

## Measurements of plasma potential, radial electric field and turbulence rotation velocity in the T-10 tokamak

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Stabilization mechanisms by  $E \times B$  shear likely play a role in the transition to better confinement plasma states: both edge and core transport barriers are related to an increase in the  $E \times B$  sheared flow. The direct experimental study of plasma radial electric field  $E_r$  is the key issue to clarify  $E \times B$  shear stabilization mechanisms. The plasma turbulence rotation velocity measurements, compared with  $E_r \times B_t$  drift rotation velocity may explain, whether the turbulence moves together with the plasma or independently.

The absolute value of the core plasma potential  $\phi$  was measured in the T-10 tokamak ( $R = 1.5$  m,  $a = 0.3$  m) by Heavy Ion Beam Probing (HIBP) diagnostic. The  $\text{Ti}^+$  beam energy of HIBP was increased up to  $E_b = 300$  keV, and the beam current up to 200  $\mu\text{A}$ . This allows us to observe the core potential at high densities and in a wide radial area for the first time. At the limiter, the plasma potential and density were measured by Langmuir probes. The core plasma turbulence was studied by correlation reflectometry (CR).

The regimes with Ohmic (OH), on- and off-axis Electron Cyclotron Resonance (ECR) heating ( $B_t = 1.55\text{--}2.4$  T,  $I_p = 140\text{--}250$  kA,  $\bar{n}_e = (1.3 - 4.1) \times 10^{19} \text{ m}^{-3}$ ,  $P_{\text{EC}} < 1.5$  MW) were studied, see Table. In the regimes with  $B_t = 1.55\text{--}2.08$  T, HIBP was able to extend the observation area from the plasma edge,  $\rho = 1$ , to the central region,  $\rho = 0.25$  ( $\Delta r = 6\text{--}30$  cm). The first regime, marked as I and II in Table (OH,  $B_t = 1.55$  T,  $I_p = 140$  kA,) is characterized by low line-averaged density, slowly evolving from  $\bar{n}_e = 1.3$  to  $2.4 \times 10^{19} \text{ m}^{-3}$  due to the gas puffing. The time traces of the main plasma parameters, including the potential  $\phi(0.21 \text{ m})$ , are shown in Fig. 1(a). The plasma edge,  $r = 0.25\text{--}0.3$  m, was probed with  $E_b = 90$  keV. To extend the profile towards the centre, we increase  $E_b$  with the step of 10 keV up to 200 keV in a series of reproducible shots. The profiles, obtained in each shot, overlap with each other. The resulting radial profiles with length 23 cm are shown in Fig. 1(b). The profiles for three line-

averaged densities  $\bar{n}_e = 1.3, 2.0$  and  $2.4 \times 10^{19} \text{ m}^{-3}$  are marked with different colours. The plasma potential has the negative sign in the whole observed area. The  $\phi(r)$  profile presents linear-like function with the lowest absolute value at the deepest point  $\phi(0.07 \text{ m}) = -1.5 \text{ kV}$ . The slope of the profile allows us to estimate the mean radial electric field  $E_r$ : for the lowest density  $E_r \sim -5.5 \text{ kV/m}$ . Figure 1(b) shows that the potential well becomes deeper, and  $E_r$  becomes more negative up to  $E_r \sim -6.5 \text{ kV/m}$  with the rise of density and energy confinement time  $\tau_E$ . This result is consistent with earlier measurements in TM-4 [1] and TJ-II [2].

The regime III, ( $B = 2.08 \text{ T}$ ,  $\bar{n}_e = 2.4 \times 10^{19} \text{ m}^{-3}$ ,  $I_p = 165 \text{ kA}$ ,  $P_{EC} = 0.9 \text{ MW}$ ) with off-axis ECRH ( $\rho_{ECRH} = 0.5$ ) has the current ramp-up to  $I_p = 212 \text{ kA}$  at the ECRH phase. The time traces of the main plasma parameters are shown in Fig. 2. The potential profile evolution is shown in Fig. 3. In OH phase,  $\phi(r)$  presents linear-like function with the lowest absolute value at the deepest point  $\phi(0.07 \text{ m}) = -1.6 \text{ kV}$ , and correspondingly the mean  $E_r$  is  $-7.0 \text{ kV/m}$ . In the ECRH phase, the absolute potential well becomes significantly shallower,  $\phi(0.07) = -1.3 \text{ kV}$ , and  $E_r$  decreases to  $\sim -5.5 \text{ kV/m}$ . After current ramp-up,  $\phi(r)$  slightly decreases, and  $E_r$  decreases up to  $\sim -4.7 \text{ kV/m}$ . The estimated error  $\Delta E_r = \pm 0.3 \text{ kV/m}$  for this regime. Note that during the ECRH phase the plasma potential profile keeps its linear-like shape. No strong irregularity has been observed on the  $\phi(r)$  profile at the area of ECRH power deposition. At the inner radii respect to the power deposition,  $\phi(r)$  still keeps its linear-like shape. After the ECRH switch-off, in the OH regime with  $I_p = 212 \text{ kA}$ ,  $\phi(r)$  returns to its initial shape, corresponding to the OH regime with  $I_p = 165 \text{ kA}$ . These observation shows that the potential is not a strong function of  $I_p$ .

The high  $B_t$  OH regime IV ( $B_t = 2.4 \text{ T}$ ,  $\bar{n}_e = 4.1 \times 10^{19} \text{ m}^{-3}$ ,  $I_p = 200 \text{ kA}$ ) allows HIBP to observe the outer half of the plasma column ( $\Delta r = 16\text{-}27 \text{ cm}$ ) only with highest possible  $E_b = 300 \text{ keV}$ . Similar to the previous cases,  $\phi(r)$  presents linear-like function, as shown in Fig. 4, with the lowest absolute value at the deepest point  $\phi(0.16 \text{ m}) = -1.2 \text{ kV}$ , mean  $E_r \sim -9.0 \text{ kV/m} \pm 0.5 \text{ kV/m}$ .

At all observed regimes,  $E_r(r) \sim \text{const}$  in the radial range of HIBP measurements. The plasma column rotates not as a rigid body due to the  $B_t(r)$  dependence. The typical values for  $E \times B$  drift velocity are  $V_{E \times B} \sim 3.0 \text{ km/s}$ ,  $\Omega_{E \times B} \sim 1.5 \times 10^4 \text{ radian/s}$  for the Ohmic stage, and  $V_{E \times B} \sim 2.4 \text{ km/s}$ ,  $\Omega_{E \times B} \sim 1.25 \times 10^4 \text{ radian/s}$  for the ECRH stage.

The broadband turbulence rotation velocity  $\Omega_{TURB}$  was measured by CR in the regime III at the same discharges as HIBP, but in different poloidal position. To compare with  $\Omega_{TURB}$ , we take  $\Omega_{E \times B} = E_r / r B_t$  with  $E_r$  obtained by HIBP and  $B_t$  along the  $x$  coordinate of CR

measurements. The experimental layout is shown in Fig. 5. CR antennae are located at 90° anticlockwise from HIBP along the torus. Figure 6 (a,B) shows that  $\Omega_{\text{TURB}}(r)$  is close to  $\Omega_{\text{E} \times \text{B}}(r)$  in the whole observed radial range both in OH and ECRH plasmas. It is important to note that during the ECRH phase,  $\Omega_{\text{TURB}}(r)$  does not show any strong irregularity in the area of ECRH power deposition, similar to  $\Omega_{\text{E} \times \text{B}}(r)$ .

Finally, the mean  $\phi(r)$  exhibits the linear-like shape suggesting  $E_r \sim \text{const}$ . Negative  $\phi(r)$  in the deepest point (smallest radii) and  $E_r$  both tends to be higher for higher densities and lower with ECRH, i.e. a stronger negative  $E_r$  is associated to better energy confinement time  $\tau_E$ . Within the achieved experimental accuracy, the broadband drift-wave turbulence tends to rotate with the plasma  $E \times B$  rotation velocity.

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#### References

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 [2] A.V. Melnikov et al., Fusion Sci. Techn. 31, 51 (2007).

Table 1. Parameters of studied regimes.

Regime	$\bar{n}_e, 10^{19} \text{ m}^{-3}$	$E_r, \text{ V/cm}$	$\Delta r, \text{ cm}$	$B_t, \text{ T}$	$I_p, \text{ kA}$	$\tau_E, \text{ ms}$
I	1.3	55	6-30	1.55	140	20
II	2.4	65	6-30	1.55	140	36
III	2.5	70	7-22	2.08	165	52
IV	4.1	90	16-27	2.4	210	58

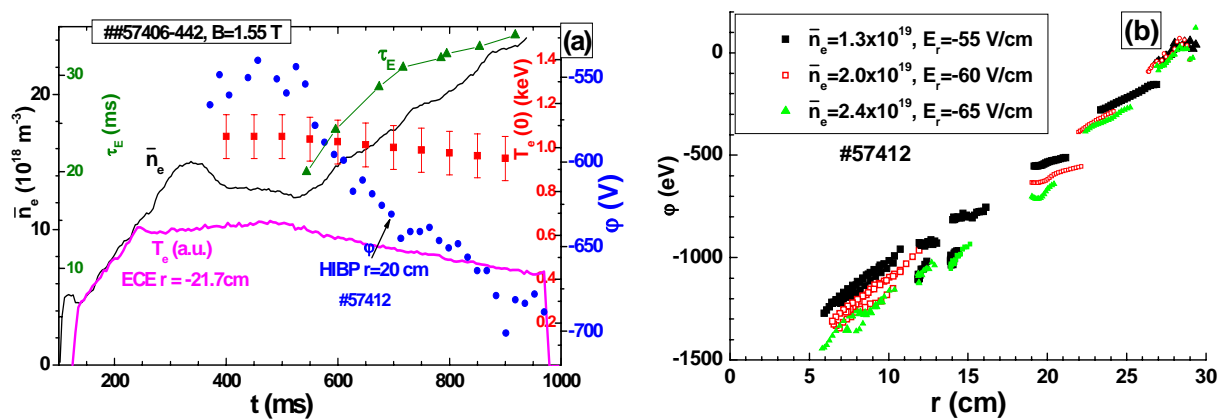


Fig. 1. (a) Evolution of density  $n_e$ , potential  $\phi$ , energy confinement time  $\tau_E$  and electron temperature  $T_e(0)$  (red ■) by SXR-spectrograph in the regime I, II with density ramp-up. (b) The potential profile combined from the set of the scans for three densities  $\bar{n}_e = 1.3$  (black ■),  $1.8$  (red □)  $2.4 \times 10^{19} \text{ m}^{-3}$  (green ▲).

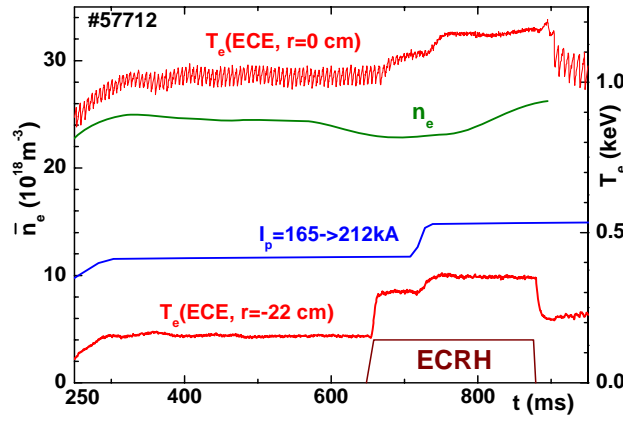


Fig. 2. Evolution of density and temperature in regime III with ECRH and current ramp-up.

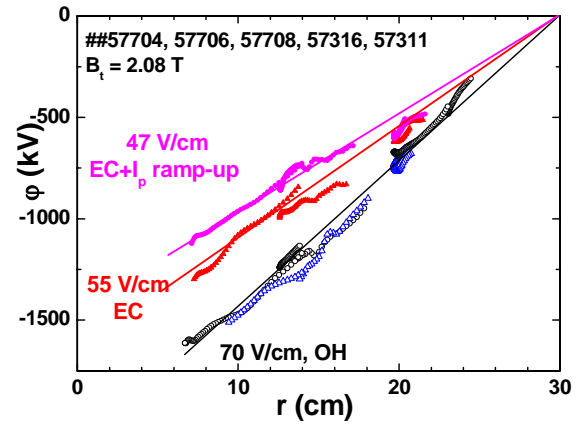


Fig. 3. Potential profiles in regimes III with ECRH and current ramp-up.

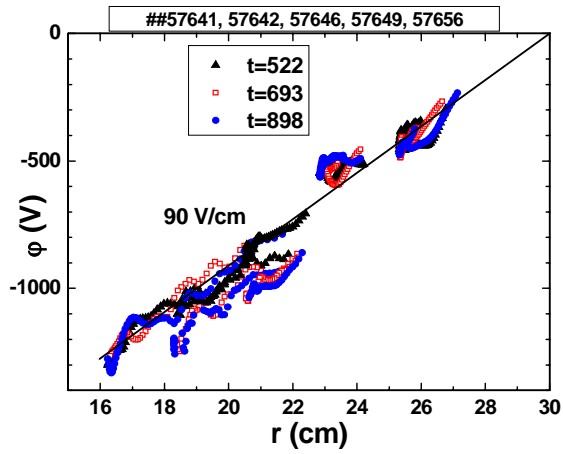


Fig. 4. The potential profiles in OH high-density regime IV.

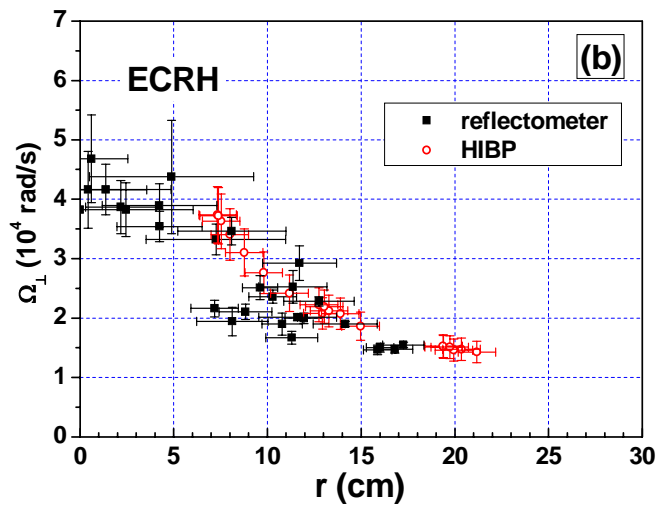
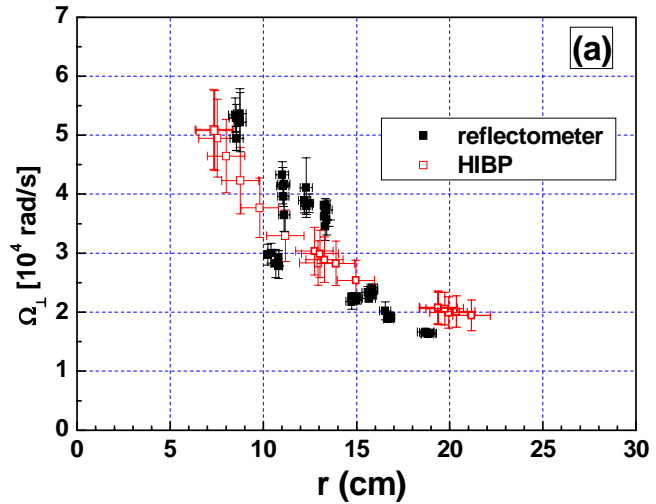


Fig. 6. Comparison of rotation velocities of density perturbations  $\Omega_{\text{TURB}}$  from CR, with core plasma rotation  $\Omega_{\text{EXB}}$  from HIBP in OH (a) and ECRH (b) plasmas.

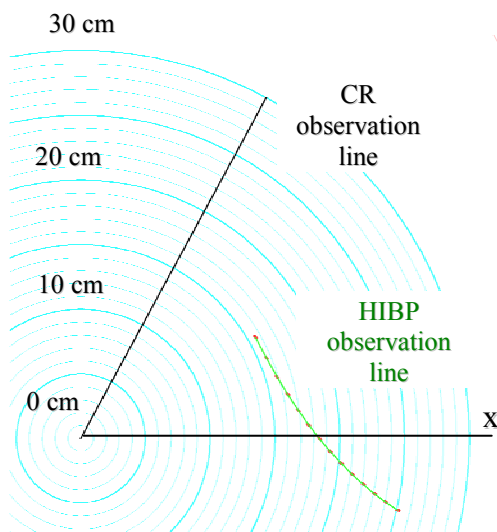


Fig. 5. Experimental layout for comparative HIBP and CR rotation measurements.