UDC 533.9

LATEST PHYSICS RESULTS OF TJ-II FLEXIBLE HELIAC

F. Castejón, C. Alejaldre, J. Alonso, L. Almoguera, E. Ascasíbar, A. Baciero, R. Balbín, M. Blaumoser, J. Botija, B. Brañas, E. de la Cal, A. Cappa, R. Carrasco, J. R. Cepero, C. Cremy, 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. Kirpitchev, V. Krivenski, I. Labrador, F. Lapayese, K. Likin, M. Liniers, A. López-Fraguas, A. López-Sánchez, E. de la Luna, R. Martín, L. Martínez-Laso, 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.Qin, 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
Asociación EURATOM-CIEMAT. Av. Complutense, 22. 28040 Madrid, Spain

This paper is devoted to the presentation of the most relevant recent Physics results obtained in the TJ-II flexible heliac. Firstly ECRH modulation and plasma breakdown studies are summarised; then the particle control techniques used to obtain reproducible discharges with density under control are presented. Transport studies show internal heat transport barriers that reduce heat conductivity to neoclassical values, and ELM-like transport events, similar to those observed in tokamaks and in other stellarators before and during H mode transition. Evidence of ExB sheared has been observed both in the proximity of rational surfaces. Finally, a high resolution Thomsom Scattering system has shown Te and ne profile structures.

1. TJ-II DESCRIPTION

The Flexible Heliac TJ-II[1] is a four period low magnetic shear stellarator with major radius R = 1.5 m, average minor radius a < 0.22 m, and magnetic field on axis $B_0 \leq 1.2$ T. Varying the currents of the central circular and helical coils allows one to vary the magnetic configuration, reaching a wide interval of iota values (iota ≈ 1.28 – 2.24) and plasma indentations and sizes (plasma volumes ≈ 0.6 – 1.1 m^3). The project was granted EURATOM preferential support phase II in November 89. At the end of 1996, the magnetic surfaces mapping was successfully conducted through, giving a good agreement between the calculated and the measured magnetic surfaces[2]. [2] and the first plasma was produced in December 1997. TJ-II started operation in 1998 and the plasmas are created and heating by EC waves launched by two gyrotrons, of 300 kW each, at X mode and 2nd harmonic. Two ECRH transmission lines, called QTL1 and QTL2, with different steering launching capabilities (fix for QTL1 vs. poloidal and toroidal variation in QTL2), with different power deposition profiles and, hence, absorbed power densities (1 in QTL1 vs. 15 W/cm3 for on-axis heating of the narrower beam line of QTL2). Presently two Neutral Beam Injectors (PNBI ≤ 3MW) are under installation. Stationary plasmas during the whole gyrotron pulse (≤ 0.3 s) with stored energies up to 1.3 kJ and 1.5 keV central electron temperature are routinely achieved. Both helium and hydrogen fuelled plasmas have been investigated and the most recent physical results are discussed in this paper.

2. ECRH EXPERIMENTS

A variety of experiments based on the capability of the ECRH system can be performed. For the moment, the results of plasma breakdown studies and power modulation experiments are available. The system for the TJ-II stellarator consists of two gyrotron oscillators at 53.2 GHz, which corresponds to the second harmonic of the electron cyclotron frequency. Each gyrotron can deliver 300 kW of microwave power at the output window and the pulse length is up to 1 s.

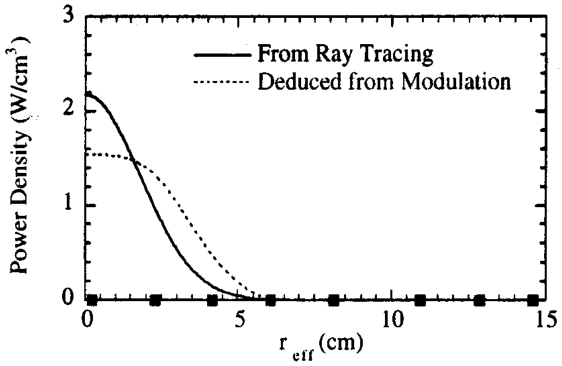


Fig.1. Power deposition profile obtained from modulation experiments compared with ray tracing calculations

The gyrotrons are driven by two anode modulators, whose voltage can be modulated up to 50 kHz. Fast modulation experiments has been performed to obtain the power deposition profile of QTL2 line. The modulation frequency is 5 kHz and the Fourier analysis of ECE signal is able to register the modulation up the 3rd channel of ECE system. It is observed that the power deposition profile is wider than the predicted by the ray tracing calculations (see Fig. 1).

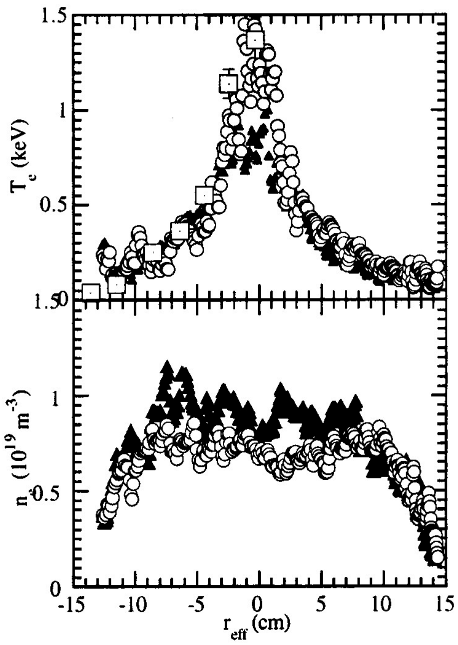
A kinetic model that takes into account the full ionisation chain has been developed to simulate plasma start-up by microwaves at 2nd harmonic of electron cyclotron frequency. The model considers the particle balance equations of the species that takes part in all the considered processes. A good agreement between the model predictions and the experimental data is obtained[3].

3. PARTICLE CONTROL AND WALL CONDITIONING

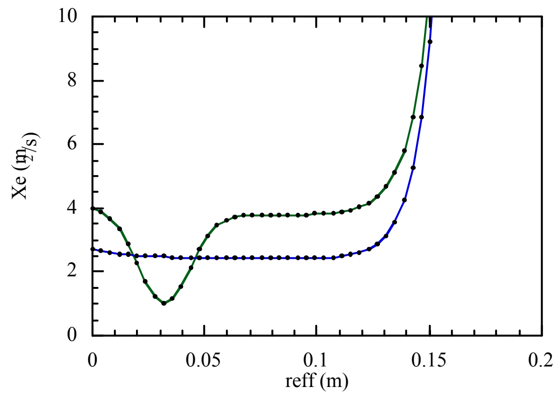
In order to get reproducible and controlled discharges under full ECH power injection, new gas control and wall conditioning techniques have been implemented. The initial procedure of wall conditioning during 1998 and 1999 campaigns was He glow discharge cleaning (GDC) at room temperature during overnight periods between operation days[4]. The main effects of this procedure in TJ-II are to remove the hydrogen implanted on the walls by plasma discharges and to produce an activated surface with a typical wall pumping behaviour. The last effect is deduced from the decrease of the residual pressure about 10-20% after the He GDC and from the residual gas analyser (RGA) measurements. The improvement of the base pressure achieved by decreasing the residual water (baking of the chamber followed by He GDC) has had an important effect over the reproducibility of the TJ-II discharges. This is due to the suppression of sources of electrons than can be accelerated during the rise of the current in the magnetic coils. During the 1999 campaign, density control for high ECRH injected power (higher than 300 kW) was still extremely difficult. The reason was that He implanted on the wall during the previous GDC conditioning was desorbed during the plasma discharge producing uncontrolled increase of plasma density[5] . As the intensive He GDC seemed to be necessary in TJ-II in order to have reproducible discharges, an additional procedure for removing the implanted He from the walls before plasma operation was required. With this aim, during the 2000 campaign Ar GDC during ≤ 30 min. prior to the TJ-II operation and after the overnight He GDC was applied. The release of He atoms from the walls by Ar bombardment has been measured. The integration of the released fluxes during the 30 min of the cleaning discharge yields a total amount of desorbed He of about 10^{21} He-atoms corresponding to ~1 mono-layer of the TJ-II vacuum chamber (S=75 m^2). The depletion of this He amount is enough to allow the operation of TJ-II under high injected power and density control by external gas puffing[6]. Low Z effective values (1.5 to 2.5 in H plasmas and 3 to 4.5 in He plasmas) and low radiated power (< 20% of injected power)[7] are typically achieved under all heating schemes applied in the 2000 experimental campaign.

4. TRANSPORT AND TURBULENCE STUDIES

Electron heat diffusivity, obtained from power modulation experiments and power balance analysis, is about 4 m^2/s in the plasma core region and increases when approaching the plasma boundary region[8]. Measurements of electron temperature profiles using electron cyclotron emission (ECE) and Thomson scattering diagnostics have shown evidence of internal heat transport barriers in the TJ-II stellarator, as illustrated in Fig. 2.a. Transport analysis shows a reduction in transport coefficients to a transport rate consistent with neoclassical predictions based on Monte Carlo simulations[9] (see Fig. 2.b). The cause of the observed confinement enhancement could be that ripple trapped electrons pumped out by ECRH may create a sheared electric field and ExB decorrelation effects could diminish the turbulent transport. Indeed, non-Maxwellian features have been observed in electron distribution functions over the 1-5 keV energy range, which could be related to an ECRH induced deformation of the distribution function.



a



b

Fig. 2. a: Thomson scattering (electron temperatre and density) profiles of helium plasmas with 300 kW injected power and different electron density. ECE temperature profile (open squares in the top box) is displayed for the low density case in which the ITB appears; b: Electron heat diffusivities for a discharge with a transport barrier (presents a minimum) and one without barrier.

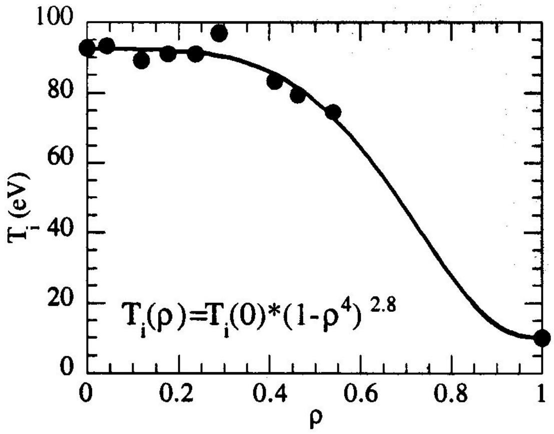


Fig. 3. Radial profile of ion temperature for the 100_44_64 configuration with 300 kW heating power

Charge exchange (CX) neutral particle energy spectra have been measured with a 5-channel spectrometer in hydrogen plasmas with line electron densities of 0.5-1.2 x 10^{19} m^{-3} and injected power P=200-600 kW. Measurements were done near to the perpendicular velocity distribution. The slope in the spectrum in the range of energies 100-200 eV provides an ion temperature, T_i, of 50-70 eV, whereas the same analysis for fast atoms with energies above 250 eV provides a temperature of 90 - 120 eV. The analyser scans a poloidal cross section along a vertical line and is placed in the cross section with the highest magnetic ripple, ensuring that charge exchange analyser measures mainly ion energy distribution of trapped particles. Radial T_i (r) profile has been measured in the 100_44_64 configuration (central iota 1.551) and is shown in Fig. 3. It can be fitted by the expression: T_i (r) = T_i (0) * $[1-r^4]^{2.8}$.

ELM-like transport events have been measured in plasmas with stored energies of about 1 kJ. The plasma develops bursts of magnetic activity (observed in the Mirnov coils), followed by a large spike in the Ha signal[10], as shown in Fig. 4. The electron temperature measured by the ECE system shows a pivot point at the plasma radius r ≈ 0.6 (where the temperature is in the range of 100-200 eV). As a consequence, the electron temperature profile flattens at this plasma position. This flattening is due to an increase by a factor 2 of the electron thermal diffusivity, caused by the triggering of the ELM instability. These events are localised at the pressure gradient region suggesting the possible role of resistive ballooning instabilities. Edge parameters (electron density and temperature) have been investigated for a fixed magnetic configuration (named 100_40_63, with rotational transform at axis 1.509) in both, H and He plasmas by means of He and Li atomic beams and Langmuir probes[11], as shown in Fig. 5.

Density and power scans have been conducted. No significant differences in electron temperatures near the last closed flux surface (LCFS) are seen as the power is changed. In most cases, a high insensitivity of edge characteristics to the operational parameters has been found, such as constant edge density for central density scan and constant edge temperatures for the power scan.

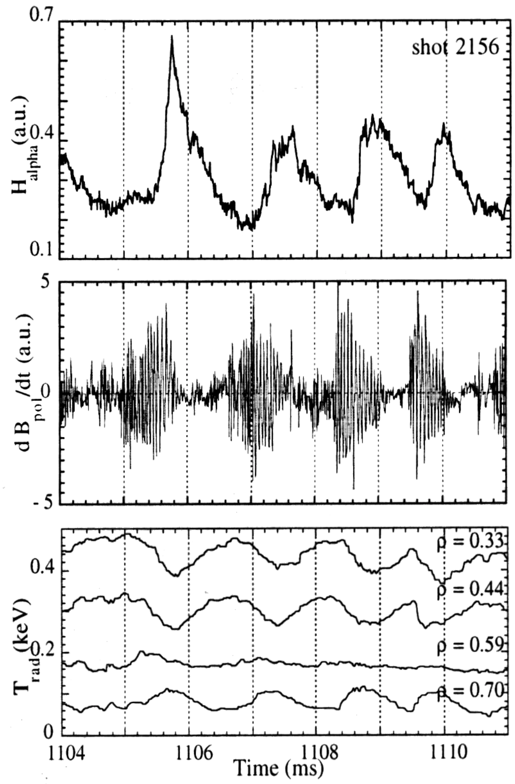


Fig. 4. Time traces of: (a) Ha signal, (b) Mirnov coil signal and (c) ECE signals at four radial positions showing ELM-like activity in TJ-II shot #2156

However, a systematic broadening of edge profiles with P/n_e has been observed. Scrape off layer (SOL) particle e-folding lengths have been also recorded, allowing the evaluation of diffusion coefficients (D) and global particle confinement times (t_p) under the assumption of no strong asymmetries. D values of the order of D_{Bohm} and t_p values ranging from 14 to 3 ms have been obtained. A clear degradation of particle confinement with injected power has been found, together with indications of confinement enhancement with density.

TJ-II has a large value of edge magnetic ripple (about 35% for the standard configuration). As a consequence relatively large fractions of trapped particles and enhanced energy and particle losses should be expected in the plasma boundary region[12]. This fact may explain the particularly low densities and temperatures observed in the plasma boundary. Experimental evidence of ExB sheared flows linked to rational surfaces has been obtained in the plasma edge region of the TJ-II for different magnetic configurations[13]. The presence of the 4/2 rational surface, predicted by vacuum magnetic field calculations, can be detected by two clear footprints, as shown in Fig. 6: the flattening in the edge profiles and the modification in the root mean squared (rms) of floating potential fluctuations. The measured correlation time of fluctuations (10 ms) turns out to be comparable to the inverse of the ExB decorrelation rate, suggesting the possible role of rational surfaces to access high confinement regimes. The resulting ExB sheared flows associated to rational surfaces would depend on the competition between mechanisms driving flows (i.e.

Reynolds stress, ambipolar electric field due to ion-electron fluxes differences) and damping flow processes (i.e. magnetic viscosity).

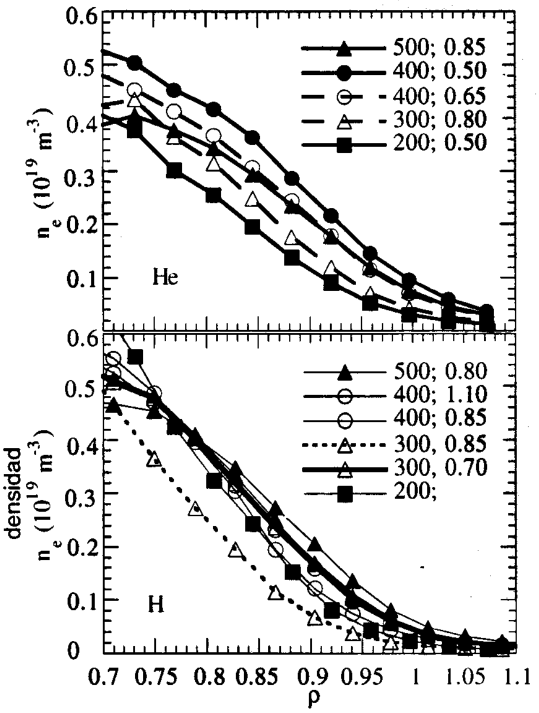


Fig. 5. Edge density profiles measured measured by means of Li atomic beam in He (top) and H (bottom) plasmas. The numbers inside the boxes indicate, for each profile, the ECRH heating power (in kW) and the line average density (in units of 10^{19} m^{-3}), respectively

In order to investigate transport characteristics close to instability thresholds, the radial profile of ion saturation current and floating potential and their fluctuations has been measured in magnetic configurations with the same rotational transform (iota (a) ≈ 1.8), but whose magnetic well ranges from 0.2 % to 2 %. The level of fluctuations at the plasma boundary increases in the plasma configuration with magnetic hill in the plasma edge. The increase in the fluctuation level is due to fluctuations in the frequency range (1-30 kHz). Interestingly, the breaking point in the frequency spectra (i.e. 1/f region) is directly related with the level of fluctuations. These experimental results show the important role of magnetic well in stabilising pressure gradient instabilities in the TJ-II stellarator and open the possibility of investigating the properties of turbulent transport in the proximity of instability thresholds[14].

5. PROFILE STRUCTURES IN TJ-II

Fine structures are found in the TJ-II electron temperature and density profiles[15] (see Fig. 7), when they are measured using a high spatial resolution Thomson scattering system. These structures consist in peaks and valleys superimposed to a smooth average.

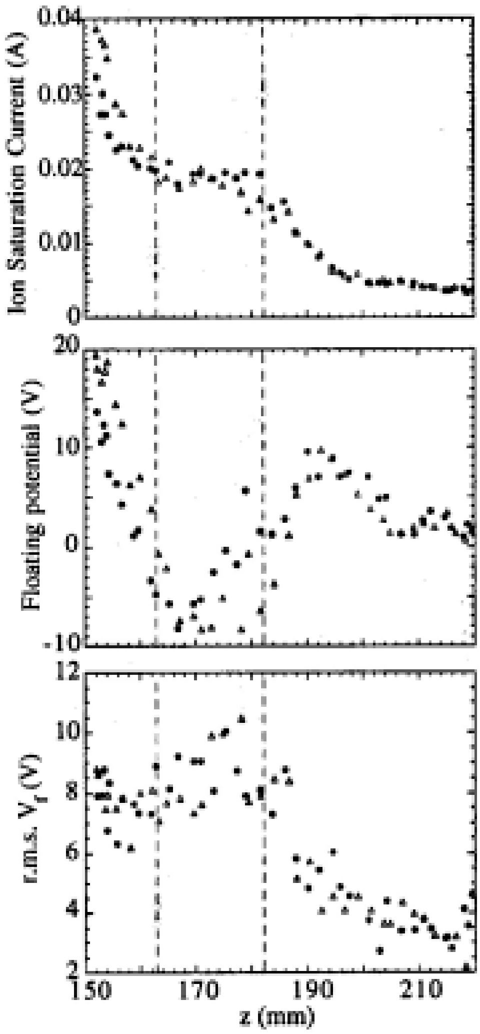


Fig. 6. Effects of the 4/2 rational surface in the plasma edge region. Top to bottom: Radial profiles of the ion saturation current, the floating potential and the r.m.s. of the floating potential

Some irregularities remain in an ensemble average of 15 reproducible discharges with similar macroscopic parameters like line density, central temperature, and plasma current. They are found in all the magnetic configurations explored in plasmas heated by electron cyclotron waves. Their possible origin is under study, but three lines of though are considered. Firstly, the effects related to magnetic topology of the device, namely iota profile and resonant surfaces. The fact that some features in the profiles survive to an ensemble average of the series of reproducible discharges would reinforce this theory. However, in order to extract clear conclusions about whether or not the rational surfaces, even the high order ones, have any influence on the profiles, a detailed knowledge of the plasma current profile is needed. Secondly, the structures can be another manifestation of the wide band plasma turbulence detected by other diagnostics, like Mirnov coils and ECE system. Finally, kinetic effects induced by high power density microwaves seem to be able to enhance the structure amplitude.

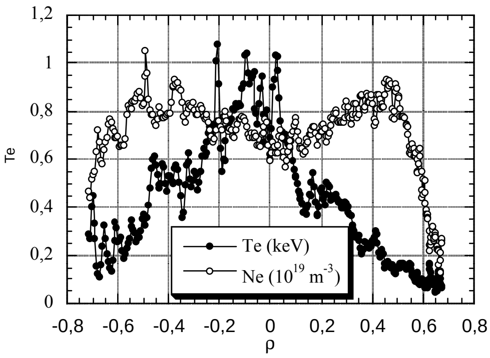


Fig. 7. Electron temperature and density profiles in TJ-II

Measurement of the wave number spectra in fusion devices is difficult due to the fact that spatially resolved information is required. A comparative study of the wave number spectra obtained using both a high-resolution Thomson scattering system (core plasma region) and Langmuir probes (edge region) is under way. The (radial) wave number spectra show a remarkable similarity in shape, which does not appear to depend significantly on either measuring technique, plasma region or plasma conditions. Specifically, the wave number spectra obtained from Thomson scattering are similar to wave number spectra obtained in various devices using different techniques, indicating that the detailed structure observed in the density and temperature[16]

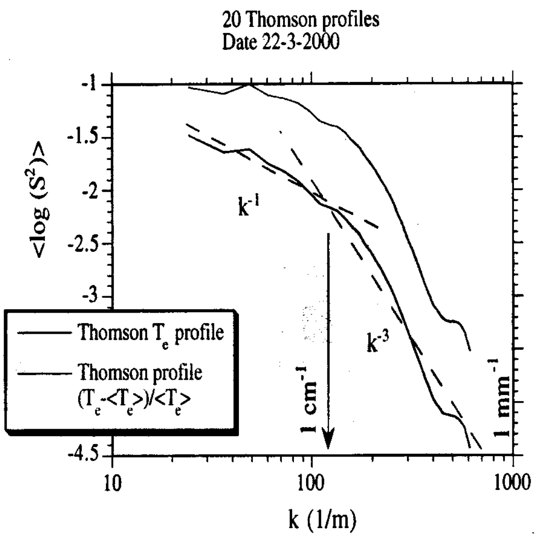


Fig. 8. Wave number spectra of Temperature profile structures for 20 accumulated shots

References

[1]C. Alejaldre et al., Plasma Phys. Control. Fusion **41** (1999) B109

[2] E. Ascasíbar et al., J. Plasma Fusion Res. SERIES 1, (1998) 183-186

[3] A. Cappa et al., “Plasma breakdown by ECRH at 2nd harmonic in TJ-II”, submitted to Nuclear Fusion.

[4]F.L. Tabarés et al., J. Nucl. Mater. 266-269 (1999) 1273-1278

[5] D. Tafalla et al., Wall conditioning and density control in TJ-II stellarator, Proc. 14th Int. Conf. on Plasma Surface Interactions, Rosenheim, Germany 2000. To appear in J. Nucl. Mater.

[6] K. J. McCarthy et al., Impurity behaviour studies in the TJ-II Stellarator, Proc. 27th EPS Conf. on Controlled Fusion and Plasma Physics, Budapest 2000. To appear.

[7] E. Ascasíbar et al., Magnetic configuration dependence of the plasma energy content in TJ-II stellarator, Proc. 27th EPS Conf. on Controlled Fusion and Plasma Physics, Budapest 2000. To appear.

[8] F. Castejón, et al., Transport evaluation of TJ-II plasmas, Proc. 12th IAEA International Stellarator Workshop, Madison Wisconsin USA (1999) (in CD-ROM)

[9] F. Castejón et al., Internal heat transport barriers in TJ-II flexible heliac, submitted to Nuclear Fusion.

[10] I. García-Cortés et al., ELM-like transport events in TJ-II stellarator, to be published in Nuclear Fusion.

[11] F.L. Tabarés et al., Edge transport characterisation of hydrogen and helium plasmas in the TJ-II stellarator, Proc. 27th EPS Conf. on Controlled Fusion and Plasma Physics, Budapest 2000. To appear.

[12] V. Tribaldos, Monte Carlo computations of neoclassical transport in TJ-II stellarator, Submitted to Physics of Plasmas..

[13] C. Hidalgo et al., Generation of sheared poloidal flows via Reynold stress and transport barrier physics, Plasma Phys. Control. Fusion 42 (2000) A153. M.A. Pedrosa et al., Edge fluctuations and transport in the TJ-II stellarator, Proc. 27th EPS Conf. on Controlled Fusion and Plasma Physics, Budapest 2000. To appear.

[14] C. Hidalgo et al., Properties of turbulent transport in the proximity of instability thresholds, Submitted for publication to EU-US TTF 2000

[15] J. Herranz et al., Profile structures of TJ-II Stellarator plasmas, accepted for publication in Physical Review Letters.

[16] B. Van Milligen et al., Measurement of the k-spectrum of turbulence in fusion devices, Submitted for publication to EU-US TTF 2000.