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Steady-state AC Plasma Current Operation in HT-7 Tokamak

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Abstract

A steady-state alternating current (AC) operation assisted by lower hybrid wave has been achieved on HT-7 superconducting tokamak with plasma current Ip=125kA, line average density $1.5 \times 10^{19} m^{-3}$, electron temperature Te = 500eV and 30-50 seconds plasma duration. Plasma current was sustained and smoothly transfer from one direction to the other without loses of ionization. Plasma position control, LHW assistance, suitable gas puffing and a good wall condition are the key issues to keep smooth transition of plasma current. Our modeling results show that the current reversal equilibrium configuration with two oppositely flowing current in the high-field-side and low-field-side during current reversal. This is agreed with experimental measurements.

Key word: Current drive, D retention, Plasma control, quasi-steady state operation, recycling.

1. Intoduction:

Alternating current (AC) operation of a tokamak reactor is an attractive scenario to generate a continues output of electric energy without need the 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. Comparing with non-inductive current drive operation, AC discharges are technically simpler and have higher cost efficiency.

AC operation was first demonstrated on STOR-1M tokamak with plasma current 4kA [1]. Plasma properties when plasma current across zero and some key technologies have been introduced in several papers [2-5]. JET has demonstrated a full cycle of AC operation with reactor relevent plasma current of 2MA but with dwell time between two half cycles from 50ms to 6s, which means the ionization was lost when plasma current across zero [6]. Multi-cycles AC operations with small plasma current have been tested in a few tokamaks. CSTN-AC obtained 20s duration, 2ms flat top, a repetition of 10ms, and plasma current 0.5kA with finite dwell times [7]. ISTTOK achieved multi-cycle alternating square wave plasma with seven half-cycles; no dwell time and plasma current 4-5kA [8]. Constant AC discharges with 2, 4 and 8 sinusoidal cycles of 4kA were obtained on CT-6B tokamak [9-10]. Due to the toroidal field duration limit, most of the AC operation was 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 lose the ionization during plasma current across zero (without dwell time). This paper presents the efforts for this object from HT-7 superconducting tokamak. After introduction, the experimental set-up and main results will be presented in section 2. Plasma property when plasma current across zero is introduced in section 3. Discussion and conclusion are followed in section 4 and section 5.

2. Experimental Setup and Main Results

HT-7 superconducting tokamak normally operated with I_p = 100-200 KA, B_T = 2 T, a = 27 cm, line-averaged density ne = 1-5×10^{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 was consisting of a multi-junction grill (4×12), 1.2MW wave system with the frequency of 2.45GHz. Efforts have been made for the steady state operation and many good results have been obtained [10]. The longest plasma duration was over 300s by LHCD. Due to old HT-7 PF power supply only can provide one direction current and voltage, it is not possible for AC operation before 2005. EAST PF power supply has been used for HT-7 tokamak since 2005 experiments. The EAST PF power supply consists 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 210MVA. The key issues in the design of the AC/DC conversion system are low cost, high availability and reliability. Two sets of the EAST PF power supplies were used since 2005. The two thyristor sets and two diode sets permit bi-directional current and voltage, which set a good base for AC operation in HT-7 tokamak.

By suing ohmic discharge only, it was difficult to obtained AC operation without dwell time due to the limitation of PF power supply ramping rate. With the assistant of LHCD of power threathod 250kW, AC operation can be easily obtained with a dwell time from 5-20ms. By precise control plasma position, suitable gas fueling when plasma current across zero under a boronized wall condition, the dwell time can be eliminated to zero. A finite plasma density from 0.1-0.4x$10^{19}$$m^{-3}$ was kept when plasma current across zero. Optical signals showed the ionization has been maintained.

Long pulse AC operation has been obtained on HT-7 superconducting tokamak with plasma parameters: Ip=125kA, line average density 1.5x$10^{19}$$m^{-3}$, electron temperature Te= 500eV. More than 10 cycles can be easily obtained. Plasma was normally terminated due to iron core saturation foe a duration beyond 10 seconds. 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 during flat-top of plasma current. Plasma parameters were controlled by a pre-programmed manner when plasma current across zero within ± 50ms with a strong gas puffing. By precisely control the plasma position, gas fueling rate, and lower hybrid wave power and its deposition position, plasma current can be easily transit from positive to negative direction and vise verse. When the dynamic real-time feed back control of the magnetic flux, the steady-state AC operation with pre-set 30-50 seconds duration can be obtained. The plasma sustainment through the plasma current zero without lose the ionization was demonstrated under steady-state condition. Fig.1 shows a typical steady-state AC operation with a preset 35s duration in HT-7 superconducting tokamak. The waveforms from top to bottom in figure 1 are plasma current, loop voltage, magnetic flux, line average density, LHCD power, soft x-ray radiation, Hα signal and CIII radiation. Plasma performance showed a stable behavior during 35 seconds.

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 the hydrogen retention. Figure 2 shows the plasma density, Ha radiation, total fueling gas, H/(H+D) ratio, recycling coefficient which shows edge recycling for a 30 second AC operation shot. After 10 seconds, plasma wall interaction indicated by Ha, edge recycling and plasma density reached a steady state condition.

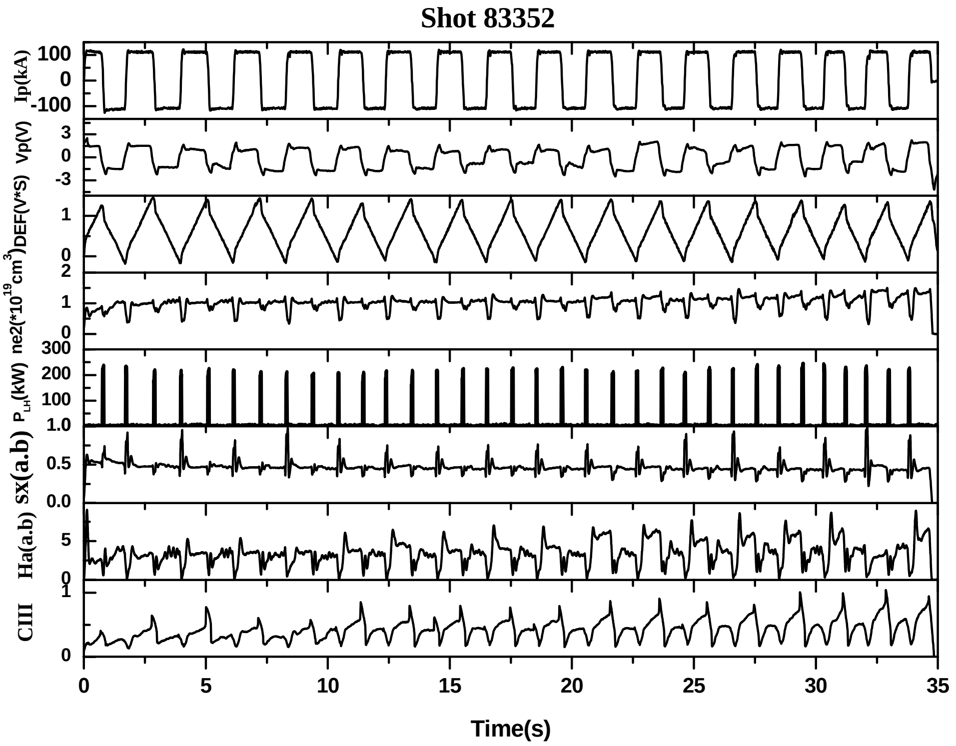

Fig. 1 A typical shot of AC operation.

By using feedback control, plasma parameters kept the same for positive and negative plasma current phases. As showed in Fig.3, plasma current Ip = 125kA, central line average density ne =1.5x10^{19}m^{-3}, electron temperature Te = 480eV, Hα, OII, CIII and other radiation were kept same for positive and negative plasma current polarities. Fig.4 is the time evolution of density profile during the two flat-top phases. After short drop of density with finite density when plasma current

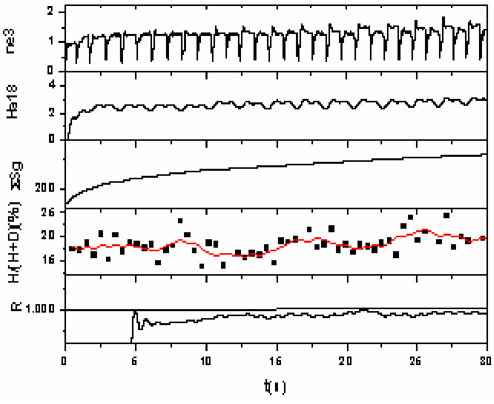

Fig.2 Density and recycling during AC operation

across zero, density increased to the flat-top with feedback control. This demonstrated that it could be used for future large tokamak reactor operation when both polarities could provide the same plasma parameters which will produce same fusion energy output.

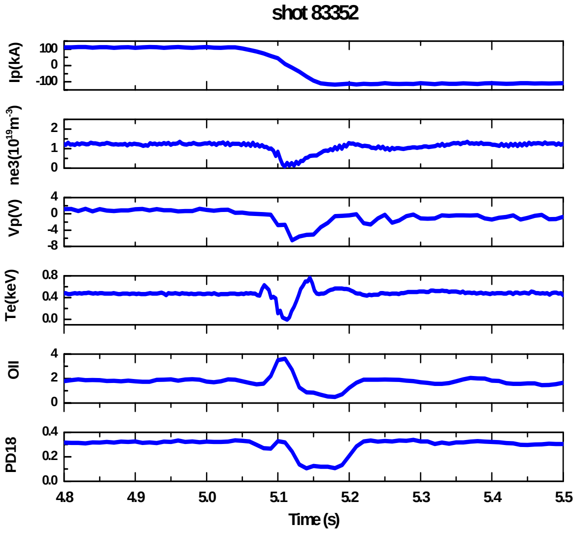

Fig.3 Plasma property at both polarities.

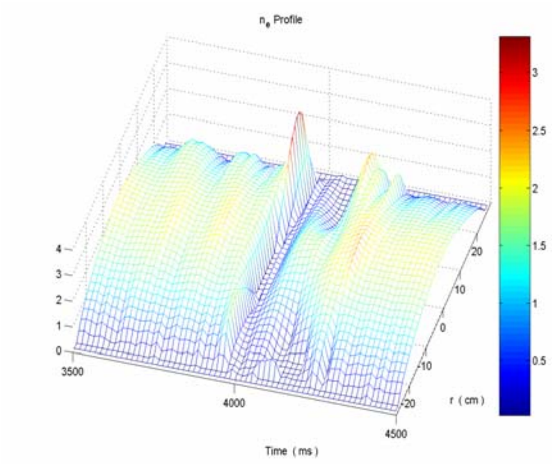

Fig.4 Temporal evolution of density profile

3. Plasma property when plasma current across zero

It is very important to know the plasma property when plasma current across zeros zero. As mentioned in previous section, plasma kept a finite density when current was zero. Plasma ionization was fully maintained by LHCD. If we carefully compare the zero current plasma properties between plasma current transition from positive to negative and from negative to positive phase, we can find some difference. Fig.5a is the main plasma properties from negative current to positive one. Fig.5b is the main plasma properties from positive current to negative one. During the whole discharge, central line average plasma density at zero current from negative to positive phase is about 0.5-1.2x$10^{18}$$m^{-3}$, density form negative to positive one is about 2.9-3.5x$10^{18}$$m^{-3}$. The radiations from H$\alpha$, OII, CIII and ECE signal from negative to positive current phase showed less ionization and lower parameters than those from positive to negative one shown in Fig.5b. Due to the limitation of very low temperature measurement by ECE (when Te<20eV, it can not be detected correctly), it is difficult to judge which temperature is higher. But the duration of zero ECE signal at Fig.5a is about 18ms and the duration in Fig.5b is about 12ms.

Density profile and its temporal trace showed different behavior. Fig.6a is the density profile from negative to positive phase, which was measured by multi-channel HCN interferometer. 30ms before zero current, the loop voltage starts reversal. Following a fast current ramp down, plasma quickly move towards outside. Density profile starts hollow. At time of zero current, central density was almost zero and there were two density peaks in low and high field sides. After about 100ms, density profile became normal parabolic shape. Fig.6b is the density profile temporal evolution from positive to negative phase transition.

Similar behavior happens. The difference is that it took only less than 50ms; density profile became normal parabolic shape.

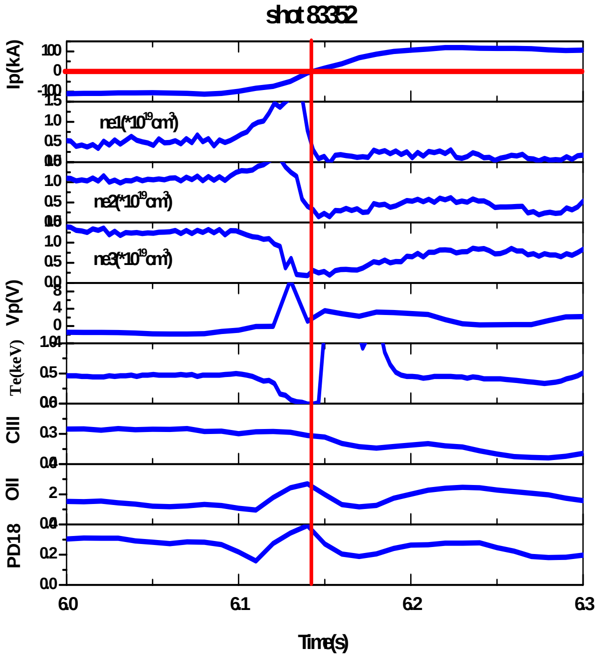

Fig.5a Plasma properties at zero current from negative to positive phase.

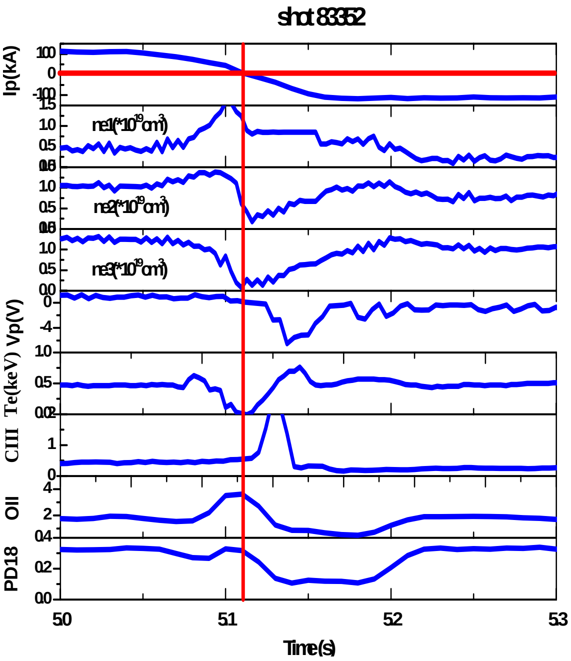

Fig.5b Plasma properties at zero current from positive to negative phase.

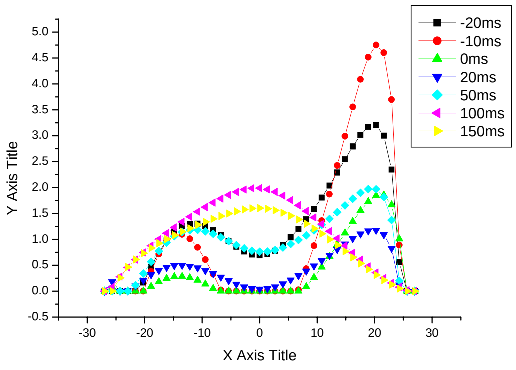

Fig.6a Density profile when plasma current from negative to positive phase.

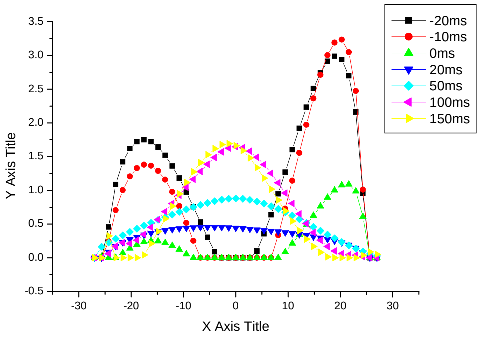

Fig.6b Density profile when plasma current from positive to negative phase

4. Discussion

It is important to know what kinds of plasma equilibrium configuration exist when plasma current across zero. What are plasma density, current and temperature profiles with zero current? A very good experiment in CT-6M tokamak was done for measuring plasma current density profile [10]. By using two internal magnetic probes, the plasma current distribution was reconstructed. Results showed that two plasma current components flow in opposite directions when the net current vanished. A few theoretic work also been carried out recently by solving Grad-Shafranov-Helmholtz equation for the equilibrium configurations with central current density reversal [12-14].

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

Our modeling results are shown as Fig.7 by using Grad-Shafranov-Helmholtz equation to try understanding the current reversal equilibrium configuration (CREC). The plasma parameters in Fig.5 were been used. At flat-top, Ip=125kA, central line average density 1.5x10^{13}m^{-3}, Te=500eV, loop voltage Vp=1.5V. At zero current time, Vp=6V, density 1.0x10^{18}m^{-3}, electron temperature is about 15eV which is estimated. Fig.7 shows that there is a current reversal equilibrium configuration with two oppositely flowing current in the high-field-side and low-field-side (HL-CREC). In this figure, the open triangles stand for the normalized plasma pressure, the open circles stand for the normalized toroidal current.

In producing the results in the figure, we have set $I_n(1)=0$, $\beta_V=2.0\text{x}10^{-6}$, $a_2=4.19\text{x}10^{-2}$(I_n, β_V, a_2 as described in ref. [14]), as the input values according to the AC operation experiment in the HT-7 tokamak experiment (Ip =0, Vp =6V, Te=15eV, ne =1x10^{18}m^{-3}.), and the output values show that the two components of toroidal current in the high-field-side and low-field-side are both about 50A (Inout =2.6x10^{-2} and Inin =-2.6x10^{-2}), the maximum value of the plasma current density is about -319kA/m^2 (jphie-max =-5.7x10^{-2}).

Both negative and positive currents on the low-field-side and high-field-side exist with about a current of 50A. Similar results were obtained in CT-6B tokamak. Since ECE measurement can't provide accurate measurement during zero current time, we just assume it has similar profile as density shown in Fig.6 and plasma pressure profile will be same as shown in Fig.7. Simulation results show that the CREC exists and it is agreeable with experimental observation.

Here we assume that the plasma current reversal is mainly due to the ohmic system, and didn't take the role of LHCD, just using ohmic part since for co-driven and counter-driven by LHCD are different and very complicated for solving Grad-Shafranov-Helmholtz equation. Due to the ionization assistant of LHW, the loop voltage at zero current time is relatively small (6V with LHCD), plasma current of 57A is very small compared with other machine [10]. Efforts will be made to add LHCD current profile into modeling to give more reasonable results.

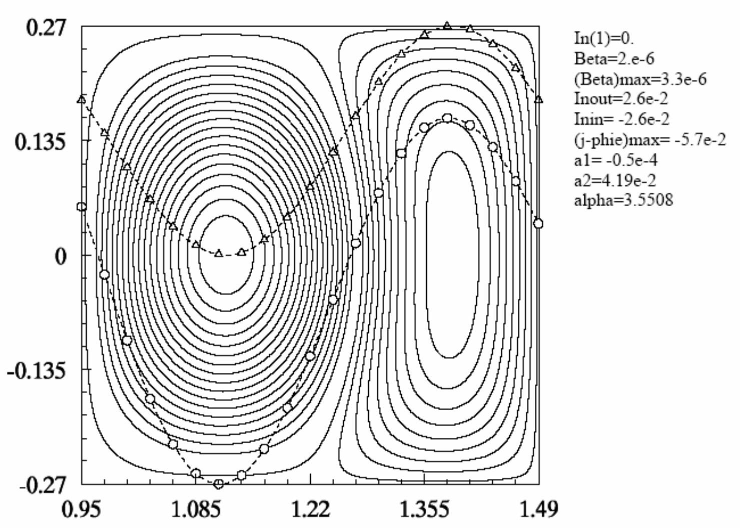

Fig.7 Magnetic flux surfaces, normalized current and normalized pressure.

As theory predicted [12], 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, the transition time from negative to positive current can not be very quick (3MA/s current ramping rate is maximum). Higher target plasma electron temperature would be favorable for a limited transition time since it has longer current diffusion time. The role of LHCD in co-driven and anti-driven directions when plasma current across zero is different. When plasma current changes from negative to positive direction, LHW provide a current driven mode and has little effect for plasma heating. While the current changes from positive to negative phase, LHW provides anti-driven mode and can effectively heat target plasma, which provide better condition for a smooth transition of plasma current polarity. Fig.5 showed the advantage for anti-driven condition. Shorter transition time (50ms back to normal flat-top condition) for anti-driven is favorable for future reactor use since future large superconducting tokamak, such as ITER, has lower current ramping rate. This suggests that a good wave heating system (ECRH for example) is favorable for assistant current reversal.

Compared with plasma discharges driven by LHCD with similar plasma parameters in HT-7 tokamak, wall heat load of AC operation is very low due to more uniform heat load on plasma facing components. Plasma discharges driven by LHCD can be sustained up to 15 seconds and terminated with high heat load on PFC. Wall temperature measurement over 1500^{o}C has been measured and hot spots have been observed for normal LHW driven plasma discharges. During 30s AC operation, the wall temperature kept under 200 ^{o}C and no hot spots have been observed. Plasma discharges were terminated by lost control of plasma density at the end of discharges in long pulse AC discharges.

As mentioned in section 2, for a good current reversal, strong gas puffing is required. During AC discharge, about ±50ms before zero current, gas puffing is not carried out by density feedback control. It was a fixed strong gas puffing rate, which means a lot of gas was puffed at this period. Particle balance calculation showed that a large a mount of gas was retended on the wall. When the AC discharge continues, the fueling gas kept retended on the wall until the wall was saturated. Eventually, out-gasing from 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 30s to 50s, but it is very difficult to obtained longer discharge. Further efforts are needed to solve this problem by carefully control the gas puffing during current reversal phase.

5. Conclusion

A steady-state alternating current (AC) operation assisted by lower hybrid wave has been achieved on HT-7 superconducting tokamak with plasma current Ip=125kA, line average density 1.5x10^{19}m^{-3}, electron temperature Te= 500eV and 30-50 seconds plasma duration. Plasma discharge was sustained and smoothly transfers from one direction to the other without lose of ionization.

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

The precise control of plasma position, enough LHCD power and proper gas fueling during plasma current across 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 steady state AC operation was easier to be realized.

Our modeling results is shown that the current reversal equilibrium configuration with two oppositely flowing current in the high-field-side and low-field-side (HL-CREC) exits during current reversal period, which is partially demonstrated by density measurement in experiments. Further efforts are required for improve modeling and hydrogen retention.

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