The coupling of mesoscale magnetic islands with micro-scale turbulence

William Hornsby, Arthur Peeters[2] and the GKW group[1], Emanuele Poli, Mattia Siccinio[3]

[1] Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[2] University of Bayreuth, Bayreuth, Germany
[3] Max-Planck-Institute fur Plasmaphysik, Boltzmannstrasse 2,Garching, Munich, Germany

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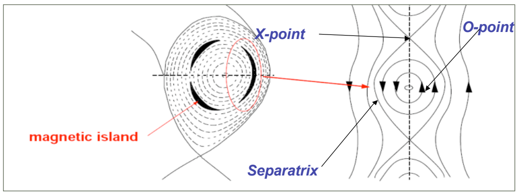
Multi-scale dynamics receives a large amount of interest in the current literature, with a wide range of application. A magnetized plasma presents a perfect system for the study of the dynamical interactions since it supports different waves and instabilities over a wide range of scales. Multi-scale dynamics is furthermore crucial for the understanding of various phenomena in astro-physics as well as laboratory plasmas. A prominent example in astro-physics is the influence of small scale dynamics on the large scale dynamo. In laboratory plasmas, the influence of meso-scale structures on small scale turbulence is expected to affect heat and particle transport properties, although the exact mechanisms are poorly understood. The interaction between small scale turbulence (of the order of the Larmor radius) and meso scale magnetic islands is investigated through the use of a massive parallel computing approach. Meso scale here refers to a scale length substantially larger than the ion Larmor radius, but smaller than all other length scales(the gradient length of the temperature and density profiles, for instance). Meso-scale magnetic islands are formed through reconnection of the magnetic field, and are commonly obtained in both laboratory and astro-physical plasmas.

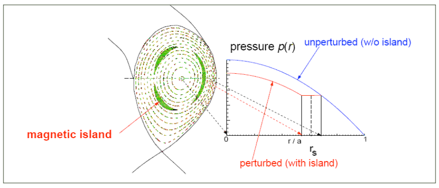
What are (Neoclassical) Tearing modes

Tearing modes are a non-ideal MHD plasma instability which, due to reconnection (Resistive diffusion):

1. Introduces a deformation of the magnetic topology in the form of a rotating magnetic island.
2. This in turn introduces a radial component of the magnetic field!! Radial magnetic field connects the outer part of the island to the inner.

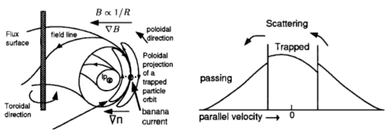


Fast parallel dynamics causes rapid radial transport causes flattening of temperature/density/pressure profiles which can be seriously detrimental to energy confinement times and can cause disruptions.



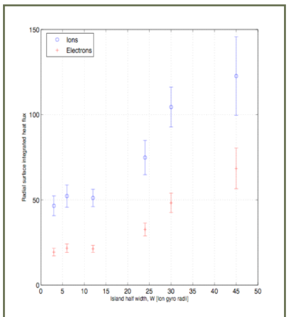
Stability of the classical tearing mode is determined by the induced plasma current.

The presence of the magnetic island adds a perturbation to the Bootstrap current, which is produced by interaction between TRAPPED and PASSING particles in combination with radial pressure gradients.



$$j_{bs} \approx -\frac{1}{\sqrt{\varepsilon}B_t}\frac{dP_e}{dr}$$

Effect of Island on confinement



The ion and electron heat fluxes for varying island widths showing a distinct increase in heat flux at large island sizes.

Fast parallel transport causes a flattening within the island, but a steepening of gradients just outside separatrix.

Zonal flows are modified to flow around island and helps move heat around island.

Net effect is to enhance the radial heat flow.

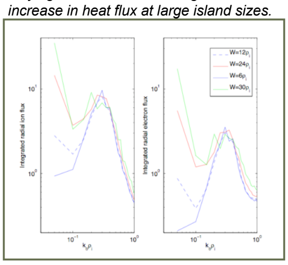
Further contribution to heat flow by vortex formed within island.

Decomposed fluxes -> Largest mode increases with island size

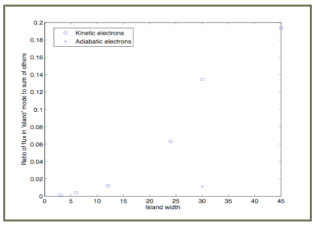
Other modes are invariant to island width.

Adiabatic treatment of electrons doesn't develop vortex.

Vortex is time varying and can become positively and negatively charged -> Not from equilibrium considerations. No collisions included so generation of vortex likely from turbulence.

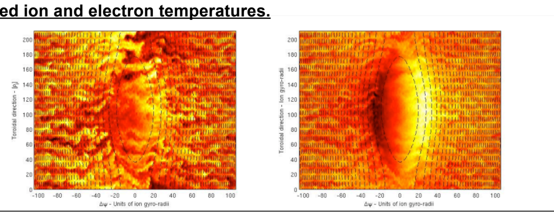


The contribution to the electrostatic heat flux from the different toroidal modes as a function of the normalized poloidal wave vector for different island sizes. The left panel shows the spectra for ions and right shows the electron spectra for four different island widths.



Fraction of radial heat flow due to vortex mode as a function of island width, W.

Perturbed ion and electron temperatures.



Assume a large islands -> The case in these simulations.

The flattening within an island is caused by the dominance of parallel flows.

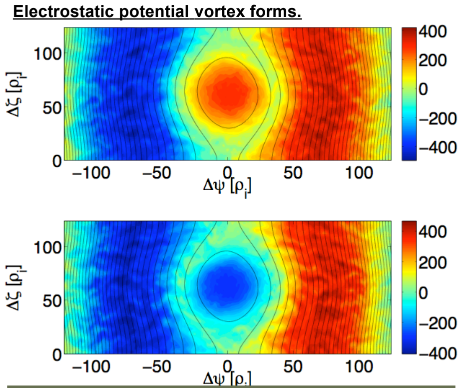
$$\chi_{\parallel}\nabla^2 T_{\parallel} + \chi_{\perp}\nabla^2 T_{\perp} = 0$$

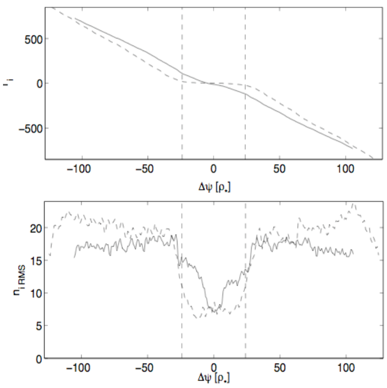
If parallel heat flow is much much larger than perpendicular then temperature becomes a flux quantity.

$$\chi_{\parallel}\nabla^2 T_{\parallel} \gg \chi_{\perp}\nabla^2 T_{\perp}$$

Electron Temperature profile should be totally flat in our simulations.

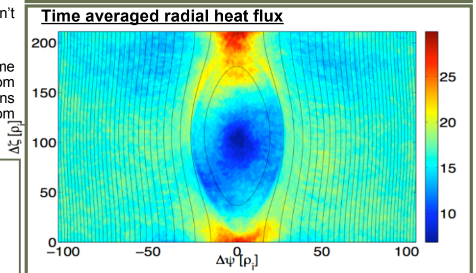
Electrostatic potential vortex forms.





Bottom panel: Root mean square ion density fluctuations through the O-points for simulation runs with $\Delta k=21k_l$ (dashed) and $\Delta k=41k_l$ (solid). Top panel: The corresponding ion temperature profiles through the O-points.

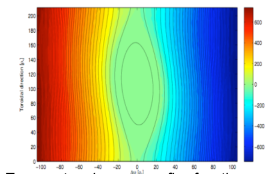
Time averaged radial heat flux



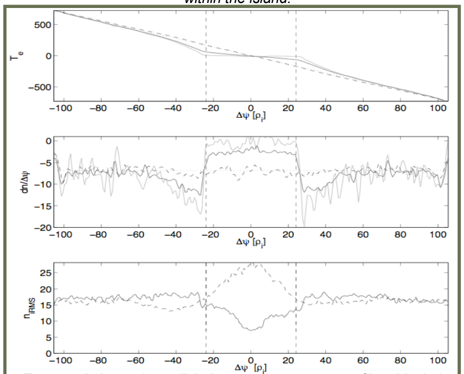
The radial heat flux in a slice through the flux tube at the low field side of the torus.

The heat mainly flows via the X-points and is largely suppressed at the O-point location. An interesting point is the poloidal asymmetry about the X-point that is present in the heat flux, and by proxy, the turbulence within the island. This suggests the mechanism by which the turbulence moves from the X-point is linked to the particle drifts with eddies able to convect through the island in the drift direction.

Total temperature.



Temperature becomes a flux function within the island.



Top panel shows the radial electron temperature profiles, black: Low field side, gray: High field side. Middle panel shows the corresponding electron temperature gradients, black: Low field side, gray: High field side.. Bottom panel shows the RMS density fluctuation profile showing a decay of the fluctuation strength within the island. Dashed lines represent lines through the X-point in all three panels.

Turbulence not generated in island. Enhanced outside separatrix.

Process of turbulence spreading -> Turbulence advected from areas where it is generated. Turbulence within island means perpendicular transport not negligible.

Passing particles flatten. *Experience the full magnetic perturbation. Parallel streaming is dominant.*

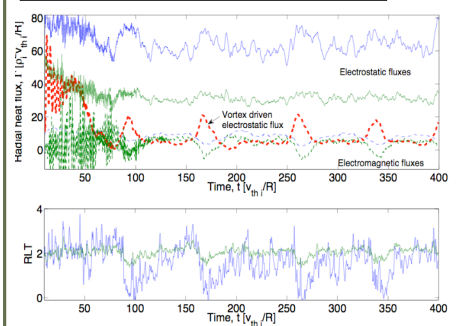
$$\chi_{\parallel}\nabla^2 T_{\parallel} \gg \chi_{\perp}\nabla^2 T_{\perp}$$

Trapped particles don't flatten. *Due to their bouncing don't experience full island. Parallel transport diminished.*

$$\chi_{\parallel}\nabla^2 T_{\parallel} \ll \chi_{\perp}\nabla^2 T_{\perp}$$

Trapped particle fraction $\sqrt{\epsilon} \sim 0.5$ therefore, as witnessed, flattening is half what is expected.

Traces of Heat Flux and the role of the vortex.



Top: time traces of the total electrostatic (full lines) and magnetic flutter (dashed thin lines) turbulent heat fluxes integrated over the whole simulation volume for ions (blue lines) and electrons (green lines) during the converged stage of a simulation with a magnetic island width of w=24rho. The thick red dotted line gives the electrostatic heat flux generated by the modes with the same poloidal wavelength as the island. Bottom: Time traces of the normalised average electron (green line) and ion (blue line) density gradients at the O-point. The drop in density gradients is a measure of the strength of the potential vortex within the island.

Perturbation in Bootstrap current needed for NTM drive. However. Without the trapped particles flattening drive is diminished.Critical island width can be estimated. If we compare the diffusion time across island, to the time it takes for particle trapping/detrapping:

$$\tau_D \sim w^2/D_{\perp} \qquad \tau_t \sim r/R\nu_s$$

Comparing the two:

$$w_c = \sqrt{2D_{\perp}r/R\nu_s}$$