NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

EX/6-5

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

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Introduction -1

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	TJ-II stellarator
R/a	**1.5/0.3 m**	**1.5/0.22 m**
B_0	**≤ 2.5 T**	**1 T**
Discharge duration	up to **1 s**	up to **0.3 s**
$\bar{n}_e$	up to **$6 \cdot 10^{19}$ m^{-3}**	up to **$5 \cdot 10^{19}$ m^{-3}**
$T_e(0)/ T_i(0)$	up to **3.2 keV/ 0.6 keV**	up **1.6 keV/ 0.12 keV**

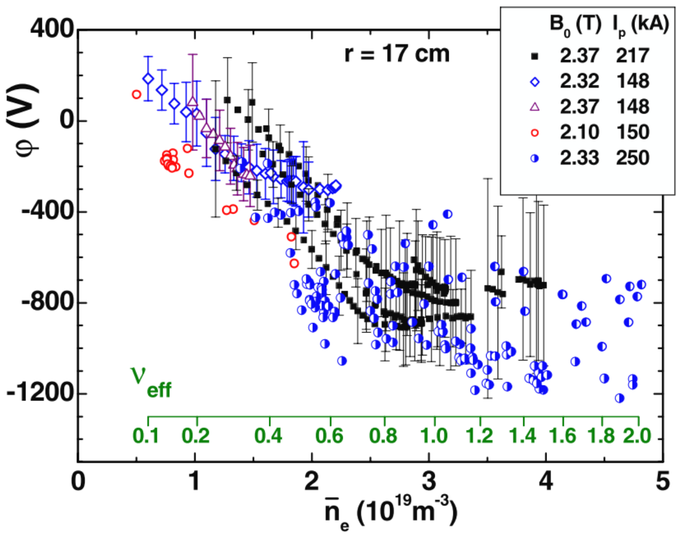
ECRH 3 gyrotrons @144 GHz +1@130 GHz

2-nd harmonic, X-mode P_{EC} ≤ **2.2 MW**

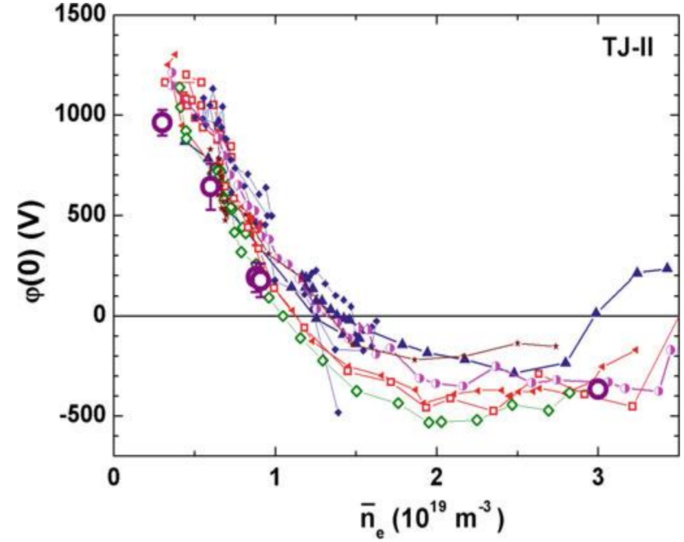
ECRH 2 gyrotrons@53.2 GHz

P_{EC} ≤ **0.6 MW**

NBI 2 H_2 injectors, E_b<32 keV, P_{NBI} ≤ **1.2 MW**



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

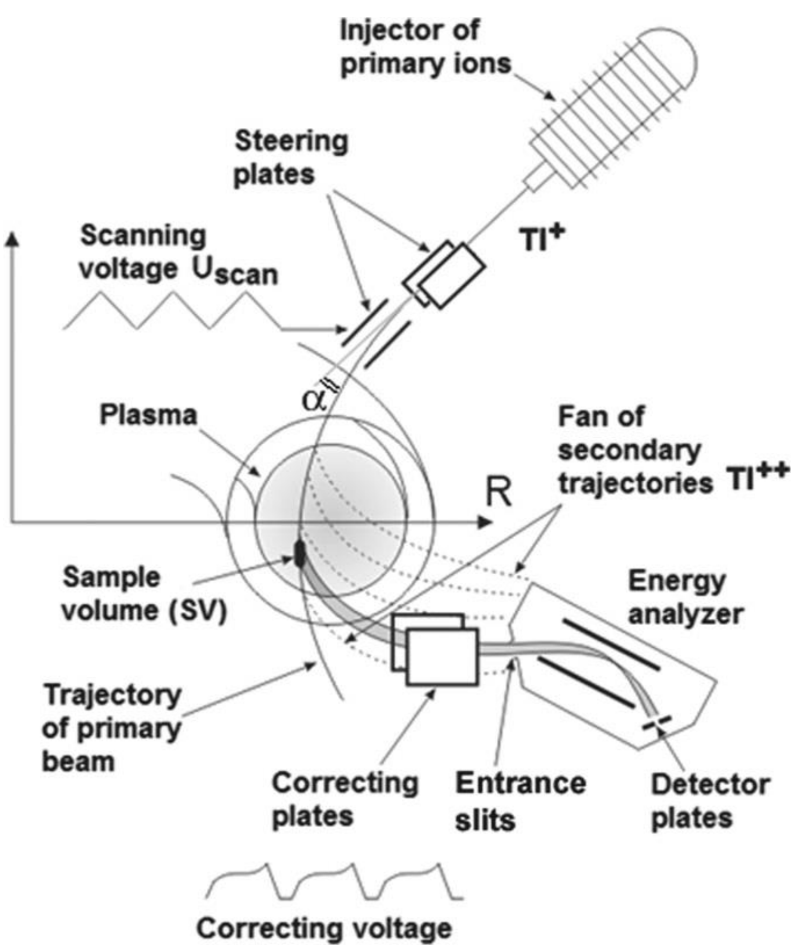


[A.V. Melnikov 2019 Electric Potential in Toroidal Plasmas (*Springer Nature Switzerland AG*)]

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

Experimental setup - Heavy Ion Beam Probe

<u>Scheme of HIBP in T-10</u>



- Tl^+ ions with energies E_b up to 330 keV
- Probing beam current up to 250 μA
- 5-slit energy analyzer
  5 separated Sample Volumes (SVs),
  SV size ≈ 1-2 cm, SV distance ≈ 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)

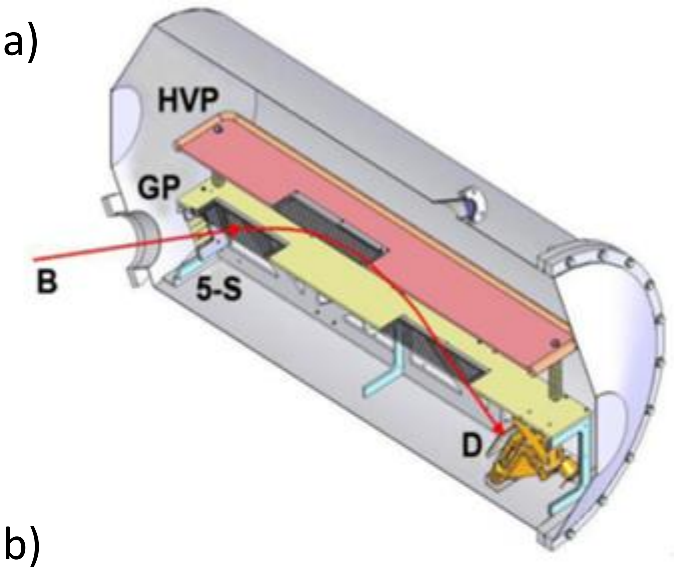
Experimental setup - Heavy Ion Beam Probe 2

(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;

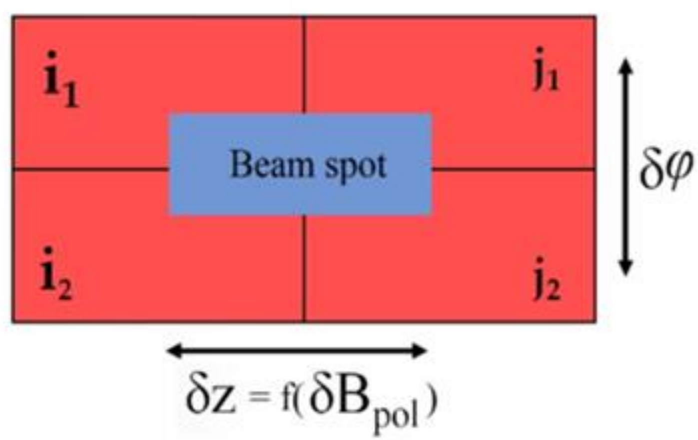
(b) beam detector schematic:
- i_1, j_1, i_2, j_2 – beam current to plates
- $\delta\varphi$ – vertical shift, E_{beam}
- δz – toroidal shift

Beam characteristics	Plasma parameters
ΔE_{beam}	$\varphi, \tilde{\varphi}$
$\tilde{I}_{beam}$	$\tilde{n}_e$
$\tilde{z}$	$\tilde{B}_{pol}$

(a)



(b)



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, $n_e \sim 1\times10^{19} m^{-3}$, $P_{EC} < 2.2$ MW.

Plasma scenario

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;

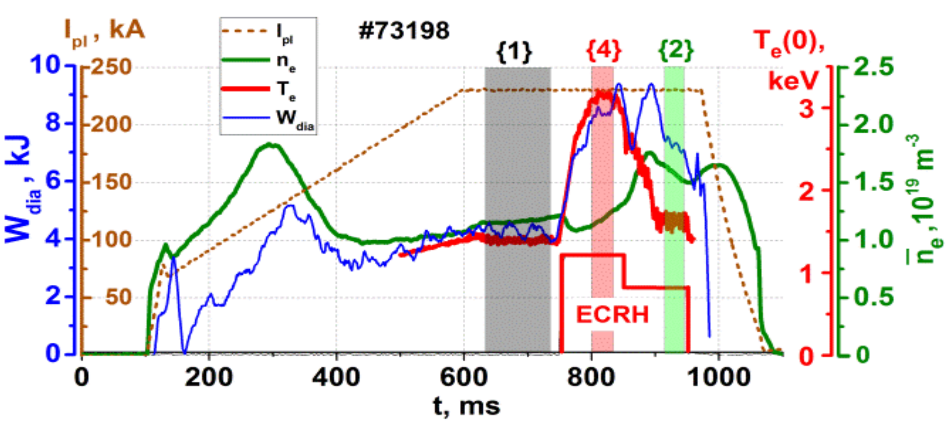
{3} – off-axis ($\rho_{EC} = 0.5$) EC heating (129 GHz, 1.7 MW), gyrotrons A+C;

{4} – combined EC heating (2.2 MW), gyrotrons A+B+C.

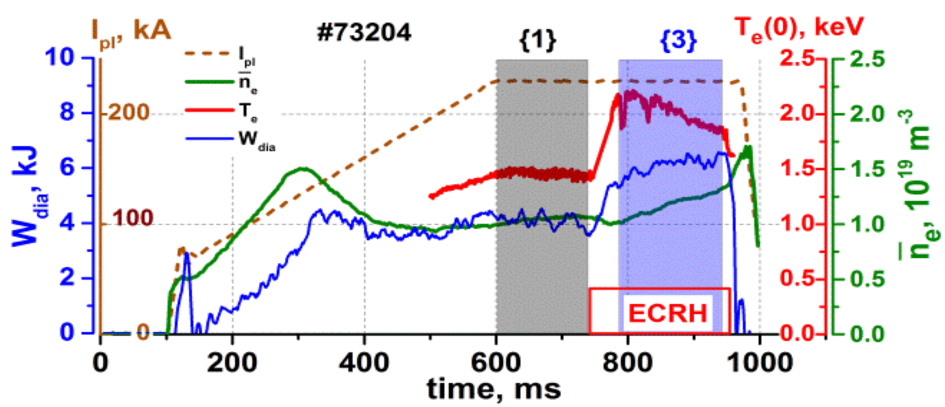
Time evolution of current I_{pl}, line averaged density $\bar{n}_e$, central electron temperature $T_e(0)$ and stored energy W_{dia} in discharge with powerful combined ECRH.

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;

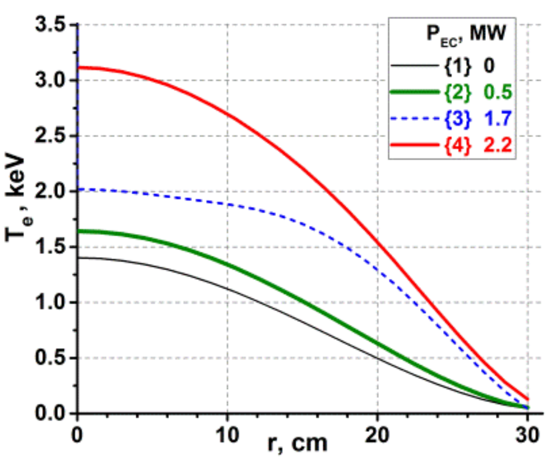
{3} – off-axis EC heating (1.7 MW), gyrotrons A+C;

{4} – combined EC heating (2.2 MW), gyrotrons A+B+C.

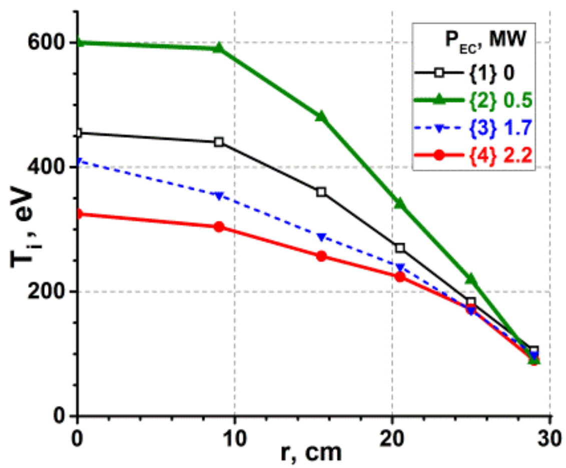
Off-axis ($\rho_{EC} = 0.5$) ECRH with P_{EC_off} = 1.7 MW (f_{EC}^{off} = 144 GHz) {3} leads to an increase of T_e (0) up to 2 keV

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

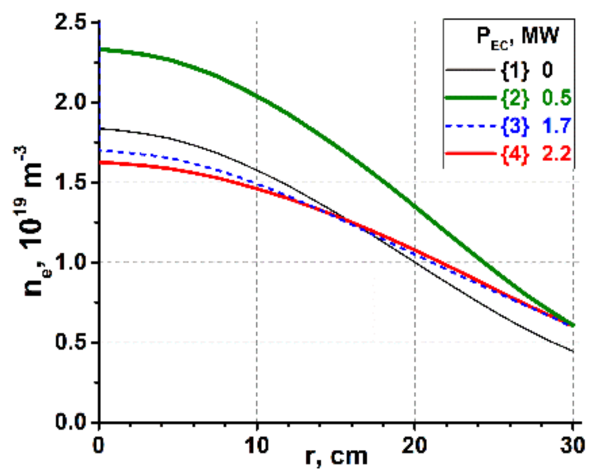
2-ω ECE-diagnostics



CXRS

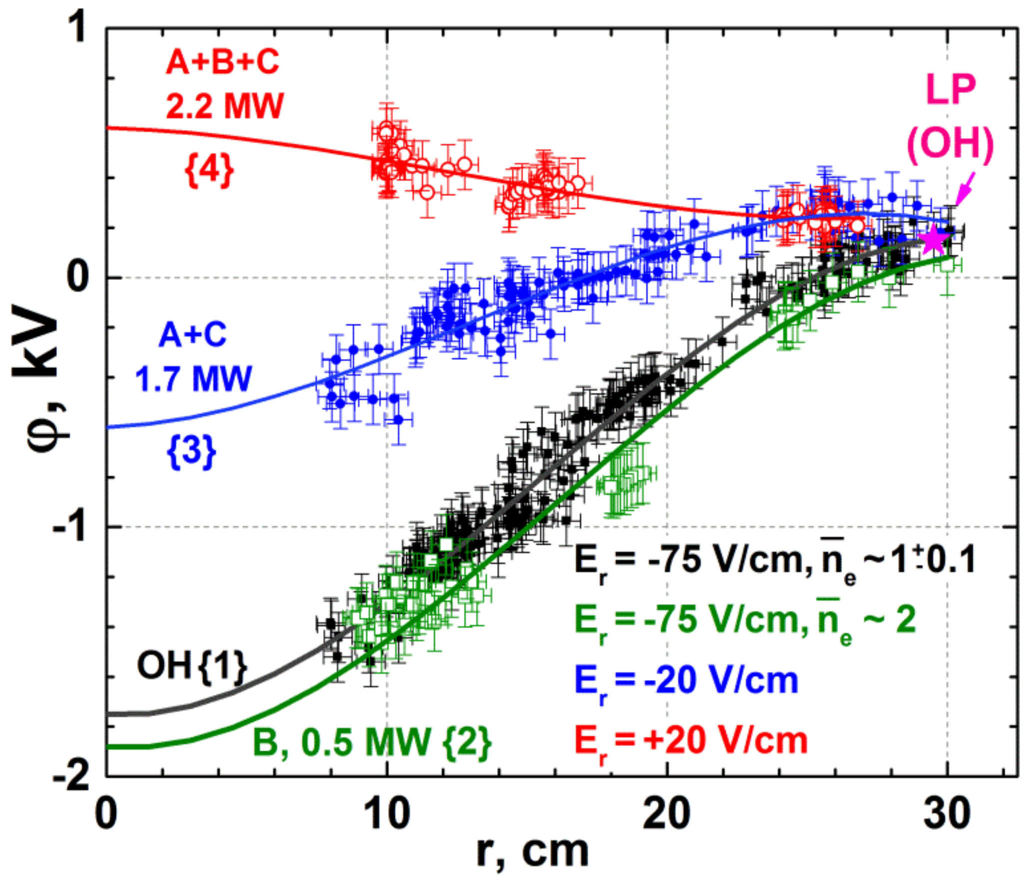


interferometry



Evolution of the mean plasma potential

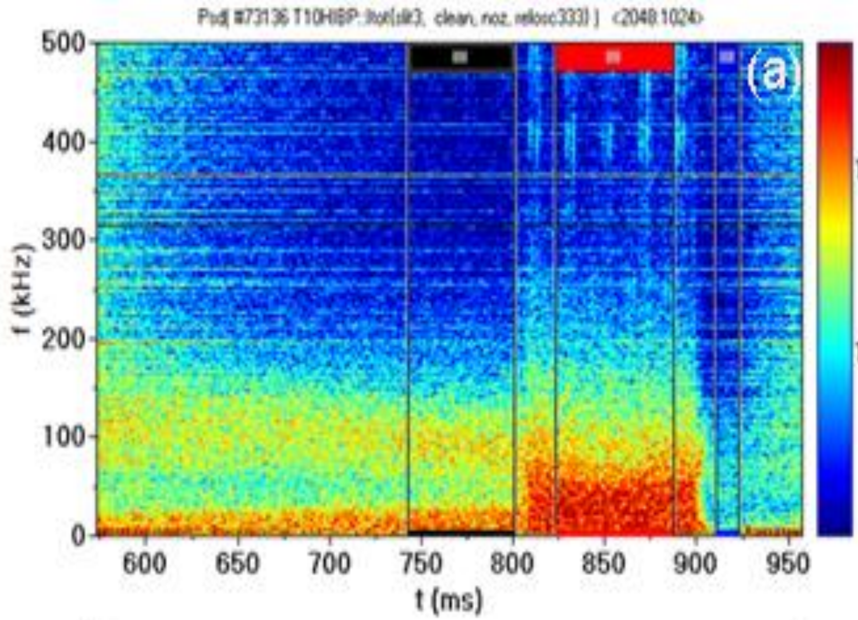
Profiles of plasma potential in the Ohmic (OH) deuterium plasmas ($\overline{n}_e = 1.0\times10^{19}$ m^{-3}, $T_e < 1.3$ keV, $T_i < 0.6$ keV) and with switch on various groups of gyrotrons A, B and C.

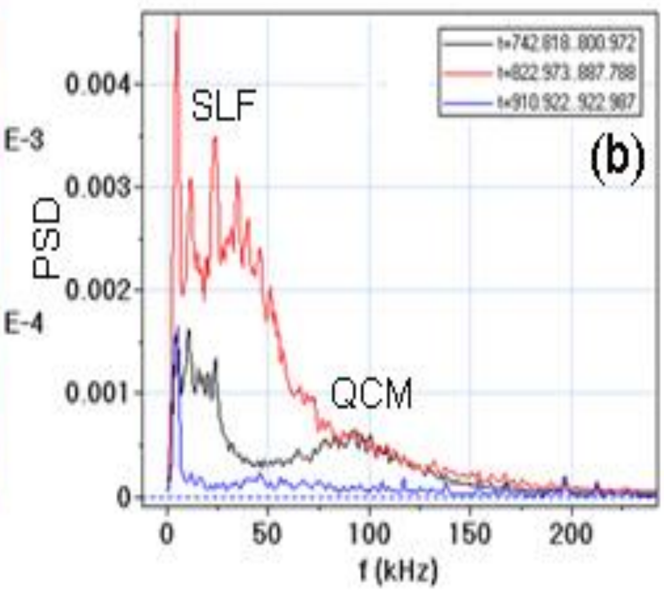


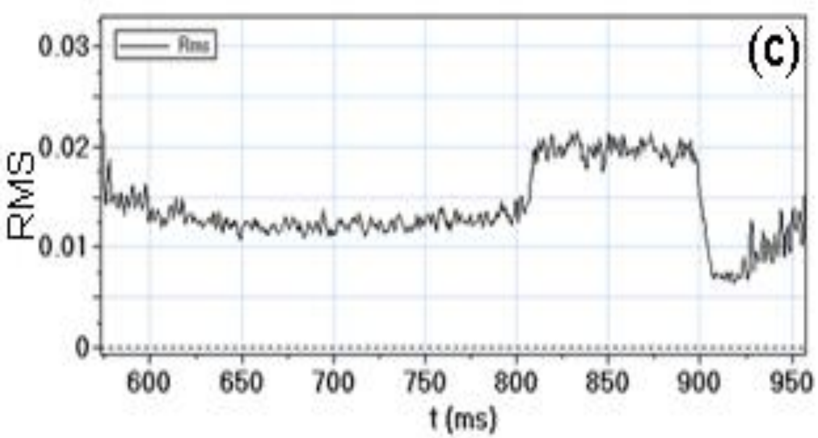
The coupling of the potential and collisionality was extended towards positive plasma potential.

Evolution of the plasma turbulence

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



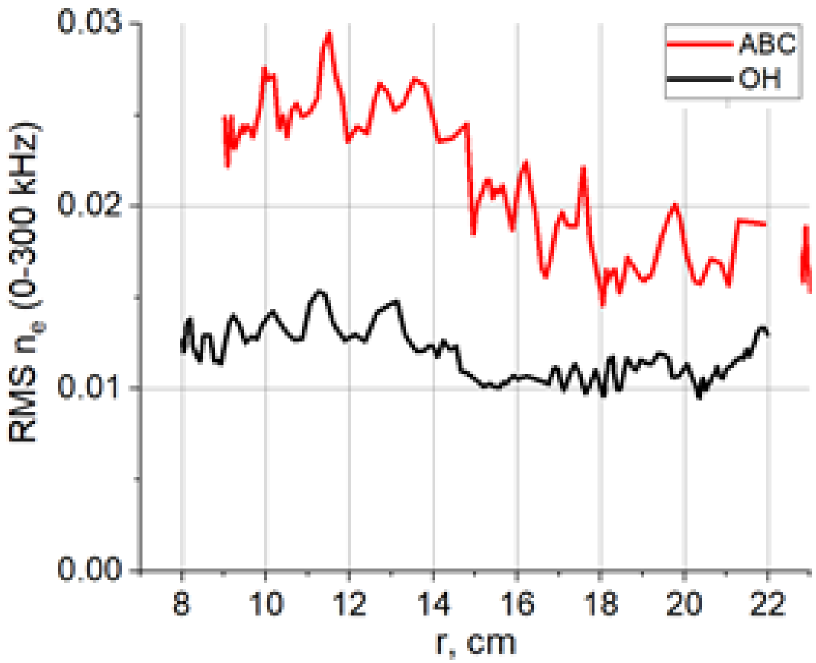


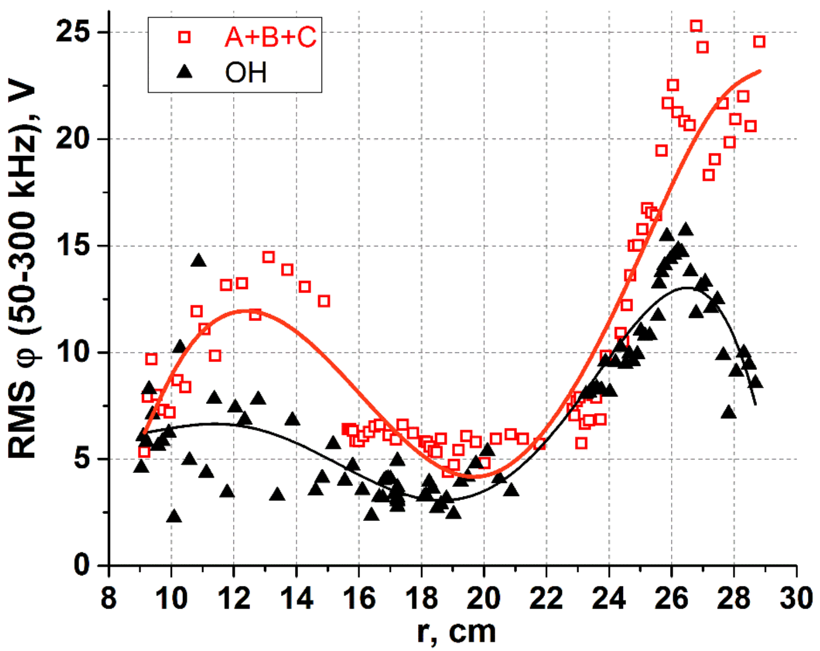


(a) Power spectrogram of the density fluctuations,
(b) power spectra in OH (black) and ECRH (red) phases of the discharge,
(c) time trace of the density RMS;
r_{HIBP}=0.12 m.

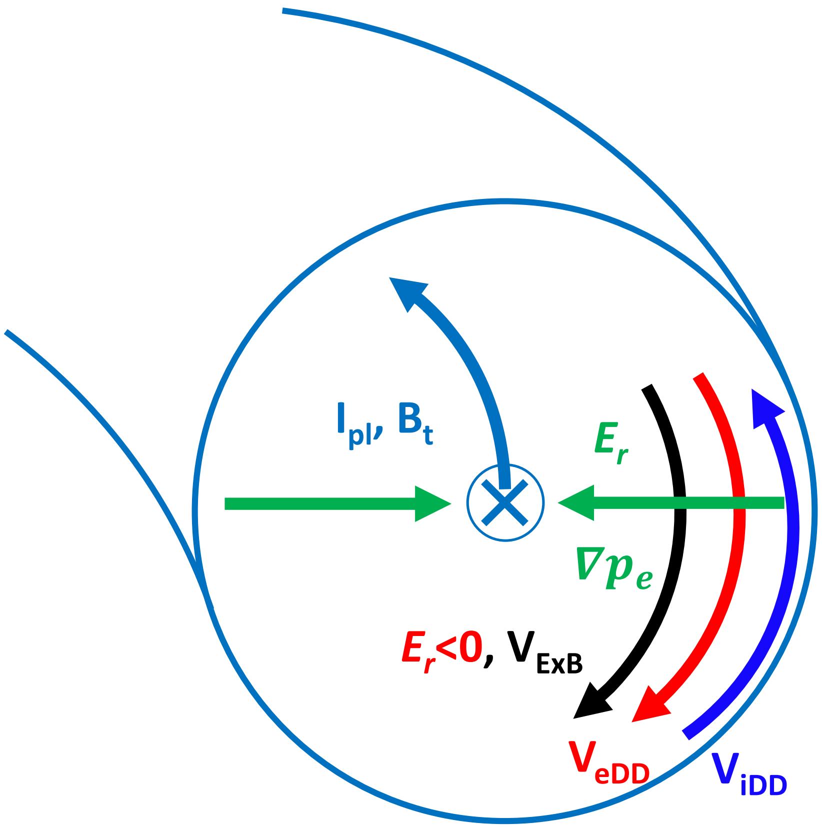
Evolution of the plasma turbulence

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





Turbulence rotation measurements

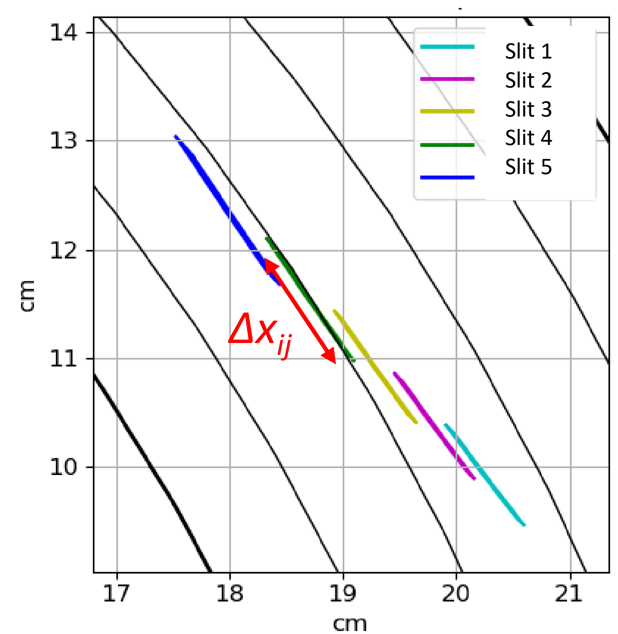


$$V_{E\times B} = \frac{c[E\times B]}{B^2}$$ ***ExB* drift**

$$V_{eDD} = \frac{c[\nabla p_e \times B]}{eB^2}$$ **Electron diamagnetic drift**

$$V_{iDD} = -\frac{c[\nabla p_i \times B]}{eB^2}$$ **Ion diamagnetic drift**

Sample volumes for 5-slit analyzer



$V_{pol} = \Delta x_{ij}\, 2\pi f / \theta_{ij}$

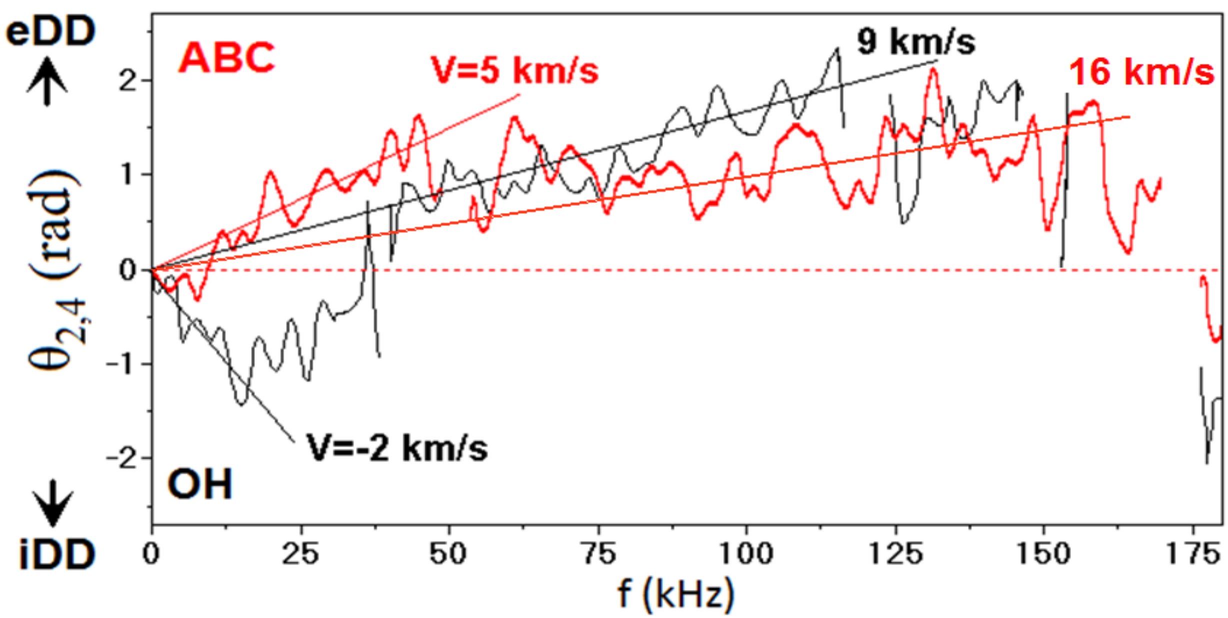
θ (I_{tot-i}, I_{tot-j}) > 0 => propagation j -> i

θ (I_{tot3}, I_{tot5}) > 0 => Electron diamagnetic drift direction **EDD**

Turbulence rotation changes with potential

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;
$B_t = 2.2$ T, $I_{pl} = 230$ kA, $E_b = 320$ keV, $r_{HIBP} = 0.09$-0.11 m.
The slope of straight lines allows to estimate the velocity of turbulence propagation (poloidal rotation) for specified spectral range.
$f < 30$ kHz - the frequency range of Stochastic Low-Frequency (SLF) mode;
$f > 50$ 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

$$V_p = k\frac{c}{eB_t}\frac{dT_i}{dr}$$

Toroidal rotation In OH, Counter I_{pl}

In OH all terms <0, consistent to experiment, $E_r < 0$.

[Rozhansky V., et al., PoP **9** (2002) 3385]:

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

NC Er is negative

Turbulent term

$$E_{turb} = -\frac{B\varepsilon}{c\,q} n_e \frac{\Pi_{V\parallel}}{\Gamma_r} + E_w \frac{\Gamma_w}{\Gamma_r}$$

$\Gamma_r = \left\langle \tilde{n}_e \cdot \tilde{V}_r \right\rangle$ Particle flux

$\Pi_{V\parallel} = \left\langle \tilde{V}_\parallel \cdot \tilde{V}_r \right\rangle$ Parallel momentum flux

At strong turbulence $\Pi_{V\parallel} < 0$ and $E_{turb} > 0$

At strong EC heating T_e increases, fluctuations n_e and φ increases

Reynolds stress $\left\langle \tilde{V}_\parallel \cdot \tilde{V}_r \right\rangle$ increases, $E_{turb} > 0$

In contrast to NC, the turbulence may give the positive contribution to the electric field, $E_{turb} > 0$.

DISCUSSION

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.

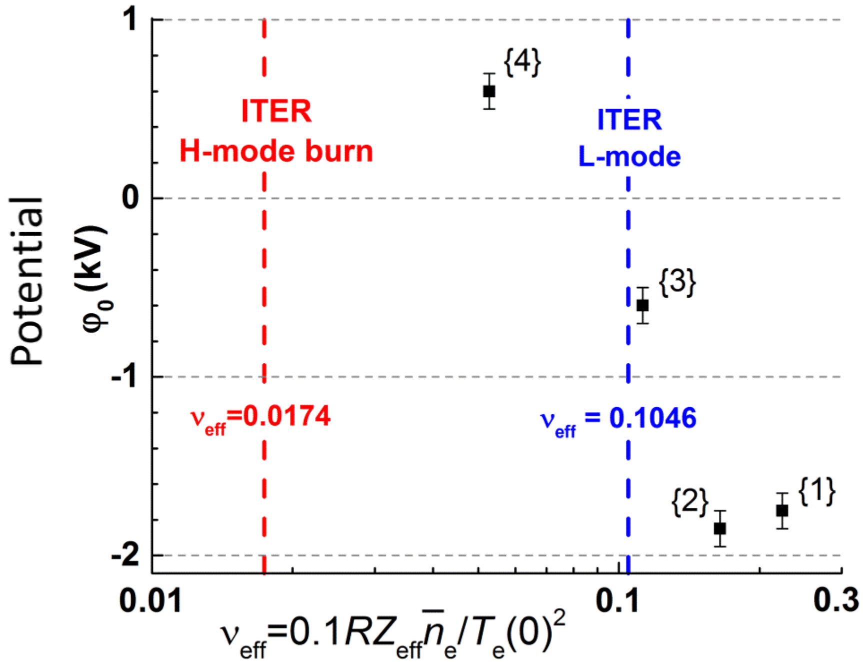
The present T-10 results compares remarkably well with the positive plasma potential obtained in the TJ-II stellarator with powerful ECRH for plasmas with similar dimensions and parameters as in T-10. The same is valid for other stellarators like CHS and LHD , where the positive potential was observed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

DISCUSSION - Predictions for ITER

Regime, gyrotrons	$\bar{n}_e$ (10^{19} m^{-3})	$T_e(0)$ (keV)	Z_{eff}	n_{eff}	φ_0 (kV)
T-10 {1}, OH	1.17	1.4	2.5	0.224	-1.75
T-10 {2}, B	1.6	1.75	2.1	0.165	-1.85
T-10 {3}, AC	1.2	2	2.5	0.113	-0.6
T-10 {4}, ABC	1.2	3.2	3	0.053	+0.6
ITER L-mode	6.2	8	1.8	0.105	
ITER H-mode burn	8.9	23.5	1.8	0.017	



Effective collisionality

Summary

- The first observation of the positive electric potential φ = +500 V near the center and a positive electric field $E_r \approx +20$ 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.