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ABSTRACT. Precise control of the shape and position of Double-Null divertor configurations in the TCV tokamak has been used to reliably trigger the transition from ELM-free to ELMy Ohmic H-Mode and back. Pre-programmed modulation of the magnetic axis height (±1.25 cm), with fixed shaping field, caused the plasma to evolve, during a single discharge, between Double-Null-Upper, Double-Null and Double-Null-Lower configurations, with both X-points remaining close to the last closed flux surface. The transition from ELM-free to ELMy and back again was observed to be synchronous with the configuration modifications. Using this method, several ELM-free and ELMy phases enabled reproducible disruption-free H-mode discharges in TCV lasting up to 1.5 seconds. The plasma density during a long-duration H-mode was directly controlled by feeding back onto the vertical height of the magnetic axis.

1. INTRODUCTION

Active control of ELMs (Edge Localised Modes) will enhance the prospects for using the H-mode [1] in future fusion devices. In an ELM-free H-mode discharge, the plasma density generally rises uncontrollably, often accompanied by impurity accumulation. ELMs may enable steady-state operation at constant plasma density and impurity levels through controlled energy and particle losses. The optimum ELM frequency is a compromise between the desired plasma density, impurity control and the degradation in confinement due to the ELMs. Previously reported methods of influencing the ELM frequency include varying the separatrix to limiter separation in ASDEX [2], ECRH near the separatrix or changes in the shape in DIII-D [3,4] , heavy gas fuelling to cool the edge combined with off-axis ICRH in JET [5], Li pellet injection in C-MOD [6] and external Resonant Magnetic Perturbations on COMPASS [7]. A characteristic of ELMs is a sudden vertical and radial displacement of the plasma. The vertical displacement is generally more severe in asymmetric Single-Null configurations, in which these excursions are strongly coupled, than in symmetric Double-Null configurations and may lead to loss of vertical position control [7].

Several magnetic configurations are referred to in this paper. A single-null divertor configuration, in which there is only one X point close to the last closed flux surface (LCFS) is referred to as SND-U or SND-L, with the former applying to a configuration in which the X-point on the LCFS is above the magnetic axis. In a DND configuration, both X-points lie on the LCFS. Since, in practice, this is rarely the case, the DND-U and DND-L configurations are defined by analogy with the SND-U and SND-L. DND will only be used when both X-points are close to the LCFS. In the TCV discharges described, the direction of the ion Grad-B drift was towards the top of the vessel so that the SND-U and DND-U configurations correspond to a favourable ion Grad-B drift (in the direction of the X-point on the LCFS).

In what follows, a method of ELM control in the DND configuration is described which allows the plasma density to be controlled during the H-mode.

2. OHMIC H-MODE IN TCV

The Tokamak à Configuration Variable (TCV), is a highly elongated tokamak ($B_{tor} = 1.46T$, $R = 0.88m$, $a = 0.24m$, $b = 0.72m$) capable of producing a wide range of plasma configurations with $I_p \leq 1MA$, $\kappa \leq 3.0$ [8,9]. The rectangular vacuum vessel has a height to width ratio of 3.0 and is completely covered by graphite tiles on the inner wall and floor, and partially covered elsewhere. The poloidal field system has an air-cored OH transformer and sixteen independently driven shaping coils located between the vacuum vessel and the toroidal field coils. The TCV Plasma Control System [10] uses analogue-digital hybrid technology and can readily accommodate various algorithms for feedback control of plasma position and shape.

Since the start of full tokamak operation in June 1993, a wide variety of limited and diverted, L-mode and H-mode discharges have been produced in TCV, with $1.0 < B_{tor} < 1.46T$, $I_p \leq 800kA$, $\kappa \leq 2.05$, $-0.7 < \delta < 0.9$ [11]. The shape parameters are determined after each discharge using a full equilibrium reconstruction code [12] based on extensive magnetic pickup and flux measurements. Prior to the first boronisation (May 1994), there was some evidence of an Ohmic H-mode transition in a SND configuration, but no sustained H-mode was observed. Following boronisation and a glow discharge in helium, a clear Ohmic H-mode was observed in SND-U deuterium discharges, an example of which is shown in Fig. 1. Ohmic H-modes are now regularly obtained with deuterium working gas, in both SND-U discharges and discharges limited on the inner wall. A clear density threshold was observed for the H-mode transition, and a plasma current scan in the SND-U configuration demonstrated that this transition was accessible with relatively low ohmic input power [11]. After boronisation, there was no evidence for H-mode in the SND-L configuration, even with 30% more ohmic power than was required for the equivalent SND-U transition [11]. This is in agreement with observations on DIII-D [13], JET [14] and ASDEX [15] that the configuration with favourable ion Grad-B drift (SND-U in TCV) has a lower H-mode power threshold than the corresponding configuration with unfavourable Grad-B drift (SND-L in TCV). Although these experiments used auxiliary heating, the power threshold for the H-mode transition appears to be independent of the heating method [2]. It was also observed that in ohmic conditions, as the power in excess of the H-mode threshold increased, the discharges tended to become ELM-free [2], which is also seen with auxiliary heating [16,17,18]. Further additional heating resulted in the reappearance of ELMs increasing in frequency with the power.

The typical SND-U discharge shown in Fig. 1 demonstrates most of the features of the Ohmic H-mode in TCV. The plasma current is shown together with the D-alpha emission, soft X-ray flux and plasma density all integrated along vertical chords which pass through the plasma core. Following the establishment of the complete magnetic configuration at 250ms, the H-mode transition occurs at the density threshold after a brief dithering period. There is an initial ELM-free period, a short period of "grassy" ELMs followed by several large ELMs, and a final period of grassy ELMs. The plasma density rises strongly in the ELM-free period, less strongly during the grassy ELMs, whereas the large ELMs result in a momentary plasma density drop. The discharge terminates in a high density disruption resulting from the density increase in ELM-free H-mode. In TCV, there is a large dispersion in the duration of these phases between discharges, depending on the wall conditioning, the gas puff programming and probably other parameters. ELMy periods of up to 1.3 seconds and ELM-free periods of up to 0.4 seconds have been recorded in which the density disruption occurred at the Greenwald limit. For comparison with the later figures, Fig. 1 also shows the reference signal used to control the plasma vertical position, which is constant during the plasma current flat top.

As indicated above, the presence of spontaneous large ELMs in TCV was unpredictable. Although they are observed to be more probable after a fresh boronisation and/or a glow discharge in helium, they could disappear and reappear without any obvious reason. A DND configuration, in which either X-point can be moved away from the LCFS during the same discharge, was investigated to see how the occurrence of the ELMs was affected.

3. ELM CONTROL EXPERIMENTS

During the initial experiments with Ohmic DND H-modes (Fig. 2), the discharge frequently switched abruptly from an initial ELMy phase to a quiescent ELM-free phase which subsequently terminated in a high density disruption. The insets in Fig. 2 show two equilibrium reconstructions from this discharge during the ELMy and ELM-free periods, indicating that the magnetic configuration evolved from DND-L ($t < 0.6s$) to DND-U ($t > 0.8s$). To indicate the proximity of the second X-point to the LCFS, Fig. 2 also shows the difference in poloidal flux between the X-points as a percentage of the flux between the axis and the LCFS. The transition from ELMy to ELM-free is seen to occur as the lower X-point moves away from the LCFS. In this discharge, the change in configuration was produced by a modification of the magnetic field in the vicinity of the lower X-point. The importance of the radial and vertical position for H-modes had already been observed in ASDEX, where small radial or vertical shifts were sufficient to decide between ELMy and ELM-free H-mode [16] although, in these experiments, the DND-U and DND-L configurations were produced in separate discharges.

If, in the DND configuration, the presence of ELMs is correlated to the presence of a DND-U or DND-L configuration, switching between these configurations would provide an ELM control mechanism. Switching between DND-U and DND-L can be achieved by modulating only the Ip*z reference signal. Figure 3 shows the result of such an experiment, in which the Ip*z perturbation causes a vertical shift of ± 1.25cm. The most striking feature is the synchronisation of the ELM-free and ELMy phases with the imposed modulation. The magnetic configurations corresponding to upper and lower displacements, inset in the figure, indicate that the ELMy phase corresponds to a DND-L, and the ELM-free phase to a DND-U configuration, as predicted. The plasma density remains bounded throughout the 1.5 second H-mode, rising during the ELM-free phases and decreasing in the ELMy phases. It is important to note that during this experiment the density reference signal, shown in the figure, caused the gas valve to open slightly when the density was too low. The soft X-ray intensity during the ELM-free phase rose faster than could be accounted for by a change in the plasma temperature and the increase in plasma density, implying an increase in impurity concentration. The decrease in the soft X-ray emission during the ELMy phases is consistent with a loss of the accumulated impurities. The ELMs are seen to stablise the average impurity concentration, albeit at a level above that obtained during the L-mode.

During some of the ELMy phases, a short transition into L-mode was observed, signalled by a rise in the intensity of the D-alpha emission and an increase in the Mirnov and broad band MHD activity to their pre H-mode levels. A strong sawtooth crash was often sufficient to cause a momentary transition into H-mode returning to L-mode with the D-alpha and MHD signature of an ELM. Although several of these H-L-H transitions were observed during some of the ELMy phases, switching to the DND-U configuration resulted in a new ELM-free period. The ability of this DND-L configuration to change between H-mode and L-mode, with no adverse effect on the discharge, implies that, at least with the plasma current and wall conditioning of this discharge, this ELMy DND-L configuration is close to an L-mode. This contrasts with the SND-U configuration in which a transition from H-mode to L-mode was generally permanent.

A series of discharges of the type shown in Fig. 3 all exhibited the same density behaviour, showing the DND configuration toggling to be a reliable method of creating long reproducible H-mode discharges. Since the plasma appears to prefer to go into an initial ELM-free period, the toggle phase in Fig. 3 was chosen to give an initial DND-U configuration. When this phase was reversed, the discharge often went into an ELM-free period despite the DND-L configuration. Following this period, the configuration toggle was often accompanied by a single ELM and a further ELM-free period after which the ELMy and ELM-free periods were as described above. The ability of the plasma in the DND-L configuration to go straight into an ELM-free or ELMy H-mode and the observation of the benign H-L-H transitions imply that in this configuration, the discharges are close to both the ELM-free and ELMy thresholds.

Configuration toggling has subsequently been applied to a different DND H-mode configuration centred in the machine vessel with lower plasma current, lower elongation, and a greater distance from the separatrix to the vessel wall than the configuration shown in Figs 3 and 4. Despite all these differences, the configuration toggling displayed the same essential characteristics, showing that this technique is not specific to a particular plasma configuration.

The duty cycle and the phase of the X-point toggling were modified and varied the plasma density evolution within the limits imposed by the machine conditioning.

4. FEEDBACK CONTROL OF DENSITY USING ELMS

The magnetic axis height can be used to determine the presence of ELMs, whose occurrence controls the evolution of the plasma density. This can be used to operate a feedback loop to control the plasma density during the H-mode.

Figure 4 illustrates this feedback. During the period indicated by vertical lines in Fig. 4, the gas valve opening was held constant. The difference between the measured and pre-programmed line integrated densities (Δn) no longer acted on the gas valve, but was directly coupled to the Ip*z control. The feedback coefficient was chosen to give approximately the same switching frequency as in Fig. 3. Although this direct feedback considerably reduces the density excursions from the reference signal during the H-mode, compared to Fig. 3, there is still a clear toggle between the DND-U and DND-L configurations. A distinct ELMy phase was required to reverse the density rise associated with the ELM-free phase. The X-point flux difference shown in Fig. 4 is of particular interest. The transitions from ELM-free to ELMy and ELMy to ELM-free, both occurred at reproducible, but different, values of the flux difference. Also, the transitions do not occur at the nominal DND symmetric position. This behaviour is also seen in Fig. 3 where the flux differences at the transitions are larger, probably due to the larger amplitude of the programmed Ip*z perturbation. This hysteresis, together with the abruptness of the ELMy - ELM-free phase change, implies that in this DND configuration the ELM activity is bistable.

Since these experiments were performed without auxiliary heating, the persistence of the ELMy H-mode in the DND-L configuration with increased heating remains an open question.

5. CONCLUSION

Toggling between DND-U and DND-L configurations, during the same discharge, has been demonstrated to be a viable method of controlling the presence of ELMs in the Ohmically heated TCV H-mode. The ELMy phase in this configuration has a lower particle confinement time than the ELM-free phase and can thereby be used to control the plasma density rise and the impurity accumulation associated with an ELM-free H-mode discharge. Feedback control of the plasma density, with a fixed gas valve opening, has been achieved by using the density error signal to act directly on the Ip*z control, thus producing repetitive switching between ELM-free and ELMy phases.

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FIGURE CAPTIONS

1. Typical SND-U Ohmic H-mode discharge in TCV. An initial ELM-free period is followed by 7 large ELMs and "grassy" ELMs. The discharge terminates in a high-density disruption.

2. Nominal Double-Null H-mode configuration in which the X-point that defines the last closed flux surface gradually switches from DND-L (ion Grad-B unfavourable) to DND-

U (ion Grad-B favourable). The ELMs disappear abruptly as the lower X-point moves away from the LCFS.

3. Pre-programmed modulation of the vertical position feedback reference Ip*z in a DND Ohmic H-mode discharge, which toggles the configuration from DND-U to DND-L causing the plasma to switch from ELM-free to ELMy H-mode and vice-versa. The plasma density is shown together with its reference signal and Δn was used to control the opening of the gas valve.

4. Density control of the plasma in an Ohmic H-mode is achieved by using the Δn signal to act directly on the Ip*z reference, producing repetitive switches between ELM-free and ELMy phases. The gas valve opening remained at a constant pre-programmed value throughout the period during which the Ip*z density feedback was active, indicated by dashed vertical lines.

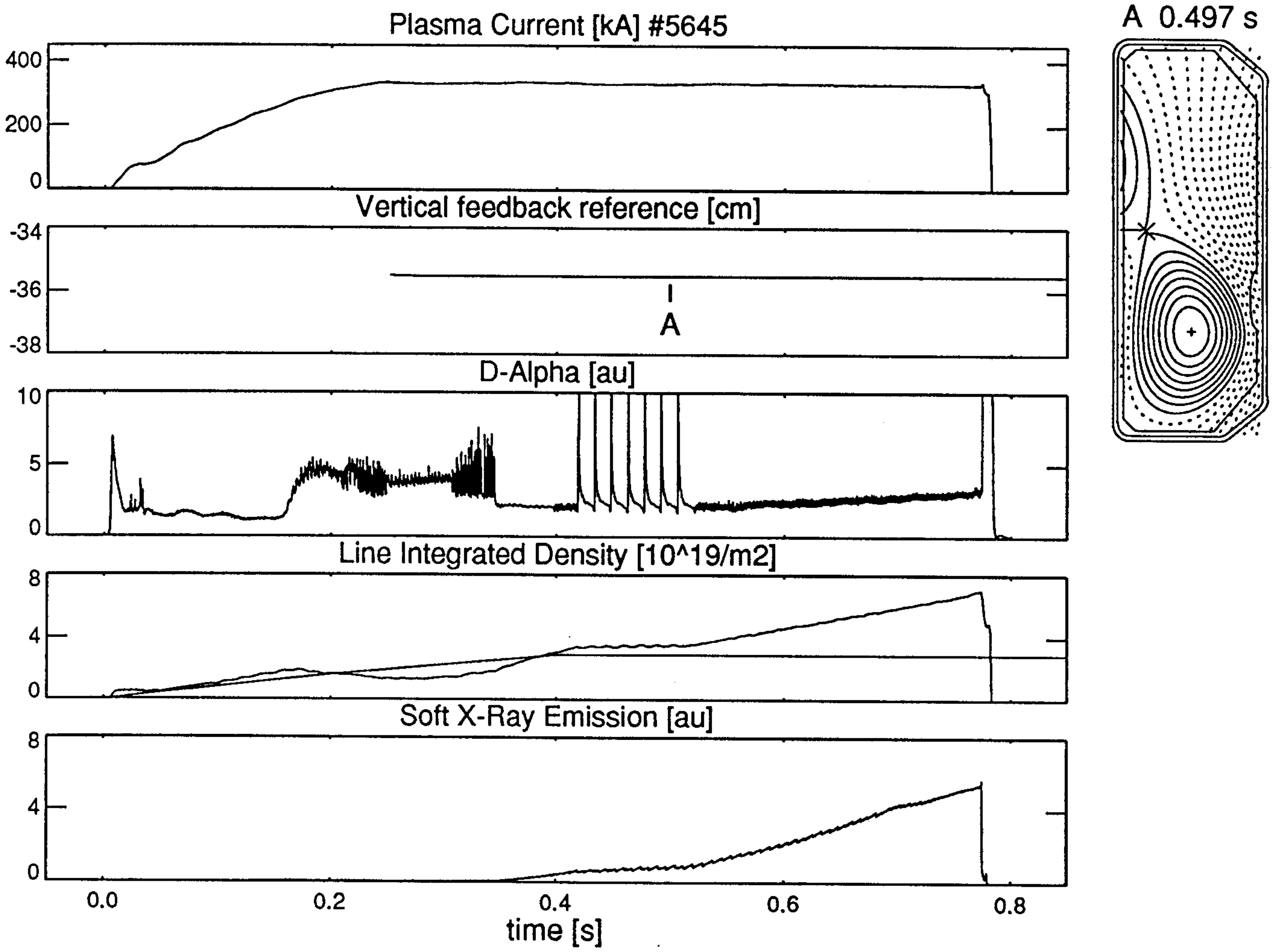
Plasma Current [kA] #5645
400
200
0
Vertical feedback reference [cm]
-34
-36
-38
A
D-Alpha [au]
10
5
0
Line Integrated Density [10^19/m2]
8
4
0
Soft X-Ray Emission [au]
8
4
0
0.0
0.2
0.4
0.6
0.8
time [s]
A 0.497 s

Fig. 1

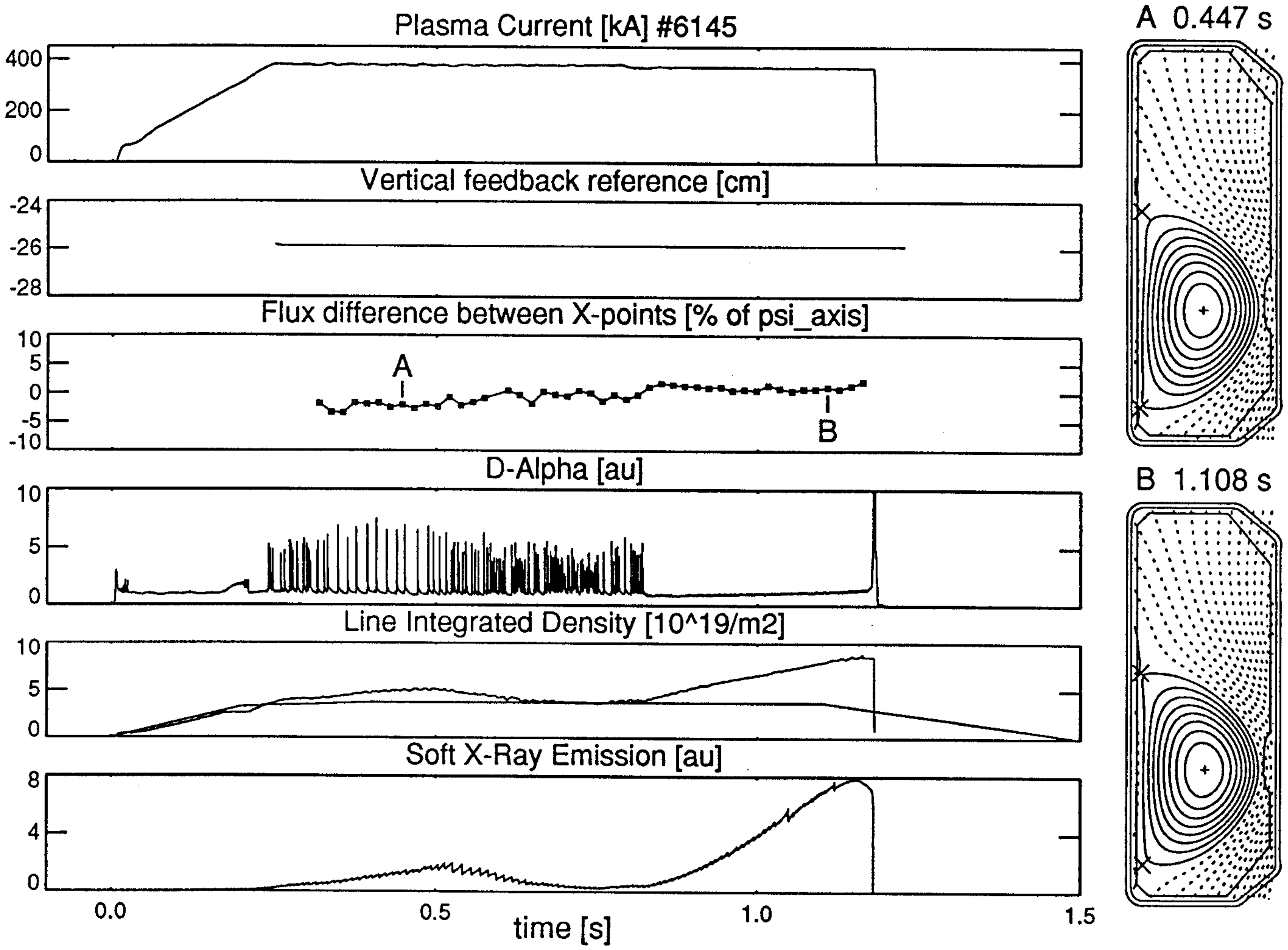
Plasma Current [kA] #6145
400
200
0
Vertical feedback reference [cm]
-24
-26
-28
Flux difference between X-points [% of psi_axis]
10
5
0
-5
-10
A
B
D-Alpha [au]
10
5
0
Line Integrated Density [10^19/m2]
10
5
0
Soft X-Ray Emission [au]
8
4
0
0.0
0.5
1.0
1.5
time [s]
A 0.447 s
B 1.108 s

Fig. 2

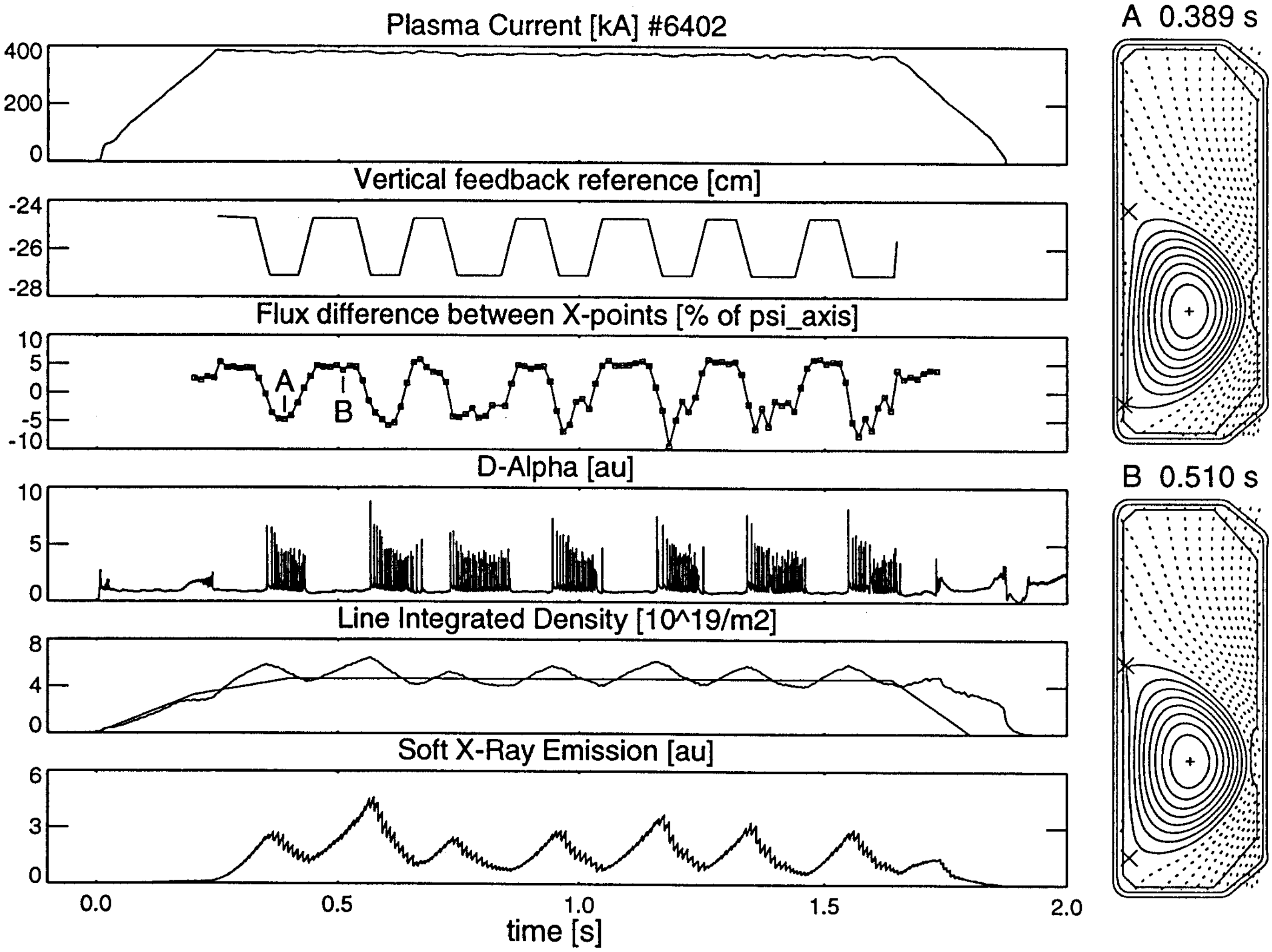
Plasma Current [kA] #6402
400
200
0
Vertical feedback reference [cm]
-24
-26
-28
Flux difference between X-points [% of psi_axis]
10
5
0
-5
-10
A
B
D-Alpha [au]
10
5
0
Line Integrated Density [10^19/m2]
8
4
0
Soft X-Ray Emission [au]
6
3
0
0.0
0.5
1.0
1.5
2.0
time [s]
A 0.389 s
B 0.510 s

Fig. 3

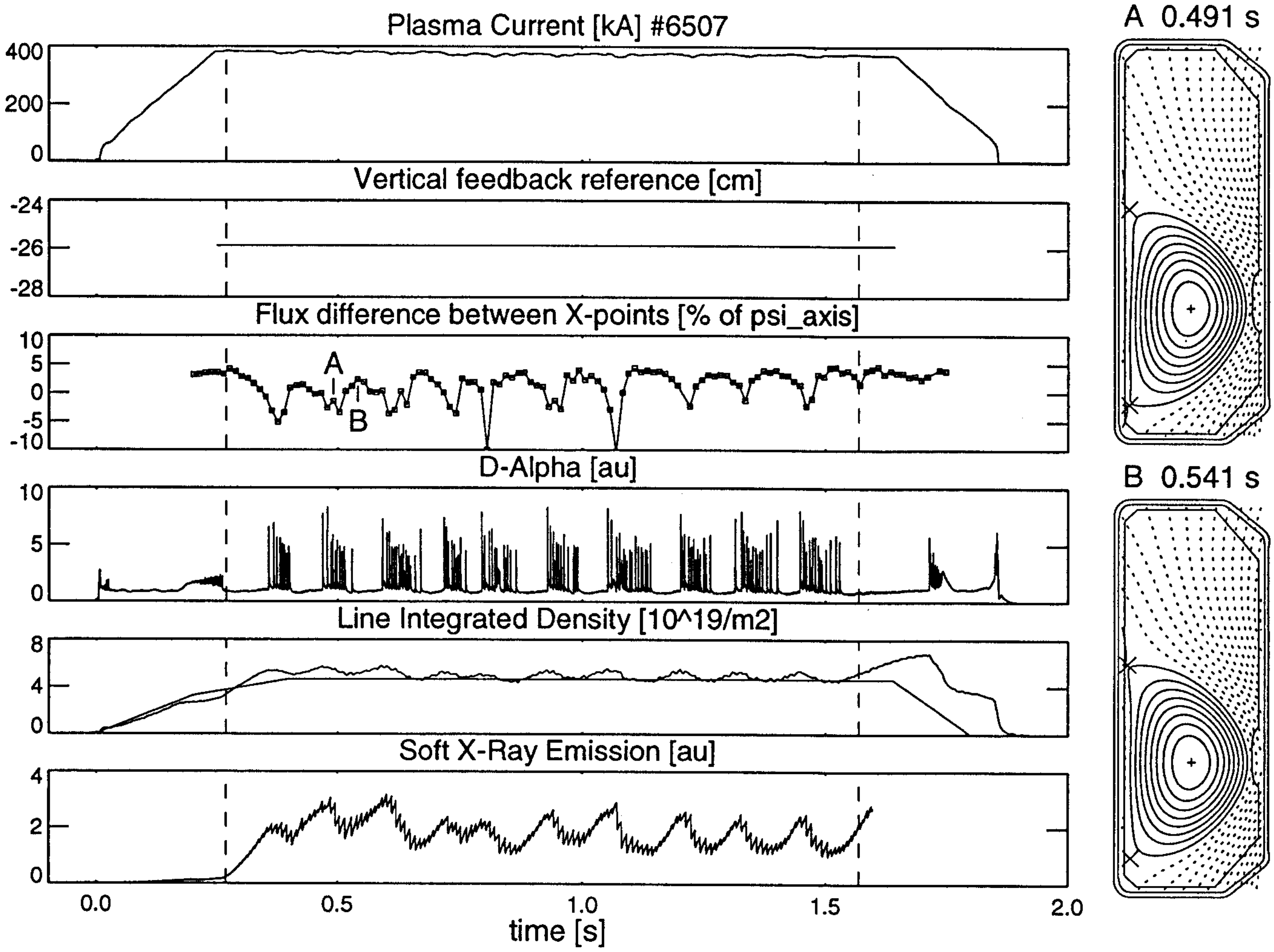
Plasma Current [kA] #6507
400
200
0
Vertical feedback reference [cm]
-24
-26
-28
Flux difference between X-points [% of psi_axis]
10
5
0
-5
-10
A
B
D-Alpha [au]
10
5
0
Line Integrated Density [10^19/m2]
8
4
0
Soft X-Ray Emission [au]
4
2
0
0.0
0.5
1.0
1.5
2.0
time [s]
A 0.491 s
B 0.541 s

Fig. 4