Development of hydrogen storage electrode for plasma biasing in the Tohoku University Heliac

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Abstract. In the Tohoku University Heliac (TU-Heliac), a new type of hydrogen storage electrode made of a palladium (Pd) was developed. This new gold (Au)-coated palladium electrode can produce high-density plasma up to ~40 shots per hydrogen gas charge. The Pd-Au electrode is the most useful tool for production of high-density plasma, compared with previous electrodes (Ti, V, and Pd). A reduced-size Au-coated palladium electrode was also developed. The electrode current was controllable in the lower voltage region and the controllability of electrode current in the small electrode current range was confirmed in only one discharge. Compared with the hot cathode experiments, the reduced-size Pd-Au electrode had the ability to produce a biased plasma, which was similar to the characteristics of the biased plasma by the hot cathode made of LaB6, even though the surface area of the electrode for the plasma was much smaller than that of the hot cathode.

1. Introduction

The H mode transition has been observed in many devices [1–5]. The radial electric field is considered important to understand the nature of LH transition. Electrode biasing experiments are effective tools for the study of improved confinement mode [6, 7]. It has been reported that the H mode can be triggered by applying sufficient voltage to an electrode located inside the plasma [8, 9], to control the driving force for plasma rotation. It is necessary to control an electrode current externally using a current control power supply. A hot cathode made of LaB6 is a useful electron emission source for electrode biasing experiments. In our previous experiments on the Tohoku University Heliac (TU-Heliac), the role of the radial electric field on the transition to improved modes has been investigated by electrode biasing experiments. In positive biasing experiments with a stainless steel (SUS) electrode (electron collection), the transition to improved confinement mode was observed clearly when the radial electric field was formed [10]. Furthermore, by negative biasing with a hot cathode electrode (electron emission), the radial electric fields can be actively controlled by changing the electrode current, \( I_e \) [11–13]. The local maxima in viscosity were found at poloidal Mach number around \( -M_p \sim 1–3 \), as predicated by neoclassical theory [14–17]. The poloidal Mach number \( M_p = -(E_r/B_0) / \Theta v_{th} \), \( \Theta = \varepsilon / q \), where \( E_r \) is the radial electric field, \( B_0 \) is the magnetic field on the axis,
\[ \varepsilon = \langle r \rangle / R_0 \] is the toroidal ripple, \( q \) is the safety factor, and \( v_{th} \) is the ion thermal velocity. At \( -M_p \sim 4 \), where the torque in the poloidal direction exceeded the local maxima in viscosity, the following characteristics were observed: increases in electron density and energy confinement time, formation of strong electric field, and suppression of fluctuation level. These phenomena were also observed in Compact Helical System (CHS) at low magnetic field [18]. However, a hot cathode made of LaB_6 (especially of the solenoid type) is fragile to electromagnetic force, and thus in the strong magnetic field biasing experiments on medium or large devices, we cannot adopt a hot cathode made of LaB_6 as the electrode with controllability of electrode current.

Consequently, a new type of electrode made of hydrogen storage metal has been developed for particle injection (electron, ion, and neutral particle). Using an electrode made of a hydrogen storage metal, such as titanium (Ti) or vanadium (V), the following can be expected: (1) the electrons injected from the negative-biased electrode allow biasing experiments for studying the LH transition by control of the electrode current, (2) the electrons/neutral particles injected from the negative-biased electrode provide production of high-beta plasma and high-density plasma, and (3) ions accelerated from the positive-biased electrode allow simulation of the orbit loss of high-energy particles if hydrogen can be stored successfully in and released from the electrode. There is no hard limit of the high-density operation in stellarators, unlike the Greenwald density limit in tokamaks, which is a great advantage for future reactor operation. Therefore, it is important to study high-density plasma production and to explore the high-density limit in stellarators. In TU-Heliac, the highest density is about \( 1 \times 10^{13} \) cm\(^{-3} \), which can be achieved by pre-filling with working gas. In additional gas puffing, broadening of neutral gas requires some time (a few milliseconds), and the plasma density increase slowly (a few milliseconds). Therefore, the discharge time (10 ms) is insufficient to increase plasma density by additional gas puffing. In contrast, biasing electrodes made of hydrogen storage metals can increase the density at the plasma core rapidly (~0.5 ms) [19, 20]. In addition, the TU-Heliac has a non-planar magnetic axis system, which is expected to stabilize high-beta plasma due to the self-stabilization effect [21–23]. Negative biasing experiments using this hydrogen storage electrode have the potential to realize high-beta experiments in some small-sized devices (e.g., TU-Heliac).

In the TU-Heliac, using a titanium (Ti) or vanadium (V) electrode after hydrogen gas charging in negative electrode biasing, the electron density and the line intensity of H\(_\alpha\) increased by about 10-fold as compared with those before biasing, the electrode current \( I_E \) increased by about 100-fold as compared with the ion saturation current [19, 20]. Specifically, with vanadium electrode biasing, the radial distribution of the electron density sloped steeply at the electrode position, and a strong negative radial electric field was formed outside the electrode. The mechanism of high-density plasma production suggests the injection of electrons/neutral hydrogen from the Ti electrode into the plasma, caused by influx of high-energy particles into the electrode. When the V electrode was negatively biased in an Ar plasma, under the low magnetic field, the \( \beta \) value increased up to about 0.5%, allowing the realization of a new field of high-\( \beta \) experiments. One of the most important performance-related factors for hydrogen storage electrodes is long life time, which means that we can produce a number of high-density shots per hydrogen gas charge. The Ti electrode can produce only 3 high-density plasma shots per hydrogen gas charge, while the V electrode can produce up to 24 shots of high-density plasma per hydrogen gas charge. However, the V electrode has a disadvantage (hydrogen embrittlement), which causes reduction of hydrogen gas evolution from the electrode surface.

Therefore, we developed a palladium (Pd) electrode, which is free from the problem of hydrogen embrittlement. If the palladium electrode could produce release of hydrogen gas efficiently, it would be expected to be useful not only for high-density plasma production but also for biasing experiments to study LH transition by controlling the electrode current. Here, we propose a new type of electrode, the results of biasing experiments with this new electrode, and comparison of similar experiments with other electrodes (Ti, V, and LaB\(_6\)).

2. Experimental setup
2.1. TU-Heliac

The TU-Heliac is a small standard heliac device (major radius $R = 0.48$ m, average plasma radius $a = 0.07$ m), with a toroidal magnetic period $n = 4$ [24, 25]. The heliac configurations are produced by three sets of coils: toroidal field coils, a center conductor coil, and vertical field coils. Various magnetic configurations can be formed easily by selecting the ratios of coil currents, and Fourier components can be varied over a wide range. The target plasma was produced by Joule heating with an 18.9 kHz alternating current in additional poloidal coils, with effective input power of about 3 kW. The vacuum vessel was filled with a working gas (H$_2$, He, Ar) before discharges. The magnetic field on axis, $B_0$, was 0.3 T in standard operation. Plasma parameters were measured with a Langmuir probe (triple probe: electron density, $n_e$; electron temperature, $T_e$; floating potential, $V_f$; plasma space potential, $V_s$) at toroidal angle $\phi = 0^\circ$ and a 6-mm microwave interferometer (electron line-density, $n_e l$) at $\phi = 90^\circ$. The line intensity of H$_\alpha$, $I_{H\alpha}$, was measured with a 25-cm monochromator coupled with a photomultiplier tube at $\phi = 159^\circ$.

2.2. Hydrogen storage electrode

The experimental setup of the hydrogen storage electrode is shown in Figure 1 (a) along with the cross-section of the magnetic flux surfaces in a vacuum at toroidal angle $\phi = 0^\circ$. The hydrogen storage electrode was inserted vertically into the plasma from the top at $\phi = 0^\circ$. It was biased positively or negatively against the vacuum vessel through a field-effect transistor (FET). The hydrogen storage electrode head (10 mm in diameter and 7 mm in length) was mounted at the end of the copper shaft housed in a glass tube as an insulating sheath (Figure 1 (b)). The hydrogen storage electrode was conditioned in the upper chamber (conditioning chamber) separated by a gate-valve. The temperature of the hydrogen storage metal head could be controlled by heating a tungsten (W) wire (0.15 mm in diameter) and was measured with a thermocouple gauge. The W wire and the thermocouple gauge were installed inside the electrode head.

The titanium stores and releases hydrogen at about 700°C, and hydrogen storage and release processes do not occur at room temperature. In contrast, vanadium and palladium store and release hydrogen at room temperature (20~250°C). The surface barrier (oxide layer) interferes with the storage and release of hydrogen gas. The surface barrier of palladium is much lower than those of other hydrogen storage metals, such as titanium or vanadium.

Figure 1. (a) The position of the hydrogen storage electrode and the computed cross-section of the magnetic flux surfaces in vacuum at $\phi = 0^\circ$. The hydrogen storage electrode was conditioned in the upper chamber (conditioning chamber) separated by a gate-valve, and was inserted vertically into the plasma from the low magnetic field side.
(b) The hydrogen storage electrode head (10 mm in diameter and 7 mm in length) was mounted at the end of the copper shaft housed in a glass tube as an insulating sheath.
3. Experimental results

3.1. Gold-coated Palladium electrode

In treatment of the palladium electrode, the electrode was first heated to about 300°C for 24 h. After baking, the electrode was conditioned in hydrogen gas \((p_{in} = 247 \text{ kPa})\) at 30°C in the conditioning chamber shown in Figure 1 (a). These conditions of temperature and gas pressure for the Pd electrode were almost the same as those for the Ti and V electrodes, but the decrease in hydrogen gas pressure \(p_{in}\) in the Pd electrode \((\Delta p_{in} \approx 48 \text{ kPa})\) was about double and about 5-fold higher than those in the V electrode \((\Delta p_{in} \approx 25 \text{ kPa})\) and the Ti electrode \((\Delta p_{in} \approx 10 \text{ kPa})\), respectively. The number of Pd atoms in the electrode, \(N_{Pd}\), was \(2.9 \times 10^{22}\). The total number of hydrogen atoms absorbed in the Pd electrodes was estimated from the decrease in hydrogen gas pressure after treatment, and was equivalent to about \(2.0 \times 10^{22}\) hydrogen atoms \((N_H)\), and the hydrogen concentration in the Pd electrode \((x = N_H / N_{Pd})\) was about 0.7. On the other hand, hydrogen concentrations \((x = N_H / N_{Ti}, V)\) were about 0.2 and 0.3 in the case of Ti and V electrodes, respectively [20]. When the Pd electrode was biased negatively after treatment, the high-density plasma was produced, similar to the Ti or the V electrode experiments. However, the production of high-density plasma was observed only twice with the Pd electrode after one treatment. When the Pd electrode was inserted into the vacuum vessel, the Pd electrode constantly released hydrogen gas, and therefore a controlled working gas pressure could not be achieved.

To avoid the above uncontrollable release of hydrogen gas from the electrode, we developed a new type electrode made of gold (Au)-coated palladium (Pd-Au). The Pd was coated with Au about 100 nm thick using an ion coater, which was variable by changing the discharge time. The electrode surface in contact with the plasma directly was coated with Au. In addition, when the electrode was conditioned, the hydrogen gas pressure \((p_{in} = 19.8 \text{ kPa})\) was reduced to \(p = 14.3 \text{ kPa}\) at 36°C \((\Delta p_{in} \approx 5.5 \text{ kPa})\). The release of hydrogen gas from the gold-coated palladium electrode was less than half that of the uncovered Pd electrode. Furthermore, the new type of electrode can produce up to \(\sim 40\) shots of high-density plasma per hydrogen gas charge. The typical time evolution of plasma parameters in Ar discharge is shown in Figure 2. When the Pd-Au electrode was biased negatively from 4 ms to 10 ms, the electrode current, \(I_E\), increased up to about 100 A, and the electron density, \(n_e\), at \(\rho = 0.54\) increased by about 5-fold as compared with those before biasing. The differences among the plasma space potential signals measured at three difference radial positions showed that the strong negative radial electric field was formed by the Pd-Au electrode. The line intensity of \(H_\alpha\), \(I_{H\alpha}\), at the central chord increased rapidly by about 10-fold as compared with that before biasing. In this experiment, the negative bias voltage was supplied against the vacuum vessel by a constant-voltage power supply. The threshold in the electrode bias voltage for production of high-density plasma was about 100 V.

Figure 3 shows the relation between the electrode bias voltage for production of high-density plasma and the electron density of target plasma before biasing in Ar discharge. The electron density was measured with the triple probe around \(\rho = 0.28 \sim 0.54\). The closed circles, open circles, open triangles, and open squares indicate the density of the gold-coated palladium electrode, the uncovered Pd electrode, the V electrode, and the Ti electrode, respectively. In the case of Pd-Au electrode biasing, the bias voltage and target plasma density necessary for production of high-density plasma were lower than for other electrodes. These results show that the Pd-Au electrode can easily produce high-density plasma. Figure 4 shows the relation between the electrode bias voltage for production of high-density plasma and the ratio of the electron density with biasing \(n_{e,\text{bias}}\) to the electron density before biasing \(n_{e,\text{no\_bias}}\) in Ar discharge. In the case of Pd-Au electrode biasing, we can see that the rate of increase in electron density was similar to those for the other electrodes (Ti, V, and Pd) in the lower bias voltage range than other electrodes.
Figure 2. Time evolutions of plasma parameters: (a) electrode voltage, $V_E$ and electrode current, $I_E$; (b) electron density, $n_e$, at $\rho = 0.54$; (c) Differences among the plasma space potential signals, $V_s$, at $\rho = 0.54$, 0.67, and 0.80; and (d) line intensity of $H\alpha$, $I_{H\alpha}$, at the central chord.

Figure 3. Relations of the electrode bias voltage for production of high-density plasma and the electron density of target plasma before biasing in Ar plasma. The electron density was measured with a triple probe around $\rho = 0.28 \sim 0.54$.

Figure 4. The relation of the electrode bias voltage for production of high-density plasma and the ratio of the electron density with biasing $n_{e,\text{bias}}$ to the electron density before biasing $n_{e,\text{no bias}}$ in Ar discharge. The close circles, open circles, open triangles and open squares denote the density of the Pd-Au electrode, the density of the Pd electrode, the density of the V electrode and the density of the Ti electrode.

Table 1 shows the performance of each of the electrodes made of hydrogen storage metal, titanium, vanadium, palladium, and gold-coated palladium [19, 20]. “Number of shots” indicates the number of rounds of production of high-density plasma per hydrogen gas charge, “Threshold of electrode biasing voltage” indicates a threshold in the electrode bias voltage for production of high-density plasma, “Minimum electrode current” indicates the minimum electrode current in high-density plasma, and “Residual gas pressure” indicates release of hydrogen gas from the electrode. Compared with other
electrodes (Ti, V, Pd), the characteristics of the Pd-Au electrode were as follows: (1) maximum number of shots per hydrogen gas charge, (2) the comparatively small amount of hydrogen gas release from the electrode, (3) lowest threshold in the electrode bias voltage for production of high-density plasma, and (4) lowest electrode current in high-density plasma. These results indicate that the Pd-Au electrode is useful for production of high-density plasma.

Table 1. The performance of each hydrogen storage metal electrode.

| Electrode material | Number of shots | Residual gas pressure (Pa) | Threshold of electrode voltage $-V_E$ (V) | Minimum electrode current $-I_E$ (A) |
|--------------------|-----------------|---------------------------|------------------------------------------|-------------------------------------|
| Ti                 | 3               | $\sim 5 \times 10^{-6}$   | $\sim 300$                               | $\sim 100$                          |
| V                  | 21              | $\sim 2 \times 10^{-3}$   | $\sim 200$                               | $\sim 100$                          |
| Pd                 | 2               | $\sim 8 \times 10^{-4}$   | $\sim 150$                               | $\sim 10$                           |
| Pd-Au              | $\sim 40$       | $\sim 6 \times 10^{-5}$   | $\sim 100$                               | $< 10$                              |

3.2. Size reduction of a gold-coated Palladium electrode

The previous electrode (Pd-Au electrode; Type 1) is a good tool for the production of high-density plasma, but the electrode current was too large to allow its control in the study of LH transition at poloidal Mach numbers around $-M_p \sim 1–3$. It was necessary to reduce the electrode current to less than 10 A. Therefore, we reduced the size of the gold-coated palladium electrode. The reduced-sized Pd-Au electrode (Type 2) head was 10 mm in diameter and 2 mm in length, and the surface area in contact with plasma $S$ was about 1.4 cm$^2$, which was half that of the previous electrodes (Type 1; $S \sim 3.0$ cm$^2$). This small-sized electrode could have less influence on the target plasma.

A high electrode current mode was observed in biasing experiments using the reduced-size Pd-Au electrode (Type 2). The electrode current of type 2 electrode was half that of the type 1 electrode. The controllability of the electrode current was examined by sweeping the electrode voltage with an external control signal. Figure 5 shows the typical time evolution of (a) the electrode voltage $V_E$, (b) the electrode current $I_E$, (c) the plasma space potential $V_s$ and (d) electron line density $n_e$. In this experiment, the electrode voltage ramped up from 0 to $-150$ V at $Time = 4$ to 10 ms. When the electrode voltage was about $-100$ V ($Time \sim 8.5$ ms), the electrode current increased suddenly and electron line density also increased. Furthermore, the electrode current increased in proportion to the electrode voltage at $V_E = -100 \sim -150$ V. A clear threshold was observed in the electrode bias voltage for high electrode current mode.

Figure 6 shows the dependence of the electrode current on the electrode voltage in negative biasing experiments with both the type 1 (#69907 ~ #69910, closed circles) and type 2 (#71450, closed triangles and #71452, open squares) electrodes in the He plasma. The electrode current was proportional to the surface area of the electrode around $V_E = -100 \sim -200$ V. In this figure, we can see that the electrode current increased in proportion to the electrode voltage. In addition, in type 2 electrode biasing experiments, we confirmed the controllability of electrode current in the small electrode current range ($I_E = -3 \sim -12$ A) in only one discharge (#71450 or #71452).
3.3. Comparison with the LaB₆ hot cathode experiments

To examine the plasma parameters produced by type 2 electrode biasing, we compared the results with those of hot cathode biasing experiments. In the TU-Heliac, to measure the plasma profile, it is necessary to use the triple probe. The high-precision measurement using the triple probe requires a similar discharge many times. The gold-coated palladium electrode had a longer life time, and it was available to measure the plasma profile and for comparison with the hot cathode biasing experiments. The LaB₆ hot cathode (10 mm in diameter and 17 mm in length) was inserted horizontally into the plasma from the low field side at toroidal angle $\phi = 270^\circ$. Figure 7 shows the typical time evolution of (a) the electrode voltage $V_E$, and the electrode current $I_E$ in the hot cathode and (b) the reduced-size Pd-Au electrode (Type 2) biasing experiments. At the same electrode voltage, even though the surface area of type 2 electrode $S$ was one third that of the hot cathode, the electrode current of type 2 was 4-fold that of the hot cathode. Figure 8 shows the radial profiles of (a) the electron density $n_e$, (b) the electron pressure $n_eT_e$, and (c) the plasma space potential $V_s$ measured with the triple probe, in hot cathode (circle) and type 2 electrode (square) biasing experiments, both before (open) and during biasing at $V_E = -150$ V (closed) in the He plasma. The electron density in the type 2 electrode biasing experiment was higher, while the electron pressure was almost the same as that in the hot cathode
biasing experiment. In the type 2 electrode biasing experiment, the electron pressure was higher around the electrode position, and it was lower in the plasma core. This was because the electron temperature was lower at the plasma core. The decrease in temperature was considered to be due to low-temperature electron emission from the electrode and to measurement errors by triple probe measurement. In both the hot cathode and type 2 electrode biasing experiments, a strong negative radial electric field was formed around the electrode. Even though the surface area of the electrode for the plasma was much smaller than the hot cathode ($S = 4.2 \, \text{cm}^2$), the reduced-size Pd-Au electrode (Type 2) had the ability to produce a biased plasma with similar characteristics of the biased plasma by the hot cathode made of LaB$_6$.

Figure 7. The typical time evolution of (a) the electrode voltage $V_E$ and the electrode current $I_E$ in the hot cathode and (b) the reduced-size Pd-Au electrode (Type 2) biasing experiments.

Figure 8. The radial profiles of (a) the electron density $n_e$, (b) the electron pressure $n_eT_e$, and (c) the plasma space potential $V_s$ measured with the triple probe in hot cathode (circles) and type 2 electrodes (square) biasing experiments, both before (open) and during biasing at $V_E = -150 \, \text{V}$ (closed) in the He plasma.

4. Summary
In the Tohoku University Heliac (TU- Heliac), we developed a new type of a hydrogen storage electrode made of a palladium (Pd). The release of hydrogen gas from the Au-coated palladium electrode was less than half that of the uncovered Pd electrode, and the new Au-coated palladium electrode could produce up to ~40 shots of high-density plasma per hydrogen gas charge (longer life time). In the case of Pd-Au electrode biasing, the bias voltage and target plasma density necessary for production of high-density plasma were lower, while the rate of increase in electron density was similar to those for the other electrodes (Ti, V, and Pd) in a lower bias voltage range than for the other electrodes. These results indicate that the Pd-Au electrode is the most useful tool for production of high-density plasma, as compared with the previous electrodes (Ti, V, and Pd). We developed a reduced-size Au-coated palladium electrode, the electrode current of which was controllable in the lower voltage region ($V_E = -100 \sim -200 \, \text{V}$), and we confirmed the controllability of electrode current in the small electrode current range ($I_E = -3 \sim -12 \, \text{A}$) in only one discharge. In comparison with the hot cathode experiments, although the surface area of the electrode for the plasma was much smaller...
than for the hot cathode, the reduced-size Pd-Au electrode (Type 2) had the ability to produce a biased plasma with similar characteristics to that produced by the hot cathode made of LaB$_6$.

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