Evolution of the electric potential and turbulence in OH and ECRH low-density plasmas at the T-10 tokamak


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Introduction

Plasma potential – an important parameter, reflecting the turbulence and confinement characteristics. Potential sign indicates predominant losses of electrons (positive core potential) or ions (negative core potential).

Tokamaks:
negative potential
in OH – always negative:
[TM-4, TEXT, JIPPT2-U, T-10, JFT-2M, ISTTOK]
in ECRH – tends to be less negative with ECRH power increase: [T-10]
in NBI – negative for both co- and counter injection: [TEXT]

Stellarators:
predominantly positive potential

ECRH – positive: [CHS, TJ-II, LHD]

NBI – negative: [CHS, TJ-II]
Introduction -2. Potential-collisionality coupling

T-10 tokamak

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/a</td>
<td>1.5/0.3 m</td>
</tr>
<tr>
<td>B₀</td>
<td>≤ 2.5 T</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>up to 1 s</td>
</tr>
<tr>
<td>$\bar{n}_e$</td>
<td>up to $6 \cdot 10^{19} \text{ m}^3$</td>
</tr>
<tr>
<td>$T_e(0)/T_i(0)$</td>
<td>up to 3.2 keV/ 0.6 keV</td>
</tr>
<tr>
<td>ECRH</td>
<td>3 gyrotrons @144 GHz +1@130 GHz</td>
</tr>
<tr>
<td></td>
<td>2-nd harmonic, X-mode</td>
</tr>
<tr>
<td>P_{EC}</td>
<td>≤ 2.2 MW</td>
</tr>
</tbody>
</table>

TJ-II stellarator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/a</td>
<td>1.5/0.22 m</td>
</tr>
<tr>
<td>B₀</td>
<td>1 T</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>up to 0.3 s</td>
</tr>
<tr>
<td>$\bar{n}_e$</td>
<td>up to $5 \cdot 10^{19} \text{ m}^3$</td>
</tr>
<tr>
<td>$T_e(0)/T_i(0)$</td>
<td>up to 1.6 keV/ 0.12 keV</td>
</tr>
<tr>
<td>ECRH</td>
<td>2 gyrotrons@53.2 GHz</td>
</tr>
<tr>
<td></td>
<td>P_{EC} ≤ 0.6 MW</td>
</tr>
<tr>
<td>NBI</td>
<td>2 H₂ injectors, $E_b&lt;32$ keV, $P_{NBI} ≤ 1.2$ MW</td>
</tr>
</tbody>
</table>

Potential-to-collisionality coupling was observed in both tokamak and stellarator.
Supported by less systematic data from TEXT, CHS, LHD

[A.V. Melnikov et al 2013 Nucl. Fusion 53 093019]

[A.V. Melnikov 2019 Electric Potential in Toroidal Plasmas (Springer Nature Switzerland AG)]
Experimental setup - Heavy Ion Beam Probe

- **Ti⁺** ions with energies $E_b$ up to 330 keV
- Probing beam current up to 250 \( \mu \)A
- 5-slit energy analyzer
  - 5 separated Sample Volumes (SVs),
    - SV size \( \approx 1-2 \) cm, SV distance \( \approx 1-4 \) cm
- Split-plate detector combined with preamplifiers
  - \( 3.3 \cdot 10^6 \) V/A, bandwidth 1 MHz
- National Instruments DAC (16 bits, 1 MHz)
Experimental setup - Heavy Ion Beam Probe 2

(a) 5-slit energy analyser:
- B – the secondary particle trajectory,
- 5-S – the entrance 5 slit assembly,
- GP – the ground plate,
- HVP – the high-voltage plate,
- G – grid,
- D – beam detector;

(b) beam detector schematic:
- $i_1$, $j_1$, $i_2$, $j_2$ – beam current to plates
- $\delta \varphi$ – vertical shift, $E_{beam}$
- $\delta z$ – toroidal shift

<table>
<thead>
<tr>
<th>Beam characteristics</th>
<th>Plasma parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E_{beam}$</td>
<td>$\varphi$, $\tilde{\varphi}$</td>
</tr>
<tr>
<td>$\tilde{I}_{beam}$</td>
<td>$\tilde{n}_e$</td>
</tr>
<tr>
<td>$\tilde{z}$</td>
<td>$\tilde{B}_{pol}$</td>
</tr>
</tbody>
</table>

Simultaneous measurements of three parameters in 5 Sample Volumes
Experimental setup - Plasma conditions.

Coupling between plasma potential and collisionality was established for both tokamaks and stellarators.

**Gap** – positive potential in the core of tokamak plasmas.

**Hypothesis** – if the low-collisionality is the cause for positive potential, it can be obtained in low-collisional tokamak plasma.

Aiming for the extension of the investigation area in plasma towards the core, the HIBP accelerating voltage was recently increased up to 330 kV, which is a sort of record: the maximal voltage ever achieved for the open-air accelerators installed in the fusion devices.

Tl⁺ (heaviest single charged m=203 a.u.) ions were used to probe the plasma.

**Contradictive demands**

\( B_0 \) – decrease to allow HIBP to reach the most central area, but keep ECRH still efficient.

\( n_e \) – decrease to reach low collisionality, but keep ECRH still efficient and avoid runaways.

\( P_{ECRH} \) – all combinations of gyrotrons up to maximum power.

**Compromise**

\[ B_{tor} = 2.2 \, T, \, I_{pl} = 230 \, kA, \, n_e \sim 1 \times 10^{19} m^{-3}, \, P_{EC} < 2.2 \, MW. \]
The discharges under study contained up to four stages, differing in the level of ECRH power $P_{EC}$ and localization of the EC-resonance zone in the plasma:

{1} – ohmic discharge, OH;
{2} – on-axis ($\rho_{EC} = 0.2$) EC-heating (144 GHz, 0.5 MW), gyrotron B;
{3} – off-axis ($\rho_{EC} = 0.5$) EC heating (129 GHz, 1.7 MW), gyrotrons A+C;
{4} – combined EC heating (2.2 MW), gyrotrons A+B+C.

Time evolution of current $I_{pl}$, line averaged density $\bar{n}_e$, central electron temperature $T_e(0)$ and stored energy $W_{dia}$ in discharge with powerful combined ECRH.

$B_{tor} = 2.2$ T, $I_{pl} = 230$ kA.

Scenario with $P_{EC} = 0.5$ MW, 2.2 MW, Scenario with $P_{EC} = 1.7$ MW.
Plasma profiles

The discharges under study contained up to four stages, differing in the level of ECRH power $P_{EC}$ and localization of the EC-resonance zone in the plasma:

{1} – ohmic discharge, OH;
{2} – on-axis EC-heating (0.5 MW), gyrotron B;
{3} – off-axis EC heating (1.7 MW), gyrotrons A+C;
{4} – combined EC heating (2.2 MW), gyrotrons A+B+C.

Off-axis ($\rho_{EC} = 0.5$) ECRH with $P_{EC_{off}} = 1.7$ MW ($f_{EC_{off}} = 144$ GHz) \{3\} leads to an increase of $T_e(0)$ up to 2 keV
Adding on-axis ($\rho_{EC} = 0.2$) ECRH with $P_{EC_{on}} = 0.5$ MW ($f_{EC_{on}} = 129$ GHz) \{4\} leads to an increase of $T_e(0)$ up to 3.2 keV

2-\(\omega\) ECE-diagnostics  CXRS  interferometry
Profiles of plasma potential in the Ohmic (OH) deuterium plasmas ( $\bar{n}_e = 1.0 \times 10^{19} \text{ m}^{-3}$, $T_e < 1.3 \text{ keV}$, $T_i < 0.6 \text{ keV}$) and with switch on various groups of gyrotrons A, B and C.

The coupling of the potential and collisionality was extended towards positive plasma potential.
Evolution of the plasma turbulence

Plasma density turbulence evolution in the shot #73136 with scenarios \{1, 3\}, $P_{EC} < 1.7$ MW.

(a) Power spectrogram of the density fluctuations,
(b) power spectra in OH (black) and ECRH (red) phases of the discharge,
(c) time trace of the density RMS; $r_{HIBP}=0.12$ m.
Evolution of the plasma turbulence

The RMS of the core plasma density $n_e$ and potential $\varphi$ fluctuations increases up to a factor 2 of in the core area for $P_{EC} = 2.2$ MW.
Turbulence rotation measurements

\[ V_{\text{pol}} = \Delta x_{ij} \frac{2\pi f}{\theta_{ij}} \]

\[ \theta (I_{\text{tot-i}}, I_{\text{tot-j}}) > 0 \Rightarrow \text{propagation } j \rightarrow i \]

\[ \theta (I_{\text{tot3}}, I_{\text{tot5}}) > 0 \Rightarrow \text{Electron diamagnetic drift direction EDD} \]

\[ V_{E \times B} = \frac{c[E \times B]}{B^2} \]

\[ V_{eDD} = \frac{c[\nabla p_e \times B]}{eB^2} \]

\[ V_{iDD} = -\frac{c[\nabla p_i \times B]}{eB^2} \]
The cross-phase of density fluctuations vs frequency for OH (black curve) and ABC (red curve) stages of the shot with changes of the potential sign, \#73197; 
\[ B_t = 2.2 \text{ T}, I_{pl} = 230 \text{ kA}, E_b = 320 \text{ keV}, r_{HIBP} = 0.09-0.11 \text{ m}. \]
The slope of straight lines allows to estimate the velocity of turbulence propagation (poloidal rotation) for specified spectral range.
\[ f < 30 \text{ kHz} \] - the frequency range of Stochastic Low-Frequency (SLF) mode;
\[ f > 50 \text{ kHz} \] - the frequency range of Quasi-Coherent Mode (QCM).

\[ E_r < 0, V_{ExB} \]

\[ E_r > 0, V_{ExB} \]

Change of potential sign to positive – change SLF rotation to eDD, increase of the QCM rotation velocity.
**THEORETICAL ESTIMATIONS**

**Radial force balance equation**

\[ E_r = (Z_i e n_i)^{-1} \nabla p_i - V_p B_t + V_t B_p \]

- **Diamagnetic term** always \(<0\)
- **NC poloidal rotation term** \(<0\)
- **Toroidal rotation** in OH, Counter \(I_{pl}\)

In OH all terms \(<0\), consistent to experiment, \(E_r < 0\).


\[ E_r (r) = \frac{T_i}{e} \left[ \frac{n_e'}{n_e} + (1 - k_{NC}) \frac{T_i'}{T_i} \right] + E_{turb} \]

- **NC Er is negative**
- At strong turbulence \(\Pi_{V||} < 0\) and \(E_{turb} > 0\)
- At strong EC heating \(T_e\) increases, fluctuations \(n_e\) and \(\varphi\) increases
- Reynolds stress \(\langle \tilde{V}_|| \cdot \tilde{V}_r \rangle\) increases, \(E_{turb} > 0\)

**Turbulent term**

\[ E_{turb} = -\frac{B \varepsilon}{c q} \frac{\Pi_{V||}}{\Gamma_r} + E_w \frac{\Gamma_w}{\Gamma_r} \]

\[ \Gamma_r = \langle \tilde{n}_e \cdot \tilde{V}_r \rangle \] Particle flux

\[ \Pi_{V||} = \langle \tilde{V}_|| \cdot \tilde{V}_r \rangle \] Parallel momentum flux

In contrast to NC, the turbulence may give the positive contribution to the electric field, \(E_{turb} > 0\).
Earlier studies have shown that core potential in tokamak plasmas was always negative in contrast to stellarators, where it was either negative or positive depending on plasma conditions.

The present T-10 results compares remarkably well with the positive plasma potential obtained in the TJ-II stellarator with powerful ECRH for plasmas with similar dimensions and parameters as in T-10. The same is valid for other stellarators like CHS and LHD, where the positive potential was observed for low-density (low-collisionality) ECRH plasmas.

Obtaining the positive potential in a tokamak fills the existed gap and completes the picture (general observations) for toroidal plasmas: the higher is the plasma collisionality, the higher is the negative potential; the lower is the plasma collisionality the higher is the positive potential. (Note that above some collisionality limit, the negative potential saturates).

Therefore, the obtained low-collisionality regime with core positive potential in the tokamak plasma allows us to predict the core positive plasma potential in the fusion reactor like ITER. The same holds for fusion reactor based on the stellarator concept.
<table>
<thead>
<tr>
<th>Regime, gyrotrons</th>
<th>$n_e \left(10^{19} \text{ m}^{-3}\right)$</th>
<th>$T_e(0)$ (keV)</th>
<th>$Z_{\text{eff}}$</th>
<th>$n_{\text{eff}}$</th>
<th>$\varphi_0$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-10 {1}, OH</td>
<td>1.17</td>
<td>1.4</td>
<td>2.5</td>
<td>0.224</td>
<td>-1.75</td>
</tr>
<tr>
<td>T-10 {2}, B</td>
<td>1.6</td>
<td>1.75</td>
<td>2.1</td>
<td>0.165</td>
<td>-1.85</td>
</tr>
<tr>
<td>T-10 {3}, AC</td>
<td>1.2</td>
<td>2</td>
<td>2.5</td>
<td>0.113</td>
<td>-0.6</td>
</tr>
<tr>
<td>T-10 {4}, ABC</td>
<td>1.2</td>
<td>3.2</td>
<td>3</td>
<td>0.053</td>
<td>+0.6</td>
</tr>
<tr>
<td>ITER L-mode</td>
<td>6.2</td>
<td>8</td>
<td>1.8</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>ITER H-mode burn</td>
<td>8.9</td>
<td>23.5</td>
<td>1.8</td>
<td>0.017</td>
<td></td>
</tr>
</tbody>
</table>

DISCUSSION - Predictions for ITER

Effective collisionality

$$\nu_{\text{eff}} = 0.1 R Z_{\text{eff}} \bar{n}_e / T_e(0)^2$$

$$\nu_{\text{eff}} = 0.0174$$

$$\nu_{\text{eff}} = 0.1046$$
The first observation of the positive electric potential $\varphi = +500 \text{ V}$ near the center and a positive electric field $E_r \approx +20 \text{ V/cm}$ in a core tokamak plasma was done.

This observation is consistent not with NC expectations, rather with turbulence effects, and it is supported by an increase of the broadband electrostatic fluctuations with powerful ECRH.

The coupling of core plasma potential and collisionality experimentally established in a wide range of plasma parameters was extended to low-collisional regime in a tokamak. Based on that, the positive plasma potential is predicted for ITER collisionless plasmas without momentum injection.