Fusion Engineering and Design 83 (2008) 689–694

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Plasma recovery after various events in HT-7 superconducting tokamak

J.S. Hu*, J.G. Li,

HT-7 team

Institute of Plasma Physics, Chinese Academy of sciences, P.O. Box 1126, Hefei, Anhui 230031, PR China

ARTICLE INFO

Article history:
Received 27 December 2007
Received in revised form 13 March 2008
Accepted 17 March 2008
Available online 25 April 2008

PACS:
52.40.Hf

Keywords:
Plasma recovery
Wall conditioning

ABSTRACT

Normal plasma recoveries after various events, such as after shutdown, various boronization, oxidation and large air leak, were investigated in the 2007 campaign of HT-7. Plasma recoveries, including disruptive plasmas, would depend on the wall status, such as impurities content and hydrogen retention. After shutdown or air leak, impurities made plasma recovery very difficult. After boronization, plasma recoveries would depend on the procedures of the boronization ($C_2B_{10}H_{12}$). After oxidation, boronization would effectively suppress impurities and would be beneficial for plasma recovery. ICRF cleanings in various working gases, such as He and D_2, would be useful for impurities and hydrogen removal. This research is important for effective operation of HT-7 and would be useful for EAST and ITER operations.

1. Introduction

Oxidation experiments on hot walls, which admitted abundant oxygen into inner-vessel, were proposed for removal of a long-term accumulation of high fraction tritium fuel in the surface or bulk material of plasma facing components in fusion devices, such as ITER [1–4]. Plasma recovery after cleanup is one of the key issues for oxidation of wall conditioning. Besides oxidation experiments, plasma recoveries after shutdown and air leak are also important for effective operation in a tokamak. By suppression of metallic and oxygen impurities, boronization had been testified as an effective way for obtaining high performance plasmas [5–8]. Plasma recovery after boronization should be investigated for optimizing the procedures of boronization.

The permanent presence of toroidal field in future tokamak will preclude GDC cleaning; therefore, ICR conditionings are envisioned for in-between pulse cleaning. High hydrogen removal rates have been reported in ICR experiments in Tore Supra with He and D [9] and Textor with He [10]. Disruptive discharge cleaning capable of operating in the presence of magnetic fields was used in TFTR for limiter conditioning [11]. Planned disruptions (i.e. without impurity injection) have utilized in order to provide localized surface heating in an attempt to promote H/D release from the C-Mod walls [12].

In the last HT-7 campaign in the spring of 2007, after various events, such as after shutdown, various boronization, oxidation and large air leak, different cleanings, especially ICRF cleaning techniques, were done for wall recovery. However, disruptive plasmas up to a few tens shots happened during plasma recovery due to the remained oxygen after leak or oxidation experiments, or due to hydrogen recycling after boroniztion. Those disruptive plasma discharges, taken a few to 10 h, strongly influenced on the operation efficiency of HT-7.

In this paper, different plasma recovery in HT-7 after various events was introduced. The main missions were that (1) to analyze plasma recovery procedures under various wall status; (2) to analyze how impurities or hydrogen recycling influenced on the following plasma operations; (3) to discuss how to optimize wall conditioning procedures, including cleanup, for easily plasma recovery. Those studies would be important for effective operation of HT-7, and would be useful for future tokamaks, such as EAST and ITER.

2. Experiments

HT-7 is a medium-sized superconducting tokamak (R = 1.22 m, a = 27 cm). Normal techniques were investigated for the impurities and hydrogen removal, such as baking, GDC and ICRF cleanings. Especially, He(D_2)-ICRF cleanings and boronization-ICRF with $C_2B_{10}H_{12}$ becomes routine methods for impurity removal or impurities suppression [13]. The oxidation experiments, including O-ICRF, O-GDC and thermal oxidation with neutral oxygen, have

* Corresponding author. Tel.: +86 551 5591353; fax: +86 551 5591310.
E-mail address: hujs@ipp.ac.cn (J.S. Hu).

0920-3796/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2008.03.001

Table 1
Main wall conditionings in HT-7 campaign in the spring of 2007

Events	Procedure of wall conditioning
After shutdown	~400 h baking and 37 h He-GDC
1st Boronization	60 min 15–20 kW He-ICRF + 120 min 20 kW B-ICRF(3 g) + 50 min 15 kW He-ICRF
2nd Boronization	60 min 15 kW He-ICRF + 132 min 5–10 kW B-ICRF(3 g) + 35 min 5 kW He-ICRF
5th Boronization	70 min 15 kW He-ICRF + 130 min 20 kW B-ICRF(3 g) + 23 min 5 kW He-ICRF
7th Boronization	75 min15 kW He-ICRF + 180 min 15 kW B-ICRF(3 g) + 60 min 15 kW He-ICRF
3rd Boronization	70 min 20 kW He-ICRF + 300 min 5–20 kW B-ICRF (9 g) + 70 min 5 kW He-ICRF
4th Boronization + air leak	77 min 15 kW He-ICRF + 120 min 5–15 kW B-ICRF(3 g) + air leak+75 min 5 kW He-ICRF + 120 min-induced baking + 60 min He-GDC
Oxidation + 6th boronization	70 min 15 kW He/O_2-ICRF+40 min 15 kW D_2-ICRF + 50 min 15 kW He-ICRF + 70 min 15 kW B-ICRF(1 g) + 90 min 15 kW He-ICRF
Oxidation in 2006*	120 min 10–40 kW O_2-ICRF + 40 min 20 kW He-ICRF + 40 min 20 kW D_2-ICRF + 40 min 20 kW He-ICRF

been performed in HT-7 in the last 2 years [14–16]. Besides of three turbo pumping stations, two cryo-pumps (nominal pumping speed 17300 l/s × 2 for water) were utilized for particles exhaust during plasma discharge and baking.

The liner of HT-7 was heated by direct current flow and the limiters were heated by thermal radiation. Two anodes were used for the GDC cleanings. The voltage for each molybdenum anode is about 270 V and the current is 2 A. The ICRF antenna at high field side was utilized for wall conditioning. The power of ICRF can attain 300 kW; the wave frequency of ICRF is 30 MHz; the wave power can be adjusted easily. The duty time of ICRF wave is 0.3 s on and 1.5 s off for cleanings. ICRF cleanings could be performed in the presence of permanent toroidal magnetic field (1.5–2 T). Boronization with $C_2B_{10}H_{12}$ material could be carried out with the association of GDC or ICRF discharges in HT-7. In HT-7, after shutdown, long baking (~150 °C) and long He-GDC cleaning was used for impurities removal. During oxidation and boronization, the wall temperature was about 100–180 °C. During the boronization, the carborane injection was depended on wall temperature of the material bottle. The baking for carborane bottle was manual controlled.

In the last HT-7 campaign in the spring of 2007, main procedures of plasma recovery happened after shutdown, large air leak, boronization and oxidation experiment, as listed in Table 1. By the way, plasma recovery after oxidation in 2006 was also listed. In the last HT-7 campaign, seven ICRF associated boronizations (B-ICRF) was operated. Normally, before B-ICRF, He-ICRF was used for obtaining cleaning walls, which should be beneficial for the deposition of boron film. After B-ICRF, He-ICRF was also used for the removal of H in the boron film, which would reduce the H recycling in the following plasma discharges. During B-ICRF, He was added by feedback control of total pressure. The 3rd boronization was specially done with 9 g $C_2B_{10}H_{12}$. The 6th boronization with 1 g $C_2B_{10}H_{14}$ was done after O-ICRF oxidation experiments. For the other boronizations, 3 g $C_2B_{10}H_{12}$ was normally used. And one large leak (pressure in the vessel reached $\sim 1 \times 10^4$ Pa) was happened after the 4th boronization.

Normally, after various events, disruptive plasmas with different shots would be required before obtaining normal plasma discharges, as listed in Table 1. After disruptive plasma discharges, normal ohmic plasma discharges could be obtained. For comparison, only standard ohmic plasma discharges were chosen. In those recovered standard ohmic plasmas, controllable plasma densities were $\sim 1.5 \times 10^{13}$ cm^{-3} and plasma currents were ~130 kA. Plasma densities in those recovered plasmas were stable for 400 ms.

3. Results of plasma recoveries

3.1. Plasma recovery after shutdown

While no leak could be detected at the initial stage of the last HT-7 campaign, long baking (~150 °C) and long He-GDC cleaning were used for impurities removal. Total duration of baking was about 400 h and that of He-GDC was about 37 h. While the superconducting coils were cooled down and base vacuum reach $\sim 3.3 \times 10^{-5}$ Pa, plasma discharge was started. However, totally 128 disruptive plasma were required before obtaining normal ohmic plasma. Including the interval of plasma discharges, totally 600 min was taken for those discharges.

At the initial stage of the last HT-7 campaign, even after long baking and He-GDC cleaning, the walls were not clean enough for plasma discharges. Partial pressure (P.P) of impurities was quite high. For example, base P.P of H_2O was at $\sim 1 \times 10^{-5}$ Pa and that of CO was at $\sim 2.5 \times 10^{-6}$ Pa. However, that of H_2, $\sim 3 \times 10^{-6}$ Pa, was not high. During disruptive plasma discharges, impurities increased. For example, P.P of CO increased to $\sim 2 \times 10^{-5}$ Pa. This possibly indicated that impurities were main possible reason for those disruptive plasma discharges.

In this case, after disruptive plasma discharge, impurities, such as C and O in the recovered ohmic plasma ($Ne \sim 1.5 \times 10^{13}$ cm^{-3}, $Ip \sim 130$ kA) were still high, which was higher than that after other cases, as shown in Fig. 1. Typical Z_{eff} in those recovered plasma were about 6–7. However, the emission of Ha was lowest than that after other cases. Those also indicated impurities but not hydrogen recycling were main factor influenced on the plasma recovery after shutdown in the last HT-7 campaign.

3.2. Plasma recovery after standard boronizations

For suppression of impurities and for high performance plasmas, seven boronizations were operated in the last HT-7 campaign. As listed in Table 1, four standard boronizations (1st, 2nd, 5th and 7th) with 3 g $C_2B_{10}H_{12}$, was carried out. Typical procedure of boronization in HT-7 was shown in Fig. 2. Before B-ICRF, He-ICRF was used for impurities removal, which would provide clean walls for the deposition of boron film. After B-ICRF, He-ICRF was also used for the removal of H in the boron film.

Due to different detail procedures, from zero to a few tens disruptive plasmas were required before obtaining normal ohmic plasma, which indicted the plasma recoveries depended on detail procedures of boronizations. Especially, after the 7th boronization, no disruptive plasma was required and the longest plasma up to 186 s in the last campaign was obtained. In the 7th boronization, the $C_2B_{10}H_{12}$ injection was controlled carefully with slow temperature increase in the material bottle in order to avoid the quench of the B-ICRF discharge ($C_2B_{10}H_{12}$ is solid at room temperature. It would gasify at ~80 °C). The boron film with high adherence was possibly uniformly deposited on the walls due to slow material injection and stable ICRF discharge. The other possible reason is that, during long B-ICRF and high power cleaning in the following He-ICRF, the H in the boron film was removed enough for plasma start-up.

Normally, after those standard boronizations, H recycling but not impurities was the main factor influence on the following D_2 plasma discharges. It was found that the impurities were greatly suppressed and H release was quite high. Base P.P of H_2O was at