Quasi-steady-state ac plasma current operation in HT-7 tokamak

2007 Nucl. Fusion 47 1071

(http://iopscience.iop.org/0029-5515/47/9/001)

Nucl. Fusion 47 (2007) 1071–1077 doi:10.1088/0029-5515/47/9/001

Quasi-steady-state ac plasma current operation in HT-7 tokamak

Jiangang Li, Jiarong Luo, Shaojie Wang, Peng Fu, Biao Shen, Fukun Liu, Baonian Wan, Jiafang Shan, Guosheng Xu, Juan Huang, Jun Yu, Jiansheng Hu, Qiping Yuan, Yeming Hu and HT-7 Team

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

E-mail: j_li@ipp.ac.cn

Received 31 December 2006, accepted for publication 13 June 2007
Published 15 August 2007
Online at stacks.iop.org/NF/47/1071

Abstract
A quasi-steady-state alternating current operation assisted by lower hybrid wave (LHW) was achieved on a HT-7 superconducting tokamak with plasma current of $I_p = 125$ kA, line-averaged density of 1.5×10^{19} m^{-3}, electron temperature of $T_e = 500$ eV and 30–50 s plasma duration. Plasma current was sustained and smoothly transferred from one direction to the other without loss of ionization. Plasma position control, LHW assistance, strong gas puffing and good wall condition are the key issues to have a smooth transition of plasma current. Our modelling results show that current reversal equilibrium configuration with two oppositely flowing currents in the high-field-side and the low-field-side during current reversal exists. This is in agreement with experimental measurements.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Alternating (AC) current operation of a tokamak reactor is an attractive scenario to generate a continuous output of electric energy without the need for a complicated non-inductive current driven system. The use of ac inductive current drive for a tokamak fusion reactor allows the reactor to operate with a minimum plant recirculating power. Compared with non-inductive current drive operation, ac discharges are technically simpler and have higher cost efficiency.

AC operation was first demonstrated on a STOR-1M tokamak with a plasma current of 4 kA [1]. Plasma properties when the plasma current crosses zero and some key technologies have been introduced in several papers [2–5]. JET has demonstrated a full cycle of ac operation with a reactor-relevant plasma current of 2 MA, but with a dwell time between two half-cycles from 50 ms to 6 s, which means the ionization was lost when the plasma current crosses zero [6]. Multi-cycle ac operations with small plasma current have been tested in a few tokamaks. CSTN-AC obtained 20 s duration, 2 ms flat-top, a repetition of 10 ms and a plasma current of 0.5 kA with finite dwell times [7]. ISTTOK achieved a multi-cycle alternating square wave plasma with seven half-cycles, no dwell time and a plasma current of 4–5 kA [8]. Constant ac discharges with 2, 4 and 8 sinusoidal cycles of 4 kA were obtained on the CT-6B tokamak [9, 10]. Due to the toroidal field duration limit, most ac operations were very short and plasma parameters were relatively low.

The operation of a tokamak reactor in an inductive ac regime would require the achievement of steady-state duration, multi-cycle, relative high plasma parameters without losing ionization when the plasma current crosses zero (without dwell time). This paper presents the efforts for the achievement of steady-state duration multi-cycle, relative high plasma parameters without losing ionization when the plasma current crosses zero from the HT-7 superconducting tokamak. After introduction, the experimental set-up and the main results are presented in section 2. The plasma property when the plasma current crosses zero is introduced in section 3. Discussion and conclusion follow in sections 4 and 5.

2. Experimental set-up and main results

HT-7 superconducting tokamak normally operated with I_p = 100–200 kA, B_T = 2 T, major radius R = 1.22 m, minor radius a = 27 cm, line-averaged density n_e = (1–5) $\times 10^{19}$ m^{-3}, T_e = 0.3–2 keV, with limiter configuration. The power for the ion cyclotron resonant frequency (ICRF) system was 0.3 MW with continuous work (CW) capacity. The lower hybrid current drive (LHCD) system consisted of a multi-junction grill (4 × 12), a 1.2 MW wave system with a frequency of 2.45 GHz. Efforts have been made for steady state operation

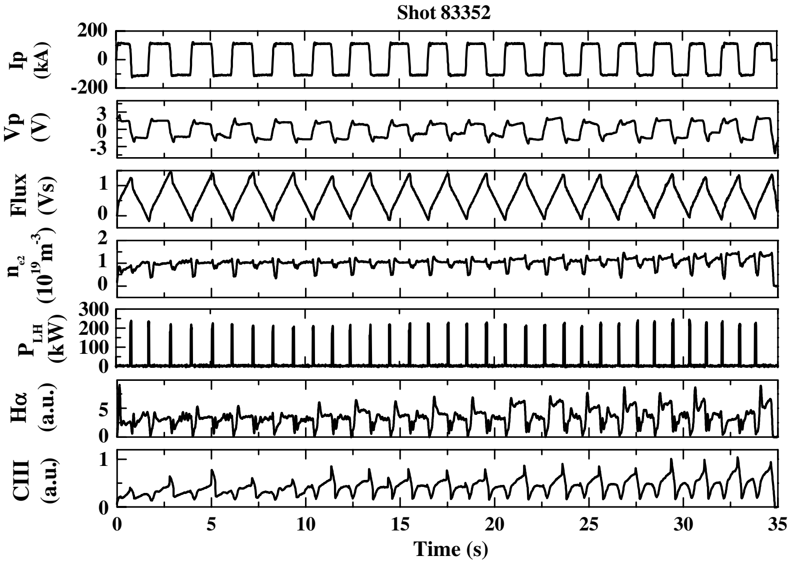

Figure 1. A typical quasi-steady-state ac operation with a pre-set 35 s duration in HT-7 superconducting tokamak. $B_T = 1.9$ T, central line-averaged density $n_e = 1.5 \times 10^{19}$ m^{-3} and central electron temperature $T_e = 500$ eV.

and many good results have been obtained during the past few years [11, 12]. The longest plasma duration was over 300 s by LHCD with a central electron temperature of 1 keV. Due to the limitation of the old HT-7 PF power supply which can only provide current and voltage in one direction, it was not possible for ac operation before 2005. Two sets of new PF power supplies, which were part of a new superconducting tokamak EAST [13], have been used for the HT-7 tokamak since 2005 which provide a possibility for ac operation on the HT-7 tokamak. The EAST PF power supply system consists of a 12 set thyristor ac/dc converters, which provide the current necessary to produce the scenario and to control the plasma shape and position. This PF converter of the power supply is rated at a total installed power of about 210 MVA. The key issues in the design of the ac/dc conversion system are low cost, high availability and reliability.

By using the ohmic discharge only, it was difficult to obtain ac operation without a dwell time due to the limitation of the PF power supply ramping rate which could provide a ramping rate of dI/dt less than 1.5 MA s^{-1}. With the assistance of LHCD of a power threshold of 250 kW, ac operation can be easily obtained with a dwell time from 5 to 20 ms. By precise control plasma position and suitable gas fuelling when the plasma current crosses zero under good wall condition, the dwell time can be eliminated to zero. A finite plasma density of $(0.1\text{–}0.4) \times 10^{19}$ m^{-3} was kept when the plasma current crosses zero. Optical signals showed that ionization was maintained.

A key issue for getting long pulse ac operation is the plasma position control when the plasma current crosses zero. For long pulse dc current operation driven by LHCD, the plasma position is feedback controlled by the plasma control system. The plasma position is calculated from the signals by magnetic loop coils which are proportional to the plasma current and the plasma shift divided by the plasma current. This method is not valid anymore when the plasma current crosses zero. A pre-set vertical field was used for position control both for negative and positive plasma currents when the plasma current approaches zero ($I_p < \pm 20$ kA). Long pulse ac operation was obtained on the HT-7 superconducting tokamak with plasma parameters: $I_p = 125$ kA, line-averaged density 1.5×10^{19} m^{-3} and electron temperature $T_e = 500$ eV. More than 10 cycles can be easily obtained after RF boronization which provides very low recycling and clean wall conditions [14].

Plasma was normally terminated due to iron core saturation for a duration beyond 10 s. A real-time dynamic control for avoiding iron core saturation has been used for overcoming this problem. Plasma current, density and position have been feedback controlled during the flat-top of plasma current. Plasma parameters were controlled in a pre-programmed manner (a pre-set vertical field) when the plasma current approaches zero ($I_p < \pm 20$ kA) with strong gas puffing. By precisely controlling the plasma position, the gas fuelling rate and lower hybrid wave (LHW) power and its deposition position, plasma current can easily transit from the positive to the negative direction and vice versa. When there is dynamic real-time feedback control of the magnetic flux, quasi-steady-state ac operation with a pre-set 30 s duration can be obtained. The plasma sustainment (without losing ionization) at the plasma current zero phase was demonstrated under steady-state condition. Figure 1 shows a typical steady-state ac operation with a pre-set 35 s duration on the HT-7 superconducting tokamak. The waveforms from top to bottom in figure 1 are plasma current, loop voltage, magnetic flux, line-averaged density, LHCD power, Hα signal and C III radiation. The plasma performance showed a relatively stable behaviour for 35 s.

Plasma–wall interaction, edge recycling and hydrogen retention are the key issues for steady-state operation. Optical diagnostics have been used for measuring the impurity; edge recycling and particle balance has been used for hydrogen retention. Figure 2 shows the plasma density, the Hα radiation, the total fuelling gas, the H/(H + D) ratio and the recycling coefficient which shows the edge recycling for a 30 s ac operation shot. After 10 s, plasma–wall interaction indicated

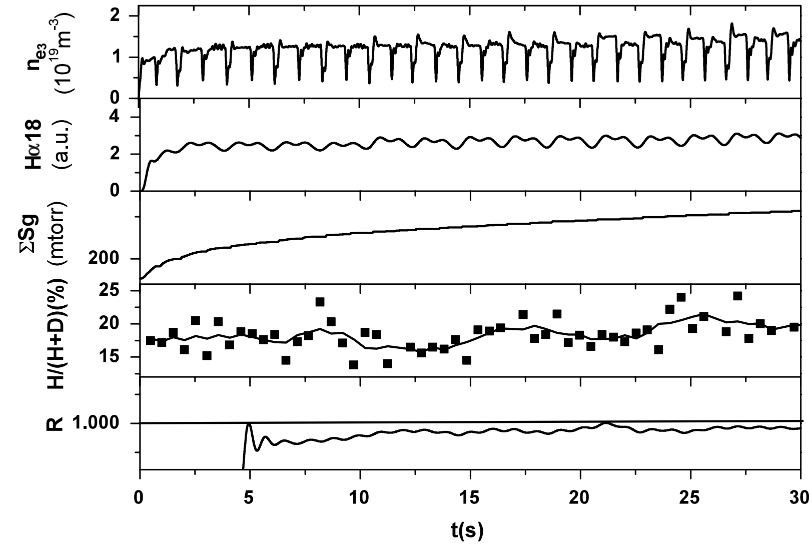

Figure 2. Plasma central density, Hα radiation, total fuelling gas, H/(H + D) ratio, recycling coefficient which shows edge recycling for a 30 s ac operation shot. $B_T = 1.9$ T, $P_{LHCD} > 250$ kW, $I_p = 125$ kA.

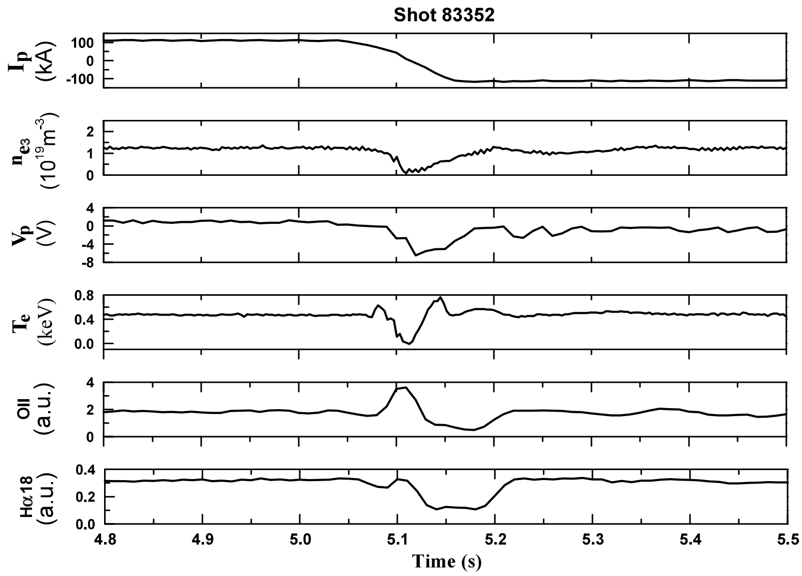

Figure 3. Plasma main parameters at flat-top of both polarities. $I_p = 125$ kA, central line-averaged density $n_e = 1.5 \times 10^{19}$ m^{-3}, electron temperature $T_e = 480$ eV, $B_T = 1.9$ T.

by Hα, edge recycling and plasma density reached a relative stable condition.

By using feedback control at the plasma current flat-top, plasma parameters were kept the same for positive and negative plasma current phases within 20 s before the wall reached the saturation condition. As shown in figure 3, plasma current I_p = 125 kA, central line-averaged density $n_e = 1.5 \times 10^{19}$ m^{-3}, electron temperature $T_e = 480$ eV, Hα, O II, C III and other radiations were kept the same for positive and negative plasma current polarities. Figure 4 shows the time evolution of the density profile during the two flat-top phases. After a short drop in density with finite density when the plasma current crosses zero, the density increased to the flat-top with the density feedback control system. This demonstrated that it could be used for future large tokamak reactor operation when both polarities could provide the same plasma parameters which could produce the same fusion energy output.

3. Plasma property when the plasma current crosses zero

It is very important to know the plasma property when the plasma current crosses zero. As mentioned in the previous section, the plasma kept a finite density when the plasma current was zero. Plasma ionization was fully maintained by LHCD. If we carefully compare the zero current plasma properties between the plasma current transition from positive to negative and from negative to positive phase, we can find some difference. Figure 5(a) shows the main plasma properties from the negative current to the positive one. Figure 5(b) shows

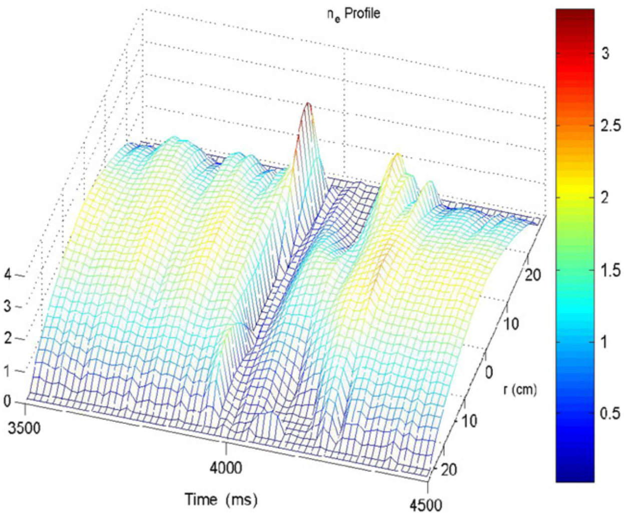

Figure 4. Time evolution of density profile during the two flat-top phases. The density scale is 10^{19} m^{-3}.

the main plasma properties from the positive current to the negative one. During the whole duration of the discharge, central line-averaged plasma density at zero current from the negative to the positive phase is about (0.5–1.2) $\times$ 10^{18} m^{-3} and density from the positive current to the negative one is about (2.9–3.5) $\times$ 10^{18} m^{-3}. The radiations from Hα, O II, C III and ECE signals from the negative to the positive current phase showed less ionization and lower parameters than those from the positive to the negative one shown in figure 5(*b*). Due to the limitation of very low temperature measurement by ECE (when $T_e < 20$ eV, it cannot be detected correctly), it is difficult to judge which temperature is higher. But the duration of the zero ECE signal (very low temperature) in figure 5(*a*) is about 18 ms and the duration in figure 5(*b*) is about 12 ms.

Density profiles and their temporal traces also showed a different behaviour for these two cases. Figure 6(*a*) shows the density profile from the negative to the positive phase, which was measured by a multi-channel HCN interferometer. The loop voltage starts reversal 30 ms before zero current. Following a fast current ramp-down, plasma quickly moves towards the outside. Density profile starts hollow, which means central density is lower than that at half radius. At the time of zero current, the central density was almost zero and there were two density peaks in the low and the high field sides which were measured by two channels of the interferometer (n_{e2} and n_{e4}). After about 100 ms, the density profile has a normal parabolic shape. Figure 6(*b*) shows the density profile temporal evolution from positive to negative phase transition. Similar behaviour occurs. The difference is that it took only less than 50 ms when the density profile has a normal parabolic shape.

4. Discussion

As mentioned in section 1, the operation of a tokamak reactor in an inductive ac regime would require the achievement of steady-state duration, multi-cycle, relative high plasma parameters without losing ionization when the plasma current crosses zero. It would be desirable if the transition time from the positive flat-top current to the negative one could be as short as possible. For future tokamak reactors, the ohmic coils will be superconducting and a limited coil current change rate can be applied on them during the plasma current transition time, which means the transition time will be not so short. Therefore, it is important to keep plasma ionization when the plasma current crosses zero. Ionization assistance by waves, such as electron cyclotron resonant frequency heating (ECRH), LHCD and ICRF, would be helpful. The best method will be ECRH for ionization assistance and start-up. Since there is no ECRH system in HT-7, LHCD was used for this purpose and it works well for getting multi-cycle, relatively high plasma current discharges.

It is important to know what kind of plasma equilibrium configurations exists when the plasma current crosses zero. What are the plasma density, current and temperature profiles with zero current? A very good experiment on the CT-6B tokamak was done for measuring the plasma current density profile [10]. By using two internal magnetic probes which were inserted into the plasma during plasma discharges on a shot-by-shot basis, the plasma current distribution was reconstructed. Results showed that two plasma current components flow in opposite directions when the net current vanished. Since this method can be done only when plasma parameters are relative low, the plasma could be sustained when the probes were inside the plasma. It is impossible to use this method when the plasma is hot enough to be sustained with a probe inside the plasma and on the HT-7 tokamak. A few theoretical work have also been carried out recently by solving the Grad–Shafranov–Helmholtz equation for the equilibrium configurations with central current density reversal [15–19].

The modelling results showed that two equilibrium configurations might exits during the zero current condition. Configuration one is that there are two oppositely flowing current components on the high-field-side and the low-field-side. This has been demonstrated on the CT-6B tokamak.

The analytical theoretical model is to solve the Grad–Shafranov equation of tokamak equilibrium as [15]

$$\left(x\partial_x \frac{1}{x}\partial_x + \partial_z^2\right)\psi = -\frac{1}{2}x^2\frac{\mathrm{d}\beta}{\mathrm{d}\psi} - \frac{1}{2}\frac{\mathrm{d}g^2}{\mathrm{d}\psi} = -xj_\phi, \qquad (1a)$$

$$-\frac{1}{2}\frac{\mathrm{d}\beta}{\mathrm{d}\psi} = a_1, \qquad (1b)$$

$$-\frac{1}{2}\frac{\mathrm{d}g^2}{\mathrm{d}\psi} = -a_2 - \alpha^2\psi, \qquad (1c)$$

$$[\psi]_{\text{boundary}} = a_2/\alpha^2. \qquad (1d)$$

where $\psi = \Psi/B_0a^2$ is the normalized poloidal magnetic flux, $x = R/a$, $z = Z/a$, $\beta(\psi) = 2\mu_0 p(\psi)/B_0^2$, $g(\psi) = F(\psi)/B_0a$, with the magnetic field represented by $\overrightarrow{B} = F(\psi)\nabla\phi + \nabla\Psi\times\nabla\phi$, ϕ is the ignorable angle in the cylindrical system (R, ϕ, Z). $p(\psi)$ is the plasma pressure; B_0 is the vacuum magnetic field evaluated at $R = R_0(x = x_0)$; R_0 and a are the major radius and the minor radius, respectively. $j_\phi = J_\phi\mu_0 a/B_0$ and J_ϕ is the toroidal current density.

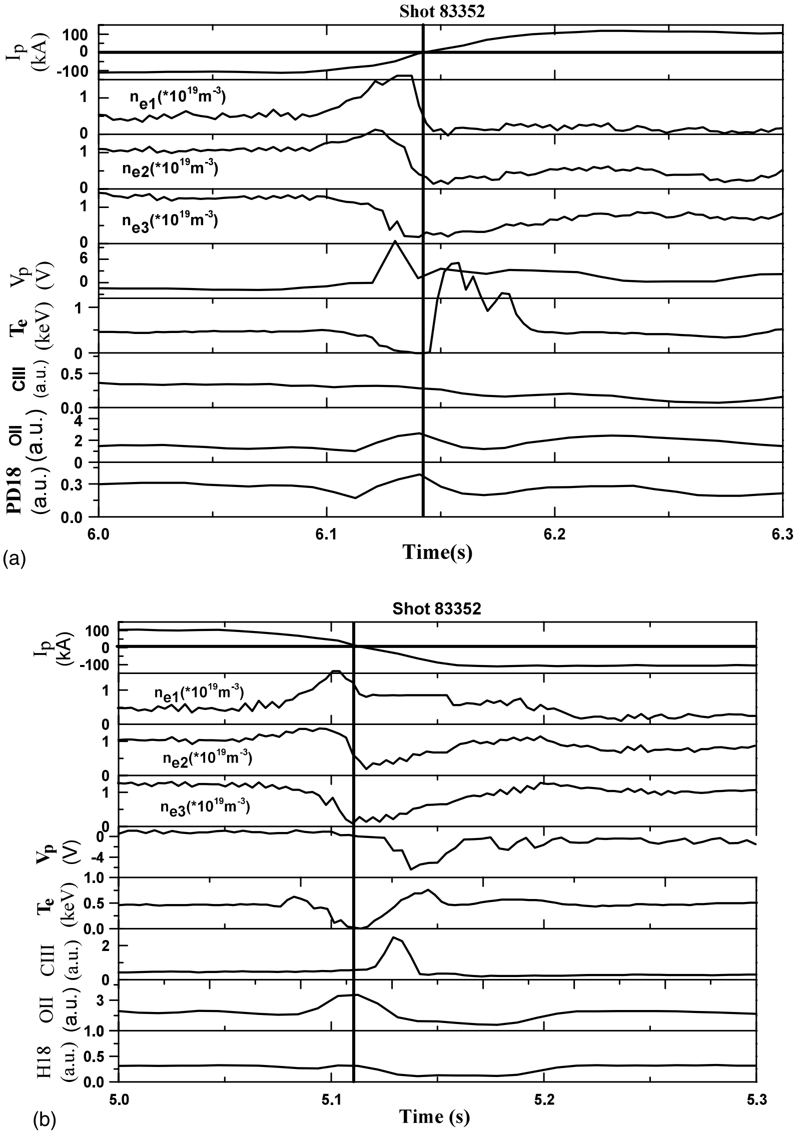

Figure 5. Plasma properties at zero plasma current phases. Shot 83352, $B_T = 1.9\,T$, $P_{LHCD} > 250\,kW$, $I_p = 125\,kA$. (*a*) From negative to positive phase. (*b*) From positive to negative phase.

a_2 and α^2 can be related to the experimental parameters which are defined as follows [16]:

$$a_2 = \frac{V_p \tau_R}{2\pi B_0 a^2}, \qquad \tau_R = \mu_0 a^2 \sigma, \qquad \sigma = \frac{n_e e^2 \tau_e}{0.51 m_e},$$

$$\tau_e = 3(2\pi)^{3/2} \frac{\varepsilon_0^2 m_e^{1/2} T_e^{3/2}}{n_i Z^2 e^4 C_l}, \qquad C_l = \ln \frac{\lambda_D}{\lambda_0}, \tag{1e}$$

$$\lambda_D = \left(\frac{\varepsilon_0 T_e}{n_e e^2}\right)^{1/2}, \qquad \lambda_0 = \frac{e^2}{12\pi \varepsilon_0 T_e},$$

where C_l is the coulomb logarithm.

Our modelling results are shown as in figure 7, by using the Grad–Shafranov–Helmholtz equation to try understand the current reversal equilibrium configuration (CREC). At the flat-top, $I_p = 125\,kA$, central line-averaged density $1.5 \times 10^{13}\,m^{-3}$, $T_e = 500\,eV$ and loop voltage $V_p = 1.5\,V$. At zero current time, $V_p = 5.5\,V$, density $1.0 \times 10^{18}\,m^{-3}$, electron temperature is about 15 eV which is estimated from the optical diagnostics. Figure 7 shows that there is a CREC with two oppositely flowing current in the high-field-side and the low-field-side (HL-CREC). In this figure, the solid line stands for the normalized plasma pressure, the dashed line stands for the normalized toroidal current. The modelling results are similar with those for the CT-6B tokamak [16].

For producing results in the figure, the input parameters are $\mu_0 = 10^{-7}\,Hm^{-1}$, $\varepsilon_0 = 8.85 \times 10^{-12}\,F\,m^{-1}$, $\beta_V = 2.0 \times 10^{-6}$ and $a_2 = 4.43 \times 10^{-2}$. According to the ac operation experiment on the HT-7 tokamak, when the plasma current flows from negative to positive at $I_p = 0$, $V_p = 5.5\,V$, $T_e = 15\,eV$, $n_e = 1 \times 10^{18}\,m^{-3}$, and the output values show the two components of toroidal current in the high-field-side (46.7 kA) and the low-field-side (−46.7 kA), the maximum value of the plasma current density is about $1.08\,MA\,m^{-2}$. When the plasma current flows from positive to negative at $I_p = 0$, $V_p = -4.0\,V$, $T_e = 15\,eV$, $n_e = 1 \times 10^{18}\,m^{-3}$, a negative current component (−33.7 kA) exists on the high-field-side and a positive one (33.7 kA) on the low field side.

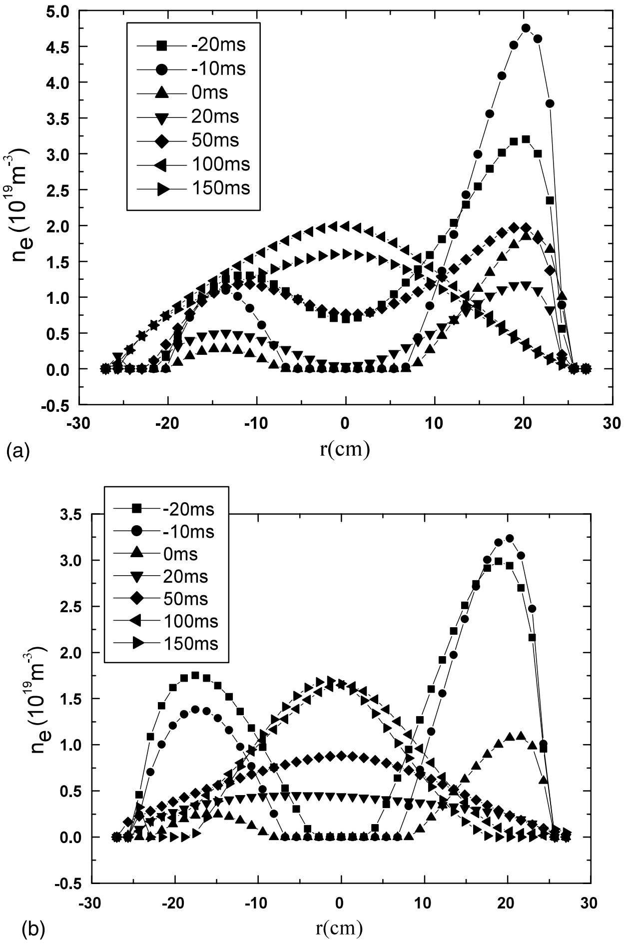

Figure 6. Time evolution of density profile at zero plasma current phases for Shot 83352. (*a*) From negative to positive phase. (*b*) From positive to negative phase.

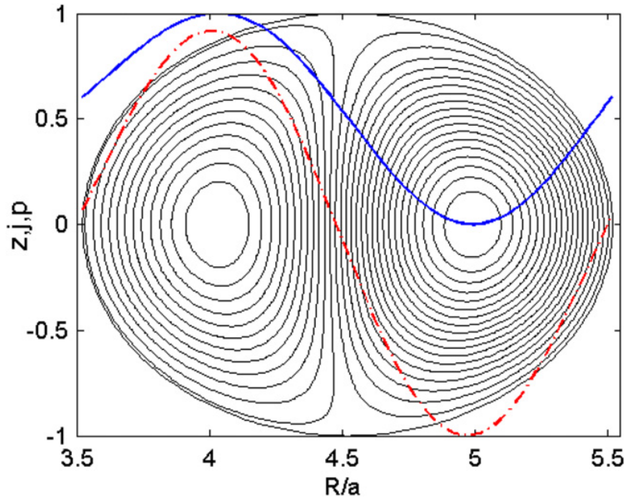

Figure 7. The simulation configuration shows the CREC with two oppositely flowing current in the high-field-side and low-field-side (HL-CREC). Solid line stands for the normalized plasma pressure; dashed line stand for the normalized toroidal current. $R/a = 4.5$ correspondent plasma centre.

Both negative and positive currents on the low-field-side and the high-field-side exist with a current between 30 and 50 kA in each transition phase. Similar results were obtained on the CT-6B tokamak. Since the ECE measurement cannot provide an accurate measurement during zero current time due to the influence of LHW, we just assume it has a similar profile as the density shown in figure 6 and the plasma pressure profile will be the same as shown in figure 7. Simulation results show that the CREC exists and it is agreeable with experimental observation.

Our modelling results assume that the plasma current reversal is mainly due to the ohmic system and does not take the role of LHCD, just using the ohmic part since being co-driven and counter-driven by LHCD during current transition phases is different and very complicated for solving the Grad–Shafranov–Helmholtz equation. Due to the ionization assistance of LHW, the loop voltage at zero current time is different at both positive and negative transition phases; the calculated plasma current component might not be the same as the simulation results. Efforts will be made to add the LHCD current profile to modelling to give more reasonable results.

As theory predicted [15], for a good current reversal for ac operation, the time scale for the flux change should be much smaller than that of current diffusion. Due to the ramping rate limitation of PF power supply ($<1.5\,\mathrm{MA\,s^{-1}}$ for plasma current), the transition time from negative to positive current cannot be very quick (<20 ms). Higher target plasma electron temperature would be favourable for a limited transition time since it has a longer current diffusion time. LHW assistance will be helpful for getting high electron temperature during the current transition time. The role of LHCD in co-driven and anti-driven directions when the plasma current crosses zero is different. When the plasma current changes from the negative to the positive direction, LHW provides a current driven mode and has little effect on plasma heating. While the current changes from the positive to the negative phase, LHW provides an anti-driven mode and can effectively heat the target plasma, which provides better conditions for a smooth transition of plasma current polarity. Figure 5 shows the advantage for the anti-driven condition. A shorter transition time (50 ms back to the normal flat-top condition) for anti-driven is favourable for future reactor use since future large superconducting tokamaks, such as ITER, would have a lower current ramping rate. This suggests that a good wave heating system (ECRH, for example) is favourable for assisting current reversal.

Compared with plasma discharges driven by LHCD with similar plasma parameters ($I_p = 125$ kA, $n_e = 1.5\times10^{19}\,\mathrm{m^{-3}}$) on the HT-7 tokamak, the wall heat load of ac operation is very low due to more uniform heat load on plasma facing components. Dc plasma discharges driven by LHCD can only be sustained up to 15 s and terminated with a high heat load on PFC. The wall temperature measurement over 1500 °C was measured and hot spots were observed for normal LHW-driven plasma discharges. For 30 s ac operation, the wall temperature was kept under 200 °C and no hot spots were observed. Plasma discharges were normally terminated by losing control of plasma density at the end of discharges in long pulse ac discharges.

As mentioned in section 2, for a good current reversal transition, strong gas puffing is required. During the ac discharge, about ±50 ms before zero current, gas puffing is not carried out by density feedback control. Instead a fixed strong gas puffing rate was used, which means a lot of gas was puffed in this period. Due to lower plasma current in this period, only very small amount of fuelling gas was ionized and contributed to plasma density. When the ac discharge continued, the strong gas puffing was kept during current reversal phases until the wall was saturated. Eventually, outgassing from the wall terminated the discharges. By using He conditioning, or low-density long pulse LHCD plasma, wall retention can be partially removed. The duration of ac operation can be extended from 30 to 50 s, but it is very difficult to obtain a longer discharge. Further efforts are needed to solve this problem by carefully controlling the gas puffing during the current reversal phase.

5. Conclusion

A quasi-steady-state ac operation assisted by a LHW has been achieved on the HT-7 superconducting tokamak with a plasma current of $I_p = 125$ kA, line-averaged density of 1.5×10^{19} m^{-3}, electron temperature of $T_e = 500$ eV and 30–50 s plasma duration. Plasma discharges were sustained and smoothly transferred from one direction to the other without losing plasma ionization.

Efforts are made for several important issues of steady-state ac operation, such as equilibrium configuration, precise feedback control of plasma position, current profile, plasma–wall interaction and fuelling and recycling during plasma current reversal under steady-state operation condition.

The precise control of plasma position, enough LHCD power and proper gas fuelling when the plasma current crosses zero are key issues to keep the smooth transition and the same plasma properties during positive and negative current flat-top phases. With a boronized wall condition, the quasi-steady state ac operation was easier to be realized.

Our modelling results have shown that the CREC with two oppositely flowing currents in the high-field-side and the low-field-side (HL-CREC) with a plasma current of 30–50 kA exists during the current reversal period, which is partially demonstrated by the density measurement in experiments. Further efforts are required for improving modelling and outgassing before the end of discharges. With these improvements, longer plasma duration and a real steady-state discharge with time duration longer than that of the wall saturation time might be obtained.

Acknowledgments

The authors would like thank Dr C.J. Xiao for useful discussions. This work is partially supported by the Chinese National Science Foundation Projects 10675127 and 10675125.

References

[1] Mitarai O. *et al* 1987 *Nucl. Fusion* **27** 604
[2] Mitarai O. *et al* 1992 *Nucl. Fusion* **32** 1801
[3] Mitarai O. *et al* 1993 *Plasma Phys. Control. Fusion* **35** 711
[4] Mitara O. *et al* 1987 *Nucl. Fusion* **36** 1335
[5] Mitarai O. *et al* 1997 *Rev. Sci. Instrum.* **68** 2711
[6] Tubbing B.J.D *et al* 1992 *Nucl. Fusion* **32** 967
[7] Hayashi K. *et al* 1996 *Proc. Int. Conf. on Plasma Physics (Nagoya, 1996)* vol 2 (Nagoya: Fusion Research Association of Japan) p 1246
[8] Cabral J.A.C., Fernandes H., Figueiredo H. and Varandas C.A.F 1997 *Nucl. Fusion* **37** 1575
[9] Yang X. *et al* 1996 *Nucl. Fusion* **36** 1669
[10] Huang J. *et al* 2000 *Nucl. Fusion* **40** 2023
[11] Li J. *et al* 2001 *Nucl. Fusion.* **41** 1625
[12] Wan B.N. *et al* 2004 *Nucl. Fusion* **44** 400
[13] Weng P. D. and EAST Team 2002 *Plasma Sci. Technol.* **4** 1579
[14] Li J. *et al* 1999 *Nucl. Fusion* **39** 973
[15] Wang S. 2004 *Phys. Rev. Lett.* **93** 155007
[16] Wand S. and Yu J. 2005 *Phys. Plasmas* **12** 62501
[17] Yu J., Wang S. and Li J. 2006 *Phys. Plasma* **13** 054501
[18] Martynov A A, Medvedev L, Villand L 2003 *Phys. Rev. Lett.* **91** 085004
[19] Rodrigues P. and Bizarro J.P.S. 2006 *IAEA 21st FEC, TH/P3-09 (Chengdu, China, October 2006)*