PIES applications to NCSX [1]

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1. Introduction

The purpose of the research presented here is two fold. We present preliminary results for the assessment of flux surface quality for a candidate configuration for the National Compact Stellarator Experiment (NCSX) experiment. We also present preliminary results of the assessment of our 3-D MHD tools, PIES[1] and VMEC[2].

We first illustrate the flux surface quality in C82 by showing PIES results for several snapshots in the evolution of the plasma from 0% β to 3.5% β. C82 is a quasi-axisymmetric candidate configuration for the NCSX experiment. Next, as part of our effort to qualify the PIES code for current carrying stellarators, we present results for a W7-AS experimental shot. Lastly, we show evidence from the PIES code that the equilibrium produced by VMEC violate the Hamada condition.

2. Flux Surface Quality for the C82 Configuration

We show in figure 1 the flux surfaces at various cross-sections in real space for the C82 configuration at 0% β and full current as predicted by the PIES code. Most pronounced is an $n/m = 3/7$ island at the lowest order rational surface. Figure 2 shows an enlarged view of the $\phi = 0$ cross-section revealing a small island at the higher order rational surfaces. In real space, these island tend to be thin at the outboard and inboard of sides of the bean shaped cross-section, and broad at the tips. The flux surface quality appears to be reasonable, but a transport simulation would be needed to get a good estimate for the enhanced transport due to the presence of the islands. However, before we perform a transport simulation, we need to converge the PIES results in the number of harmonics and radial zones. In fact, convergence studies need to be done for all the results presented in this report and this is the reason the results have been labeled preliminary. Figure 3 is a plot of the flux surfaces at the $\phi = 0$ cross-section in toroidal background coordinates. This view is usually best for revealing the topology of the flux surfaces, but may give misleading impressions concerning transport as illustrated by figure 2.

Figure 4 shows the C82 topology at 3 0% β at full current. The topology is about the same as that at 0% β. The islands are about the same number and size as the 0% β case and differ primarily in their phase.

The results in the previous figures were calculated by starting from the VMEC solution and using the VMEC coordinates as the background coordinates. This is the reason that the flux surfaces are approximately straight lines when plotted in background coordinates. However, when we attempt to simulate the full β ($\approx 3.9\%$), full current case using the VMEC solution at full β and full current, we find a large stochastic region exists on the outside half of the plasma. This stochastic region is not a good starting guess for the PIES iterative procedure. Therefore, to reach the highest β expected for NCSX, we have started the PIES calculation from the 3 % β case and have grown the plasma by slowly increasing the pressure throughout the PIES iteration procedure. The results for 3.5 % β are shown in figure 5 and figure 6. There is now a significant fraction of the plasma occupied by island and the flux surface quality is becoming questionable. Again, we remind the reader that these results need to be converged.

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3. W7-AS Equilibria Calculations by PIES

One of the distinguishing features of the proposed NCSX experiment is that the plasma will carry a significant current. This current is due to the neoclassical bootstrap effect and can not be avoided in a quasi-axisymmetric device. As a start in an undertaking to validate the PIES code for current carrying stellarators, we here present results for the W7-AS stellarator[3], in which a significant current was driven by ohmic means. We have run PIES on a $30KA$ discharge. Figure 7 is taken from a 1996 paper by Erckmann et al[4]. It shows that the confinement at this low β is fairly independent of current for the cases where the current flows in the positive direction. (The exception for negative current is probably due to the fact that the iota is driven toward zero in these cases.) There are significant iota changes in the plasma as the current changes from zero to $30KA$. Iota changes from $.35$ on axis to about 1.0 as the current makes this swing. The PIES results for this case are displayed in figure 8 and show good flux surface quality. This is consistent with the experimental results of figure 7.

4. Violation of the Hamada Condition in VMEC Equilibria

In attempting to understand why the VMEC solution for the full β, full current C82 case is so very far from a simply nested solution when PIES goes through one iteration, we have discovered that the VMEC solution appears to be violating the Hamada condition. It is important to understand this discrepancy since we would like to put a diagnostic into VMEC so that the solutions our optimizer finds can be chosen to be fairly free of islands when analyzed by the PIES code. The evidence that VMEC is violating the Hamada condition is shown in figures 9 - 11. Figure 9 shows the harmonic amplitude of the jacobian times the current density, $\mathcal{J} * J$, as a function of radius at various resolutions used in the PIES calculation. This figure is for the full β, full current C10 case (C10 is an older candidate configuration) and all harmonics are plotted. Here, PIES uses the VMEC magnetic field and calculates the jacobian in straight field line coordinates. The resonant Pfirsch-Schlüter currents are clearly evident and show that the jacobian is not going to zero at the resonant surface. The PIES calculation was done with 1400 harmonics and the VMEC calculation was done with 375 harmonics and 400 radial zones. The currents, as calculated by the PIES code, are plotted in figure 10 in background coordinates and again the singular currents are evident. Figure 10 is to be contrasted with figure 11 where the VMEC calculated currents are plotted in background coordinates. Figure 11 shows no signs of resonant currents.

5. Summary and Remarks

We have used the PIES code to examined the equilibrium of the C82 plasma for various snapshots without the constraint of simply nested flux surfaces used in the VMEC evaluation of these equilibria.

At 3.5% β, the C82 plasma shows significant island structure. Before we begin studies to assess the effect these island would have on transport, convergence studies of the PIES results will be performed. Also, we are enlisting two other MHD equilibrium codes, M3D and HINT, to confirm these PIES results.

In order to validate the PIES results, we have begun to look at experimental results of stellarator equilibria. We presented here a low beta, high current discharge from W7-AS. We plan to examine higher beta cases from W7-AS and other stellarators equilibria such as LHD and CHS.

We have presented evidence that the VMEC equilibria are not converging to the weak solution. We are searching for the source of the discrepancy between the PIES code and the VMEC code by doing convergence studies with both codes. However, we point out that it has been noted by Gardner and Blackwell[5] that VMEC solutions do not show resonant behavior.

Acknowledgments

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Figures

Fig. 1 C82 at full current and 0 $\%\beta$ at various cross-sections in real space.

Fig. 2 C82 at full current and 0 $\%\beta$ at the $\phi = 0$ cross-section in real space.

Fig. 3 C82 at full current and 0 $\%\beta$ at the $\phi = 0$ cross-section in background coordinates.

Fig. 4 C82 at full current and 3.0 $\%\beta$ at the $\phi = 0$ cross-section in background coordinates.

Fig. 5 C82 at full current and 3.5 $\%\beta$ at the $\phi = 0$ cross-section in background coordinates.

Fig. 6 C82 at full current and 3.5 $\%\beta$ at the $\phi = 0$ cross-section in real space.

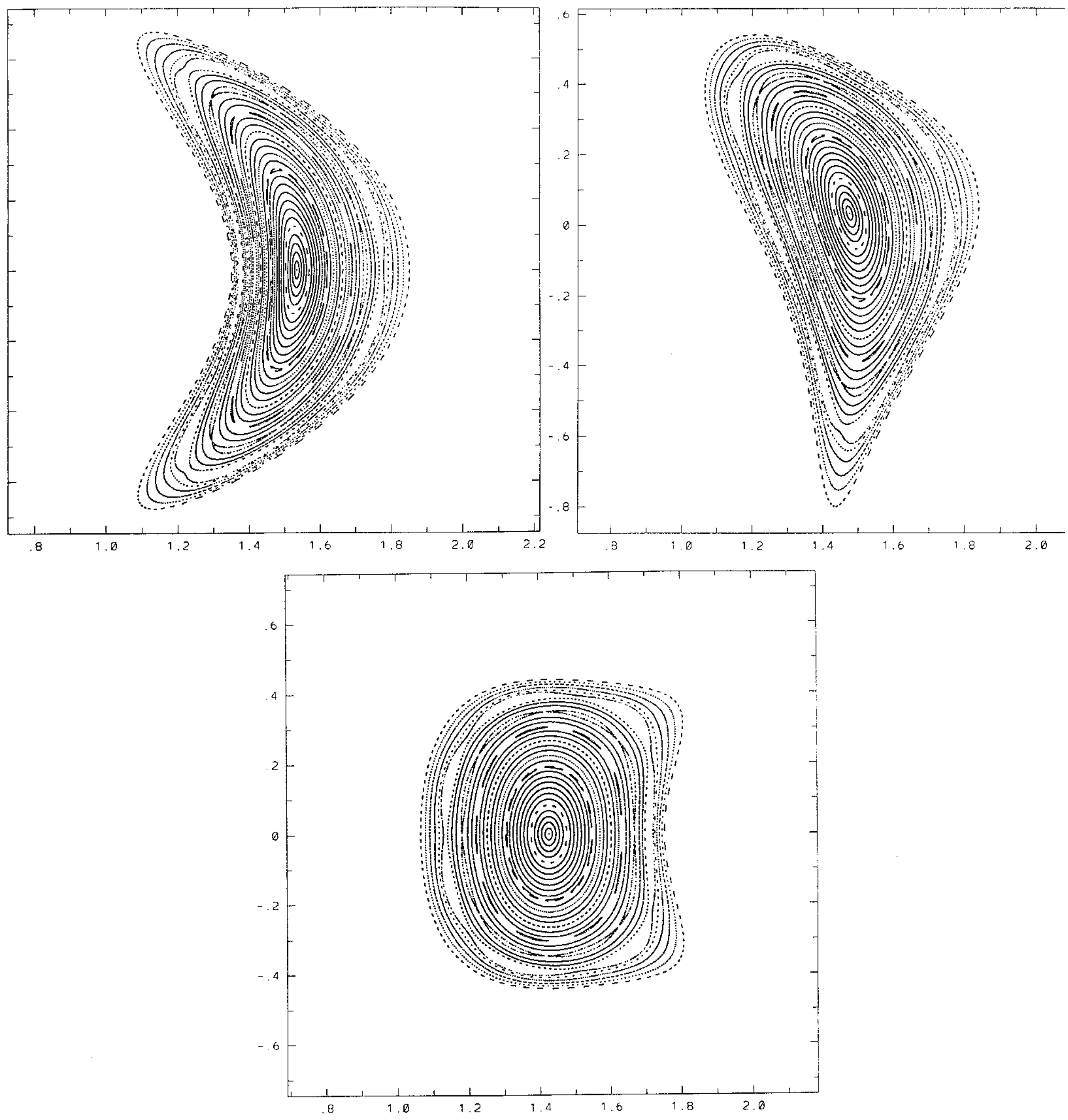
Fig. 7 Central electron temperature for discharges with different plasma currents in W7-AS.

Fig. 8 W7-AS with +30 KA current and .1 % β

Fig. 9 Harmonic amplitude of the jacobian times the current density, $jacobian * j^{\phi}$, vs radius for the C10 plasma in magnetic coordinates at full current and full β, for various radial resolution in PIES, showing evidence of resonant Pfirsch-Schlüter currents

Fig. 10 Harmonic amplitude of the jacobian times the current density, $jacobian * j^{\phi}$, vs radius for the C10 plasma in background coordinates at full current and full β, at 120 radial zones in PIES, showing evidence of resonant Pfirsch-Schlüter currents

Fig. 11 Harmonic amplitude of the jacobian times the current density, $jacobian * j^{\phi}$, vs radius for the C10 plasma in background coordinates at full current and full β, at 400 radial zones in VMEC, showing no evidence of resonant Pfirsch-Schlüter currents



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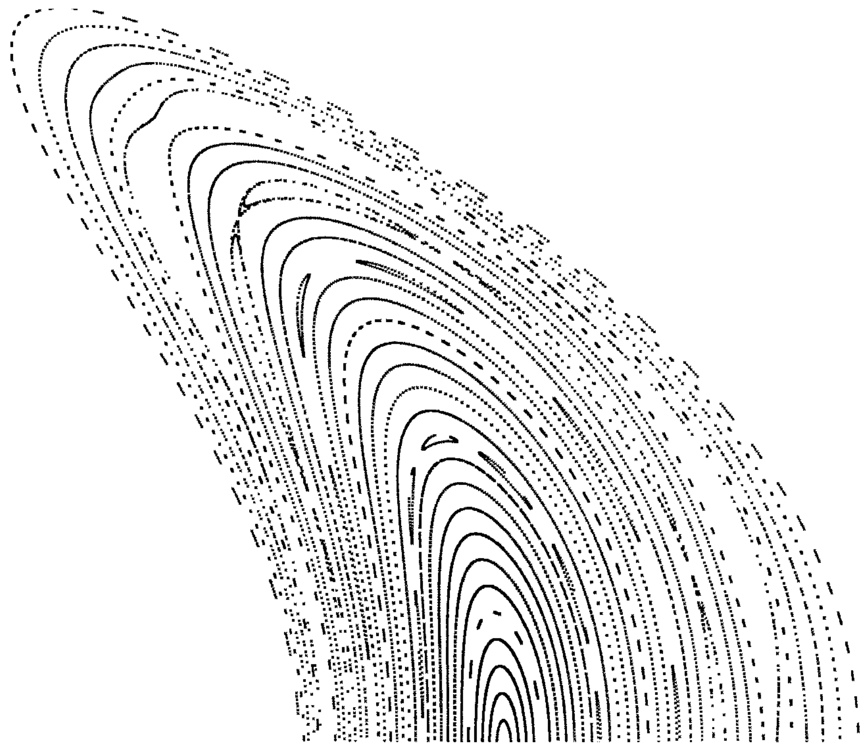

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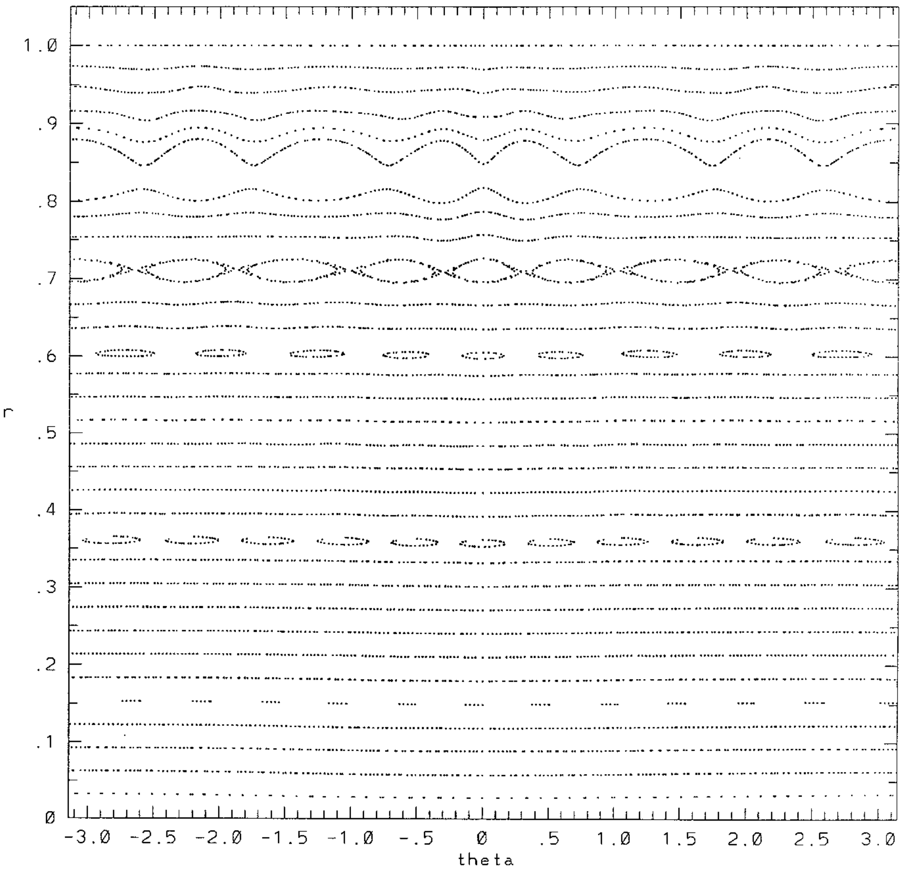

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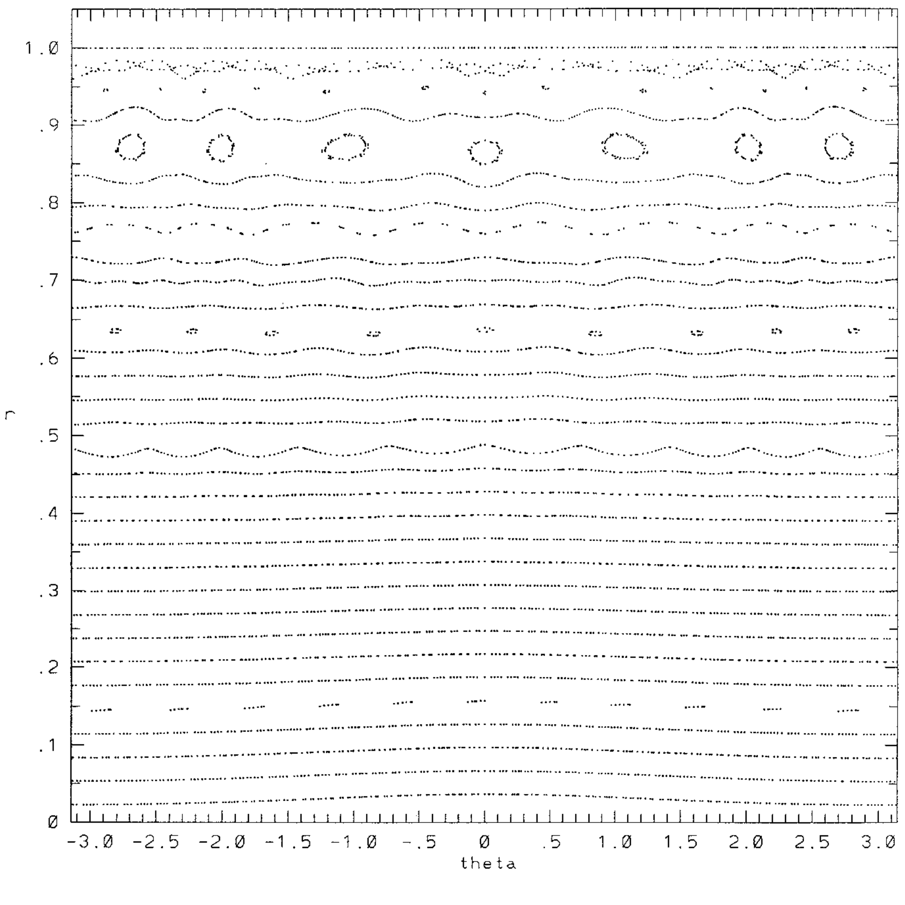

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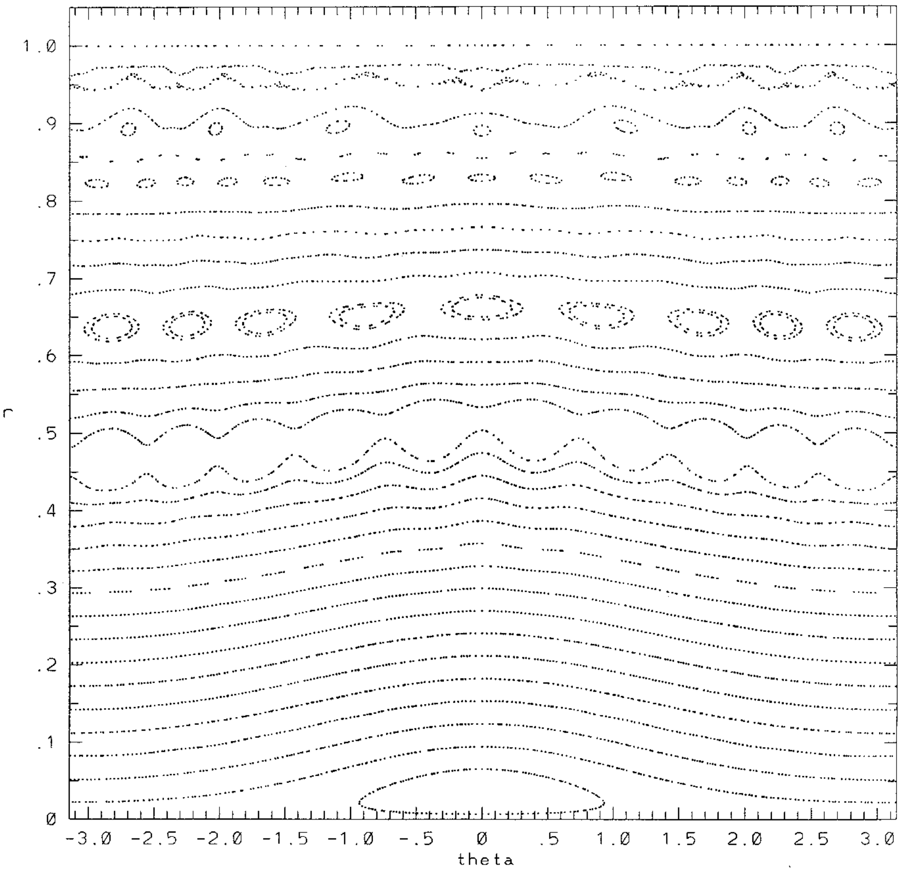

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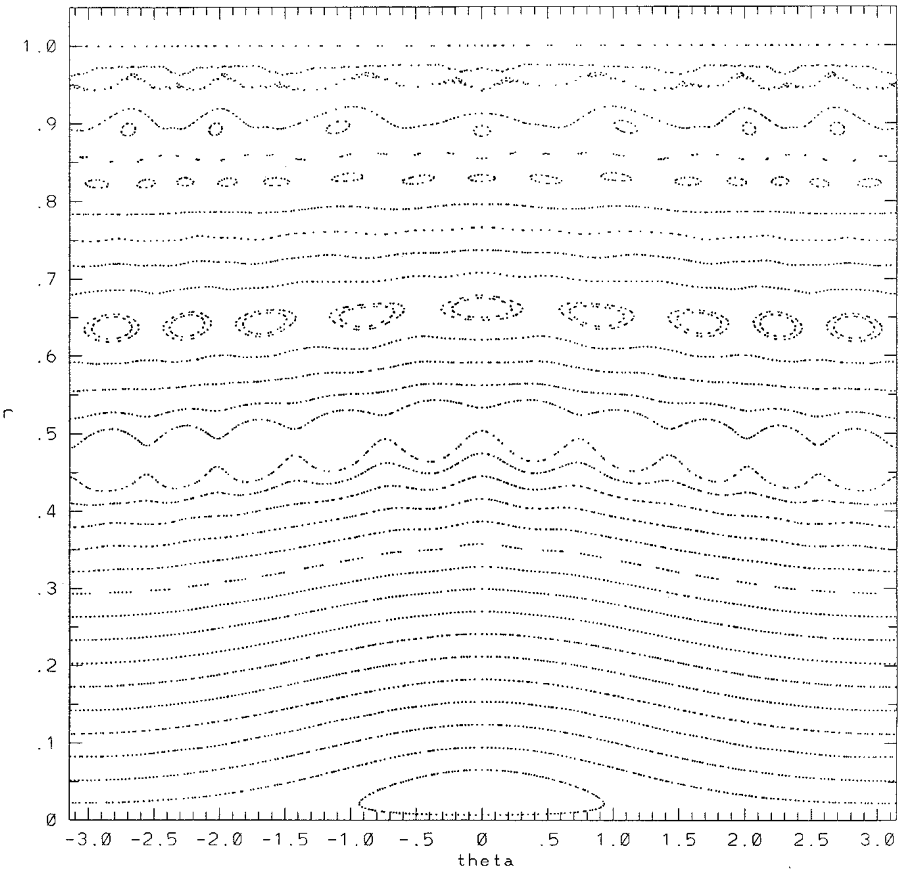

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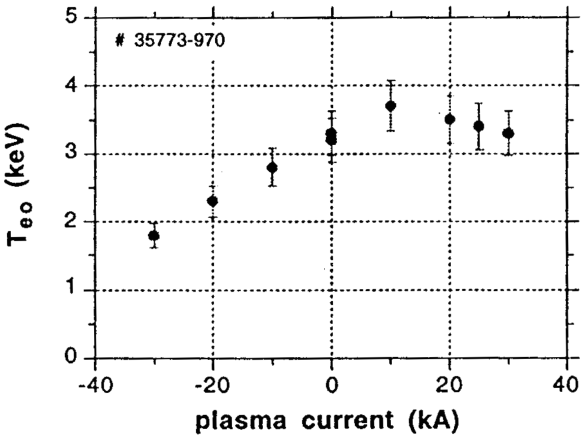

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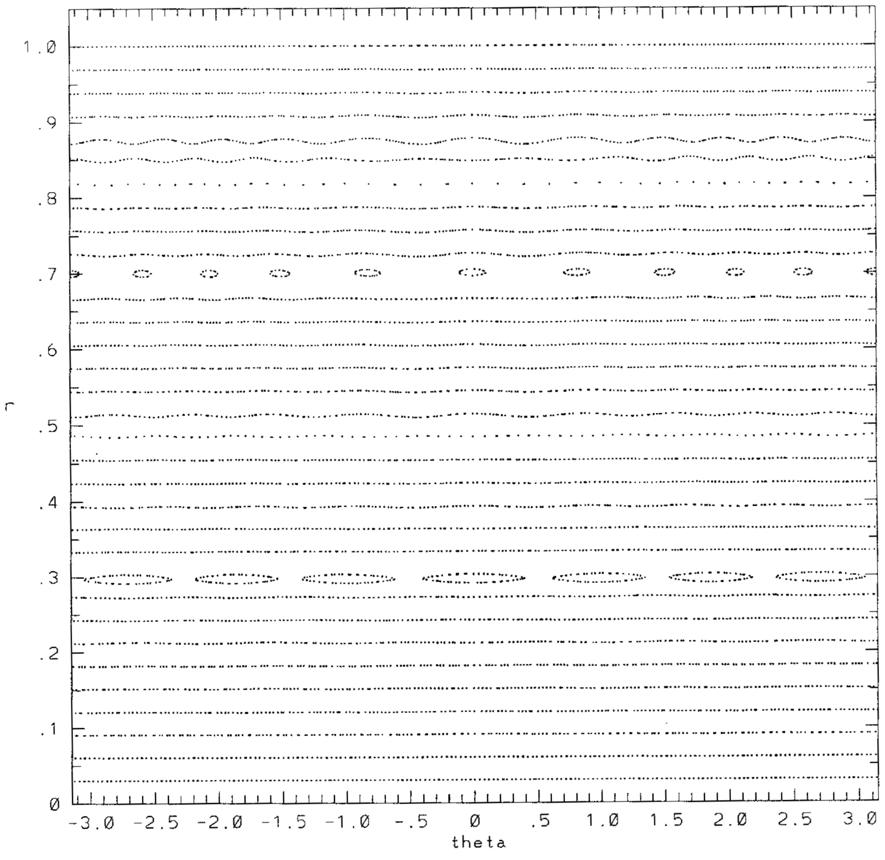

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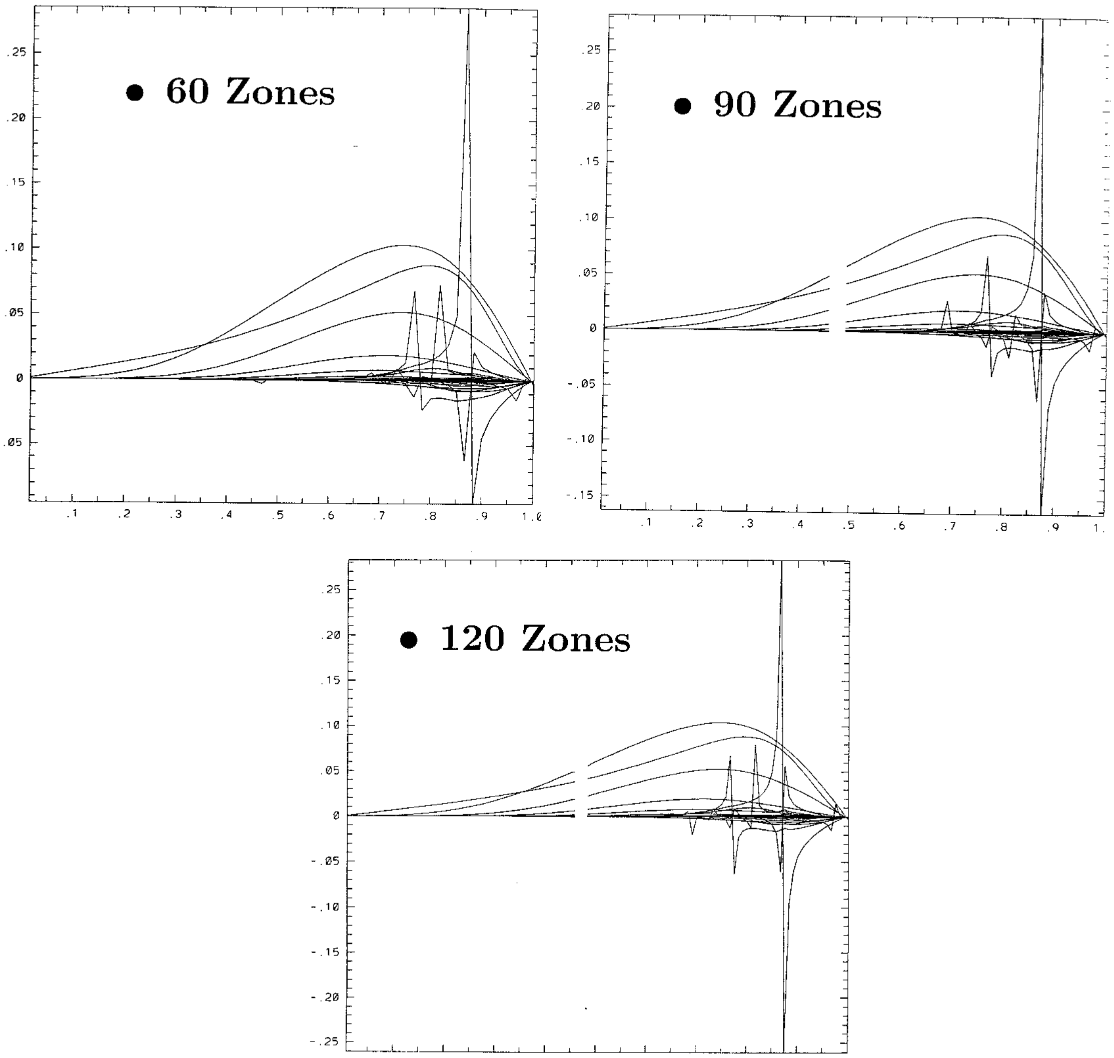

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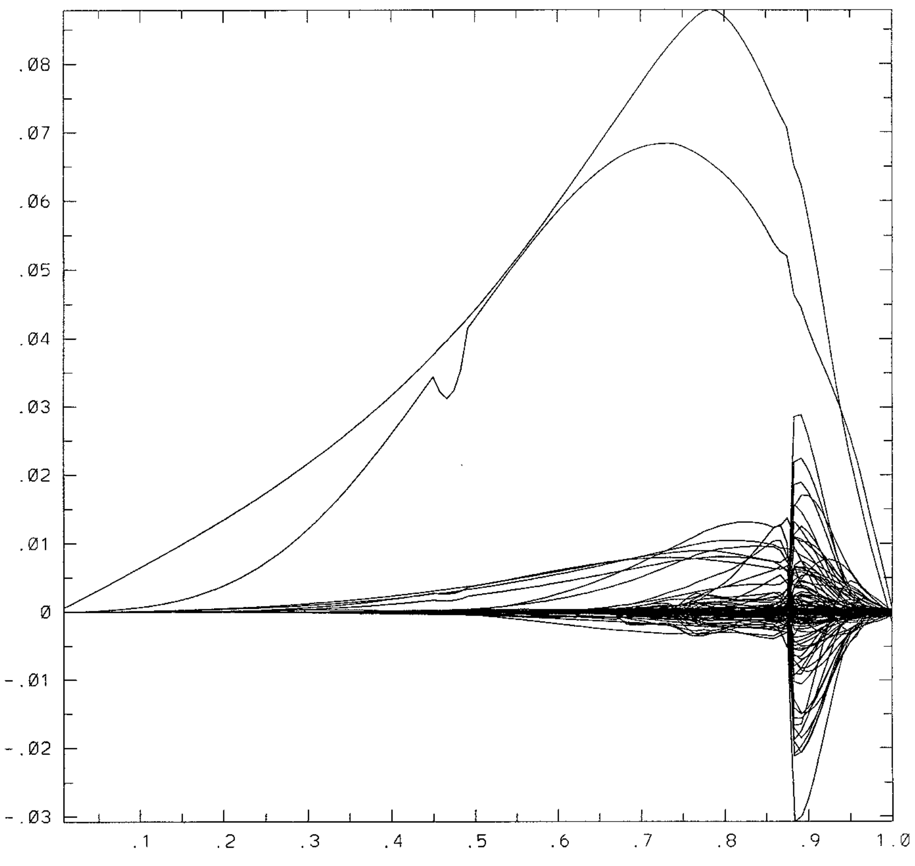

Figure 10:

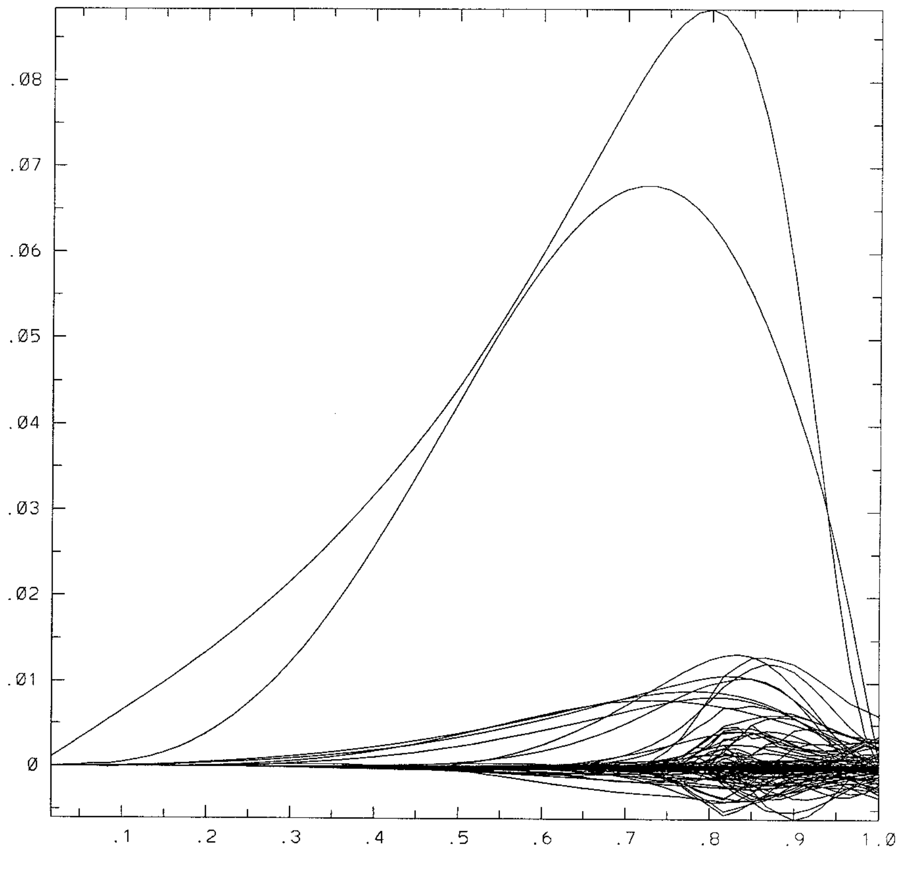

Figure 11: