Study of TJ-II density limit dependence on magnetic configuration

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Introduction.

In all stellarator and heliotron devices, a non MHD-driven plasma density limit appears that depends on the absorbed power density and the magnetic field [1]. The dominant mechanism that limits the maximum attainable density in steady state is the thermal collapse. As in the case of reverse field pinches (RFP) and opposite to tokamaks, no current disruption can occur when the thermal collapse develops and, moreover, the plasma can restart if the auxiliary heating is maintained. Depending on plasma composition, thermal instabilities may originate at some point of the plasma column and easily provoke radiative collapses. The use of wall conditioning techniques with low-Z (C, B or Li) materials or divertors [2, 3] to reduce the average impurity radiation strength, and the injection of pellets to centrally fuel the plasma, led to notable extensions of the density limit. These facts reinforce the common belief that the density limit is also an edge phenomenon, as in tokamaks and RFPs. In TJ-II, a medium-size flexible heliac with moderate heating power capability (< 2.6 MW), the main action to control and increase the electron density has been wall-coating with low-Z materials [4]. The change from boron to lithium walls yielded an increment of a factor of two in τ_E and 1.6 in maximum electron density [5] at low input power. During the last campaigns, further efforts to improve the plasma-wall interaction have been done to produce more stable plasmas at full power and to widen the operative magnetic configurations map. After the recent installation of one liquid lithium limiter (LLL), a marked reduction of carbon impurities has been achieved, especially in plasmas with strong interaction with the vessel walls.

In this report, an updating of TJ-II database is presented, bringing to the foreground the magnetic configurations that yield the larger increments over the Sudo limit [1].

Operation domain.

TJ-II is a four-period flexible Heliac with low magnetic shear and major and averaged minor radii of 1.5 m and ≤ 0.22 m, respectively [5], and operated at B=0.95 T. For this study, plasmas of different magnetic configurations were started with electron cyclotron resonance heating (ECRH) (P_{in} ≈ 600 kW, 2 gyrotrons, at 53.2 GHz, 2^{nd} harmonic, X-mode polarization) and maintained with two tangentially injected neutral beams (co and counter) delivering $P_{in} \leq 700$ kW port through each. The considered ranges in the parameters of interest are: input power density 0.33 - 1.55 MW/m^{-3}; average electron density 2 - 8 x10^{19} m^{-3}; minor radius 15.0 - 19.3 x10^{-2} m; iota$_{2/3}$ 1.33 - 1.63, and plasma volume 0.67-1.1 m^{-3}.

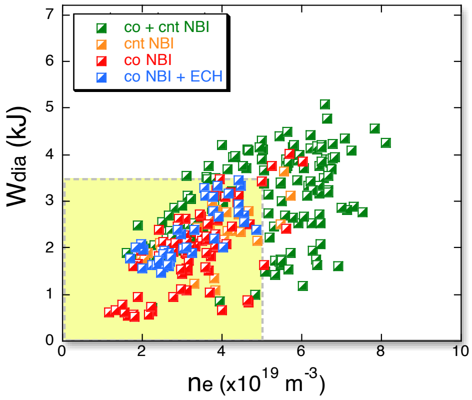


Figure 1. Diamagnetic energy versus line average electron density for the studied discharges. The yellow rectangle represents the last reported accessed operation region [5].

Since 2008, TJ-II wall is regularly coated with lithium. This practice has enabled for the extension in plasma parameters range and density control. Figure 1 shows the comparison between previous [yellow rectangle, see ref. 5] and present operation regions. Increments of about 1.5 in W_{dia} and 1.7 in n_e have been obtained. The different heating schemes for each shot are indicated in the legend.

Comparison of TJ-II data with scalings.

Data from TJ-II were considered in a comparative inter-machine analysis to build the unified scaling law for the energy confinement time in stellarators, the ISS04 [6]:

$$\tau_E^{ISS04} = 0.134 a^{2.28} R^{0.64} P^{-0.61} n_e^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

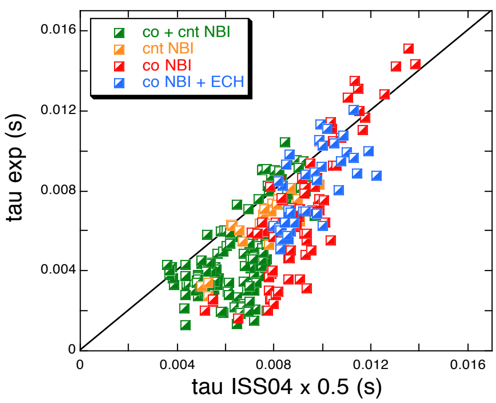


Figure 2. τ_E (exp) for NBI discharges vs. the inter-machine energy confinement time τ_E (ISS04) x 0.5.

In that analysis, data from ECRH-only heated discharges were included, but with a 'high ripple' renormalization factor of 0.25. For the present set of NBI-heated discharges, as can be seen in Figure 2, it is apparent that the renormalization factor must be relaxed in a factor of 2. Then, the evident uneven behaviour of TJ-II with respect to other medium size stellarators, ATF/CHS/H-E, [see Table 3 in ref. 6] seems to be corrected.

This is due to the fact that the negative effect of large ripple on transport is reduced for large collisionality. In fact, the comparison with the Sudo scaling, as is shown in Figures 3a and 3b, is rather good. However, it is observed that τ_E (exp) can surpass the limit for all heating schemes, whilst n_e (exp) seems to stay below the limit. Several plasma density

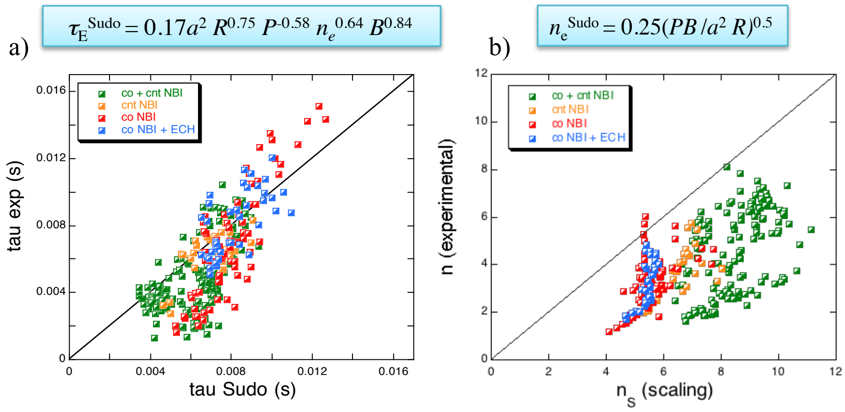
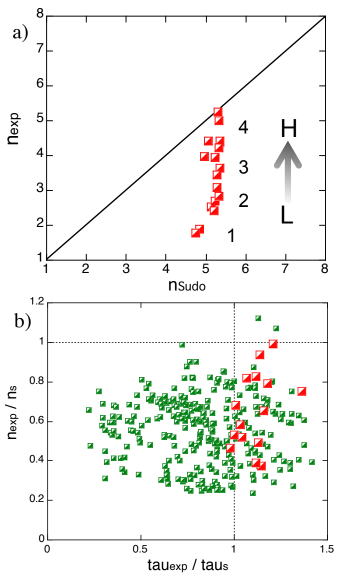


Figure 3. Comparison of TJ-II data with Sudo limits [1] scalings: a) τ_E (exp) vs. τ_E (Sudo) and b) n_e (exp) vs. n_e (Sudo). Note: n_e's are in 10^{19} m^{-3} units.

scans were performed under fresh Li-coated at constant magnetic configuration and input power to approach the maximum density in a controlled way. As an example, the behaviour of a series of 15 shots with increasing density, configuration ι(a)=1.65, and 390 kW co-injected NB power is represented in Figure 4. From densities labelled '3', plasmas with this magnetic configuration are prone to enter in H-mode, characterized by an increase of the confinement time, likely due to the reduction of the MHD activity. It is seen that the ratio $\tau_{exp}/\tau_{Sudo} \geq 1$, whereas n_{exp}/n_{Sudo} is kept ≤ 1.



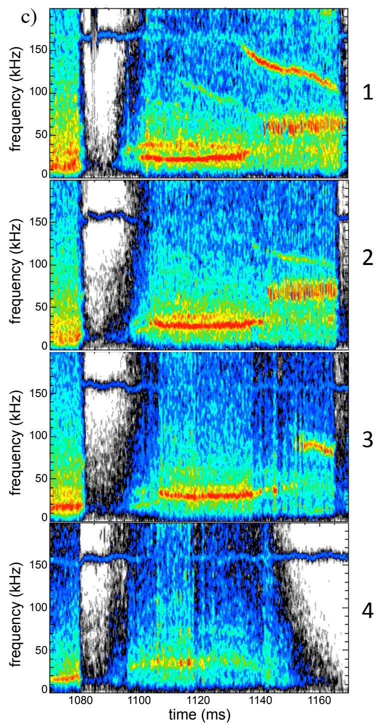


Figure 4. a) Experimental vs. scaling values for a series of increasing density. b) Shots parameter location in the Sudo scaling map. c) Mirnov spectra from four of the shots with increasing density (1-> 4).

Best performance: re-starting discharges.

In many of the explored magnetic configurations and especially under high (Pin ≥ 1MW) heating power, discharges that collapse at low densities can recover. Moreover, during the second heating phase, the energy content and the average density increase in a factor of 2 and 3, respectively, whilst radiation only increases in a factor of 0.5 (see Figure 5a). The emissivity profiles reveal the development of a radiative instability that begins at the edge and propagates toward the core. Then, plasma cools down to <Te> ≈ 40 eV, and the density profile becomes strongly peaked, conditions rather adequate to optimize heating beams absorption. During the reheated phase, the plasma core can reach densities of 1 x 10^{20} m^{-3}, the profiles shape are the typical of the H-mode, the estimated Z_{eff} can be as low as 1.2, and the MHD activity in the whole plasma column is reduced with respect to H-mode.

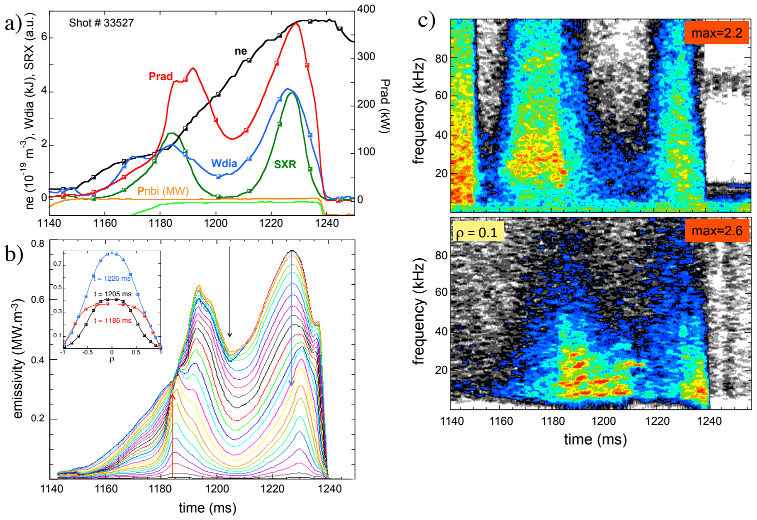


Figure 5. a) Time evolution of representative plasma parameters. b) Radial evolution of emissivity for discharges that collapse twice. Inset: Emissivity profiles at collapses and restarting times, marked with arrows. c) Mirnov and bolometer spectra from shot #33527.

Conclusions

Higher density plasmas are obtained with regular Li-coating of TJ-II walls, leading to a reduction of the plasma-wall interaction. For low NBI input power, co-injection yields better performance than counter-injection, mainly due to asymmetric fluxes.

ECH applied to co-injection NBI or gas base dilution with He does not help to increase plasma density. Although in this study the explored iota range is rather narrow, our results suggest that the scaling dependence on that parameter likely should be reconsidered.

MHD activity is strongly reduced approaching the maximum density, when the best confinement is obtained, probably due to the reduction of ion radial orbits for high collisionality.

For absorbed powers ≤ 1.55 MW.m^{-3}, in this ripple dominated device, the maximum attainable density, seems to be still limited by thermal collapse.

Acknowledgments

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