# Observation of chaotic ELMs in HL-2A tokamak*

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The high confinement mode (H-mode) operation is recently obtained in HL-2A divertor configuration, the corresponding edge localized mode (ELM) is recognized as being of type III. Time intervals in ELM time series are analysed to obtain the information about the ELM process. Signatures of unstable periodic orbits (UPOs) are detected, which are indicators of chaos and may be used to control the big ELM events.

**Keywords:** tokamak plasma, plasma confinement, edge localized modes, chaotic systems

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## 1. Introduction

Since the ELMy H-mode[1] was discovered at the ASDEX in 1981, the H-mode has also been realized in many tokamaks. The edge-localized mode (ELMs)[2] are usually detected by distinctive spikes in the deuterium-alpha ($D_\alpha$) radiation and are easy to find particularly by detecting the $D_\alpha$ emission from the divertor region. ELM event is a direct and obvious evidence of H-mode operation, which features the repetitive bursts[3,4] of megnetohydro dynamics (MHD) activities and the increased edge plasma transport that occurs under certain conditions, therefore removing particles and impurities from the core plasma and resulting in pulsed release of up to 10 percentage of the stored plasma energy. Even though the ELM has a degrading effect on the plasma confinement, it can help to sustain stationary and clean H-mode plasma for a longer time by controlling plasma density and exhausting impurities. With the achievement and database of H-mode operation in about 30 years, ITER (international thermonuclear experimental reactor)[5] is being designed and will be the first tokamak device to demonstrate the scientific and technological feasibility of fusion energy for peaceful application. Its basic operational regime[6] is the ELMy H-mode, in which $\sim$500 MW power could be produced through the D–T fusion reaction with power amplification factor $Q\sim10$ for 400 s. Dimensional analysis, experiment and modeling all predict that transient heat load exceeds the limit of materials used in ITER divertor by at least one order of magnitude during a type-I ELM of ITER H-mode. The consequence will be rapid erosion of the divertor target, core plasma pollution and increased disruption frequency. Therefore, ELM loss has been considered as an important and urgent issue in ITER. It is absolutely necessary that ELM be eliminated or mitigated in ITER. As prerequisite work, extensive studies of ELM dynamics[7,8] and models/theories of ELMs[9] have been made for a reliable prediction of ELM loss and how large the fraction of the ELM loss flowing to the target plates is in ITER.

Several types of ELM behaviours,[10] especially type-III and/or type-I ELMs have been commonly observed in most tokamaks. Generally, type-I ELMs are associated with peeling-ballooning modes and type-III ELMs with resistive ballooning modes. Type-I ELMy plasmas have good confinement properties, the ELM frequency increases linearly with the heating power and the ELM loss is usually large. Compared with type-I ELMy plasmas, type-III ELMy plasmas have worse performances, smaller ELM loss and the ELM frequency decreasing with the heating power. ELM loss is inversely varied with the increase of ELM frequency, so the pellet pacing and the external resonant magnetic perturbation (RMP) have been investigated to mitigate or suppress the ELM by increasing ELM frequency. Another method for supressing type-I ELMs was first introduced by controlling unstable periodic orbits (UPOs) of the ELM time series, which

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is based on the idea that chaos can be controlled efficiently using feedback schemes to stabilize UPOs described by Ott, Grebogi and Yorke (OGY).[11] Many experimental results show that ELMs exhibit irregular behaviours, which may be explained by the fact that a cyclic system is driven by noisy environment, or that the system is in a chaotic state. These two cases may be distinguished by the existence of UPOs. The ELM time series on JT-60U,[12] JET[13] and TCV[14,15] show chaotic behaviours, but they are not observed in most cases on ASDEX Upgrade.[16] It is considered that the analysis technique for UPOs statistical test has a shortcoming, because many time series of type-I ELMs on ASDEX Upgrade fit a non-chaotic ARMA (auto regressive-moving average) system with Gaussian input noise. By using an improved technique, the chaotic dynamics is quite confidently observed in ELMs on TCV.[4] Initial experimental results on HL-2A tokamak show that ELMs exhibit chaotic behaviour, but available data are not enough yet to draw a conclusion. Further experiments are still needed under different plasma parameters from present tokamaks to make fundamental studies as a method to control ELMs in future larger tokamaks (such as ITER, JT-60SA).

## 2. Preliminary results

In HL-2A divertor configuration, the ELMy H-mode operation was first achieved in a 2009 experiment campaign,[17] by combining the auxiliary heating of NBI ($P_{\rm NBI} < 0.8$ MW) and ECRH ($P_{\rm ECW} < 1.2$ MW) with 2nd harmonic x-mode, which was strongly dependent on the optimized discharge conditions, including the total power of the auxiliary heating, good wall conditioning and divertor configuration, titanium gettering in divertor chamber, supersonic molecular beam injection (SMBI) fuelling and density feedback, suitable density range, etc. The main discharge conditions were that $1.1 \times 10^{13} \leq B_{\rm T} \leq 1.4$ T, $140 \leq I_{\rm p} \leq 185$ kA and $1.1 \times 10^{13}$ cm$^{-3}$ $\leq n_{\rm e} \leq 2.3 \times 10^{13}$ cm$^{-3}$. The ECW power of 4 gyrotrons (68 GHz/500 kW/1 s) was launched into plasma from low field side, the total NBI power was about 0.7 MW from 4 ion sources with a beam energy of 35 keV and a beam current of $\sim$14 A sustaining about 0.4 s. The type III ELM with a typical frequency of $\sim$400 Hz can be sustained more than ten times the energy confinement time with enhancing confinement factor $H_{89}$ up to 1.5. An example of shot 11606 plasma parameters is given in Fig. 1. Under these plasma conditions, ELM time series are analysed in order to extract information about the ELM process and signatures of UPOs become visible. In this paper these observations are presented.

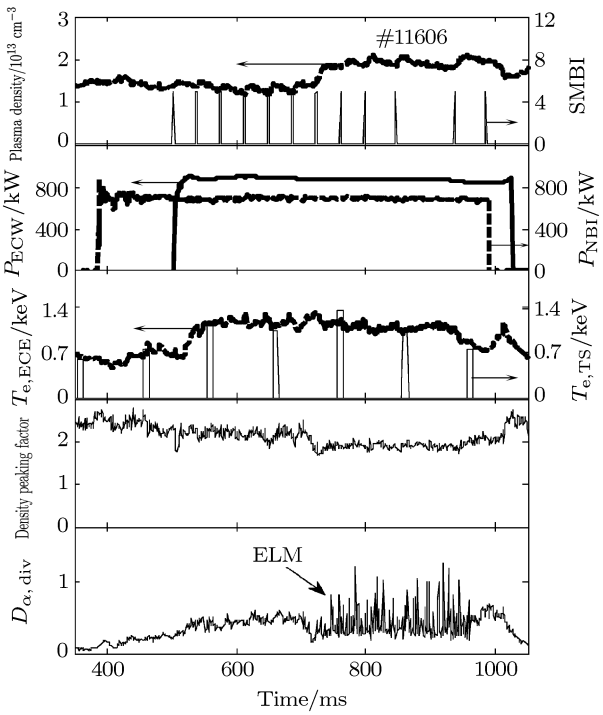



**Fig. 1.** ELMy H-mode plasma parameters in discharge number 11606. From top to bottom: electron density $n_{\rm e}$ measured by HCN laser interferometer; control signal for SMBI valve; ECRH waveform with 900 kW power from 500 to 1030 ms; NBI waveform with 745 kW power from 390 to 990 ms; electron temperature $T_{\rm e}$ measured by Thomson scattering $T_{\rm e,TS}$ diagnostic and ECE radiometer $T_{\rm e,ECE}$; density peaking factor; $D_\alpha$ radiation from diverter chamber $D_{\alpha,\rm div}$. The H-mode phase with ELM events is from 720 to 970 ms.

From the divertor $D_\alpha$ signal, the inter-ELM period and the corresponding ELM amplitude can be obtained by a threshold detection technique for determining the occurrence time of an ELM. If the ELM with amplitude $A_i$ occurs at time $t_i$, then the time interval $\Delta T_i$ is defined by the time variance from this ELM to the next ELM: $\Delta T_i = t_{i+1} - t_i$. Therefore, a rapidly sampled time series of experimental signals containing ELMs is reduced into a discrete set of time intervals between two consecutive ELM events. Using these definitions, the evolutions of the ELM intervals and amplitudes for a single discharge are shown in Fig. 2. It is shown obviously that ELM events exhibit an irregular behaviour.

There are two extreme considerations regarding the reason why such an irregular behaviour can arise:

the system is random, or the system is in a chaotic state. A dynamical system is in chaotic state when it is bounded and if all its periodic solutions are unstable to small perturbations, thus recurrent nonperiodic behaviour occurs subsequently. When the solution is close to an unstable periodic solution (or orbit), its displacement from the periodic solution is briefly described by the linearized system. In principle, a chaotic system may be recognized by the existence of UPOs. A UPO occurs when the state of the system momentarily approaches and then exponentially diverges from one of these unstable solutions. During this short duration, the system behaves in a linear way and presents a characteristic signature in the time series of each dependent variable. As to ELMs, we first obtain the time interval between ELMs and then search for sequences of such points (defined as UPO candidates[15]) in the time series of $\Delta T$'s and then create a scatter plot of all the consecutive periods $\Delta T_i$ against $\Delta T_{i+1}$ in the figure of first return map, because UPOs show identification structures. The diagonal with slope $s_{\rm d} = 1$ divides the first return map into two regions.

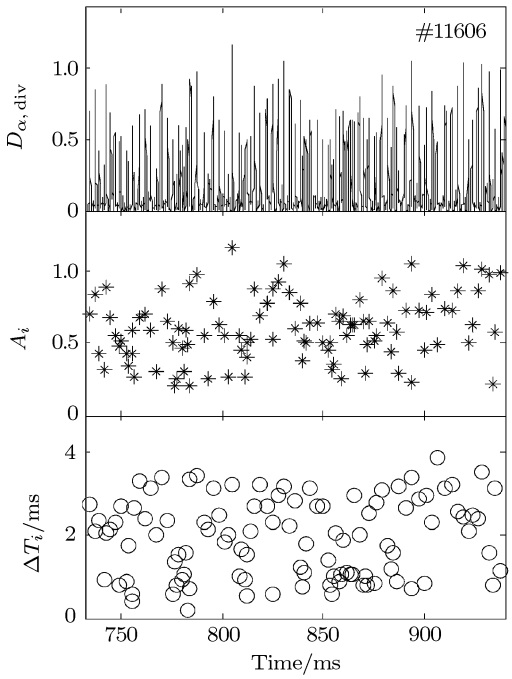



**Fig. 2.** Divertor $D_\alpha$ signal, inter-ELM time $\Delta T_i$, and corresponding ELM amplitude $A_i$ in shot 11606. The ELM behaviour is obviously irregular.

The concept of UPO in dynamical system and the method of detecting its time series data were introduced in Refs. [18] and [19]. Usually UPOs can be searched by the recurrence method[15,16] and the fixed point transform method.[12,16] The former is used in this work. The recurrence method simply fits some consecutive points to a straight line on the first return map and if the absolute value of the linear regression coefficient is more than 0.98, a UPO is found. The specific criteria are

(i) Departure phase: There occur at least three consecutive collinear points (($\Delta T_i$, $\Delta T_{i+1}$), ($\Delta T_{i+1}$, $\Delta T_{i+2}$), ($\Delta T_{i+2}$, $\Delta T_{i+3}$)) with linear regression coefficient larger than 0.98 and a slope $s_+ < -1$. These points can be linearly best fitted to a straight line, which intersects with the diagonal of the first return map. Their cross point is right the fixed point $\Delta T^*$ of a UPO. The value of the fixed point $\Delta T^*$ and the slope $s_+$ carry information about the dynamical system. It is often found that there exist a number of discrete fixed points in a low order chaotic system, which typically shows the frequent recurrence of UPOs with nearly identical values of $\Delta T^*$ and $s_+$ in a chaotic time series. This tendency for recurrence is a useful property for identifying chaotic system in statistical tests.

(ii) Approach phase: The line obtained by connecting the fixed point ($\Delta T^*$, $\Delta T^*$) with the point ($\Delta T_{i-1}$, $\Delta T_i$) has a slope $s_-$ between 0 and $-1$. For a UPO, the point ($\Delta T_{i-1}$, $\Delta T_i$) and the point ($\Delta T_i$, $\Delta T_{i+1}$) of departure phase are also required to be located, separately, on both sides of the diagonal.

This technique is routinely used to study periodic or chaotic behaviours of a non-linear dynamical system and has succeeded in distinguishing random behaviour from deterministic behaviour over a variety of fields. On the first return map, the transient approach and departure phases of a UPO appear as sets of consecutive points that follow straight lines as shown in Fig. 3.

The approach phase is represented by a black line and the departure phase is denoted by a dashed line. These straight lines result directly from the exponential decay and subsequent growth in $\Delta T - \Delta T^*$. Assuming that $\Delta T - \Delta T^* \ll \Delta T^*$, the slopes ($s_+$ and $s_-$) of these lines are approximately related to the exponential constants ($\lambda_+$ and $\lambda_-$) of the linearized system by $|s_\pm| \approx \exp(\lambda_\pm \Delta T^*)$ respectively. The system first decays exponentially towards $\Delta T^*$ according to the characteristic exponent $\lambda_-$ with $\mathrm{Re}\,\lambda_- < 0$ or its corresponding eigenvalue $s_-$ with $|s_-| < 1$ in the approach phase and subsequently diverges exponentially according to $\lambda_+$ with $\mathrm{Re}\lambda_+ > 0$, or $|s_+| > 1$ in the departure phase. Instability is indicated by $|s_+| > 1$,

while $s_+ < -1$ indicates that $\lambda_+$ has an imaginary part given by $\pi/\Delta T^*$.[4] This transient behaviour indicates the existence of UPOs as shown in Fig. 4.

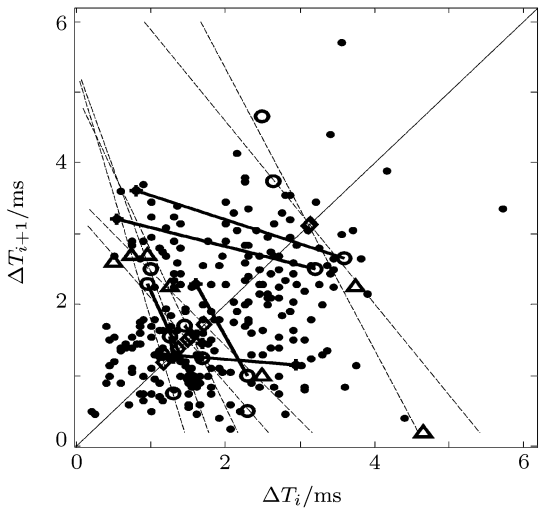



**Fig. 3.** The first return map of shot 11617 ELM time series. Seven UPOs are detected, they distribute as two distinct groups, one group has two UPOs and the other has five UPOs. For each UPO with different patterns, the asterisk denotes the beginning of the approach phase, the triangle refers to the end of the departure phase, the open circles denote the middle points and the diamond denotes the fixed point.

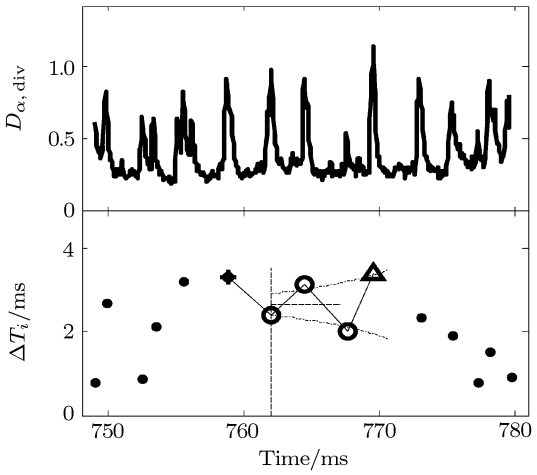



**Fig. 4.** A detected UPO in ELM time series in shot 11606 as given in Fig. 2. The asterisk denotes the beginning of the approach phase, the triangle refers to the end of the departure phase. The position of the fixed point is denoted by a dashed horizontal line and the exponential departure phase is shown by dashed curves. The dashed vertical line denotes the point of closest approach.

Because there is a casual occurrence of points that satisfy the above criteria, all UPOs found are initially regarded as UPO candidates. If a chaotic system is affected by noise, the number of UPO candidates may increase and the estimated values of fixed points will vary a little. However, their distribution will be more closely grouped than that in random case as long as the noise is insufficient to dominate the system. An example is presented in Fig. 3, clearly showing two different groups of UPOs, one group has two UPOs and the other has five UPOs. Each group has its own property and is indicated as multiple recurrence of the same unstable fixed points.

## 3. Discussion

Chaotic dynamical systems each have an infinite number of periodic solutions that are unstable and the signature of chaotic systems. The motivation of this work is to control chaos by stabilizing UPOs,[11] even without any prior analytical knowledge of the system dynamics. In this control scheme very small perturbations of available control parameters of the system are used to control the ELM events. By choosing a UPO with a low $\Delta T^*$, such a control is able to minimize the probability of a long ELM interval and also the probability of a big ELM, because ELM interval and ELM size are correlated with each other. To do so, the control parameters need to be identified which are capable of influencing the orbit in the neighbourhood of the fixed point and UPOs occurring from noise need to be distinguished from UPOs of chaotic ELM process. It has been noted that the finding of any single UPO candidate possesses little significance by itself. The importance is to check whether the statistical properties of UPO candidates found in a time series are significantly different from those of the surrogate sets, i.e., to test the 'null hypothesis'.[13] On TCV tokamak,[4,14] the standard and the improved test methods are used and a large number of UPO candidates in ELM time series are found to have distinct properties compared with surrogates generated from the original data. While on ASDEX-Upgrade,[16] chaos was not observed in most ELMy H-mode discharges. Better or new test method is still needed to investigate the chaotic behaviours in ELM dynamics. Initial experimental results on HL-2A tokamak show that ELMs exhibit chaotic behaviour, but available data are not enough yet for drawing a conclusion. Further analysis can be made with more ELM data on HL-2A tokamak to compare the total number of UPO candidates found in all the ELMy H-mode discharges with the distribution of the total number of fake UPOs found in the surrogates and even to compare the number of UPO candidates in each discharge with the distribution of the number of fake UPOs in the corre-

sponding surrogate sets of that discharge. This would study the conditions when chaotic process is operating in ELM dynamics on HL-2A tokamak and the most suitable control parameters to influence the ELM dynamics. The results of these investigations will be presented in another paper.

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