Study of Current Decay Time during Disruption in JT-60U Tokamak

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Abstract. The plasma current decay time during initial phase of the radiation induced disruption in JT-60U tokamak is studied based on the plasma inductance and resistance estimated by experimental data. The features of this study are as follows; (i) the electron temperature profile during the current quench is estimated by the electron cyclotron emission (ECE) diagnostic systems and the measurement of He I line emission intensity ratios, and the plasma inductance is estimated by the CCS (Cauchy-Condition Surface) method with the magnetics [1]. (ii) in the radiation induced disruption plasmas, it is found that the time change rate of the plasma inductance during current quench is an important parameter as well as the plasma resistance to predict the current decay time.

1. Introduction

Disruption is one of the most crucial issues for the tokamak fusion reactors. Intense eddy currents and large halo currents generated during the current quench of the disruption induce large electromagnetic forces on the vacuum vessel and in-vessel components. The forces could be large enough to mechanically break the in-vessel components [2]. In order to estimate the force induced by eddy currents, precise prediction of plasma current decay time is important. The database for ITER (International Thermonuclear Experimental Reactor) [3] is established by using the current decay time τ normalized by the plasma cross-sectional area S. The area-normalized τ is induced by the L/R model based on a simple series circuit of the plasma resistance R_p and inductance L_p, where τ can be described by L_p/R_p. In this model, τ/S can be represented by $(L_p/2\pi R_0)/\eta_p$, it is little dependence on the device size and is strongly dependence on the electron temperature T_e and effective charge Z_{eff}, where R_0 and η_p are the plasma major radius and resistivity, respectively. In the database, the lower bound on area-normalized τ, which is taken as 1.7 ms/m^2 [4], is used as the criterion value for design of ITER.

In order to experimentally evaluate the validity of the L/R model, very low T_e and Z_{eff} during current quench must be measured by the diagnostic system with high time resolution. D. G. Whyte and D.A.Humphrevs had estimated the T_e and Z_{eff} during current quench using measurement of helium recombination radiation and reported the relation between the current decay time and classical resistivity [5,6]. However, the systematic analysis of the current decay time and electron temperature during current quench has not reported yet.

In this paper, the T_e profile during current quench is estimated by ECE diagnostic systems and measurement of He I emission intensity ratios. We verify the validity of L/R model using the initial phase of current quench of radiation induced disruptive plasma with $\tau/S = 5 \sim 40$ ms/m^2. The measurement of T_e using ECE diagnostic systems in plasma core region is

possible during initial phase of slow current decay disruption in JT-60U Tokamak. In the edge region, T_e can be estimated by He I emission intensity ratio. The fundamental validity of the T_e measurement based on He I emission line intensity ratio was confirmed by comparing with T_e measurement by Langmuir probes in JT-60U [7] and NAGDIS-II [8], etc. According to ref. 7, T_e estimated by He I line intensity ratio is almost same with T_e by the probe within the factor of 2 and the former is systematically smaller than the latter.

We analyze 9 disruptive plasma shots with massive neon gas puffing. The safety factor, toroidal magnetic strength and NBI power just before current quench is not same among the shots. In addition, the time evolution of plasma inductance during current quench is focused, and relation between current decay time and plasma inductance is evaluated. The equilibrium calculation of MHD, which is calculated by the CCS method, is used to estimate the plasma inductance.

2. Model of Current Decay Time

If tokamak plasma is assumed to be represented by a simple series circuit consisting of R_p and L_p, the energy conservation equation is expressed as

$$\frac{1}{2}L_p I_p^2 + \int_0^t R_p I_p^2 dt = \int_0^t V_{ex} I_p dt + \frac{1}{2}L_{p0} I_{p0}^2 \quad , \qquad (1)$$

where I_p and V_{ex} is the plasma current and the externally applied voltage, L_{p0} and I_{p0} is plasma inductance and current just before current quench, respectively. When Eq. 1 is transformed, it becomes the following circuit equation:

$$\frac{1}{2}\dot{L}_p I_p + L_p \dot{I}_p + R_p I_p = V_{ex} \quad . \qquad (2)$$

In the small tokamaks, the right-hand side of Eq. 2 cannot be neglect because the absolute value of the left-hand side of Eq. 2 is the same order of magnitude as the absolute value of V_{ex} [9]. On the other hand, the absolute value of V_{ex} is usually smaller than the left-hand side of Eq. 2 in the large tokamaks. This characteristic becomes more remarkable when device size becomes large. If R_p and L_p are constant in time, and V_{ex} can be neglect, the temporal evolution of I_p can be expressed by the following equation,

$$I_p = I_{p0} \exp(-t / \tau_{L/R}), \qquad (3)$$

where $\tau_{L/R} = L_p/R_p$ is the time constant of I_p decay. Equation 3 is valid when the current decay time is very short and plasma resistance is sufficiently large. When the current decay time can be approximated by $\tau_{L/R} = L_p/R_p$, the area-normalized current decay time τ/S can be expressed as

$$\frac{\tau_{L/R}}{S} = \frac{L_p / 2\pi R_0}{\eta_p} \quad , \qquad (4)$$

where R_0 is the plasma major radius, η_p is the plasma resistivity, and $\eta_p = R_p S/2\pi R_0$. $\tau_{L/R}/S$ has little dependence on the device size, because L_p is approximately proportional to R_0, and has a strong dependence on η_p, which is primarily determined by T_e and Z_{eff} in the classical Spitzer formula [10]. Thus, the database for ITER prediction is established in terms of the area-normalized current decay time τ/S [3]. However, when R_p and L_p greatly change in time, Eq. 4 cannot be valid. Therefore, to verify the L/R model, it is necessary to measure L_p and R_p in time during current quench experimentally.

3. Experimental Result

3.1. Relation Between Area-normalized Current Decay Time and Plasma Resistivity

In this paper, we study the current decay time in the radiation induced disruption by the massive neon gas puffing. The typical waveform of plasma current I_p, line integrated electron density $\overline{n}_e$, plasma stored energy W_p and gas pressure of neon at disruption are shown in Fig. 1. After neon gas puffing, line integrated n_e is gradually increased and W_p is decreased, and then the current quench and rapid increase of line integrated n_e are observed.

We focus on the current decay during the initial phase of the current quench shown by the region enclosed by dotted line in Fig. 2(a), where I_p drops by 10%, because the T_e profile can be estimated by ECE diagnostic systems experimentally. The experimental current decay time during initial phase of current quench is defined by the following equation,

$$\tau_{100-90\%} = I_{p0}\big/(\Delta I_p / \Delta t), \qquad (5)$$

where I_{p0} is the plasma current at the current quench start time. In this discharge, thermal quench is happened around at 12.089 sec and current quench is started about at 12.092 sec. From Fig. 2(c), it is found that T_e profile becomes flat at thermal quench and then returns to a peaked profile in the initial phase. In this phase, T_e in the core region is about 400 eV. Roughly speaking, because the optical thickness is small at $T_e < 100$ eV, the sensitivity of ECE diagnostic systems becomes low and T_e at normalized minor radius $\rho > 0.4$ cannot be estimated by ECE diagnostic systems. Here we use the He I emission intensity ratio method in
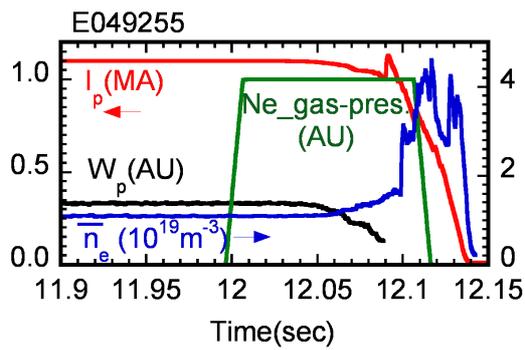
FIG. 1. The typical waveform of radiation induced disruption in JT-60U.
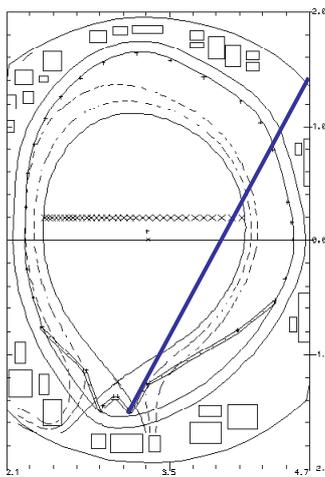
FIG. 3. Poloidal cross-section view of JT-60U plasma. Blue line means the line of sight for HeI spectroscopy.
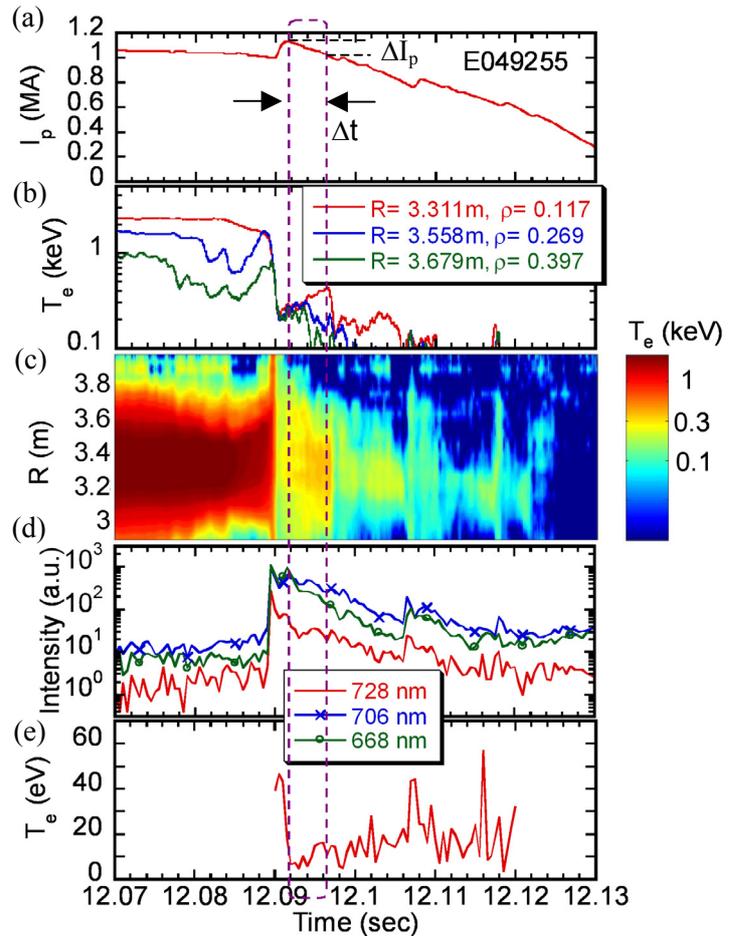
FIG. 2. The evaluation of (a) plasma current I_p and (b) electron temperature T_e measured by ECE diagnostic system, (c) major radial profile of T_e. , (d) He I emission intensity and (e) electron temperature by using HeI emission Intensity ratios method.

the case that the estimated T_e by ECE is less than 100 eV. In order to measure the electron temperature, it is necessary to to measure three He I lines at the same time of 667.8 (2^1P – 3^1D), 706.5 (2^3P – 3^3S) and 728.1 nm (2^1P – 3^1S) respectively. A spectrometer equipped with three band pass interference filters makes it possible to measure the time evolution of T_e with a sufficient time resolution. Figure 3 shows the line of sight for measurement of ECE (crosses) and He I emission intensity (solid line). The He I emission intensity is measured from the outer diverter region though the edge region of $\rho > 0.7$. Figure 2(d) and (e) shows the measurement result of He I emission intensity and the estimated electron temperature. From Fig. 2(d), it is found that He I emission intensity increase rapidly about at $t = 12.089$ sec, which is the thermal quench start time.

Before the thermal quench, the He I emission mainly comes from the diverter region because He neutrals only exist in this region. On the other hand, after the thermal quench, the He I emission comes from the edge region also because T_e rapidly decreases in the whole region due to the thermal quench. Since the measurement value of He I emission intensity is the integration value on line of sight and the measurement position of T_e estimated by He I emission intensity ratio cannot specify, it's position is assumed $\rho = 0.7$.

Figure 4 shows the assumed T_e profile using measurement values of ECE diagnostic systems and He I emission intensity ratios method at $t = 12.094$ sec. In this figure, opened circles and cross mean T_e estimated by ECE systems and He I spectroscopy, respectively. The T_e of $\rho = 0.4 - 0.7$ and $0.7 - 1$ is assumed by a linear function. Unfortunately, we cannot obtain the accurate profile of the plasma resistivity because the plasma effective charge Z_{eff} cannot be measured in the initial phase of current quench. In order to speculate Z_{eff}, we use the ionic fraction data of neon calculated by Arnaud and Rohtenflug [11]. If the mixing ratios of deuterium and neon gas are 9 : 1, 7 : 3 and 1 : 1 and these ratios are uniform in space, the calculation results of Z_{eff} and η_p are shown in Fig. 5. The η_p is calculated by Spitzer formula and assumed Z_{eff}. In Fig. 5, the upper and lower values of error bar are values calculated using assumptions of D : Ne = 1 : 1 and 9 : 1, respectively. The values of Z_{eff} in the core and edge region are about 7 and 2, respectively.

In order to investigate the relation between area-normalized τ and plasma resistivity, we
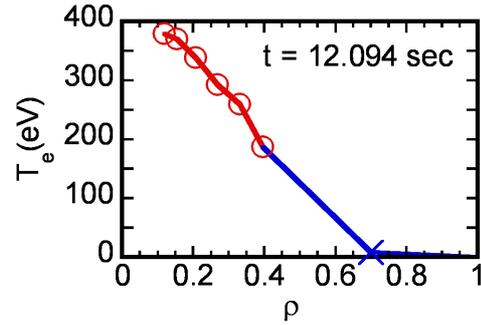
FIG. 4. Profile of electron temperature measured by ECE systems and He 1 spectroscopy at t = 12.094 sec.
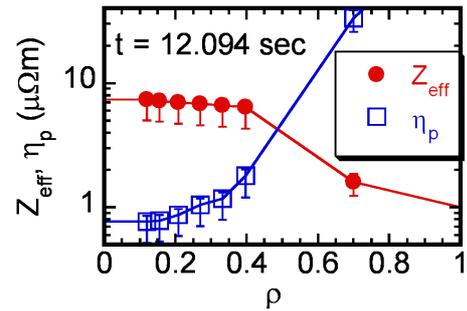
FIG. 5. Profile of plasma effective charge and resistivity at t = 12.094 sec. The effective charge is calculated using the assumption of D : Ne = 9 : 1, 7 : 3 and 1 : 1.
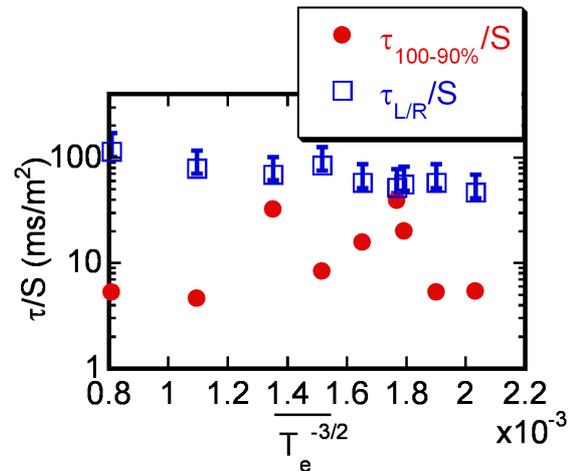
FIG. 6. The area-normalized current decay time as a function the area-averaged $T_e^{-3/2}$

use area-averaged $T_e^{-3/2}$ calculated by

$$\overline{T_e^{-3/2}} = S \Big/ \sum (\Delta S / T_e^{-3/2}), \qquad (6)$$

where S is the plasma cross-section area. This value is proportional to the area-averaged plasma resistivity $\overline{\eta}_p$ with $Z_{eff} = 1$. The area-averaged η_p can be estimated by η_p profile in Fig.5 and following equation,

$$\overline{\eta}_p = S \Big/ \sum (\Delta S / \eta_p). \qquad (7)$$

The relation between area-normalized τ and area-averaged $T_e^{-3/2}$ is shown in Fig. 6. In Fig. 6, the $\overline{T_e^{-3/2}}$ is calculated by Eq. 6 and the profile of time averaged $T_e^{-3/2}$ during the initial phase of current quench. In the similar way, $\tau_{L/R}/S$ is calculated by Eq. 4, 7 and the profile of time averaged η_p. The upper and lower values of error bar of $\tau_{L/R}/S$ are values calculated using assumptions of D : Ne = 9 : 1 and 1 : 1, respectively. It is found that the experimental area-normalized τ is independent of the area-averaged $T_e^{-3/2}$ and the prediction area-normalized decay time $\tau_{L/R}/S$ calculated from L/R model is much longer than the experimental value, especially in the case of small experimental values. It seems that this result means the L/R model does not verify and L_p is not constant and greatly changes in time during initial phase of current quench.

3.2. Time Evolution of Plasma Inductance using CCS Method

We use the CCS method using magnetic sensor signals due to evaluate the temporal evolution of plasma inductance and plasma shape. This method can obtain the exact analytical solution based on the boundary element method using a static Maxwell equation with a Green function in a toroidal axisymmetric region [1]. In a case of several magnetic sensors, we can obtain the approximate solution of the magnetic field and flux according to the accuracy and the number of sensors. It was confirmed that the error of Shafranov lambda value calculated by this method is less than 0.1 in JT-60U measurement systems, which have 12 magnetic coils and 15 magnetic flux loops. Figures 7 show the results calculated by using a Cauchy condition (both Dirichlet and Neumann conditions) on a hypothetical surface. From Fig. 7(d), because R_0 is almost constant and S changes a little, plasma column hardly moves in the initial phase of current quench. In Fig. 7(b), since the plasma internal inductance l_i is decrease rapidly around at $t = 12.089$ sec, the current density profile becomes flat at thermal quench. This result is consistent of the measurement of T_e using ECE systems as Fig. 1(c). After the flatting of current density profile, it is found that l_i much
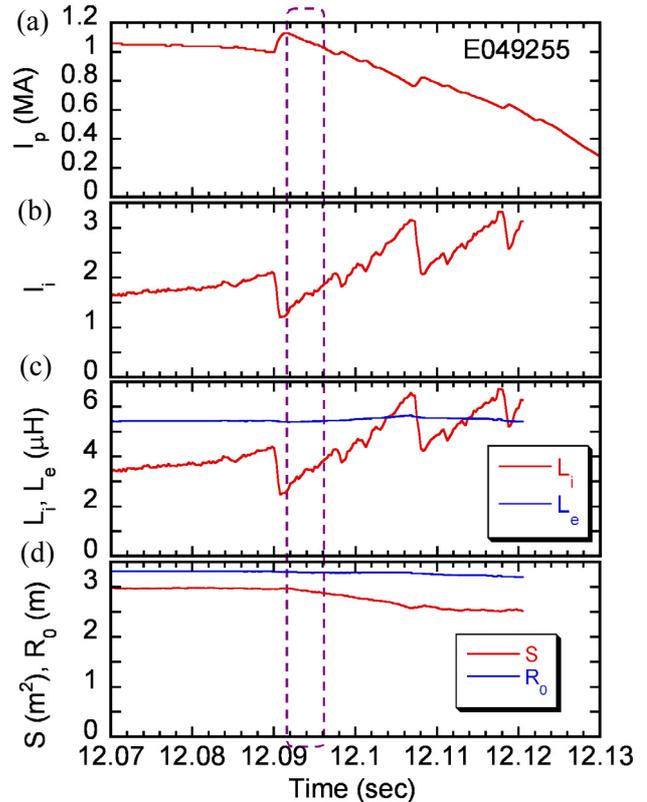
FIG. 7. The evolution of (a) plasma current, (b) plasma internal and inductance,(c) plasma internal and external inductance and (d) plasma cross-section and major radius evaluated by CCS method .

increases in time. This result is also consistent of ECE measurement results because T_e profile changes peaked profile in   Fig.1 (c). In Fig. 7(c), the plasma internal and external inductance is calculated by following equations,

$$L_i = \mu_0 R_0 l_i / 2, \qquad (8)$$

$$L_e = \mu_0 R_0 \left(\ln 8 R_0 / a - 2 \right), \qquad (9)$$

where a is the plasma minor radius. It is found that time change rate of L_i is much larger than that of L_e and time change rate of L_p is mainly determined by that of L_i.

FIG. 8. The plasma resistance R_p, the plasma inductance L_p and the time change rate of the plasma inductance as a function of current decay time.

Figure 8 shows the comparison of absolute value of R_p, L_p and time change rate of L_p in the initial phase of current quench. The R_p and L_p are calculated by $R_p = 2\pi R_0 \overline{\eta}_p / S$ and $L_p = L_i + L_e$, respectively and these values are time averaged values during initial phase of current quench. It is found that the absolute value of time change rate of L_p is the same order of magnitude as that of R_p or much larger than R_p in the short current decay time region. In addition, the experimental current decay time is dependent on the time change rate of L_p. Therefore, it is necessary that the time change rate of L_p is taken into account in the circuit equation in order to accurately predict the current decay time in the initial phase of current quench.

3.3. Current Decay Model during Initial Phase of Current Quench

From Eq. 2 with $V_{ex} = 0$, we obtain the following equation:

$$\frac{\dot{I}_p}{I_p} = -\frac{\dot{L}_p / 2 + R_p}{L_p}. \qquad (10)$$

To simplify the equation, if $\dot{L}_p = \Delta L_p / \Delta t$, R_p and L_p is constant in time, the prediction current decay time τ_{model2} can be represented by

$$\tau_{model2} = \frac{L_p}{\Delta L_p / 2\Delta t + R_p}. \qquad (11)$$

FIG.9. The comparison of the experimental value and the model prediction value of current decay time in initial phase of current quench.

Figure 9 shows the comparison of prediction times, which are calculated by L/R model and Eq. 11, and experimental time. As shown in Fig.8, although is $\tau_{L/R}$ much larger than the experimental decay time in the short decay time region, τ_{model2} is same order of magnitude as experimental decay time in some disruptive discharges and experimental decay time increases with τ_{model2}. The time evolution of plasma inductance is almost determined by the change rate of plasma internal inductance. The above result indicates that the change rate of the plasma internal inductance associated with current profile plays a key role to predict the precise current decay time during initial phase of current quench in JT-60U radiation induced disruptive plasmas. Here it should be noted the absolute value of τ_{model2} is not quite same as that of the experimental decay time in Fig. 9. This result is mainly from an estimation error of plasma inductance because the

dependency of experimental decay time on T_e would be smaller than that on time change rate of L_p. As the candidate of the estimation error of inductance, the neglect of the eddy current during current quench in the CCS method should be considered in near future.

4. Summary

We have investigated the current decay time using the initial phase of JT-60U radiation induced disruptive discharges experimentally. The plasma resistance is estimated by ECE diagnostic systems and He I emission intensity ratios and the plasma inductance is calculated by CCS method using magnetic sensor signals. It is experimentally confirmed that the area-normalized decay time in initial phase of current quench is independent of the electron temperature and decay time calculated from L/R model is larger than the experimental decay time. This result indicates that the plasma inductance greatly changes in time.

The time change rate of plasma inductance estimated by CCS method is the same order of magnitude as plasma resistance or much larger than plasma resistance. So, we consider a new model of the current decay time, which is taking the time evolution of the plasma inductance into account in the circuit equation. The prediction of the current decay time predicted by the new model is strongly dependent on the experimental time and these absolute values are almost same. Therefore, the change rate of the plasma internal inductance plays a key role to predict the precise current decay time during initial phase of current quench in JT-60U tokamak. Here, it should be noted the new prediction value is not quite same as the experimental value. As the reason of this result, the neglect of the eddy current during current quench in the CCS method is considered. As the future works, we should improve the CCS method by taking the eddy current effect into account and make sure the validity of the CCS method through the direct measurement of the current profile like the MSE. In this paper, we have just investigated the validity of L/R model. As a next step, we should investigate what dominate the time change rate of the plasma inductance. This is one of our future subjects.

References
[1]   Kurihara K., Fusion Eng. Des., **51-52** (2000) 1049.
[2]   Masaki K., Ando T., Kodama K., Arai T. et al., J. Nucl. Mater. **220-222** (1995) 390.
[3]   Progress in the ITER Physical Basis, Nuclear Fusion **47** (2007) S171.
[4]   Wesley J.C., Hyatt A.W., Strait E. J. and Schissel D. P. et al., Proceedings of 21st IAEA
       Fusion Energy Conference, Chengdu, 16-21 Oct. (2006) IT/P1-21.
[5]   Whyte D.G., Humphrevs D.A. and Taylor P. L., Phys. Plasma **19** (2000) 4052.
[6]   Humphrevs D.A. and Whyte D.G., Phys. Plasma **19** (2000) 4057.
[7]   Kubo H., Goto M. and Takenaga H. et al., J. Plasma and Fusion Res., **75** (1999) 945.
[8]   Kajita S., Ohno N. and Takamura S. et al., Physics of Plasmas, **13** (2006) 013301.
[9]   Okamoto M., Ohno N. and Takamura S., J. Plasma and Fusion Res., **3** (2008) 006-1.
[10]   Spitzer L. and Härm R., Physical Review **89 (**1953) 977.
[11]   Arnaud M., Rohtenflug R., Astron. Astrophys. Suppl. Ser. **60** (1985) 425.