Radial electric field evolution in various operational modes in the TUMAN-3M tokamak

L G Askinazi1, V A Kornev1, S V Krikunov1, L I Krupnik2, S V Lebedev1, A I Smirnov1, M Tendler3, A S Tukachinsky1, M I Vildjunas1 and N A Zhubr1

1 Ioffe Institute, St Petersburg 194021, Russia
2 IPP, Kharkov Institute of Physics and Technology, 61108 Kharkov, Ukraine
3 Alfven Lab., Euratom NFR Association, Royal Institute of Technology, Stockholm, Sweden

E-mail: leonid.askinazi@mail.ioffe.ru

Abstract. Radial electric field evolution has been studied on the TUMAN-3M tokamak in different modes of operation: ohmic and NBI heating, L- and H-modes, with and without strong MHD activity. Peripheral radial electric field was measured using Langmuire probes, which were inserted up to 2cm inside LCFS, while core plasma potential evolution was measured using HIBP diagnostic. It was found, that in presence of strong MHD activity radial electric field in a vicinity of the island changed sign from negative to positive and could reach up to 4kV/m. Central plasma potential exhibited a positive perturbation of ~700V during the MHD burst. This positive radial electric field might lead to H-mode termination, both in ohmic and NBI heating cases. Possible mechanism of the positive $E_r$ generation, namely the electron losses along ergodized magnetic field lines in the presence of MHD-island, is discussed. The same mechanism might be responsible for the positive potential spikes during a saw-tooth crash, also observed using HIBP. Another phenomenon observed using HIBP was quasi-coherent potential oscillations with the frequency close to one of the GAM. Possible location of these oscillations in the core region $r/a \sim 0.33$ is discussed.

1. Introduction
Radial electric field is known to play a key role in various important processes in tokamak plasma. Among them are confinement mode transitions, toroidal and poloidal rotation of the plasma, MHD island rotation. Besides, quasi-stationary or oscillating radial electric fields is exited by zonal flows and its higher frequency branch – the Geodesic Acoustic Mode (GAM), which, in turn, plays a role of mediator between turbulence and transport.

Spatial structure and temporal dynamics of the radial electric field in the small tokamak TUMAN-3M ($R = 0.55m$, $a = 0.22m$, $I_p^{max} = 0.16MA$, $B_t^{max} = 0.8T$, $n_e < 5 \times 10^{19}m^{-3}$, $T_e < 500eV$, $T_i < 200eV$, cylindrical $q_{lim} \sim 2.3 - 2.6$) was studied in different modes of plasma heating and confinement, namely, in the ohmic L- and H-modes and NBI, with and without low frequency MHD oscillations. Central plasma potential was measured by heavy ion beam probe (HIBP) [1], which gives a rare possibility of direct measurement of hot dense plasma potential. Due to the geometrical limitations, only a region of $0 < r < 16cm$ (i.e. $0 < r/a < 0.73$) is typically covered by the HIBP. Peripheral radial electric field was measured using Langmuire probes [2]. Thanks to the proper design and materials used (and of course, moderate electron temperature and density of the TUMAN-3M peripheral plasma), the probes may have been inserted up to 2cm ($r/a = 0.91$) inside LCFS, thus allowing $E_r$ measurement in the peripheral
region of the core plasma. So, range $0.73 < r/a < 0.91$ is still unreachable for both Langmuire probes and HIBP, and obtaining information on $E_r$ structure in this region is a challenge for future experiments. Useful information on plasma rotation in this region, qualitatively corresponding to $E_r$ evolution measured with probes and HIBP has been obtained using microwave reflectometry [3].

2. Radial electric field and plasma potential evolution in the presence of rotating magnetic island

Earlier, radial electric field evolution in a vicinity of the rotating MHD island created by a resistive tearing mode has been measured in the TUMAN-3M tokamak using Langmuire probes [2] and reflectometry [3]. The probes were inserted from high filed side and located close to the island separatrix, staying at least 1cm away from it even when the island had the largest size. It has been found [2] that when the island is small and its rotation velocity is high, measured $E_r$ is negative and close to the theoretical predictions [4]. This theory is based on neoclassical description of plasma flow near the island and takes into account anomalous viscosity. The theory predicts, in particular, that in order to maintain the common rotation speed of the island and the ambient plasma, the should exist radial electric field $E_{r\text{ island}} = -\langle B_t \rangle \omega r_s/m$ in a vicinity of the island ($\langle B_t \rangle$ is magnetic surface averaged toroidal field, $\omega$, $r_s$ and $m$ are the island rotation frequency, resonance surface radius and poloidal mode number, respectively). Later, as the island grows and rotation decelerates, measured $E_r$ changes sign and becomes positive (directed to the plasma boundary). It should be stressed, that there exists not only a quantitative disagreement between $E_r$ and the island rotation velocity values, but also the positive direction of $E_r$ contradicts to the cw direction of the island’s poloidal rotation. The most probable cause of positive $E_r$ build up is thought to be electron losses due to stochastical perturbation of the magnetic field lines in a vicinity of the island [5]. Measurements of the HXR emission from the limiter shows strong increase in electron losses during the MHD bursts [6]. In the recent experiments, these results were supplemented with the HIBP measurements of the central plasma potential evolution performed in similar experimental conditions. Figure 1 presents the results of peripheral $E_r$ evolution measurements by probes discussed in detail in [2]. Initially, radial electric field is negative $E_r \sim -2\text{kV/m}$, which is in good agreement with the theoretical formula $E_{r\text{ island}} = \langle B_t \rangle \omega r_s/m$, see figure 1.

![Figure 1](#05041522 r=190 m=3)

**Figure 1.** Top: MHD mode frequency evolution (black open squares), measured radial electric field $E_r = -\nabla \Phi_{\text{float}}$ near the island (closed blue circles) and theoretical value $E_{r\text{ island}} = -\langle B_t \rangle \omega r_s/m$ from [4] (closed blue triangles); bottom: magnetic probe signal $dB_p/dt$ (a.u.).
Formation of positive $E_r \approx 4$ kV/m is clearly seen after $t \approx 55$ ms. Figure 2 displays the HIBP results of central plasma potential evolution in a shot with relatively short burst of MHD oscillations ($m/n = 2/1$ mixed with $3/1$). In these measurement, the initial location of the sample volume was at $r = 12$ cm, changing slowly to $r = 10$ cm due to the $B_t$ non-constancy. Hence, the point of potential measurement was located deeper in the core plasma than the magnetic islands resided near $r = 17-19$ cm. The location of the island was obtained from the analysis of the MHD-caused perturbations on the chord signals of microwave interferometer, see [7] for details. It was observed, that core plasma potential had exhibited strong positive perturbation up to $\Delta \phi = 600-700$ V correlated with the MHD burst, so the change in average radial electric field between the point of HIBP measurement and the wall is $\Delta \phi / \Delta r \approx 0.7$ kV/0.11 m = 6.4 kV/m. This value agrees well with the change in peripheral radial electric field $\Delta E_r \approx 6$ kV/m measured by probes. It should be stressed that in this experiment HIBP measured plasma potential at the distance of 10-12 cm from the wall; this is significantly deeper than the peripheral the ergodic layer created by the MHD oscillations where positive radial electric field is generated. The positive radial electric field generated in the presence of magnetic island may have a dramatic effect on plasma confinement. In particular, if the MHD island perturbation develops during H-mode phase of the discharge, it may lead to H-mode termination and backward confinement transition. This situation is discussed in more detail in the next section of the paper.

![Figure 2](image.png)

Figure 2. Positive perturbation of core plasma potential caused by the MHD burst.

As for the mechanism of positive $E_r$ generation by the MHD island, the most probable candidate is thought to be the loss of electrons along ergodized magnetic field lines. Such an ergodic layer should exist near the island’s separatrix. To sustain quasi-neutrality, this electron out flux must be compensated by an ion current, which, in turn, requires a positive radial electric field generation. This situation has a lot in common with plasma biasing experiments performed on a number of tokamaks (and in the TUMAN-3M, in particular [8]), when plasma responses with the transverse conductivity current to the externally exited biased electrode current. The idea of electron losses due to the magnetic lines ergodization was used to describe the $E_r$ evolution during the Dinamic Ergodic Divertor (DED) operation on the TEXTOR tokamak [9]. A quantitative theoretical model of this mechanism of $E_r$ generation in the presence of MHD island may be found in [10]. This theory gives $E_r$ values close to ones measured on the TUMAN-3M tokamak. Moreover, this theory takes into account transverse inward transport of toroidal momentum and as a result, is capable of explaining deep penetration of $E_r$ created at the plasma edge. The direct experimental evidence to electron losses was obtained in the measurements of HXR emission from the limiter. The significant increase in the emission in the
presence of the MHD island was found [6]. The oscillating fraction of the HSR emission is observed to be in phase with magnetic probe signal, indicating an effect of local field line topology on the electron losses. So, it supports the hypothesis of the increased longitudinal electron losses caused by magnetic field lines ergodization by the presence of the MHD island.

3. Plasma potential evolution in counter-NBI heated plasma

Central plasma potential studies were carried out in a scenario with ohmic L-H transition followed (with a delay of ~ 10ms) by counter-NBI heating pulse. Co- or counter- injection of the neutral beam in the TUMAN-3M tokamak is selected by switching the plasma current direction, with the injection direction being constant (pointed reversely with respect to the toroidal field). Generally speaking, co-NBI is much more favorable from the point of view of fast ion confinement, and this holds for the TUMAN-3M experiments also [11]. Unfortunately, co-NBI heating on the TUMAN-3M is not compatible with the HIBP diagnostic set up due to the wrong direction of toroidal displacement of the primary and secondary ions trajectories, which prevent secondary beam from passing through the exit port. The NBI application was performed by probing the core plasma with 80keV K$^+$ ions. Figure 3 (upper box) displays the plasma potential evolution measured with HIBP in two shots: #06111730, ohmic H-mode plus counter-NBI (red lines) and #06111724, ohmic H-mode only (blue lines). For a comparison, the potential evolution measured in ohmic L-mode shot is also displayed in the same box (black line). It is clearly seen that potential tends to be more negative after the L-H transition, though it changes rather slowly during ~8ms after the transition. The location of the point of potential measurement (shown by black squares in a separate box in the same figure) was nearby $r = 6 - 8 cm$, $r/a = 0.25 - 0.33$, that is well inside the edge transport barrier located near $r = 20 cm$. A slow drift of the sample volume is caused by the temporally non-constant $B_t$. A relatively slow evolution of the central potential corresponds to a gradual change in plasma density profile after the edge transport barrier formation. After the start of NBI heating, central plasma potential gradually becomes even more negative (by ~200V) than it was in ohmic-H-mode phase. Numerical modeling of the counter-NBI injection

Figure 3. Core plasma potential evolution measured with HIBP in ohmic H-mode shot (blue) and ohmic H-mode plus counter-NBI (red). Ohmic L-mode shot is also displayed (black).
scenario in the TUMAN-3M performed using ASTRA code shows that due to the high orbit loss term the efficiency of direct power and momentum transfer is low [11]. Hence, the negative potential perturbation caused by the NBI may be a result of the orbit losses of fast ions created by the neutral beam ionization, with minor additional effect of toroidal momentum and plasma pressure input from the injection. In some shots a burst of MHD oscillations was excited in the H-mode stage of the discharge at the front of NBI heating pulse, see figure 4. In this case, similarly to the ohmic heating situation, the MHD burst was accompanied by a positive perturbation (by ~700V) of the central plasma potential. As may be concluded from figure 4, the MHD burst and positive perturbation of plasma potential were followed by H-L transition, which was featured by an increase in $D_\alpha$ emission, electron density and SXR radiation decay after $t \sim 61$ms. The average radial electric field needed to create such a perturbation of the potential may be estimated as $\Delta \Phi / \Delta r \sim 0.7 \text{kV/m}$. This radial electric field perturbation resulted, apparently, in decrease of the peripheral radial electric field shear, which, in turn, led to turbulent transport reduction termination, and the low mode of confinement recovery. However, the experimental data available at present are not enough to quantitatively support this mechanism; more sophisticated multi-point measurement at the edge is needed to evidence it. Earlier, a similar effect of H-mode degradation due to the MHD activity burst was observed in pure ohimically heated TUMAN-3M plasma [2]. A positive perturbation of the peripheral radial electric field $\Delta E_r \sim 5 \text{kV/m}$ was measured by the Langmuire probes in that regime.

![Figure 4](image-url).

**Figure 4.** Core plasma potential evolution measured with HIBP in ohmic H-mode plus counter-NBI with (blue) and without (red) MHD burst.

4. Observation of Geodesic Acoustic Mode in core plasma

Another interesting phenomenon observed with the HIBP on the TUMAN-3M is quasi-coherent oscillations of plasma potential. These oscillations exist in the TUMAN-3M plasma at the initial stage of the discharge, while the current profile is not stable, usually disappearing after the current density profile becomes stationary, but sometimes surviving to the end of the shot. These oscillations has frequency around ~30kHz and relative amplitude up to $\delta \Phi / \Phi \sim 0.3$. At the same time, local density signal (which is simply proportional to the intensity of the secondary beam of the HIBP) does exhibit only a very low level oscillations ($\delta n / n \leq 0.05$), if any. No oscillations near that frequency were seen.
on any other diagnostic signals, such as Mirnov coils, interferometer and SXR chords. For example, spectral range of low frequency MHD oscillations in the TUMAN-3M have higher boundary of approximately 12 - 13kHz. The frequency of the potential oscillations is close to the geodesic acoustic mode scaling (GAM) \( f_{\text{GAM}} \sim 1/(2\pi R)(2T_e/m_i)^{1/2} \sim 30 \text{kHz} \), provided that \( T_e \sim 100 \text{eV} \). Another feature, namely \( \delta \Phi \Phi \gg \delta n/n \) is also typical for the GAM, especially when observed in equatorial plane [12]. In the GAM studies, the sample volume was located close to the equatorial plane of the tokamak in a region of \( r_{sv} \sim 8 \text{cm} \), that corresponds to \( r/a \sim 0.33 \), according to numerical calculations of probing beam trajectories. It is not very usual for GAMs, which, as a rule, are located at the very edge of the plasma column [13]. Therefore, the central location of the GAM in our experiment had to be cross-checked. Two important issues should be considered in this connection. First, it would be useful to obtain independent experimental evidence to the central location of the sample during the GAM studies. Such evidence may be found in a shot with strong saw-tooth oscillations co-existing with GAM oscillations of the plasma potential, figure 5.

In this shot, the GAM frequency is clearly seen in HIBP potential signal and its spectrum, figure 6 and figure 7. At the same time, the saw-tooth oscillations were simultaneously registered by HIBP density channel and by the multi-chord microwave interferometer. Analyzing phase relations between the HIBP density channel and interferometer chord signals, it was found that the HIBP sample volume resided somewhere in a region \( r < 8 \text{cm} \). So, the sample volume location around \( r_{sv} \sim 8 \text{cm} \) found from the calculation of the HIBP trajectories does look reliable. Second issue is of more general nature and is connected with the fact that HIBP diagnostic actually measure a potential difference between sample volume location \( r_{sv} \) and the wall located at \( r_w \). This potential difference is caused by a radial electric field located (or spread) anywhere in a range \( r_{sv} < r < r_w \). This radial electric field may have an arbitrary spatial structure \( E_r(r) \), provided that integral of \( E_r(r) \) over the range \( r_{sv} < r < r_w \) is kept constant. In other words, local single point measurement of plasma potential does not mean local measurement of radial electric field and give only \( E_r \) averaged over \( r_{sv} < r < r_w \) interval. Therefore, additional information is required to draw a conclusion on of \( E_r \) structure from single point plasma potential measurement. In case of GAMs, such information may be found in zonal structure of this mode. Being a higher frequency branch of zonal flows, GAM is thought to consist of two or more narrow adjacent (in radial direction) spatial regions with alternating direction of poloidal velocity and

![Figure 5. HIBP signals (density and potential) and signals of 4 central chords of microwave interferometer, showing coexistence of GAM and saw-teeth.](image-url)
radial electric fields. Hence, radial electric field averaged over the region occupied by GAM should be small: \( \int E_r(r)dr \sim 0 \). If the GAM was localized inside \( r_{sv} < r < r_w \) interval, it would hardly be seen by the HIBP. And vise versa, if HIBP register non-zero GAM oscillation, it means that sample volume location \( r_{sv} \) is somewhere inside the radial correlation length of GAM. In other words, in case of the presence of GAM oscillations in the HIBP signal one may expect that the location of the investigated object coincides with the sample volume location. For our studies, it means that GAM is very probably localized in core plasma in a vicinity of \( r = 8 \text{ cm} \).

Another interesting observation about this shot is strong (~200V) positive perturbation of central plasma potential in tact with saw-tooth crash, clearly seen in figure 5. It may be caused by the loss of fast electrons as a result of the crash, in a way similar to that discussed above for the MHD island.

5. Conclusion

Strong positive perturbation of the core plasma potential was registered by the HIBP during the burst of peripheral MHDs with low \( m, n \). If such a burst takes place in the H-mode (both ohmic and counter-NBI heated), the positive potential perturbation leads to H-mode termination. The most probable mechanism of the positive field build-up during MHD burst is though to be a loss of fast electrons along partly disturbed magnetic field lines near the island's separatrix [5, 6]. This mechanism is similar to the ergodic divertor’s action on the TEXTOR [9], where radial electric field modification by the electron loses was also discussed. A quantitative analysis of the subject may be found in [10]. Similar mechanism may be responsible for a positive perturbation of central plasma potential registered in the saw-tooth crashes. The positive radial electric field caused by MHD activity is capable of H-mode termination, most probably through the canceling the H-mode “natural” negative radial electric field.

In a scenario with counter-NBI it was found using HIBP that, due to the NBI effect (most probably, orbit loss with some heating and momentum impact), core plasma potential plasma gradually became more negative (by ~200V).

The GAM with \( \delta \Phi / \Phi \sim 0.3 \) and \( \delta \Phi / \Phi \gg \delta n / n \sim 0.05 \) where observed with HIBP in a core region of the TUMAN-3M \( r/a \sim 0.33 \) in the current ramp phase. Further studies are planned to reveal a possible connection between the GAM properties (localization, plasma condition dependence) and plasma confinement in the TUMAN-3M.
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