Comparison of Hydrogen and Deuterium Plasmas in ECH Start-Up Experiment in the TST-2 Spherical Tokamak

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In the TST-2 spherical tokamak, non-inductive start-up experiment using electron cyclotron heating (ECH) at 2.45 GHz are performed. Hydrogen and deuterium discharges were compared after sufficient wall cleaning by Ohmic discharges to ensure discharge reproducibility. After the wall cleaning, wall recycling seemed to be reduced, because additional gas puffing was necessary to sustain a discharge. Even in that case, hydrogen emission measurement revealed the existence of finite wall recycling source. A current jump occurred earlier in the deuterium plasma than in the hydrogen plasma. Except for the timing of the jump, the discharge time evolution and various values such as the plasma current were almost the same for the deuterium and hydrogen plasmas.

Keywords: non-inductive start-up, ECH, current jump, wall discharge cleaning

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1. Introduction

A spherical tokamak reactor can confine high beta plasma, resulting in a lower magnetic field and an economical reactor. However, to keep the size compact, the central Ohmic solenoid should be removed, and a non-inductive start-up and heating scenario should be established. Among various non-inductive start-up methods, wave heating is a flexible method because various heating modes are available [1–3]. In the TST-2 spherical tokamak (ST), iit has been confirmed that a non-inductive start-up plasma can be sustained not only by electron cyclotron heating (ECH) (2.45 GHz) but also by RF (21 MHz) heating [3]. This paper compares deuterium and hydrogen discharges in ECH start-up experiments.

Although the ionization energy of deuterium (14.9 eV) is higher than that of hydrogen (13.6 eV), the threshold power for sustaining an ST configuration was found to be lower for deuterium than for hydrogen when we use RF (21 MHz) heating [3]. In general, we can expect a longer confinement time for deuterium due to the isotope (mass) effect. On the other hand, EC waves couple to electrons, and no difference in the heating efficiency is expected. Therefore, comparing hydrogen and deuterium discharges should provide important information on these issues.

The current jump and ST configuration formation are interesting phenomena that have been studied using visible camera images [3] and equilibrium analysis [4]. In addition, various parameter dependences of pre-jump plasmas have been studied [2]. However, the effects of particle confinement and neutrals, including wall recycling, have not been studied in detail. In this comparison experiment, the reproducibility of the time evolution of the plasma current, which depends on the gas pressure, must be confirmed. Since the gas is supplied both by puffing and wall recycling, sufficient wall cleaning is necessary. After cleaning, an identical plasma current evolution can be reproduced by the same operational conditions, even if we insert another type of discharge, such as Ohmic discharge, between these discharges. In an ECH start-up discharge, a tokamak configuration forms after a current jump. When the initial filling pressure or the pressure during a discharge is high, the current jump does not occur, and when the pressure is low, the tokamak configuration cannot be sustained for long [2]. To preserve the reproducibility, wall recycling must be stabilized.

In this paper, we analyze the time evolution of various quantities before a current jump in detail. In particular, we compare the time evolution of the plasma current in hydrogen and deuterium discharges. We also monitor the progress of wall cleaning by spectroscopy.

2. Experimental Setup

A tokamak plasma can be started up by ECH alone without Ohmic heating in the TST-2 spherical tokamak. The plasma current of the ECH start-up discharge [2–4]

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is two orders of magnitude lower than that of Ohmic discharge [5]. A magnetron is used to launch an EC wave from a port 0.25 m below the midplane. The incident and reflection power of the ECH are measured at the transmission line from the magnetron. Two spectrometers are used in this experiment. One covers a broad wavelength range (180-850 nm). Time-integrated emission from impurities, hydrogen, and deuterium are measured in each shot to monitor the degree of wall cleaning. The other, a high-resolution spectrometer, is used to measure H_β and D_β, and the ratio H_β/D_β is calculated to confirm the ratio of these species in the plasma.

Vertical fields are measured by pickup coils near the inboard limiter at $R = 0.12$ m and near the outer limiter $R = 0.677$ m, where R is the major radius. The filling pressure is measured by an ionization gauge with gas puffing alone. The gauge sensitivities for hydrogen and deuterium are different, and the differences are corrected. The ECH power and vertical field strength were kept constant during a discharge.

3. Reproducibility

In the TST-2, the ECH startup discharge, which has a density two orders of magnitude lower than that of Ohmic discharges, is more sensitive to the wall recycling gas. The wall can be cleaned more rapidly by Ohmic discharge than by the ECH start-up discharge, although the duration of the Ohmic discharge is an order of magnitude shorter than that of the ECH start-up discharge in TST-2.

Just after the start of vacuum pumping of the TST-2 vessel, the current jump timing becomes earlier shot by shot, as shown in Fig. 1 (a). The green curve represents the discharge in a first-day shot. The initial and final shots the next day are represented by the sky blue and blue curves, respectively. Although the operational sequences are the same, the timing of the current jump gradually became earlier and asymptotically approached the blue line in Fig. 1 (a). However, the discharge represented by the red curve was obtained after the Ohmic (wall cleaning) discharges. The filling pressure of this discharge was higher than that of the other discharges, and the plasma current was not sustained. In this case, further particle fueling was necessary to sustain the tokamak configuration, suggesting that wall recycling was reduced by the cleaning. After the appropriate Ohmic discharges, the plasma current waveform stabilized [Fig. 1 (b)]. We found that Ohmic discharge is better for wall cleaning than ECH start-up discharge. Further Ohmic discharge does not affect the time evolution and the wall recycling; as a result, we succeeded in cleaning the wall using Ohmic discharge.

Figure 2 shows the time-integrated visible emission measured by the spectrometer for ECH start-up discharges. Before the Ohmic discharge (blue curves in Fig. 2), the emission increased shot by shot. The emission in the older shots is plotted in front of that in the newer shots. After cleaning (red curves), the emission becames the same in all shots. In this case, the emission in the newer shots is plotted in front of that in the older shots. Note that on the red series day, we had to increase the filling pressure from 37 μtorr to 51 μtorr to sustain the discharges. The increase in filling pressure implies that recycling was reduced, and the low-impurity emissions imply that the wall was cleaned. After confirming the reproducibility of hy-

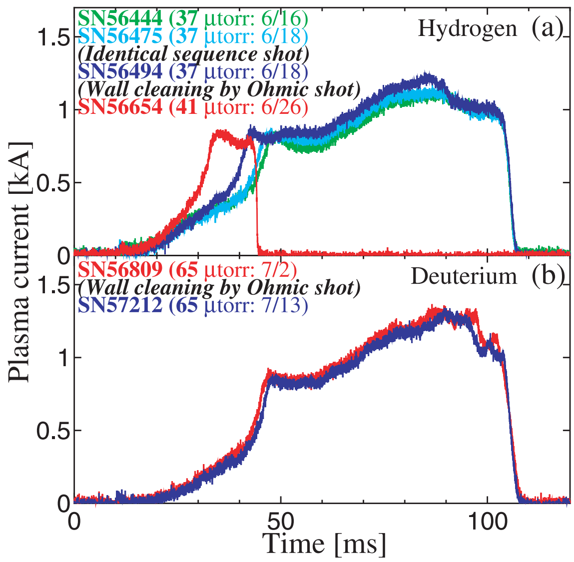

Fig. 1 Waveforms of plasma current after the start of vacuum pumping. (a) ECH start-up discharges before and after about 100 Ohmic discharges. (b) Similar sequence, but the effect of the Ohmic discharges is negligible.

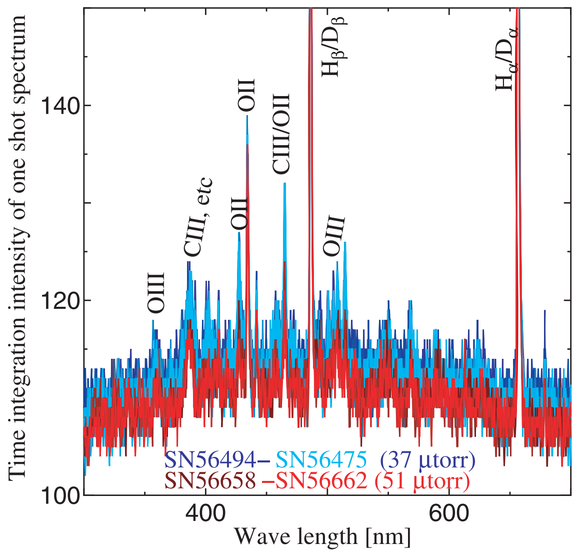

Fig. 2 Spectra of time-integrated visible emission. Before the Ohmic discharge, the oldest shot emission (sky blue) is weaker than that in newer shots (blue). Emissions after the Ohmic discharge (red) are identical and are weaker than those before cleaning. Note that the filling hydrogen pressure was higher after cleaning.

drogen ECH start-up discharges, we switched the working gas from hydrogen to deuterium and performed experiments with a similar operational sequence.

The emission of H_β and D_β are plotted in red and blue curves, respectively, in Figs. 3 (d) and (e). In the deuterium filling plasma [Fig. 3 (d)], the hydrogen emission from wall recycling approaches the level of the deuterium emission.

4. Comparison of Hydrogen and Deuterium

The current jump occurs earlier in deuterium plasma than that in hydrogen plasma (Fig. 3). The operational sequence was identical except for the gas species. The time evolution and the values such as the sustained plasma current are similar except that the timings of the current jumps differ. Note that the recycling gas is mainly hydrogen and is at a nonnegligible level compared to the puffed gas. These results (the transition of the current jump due to wall cleaning and the recycling comparable to that of puffed gas) indicate that the level of recycling became low due to wall conditioning, and additional comparable gas puff was required to sustain a discharge.

Here, we describe the detailed time evolution before, during, and after a current jump and show the similarities and differences between hydrogen and deuterium discharges. Initially, ionization in the ECH resonance layer occurred, and intense hydrogen or deuterium emission continued for about 10 ms. Then, the emission decayed. This decay implies a decrease in neutral gas, which is also indicated by a quick decrease in the ionization gauge signal. In the deuterium discharge, the H_β emission in this first phase is very low [Fig. 3 (d)], suggesting that wall recycling is insignificant in this phase. The H_β emission increased gradually, and the D_β emission decreased; they eventually became comparable.

The ECH reflection power is enhanced at $t > 30$ ms and $t > 40$ ms for deuterium and hydrogen, respectively [Fig. 3 (b)]. The enhancement begins earlier for the deuterium plasma than that for the hydrogen plasma, and it occurs close to the time when the plasma current is about 0.2 kA [Fig. 3 (a)]. The enhanced levels are similar. Figure 3 (c) shows the magnetic probe signals. In these signals, the fields due to external coils are subtracted, and only

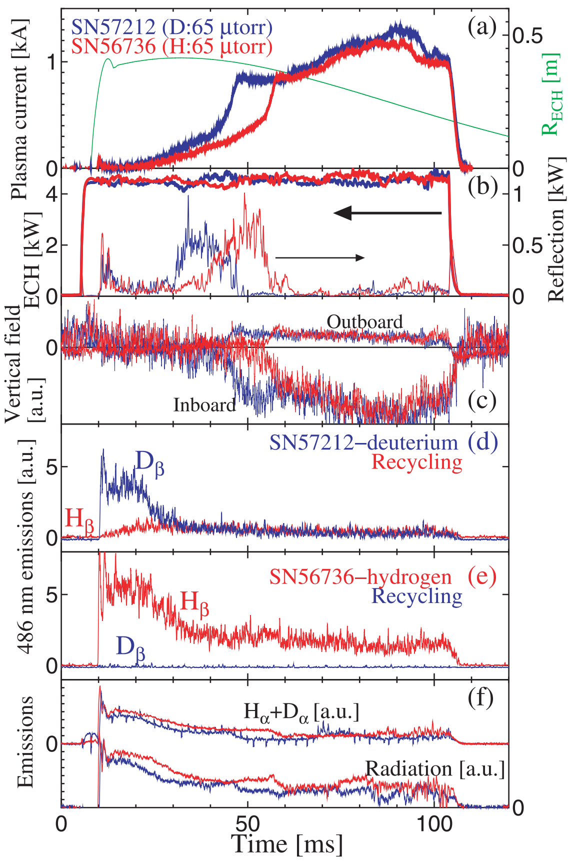

Fig. 3 Comparison of hydrogen and deuterium. Current (a) jump occurs earlier in the deuterium discharge than that in hydrogen in the same operational sequence. Plasma current begins when R_{ECH} (radius of the ECH resonance layer) is generated. Incident ECH power (b) is kept constant. Reflection power (b) is detected in the transmission line of the ECH. Vertical field (c) generated by the plasma current alone is measured outboard and inboard in the vacuum vessel H_β and D_β emissions of SN57212 and SN56736 are presented in (d) and (e), respectively. H_α+D_α and total radiation are indicated in (f).

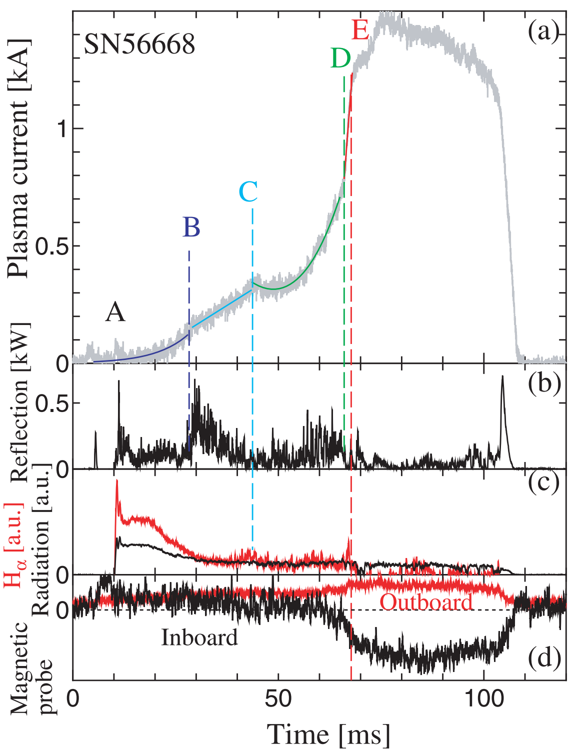

Fig. 4 Current jump with a strong vertical field. Current jump is divided into four phases on the basis of the plasma current waveform (a). ECH reflection power (b), hydrogen emission and radiation (c), and outboard and inboard vertical fields (d) are also plotted.

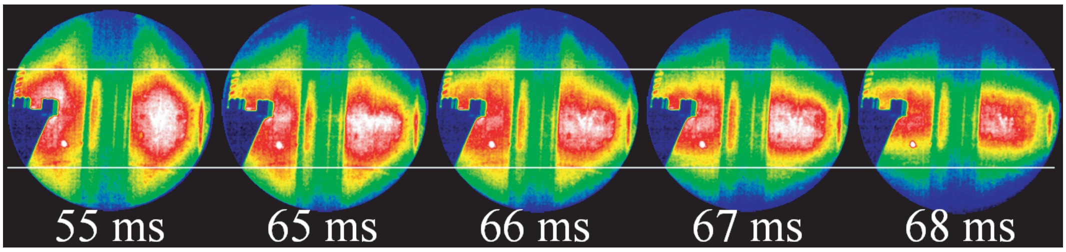

Fig. 5 Visible camera images during a current jump. Image at 55 ms is a sample before the vertical shrinkage. At 66 ms, the ECH reflection signal is attenuated. The vertical field at the outboard signal reaches maximum value at 67 ms.

the effect of plasma current is shown.

To observe the current jump in detail, a discharge with a strong vertical field was performed (Fig. 4), leading to a long period before the current jump. Initially (A), the plasma current grew gradually with a time constant of about 5 ms. Next (B), the plasma current increased linearly (B-C), and the hydrogen emission became constant. The reflection power was enhanced (B-D). The plasma current started to grow at C, leading to a current jump and the formation of an ST configuration. The formation was also indicated by the inboard vertical field [Fig. 4 (c)] and by visible camera images (shown later). After about 30 ms, ionization and recycling seemed to be balanced. Note that we needed additional gas puffing to maintain the balance and sustain the discharge.

Within a very short period (around 66 ms, D), the plasma shrank, and a tokamak configuration was formed (Fig. 5). Before 66 ms, the brightness of the camera image decreased gradually, but the shape was almost unchanged. For example, the 55-ms image does not show vertical shrinkage, and the 65-ms image does. After 65 ms, the plasma shrinks in the vertical direction within several ms. The vertical field at the outboard signal becomes maximum at about 67 ms. The plasma image continues to shrink in the vertical direction. As described above, the ECH reflection power correlates well with the variations in the plasma current waveform and the visible camera image. The enhanced reflection power can be interpreted as a change in the cutoff layer, as follows. According to multichord interferometer measurements, the cutoff layer seems to be located near the outboard boundary [6]. Since the EC wave is injected along the major radius from a lower port (whose position and direction roughly coincide with the lower white line in Fig. 5), the trajectory of the reflected wave is sensitive to the shape of the boundary. The camera images in Fig. 5 suggest that the boundary shape changes from being vertically elongated to a horizontally elongated one. Before the jump, the boundary shape is rather flat due to vertical elongation of the plasma, and as a result the reflection is large. After the jump, the cutoff surface becomes curved due to the shrinkage of the plasma, reducing the reflection power.

5. Discussion and Summary

The deuterium plasma can induce a current jump within a shorter period than the hydrogen plasma [Fig. 3 (a)]. One possible interpretation is that the plasma current is enhanced by improved confinement. A theory [7], indicates that the current in the open field line region is proportional to the stored energy. In addition, experiments have shown a linear dependence of the plasma current on the stored energy during the initial current formation phase [4]. Assuming that ambipolar particle transport dominates the confinement, the parallel transport is determined by slow ions, leading to better confinement for deuterium because it is heavier. Since the discharge duration is finite in practical experiments, the shorter time is advantageous for generating an ST configuration with higher plasma current.

The time evolution after the jump is almost the same, implying that isotope effects such as the effect on confinement are not important in the ST sustained phase. This is similar to the fact that a difference in the plasma current waveform due to the isotope effect was not found during current sustainment by low-frequency RF wave heating [3]. These results indicate that the sustained ST configuration is quite robust.

In summary, hydrogen and deuterium plasmas were compared in ECH start-up experiments. The current jump is induced earlier in deuterium, but other behaviors are very similar. The usefulness of Ohmic discharge cleaning and H_β/D_β measurement were demonstrated.

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