Highlights from Sherwood 2015

International Sherwood Fusion Theory Conference

March 16-26, Courant Institute at NYU
New York City, New York




Dimitri Ryutov (LLNL) kicked off the Sherwood meeting with his review talk, **"Divertor theory: plasma transport in complex geometries"**. He covered the history and purpose of various divertor geometries, in particular the idea of improving divertor performance by modifying the poloidal magnetic field structure. Two other review talks were given by **Alexander Schekochihin** (U. of Oxford, UK) on **"Phase mixing vs. turbulence in a drift kinetic plasma"**, and **Todd Evans** (General Atomics) on **"3D Magnetic perturbation effects on confinement during ELM control experiments".**

Altogether, there were 15 invited talks spanning the field of fusion theory on topics such as three-dimensional edge plasma and neutral gas modeling, neoclassical tearing modes, two-fluid simulations, turbulence, thermal island destabilization, and non-axisymmetric MHD equilibria. Author-provided summaries of several of the invited talks are included on pages 7 to 15 of this document.

There was a very strong showing by graduate students, postdocs, and young scientists at the meeting. More than 35 students from around the world presented papers. A list of all participating students can be found on page 5.

From left to right:

Plenary speakers Dr. Alexander Schekochihin (University of Oxford, UK), Dr. Dmitri Ryutov (Lawrence Livermore National Laboratory), and Dr. Todd Evans (General Atomics).

Images from the Sherwood Poster Sessions (top to bottom, left to right):

Alan Turnbull (GA), Bruno Coppi (MIT), and Alan Glasser (U. of Washington); Antoine Cerfon (NYU) and Xianzhu Tang (LANL); Dylan Brennan (PPPL), Carl Sovinec (U. of Wisconsin) and Fatima Ebrahimi (Princeton U.); Chris Hegna (U. of Wisconsin) and Scott Kruger (Tech-X Corporation); Hank Strauss (HRS Fusion), Linda Sugiyama (MIT), and Guoyong Fu (PPPL); James Callen (U. of Wisconsin) and Jesus Ramos (MIT).

Six "Student Poster Awards" were given to the following students for their exceptional presentations:

Ioannis Keramidas Charidakos (University of Texas at Austin)
"A Hamiltonian Five Field Gyrofluid Model"

Carson R. Cook (University of Wisconsin)
"Analytical theory and numerical investigation of the shear Alfvén continuum in the presence of an island"

C. Leland Ellison (Princeton Plasma Physics Laboratory)
"Incorporation of Collisional Effects in Variational Algorithms for Guiding Center Test Particle Trajectories"

Dov J. Rhodes (Columbia University)
"Sharp-Boundary Non-Ideal Plasma Response Model with a Ferritic-Resistive Wall"

Wrick Sengupta (University of Maryland)
"Closed set of full-f low flow ordered drift kinetic equations to study evolution of profiles"

Ryan L. White (University of Texas at Austin)
"Resistive Instabilities with Equilibrium Rotation and Velocity Shear"

Student Poster Award Winners (from left to right): Wrick Sengupta, Dov Rhodes, Carson Cook, Alexander Wurm (Chair of the Sherwood Executive Committee), C. Leland Ellison, Ryan White; not pictured: Ioannis Keramidas Charidakos. Congratulations!

Students presenting papers at Sherwood:

1. Stephen Abbott, U. of New Hampshire
2. Jian Bao, Peking University
3. Joshua Burby, PPPL
4. Timothy Collart, Georgia Tech
5. Carson Cook, U. of Wisconsin
6. Tyler Cote, U. of Wisconsin
7. Vinicius Duarte, PPPL
8. C. Leland Ellison, PPPL
9. Silvia Espinosa-Gutiez, MIT
10. Benjamin Faber, U. of Wisconsin
11. Dustin Fisher, Dartmouth College
12. Manaure Francisquez, Dartmouth College
13. Michael Halfmoon, U. of Tusla
14. Jonathan Hebert, Auburn U.
15. Eric C. Howell, U. of Wisconsin
16. Wenlong Huang, U. of Sci.&Tech of China
17. Spencer James, U. of Tulsa
18. Ioannis Keramidas Charidakos, U. of Texas
19. Isabel Krebs, PPPL
20. Calvin K. Lau, UC Irvine
21. Wonjae Lee, UCSD
22. Meng Li, U. of Texas
23. Chang Liu, PPPL
24. Jingfei Ma, U. of Texas
25. Dov Rhodes, Columbia U.
26. Nicholas A. Roberds, Auburn U.
27. Adam Stahl, Chalmers U.
28. Joshua Sauppe, U. of Wisconsin
29. Wrick Sengupta, U. of Maryland
30. Eric Shi, PPPL
31. Tengfei Tang, LLNL
32. Qian Teng, PPPL
33. Ryan White, U. of Texas
34. George Wilkie, U. of Maryland
35. Hua-sheng Xie, Zhejiang U.
36. Liu Yaqi, Peking University
37. Yao Zhou, PPPL
38. Ben Zhu, Dartmouth College

Included on the following pages are highlights from several Sherwood Invited Speakers:

3D Magnetic Perturbation Effects on Confinement during ELM Control Experiments
Todd E. Evans, General Atomics

3D Two-Fluid Braginskii Simulations of the Large Plasma Device
Dustin M. Fisher, Dartmouth College

Phase-Locking of Multi-Helicity Neoclassical Tearing Modes in Tokamak Plasmas
Richard Fitzpatrick, University of Texas at Austin

Three-dimensional edge plasma and neutral gas modeling with the EMC3-EIRENE code on the example of RMP application in tokamaks - status and development plans
Heinke Frerichs, University of Wisconsin

Universal instability, non-modal amplification, and subcritical turbulence
Matt Landreman, University of Maryland

Computation of singular currents at rational surfaces in non-axisymmetric MHD equilibria
Joaquim Loizu, Max-Planck/Princeton Center for Plasma Physics

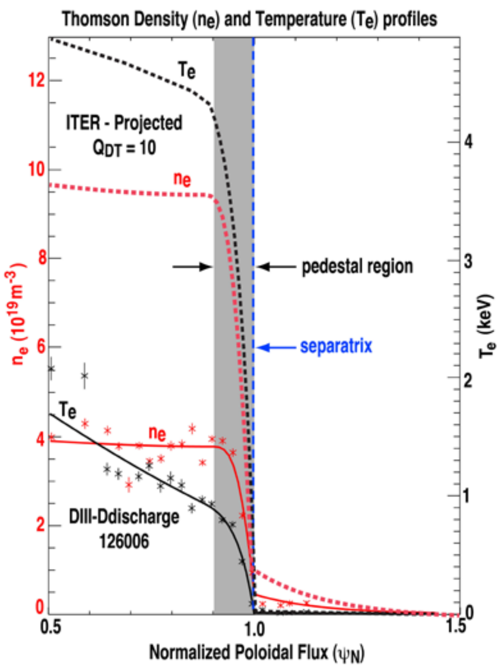
Seed island for NTM driven by turbulence
Magali Muraglia, Aix-Marseille Université, France

TEM turbulence in stellarators - its simulation and its optimization
Josefine Proll, Max-Planck/Princeton Center for Plasma Physics

Thermal island destabilization and the Greenwald limit
Roscoe B. White, Princeton Plasma Physics Laboratory

3D Magnetic Perturbation Effects on Confinement during ELM Control Experiments* T.E. Evans**,** General Atomics, San Diego, CA 92186-5608, USA

Experiments in Ohmic to L-mode and H-mode plasmas have demonstrated that the energy, momentum and particle confinement is significantly more sensitive to small 3D magnetic perturbation than theoretically expected. In Ohmic plasmas with relatively strong vacuum field stochasticity, the thermal diffusivity is increased by approximately 2 orders of magnitude in the edge stochastic region while the core energy confinement is maintained or moderately improved. In low triangularity H-mode plasmas with electron density and temperature profiles such as those shown in the figure on the right, ion and electron temperatures can increase significantly in the core and slightly in the edge due to the applied 3D magnetic field perturbations, while the particle confinement in the edge is typically degraded. Moderate improvements in the particle confinement have also been observed in the core plasma with some plasma configurations. These results contradict theoretical expectations based on the existence of an edge stochastic layer due to overlapping resonant magnetic islands as determined from vacuum magnetic field modeling. In H-mode plasmas, one hypothesis is that strong electron fluid poloidal flows in the pedestal region screen the resonant field components, which prevents the formation of a stochastic layer. If this is the case, then a mechanism is needed to explain the relatively large drop in the edge particle confinement while maintaining reasonably good H-mode energy confinement. Understanding the plasma response to these applied 3D magnetic perturbations has become a high priority in fusion research as a result of recent successes in stabilizing Edge Localized Modes (ELMs) with Resonant Magnetic Perturbation (RMP) fields. This talk provided experimental results found during the application of RMP fields in various tokamaks including changes in the particle, energy and momentum confinement during ELM suppression. Implications of these results for ITER and fusion energy research were also be discussed.



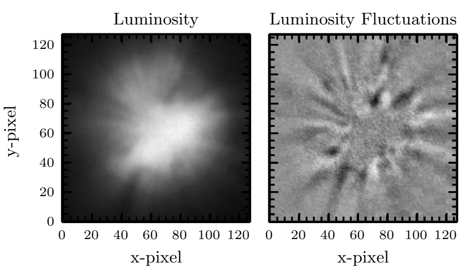
Comparison of edge profiles in DIII-D with those projected in ITER

*This work was supported in part by the US Department of Energy under DE-FC02-04ER54698 and DE-SC0012706.

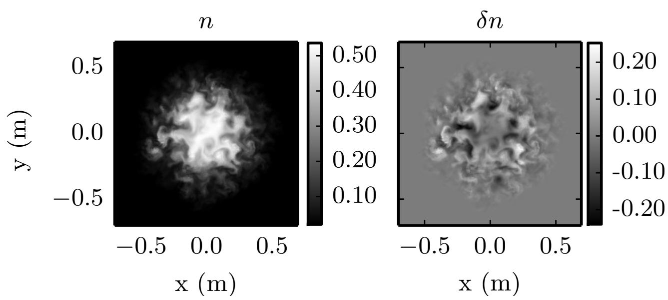
3D Two-Fluid Braginskii Simulations of the Large Plasma Device

Dustin M. Fisher*, Barrett Rogers*, Giovanni Rossi†, Danny Guice†
*Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755
†Department of Physics and Astronomy, University of California, Los Angeles, California 90095

The Large Plasma Device (LAPD) is modeled using the 3D Global Braginskii Solver code (GBS). Comparisons to experimental measurements are made in the low-bias regime in which there is an intrinsic E×B rotation of the plasma due to sheath effects. Comparisons show good agreement with the equilibrium electric potential, density, and temperature profiles, the radial dependence of the density fluctuations, cross-correlation lengths, radial flux dependence outside of the cathode edge, and camera imagery. Kelvin Helmholtz (KH) turbulence at relatively large scales is the dominant driver of cross-field transport in these simulations with smaller-scale drift waves playing a secondary role. Plasma holes and blobs arising from KH vortices in the simulations are consistent with the scale sizes and overall appearance of those in LAPD camera images. The addition of ion-neutral collisions in the simulations at previously theorized values reduces the radial particle flux by about a factor of two, from values that are somewhat larger than the experimentally measured flux to values that are somewhat lower than the measurements. This reduction is due to a modest stabilizing contribution of the collisions on the KH-modes driving the turbulent transport.

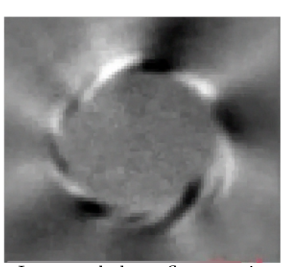


CCD luminosity data from a Phantom camera looking down the length of the LAPD. Total luminosity (left); Luminosity fluctuations (right). Radii larger than 60 cm are affected by lens distortion and the chamber wall.

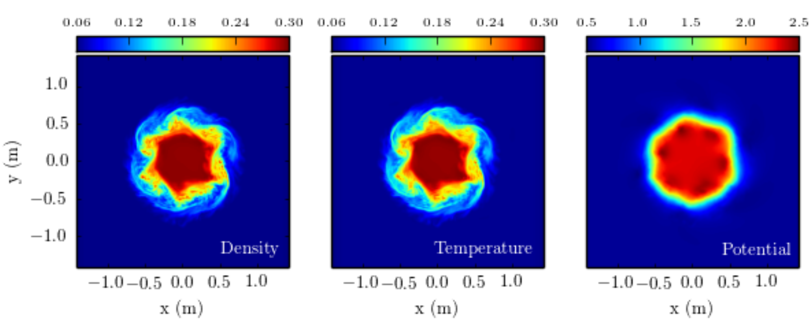


A typical density cut showing a density hole interior to the cathode edge and density blobs outside of the ionization front (left); Density fluctuations found by subtracting the time-averaged mean density (right).

Preliminary work on modeling the LAPD with a biased limiter has shown the emergence of an $m \simeq 6$ mode that arises when the plasma rotation is increased. This mode is also seen in the experiment and is likely due to KH turbulence. Similar work has been done to decrease the shear flow by biasing the limiter in the opposite direction and current simulations are aimed at nulling this shear flow to study drift wave modes in the absence of Kelvin-Helmholtz.



Increased shear flow run in LAPD using a biasable limiter.



Simulation data showing cross-field cuts of the density, temperature, and potential. An $m \simeq 6$ mode can be seen similar to that in LAPD.

Phase-Locking of Multi-Helicity Neoclassical Tearing Modes in Tokamak Plasmas

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The University of Texas at Austin, Austin, TX

Conventional high-beta tokamak plasmas are characterized by a single, relatively benign, neoclassical tearing mode (NTM)---typically, the m=3, n=2 mode. The so-called hybrid scenario combines comparatively high q_95 operation with improved confinement compared with the conventional H_98, y2 scaling law. If this kind of scenario could be reproduced on ITER then it would enable high-Q operation at reduced plasma current. Somewhat unusually, hybrid discharges tend to exhibit simultaneous NTMs with different mode numbers. For example, 2,1 and 3,2 NTMs have been observed simultaneously in both DIII-D and JET hybrid discharges. In addition, 4,3 and 5,4 NTMs have been observed simultaneously in JET hybrid discharges. In most cases, the different modes are eventually observed to phase-lock to one another, giving rise to a significant flattening, or even a reversal, of the core toroidal plasma rotation profile. This behavior is highly undesirable because the loss of core plasma rotation is known to have a deleterious effect on plasma stability (because it facilitates locked mode formation).

We present a simple cylindrical model of the phase-locking of two or more NTMs with different poloidal and toroidal mode numbers in a tokamak plasma. Such locking takes place via a combination of nonlinear three-wave coupling and conventional toroidal coupling: e.g., 2,1+2,1=4,2 and 3,2+1,0=4,2, where the 1,0 perturbation corresponds to the Shafranov shift of the equilibrium flux-surfaces.

In accordance with experimental observations, the model predicts that there is a bifurcation to a phase-locked state when the frequency mismatch is reduced to half of its original value. Furthermore, the phase-locked state is characterized by the permanent alignment of the X-points of the NTM island chains on the outboard mid-plane, and a modified toroidal angular velocity profile interior to the outermost coupled rational surface that is such that the core rotation is flattened, or even inverted.

Three-dimensional edge plasma and neutral gas modeling with the EMC3-EIRENE code on the example of RMP application in tokamaks - status and development plans

H. Frerichs

The development of a reliable computational model for the plasma edge in non-axisymmetric configurations is essential for both the interpretation of present day magnetic confined fusion experiments and for guiding the design activities for future next step devices such as ITER and Wendelstein 7-X. Three-dimensional models are required for a detailed analysis of the impact of resonant magnetic perturbations (RMPs) in tokamaks and for intrinsically non-axisymmetric stellarator configurations. One such tool is the EMC3-EIRENE code, a coupled transport solver for the fluid edge plasma in self-consistent interaction with neutral gas.

An overview on recent results from application of the model to scenarios with RMP fields at the DIII-D tokamak has motivated model extensions such as corrections to the classical parallel electron heat conduction and a modification of the magnetic field structure due to MHD effects. Nevertheless, it has been demonstrated that the experimental observation of a clear striation pattern in the target particle load without such a pattern in the target heat load can be reproduced by adjusting recycling conditions in the simulations (figure 1), although some discrepancies regarding the total power balance remain.

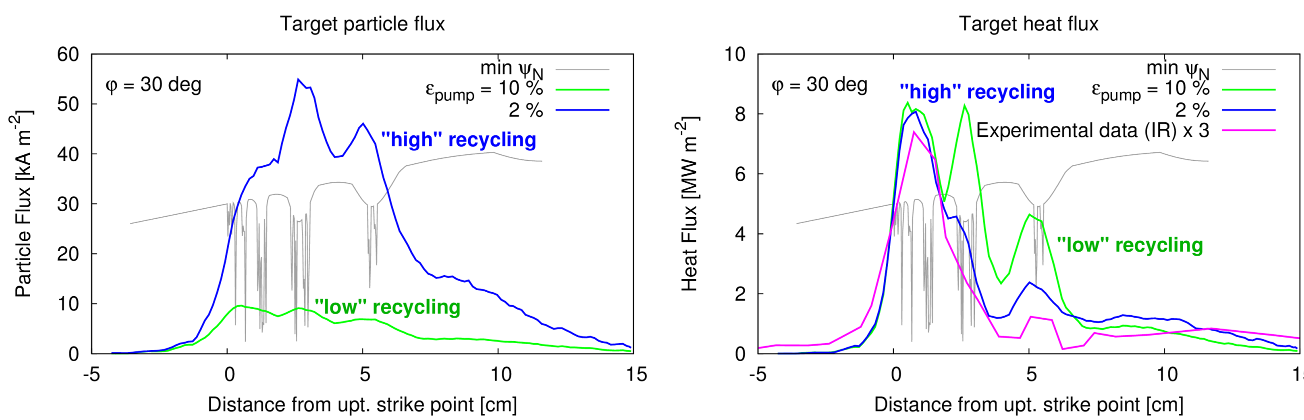

Figure 1. Particle and heat flux profiles at the inner strike point. Recycling conditions are controlled by adjusting the pumping coefficient ε_{pump}.

Of particular interest for magnetic confined fusion are so called 'detached' divertor plasmas with significantly reduced particle and heat loads onto divertor targets. However, numerical access to these conditions is challenging, and it has been demonstrated by a two-point model (2PM) analysis that numerical instabilities might be related to the nature of the simulation procedure itself. An adaptive relaxation scheme has been introduced which allows to stabilize simulations (figure 2).

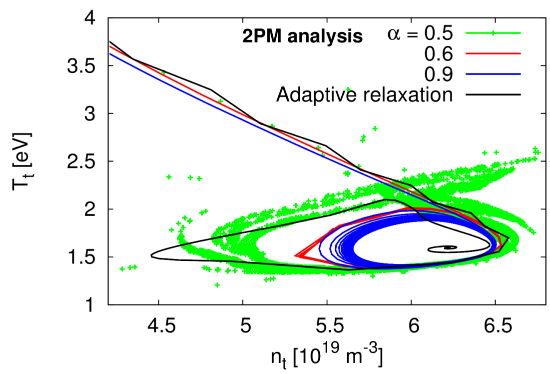

Figure 2: Iterated target density and temperature for fixed and adapted relaxation.

Universal instability, non-modal amplification, and subcritical turbulence

Matt Landreman[1], Gabriel G. Plunk[2], Thomas M. Antonsen Jr.[1], William Dorland[1]
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The "universal instability" has been discounted since several widely-cited papers in 1978 [1-3] concluded this drift wave was absolutely stable for any nonzero magnetic shear, but we challenge these earlier findings and demonstrate a variety of interesting behaviors in the system. First, contrary to [1-3], the drift wave in a sheared magnetic field can be absolutely unstable even with no temperature gradients, no trapped particles, and no magnetic curvature [4]. Our findings differ from the 1978 results because the earlier work used an eigenmode equation limited to $k_x \rho_i \ll 1$, whereas we find instability at $k_x \rho_i > 1$ using a gyrokinetic approach that is not similarly limited. Second, even with parameters for which the system is linearly stable, many orders of magnitude of transient (non-modal) linear amplification can occur before exponential decay sets in [5]. Non-modal amplification has been widely studied in other systems with sheared flows, but the drift-wave system provides a unique example in which large linear transients can arise without flow shear. Third, turbulence can be sustained nonlinearly in this system even when all eigenmodes are decaying [5], a phenomenon seen previously in fluid models [6-7] and which we demonstrate kinetically. Generalizing an argument from neutral Navier-Stokes dynamics [8], we prove transient linear amplification (in the gyrokinetic free-energy norm) is required for sustained turbulence. While the standard eigenvalue analysis of the linearized problem does not give a necessary condition for sustained turbulence, a modified eigenvalue problem does provide a necessary condition [5].

[1] Ross & Mahajan, *Phys. Rev. Lett.* **40**, 324 (1978).
[2] Tsang & Catto, *Phys. Rev. Lett.* **40**, 327 (1978).
[3] Antonsen, *Phys. Rev. Lett.* **41**, 33 (1978).
[4] Landreman, Antonsen, & Dorland, *Phys. Rev. Lett.* **114**, 095003 (2015).
[5] Landreman, Plunk, & Dorland, arXiv:1501.02980 (2015).
[6] Scott, *Phys. Rev. Lett.* **65**, 3289 (1990).
[7] Drake, Zeiler, & Biskamp, *Phys. Rev. Lett.* **75**, 4222 (1995).
[8] DelSole, *J. Atmos. Sci.* **61**, 1086 (2004).

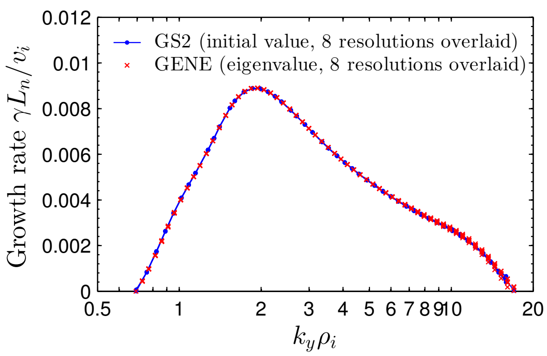

Figure 1: Demonstration that absolute linear instability is seen by multiple gyrokinetic codes in the presence of magnetic shear and a density gradient, even with no temperature gradients, no trapped particles, and no magnetic curvature [4].

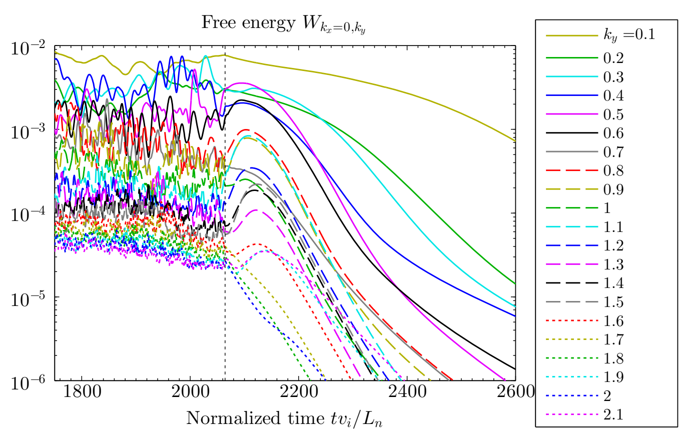

Figure 2: Gyrokinetic turbulence without linear instability [5]. Following a period of saturated turbulence, the nonlinear term is turned off at the time denoted by the vertical dashed line. All Fourier components of the energy then decay since there is no linear instability (as the instability of Figure 1 is suppressed at the collisionality used here), though certain components first display transient linear amplification.

Computation of singular currents at rational surfaces in non-axisymmetric MHD equilibria

J. Loizu[1], S. Hudson[2], A. Bhattacharjee[2], S. Lazerson[2] and P. Helander[3]

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[2] *Princeton Plasma Physics Laboratory, PO Box 451, Princeton NJ 08543, USA*
[3] *Max Planck Institute for Plasma Physics, Wendelsteinstr. 1, 17491 Greifswald, Germany*

Ideal MHD predicts the existence of singular current densities forming at rational surfaces in three-dimensional equilibria with nested flux surfaces. These current singularities consist of a Pfirsch-Schlüter 1/x current density that arises around rational surfaces as a result of finite pressure gradient and a Dirac δ-function current densiy that develops at rational surfaces and presumably prevents the formation of islands that would otherwise develop in a non-ideal plasma. These currents play a crucial role in describing (1) the plasma response to non-axisymmetric boundary perturbations, (2) the equilibrium and stability of non-axisymmetric, toroidally confined plasmas, and (3) the triggering of reconnection phenomena such as tokamak sawteeth. While analytical formulations have been developed to describe such currents in simplified geometries, a numerical proof of their existence has been hampered by the assumption of smooth functions made in conventional MHD equilibrium models such as VMEC. Recently, a theory based on a generalized energy principle, referred to as multiregion, relaxed MHD (MRxMHD), was developed and incorporates the possibility of non-smooth solutions to the MHD equilibrium problem. Using SPEC, a nonlinear implementation of MRxMHD, we provide the first numerical proof of their mutual existence and a novel theoretical guideline for the numerical computation of three-dimensional ideal MHD equilibria with singular currents [1]. Examples of such kind of equilibria are shown for both slab and cylindrical geometries (Figure 1), and the numerical results are thoroughly verified against analytical predictions from linearly perturbed ideal MHD equilibria. Based on these results, we present the hypothesis that non-axisymmetric MHD equilibria with nested surfaces and discontinuous rotational transform at resonant surfaces are well defined and can be computed perturbatively. This rescues the possibility of constructing MHD equilibria with continuous and smooth pressure profiles.

[1] J. Loizu, S. Hudson, A. Bhattacharjee and P. Helander, Phys. Plasmas **22** 022501 (2015)

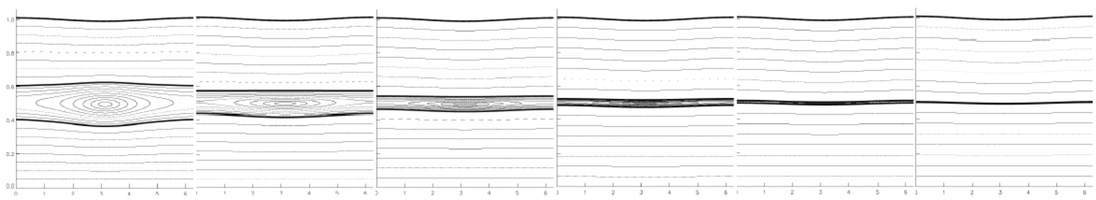

Figure 1. Sequence of MRxMHD equilibria demonstrating the shielding of an island in slab geometry. The island is produced around the rational surface that resonates with the perturbation at the boundary. In the fully shielded state, a singular current density manifests in the form of a discontinuity in the magnetic field.

Seed island for NTM driven by turbulence

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2. CeLIA, University Bordeaux – CNRS – CEA, Talence 33405, France
3. CEA, IRFM, Saint-Paul_lez_Durance, France
4. Institute for Plasma Research, Bhat, Gandhinagar 382428, India

Magnetic reconnection can be problematic for tokamak plasmas: tearing modes (neoclassical or otherwise) grow slowly expelling energetic particles from the plasma core and possibly lead to disruption phenomena that can terminate the discharge and cause damage to the plasma facing components. However, the neoclassical tearing modes (NTMs) are not associated to a linear instability (the so-called Δ' parameter is negative) and require pre-existing seed islands to grow [1]. In experiments, precursors such as sawtooth oscillations, fishbones instabilities or edge localized modes could appear before a NTM. These precursors are supposed to trigger the requested seed island. However, sometimes, a NTM can grow without any noticeable MHD event [2]. Thus, the question of the origin of the seed magnetic island is still an open question for fusion reactor and we investigate the possibility that seeds are trigger the turbulence. Indeed, first, in tokamaks, macro-scale MHD instabilities (magnetic islands) coexist with micro-scale turbulent fluctuations and zonal flows [3], and some recent works have shown the microturbulence impact on the island dynamics [4, 5, 6]. Second, in [4], 2D nonlinear simulations have shown that the nonlinear beating of the fastest growing small-scale interchange modes on a given rational surface drives a magnetic island located on the same surface. Here, we show that such turbulent driven seed islands can be amplified by the current bootstrap leading to a self-consistent generation of a NTM, as illustrated on Fig. 1: a large magnetic island is well observed during the nonlinear asymptotic regime. Moreover, such turbulence driven NTMs present a significant signature : the pressure flattening inside the island is partial, *i.e.* the pressure gradient inside the island is finite and constant in space and in time [7].

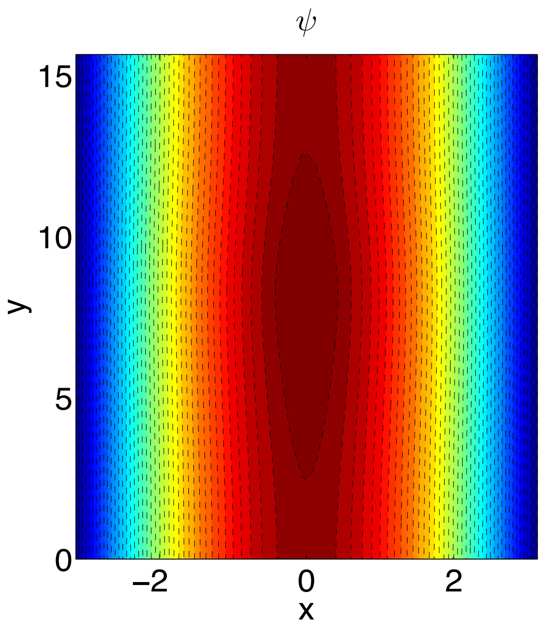


Fig. 1 : Poloidal cut of the magnetic flux during the nonlinear regime

[1] R.J. La Haye and O. Sauter, NF, **38**, 7 (1998)
[2] A. Isayama *et al.,* JPFR, **8**, 1402013 (2013)
[3] B.J. Ding *et al.*, PPCF, **46**, 1467 (2004)
[4] M. Muraglia *et al.*, PRL, **107**, 095003 (2011)
[5] A. Ishizawa *et al.*, NF, **53**, 053007 (2013)
[6] A. Poyé *et al.*, POP, submitted
[7] O. Agullo *et al.*, POP, **21**, 092303 (2014)

TEM turbulence in stellarators - its simulation and its optimization

J.H.E. Proll[1,2], B.J. Faber[3], P. Helander[2], S.A. Lazerson[4], H.E. Mynick[4] and P. Xanthopoulos[2]

[1] Max-Planck/Princeton Center for Plasma Physics
[2] Max Planck Institute for Plasma Physics, Wendelsteinstr. 1, 17491 Greifswald, Germany
[3] Department of Physics, UW-Madison, Madison, WI 53706, USA
[4] Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

Stellarators, the twisted siblings of the axisymmetric fusion experiments called tokamaks, have historically suffered from confining the heat of the plasma insufficiently compared with tokamaks and were therefore considered to be less promising candidates for a fusion reactor. This has changed, however, with the advent of stellarators in which the neoclassical transport is reduced to levels below that of tokamaks by shaping the magnetic field accordingly. As in tokamaks, the turbulent transport remains as the now dominant transport channel and the question arises how the optimization towards low neoclassical transport affects the microinstabilities that drive the turbulent transport, such as the trapped-electron mode (TEM). Recent analytical theory [1] suggests TEMs are stable in large parts of parameter space in perfectly quasi-isodynamic stellarators. In these configurations, the propagation of drift waves is in opposite direction than the precessional drift of the trapped particles. TEMs, which can be understood as drift waves being driven unstable by resonant trapped particles, should therefore be stable. It was shown in linear numerical simulations [2] that even configurations like Wendelstein 7-X, which is only approaching quasi-isodynamicity, benefit from enhanced TEM stability. Here, first-of-a-kind density-gradient-driven TEM turbulence simulations are presented demonstrating that this enhanced stability also results in reduced transport compared with the tokamak DIII-D or with HSX, a quasi-helically symmetric stellarator in Madison, Wisconsin. In HSX, some of the trapped particles are resonant with the drift waves, which explains the increased level of TEM turbulence.

When designing a method of optimization for future stellarators we thus aim at changing the magnetic field such that this resonance exists for as few particles as possible. This purely geometric property of a configuration can be calculated without the need for turbulence simulations and is therefore suited to be used in optimization codes like STELLOPT [3]. A first proof-of-principle optimization has been performed with HSX as the starting equilibrium. The resulting optimized configuration does indeed have lower TEM transport levels compared with HSX, however, the requirement of helical symmetry was not included in the optimization (Fig.1).

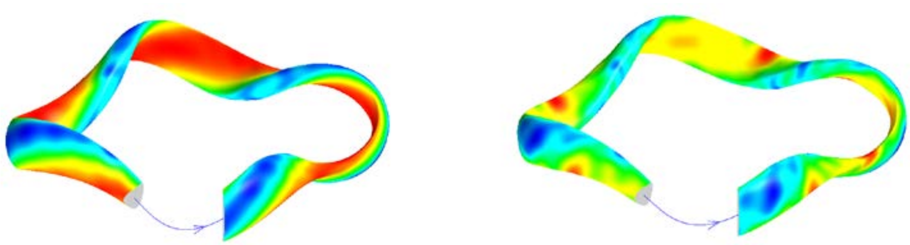


Figure 1: The magnetic field strength B of the initial HSX on the left and the TEM-optimized equilibrium on the right. Maxima of the field are shown in red, minima in blue. The TEM-optimized field is not helically symmetric anymore.

[1] P. Helander, J.H.E. Proll and G.G. Plunk, Phys. Plasmas **20** 122505 (2013)
[2] J.H.E. Proll, P. Xanthopoulos and P. Helander, Phys. Plasmas **20** 122506 (2013)
[3]D.A. Spong, *et al*. Nucl. Fusion **41** 711 (2001)

Thermal island destabilization and the Greenwald limit

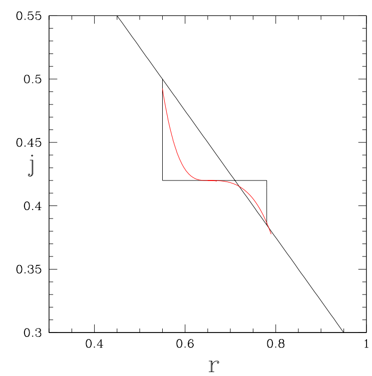
R. B. White, D. A. Gates, and D. P. Brennan

Princeton Plasma Physics Laboratory

Disruption is a serious issue in a tokamak, often preceded by the growth of a large m=2 magnetic island. Predicting disruption onset in a burning plasma is important.

A magnetic island saturates at a width which produces a minimum in the magnetic energy of the configuration. Because field lines in an island are isolated from the outside plasma an island can heat or cool depending on the balance of Ohmic heating and radiation loss in the interior, changing the resistivity and hence the current in the island.

Island evolution is determined by the instability of the initial profile, $\Delta'(w)$, and by additional terms due to current perturbation in the island. The first is well known, a perturbation δj contributing to neoclassical tearing, $\Delta'_{\delta j}(w)$. Due to the large slope of the perturbed helical flux in the island, an island is asymmetric, larger toward the inside of the plasma than toward the outside. Current flattening produces a net negative current perturbation in the island giving a large contribution due to island asymmetry $\Delta'_A(w)$.

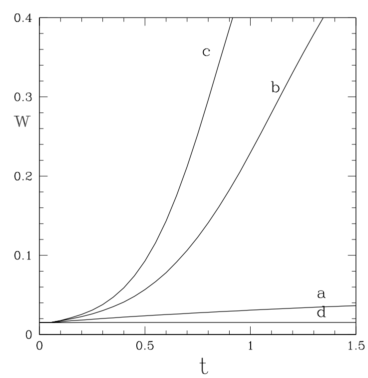


1. Cut through island O-point. Island asymmetry produces a negative current modification.

Evolution of island width w is then given by

$$\frac{dw}{dt} = r_s^2[\Delta'(w) + \Delta'_{\delta j}(w) + \Delta'_A(w)]$$

with time in units of the resistive time $\tau_R = r_s^2/\eta$. The new destabilizing term, along with island cooling of one percent producing a positive $\Delta'_{\delta j}(w)$ proportional to w, gives exponential island growth to large width, potentially leading to large scale plasma loss, leading to a density and impurity dependent limit, a candidate for the Greenwald limit. Models for radiation and heating are being developed, and this effect is also being investigated with fully 3-D codes including heat transport.



2. Island evolution with a) radiation and heating balanced, b) and c) radiation dominated, d) heating dominated.