langmuir probe tips and magnetic pick-up coils, has been widely implemented to investigate the ELM induced filament structures and dynamics in the SOL and limiter vicinity[10].

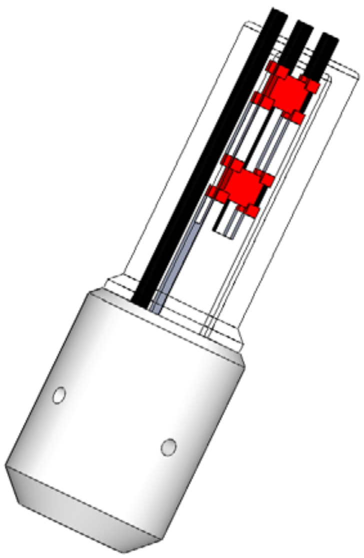

FIG. 1. Schematic drawing of the filament probe head on EAST

In order to study the behavior of filament structures experimentally, a new probe measuring filament dynamics has been installed on the reciprocating manipulator on EAST. As local magnetic perturbations fall off fast, probes far away are not suited to pick up localized magnetic structures. The probe is located at the low field side at almost the same vertical position with the magnetic axis and can be moved radially by a mechanical drive from a safe position behind the limiters towards the plasma [11]. The probe consists of three Langmuir pins (black components in FIG.1) to provide the information for spatial evolution of filaments and two magnetic pick-up coils with 1MHz bandwidth (red components in FIG.1), which allows for measurements of the magnetic signature of filaments. The Langmuir tips are poloidally separated by 5mm on the top of cylindrical graphite case to measure the floating potential. Inside the case, 1cm behind the front side, two magnetic coils radially separated by 1 cm are served to detect the time derivative of the three magnetic field components. The fluctuation data here was digitized at 5 MHz with 12-bit resolution using a multi-channel digitizer. In addition to the filament probe mentioned above, the divertor probe and Mirnov probe array are also involved to observe the time/spatial evolution of current filaments. Different ELM regimes on EAST are reviewed in this conference [12].

3 Structure and characteristics of the ELM precursor oscillation

Type-III ELMs are observed near the H-mode power threshold and produce small energy dumps (1-3% of the stored energy) on EAST. The ELM frequency ranges from 0.2 to 0.8 kHz and the probability peaks at 0.4 kHz. The experiment was performed with plasma current Ip=500KA, a toriodal field B_0=1.8T on the magnetic axis, and total input power P_{tot} is 1.2MW with double null divertor (DN) configuration. Clear precursors are also seen on the magnetic coils located in the far SOL as illustrated in FIG.2.It shows the pre-crash oscillation (dB/dt), as measured by two magnetic pickup coils. There is frequently a relative long (0.7ms) period of stable oscillation at 30–150 kHz. Similar to other machines, this precursor is of intermediate toroidal mode number 5 < n < 15. The amplitude grows with a characteristic growth rate, γ=1–3×10^5 s^{-1}. Nevertheless, the precursor can not be detected in Langmuir tips (ion saturation current and floating potential) in the SOL unless the tips go across the last closed flux surface (LCFS) and deeper. It may imply the coherent oscillation origin from the pedestal region and do not contribute to the particle and heat transport, as well as current filaments. Correlation analysis from two coils show the coherent mode has no propagation in radial direction. The experiment evidences verify the coherent oscillation initiating at the ELM crash are MHD modes well confinement inside the pedestal. It should be pointed out a pronounced phase delay between radial and poloidal oscillation components start to develop from zero at its initial phase. The oscillation stops to grow at 30 KHz with saturated amplitude where the phase delay is locked at π/2 (FIG.3). This phenomenon has been found to be ambiguously valid across the available data, and seems to work as a trigger condition for type-III ELM. It may suggest the existence of perturbing current structure along the field line at the onset of ELM crash, from which the pattern of generated magnetic field is a good candidate for the 'locked phase' (i.e $B_r^2 + B_p^2 = c$ around the current, c is a constant in a cylinder magnetic surface). However, the

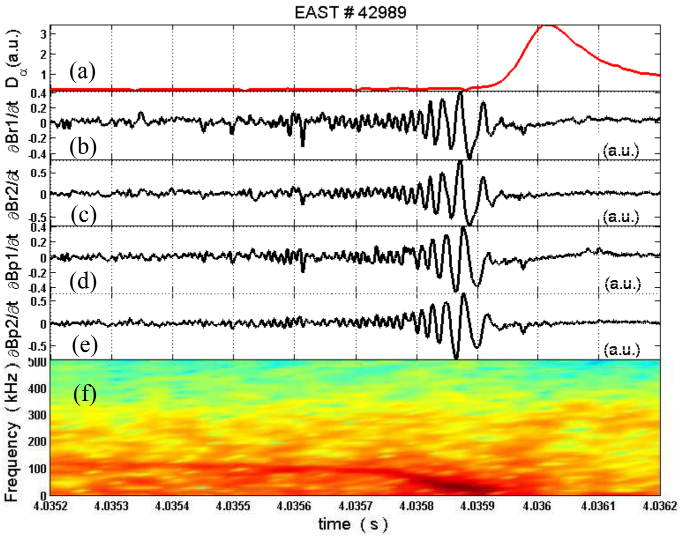

FIG.2.(a) time evolution of Dα, (b)(c)(d)(e)time derivative of the radial (∂Br1/∂t from outer coil and ∂Br2/∂t from inner coil) and poloidal (∂Bp1/∂t from outer coil and ∂Bp2/∂t from inner coil) magnetic field components from type-III ELM, and (f)power spectrum from ∂Br2/∂t

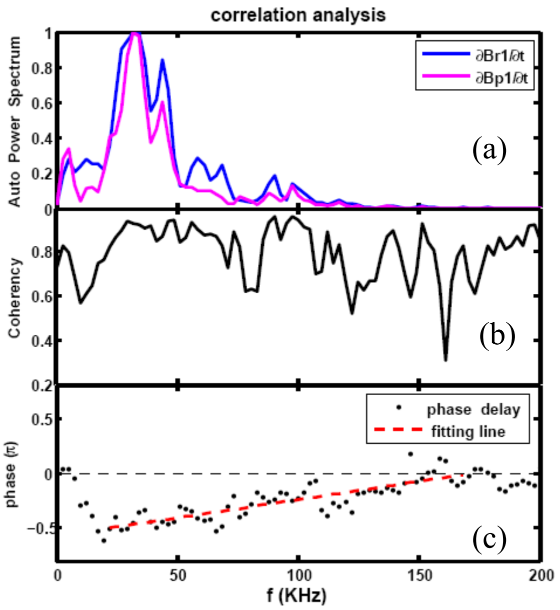

FIG.3. Correlation anylasis between radial and poloidal components of magnetic precursor initialed at the crash of Type-III ELM (a) auto power spectrum (b) coherency spectrum (c) phase delay at different frequency

trigger mechanism behind this behaviour hasn't been fully understood yet.

Further more, after the Dα rise, magnetic signature associated with current filaments are not obtained at any radial position in the SOL. As is shown in the FIG. 2, there is no burst structure presenting on any magnetic signal and corresponding spectrum (>4.0359s). Other extensive research has been made to find the sign of filaments in the crash stage with Langmuir probe on EAST. Yet, no considerable sharp burst/filament structures are observed on the measurements except the gentle transport background, which is different with the reports from type-I ELM process [3]. It is unlikely all the filaments missed the probe head during experiment. Thus, the observations convince us there are no current structures releasing from the pedestal of EAST during the crash stage of type-III ELM.

4 Observation of current structures during type-I like ELM

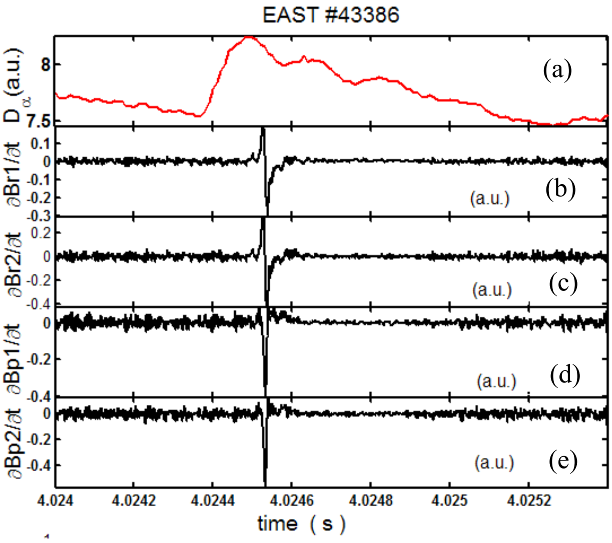

FIG.4.(a) time evolution of Dα signal, (b)(c)(d)(e)time derivative of the radial (∂Br1/∂t from outer coil and ∂Br2/∂t from inner coil) and poloidal(∂Bp1/∂t from outer coil and ∂Bp2/∂t from inner coil) magnetic field components from type-I like ELM

The magnetic probe arrays also allow study of the dynamics of the ELM filaments as they propagate through the SOL and to verify the current pattern inside the filaments. A pronounced magnetic signature has been commonly observed in type-I ELM like regime H mode. The 'Type' of these ELMs is, as yet, not clear. Nonetheless, it shares the type I ELM operation regime on EAST and no precursor is prior to the ELM Crash. The main plasma parameters here are Ip=400KA, B_0≈2T, P_{tot}≈2MW, with DN configuration. As can been seen in FIG.4, the magnetic signature exhibits sinusoidal oscillation on radial magnetic fluctuations and single peak structures on the poloidal fluctuation components. Further analysis show it may be interpreted as the passage of current filaments nearby magnetic coils. The magnetic pattern is consistent with the scenario that a monopolar toroidally extend current filament propagates radially through the SOL. The detail information can be found in FIG.5, which shows the time evolution of magnetic signal in simulation with envisaged current structures. In FIG.5.(a), we use the current filament move radially with velocity v_r=*1km/s* , above coils by 2cm. The radius and current intensity of filament are not defined here, so we use the arbitrary unit system to describe the magnetic fluctuation. It should be emphasized that the number of filaments during one ELM ranges from 1 to 3. In most case, one filament is releasing from one ELM crash. As is shown in the FIG.5, a remarkable agreement between the experiment observation and numerical simulation has been achieved on the magnetic perturbation pattern. It potentially provides the evidence for the current carried in the filaments. Another evidence to support the monopolar distribution of current inside the filaments is derived from the elliptic hodogram of radial and poloidal magnetic field components. In theory, the radial and poloidal magnetic components measured during the passage of monopolar current filament are supposed to obey an ellipse orbit [7]. As is shown in the FIG.5 (b), the hodogram from the measured radial and poloidal magnetic field components can construct an ellipse, which matches the prediction from monopolar current model. The data close to origin of coordinate which present the filaments away from the coils are not shown here, as they to some extend are influenced by the integral error from the background magnetic fluctuation. In other word, it is very difficult to extract the signal originating from the current in a filament, if the noise is larger than the signal. Nevertheless, this gaps of ellipses are expected to face to origin of coordinate and the central axis are supposed to extend along x/y direction in reality, since the uncertain from the integral error will cause the ellipse to shift in x/y direction rather than to rotate the ellipse in the plane of (x, y). In particular, the hodogram only occupy two quadrants, which also suggest the monopolar current distribution [7]. Thus, our measurements are reliable to identify the existence of current filaments associated with the magnetic perturbation. It is worth noting the outer inductive signal from inner coils is much weaker than the signal on inner coils, which may suggest the current loss during the propagation. The correlate analysis shows this current filament travel with radial velocity (1km/s-1.5km/s).

The current orientation is investigated by minimum variance analysis (MVA). To estimate the orientation of current (vector **n**), this MVA method identifies the direction in space along which the field-component set $\{\mathbf{B}^{(m)}\cdot\mathbf{n}\}$ has minimum variance. As is shown in the FIG.5 (c) and (d), the current orientation is found to be almost aligned with the local magnetic field line whose direction is constructed by EFIT. Thus, during the radial movement, the current filaments probably do not suffer from J×B force. This conjecture can be supported by two other details: (1) The patterns of magnetic perturbation observed from two magnetic coils are almost the same, which indicates that no torque on the filaments has been applied during its propagation. Otherwise the symmetric pattern on the two coils would be broken, as it is sensitive to the direction of filaments (i.e. the injection degree of filaments to the magnetic coils). (2) There is no remarkable acceleration/deceleration progress on the filaments, as the inductive signature recorded by two coils demonstrates the same time duration. However, the origin of initial velocity is missing here. The current density is estimated with the indication from FIG.5 (a). The radial velocity of the filament is about 1.2km/s, which is deduced from the correlation of the signal on two coils. The time delay between the positive (negative) peak of *∂Br/∂t* and valley bottom on *∂Bp/∂t* is about 30 μs. The filaments can travel 3.6 cm within this time slice. Thus, the vertical distance ~3.6 cm between the filaments and coils are adopted as the inductive signature on the coils are supposed to experience the maximum (minimum) value when

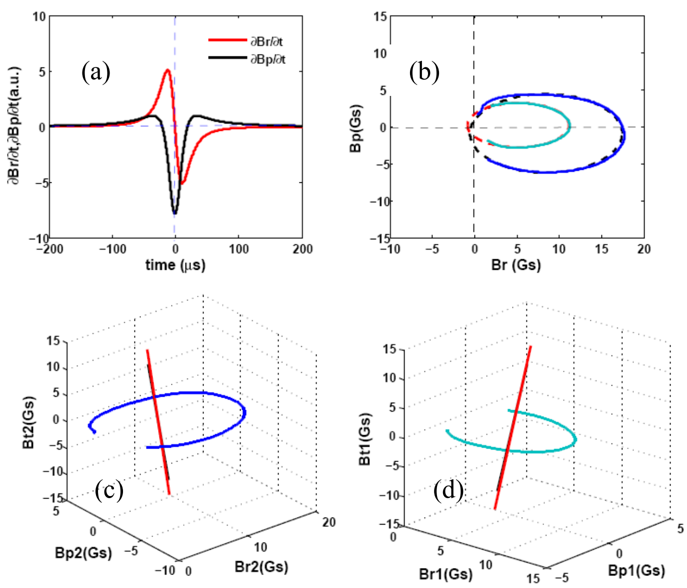

FIG.5.(a) time evolution of time derivative of the radial and poloidal magnetic field components during the passage of a current filament by the magnetic coils(simulation) (b) hodogram of radial and poloidal magnetic field components from inner coils(blue) and outer coils (cyan) and corresponding elliptical fitting trace (black and red dash line respectively) (c)trajectory of measured three magnetic components (from inner coils) associated with the filaments together with the current orientation (black line)and direction of equilibrium field (red line) (d) trajectory of measured three magnetic components (from outer coils) associated with the filaments together with the current orientation (black line)and direction of equilibrium field (red line)

perpendicular distance between coils and filaments are equal at radial and poloidal projection in this case. The radius of current filaments might be smaller than 2 cm, otherwise the current are not able to build up for the interaction with the graphite material outside the coils. With these parameters, the current can be derived as about 0.27 kA using Biot-Savarts law in this case. The current dynamic does not always behave in a simple way as shown here in FIG.4. It has been observed that the filaments rotate poloidally/toroidally by the Mirnov system as well as the fast magnetic coils. Further confirmations for the current transport character of filaments have been achieved in that complex situation. These results will be reported elsewhere.

5 Current filaments and magnetic quasi-coherent mode in gaint ELM

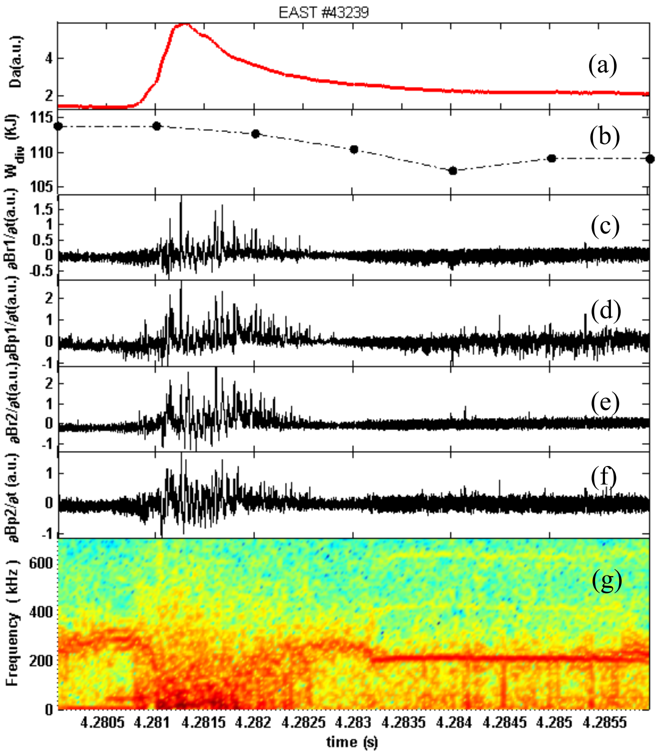

FIG.6. (a)Time evolution of Dα signal, (b)stored plasma energy W_{div} , (c)(e)radial(∂Br1/∂t from outer coil and ∂Br2/∂t from inner coil) and (d)(f)poloidal (∂Bp1/∂t from outer coil and ∂Bp2/∂t from inner coil) magnetic fluctuations, (g) frequency spectrum of ∂Br2/∂t in the gaint ELM period

Giant ELMs are achieved assisting with auxiliary heating power above 2.5MW, with Ip ranging from 300KA to 400 KA on EAST. In Shot 43239, the transport behaviors of giant ELM has been captured by the compound magnetic probe head. In FIG.6, it is worth to be noted that a 'precursor' mode with 40 KHz has been frequently observed in the trigger phase of giant ELM, which can last 0.3ms together with some high frequency mode components (200 KHz-350 KHz). Succeeding to the magnetic precursor, many 'current filaments like' structures emerge after increase of *Dα* (4.281s-4.283s), producing magnetic oscillation. Radial and poloidal components of such magnetic fluctuations are well correlated, but always out of phase to some degree. These structures are quite similar with the filaments structure observed in JET using Langmuir probe head [3], but there is no evidence show these filaments can carry current in these measurements. The number of filaments in this period is several tens. The same analysis method as in section 4 has been applied to these magnetic signatures. Some current structures are realized associated with these burst embedded in the magnetic fluctuation, which will be reported elsewhere. Further more, as is shown in the FIG.6, after about 4.283s, a clear quasi-coherent mode with the frequency around 210 KHz appears at the exhaustive stage of gaint ELMs on EAST. At the quasi-coherent mode dominated stage, the phase delay of radial fluctuations and poloidal fluctuations has been found to be always at π/2, which is suspected to be caused by the rotation of current filaments as $B_r^2 + B_p^2 = c$ are valid at the current induced cylindrical magnetic surface. In addition, this quasi-coherent mode exhibits strong harmonic components around (420 KHz and 630KHz). The rich harmonic structure hints at strong localization of the current source that produces the magnetic fluctuation. Most importantly, this quasi-coherent mode occurs commonly after the L-H transition as well. It last the entire ELMy free phase, but the frequency slightly decrease with raising the plasma density after the L-H transition. In shot 43239, the probe head locate in the limiter shadow, where the plasma has too low density to give signal on Langmuir pins. Therefore, the electrostatic feature is unavailable here. As can be seen in FIG.6, more than 5% stored energy was taken away at the exhaustive stage of ELM. The further investigation shows this mode have no remarkable effect to improve the energy confinement.

6 Observation of SOL current during the trigger phase of ELM

The SOL current has been explored in the SOL of EAST. The key diagnostics besides the fast reciprocating probe used for this work are divertor triple probe arrays [13], which consist of 222 graphite probe tips being embedded in the inboard, outboard and dome graphite plates in the lower and upper divertors. These 222 tips are configured as 74 groups of poloidal triple probes with spatial resolution of 10mm to 15mm at the target surfaces, and 4 groups of which are located at the dome. The negative-going ion saturation current has been frequently observed on the divertor probe array during the ELM crash, which is usually believed to be caused by the fast electron loss associated with magnetic reconnection progress [14]. As is shown in FIG.7, the negative-going ion saturation current (i.e. electron streams) start to prevail on the Langmuir pin named UOis13 before the ELM crash indicated by the rise of *Dα*. During the corresponding time, the opposite fluctuations are detected in the radially separated coils， which locate in the SOL about 1cm away from the separatrix (*i.e* $\triangle r \approx 1cm$). As aforementioned, the radial distance of two coils is 1 cm. It may suggest a current structure is hanging over or locate in this narrow region between two coils. To remove the doubt on impact from the equipment, it should be clarified the winding direction of two coils are exactly the same. According to the measurements, the current is expected to flow mainly along the toroidal direction rather than the radial direction. Nevertheless, this kind SOL current can not be captured easily by the magnetic coils equipped in the reciprocating manipulator on the outboard mid-plane as well as the Mirnov system on EAST. The further estimation show the SOL current is about several tens ampere, which is relative weak. No significant impact on the ELM crash has been observed from such current. In addition, as can be seen in the FIG.7, the time scale can last 50 μs. It is a relative slow progress, producing small and gentle magnetic fluctuations. Further more, the electron

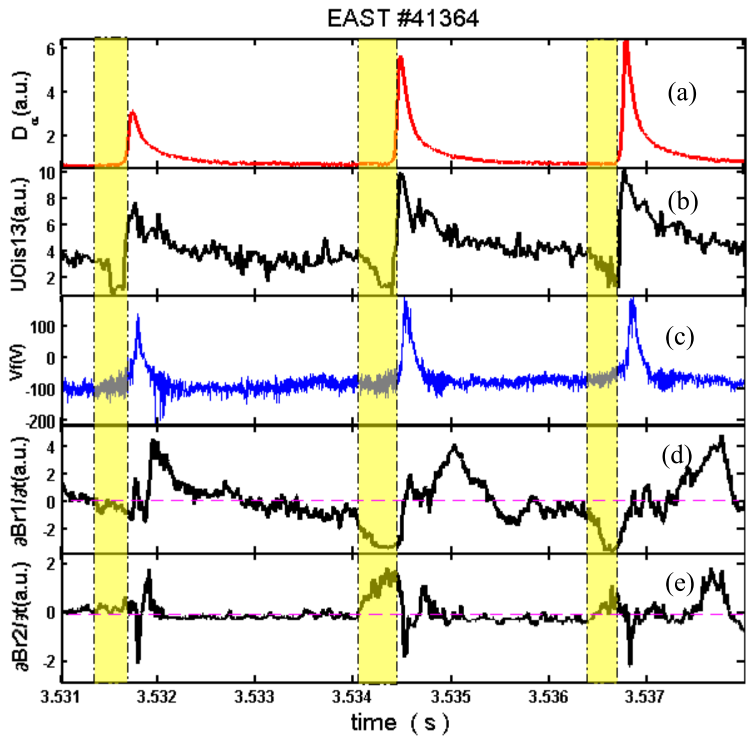

FIG.7. (a) Time evolution of Dα signal,(b) One ion saturation current signal UOis13 at the upper outer divertor target, ($\triangle r \approx 1cm$) mapped to the outboard mid-plane with the EFIT code in DN configuration, (c) floating potential Vf ,(d)(e) radial magnetic perturbation (∂Br1/∂t from outer coil and ∂Br2/∂t from inner coil).

streams in this shot can only be detected in the upper outer divertor target, yet it is absent in the lower outer target. Here, in shot 41364, the DN magnetic configuration is adopted.In the reversed toloidal magnetic field discharge with DN divertor configuration, this electron streams can only be detected in the lower outer target, but it is unavailable at other targets. Thus, the direction of current is field dependent in SOL. However, it is still not clear how the current be generated and if there is causal relationship between the SOL current and ELM crash. Thus, no strong physics conclusion is arrived on this current. It is worth commenting that response to the ELM crash could only be found in the outer target. Inner targets doesn't present considerable transport associated with ELM crash in the DN divertor configuration, regardless the direction of toroidal magnetic field. Such observations significantly suggest the ballooning characteristics of ELMs. The details will be reported in the near future.

7 Summary

In summary, several different current existence regimes have been explored using magnetic probe on EAST. Our observation show there is no current structure related with the type-III ELM. But contrary, a clear field line aligned structure is detected during type-I like ELM. The current filaments propagate through the SOL with radial velocity ranging from 1km/s-1.5km/s. The poloidal/ toroidal rotation on filaments spin up in some case. However, the number of filaments is limited in this ELM regime. In gaint ELM on EAST, many current filaments discharge immediately after the crash of ELMs. After the eruption of filaments, a clear quasi-coherent magnetic mode is observed at the exhaustive stage of gaint ELM, which poses a signature of current rotation inside the separatrix. The SOL current is captured by the radial separated coils, which evolves prior to the ELM crash. The direction of SOL current shows a strong dependence on the direction of toroidal magnetic filed. Nonetheless, some key physics issue as the mechanism of current transport is still not clear in this work, which will need further attention in our further research.

Acknowledgements

This work was supported by the National Magnetic Confinement Fusion Science Program of China under Contracts No. 2011GB107001, 2010GB104001 and 2012GB101000, the National Natural Science Foundation of China under Contracts No. 11075181, No. 11021565, No. 10990212, No. 10725523 and the Sino Danish Center for Education and Research.

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