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Analysis of PWI footprint traces and material damage on the first walls of the spherical tokamak QUEST

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ABSTRACT

After several non-inductive current startup experimental campaigns in the spherical tokamak QUEST, its metallic first walls have revealed various kinds of damages as a signature of strong plasma wall interaction (PWI). Several types of footprint traces, namely colored regions formed due to material erosion/redeposition, melting of plasma facing components (PFCs) and numerous arc tracks on the chamber walls are recognized. Analysis of the re-deposited materials on collector probes is carried out using X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDS). Redeposition of several impurity materials such as carbon, oxygen and tungsten is identified. The footprint traces are majorly formed on the lower side PFCs, showing a large up/down asymmetry. Both toroidally symmetric and asymmetric footprint traces are formed on the bottoms side divertor plate and the lower part of the outboard side walls, respectively. Localized melting occurred on the outboard side limiters is attributed to the loss of energetic electrons produced via electron cyclotron resonance (ECR) heating. The observed damages are discussed in view of localized PWI, loss of energetic electrons, particle drifts, sputtering, arcing and redeposition of eroded materials. Material analysis and numerically calculated guiding center orbits of the charge particles are used to discuss these damages.

1. Introduction

The deleterious effects caused by the interactions between the edge plasma and plasma facing components (PFCs) are nearly unavoidable in the fusion scaled plasma devices regardless of the edge plasma characteristics or PFC properties [1–5]. Plasma wall interaction (PWI) is usually responsible for various adverse effects such as material erosion, redistribution of eroded materials and severe damages like melting of the PFCs [4–7]. The erosion and redeposition of materials in the tokamaks can cause significant changes in the physical properties of the PFC materials and may lead to the further enhancement of material erosion [1]. Re-trapping of the fuel particles beneath the re-deposited materials causing the enhanced tritium retention is another serious issue of PWI [8]. The material release from the first walls can affect the core plasma performance. There have been considerable evidences that by no mean all the impurities removed from the tokamak chamber walls actually reach the center of the plasma. The radiated power from the metallic impurities in tokamak plasma dominates the power balance and is generally responsible for the cooling of the plasma core. The metals observed are predominantly iron from the stainless steels walls, copper from RF antennas, and tungsten or molybdenum from the limiters/divertors [1]. It is generally seen that when the torus has been exposed to atmosphere, oxygen and carbon impurities are dominant, however as the hydrogen discharge cleaning advances, the low Z-impurities are generally reduced with time and the metal impurities are mainly responsible for the radiation in the later stage [9]. Sputtering, arcing, evaporation, and melting are the main mechanisms, which can introduce metallic impurities into the plasma [9,10]. Sputtering has been considered to be the dominant impurity producing processes and well understood theoretically as well as experimentally [10]. On the other hand arcing is not well understood and still unpredictable in tokamaks. However the presence of enormous arcing in several

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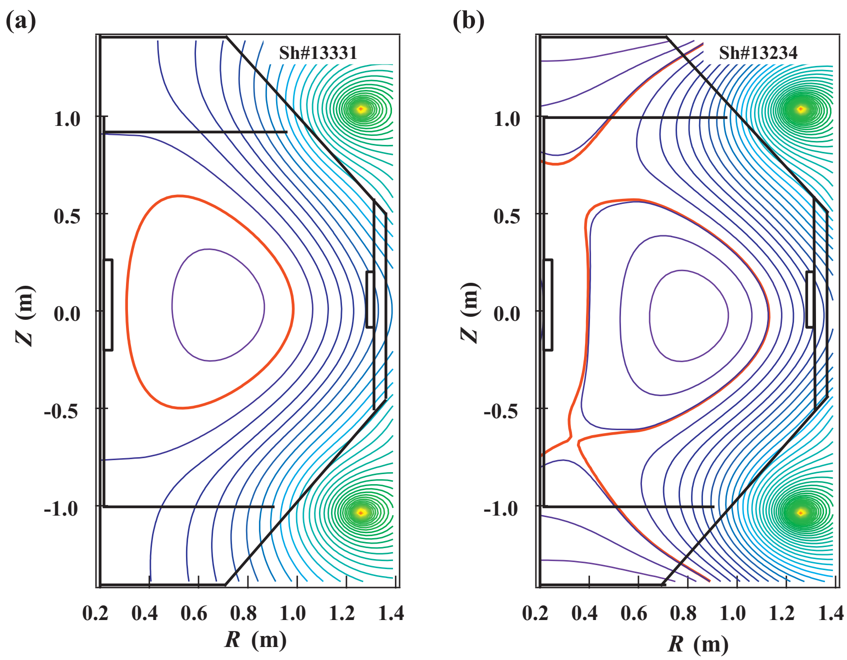

Fig. 1. Typical magnetic field configurations, (a) limiter configuration and (b) divertor configuration in the QUEST device.

tokamaks suggests that it can also play an important role in erosion in portions of limiters and divertors [11]. An understanding of the PWI damage behavior and identifications of eroded/redeposited materials in tokamaks are necessary to confirm the safe and trouble free steady state plasma operations [12].

In the spherical tokamak QUEST [13], several types of footprint traces (i.e. colored regions formed due to the material erosion and redeposition), melting of PFCs and numerous arc tracks on the bottom side divertor plate and inboard side limiters of the QUEST device are identified. The motivation behind this work is to clarify the mechanisms of the formation of the localized and systematically formed footprint traces, arc tracks and severe damages like melting of PFCs in QUEST. Analysis of the deposited materials on the collector probes is being performed using X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDS) to identify the eroded and redeposited materials in QUEST.

This paper is organized as follows. In Section 2, the experimental setup and conditions are presented. In Section 3, the details of the observed footprint traces and other PWI caused damages are explained. In Section 4, XPS, SEM and EDS analysis carried on the attached collector probes are discussed. In Section 5, the results are discussed in view of localized PWI, loss of energetic electrons, sputtering, arcing and redeposition of impurity materials. Finally, a conclusion is given in Section 6.

2. Experimental device and conditions

QUEST is a medium sized spherical tokomak device [13,14]. The major purpose of the device are (1) to examine the steady state current drive and the generation of closed flux configuration by electron Bernstein wave (EBW) current drive, (2) to establish recycling control with high temperature first walls, (3) to improve diverter concepts and (4) to obtain relatively high β (10%) plasma. The major and minor radii are ~0.68 m and ~0.4 m, respectively. The toroidal magnetic field B_T in these experiments was ~0.25 T. Hydrogen plasma was produced using 8.2 GHz RF system via electron cyclotron current derive and heating (ECCD and ECRH) with a typical RF input power of ~100 kW. The ohmic plasma was occasionally produced using a combination of central solenoid coils and the 8.2 GHz RF system; however the main focus of these experiments was on the non inductive current startup and current drive. Typically, the plasma discharge widths were kept within 1–3 s. Longer plasma discharges up to 42 s were also produced. The integrated discharge time until the last campaign exceeds 15,000 s. In the last experimental campaign, single null divertor plasma was also produced. The maximum achieved non inductive plasma current I_P was ~20 kA. Typical plasma density and temperature during these operations were ~10^{18} m^{-3} and <100 eV respectively. Typical magnetic field configurations (limiter and divertor) showing the magnetic flux surfaces using the measured flux values [15] are depicted in Fig. 1. The vacuum chamber consists of all metallic (stainless steel and tungsten) first walls. The top and bottom side divertor plates consist of atmospheric plasma sprayed (APS) tungsten, whereas cover of center stack (CS) consist of vacuum plasma sprayed (VPS) tungsten deposited on stainless steel. The inboard and outboard side limiters are made of bulk tungsten. Except the last campaign, the loss of positively charged ions due to their drifts caused by the inhomogeneous magnetic fields and curvature was towards the bottom side. In the last campaigns (winter 2010–2011), the direction of toroidal magnetic field was reversed causing the plasma ions drifted towards the top side. The temperature of the chamber walls was kept at ~100 °C. Hydrogen gas was fed into the vessel in pulse mode prior to the discharges with the help of a piezo electric valve. The pumping system for QUEST chamber consists of a turbo-molecular pump, having a pumping speed of ~1100 l/s and two externally installed cryo-pumps, each having a pumping speed of ~10,000 l/s. A more detail description of QUEST is given in [13,14].

3. Observed PWI caused damages

After three consecutive experimental campaigns in QUEST, which were mainly focused on the non-inductive current drive, the chamber walls have been examined for the post experimental analysis in view of investigating the PWI caused damages. Detailed description of the observed damages on the chamber walls would be presented in the following subsections.