Improved confinement transition in high density deuterium discharges at the FT-2 tokamak accompanied by onset of negative triangularity

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In FT-2 ($R = 55$ cm, $a = 7.9$ cm) ohmic-heated discharges with high densities $n_e \leq 10^{20}$ m^{-3} a significant effect of the isotope content on the global energy confinement was discovered recently [1]. At the achieved plasma densities ($\langle n_e \rangle \approx 9\times10^{19}$ m^{-3}), it was shown that the total energy confinement time in deuterium (D) is twice as long as in hydrogen (H) plasma. Such a significant difference was explained by the spontaneous transition to the improved confinement regime, initiated solely by density increase and observed only in D-plasma while the hydrogen plasma remained in L-mode in all comparable discharge scenarios.

In the present paper a detailed analysis of the improved confinement transition in high density D-plasma is performed. Reconstruction of plasma magnetic configuration, based on interferometer and laser Thomson scattering measurements, is provided by full-wave code modeling (CUWA code) and ray tracing computations taking into account strong refraction effect due to high density. The reconstruction reveals a growth of the magnetic surfaces triangularity above the natural level [2] for the FT-2 tokamak after the transition of the D-plasma into the improved confinement regime. Magnetic surfaces of D-plasma in L-mode keep circular shape natural for the circular cross section of the FT-2 vessel.

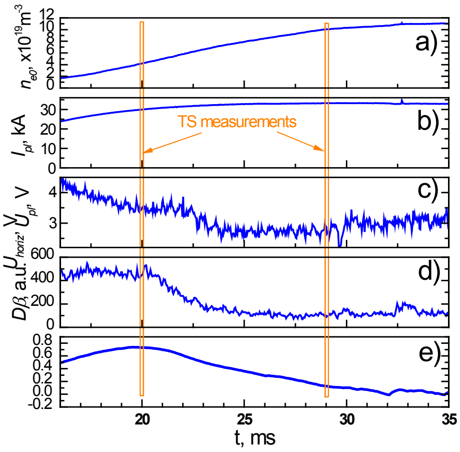


Fig. 1. the scenario of plasma discharge with growing density and spontaneous L-H transition: dynamics of a) central interferometry phase, b) plasma current, c) loop voltage, d) D_β line emission, e) horizontal equilibrium signal.

Experimental approach

Special series of high density ohmic discharges are performed at FT-2 tokamak ($a = 0.08$ m, $R = 0.55$m, $I_{pl} \sim 32$-35 kA, $B_T \sim 2.2$ T, $q_{95} \sim 3$-3.5) in deuterium. Electron temperature profiles were measured with laser Thomson scattering diagnostics, which was used in combination with microwave interferometry to determine the electron density profile. Ion temperature profile in the central zone was measured with NPA diagnostics.

Fig.1 presents the typical scenario of the high density deuterium discharge, which is characterized by plasma density growth (fig.1a) up to values

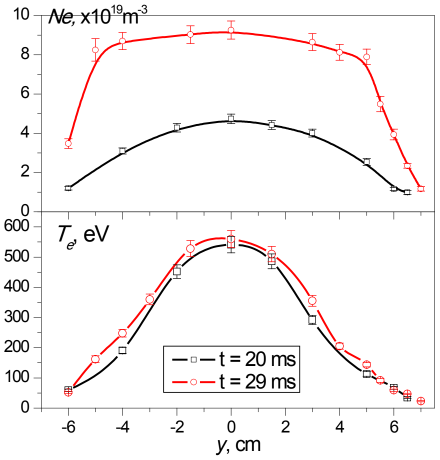


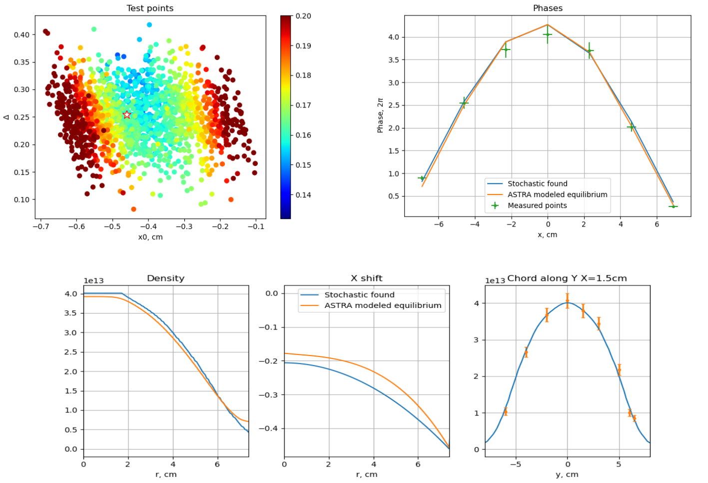
Fig. 2. Thomson scattering profiles, measured along vertical laser probing chord ‘y’, shifted 15mm outward from the camera center: before L-H transition (black) and after (red).

$n_{e0} \approx 1\times10^{20}$ m^{-3}. The horizontal equilibrium signal (fig.1e) indicates the plasma outward shift starting from about $t \sim 20$ ms, which is caused by the density growth and the corresponding application of control poloidal field to keep plasma centered within the vessel poloidal limiter. At some critical density $n_{e0} \approx 6\times10^{19}$ m^{-3} the features of fast spontaneous plasma transformation appear, that can be seen on loop voltage U_p drop and line emission D_β dynamics (fig.1 c,d). Thomson scattering measurements of electron temperature and density were provided before and after this transition (orange marks on fig.1). The measured T_e and n_e profiles along TS probing chord “y” are shown in fig.2, demonstrating strong effect on plasma density, namely the formation of steep gradient on plasma periphery. All these experimental facts could be interpreted as a transition to improved confinement, induced simply by density growth and control poloidal field application.

Magnetic configuration reconstruction

The conventional way of magnetic configuration reconstruction at FT-2 is based on principles of nested circular magnetic surfaces. The interferometry phases are used to restore magnetic surfaces under the assumption of straight-line probing wave propagation. This way fits well wide range of plasma regimes at low and moderate densities up to $\langle n_e \rangle \approx 5\times10^{19}$ m^{-3}. At higher densities refraction effect must be taken into account. Taking into account Thomson scattering density profiles and randomly generated magnetic configuration, it’s possible to get the 2D spatial density distribution. This distribution makes it possible to obtain synthetic interferometer signals via either full-wave microwave CUWA code [3] or the ray-tracing procedure. These synthetic phases are compared with measured ones. Iterating over big number (>1000) of randomly magnetic surface geometry it’s possible to define the most matched configuration in terms of mean square difference between measured and synthetic phases. With founded configuration the ASTRA code modeling is performed to obtain the plasma equilibrium according to Grad-Shafranov equation.

As for the regime under discussion the same procedure was applied to reconstruct magnetic surfaces at $t = 20$ ms (before supposed L-H transition) and at $t = 29$ ms (after transition). Fig.3 shows the results of restored configuration for L-mode stage of the discharge. Up left graph shows mean square difference between measured and synthetic interferometer signals against two main optimization parameters – plasma horizontal shift and Shafranov shift. Fig. 4 presents 2D density distribution of circular magnetic surfaces.



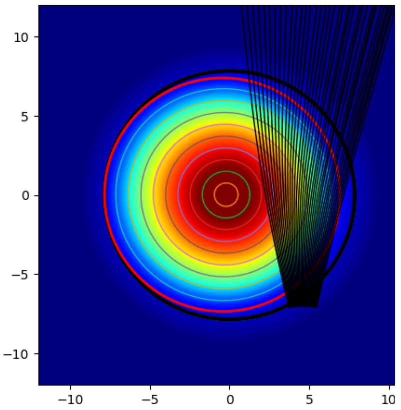


Fig.3. Tested and restored configuration of L-mode. Up left: mean square difference between measured and synthetic interferometer signals. Up right: calculated and measured interferometry phases. Bottom row: blue curves present stochastic found magnetic configuration, and obtained from it density profile used for ASTRA modeling; ASTRA results (profile and equilibrium) are presented with orange lines. Bottom right presents slice along laser chord and comparison with Thomson scattering measured values.

Fig.4. 2D density distribution with the illustration of the traced rays

Application of the same approach to “H-mode” of the discharge (t = 29 ms) does not allow to find any appropriate equilibrium solution using circular shape of magnetic surfaces. Optimization procedure gives the value of the Shafranov shift as $\Delta_{Sh} \sim 2.5$ cm., that is much higher than the estimated plasma equilibrium values $\Delta_{Sh} \sim 0.7$ cm. Measured interferometry phases does not fit the restored ones (fig.5). No configuration is found here with feasible values of Δ_{Sh} and reasonable coincidence of phases, indicating that the circular shape surfaces model is not applicable for H-mode discovered in deuterium. The obvious way to avoid this discrepancy is to take into account plasma shaping – elongation and triangularity, that is quite realistic scenario on FT-2, taking into account the application of strong poloidal control fields in these discharges. Optimization procedure allows determining the configuration with good coincidence of phases and ASTRA calculated equilibrium. The results are shown in fig. 6,7. One can see good coincidence of measured and synthetic phases and appropriate value of the Shafranov shift. Steep density gradient, measured by Thomson scattering, fits quite well with reconstructed density profile.

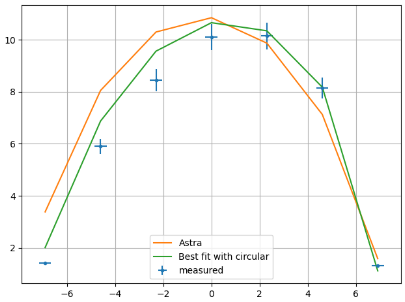


Fig.5: Measured interferometry phases do not fit the restored ones in case of circular configuration

Turbulence behavior

The negative triangularity onset, according to [4, 5], is leading to the turbulence suppression and confinement improvement. To investigate this effect in FT-2 high density discharges the drift instabilities were analyzed with the linear gyrokinetic GENE code whereas the plasma rotation was measured using a set of microwave diagnostics.

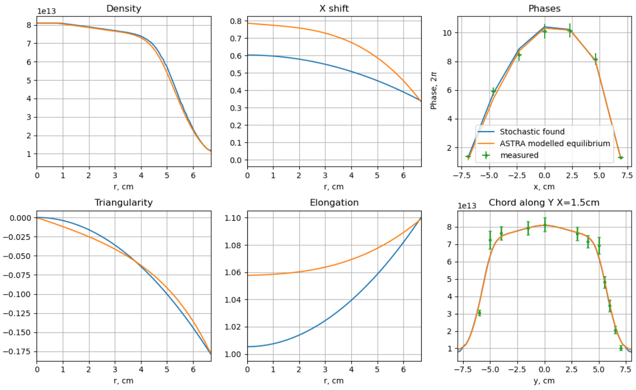


Fig.6: restored configuration of H-mode stage. Colors and descriptions mean the same as at fig. 5. Elongation and Triangularity are added.

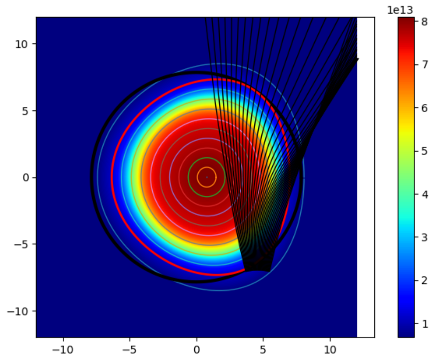


Fig.7: 2D density distribution with negative triangularity ~ -0.18 and elongation ~ 1.1

Fig.8 shows the results of measurements of dynamics of the rotation shear ω_{ExB} as well as the GENE estimation of the instability growth rate γ before and after L-H transition. As it is seen the negative triangularity is in fact leading to the growth rate decrease after the transition. So that the measured value of rotation shear at the plasma edge after the transition exceeds substantially the growth rate.

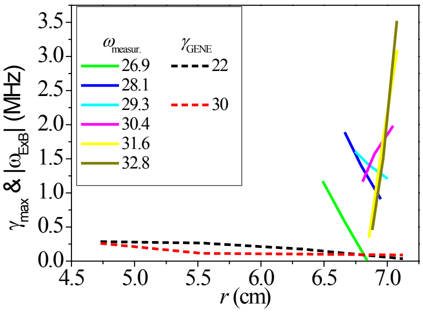


Fig.8: measured ω_{ExB} shear and calculated values of turbulence growth rates γ dynamics during L-H transition

Discussion

Plasma shaping is applied to restore magnetic configuration in deuterium H-mode discharge. The negative triangularity ~ -0.18 and elongation ~ 1.1 are found as the possible optimal solution for that case. The transformation of magnetic surfaces can be caused by self-consistent combination of processes: density growth, application of strong poloidal control fields, formation of peripheral barrier, L-H transition. Transition to H-mode with shaped magnetic configuration provides increase of peripheral ω_{ExB} shear, suppressing most of possible turbulent modes on plasma periphery.

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