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AM REFLECTOMETRY MEASUREMENTS IN THE STELLARATOR TJ-II

Estrada, T.*, Sánchez, J., van Milligen, B.Ph., Cupido, L.(1),
Zhuravlev, V.(2), Silva, A.(1), and Manso, M.E.(1)

Laboratorio Nacional de Fusión, Asociación Euratom-CIEMAT, 28040 Madrid, Spain.
(1) Associação Euratom-IST, CFN, Instituto Superior Técnico, 1096 Lisboa, Portugal
(2) Institute Kurchatov, Institute of Nuclear Fusion, 123182 Moscow, Russia

* Electronic mail: teresa.estrada@ciemat.es

Abstract: An Amplitude Modulation reflectometry system is in operation at the stellarator TJ-II. In general, the electron density profiles measured by the reflectometer show good agreement with profiles measured by the Thomson scattering and Lithium beam diagnostics. This paper focuses on the capability of the AM reflectometer to determine the electron density profile under various plasma conditions in TJ-II: during a magnetic well scan, in cold pulse propagation experiments, during rotational transform scans and during OH current drive experiments. The contribution of these measurements to the study of the physical phenomena is also addressed.

1. Description of the reflectometer and its calibration procedure

The reflectometer is an Amplitude Modulation system, operating in the 26-50 GHz range with extraordinary mode polarisation. A detailed description of the system can be found in [1]. The reflectometer covers almost the whole density range during the ECRH phase in all the magnetic configurations of TJ-II (B = 1 T, f_{ECRH} = 53.2 GHz, $n_{cut} = 1.75 \cdot 10^{13}$ cm^{-3}). The lowest reflecting densities at the plasma edge are between 0 and $3 \cdot 10^{11}$ cm^{-3}. These low cut-off densities, together with the fact that the magnetic field is more accurately known in stellarators than in tokamaks, alleviate the initialisation problem in the profile reconstruction procedure.

The standard calibration method involves measuring the time delay of the signal reflected on the inner vessel wall. In TJ-II, this signal is very weak because of the shape of the inner wall. The vacuum chamber cross section is not circular, and it has a groove (at the position of the central coil) just in front of the antennas. Thus, the inner vessel wall is not a concave but a convex surface. Nevertheless, the time delay of the signal reflected on the wall can be measured well except at the high frequencies (the signal amplitude drops at f > 43 GHz). Therefore, it is possible to calibrate the system, and correct for any change in the microwave transmission line, in the frequency range from 25 to 43 GHz during the experimental campaign. This range limits the maximum probed density to $n_{max} = 0.9 \cdot 10^{13}$ cm^{-3} at the typical magnetic field of TJ-II. Nevertheless, due to the typical flat density profiles, central densities are not accessible even for low plasma density discharges

At TJ-II, the position of the Last Closed Magnetic Surface (LCMS) and the magnetic field profile depend on the magnetic configuration. In the reconstruction of the density profile, we use the theoretical position of the LCMS to initialise the profile, combined with a linear density ramp up to the first reflecting point. A continuous density gradient is imposed at the first probed density to determine the slope of this initial profile.

The reflectometry density profiles are regularly compared to the profiles obtained by the Thomson scattering diagnostic [2]. In general the agreement is very good (an example is shown in section 2.4). Also a good agreement is found when comparing the reflectometry profiles to the Lithium beam diagnostic measurements [3].

The assumption of zero density at the LCMS may introduce an error in both the shape of the density profile and the absolute position of the profile within the vacuum vessel. The uncertainty in the absolute plasma position is about half a centimetre [1]. However, the density gradient is almost insensitive to the position of the plasma edge, such that the evolution of the profile shape may be studied without additional information from other diagnostics. In the reconstruction of the density profiles reported bellow, we have taken the LCMS as the starting point for the profile initialisation.

2. Experimental results

2.1 Scan in Magnetic well

Due to the low magnetic shear of TJ-II, the plasma stability is provided by the existence of magnetic well all along the plasma radius. The magnetic configuration flexibility of TJ-II allows the modification of the magnetic well profile and magnetic well depth over a broad range of values. Previous experiments carried out in TJ-II have showed that the magnetic well controls the onset of the fluctuations, increasing the fluctuation level, the degree of intermittence and the radial correlation length, as the magnetic well decreases [4]. Additional experiments have been carried out in the last experimental campaign in which the magnetic well depth has been reduced in a shot to shot basis from 2.4% to 0.9%. The radial profiles of the magnetic well in the extreme configurations of the scan are shown in Fig. 1.a, while the density profiles measured by the AM reflectometer are displayed in Fig. 1.b. These measurements show a reduction in the gradient of the density profile in the unstable configuration, as the magnetic well depth is decreased to 0.9%. The reduction in the density gradient is also accompanied by a decrease in the plasma energy content measured by the diamagnetic loops [5] and by an increase in the edge turbulent transport [6].

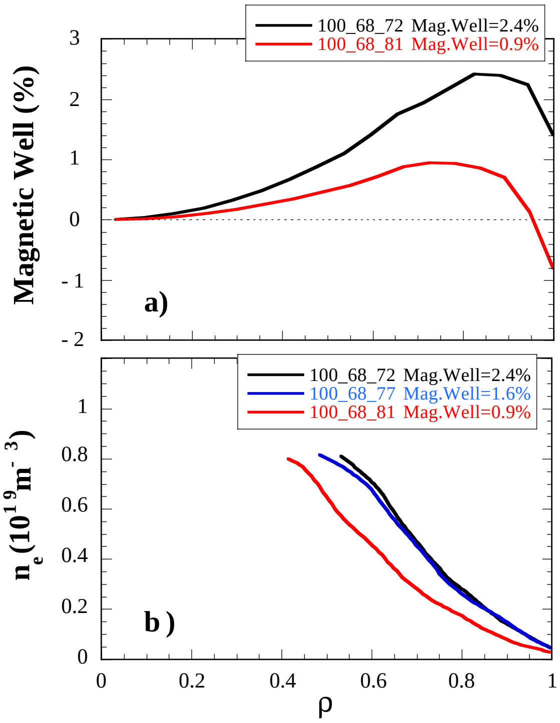

Fig 1: (a) Magnetic well profiles in two extreme configurations and (b) density profiles measured by reflectometry in three configurations with decreasing magnetic well

2.2 Cold pulse propagation experiments

Recently, nitrogen pulses have been injected in the TJ-II edge region [7]. To illustrate the response of the density profile to the injected pulse, we have chosen a discharge in which the amount of nitrogen is rather large. The average electron density, as measured by the microwave interferometer, increases by nearly 15% (see Fig. 2.a). Reflectometry measurements show an increase in density when the nitrogen pulse is injected. Three density profiles obtained just before the pulse, and 2 and 6 ms later, are displayed in Fig. 2.b. Two milliseconds after the pulse, the most pronounced increase in the density is measured between r_{eff} = 13 - 16 cm, and in the next milliseconds the perturbation in the density propagates to more internal radial locations. Within the time resolution of 2 ms, the perturbation occurs simultaneously in the most external radial locations. Further inside, it is possible to measure the inward propagation of the pulse and deduce the particle diffusion coefficient: $D = 0.1\ m^2/s$ at ρ = 0.5 - 0.7. This value is comparable to the neoclassical particle diffusion coefficient calculated using the mono-energetic Monte Carlo technique [8]. Although the error in the determination of the diffusion coefficient is large, mainly due to the low temporal resolution of the profile measurements, these measurements provide the first experimental estimates of the particle diffusion coefficient in the plasma interior of TJ-II.

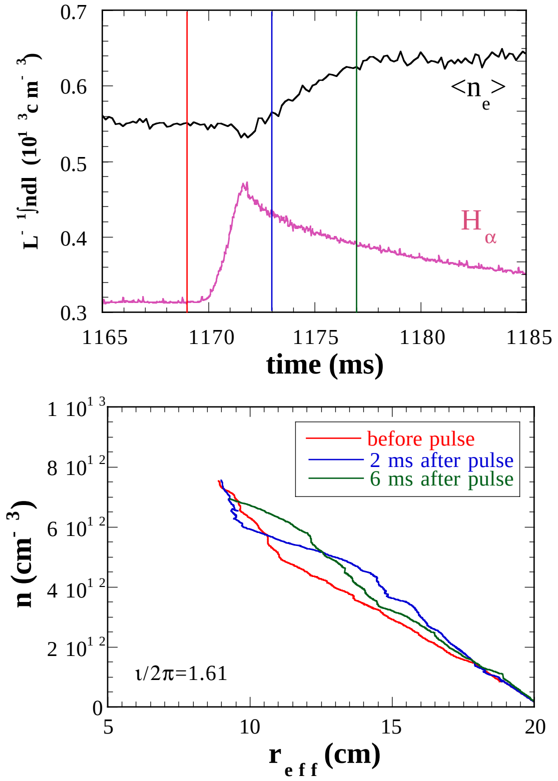

Fig 2: Evolution of the line-averaged density and Hα signal (a) and modification in the density profile (b) due to the nitrogen pulse injected in the plasma edge.

2.3 Low order rational surfaces

The flexibility and low magnetic shear of TJ-II allows a very precise control of the rotational transform profile and the corresponding rationals [9,10]. Reflectometry measurements were carried out during a magnetic configuration scan in which the rational surface $\iota/2\pi = 4/2$ was moved from the SOL into the plasma confinement region. The presence of this low-order rational surface inside the plasma causes a local flattening of the electron density profile. Fig. 3 displays the density profiles obtained in three magnetic configurations. In these magnetic

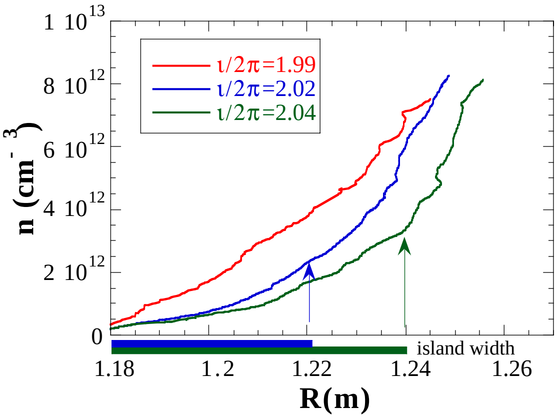

Fig 3: Density profiles obtained in a magnetic configuration scan in which the rational surface iota = 4/2 moves from the SOL into the plasma confinement region.

configurations, the plasma centre is located at R = 1.27 m. The 4/2 rational surface is just outside the LCMS in the magnetic configuration with $\iota/2\pi = 1.99$ at r = a. By decreasing the current in the circular coil and increasing the current in the helical coil, iota increases and the rational surface moves into the plasma. The island width, estimated using field line mapping codes, increases from w = 0.04 m in the configuration with $\iota/2\pi = 2.02$ to w = 0.06 m in the configuration with $\iota/2\pi = 2.04$. It spreads from the plasma edge to the positions marked with arrows in Fig. 3. We observe that the radial range of the flattening in the density profile increases in the same way as the radial extent of the theoretically predicted magnetic island.

2.4 Ohmic current drive experiments

Ohmic current drive experiments have been carried out in TJ-II. The plasma current was inverted during the plateau of the discharge, going from 1kA to –3kA. During the negative plasma current phase, an improvement in the confinement properties was observed. In this phase, the reflectometry density profiles show an increase in the density gradient and a broadening of the profile. Fig. 4 shows the density profiles measured without and with negative ohmic current in discharges with the same line-averaged density. The Thomson scattering profiles are also displayed. Using these reflectometry measurements, a more precise calculation of the plasma kinetic energy enhancement was possible.

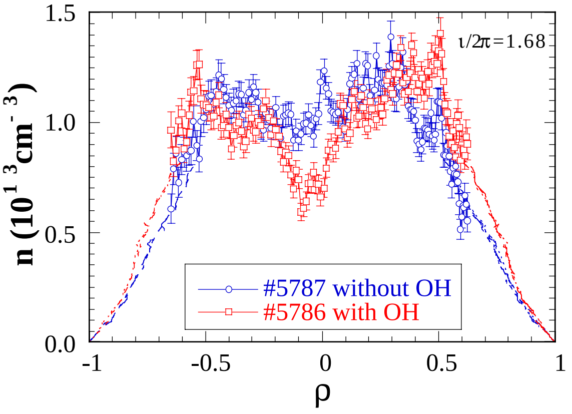

Fig 4: Density profiles measured without and with negative ohmic current

3. Conclusions and future plans

Electron density profiles have been measured in TJ-II using AM reflectometry. The agreement between reflectometry profiles and profiles from other diagnostics is satisfactory. The experimental results presented in this paper show the importance of this kind of measurement for the experiments carried out in TJ-II. However, in its present configuration, the time resolution of the system is not sufficiently high, to track the detailed evolution of fast events. In the near future the time resolution will be improved and the system will be modified to operate simultaneously in the AM and FM-CW modes.

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