SPECTROSCOPIC MEASUREMENT IN THE TANDEM MIRROR GAMMA 10 FOR PLASMA CONFINEMENT AND IMPURITY DIAGNOSTICS

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ABSTRUCT

We have constructed two dimensional Hα line emission measuring system to study neutral hydrogen behavior. Then we can obtain the two dimensional radial profiles of hydrogen density by considering atomic processes including collisional-radiative model. While in the range of vacuum ultraviolet (VUV) we have constructed space- and time-resolving spectrograph (15 - 105 nm) to study ion density profiles which directly related to the impurity transport. We measured both Hα line-emission and VUV spectra on the hot ion mode experiments in the GAMMA 10 for studying plasma particle confinement and impurity diagnostics. Then we found that the particle confinement and energy confinement of GAMMA 10 plasma were improved slightly better during electron cyclotron resonant heating(ECRH) than without ECRH. From the VUV measurement we could identified that the impurity ions mainly came into the plasma during its rising time.

I. INTRODUCTION

Measurements of spatial and temporal variation of the spectra are necessary to determine the radiation power losses, density profiles of both ions and atoms which directly relate to the particle transport, confinement, sources and other plasma parameters which obtained by using some models on plasma spectroscopy in the magnetically confined plasmas. We have constructed a two dimensional Hα line-emission measuring system to measure both horizontal and vertical radial profiles of Hα line-emissions in the central cell of the GAMMA 10 tandem mirror. Then we can obtain the two dimensional radial profiles of hydrogen density by considering atomic processes including collisional-radiative (CR) model. Neutral hydrogen behavior is an important subject to clarify in order to discuss particle balance and particle confinement on magnetically confined plasmas. In plasmas produced in the tandem mirror GAMMA 10, the electron temperature is rather low, about several tens of eV, compared with the ion temperature, several keV, in the central mirror region.[1,2] Then vacuum ultraviolet (VUV) spectroscopic measurements provide information about confined core plasma. Recently, we have constructed space- and time-resolving spectrographs in VUV region by using an entrance slit, a concave grating, a two dimensional detector and a charge coupled device camera.[3-7]

This article describes the Hα line-emission measuring system and analyzing method to obtain the two dimensional Hα radial emissions. Moreover we show the results of measurements of both Hα line-emissions and VUV spectra on the hot ion mode experiments in the GAMMA 10 for studying plasma particle confinement and impurity diagnostics. Then we found that the particle confinement and energy confinement of GAMMA 10 plasma were improved slightly better during electron cyclotron resonant heating(ECRH) than without ECRH. From the VUV measurement we could identified that the impurity ions mainly came into the plasma during its rising time.

II. TWO DIMENSIONAL Hα LINE-EMISSION MEASUREMENTS ON THE GAMMA 10

A. Hα Line-Emission Measuring System

We used two Hα line-emission detector arrays set at near the midplane of the GAMMA 10 central cell (Fig. 1). One is for vertical measurement of Hα emission and another is for horizontal one. Each Hα

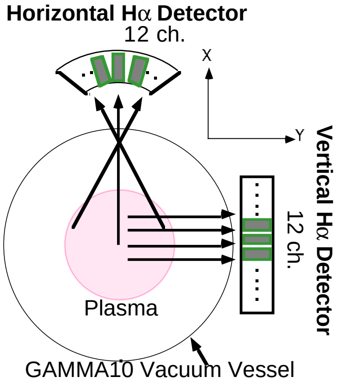

Figure 1. Two dimensional Ha line-emission measuring system set at near the midplane of the GAMMA 10 central cell.

line-emission detector array has 12 sets of detection systems. Each of detection systems has interferometer filter (Shinkuukougaku, DIF-B 655.3nm), collection lens, aperture, optical fiber and photomultiplier tube (PMT, Hamamatsu, R1547). On the opposit side wall of the plasma vessel of the vertical Hα line-emission detectors a light damp made of knife edge blades was installed, while for horizontal one there are no light damp because of no space to set. The output signal from the PMT leads to the amplifier and ended to CAMAC system. The array of horizontal Hα line-emission detector has fin type line of sight and vertical one has parallel line of sight. We choose the algebraic reconstruction technique (ART)[8] to obtain two dimensional radial distribution of Hα emissivity. The advantages of the ART method are easy to adapt to unaxisymmetric data and short calculation time. Then we can obtain the two dimensional radial distribution in a figure of contour in each interval of the experimental two plasma shots. After that we used (CR) model to know the hydrogen density in the quasi steady state.

B. Experiments

GAMMA 10 is a tandem mirror device which consists of an axisymmetric central-mirror cell, anchor-cells with minimum-B coils, and plug/barrier cells with axisymmetric mirrors.[1,2] The length of the central-cell is 6 m and the magnetic strength is normally 0.43 T. Both ends of the central cell are connected to the anchor-cells through the mirror throat regions. Initial plasma is injected from both ends by plasma guns, then a plasma is built up with ion cyclotron range of frequency (ICRF) wave together with gas puffing. The plug potential is produced by means of ECRH at the plug/barrier region. Typical plasma in the hot ion mode experiment was shown in Fig. 2. Figure 2(a) shows diamagnetism, Fig. 2(b) shows plasma line density, and Fig. 2(c) shows Hα line-emission, respectively. Figure 3 shows vertical radial profile of hydrogen density using CR model.

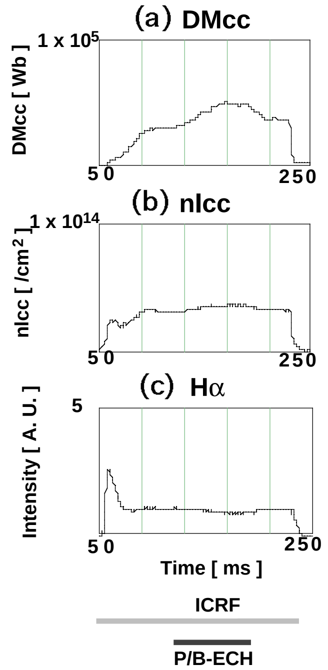

Figure 2. Typical plasma in the hot ion mode experiments. (a) is diamagnetism, (b) shows plasma line density, and (c) show Hα line-emission, respectively.

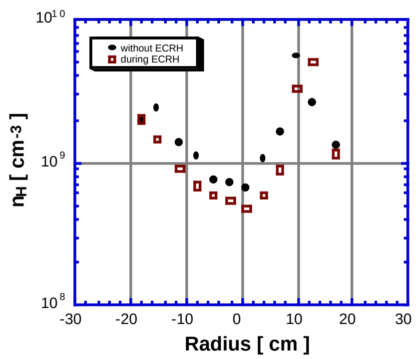

Figure 3. Vertical radial profile of hydrogen density using CR model.

C. Discussion of Hα Line-Emission Measurements

1. Particle confinement. Ion particle balance equation is written neglecting the contribution of impurities, i.e., Z_{eff} is nearly equal to unity, as

$$\frac{dn_e}{dt} = sn_e n_0 - \frac{n_e}{\tau_p} - \alpha n_e n_0 \qquad (1),$$

where n_e is electron density ($n_e \approx n_i$), first term of $sn_e n_o$ is ionization source current density, where s is ionization rate, n_0 is neutral hydrogen density, second term of n_e/τ_p is particle buildup density rate, where τ_p is particle confinement time, and final term of $\alpha n_e n_0$ is recombination density, where α is recombination rate. The ionization source can be estimated from Hα line-emissivity and the consideration of atomic process including CR model. Figure 4 shows the ionization source of radial dependence, $S(r) = sn_e n_o L$, here L is central cell plasma length and r is radius, after considering axial Hα emission.[9] The ionization source in the throat region is about 3 times larger than that of near the midplane region. Moreover the total ionization

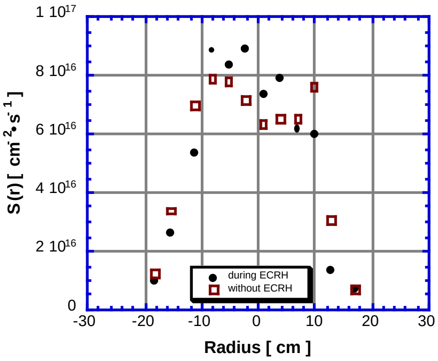

Figure 4. Ionization sourece of radial dependence.

source in the throat region is comparable to that of around the midplane region. Figure 5 shows the end loss ion flux measured by end loss analyzer (ELA). The

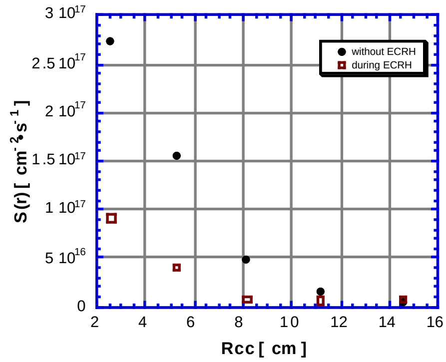

Figure 5. End loss ion flux measured by ELA.

end loss ion flux was cut by the movable limitter of 11.5 cm in radius. We compare the total end loss ion flux to total ionization source to know both are nearly equal. Moreover the value of end loss ion flux is larger than the ionization source in the centeral cell. It shows that the ionization source in the anchor cell is efficiently to the end loss ion flux. The plasma particle confinement time, τ_p, is about 7 ms during ECRH and 6 ms without ECRH. This shows that in the plasma with ECRH the plasma particle confinement was improved, because the particle source was less than that without ECRH, though the plasma particle in the central cell was increased.

2. Ion energy confinement. We examine power balance of the hot ions in a core region (r ≤ 10 cm) of the central cell to investigate the ion energy confinement. The following equation is assumed.

$$\frac{dn_i T_i}{dt} = P_{in} - = n_i T_i \left(\frac{1}{\tau_{ie}} + \frac{1}{\tau_{cx}} \right) \qquad (2).$$

Here, n_i is ion density, T_i means the perpendicular ion temperature $T_{i\perp}$, and the parallel ion energy is neglected (usually $T_{i//}$ is about one tenth of $T_{i\perp}$). The first term of the right hand side, P_{in}, is equal to ICRH power P_a absorbed by the core hot ions per unit volume. τ_{ie} is ion energy confinement time. The charge exchange time is denoted by τ_{cx},

$$\tau_{cx} = \frac{1}{n_0 \langle \sigma v \rangle_{cx}} \qquad (3).$$

The τ_{cx} which effects the ion energy confinement time was obtained by the Hα emissivity. Figure 6 shows radial profile of τ_{cx}. This shows that the plasma energy confinement is improved with ECRH on the GAMMA 10.

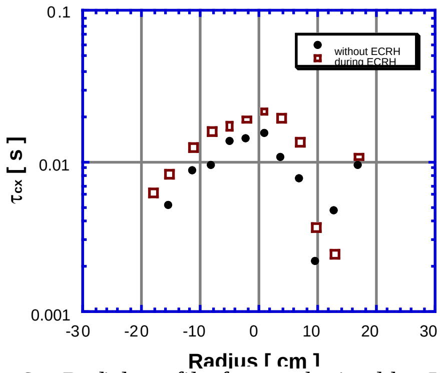

Figure 6. Radial profile fo τ_{cx} obtained by Hα line emission measruements.

III. VUV SPECTROSCOPY ON THE GAMMA 10

A. VUV Spectrograph Description

Figure 7 shows the schematic of the VUV spectrograph on the GAMMA 10. The chamber was kept below 1×10^{-7} Torr by using two turbomolecular pumps. The VUV spectrograph can provide spatial and spectral distributions of plasma radiation in the wavelength range 15 - 105 nm. Detail of the spectrograph has been described in the previous papers.[3-7] The VUV spectrograph consists of an entrance slit of limited height (100 µm × 2 mm), an aberration-corrected concave grating with varied spacing grooves (Hitachi P/N001-0266) which gives a flat-field spectral output plane, and an image-intensified two-dimensional detector system. One can observe the upper half of the plasma with a field of view of about 25 cm diameter. The detector system consists of a microchannel plate (MCP) intensified image detector assembly (Hamamatsu F2814-23P, 50×50 mm^2) and a high speed solid state camera (Reticon MC9256) with fast scanning controller (CCD RS9100). The frame rate with full image size, 256×256 pixels, can be changed from 4 to 106 frames/s. When the number of lines whose data are to be read is reduced and remainder lines are skipped, one can increase the frame rate up to 1000 frames/s. Then we can obtain sequential space-resolving spectra in a single plasma shot with a temporal resolution.

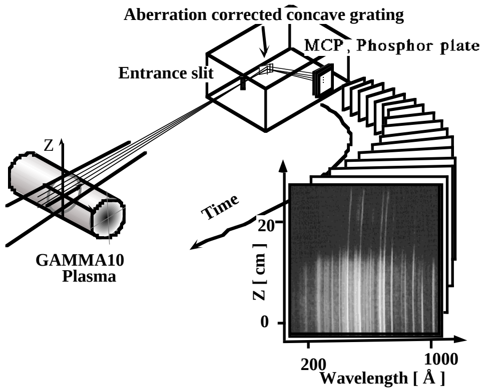

Figure 8. Schematic of the VUV spectrograph on the GAMMA 10.

B. Space- and Time-Resolved Spectra in the GAMMA 10

The VUV spectrograph has been settled at the central cell of the GAMMA 10. Space- and time-resolved VUV spectra have been obtained successfully in the GAMMA 10 experiment. Figure 8 shows the typical inverted spectral image taken by the high speed camera as a recording system with frame rate of 20 frames/s in one plasma shot. Almost all lines

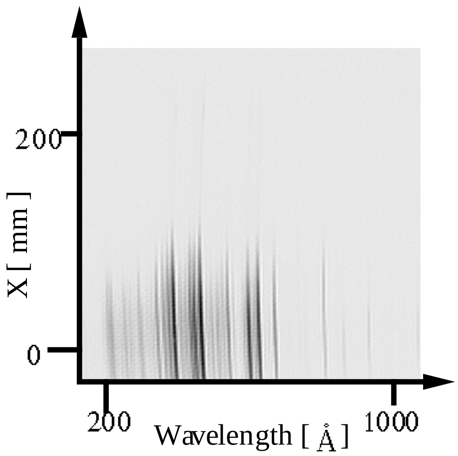

Figure 8. Typical inverted spectral image taken by the high speed camera as a recording system with frame rate of 20 frames/s.

distribute within a region of about 10 cm radius, because the plasma density profile has about 10 cm radius in full width at half maximum.

C. Discussion of VUV Spectroscopy

We analyzed a spatially resolved VUV spectrophotograph using following procedure. First, we have to correct the distortion of image plane due to curved spectral lines because of concave grating. The geometric distortion along space direction has been corrected by using the distortion correction function determined from ray tracings.[3] Second, the brightness profile for a given wavelength interval was obtained from space resolved spectral image. This procedure was carried out along the full wavelength range in the spectrophotograph. Third, the brightness profile of each wavelength was transformed to an Abel inverted profile. Then each Abel inverted profile was reconstructed in a two-dimensional image. Thus one can investigate the emissivity profile of each spectral source in a visual way from a spatially resolved VUV spectrophotograph. Figure 9 shows the spectral distribution of the recorded VUV spectrum after correction.

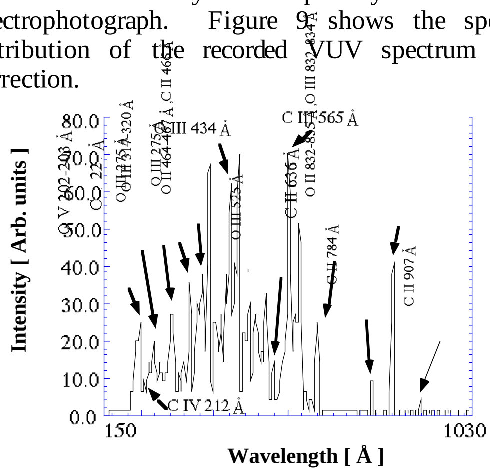

Figure 9. Spectral distribution of the recoreded VUV spectrum after correction.

The temporal behaviors of CII, CIII, CIV and CV line radial profiles are shown in FIG. 10. Each radial profile of C ions can be compared with each of their intensity as their own population density. One can find the peak position moves from the core region to the outer region until 100 ms after the beginning of plasma discharge. This indicates the rise in electron temperature at the core region and the plasma radius is extended. From the results of C ions behavior, we make the model of impurity transport. First the impurity gasses come into the plasma by electron impact and charge exchange neutral particle impact to the vacuum vessel or so during the plasma rising time, first 40 ms during plasma discharge. Next the impurity gasses are ionised by electron impact, ion impact and charge exchange. As plasma glow up, the charges of impurity ions go to be higher, and the region of each impurity ion speacies goes to the outer region. When ECRH is on, plug potential is made. Then the ions, hydrogen ion and impurity ions, are confined by the plug potential. After ECRH off, the impurity ions appear at the same region with that before ECRH is on. The impurity ions come into the plasma only during plasma rising time. If the impurity come there another time sequence, the impurity ion intensity glows at that time. From this measurement, we obtained the impurity ion confinement time, $\tau_{imp} < 20$ ms. This is comparable to the $\tau_p \sim 7$ ms from the Hα line-emission measurement.

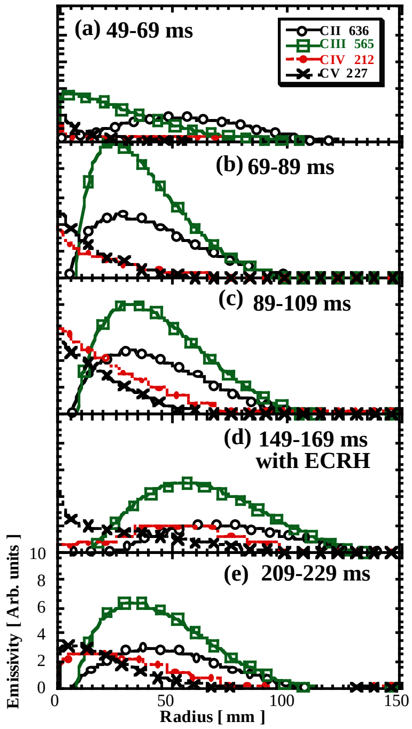

Figure 10. Temporal behaviors of C ions' radial profiles.

IV. CONCLUSION

We have constructed two dimensional Hα line-emission measuring system and spatial imaging VUV spectrograph. Then we adapted both of them to the GAMMA 10 tandem mirror hot ion mode experiments. Then we studied the plasma particle confinement and ion energy confinement which were improved slightly better during ECRH than without ECRH. Moreover we identified that the impurity ions mainly came into the plasma during its rising time.

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