TRANSPORT AND PLASMA CONTROL IN THE TJ-II STELLARATOR

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This paper shows the effect of 3D geometry on transport and plasma control in the TJ-II stellarator. The fuelling and impurity transport are affected due to the enhancement of neoclassical (NC) transport and subsequent onset of a radial electric field. Turbulence affects not only plasma but also neutral density, with effects on the fuelling. SOL is shown to be affected by plasma edge turbulence. The properties of stability and MHD modes are also explored. The plasma flow is shown to be affected by 3/2 magnetic island. Promissing experimental results show the possibility of controlling Alfvén modes by ECRH, and magnetic configuration by rotational transform and magnetic well scans.

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INTRODUCTION

Stellarator devices are ideally suited to study the relation between 3D magnetic topology, electric fields and transport. This is a relevant topic not only for stellatarors, but for tokamaks. The break of axisymmetry implies the enhancement of NC transport, with the subsequent onset of an ambipolar electric field, and the strong modification of the dispersion relation of waves in the plasma. The TJ-II heliac is used to explore those effects in this work taking advantage of its flexible magnetic configuration. Recent improvements in TJ-II plasma diagnostics, including the operation of a dual Heavy Ion Beam Probe (HIBP) and a pellet injection system, have allowed us to get a better understanding of plasma confinement properties. The duplication of the HIBP system enables the measurements in two distant toroidal planes [1].

1. IMPURITY TRANSPORT

Impurity accumulation is a key open issue in stellarators and in more general 3D geometries. Nevertheless, impurity accumulation is prevented in some experiments: in the impurity hole regime in LHD [2] and in the HDH mode in Wendelstein 7-AS [3]. Theoretical models predict that impurity transport is affected by the variations of the first order NC electric potential on the flux surface, Φ_1, or potential asymmetries, showing that impurity confinement can be reduced in comparison with that of bulk ions for given values of the potential asymmetries. Variations of Φ_1 and its impact on impurities have been further studied. A comparison across devices (TJ-II, W7-X and LHD) have shown that [4]: the spectrum of Φ_1 its coupling with the distribution function of the impurities and the resulting transport level is highly sensitive to the parameters considered; the impact of Φ_1 can result in a mitigation or enhancement of the inward impurity flow. This is clear in the LHD cases where both situations are presented (Figs. 1 and 2). W7-X exhibits low potential variations and impact on impurity transport. Regarding TJ-II, Φ_1 is found to be the largest at similar collisionalities. This supports the suitability of TJ-II for the measurement of Φ_1 and study of its impact on the impurity behaviour.

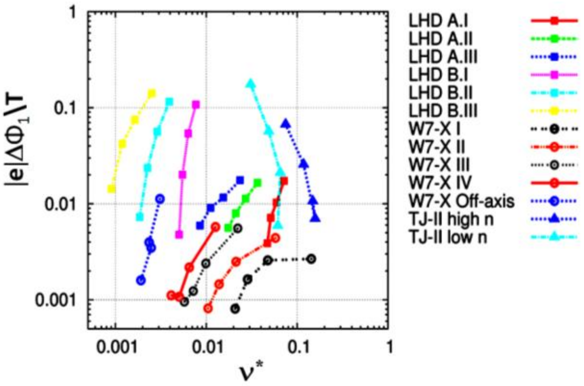

Fig. 1. Ratio $e\Delta\Phi_1/T$ as a function of the normalized collision frequency

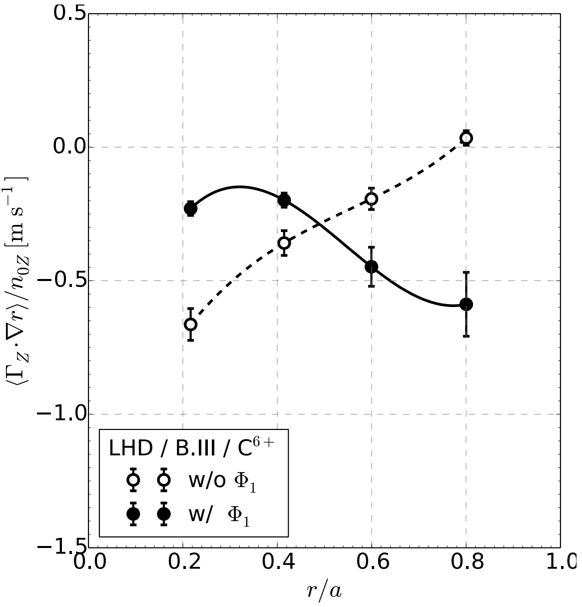

Fig. 2. Radial particle flux of CVI in LHD normalized to the density, with and without Φ1

Experimental studies searching for asymmetries have thrown direct observations of electrostatic potential variations within the same magnetic flux surface [5] in TJ-II. Significant asymmetries observed in electron-root wave-heated plasmas are reduced in ion-root NBI-heated conditions. The observed Φ_1 is of tens of volts, in agreement with NC Monte Carlo calculations.

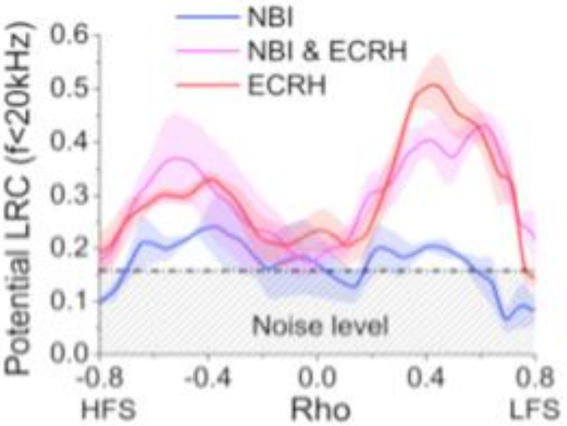

Fig. 3. Long Range correlation (LRC) of potential

Significant progress has been made regarding the understanding of empirical actuators, such as ECRH heating, to avoid core impurity accumulation. These results were obtained using the two HIBP systems located at two different toroidal ports separated by 90^0. Experiments with combined NBI and ECR heating have shown direct experimental evidence of the influence of ECRH on turbulent mechanisms, increasing both the level of fluctuation and the amplitude of Long-Range-Correlations (LRC), as a proxy of Zonal Flows (ZFs) for potential fluctuations (Fig. 3) but not for density and poloidal magnetic fluctuations (not shown). Whereas ECRH influences the level of fluctuations in a wide range of plasma densities, ECRH induced reversal of the NC Er has been observed only in low-density plasmas.

2. PLASMA FUELLING AND NEUTRAL DYNAMICS

Core density control is a critical issue on the path towards the development of steady- state scenarios in 3-D devices. First core plasma fuelling experiments, using a cryogenic pellet injector system have been performed in TJ-II, which has enabled particle fuelling and transport experiments [6].

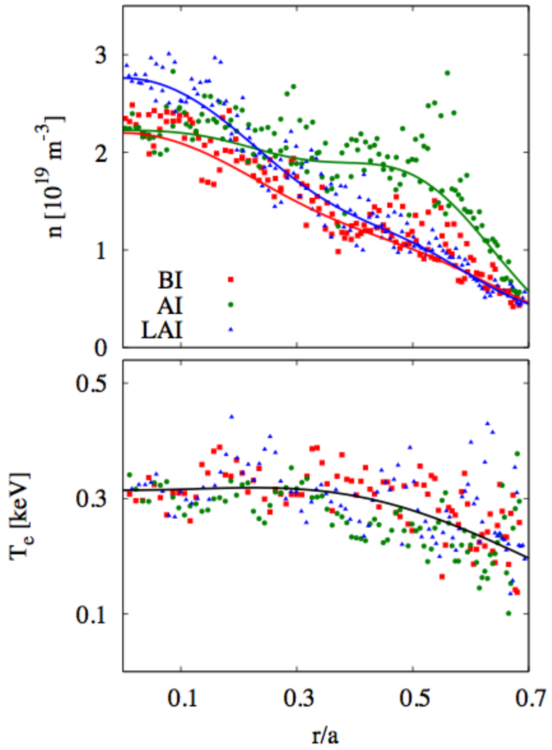

Fig. 4. Electron density and temperature profiles before the pellet injection (BI, #39063), immediately after the pellet injection (AI, #39062), and long after the pellet injection (LAI, #39065)

A small pellet is injected at an intermediate radial position and density evolution is measured with Thomson Scattering and interferometry. A density increase due to ablation is initially observed outside the core moving inwards and reducing with time. Finally, we observe a core density increase after the complete ablation of the pellet, a phenomenon that has been described using NC simulations with DKES code (Fig. 4). This phenomenon, if extensible to other helical devices, is of prime relevance: it would mean that pellets that do not reach the magnetic axis may still be able to mitigate core density depletion.

Pellet injection has been used also to perturb the plasma equilibrium potential and to study the subsequent relaxation. A sudden perturbation of the plasma equilibrium is induced by the injection of a cryogenic hydrogen pellet in the TJ-II stellarator, followed by a damped oscillation in the electrostatic potential, which is observed for the first time [7]. The waveform of the relaxation is consistent with the gyrokinetic (GK) theory.

Usually, fuelling simulations assume a cloud distribution of neutrals, given by the puffing characteristics. Here, we explore the possible response of neutrals to plasma turbulence, which could modify fuelling properties. With this aim, the helium line-ratio technique was applied with a spectroscopic high-speed camera set-up looking to the emission of helium puffed close to the separatrix. In this way, we obtain the two-dimensional image of the edge plasma electron density with a few millimetres spatial resolution and exposure times down to 15 µs. This technique allows us to measure the turbulent coherent electron density-structure of Blobs that have been compared with the raw helium emission. The differences between plasma density and raw emission structures can gives insight on the neutral distribution, showing indications of thermal neutrals react to the plasma fluctuations becoming also turbulent at frequencies of 10…100 kHz, with dimensions of one to several centimetres. The responsible mechanism to bring neutrals spatially and temporally inhomogeneous would be the turbulent local electron impact ionization by the plasma Blobs and Holes [8]. This can substantially modify the fuelling properties.

Another key topic for fuelling is whether anomalous transport driven at the plasma edge influences the scrape-off layer (SOL) width. Experiments in the TJ-II Stellarator and have found that the SOL density profile is affected by the structure of edge radial electric fields and fluctuations. It is concluded that SOL profiles are coupled with edge plasma parameters.

3. INNOVATIVE POWER EXHAUST SCENARIOS AND PFCs

Novel solutions for plasma facing components based on the use of liquid metals like Li and SnLi alloys have been developed. The TJ-II program on liquid metals addresses fundamental issues like the self-screening effect of liquid Li driven by evaporation to protect plasma-facing components against huge heat loads and tritium inventory control, using recently installed Li and SnLi liquid limiters (LLL). Biasing of Li limiters with respect to carbon ones has evidenced the important role of the secondary electron emission of plasma-exposed surfaces in the development of enhanced confinement modes. Very recently, LiSn alloys have been exposed to TJ-II plasmas in a Capillary Porous System (CPS). The evolution Zeff during the discharge shows that the influx of impurities in the plasma is very small. The main results obtained are:

- H retention values of ~ 0.01 % H/(Sn+Li) at T< 450º C were deduced from Thermal Desorption Spectroscopy (TDS) at the laboratory in agreement with previous reports and in situ TDS in TJ-II.

- Insertion of a LiSn sample into the edge of TJ-II does not lead any significant perturbation of the plasma parameters. Zeff values typically below 1.5 and very low Prad/Pin values (< 2 %) were deduced.

- Conversely, plasma operation became impossible if the alloy is directly deposited on the SS support.

- Only Li emission was detected. No traces of Sn were detected by visible and UV spectroscopy.

- H recycling did not evolve with temperature.

These results provide good perspectives for use of LiSn alloys as a PFC in a Reactor.

As a further example of the beneficial effect of Li coating, we achieved plasma start up in TJ-II under lithium coated walls using only NBI, without the help of any other external power supply. This has been achieved despite the large shine through in the phase of plasma creation.

4. PLASMA STABILITY STUDIES

Experiments on TJ-II have shown that stability at high beta values is better than predicted by Mercier criterion linear stability analyses. One of the possibilities offered by TJ-II flexibility is to change the magnetic well keeping the same rotational transform profile. It has been shown that a reduction of magnetic well has a direct impact on fluctuations without reducing plasma confinement drastically [9]. In fact, confinement time depends more on NC effects and on the size of the configuration (Fig. 5) than on magnetic well. This result suggests that Mercier stability calculations are missing some stabilization mechanisms, which could be explained by self-organization mechanisms involving transport and gradients. The effect of the magnetic well scan on electromagnetic modes has also been studied, showing consequences on the onset of Geodesic Acoustic Modes (GAMs) and on the Alfvén Eigenmode (AE) properties [10], as will be shown in Section 7.

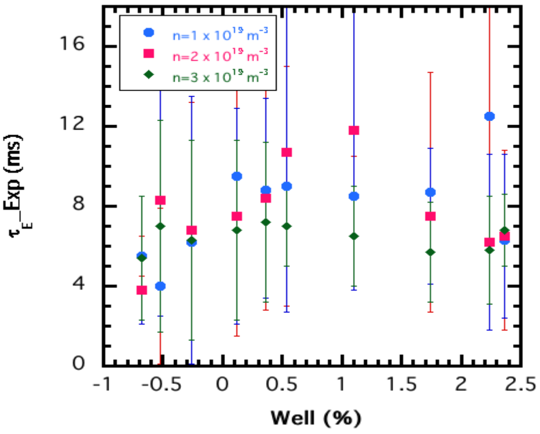

Fig. 5. Energy confinement times for three values of the plasma density and the values of the magnetic well. Those configurations with negative magnetic value should be unstable

GAMs are relevant for confinement, given their interaction with broadband turbulence and fast particles, and they are expected to be strongly damped in TJ-II. The latter reason implies that GAMs must be driven steadily to overcome the damping [11]. In the former case, energetic ions can act as a driver, giving rise to EGAMs. On top of this driver, EGAMs have been also identified with fast electrons acting as a driver in TJ-II plasmas [12].

5. MOMENTUM TRANSPORT

TJ-II has provided clear evidence that three-dimensional magnetic structures have a significant impact on plasma confinement and L-H transitions. We have performed experiments on the effect of magnetic islands on the plasma perpendicular flow and density turbulence. Doppler reflectometry have been used to study the plasma flow in Ohmically induced magnetic configuration scans, which changed the rotational transform profile and the location of the rational values of the rotational transform [13]. A characteristic signature of the 3/2 magnetic island as it crosses the Doppler reflectometer measurement position is clearly detected, showing a modulation in the perpendicular flow that changes twice its direction. The perpendicular flow reverses at the centre of the magnetic island and a flow shear develops at the island boundaries. An example is shown in Fig. 6, where the 3/2 magnetic island, in its way from the plasma centre to the plasma edge, crosses the Doppler reflectometer measurement region, showing a change in the turbulence (b), a inversion in the flux (c) when the net plasma current is about -5 kA (d). These observations could explain the link between magnetic islands and transport barriers in fusion devices.

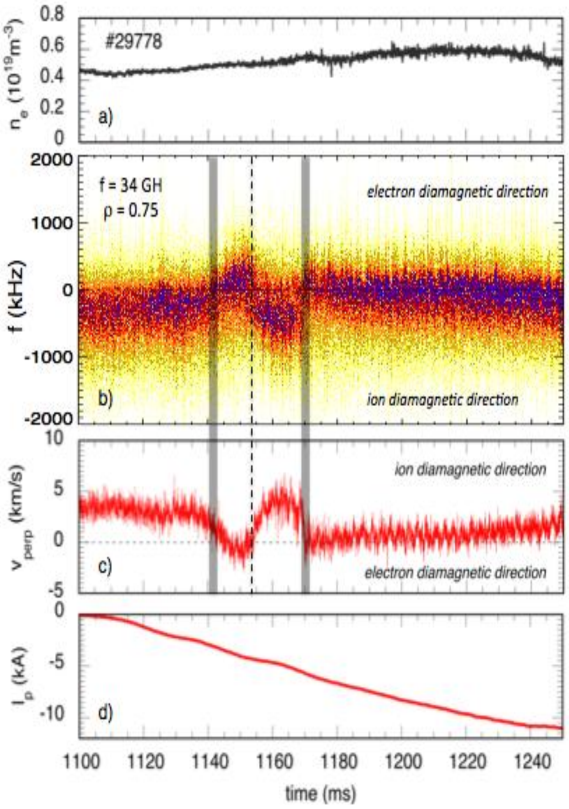

Fig. 6. Time evolution of line density (a), spectrograms of turbulence measured by DR (b) perpendicular flows measured by DR (c) and plasma current (d)

6. CONTROLLING FAST ION CONFINEMENT

The study and control of AEs is basic in plasma devices given the influence of these modes on fast ion confinement. Here we explore several mechanisms to control and mitigate AEs. The HIBP diagnostic is capable to measure simultaneously the oscillations of plasma electric potential, density and poloidal magnetic field and the Mirnov coils can measure the magnetic fluctuations.

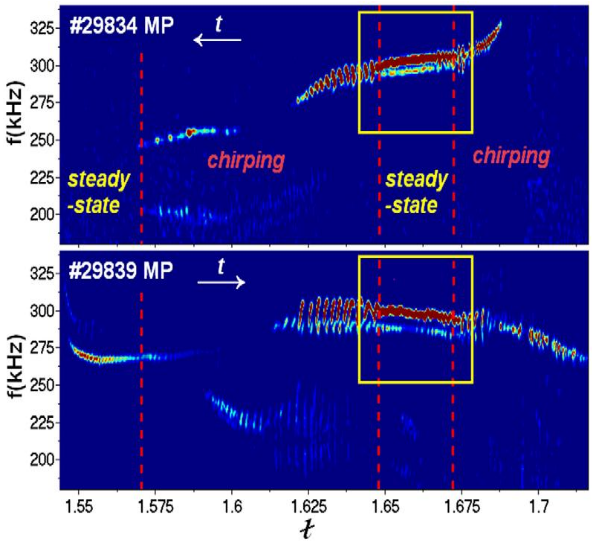

Fig. 7. Evolution with spectrogram with iota, which varies with time in a single discharge. Chirping appears always for the same values of iota

First of all, ECRH was applied on NBI-heated discharges of TJ-II. A change from steady to chirping frequency or even to a mitigation of the AEs was observed [14]. As the ECRH power increases (power scan from 80 to 225 kW), the amplitude of produced chirping AE mode increases while the bursts periodicity becomes more regular. HIBP measurements show that the chirping mode has a ballooning structure in plasma potential but an anti-ballooning structure in B_{pol}. Beyond ECRH, configuration scan appears as another tool for AE control. Fig. 7 shows the time traces of the evolution of the mode spectrum as the rotational transform varies during the configuration scan. The chirping appears always for the same values of rotational transform (marked with stripes) [15]. On top of the rotational transform, we explore the effect of the magnetic scan on AEs, which opens new ways to control such modes and, hence, their effect on fast ion confinement.

The importance of distinguishing chirping from steady behaviour relies on the different effect of the mode on fast ion confinement. We use the fast neutral flux, measured by the Compact Neutral Particle Analyser (CNPA), as a proxy for the fast ion density, so the larger the CNPA flux the larger the fast ion concentration. Hence, we can compare the fast ion confinement of different experiments by comparing the CNPA spectra: in case that the fast ion source is the same, the larger the fast neutral spectrum the larger the fast ion confinement. Fig. 8 shows that the CNPA spectra for three cases: steady, chirping and mitigated AEs. It is seen that the confinement is better in the cases with chirping and mitigated AE than in the one with steady AE.

We have also investigated the influence of magnetic well on AEs properties, taking advantage of the TJ-II flexibility. We have found a strong influence of this parameter on AEs on both, frequency, mode number and amplitude of the mode. The complexity of dispersion relation in TJ-II provokes such a strong change in the mode properties. In particular, it is observed that the frequency of the destabilised modes is decreasing with the magnetic well, which allows one to change the population of resonant ions: the lower the magnetic well the lower the frequency for similar plasma densities. One expects that the energy of the resonant ions is lower in the case of lower AE frequencies.

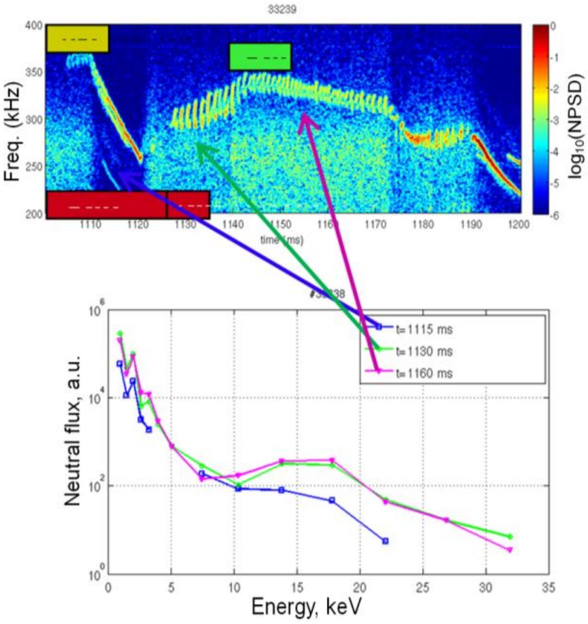

Fig. 8. shows that the CNPA spectra for three cases: steady, chirping and mitigated AEs, demonstrating a better confinement for the chirping case

CONCLUSIONS

The influence of 3D geometry on confinement physics has been explored taking advantage of the TJ-II flexibility. The break of axisymmetry causes that NC transport is not automatically ambipolar, giving rise to the onset of a radial electric field, which has strong influence on particle transport and fuelling. The first order NC theory predicts the existence of asymmetries on the magnetic surfaces, which have been observed experimentally in TJ-II, and can have strong influence on impurity transport form both NC and turbulent approaches.

We have shown core depletion density can be overcome by injecting a pellet, even it is ablated before reaching the plasma centre. Pellet injection has also allowed us to obtain for the first time a direct observation of the electric field relaxation, with good agreement with GK simulations. Another important characteristic of the fuelling in TJ-II is the structure of the neutrals that reflect the blobs that are found in density turbulence. The coupling of the edge plasma parameters with SOL density profiles has also influence on fuelling as has been explored here. As the fuelling experiments demonstrate, the plasma wall interaction in TJ-II depends strongly on the 3D geometry and makes TJ-II a well-suited laboratory to explore innovative solutions for plasma facing components based on the use of liquid metals like Li and SnLi alloys.

The 3D geometry has also strong effects on plasma stability and turbulence. We have obtained stable plasmas in theoretically Mercier-unstable configurations. EGAMs driven by fast ions and also by fast electrons are also detected and studied in TJ-II.

The plasma flow is affected by the magnetic island, as can be directly measured by Doppler reflectometry.

The dispersion relation of AEs is also affected by the 3D geometry. In particular, we have shown that the magnetic well is a governing parameter of the frequency of the mode: the larger the well, the higher the frequency. The rotational transform plays a key role in the AEs properties: we have found the rotational transform windows in which the mode presents a chirping nature (without ECRH, used before for AE control) and the ones in which its frequency varies steadily, following plasma current and density. This poses the magnetic configuration as another important knob for controlling AEs and, hence, fast ion confinement, beyond ECRH.

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ПЕРЕНОС И КОНТРОЛЬ СОСТОЯНИЯ ПЛАЗМЫ В СТЕЛЛАРАТОРЕ TJ-II

F. Castejón and the TJ-II team and collaborators

Статья посвящена влиянию 3D-геометрии на перенос и контроль состояния плазмы в стеллараторе TJ-II. Усиление роли неоклассического переноса (НС) и возникновение радиального электрического поля влияет на результат инжекции крупинок и перенос примесей. Турбулентность оказывает влияние не только на плазму, но и на плотность нейтралов, то есть на результат инжекции крупинки. Параметры плазмы в SOL зависят от турбулентности на границе плазмы. Исследованы свойства плазмы в стабильном состоянии и при появлении МГД-колебаний. Появление острова 3/2 оказывает влияние на плазменный поток. Перспективными представляются результаты, указывающие на возможность контроля Альфвеновских мод при ЭЦР-нагреве и магнитной конфигурации изменением вращательного преобразования и величиной магнитной ямы.

ПЕРЕНОС ТА КОНТРОЛЬ ЗА СТАНОМ ПЛАЗМИ В СТЕЛАРАТОРІ TJ-II

F. Castejón and the TJ-II team and collaborators

Стаття присвячена впливу 3D-геометрії на перенос та контроль стану плазми в стеллараторі TJ-II. Збільшення ролі неокласичного переносу (НС) і поява радіального електричного поля впливає на результат інжекції крупинок та перенос домішок. Турбулентність впливає не тільки на плазму, але й на густину нейтралів, що з’являються в результаті інжекції крупинки. Параметри плазми в SOL залежать від турбулентності на границі плазми. Вивчено властивості плазми у стабільному стані та при появі МГД-коливань. Плазмовий потік змінюється при появі острова 3/2. Здається, що результати, яки вказують на можливість контролю Альфвенівських мод при ЭЦР-нагріві та магнітної конфігурації зміною обертального перетворення і величини магнітної ями є перспективними.