Experiments of full non-inductive current drive on HT-7

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Abstract. Some experimental results of steady-state operation and full non-inductive current drive have been obtained on HT-7. Three types of experiment are used to study long pulse discharge, quasi-steady-state operation and full non-inductive current drive. The experiments show that the plasma current in the full non-inductive drive case is instable due to no adjusting effect of OH heating field, when the waveguide tube discharge lead to the LHW power injecting tokamak plasma decrease. This instability of plasma current will increase the interaction of plasma with limiter and first surface and bring impurity. All discharges of full non-inductive current drive are terminated because of impurity spurting. To adjust the LHW injection power for control the loop voltage during long pulse discharge is the most effective method for steady-state operation on HT-7.

1. Introduction

The research of steady-state operation conditions is one of the main goals of the ITER for the future fusion reactor. The development of technologies and physics required for long pulse discharge and steady-state operation are necessary. To meet this goal many devices have performed some experiments on steady-state operation and long pulse discharge [1-7]. In a steady-state tokamak, the plasma current is entirely sustained by non-inductive current drive means and the self-generated bootstrap current.

The HT-7 superconducting tokamak is designed and improved for exploring long pulse discharge and steady-state operation conditions. During past few years, many new technologies are developed and some experimental results of steady-state operation and full non-inductive current drive have been obtained on HT-7. In full non-inductive current drive plasma, the plasma current driven with only lower hybrid wave (LHW) and drive efficiency are determined by various plasma parameters such as electron density, temperature and their profile. During long pulse discharge, the interaction of plasma and surface or target material for exhaust heat is unavoidable, so the impurity from the surface and target material will go into plasma and affect the drive efficiency. At the same time, the high performance regimes have been explored on HT-7 in conditions of steady-state operation and long pulse discharge, especially for the experiments on synergy of high power LHCD (300-600 kW, 2.45 GHz) and high power IBW (200-350kW, 27 MHz) heating [8-12].

The HT-7 Tokamak is a medium size machine, with a major radius R=1.22m, minor radius a = 0.27m, toroidal magnetic field B_T = 1.0~2.5T, and maximum plasma current I_P = 250KA. There are two high thermal conductive toroidal limiters and a high filed side belt limiter covered with doped graphite tiles. The high thermal soft graphite sheets between the tiles and heat sink are used to improve heat touch. A lower hybrid wave system is installed on HT-7 for the goal of long pulse discharge and current drive experiments. The LHW antenna is multi-junction grill type, composed of three rows and 4×4 columns of stainless steel waveguides. The power spectrum of the launched wave can be adjusted to be in the range $1.25 \leq N_{//} \leq 3.45$ by means of the feedback control mode.

2. Experiments of Long Pulse Operation

Since HT-7 was set up, the experiments for steady-state operation and long pulse discharge are not stopped (see *Fig. 1*), many experiments for the above-mentioned goal on HT-7 are carried out at the following parameters: toroidal magnetic field B_T = 1.8~2.0T, keep plasma current $I_P \approx$ 50KA, central electron density $n_{e0} \approx 0.7\sim1.0\times10^{19}/\mathrm{m}^3$, LHW frequency f = 2.45 GHz, LHW power spectrum $N_{//} \approx 2.35$, LHW power P_{LHW} = 100KW~400KW can be adjusted to meet the requirements of long pulse discharge or non-inductive current drive.
The experimental results show that there are three types of experiment on HT-7 tokamak can be used to study the conditions and physics of long pulse discharge, quasi-steady-state operation and full non-inductive current drive.

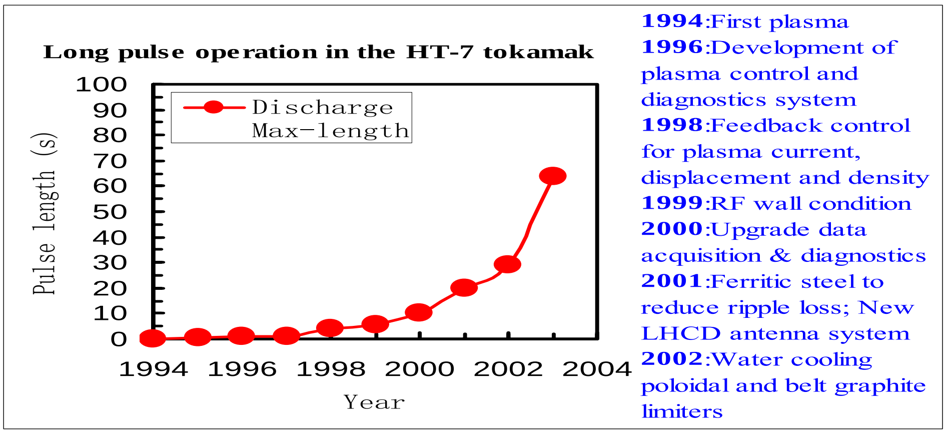


Fig. 1 The development of long pulse operation on HT-7

2.1. Long Pulse Discharge

The first type of long pulse operations on HT-7 is a fraction of OH plasma current together with the current droved by LHW. In this case, there is a little of loop voltage and that is always positive, the OH heating coil current will increase slowly to supply fractional plasma current during discharge. Due to the limited of volt-second of iron core, at some time the magnetic flux in the iron core will be saturated and the control system will switch the OH heating coil current I_{OH} off, so the discharge will be terminated. In this type discharge, the pulse length should be determined by the volt-second of iron core; in other words, a longer discharge pulse can be got only with small OH plasma current fraction, but it cannot be called as steady-state operation because of the limit of OH heating field.

2.2. Steady-State Operation

The second type of long pulse operations is to keep the plasma current constant and the loop voltage come close to zero ($V_l \approx 0$) by means of adjusting the LHW power for steady-state operation or quasi non-inductive current drive, the OH heating field still has a little feedback control effect when the current droved by LHW or the injection power is instable. The OH heating field will supply small positive or negative compensation to sustain the plasma current or larger positive compensation when the plasma degrade.

In the past, the injection power of LHW was adjusted to meet the requirements of plasma parameters and plasma current, during discharge that is constant. If there are a little change of plasma parameter such as density and impurity, the constant LHW power is not fit for plasma current set before discharge, so that OH heating field must supply some positive or negative compensation to sustain the plasma current. The positive compensation belongs with the first type of long pulse operation and the negative compensation belongs with the third one. It is very difficult to get a stable discharge for very long pulse operation.

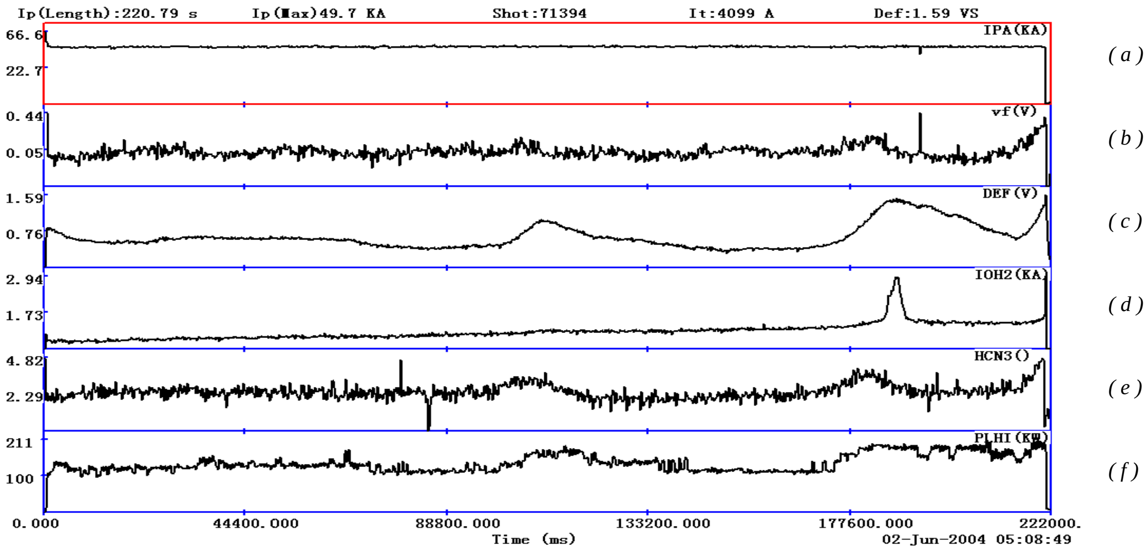


Fig. 2 shot: 71394 (a) plasma current I_P; (b) loop voltage V_l; (c) Volt-Second DEF; (d) OH heating; coil current I_{OH}; (e) plasma density n_e ($\times$1.25/5)$10^{19}cm^{-3}$; (f) LHW power P_{LHW}

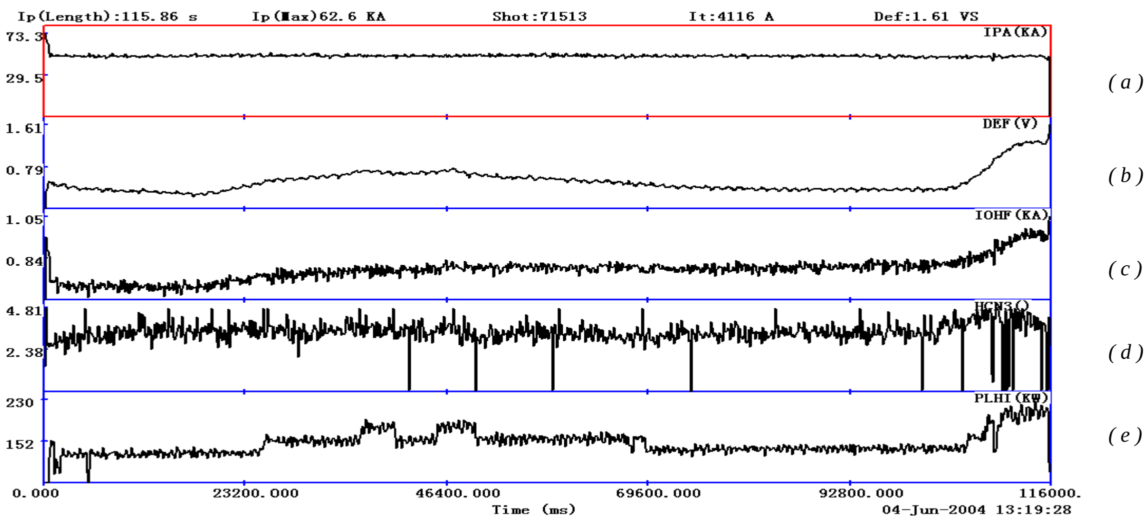


Fig. 3 shot: 71513 (a) plasma current I_P; (b) Volt-Second DEF; (c) OH heating coil current I_{OH}; (d) plasma density n_e ($\times$1.25/5)$10^{19}cm^{-3}$; (e) LHW power P_{LHW}

In a high-performance tokamak for steady-state operation goal, a little turbulence of plasma parameter and current drive system during the discharge due to the instability (such as: MHD; ELMs; impurity; injection power of LHW for current drive; heating power; recycle and so on) is not unavoidable. If the injection power of LHW cannot be adjusted, steady-state operation is difficult. These little turbulences will wear down the OH heating field gradually, lead to switch OH heating coil current off and terminate the discharge.
During the last year, some new experimental technologies in high thermal conductive toroidal limiters and feedback control system of LHW power for steady-state operation goal have been developed on HT-7. The LHW power is a real-time feedback control system and which can be adjusted to sustain the plasma current during long pulse discharge when some plasma parameters appear a small fluctuation. The adjust value cannot be large, to the larger turbulence which is also powerless and the discharge will be terminated quickly (*see Fig. 2 and 3*). Shots 71513 and 71394 show an obvious effect when the plasma density appears a small fluctuation. At last, the long pulse discharge will be terminated because of a larger rise in plasma density and impurity.
In a genuine-steady-state operation, the average value of OH plasma coil current I_{OH} should not be a larger change in period of long pulse operation, but in a brief time the OH heating field can supply some positive or negative compensation to sustain plasma current. After the LHW power is adjusted and which can sustain the plasma current, the OH heating coil current I_{OH} will reduce or increase to the initial value.

2.3. Full non-Inductive Current Drive

In the third type of experiments, the current droved by LHW is larger than the plasma current kept by feedback control system of OH heating field for full non-inductive current drive, and there are two phases in discharge plasma (see *Fig. 4*). Phase I: constant plasma current and negative loop voltage, the OH heating coil current I_{OH} is reducing gradually; Phase II: the loop voltage and the current of OH heating coil are zero, in other words, the OH heating coil current sustains at zero and the magnetic flux in the iron core is saturated, so that the plasma

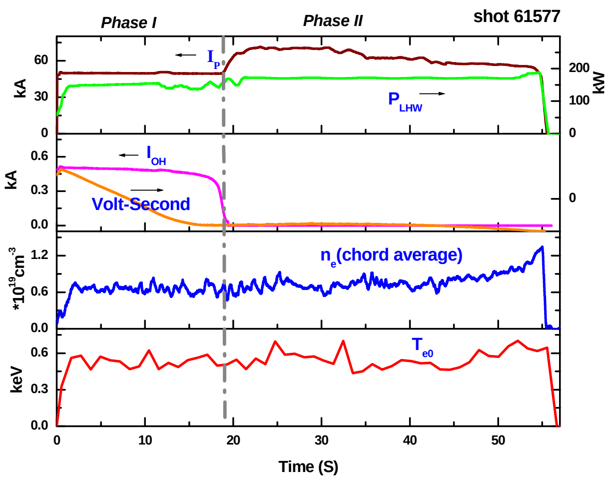


Fig. 4 The third type of discharge, the full non-inductive drive current is sustained 35 s.

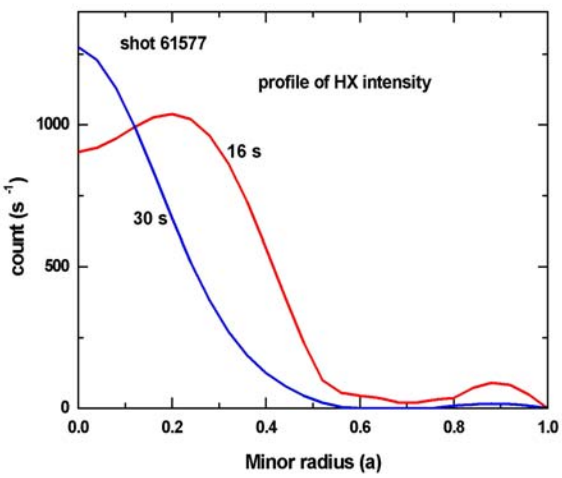
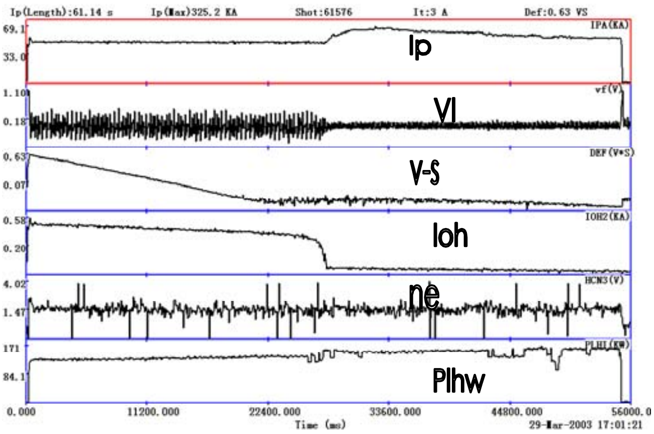


Fig. 5 The profile of hard X-ray intensity in shot: 61577



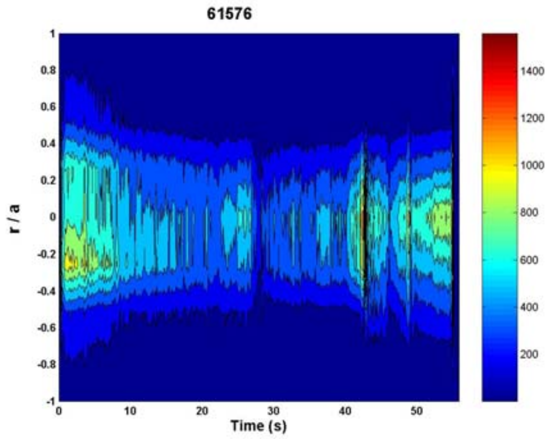


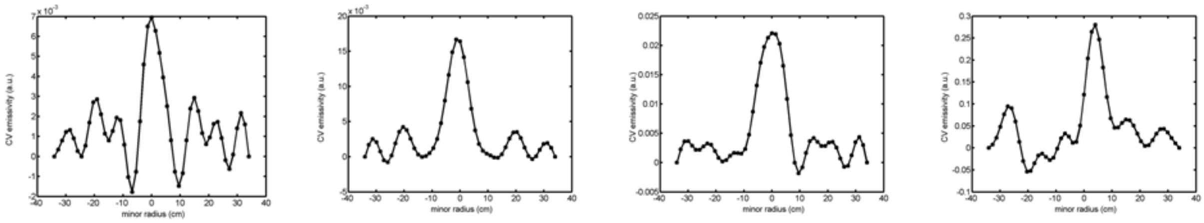
Fig. 6 Full non-inductive current drive shot:61576
Fig. 7 Profile of hard X-ray shot:61576

current is not controlled by OH heating field and the plasma current droved by LHW is larger than the plasma current in phase I set in the feedback control system of OH heating field. When the iron core saturate, the plasma current increase quickly in a short time due to no any control of mutual inductance and self- induction of plasma current with OH heating field system. The phase II is known as full non-inductive current drive plasma because of no mutual inductance and self- induction.

The experimental results on HT-7 show that the plasma current in the full non-inductive drive case is instable (*see Fig. 4 and 6*). In the early phase II, the plasma current increase quickly to a larger current, but which cannot be sustained at a constant value and always reduces gradually. Due to no adjusting effect of OH heating field and self-induction, any change of plasma parameters and LHW power will lead to a larger change of plasma current and profile (*see Fig. 7*). This instability of plasma current and profile should increase the interaction of plasma with limiter and first surface and bring impurity or plasma density rise, which is more unfavorable for LHW to drive plasma current. All discharges of full non-inductive current drive are terminated because of impurity spurting.

The off-axis deposition of LHW power will drive fast electrons generation halo plasma current profile in phase I (*see Fig. 5and 7*) and on-axis deposition in phase II. The impurity signal of CV shows that the CV radiation layer is consistent with the deposition region of LHW power and the C impurity will accumulate gradually (*see Fig. 8*).

The other kind of full non-inductive current drive experiments have be studied on HT-7. In the early discharge, the feedback control system of OH heating coil current I_{OH} is put in and I_{OH} will be sustained at a constant value that must be suitable. In this case, the loop voltage is



(a) (b) (c) (d)

Fig. 8 shot: 61576 The profile of CV emissivity at the time of 4s(a); 18s(b); 38s(c); 51s(d) center maximum value: (a) 7×10^{-3}; (b) 1.7×10^{-2}; (c) 2.2×10^{-2}; (d) 0.28

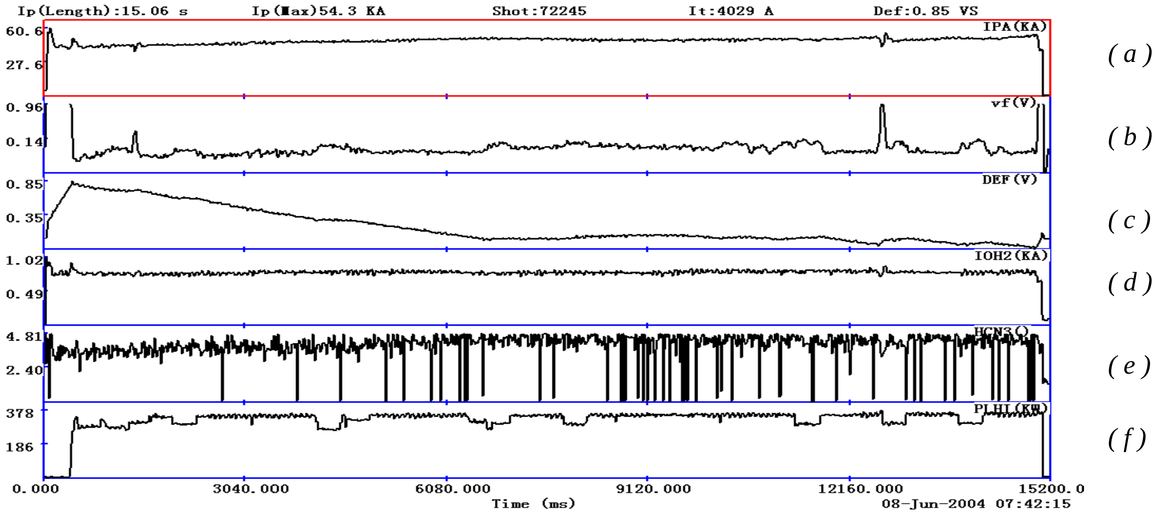


Fig. 9 shot: 72245 (a) plasma current I_P; (b) loop voltage V_l; (c) Volt-Second DEF; (d) OH heating coil current I_{OH}; (e) plasma density n_e ($\times$1.25/5)$10^{19}cm^{-3}$; (f) LHW power P_{LHW}

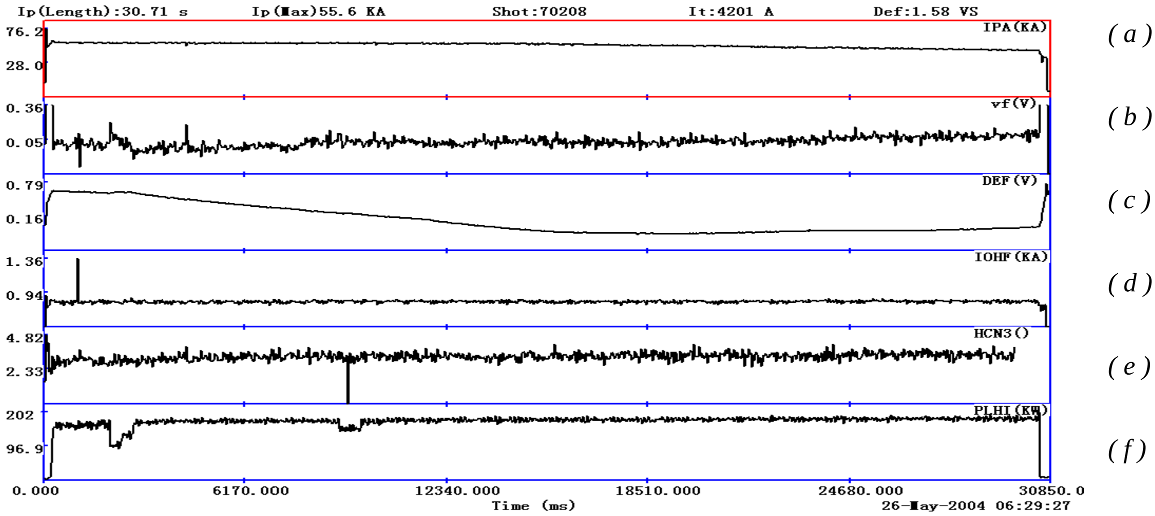


Fig. 10 shot: 70208 (a) plasma current I_P; (b) loop voltage V_l; (c) Volt-Second DEF; (d) OH heating coil current I_{OH}; (e) plasma density n_e ($\times$1.25/5)$10^{19}cm^{-3}$; (f) LHW power P_{LHW}

not zero, and may be positive or negative determined by the change of plasma current. The OH heating field des not supply any loop voltage to drive current; the measured loop voltage comes from the self-induction that will retard the change of plasma current. Actually there is a fraction of plasma current droved by the self-induction loop voltage, which can supply some compensation and want to sustain the plasma current constant (*see Fig. 9 and 10*). The experiments show that this kind of discharge is stable because of no sudden change of plasma current and fluctuation. These long pulse discharge for full non-inductive current drive always terminated by bringing impurity and plasma density rise.

3. Conclusion

Experiments for steady-state operation and full non-inductive current drive on HT-7 are presented. The results show that a stable “full” non-inductive plasma current droved by LHW

cannot be obtained in the case of “real” non-induction (no mutual and self-induction). A fraction of compensating plasma current in short time for steady state operation is needed, whether the compensating fraction is supplied by OH heating field, or self-induction loop voltage. We only put emphasis on the long-term effect of OH heating field and not short-term one, in a short time, the OH heating field should be allowed to supply some compensating plasma current and keep the stability of discharge when a small fluctuation of plasma appears during discharge, which will return to the initial value after fluctuation. This kind of long pulse discharge should be call “full non-inductive or non-inductive current drive”; actually that is “full non-inductive current drive” in full space of time and “inductive one” in local space of time. The final goal of steady-state operation is how to sustain a stable discharge with high performances in long time and which is a suit of operation mode for ITER.
On HT-7 the LHW power can be adjusted by means of feedback control system according to the change of *DEF* signal (Volt-Second), because of a small adjusting value, that is powerless for a larger fluctuation. The plasma fluctuations on HT-7 are only impurity and plasma density in steady-state operation. The longest discharge of 4 minute has been achieved in this mode in 2004. The experiments of constant I_{OH} show that the self-induction loop voltage cans also stabilize a larger fluctuation and retard a sudden change of plasma current in short time.

Acknowledgements

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