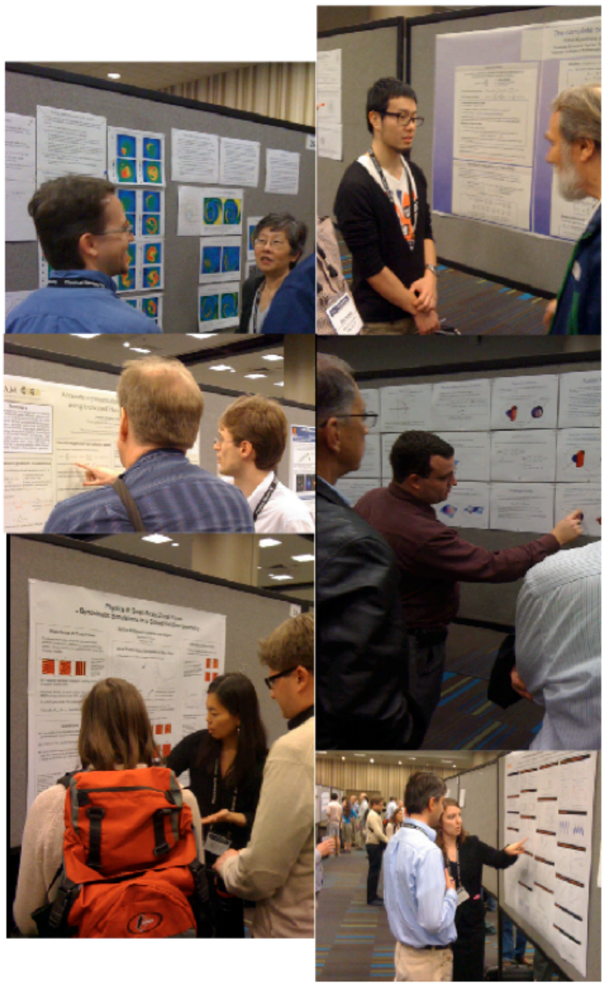
Highlights from the 2012 International Sherwood Fusion Theory Conference, Atlanta, GA



Photos from the Sherwood poster session. Clockwise from top left: Linda Sugiyama, MIT, and Paul Cassak, West Virginia University; Yohei Kawazura, University of Tokyo, and Phil Morrison, UT Austin; David Johnston, College of William and Mary; Jessica Baumgaertel, PPPL and Gian Luca Delzanno LANL; Sumire Kobayashi, Dartmouth; Joseph Parker, Oxford University.

The 2012 International Sherwood Fusion Theory Conference was held in Atlanta, GA from March 31st-April 3rd. There were 14 invited talks spanning the field of fusion theory on topics such as plasma-wall interactions, resonant magnetic perturbation (RMP) field penetration in tokamaks, gyrokinetic simulations of beta induced Alfven eigenmodes, nonlinear dispersion relation for geodesic acoustic modes (GAMs), and rotation of tokamak halo currents. Author-provided summaries of several of the invited talks are included on pages 4-9 of this Highlight. **The plenary Sherwood talk was by Dennis Whyte, MIT, on "The future of boundary plasma and material science".**

There was a very strong showing by graduate students, postdocs, and young scientists at the meeting. More than 20 students from around the world presented papers. A list of all participating students can be found on page 3 of this Highlight.

Student poster award winners (left to right): Jessica Baumgaertel, PPPL; Martina Giraudo, LANL; John O'Bryan, Wisconsin; Thibaut Vernay, EPFL; and Justin Angus, UCSD; (not pictured Ge Wang, UT Austin). Congratulations!

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

Justin Angus, University of California San Diego,
"Blob theory and modeling";
Jessica Baumgaertel, Princeton Plasma Physics Laboratory,
"Linear gyrokinetic studies in NCSX, W7-AS, and W7-X stellarators using GS2";
Martina Giraudo, Los Alamos National Laboratory
"Theoretical and computational studies of the sheath of a planar wall";
John O'Bryan, University of Wisconsin Madison,
"Simulations of current-filament dynamics and relaxation in the Pegasus ST";
Thibaut Vernay, Ecole polytechnique fédérale de Lausanne, Switzerland,
"Simulations of collisional trapped-electron-mode turbulence with the global gyrokinetic delta-f particle-in cell-code ORB5";
Ge Wang, University of Texas Austin
"Self-consistent frequency sweeping of TAE mode".

Sherwood was co-located with the April APS meeting this year. Ellen Zweibel, UW Madison, gave a plenary talk on "The plasma physics of cosmic rays", and several other APS-DPP plasma physicists gave invited talks at APS, including Michael Barnes, MIT; Bill Heidbrink, UCI; Stan Kaye, PPPL; and Don Spong, ORNL. Their talks provided positive connections between APS and Sherwood. The APS talks given by DPP members were very well attended.

Students presenting papers at Sherwood:

1. Onnie Luk, UC-Irvine;
2. Anjor Kanekar, Maryland;
3. Ge Wang, Texas;
4. Zhixuan Wang, UC-Irvine;
5. Cheonho Bae, Georgia Tech;
6. Andy Montgomery, Wisconsin;
7. John O'Bryan, Wisconsin;
8. Carson Cook, Wisconsin;
9. John Patrick Floyd, Georgia Tech;
10. PW Xi, Peking/LLNL;
11. JB Parker, PPPL;
12. Michael Halfmoon, Tulsa;
13. Mordechai Rorvig, Wisconsin;
14. Joseph McClenaghan, UC-Irvine;
15. JA Baumgaertel, PPPL;
16. SD James, University of Tulsa;
17. Justin Angus, UCSD;
18. Martina Giraudo, LANL;
19. Joseph Parker, Oxford;
20. BC Lyons, PPPL;
21. Chris Stewart, Georgia Tech;
22. Thibaut Vernay, EPFL
23. Matthew Beidler, West Virginia University

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

A Self-Consistent Mechanism for Incomplete Reconnection in Sawteeth
Matt Beidler, West Virginia University

Unveiling the kinetic mechanism of RMP penetration
C. S. Chang, Princeton Plasma Physics Laboratory

Axiomatic approach to wave-particle interactions and its applications to waves with trapped particles
Y. Dodin, Princeton Plasma Physics Laboratory

The nonlinear dispersion relation of geodesic acoustic modes
Robert Hager, IPP Max Planck Institute for Plasma Physics, Germany

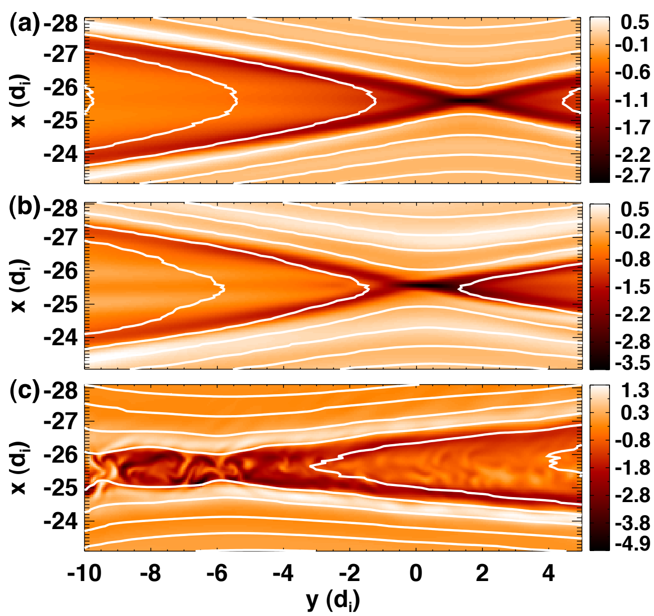
Gyro-fluid model and 5-field model for ELM simulation using BOUT++
T.Y.Xia, Lawrence Livermore National Laboratory

A Self-Consistent Mechanism for Incomplete Reconnection in Sawteeth

Matt Beidler, West Virginia University

A prevailing impediment to core confinement in fusion devices is the occurrence of large sawtooth events. Experiments show that the crash phase often ends before all of the available magnetic flux is reconnected, i.e., reconnection is incomplete, but this is inconsistent with the Kadomtsev model. We present a model for incomplete, or partial, reconnection in sawtooth crashes [1] resulting from diamagnetic effects on the nonlinear phase of magnetic reconnection.

The reconnection inflow self-consistently convects the high pressure core and low pressure edge of a tokamak toward the m=n=1 rational surface, thereby increasing the pressure gradient at the reconnection site. Previous work has shown that reconnection is throttled if the diamagnetic drift speed at the reconnection site exceeds a threshold. We argue that if the pressure gradient at the rational surface becomes large enough due to the self-consistent evolution, incomplete reconnection will occur. Physically, we attribute the suppression to the interaction of the exterior pressure gradient with the pressure quadrupole that inherently occurs during collisionless (Hall) reconnection in the presence of a strong guide-field.



Out-of-plane current density zoomed in near the X-line with magnetic field lines superimposed (a) before (t = 125), (b) after (t=180), and (c) significantly after (t=210) the pressure gradient reaches the reconnection site. The x and y axes correspond to the radial and poloidal directions, respectively.

We show that predictions of this model are borne out in large-scale proof-of-principle simulations of reconnection in a two-dimensional slab geometry. We also show that the predictions are consistent with data from the Mega Ampere Spherical Tokamak.

Knowing the conditions at the end of a sawtooth crash is important for predicting the amount of transport that is introduced by sawteeth in fusion devices. At present, modeling of this behavior is ad hoc, so a self-consistent description would make transport models more accurate and more transferable to future machines, which is important for the development of a clean and renewable energy source. Additionally, the model is dependent on local physics, so the results should apply across tokamaks, including ITER.

[1] M. T. Beidler and P. A. Cassak, Phys. Rev. Lett., 107, 255002 (2011)

Unveiling the kinetic mechanism of RMP penetration

C.S. Chang, Princeton Plasma Physics Laboratory

ITER relies upon high edge pedestal pressure to achieve good fusion efficiency, which is normally accompanied by a sharp pressure gradient. However, buildup of the sharp pedestal pressure gradient causes the pedestal to crash via edge-localized modes (ELMs). ELMs can rapidly erode the plasma facing material by rendering a high-power pulse of plasma flux - a serious issue for the ITER program. A promising method to suppress ELMs is to ease the sharp pressure gradient by introducing external resonant magnetic perturbations (RMPs), in an attempt to create stochastic magnetic field structure in the edge pedestal region. Experiments on the DIII-D have indeed demonstrated ELM suppression from external RMPs, giving a green signal to the ELM suppression in ITER. However, the response of the ELM suppressed pedestal plasma to the external RMPs has been contradictory to the physics understanding based on the vacuum RMP distribution. More seriously, the desired plasma response, leading to the ELM suppression, occurs only in a narrow q_{95}-value window while the vacuum RMP distribution does not show such a preference to the q_{95} window. It has been a common opinion of the fusion physics community that the plasma responded RMP distribution must be understood before a confident extrapolation of RMP physics to ITER plasma can be made. This has been a formidable research subject do to the nonlinear interaction and self-organization nature between the stochastic magnetic field penetration, kinetic parallel electron dynamics in the presence of mode rational surfaces, kinetic perpendicular ion dynamics, radial electric field, and plasma flows. Moreover, the magnetic separatrix surface adds additional topological complication to the kinetic self-organization.

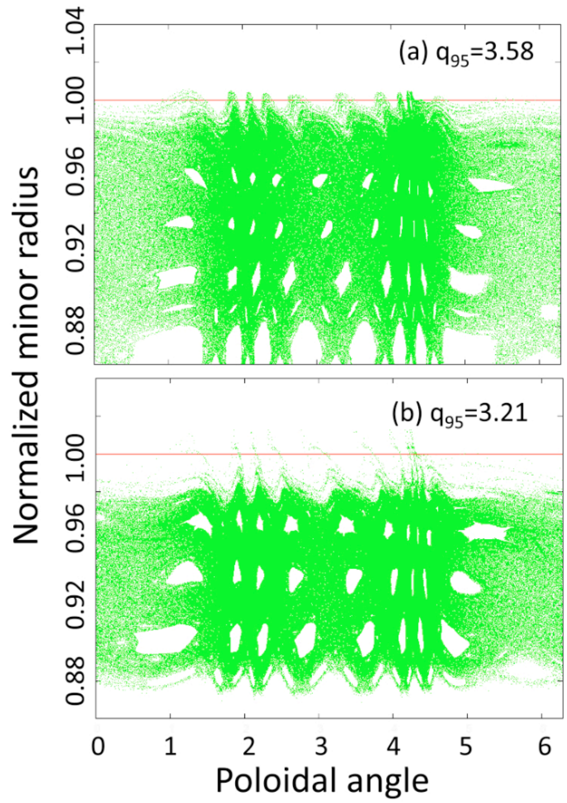


FIG: Penetration of resonant magnetic field into plasma. Structure of magnetic stochasticity and islands (a) inside and (b) outside the "ELM suppression q_{95} window." In this DIII-D shot, the ELM suppression window is between $3.52<q_{95}<3.62$.

We have achieved such a study and understanding through a large-scale comprehensive kinetic simulation in realistic divertor geometry. It is found that i) it is not only the primary plasma current response to the external RMPs, but also the secondary current response being critical in the understanding of the RMP penetration, ii) in the “suppression q_{95} window” the stochastic and island magnetic perturbation extends close to the magnetic separatrix, forcing a stronger connection of the pedestal magnetic field to the material wall [see FIG a], and iii) RMP effect becomes weaker at higher electron collisionality. These findings, including responses of all the plasma and radial electric field profiles, are consistent with experimental observations for the first time.

Axiomatic approach to wave-particle interactions and its applications to waves with trapped particles

I. Y. Dodin

We report a new fundamental mathematical formulation of both linear and nonlinear wave dynamics in plasmas, drawing on the Lagrangian approach that is traditionally attributed to Whitham [e.g, see G. B. Whitham, Linear and Nonlinear Waves (Wiley, NY, 1974)]. We extend Whitham's formulation and show how it becomes particularly useful for plasma-physics applications, where the wave Lagrangian can often be constructed explicitly, including for nonlinear waves. Instead of repeating the conference abstract here, below we expand on two fundamental results that are particularly newsworthy and may also be of interdisciplinary interest:

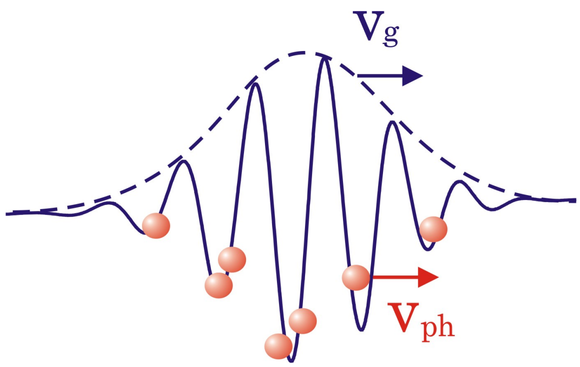


Fig 1. A cartoon illustrating the general idea of a wave carrying trapped particles.

1. Knowing the frequency shift experienced by a wave in a weakly nonlinear medium is, in principle, enough to approximately describe also the wave evolution, namely, in terms of the nonlinear Schrodinger equation (NLSE). This statement can be found in virtually any textbook on nonlinear wave dynamics and is adopted, often tacitly, as a starting point of numerous physical models. What we found, however, is that the applicability of the NLSE is not as general as it is usually thought, which undermines some of the well-established theories. In particular, waves in plasmas can be special when carrying particles trapped in autoresonance, the long-known BGK modes being an example [1-4]. If the trapped particle inertia is large enough, it yields a dominant

contribution to the wave energy flux, so the latter depends on phase velocity but not on the wave amplitude. This unusual feature invalidates the textbook understanding of the nonlinear wave dynamics and may explain, in particular, why existing analytical models are largely unable to adequately describe the evolution of nonlinear plasma waves with trapped particles.

2. An unexpected spin-off of our research is in shedding light on the Abraham-Minkowski controversy that pertains to the definition of the photon momentum in dispersive medium [5]. This hundred-year-old debate, on whether one should, roughly speaking, multiply or divide the "vacuum" formula by the refr

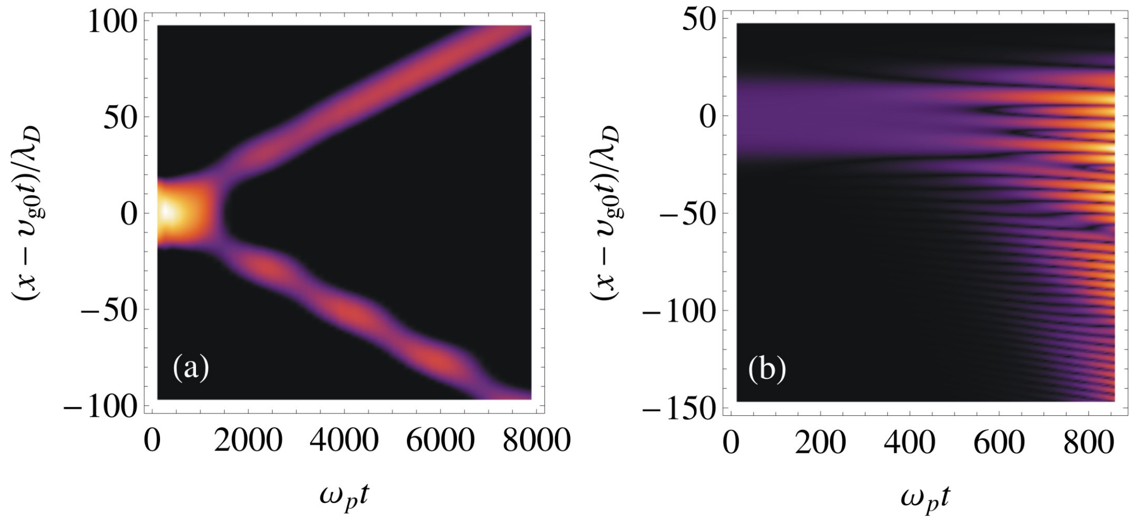


Fig 2. The result of a nonlinear "ray-tracing-like" simulation, showing the evolution of a perturbation to a homogeneous Langmuir wave loaded with deeply trapped electrons. (a) The energy flux carried by trapped particles is below the instability threshold. The pulse is stable and exhibits the group-velocity splitting, like any other stable nonlinear wave. (b) The energy flux carried by trapped particles is above the instability threshold. The pulse exhibits the trapped-particle modulational instability (TPMI) in the regime where the traditional theory predicts no instability.

action index, was somewhat resolved recently by Barnett [PRL 104, 070401 (2010)], who argued that both approaches are correct and simply describe different types of the photon momentum. Barnett's explanation, however, is oversimplified in many respects, and, while putting it in a more precise form, we made an intriguing discovery. It turns out that, under fairly weak assumptions, the mechanical properties of a wave and the force it produces on the underlying medium are completely insensitive to what the wave "is made of", whether that be, say, electromagnetic radiation or oscillations of the gas pressure. (Instead, they depend only on the medium dispersive properties and, naturally, on the wave energy density.) The abstract mathematical formulation through which this result is yielded can also replace and advance multiple existing theories of wave dynamics and, on the score of being transparent, potentially leads to identification of physical effects that would be hard to anticipate otherwise.

[1] I. Y. Dodin and N. J. Fisch, Nonlinear dispersion of stationary waves in collisionless plasmas, Phys. Rev. Lett. 107, 035005 (2011)., [2] I. Y. Dodin and N. J. Fisch, Adiabatic nonlinear waves with trapped particles: I. General formalism, Phys. Plasmas 19, 012102 (2012).
[3] I. Y. Dodin and N. J. Fisch, Adiabatic nonlinear waves with trapped particles: II. Wave dispersion, Phys. Plasmas 19, 012103 (2012).
[4] I. Y. Dodin and N. J. Fisch, Adiabatic nonlinear waves with trapped particles: III. Wave dynamics, Phys. Plasmas 19, 012104 (2012).
[5] I. Y. Dodin and N. J. Fisch, Axiomatic geometrical optics, Abraham-Minkowski controversy, and photon properties derived classically (to be submitted shortly); for preview see
http://www.princeton.edu/~idodin/files/amc.pdf

The nonlinear dispersion relation of geodesic acoustic modes

Robert Hager – IPP Max Planck Institute for Plasma Physics

Geodesic acoustic modes (GAM) in tokamak plasmas are large scale, oscillating plasma flows associated with electric fields in the minor radial direction. The turbulence can affect the GAMs by modifiying the GAM frequency and by transferring energy to them. Both of these interaction channels were studied using two-fluid turbulence computations. Surprisingly, the turbulent GAM dispersion relation turned out to be qualitatively equivalent to the non-turbulent one but can have drastically enhanced radial group velocities comparable to the velocities of the turbulence. Such group velocities would allow for deviations from the originally expected scaling of the GAM frequency with the square root of the plasma temperature on the scale of centimeters. Indeed, similar features were found in GAM measurements on ASDEX Upgrade.

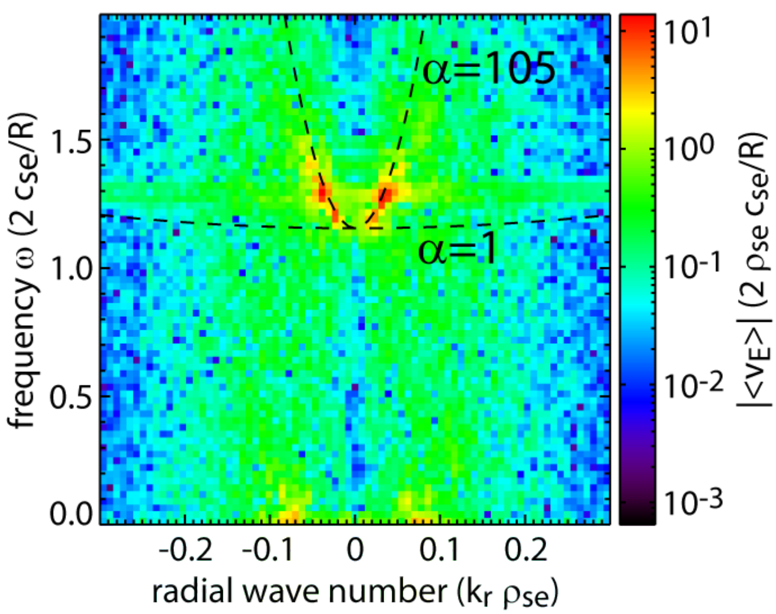


Figure: Result of two-fluid turbulence computation. Intensity of the flux-surface average poloidal ExB velocity plotted versus the radial GAM wave number and the mode frequency. The dashed line with alpha=1 corresponds to the GAM frequency without turbulence, the line with alpha=105 corresponds to the turbulence induced nonlinear dispersion relation.

The energy transfer between the GAMs and the turbulence was shown to be sensitive to the up-down symmetry of the confining magnetic field. Using a divertor configuration -- which is used in many tokamak devices -- the reported numerical studies revealed, that the phase velocity of the turbulence generated GAMs depended on the orientation of the curvature drift velocity with respect to the magnetic X-point. Considering also the radial variation of the GAM frequency, this phase velocity selectivity can lead to simultaneous periodic bursts of the turbulence and the GAM intensity if the curvature drift is directed towards the X-point. This behavior displays similarity to the GAM bursts during the I phase in ASDEX Upgrade and periodic phases of low turbulence activity in NSTX. Interestingly, the power threshold for the transition from a low (L mode) to a high confinement state (H mode) in tokamak plasmas is also lower with the curvature drift towards the X-point. Regarding the frequent observations of GAMs closely prior to the L-H in experiments and the geometry induced effects on GAMs reported in this talk, further research focused on a potential correlation between both phenomena seems appealing.

Gyro-fluid model and 5-field model for ELM simulation using BOUT++

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This paper reports the theoretical and simulation results of a gyro-Landau-fluid (GLF) extension of the BOUT++ code in the increasing physics understanding of edge-localized-modes (ELMs). The large ELMs with low-to-intermediate-n peeling-ballooning (P-B) modes are significantly suppressed when ion temperature increases due to finite Larmor radius (FLR) effects; however small ELMs with an island of instability at intermediate n values are driven unstable due to the acoustic waves in two-fluid model. This result is good news for high ion temperature ITER with the large FLR stabilizing effects. The initial simulation results are shown to be consistent with the previous two-fluid model with the ion diamagnetic drift for type-I ELMs, which retains the first-order FLR correction. The maximum growth rate is inversely proportional to T_i because the FLR effect is proportional to T_i. The FLR effect is also proportional to toroidal mode number n, so for high n cases, the P-B mode is stabilized by FLR effects. Nonlinear gyro-fluid simulations show results that are similar to those from the two-fluid model, namely that the P-B modes trigger magnetic reconnection, which drives the collapse of the pedestal pressure. The hyper-resistivity is found to limit the radial spreading of ELMs by facilitating magnetic reconnection. Furthermore, the ELM size is found to be insensitive to the hyper-resistivity for large ELMs. Due to the additional FLR-corrected nonlinear ExB convection for the ion gyro-center density, the gyro-fluid model further limits the radial spreading of ELMs and the FLR effect can significantly decrease the ELM size when pedestal ion temperature increases from 1keV to 4keV as shown in Fig.1 because high-n modes are stabilized. The five-field simulations show that the effects of parallel thermal conductivity reduce the growth of the turbulence and decrease the energy loss in the pedestal region.

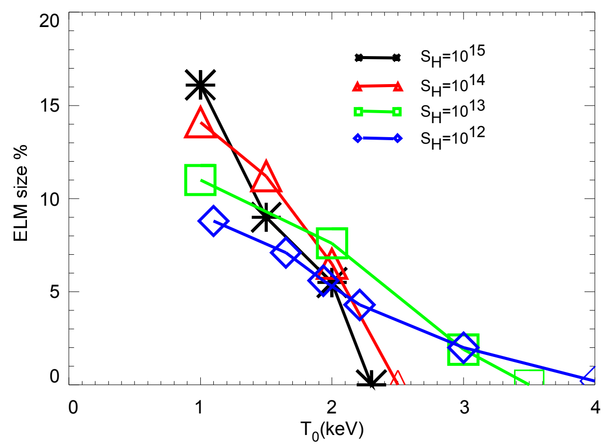

Fig1. ELM size vs ion temperature T_i and hyper-resistivity η_H ($\approx S_H^{-1}$).

This work supported in part by the US DOE under DE-AC52-07NA27344, LLNL LDRD project 12-ERD-022, LDRD project 11-ERD-058, and LDRD project 11-ERD-058, the China Scholarship Committee under contract N0.2011601099, and the China Natural Science Foundation under Contract No.10721505.