*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-1.110 (2005)*

Neoclassical transport for LHD in the $1/\nu$ regime analyzed by the NEO code *

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Introduction

For LHD (Large Helical Device) the diffusion coefficients in the $1/\nu$ regime are frequently calculated with the GIOTA code [1-4]. For a number of optimized stellarator configurations the NEO code [5] was used for such calculations. Here, this code is applied to compute the $1/\nu$ transport also in LHD. In particular, these calculations allow for a benchmark between NEO and GIOTA and, in addition, reveal the pertinent advantages of both codes when compared to each other. This is of interest because both codes are much faster than codes based on Monte-Carlo techniques (e.g., DCOM [6]). Computations are performed for magnetic configurations resulting from fixed boundary VMEC equilibria. Especially inward shifted LHD configurations are analyzed. Calculations for such configurations are of interest since DCOM calculations [6] have found reduced $1/\nu$ transport for such configurations in LHD (especially for R_{ax}=3.53 m). Experimental findings in LHD [7] also show that good MHD stability and favorable transport are compatible in the inward shifted configuration (R_{ax}=3.6 m). A rather wide range of radii R_{ax} of the magnetic axes is considered to find an optimum value of R_{ax} from the viewpoint of $1/\nu$ transport. The results are benchmarked with the corresponding results obtained recently with the GIOTA code [3,4] as well as with Monte-Carlo calculations from the DCOM code [6,9].

Peculiarities of the NEO code

The numerical field line following code NEO has been introduced in [5] for the purpose of computation of $1/\nu$ transport in arbitrary stellarator type magnetic fields. Analytical formulas are used for averaged densities of particle and heat fluxes across a magnetic surface, $\psi = const$. The total role of the magnetic field geometry manifests itself through the geometrical factor $\varepsilon_{\rm eff}^{3/2}$ ($\varepsilon_{\rm eff}$ being the so called equivalent helical or effective ripple) which is calculated numerically using integration along magnetic field lines in a given magnetic field. The $1/\nu$ transport coefficients are proportional to the $\varepsilon_{\rm eff}^{3/2}$ parameter. The code is intended for computations with magnetic fields given in real-space coordinates as well as in magnetic coordinates. Therefore, in general the ψ function is not the toroidal magnetic flux but it is a single-valued integral of the magnetic field line equations (the magnetic surface integral). However, for computations in magnetic coordinates the toroidal flux $2\pi\psi$ can be used. The role of the gradients of the

*This work was partly supported by the Association EURATOM-ÖAW. The content of the publication is the sole responsibility of its authors and it does not necessarily represent the views of the Commission or its services. The authors are indebted to Dr. M. Yokoyama (NIFS) for providing GIOTA results, Boozer data for finite beta equilibrium and discussion. Also the authors are indebted to Dr. K.Y.Watanabe (NIFS) who had prepared the corresponding VMEC boundaries.

particle density and temperature, respectively, manifests itself through the $\nabla\psi$ value averaged over the magnetic surface, $\langle|\nabla\psi|\rangle$. Contributions to the transport fluxes are taken into account from particles being trapped within a single magnetic field ripple as well as from particles being trapped within an unlimited number of neighboring ripples. The code has been used in a number of references for calculating the $1/\nu$ transport in optimized stellarator configurations (e.g., in [8]).

Calculations in the zero beta case

All calculations here are carried out for magnetic fields presented in Boozer magnetic coordinates. Configurations with five different positions of the magnetic axis R_{ax} are analyzed: 3.75 m, 3.60 m, 3.55 m, 3.53 m and 3.50 m. Necessary Boozer data are computed using the VMEC code with fixed boundary surfaces corresponding to the five axial positions. The quantity $\varepsilon_{\rm eff}^{3/2}$ in the NEO code (as well as in the GIOTA code, see [4]) is normalized using R_0^2 and B_0^2 with B_0 and R_0 being the reference magnetic field and the major radius of the torus, respectively. Within this paper, B_0 is chosen to be the Boozer component $B_{0,0}$ on the magnetic axis. To make the comparison of transport coefficients independent of R_0 all NEO computations are performed with the same value of R_0, R_0=3.75 m. The computational results are presented in Figure 1. For $r/a \leq$0.8 the results confirm the recent conclusions [3,4,6] that the optimum configuration corresponds to R_{ax}=3.53 m. However, as it follows from Figure 1 for $r/a >$0.8, the configuration corresponding to R_{ax}=3.55 m is preferable.

Figures 2 and 3 demonstrate the comparison of NEO results with GIOTA results [3,4,9] corresponding to β=0. One can see that for $r/a >$0.5 the curves corresponding to GIOTA results (red, squares) are somewhat lower than those corresponding to NEO results (black, points). The only exception is the case R_{ax}=3.75 m. These differences can be explained by the following reasons. When computing $\varepsilon_{\rm eff}^{3/2}$ GIOTA and NEO use different definitions for the minor radius r. GIOTA [4,9] uses the definition $r=\sqrt{2\psi/B_0}$ whereas NEO [5] uses $\langle|\nabla\psi|\rangle^2$ as value for $(d\psi/dr)^2$. In addition, in GIOTA computations $R_0 = R_{ax}$. So, to make NEO and GIOTA results more comparable one can multiply NEO results by two factors, f_ψ and f_R, with

$$f_\psi = \frac{\langle|\nabla\psi|\rangle^2}{(d\psi/dr)^2}, \quad f_R = \left(\frac{R_{ax}}{3.75}\right)^2. \qquad (1)$$

These adjusted NEO results are shown in Figures 2 and 3 by blue curves marked with triangles. They are somewhat lower than the standard NEO results and therefore closer to GIOTA results, however, a marked difference to GIOTA results remains. One can suppose that this remaining discrepancy results from different approaches to compute contributions from various classes of trapped particles to the transport. In the GIOTA code the contribution to the transport from trapped particles is summed up only within each helical ripple [4] whereas in the NEO code all classes of trapped particles are taken into account. Note, that only for the case with R_{ax}=3.75 m this difference is small but also in this case it is still visible near the edge of the configuration. In Figures 2 and 3 DCOM results [9] are also shown for r/a=2/3 with one data point (asterisks) for every R_{ax} value. These DCOM results do not strongly differ from pertinent NEO and GIOTA results, however, they are more close to NEO results. A comparison of the effective ripple also can be made with DCOM results [6] for the R_{ax}=3.53 m case (see Figure 4 in [6]). It turns out that adjusted $\varepsilon_{\rm eff}$ results from NEO (corresponding to R_{ax}=3.53 m in Figure 2) are more close to DCOM results than $\varepsilon_{\rm eff}$ from GIOTA (especially for 0.75$< r/a <$0.9).

Note that for the f_ψ factor the highest difference from unity (f_ψ=0.722) takes place near the edge of the configuration with R_{ax}=3.60 m. In case of complicated shapes of magnetic surfaces f_ψ can essentially differ from unity. E.g., one can find that for the configurations considered in [8] f_ψ reaches values as high as 1.73.

Calculations with finite beta

It follows from [3,4] that for configurations with a vacuum axis position $R_{ax} \geq$3.53 m the results for $\varepsilon_{\rm eff}^{3/2}$ are increased when β is increased. Concurrently, with increased β the corrected position of the magnetic axis, $R_{ax,\beta}$, is also increased reflecting the role of the Shafranov shift. The behavior of $\varepsilon_{\rm eff}^{3/2}$ in finite beta equilibria correlates with the real position of the magnetic axis approximately in the same way as in the zero beta case. Figure 4 reveals interesting results for the distribution of $\varepsilon_{\rm eff}^{3/2}$ over r/a for the configuration with R_{ax}=3.50 m which is not the optimal one in the vacuum case. For β=1%, $\varepsilon_{\rm eff}^{3/2}$ values in the vicinity of the magnetic axis ($r/a \leq 0.5$) are noticeably smaller than those for the zero beta case. The reason for this is the fact that the major radius of the magnetic axis $R_{ax,\beta}$ approaches its optimum value of $\approx$3.53 m because of the Shafranov shift. A further increase of β to β=2% shifts the magnetic axis further out thus resulting in $R_{ax,\beta}$ values larger than the optimal one. This is clearly reflected by the now larger values of $\varepsilon_{\rm eff}^{3/2}$ for $r/a \leq$0.5. In the vicinity of the boundary the results are close to those for the vacuum case since the fixed boundary condition limits the possible changes of magnetic surfaces in this region. From Figure 4 also follows that GIOTA results are somewhat smaller than NEO results even if NEO results are adjusted as in the previous section.

Summary

The results obtained with NEO confirm recent conclusions [3,4,6] from GIOTA and DCOM calculations that for LHD the optimum configuration corresponds to the inward shifted configuration with R_{ax} close to R_{ax}=3.53 m. For the configuration without inward shift of the magnetic axis (R_{ax}=3.75 m) there is no essential difference between $\varepsilon_{\rm eff}^{3/2}$ results obtained by NEO and GIOTA. However, for inward shifted configurations $\varepsilon_{\rm eff}^{3/2}$ values obtained from NEO are somewhat bigger than those obtained from GIOTA (see Figures 2 and 3). Partly, this difference is related to different definitions of the minor radius in GIOTA and NEO. This difference can easily be adjusted. The remaining difference my be connected with the different treatment of the contributions of various classes of trapped particles to the transport. In contrast to GIOTA, the NEO code takes all classes of trapped particles into account. The benchmark with Monte-Carlo results from DCOM shows essentially smaller differences for NEO than for GIOTA. This may also be attributed to the different treatment of all classes of trapped particles.

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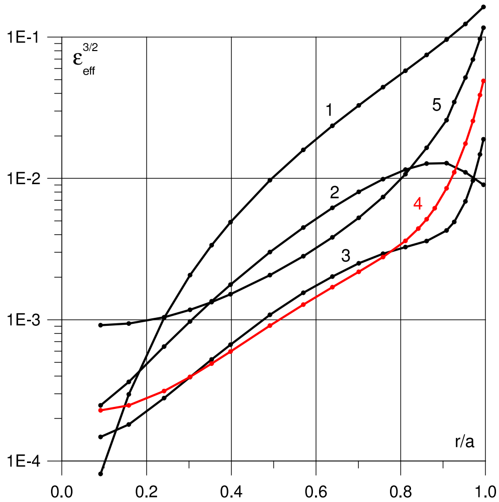

Fig. 1. NEO results for the $\varepsilon_{\rm eff}^{3/2}$ parameter for R_{ax} of 3.75 (curve 1), 3.60 (curve 2), 3.55 (curve 3), 3.53 (curve 4) and 3.50 m (curve 5).

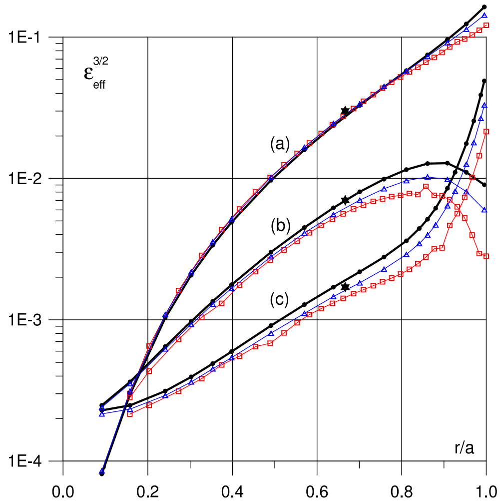

Fig. 2. Comparison of NEO (black points) and GIOTA (red squares) results for $\varepsilon_{\rm eff}^{3/2}$; blue curves with triangles correspond to adjusted NEO results; also DCOM results (asterisks) are shown for r/a=2/3; the sets (a), (b) and (c) correspond to R_{ax} =3.75, 3.60 and 3.53 m , respectively.

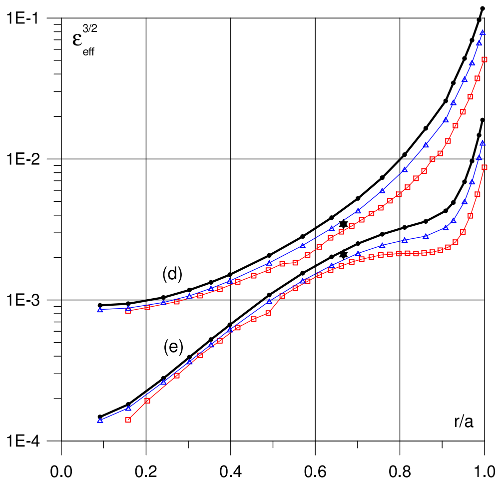

Fig. 3. The same as in Fig. 2 for R_{ax}=3.50 (set (d)) and 3.55 m (set (e)).

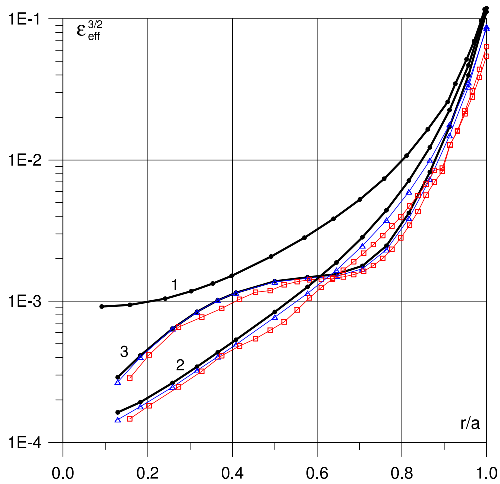

Fig. 4. NEO and GIOTA results of $\varepsilon_{\rm eff}^{3/2}$ for R_{ax}=3.50 m. 1: NEO for β=0; 2 and 3: sets of curves corresponding to $\langle\beta\rangle$=1% and 2%, respectively; red squares for GIOTA results, blue triangles for adjusted NEO results.