Isotope effect physics, turbulence and long-range correlation studies in the TJ-II stellarator

B. Liu, M. A. Pedrosa, B. Van Milligen, C. Hidalgo, C. Silva*, B. Zurro, K. J. McCarthy, A. Cappa, M. Liniers

Laboratorio Nacional de Fusion, EURATOM-CIEMAT, 28040 Madrid, Spain

**Associação EURATOM-IST, Instituto de Plasmas e Fusão Nuclear, Lisboa, Portugal*

I. Introduction

Understanding the mechanism of plasma confinement scaling with isotope mass has been a long-standing open issue in magnetic fusion research. It has been observed in most tokamak experiments that the plasma confinement time increases with increasing ion mass under similar plasma conditions [1]. However, standard transport theories fail when predicting the isotope effect. According to diffusive-like transport theories, the diffusivity is $D \propto L_r^2/\tau_c$, where L_r is characteristic radial scale length, τ_c is characteristics time scale. If L_r scales as $L_r \sim \rho_i$, then an increase of ion mass implies a deleterious effect on plasma confinement. Interestingly, the isotope effect is reported to be weaker in stellarators than in tokamaks [2].

Recently, a multi-scale mechanism, based on experimental observations in TEXTOR [3] and TJ-II [4], has been proposed to explain the isotope effect. The basics idea is that the smallest scale (related to the Larmor radius) in a plasma can affect the formation of turbulence structures and the development of large-scale zonal flows affecting plasma transport.

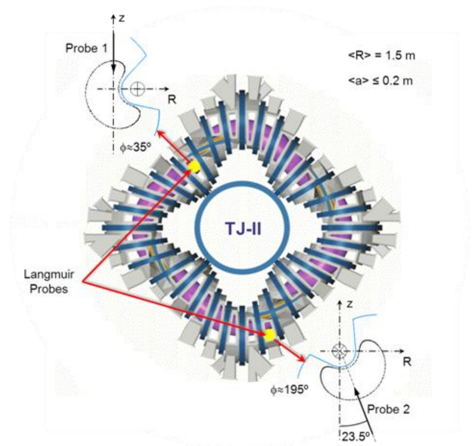

Fig. 1: TJ-II

In this paper we present a study of isotope effect on development of long-range correlation (LRC) and radial correlation length (L_r) in the TJ-II stellarator.

II. Experimental set-up

Experiments were carried out in the TJ-II stellarator, in Electron Cyclotron Resonance Heated (ECRH) plasmas ($P_{ECRH} \leq 400\ kW$, toroidal magnetic field $B_T = 1\ T$, plasma major radius $\langle R \rangle = 1.5\ m$, plasma minor radius $\langle a \rangle \leq 0.22\ m$, $\iota(a)/2\pi \approx 1.6 - 1.9$). For this the plasma density was in range $(0.35 - 1) \times 10^{19} m^{-3}$ in ECRH plasmas. Two Langmuir probe arrays, indicated in Fig.1 as probe 1 and probe 2, were installed at different toroidal locations in TJ-II, approximately 160° apart (5 m). Probe 1 consists of 4×5 tips, 4 in the poloidal direction spaced 3 mm apart plus 5 in the radial direction spaced 5 mm apart. Probe 2 has a similar configuration with 3 × 6 tips, spaced 2 mm and 3 mm in poloidal and radial directions respectively. This setting allows us to analyze the properties of turbulence locally as well as large scale coherent structures.

To study the dependence of plasma properties on ion mass systematically, the plasma composition changed steadily shot-by-shot from hydrogen dominated to deuterium dominated plasmas up to the ratio of D/H~2 and back to H dominated in the same way. At the same time, plasma conditions were kept almost identical for all shots.

III. Isotope effect on long-range correlation (LRC)

LRC is defined as the normalized cross-correlation between two toroidally separated signals x(t) and y(t). It is computed as follows:

$$\gamma_{12}(\tau) = \frac{E\{[x(t+\tau)-\bar{x}][y(t)-\bar{y}]\}}{\sqrt{E\{[x(t)-\bar{x}]^2\}.E\{[y(t)-\bar{y}]^2\}}}$$

The maximum LRC is estimated as the correlation coefficient at time lag τ=0 of the correlation function.

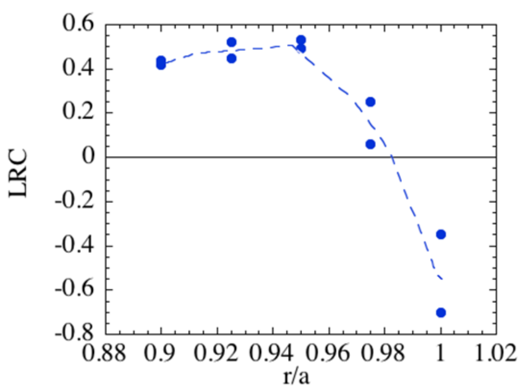

Fig. 2: A profile of LRC

A typical profile of maximum LRC can be seen in Fig. 2. The profile was obtained by computing the correlation coefficients between floating potential signals measured by a reference tip (usually the innermost one) in probe 2 and a row of radial tips in probe 1. The peak of a LRC profile quantifies the amplitude of LRC at the probe measurement region. We also see that the LRC profile has a characteristic radial scale in the order of a few centimeters.

Fig. 3a plots the variation in the amplitude of LRC with respect to the D/H ratio at a plasma density in the proximity of the electron-ion root transition ($n_e = 0.6 \times 10^{19} m^{-3}$). We see that the amplitude of LRC does not increase with increasing D/H ratio (or effective ion mass), or even shows some slight tendency to decrease. This is in contrast with recent finding in the TEXTOR tokamak, which observed a systematically increase in the amplitude of LRC with ion mass [3].

Fig. 3b compares the evolution of the amplitude of LRC versus density for plasmas with different D/H ratios: pure H, D/H~0.8 and D/H~2. It seems that the amplitude of LRC decreases more clearly with ion mass at plasma densities below the electron-ion root transition ($n_e < 0.6 \times 10^{19} m^{-3}$). Furthermore, a slight decrease in LRC amplitude is observed at plasma densities above the threshold density ($n_e > 0.6 \times 10^{19} m^{-3}$) in agreement with previous observations [5].

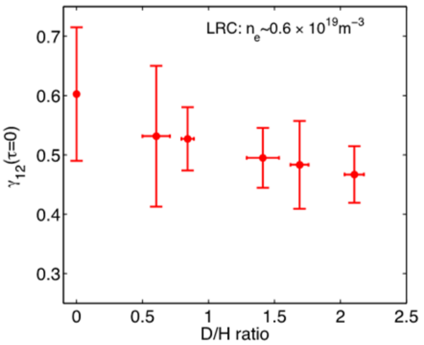

Fig. 3a: the amplitude of LRC at a plasma density in the proximity of the electron-ion root transition (ne=0.6)

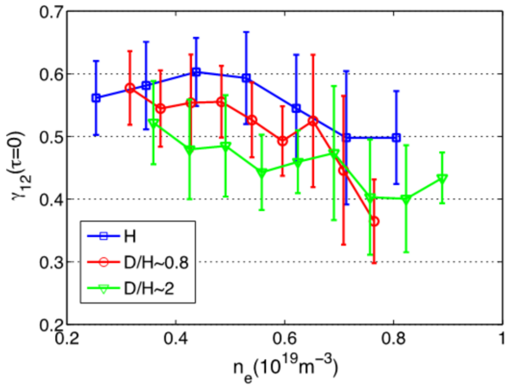

Fig. 3b: the amplitude of LRC versus plasmas density for different D/H ratios.

IV. Isotope effect on radial correlation length (L_r)

Five radially spaced (5 mm apart) tips of probe 1 measuring floating potentials are employed to characterize the radial correlation length (L_r). Fig. 4a illustrates an example of computing L_r. The upper part of Fig. 4a shows a group of functions of the correlation between signals measured by the reference probe tip (the middle one) and all radial tips. The lower part of Fig. 4a is a contour of the correlation coefficients after linear interpolation of the correlation functions along the radial direction. L_r is then defined as the full width at 1/e of the maximum of the correlation function. Assuming a Gaussian distribution of correlation coefficients, L_r is computed as follows:

$$L_r = 2\sqrt{\frac{2\sum(r_i - \bar{r})^2 \gamma(r_i, \tau_j)}{\sum \gamma(r_i, \tau_j)}}$$

where $\bar{r}$ is the mean value of the radial position, and $\gamma(r_i, \tau_j)$ is the correlation coefficient between signals at radial position r_i and $\bar{r}$, and the time delay τ_j.

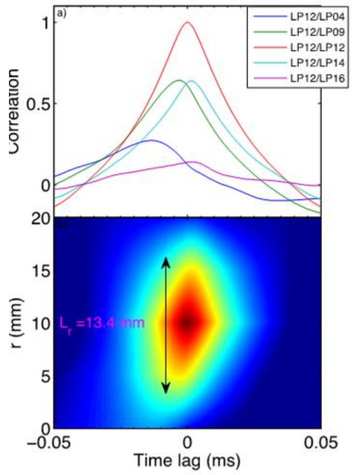

Fig. 4a: An example of computing L_r

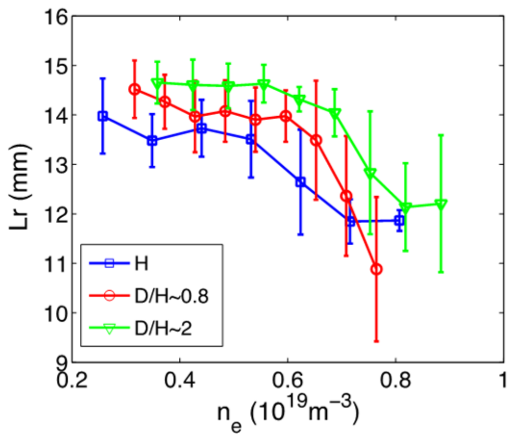

Fig. 4b: the evolution of radial correlation length (L_r) versus plasmas density.

Fig. 4b compares the evolution of L_r versus density for different D/H ratios. We observe that L_r slightly increases (of the order of 10%) with increasing effective D/H ratio over almost the whole density regime. This is in consistent with results from TEXTOR [3] and TJ-K [6]. It can also be seen that L_r decreases slightly when the plasma transits to the ion root ($n_e > 0.6 \times 10^{19} m^{-3}$) in a similar way to the change of LRC amplitude with plasma density.

V. Conclusion

The influence of the isotope effect on the development of long-range correlation and radial correlation of plasma turbulence has been investigated in ECRH plasmas in the TJ-II stellarator with the following conclusions: a) the amplitude of the long-range correlation does not increase, or even slightly decreases with ion mass in contrast with TEXTOR [3] results, b) the local correlation length L_r increases with ion mass in agreement with TEXTOR [3] and TJ-K [6] results. Those findings show the impact of the isotope effect on both the largest scales (LRC determined by the size of the device) and the characteristic radial scale of turbulent structures.

Acknowledgment
This work was supported by the European Commission and carried out within the framework of the Erasmus Mundus International Doctoral College in Fusion Science and Engineering (FUSION-DC).

[1] M. Bessenrodt-Weberpals, F. Wagner et al, Nucl. Fusion **33**, 1205 (1993).
[2] U. Stroth, Plasma Phys. Control. Fusion **40**, 9 (1998).
[3] Y. Xu, C. Hidalgo, I. Shesterikov et al., Phys. Rev. Lett. **110**, 265005 (2013).
[4] M. A. Pedrosa, C. Hidalgo, B. Liu et al., in *EPS* (2013)
[5] M. A. Pedrosa, C. Silva, C. Hidalgo et al., Phys. Rev. Lett. **100**, 215003 (2008).
[6] M. Ramisch, N. Mahdizadeh, U. Stroth et al., Phys. Plasmas **12**, 32504 (2005)