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LONG PULSE DISCHARGES SUSTAINED BY SECOND HARMONIC ELECTRON CYCLOTRON HEATING USING A 35GHz GYROTRON IN THE ADVANCED TOROIDAL FACILITY

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ABSTRACT

A second harmonic electron cyclotron heating (ECH) discharge was sustained for ~ 20 s in the Advanced Toroidal Facility (ATF) at relatively weak magnetic field of B = 0.63 T. The high electron temperature (T_{eo} ~ 700 eV), helium plasmas were produced with ECH power of P = 100-200 kW from a 35 GHz gyrotron. The line-averaged electron density, $\bar{n}_e$, and stored plasma energy, W_{dia}, were 2.3×10^{18} m^{-3} and 300-500 J, respectively. The stored energy follows closely the gyro-reduced Bohm confinement scaling law. The maximum discharge duration was limited by ECH pulse duration but not by plasma collapse. Diagnostic signals showed attainment of a quasi-stationary plasma and no impurity build-up was indicated by soft x-ray and VUV spectroscopic signals.

Keywords : helical device, ATF device, steady-state plasma, ECH plasma, gyrotron

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I. Introduction

Long pulse containment of high-temperature plasmas is a key issue for developing toroidal fusion reactors. Sustainment of fusion plasmas for more than several hundred seconds is planned in the next generation helical device, LHD and tokamaks, such as ITER and NET. In tokamaks, plasma current plays a crucial role for confinement and must be driven by non-inductive driving methods which are yet to be developed. A long pulse discharge of 70 min ($\bar{n}_e$ = $2x10^{18}$ m^{-3}, T_{eo} = 600 eV) was realized in TRIAM-1M superconducting tokamak[1] by using lower hybrid current drive at B = 5 T. Development of efficient current drive in higher density regime is a key issue for future tokamak programs.

In Heliotron/stellarator system, however, equilibrium of plasma is provided by external coil currents. This is an advantage for steady-state fusion reactors. The LHD device is equipped with a superconducting coil system and helical divertor so that steady-state operation is proposed as one of important research programs[2]. A second harmonic ECH discharge with 20 s pulse duration was previously obtained in the Advanced Toroidal Facility (ATF).[3] At that time, the discharge ($\bar{n}_e$ = $4x10^{18}$ m^{-3}, T_{eo} ~ 1 keV) was sustained using 53.2GHz gyrotron with power of ~ 100 kW at B = 0.95 T. Although the helical coils of ATF are designed to withstand steady-state operation at B = 1 T, a helical coil accident in 1991 prohibited a long pulse operation at B = 1 T. In this report, we describe an experiment in which we extended discharge pulse at lower magnetic field of 0.63 T. A 35 GHz gyrotron was used to heat the plasmas with the second harmonic electron cyclotron resonance heating.

2. Experimental procedure

The ATF is a Heliotron/Torsatron type toroidal magnetic confinement device with major and average minor radii of R = 2.1 m and a_p = 0.27 m, respectively. The helical field has poloidal and toroidal field periods of l = 2 and M = 12. At the time of this experiment, the maximum flat-top time of the confining field was limited to 25 s at B = 0.63 T due to inability of cooling of a helical coil joint. A 35GHz gyrotron was used for this experiment which generates ECH power of $\leq$ 200 kW. Some microwave components were manufactured in Japan for this long pulse experiment. A 10-degree water-cooled waveguide bend was used to connect the wave guide from the 35 GHz gyrotron to one of the original transmission lines for 53.2 GHz gyrotrons. Ninety-degree Miter bends and Vlasov launchers were also prepared. Helium was chosen as working gas because of easier electron density control. The electron density could be kept constant during the discharge by piezo electric valves and feedback control electronic circuit.

3. Experimental results

Duration of ECH pulse was extended through repeated short-pulse (0.1-0.3 s) conditioning. During this conditioning phase of the gyrotron, confinement properties of the plasmas were studied by comparing them with predictions by the gyro-reduced Bohm scaling law. The electron density was varied from 1×10^{18} m^{-3} to 6×10^{18} m^{-3} and stored energy, W_{dia}, changed from 200 J to 600 J depending on the density. Figure 1 shows measured stored energy, W_{dia} as a function of W_p(gyro-Bohm) expected from the gyro-reduced Bohm scaling. The data of 53.2 GHz experiment are also plotted in the figure. We can see values of W_{dia} follow closely those predicted by the gyro-reduced Bohm scaling including B dependence.

The ECH pulse could be extended to 6 s after ~ 80 conditioning discharges. Figure 2 shows temporal behavior of a 6-s discharge in this phase. The gyrotron power, P_{ECH} indicates fairly large variation during the shot. However, this signal is very sensitive to oscillating condition of the gyrotron so that the real power is considered to be more steady than the signal indicates. The electron density is kept almost constant with the gas puffing at $\bar{n}_e$ = 2.3×10^{18} m^{-3} (1/3 of the cut-off density) except for the initial period for ~ 0.5 s. The density profile measured by the multi-chord FIR interferometer shows that it is almost unchanged during the discharge. The input gas flow rate, ϕ is 0.4 torr.l s^{-1} and nearly constant at $t \geq 0.5$ s. This flow rate corresponds to a rather small particle input of ~ 1×10^{19} s^{-1}. Thus, recycling coefficient of this helium plasma is fairly close to 1. The signal of H_α indicates that hydrogens which were used in earlier experiments are still present in the wall. The stored energy is also nearly constant at ~ 500 J. The electron temperature profile was derived from Thomson scattering measurement. Although the accuracy was not so good, the central electron temperature was estimated to be ~ 700 eV at t = 1.5 s. This value is consistent with that of W_{dia}. The magnetic diffusion time in the plasma (= $\mu_0 \sigma a_p^2$, σ : conductivity) is estimated to be ~ 0.5 s. Therefore, the discharge was maintained for the time much longer than the resistive time scale. In this experiment, we confined the plasmas with almost the same pressure as those in TRIAM-1M at much weaker magnetic field intensity. The central beta value is 0.54 % which is ~ 80 times of that in TRIAM-IM.

The central-chord soft x-ray signal shows again quasi-stationary time behavior, implying no sign of impurity accumulation. Figure 3 shows spectroscopic data of VUV line intensities for both oxygen (O VII, wavelength : 162.3 nm) and iron (Fe XVI, 36 nm), indicating again no sign of impurity accumulation during the discharge.

After further conditioning of the gyrotron, we could extend the discharge duration to 20.2 s which is the record discharge duration in ATF. As shown in Fig.4, this discharge was interrupted by a momentary turn-off of the gyrotron power at t = 19.7 s. The gyrotron resumed oscillations from t = 19.9 s to t = 20.2 s, but the plasma was too cold to reheat itself. The stored energy, W_{dia} is a somewhat smaller than that in the 6-s discharge, but temporal behavior of the plasma is basically the same. No sign of impurity accumulation is observed in this shot. It is noted that in Heliotron E, impurity transport was anomalous in the ECH plasmas but a sign of accumulation was observed in the NBI plasmas[4].

Temperature rise of the vacuum vessel was monitored by the thermocouples attached to atmospheric side. It showed linear increase with time during the discharge and no saturation. The maximum temperature rise was 2 ^{o}C at the inboard side of the torus where ATF magnetic surface is closest to the wall.

In conclusion, we could sustain the hot electron plasmas for ~ 20 s at relatively weak magnetic field of 0.63 T. Further extension of discharge pulse would be possible if aging of the gyrotron was continued and longer flat-top time of the magnetic field was obtained. From this experiment, we could gain confidence for future steady-state containment of plasma operation in ATF.

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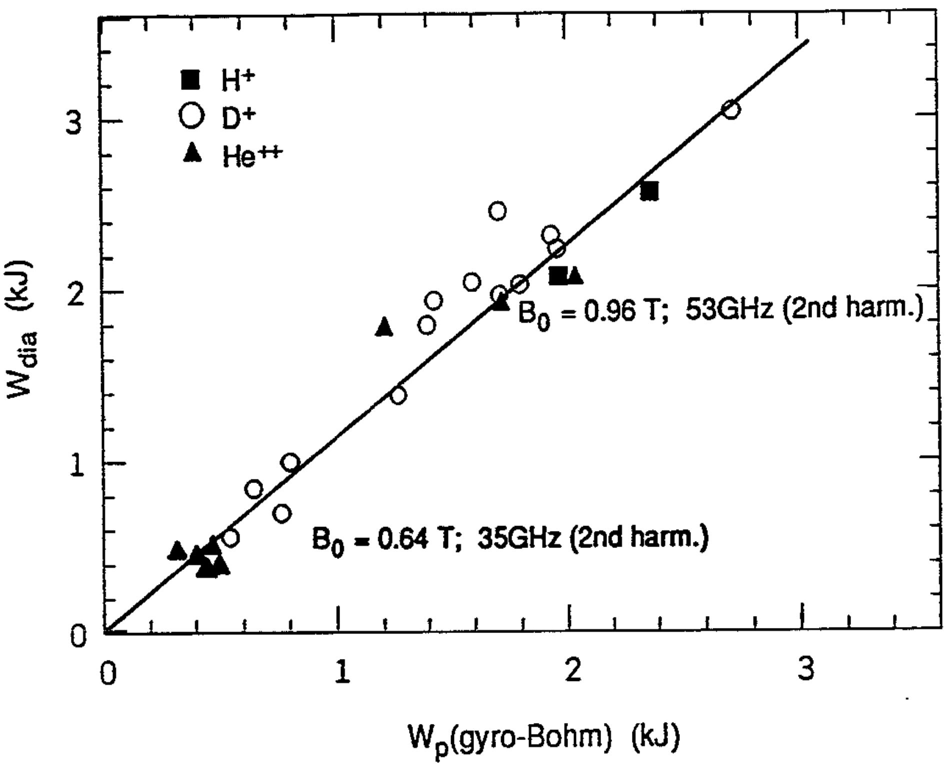

$$\tau_E(GrB) = 1 \times 10^{-9}\, n^{0.60}\, B^{0.80}\, P^{-0.60}\, R^{0.60}\, a^{2.4}\, \kappa\, A_i^{-0.2}$$

Fig. 1 Stored plasma energy, W_{dia} versus the gyro-reduced Bohm scaling prediction, W_p(gyro-Bohm).

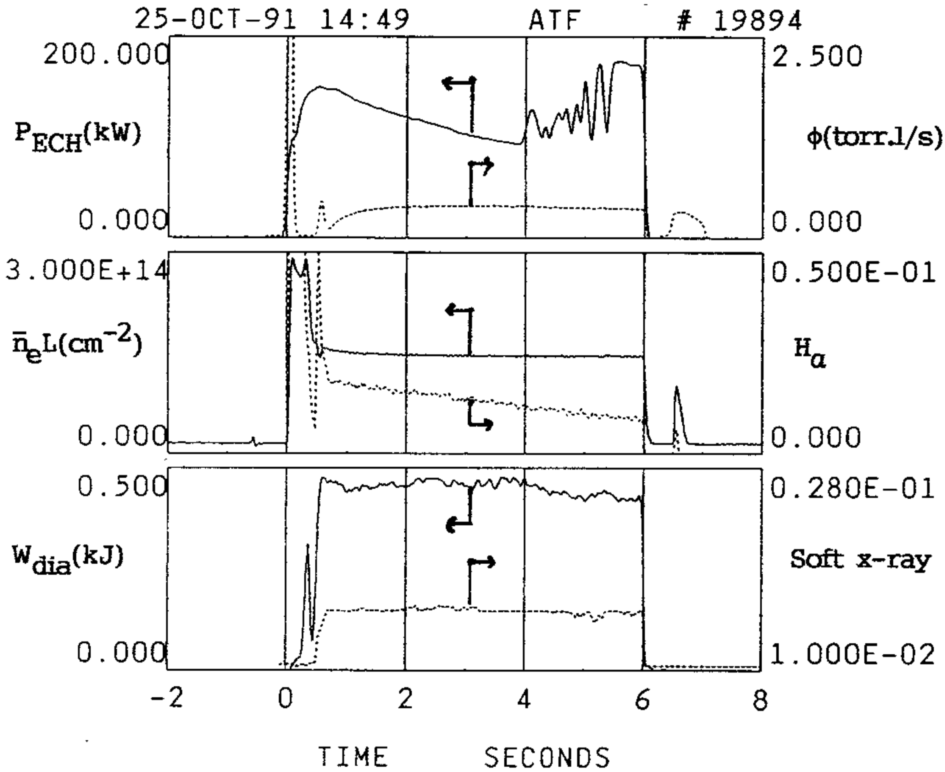

Fig.2 Temporal behavior of the 6-s discharge. The average electron density in the quasistationary phase is $2.3x10^{18}m^{-3}$.

(a)

(b)

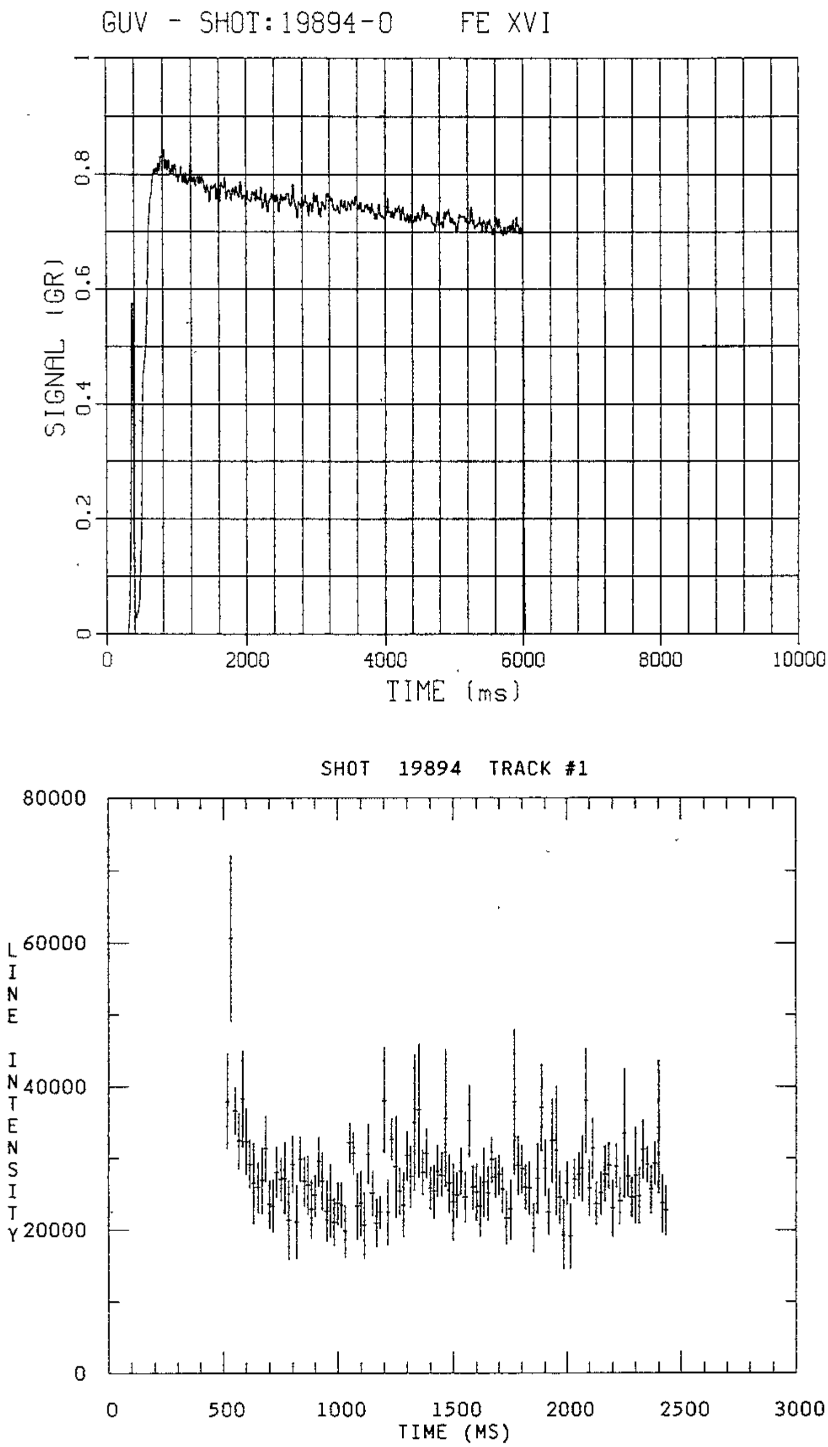

Fig. 3 Spectral line intensities (arbitrary units) in the 6-s discharge. (a) Fe XVI, 36 nm and (b) O VII, 162.3 nm.

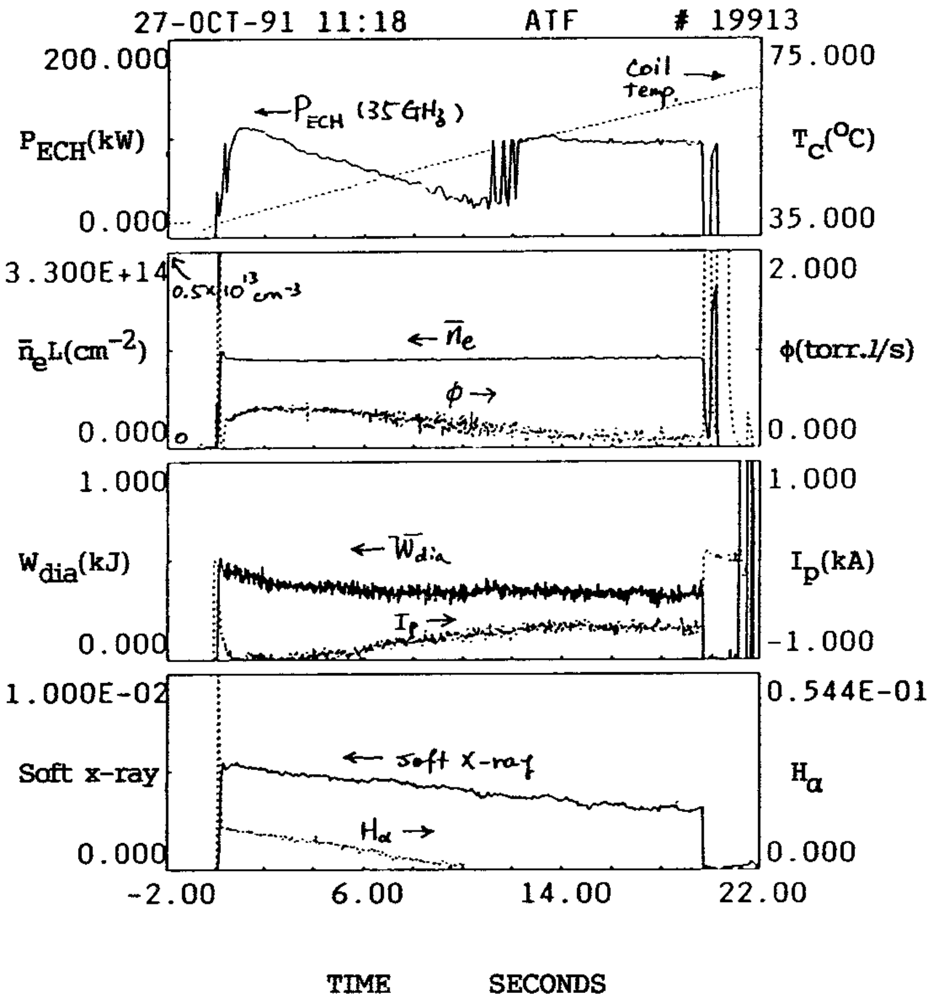

Fig. 4 Temporal behavior of the 20-s discharge. T_c is temperature of a helical coil joint.

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