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Dynamic interaction between disruptive plasma and wall in the small tokamak HYBTOK-II

M. Okamoto [a,*], T. Yamada [a], T. Hiraishi [a], Y. Kikuchi [b], N. Ohno [c], S. Takamura [a]

[a] *Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan*
[b] *Department of Electrical Engineering and Computer Sciences, Graduate School of Engineering, University of Hyogo, Hyogo 671-2280, Japan*
[c] *EcoTopia Science Institute, Nagoya University, Nagoya 464-8603, Japan*

Abstract

Dynamic behaviour of plasma–wall interactions has been investigated by using triple probe and H_α line emission of disruptive plasma in small tokamak HYBTOK-II. As the features of the disruption discharge of HYTOK-II, it was found that the waveform of plasma current quench has two phases of the first slow and the subsequent fast decays. The interaction between plasma and wall was found to be largest during fast decay phase in the course of whole discharge. The increase of plasma–wall interactions is thought to be caused by both of convective pump-out of the plasma particles in the core region and the rapid movement of plasma to the inner wall at the start time of two decay phases.

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1. Introduction

The tokamak disruption, which is accompanied by an intense heat load on the divertor during thermal quench and a large electromagnetic force on in-vessel components during current quench, is one of the most crucial issues for the next generation tokamak, like ITER. Expected energy fluxes at the thermal quench of ITER disruptions were estimated in the 1999 ITER Physics Basis [1] to be in the range of $\sim$30 MJ m^{-2} with a timescale of $\sim$1 ms. Energy fluxes in this range would cause vaporization and melting, possibly leading to a serious erosion and consequently to a reduction in component lifetime. If disruptions cannot be avoided then the heat load to the material surfaces must be mitigated. Recently, disruption mitigation by high-pressure gas jet in some tokamaks has successfully decreased the heat loads [2].

It is important to study the behaviour of heat fluxes to the wall in order to establish disruption mitigation techniques. The direct measurement

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[*] Corresponding author. Fax: +81 52 789 3944.
E-mail address: m-okamoto@ees.nagoya-u.ac.jp (M. Okamoto).

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inside the plasma during disruption may give a lot of information. However, it would be quite difficult in large tokamak devices. Small tokamaks have an advantage of inserting probes inside the plasma. It is realized indeed that the internal plasma parameters are measured by the triple probe inserted into the small tokamak HYBTOK-II. Simultaneously, the light emission from the wall region has been measured.

2. Experiments

HYBTOK-II is a small tokomak with a circular cross-section of limiter configuration. The major and minor radii are 40 and 11 cm, respectively [3]. The device is equipped with an insulated gate bipolar transistor (IGBT) inverter power supplies for Joule as well as vertical field coils so that plasma current and the horizontal position of plasma column may be well controlled by a priori specified waveform. In addition, the IGBT inverter power supply for Joule circuit is switched to a condenser bank during a discharge in order to avoid an unnecessary power input from the IGBT power supply during disruption. Real-time feedback control of the plasma horizontal position makes it possible to enhance the reliability of the observations. The plasma horizontal position was calculated by using MHD equation.

Fig. 1 shows the schematic view of poloidal cross-section of HYBTOK-II tokamak. The triple probe and the magnetic probe were installed at the bottom port. The light emission from the inner wall region of the tours is transmitted through optical filter to the spectroscope, and H_α line emission is detected by photomultiplier tubes. The examples of the discharge waveforms with disruption are shown in Fig. 2. Disruption has been driven by ramping-up the plasma current to reduce the plasma surface safety factor q_a ($=aB_t/RB_\theta$). In this experiment, the current quench occurred below $q_a = 3$ and it was observed that the horizontal position of plasma center shifted high field side. The waveform of plasma current quench was found to have two phases of slow and fast decays. Unfortunately, the plasma horizontal position during fast decay phase cannot be calculated.

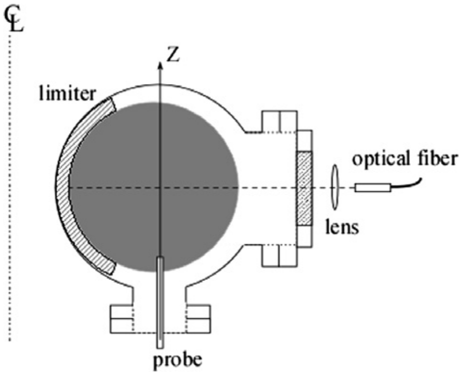

Fig. 1. Schematic view of poloidal cross-section. The limiter radius is 11 cm. The triple probe and the magnetic probe were scanned vertically for the measurement of internal plasma parameters and magnetic filed, respectively. The light emission is measured from the horizontal direction.

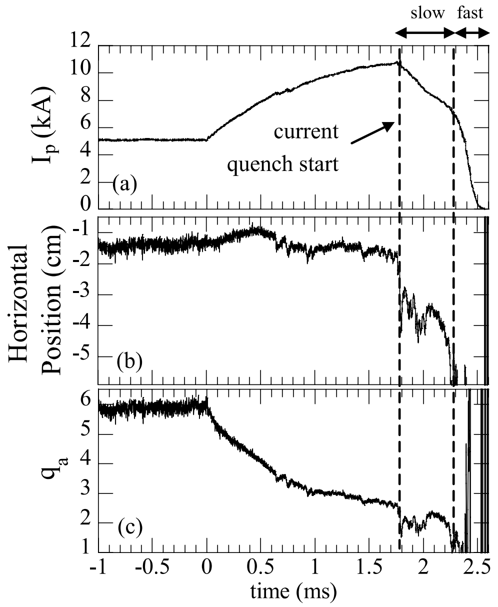

Fig. 2. Typical disruption waveform in HYBTOK-II ($B_t \sim 0.25$ T). Temporal evolutions of (a) plasma current I_p and (b) plasma horizontal position and (c) plasma surface safety factor q_a. The negative value of the plasma horizontal position corresponds to high field side.

3. Experimental result

3.1. Change of plasma energy and plasma–wall interactions during current quench

Dynamic behaviour of interaction between the plasma and the wall is discussed during current quench (CQ). Fig. 3 shows the temporal evolution of plasma current, horizontal position and H_α emission intensity at $z = 0$ cm during the current quench. The emission intensity of H_α increases from the

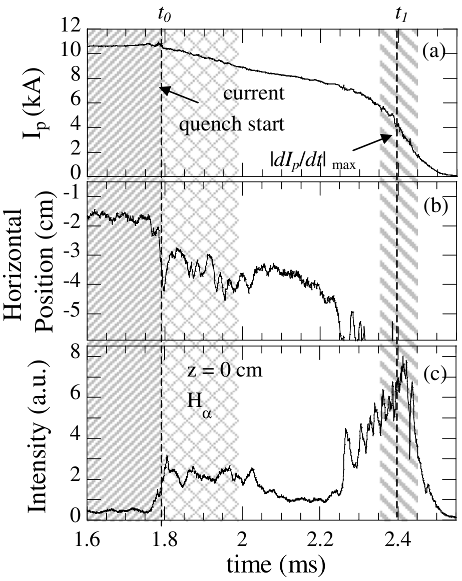

Fig. 3. Temporal evolutions of (a) the plasma current I_p and (b) the plasma horizontal position and (c) H_α line emission intensity at $z = 0$ cm during current quench.

current quench starting time t_0. The increase of plasma–wall interactions comes from an inward shift of the plasma column. However, it does not remain over the whole slow phase but decrease slightly during the latter half of slow decay phase. The detailed discussion of plasma–wall interactions during slow decay phase is described in next subsection. The emission intensity of H_α becomes largest at around t_1 during the fast decay phase when $|dI_p/dt|$ reaches maximum. Fig. 4 shows profiles of the electron pressure at three different timings: just before CQ (closed circles), slow decay (open squares) and fast decay phase (crosses). It is observed that the profile changes during the slow decay phase but the total electron kinetic energy remains almost constant. And the electron pressure during the fast decay phase becomes very low. So we understand a large part of the electron kinetic energy is lost during the fast decay phase due to the complete broken magnetic surface. It should be noted that the plasma position during fast decay phase might be shifted to inside tours compared with that during slow decay phase.

3.2. Cause of the change of plasma–wall interactions during slow decay phase

The dynamic interaction between plasma and wall during the slow decay phase is discussed here in more detail. Fig. 5 shows temporal evolutions of the plasma current and the electron pressure at the periphery $z = -10$ cm in the slow decay phase. In the previous subsection, it is considered that the increase of H_α line emission intensity is caused by shift of the plasma column. But it is impossible to explain the increase of the electron pressure in the edge region by only the shift of plasma. Fig. 6 shows the electron pressure profiles and ratios of the electron pressure and density and temperature profiles just before and after t_0. In the core region, the electron pressure and density after t_0 are lower than

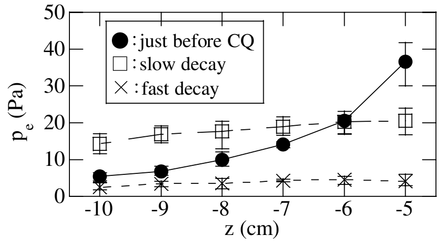

Fig. 4. Profiles of the electron pressure before current quench (closed circles), during slow decay phase (open squares) and during fast decay phase (crosses). The profile before the current quench is obtained by averaging over $t_0 \sim t_0 - 200$ µs. The profile during slow decay corresponds to the time averaged profile over 200 µs between t_0 and $t_0 + 200$ µs. t_0 means the timing of the current quench start as shown Fig. 3. Fast decay corresponds to time averaged profile over 100 µs time period centered at t_1. t_1 means the timing when $|dI_p/dt|$ reaches maximum as shown Fig. 3.

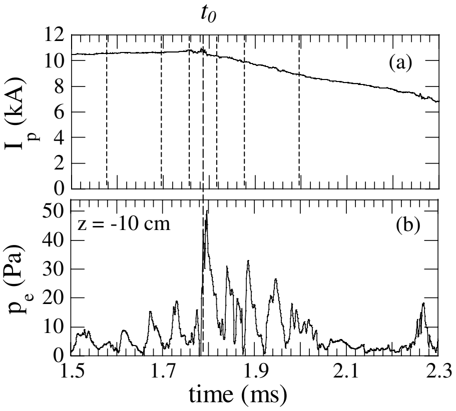

Fig. 5. Temporal evolutions of (a) the plasma current I_p and (b) the electron pressure p_e at $z = -10$ cm around current quench starting time t_0. Vertical dotted lines mean timings of $t = t_0 - 210$ µs, $t_0 - 90$ µs, $t_0 - 30$ µs, t_0, $t = t_0 + 30$ µs, $t_0 + 90$ µs and $t_0 + 210$ µs. t_0 means the timing when the current quench starts.

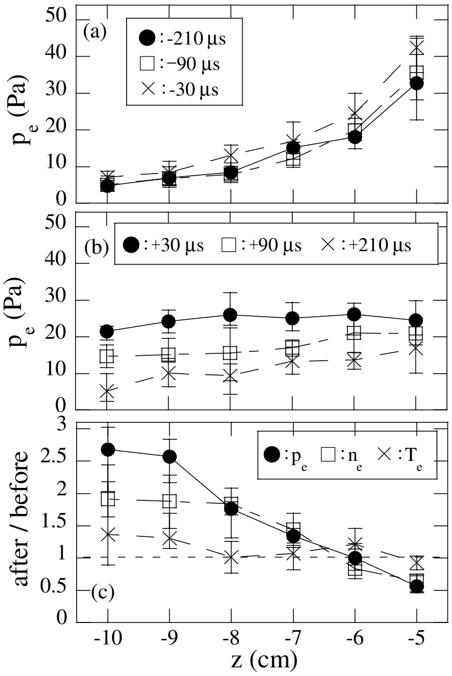

Fig. 6. (a) Electron pressure profiles averaged over 60 μs time period centered at $t = t_0 - 210$ μs, $t_0 - 90$ μs and $t_0 - 30$ μs as shown Fig. 5. (b) Electron pressure profiles averaged over 60 μs time period centered at $t = t_0 + 30$ μs, $t_0 + 90$ μs and $t_0 + 210$ μs. (c) Ratios of the electron pressure, density and temperature profiles obtained at $t = t_0 - 30$ μs and $t_0 + 30$ μs.

those before t_0. In the edge region, they become higher after t_0 than before t_0. It is found that the difference between T_e profiles before and after t_0 is small compared with the n_e difference because the n_e profile is peak compared with the T_e profile before the current quench. Therefore, it is considered that the convective pump-out of the plasma particles from the core region to the periphery occurred at t_0. Consequently, the inner wall in the high field side received particle fluxes instantaneously by both convective pump-out of the plasma particles from the core region and the shift of the plasma column. After t_0, the electron pressure profile returns to the peaked profile. It means that the confinement of the plasma particles is recovered and the loss of the plasma energy decreases. As a result, it is observed that plasma–wall interactions decrease during a latter half of the slow decay phase.

3.3. Cause of pump-out of plasma particles

Previous disruption research in HYBTOK-II, reveals that a rapid pump-out (~10 μs) of plasma current in the core region occurs at the current quench starting time [4]. According to various measurements, the following results were obtained: $m/n = 2/1$, 3/1 tearing modes grow during the plasma current ramp-up phase and that the value of plasma central safety factor q_0 may become below 1 just before current quench starting time. Therefore, It is speculated that the pump-out of the plasma current is caused by a nonlinear interaction between $m/n = 1/1$ internal kink mode and $m/n = 2/1$, 3/1 tearing modes.

Fig. 7 shows the temporal evolution of the plasma current, the internal poloidal magnetic field at $z = -5.5$ cm and the electron pressure at $z = -5$ cm around the current quench starting timet_0. We should note that $z = -5.5$ cm is close to the core region. It is observed the dramatic change of the internal poloidal magnetic field and the electron pressure just before t_0. The dramatic change of the internal poloidal magnetic field and the electron pressure correspond to the pump-out of the plasma current and particles in the core region, respectively. It is considered that the pump-out of the plasma particles is caused by the magnetic field line reconnection between the core and edge region due to a nonlinear interaction between $m/n = 1/1$ internal kink mode and $m/n =$ 2/1, 3/1 tearing modes. In fact, it is considered that the plasma particles in core region flow to the edge

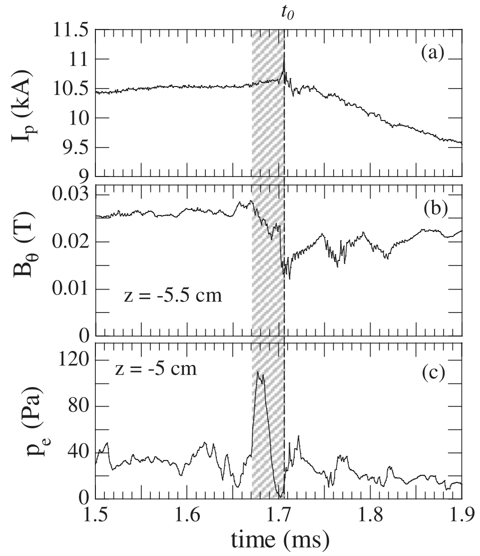

Fig. 7. Temporal evolution of (a) the plasma current I_p and (b) the internal poloidal magnetic field at $z = -5.5$ cm (c) the electron pressure p_e at $z = -10$ cm around current quench starting time t_0.

region following the connected magnetic field line. On the other hand, the magnetic field structure seems to return in the original structure, which has a long plasma confinement time, because the confinement of the plasma particles has been recovered at a latter half of slow decay phase.

4. Summary

In disruption discharge of HYBTOK-II tokamak, the waveform of plasma current quench has two phases. The wall received particle fluxes instantaneously by both convective pump-out of plasma particles in core region and the shift of the plasma column at current quench starting time. It is speculated that pump-out of the plasma particles is caused by the magnetic field line reconnection between the core and edge region due to a nonlinear interaction between $m/n = 1/1$ internal kink mode and $m/n = 2/1$, $3/1$ tearing modes. However, the total electron kinetic energy is not lost perfectly but remains at some extent by recovery of plasma particles confinement during a latter period of the slow decay phase. Finally, it is observed that the interaction between plasma and wall is largest during the fast decay phase but the mechanism of fast decay phase is not yet understood in the present study and it will be clarified in future.

Acknowledgement

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