Chapter 6

Applications of a Novel Matrix-Type Semiconductor X-ray Detector

6.1 Analyses of Irreproducible MHD Phenomena During a Single Plasma Discharge

Experiments for investigating anchor MHD stabilization details are carried out by the use of a plasma discharge after the time of t=110 ms (figure 6-1). Around that time, quasi-steady plasmas are attained when no additional gas puffing in the anchor region is applied. The plasmas are heated and maintained with both slow and fast Alfvén waves as described in chapter 2. At t=110 ms, cold gas puffing alone from the NBI port (see chapter 2) without fast neutral beams is incident into ICH produced anchor hot ion plasmas with T_i of a few keV [23]. Following a decrease in the anchor diamagnetism signal [figure 6-1(a)], a decrease in the central cell diamagnetism signal also takes place [figure 6-1(b)]. Electron temperatures decrease due to the reduction in slowing down powers from these hot ions to the electrons [10,11]; thereby, X-ray signals viewing through r_c=130 mm with a 15 and a 110 nm thick "SiO_2 filter" in the central cell also decrease as shown in figures 6-1(c) and (d), respectively. Such closely communicated properties of plasmas between the two neighboring regions are anticipated through the processes of axially easily transferring electron motions; that is, cooled down anchor electrons [figure 6-1(e)] due to the reduction in T_i of the anchor hot ions may transfer into the central cell, and then a reduction in T_i of the central cell hot ions due to an increase in the electron Coulomb drag is expected as shown in figure 6-1(b). Here, various structural materials including ICRF antennas and limiters block the direct transfer of the incident cold gas into the central cell.

After about 130 ms, sawtooth oscillations appear in the X-ray signals in figures 6-1(c)-(e). During the period of t=130-140 ms, more detailed data set of the temporal evolution of the central cell X-ray signals viewing through r_c=-130, -87, -43, 0, 43, 87, and 130 mm is shown in figures 6-2(a)-(g), respectively. Here, data from the detector row of (ii) in figure 5-1(b) are employed, and the sign of plus for r_c is defined as the direction of the upper side from the midplane (r_c=0). One can see the difference of phase in the sawtooth signals. For instance, at $t=t_1$ (135.20 ms), the peak of the oscillatory amplitude appears in figure 6-2(b), while the bottom in figure 6-2(g). As compared with the phase relation at $t=t_1$, the inverse phase relation is found at $t=t_2$ (135.32 ms) for the signals in figures 6-2(b) and (g).

Figure 6-3 shows an overview of the temporal variation of the X-ray radial profiles obtained from the detector row of (ii) in figure 5-1(b). One can see the oscillatory motion of the peak positions of the X-ray brightness profiles (i.e. the thick solid curve in figure 6-3) with time.

Tomographically reconstructed six X-ray profiles are shown in figures 6-4(a)-(f) at t=110.00, 138.92, 139.01, 139.10, 139.19, and 139.28 ms, respectively. Here, the data from the matrix row of (v) [see figure 5-1(b)] are employed. The rotational motion of the peak positions is clearly found in these three dimensional plots as well as their contour mappings in figures 6-4(b)-(f). Here, the locations of P, Q, R, and S are labelled in each figure. In particular, a half cycle of the rotation from t=138.92 to 139.28 ms is found from figures 6-4(b) to 6-4(f). It is worth noting that the shapes of the X-ray profiles during the rotational motion are maintained to be nearly the same.

Furthermore, the matrix detector is employed for the analyses of T_e for these shot-to-shot irreproducible X-ray signals. In figures 6-5(a)-(e), the three dimensional displays of bulk T_e during a sawtooth oscillation period at a single plasma discharge are obtained by the use of the X-ray data from the various matrix rows. In figures 6-5(a)-(e), the data at the same times as in figures 6-

4(b)-(f) are analysed. The shape and structure of the bulk T_e profile during the rotational motion is found to be nearly the same. On the other hand, temporal evolution of bulk T_e profiles during no X-ray oscillatory behaviour around $t=t_0$=110.00 ms in figure 6-1(c) is analysed in figures 6-5(f)-(j). Here, nearly the same time interval (from t=110.00 to 110.35 ms) as in figures 6-5(a)-(e) is employed. It is found that a quite stable peaked T_e profile before the oscillation is somewhat broadened out after the oscillation begins.

In figure 6-6, the values of T_e at $t=t_0$ as well as after $t=t_3$ in figures 6-4 and 6-5 (i.e. before and after the oscillations) are compared by the use of the open and the filled circles, respectively. Here, the X-ray "absorption method" [4,10,11,17] with the different thicknesses of "dead layer filters" [figures 5-1(b) and (c)] is employed. For the interpretation of such a profile variation before and after the rotation, further information on the hot ion profiles is necessary to check whether the energy transport properties are varied. Here, during the plasma rotation, no appreciable changes in impurity emission (the effective charge number $Z_{eff}\approx 1$) are observed. The "detached" properties of the plasmas in figures 6-4 and 6-5 seem to be consistent with no changes in impurities, suggesting no appreciable additional radial transport towards the vacuum wall due to the rotation.

From the viewpoint of an overall view of the plasma motion, the axially observable signals are then analysed. In figure 6-7, end loss ions flowing along the axially expanded tandem mirror magnetic lines of force are analysed with the ion energy spectrometer array (see chapter 2). Here, data from the spectrometer detector units placed at the plasma peripheral region are employed [31]. Data in figures 6-7(b) and (c) are obtained at the locations of Q and R in figure 6-4, respectively. These locations are mapped into r_c=112 mm along the magnetic flux tube, where almost no appreciable signals are observed [see also figure 6-4(a)] before the X-ray oscillatory signals appear (figure 6-2). After the oscillations start, oscillatory behaviour in the data on end loss ions is then observed [figures 6-7(b) and (c)]. It is of importance to note that the X-ray signal in figure 6-7(a) viewing through the location of P (see figure 6-4) begins to increase and have a peak intensity at $t=t_3$, and then similar rising and peaking in the end loss ion signals at Q and R are followed (see the ion signals from $t=t_4$ to t_6), and finally the X-ray signal in figure 6-7(d) viewing through the location of S rises and has a peak at $t=t_7$. Consequently, the temporal evolution of both central cell electron and end loss ion signals in figures 6-7(a)-(d) is synchronized and consistently behaves as shown in figure 6-4 for the central cell electrons. Difference in the shapes of temporal variations in X-rays and end loss ions may come from the difference in their energy responses (i.e. the existence of the low energy limit for the X-ray response [see the curve (ii) in figure 5-1(c)] and no limits for the ion spectrometers.)

Physics interpretations of the rotational motion in figures 6-4, 6-5 and 6-7 are investigated in figure 6-8. Temporal variation in the frequency of the oscillation, f_0, in the X-ray signal [figure 6-8(a)] is plotted in figure 6-8(b) for identifying the characteristic properties and power source of the rotation phenomena. Parabolically shaped potential profile data on the central plasmas are obtained by the use of a heavy ion beam probe [61] as well as the ion energy spectrometer array [31,62]. In figure 6-8(c), the temporal evolution of the value of the potential tip, Φ_{C0}, is plotted. This curve is similarly and consistently behaved as compared with the plot of the peaked value of a T_e profile, T_{e0}, [figure 6-8(d)] traced with time by the matrix detector. In figure 6-8(e), some typical data points in f_0 at t=130.58, 132.30, 136.23, and 138.35 ms are plotted as a function of $-(\mathrm{d}\Phi_C/\mathrm{d}r)/r$ as a representative index of the frequency of an $\boldsymbol{E}\times\boldsymbol{B}$ rotational motion at each r (i.e. the ratio of the $\boldsymbol{E}\times\boldsymbol{B}$ velocity to $2\pi r$, where r denotes the distance from the peak position of Φ_C). Here, the data at three radial positions of r=4, 9, 13 cm are marked with the open and filled circles, and square, respectively, at each time. One can find in figure 6-8(e) that f_0 is well proportional to $-(\mathrm{d}\Phi_C/\mathrm{d}r)/r$, and in particular, the values of f_0 in the different radial positions at each t are nearly the same numbers. This fact shows that the plasmas have the same rotational angular velocity radially (i.e. a rigid rotation). In addition, the absolute value of the frequency of an $\boldsymbol{E}\times\boldsymbol{B}$ rotational motion of $-(\mathrm{d}\Phi_C/\mathrm{d}r)/(2\pi rB)$ is calculated to be consistent with the data on f_0; for instance, the value of f_0 at t=130.58 ms is estimated to be 5 kHz [see the data on f_0 in figure 6-8(b)] by the use of the data on $-(\mathrm{d}\Phi_C/\mathrm{d}r)/r$ of 1.26 V cm^{-2} at r=13 cm and B=0.4 T.

Such MHD plasma behaviour is experimentally reported from the viewpoint of data plots of the relation between the central cell diamagnetism $\Delta\Phi_c$ to the anchor diamagnetism $\Delta\Phi_a$ [24]. The open circles in figure 6-9 show the diamagnetism relation with which stable plasmas are attained. This figure highlights the existence of a boundary for maintaining stable plasmas (see the solid line in figure 6-9). In addition, the temporal evolution of the diamagnetisms in figure 6-1 from 130 to 140 ms is superimposed with a thick solid curve (i.e. continuous filled circles) on figure 6-9 along with the notes of the diamagnetism relations at $t=t_0$, t_1, and t_7 in figures 6-2, 6-4 and 6-5. It is of importance to point out that the remarkable growth of the plasma oscillations after around t=135 ms ($\approx t_1$) (see figure 6-1) agrees well with the time when the thick solid curve approaches ($t=t_1$) and almost crosses ($t=t_7$) the stability boundary in figure 6-9.

For more detail, the peaking times of the central cell (at r_c=130 mm) and anchor X-rays (at r_c=100 mm) are synchronized each other [see figures 6-1(c)-(e)], showing the existence of not only the synchronized rotational motion between the central cell electrons and end loss ions but such a whole plasma rotation including the anchor electrons with the same phasing along the axial direction.

From the above described experimental evidence, the observed rigid rotational phenomena for both bulk electrons and ions are consistently interpreted in terms of a flute interchange mode driven by the pressure difference [24,25,27] between the central cell and the anchor region caused by the anchor cold gas puffing. This is also consistent with the results from previously reported electrostatic probe measurements in the peripheral plasma regions of the central cell and the anchor; that is, fluctuations having an azimuthal mode number of m=-1 (i.e. the ion diamagnetic drift direction) are observed with the phase velocity of the $\boldsymbol{E}\times\boldsymbol{B}$ rotation at least in the peripheral plasmas. In the present investigations, the direct bulk plasma observations and the interpretations of the relation between the internal plasma structural behaviour and the instability boundary scaling in figure 6-9 are made. This provides internally "visible" structural information on the important role of the minimum-B inboard anchor in MHD plasma stabilization.

6.2 Analyses of Power Balance on Typical Plasma Confinement Experiments

The temporal evolution of the radial profiles of line-integrated X-ray intensities (brightness) in the central cell of GAMMA 10 is obtained during a single plasma discharge by the use of X-ray signals in six different energy ranges from the six different detector rows of the matrix detector. Figure 6-10 shows temporal evolution of the central-cell X-ray radial profiles obtained from the detector row having 15-nm-thick dead layer. One can see by the X-ray increase during the injection period of plug and barrier ECH producing ion and electron confining potentials. A significant increase in the X-ray intensities take place due to the direct electron cyclotron heating in the central cell. These line-integrated data are then tomographically reconstructed for attaining spatially resolved X-ray emissivity in plasmas. Similarly six data sets from the six rows of the matrix detector are employed for T_e analyses.

Figure 6-11 summarizes the first analyzed result of temporally and spatially resolved T_e profiles for electron cyclotron heated plasmas in a single plasma discharge alone by the use of the above-described method and data (Fig. 6-10). Figures 6-11(a) and 6-11(b) show the tomographically reconstructed X-ray profiles at t=105 ms and t=115 ms in Fig. 6-11 (i.e. before and after central ECH injections, respectively).

In Fig. 6-11(c), the value of T_e at t=105 ms and t=115 ms are compared by the use of the filled and open circles, respectively. As one can see by the X-ray increase during the injection period of central ECH in Fig. 6-10, the analyzed value of T_e, in fact, increases by 30% (Fig. 6-11(c)) due to the central ECH.

Here, the axi-symmetric tandem-mirror positive potentials protect the core plasmas from the incidence of positively charged impurity ions, if any, along with the assistance due to the ***E***×***B*** rotating motions of incident impurities in the azimuthal directions of the peripheral region. In fact, no appreciable impurity line radiation is observed in the X-ray energy spectra using a Si(Li) detector as well as an ultra-low-energy measurable pure Ge detector (10% quantum efficiency being over 200-eV photons) [63]. Furthermore, good agreement in T_e due to both X-ray diagnostics and electron-cyclotron emission measurements confirms the above-described results [64].

The next issue is to clarify the predominant factor in determining T_e. This has been one of the unresolved problems in tandem mirrors. In Fig. 6-11(d), the scaling of T_e with electron-confining thermal-barrier potentials ϕ_b on the magnetic axis are plotted. The value of T_e before and after the central ECH are compared by the use of the filled and open circles, respectively. In order to find out generalized physics interpretations covering over these experimental results, theoretical analyses are carried out by the use of a widely applicable energy-balance equation (6-1):

$$\frac{d}{dt}\left(W_e V_{BB}\right) = P_{wb} V_{BB} + P_{hb} V_h + \eta P_{C-ECH} V_{BB} - \frac{W_e V_{BB}}{\tau_{Ee}}, \qquad (6\text{-}1)$$

where W_e and τ_{Ee} denote the bulk-electron energy density of $3/2 n_c T_e$, and the electron energy-confinement time, respectively. Slowing-down power densities to the bulk electrons from the warm electrons, and the hot ions are defined as P_{wb} and P_{hb} [5,10,11,62], respectively. Effective central ECH power densities are represented by $\eta P_{C\text{-}ECH}$. The volume of the warm electrons, flowing from the plug regions and thus existing between both barrier regions, is designated as V_{BB}. Diamagnetic-loop-array signals for hot-ion profile measurements are analyzed to identify the axial profile and the volume of hot ions V_h [65].

In Fig. 6-11(d), the thick-solid and dashed curves show the calculated results from the power balance equation (6-1) with the use of the energy confinement time from the generalized Pastukhov's theory modified by Cohen et al [53,54]. These curves are calculated with the warm-electron temperatures

T_{ew}=1 keV, and its ratio of n_{ew}/n_c=0.1% to the central-cell density n_c=2×10^{18} m^{-3}, and T_i=1 keV. One can see good agreement between the data and the calculated results, and interpret these results by the electron energy-balance treatment due to the generalized Pastukhov's potential-confinement mechanism [53,54].