Runaway electron behaviors on AC operation of the HT-7 tokamak

H. W. Lu, L. Q. Hu, S.Y. Lin, S.F. Wang, G.Q. Zhong, K.Y. Chen, P. Xu, Y.M. Duan, J.Z. Zhang, S.T. Mao, and HT-7 team

Institute of Plasma Physics, China Academy of Sciences, Hefei 230030, P.R. China

E-mail of corresponding author: luhw@ipp.ac.cn

Abstract

Operation of the HT-7 tokamak in a multicycle alternating square wave plasma current regime is reported. A set of carefully performed AC operation experiments, including LH heating to help plasma ionization during the current transition and current sustainment, is described. The particle confinement time of the positive current plasma is observed to be lower than that of the negative current plasma. High energy runaway electrons (~MeV) are found to circulate predominantly in opposite direction to the plasma current, while the number of low energy runaway electrons (~ tens to hundreds keV) circulating along the plasma current and opposite to it are more comparable. AC operation with LHCD is observed to have the additional benefit of suppressing the runaway electrons if the drop of the loop voltage is large enough.

Keywords: runaway electron, alternating current (AC), LHCD, loop voltage

1. Introduction

Alternating current (AC) 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. Thus AC operation will be a very important mode of operation for a next-step device such as the International Thermonuclear Experimental Reactor (ITER) and commercial tokamak reactors [1].

A quasi-steady-state multicycle alternating flat-top plasma current operation was achieved successfully with more than one minute on the HT-7 superconducting tokamak with a plasma current I_p=100kA, line-averaged density of $n_e = 1.25\times10^{19}m^{-3}$ ($0.1\text{-}0.4\times10^{19}m^{-3}$ at the time of current transition), electron temperature T_e=500eV, by the careful control of the configuration, intensified gas puffing, upgraded PF power supply system and the lower hybrid wave (LHW) assistance [2].

2. Experimental set-up

Hefei Tokamak-7 (HT-7) which was rebuilt from the original Russian T-7 tokamak in 1994 is a medium-sized tokamak with superconducting toroidal coils and water-cooled graphite limiters, constructed to achieve high-performance long pulse plasma discharges and to study relevant physics. The machine runs normally with plasma current I_p=100-225kA, the toroidal magnetic field B_T=1.5-2T, the central line-averaged plasma density n_e =(1-6)×$10^{19}m^{-3}$, major radius R=122cm, minor radius a=27cm, central electron temperature T_e=0.5-3.0keV, central ion temperature T_i =0.2-1.5keV, with circular cross section [3]. The plasma current, position and central line-averaged electron density were feedback controlled during discharges. A stainless-steel liner was installed in the vacuum chamber at the radius of 0.32m [4, 5].

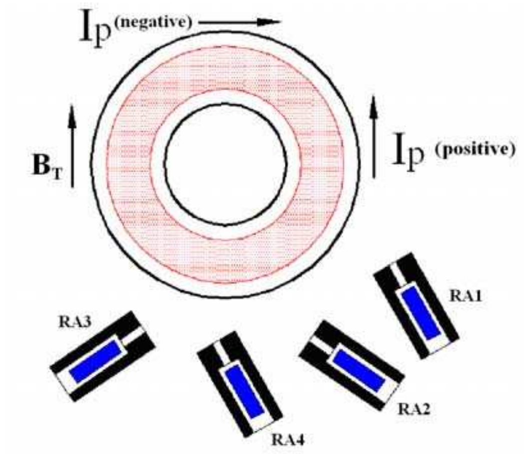


Fig.1 Schematic view of runaway electron diagnostics (down view); RA1(CdTe); RA2(CdTe); RA3(NaI); RA4(NaI)

The two NaI(TL) scintillator detectors are used to monitor the high-energy hard X-ray radiation in the energy ranges of 0.3-7MeV， and two CdTe detectors (hemispherical, with volume of $65mm^3$) are used to monitor the low-energy hard X-ray in the energy range of 0.3-1.2 MeV as shown in Fig. 1.

3. AC discharge with LHCD at the time of current transition.

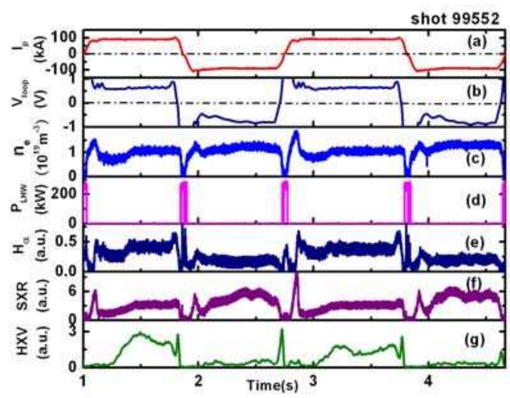


Fig.2 Typical AC discharge (shot No.99552)

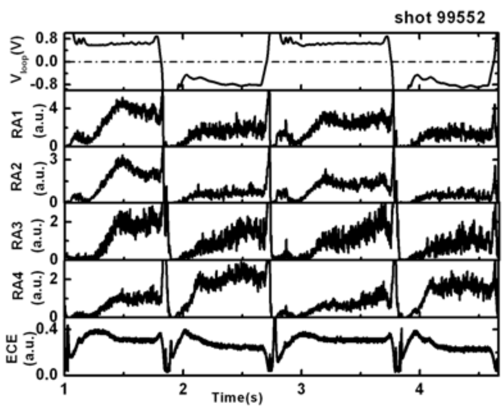


Fig.3 The trace of emission signal in shot No.99552.

We can see from Fig. 2 that H_α line emission is higher during the positive phase than that of the negative phase with a factor of 2 (from 0.4 to 0.2 in arbitrary unit). These observations, taking into the slight changes in the line average density between both current phases (Fig.2), suggest that the particle confinement of the positive plasma (τ_p~17 ms) is lower than that of the negative current plasma (τ_p~31 ms).

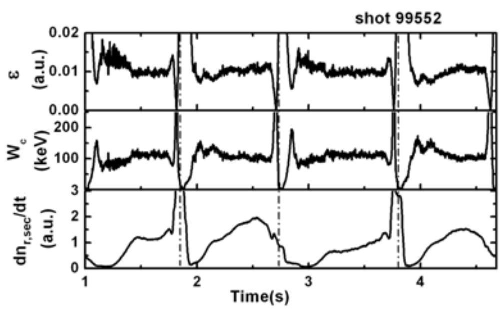
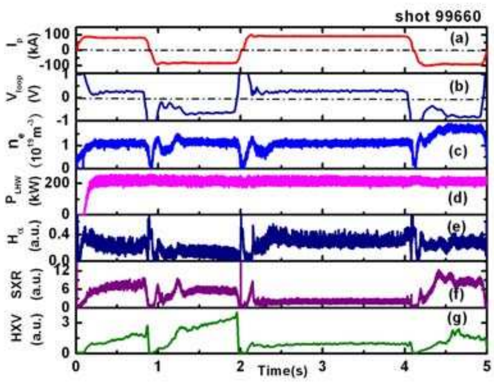


Fig.4 The trace of calculated critical energy for runaway generation $\boldsymbol{W_c(t)}$, the parameter $\varepsilon(t)$.

We can also see from Fig.3 that high energy (~MeV) runaway electrons are mostly circulating in opposite direction to the plasma current. This is consistent with the fact that high energy runaway electrons are basically collisionless and. hence, essentially accelerated by the electric field in opposite direction to the current. However, the intensity of low energy hard x-ray emission, both in RA1 and RA3 detectors, shows a similar time behavior, the emission being larger during the positive current phase, suggesting that a more comparable number of low energy (~tens to hundreds keV) runaway electrons are flowing along the plasma current and opposite to it.

As is shown in Fig.4, the runaway Dreicer generation process plays a more important part in the current ramp-up phase, while the avalanche process (the creation of runaways through close collisions of already existing runaways with thermal electrons) plays an important role during the current flat-top phase.

4. AC discharges with LHCD during the current flat-top



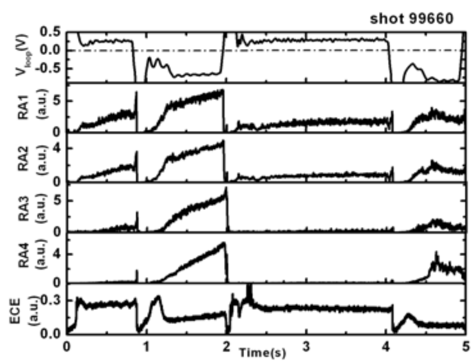


Fig.5 Typical AC discharge (shot No.99660) with LHCD

Fig.6 The trace of emission signal in shot No.99660.

In AC plasmas, besides to help plasma ionization during the current transition and current sustainment, AC operation with LHCD could have the additional benefit of suppressing the runaway electrons if the drop of the loop voltage is large enough.

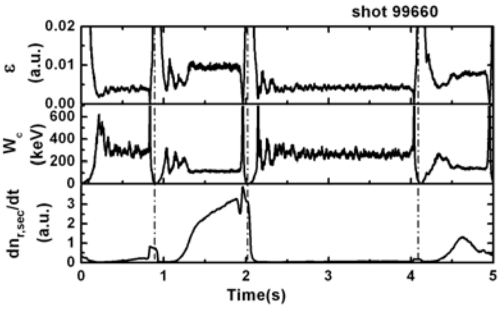


Fig.7 The trace of calculated critical energy for runaway generation $\boldsymbol{W_c(t)}$, the parameter $\varepsilon(t)$

From the Fig. 7 we can see that the runaway avalanche generation yield during the positive phase was also lower than that during the negative phase because of the lower loop voltage in the positive phase than in the negative phase. And the avalanche production rate was very high only at 1.3s-2s. During the negative current phase, due to the higher electric field, the runaway electron production as well as the energy of the generated runaway electrons increase, and the resulting emission measured by the hard X-ray detectors (RA1-RA4) is substantially larger.

5. Conclusions

In conclusion, in all the experiments, H_a line emission is observed to be higher during the positive current phase than that of the negative current phase, no matter whether there was LH wave injection or not, suggesting that the particle confinement time of positive current plasma is lower than that of negative current plasma. Runaway Dreicer generation process plays an important role during the current ramp-up of every current phase, while the avalanche generation process seems to play a role during the current flat-top. AC operation with LHCD, besides helping plasma ionization during the current transition and current sustainment, shows the benefit of suppressing the high energy runaway electrons during the current drive phases if the drop of the loop voltage is large enough.

Acknowledgements

This work has been supported by the National Nature Science Foundation of China, No.10675124 and No. 10775041.

References

[1] Mitarai O, et al, 1993 Plasma Phys. Control. Fusion. **35** 711.

[2] Gao W, et al, 2008 Plasma Phys. Control. Fusion **50** 115003

[3] Baonian W, et al, 2003 Phys. Plasma **11** 2543

[4] Gao X, et al, 2008 Plasma Phys. Control. Fusion **50** 035006

[5] Kuang G L, et al, 1999 Nucl. Fusion **39** 1769