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The Role of Integer-mode Rational Surface on Peaked Profile Formation in Toroidal Rotation Velocity and Ion Temperature

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A particular role of integer-mode rational surfaces on the formation of peaked $T_i(r)$ and $V_t(r)$ is observed. In the case of JT-60 hot-ion regime, the plasma spontaneously changes its peaking region from the inside of q=2 surface to that of broader q=3 surface.

Keywords: JT-60, Hot-ion mode, $T_i(r)$, $V_t(r)$, Peaked Profile,
Integer-mode Rational Surface

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整数モード有理面内におけるトロイダル回転とイオン温度分布のピーキングの形成

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イオン温度とトロイダル回転速度の空間分布測定により，これらが整数モード有理面の内側でピークする事がわかった。ＪＴ－60で得られた高イオン温度モードでは，q＝2面からq＝3面内のピークへと，プラズマが自発的に移行することがわかった。

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It has been empirically shown that there exists a difference in confinement property between the inside and the outside of the q=1 surface: impurity accumulates inside the q=1 surface during the sawtooth-free period[1] and a peaked density profile is formed inside the q=1 surface by deeply fueled pellets[2]. These observations should be the indicative that the q=1 surface serves as a barrier for the particle transport. We find, in the case of sawtooth-free phase, that the location of q=1 surface is also essential for the peaking region of ion temperature ($T_i(r)$) and toroidal rotation velocity ($V_t(r)$) and that q=2 and q=3 surfaces are related to their peakings as well as the q=1 surface. This Letter is the first report that all the rational surfaces with q-value of 1, 2, and 3 are closely related to the improvements in thermal and momentum confinement. Spontaneous reconstruction of the peaking region of $T_i(r)$ and $V_t(r)$ from the inside of q=2 surface to the inside of the q=3 surface is also observed. It is clear that information of this type is essential to an understanding of the mechanism of plasma confinement.

For the experiments reported here, JT-60 is operated with a divertor configuration, plasma major and minor radii of 2.9 and 0.65 m, plasma current (I_p) of 0.5-1.0 MA, toroidal magnetic field (B_t) of 4.0-4.5 T, and hydrogen neutral beam (NBI) of 20 MW with energy of 60-70 keV, injected into a hydrogen plasma. Beam-injection angle is almost perpendicular (~75°) to the magnetic axis, and the injected power ratio of co-units to ctr-units is 1.18, where co-direction is the same direction as plasma current and ctr-direction vice versa. Line-average density $\overline{n_e}$ of ohmically heated target plasma is kept below 1×10^{19} m^{-3} by wall conditioning such as He-TDC, and $n_e(0)$ rises to ~7×10^{19} m^{-3} in the heating phase. Z_{eff} deduced from visible bremsstrahrung[3] ranges from 2 to 5, where the lower value of 2-3 is obtained with titanium flash technique. $T_i(r)$ and $V_t(r)$ are measured with charge exchange recombination spectroscopy (CXRS)[4] with 8 tangential chords and time and spatial resolutions of 50 msec and 10 cm, respectively. The transition of CVI at 5290.5 Å (n=8-7) is used to evaluate these quantities. The heating beam relevant to this measurement is modulated in order to subtract the background radiation for this transition. In calculating V_t from the Doppler shift of the spectrum, we tacitly assume that V_t is 0 in the whole plasma region just after the plasma initiation. This brings the most systematic errors within 2×10^4 m/sec. The location of rational surfaces is inferred from the fluctuation pattern, i.e. its node and phase, of soft X-ray radiation measured with 30-channel PIN diode array[5]. Time and spatial resolutions of this measurement are 40 μs and 3.6 cm, respectively.

Typical peaked profiles of $V_t(r)$ and $T_i(r)$ are shown in Fig.1(a), where I_p=0.67 MA and B_t=4.5 T. The effective q-value is 7.6 which is defined by the following analytic formula[6],

$$q_{eff}=\frac{2\pi a^2 B_t}{\mu_0 R I_p}\{1+(\frac{a}{R})^2(1+(\beta_p+l_i/2)^2/2\} \quad \cdots \quad (1)$$

In this figure, V_t peaks within r=15 cm in the co-direction (open circles) and is almost zero outside the region. From the measurement of MHD oscillation with poloidal-mode number m=1, the inferred location of q=1 surface (shown with $r_{q=1}$) is r=0.14 cm, which roughly agrees with the edge of peaking region of $V_t(r)$. $T_i(r)$ also shows the peaking profile in a similar region (closed circles). The peaking inside the q=3 surface is shown in Fig.1(b), where I_p=0.49 MA, B_t=4.5, and q_{eff} =12.8. m=1 oscillation is not observed in this range of q_{eff}. The m=2 mode disappears during NBI heating after the period of coexistence with m=3 oscillation. These profiles are obtained at 300 msec after the disappearance of m=2 mode. The fact that m=3 mode always appears outside the m=2 oscillation affords a basis for our interpretation that the observed m=3 mode is located around the q=3 surface i.e. toroidal mode number n is unity (shown with $r_{q=3}$). The peaking region of $V_t(r)$ (open circles) in this case is expanded to r~0.28 m and agrees with the location of q=3 surface. Although the edge of peaking region of $T_i(r)$ (closed circles) is less obvious than in $V_t(r)$, its time evolution clearly shows that the peaking region is expanded from q=2 surface to q=3 surface as later discussed in connection with Fig.3(b).

Because $n_e(r)$ also peaks with q_{eff}, we check the possibility that the above-mentioned characteristic peaking is merely due to the change in the deposition profile of NBI power. Two shots with the same $\overline{n}_e$ are compared, where q_{eff} of one of them is 5.0 and it is accompanied by sawtooth, and q_{eff} for another is 12.9. In the former case, $T_i(r)$ is broad and $T_i(0)$ is reduced by half compared with that in the high q_{eff} case and $V_t(r)$ is almost flat and is $\leq 2\times10^4$ m/sec in the whole radius. Calculation[7] shows that the power deposition on ion in the central region of $r \leq a_p/3$ is higher in the latter case by 30 %. This difference is too small to explain the 2-fold difference in $T_i(0)$ and large difference in $V_t(0)$. We thus consider that the peaking in $T_i(r)$ is the indicative of some kind of improvement in thermal transport. The peaking in $V_t(r)$ suggests the improvement in momentum confinement inside the peaking region. This elucidation may be oversimplified because V_t is arranged so that it is balanced with the gradients of pressure and electric potential as discussed in Ref.9, including the component of poloidal rotation which is not measured. Even so, as seen from the similarity of peaking region in $V_t(r)$ and $T_i(r)$ and the remarkable difference in these profiles between inside and outside the edge of peaking region, the study of the peaking region of $V_t(r)$ is important.

In Fig.2, the radius of edge of peaking $V_t(r)$ (r_{Vt} shown in the ordinate) is plotted as a function of rational-surface radius (r_q) deduced from MHD activities, where I_p is 0.5-1.0 MA, B_t is 4.0-4.5 T, the corresponding q_{eff} is 7 to 13. They are normalized to the average plasma radius (a_p). With lower q_{eff} the above values, sawtooth activity with a period of ~100 msec prevents V_t from peaking. With higher q_{eff} above 15, MHD mode often becomes complicated and is difficult to be identified. Such cases are eliminated in this plot. Observed MHD activities are distinguished by the identified poloidal-mode number with different symbols in this figure. Error bars for each axis correspond to the spatial resolution of PIN diode array and CXRS system. We find that, within experimental uncertainty, the edge of peaking region agrees in the range of r/a_p=0.2-0.5 with the locations of rational surfaces, i.e. q=1, 2, and 3 surfaces. The m=1 oscillation is often observed with q_{eff} below 11, and the peaking radius is about 20 % of a_p (shown with closed circles). $T_i(0)$ reaches as high as 10 keV as previously shown in Fig.1(a), but its contribution to the total stored energy is at most 10 % due to the small volume of improved region[8]. In the range of 11< q_{eff} <13, MHD activity often changes from m=2 to m=3 oscillation during the heating period. The peaking region is simultaneously expanded from 25 to 50 % of a_p (Detailed profiles in the expanding phase are discussed later in connection with Fig.3). The volume of improved region thus comes to contribute substantially to the total stored energy in this stage. One of the reasons why maximum improvement is obtained with this range of q_{eff} is ascribed to this expanded improved region (JT-60 hot-ion regime[9]). Although the requirement of low-density target plasma, the highly-peaked $T_i(r)$ pulled up to $\geq 2\times T_e(r)$, and the peaked $n_e(r)$, are similar to TFTR supershot[10,11], JT-60 experiments show a q-dependence of the peaking region.

Next we discuss the phase when the peaking region is expanding and show that the q=3 surface takes over a role of the edge of peaking region from the q=2 surface. Figure 3(a) shows the time evolution of $V_t(r)$, where I_p=0.5 MA, B_t=4.5 T, and q_{eff}=12.4. The underlined figures and vertical arrows stand for the time and the locations of rational surfaces at each timing, respectively. At t=6.0 sec (1.5 sec after the beginning of NBI with constant power), the q=2 surface is located at r~16 cm and $V_t(r)$ peaks inside this radius (open circles). The location of the q=2 surface gradually moves to the center (r=16→12.6 cm during t=6.0→6.7 sec) followed by its disappearance at the plasma center (r~0) at t=6.85 sec. The observation of gradually narrowed rational surface may be attributed to the growth of bootstrap current[9]. It appears, in this figure, that a hollow structure around the q=2 surface in $V_t(r)$ moves toward the center during t=6.0–6.8 sec (open circles → closed circles → open triangles). Returning to t=6.6 sec when the m=2 mode is present, the m=3 mode comes to coexist with the m=2 mode and the q=3 surface is located at r~32 cm. Then $V_t(r)$ speeds up in co-direction inside the q=3 surface (closed circles) and a broader profile is formed. $V_t(r)$ grows in the intermediate region between q=2 and q=3 surfaces (open triangles) just before the disappearance of m=2 mode. In this sense, q=2 surface seems to hold down the growth of $V_t(0)$. The central rise in $V_t(r)$ appears after the disappearance of m=2 mode (closed triangles and squares). As for $T_i(r)$ shown in Fig.3(b), it is common with the case of V_t that the profile peaks inside the q=2 surface at t=6.0 sec and that $T_i(0)$ is raised after the disappearance of q=2 surface. The relation of the effect of q=2 surface as a suppressor both for T_i and V_t just before its vanish with the effect as the edge of peaking region, is not made clear in our experiments. However there is no doubt from these observation that plasma spontaneously reconstruct its equilibrium under the essential role of integer-mode rational surfaces.

In summary, the peaking profiles of $V_t(r)$ and $T_i(r)$ are studied, using the MHD activities as the indication of rational-surface location. It is found that the edges of their peaking regions agree with each other and are characterized by the location of integer-mode rational surfaces. In the quasi-steady state, the peaking region is formed inside the innermost integer-mode rational surface. In the transient phase, the plasma spontaneously reconstructs its equilibrium so that the outer rational surface with integer mode forms the peaking region. The largest dimension of the peaking region is q=3 surface obtained with q_{eff}~12 in our experiments, which reaches ~50 % of a_p. One of the reasons why the JT-60 hot-ion mode with $\beta_p \geq 3$ is obtained with the relatively high q_{eff} is that such a broad region is allowed for confinement zone in this range. No reason is found why $T_i(0)$ and $V_t(0)$ are suppressed just before the q=2 surface vanishes near the plasma center, which is contrary to the property as the edge of peaking region. Remarkable peaking characterized with non-integer mode rational surfaces has not been observed in this experiment.

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References

1 DOUBLET III Group, J. Nucl. Mater. **93 & 94**, 259 (1980).

2 Y. Kamada, R. Yoshino, M. Nagami, T. Ozeki et al., *in Proceedings of the Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington, DC, United States of America, 1990.*

3 Y. Kawano et al., in Review of JT-60 Experimental Results from January to October 1989, JAERI-M 90-066 (1990).

4 Y. Koide, A. Sakasai, H. Kubo, T. Sugie et al., in Review of JT-60 Experimental Results from June to October, 1988, JAERI-M 89-033 (1989).

5 T. Nishitani., Experimental Study of Radiation Losses on the JT-60 Tokamak, JAERI-M 90-087 (1990).

6 T. N. Todd., *in Proceedings of Second European Tokamak Programme Workshop, Sault-Les-Chartreux (1983).*

7 T. Hirayama, Y. Koide, S. Ishida, M. Kikuchi et al., in Review of JT-60 Experimental Results from January to October, 1989, JAERI-M 90-066 (1990).

8 Y. Koide, A. Sakasai, H. Kubo, T. Hirayama et al., in Review of JT-60 Experimental Results from June to October, 1988, JAERI-M 89-033 (1989).

9 S. Ishida, M. Kikuchi, T. Hirayama, Y. Koide et al., *in Proceedings of the Thirteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington, DC, United States of America, 1990.*

10 R. J. Goldston et al., *in Proceedings of the Eleventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, Japan, 1986* (International Atomic Energy Agency, 1987), Vol. 1, p.75.

11 R. J. Fonck, R. Howell, K. Jaehnig, L. Roquemore et al., Phys. Rev. Lett. **63**, 520 (1989).

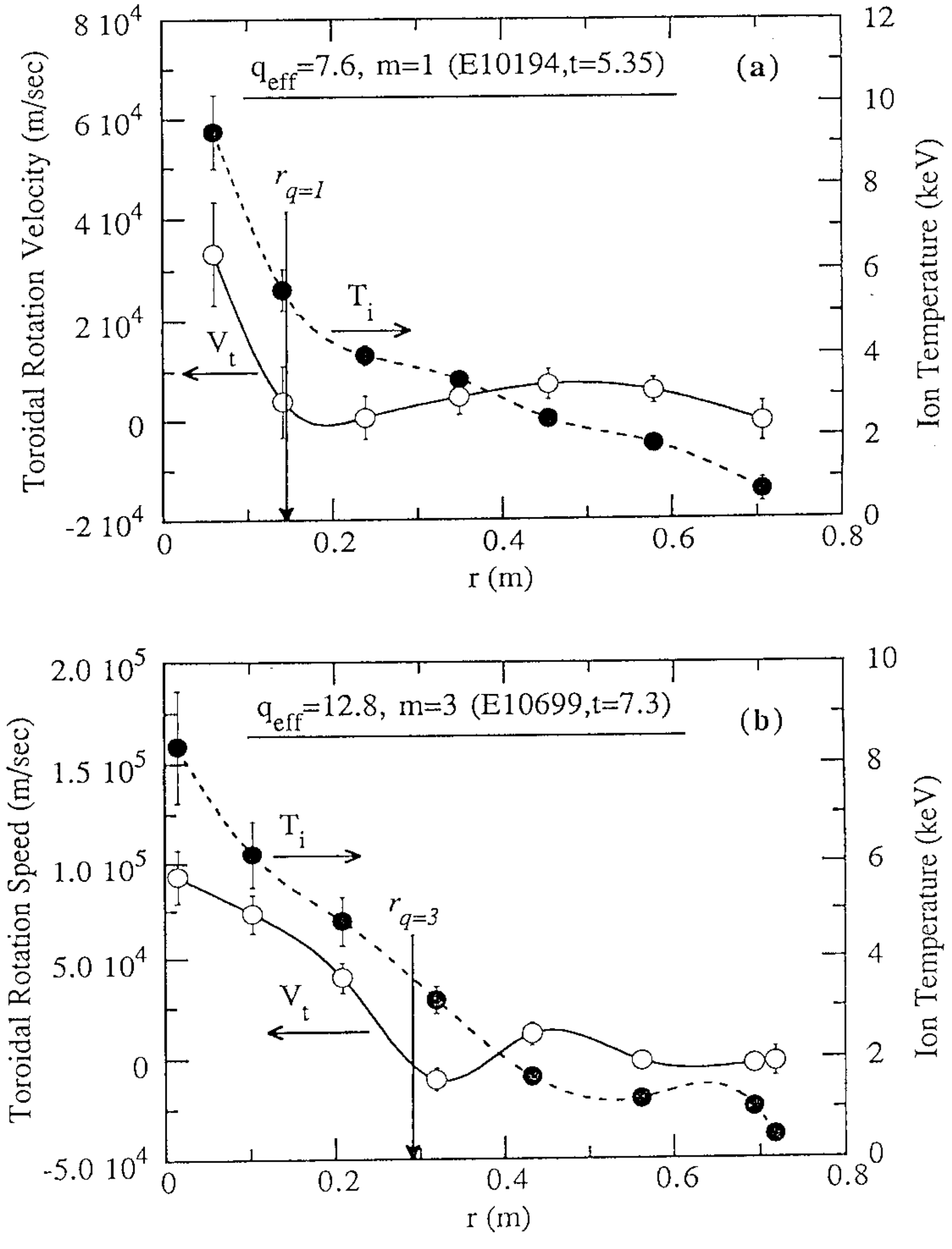

Fig.1 Typical peaked profiles of $V_t(r)$ and $T_i(r)$ (shown with open and closed circles, respectively). The positive value of V_t corresponds to the co-directed rotation. (a) In the case of q_{eff}=7.6, m=1 oscillation is observed and the location of q=1 surface deduced from it is r~0.14 m (indicated with $r_{q=1}$), which agrees with the edge of the peaking region of $V_t(r)$ and $T_i(r)$. (b) As for the case of q_{eff}=12.8, where q=3 surface is located at r~0.28 m, the both of $V_t(r)$ and $T_i(r)$ peak inside this radius.

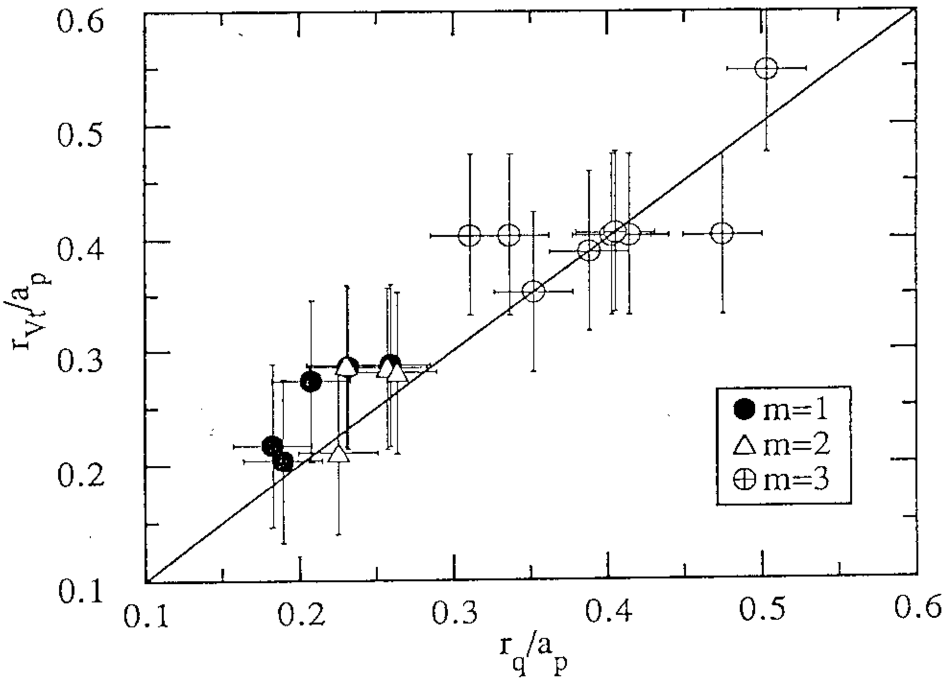

Fig.2 Comparison of the edge-location of peaking region of V_t with the location of rational surface. I_p=0.5-1.0 MA. B_t=4.0-4.5 T. q_{eff}=7-13. Identified MHD poloidal-mode number, e.g. m=1, 2, or 3, is distinguished with different symbols. Close relation between them is recognized.

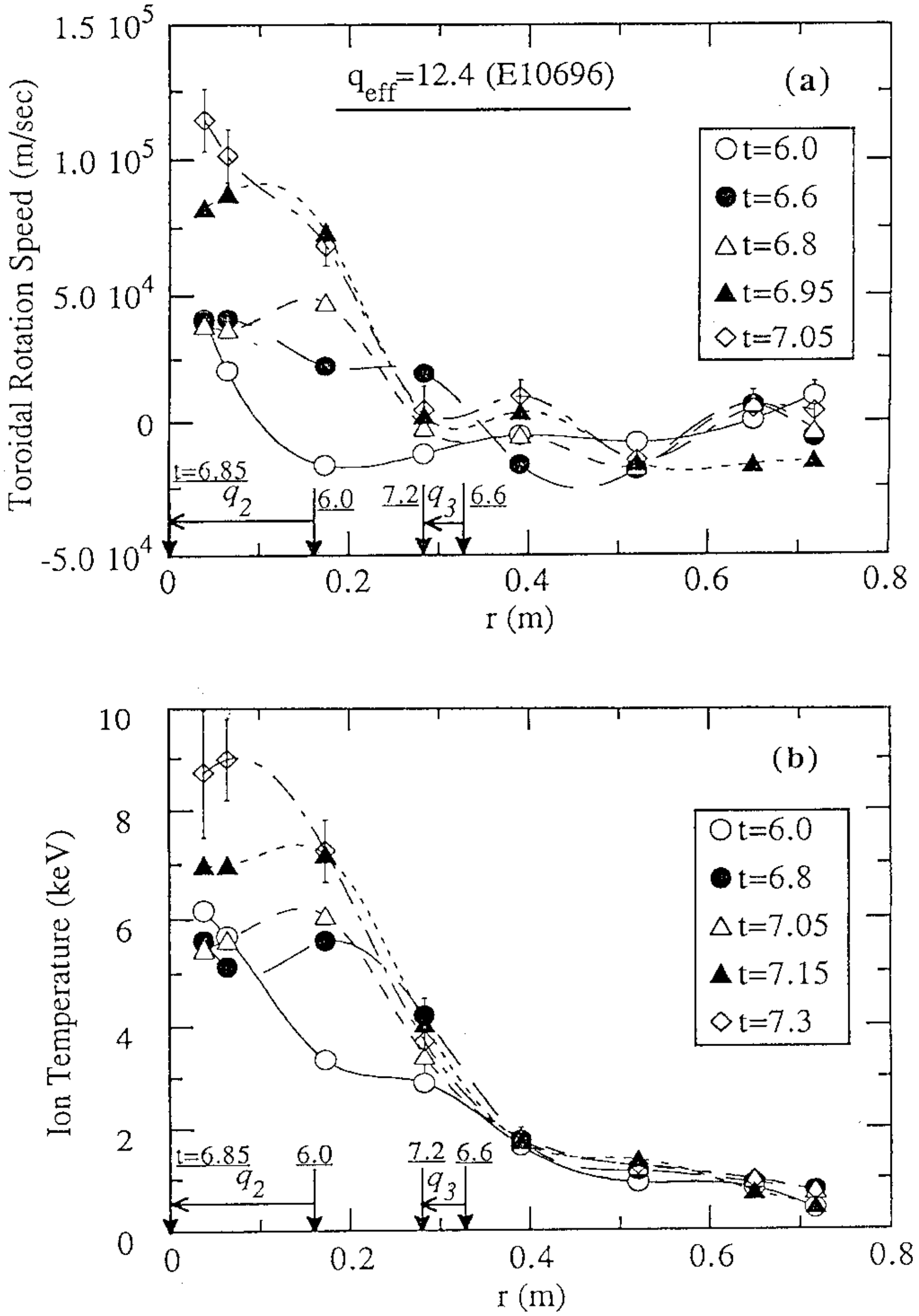

Fig.3 Transient profiles of (a) $V_t(r)$ and (b) $T_i(r)$ when MHD activity changes from m=2 mode to m=3 mode. Peaked profile formed inside the q=2 surface at t=6.0 sec is expanded to the location of q=3 surface during the coexistence phase (t~6.6 sec) of m=2 and m=3 modes. The central peaking grows after the disappearance of q=2 surface in the central region.