EX/6-5

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

Stellarators:
predominantly positive potential

ECRH – positive: CHS, TJ-II, LHD

NBI – negative: CHS, TJ-II, LHD

Introduction - 2: Potential-collisionality coupling

T-10 tokamak

R/a 1.5/0.3 m

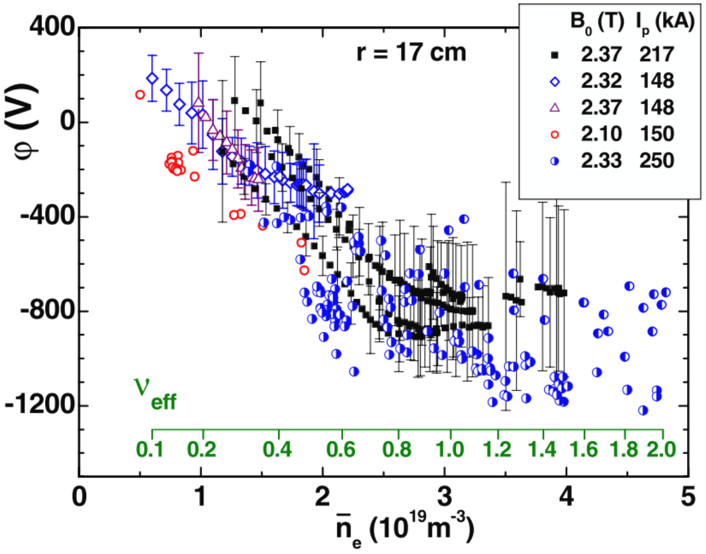
B_0 ≤ 2.5 T

Discharge duration: up to 1 s

$\bar{n}_e$: up to $6 \cdot 10^{19}$ m^{-3}

$T_e(0)$/ $T_i(0)$: up to 3.2 keV / 0.6 keV

ECRH (three 144 GHz gyrotrons +130 GHz, 2-nd harmonic, X-mode, up to 2.2 MW total power)



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

TJ-II stellarator

1.5/0.22 m

1 T

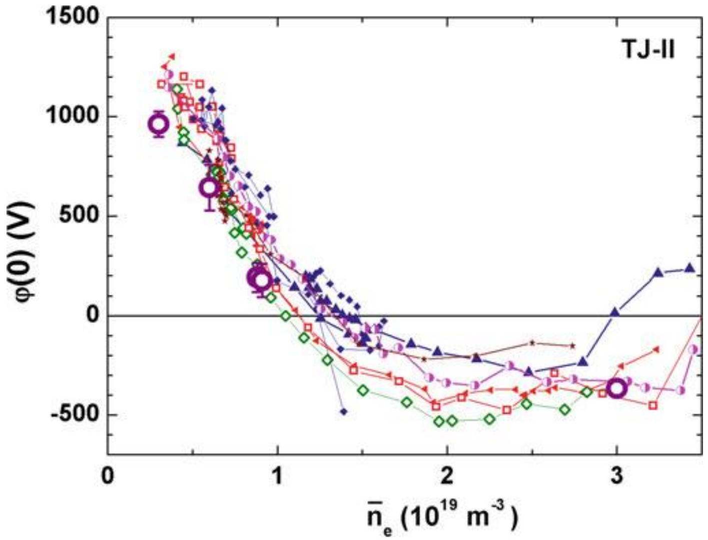
up to 300 ms

$\bar{n}_e$: up to $5 \cdot 10^{19}$ m^{-3}

$T_e(0)$/ $T_i(0)$: up 1.6 keV/ 0.12 keV

ECRH (two 53.2 GHz gyrotrons, up to 300 kW each, 2^{nd} harmonic, X-mode)

NBI (two 600 kW H_2 injectors, E_b<32 keV)



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

Potential-to-collisionality coupling was observed in both tokamaks and stellarators

Experimental setup - Plasma conditions

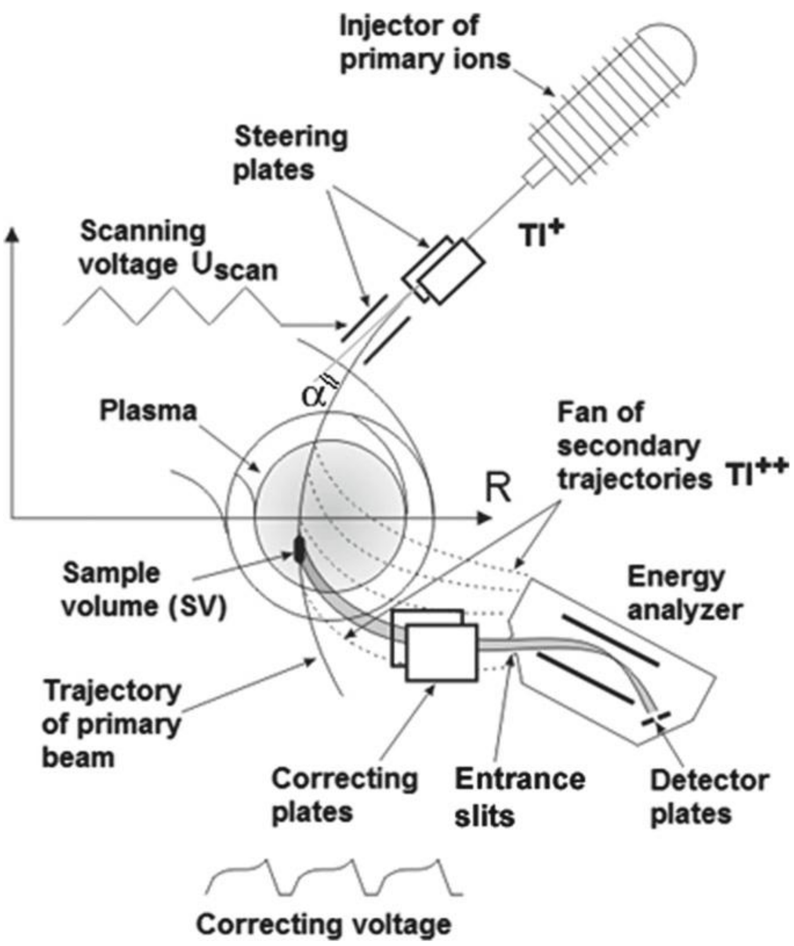
Coupling between plasma potential and collisionality $\nu_{eff} \sim n_e/T_e^2$ was established for both tokamaks and stellarators
Gap – positive potential in the core of tokamak plasmas.
Hypothesis – if the low collisionality is the cause for positive potential, one may obtain it in low-collisional tokamak plasma

Trade-off

- To obtain the low-collisional plasma, we may decrease the density n_e, but avoiding run-away electrons and providing a good absorption of EC power.
- We cannot vary the toroidal field **B**, because we have to provide the optimal deposition of EC waves with existing gyrotrons.
- Aiming to extend the investigation area towards the plasma core, the HIBP accelerating voltage was recently increased up to 330 kV, which is a record: the maximal voltage ever achieved for the open-air accelerators installed in the fusion devices. In most of experiments, we used Tl^+ ions with E_{beam}=300 keV.

Experimental setup
Heavy Ion Beam Probe

Sheme of HIBP in T-10



- 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)

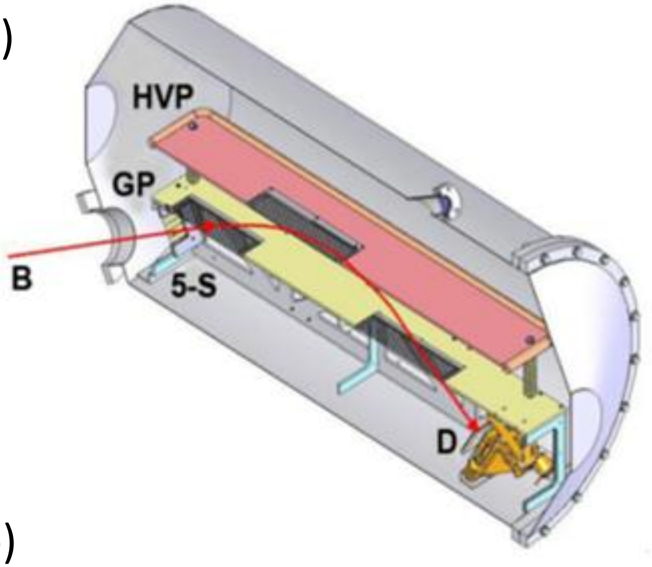
Experimental setup
Analyzer for Heavy Ion Beam Probe

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

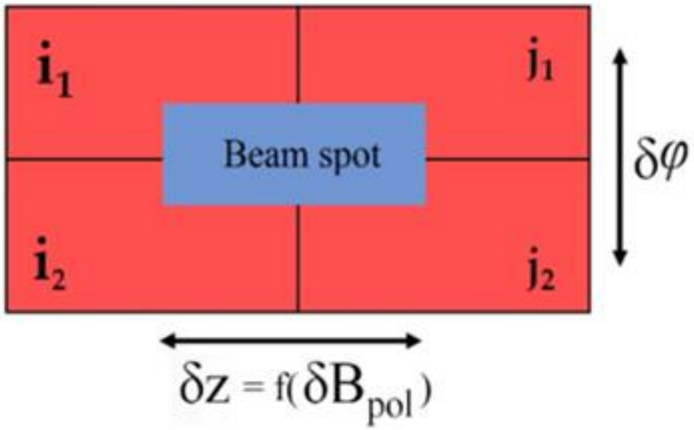
(b) HIBP detector schematic: i_1, j_1, i_2, j_2 are current to plates, $\delta\varphi$ is signal of potential, δz is toroidal shift proportional to poloidal magnetic field.

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

(a)



(b)



Experimental results

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:

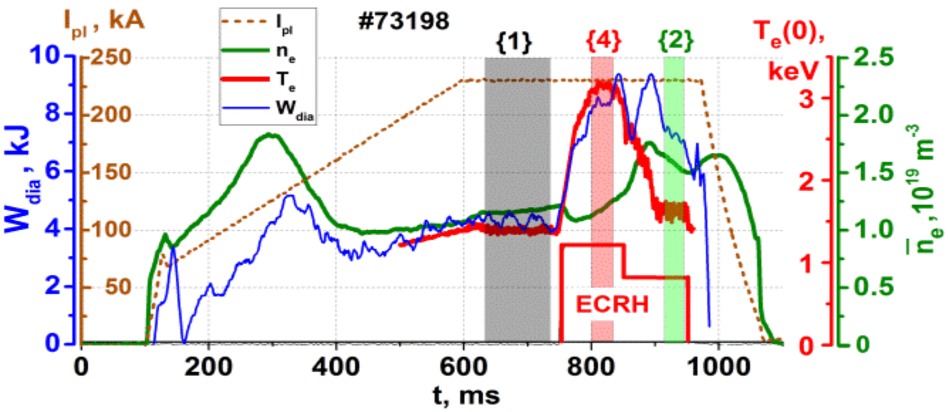
{1} – ohmic discharge, OH;

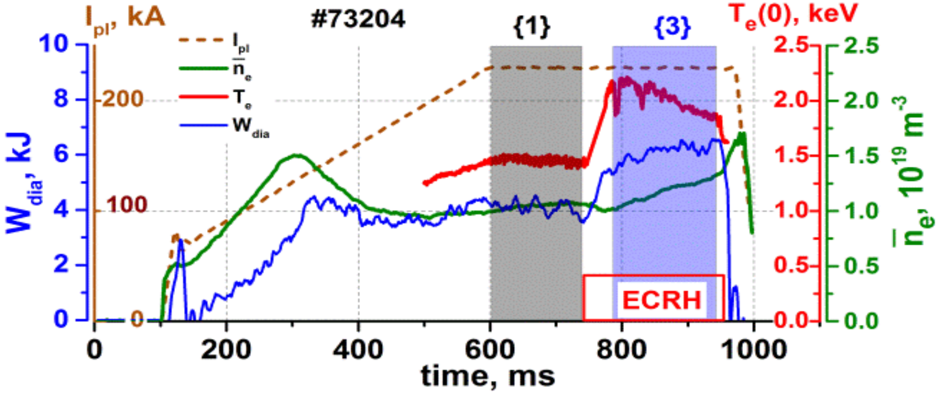
{2} – on-axis EC-heating (144 GHz, 0.5 MW), gyrotron B;

{3} – off-axis 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. (left) scenario with P_{EC} = 0.5 MW, 2.2 MW, (right) scenario with P_{EC} = 1.7 MW.
B_{tor} = 2.2 T, I_{pl} = 230 kA.





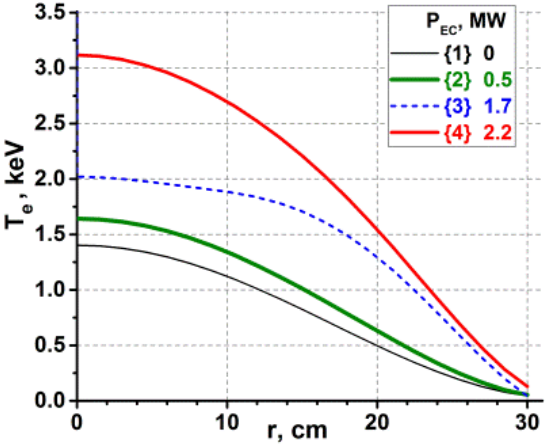
Experimental results

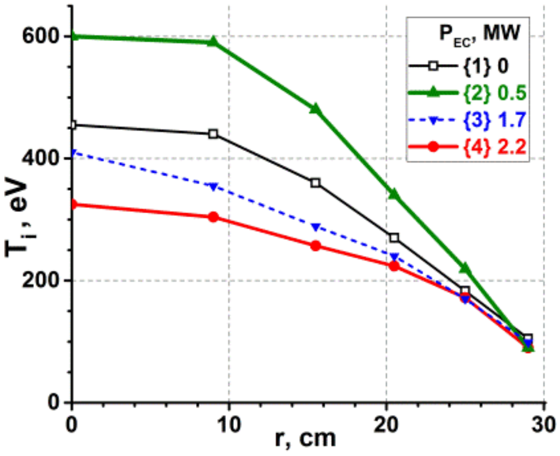
The discharges under study contained up to four stages, differing in the level of ECRH power P_{EC} and localization of the EC-resonance zone in the plasma:

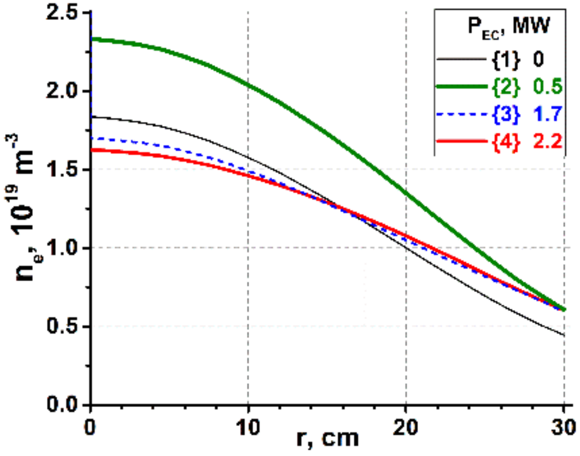
{1} – ohmic discharge, OH;
{2} – on-axis EC-heating (0.5 MW), gyrotron B;
{3} – off-axis EC heating (1.7 MW), gyrotrons A+C;
{4} – combined EC heating (2.2 MW), gyrotrons A+B+C.

Powerful off-axis ($r_{EC} = 0.5$) second harmonic X-mode ECRH with $P_{EC\_off} \leq 1.7$ MW ($f_{EC}^{off} = 144$ GHz), leads to an increase of T_e up to 2 keV in the center, as measured by 2-ω ECE-diagnostics

Profiles

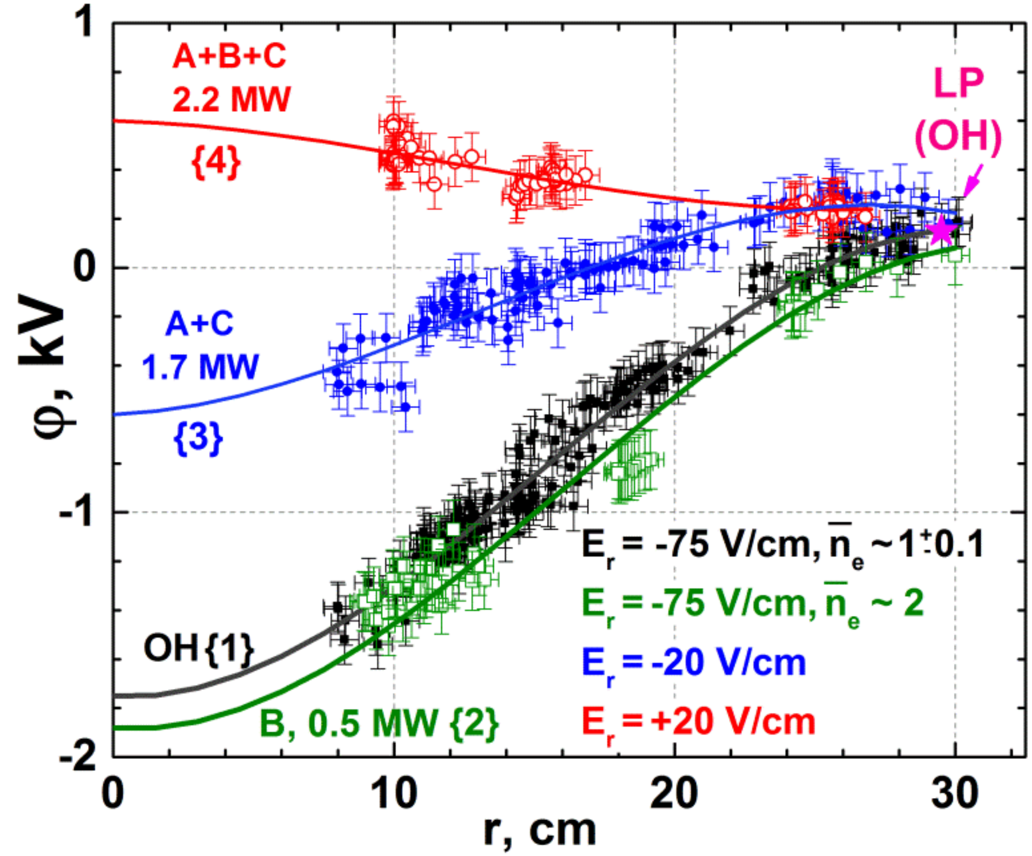






Evolution of the mean plasma potential

Profiles of potential in the Ohmic (OH) deuterium plasmas ($\bar{n}_e = 1.0\times10^{19}\ \mathrm{m}^{-3}$, $T_e < 1.3$ keV, $T_i < 0.6$ keV) and with switch on various groups of gyrotrons A, B and C ($T_e < 3.2$ keV).



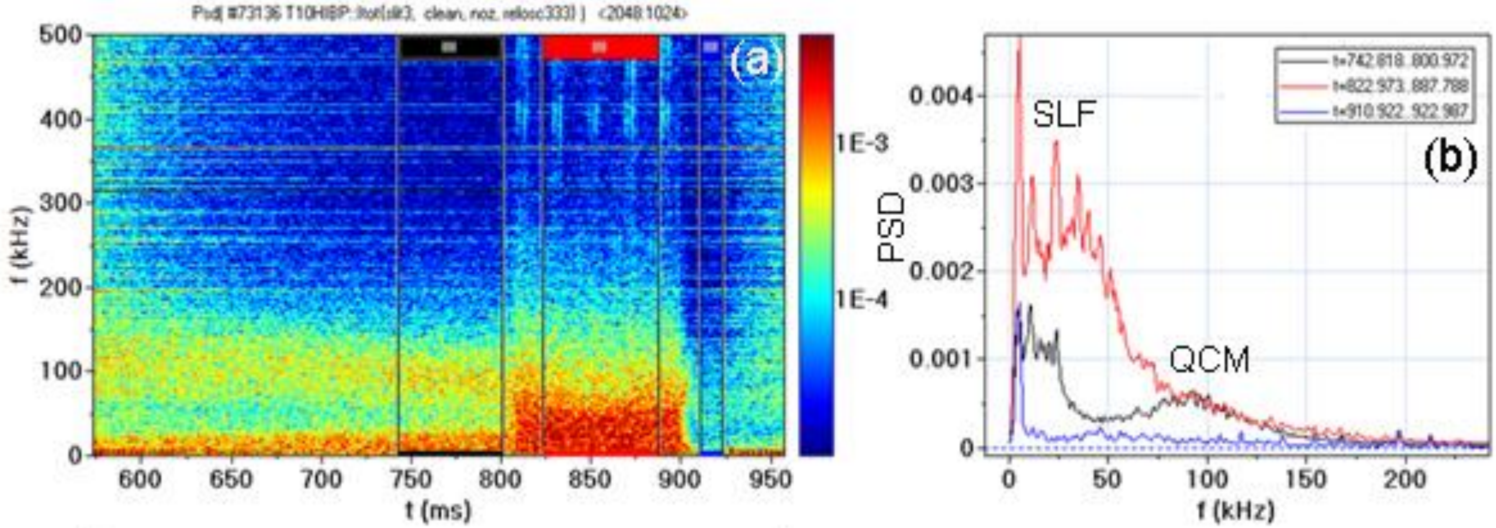
Evolution of the plasma turbulence

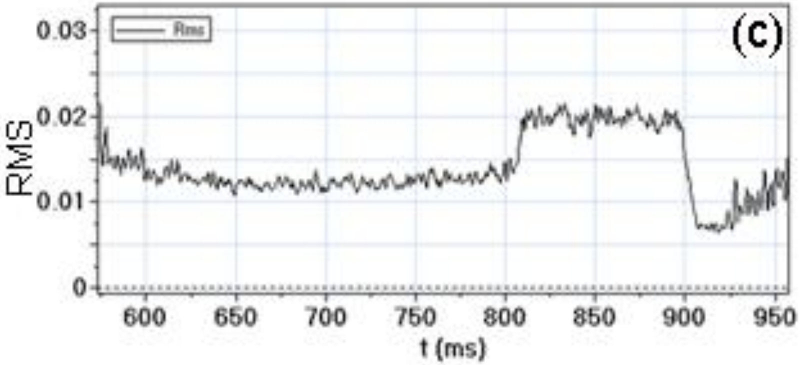
Plasma density turbulence evolution in the shot #73136 with scenarios {1, 3}, $P_{EC} < 1.7$ MW.

(a) Power spectrogram of the density fluctuations,

(b) power spectra in OH (blue and black) and ECRH (red) phases of the discharge,

(c) time trace of the density RMS; $r_{HIBP}=0.12$ m.



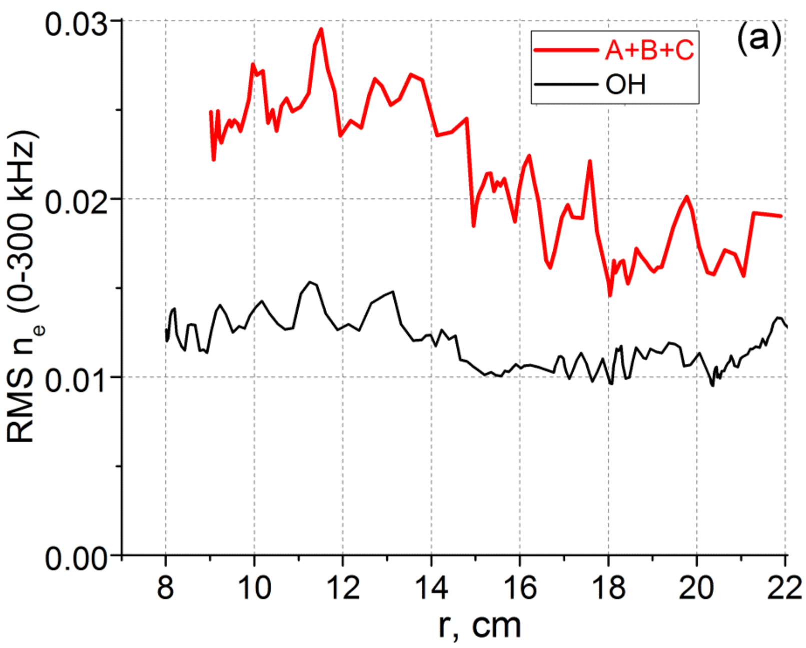


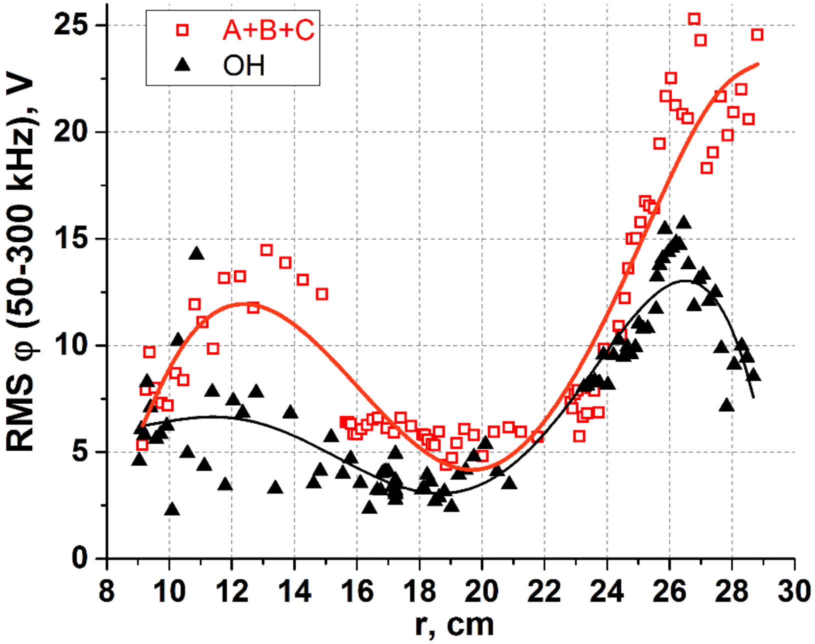
SLF-stochastic low-frequency mode

QCM-quasi-coherent mode

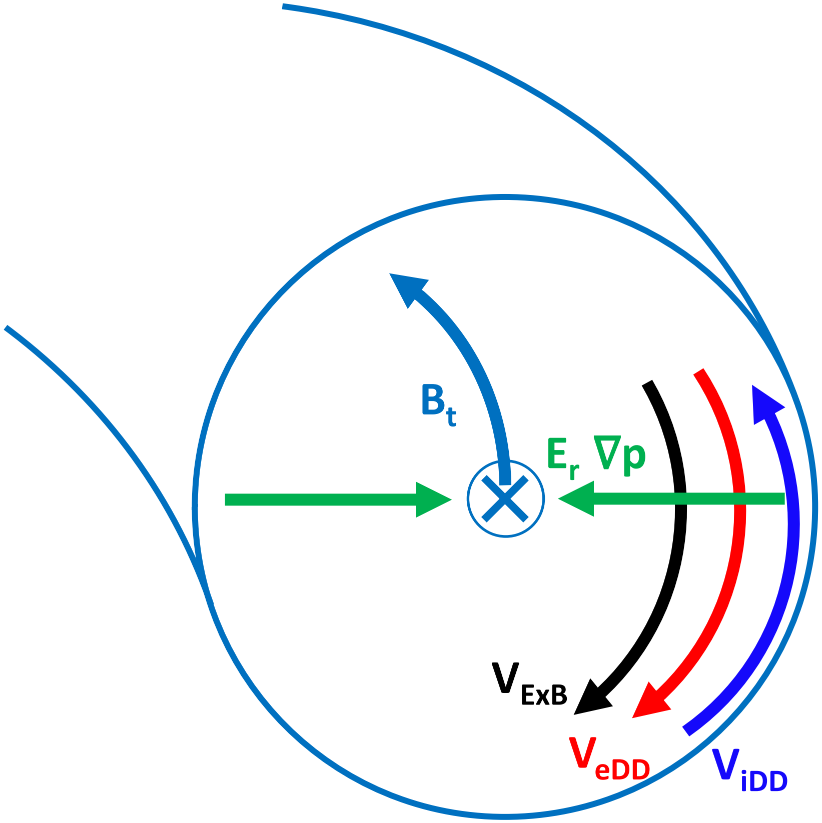
Evolution of the plasma turbulence

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





Turbulence rotation measurements

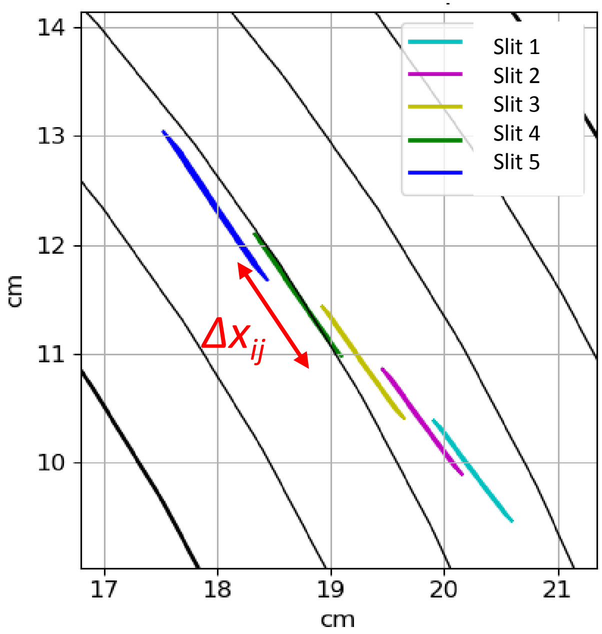


$$V_{E\times B} = \frac{c[E\times B]}{B^2}$$ ***ExB* drift**

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

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

Sample volumes for 5-slits 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**

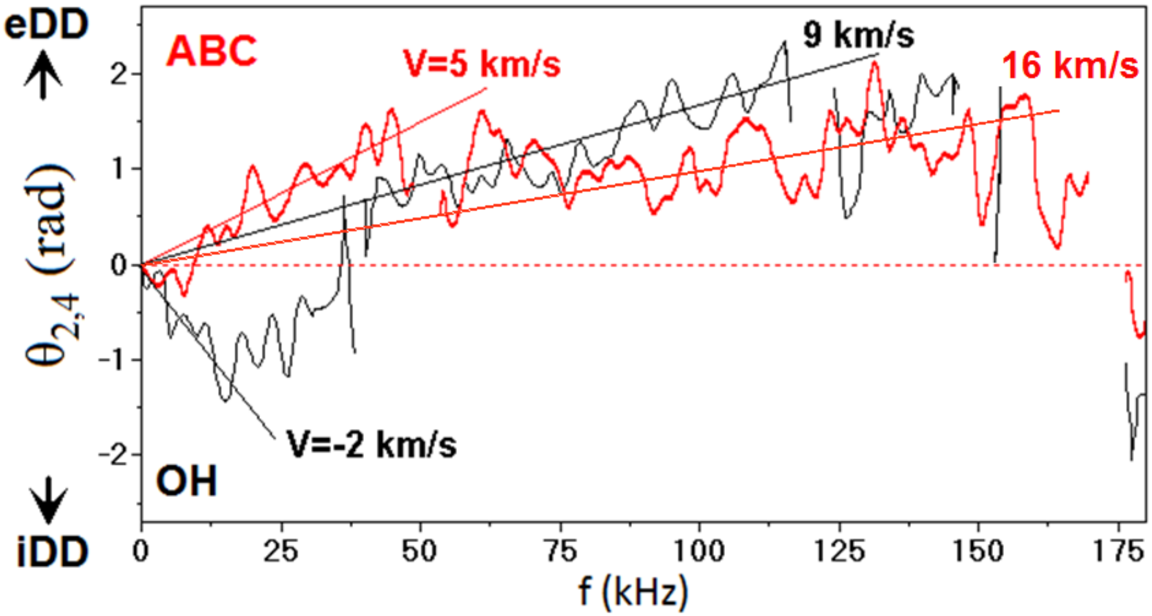
Turbulence rotation measurements

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, $r_{HIBP} = 0.09\text{-}0.11$ m.

The slope of straight lines allows us 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).



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} ⟹ φ <0

Neoclassical theory:

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

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

NC E_r is negative

Turbulent term:

$$E_{\mathrm{turb}} = -\frac{B\varepsilon}{cq}n_e\frac{\Pi_{V\|}}{\Gamma_r} + E_w\frac{\Gamma_w}{\Gamma_r}$$

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

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

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

At strong EC heating T_e increases, fluctuations n_e and φ increases
Reynolds stress $\left\langle \tilde{V}_\| \cdot \tilde{V}_r \right\rangle$ increases, $E_{\mathrm{turb}}>0$

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

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.

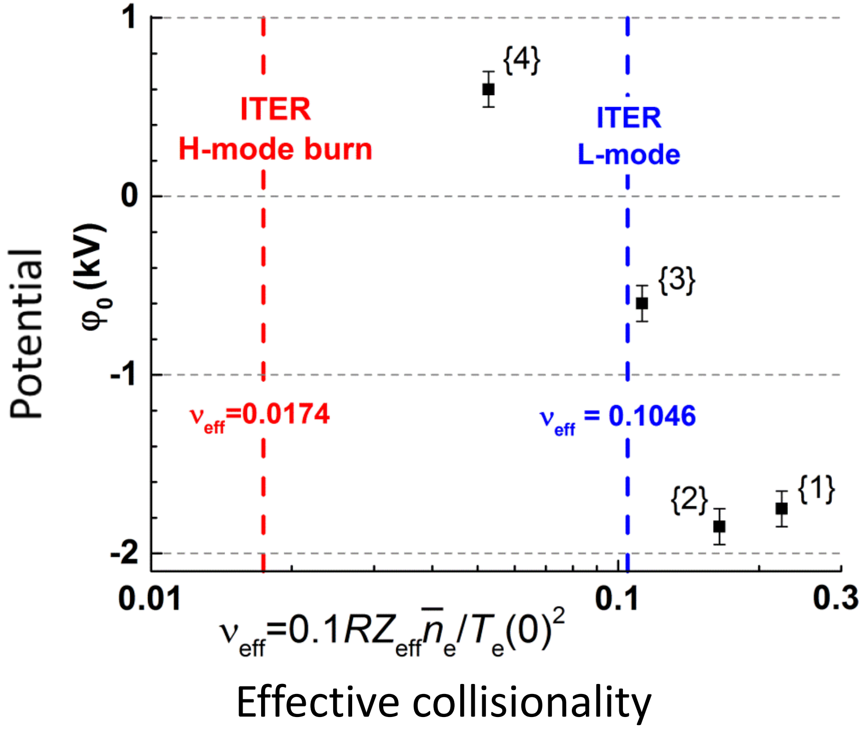
The present T-10 results compares remarkably well with the positive plasma potential obtained in the TJ-II stellarator with powerful ECRH for plasmas with similar dimensions and parameters as in T-10. The same is valid for other stellarators like CHS and LHD , where the positive potential was observed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

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	



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 stablished 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.