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Isotope effect, operational limits and Zonal Flows in the TJ-II stellarator

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The influence of plasma scenarios on the amplitude and radial structure of Zonal Flows has been investigated in the plasma edge of the TJ-II stellarator. The main results reported in this paper include: i) first experimental observation of the influence of the ion mass in the radial width of Long Range Correlations (LRC) as proxy of zonal flows; ii) the investigation of the influence of operational limits on Zonal Flows showing a decreasing in the amplitude of LRC as approaching the plasma density limit.
Plasma scenarios and experimental set-up. Plasma scenarios sustained by electron cyclotron resonance heating (ECRH) (two gyrotrons, 53.2 GHz, P ¬≈ 300 kW each, suitable for X2 heating in B = 1 T) and neutral beam injection (NBI) heating (two H0 injectors, E ¬ 30 kV, P ≈¬ 600 kW each) have been investigated in Hydrogen (H) and Deuterium (D) dominated plasmas in TJ-II. Direct generation of NBI plasmas in TJ-II⊠with lithium-coated walls has allowed to investigate the influence of magnetic fields [B = 0.7 −1 T] in the density limit. A dual system of multi-probes arrays, placed at two different toroidal and poloidal locations, has been used to characterize the properties of LRC in floating potential fluctuations in the TJ-II plasma edge [⊠ ≈ 0.85 −1].
Influence of isotope mass and plasma heating on the radial width of LRC. The mechanism governing the influence of the ion mass on plasma transport is still one of the main scientific conundrums facing the magnetic fusion community after more than twenty years of intense research.
In stellarators, the ambipolarity condition determining the radial neoclassical electric field (Er) has two stable roots: the ion root with typically negative Er, usually achieved in high density plasmas heated by NBI, and the electron root with positive Er, that is typically realized when electrons are subject to strong heating in ECRH scenarios. Therefore, plasmas produced by different heating schemes (ECRH and NBI) are characterized by different mean radial electric field (Er) in TJ-II in agreement with neoclassical predictions 1.
LRC in floating potential signals are dominated by frequencies below 20 kHz. As the frequency decreases, the oscillating Er structure asymptotically approaches to the mean potential profile. Mean Er profiles are comparable in H and D plasmas both in L-mode and H mode scenarios 2. The width of the oscillating Er structures depends on its frequency as well as the heating scheme, being the radial size of the LRC profile larger in the case of the ECRH phase than in the NBI phase both in H and D plasmas [Fig. 1]. The level of edge broadband turbulence [in the range 20 −500 kHz] is significantly reduced in the transition from ECRH to NBI scenarios. Normalized values of density fluctuations and rms in floating potential are in the range of 10 - 20% and 5 - 10 V in D and H plasmas respectively [⊠ ≈ 0.9].
In ECRH plasmas the LRC radial structure could not be fully explored due to the limited edge plasma region accessible to the dual probe system. Within experimental uncertainties, both the amplitude and radial width of LRC are comparable in H and D plasmas with a slight but systematic increases in the amplitude of LRC in D as compared to H scenarios. The case of NBI plasmas is different. Although the maximum amplitude of LRC is similar in H and D scenarios, its radial position is shifted radially inwards (in the range of 0.5 cm) in the case of D plasmas with respect to pure H plasmas. Furthermore, the radial size of the LRC is of about 1.5 times larger in D than in H plasmas, which is comparable to the ratio of ion Larmor radius (D vs H) in NBI plasmas [Fig. 1].
TJ-II findings show that whereas the neoclassical transport determines the radial electric field on long length scales (in the range of few tens of gyro-radius) zonal flows can control short radial length scales (in the range of few gyro-radius) that increases with Larmor radius. Furthermore, TJ-II results have shown that both Er scales are strongly intertwined and that turbulent and neoclassical mechanisms are involved in the dynamics of edge Zonal Flows [3]. These results emphasize the role of multi-scale mechanisms to unravel the physics of the isotope effect and pave the way for the validation of the influence of ion mass in GK simulations [4].
Influence of plasma density limit on LRC. Density limit is manifested in tokamaks, stellarators and RFPs. In stellarator the density limit is related to radiation collapse mechanisms [5] whereas in tokamaks edge transport can play an important role [6].
LRC in floating potential fluctuations has been investigated in the proximity of the density-limit in the NBI plasma scenarios in TJ-II [Fig. 2]. The density limit decreases with the magnetic field (B = 0.7 −1 T) in qualitative agreement with the empirical stellarator scaling law for density limit [5]. At low densities the LRCs, measured at rho ≈ 0.9 for frequencies below 20 kHz, are quite large (≈ 0.8) and vary only slightly with increasing density. When approaching the density-limit the amplitude of LRC reduces rapidly with increasing plasma density, in agreement with previous results [7]. The reduction in the LRC as approaching the density limit is accompanied by a reduction in edge mean radial electric field and the level of plasma turbulence. Results point to the role of collisionality, mean E × B flows and level of turbulence on the amplitude of zonal flows in the proximity of the density limit.

TJ-II findings suggest that at a threshold radiation value for the density limit the degradation of confinement would be partially due to the damping of Zonal Flows as recently pointed out [8]. If this is the case, density limit in stellarators would depend on the transport optimization criteria, a prediction that could be validated experimentally.

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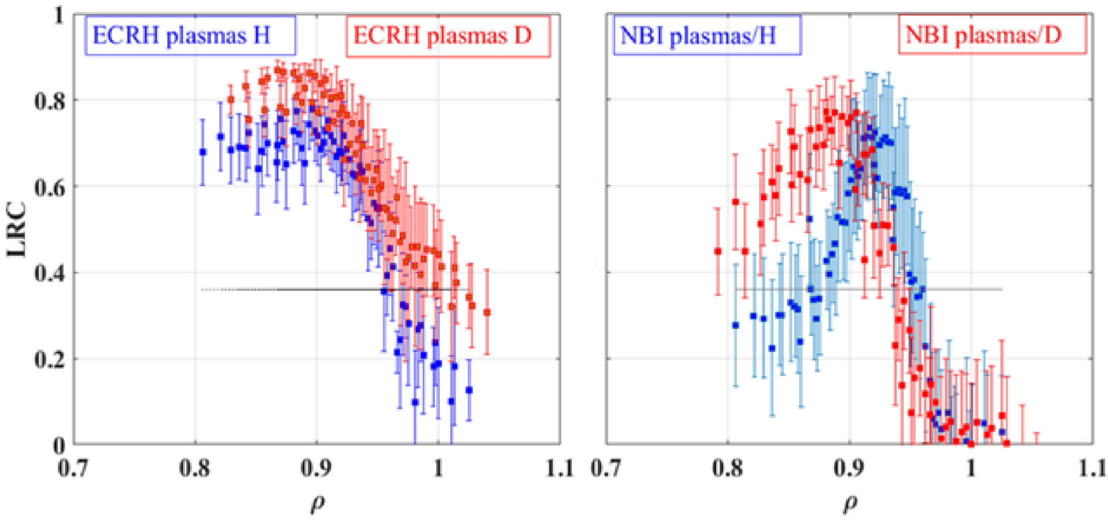

Figure 1: Influence of the ion mass on the radial profile of LRC in ECRH and NBI scenarios in TJ-II. The radial width of LRC is affected by the ion mass in NBI scenarios and is strongly reduced in the transition from ECRH to NBI plasmas.

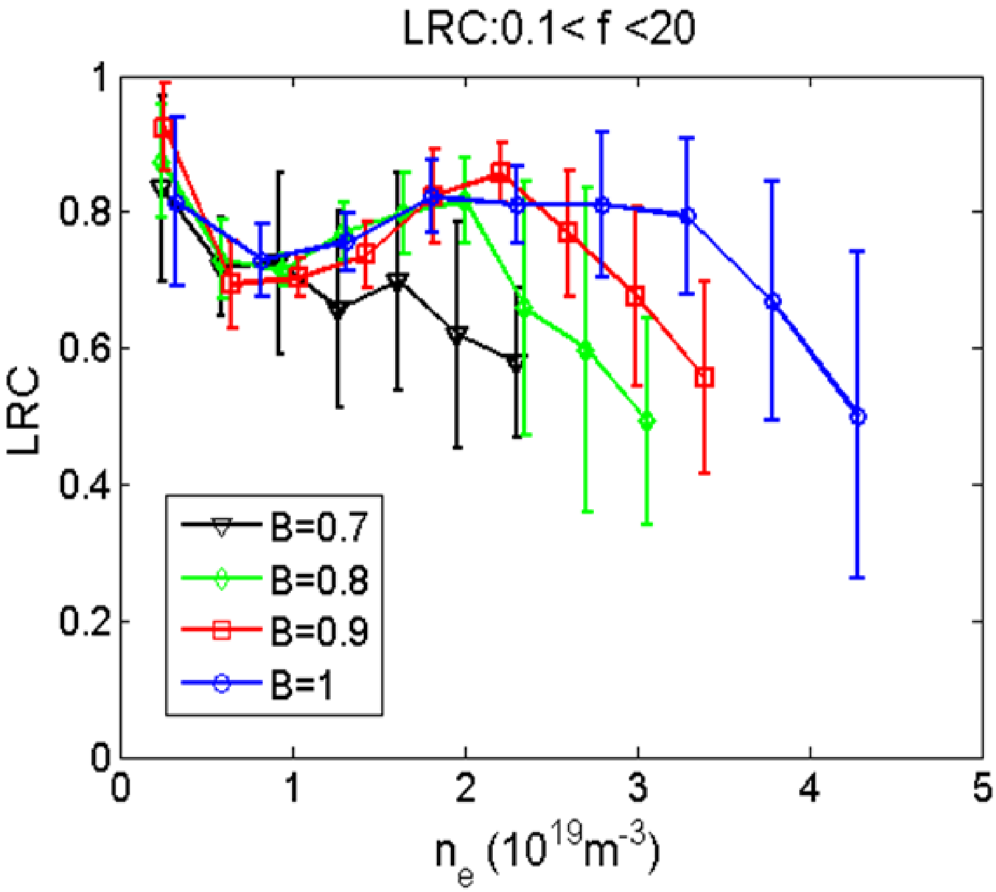

Figure 2: Influence of density limit in the amplitude of LRC in NBI plasma scenarios with different magnetic fields. LRC are strongly reduced as approaching the density limit.

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