Development of Real-Time Measurement System of Charge Exchange Recombination Spectroscopy and Its Application to Feedback Control of Ion Temperature Gradient in JT-60U

Shinji KOBAYASHI, Maiko YOSHIDA[1)], Hidenobu TAKENAGA[1)], Shinya SAKATA[1)], Yutaka KAMADA[1)], Yoshiteru SAKAMOTO[1)], Yoshihiko KOIDE[1)] and the JT-60 Team

Institute of Advanced Energy, Kyoto University, Gokasho, Uji 611-0011, Japan
[1)]*Japan Atomic Energy Agency, Naka 311-0193, Japan*

(Received 4 December 2006 / Accepted 27 June 2007)

Real-time measurement system of the ion temperature profile has been developed for the feedback (FB) control of the ion temperature gradient (grad-T_i) with the filter charge exchange recombination spectroscopy (CXRS) system in JT-60U. The rapid analytical scheme without non-linear least square fitting enables us to calculate the ion temperature with four spatial points every 10 ms using a real-time processor system. The FB control experiment of grad-T_i has been demonstrated in ELMy H-mode plasmas by use of the neutral beam injectors having different deposition profiles as actuators. Grad-T_i was controlled to the reference value in the ramp-down phase, however, it did not recovered in the ramp-up phase because the internal transport barrier or transport was affected by the ramp-down of grad-T_i. From the transient response analysis of grad-T_i, the increase in the central T_i using the additional heating was required to recover the deteriorated grad-T_i.

Keywords: filter charge exchange recombination spectroscopy, real-time measurement, feedback control of temperature gradient

DOI: 10.1585/pfr.2.S1049

1. Inroduction

In magnetically confined plasmas, the real-time feedback control of the radial profile of the plasma pressure (density times temperature) is subject not only for sustaining the high performance plasma with internal transport barrier (ITB) but also for avoiding the disruptive MHD instabilities due to the steep pressure gradient [1]. The feedback control of the plasma pressure requires the special resolved real-time measurements in both densities and temperatures of the ions and electrons, In the progress in the feedback control system of JT-60U, the real-time measurement system of the electron density has been developed using the far-infrared interferometer [2]. The feedback control of the radial profile of the electron temperature has been demonstrated with the fast electron cyclotron emission radiometer system [3]. For the radial profile of the ion temperature (T_i), on the contrary, the real-time measurement system has not been proceeded because of the complicated analytical scheme of the ion temperature.

Recently, we developed the high time-resolved measurement system of the ion temperature and its rapid analytical scheme using the filter charge exchange recombination spectroscopy (filter CXRS) [4]. Utilizing the filter CXRS system to the real-time monitor of the ion temperature, we carried out the demonstration of the feedback control experiment of the core T_i in JT-60U [5]. In order to control the gradient of the ion temperature (grad-T_i) in real-time, we expand the filter CXRS system to the real time monitoring system of the radial profile of the ion temperature. One of the simplest ways of the feedback control of grad-T_i is to change the core T_i with changing the total heating power such as neutral beam (NB) injection. In this scheme, the scale length of the ion temperature gradient (grad-T_i/T_i) would be constant within the limit of the critical gradient. The control of the deposition profile of the heating is another way to change grad-T_i. This method has some possibility of controlling the pressure gradient near the rational surfaces where MHD instabilities occur. In this study, the feedback control experiment of grad-T_i is demonstrated in the ELMy H-mode plasmas with ITB using two NB deposition regions, core and edge depositions. By use of the feedback control scheme, the transient response of the grad-T_i is analyzed to discuss the problem in the feedback control of grad-T_i together with the plasma confinement.

author's e-mail: kobayashi@iae.kyoto-u.ac.jp

2. Experimental Apparatus

T_i in fusion plasmas is generally evaluated from the charge exchange recombination spectroscopy [6]. The charge exchange recombination (CXR) reaction is a collision between the impurity ions and hydrogen atoms, resulting the subsequent decay with photon emission. In the standard CXRS system, the spectral profile of the CXR

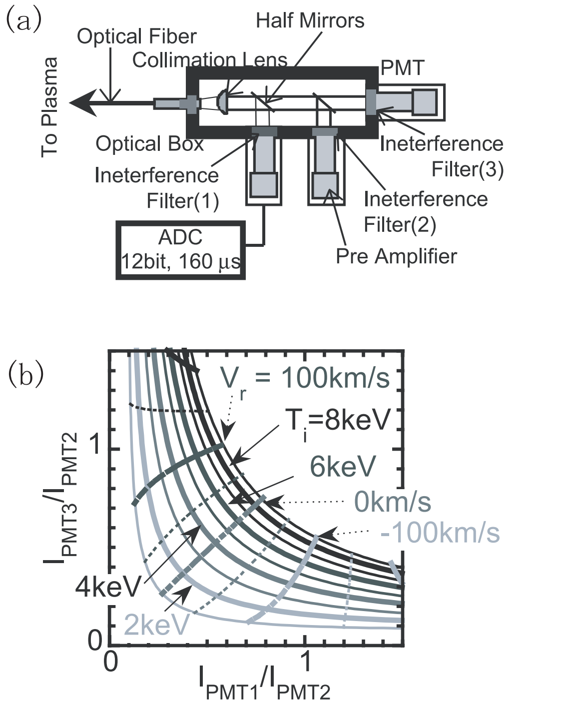

Fig. 1 (a) Schematic view of the filter charge exchange recombination spectroscopy, and (b) relation between intensity ratios of I_{PMT1}/I_{IPMT2} and I_{PMT3}/I_{PMT2} and the ion temperature and rotation velocity.

emission from the collisions with the energetic neutrals of NB is obtained using the monochromator and the CCD camera system. T_i and rotation velocity (V_r) are estimated from the Doppler broadening and the Doppler shift of the spectral profile of the CXR emission using the non-linear least square fitting procedure, respectively. In the filter CXRS system, on the contrary, the three-filters assembly is used to determine the Doppler broadening and the Doppler shift. As shown in Fig. 1 (a), the filter CXRS system for the carbon CXR line (CVI $n = 8 \rightarrow 7$, $\lambda_0 = 529.06$ nm) consists of a fiber-optic bundle, a collimation lens, beam splitting mirrors, and three Fabry-Perot interference filters mounted in front of the high-sensitivity photomultiplier tubes (PMTs, HAMAMATSU: R-1104). The collimation lens is used to make a parallel light, and one-third and half-mirrors split the light to the each PMTs. The bandwidth of each filter at full width at half-maximum (FWHM) $\Delta\lambda_{FWHM}$ is used from 0.2 nm to 1.0 nm according to target T_i and V_r. Three interference filters in the assembly have slightly different center wavelengths (CWL) to obtain the spectral emission of the CXR reaction. For instance, for the target value of T_i around 1keV, the bandwidth of the each filter is 0.2 nm and the differences between the center wavelengths of the three filters λ_{CWL} and λ_0, $\Delta\lambda_{CWL}$ (i.e. $\Delta\lambda_{CWL} - \lambda_0$) is selected to be −0.2, 0.0, and +0.2 nm, respectively.

The analytical method for the determination of T_i used in the three-filters assembly is as follows: The measured

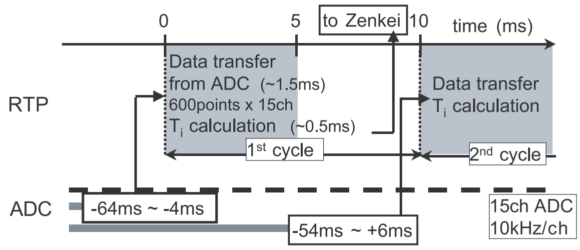

Fig. 2 Time chart of the data analysis in the real-time processor system for real time monitoring of ion temperature profile using the filter CXRS system.

intensity of the CXR emission of j-th channel I_{PMTj} is represented by

$$I_{PMTj} \propto \int \eta_j \alpha_j(\lambda) f(\lambda) d\lambda \qquad (1)$$

where η_j and $\alpha_j(\lambda)$ are the sensitivity of PMT and the spectral transmission profile of the interference filter at j-th channel, respectively. In this formula, we assume a Maxwellian distribution function of T_i to obtain the spectral profile of the CXR emission $f(\lambda)$, depending on both T_i and V_r. Then, the intensity ratios, which are defined as the ratios of the intensity at the central wavelength channel to that of the shorter wavelength channel I_{PMT1}/I_{PMT2} and to the longer wavelength channelI_{PMT3}/I_{PMT2}, can be determined as functions of T_i and V_r. The spectral sensitivity of the filter assemblies $\eta_j\alpha_j(\lambda)$ is determined from the calibration experiment. The relation between the intensity ratios, I_{PMT1}/I_{PMT2} and I_{PMT3}/I_{PMT2}, and T_i and V_r is shown in Fig. 1 (b). Finally, the fitting function of T_i can be summarized following formula,

$$T_i = 10^{\left\{\sum_{i,j=0}^{4} a_{ij} \mathrm{Log}(I_{PMT1}/I_{PMT2})^i \times \mathrm{Log}(I_{PMT3}/I_{PMT2})^j\right\}} \qquad (2)$$

The above analytical method without non-linear least square fitting enables us to calculate T_i rapidly with the filter CXRS system.

Real-time processor (RTP) system in JT-60 has been improved in order to apply the filter CXRS system to the real-time measurement of the radial profile of T_i [7]. Figure 2 shows the time chart of the data processing in RTP. To prevent the scattering of T_i, the raw data acquired in an analog-digital converter (ADC) is averaged for 60 ms (600 points). In this system, four spatial points of T_i can be calculated using the fitting functions. These processes are managed in less than 5 ms and the obtained T_i profile is transferred to the discharge control system of JT-60U, Zenkei, in every 10 ms. The detailed radial profile of T_i and V_r is measured with the conventional CXRS system using the monochromator and the CCD camera [8].

3. Feedback Control of Ion Temperature Gradient

The control scheme of grad-T_i is described as follows:

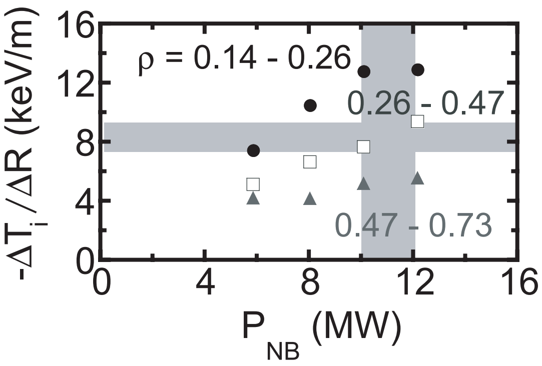

Fig. 3 Dependence of the ion temperature gradient on the NB heating power in the ELMy H-mode discharge at I_p/B_t = 1.0 MA/2.67 T and n_e = 2.0-2.4 × 10^{19} m^{-3}.

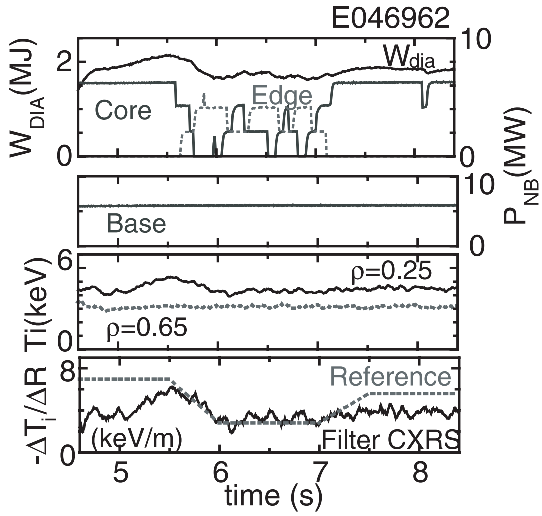

Fig. 4 Time evolution of the plasma stored energy, the NB power for core, edge and base heating, the ion temperature and the ion temperature gradient of the reference value and measurement obtained in the real-time feedback control experiment of ion temperature gradient.

(i) By use of the real-time measurement system of T_i profile with the filter CXRS system, the gradient of observed T_i between two spatial positions ($\Delta T_{CXR}/\Delta R$) is compared with the pre-programmed reference value ($\Delta T_{REF}/\Delta R$). (ii) In order to control grad-T_i, we try to change the heating deposition profiles using NB injections. Several units of NB are categorized into two groups; core and edge heating depositions. One of the NB units for the base plasma heating is also used for the CXRS diagnostic. The number of NB units is determined as,

$$U_{Core} = G_p^{Core}\,\Delta T\,(t) + G_D^{Core}\,\frac{\Delta T\,(t)\;-\;\Delta T\,(t\;-\;\Delta t)}{\Delta t} \qquad (3)$$

$$U_{Edge} = G_p^{Edge}\,\Delta T\,(t) + G_D^{Edge}\,\frac{\Delta T\,(t)\;-\;\Delta T\,(t\;-\;\Delta t)}{\Delta t} \qquad (4)$$

where U, G_p, G_D and $\Delta T(t)$ are the number of NB units, proportional gain, differential gain and the difference of grad-T_i between the measurement and reference values (i.e. $\Delta T_{REF}/\Delta R - \Delta T_{CXR}/\Delta R$) at time t, respectively. The subscripts or superscripts of "Core" and "Edge" mean the core and edge NB heating depositions, respectively. The first term of the formula shows that the NB units for core or edge heating are determined according to the deviation from the reference value. The second term is used to restrict the rapid change in ΔT in the case of the overshoot or undershoot of grad-T_i by the change in the NB heating power.

Prior to the feedback control experiment of grad-T_i, we investigated the target range of grad-T_i from the power scan experiment obtained in JT-60U. Figure 3 shows the dependence of the grad-T_i on the NB heating power (P_{NB}). In this discharge, P_{NB} was increased step by step in the ELMy H-mode plasma at I_p/B_t = 1.0 MA/2.67 T, where I_p and B_t are the plasma current and the magnetic field strength, respectively. One unit of NB almost corresponds to the injection power of 2 MW. Grad-T_i at the core region between ρ = 0.14 and 0.26 increased with P_{NB} and almost saturated above 10 MW. It was found that the grad-T_i also increased as close to the center position. The result shows that the NB power of 10 or 12 MW (i.e. five or six NB units) are needed to obtain the grad-T_i around $-7\sim-9$ keV/m at the radial position from ρ = 0.26 to 0.47. In that case, the ratio of the core NB power to the total NB power was around 0.2.

The demonstration of grad-T_i feedback control experiment is shown in Fig. 4 observed in the ELMy H-mode plasmas at I_p/B_t = 1.0 MA/2.27 T. In this experiment, the reference value of the temperature gradient $\Delta T_{REF}/\Delta R$ was pre-programmed to be in the range from −6.9 to −2.8 keV/m at the measurement positions between ρ = 0.26 to 0.65. The maximum NB units for the base, core and edge heating was 3 (= 6 MW) each other. We adopted the same proportional gain by 1.2 for core and edge heating, that is, the minimum value of the controllable grad-T_i was equivalent to ±0.8 keV/m and the total NB unit for core and edge heating was kept constant. As shown in Fig. 4, the core and edge NB heating was controlled in real time according to the difference in grad-T_i. In the earlier phase, measured gradient $\Delta T_{CXR}/\Delta R$ reached to the reference value at 5.5 sec as ITB grew, and $\Delta T_{CXR}/\Delta R$ was almost controlled to the reference in the ramp down phase. In the ramp-up phase after 7.2 sec, however, $\Delta T_{CXR}/\Delta R$ did not recover up to the reference.

To clarify the transient response of the grad-T_i on the heating, the relation between grad-T_i and the ratio of the core NB power to the total NB power ($P_{NB}^{core}/P_{NB}^{total}$) is examined. Figure 5 shows the time history of grad-T_i at ITB between ρ = 0.25 and 0.45 deduced from the CCD CXRS system as a function of $P_{NB}^{core}/P_{NB}^{total}$ in the phases of ramp-down (5.4 s < t < 6.0 s) and ramp-up (6.8 s < t < 7.4 s).

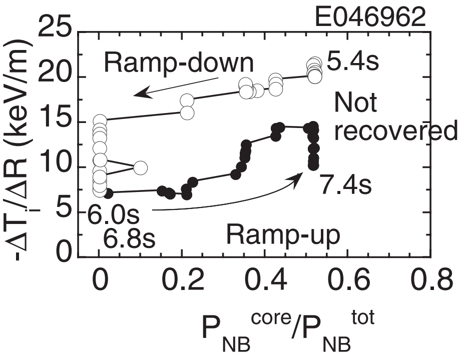

Fig. 5 Time history of the ion temperature gradient at ITB as a function of the NB core heating efficiency.

In the ramp-down phase, grad-T_i decreased with decreasing the core heating efficiency. In the ramp-up phase, it did not recover to the initial condition even in the same core heating fraction, because increase in core T_i was insufficient as shown in Fig. 4. This phenomenon is ascribed to the degradation of ITB or the deterioration of the plasma transport due to the change in the heating deposition profile after the ramp-down of grad-T_i. Although the transport analysis has not been carried out yet, the degradation of the global confinement was expected from the beam absorption analysis. That is, the stored energy decreased about 10 % after the ramp-down of grad-T_i, however, the reduction in the NB absorption power in the low grad-T_i phase at $t = 6.8$ s was less than 5 % of that at $t = 5.2$ s (high grad-T_i phase). The recovery of the grad-Ti may be prevented by the change in the confinement. An MHD activity rotating with the plasma rotation was destabilized after $t = 5.5$ s, which was one of the reasons for the confinement degradation. The histeresis-like characteristics of grad-T_i shows the increase in the central T_i using the additional core heating is required to recover the grad-T_i in the case where ITB was degraded.

4. Issue and Future Plan

In this study, the grad-T_i was determined from the temperature differences between only two locations. In order to select the suitable location of the target gradient to be controlled, the measurement points of T_i should be improved. The combination of the feedback controls for central T_i and grad-T_i is one of the ways to control deteriorated grad-T_i, because the recovery of central T_i may improve the transport. To clarify the profile controllability on the heating actuators, further experiment and analysis are needed with respect to the relation of time scales of grad-T_i toward the change in the heating deposition profile.

Acknowledgments

The authors acknowledge the members of the Japan Atomic Energy Agency (JAEA) who have contributed to the JT-60U projects. The authors would like to thank Dr. Oyama and Dr Matsunaga of JAEA for their helpful discussions and suggestions. This work was supported by the collaboration program between JAEA and Kyoto University.

[1] Y. Shimomura *et al.*, Plasma Phys. Control. Fusion **43**, A385 (2001).
[2] T. Fukuda *et al.*, Fusion Sci. Tech. (JT-60 Special Issue) **42**, 357 (2002).
[3] N. Isei *et al.*, Fusion Eng. Des. **53**, 213 (2001).
[4] S. Kobayashi *et al.*, J. Plasma Fusion Res. **79**, 1043 (2003).
[5] M. Yoshida *et al.*, Trans. Fusion Sci. Tech. (submitted).
[6] R.J. Fonck, D.S. Darrow and K.P. Jaehnig, Phys. Rev. **A 29**, 3288 (1984).
[7] S. Sakata *et al.*, Fusion Eng. Des. **48**, 225 (2000).
[8] Y. Koide, A. Sakasai, Y. Sakamoto *et al.*, Rev. Sci. Instrum. **72**, 119 (2001).