Plasma rotation evolution near the peripheral transport barrier in the presence of low-frequency MHD bursts in TUMAN-3M tokamak


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OUTLINE OF TALK

1. Influence of MHD activity on peripheral transport barrier
2. Characteristics of MHD activity burst
3. Microwave Doppler reflectometry on TUMAN-3M tokamak
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5. Summary and discussion
The ohmic H-mode transition was accompanied by a sharp drop in $D_\alpha$ emission and a simultaneous increase in plasma density.

Just after the H-mode transition a short burst of MHD activity was observed, which was probably a result of the plasma current profile modification by gas puffing.

The excitation of the MHD burst was accompanied by a transient deterioration of the plasma confinement. This was manifested by a reduction of plasma density growth rate and an increase in $D_\alpha$ emission.

The MHD burst is accompanied by some flattening of the density gradient at plasma periphery and simultaneous steepening of the gradient in the core region.
The dominating mode was the $m/n = 2/1$ mode, with some admixture of second harmonic $m/n = 4/2$ and tightly coupled $m/n = 3/1$ mode.

It was found that the $m/n=2/1$ island usually developed near resonant radius $r_s = 17$ cm, with a width of approximately 3-4 cm.

The analysis reveals that the magnetic island rotation slows down during the burst development. Then, after the maximum of MHD burst, rotation accelerates again.

The observed rotation of the island always followed the electron diamagnetic drift direction, which coincides with the ExB drift direction in negative radial electric field ($E_r < 0$).
Microwave Doppler reflectometry on TUMAN-3M

\[ \Delta f_D = k_0 V_0 / 2\pi \]
\[ k_0 = \frac{4\pi F}{c} \sin \alpha \]

\( \Delta f_D \) - Doppler frequency shift
\[ V_0 = V_{ph} + V_{E \times B} \]
\[ V_{E \times B} \] - \( E \times B \) drift velocity
\[ V_{ph} \] - phase velocity of scattering fluctuations

F = 18 – 25 GHz – incident beam frequency
O – mode radiation
\( \alpha = 10^0 \) – antenna tilt angle
2 MHz – IQ-detector frequency band

The Doppler reflectometry is based on deriving of the plasma poloidal rotation velocity from the Doppler frequency shift \( \Delta \omega_D = k \cdot V \) of backscattered radiation expected under an oblique incidence of microwave beam onto cutoff surface.

The expected Doppler shift of the scattered radiation is assumed to be proportional to the plasma fluctuation poloidal velocity in a vicinity of turn point of the microwave beam trajectory.

If the phase velocity of the density fluctuation is negligible, then measured \( V_\phi \) may be interpreted as the \( E \times B \) drift velocity.
The evolution of the derived poloidal velocity during the transition to the ohmic H-mode for two similar shots: one with a burst of MHD activity (black lines) and another virtually without MHD activity (red lines).

In the first case, there is a gradual reduction of poloidal velocity associated with the cut-off movement towards the LCFS.

In presence of the MHD activity burst, there appeared a strong perturbation of the observed fluctuation velocity. A sharp decrease in the velocity occurred, and moreover, an inversion of the velocity took place.

After the burst, the velocity reverted nearly to its initial value.

\[ V_{\text{MHD}} = \frac{2\pi f_{\text{MHD}}}{m/rs} \]  \[ m=2, \, r_s=17 \, \text{cm} \]

\[ V_\theta = \frac{2\pi \Delta f_D}{k_\theta} \]
The comparison of the fluctuations poloidal velocity evolutions for two different incident microwave frequencies (19.45GHz and 25.61GHz), which corresponds to the cut-off radii separation of approx. 4cm.

One can see that the larger is the distance between the resonant radius $r_s$ of the magnetic islands $m/n = 2/1$ and the cut-off radius $r_c$, the greater is the change of the derived poloidal velocity. In other words, the closer cut-off is located to the magnetic island, the less pronounced is a difference between the derived fluctuation velocity and the island rotation velocity.

However, the velocity difference remained rather high and was about the electron diamagnetic drift velocity.
The poloidal fluctuation velocity radial profiles measured for various microwave frequencies in a sequence of the reproducible tokamak shots for different phases of a discharge with the MHD burst.

The L-H transition was manifested by the fast increase in the velocity near plasma periphery ($r = 19$-$20$ cm, time = 51 ms).

In a few milliseconds after the beginning of the MHD burst, the velocity decreases and even changes direction ($t = 53$-$56$ ms). The highest velocity in the ion diamagnetic drift direction was achieved at most peripheral region, and the weakest change of the velocity was observed near the resonant radius $r_s$ of the magnetic islands.

During the MHD burst decay, plasma rotation gradually returns to its initial state.
Discussion

The main effect observed during the MHD burst is the excitation of the plasma fluctuation rotation in the ion diamagnetic drift direction at r=18-21cm.

POSSIBLE REASONS OF THE DERIVED POLOIDAL VELOCITY REVERSAL DURING THE MHD ACTIVITY BURST

1. Increasing of phase velocity of the scattering fluctuation in a direction of the ion diamagnetic drift

2. An influence of magnetic island rotation

3. Positive radial electric field penetration into peripheral transport barrier region
Phase velocity estimation

The actual velocity extracted from the Doppler frequency shift is a sum of the scattering fluctuation phase velocity and the plasma rotation velocity with respect to the lab frame.

\[ V_0 = V_{\text{ph}} + V_{E\times B} \]

So, to explain the appearance of the rotation in ion diamagnetic direction, one could assume that the phase velocity directed in ion diamagnetic drift becomes higher than plasma rotation velocity.

The ratio between the neoclassical poloidal velocity \( V_{\text{NEO}} \) and the phase velocity of the ion temperature gradient (ITG) modes \( V_{\text{ITG}} \) has been computed.

The phase velocity of the fluctuations is always less than the neoclassical poloidal velocity approximately by a factor of 3. Hence, the measured velocity is mainly the \( E\times B \) drift velocity.

\[ V_{\text{NEO}} = -\tau V_{\text{De}} (1 + K(n_i^*) \eta_i); \quad \eta_i = (d \ln T_i / dr) / (d \ln n / dr); \quad \tau = T_i / T_e \]

\[ V_{\text{ITG}} = \frac{V_{\text{De}}}{2(1 + (k \rho_\eta)^2)} \left[ 1 - \frac{2}{R (d \ln n / dr)} - \tau \frac{20}{3R (d \ln n / dr)} \right] \]
Influence of magnetic islands rotation

Theories based on an assumption of zero perturbed parallel electric field predict that, inside the island, plasma rotates with the island's velocity in the lab frame.

Indeed, the difference between the MHD rotation velocity and the measured poloidal velocity of the fluctuations is slightly reduced when the cut-off is located closer to the island chain. However, the velocity difference remained substantial.

This discrepancy could occur due to an inherent phase velocity of the islands. According to linear theory, the island velocity in the lab frame is a sum of the electron diamagnetic drift and the $E \times B$ drift velocities. In non-linear stage, no such a simple relation for the island rotation velocity exists. Nevertheless, this velocity is expected to remain greater than the plasma rotation velocity outside of the island.

In any case as the island was always observed to rotate in the electron diamagnetic drift direction, this rotation by itself could not be a reason of the surrounding plasma rotation in the ion diamagnetic drift direction.
Positive electric field emergence in plasma inner

Following the point of view that the Doppler reflectometry allows recovering of the plasma rotation velocity, one can assume that the observed velocity reversal is mainly due to the positive radial electric field penetration into the peripheral transport barrier.

POSSIBLE REASON THE POSITIVE ELECTRIC FIELD EMERGENCE IN PLASMA INNER REGION

The most likely reason of the positive electric field propagation into the plasma inner is a substantial perturbation and chaotic behavior of the magnetic lines induced by large magnetic island developing.

In that case, the reversal of the radial electric could be due to a dramatic change of the electron-ion balance caused by the parallel escape of the fast electrons to the limiter. This change of the balance and hence the electric field reversal should appear, predominantly, at the plasma periphery, as it is observed in the experiment.

This is in a qualitative agreement with the results of direct measurements of the radial electric field performed with Langmuire probes.

The positive $E_r$ perturbation at the plasma edge obviously leads to a transient deterioration of the H-mode transport barrier. On the other hand, the inward propagation of the positive electric field increases the shear of plasma rotation in deeper region. Such a displacement of the shear pattern might cause a transport barrier shift towards inner region of the plasma column.
Scattering spectra

Frequency, kHz

S(f), a.u.

48 ms
55 ms

Time, ms

MHD, a.u.

D, a.u.
DOPPLER FREQUENCY SHIFT EVOLUTION

- L-H
- MP signal, a.u.
- LCFS

\[ \Delta F, \text{kHz} \]

\[ D_a, \text{a.u.} \]

\[ r_c, \text{cm} \]

\[ \text{Time, ms} \]
COMPARISON WITH PROBE DATA AND FT-2 EXPERIMENT

Probe measurements

FT-2 experiment

#05052022 #05052024 r=190 m=3

Er, kV/m

D, a.u.

L-mode | H-mode

MHD, a.u.

MHD burst

n, 10^19 cm^-3

time, ms

25.94 GHz
30.17 GHz
36.37 GHz

V, 10^6 cm/sec

r_cutoff, cm

E > 0

E < 0

RF