Highlights from Sherwood 2017

International Sherwood Fusion Theory Conference

May 1st-3rd
Hosted by the Plasma Science and Innovation Center,
Massachusetts Institute of Technology
The Westin Hotel
Annapolis, MD
Frank von Hippel (Princeton University) kicked off the Sherwood meeting with his plenary talk, “The Iran Nuclear Deal: How we got here and our options going forward”. The plenary talks for the second and thirds days were given by Doug Kothe (Oak Ridge National Laboratory) on “Exascale Applications: Opportunities and Challenges” and James Drake (University of Maryland) on “Electron and ion heating, acceleration and energy partition during magnetic reconnection in space and astrophysical systems”, respectively.

Altogether, 112 scientists attended the conference where 3 plenary and 12 invited talks were given that span the field of fusion theory. Topics such as momentum transport, L-H transition, and runaway electron dynamics were discussed. Author-provided summaries of eleven of the invited talks are included on pages 6 to 16 of this document.

There was a very strong showing by graduate students, postdocs, and young scientists at the meeting. More than 30 students attended the conference with a overwhelming majority presenting papers. A list of all participating students can be found on page 5.
Images from the Sherwood banquet (courtesy Alan Glasser.)
Six “Student Poster Awards” were given to the following students for their exceptional presentations:

James Juno (University of Maryland) “Continuum Vlasov Simulations of Magnetized Shocks”
Benjamin Faber (University of Wisconsin-Madison) “Examining the zero-magnetic-shear approximation for low-shear stellarators”
Caoxiang Zhu (Princeton Plasma Physics Laboratory) ”Flexible optimized coil designing method using space curves”
Tyler Cote (University of Wisconsin-Madison) “Ballooning stability of tokamak pedestals in the presence of strong applied 3D magnetic perturbations”
Elizabeth Paul (University of Maryland) “Rotation and Neoclassical Ripple Transport in ITER”
Adrian Fraser (University of Wisconsin-Madison) “Coupling of Damped and Growing Modes in Shear Flow Turbulence”

Student poster award winners. From left to right: Emily Belli (Generat Atomics - Chair of the Sherwood Program committee), Adrian Fraser, Elizabeth Paul, Tyler Cote, Benjamin Faber, James Juno, Caoxiang Zhu, and Anne White (MIT – Chair of the Sherwood organizing committee)
List of student attendees:

Jian Bao (University of California, Irvine)
Torrin Bechtel (University of Wisconsin-Madison)
Bin Chen (Lawrence Livermore National Laboratory)
Jianguo Chen (Peking University, P. R. China)
Tyler Cote (University of Wisconsin-Madison)

Ola Embreus (Chalmers University of Technology) [invited speaker]
Silvia Espinosa (Massachusetts Institute of Technology) [invited speaker]

Benjamin Faber (University of Wisconsin-Madison)
Xiang Fan (University of San Diego)
Christopher Flint (College of William and Mary)
Adrian Fraser (University of Wisconsin-Madison)

Linnnea Hesslow (Chalmers University of Technology) [invited speaker]

James Juno (University of Maryland)
Dmitrii Kiramov (University of Texas-Austin)
Nami Li (Lawrence Livermore National Laboratory)
Mike Martin (University of Maryland)
George Miloshevich (University of Texas-Austin)
Omar Lopez (Auburn University)
Denis St-Onge (Princeton Plasma Physics Laboratory)
Henry Oliver (University of Texas-Austin)
Elizabeth Paul (University of Maryland)
Dov Rhodes (Columbia University)
Audun Theodorsen (The Arctic University of Norway)
Ian Waters (University of Wisconsin-Madison)
Garth Whelan (University of Wisconsin-Madison)
Zachary Williams (University of Wisconsin-Madison)
Yanzeng Zhang (University of San Diego)
Yao Zhou (Princeton University)
Ben Zhu (Dartmouth College)
Caoxiang Zhu (Princeton Plasma Physics Laboratory)
The Iran Nuclear Deal: How we got here and our options going forward

Frank von Hippel
Program on Science and Global Security and
International Panel on Fissile Materials
Princeton University
Plenary, International Sherwood Fusion Theory Conference, Annapolis, 8:30 AM, 1 May 2017

The international crisis over Iran’s nuclear program began in 2002 when it became public that Iran, a non-weapon-state party to the Nonproliferation Treaty, had, without informing the IAEA, begun building a uranium enrichment plant and a heavy water reactor, both providing potential routes to a nuclear weapon. Beginning in 2013, a nuclear deal was negotiated under which Iran agreed to a strictly monitored program, much reduced in scope, for more than a decade in return for a lifting of nuclear-related sanctions. The agreement between Iran and the five permanent members of the UN Security Council plus Germany (P5+1) went into force on 16 January 2016. Iran has complied scrupulously with its commitments but the constraints on Iran’s enrichment capacity will begin to expire after ten years. Iran’s enrichment program is but the latest example of the threat to the nuclear nonproliferation regime from national enrichment programs, however. What is needed is a generic solution. One possibility would be to put all civilian enrichment programs under multinational control. The U.S. is well positioned to promote this idea since it allowed the privatized U.S. Enrichment Corporation to go bankrupt in 2014. Today, the only operating enrichment plant in the United States is owned by the multinational (Germany-Netherlands-UK) URENCO, which operates about one third of global enrichment capacity. Russia, which owns almost one half of global capacity has sold a share of its capacity to Kazakhstan as an alternative to that country building its own enrichment capacity. Could some of Iran’s neighbors and some of the members of the P5+1 join into a consortium to add a layer of multinational control over Iran’s enrichment enterprise as an alternative to the construction of additional national enrichment facilities in the Middle East?
Parasitic momentum flux in the tokamak core

Timothy Stoltzfus-Dueck

Tokamak plasmas rotate spontaneously in the absence of applied torque. This so-called 'intrinsic rotation' may be very important for future low-torque devices such as ITER, since rotation can stabilize certain instabilities. In the mid-radius 'gradient region,' which reaches from the sawtooth inversion radius out to the pedestal top, intrinsic rotation profiles are sometimes flat and sometimes hollow. Profiles may even transition suddenly between these two states, an unexplained phenomenon referred to as rotation reversal. Theoretical efforts to identify the origin of the mid-radius rotation shear have focused primarily on quasilinear models, in which the phase relationships of some selected instability result in a nondiffusive momentum flux ("residual stress"). In contrast to these efforts, the present work demonstrates the existence of a robust, fully nonlinear symmetry-breaking momentum flux that follows from the free-energy flow in phase space and does not depend on any assumed linear eigenmode structure. The physical origin is an often-neglected portion of the radial ExB drift, which is shown to drive a symmetry-breaking outward flux of co-current momentum whenever free energy is transferred from the electrostatic potential to ion parallel flows [1]. The resulting rotation peaking is counter-current and scales as temperature over plasma current. As originally demonstrated by Landau [2], this free-energy transfer (thus also the corresponding residual stress) becomes inactive when frequencies are much higher than the ion transit frequency, which may explain the observed relation of density and counter-current rotation peaking in the core. Simple estimates suggest that this mechanism may be consistent with experimental observations, in both hollow and flat rotation regimes.

The competition between parallel and perpendicular transport sets the width of the scrape-off layer for plasma particle and energy exhaust. Transport along the magnetic field is dominated by parallel streaming, which is a fast process constrained by ambipolarity. This becomes most transparent at the divertor surface, where the non-neutral sheath regulates the exhaust flux in terms of the boundary plasma density, temperature, and flow. The exit flow speed itself is constrained by the Bohm criterion to a local sound speed, which is set by the plasma temperature. For a warm ion plasma, the highest local parallel sound speed in the literature for Bohm criterion analysis is

\[ c_{s||} \equiv \sqrt{\frac{k_B (T_{e||} + 3T_{i||})}{m_i}}, \]

with \( T_{e||} \) and \( T_{i||} \) the electron and ion parallel temperature.

Direct kinetic-Maxwell simulations [1] reveal that the plasma exit flow robustly exceeds \( c_{s||} \) at the sheath entrance, contradicting a foundational plasma theory prediction. Furthermore, the plasma exit flow (or Bohm) speed is observed to increase significantly with higher collisionality, opposite of what one would expect with sound speed scaling in a more collisional plasma. To resolve these outstanding discrepancies, we have performed a new inner layer analysis of the Bohm criterion using the extended CGL formulation that is appropriate for a nearly collisionless sheath [2]. Our work reveals that the gradient term, such as the divergence of the heat flux, must be retained in the (inner layer) sheath analysis. The Bohm speed is found to have the general expression:

\[ u_{Bohm} \equiv \sqrt{\frac{3k_B (T_{i||} + Z\beta T_{e||})}{m_i} - Z\beta \frac{m_e}{m_i} \left( \frac{en_e}{en_e} \right)^2}, \] (1)

where \( j \) is the net current density to the wall and \( Z \) the ion charge number. The most important and interesting quantity is the heat flux factor \( \beta \), which depends on the parallel heat flux [3],

\[ \beta \equiv \left[ 1 - \frac{\partial}{\partial \Phi} \left( \frac{q_n^i}{Zen_e u_{n e}} \right) \right] / \left[ 1 + \frac{\partial}{\partial \Phi} \left( \frac{q_n^e}{en_e u_{n e}} \right) \right], \] (2)

where \( q_n^i \) is a component of ion (electron) parallel heat flux, \( \Phi \) the plasma potential, \( u_{e,i} \) the electron (ion) parallel flow speed, and superscript “se” denotes sheath entrance.

With this new formulation, we are able to resolve a number of observed contradictions between simulations and traditional theory. Examples include: (1) the celebrated Bohm result \( u_{Bohm} = c_s = \sqrt{k_B T_{e||}/m_i} \) for a cold ion plasma, which is based on isothermal electron assumption, is recovered for a collisionless sheath of a collisional plasma (with cold ions), only because the electron parallel heat flux is able to produce the limiting result of \( \beta = 1/3 \) to cancel out the front factor of 3, which is the adiabatic index of collisionless electrons in the neighborhood of the sheath; (2) increasing \( u_{Bohm} \) with higher collisionality is understood as a result of reduced \( q_n^e \), which comes about for the collisional filling of the void region in the electron distribution that forms due to the electron absorbing wall; (3) decreasing \( u_{Bohm} \) with increasing plasma current \( j \) to the wall, due to the electron inertia effect, but subtly modified by the heat flux factor \( \beta \).

This work was supported by OFES.

Self-consistent simulation of limit cycle oscillations and hysteresis of plasma edge transport bifurcation

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The nonlinear evolution of turbulence and flows in the edge region of magnetically confined plasmas are investigated in a fluid turbulence simulation of the transition between two confinement regimes. Edge transport bifurcations are key tools for enhancing plasma confinement properties of magnetic fusion devices. Therefore the development of validated models of the trigger for the low to high confinement transition requires physics understanding (e.g. the underlying physical mechanism of edge shear flow generation). This is essential for predicting the performance of ITER (e.g. transition power threshold) with confidence. This paper addresses this important issue by reporting the self-consistent simulations of shear flow generation and transport bifurcation in plasma edge turbulence using drift-reduced Braginskii equations. The simulation results such as limit cycle oscillations, hysteresis, and flux-gradient relationship display phenomena very similar to the experiment.

In collaboration with X. Q. Xu (LLNL). Work supported by the MOST of China Grant No. 2013GB12006, US DOE Contract No. DE-FC02-08ER54966, US DOE by LLNL under Contract DE-AC52-07NA2734.

Reference:

Figure 1: Typical phase space of turbulence intensity $K$ and mean $E \times B$ flow energy $U$ from the L to H regimes. The arrows and colors indicate the time sequence.

Figure 2: Edge mean pressure gradient $|\nabla p|$ versus the pressure measured at the boundary of source region through the forward and back transitions. Each point represents an average over a period of time.
Pedestal Shear Suppression: Theory and Computation
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The suppression of turbulence by sheared flows is thought to be the main mechanism underlying the formation and sustenance of the H-mode edge transport barrier (called the pedestal). Since the residual turbulence mediates the structure of the pedestal and, by extension, largely determines plasma confinement, it is of central importance to fusion energy. A combined analytic and computational gyrokinetic approach is used to address the question of the scaling of pedestal transport with ExB shear in regimes spanning the weak and strong shear limits. In effect, we answer the following question: how does pedestal turbulence react to a systematic reduction of flow shear rate?

Due to strong gradients and shaping in the pedestal, the instabilities of interest are not curvature-driven (as is typical for instabilities in the plasma core) and are consequently insensitive to the toroidal effects upon which many theories of shear suppression are based. As a result, despite the major computational challenges inherent in pedestal gyrokinetic simulations, the earliest analytical theories [1-3], which are completely unaware of geometry and the details of instability drive, are found to be most relevant. We present detailed comparisons between gyrokinetic simulations and a theory closely related to [3], which is valid for arbitrary shear rates and accounts for the self-consistent variation of fluctuation amplitude with nonlinear diffusivity. The gyrokinetic simulations entail scans of ExB shear rate for a range of scenarios starting with local simulations with constant shear rate and culminating with global simulations using non-monotonic flow profiles. With the flexibility of only a single order-unity free parameter, the analytic theory quantitatively reproduces the scaling of the gyrokinetic simulations across the strong to weak shear limits in all cases studied. This represents striking agreement between gyrokinetic simulations and basic analytic theory and demonstrates that the physics of shear suppression in the pedestal is described by a few simple physical ingredients: advection from both background shear flow and turbulent flow, in combination with a gradient drive mechanism. In light of the expected decrease of ExB shear rates over the transition to low $\rho^*$ burning plasma regimes, the implications of this work are substantial.


Figure 1 Comparison between gyrokinetic simulations and the theory outlined in Ref. [3]. $P^{-1}$ is the normalized fluctuation amplitude and $W$ is the normalized shear rate.
Gyrokinetic simulation of a fast L-H like bifurcation dynamics in a realistic diverted tokamak edge geometry

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Despite its critical importance in the fusion program and over 30 years of H-mode operation, there has been no fundamental understanding at the kinetic level on how the H-mode bifurcation occurs. We report the first observation of an edge transport barrier formation event in an electrostatic gyrokinetic simulation carried out in a realistic C-Mod like diverted tokamak edge geometry under strong forcing by a high rate of heat deposition. The results show that the synergistic action between two multiscale dynamics, the turbulent Reynolds-stress driven [1] and the neoclassical X-point orbit loss drive [2] sheared E×B flows, works together to quench turbulent transport and form a transport barrier just inside the last closed magnetic flux surface. The synergism helps reconcile experimental reports of the key role of turbulent stress in the bifurcation [3] with some other experimental observations that ascribe the bifurcation to X-point orbit loss/neoclassical effects [4,5]. The synergism could also explain other experimental observations that identified a strong correlation between the L-H transition and the orbit loss driven E×B shearing rate [6,7]. The synergism is consistent with the general experimental observation that the L-H bifurcation is more difficult with the VB-drift away from the single-null X-point, in which the X-point orbit-loss effect is weaker [2].

Figure 1  (Left) Turbulence power spectrum. The turbulence suppression of lower frequency occurs and higher frequency turbulence is generated at \(t=0.17\)–\(0.21\)ms. Suppression of lower amplitude turbulence follows at \(t>0.21\)ms. (Right) Dynamics between turbulence intensity, ExB flow, and ExB flow shear.

Intermittent fluctuations in the scrape-off layer of tokamak plasmas

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A first-principles based understanding of scrape-off layer (SOL) fluctuations and transport is needed in order to anticipate plasma-wall interaction conditions in a reactor-scale device. Fluctuations in the SOL of magnetically confined plasmas are universally found to have large amplitudes and to be strongly intermittent. This is attributed to radially outwards motion of blob-like plasma filaments, which contain excess particles and heat compared to the ambient plasma.

Recently, the statistical properties of the intermittent fluctuations have been revealed by exceptionally long data time series from numerous tokamak experiments. Based on these properties, a stochastic model has been presented which describes the fluctuations as a superposition of uncorrelated exponential pulses. The model describes the plasma in the SOL as entirely due to filament structures propagating from the closed magnetic field line region.

In this contribution it is demonstrated that all predictions of this model are in excellent agreement with experimental measurements. This includes the lowest order statistical moments, probability density function, and the frequency power spectral density. When pulses overlap significantly, the resulting signal resembles random noise with normally distributed fluctuation amplitudes. In the case of weak pulse overlap, the signal is strongly intermittent and dominated by large-amplitude bursts. The frequency power spectrum is demonstrated to be independent of the degree of pulse overlap and is determined solely by the shape of the underlying exponential pulses. These findings run contrary to the prevailing theories that the shape of the power spectrum arises from the interaction of turbulent eddies and or self-similar processes.

Finally, the stochastic model predicts the rate at which a signal crosses a given threshold level and the excess times that it spends above this threshold level. This provides novel predictions describing threshold phenomena, which result in plasma-wall interactions such as sputtering. It is further demonstrated how the parameters of the stochastic model can be estimated from measurement data, strongly indicating universality of the statistical properties of the fluctuations with respect to changes in plasma parameters and across experimental devices. Suggestions for new experimental measurements in order to test this theory are also given.
Electron and ion heating, acceleration and energy partition during magnetic reconnection in space and astrophysical systems

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Magnetic reconnection converts energy into high-speed flows, thermal and energetic particles in a broad range of systems both in the heliosphere and the broader universe. The most detailed measurements are within the heliosphere, which therefore acts as an effective laboratory for many issues related to reconnection. While the mechanisms for fast reconnection are now fairly well understood, the energy conversion mechanisms and the partitioning between species are active topics. In solar flares the energy released is roughly equally partitioned between the thermal particles and the energetic components. In the magnetosphere and the laboratory thermal ions carry the bulk of the released energy and the scaling of the temperature increments of both species with the available free energy per particle $m_e c^2 A_{up}$ has recently been established. Models and simulations are advancing the physics in both relativistic and non-relativistic reconnection. Most of the energy conversion takes place in the exhaust where newly reconnected field lines release their tension and during the merger of magnetic islands.\textsuperscript{1} The three basic mechanisms for energy conversions are Fermi reflection, parallel electric fields and betatron acceleration. The former two mechanisms are typically the most important with Fermi reflection dominating the energy gain of the most energetic particles in both electron-ion\textsuperscript{2,5} and pair plasma. The partitioning of energy between electrons and ions is not universal but is controlled by the development of a large-scale electric potential that acts to contain hot electrons in the reconnection exhaust.\textsuperscript{4} The production of particles with energy greatly exceeding $m_e c^2 A_{up}$ requires the interaction with multiple magnetic islands. The dominant energy gain is parallel to the local magnetic field and as a consequence significant anisotropy develops, which is likely to impact synchrotron signatures in astrophysical systems. During magnetic reconnection in 3D systems the production of the most energetic electrons increases dramatically.\textsuperscript{3} Why the powerlaw distributions that are typically seen in nature are produced remains an open question since they are not seen in non-relativistic reconnection PIC simulations.\textsuperscript{2,3,5}

\textsuperscript{1}J. F. Drake et al, Nature \textbf{443}, 553, 2006

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Kinetic effects of partially screened impurities in runaway-electron mitigation scenarios

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Runaway electrons constitute a significant threat to tokamak devices. In order to develop runaway mitigation schemes with material injection, accurate kinetic models are needed to describe the interaction between electrons and partially ionized atoms. Such models require the partial screening of the nuclei by the bound electrons to be taken into account.

In this contribution, we analyze the dynamics of fast electrons in plasmas containing partially ionized impurity atoms. A generalized collision operator is derived from first principles using quantum-mechanical models. We obtain analytical expressions for the deflection and slowing-down frequencies, which are increased significantly compared to the results obtained with complete screening. This leads to a large enhancement of the critical electric field for runaway acceleration.

Moreover, we implement the generalized collision operator in the continuum kinetic-equation solver code [1, 2] and demonstrate that interaction with partially ionized atoms greatly affects fast-electron dynamics by enhancing the rates of angular deflection and energy loss. In particular, we investigate the decay of a runaway-electron current coupled to a self-consistent electric field, and find that in a runaway decay scenario, the induced electric field is close to the effective critical field obtained when taking effect of partial screening into account, as can be seen in Fig. 1. The prediction in Ref. [3] may therefore be generalized to include the effect of partially ionized atoms, which allows for simplified estimates of the runaway current decay time. Due to the large effects on the collision frequencies, distribution and current decay of runaway electrons, the effect of the interaction with partially ionized impurities has important implications for the efficacy of mitigation strategies for runaway electrons in tokamak devices.

References

The conversion of a large fraction of the plasma current into runaway electrons poses one of the principal risks to the success of the tokamak concept. The exponential growth of the runaway electron population via an avalanche instability during a disruption is thought to be the most efficient means through which this conversion can occur. As a means of accurately modeling the avalanche process, a set of large-angle collision operators of varying complexity, ranging from a simple source term to a novel energy-momentum conserving form, are developed and implemented. The use of a conservative form allows for the back reaction of the secondary electrons onto the primary electrons to be self-consistently accounted for. The incorporation of such a feedback process is shown to require the modification of the Coulomb logarithm in order to avoid double counting collisions [1]. A systematic procedure for delineating small and large angle collisions, and thus avoiding the double counting of collisions, has been developed. Such a procedure allows for the use of a mixed Fokker-Planck/Boltzmann description of runaway dynamics, thus placing this area of research on a firm theoretical footing.

Utilizing this framework, it is found that the avalanche threshold is tightly linked to the merger of an O and X point in momentum space. The origin of such a close correlation can be understood as follows. Above the O-X merger threshold, the momentum space can be separated into two distinct regions separated by an X point (left panel, Fig. 1). At high energy, an O point in the momentum space flux is clearly evident. This O point, or runaway vortex [2], provides a mechanism of confining runaway electrons, and thus sustaining the avalanche process. However, once the O-X merger threshold has been crossed (center panel, Fig. 1), all of the fluxlines return to bulk, thus removing any confinement of the runaway electrons. Under such circumstances the avalanche process is terminated. An analytic model of this merger has been developed and shown to accurately describe the avalanche threshold over a broad parameter range (right panel, Fig. 1).

Figure 1: Schematic of momentum space topology above (left) and below (center) the O-X merger threshold $E_{OX}$. Right: Comparison of the O-X merger model $E_{OX}$ (vertical axis) with the avalanche threshold $E_{av}$ (horizontal axis). The value of the electric fields are normalized to the Connor-Hastie electric field $E_c$ and each marker indicates a different set of parameters.

Avalanche runaway generation is a critical threat to large tokamaks such as ITER: according to the Rosenbluth-Putvinski theory [1], a small seed population of fast electrons can multiply through knock-on collisions by up to a factor of order \( \eta \sim \exp(3I/[\text{MA}]) \), which for plasma currents of order \( I = 10-15 \text{ MA} \) means that any runaway seed could convert the entire ohmic current to runaway current.

The exponential sensitivity of the avalanche multiplication factor \( \eta \) to the details of the runaway-generation dynamics demonstrates a need for more accurate models of large-angle collisions. Existing models of large-angle collisions that have been used in magnetic-confinement fusion studies [1, 2] have two main flaws: (i) they do not conserve electron momentum or energy, and (ii) they double count collisions with small-angle collisions, which are typically accounted for with a Fokker-Planck collision operator. We have developed a new large-angle collision operator based on the full relativistic Boltzmann equation which resolves these issues. We use kinetic simulations to show how the new improved collision operator modify the avalanche growth rates obtained with previous models. In particular, we compare results with the steady-state theory of Rosenbluth and Putvinski, as well as with theoretical predictions of a recent study [3] for avalanche generation in near-threshold electric fields \( E \sim E_c \) in the presence of synchrotron-radiation losses.

References