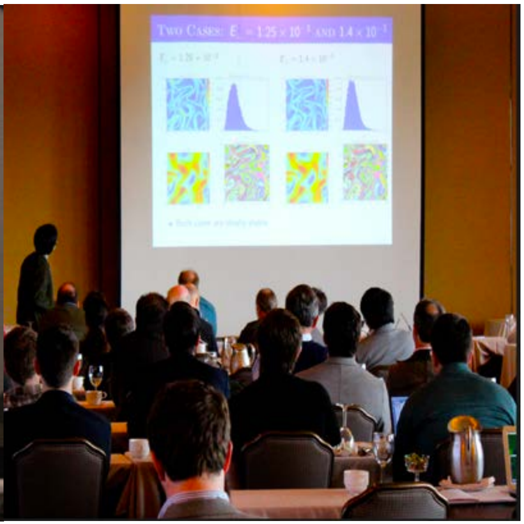
Highlights from Sherwood 2014

International Sherwood Fusion Theory Conference

March 24-26, Bahia Resort Hotel,
San Diego, California



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Rob Goldston (PPPL) kicked off the Sherwood meeting with his review talk, **"Understanding and innovation in magnetic fusion"**. He covered a history of results from tokamak experiments in the areas of core confinement, stability, sustainment – tying the paradigms for understanding all three to the plasma edge, where outstanding questions remain. Two other review talks were given by **Russel Caflisch** (UCLA) on **"Accelerated simulation of coulomb collisions in plasmas"**, and **Dan Barnes** (Tri Alpha) on **"Plasma theory as private enterprise".** Altogether, there were 15 invited talks spanning the field of fusion theory on topics such as nonlinear gyrokinetic simulations of the tokamak edge, plasma-wall modelling, toroidal rotation, zonal flows, magnetic field-line reconnection, coulomb collisions, and intrinsic momentum transport. Author-provided summaries of several of the invited talks are included on pages 7 to 14 of this document.

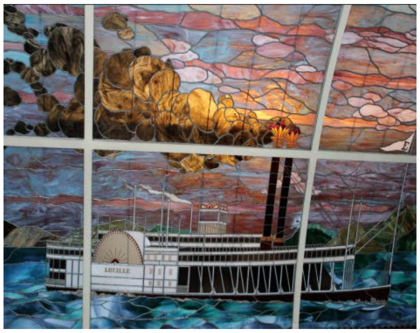
There was a very strong showing by graduate students, postdocs, and young scientists at the meeting. More than 25 students from around the world presented papers. A list of all participating students can be found on page 5 of this document

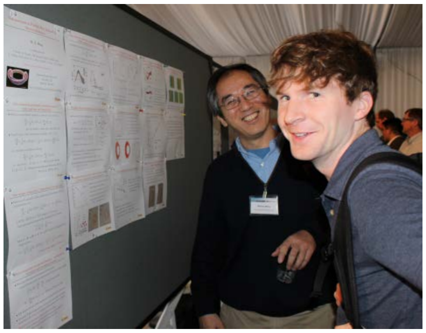
From left to right:

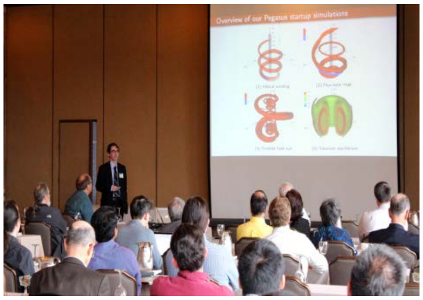
Plenary speakers Prof. Jeff Freidberg (MIT) and Prof. Rob Goldston (PPPL), with Prof. Sergei Krashenninikov (UCSD), Chair of the Sherwood Local Arrangements Committee.

STUDENT POSTER AWARDS

Six students were honored with the Sherwood Poster Award, for their outstanding presentations. Thirty-three graduate students attended Sherwood 2014; the full list is provided on page 5.







Student Poster Award Winners (from left to right): Spencer James, Josh Burby, Christopher Hansen, Jingfei Ma, Chenhao Ma, Joshua Sauppe with Prof. Chris Hegna, Chair of the Sherwood Executive Committee. Many Congratulations!

Top right photos: Weixing Wang, PPPL and Justin Ball, Oxford University graduate student, discussing a poster; John O'Bryan, Wisconsin graduate student, presenting his talk.

Images from the Sherwood Poster Sessions (top to bottom, left to right): Weixing Wang, PPPL; Brendan Lyons, PPPL; Gaimin Lu, SIP, and Alan Turnbull, GA; Samual Lazerson, PPPL, and Jonathan Hebert, Auburn; Jacob King, Tech-X, and Maxim Umansky, LLNL; Abhay Ram, MIT, and Lisa Marie Imbert-Gerard NYU Courant Institute; Carl Sovinec, Wisconsin; George Hagstrom NYU Courant Institute; Alex Wurm, Western New England Univ.; Michael Halfmoon, University of Tulsa; Caroline Martins, UT Austin; Gary Staebler, GA; Phil Morrison, UT Austin; Deng Zhao, Peking University; Andrea Bercerra, Wisconsin; Alan Boozer, Columbia.

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

Joshua Burby (Princeton Plasma Physics Laboratory)
“Variational integrators for perturbed non-canonical Hamiltonian systems”
Christopher Hansen (University of Washington)
“The PSI-TET framework for 3D MHD: application to injector coupling and current drive in HIT-SI”
Spencer James (University of Tulsa)
“Self-consistent calculations of the interaction between drift wave turbulence and the tearing mode”
Chenhao Ma (LLNL, Peking University)
“Global gyro-Landau-fluid simulations in BOUT++ framework”
Jingfei Ma (University of Texas)
“Global Two-Fluid and Gyro-Landau-Fluid simulations of the pedestal turbulence in DIII-D divertor geometry”
Joshua Sauppe (University of Wisconsin-Madison)
“Helicity Conservation and Two-Fluid Relaxation Modeling for Reversed-Field Pinches”

Students presenting papers at Sherwood:

1. Justin Ball, Oxford University (UK)
2. Jian Bao, UC Irvine
3. Andrea Becerra, U. of Wisconsin
4. Joshua Burby, PPPL
5. Brent Covele, U. of Texas
6. Leland Ellison, PPPL
7. William Farmer, LLNL
8. Christopher Flint, William & Mary
9. Daniel Fulton, UC Irvine
10. Jerome Guterl, UC San Diego
11. Michael Halfmoon, U. of Tulsa
12. Christopher Hansen, U. of Washington
13. Jonathan Hebert, Auburn U.
14. Eric Howell, U. of Wisconsin
15. Spencer James, U. of Tulsa
16. Wonjae Lee, UC San Diego
17. Dongjian Liu, UC Irvine
18. Brendan Lyons, PPPL
19. Chenhao Ma, LLNL, Peking U.
20. Jingfei Ma, U. of Texas
21. Joseph McClenaghan, UC Irvine
22. John O’Bryan, U. of Wisconsin
23. Armen Oganesov, William & Mary
24. Joshua Sauppe, U. of Wisconsin
25. Wrick Sengupta, U. of Maryland
26. Benjamin Sturdevant, U. of Colorado at Boulder
27. Choongki Sung, MIT
28. Zhixuan Wang, UC Irvine
29. Deng Zhao, Peking U., General Atomics

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

A local solution to a global problem: treating radial profile variation and intrinsic momentum transport in a flux tube gyrokinetic code
Michael Barnes, University of Texas at Austin

An enstrophy minimizing method for 3D MHD equilibrium with flow
Samuel A. Lazerson, Princeton Plasma Physics Laboratory

On the formation of phase space holes and clumps
Matthew Lilley, Imperial College, London, UK

Simulated flux-rope evolution and relaxation in the Pegasus ST
John O’Bryan, University of Wisconsin - Madison

Nonlinear Gyrokinetic Simulation of the Edge Pedestal
Scott Parker, University of Colorado - Boulder

Dynamic boundary plasma-wall modeling of ELMy H-mode
Alexander Pigarov, UC San Diego

Trapped particle precession and effective mass in Rosenbluth-Hinton residual zonal flows
Wrick Sengupta, University of Maryland - College Park

Modeling of tungsten and beryllium dust impact on ITER-like plasma edge
Roman Smirnov, UC San Diego

A local solution to a global problem: treating radial profile variation and intrinsic momentum transport in a flux tube gyrokinetic code

M. Barnes, F. I. Parra, J. P. Lee, E. A. Belli, M. F. F. Nave, and A. E. White

Tokamak plasmas are routinely observed to rotate even in the absence of an externally applied torque. This `intrinsic' rotation exhibits several robust features, including rotation reversals with varying plasma density and current. Conservation of toroidal angular momentum dictates that the intrinsic rotation is determined by momentum redistribution within the plasma, which is dominated by turbulent transport. For up-down symmetric magnetic equilibria, the turbulent momentum transport, and thus the intrinsic rotation profile, is driven by formally small effects that are usually neglected in simulations and analysis.

We present a gyrokinetic theory that makes use of the smallness of the poloidal to total magnetic field ratio to self-consistently treat the dominant effects driving intrinsic turbulent momentum transport in tokamaks. These effects have now been implemented in the local, delta-f gyrokinetic code GS2. We describe important features of the numerical implementation; in particular, the novel WKB-like method used to capture 'global' effects in a flux tube simulation domain. Finally, we present numerical results illustrating the impact of these formally small effects on intrinsic turbulent momentum transport and compare with experimental observations of intrinsic rotation reversals. Numerical results indicate that inclusion of diamagnetic corrections to the equilibrium Maxwellian lead to a reversal of rotation direction with collisionality, consistent with experimental results.

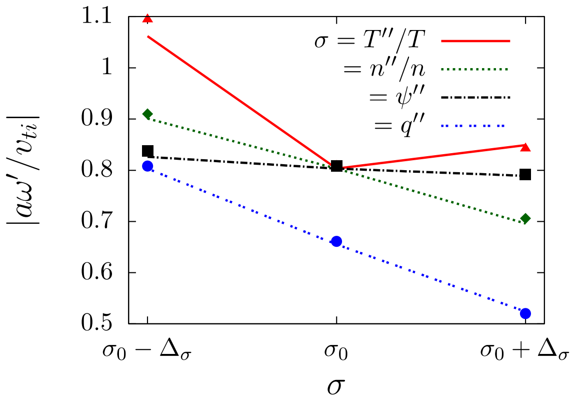


Fig. 1: Radial variation in micro-instability growth rate obtained by flux tube simulations with GS2 at multiple radii (lines) and by the WKB approach in a single GS2 simulation (points).

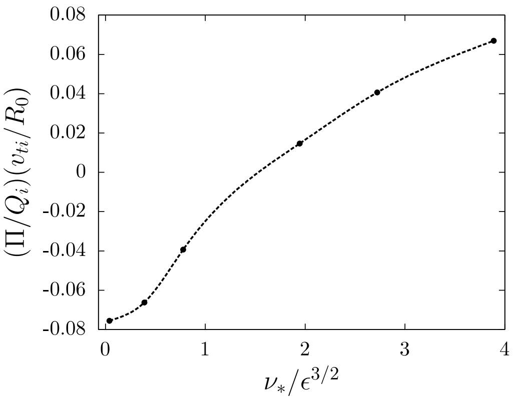


Fig. 2: Variation of intrinsic momentum flux with collisionality arising from diamagnetic effects. Sign reverses direction with increasing collisionality, corresponding to transition from co- to counter-current rotation

An enstrophy minimizing method for 3D MHD equilibrium with flow

Samuel A. Lazerson

A method for inclusion of finite plasma velocity in 3D equilibrium is explored. In this method a variation technique is used which simultaneously minimizes flow enstrophy and magnetic energy. This follows from the turbulent evolution of flows, in which enstrophy is minimized in physical systems. The minimization is constrained by flow, magnetic and cross helicity equations. The resulting set of Euler-Lagrange equations are

$$\nabla \times \vec{B} = \lambda_{mag}\vec{B} + \lambda_{X}\vec{\omega}$$

$$\nabla \times \vec{\omega} = \lambda_{flow}\vec{\omega} + \lambda_{X}\vec{B}$$

where $\vec{\omega} = \nabla \vec{\times} u$ is the flow vorticity, $\vec{B}$ is the magnetic field, and the μ's are constant helicity multipliers. This formulation recovers the Taylor state for the magnetic field and the relaxed swirling flow state in the limit that the cross helicity multiplier (μ_X) vanishes. This is important as these two states have been experimentally verified in the both the magnetohydrodynamic and hydrodynamic limits. As the two equations couple a flow driven current density emerges, which is not necessarily force free. What is missing from this formulation is specification of the internal energy. Restricting the solution space to those solutions where $\vec{\omega} = C\vec{B}$ we recover a force free state with flow. If however, the flow induced $\vec{j} \times \vec{B}$ force is an allowed solution, we are free to choose the pressure profile to balance said force. While not all solutions produce physical pressure profiles, some do suggesting that a thermal term be incorporated into the variational principle in the future.

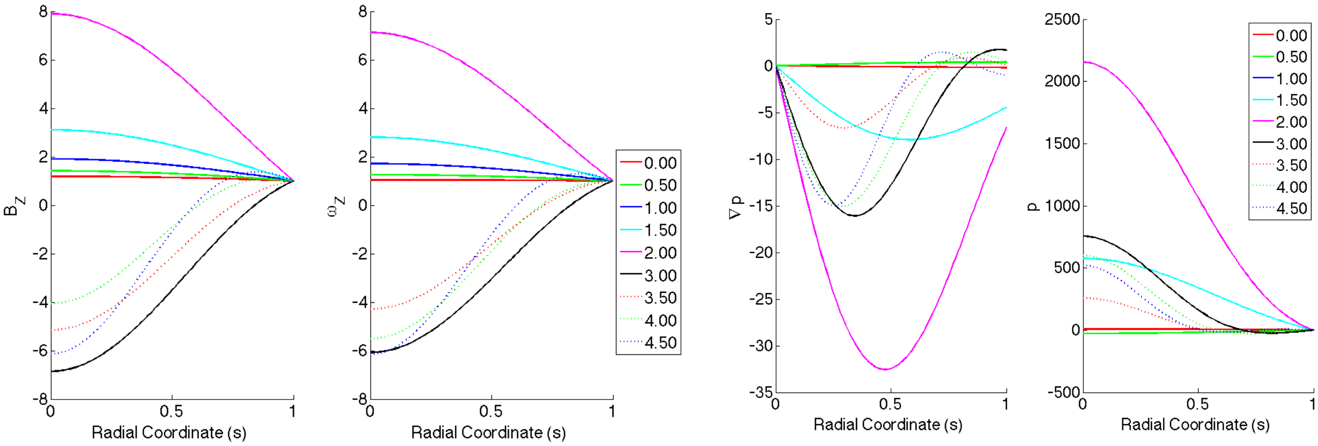


Figure 1 Toy 1D model of minimized flow where magnetic helicity is set to 1, flow helicity to 0.5, and cross helicity is scanned. Axial vorticity and magnetic field are plotted along with pressure profiles from force balance. All units dimensionless.

On the formation of phase space holes and clumps

M. K. Lilley [1], *R. M. Nyqvist* [2]

[1] *Physics Department, Imperial College, London, SW7 2AZ, UK, m.lilley05@imperial.ac.uk*

[2] *Department of Earth and Space Science, Chalmers University of Technology, 41296*
Göteborg, Sweden

Phase space holes and clumps are an intrinsic part of the story of violent instabilities of fast particle populations in fusion devices, so called chirping modes. These instabilities can redistribute and potentially eject fast particles from fusion device prematurely.

Despite all previous modelling efforts, two fundamental questions have so far remained unanswered, namely why and how the holes and clumps form. Part of the reason behind this knowledge gap lies in the previously reported result that hole/clump formation only occurs when the background dissipation processes are sufficiently large to compete with the kinetic drive, i.e. when the initial seed wave is only marginally unstable. However, the notion that holes and clumps are near-threshold phenomena has obscured the understanding of the role played by dissipation. In fact this notion is simply not true. We show that any amount of background dissipation results in chirping instabilities, meaning that holes and clumps can be generated far from, as well as close to, the instability threshold.

The underlying physics is that holes and clumps develop from negative energy waves, which grow rather than damp as a result of dissipation. Their existence relies on the presence of a nearly unmodulated plateau in the fast particle distribution, whose interface with the surroundings is sharp enough to alter the dielectric response of the fast particles as to support waves near the plateau edge. Such plateau states may arise, e.g., as a result of phase mixing and subsequent dissipative decay of an initially unstable bulk plasma wave (see Fig 1). In general, though, initial seed instability is not a requirement, it is only essential that the system has the ability to generate a plateau. In addition, we observe repetitive cycles of plateau generation and erosion, the latter due to hole/clump formation and detachment, which appear to be insensitive to initial conditions and can persist for a long time. We present an intuitive discussion of why this continual regeneration occurs.

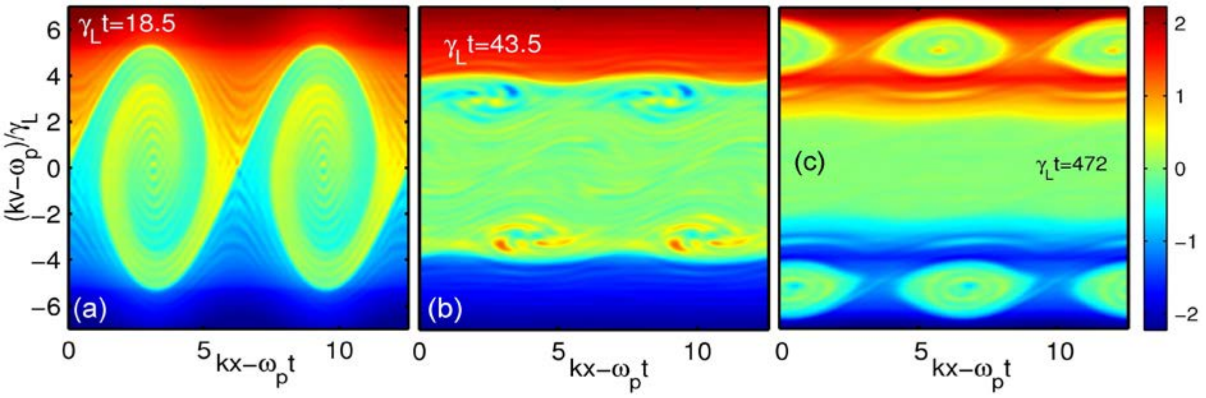


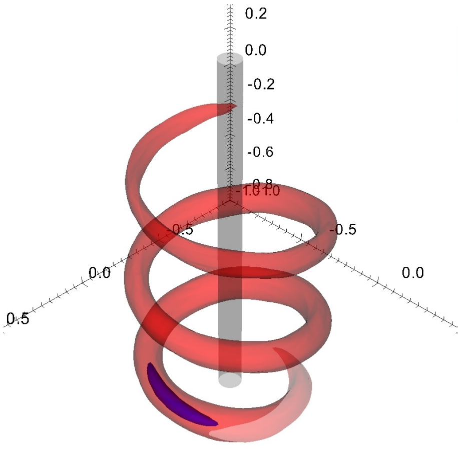
Fig 1 Snapshots of the resonant fast particle distribution function showing hole clump formation far from the instability threshold. a) the initial phase mixing followed by b) the almost spatially uniform plateau with sideband trapping regions forming close to the edge, and finally c) a detaching hole/clump pair.

Simulated flux-rope evolution and relaxation in the Pegasus ST

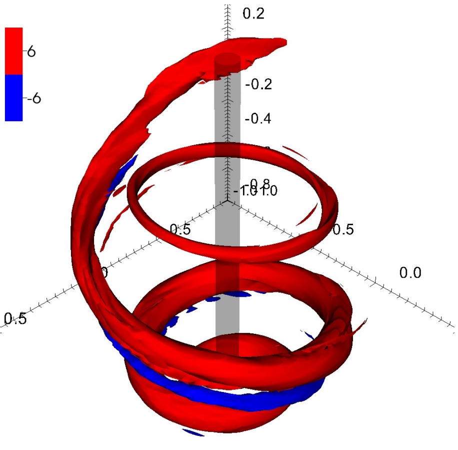
J.B. O'Bryan and C.R. Sovinec, University of Wisconsin—Madison

The dynamics and relaxation of magnetic flux ropes produced during non-inductive startup of the Pegasus Toroidal Experiment [Eidietis, *JFE.* 2007] are simulated with a nonlinear two-fluid plasma model. Our numerical simulations provide a detailed self-consistent description of the entire evolution—only a single localized helicity injector is prescribed—starting from vacuum magnetic field and 'cold fluid.' The NIMROD code (nimrodteam.org) is used to solve the system.

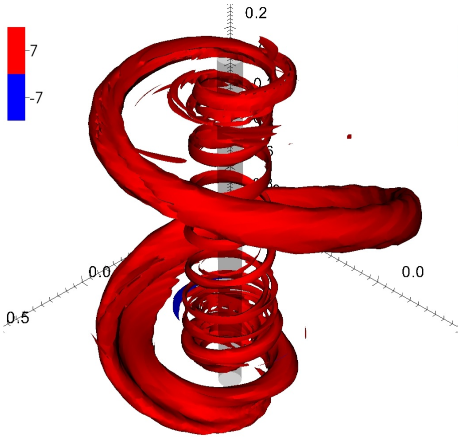
Initially, the vacuum magnetic field-lines direct the flux rope along a helical path. The attractive Lorentz force between adjacent passes of the flux rope excites vertical oscillations. With sufficient injected current, adjacent passes merge and reconnect, releasing a flux-rope ring. The rings provide a concentration of poloidal flux that spreads and accumulates across multiple cycles, eventually leading to the formation of global poloidal magnetic field null that redirects the current channel path and forming a hollow current shell around a large region of amplified flux.[O'Bryan, *POP.* 2012] After cessation of current drive, the plasma rapidly relaxes toward a tokamak equilibrium state with good flux surfaces that encompass a large volume.



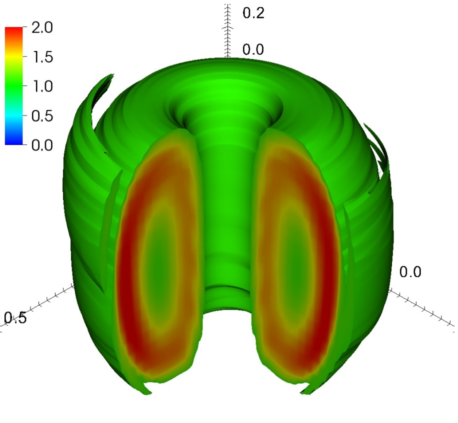
Helical winding



Flux-rope ring



Hollow current shell

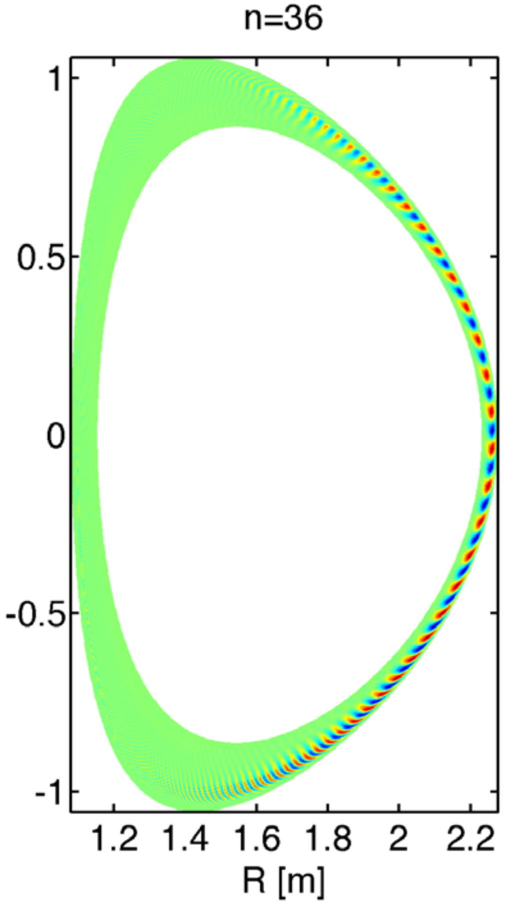


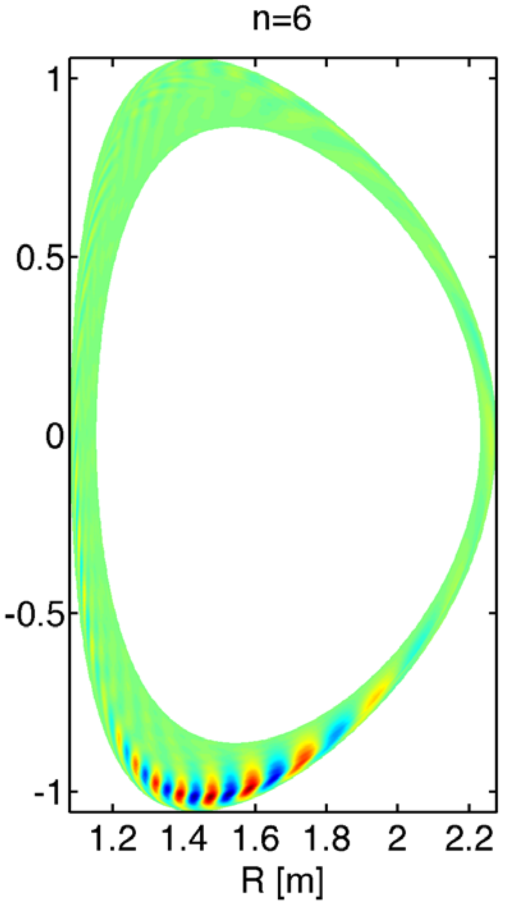
Tokamak equilibrium

Making connections to other open field-line studies, we compute the squashing degree Q to identify the quasi-separatrix layer (QSL) during the formation of a flux-rope ring.[O'Bryan, *PPCF.* 2014] For the Pegasus fields, the QSL does show separatrix-like behavior, but field-line trajectories of high Q bifurcate at the poloidal field null between non-reconnecting passes in addition to bifurcating at the reconnection site.

Nonlinear Gyrokinetic Simulation of the Edge Pedestal

A talk presented by Scott E. Parker and collaborators Weigang Wan, Yang Chen and Jugal Chowdhury, University of Colorado, Boulder presented the first nonlinear simulations of the onset of a large Edge Localized Mode (ELM) using global gyrokinetic simulations. These are enormously challenging calculations due the steep gradients and strong profile variation found in the edge pedestal region. In the two figures shown below are two important modes the GEM code finds just prior to the onset of the ELM, consistent MHD based theories.





Dynamic boundary plasma-wall modeling of ELMy H-mode

A. Yu. Pigarov[1], S. I. Krasheninnikov[1], T.D. Rognlien[2], E.M. Hollmann[1],
J.H. Yu[1], C.J. Lasnier[2], E. Unterberg[3]

[1]University of California, San Diego; [2]Lawrence Livermore National Laboratory; [3]Oak Ridge National Laboratory

A new version of the UEDGE code, called UEDGE-MB [A. Pigarov, PoP 19, 072516(2012)], has been developed for self-consistent modeling of boundary plasma transport and hydrogen wall inventory in ELMy H-mode tokamak discharges. UEDGE-MB implements the Macro-Blob approach [A. Pigarov et al., PoP 18, 092503(2011)] allowing simulation of spatio-temporal effects of the highly intermittent, filamentary, non-diffusive transport observed during ELMs. It also incorporates time-dependent models for particle recycling, wall temperature, and deuterium inventory for each material boundary of 2-D modeling domain.

We present the results of UEDGE-MB simulations for H-mode shots on DIII-D with type-I ELMs and with different pedestal plasma densities and ELM frequencies. We show that, in a periodic sequence of many ELMs, deuterium inventories of pedestal and wall simultaneously evolve on about a second time scale to a dynamic equilibrium. UEDGE-MB is capable of matching the experimental data on temporal evolution of pedestal plasma, particle and power loads on divertor plates and chamber wall, surface temperature, and wall inventory, Fig. 1. In agreement with experimental data, the wall switches from the net deuterium deposition during an ELM to the net outgassing between ELMs. The outgassing rate in DIII-D is high, a roughly constant rate $\sim 10^{21}$ D/s, which is much larger than NBI fueling and pumping rates. We anticipate that ion-stimulated desorption is the dominant process of wall outgassing between ELMs and have evaluated its yield as 0.5%. We also simulated a discharge with a transition from frequent to infrequent ELMs (20 to 50 ms in the ELM period) showing that the characteristic time for pedestal density increase of about 0.6 s is consistent with the wall outgassing rate.

The parameter $\eta = N_{elm}/N_{soldiv}$ is used as a figure of merit, where N_{elm} is the total particle loss from the pedestal plasma during an ELM and N_{soldiv} is the particle inventory of the SOL and divertor regions before the ELM event. We show (Fig. 2) that in the case when η is small, $\eta \leq 2$, particles are dominantly retained in SOL and divertor regions. Pedestal recovery in this case is determined by the edge plasma processes (e.g., by neutral atom transport, anomalous inward pinch, etc). In the case when η is large, $\eta \geq 4$, the pedestal recovery is determined by wall physics (and therefore choice of wall material). This case corresponds to the infrequent ELMs with period >30 ms in DIII-D.

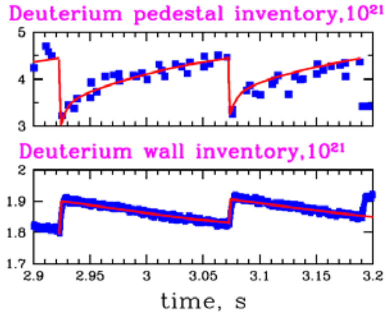


Fig. 1: Comparison between the calculated (lines) and experimental (points) data on temporal evolution of deuterium inventories in the pedestal and wall.

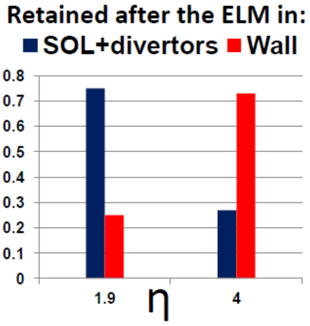


Fig. 2: Fractions of pedestal particle losses retained after an ELM in the wall and in the SOL are shown as functions of parameter η.

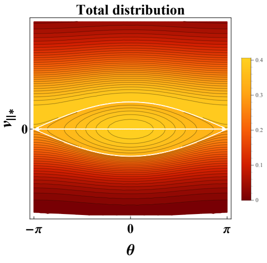
Trapped particle precession and effective mass in Rosenbluth-Hinton residual zonal flows

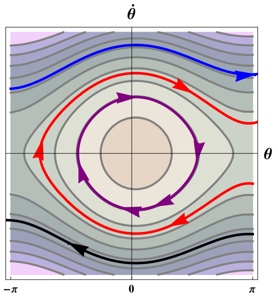
W. Sengupta, A.B. Hassam *

IREAP, University of Maryland, College Park, MD 20742

In tokamak turbulence, stresses acting perpendicular to the B field can impart ExB flows. An initial radial Electric field $\boldsymbol{E}$ results in GAM oscillations, which Landau damp, leaving a residual $\boldsymbol{E}$,[1] smaller by a large factor (the Rosenbluth-Hinton factor). Consistent with conservation of toroidal angular momentum, a residual zonal parallel flow is generated. As is well-known, trapped particles (TPs) will precess toroidally in a steady $\boldsymbol{E}$. We observe that the toroidal momentum in the precessing TPs is much larger than the residual Rosenbluth-Hinton (RH) toroidal momentum. This raises the question of the missing TP momentum in the zonal flow. Further, upon calculating the average TP toroidal flow from the RH solution, using conventional methods, we find this flow speed to be much smaller than the expected precession speed. Also, the calculation yields a nonzero poloidal flow for TPs. Finally, the RH "effective inertia" is smaller than one might expect from a simple toy model of a constrained bead on a massless rod, given the rapid TP precession.

We show that these apparent discrepancies can be resolved by transforming to energy coordinates shifted with respect to the $v_{\|}$ coordinate, with the shift proportional to u_E. Even in the limit of small $\boldsymbol{E}$, this small Jacobian shift must be retained in taking velocity moments as it acts on the lowest order distribution function. With this shift, the correct precession is recovered as well as a zero poloidal flow of the TPs. The RH final parallel flow as well as the effective mass are, however, unchanged. To understand the origin of the lower than expected flow/inertia we upgrade our toy model to include barely circulating particles (CP). We find that the barely CPs move counter to and almost cancel the fast TP precession. The reason for this counter flow is conservation of angular momentum together with adiabatic invariance of phase space.





Figures:

1. Total distribution: CP flux balance TP flux

2. Barely CPs preferentially flowing to the top

The calculations are done in the sub-bounce-frequency limit, an assumption that fails near the separatrix. A more general calculation based on action-angle coordinates has been commenced which allows both GAMs and residual zonal flows. Results confirm the validity of the original RH factor.

In conclusion, we demonstrate that the shifted coordinates are the natural coordinates to work with in the presence of a radial electric field. The physics of TPs and barely CPs becomes transparent in these coordinates.

References

1. Rosenbluth, M. N. and Hinton, F. L. 1998 Phys. Rev. Lett. 80, 724.

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*Work supported by the USDOE

Modeling of tungsten and beryllium dust impact on ITER-like plasma edge

R.D. Smirnov[1], S.I. Krasheninnikov[1], A.Yu. Pigarov[1], B.T. Brown[1], T.D. Rognlien[2], and A. Kukushkin[3]

[1]*University of California, San Diego, La Jolla, CA 92093, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[3]*ITER Organization, Vinon-sur-Verdon, St. Paul Lez Durance 13067, France*

With the progress of magnetic fusion toward increasing power and duration of plasma discharges, the interactions of plasma with inner surfaces of fusion devices gain growing importance due to operational limits of materials. The large plasma particle and heat fluxes can damage plasma-contacting components, such as tungsten and beryllium tiles of chamber inner wall in the next step fusion experimental reactor ITER [1]. It is well known that such interactions can produce tiny debris of wall material (typically of sub-millimeter size), called dust, which can be ejected into the fusion plasma from the damaged surfaces. Production and propagation of such dust is an important mechanism of hydrogen fusion plasma contamination with wall constituent elements. The authors of the present research have developed a computer simulation code DUSTT/UEDGE [2], which they use to model transport of dust grains in fusion plasmas. This study presents the simulations of self-consistent dust-plasma interactions and dynamics in the ITER tokamak to predict how various doses of tungsten and beryllium dust of sizes from 1 to 100 micrometers can affect ITER fusion plasma operation. The obtained results demonstrate that dust produced with rates as low as a few mg/s inside ITER can already lead to dangerous relative levels ~10ppm of tungsten contamination in the core of fusion plasma (see Fig.1), which would significantly affect plasma parameters and impair fusion reaction in ITER. The found critical tungsten dust production levels appear to be much lower than that possible in ITER, which potentially may reach 1g/s [3]. The presented simulations show that both beryllium and tungsten dust produced with such high rates can prevent ITER plasma discharge operation. The authors have also found that plasma contamination with impurities in fusion devices can lead to generation of undesirable oscillations of peripheral plasma parameters (see Fig.2). These oscillations will cause periodic change of the heat load to plasma contacting surfaces that can facilitate additional dust production due to associated thermal stresses and material damage. The mechanism of generation of such oscillations was analyzed by the authors, which found that thermal force acting on impurity particles in plasma with non-uniform temperature profiles plays crucial role in generation of the oscillations. The reported results reveal the critical impact that dust contamination of fusion plasmas produced by plasma-material interactions can have on performance of future fusion reactors. This underlines the necessity to further advance our understanding of fusion plasma boundary to pave the way for magnetic fusion success.

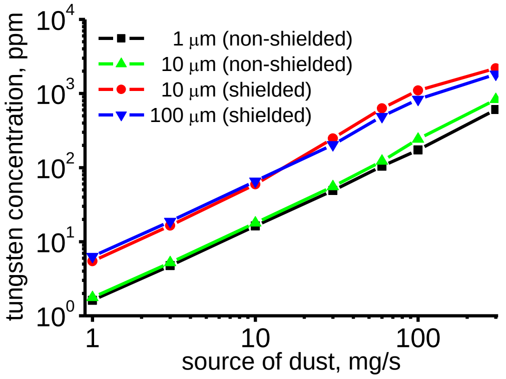

Fig. 1

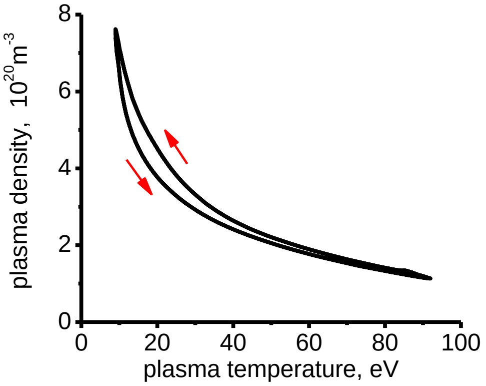

Fig.2

[1] R.A. Pitts, S. Carpentier, F. Escourbiac, et al., *J. Nucl. Materials* **438** (2013) S48.
[2] R.D. Smirnov, S.I. Krasheninnikov, A.Yu. Pigarov, et al., *J. Nulc. Mater.* **415** (2011) S1067.
[3] V.A. Makhlaj, et al., *J. Nucl. Materials* **438** (2013) S233.