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# NEOCLASSICAL TRANSPORT AND IOTA SCALING IN THE TJ-II STELLARATOR

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## **Abstract**

Neoclassical transport properties are studied in TJ-II, taking effective ripple as the figure of merit. This quantity has been estimated using DKES code run by grid computing techniques, as a function of rotational transform and plasma volume. It was found that the effective helical ripple increases with plasma volume or rotational transform increase. This finding suggests degradation of confinement with iota or volume, which is in contradiction with the energy confinement scaling laws and with the TJ-II experimental results. Possible reasons for that are discussed.

## I.-INTRODUCTION

Due to the complex nature of phenomena that define the plasma confinement in magnetic fusion devices, including transport and plasma-wall interaction, energy confinement time,  $\tau_E$ , scaling laws are very useful tools to predict the properties of new devices and to check the validity of new theories. Experimental scalings show the parametric dependence of confinement on several plasma parameters, taking as basis the experimental results of a lot of plasma discharges of several machines of the same family but with different characteristics. Scaling laws are built based on the statistical properties of plasma confinement.

Scalings are used both in tokamaks and stellarators, but the strong differences between the two families of devices make that different scaling laws are built. In fact, it seems that turbulent transport dominates in the whole tokamak plasma (see e. g. Ref. 1), while neoclassical transport well explains the confinement of the stellarator core<sup>2</sup>. The toroidal symmetry and the existence of large plasma currents that contribute to create the magnetic field is the main difference between tokamaks and existing stellarators, which causes that the nature of transport be very different in both types of devices. Despite of this fact, both types of scalings show a positive dependence on the rotational transform,  $\iota/2\pi$ , the inverse of the safety factor,  $q$ . In tokamaks, Lackner-Gottardi scaling law<sup>3</sup> shows the following dependences for plasmas in the plateau regime with additional heating:

$$\tau_{Eplateau}^{LG} = C_p I_p^{4/5} (n_e / P)^{3/5} R^{9/5} a^{2/5} q^{2/5} \kappa / (1 + \kappa)^{4/5} \quad (1)$$

$q$  is taken at  $\rho=2/3$ , being  $\rho$  the normalised minor radius. Where the constant  $C_p \approx 1.2 \cdot 10^{-13}$ ,  $I_p$  is the plasma current in MA,  $n_e$  the line average electron density in  $m^{-3}$ ,  $P$  the total injected power in MW,  $R$  the major radius in m,  $a$  the minor radius in m, and  $\kappa$  is the elongation. This scaling is written involving the parameters that fully define the tokamak configuration. The expression (1) can be written in terms of the rotational transform at the same position as:

$$\tau_{E_{plateau}}^{LG} = C_p \left( \iota / 2\pi \right)^{2/5} \left( n_e / P \right)^{3/5} R a^2 B^{4/5} \kappa \quad (2)$$

A similar process produced the ISS95 scaling for stellarators, with a limited number of devices<sup>4</sup>:

$$\tau_E^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} n_e^{0.51} B^{0.83} \left( \iota_{2/3} / 2\pi \right)^{0.4} \quad (3)$$

This expression includes discharges from ATF, CHS, Heliotron-E torsatrons, from W7-A shearless classical stellarator, and from W7-AS shearless optimised stellarator. In equation (3) all the quantities are in the same units of equations (1) and (2) but the density, which is written in  $10^{19} m^{-3}$ . These latter units are also used in equations (4-8) of this paper. The first problem is that the stellarator configuration is much more complex than the tokamak one and cannot be defined by a few number of parameters. In fact, the authors of such scaling discussed the possibility of introducing a new parameter to distinguish the two latter stellarators

from the three former torsatrons. The rotational transform varies with radius so the convention of considering its value at normalised radius  $\rho = 2/3$  is taken.

The more recent ISS04 scaling includes more stellarators all over the world with more discharges<sup>5</sup>:

$$\tau_E^{ISS04} = 0.134 a^{2.28} R^{0.64} P^{-0.61} n_e^{0.54} B^{0.84} (l/2\pi)^{0.41} \quad (4)$$

This equations is written in the same units as equation (3) and a positive dependence with respect to the rotational transform, taken again at  $\rho = 2/3$ , is observed. In such a work it was pointed out the necessity of establishing groups of devices with different devices that can be grouped by a factor  $f_{ren}$ , which accounts for the different confinement quality. In reference 6, the scaling is estimated including such a factor, finding:

$$\tau_E^{ISS04} / f_{enh} = 0.148 a^{2.33} R^{0.64} P^{-0.61} n_e^{0.55} B^{0.85} (l/2\pi)^{0.41} \quad (5)$$

This parameter depends on the configuration and can be related to the effective ripple as  $f_{enh} \sim \epsilon_{eff}^{0.4}$ , showing that Neoclassical transport is an important ingredient in stellarator confinement.

Here, the factor  $f_{enh}$  represents the characteristics of the stellarator magnetic configuration that cannot be reflected by the scaling parameters. This factor is introduced in order to make possible to fit all the confinement times of the devices

to a single law. In any case, a positive dependence with the rotational transform is found again.

The rotational transform is a measurement of how twisted the magnetic field lines are. In fact, it is mandatory that the rotational transform is different from zero, in order that the confinement time reaches values of the order of ms or longer, since it is necessary to create magnetic surfaces and to avoid the ExB drift that would launch all the particles against the walls. Taking this fact into account, it is not striking that this positive dependence is found both in tokamaks and stellarators. We discuss here the relation between the rotational transform scaling and the neoclassical properties of TJ-II stellarator. The reminder of this paper is organised as follows. Section II is devoted to explain the properties of TJ-II confinement and its relation with the stellarator scaling laws. Section III discusses the neoclassical confinement properties of TJ-II, including their dependence on the rotational transform and volume and how this is related to the experimental confinement. The conclusions and discussion come in Section IV. We think that it is valuable to include an Appendix where the computational techniques used for this work are described, since they are not customary in the fusion community and involve some novelty themselves.

## **II.-TJ-II CONFINEMENT.**

TJ-II is a four period flexible heliac<sup>7</sup>, in operation since 1997. Its coil structure is composed of 32 toroidal field coils, four vertical field coils and a central conductor made of two coils: a circular one and a helical one, which describes a four period

helix around the circular coil (see figure 1). TJ-II flexibility comes from the fact that the properties of its magnetic configuration can be modified changing the currents that circulate in the coils. In particular, it is possible to substantially modify the plasma shape and volume, and the rotational transform of the configuration, allowing one to explore the influence of these quantities in the confinement.

After several years of experiments a large database of discharges under different magnetic configurations is available and has made possible to extract the confinement properties of TJ-II. The scaling for the energy confinement time of TJ-II in metallic wall is given by<sup>8</sup>:

$$\tau_E = 0.0131a^{1.9}P^{-0.79}n_e^{0.68}(\iota_{2/3}/2\pi)^{0.6} \quad (6)$$

while it is the following one for boronised wall:

$$\tau_E = 0.0295a^{1.99}P^{-0.62}n_e^{1.01}(\iota_{2/3}/2\pi)^{0.35} \quad (7)$$

The dependence on the major radius and the magnetic field has been suppressed in these expressions, since they cannot be varied in TJ-II. After a long period in which the TJ-II walls were covered with Boron, Li-coating techniques<sup>9</sup> were used to reduce the recycling, hence improving the density control and achieving larger values of the density in the device thus widening the operational regime, although the dependence with rotational transform is under study yet. In fact, H mode confinement regime was achieved in TJ-II under these conditions<sup>10</sup>.

These scaling laws show a positive dependence with the rotational transform as does the ISS04 scaling law. The dependence of confinement on the rotational transform extracted from equations (5) and (6) has two valuable properties. The first one is that TJ-II is an almost shearless device, hence the value of the rotational transform is almost the same in all the plasma and a single value can be assigned approximately to the global confinement. The second one is that the range of variation of this value in TJ-II flexibility diagram is the widest in the world, since it can vary from 0.9 to 2.5, so the dependence of energy confinement time on rotational transform can be explored experimentally in this device.

The approximately quadratic dependence of the confinement time with the minor radius in all the scalings seems easy to understand. The larger the volume the better the confinement, since the heat and the particles take longer to escape from the plasma. The volume is proportional to  $a^2$ , so this quadratic exponent shows just a linear dependence with the volume. Nevertheless, it is seen that the dependence with the volume is weaker than linear in TJ-II, which can be attributed to the properties of such a device. On the one hand, the confinement is improved for larger volume due to the effect of plasma size, on the other hand, the larger the volume, the larger the magnetic ripple, so the neoclassical transport of the outermost magnetic surfaces is worse, which mitigates the beneficial influence of the volume.

Scalings are basic to design new devices and to check the validity of new theories. It is necessary to work on the understanding of the dependence on the different parameters, including the rotational transform.

### III.-SCALINGS AND NEOCLASSICAL CALCULATIONS

The parameters that appear in the ISS04 scaling law can influence the confinement properties in different ways, depending on the combination of parameters that are chosen, which is an effect of the fact that they are related among them. In fact, the ISS95 scaling law presented similar dependencies, as can be seen in equation (3), despite of the fact that it is based on the results of fewer devices than the ISS04 scaling law, which includes TJ-II, for instance. The dependence with  $R$  and  $a$  changes in this scaling law if one suppresses the rotational transform dependence, i. e., when less parameters of the configuration are included in the scaling:

$$\tau_E^{ISS95} = 0.0132 a^{1.51} R^{1.04} P^{-0.62} n_e^{0.53} B^{0.81} \quad (8)$$

The regression analysis has RMSE (Root Mean Square Error) equal to 0.0902 when  $\iota$  is considered in comparison with 0.0909, when it is not. This increase, although small, is statistically significant. The change is due to the fact that the ISS95 scaling law was built with the results of an optimised advanced stellarator (W7-AS) and three torsatrons (ATF, H-E, CHS), and in these latter devices  $\iota$  is related to the ratio  $R/a$ , the aspect ratio.

No explanation has been given up to now for the positive scaling of the confinement time with the rotational transform. Hinton and Hazeltine<sup>11</sup>, and more recently Belli and Candy<sup>12</sup>, obtained the neoclassical transport coefficients semi-analytically for a large aspect ratio tokamak, showing an explicit dependence on the rotational transform, which drives one to believe that this parameter has influence on the neoclassical properties of the device. For a given effective collisionality, the neoclassical transport coefficients vary with iota as  $D_{NC} \propto q^2 = (\iota/2\pi)^{-2}$ , in the banana regime, showing the same tendency as the scaling laws that predict an improvement of the confinement with the inverse of  $q$ . In the plateau regime,  $D_{NC} \propto \iota^{-1}$ , yielding the result  $\tau_E \propto \iota^{0.4}$ . So the variation with iota of the neoclassical confinement in a tokamak is in agreement with the one of scaling laws. In a tokamak, neoclassical transport and turbulent one diminish with the rotational transform.

The main configuration ingredient that originates neoclassical transport is the magnetic ripple. In an axisymmetric tokamak, the magnetic ripple along a field line appears because of the variation of the magnetic field as the poloidal angle is evolved, therefore it is related to the rotational transform. In a stellarator no such a clear dependence can be extracted, since there is more freedom to design the magnetic configuration. In order to check the possible relation between the iota scaling and the neoclassical transport in stellarators, extensive neoclassical transport calculations have been performed in TJ-II by the use of the DKES code<sup>13</sup>. These calculations have been performed using advanced grid computing techniques that are described in the Appendix.

The neoclassical transport properties of a configuration are summarised in a single parameter, the effective ripple,  $\varepsilon_{eff}$ , given by<sup>14</sup>:

$$\varepsilon_{eff} = \lim_{\nu^* \rightarrow 0} \left[ 2 \left( \left( \frac{3\pi}{4} \right)^{1/2} \nu^* D_{11}^* \right)^{2/3} \right] \quad (9)$$

Where  $\nu^*$  is the effective collisionality ( $\nu^* = \nu q R / v$ ) and  $D_{11}^*$  is the first mono-energetic coefficient of neoclassical transport matrix. The effective ripple gives a clear idea of the quality of the magnetic configuration for the neoclassical confinement, without the necessity of exploring different collisional regimes. The effective ripple can be estimated in a quicker way using a formula introduced in Ref. 15 in the  $1/\nu$  regime. Nevertheless, we have used the method of equation (9) because we have already ported the DKES code to the grid and can take advantage of such a computing platform.

Given the flexibility of TJ-II, independent scans of rotational transform and volume can be performed. The magnetic ripple rises with the volume since the plasma is closer to the coils in the larger configurations, being more sensitive to the variation of the magnetic field. So it is possible to explore the effect of both quantities on the effective ripple.

We have taken 5 different volumes, with similar values of the rotational transform, and 6 different values of the rotational transform for approximately constant volume. In this way, we have considered 30 configurations that scan volume and rotational transform. Figure 2 shows these 30 configurations located in the so called flexibility diagram, showing the different rotational transform and the volume values. Figure 3 shows the magnetic surfaces at toroidal angle  $\phi=0$  for 4 extreme configurations plus the central one: minimum iota and minimum volume, minimum iota and maximum volume, maximum iota and minimum volume, maximum iota and maximum volume and intermediate values of iota and volume. It can be seen that the distance of the plasma to the toroidal coil is smaller for the larger volume, therefore those configurations present larger magnetic field ripple. So one can expect that these configurations present worse neoclassical transport properties.

The large iota configurations present indented magnetic surfaces, which makes the plasma-wall interaction (PWI) to be weaker in these cases, since the zone of the groove of the TJ-II vacuum vessel presents the strongest PWI in the device [16], so elongated configurations will have less influence of PWI. This dependence of plasma-wall interaction and the rotational transform can explain the different scaling laws with the rotational transform found in TJ-II for the different first wall material, being stronger in the cases of metallic wall where the plasma-wall interaction has stronger influence on confinement.

The effective ripple given by equation (9) is calculated for every radial position of these configurations. In fact we take 23 radial points for every configuration,

therefore with slightly different values of  $\iota$ . The effective ripple is shown in Figure 4 for all the configurations and radii, as a function of volume and  $\iota$ . As the rotational transform is not constant along the minor radius, a curve of  $\varepsilon_{eff}$  is shown as a function of  $\iota$  for a given magnetic configuration. We see that  $\iota$  is negative in TJ-II, because of choice of the magnetic coordinate system, but the absolute value of  $\iota$  must be taken in the above shown scaling laws.

In order to explore the variation of  $\varepsilon_{eff}$  at different radial positions and, hence, how the neoclassical transport depends on those two parameters in the long mean free path, we plot the effective ripple at three positions:  $\rho=0, 0.65, 1$ . Figures 5a and 5b show the variation of  $\varepsilon_{eff}$  as a function of the rotational transform and the volume at the position  $\rho=0$ , showing that the effective ripple increases slightly with the volume at this radial position, which is not surprising, given the characteristics of the TJ-II stellarator and the larger excursion of the magnetic axis for larger magnetic configurations. The dependence with the rotational transform is not monotonic and depends on the configuration that is considered, although an increasing trend with increasing absolute value of  $\iota$  can be seen.

Figures 6a and 6b show the same as figures 5a and 5b for  $\rho=0.65 \approx 2/3$ , located in the pressure gradient zone of the plasma, hence having more influence on transport. Again, an increase of the effective ripple with the volume is shown, as can be understood following the discussion above about Figure 3, and a less pronounced non-monotonic behaviour with  $\iota$  appears. In fact, the effective ripple almost rises with the rotational transform, which should provide a

dependence with rotational transform opposite to the one observed in the scaling laws and in the semianalytical calculations for tokamaks.

Finally,  $\epsilon_{eff}$  is plotted as a function of iota and the volume in Figures 7a and 7b for  $\rho=1$ , with the same tendency with volume and a non-monotonic variation with iota for the larger volumes and an increasing ripple for small volumes, showing again a behaviour opposite to what it is expected from the scaling laws and the semianalytical estimates for tokamaks.

As it has been pointed above, the parameter that appears in the ISS04 scaling,  $f_{enh}$ , can be related with the effective ripple as  $f_{enh} \sim \epsilon_{eff}^{0.4}$ , showing that effective ripple is an important ingredient in stellarator confinement.

Elongation is observed to play an important role in tokamak confinement in the plateau regime, as it is shown in equations (1) and (2). In Reference 5, it is pointed that it plays also a role in LHD plasmas, where confinement is improved for larger values of elongation. We have estimated the average elongation of TJ-II for the configurations considered here. The elongation is defined in a tokamak as:  $\kappa = (Z_{max} - Z_{min}) / (R_{max} - R_{min})$ . As the magnetic surfaces of TJ-II are concave, and their shape change with the toroidal angle, we define the elongation as:  $\kappa = \langle Z_{max} - Z_{min} \rangle / \langle R(\theta = 4\varphi) - R(\theta = 4\varphi + \pi) \rangle$ . Here, the average is taken in the toroidal angle  $\varphi$ , and the radial width is taken at the line created by the magnetic axis and the centre of the central conductor. Figure 8a shows that the elongation decreases slightly with the volume, and figure 8b shows that this quantity

increases with rotational transform, which implies an improvement of confinement with this quantity, as it increases monotonically with rotational transform in TJ-II in this set of configurations.

LHD team has shown that, in this device, the neoclassical confinement properties can be improved by changing the position of magnetic axis and, hence, the value of major radius: DKES calculations show that the lower the radius the better the neoclassical confinement properties<sup>17</sup>. Moreover, gyrokinetic calculations show that improving the neoclassical confinement goes in the same direction as doing it with the turbulent transport<sup>18</sup>. According to this result, optimizing a device from the neoclassical point of view would be also beneficial for reducing turbulent transport. Experiments in HSX show that the quasisymmetric configuration presents lower viscosity than the mirror one<sup>19</sup>, together with better confinement properties. So the neoclassical viscosity plays also a role on confinement. In fact, recent results in TJ-II show that it is possible to reduce the neoclassical viscosity in the point where the electric field passes from electron to ion root, which decreases strongly the flow damping<sup>20</sup>. Nevertheless, scaling law of Eq. 9 has shown that iota value is linked to the aspect ratio in torsatrons, which is also related to magnetic ripple. So the link between neoclassical and turbulent optimization cannot be extended to all the stellarator configurations.

The dependence of the confinement with the rotational transform cannot be explained in terms of the neoclassical properties of the device, as calculations for TJ-II show. On the opposite, a global increase of the effective ripple with iota could

be extracted for small volumes in TJ-II discharges that goes against the scaling laws that have been obtained up to know.

All these facts mean that the neoclassical optimization helps to the reduction of turbulent transport, but it is not the only ingredient to be considered in the turbulent optimization of the stellarators. The positive rotational transform dependence of confinement must be attributed to a turbulent mechanism and open new doors to stellarator optimization.

#### **IV.-CONCLUSIONS AND DISCUSSION**

We have shown that the neoclassical confinement of a device are not necessarily improved for higher values of the rotational transform. In fact, TJ-II characteristics show that the neoclassical transport properties in the  $1/\nu$  regime, given by the effective ripple, are improved with the volume and not with the rotational transform. This latter parameter is coupled to the poloidal ripple in an axisymmetric tokamak, hence showing influence on the neoclassical transport, while it is decoupled in a stellarator, since the magnetic configuration is created by external coils and not by the plasma current. Nevertheless, torsatrons present also some relation between the aspect ratio and the rotational transform, which implies some relation between neoclassical optimization and increasing  $\iota$ .

Therefore, the explanation for the improvement of confinement with the rotational transform cannot be given by neoclassical transport in the  $1/\nu$  regime. It is necessary to explore the turbulence properties of the configuration in relation with

such a parameter. This assessment implies that the reduction of turbulent transport in a stellarator cannot be performed only by optimising the neoclassical transport, since there are other phenomena that must be considered.

Electrostatic turbulence could play a role as well as MHD. For instance, Global Acoustic Modes, which are able to regulate turbulence<sup>21</sup>, in a similar way in which Zonal Flows do, are shown to suffer more damping for large values of  $q$ , or, equivalently, for small values of the rotational transform. In a tokamak, the growth rate is given by  $\gamma_{GAM} \propto [-\exp(-cq^2)]$  (See referene 22). We do not expect that this simple formula is working for stellarators, but it has been shown that the damping of the GAMs behaves in TJ-II in the same way of tokamaks: it rises with  $q$ , as can be seen in Reference 23. More experimental and theoretical work is needed to clarify the reasons for the positive influence of  $i$  on the confinement.

## **APPENDIX**

Grid computing emerged as a powerful infrastructure for executing distributed applications. Mainly developed to give computing support to the four Large Hadron Collider (LHC) experiments, it was adopted by other scientific disciplines such as Biomedicine, Bioinformatics, Earth Sciences or Fusion. In the latter case, grid computing techniques were incorporated to fusion research for calculations that can be performed in a distributed way<sup>24</sup>. Examples of the successful use of Grid Computing for fusion are the porting codes devoted to the simulation of different phenomena such as Neutral Beam Injection<sup>25</sup>, ion orbits inside the plasma<sup>26</sup>, optimization of stellarators<sup>27</sup>, or core turbulence simulations<sup>28</sup>. Grid is

also used coupled to a parallel supercomputer, creating a heterogeneous workflow to estimate electron Bernstein wave heating in TJ-II (see reference 29). Grid computing has been also used to calculate large datasets that can be introduced in a database, as the case of the estimation of the monoenergetic neoclassical coefficients using the grid version of DKES, which is used for the present work<sup>30</sup>.

Nevertheless, grid infrastructures have some caveats, as the missing of jobs, that affect the computational efficiency, so several methodologies have been developed in the latest years to improve it. Among them, we have developed a method based on the use of pilot jobs, i.e. a master-slave approach within a grid environment that reduces the waiting time in remote queues by means of remote a slot appropriation. Thus, when a pilot job starts running on a node, it allows the workload management system to directly use and monitor that node.

Moreover, the interest in monitoring the pilots is not only related to effectively characterise the assigned resources (the Working Nodes) by simply notifying the existent configuration and properties to the master. Monitoring is indispensable to check and prepare the environment (downloading and installing software) needed by many scientific applications. Therefore, this mechanism enables compatibility with legacy systems.

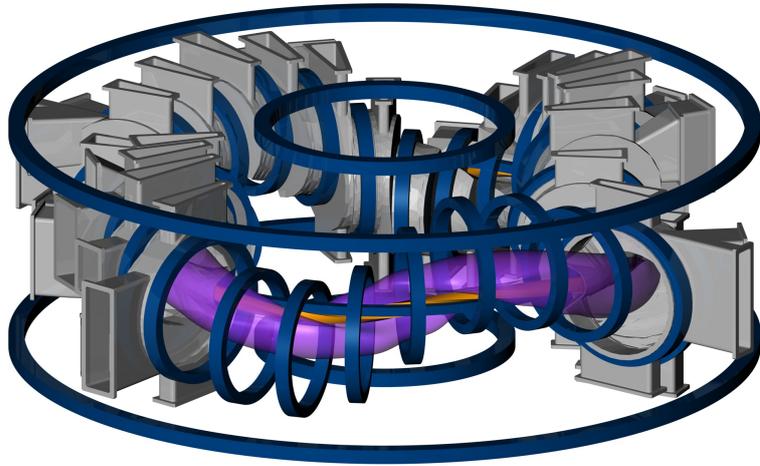
Fusion community has successfully tested several pilot systems to improve its scientific throughput. In this sense, ISDEP has been adapted to Ganga and DIANE<sup>31</sup>, and tested on DIRAC test-bed, but this approach has not actually come into production because of adaptability and maintenance issues. Additionally, specific

implementations similar to pilot-jobs have been done to adapt the DAB stellarator optimization code<sup>32</sup>.

Recently, a new pilot-job approach<sup>33</sup> has been implemented to complement the meta-scheduler GridWay ecosystem<sup>34</sup>. GWpilot provides an automatic and unattended use of pilot jobs by both users and developers. It maintains all the GridWay features but adding new ones that can be useful for any multidisciplinary community. Therefore, this framework can directly support the execution of the aforementioned fusion applications, and it also enables the straightforward adaptation of any legacy one coming from other scientific areas. GWpilot has been used to run DKESG, which has been used to obtain the effective ripple given by Eq. (9) of this work.

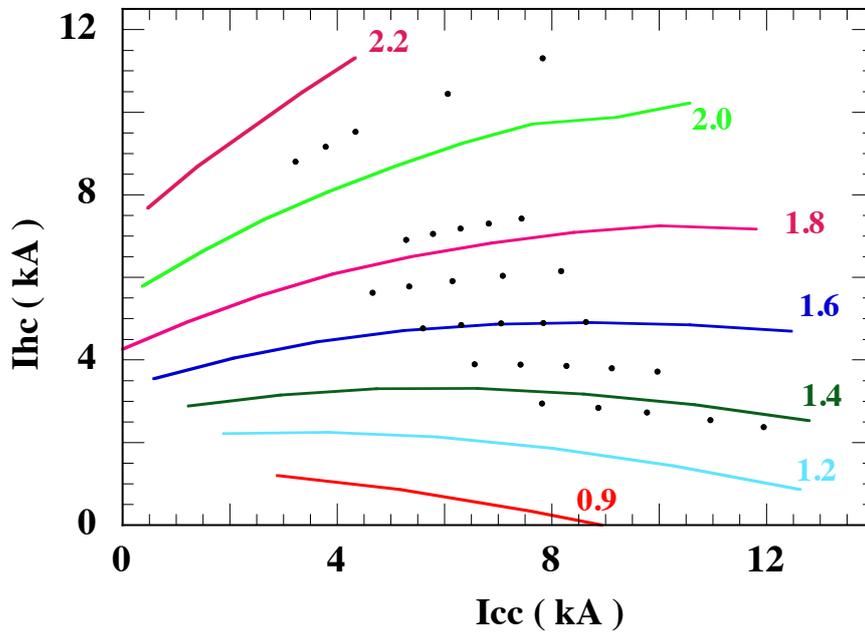
### **Acknowledgements**

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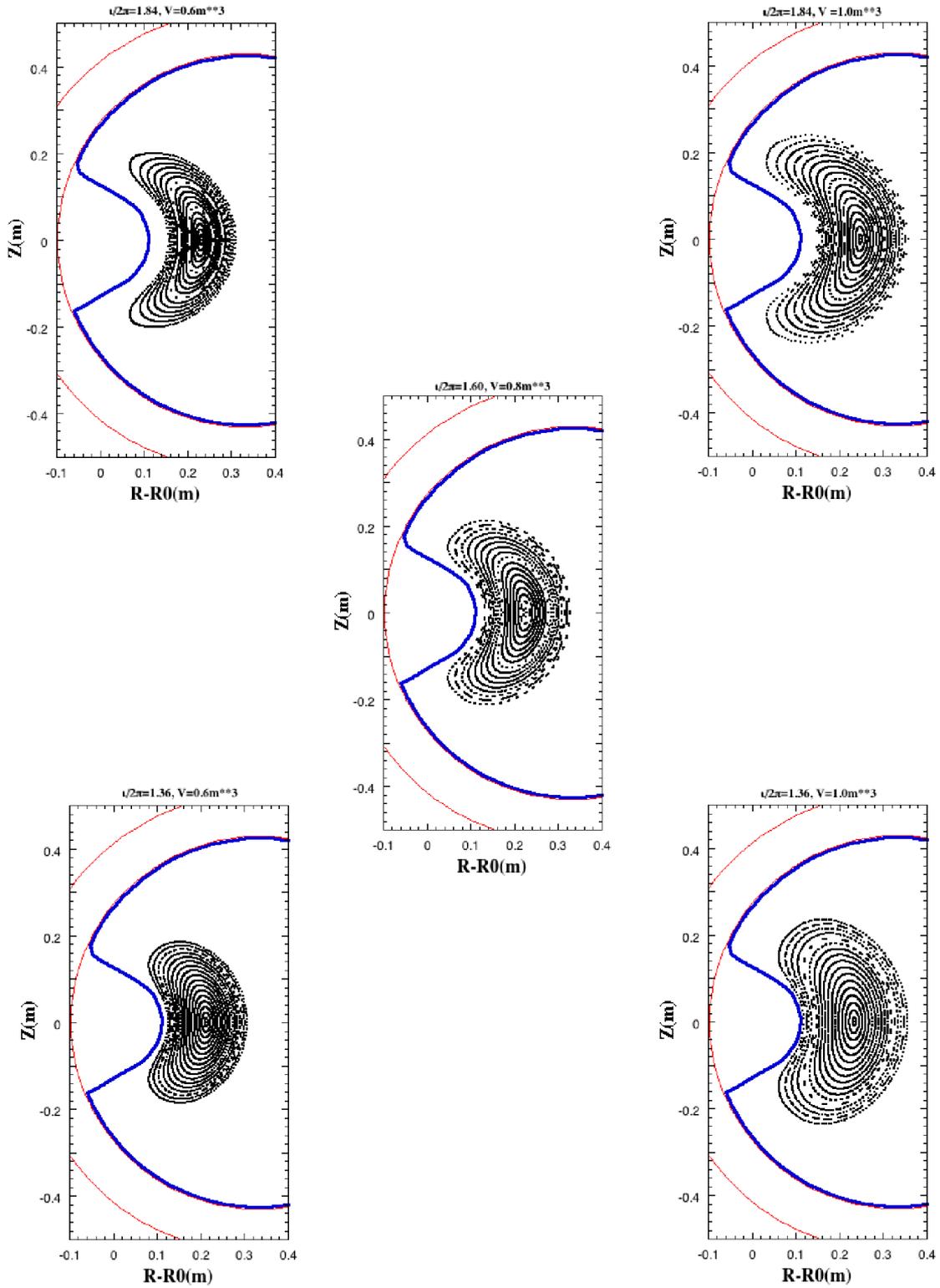


**Figure 1:** Coil structure (blue and orange), plasma (violet) and vacuum chamber of TJ-II flexible heliac.

## Central Iota values

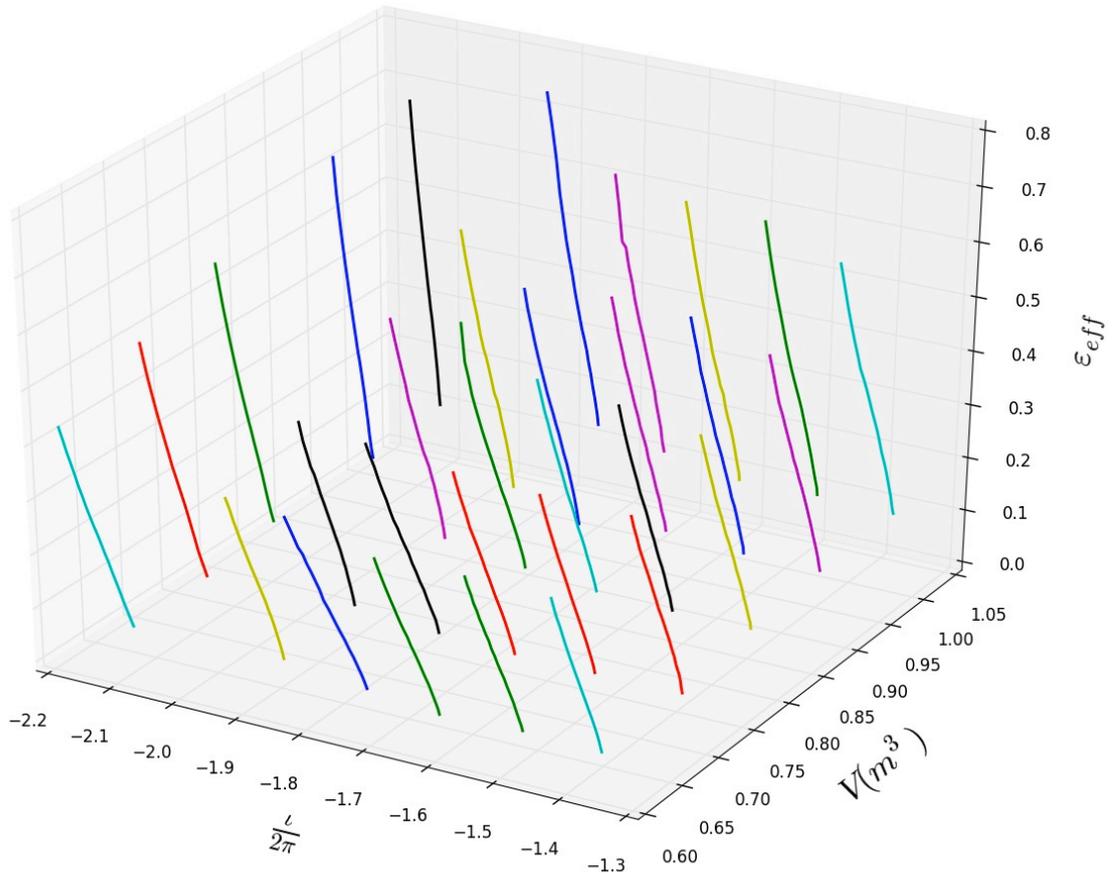


**Figure 2:** Location of the 25 TJ-II configurations used in this work in the flexibility diagram.  $I_{hc}$  and  $I_{cc}$  are the currents that circulate by the helical and circular coils, respectively, of the central conductor. The lines correspond to constant values of the rotational transform on the axis. The dots are located in parallel direction of constant rotational transform while the larger the  $I_{cc}$  current, the bigger the volume of the configuration.

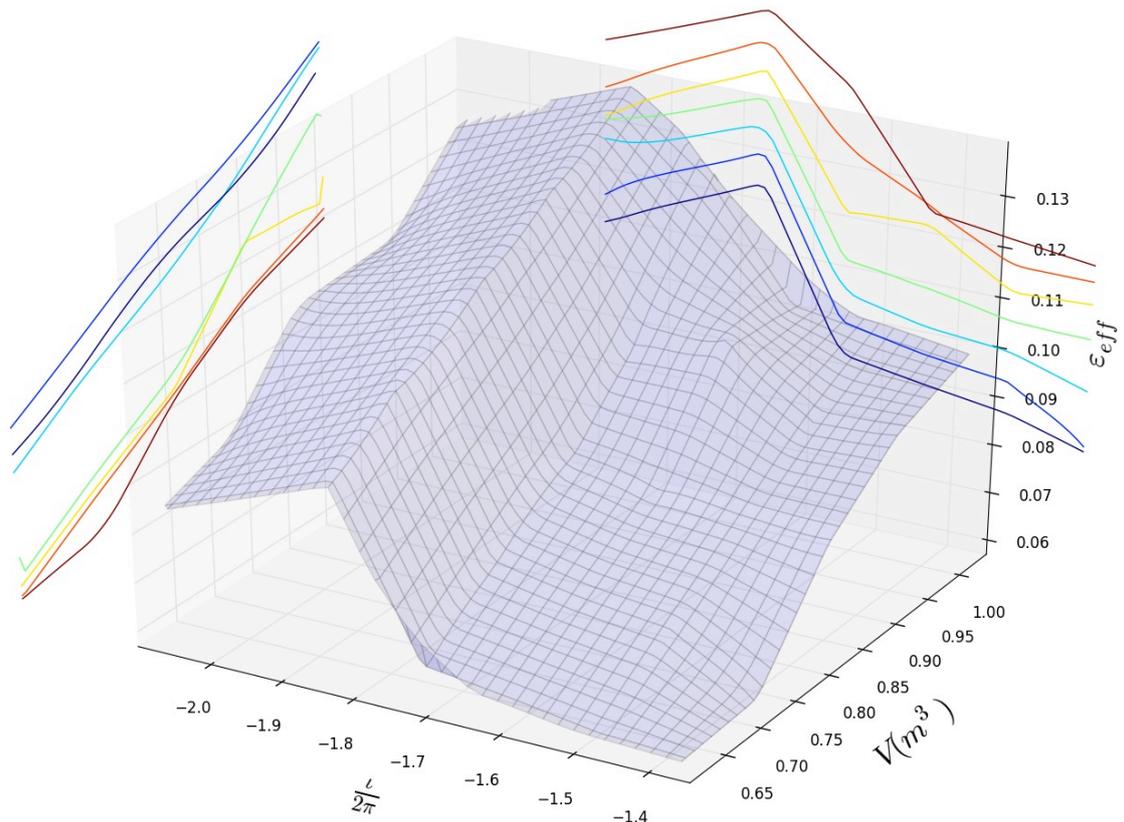


**Figure 3:** Magnetic surfaces of 5 TJ-II configurations of the scan. The toroidal coil is represented in red and the vacuum chamber in blue. Top two configurations correspond to the highest rotational transform, while the bottom ones correspond

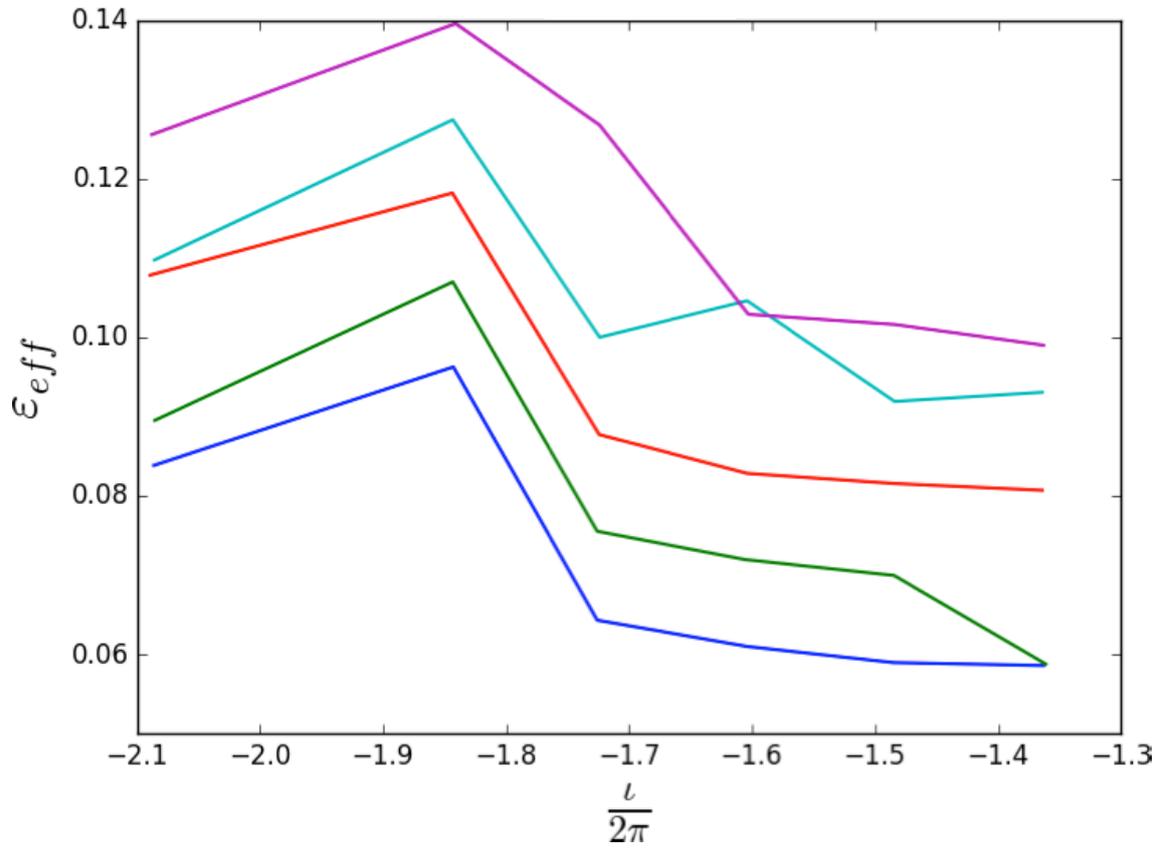
to the lowest  $\iota$  values. The right configurations correspond to the larger volumes, while the left ones have smaller volumes. The central one corresponds to intermediate values of volume and  $\iota$ .



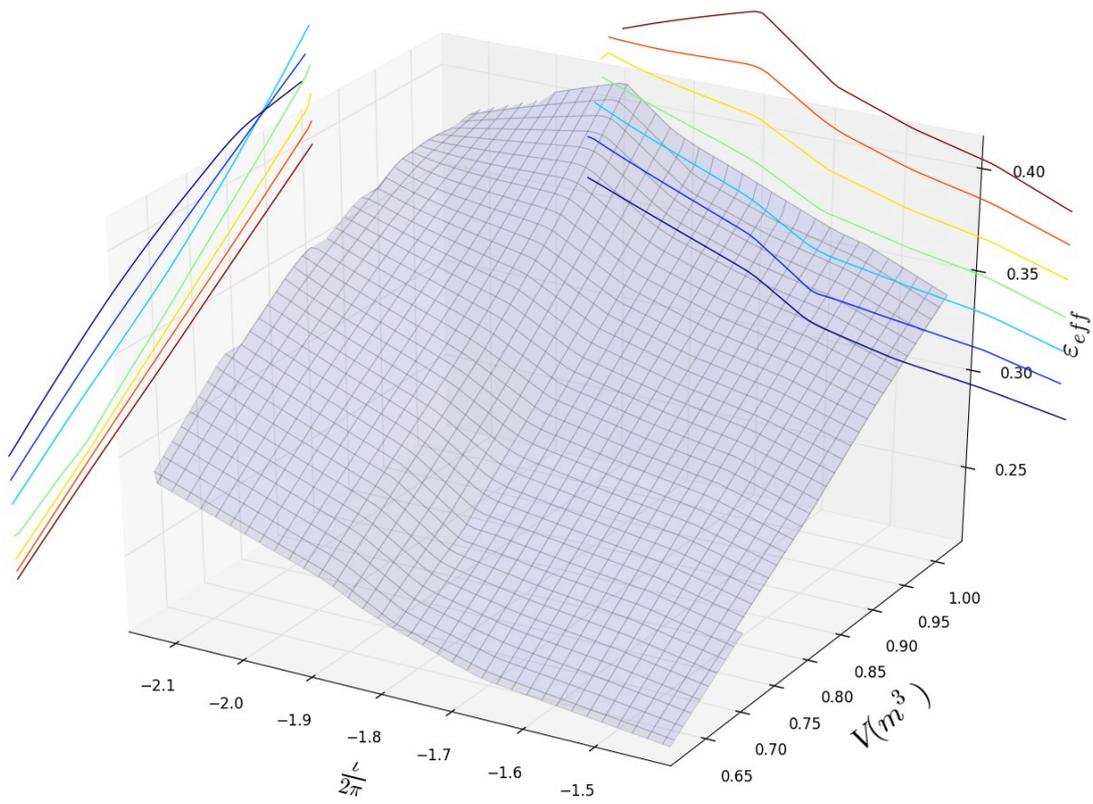
**Figure 4:** Representation of the effective ripple, as a function of volume and rotational transform in TJ-II. The lines show the different values at different radial positions, where different values of the rotational transform appear.



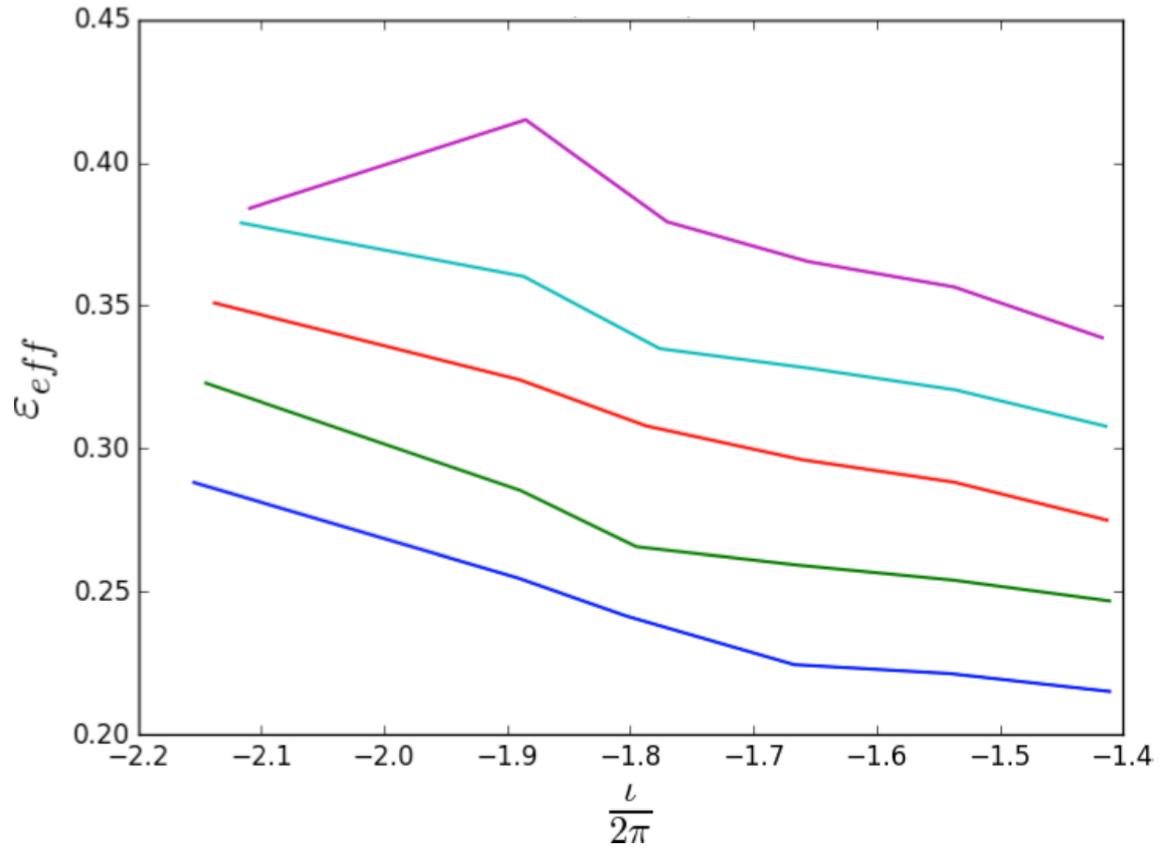
**Figure 5a:** Representation of the effective ripple, as a function of volume and rotational transform in TJ-II for  $\rho=0$ . The lines extract the dependence of the effective ripple with iota for constant volume and with volume for constant iota.



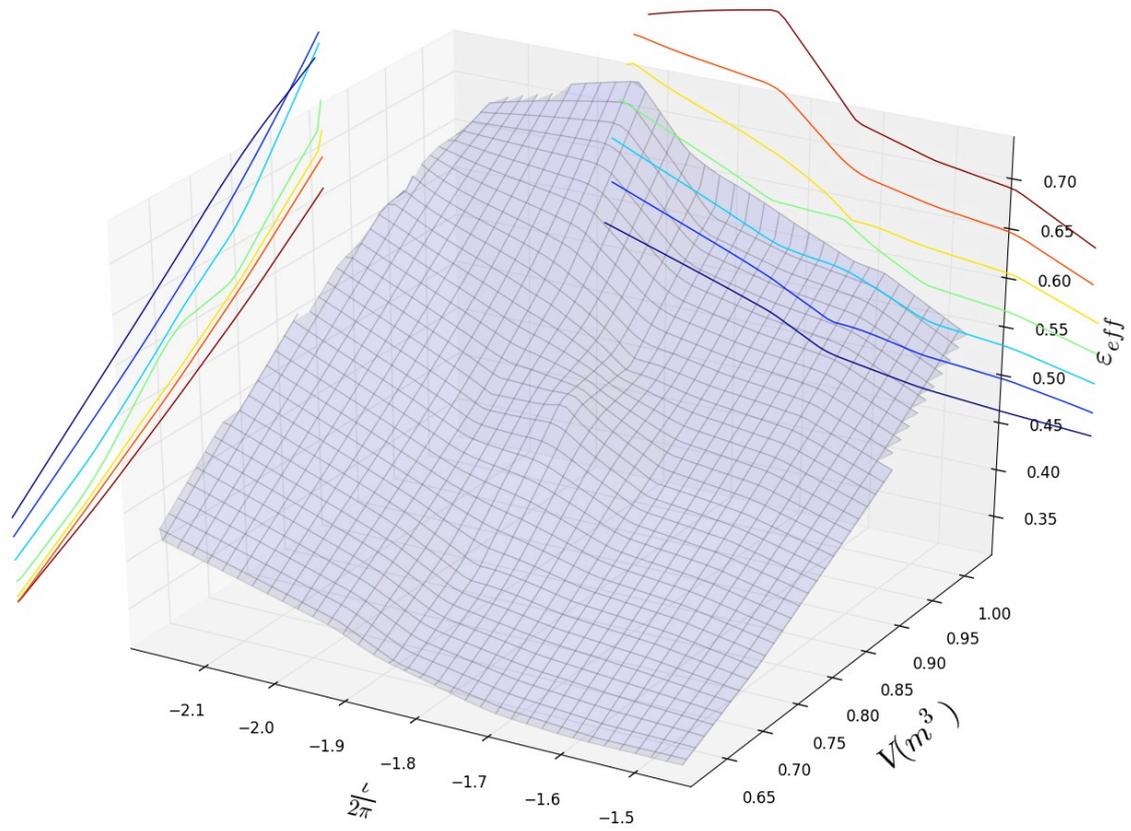
**Figure 5b:** Representation of the effective ripple, as a function of rotational transform for five volumes in TJ-II for  $\rho=0$ . The five curves correspond to increasing values of the volume for increasing values of the volume.



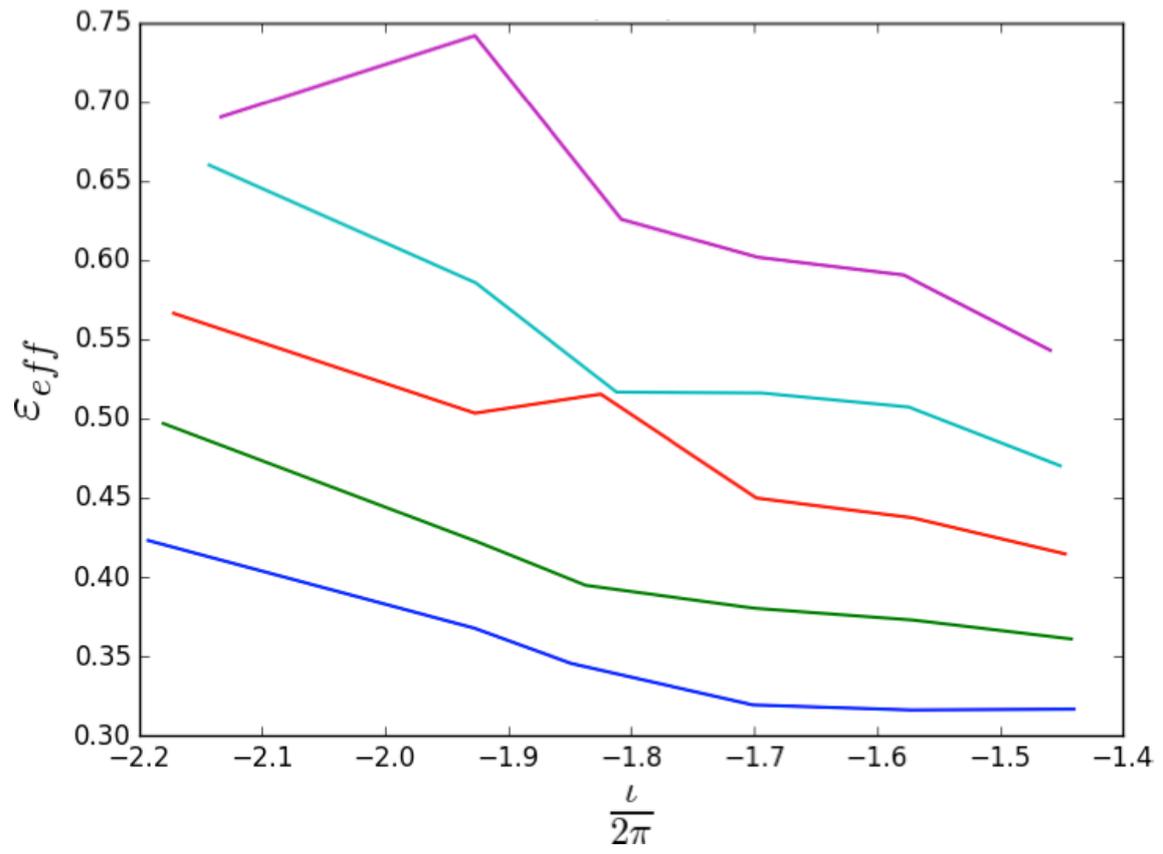
**Figure 6a:** The same as figure 5a for  $\rho=0.65$ .



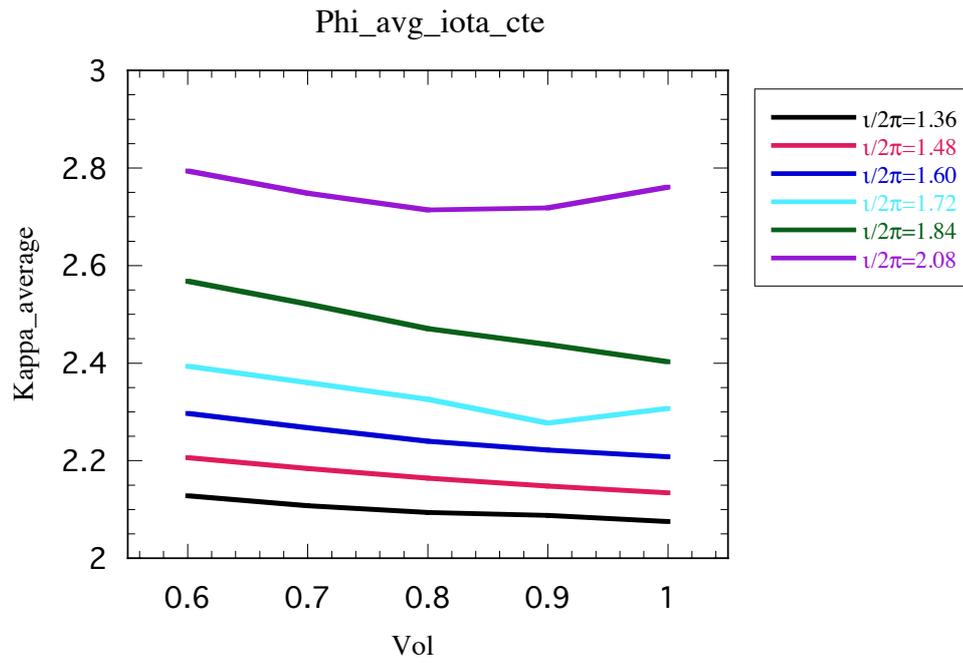
**Figure 6b:** The same as figure 6a for  $\rho=0.65$ .



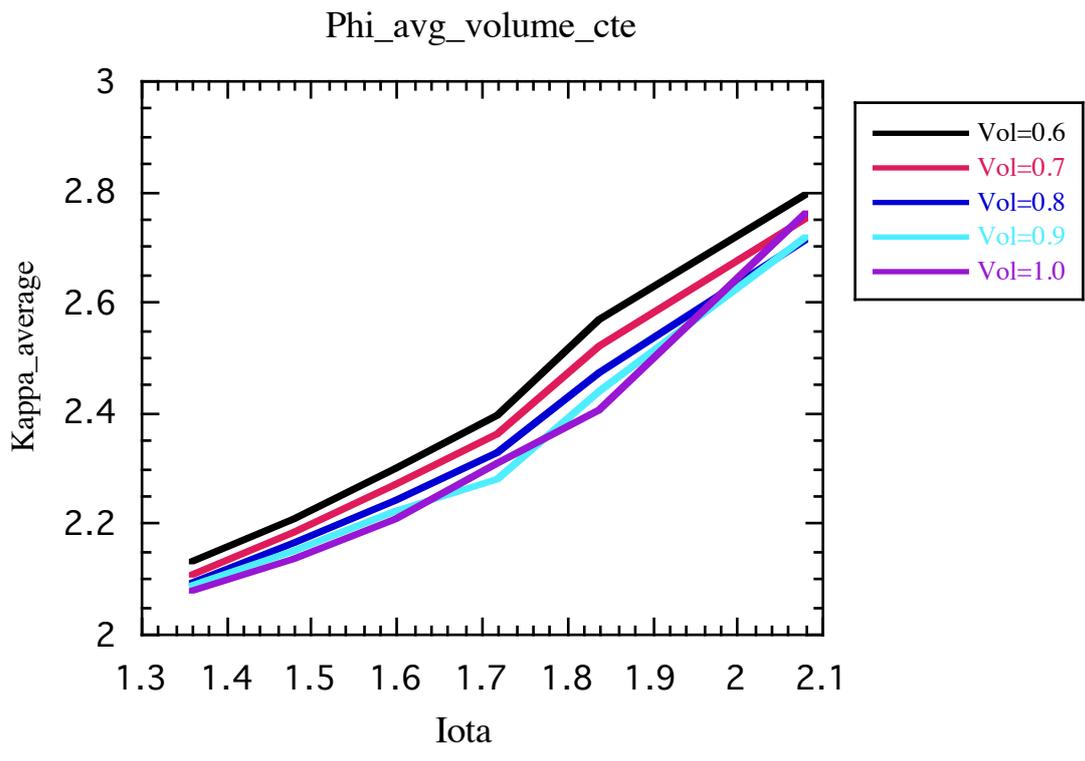
**Figure 7a:** The same as figures 5a and 6a, for  $\rho=1$ .



**Figure 7b:** The same as figures 5b and 6b, for  $\rho=1$ .



**Figure 8a:** Average elongation as a function of the volume, for the several values of rotational transform.



**Figure 8b:** Average elongation as a function of the rotational transform, for the several values of the volume.

## References

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- <sup>1</sup> A. YOSHIZAWA et al. Plasma Physics and Controlled Fusion 43 (2001) R1–R144.
  - <sup>2</sup> H. MAASBERG et al. Physics of Plasmas 7(2000) 295.
  - <sup>3</sup> K. LACKNER AND N.A.O. GOTTARDI. Nuclear Fusion 30 (1994) 767
  - <sup>4</sup> U. STROTH et al. Nuclear Fusion 36 (1996) 1063.
  - <sup>5</sup> H. YAMADA et al. Nuclear Fusion 45 (2005) 1684
  - <sup>6</sup> J. HARRIS. Plasma Physics and Controlled Fusion 46 (2004) B77–B90
  - <sup>7</sup> C. ALEJALDRE et al. Fusion Science and Technology 17 (1990) 131.
  - <sup>8</sup> E. ASCASÍBAR, T. ESTRADA, F. CASTEJÓN, A. LÓPEZ-FRAGUAS, I. PASTOR, J. SÁNCHEZ, U. STROTH, J. QIN AND TJ-II TEAM. Nuclear Fusion 45 (2005) 276
  - <sup>9</sup> F. TABARÉS et al. Plasma Phys. Control. Fusion 50 (2008) 124051
  - <sup>10</sup> J. SÁNCHEZ et al. Nuclear Fusion 49 (2009) 104018
  - <sup>11</sup> F. L. HITON AND R. D. HAZELTINE. Reviews of Modern Physics 48 (1976) 239
  - <sup>12</sup> E. A. BELLI AND J. CANDY. Plasma Physics and Controlled Fusion 50 (2008) 095010
  - <sup>13</sup> S. P. HIRSHMAN, K. C. SHAINGH, W. I. VAN RIJ, C. O. BEASLEY, JR., AND E. C. CRUME, JR.. Physics of Fluids 29 (1986) 2951
  - <sup>14</sup> C. BEIDLER et al. Nuclear Fusion 51 (2011) 076001
  - <sup>15</sup> V. V. NEMOV, S. V. KASILOV, W. KERNBICHLER AND M. F. HEYN, Phys. Plasmas 6 (1999) 4622
  - <sup>16</sup> F. CASTEJÓN et al. Nuclear Fusion 49 (2009) 085019

- 
- <sup>17</sup> S. MURAKAMI, A. WAKASA, H. MAAßBERG, C.D. BEIDLER, H. YAMADA, K.Y. WATANABE AND LHD EXPERIMENTAL GROUP. *Nuclear Fusion* 42 (2002) L19–L22
- <sup>18</sup> H. SUGAMA, K. Y. WATANABE, *Physical Review Letters* 94 (2005) 115001
- <sup>19</sup> S. P. GERHARDT, J. N. TALMADGE, J. M. CANIK, AND D. T. ANDERSON *Physical Review Letters* 94 (2005) 015002
- <sup>20</sup> J. L. VELASCO, J. A. ALONSO, I. CALVO, AND J. ARÉVALO. *Physical Review Letters* 109 (2012) 135003
- <sup>21</sup> T. IDO et al. *Nuclear Fusion* 46 (2006) 512
- <sup>22</sup> Z. GAO et al. *Physics of Plasmas* 15 (2008) 072511
- <sup>23</sup> E. SÁNCHEZ et al. *Plasma Physics and Controlled Fusion* 55 (2013) 014015.
- <sup>24</sup> F. CASTEJÓN AND A. GÓMEZ-IGLESIAS. “Advances in Grid Computing”, Chapter: “Grid Computing for Fusion Research”. Ed.: Intech. Rijeka, Croatia, 2011. ISBN 978-953-307-301-9
- <sup>25</sup> M. RODRÍGUEZ-PASCUAL, J. GUASP, F. CASTEJÓN, A. J. RUBIO-MONTER, I. M. LLORENTE, R. MAYO. *IEEE Trans. Plasma Sci.* Sept 2010; 38(9):2102–2110
- <sup>26</sup> M. RODRÍGUEZ-PASCUAL, A. J. RUBIO-MONTERO, R. MAYO, A. BUSTOS, F. CASTEJÓN, et al. *Proc of the 18th Euromicro Int. Conf. on Parallel, Distributed and Network-Based Processing (PDP 2011)*, IEEE CS Press: Ayia Napa, Cyprus, 2011; 380–384.
- A. BUSTOS, F. CASTEJÓN, L. FERNÁNDEZ, J. GARCÍA, V. MARTIN-MAYOR, J. REYNOLDS, R. SEKI R, J. L. VELASCO. *Nuclear Fusion* 50 (2010) 125.
- <sup>27</sup> F. CASTEJÓN et al. *Plasma Physics and Controlled Fusion* 55 (2013) 014003

- 
- <sup>28</sup> M. RODRÍGUEZ-PASCUAL, T. SCOTT B, RIBEIRO, F. CASTEJÓN, R. MAYO. IEEE Transactions on Plasma Science 38 (2010) 2111.
- <sup>29</sup> A. CAPPA, D. LÓPEZ-BRUNA, F. CASTEJÓN, M. A. OCHANDO, J. L. VÁZQUEZ-POLETTI, et al. Contributions to Plasma Physics 51(2011) 83.
- <sup>30</sup> A. J. RUBIO-MONTERO, F. CASTEJÓN, M. A. RODRÍGUEZ-PASCUAL, E. MONTES, R. MAYO IEEE Transactions on Plasma Science 38 (2010) 2093.
- <sup>31</sup> J. T. MÓSCICKI, A. BUSTOS, F. CASTEJÓN, J. L. VELASCO, P. MÉNDEZ. "The HEP-Fusion technology transfer using Ganga andDIANE in the EGEE Grid". Proc. of 4th EGEE User Forum 2009. Catania, Italy.
- <sup>32</sup> A. GÓMEZ-IGLESIAS, M. A. VEGA-RODRÍGUEZ, F. CASTEJÓN. Applied Soft Computing 13 (2013) 2547.
- <sup>33</sup> A. J. RUBIO-MONTERO, E. HUEDO, F. CASTEJÓN, R. MAYO-GARCÍA. Future Generation Computer Systems 45 (2015) 25.
- <sup>34</sup> E. HUEDO, R. S. MONTERO, I. M. LLORENTE. Future Generation Computer Systems 23 (2007) 252.