

PARAMETRIC SCALING STUDIES OF THE ENERGY CONFINEMENT TIME
FOR ECR HEATED TJ-II PLASMAS

Ascasíbar, E.⁽¹⁾, Stroth, U.⁽²⁾, López-Fraguas, A.¹, Estrada, T.¹, F. Castejón¹, F. L. Tabarés¹, I. García-Cortés¹, J. Romero¹, R. Balbín¹, B. Brañas¹, A. Cappa¹, A. Fernández-Curto¹, J. Guasp¹, J. Herranz, C. Hidalgo, J. A. Jiménez¹, K. Likin¹, E. de la Luna¹, B. van Milligen¹, M. Ochando, I. Pastor¹, A. B. Portas¹, J. Qin³, E. Sánchez¹, J. Sánchez¹, D. Tafalla¹, V. Tribaldos¹, J. Vega¹, B. Zurro¹ and TJ-II Team

1 Laboratorio Nacional de Fusión por Confinamiento Magnético, Asociación Euratom-Ciemat, 28040 Madrid, Spain

2 IEAP, University of Kiel, 24098 Kiel Germany

3. 304-2730 Acadia Rd., Vancouver, BC V6T 1R9 Canada

1. Introduction

TJ-II is a medium size stellarator ($R=1.5$ m, $\langle a \rangle \leq 0.22$ m, $B(0) \approx 1$ T) working in Madrid since 1998. After more than four years in operation with metallic wall (stainless steel AISI 316L) the TJ-II stellarator dataset is compared with those of other stellarators included in the International Stellarator Scaling (ISS95) database [1]. The objective of this comparison is twofold: it can indicate how close to the expected optimum confinement have we pushed the TJ-II performance, and give some hints on the physics governing it. On the other hand, TJ-II data might help in extending the ISS95 database operational space. Specifically, the TJ-II broad rotational transform range (1 to 2.2) should serve to provide new data in the high iota region.

2. Experimental data and computed plasma parameters

All the discharges used in this work correspond to ECR (Electron Cyclotron Resonance) heated plasmas using 2nd harmonic (53 GHz) and X-mode polarisation.

The energy data used in this study are thermal and diamagnetic. The thermal plasma energy content has been computed from the electron and ion contributions. The electron density (n_e) and temperature (T_e) profiles are provided by the Thomson Scattering diagnostic (T.S.) [2]. An accurate calibration of the n_e value is obtained from the line integrated electron density measured by the microwave interferometer. In the plasma edge region, where the T.S. diagnostic can hardly measure, both n_e and T_e are fitted numerically up to the normalised effective plasma radius, $\rho=1$, assuming a parabolic dependence. The ion contribution to the plasma energy is calculated by assuming that the shape of the ion temperature profile (T_i) is the same as the n_e one. Central T_i has been measured using the charge-exchange spectrometer for a number of plasma hydrogen plasma discharges. The obtained value is usually in the 90 to 110 eV range, so a value of 100 eV is assumed for the hydrogen and helium plasma shots. Ion density (n_i) estimations are obtained by assuming values of effective charge (Z_{eff}) 2 and 3 for hydrogen and helium plasmas, respectively. The data on diamagnetic energy are extracted from the temporal traces measured by the diamagnetic loops installed inside the TJ-II vacuum vessel [3]. In most of the studied shots, whenever is possible, the energy value is taken in the plasma stationary phase at the end of the discharge to minimise the error introduced by the vacuum magnetic flux compensation. Since the diamagnetic energy measurement is contaminated by a spurious pick-up of poloidal magnetic field component due to the plasma current the present study is based on the thermal data. Still it must be noted that the exponents of the different parameters in the obtained scaling law deduced from both thermal and diamagnetic energy datasets are remarkably consistent

3. Parameter space of the TJ-II dataset

A data set with 369 shots (both hydrogen and helium) has been selected from the 2000 experimental campaign for the statistical analysis presented here.

As configuration parameters in TJ-II we have minor plasma radius, a , and rotational transform. Major radius is fixed, with a value of $R = 1.5$ m. It must be noted that this value fills a gap in this parameter of the devices contained in the ISS95: CHS has $R = 0.94$ m and the rest have an R -value of about 2 m.

In all the selected discharges the plasma is limited by the groove that protrudes into the TJ-II vacuum vessel in order to allow room for the central coils that are located just outside the vessel [4]. It acts as a kind of toroidal (helical) limiter that penetrates towards the magnetic axis into the TJ-II plasma giving rise to the characteristic bean-shaped cross sections of the heliac plasmas. The connection length depends on the magnetic configuration but presents relatively short values, from 2 to 15 m [5]. The reason for excluding poloidally limited configurations in this first study is the large inaccuracy in assigning a value to the minor plasma radius in these shots due to the shape of the old TJ-II limiters [6]. However plasma boundary studies conducted with these old limiters revealed that a better confinement was achieved for poloidally limited plasmas [6]. The nominal plasma minor radius has been varied in the range 0.12 to 0.21 m just by selecting different magnetic configurations. In the low radius range plasma volume roughly scales with the sum of the currents through the central conductors.

There is a very robust experimental evidence of a quite flat electron temperature profile in the plasma edge, for values of the normalised effective radius, ρ , greater than 0.8. This feature has been measured not only by the T. S. diagnostic but also by the ECE (Electron Cyclotron Emission) radiometer [7], the Langmuir probes located at the poloidal limiter and the He beam diagnostic [7]. In addition, in the TJ-II case, the high value of magnetic ripple in the edge (higher than 35% for the larger configurations) would enhance the neoclassical diffusion in this zone [9]. With this knowledge in mind, choosing the value of the nominal plasma minor radius given by the equilibrium codes as the scaling parameter would result in an artificially low deduced global confinement. So, in order to compare with the rest of machines included in the ISS95, we have to define a "confinement minor radius". With this purpose, we have studied the dependence of the incremental thermal energy content as a function of the effective normalised radius for a set of configurations with central iota ranging from 1.37 to 1.77. The result show that more than 95% of the total plasma energy content is contained within $\rho = 0.8$, so that we will consider in this study that the TJ-II "confinement minor radius" is $a_{\text{eff,conf}} = 0.8 a_{\text{eff,nominal}}$, being $a_{\text{eff,nominal}}$ the value given by the equilibrium calculation

As mentioned before, TJ-II has a wide iota range, spanning more than a factor two. Iota also roughly scales with the central conductor's currents, but being the helical coil closer to the plasma, its effect is stronger. This fact is crucial in decoupling plasma radius and iota, that otherwise would be highly correlated. The value of the rotational transform at $\rho = 2/3$ (ranging from 1.25 to 2.17) has been used as the scaling parameter.

It must be noted that TJ-II is a low shear device. Therefore, the low order resonances included in the studied iota range (the main ones are $n/m = 4/3, 3/2, 5/3$ and $4/2$) introduce a variety of transient effects in the stability of the discharges, when crossing their influence area on the configuration space [10, 11]. These effects seem to be a consequence of the interaction between the ECRH heating and the magnetic configuration, and can affect strongly the global confinement, as measured by the plasma energy content. This is especially true in the $4/2$ case, because of the large size of the associated magnetic island, and in the $4/3$ case because this iota range can be only achieved for small size plasmas. From this point of view, we think that the TJ-II dataset available for this work is not comprehensive enough. It would need more discharges in the configuration region far beyond $\text{iota}=2$ in order get fully rid of the

associated perturbation and to strengthen the conclusions about iota-dependence. The problem is that this region is not an easy one to work in, due to the extremely high current density needed in the helical coil [12].

The plasma parameters that we can vary are absorbed power and plasma density. The magnetic field value is fixed at the electron cyclotron resonant value of 0.95 T in the magnetic axis. Although there are hydrogen and helium plasma discharges in the dataset, no dependence can be deduced on the mass of the species.

Two gyrotrons (300 kW nominal power each) were available for this experimental study. The two corresponding transmission lines have very different power density, 1 and 15 W cm⁻³ but this fact has not been considered in the present study [13]. Theoretical calculations taking into account the detailed real TJ-II geometry predict full single pass absorption for the high power density line [14]. The port-through power fraction of the total injected power has been measured in 300 kW nominal discharges. It has been found to be 85% of the nominal power and it has been assumed that this proportion remains constant across all the available power range: 150 to 600 kW. The radiated power has been measured for a small fraction of the discharges in the dataset with bolometry techniques [15]. The values obtained are in the range of 10 to 30% of the port-through power, but they can be underestimated due to the assumption of symmetry, as discussed later. ECH modulation experiments allow the estimation of absorbed power in some cases [16]. The results yield an upper bound estimate of 70% of the port-through power. So, we will assume this fraction as the total absorbed power, P, in all cases. This rough assumption is a weak point in this study.

The plasma line-averaged electron density, n, has been varied in the range 3.3 10¹⁸ to 1.3 10¹⁹ m⁻³. The upper limit is imposed by the ECH density cut-off.

4. Regression analysis

The correlation matrix between the logarithms of configuration and plasma show relatively low correlation values indicating no intrinsic statistic limitations of the dataset. The highest correlation (0.43) is found between power and density

In order to fit the data with a model we make the usual assumption of considering that the global energy confinement time ($\tau_E = W/P_{\text{abs}}$) has a factorial dependence on the four parameters described in the previous section: $\tau_E = 10^{\alpha_x} a^{\alpha_a} i^{\alpha_i} P^{\alpha_P} n^{\alpha_n}$

	α^x	α^a	α^i	α^P	α^n	α^R	α^B	RMSE
TJ-II	-1.63±0.08	1.93±0.10	0.51±0.10	-0.74±0.03	0.61±0.04	<u>0.65</u>	<u>0.83</u>	0.055
ATF	-1.58±0.02	<u>2.00</u>	0	-0.59±0.03	0.51±0.02	<u>1</u>	0.77±0.05	0.099
CHS	-1.71±0.03	<u>2.00</u>	0	-0.89±0.04	0.72±0.04	<u>1</u>	0.89±0.03	0.063
HeliotronE	-1.50±0.03	<u>2.00</u>	0	-0.62±0.04	0.56±0.04	<u>1</u>	0.59±0.08	0.093
W7-AS	-1.02±0.09	2.21±0.09	0.43±0.08	-0.54±0.02	0.50±0.02	<u>1</u>	0.73±0.05	0.087

Table 1: Regression results of TJ-II and the stellarators included in the ISS95 database

Table 1 shows the regression results for TJ-II data together with the ones from the machines included in ISS95. The power and magnetic field dependencies have been imposed as the ISS95 values [1]. The last column corresponds to the root mean square errors of the log₁₀ values. The parameter-dependence observed in TJ-II is consistent with the rest of machines. Figure 1 represents the actual values of log τ_E versus the prediction of ISS95_s scaling law.

5. Discussion

-The positive iota-dependence of the confinement extracted from TJ-II data is consistent with the ISS95 scaling, which is based, in this respect, mainly on W7-AS data. When TJ-II data are put together with the rest of machines the overall iota dependence factor is decreased to a value of 0.27.

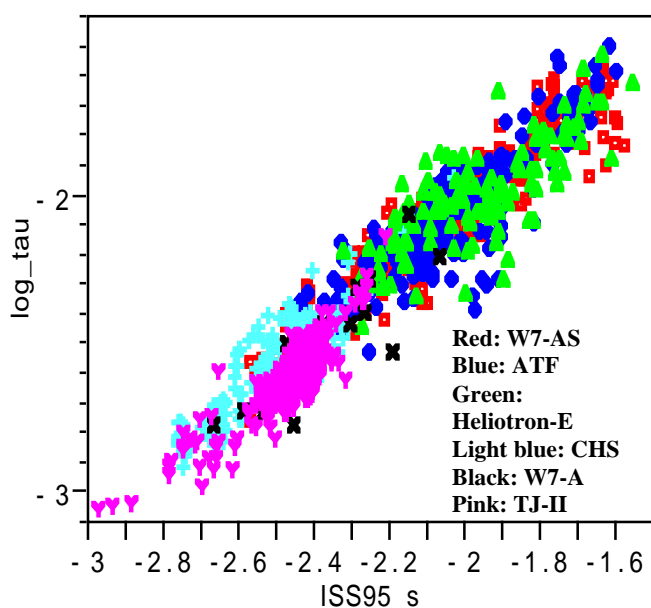


Fig. 1: Actual values of the $\log \tau_E$ vs ISS95_s prediction for TJ-II and the rest of devices

can account for only a relatively small fraction of the total injected power [9]. This might be a further indication of the existence of different, asymmetric contributions to the energy loss channel. The high magnetic ripple in the TJ-II edge would point to direct losses of ripple trapped particles. This argument also supports the uncertainty in the value chosen for the absorbed power

c) The data used in this study correspond to the TJ-II metallic wall phase with helical limiter. The edge temperature values are very low. Recently, the TJ-II vessel has been boronized and the subsequent plasmas show an increased edge temperature. The boronized plasmas database is still very limited, so they have not been included in this work. It can be expected that the boronization will have an impact on the value of TJ-II plasma confinement radius discussed in section 3.

References

- [1] Stroth U. et al., Nuclear Fusion 36 (1995) 1063
- [2] Herranz J. et al., Phys. Rev. Lett., 85 (22), (2000) 4715-4718
- [3] Ascasíbar E., 12th Stellarator Workshop, Madison, Wisconsin 1999 (in CD-ROM)
- [4] J. Botija et al., Proc. 18th Symp. on Fusion Tech., Karlsruhe 1994, in Fusion Technology 1 (1994) 771-774
- [5] Tabarés F., et al. Proc. 26th EPS Conf. on Controlled Fusion and Plasma Physics, Maastricht, The Netherlands 23J (1999) 369
- [6] de la Cal, E. et al., Proc. 14th Int. Conf. on Plasma Surface Interactions, Rosenheim, Germany 2000, J. Nucl. Mater. 290-293 (2001) 579-583
- [7] C. Alejaldre et al., Plasma Phys. Contr. Fusion 41 (1999) A539
- [8] F. L. Tabarés et al., Plasma Phys. Contr. Fusion 43 (2001) 1023
- [9] V. Tribaldos, Physics of Plasmas 8 (2001) 1229
- [10] T. Estrada et al, accepted for publication in Plasma Phys. Contr. Fusion (2002)
- [11] E. de la Luna et al, this workshop
- [12] J. Alonso et al., Proc. 17th SOFT., Rome 1992, Fusion Technology 1 (1992) 763-767
- [13] R. Martín et al., Proc. 20th SOFT, Marseille 1998, in Fusion Technology 1 (1998) 403-406
- [14] V. Tribaldos et al., Plasma Phys. Control. Fusion 40, (1998) 2113
- [15] M. Ochando et al, this workshop
- [16] S. Eguilior et al, 28th EPS Conference on Controlled Fusion and Plasma Physics, ECA 25A (2001) 1169-1172

-TJ-II global energy confinement data are well fitted by the ISS95 predictions. Some comments can be done in this respect:

a) There is experimental evidence of toroidal radiation asymmetries and ripple trapped suprathermal electron losses in some shots depending on the plasma conditions and on the magnetic configuration [15]. This fact would introduce large errors, when assuming toroidal symmetry in the calculation of the radiated power and would result in an overestimation of the absorbed power.

b) Experimental studies of the conductive energy flux lost through the TJ-II plasma periphery (assuming toroidal symmetry) indicate that they