

OVERVIEW OF TJ-II FLEXIBLE HELIAC EXPERIMENT

E. Ascasíbar, C. Alejaldre, J. Alonso, L. Almoguera, A. Baciero, R. Balbín, M. Blaumoser, J. Botija, B. Brañas, A. Cappa, J. Castellano, R. Carrasco, F. Castejón, J. R. Cepero, J. Doncel, S. Eguilior, T. Estrada, A. Fernández, C. Fuentes, A. García, I. García-Cortés, J. Guasp, J. Herranz, C. Hidalgo, J. A. Jiménez, I. Kirpichev, F. Lapayese, K. Likin, M. Liniers, D. López-Bruna, A. López-Fraguas, J. López-Rázola, A. López-Sánchez, E. de la Luna, R. Martín, M. Medrano, P. Méndez, K.J. McCarthy, F. Medina, B. van Milligen, M. Ochando, L. Pacios, I. Pastor, M.A. Pedrosa, A. de la Peña, A. Portas, J. Romero, L. Rodríguez-Rodrigo, A. Salas, E. Sánchez, J. Sánchez, F. Tabarés, D. Tafalla, V. Tribaldos, J. Vega and B. Zurro.

*Laboratorio Nacional de Fusión por Confinamiento Magnético, Asoc. Euratom-Ciemat, 28040 Madrid, Spain  
E.mail: enrique.ascasibar@ciemat.es*

**Abstract**

This paper summarises recent physics results obtained in TJ-II in the areas of stability, confinement and transport and fluctuations studies. TJ-II is a low shear, four period stellarator (heliac type,  $R=1.5$  m,  $a<0.21$  m,  $B_0\leq 1.2$  T) with high degree of flexibility, that allows to control, almost independently, the rotational transform profile and the magnetic well across the plasma radius.

**1. Introduction**

This paper summarises recent physics results obtained in TJ-II<sup>1</sup> in the areas of stability, confinement and transport and fluctuations studies. They have been obtained in plasmas produced by up to 600 kW of ECH (at a frequency of 53.2 GHz, 2<sup>nd</sup> harmonic, X-mode of polarisation). In these plasmas the line-averaged density is up to  $1.2 \cdot 10^{19}$  m<sup>-3</sup>, the electron temperature at the centre of the plasma is up 1.5 keV and the ion temperature about 0.1 keV. The thermal energy content is up to 0.6 kJ and the net plasma current (in absolute value) is lower than 1 kA.

**2. Stability studies and configurational effects**

Magnetic well is the main stabilising mechanism in TJ-II<sup>2</sup>. Due to the flexibility of the TJ-II configuration, the magnetic well depth may be modified over a broad range of values, i.e. from 0% to 6 %, while the radial extent of the magnetic well can also be strongly modified. Recent experiments have shown that, as expected from the theoretical point of view, the level of edge fluctuations and the degree of intermittency show a significant increase when magnetic well is reduced in the TJ-II stellarator<sup>3</sup>. Fluctuation-induced E×B particle transport has been computed in the edge of plasmas in different magnetic configurations changing the magnetic well depth. Results show that the turbulent flux decreases as the well is increased. Electron density profiles measured by reflectometry during the magnetic well scan show a widening of profiles and an increase of the gradient as the magnetic well increases<sup>4,5</sup>.

MHD instabilities coupled together to ELM-like<sup>6</sup> transport events have been observed in the TJ-II stellarator<sup>7</sup>. During the last experimental campaign some specific experiments have been carried out in order to investigate the influence of the presence of low order resonances in the confined plasma region, on the occurrence of ELM-like<sup>8</sup>. The iota profile has been modified in discharges with similar pressure profiles by two different methods: configuration scan by fine tuning of the external coil currents and electron cyclotron current drive in co and counter directions. It has been concluded that the appearance of ELM-like transport events requires the presence of a low order resonance in the confinement region. These events are larger when the resonance is close to the shoulder of the density profile.

Cold pulses have been generated in TJ-II using nitrogen injection by means of a fast injection system.<sup>9</sup> The response of the ECE radiometer temperature traces consists in a sudden drop

followed by a slow recovery. The time of arrival of the cold pulse front to a certain position inside the plasma can be considered a probe of the transport properties of the *unperturbed* plasma. The analysis shows that the propagation speed is of the order of  $v = 10\text{--}20$  m/s in the outer half of the plasma ( $\rho \geq 0.4$ ), whereas it speeds up to around  $v = 50\text{--}80$  m/s in the central part ( $\rho < 0.4$ ). This behaviour is not at all in accordance with diffusive propagation, which would slow down as it propagates (travelled distance  $\propto \sqrt{t}$ ). The frequency analysis of a Mirnov coil signal shows that a 43 kHz MHD mode is triggered at the time the cold pulse reaches the plasma core (i.e. when it arrives at  $\rho \approx 0.3\text{--}0.4$ ). Most likely, the mode is a  $n/m = 3/2$  mode. The central value of  $\iota$  of the vacuum field configuration,  $\iota = 1.51$ , is just above this value. However, in these experiments a small net plasma current was measured by a Rogowski coil ( $I_p \approx -0.2$  kA), placing the  $\iota = 3/2$  rational surface at approximately  $\rho \approx 0.3$ , consistent with the existence of the mode. Qualitatively, the pulse propagation behaviour is very similar to the pulse propagation seen in a simulation of resistive pressure-gradient driven turbulence in cylindrical geometry. Thus, the most likely explanation for the observed propagation of the cold pulse front is the sequential triggering of pressure-gradient driven modes, in an avalanche-like fashion.

### 3. Confinement studies and configurational effects

#### *Magnetic surface mapping*

The range of explored magnetic configurations in TJ-II has become wider as the coil currents upper limits have been approached. As shown all along the present paper, a very precise knowledge of the magnetic topology is being required in order to interpret many of the experimental results. As a consequence, an additional extended campaign of magnetic surface mapping *experiments* (more than fifty new configurations) has been performed with the main goal of checking the validity of the magnetic field model built up in the TJ-II start-up phase<sup>10,11</sup>. The measured magnetic surfaces show an excellent agreement with the predictions.

#### *Global energy confinement*

TJ-II stellarator dataset has been compared with the data from other stellarators included in the International Stellarator Scaling (ISS95) database<sup>12,13</sup>. TJ-II global energy confinement time and plasma parameter dependencies are consistent with ISS95 predictions.

#### *Radiation asymmetry*

Intermittent toroidal asymmetries in the plasma edge emissivity have been detected in the TJ-II plasmas<sup>14</sup>. As the asymmetries reveal variations in the wall desorption near the gyrotron port, the toroidal radiation asymmetry is interpreted in terms of a sudden increase of ECRH driven convective flux of ripple-trapped suprathermal electrons. Observations suggest that the magnetic structure may play a relevant role in moderating the ripple losses<sup>15</sup>.

#### *Impurity injection experiments*

First impurity injection experiments by the laser ablation technique have been carried out<sup>16</sup>. The main goal of these experiments is to explore the existence of non-exponential relaxation in TJ-II. Such behavior has been associated with the presence of particle trapping and de-trapping whose occurrence in a plasma might be associated with the presence of small island chains across the radius. First results suggest that this perturbation can be analyzed by a stretched exponential while particle confinement times of up to 100 ms have been observed

#### *Transport and fluctuations studies*

A transient behaviour has been observed in the plasma core of TJ-II with fast drops in the electron temperature<sup>17,18</sup>. Changes in the line-averaged density occur synchronised with temperature drops. The transient behaviour resembles both, the electric pulsation discovered in CHS and the “electron root” feature reported by the W7-AS team. In TJ-II, the fast spontaneous transitions appear related to the magnetic topology in conditions of fixed plasma density and ECH power. The flexibility and low magnetic shear of TJ-II have allowed the identification of the plasma current as the control parameter for the appearance of this

phenomenon. The results obtained during the magnetic configuration scans carried out in TJ-II points to the hypothesis that the transient behaviour is connected with the presence of a rational surface close to the plasma centre. Equilibrium calculations performed with the VMEC code reinforce this hypothesis. In spite of the connection rational/transient found, the physical mechanism causing the transport change remains unknown. It seems reasonable to consider that the rational surface is affecting the radial electric field, as discussed in the next paragraph.

The presence of natural resonances has clearly been observed as a flattening in the edge plasma profiles of the TJ-II and LHD stellarators<sup>19,20</sup>. Structures in plasma profiles have been observed in the case of low-order rational surfaces ( $n=8 / m = 5$ ,  $n=4 / m = 2$ ) in TJ-II. Both in TJ-II and LHD devices there is a significant variation in plasma potential just outside the flattening region. These results have been interpreted as an increase of the sheared  $E \times B$  flow linked to the radial location of rational surfaces. The resulting radial gradient  $(dE_r/dr) B^{-1}$  can reach values of about  $10^5 \text{ s}^{-1}$  and this value turns out to be comparable to the inverse of the decorrelation time of fluctuations usually measured. Recent experiments in TJ-II stellarator have shown that the local  $E \times B$  fluctuation induced fluxes are significantly modified in the proximity of rational surfaces<sup>21</sup>. In the case of measurements taken in the proximity of the  $n = 4/m = 2$  ( $v/2\pi \approx 2$ ) resonant surface, located near the plasma boundary, the local  $E \times B$  fluctuation particle flux shows a reverse direction (from outwards to inwards). The absolute value of the measured local  $E \times B$  transport is similar in both cases with (inward) and without (outward) transport. This modification is due to a change in the phase relation between density and electric field fluctuations. Although the mechanism responsible of the observed inward transport has not been identified, it may be related with the presence of convective cells linked to rational surfaces. The fact that no significant differences are found in the global confinement strongly suggests a local nature of the measured turbulent transport.

In this context the relevance of the HIBP (Heavy Ion Beam Probe) diagnostic appears absolutely clear. First plasma potential measurements by the HIBP have already been obtained in TJ-II<sup>22</sup>. An important improvement in the signal to noise ratio allows the measurements of plasma potential fluctuations, with resolution better than 20 V. It has been found that plasma potential depends on plasma density: as plasma density increases, plasma potential decreases. Localised bursts in fluctuations have been observed which might be related to the presence of a rational surfaces, namely,  $n=2$ ,  $m=3$ .

#### *Improved confinement modes*

An enhanced particle confinement regime (EPC) has been found for TJ-II plasmas in all metal scenario<sup>23</sup>. It consists of a spontaneous transition to a highly peaked density profile mode that leads to a decay of the electron density in the edge region and to an increase of the total particle content. It corresponds to an enhancement of the global particle confinement of a factor up to 3. The EPC has been found almost independent of heating power and density in hydrogen plasmas. The only external requirement to be fulfilled seems to be an electron density value over a certain threshold ( $0.65 * 10^{19} \text{ m}^{-3}$ ), together with a given puffing waveform. The critical density is basically constant for all heating powers and magnetic configurations. As a general rule, no transition has been observed in He plasmas for constant heating power.

Another type of spontaneous improvement in particle and, also, energy confinement has been observed in some TJ-II plasmas using the fuelling rate from the wall as the only external knob<sup>24</sup>. The spontaneous transition to an improved regime is identified by a sudden increase in the electron and ion temperatures and electron density. At the same time, the temperature and density measured by Langmuir probes at the limiter drop.

Recent experiments have been conducted in TJ-II trying to control plasma and energy confinement time by means of a small toroidal current ( $I_p < 5$  kA) induced with the air core transformer<sup>25</sup>. It has been found that confinement improves when the current is in opposite sense to the toroidal field (negative, according to the usual criterion) and viceversa. Among several possible explanations, the experimental results favour magnetic shear as the main cause of the confinement changes.

## 5. Conclusions

Magnetic well scan experiments have shown that turbulent transport and fluctuations increase as the well is decreased. Density profiles and global confinement are also modified with magnetic well.

Low order rationals present in the iota profile have a clear influence in several MHD and transport related processes observed in TJ-II: ELM-like events are associated with a rational at the density gradient region. The observed transient behaviour in the core region is connected with the presence of a rational surface in the plasma centre. Cold pulse propagation (much faster than expected from pure diffusion) can be explained in terms of successive triggering of instabilities at different rational surfaces. Indications of trapping and de-trapping processes associated with the presence of rational have been observed also in radiation profiles and dedicated impurity injection experiments. Local *EXB* fluctuation induced fluxes are significantly modified near rational surfaces. The possibility of measuring the electric field perturbations associated with the rational surfaces by means of the HIBP diagnostic gives TJ-II a privileged position in this research area.

TJ-II global energy confinement time and as well as iota-scaling are consistent with ISS95 predictions.

Several enhanced particle and energy confinement modes have been observed in TJ-II. In some cases they are related with the fuelling rate. In others they seem to be governed by the magnetic shear

---

<sup>1</sup> C. Alejaldre, et al., Nucl. Fusion 41 (2001) 1449

<sup>2</sup> A. Varias, C. Alejaldre, A. L. Fraguas et al, Nucl. Fusion 30 (1990) 2597

<sup>3</sup> J. Castellano et al., Phys Plasmas 9 (2002) 713

<sup>4</sup> C. Hidalgo et al, this workshop

<sup>5</sup> T. Estrada, J. Sánchez et al, this workshop

<sup>6</sup> F. Wagner, et al., Plasma Phys. Control. Fusion **36** (1994) [6].

<sup>7</sup> I. García-Cortés et al., Nucl. Fusion **40** (11) (2000) 1867

<sup>8</sup> J.A. Jiménez et al, this workshop

<sup>9</sup> B.P. van Milligen et al., this workshop

<sup>10</sup> E. Ascasibar et al., J. Plasma Fusion Res. SERIES, **1** (1998), 183.

<sup>11</sup> A. López-Fraguas et al., this workshop

<sup>12</sup> E. Ascasibar, U. Stroth et al, this workshop

<sup>13</sup> U. Stroth et al, Nucl. Fusion 36 (1996) 1063

<sup>14</sup> M. Ochando et al., this workshop

<sup>15</sup> F. Medina et al., Rev. Sci. Instrum. 72, (2001) 471

<sup>16</sup> B. Zurro et al., this workshop

<sup>17</sup> T. Estrada, E. de la Luna, et al. Submitted to Plasma Phys. Control. Fusion

<sup>18</sup> E. de la Luna et al., this workshop

<sup>19</sup> C. Hidalgo et al., Plasma Phys. Control. Fusion 42 (2000)

<sup>20</sup> K. Ida et al., Phys. Rev. Lett. 88 (2002)

<sup>21</sup> M.A. Pedrosa et al., Plasma Phys. Control. Fusion 43 (2001) 1573.

<sup>22</sup> A. Chmyga et al., this conference

<sup>23</sup> F.L. Tabarés et al., 28<sup>th</sup> EPS Conference on Contr. Fusion and Plasma Physics, ECA Vol 25A (2001) 737-740

<sup>24</sup> I. García-Cortés et al., this conference

<sup>25</sup> J. Romero et al. Submitted to Nuclear Fusion