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Heat Diffusion Across Magnetic Islands and Ergodized Plasma Regions in Realistic Tokamak Geometry

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Introduction

Heat diffusion processes play a crucial role, e.g., for NTM stability [1] and ELM mitigation by resonant magnetic field perturbations [2]. We present numerical simulations of heat diffusion in tokamak geometry with realistic plasma parameters for both, the plasma core and the boundary. Heat transport across magnetic islands and ergodic layers is investigated and the possible role of stochastisation for FIR-NTMs [3, 4] is discussed. Heat transport across single magnetic islands is compared to measurements at the ASDEX Upgrade tokamak. Furthermore, the effect of an ergodic plasma boundary on the temperature profile is examined.

Model

The steady state heat diffusion equation $\nabla \cdot \vec{q} = P$ is solved, where $\vec{q} = -n_e \chi_\perp \left[\chi \nabla_{||} T + \nabla T\right]$ denotes the heat flux, P the heat source, n_e the electron density, $\chi_{||}$ resp. $\chi_\perp$ the heat diffusivities parallel resp. perpendicular to the magnetic field lines, and $\chi = (\chi_{||} - \chi_\perp)/\chi_\perp$. The finite difference scheme described in [11] is used in unsheared helical straight field line coordinates where no coordinate line is exactly parallel to the magnetic field lines. Adapting the coordinate helicity to the physical problem allows to reduce the required toroidal resolution significantly. For computations regarding the edge plasma, a simple straight field line coordinate system is employed which is extended across the separatrix continuously.

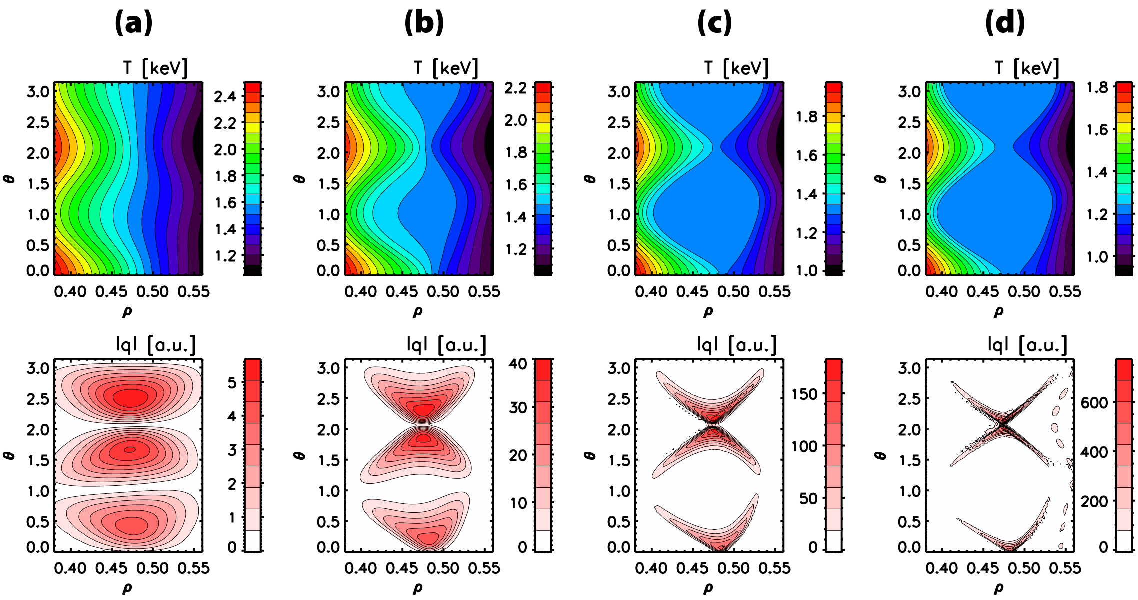

Figure 1: Contour plots of temperature T (top) and heat flux $|\vec{q}|$ (bottom) at a $3/2$ magnetic island with $w/w_c = 1.1$, 2.1, 4.2, and 8.4.

Magnetic Islands

For typical values of w/w_c, the temperature inside the separatrix of an island is mainly flattened as observed from ECE measurements [14]. Here, w denotes the island width and w_c the so-called critical island width [1]. Fig. 1 shows numerical results for temperature and heat flux at a large $3/2$ island (width about 13 percent of the minor radius) for different values of w/w_c. If $w/w_c \gtrsim 2$, the temperature flattens completely at the island o-point, and with increasing w/w_c, the flattened region gradually extends towards the island separatrix. The heat flux, accordingly, becomes localized to a thin heat conduction layer around the island separatrix.

Timetraces of single ECE channels resolve poloidal "cuts" through islands. We study the structures observed close to the resonant surface. As seen from Fig. 1, the width of these structures along θ direction (and also their height) depends on the anisotropy of the heat diffusion tensor. With the available radial resolution, a characteristic distribution of the measured structures can be expected as the distance of the considered ECE channel from the resonant surface varies. Fig. 2 shows height ΔT vs. poloidal width $\Delta\theta$ of these structures at randomly chosen timepoints of two ASDEX Upgrade discharges. Timepoints around FIR-crashes or with exceptionally large noise were excluded. The distributions represented by the dashed, solid and dotted curves correspond to numerical simulations using parallel heat diffusivities according to Spitzer-Härm (χ_{SH}), the heat flux limit (χ_{hfl}), and $\chi_{hfl}/4$. Whereas less pronounced structures can easily be obtained from the experiment by slight phase shift errors, larger temperature gradients along θ should not occur accidently. Thus, the experimental measurements are compatible with numerical results produced applying the heat flux limit [6]. Agreement with computations for Spitzer-Härm diffusivity is worse but cannot be ruled out completely, while parallel diffusivities significantly lower than χ_{hfl} cannot explain the experimental data.

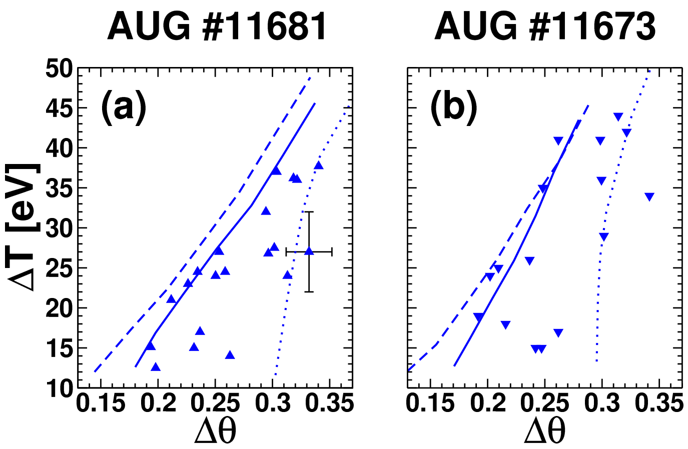

Figure 2: Height ΔT vs. poloidal width $\Delta\theta$ of temperature structures observed close to the resonant surface. The dashed, solid and dotted curves show numerical results using χ_{SH}, χ_{hfl} and $\chi_{hfl}/4$ as parallel heat diffusivity.

Ergodic Layers and FIR-NTMs

Flattening of the temperature profile inside magnetic islands perturbes the bootstrap current, which amplifies the initial magnetic perturbation (NTM) [1, 13]. At high values of the normalized plasma pressure β_N, a frequent interruption of the NTM growth by a sudden amplitude drop has been observed such that the mode cannot saturate [3]. This effect has been shown to be linked to three wave-coupling [4] and alleviates the average confinement degradation [12].

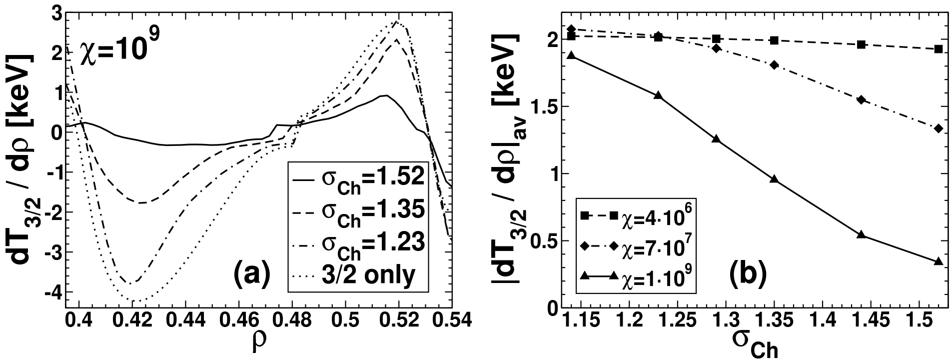

Figure 3: **(a)** Radial profile of $dT_{3/2}/d\rho$ at $\chi = 10^9$ for a single 3/2 island and for an additional 4/3 perturbation of increasing amplitude. **(b)** Average of $|dT_{3/2}/d\rho|$ in the island region vs. the Chirikov parameter σ_{Ch} for three different values of χ.

While the NTM grows on a time scale of about 50 ms, the amplitude drop takes only about 1 ms, which might be caused by field stochastisation from the interaction with another mode locked to the NTM [4]. For an m/n NTM, this is usually an $m+1/n+1$ mode. Although the mode responsible for the field ergodization is unlikely to create an island at its rational surface, for simplicity we discuss the overlapping of two magnetic islands in the following.

The degree of field stochastisation caused by 3/2 and 4/3 islands is measured by the Chirikov parameter $\sigma_{Ch} = (w_{3/2} + w_{4/3})/[2(r_{3/2} - r_{4/3})]$ [7]. We examine a 3/2 NTM with $w = 8.1$cm and an additional 4/3 perturbation of variable amplitude which corresponds to a σ_{Ch} scan.

Part (a) of Fig. 3 shows the first derivative of the temperature mode $T_{3/2}$ for different values of σ_{Ch} at $\chi = 10^9$. In part (b) of this figure, the dependence of the averaged absolute value of $dT_{3/2}/d\rho$ in the island region,

$$|dT_{3/2}/d\rho|_{av} = \frac{\int_{0.4}^{0.54} d\rho\ |dT_{3/2}/d\rho|}{\int_{0.4}^{0.54} d\rho},$$

is shown for three different values of χ. This quantity and thereby also the resonant bootstrap current perturbation $j_{b,3/2} \propto dT_{3/2}/d\rho$ is suppressed strongly for $\sigma_{Ch} \gtrsim 1.2$ and large heat diffusion anisotropies. This drop can take place on a short timescale as the stochastisation enables a fast decay of the bootstrap current perturbation along magnetic field lines.

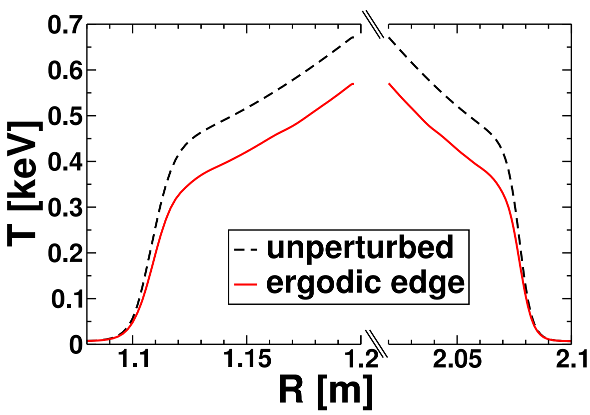

Figure 4: Temperature change in the midplane at low and high field sides from an edge ergodization.

Ergodic Edge

Perturbation field coils have been installed or are planned at several tokamak devices and can be used for mitigation of edge localized modes (ELMs) [8, 9, 10]. The transport of electrons along stochastic field lines is an important element in this process and leads e.g. to an increased heat conduction [2]. At the example of the active coil set projected for ASDEX Upgrade [10], we investigate the effect of an ergodic magnetic field on temperature gradients. The magnetic field generated by the perturbation coils is determined neglecting the plasma response. To account for plasma shielding [5], the coil currents are reduced in return. From Fig. 4, a clear reduction of temperature gradients is observed which reduces the pedestal height by about 20 percent.

Conclusion

Numerical heat diffusion computations are demonstrated in real tokamak geometry with realistic plasma parameters for both the plasma core and boundary. The finite difference scheme used allows to employ coordinates not exactly aligned to the magnetic field direction. Comparing results for heat transport across magnetic islands to experimental measurements indicates that the heat flux limit is essentially valid in fusion plasmas. To find an explanation for the amplitude drop in the FIR-NTM regime, the effect of stochastisation on the resonant bootstrap current perturbation was studied and a strong reduction was observed. Furthermore, the effect of an ergodic plasma boundary on heat transport was investigated revealing a significant reduction of pedestal temperature gradients. The results are discussed in more detail in [15].

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References

[1] R. Fitzpatrick. Phys. Plasmas **2**, 825 (1995).

[2] M. Bécoulet, *et al.*. *20th IAEA Fusion Energy Conference, Vilamoura, Portugal, 2004* (International Atomic Energy Agency, Vienna, 2004), TH/1-3Rc.

[3] S. Günter, *et al.*. Phys. Rev. Letters **87**, 275001-1 (2001).

[4] A. Gude, *et al.*. Nucl. Fusion **42**, 833 (2002).

[5] Q. Yu, *et al.*. Nucl. Fusion **48** 024007 (2008).

[6] Q. Yu. Phys. Plamas **13**, 062310 (2006).

[7] Ph. Ghendrih, *et al.*. Plasma Phys. Control. Fusion **38**, 1653 (1996).

[8] T. E. Evans, *et al.*. Phys. Rev. Letters **92**, 235003 (2004).

[9] O. Neubauer, *et al.*. Fusion Engineering and Design **75–79** 495 (2005).

[10] W. Suttrop, *et al.*. to be published, Proc. of the 35th EPS Plasma Physics Conf. (2008).

[11] S. Günter, *et al.*. J. Comput. Phys. **209**, 354 (2005).

[12] S. Günter, *et al.*. Nucl. Fusion **44**, 524, (2004).

[13] M. Hölzl, *et al.*. Phys. Plamas **14**, 052501 (2007).

[14] J. P. Meskat, *et al.*. Plasma Phys. Control. Fusion, **43**, 1325 (2001).

[15] M. Hölzl, *et al.*. to be published, Phys. Plasmas (2008).