Non-inductive plasma start-up and sustainment by wave heating at two frequencies in the TST-2 Spherical Tokamak

Osamu Watanabe, Takuya Oosako, Akira Ejiri, Yoshihiko Nagashima, Hiroki Kurashina, Takashi Yamaguchi, Yuuki Adachi, Hiroshi Tojo, Kotaro Yamada, Yuichi Takase, Hazuki Matsuzawa, Hiroaki Kobayashi, An Bung Il[1)], Hiroyuki Hayashi, Makoto Sasaki[1)] and Tetsuya Masuda

Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa 277-8561, Japan
[1)] *Graduate School of Science, The University of Tokyo, Kashiwa 277-8568, Japan*

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Non-inductive plasma start-up and sustainment experiments were performed in the TST-2 spherical tokamak (ST) device by injecting waves at 21 MHz (RF) and 2.45 GHz (EC). The fundamental electron cyclotron resonance layer exists in the vacuum vessel, and the EC heating (ECH) can generate and sustain the ST plasma. When the RF power was injected to the EC plasma, with a short overlapping of both powers, a current jump was induced and the current was sustained. The RF heating can sustain the plasma current at a lower magnetic field than the field necessary for the ECH-sustained plasma. Contrary to the EC sustainment, the RF sustainment requires fine adjustments of the RF injection timing and the vertical field strength. The plasma current disappears quickly, when the RF injection is too late or the vertical field is too weak. When the RF injection is too early or the vertical field is too strong, the plasma current decreases after the end of the ECH pulse.

Keywords: Non-inductive start-up, RF heating, RF sustainment, TST-2, current jump

1. Introduction

Non-inductive plasma start-up and sustainment using wave heating have been studied in several spherical tokamak (ST) devices[1–3]. If tokamak configurations are generated and sustained by the wave heating alone, the central Ohmic solenoid can be eliminated, leading to a more compact and economical reactor. Waves such as electron cyclotron wave, electron Bernstein Wave (EBW) , and high harmonic fast wave (HHFW) are used in ST experiments. Although the ECH start-up scenario has been studied in many ST devices, the current drive and current jump mechanisms are not clearly understood. In order to clarify the role of EC current drive (ECCD) and EBW current drive (EBWCD), it is quite important to compare experiments with EC and with non-EC wave injections. Experimental features of HHFW in a very low density plasma are not well understood. According to the dispersion relation, the wave can propagate toward the core when the injected $k_{\parallel}$ is as low as 3 m^{-1}. High energy electrons with the energy of order 1 keV must be presented to absorb this wave. In addition, the heating is not a strong function of the toroidal magnetic field strength. Due to the insensitivity on the field strength and the availability of high power, establishment of non-inductive start-up using a lower frequency wave is important.

In TST-2, ECH start-up experiments were performed, and various features, including the condition for the current jump and the current sustainment, were revealed [3]. Recently, we found that a current jump was induced and the plasma current was sustained by RF power alone, and it is confirmed that the deuterium plasma has a lower power threshold for RF sustainment than the hydrogen plasma [4], but other conditions have not been identified.

In this paper the characteristic of RF sustainment is examined. The operational conditions for a successful current sustainment were obtained.

2. Experimental setup and typical waveforms

Typical start-up operation requires a stationary toroidal field, a stationary vertical field with appropriate curvature, and heating power. In TST-2 experiments, the vertical field is generated by the poloidal field coils PF1 and PF2 shown in Fig. 1. In practice, the coil current has a sawtooth waveform, but the vertical field inside the vacuum vessel is almost constant due to the finite penetration time through the vessel. Deuterium gas is injected into the vacuum vessel before each discharge.

The TST-2 device is equipped with an ECH source (2.45 GHz/ 5 kW) and an RF source (21 MHz/ 400 kW). The RF antenna has two current straps, but only one strap is used in this experiment. The process of the toloidal plasma formation was observed by a

author's e-mail: rwata@fusion.k.u-tokyo.ac.jp

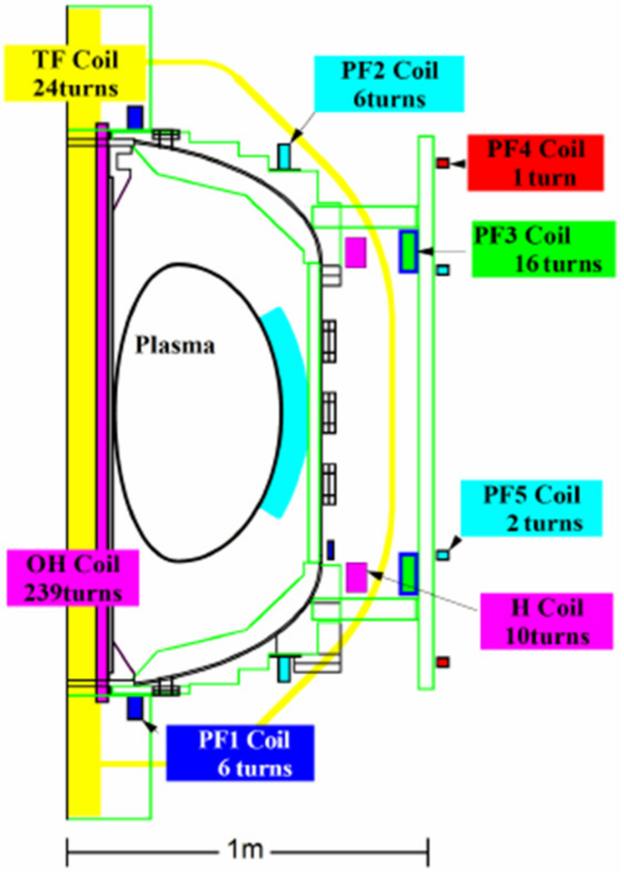

Fig. 1 Cross section of TST-2 and poloidal coils. In this experiment, the vertical field is generated by the PF1 and PF2 coils connected in series. Only PF1, PF2 and TF coils were used. In the discharge shown in Fig. 6, the PF1 coil was operated with 9 turns.

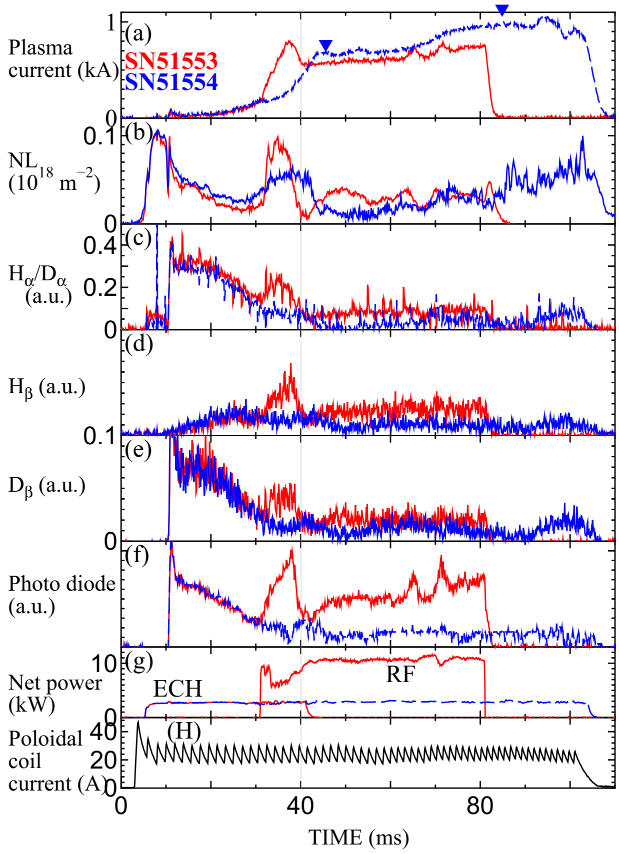

Fig. 2 Discharge waveforms of RF-sustained (red solid line, SN51553) and ECH-sustained (blue dashed line, SN51554) plasmas; (a) the plasma current, (b) the line density (R=0.28 m), (c) the H_α and D_α emission, (d) H_β emission, (e) D_β emission, (f) total light emission, (g) ECH and RF net injection powers, and (h) the poloidal field coil current.

high-speed CCD camera.

Figure 2 shows waveforms of two typical discharges: one with ECH alone (blue), and the other with ECH and RF (red). In the latter discharge, the heating powers were switched from EC to RF with a short overlapping period. According to the measurement of antenna loading, the typical radiated RF power was 30% of the net (incident minus reflected) power shown in the figure. Triangles in (a) indicate the timings of additional gas puffs of deuterium to the ECH-sustained plasma. The line density was measured by interferometers (104 or 140 GHz) at the major radii of R=0.28, 0.39 m. H_β and D_β were measured by a spectrometer, and the intensities are calculated by summing up the corresponding wavelength channels. A photo diode measures H_α and D_α through an interference filter, and these lines are not resolved. The total light intensity is measured by a different photo diode (AXUV, IRD Inc.). In addition, a high speed CCD camera recorded the visible image of the plasma.

In the ECH-sustained discharge (blue curves), it is thought that the current jump phase is finished by forming closed magnetic surfaces at 44 ms. The emission region (observed in the CCD camera image) shrank toward the equatorial plane by 44 ms and was almost steady afterwards. In the RF-sustained discharge (blue curves), it is thought that the current jump phase is started by the RF injection, and finished by forming closed magnetic surfaces at 40 ms. The start of current jump became earlier due to the additional RF heating. After the current jump phase, the shape of the CCD camera image hardly changed. The emission intensities (H_α, D_α, H_β, D_β and total light) of the ECH-sustained plasma are weaker than those of the RF-sustained plasma. The rapid increases in the emissions and the line integrated density just after the RF injection were accompanied by the shrinking of the plasma. After the current jump, the total light intensity of the RF-sustained plasma is about three times of the ECH-sustained plasma. It should be noted that the H_β emission increased during the RF injection, implying hydrogen release from the RF antenna or vessel wall. In addition, neutral copper line appears during the RF injection. These results imply that the RF power enhances the plasma wall interaction. Note that copper is the plating material of the RF antenna.

3. Condition of current jump and RF sustainment

The condition necessary for RF sustainment is surveyed. The difference due to the RF injection timing is shown in Fig. 3. The optimum RF injection timing for the RF sustainment is located in a short period before the EC current jump. When the start of RF heating is too early, the plasma current disappears after the ECH pulse is stopped (blue). The discharge is terminated by the RF when the start of the RF is too late (red). Although the input power to the RF amplifier was the same, the resultant net power depends on the plasma loading. Thus, the incident power is not the same for these discharges.

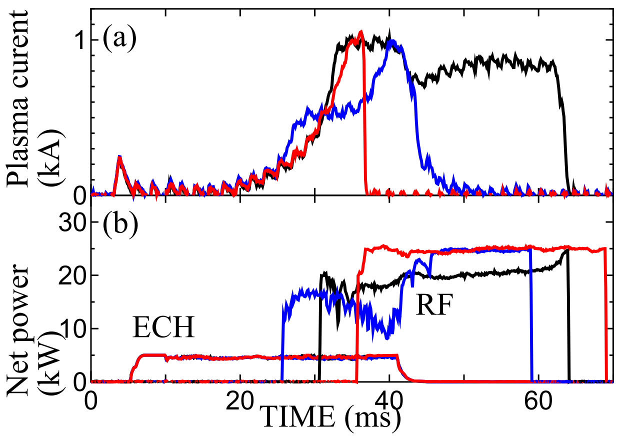

Fig. 3 Three discharges with different RF injection timing; (a) the plasma current and (b) the net injection powers.

The effect of the vertical field strength is shown in Fig. 4. When the vertical field is too weak, the current disappears quickly when the RF power is injected (red). To complete the current jump phase and achieve current sustainment, a strong magnetic field requires a strong heating. However, when the magnetic field is too strong, the current jump is delayed (blue).

Figure 5 shows the effect of the toroidal field strength in ECH-sustained plasmas. In these discharges the toroidal field coil circuit was modified to make a decaying waveform. Figure 5(c) shows the trajectories in the plane of R_{ECH}-plasma current. Here, the major radius of the ECH resonance layer is proportional to the toroidal magnetic field. The current sustainment by ECH alone is terminated when the resonance layer becomes close to the inboard limiter (R=0.13 m). The current jump becomes steeper with the decrease in the magnetic field as long as $R_{ECH} > 0.3$ m. Figure 6 shows the RF sustainment discharges with decaying toroidal field strength. In contrast to the ECH-sustained discharges, the current can be sustained at much lower toroidal field strengths. Note that in this case, the discharge is terminated by the decrease in the vertical field.

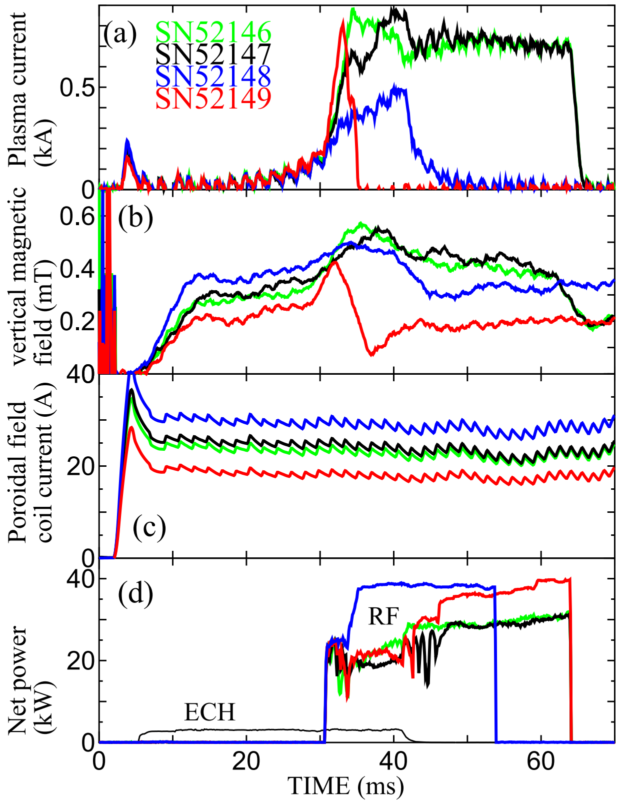

Fig. 4 Four discharges with different vertical field strengths; (a) the plasma current, (b) the outboard vertical field, (c) the poloidal coil current and (d) the net injection power.

4. Discussion and conclusions

Non-inductive plasma start-up and sustainment experiments by wave heatings at two frequencies in the TST-2 Spherical Tokamak were carried out. The RF heating can sustain the plasma current when the plasma and a small plasma current is generated by the ECH. The conditions for the RF sustainment were surveyed. It was found that appropriate RF injection timing and vertical field strength exist for successful sustainment of the current. The operational window was rather narrow compared with the condition for EC sustainment reported in Ref. [3]

The RF sustainment was achieved at a very low toroidal field, which is less than half for EC (2.45 GHz) sustainment. While this insensitivity to the magnetic field is consistent with the wave accessibility, the rea-

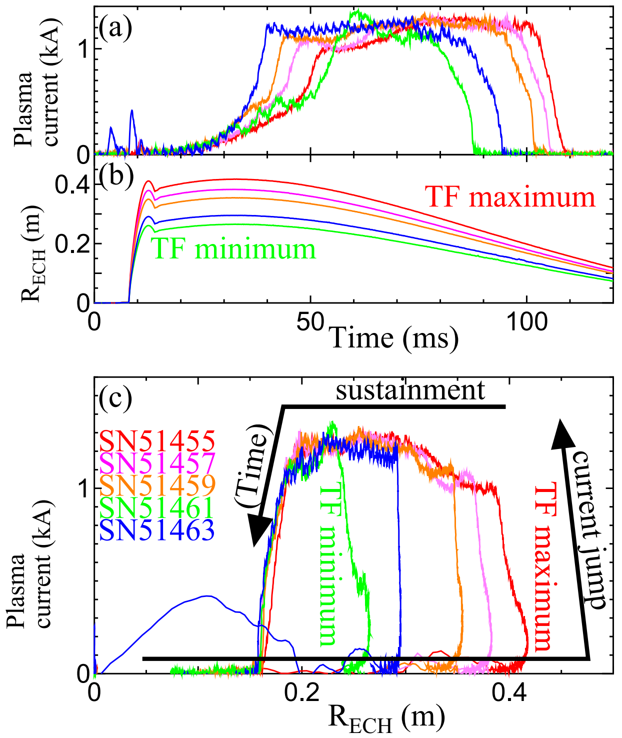

Fig. 5 Five different discharges with different toroidal field strengths; (a) the plasma current, (b) major radius of the ECH resonance layer and (c) time evolution of the plasma current and the major radius of the ECH resonance layer.

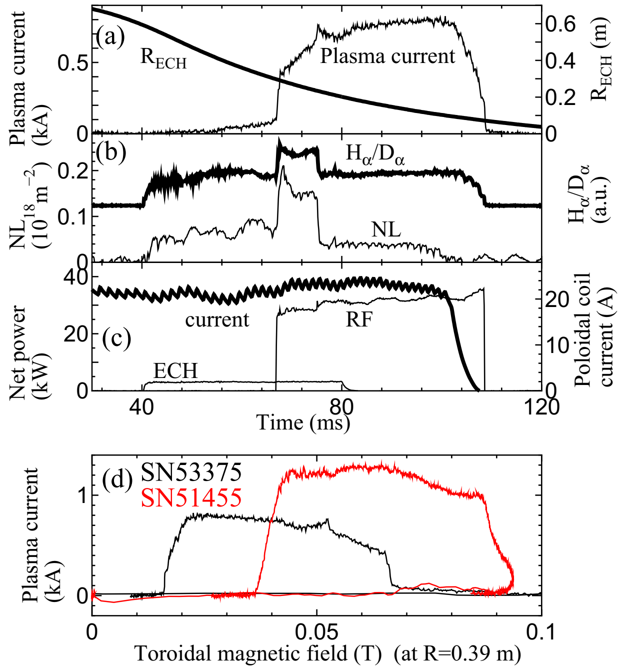

Fig. 6 Discharge waveforms for an RF-sustained plasma with decaying; (a) the plasma current and radius of the EC resonance layer, (b) the line density and H_α and D_α (R=0.39 m/140 GHz), (c) the net powers of the ECH and RF and the poloidal coil current, (d) the discharge trajectory in the toroidal field ($\propto R_{ECH}$) - plasma current plane. The trajectory for ECH-sustained plasma (red) is also shown.

sons for the narrow operational windows in the vertical field strength and in the RF injection timing are unknown.

The typical electron density in Ohmic plasmas are 1×10^{19} m^{-3}, and the HHFW can propagate and reach the core region. On the other hand, the density in non-inductive start-up plasmas is presently less than 1×10^{17} m^{-3} , and a substantial part of the injected RF power is expected to be reflected near the antenna. However, a low $k_\parallel$ component, which is minor in power, can propagate and heat high energy electrons. Soft X-ray energy spectrum with a slope of 70 eV was observed in high power experiments, suggesting electron heating. The magnetic field strength at the ECH resonance layer is 0.0875 T and at this field strength 21 MHz corresponds to the 30th harmonic of the deuterium ion cyclotron frequency. Therefore, ion cyclotron resonance heating is not expected with the RF wave, and the measured impurity ion temperatures were very low.

The result that a toroidal plasma can be sustained without the Ohmic solenoid is very important. Figure 3 shows that the increase of the vertical field lowers the ramp-up rate of the plasma current. Although the strong vertical field is necessary for high plasma current, the high plasma current will require enough RF heating power. The insensitivity on the field strength and steady state operation may lead to industrial applications of the RF-sustained plasma, as long as the mechanism of this RF current drive and the equilibrium with the lower toroidal field are understood.

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