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Internal collapse of the plasma during the long pulse plasma discharge and its influence on the plasma performance

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Abstract

The main mission of the HT-7 machine is to explore high-performance plasma operation under steady-state conditions and relevant physics. The key issues for pursuing such study are wall recycling, high impurity radiation, and MHD instability. During the operation scenario of long pulse discharge, internal collapse of the plasma, apparently exhibited on the radiation signals of the soft X-ray (SXR), was observed. Following the event, the plasma was cooled down, accompanying strong plasma and wall interaction, finally the plasma thermal quench occurred. There is no apparent precursor except the peaking of the SXR radiation. Another type of internal collapse was also observed in the other operation scenario of synergy discharge of LHCD and IBW. In this paper, the relative phenomena are analyzed and discussed in detail.
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1. Introduction

In a steady-state tokamak, the plasma current is entirely sustained by means of non-inductive current drive and the self-generated bootstrap current. The problems involved can be solved by using superconducting techniques, development of non-inductive current drive, plasma control, efficient heating, advanced fuelling, removal of particles and heat flux to the first wall, etc. Very long pulse discharge has been realized and significant progress in steady-state physics and technology has been achieved in the various superconducting devices [1–3]. To accommodate the mission of the exploration of high-performance plasma operation under steady-state conditions and the study of relevant physics in a medium-sized superconducting tokamak, HT-7, and to extend the plasma discharge duration to several minutes, several important technical modifications have been made these years on the key issues of wall recycling, high impurity radiation, and plasma control. These modifications included double-ring graphite limiters symmetrically located at the top and bottom of the inner wall with active water-cooling ability to promote power removal capacity, which were made from special doped graphite coated by SiC film. A new poloidal field power supply with a real-time operation system was employed to eliminate the limitation on the

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discharge duration of the old operation system. Three upgraded RF systems of a 1.2 MW/2.45 GHz lower hybrid wave current system (LHCD, a multi-junction coupler, $n_{\|} = 1.8–3.5$), a 1.5 MW ion cyclotron resonance frequency system (ICRF, 30–110 MHz) and a 0.35 MW ion Bernstein wave system (IBW, 15–30 MHz), all with CW operation capacities, were applied to heat and drive the HT-7 plasma for active control of the current density and pressure profiles. Information on the temperature rise from embedded thermocouples on PFCs and from the IR camera helped in the determination and preset of the plasma position. New manual control of the plasma position and magnetic flux feedback control of the transformer by adjusting the variation of volt-seconds of the iron core were adopted for steady-state operation to alleviate interaction between the plasma and the wall. Based on the understanding of plasma surface interaction and combined with good wall boronization and conditioning by means of RF produced plasmas, nearly fully non-inductive current driven plasma ($I_p = 120–180$ kA, $B_t = 1.5–2.0$ T, $T_e(0) = 2–4$ keV, and $\overline{n_e}(0) = 1.0–2.5 \times 10^{19}\ \mathrm{m}^{-3}$) was achieved by LHCD with a duration up to 10 s. For lower performance operation ($I_p = 55$ kA, $T_e(0) \sim 1.0$ keV, and a central $n_e(0) = 0.7–1.0 \times 10^{19}\ \mathrm{m}^{-3}$), reproducible long pulse discharges with a central electron density $\sim 0.8 \times 10^{19}\ \mathrm{m}^{-3}$ and an operational duration up to 306 s were sustained by LHCD (<200 kW), almost in steady-state conditions.

In HT-7, the duration of the plasma discharges was mainly limited by particle recycling due to uncontrollable density rise. The temperature of the limiter measured by embedded thermocouples inside the graphite tiles could be over 800 °C, which causes strong outgassing from the limiter surface and a significant contribution to the particle recycling. Also, abundant impurities were induced by chemical sputtering, therefore long pulse-length plasma discharges could not be sustained. Therefore, solving problems related to issues such as non-inductive current drive, wall conditioning, reduction of high impurity radiation, heat exhaust and particle removal, etc., is the key to achieving steady-state plasma discharges. Besides the conventional phenomena of outgassing, impurity generation and uncontrollable density rise, another event, called internal collapse of the plasma, was observed in the operation scenario of quasi-steady-state plasma discharge sustained by LHCD and synergy discharge of LHCD and IBW. The analysis and discussion of internal collapse phenomena are presented in this paper.

2. Internal collapse during long pulse plasma discharges approaching steady-state operation

During the operation scenario of quasi-steady-state plasma discharge, heat exhaust and removal are inescapable due to the interaction between plasma and plasma facing material, so the variation of plasma parameters and injected LHW power is unavoidable because of uncontrollable events such as recycling, impurity production, and MHD instabilities (2/1, 3/2, mode coupling between 1/1 and 2/1 or 3/2) [5], therefore the available plasma duration is limited by decreasing drive efficiency of LHCD and the finite volt-second of the iron core. Most discharges during fully non-inductive current drive of the HT-7 device were destroyed by impurity spurting or uncontrollable density rise [4,6]. Another cause for the destruction of long pulse plasma discharges was observed, in which an internal collapse appeared on the radiation signals of the soft X-ray (SXR), shown in Figs. 1 and 2, and which normally accompanied the termination of the plasma discharge, although in a manner different from that mentioned in Ref. [7]. Before the set-up of the internal collapse event at 138.828 s, the electron density profile was a varied parabola distribution, given in Fig. 3(a), either peaking up or flattening down, while the SXR radiation profile was peaking gradually as illustrated in Fig. 3(b), there is no any apparent MHD instability on the signal of the magnetic pick-up coil. During the event, the electron density profile varied in that the central density decreased, flattened, and showed a slightly hollow profile at 138.885 s, while the central SXR radiation dropped to nearly zero (see Fig. 4(a)). At the same time of the occurrence of the event, a strong increase in plasma radiation (bremmstralung, XUV, ECE, light impurity like carbon and oxygen) could be seen in Fig. 2, indicating that strong plasma and wall interaction (such as carbon bloom) could be the main reason for plasma cooling indicated by the decreasing peaking and final abrupt collapse of the SXR radiation shown in Fig. 4(b). After the event, theplasma was cooled down, indicated by SXR radiation at a very low level, and then the plasma quenched thermally. The large ECE signal suggested that a high fraction of superthermal electrons were excited during the event. Unfortunately there is no fine information on the electron temperature since

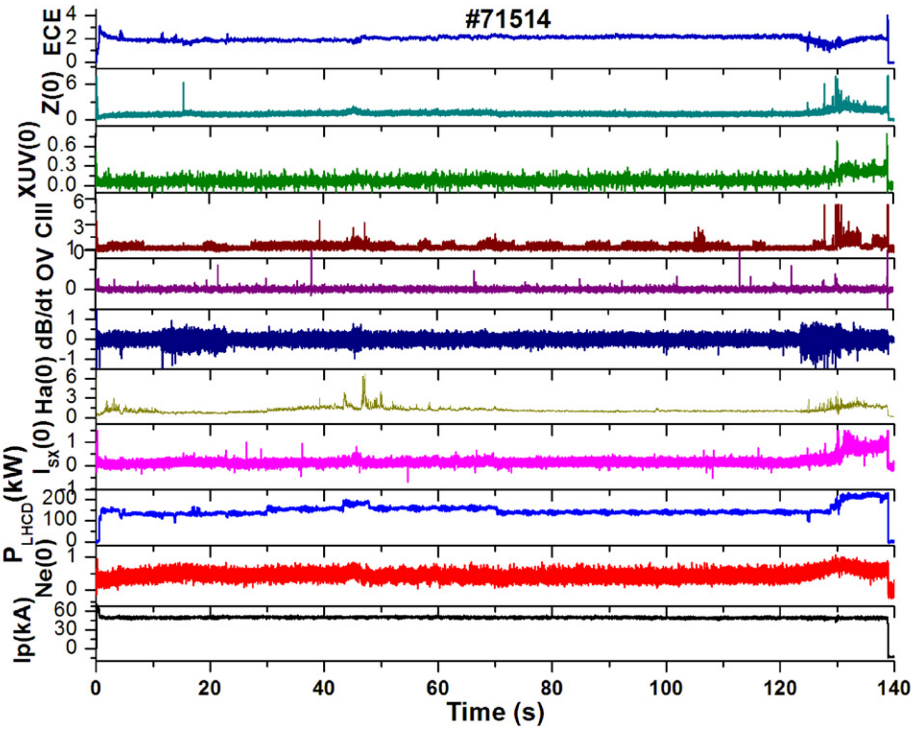

Fig. 1. 139 s long sustained plasma discharge ($I_p = 55$ kA, central electron temperature $T_e(0) \sim 1.0$ keV, and a central electron density $n_e(0) = 0.7–1.0 \times 10^{19}$ m^{-3}).

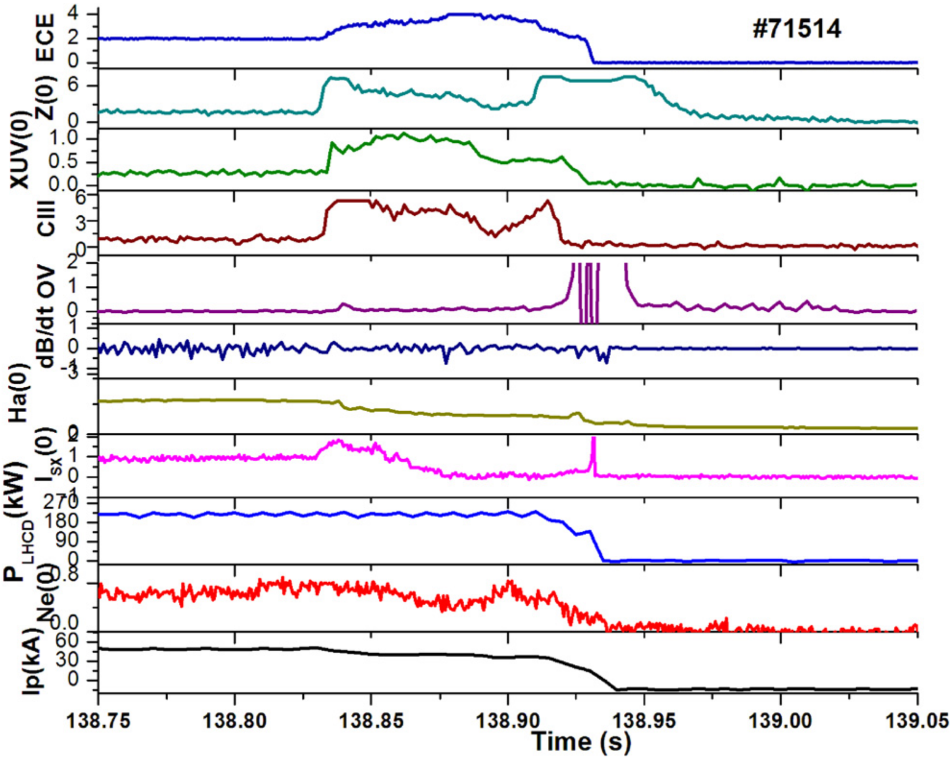

Fig. 2. Internal collapse in the expanded traces of the 139 s long pulse discharge shot 71 514 shown in Fig. 1.

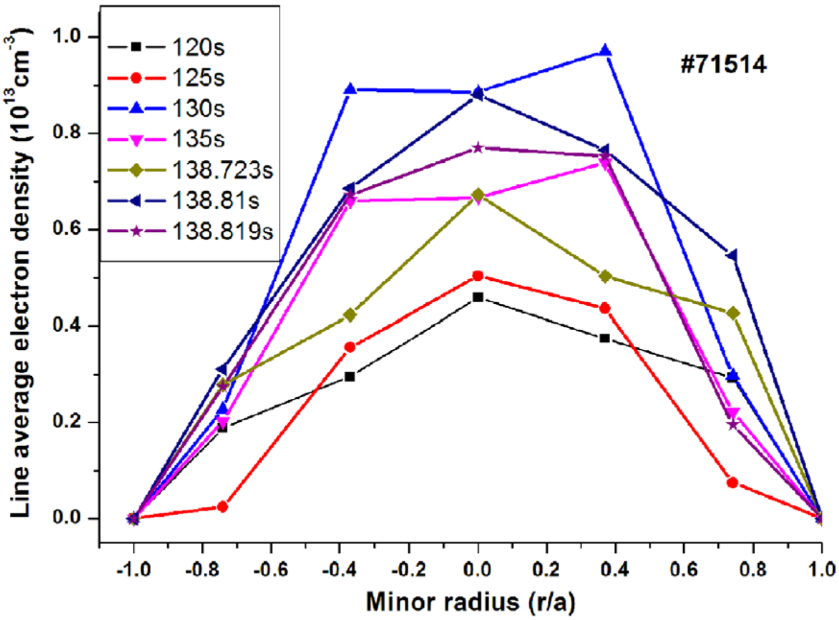

Fig. 3(a). Time evolution of line average electron density before the event for the shot in Fig. 1.

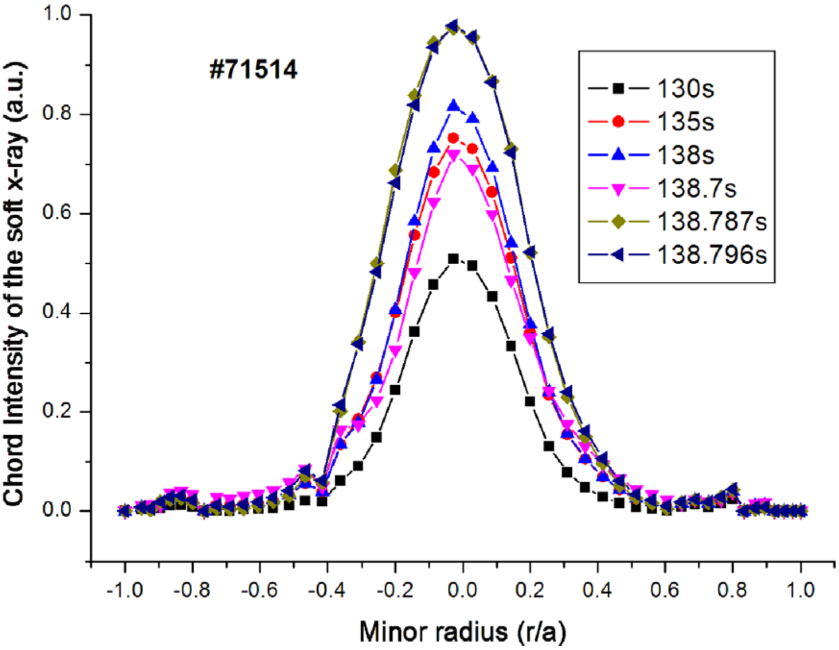

Fig. 3(b). Evolution of soft X-ray intensity profile before the event for the shot in Fig. 1.

the conventional ECE diagnostic is affected by super-thermal electron radiation and the soft X-ray PHA for temperature measurement was set on a time resolution of several hundreds of millisecond. The time interval between the event and the plasma thermal quench varied from several milliseconds to hundreds of milliseconds and had no relation with the wall saturation time τ_W (~200 s). The event could

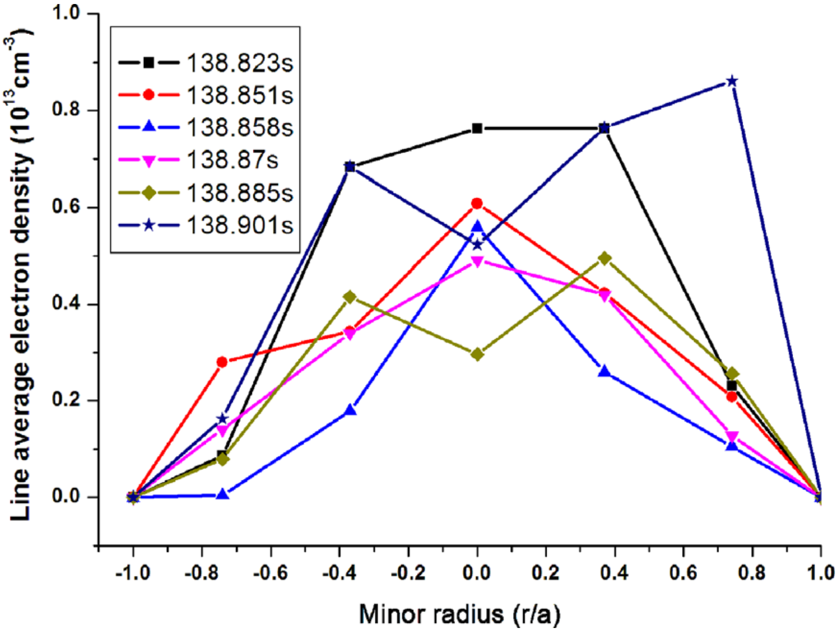

Fig. 4(a). Time evolution of the line average electron density during the internal collapse.

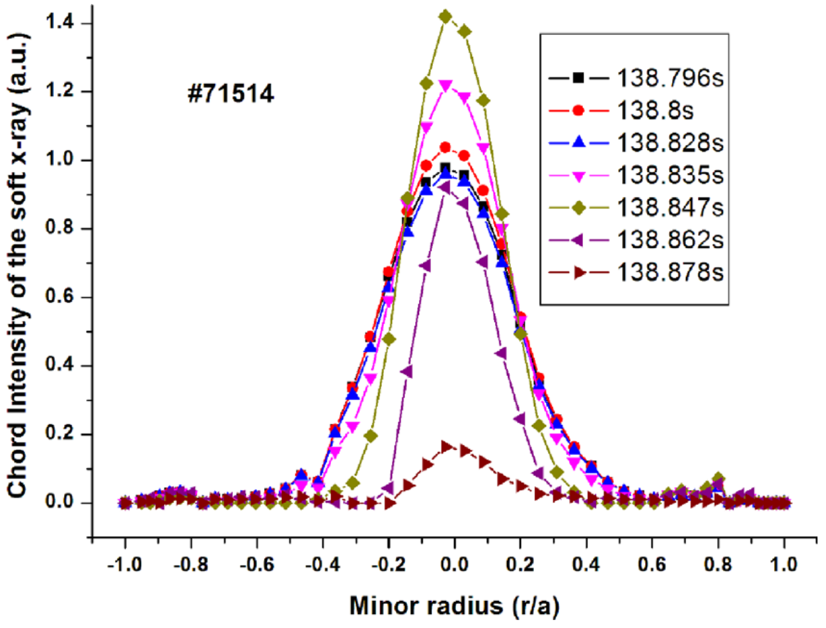

Fig. 4(b). Evolution of soft X-ray intensity profile during the internal collapse.

appear at an early discharge phase of tens of seconds, or a later time of close to τ_W, however, it did not appear at a time of more than τ_W. If the internal collapse was not serious and the central SXR radiation maintained some value, the plasma could survive. Since such an event normally follows the termination of the long pulse plasma discharge, much attention has been given to it, however, its random occurrence makes it difficult to avoid. Generally, it could be avoided or postponed by careful adjustment of the plasma displacement to ameliorate the power load of the plasma on the wall.

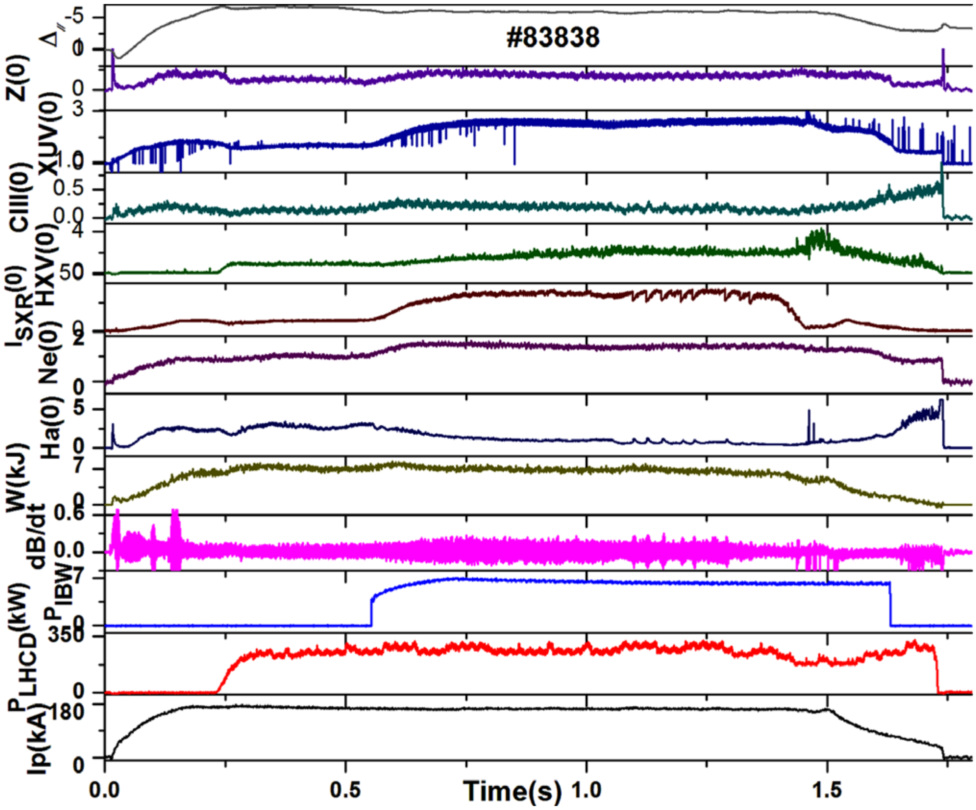

Fig. 5(a). Internal collapse in the synergetic shot of LHCD and IBW.

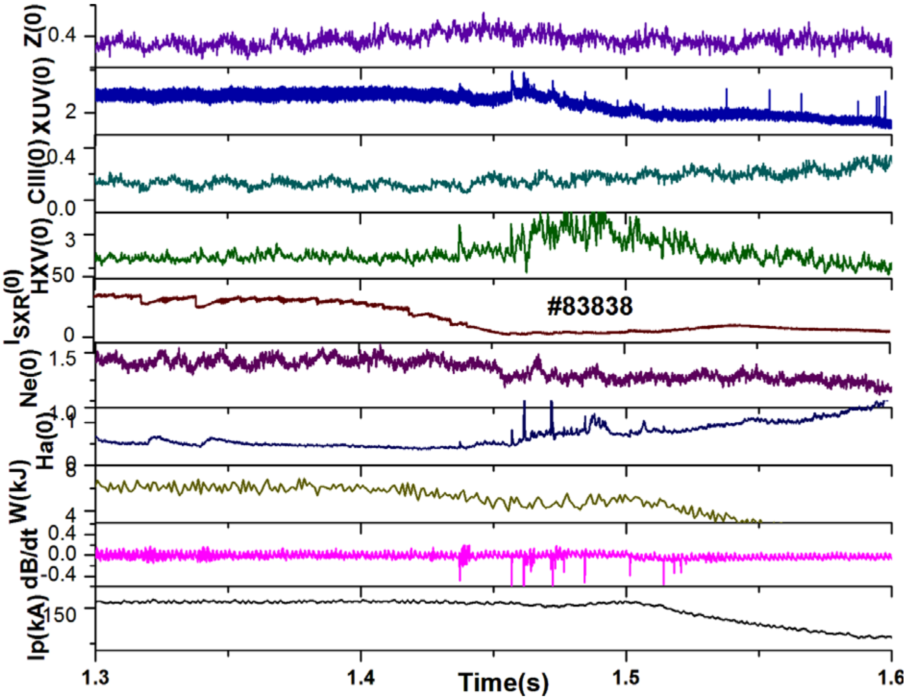

Fig. 5(b). Expanded traces of the internal collapse for the shot in Fig. 5(a).

3. Internal collapse during the high-performance discharge by synergy of LHCD and IBW

In the long-sustained high-performance discharge by synergy of LHCD and IBW, it is very important to utilize the IBW local heating to increase the high-confinement volume [8,9]. Two operation scenarios of off-axis IBW with on-axis LHCD or off-axis LHCD are routinely employed. Another type of internal collapse was also observed in this operation scenario, which is shown in Fig. 5. Preceding the event at 1.45 s, the SXR peaking

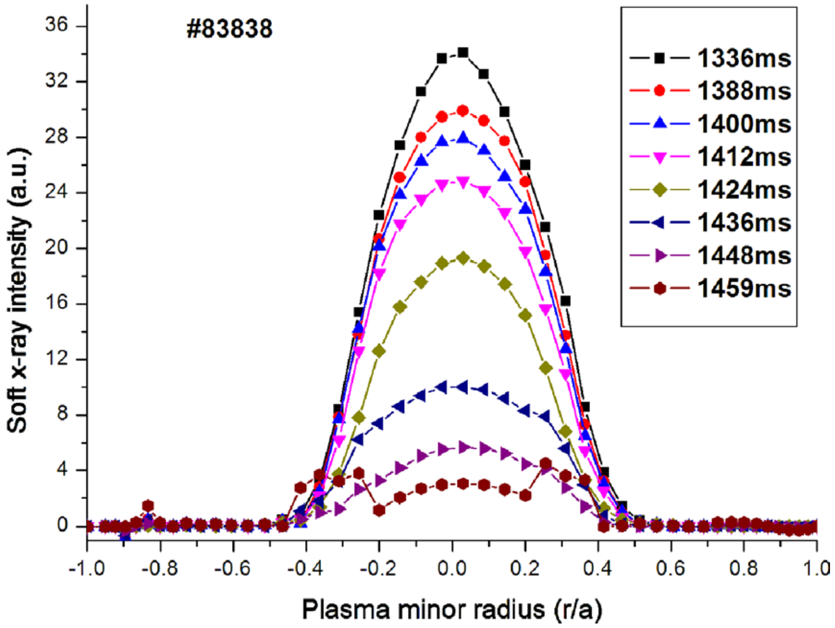

Fig. 6(a). Evolution of soft X-ray intensity profile during the internal collapse.

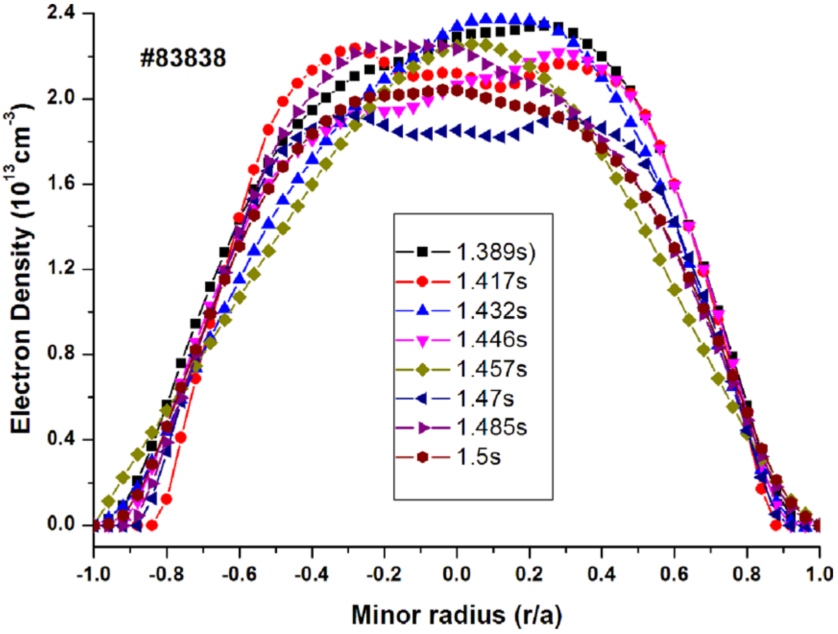

Fig. 6(b). Evolution of electron density profile during the internal collapse.

profile could be observed after suppression of the sawtooth activity. During the event, the peaking of the SXR intensity profile decreased sharply until the core collapse occurred (see Fig. 6), however no strong variations were found on other signals. After the SXR collapsed, apparent plasma and wall interaction was observed with an increase of hard X-ray and Hα signal, and a reverse sawtooth on the XUV signal, and a flat electron density profile. In such kinds of discharges, the plasma normally survived, sometimes the plasma could withstand two or more such large internal collapses (indicated by the central SXR radiation decreasing to nearly zero) during one plasma shot. It was understood that the plasma had a large stored energy in such discharges and internal collapse did not exhaust too much of the stored energy, and hence the plasma survived. The measured emission profiles of the hard X-ray indicated that the hard X-ray increase mainly came from the low energy range of 20–60 keV.

4. Summary

Two different types of internal collapse were observed and analyzed, which are in a long duration discharge by LHCD and in a synergy discharge of LHCD and IBW. They have different characteristics and different influences on the plasma performance, which are related to the operation scenarios. For the internal collapse in the long pulse plasma discharges approaching steady-state operation, the plasma was sensitive to the event and following effect on the plasma was harmful, therefore it is necessary to avoid its occurrence.

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References

[1] J. Jacquinot et al., 20th IAEA Fusion Energy Conference (2004), OV/2-2.
[2] H. Ide et al., 20th IAEA Fusion Energy Conference (2004), OV/1-1; NIFS-PROC-60, September 2005.
[3] H. Zushi et al., 20th IAEA Fusion Energy Conference (2004), OV/5-2.
[4] B. Wan, J. Luo, J. Li, et al., Nucl. Fusion 45 (2005) S132.
[5] L.Q. Hu et al., Proceedings of the 31th European Physical Society conference (EPS) on Plasma Physics and Controlled Fusion, London, UK, 28 June–2 July, ECA, vol. 28B, P1.112, 2004.
[6] X.D. Zhang et al., Proceedings of 20th IAEA Conference in Fusion Energy, EX/P4-36, Vilamoura, Portugal, November 2004.
[7] F.C. Schueller, Plasma Phys. Control. Fus. 37 (1995) A135.
[8] Baonian Wan, Jiangang Lifor Ht-7 Team, Nucl. Fusion 43 (2003) 1279.
[9] F. Paoletti et al., Phys. Plasmas 6 (1999) 863.