Study of TJ-II configurations with net toroidal current
using the PIES code

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Introduction

The TJ-II stellarator is very well suited for investigating confinement properties in different magnetic configurations, as it covers an ample range of rotational transform profiles. In addition to this, a set of coils designed to induce toroidal plasma currents, I_p, can be used to change the rotational transform profile during a discharge. This has been used in past experiments to study the confinement in TJ-II under positive and negative induced plasma currents [1], using the magnetic configuration called 100_44_64. The main result found in those experiments was that $I_p < 0$ causes an increase in density, probably due to an improvement of confinement, in a very reproducible way. The equilibria in these experiments were analyzed with the VMEC code, which showed the appearance of low- and medium-order resonances in the discharges [2]. However, it has been suggested that magnetic islands can have an impact on the confinement [2,3], and VMEC assumes that the configuration is formed only by nested flux surfaces. The PIES code [4], which does not suffer from this limitation, is able to study configurations with islands and stochastic regions and has already been used in the past to study TJ-II equilibria with large islands [5]. The present report presents the first, preliminary free boundary results obtained with the PIES code for TJ-II configurations with net toroidal current corresponding to the mentioned experiments.

PIES runs

The standard way to run the PIES code, which is the one we have used in this work, is to run first VMEC, which is faster, and then to use the VMEC output as input for PIES. But, owing to the complexity of the TJ-II configurations, neither the VMEC runs nor the PIES runs were simple routine application of the codes. We first made some tests with free boundary PIES applied to configuration 100_44_64 with β=0 to get an idea of the number of modes and radial surfaces needed, which confirmed what we already knew from past experience with TJ-II configurations, i.e., that in order to get meaningful results we needed a large number of

modes, larger than for most other machines (see Fig. 1, which shows that a reasonable choice for the maximum poloidal and toroidal numbers might be *M=16, N=11*).
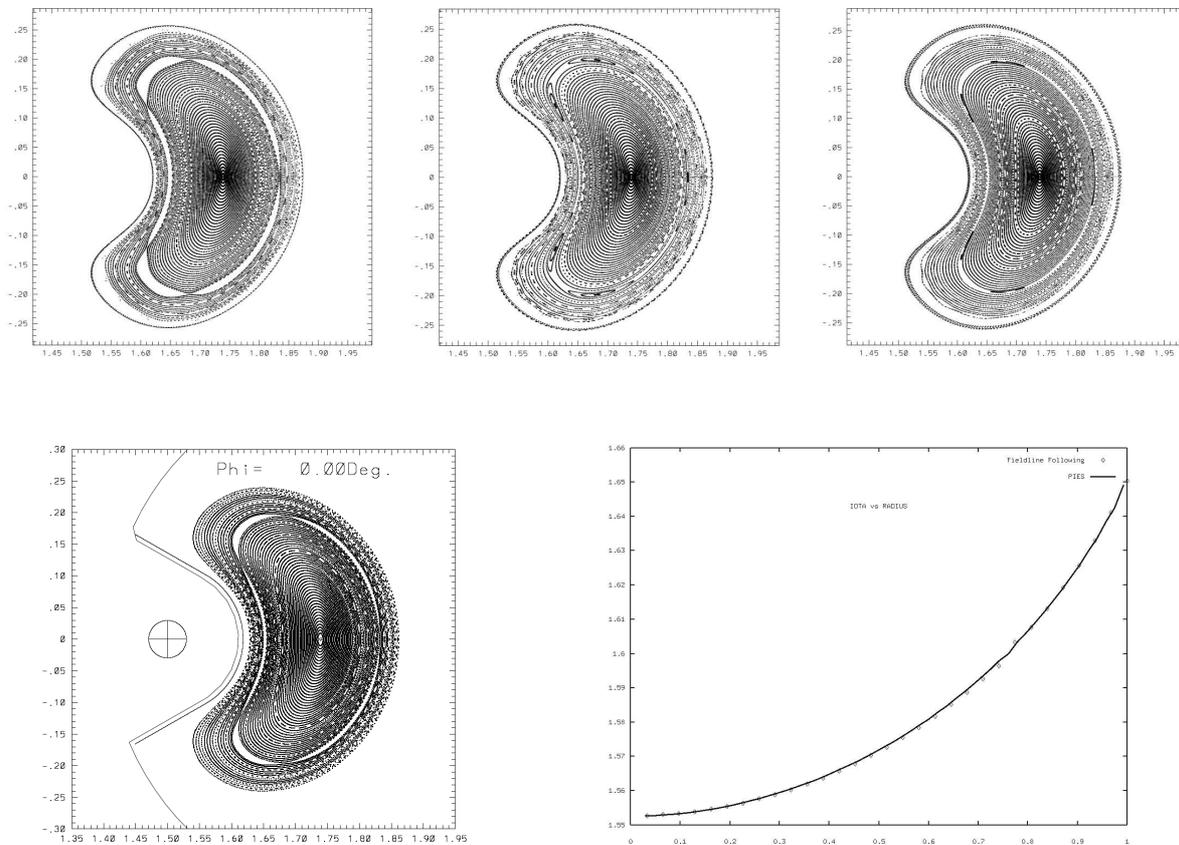
Fig. 1: Poincare plots for TJ-II vacuum equilibrium configuration: calculated with PIES with (M,N) = (12,7) [top left], (14,9) [top middle], and (16,11) [top right]; obtained following field lines with HL [bottom left]. Comparison between the iota profiles obtained for the same configuration with PIES, M=16, N=11 (solid line) and with HL (diamonds) [bottom right].

The runs currently in progress, with finite β and toroidal current, have 60 radial zones and *M=16, N=11*. But it was a challenge to get the codes working with so many modes, and actually the VMEC runs have been made with fewer modes, *M=8, N=12*. In order to have PIES handle the large numbers of modes required several improvements have been made to the code, specially to increase the speed. Several subprograms have been converted for using splines instead of the previous, slower, Fourier description. The mapping routines have been sped up also. Now finally the code seems to be running smoothly for three different cases with the same magnetic configuration (100_44_64), the same average β (0.23%) and pressure profile, and different total toroidal currents, I_p = -4 kA, 0 kA, and +4 kA,

respectively, but with the same relative radial profiles. The Poincare plots at $\phi = 0$ and the rotational transform profiles (with negative ι) are shown in Fig. 2 for iteration number 115, which was the last one available at the time of this writing. Notice that the Poincare plots go well beyond the inner surface of the vacuum vessel wall, which is also shown in the plots and that in the real experiments acts as a limiter. Typically PIES is run for 500 iterations to achieve reasonable convergence, so that these should be considered provisional results.
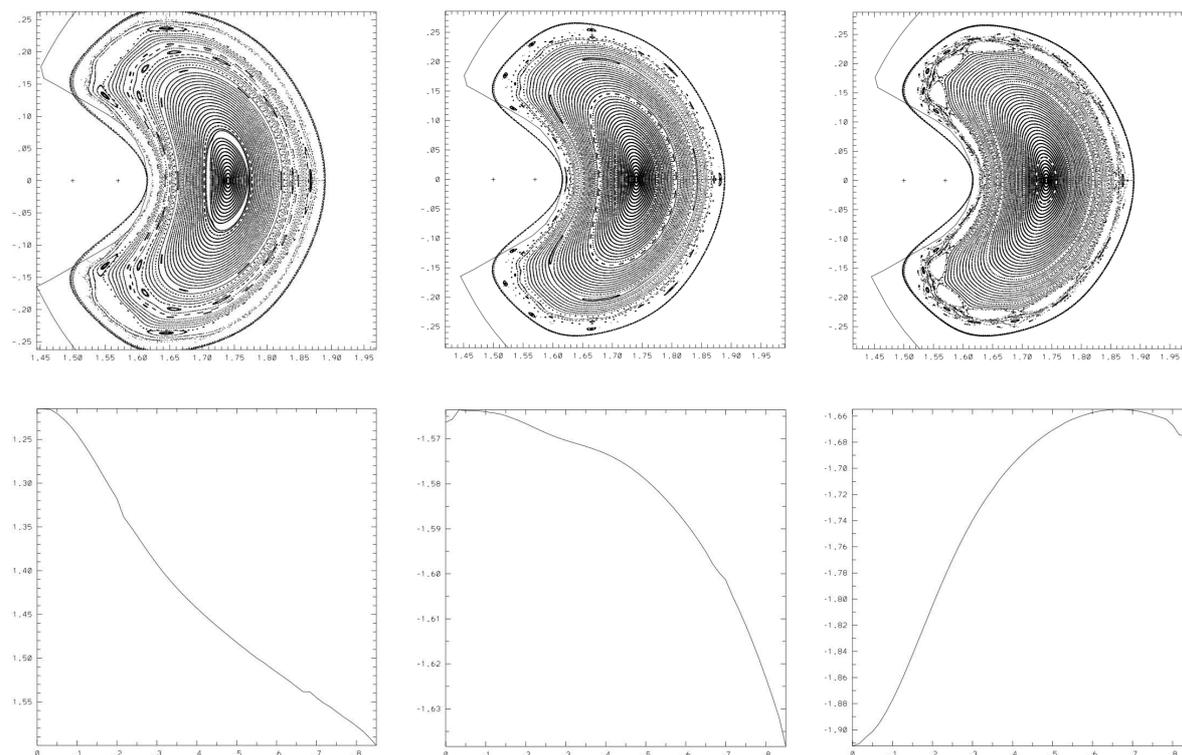
Fig. 2: *TJ-II equilibrium configurations with total toroidal current -4 kA [left], 0 kA [middle], and +4 kA [right], after 115 PIES iterations.*

It is clear that the rotational transform and therefore also the island distribution are changed considerably by the toroidal current. From the Poincare plots shown in Fig. 2, and from other Poincare plots at different values of ϕ that we have not shown, it appears that the volume of the islands inside the limiter is larger for $I_p = +4$ kA than for $I_p = 0$, but that it is also larger for $I_p = -4$ kA than for $I_p = 0$. Thus, a simple model which should take into account only the volume of the islands and stochastic regions and associate them with degraded confinement would indicate better confinement for $I_p = 0$ than for $I_p = +4$ kA, as expected, but worse confinement for $I_p = -4$ kA than for $I_p = 0$, against the experimental results. Of course, the model we want to apply [3] is more complex, and our conclusions will have to wait for a

more detailed analysis. Finally we would like to mention that an obvious candidate for why negative current is better is bootstrap current, because it causes the shear to be negative, and negative shear is known to decrease island widths. But we have looked at the bootstrap current and we think that this effect should be small in the shots we are looking at. However, PIES does have a bootstrap model and we may take up this issue in the future.

Future plans

As already stated this is ongoing work. Our future plans are the following, although some of them may take some time or not be executed at all: (1) proceed further with the current runs (more iterations), perhaps making adjustments for current and pressure profiles as mentioned below, and make other runs with slightly different pressures and currents to simulate the changing conditions of the experiments; (2) refine the current profile with more precise experimental data; (3) refine the pressure profile also, although this is much less important (in the current runs we have used $\langle\beta\rangle$=0.23%, which is somewhat higher than the value of $\langle\beta\rangle$ in the experiments); (4) use the PIES output to make a study of the stability due to the effect of the toroidal current, following the model of Mikhailov and Shafranov [3]; (5) improve the limiter model to take into account the actual shape of the physical limiter; (6) speed up the code further, for the case of many modes.

Acknowledgements

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