ASDEX Upgrade

Modeling of Diffusive Heat Transport across Magnetic Islands and Stochastic Layers

Matthias Hölzl

Outline

1. Motivation and Introduction
2. Numerical Model
3. Magnetic Islands
4. Ergodic Layers
5. Comparison to Experiment
6. Conclusions and Outlook

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Heat Conduction

Perpendicular Transport

- Limited mobility perpendicular to magnetic field lines
- Dominated by gradient-driven turbulence

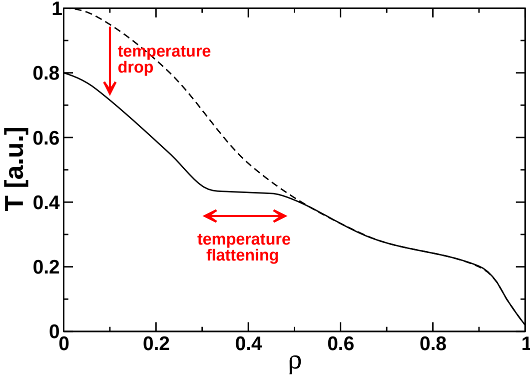
$\Rightarrow \chi_\perp = \mathcal{O}\left(1\ \text{m}^2/\text{s}\right)$

Parallel Transport

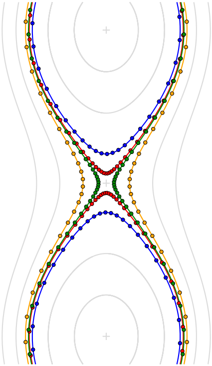
- High mobility along field lines
- Spitzer Härm-conductivity: Random walk-process of electrons with step width = mean free path
- But: Mean free path $\mathcal{O}(\text{ km })$!
- "Heat-Flux-Limit": Limit to free streaming electrons

$\Rightarrow \chi_{||} = ?$

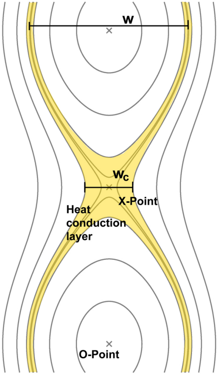
Transport across magnetic islands



Transport across magnetic islands



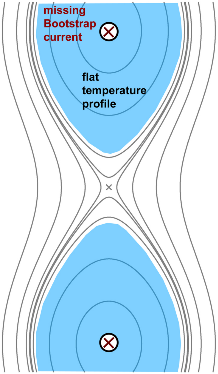
Transport across magnetic islands



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

- Competition between parallel and perpendicular transport
- Scale island width $w_c \propto (\chi_{||}/\chi_{\perp})^{-1/4}$ ◦
- Flattening of temperature profile depends on w/w_c only

Neoclassical Tearing Modes

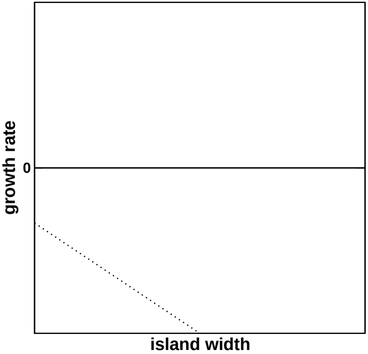


Consequences of temperature perturbation

- Resonant perturbation of Bootstrap current ($j_{bs} \propto \nabla p$)
- Effective lack current causes further island growth

$\Rightarrow$ Neoclassical Tearing Mode (NTM)

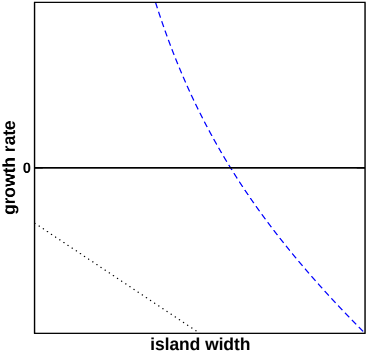
Evolution of (Neoclassical) Tearing Modes



Rutherford Equation

$$\frac{\mathrm{d}w}{\mathrm{d}t} \propto \Delta'(w)$$

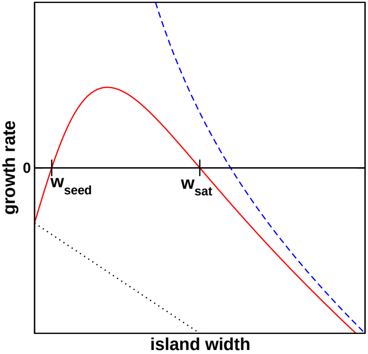
Evolution of (Neoclassical) Tearing Modes



Rutherford Equation

$$\frac{\mathrm{d}w}{\mathrm{d}t} \propto \Delta'(w) + \underbrace{\frac{C}{w}}_{\Delta'_{bs}}$$

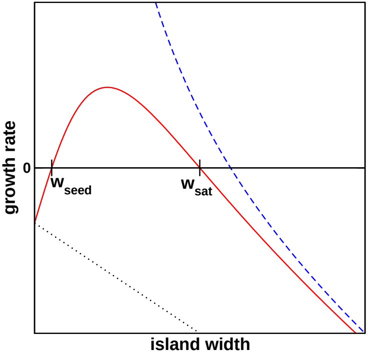
Evolution of (Neoclassical) Tearing Modes



Rutherford Equation

$$\frac{dw}{dt} \propto \Delta'(w) + \underbrace{\frac{C}{w}\left(\frac{w^2}{w^2 + (1.8 w_c)^2}\right)}_{\Delta'_{bs}} \qquad w_c \propto \left(\frac{\chi_{||}}{\chi_{\perp}}\right)^{-1/4}$$

Evolution of (Neoclassical) Tearing Modes



Rutherford Equation

$$\frac{dw}{dt} \propto \Delta'(w) \underbrace{+ \frac{C}{w}\left(\frac{w^2}{w^2 + (1.8 w_c)^2}\right)}_{\Delta'_{bs}} + \Delta'_{pol} + \ldots \qquad w_c \propto \left(\frac{\chi_{||}}{\chi_{\perp}}\right)^{-1/4}$$

Rutherford Equation

Open questions

- Is Fitzpatrick's expression for Δ'_{bs} correct?

$$\Delta'_{bs} = \frac{C}{w}\left(\frac{w^2}{w^2 + (1.8 w_c)^2}\right)$$

- How large is the heat diffusion anisotropy in experiments (determines w_c)?

Approach

- Compute diffusive heat transport numerically
- Compare to predictions and measurements

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Anisotropic heat conduction

Heat conduction equation

$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} + \nabla \cdot \mathbf{q}_e = P_e$$

$$\mathbf{q}_e = -n_e \left[\chi_{||} \nabla_{||} T_e + \chi_{\perp} \nabla_{\perp} T_e \right]$$

n_e	electron density
T_e	electron temperature
q_e	heat flux density
P_e	heat source
$\chi_{\|\|}$	parallel- and
$\chi_{\perp}$	perpendicular heat diffusivity
$\chi_{\|\|}/\chi_{\perp}$	heat diffusion anisotropy

Numerical method

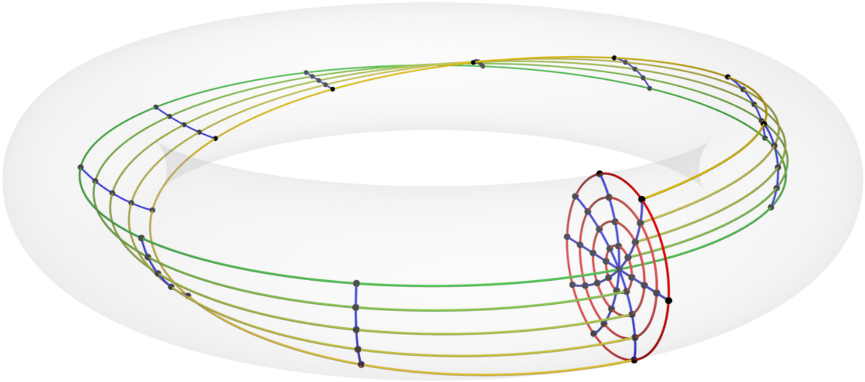
- Problem: Numerical diffusion
- Possibility: Align coordinates to field lines

  Hard to do with dynamic equilibria or ergodization
- Other approach: Symmetric finite differences with staggered grids

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

$\Rightarrow$ No exact alignment of coordinates required

Helical coordinate system



- Flux and Straight field line coordinates
- Transformation of poloidal coordinate

⇒ Unsheared helical coordinate system

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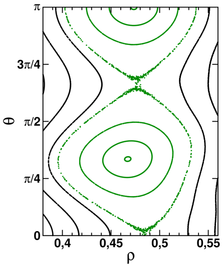
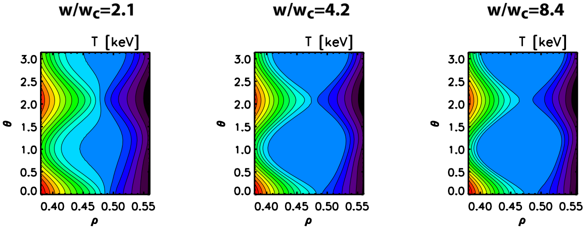
Temperature flattening





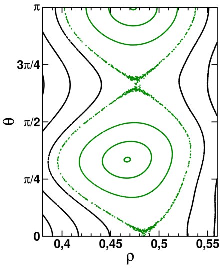
w: island width

$w_c \propto (\chi_{||}/\chi_\perp)^{-1/4}$:
scale island width

[M. Hölzl et.al. *Phys. Plasmas* **15** 072514 (2008)]

- 3/2-island in ASDEX Upgrade
- Flattening for $w/w_c \gtrsim 2$

Temperature flattening



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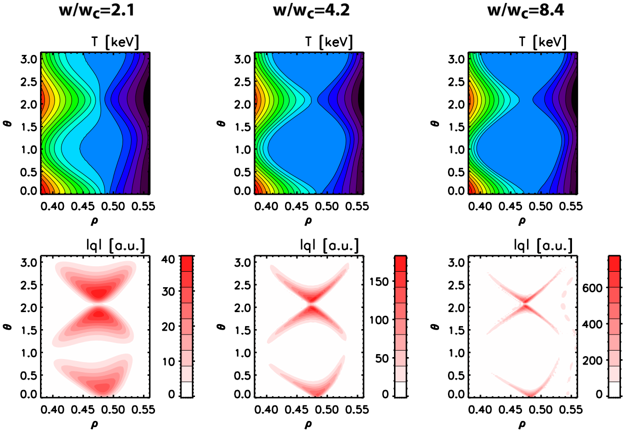

[M. Hölzl et.al. *Phys. Plasmas* **15** 072514 (2008)]

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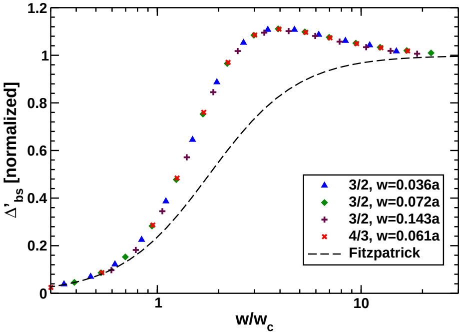
Neoclassical island drive



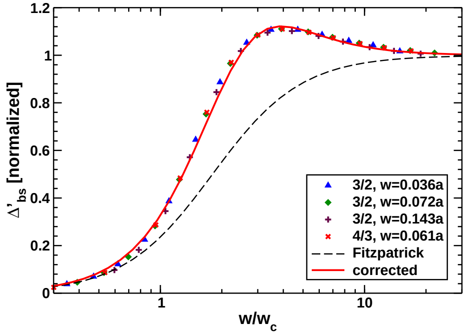
[M. Hölzl et.al. *Phys. Plasmas* **14** 052514 (2007)]

NTM stability

- Destabilization by temperature flattening underestimated by Fitzpatrick (limiting cases agree very well) ◦

$$\Delta'_{bs} = \frac{C}{w}\left(\frac{w^2}{w^2 + w_d^2}\right) \qquad w_d = 1.8 w_c$$

Neoclassical island drive



[M. Hölzl et.al. *Phys. Plasmas* **14** 052514 (2007)]

NTM stability

- Destabilization by temperature flattening underestimated by Fitzpatrick (limiting cases agree very well)

$$\Delta'_{bs} = \frac{C}{w}\left(\frac{w^2}{w^2+w_d^2}\right)\left(1+\frac{2.2}{(w/w_d)^2+3w_d/w}\right) \qquad w_d = 1.8 w_c$$

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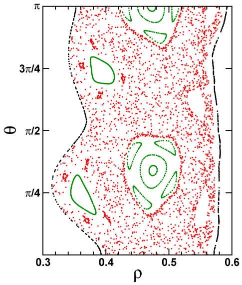
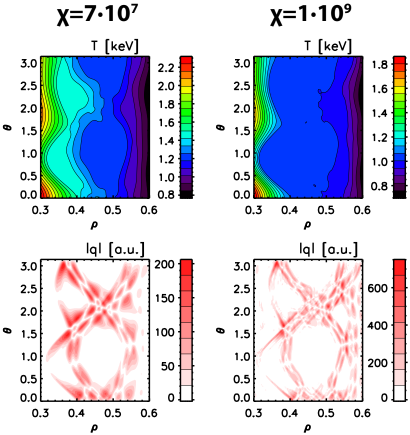
Temperature flattening

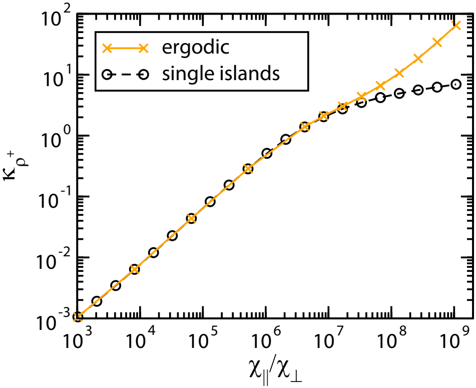


[M. Hölzl et.al. *Phys. Plasmas* **15** 072514 (2008)]



- Small to moderate anisotropies: Island effects dominate
- High anisotropies: Flattening of whole ergodic layer

Island and ergodic effects



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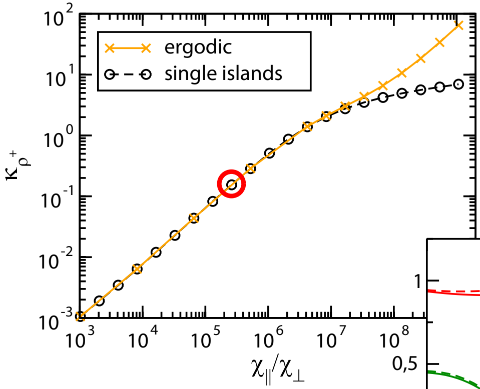
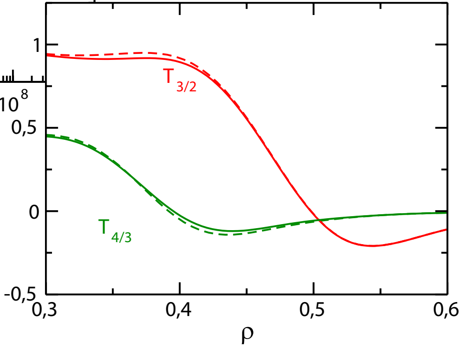
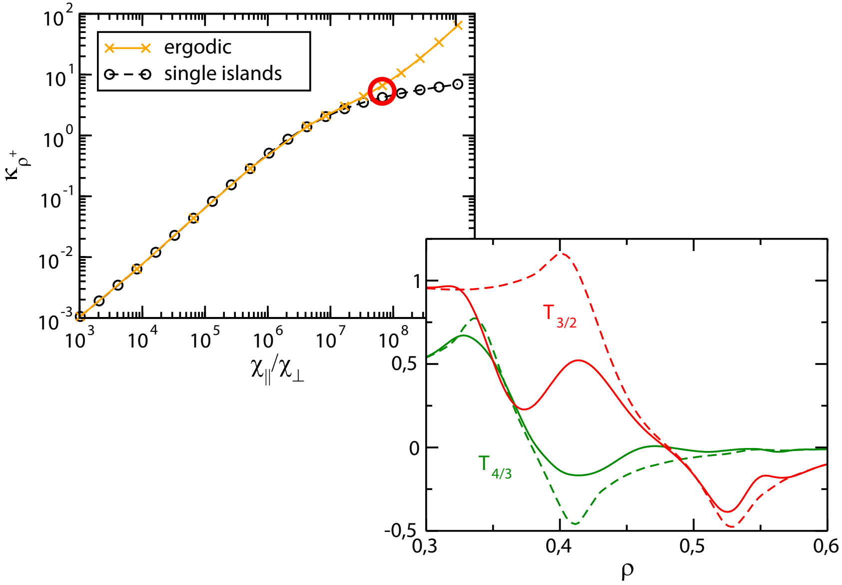
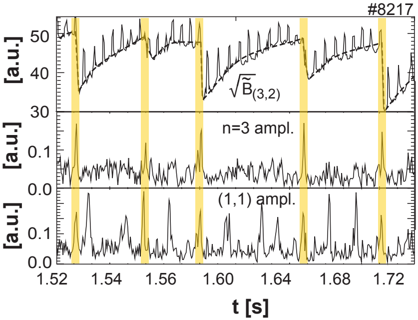


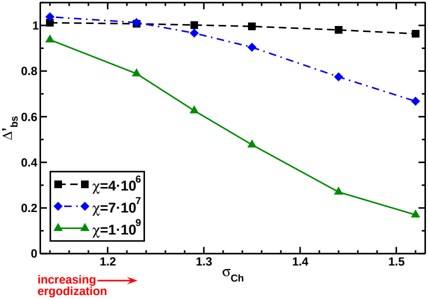


Island and ergodic effects



NTMs in the frequently interrupted regime (FIR-NTMs)





[A. Gude et.al. *Nucl. Fusion* **39** 127 (1999)]

[S. Günter et.al. *Nucl. Fusion* **43** 161 (2003)]

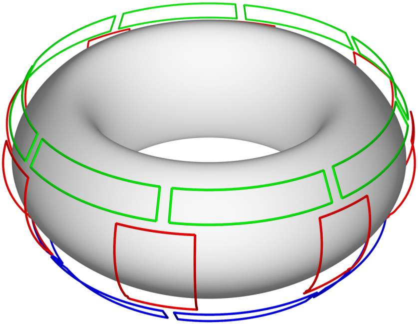
[M. Hölzl et.al. *Phys. Plasmas* **15** 072514 (2008)]

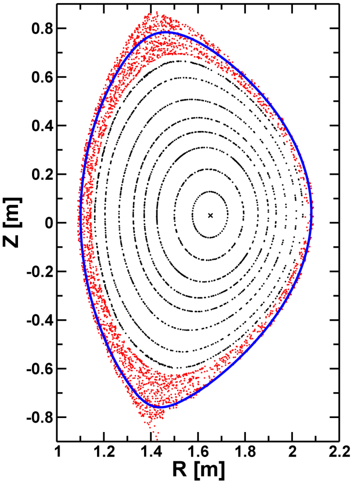
- High plasma pressure: Frequent amplitude drop

$\Rightarrow$ Reduced average amplitude

- Correlated with other mode activity
- Possible explanation: Ergodization

Ergodic plasma boundary

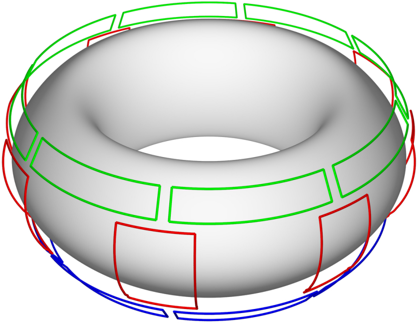


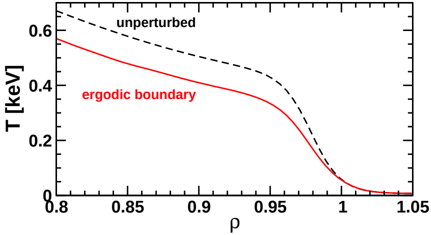


ASDEX Upgrade

- Ergodization of the plasma boundary by auxiliary coils
- Aim: Suppression of ELMs

Ergodic plasma boundary





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[M. Hölzl et.al. *Phys. Plasmas* **15** 072514 (2008)]

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Comparison to Experiment

Approach

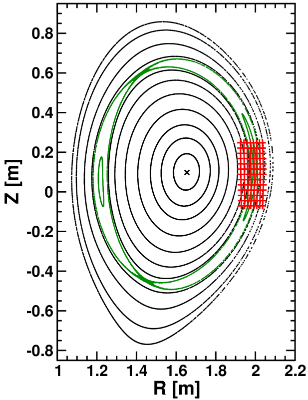
- Consider electron temperature at magnetic island
- Simulations with several island widths, w, and heat diff. anisotropies, $\chi_{||}/\chi_{\perp}$
- Select simulation that reproduces measurements best (minimize quadratic differences)

$\Rightarrow$ Determine w and $\chi_{||}/\chi_{\perp}$ independently for each transit

Comparison to Experiment

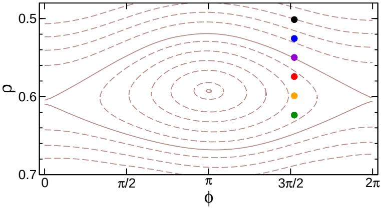
ECE-Imaging

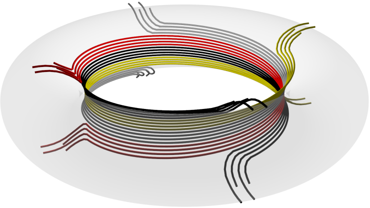
- Electron cyclotron emission spectroscopy with several lines of sight
- Noise reduction by singular value decomposition ◦
- Select one line of sight:
  - Radial coverage
  - Channel quality
  - Channel positions



- Radial information: Several channels
- Toroidal information: Time-traces
- Calibration against 1D ECE
- Fine-calibration to ensure that T is approximately flat inside large island

Comparison with 2/1 island in TEXTOR





[M. Hölzl et.al. *Nucl. Fusion* **49** 115009 (2009)]

- Produced by DED-coils; comparison while island grows

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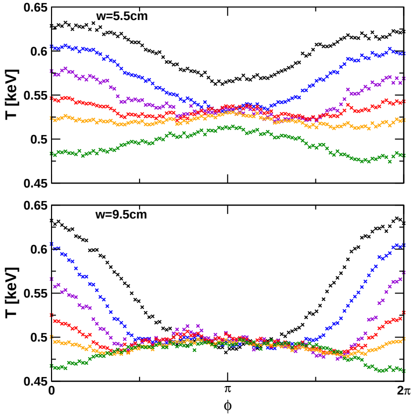

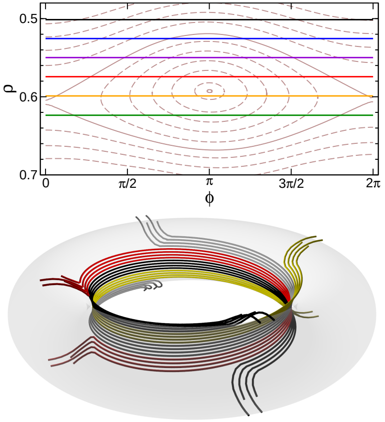

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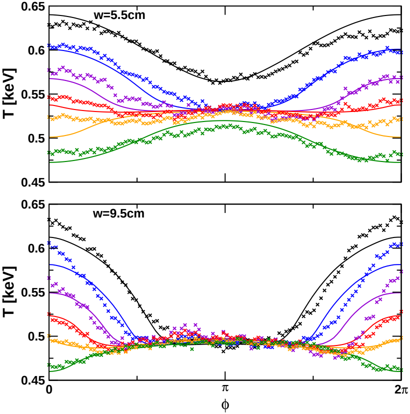

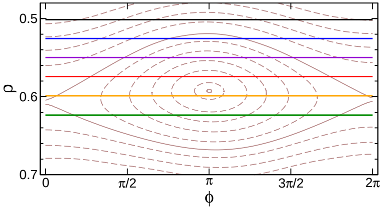

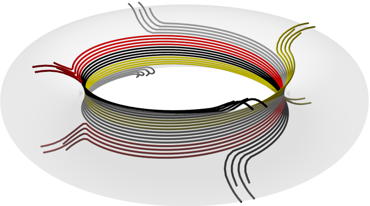

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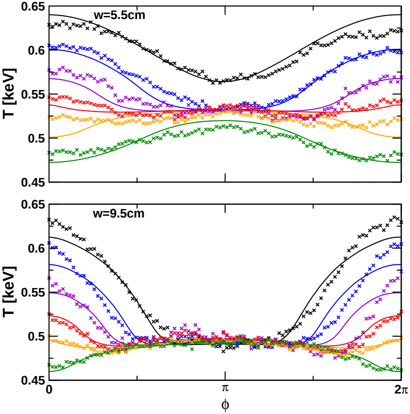

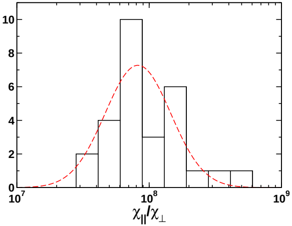

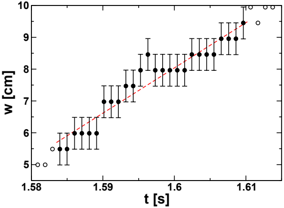

[M. Hölzl et.al. *Nucl. Fusion* **49** 115009 (2009)]

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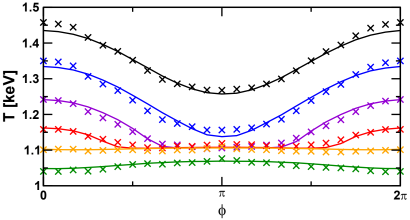
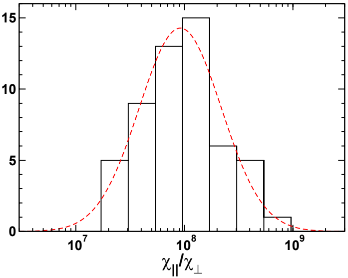
Comparison with 2/1 NTM in ASDEX Upgrade

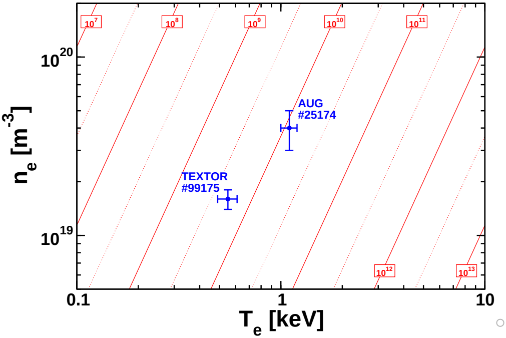




Overview

- Discharge #25174, $t = 2.037$ s … 2.142 s
- 2/1 NTM ($\approx$ 5 kHz, 540 transitions)
- ECE-Imaging (100 kHz sampling frequency)
- Noise suppression: SVD + average of 10 transitions

Summary: Comparison with Experiments



TEXTOR:	2/1 RMP-island	$T_e = 0.6\text{keV}$	$n_e = 1.6 \cdot 10^{19}\text{m}^{-3}$	$\chi^{SH} = 10^{9.8 \pm 0.2}$	$\chi = 10^{8.0 \pm 0.4}$
AUG:	2/1 NTM	$T_e = 1.1\text{keV}$	$n_e = 4.0 \cdot 10^{19}\text{m}^{-3}$	$\chi^{SH} = 10^{10.1 \pm 0.3}$	$\chi = 10^{8.0 \pm 0.4}$

$\Rightarrow$ "Measurement" of heat diffusion anisotropy

$\Rightarrow$ Clear indication for heat-flux limit, more data needed!

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Conclusions and Outlook

Summary

- Heat transport across magnetic islands and stochastic layers
- Δ'_{bs} larger than analytically predicted
- Island effects at stochastic layers
- FIR-NTM: Reduction of Δ'_{bs} by ergodization
- Transport across ergodic plasma boundary
- Determination of $\chi_{||}/\chi_{\perp}$ by comparison to experiments

Outlook

- Work with and improve nonlinear MHD code `JOREK`
- But also continue the presented work...

Additional comparisons with experiments

Aims

- NTM with power ramp-down
  - $\Rightarrow$ Verify heat flux limit theories
  - $\Rightarrow$ Determine marginal w/w_c
- NTM with ECRH
  - $\Rightarrow$ Investigate $\chi_\perp$ inside island

Requirements

$T_e(r)$: 1D and 2D ECE

$n_e(r)$: IDA

$T_i(r)$, $v_{tor}(r)$: CXRS $\quad\Rightarrow\quad$ $P_e(r)$: TRANSP

Separate discharge with 0.5% B_t-ramp in quiescent phase for calibration

Acknowledgments

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ASDEX Upgrade Team

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Ivo Classen

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Rainer Fischer

Erika Strumberger

Scale island width, w_c

$$w_c = \left(\frac{\chi_{||}}{\chi_\perp}\right)^{-1/4} \left(\frac{8 R_0 q_s}{n \left(\partial q / \partial r\right)_s}\right)^{1/2}$$

q_s Resonant value of the safety factor

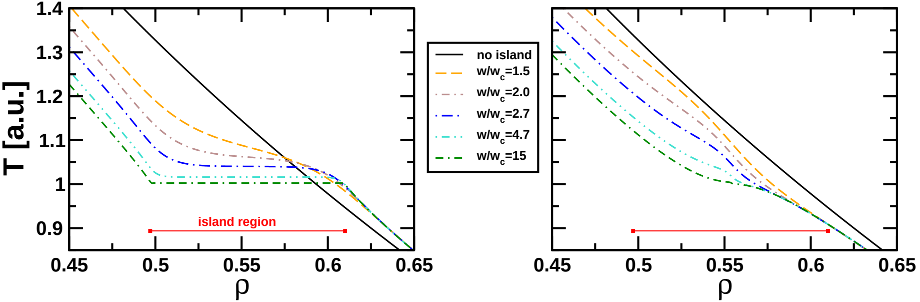
R_0 Major radius

n Toroidal mode number

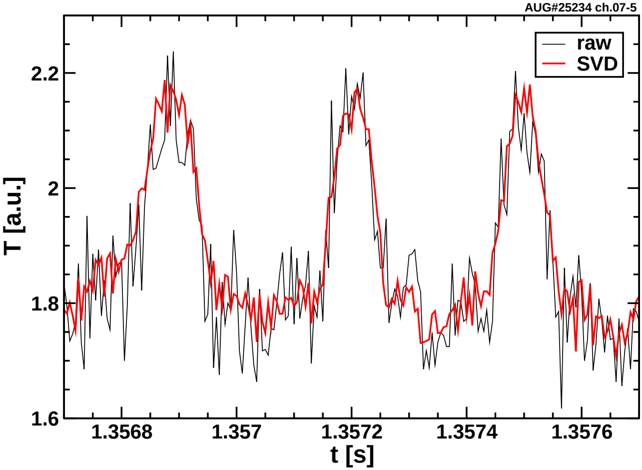
Spitzer Härm diffusivity

$$\chi_{||}^{SH} = 3.16 \cdot v_{th,e} \cdot \lambda_{mfp,e} \approx 3.6 \cdot 10^{29}\ \mathrm{m^2/s} \cdot \frac{T_e^{5/2}[\mathrm{keV}\ ]}{n_e[\mathrm{m}^{-3}\ ]}$$

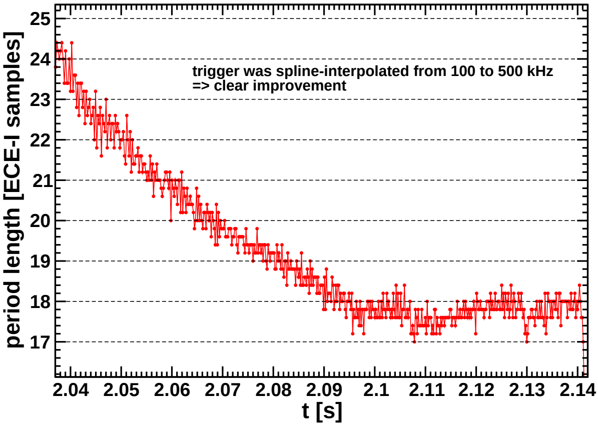
Temperature distribution at O- and X-Points



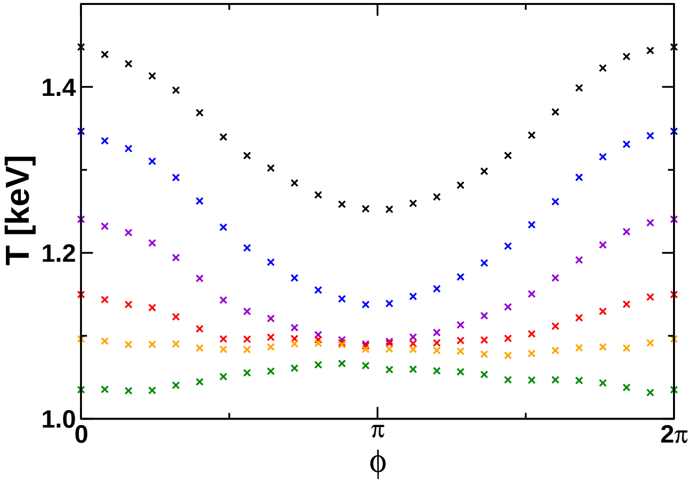
Singular Value Decomposition



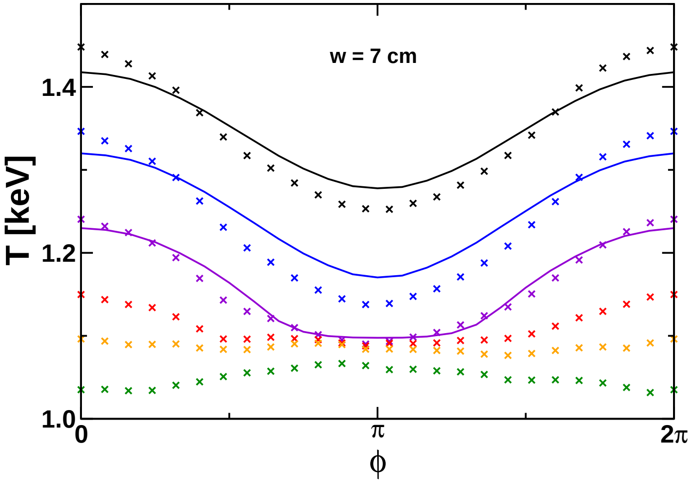
AUG: Period length of 2/1 NTM



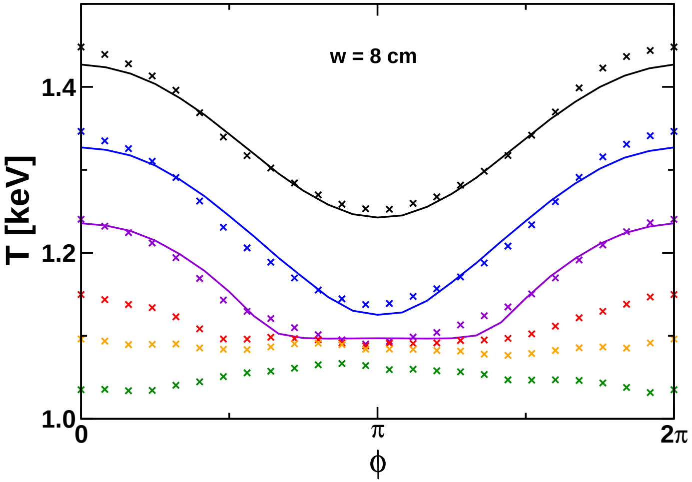
Sensitivity



Sensitivity



Sensitivity



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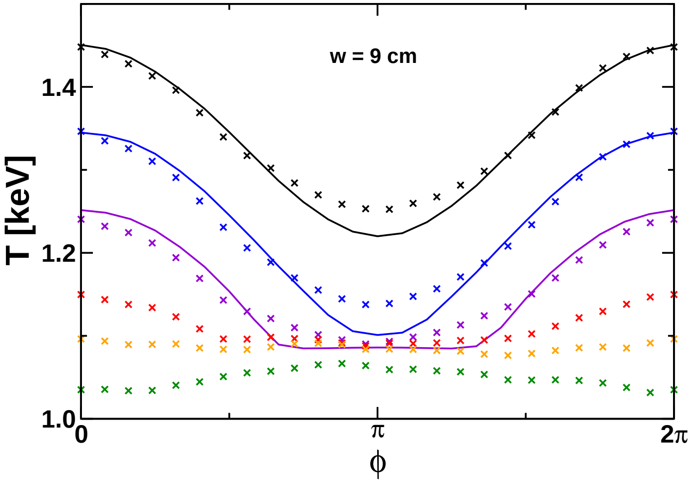

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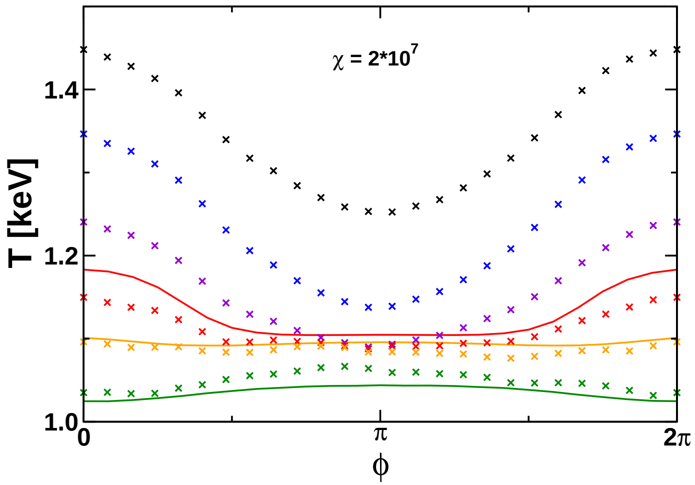

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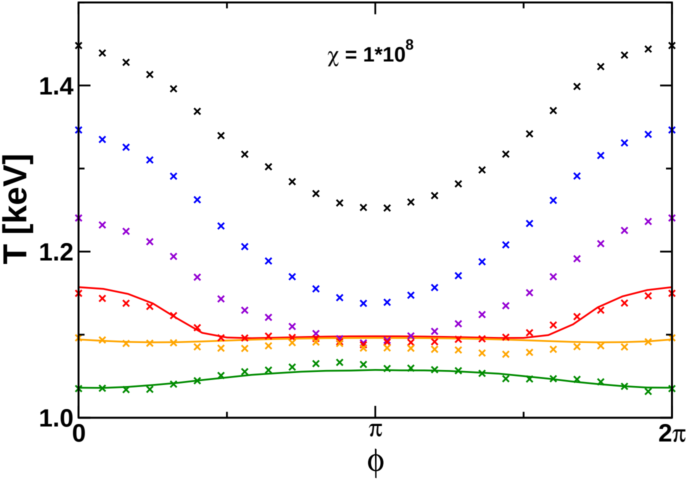

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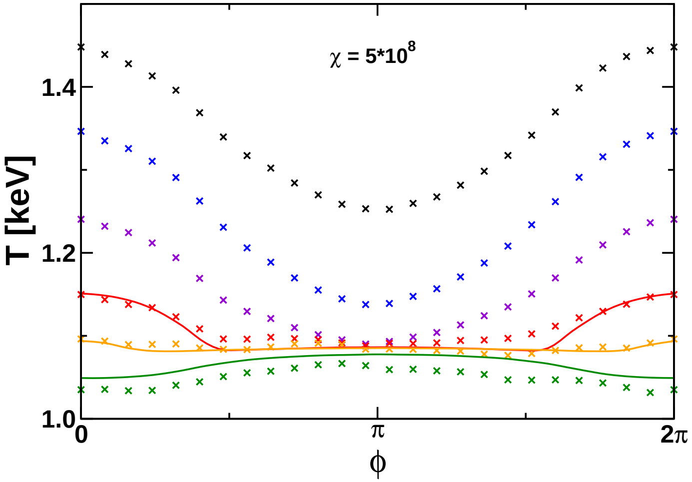
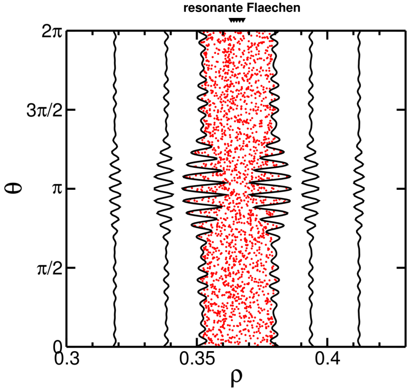
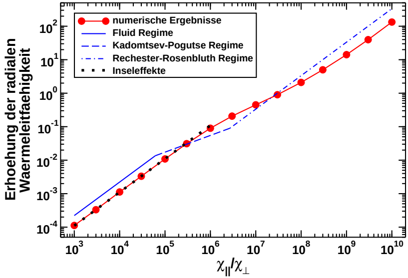


Strong ergodization





[M. Hölzl et.al. *Phys. Plasmas* **14** 052514 (2007)]

Highly ergodic configuration

- Artificial case: Five helical perturbations, cylindrical geometry
- Allows for comparison to analytical theories