Low Loop Voltage Startup in the HT-7 Tokamak with Ion Cyclotron Range of Frequency and Lower Hybrid Waves

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Abstract: The low voltage startup plasma has been studied in the HT-7 (R=1.22m,a=0.27m) tokamak with Ion Cyclotron Range of Frequency (ICRF) wave and Lower Hybrid Wave (LHW) for pre-ionization. Successful low loop voltage startup experiment results had been obtained with ICRF (about 150KW) and LHW (about 200KW) , for example, $E \approx 0.5V/m$ (with), $E \approx 2.5V/m$ (without). The ICRF and LHW assisted startup experiments on HT-7 have been successful in showing the positive effect on plasma pre-ionization and target plasma formation; reduction of the volt-second consumption during the period of the breakdown and the ramp-up; reduction of the loop voltage in the breakdown; and setting of a beneficial ramp-up rate for the whole the superconducting tokamak.

1. Introduction

Low loop voltage tokamak start-up is a very important feature for reactor scale fusion devices, especially for the superconducting tokamak. For example the HT-7U tokamak (the next superconducting tokamak in China, scheduled for operation at the end of 2003) [1], the inductive electric field at startup is limited to the value of $E \approx 0.5V/m$. In this paper it is shown that to perform startup reliably at such a low electric field, non-inductive pre-ionization and target plasma production are desirable. Earlier experiments typically resulted in smaller reduction of the overall flux consumption during the current rise phase with ECH pre-ionization [2]. With the exception of the experiments on ISX-B [3], and possibly those on WT-1 [4], there was little attempt to conduct systematic scaling experiments that might permit extrapolation to large devices. The DIII-D experiment showed that Electron Cyclotron Heating (ECH) assisted startup offers many advantages, particularly in terms of improved reliability and on extended range of pre-fill pressure and stray magnetic field over which operation is possible[5]. The same experiment was set up on TEXTOR-94 in 1996, the ICRF was used. The experiments on TEXTOR-94 pointed to a positive effect on plasma pre-ionization and target plasma formation by the period on current start-up with ICRF, for example, reduction of the poloidal magnetic flux (volt-second) consumption; achievement of a low rate on the current ramp-up at low loop voltage stage. The sensitivity of RF start-up on various parameters was investigated and the reproducibility was improved [6].

An alternative to plasma production by ECH is the use of the ICRF and LHW in the HT-7 tokamak. Like ECH pre-ionization, the methods are based on RF energy absorption by electrons in the presence of a toroidal magnetic field. Plasma production with ICRF power coupling using conventional double-loop screened and screenless antennas has been successfully achieved in the tokamak TEXTOR-94 [6]. Such results have been also achieved in the HT-7 with ICRF and LHW. The ICRF power is about 150kW and the LHW power 200kW, which assisted startup with $E \approx 0.5V/m$ (without ICRF and LHW, $E \approx 2.5V/m$), and the breakdown loop voltage drops from 25V(without) to 4.0V(with). The ICRF and LHW assisted startup allows reliable plasma formation and current ionization with low electric fields and leads to reduced runaway production during the breakdown phase. Unlike low loop voltage startup with ECH, in this case, it is generally required to control more carefully the gas pressure and the stray fields produced by the OH transformer itself and by the image currents flowing through the vessel. The experimental results are discussed in this paper.

2. Experimental Configuration

2.1 HT-7 tokamak

HT-7 is a midsize (Ro=1.22m,a=0.28m) iron-core superconducting tokamak. The OH coil consists of a solenoid and outer dispersed turns designed to guide the return flux outside of the plasma region. The decoupling of the vertical field and the iron-core OH coil allows accurate plasma position control at any OH coil current. The vacuum vessel is designed as a continuous resistive shell, with a total toroidal resistance of $0.4 m\Omega$. For the experiments described here the working gas is deuterium and the ICRF cleaning discharge conditioning is employed, which ensures reproducible, low impurity plasma production [7].

2.2. ICRF system[8]

The ICRF system is composed of the following subsystems: generator; transmission line; impedance matching network; antenna and feed-through; RF-assisted vacuum carbonization system and RF leakage detection system. The range of the frequency is 15-30MHz; the maximum pulse width is about 60 s with a repetition rate of one pulse every 10 min. and the maximum output power is about 300kW. In this experiment the power is about 150kW, the frequency is about 30MHz and the loop antenna is used. It is positioned at the low magnetic field side (LFS) of the tokamak, and is at the minor radius location r = 0.285 m; it is optimized for heating and not for plasma production. Because it is hard to switch the impedance matching point from vacuum to plasma loading in real time, the impedance matching point for startup is chosen for vacuum.

2.3. LHW System[9]

The LHW system is composed of the following main subsystems: low power RF exciter module with phase and amplitude control for the 12 klystrons; High Power Klystron Amplifiers (HPKA); circulators and connected wave-guide transmission lines; grill coupler (the arrays of 2×12 sub-wave-guides); High Voltage Power Supplies (HVPS); wave monitoring and phase feedback control; system protections and water-cooling system. The frequency is 2.45GHz; the maximum pulse width is about 10s and the maximum output power is about 1.2MW. The 12 klystron amplifiers in the LHCD system are fed by 2 high voltage power supplies and driven by one RF exciter module. Their waves are launched to HT-7 plasmas by one grill coupler. The $N_{//}$ spectrum is feedback controlled to a preset value from $N_{//} = 0$ to $N_{//} = 4.4$. In this experiment the value of the $N_{//}$ changes from $N_{//} = 0$ (before the discharge) to $N_{//} = 3.0$, and the power is about 200kW.

2.4. Experimental Setup

The current ramp-up scenario employed in the experiments described here is illustrated in Fig.1. The pulse of the pre-gas-injection is programmed in order to produce the plasma, then the ICRF power is turned on for the pre-ionization, just after which the LHW power is turned on ($N_{//}$ is controlled to zero) to augment the pre-ionization effects. When the plasma starts the ramp-up stage, the feedback control for the plasma density begins to work, and the feedback control for the plasma current and position system begins to work after a delay time. In general the high loop voltage is helpful for startup of the plasma, but there are two effects contradicting this idea: (1) A large electric field implies a large consumption of the flux capacity of the transformer core. Since the capacity is limited, the consumption in the breakdown phase influences the maximum duration of the ohmic plasma current. (2) A large electric field may also cause a runaway discharge. Besides this, in the whole superconducting tokamak case, the character of the poloidal field coils, which are made by the superconductor, limits the plasma current ramp-up rate. After 1990 low loop voltage startup scenarios became popular topics for large tokamaks especially for superconducting tokamaks. In DIII-D (R=1.67m,a=0.42m) importanr results were obtained by ohmic startup with $E \approx 0.25V/m$ and $E \approx 0.15V/m$ with the ECH [5]. In TEXTOR-94 (R=1.75m,a=0.46m) successful low loop voltage startup was achieved with $E \approx 0.5V/m$ using the ICRF system [6].

There are strong error fields in the HT-7 superconducting tokamak. An error field is the effect of misalignment of the toroidal magnetic field coils and of eddy currents in the vacuum vessel and in the supporting structure. In order to reduce the error fields in the plasma area, compensation coils are setup to compensate for the error field in the HT-7 tokamak, which is of benefit for the breakdown period. In fact, it is very hard to compensate for the fields completely in the HT-7 tokamak. In the experiments the average of the error fields is about $|B_{error}| \leq 50\ G$. A large variety of techniques exist to decrease Zeff in HT-7. Baking the vessel, glow cleaning discharge, boronization, siliconization and ICRF cleaning discharge are the techniques used to free adsorbed gas from the vacuum vessel. Reference [7] gives a descriptions of these techniques.

3. Experimental Results

The experiments demonstrate that the ICRF and LHW pre-ionization allows reliable plasma formation and current initiation with low electric fields. Figure 2 shows a waveform of a typical shot with low loop voltage startup with the ICRF and LHW assistance. The $N_{//}$ spectrum of the LHW is switched form $N_{//} = 0$ to $N_{//} = 3.0$ just after the breakdown in order to enhance the current driver effects. The constant preset current ramp rate is maintained (typically $dI_p/dt \sim 0.15\ MA/s$ for the experiments) until the final flattop value of $I_p \sim 0.1MA$ is reached at a time $t \sim 700\ ms$. This rate of the ramp-up is an important parameter for the superconducting tokamak; for example, the rate is limited by the engineering design of the HT-7U tokamak. Typical values at the transition, for OH startup ($V_p = 20V$), are $I_p \geq 0.15\ MA$ and $t \sim 200\ ms$. In general, the loop voltage is about $\sim 20V$ for ohmic startup in HT-7, and the electric field at R = 1.22 m is about $\sim 2.5V/m$. However, when the loop voltage drops to $\sim 10V$, the delay time for breakdown increases for decreasing E. Table I show some results for the experiment. If the loop voltage decreases to less then 10V, breakdown with ohmic only is difficult.

With ICRF and LHW assistance, low voltage startup is significantly improved. The helpful pre-ionization allows prompt and reliable startup with voltages as low as 4.0V ($E \sim 0.5V/m$). The effect of reducing the loop voltage progressively from 20 V to 6.0 V with the assistance of ICRF is illustrated in Fig.3. The electron density could be easily maintained at a low level without generation of runaways. An attempt to delay the density ramp-up without the use of ICRF leads to excessive runaway production because of the higher electric field. Here the ICRF power is about 150 kW, and the toroidal magnetic field (at $R = R_0$) is about 1.8T. In this case, the breakdown is extremely prompt, as shown by the H_α emission, and there is only a little delay. The line average density n_e typically reaches

$\sim 3-5\times 10^{18}\,m^{-3}$ during the ionization phase with a slow ramp-up rate. Such a rate and density are helpful to control the plasma density. The figure also shows that the volt-second consumption is reduced by 20%-50% during the period of the breakdown and the ramp-up. An important concern in the startup study is plasma formation during the initial phase of the discharge (before starting to set on the plasma position control). Analysis of the line-averaged density profiles, from the 5-channel HCN-interferometer, indicates that during pure ohmic start-up, the plasma formation occurs initially at low major radius, where the inductive electric field is highest. With ICRF pre-ionization, plasma formation is clearly more central with additional broadening of the profile to the LFS (antenna location); however, this does not lead to any reduction in radiated power, as takes place with ECH pre-ionization [5].

Table I. The relationship between the delay time and the toroidal electric field

Loop Voltage (V)	Electric Field (V/m)	Delay Time (ms)
24	3.0	1
18	2.3	2
15	1.9	6
13	1.6	9
10	1.3	13

Figure 4 gives an example of the results with LHW assistance. During ECH assisted startup, the prompt breakdown and density rise in advance of the current rise prevent runaway generation, and no significant hard X-ray emission is observed [6], but unlike the ECR assistance, in the LHW assistance case, the hard X ray emission is strong in the pure OH case. This problem may come from the LHW, since after the breakdown the super-thermal electronics production from low hybrid current driven effect. However, when the LHW is turned off, the hard X ray emission is still strong, the experimental phenomenon is not clear. The pre-fill pressure is another important feature for low voltage startup with ICRF and LHW. The experimental results shows that, unlike the ECR case, the pressure is increasing, and the breakdown delay time is decreasing.

4. Summary

Initial startup experiments on HT-7 point to a positive effect on plasma pre-ionization with ICRF and LHW assistance. As in the case of ECH assistance, a reduction in volt-second consumption is observed when ICRF is applied in the low loop voltage case, which leads to reduce runaway generation. With LHW assistance a low ramp-up rate for the plasma current is obtained, typically $dI_p/dt \sim 0.15\,MA/s$ in the experiments. Adjusting the pre-fill and error field is necessary for these experiments, and successful ICRF (150kW) and LHW (200kW) assisted startup with $E \approx 0.5V/m$ is achieved in the HT-7 superconducting tokamak. Further experiments are necessary to investigate the sensitivity of the various parameters, also to improve techniques in order to try operating startup with no poroidal field on the superconducting tokamak.

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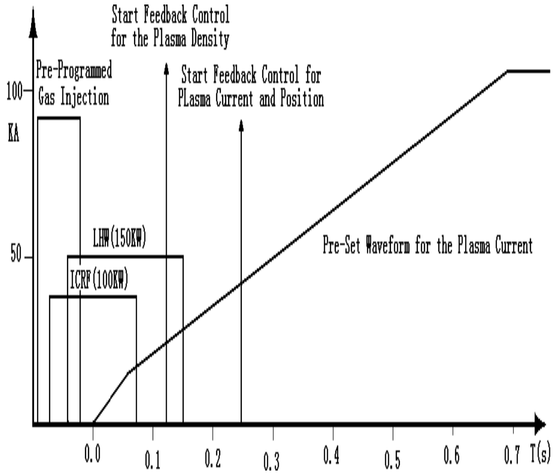

Fig 1. Time sequence for the experiment.

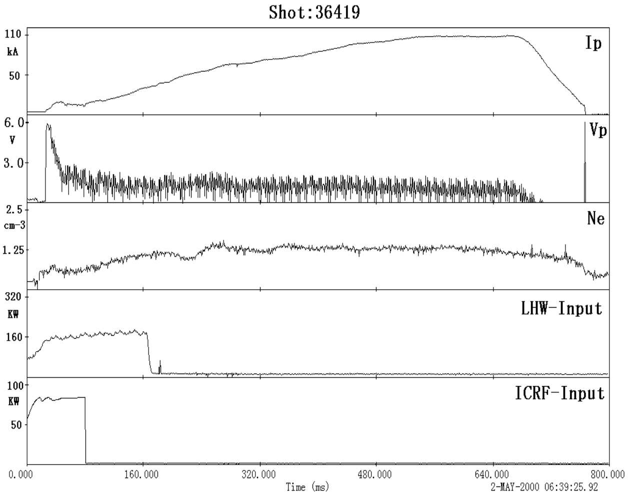

Fig. 2 Typical shot waveform with the low loop voltage with ICRF and LHW assistance.

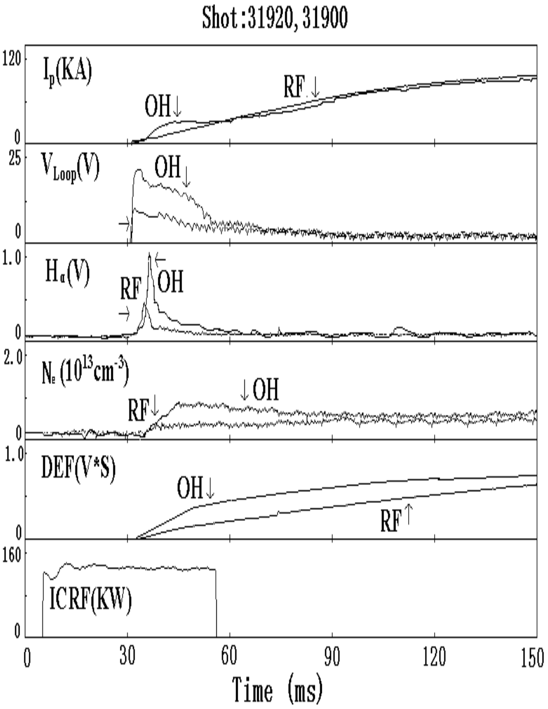

Fig. 3 Typical shot waveform with the low loop voltage with ICRF assistance.

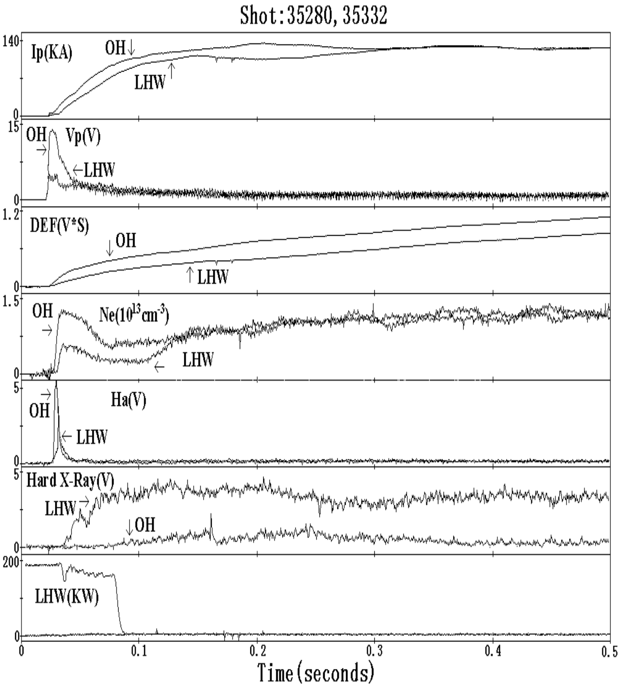

Fig. 4 Typical shot waveform with the low loop voltage with LHW assistance.