Highlights from Sherwood 2019

International Sherwood Fusion Theory Conference

April 15th-17th, Princeton, NJ

Hosted by the Princeton Plasma Physics Laboratory

Fusion theorists turned out in force for Sherwood 2019. Bolstered by proximity to PPPL, the total attendance (189) and student attendance (71) were strong. There was also a strong international presence, including four international invited talks. Engaging plenary speakers filled the early morning sessions—Mark Herrmann speaking on latest developments on NIF; Carl Bender (pictured) speaking on PT symmetry; and Alex Schekochihin speaking on astro-fusion synergies underlying gyrokinetic simulations of astrophysical plasmas.

Figure 1 Carl Bender

Figure 2 Diego del Castillo Negrete, Bruno Coppi, and Carl Bender (left to right)

Extra-curricular highlights included a Monday-evening reception at Steve Cowley's home in Princeton and a Tuesday afternoon tour of PPPL. A notable highlight was an extemporaneous speech by physicist Russell Kulsrud during the April 16 banquet. Kulsrud, who joined PPPL in the 1950s when it was Project Matterhorn and Sherwood conferences were classified, noted that this year's conference fell on the sixtieth anniversary of the declassification of the event. He discussed the scientific atmosphere and major theoretical fusion discoveries made during the Lab's early days and called on researchers to maintain the same enthusiasm to make controlled fusion work.

Figure 3 PPPL director Steve Cowley's Princeton home, site of a Monday evening reception.

The student poster prizes were awarded to:

Guillaume Brochard	CEA Cadarache, IRFM
Alex Glasser	Princeton University
Plamen Ivanov	University of Oxford
Noah Mandell	PPPL
Michael Nastac	University of Maryland
Denis St.-Onge	PPPL

Figure 4: Student poster prize winners with conference dignitaries (photo courtesy of Saralyn Stewart)

Photos of courtesy of Alan Glasser, David Hatch, and Fatima Ebrahimi:

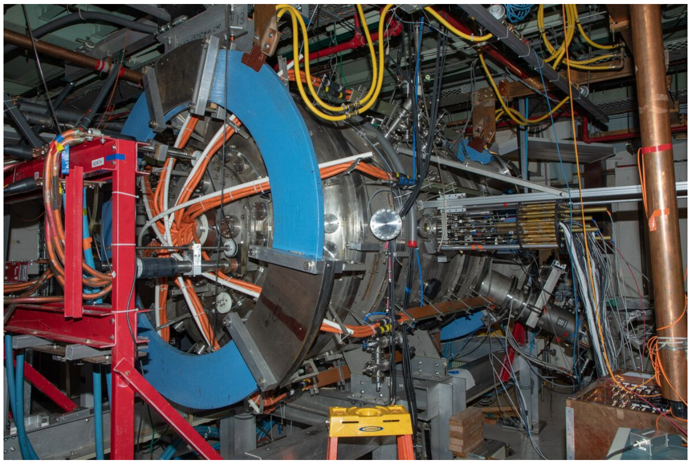


Figure 5 Ben Zhu, Mana Francisquez, and Rogerio Jorge.

Figure 6 Jeff Parker thinking.

Figure 8 Bill Dorland with his bale of terrapins.

Figure 7 Alan Glasser

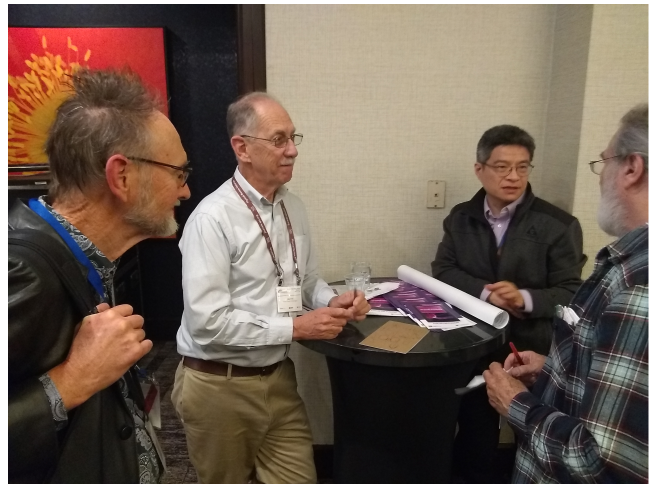


Figure 9 Bob Dewar's mind blown in conversation with John Finn, Hong Qin, and Phil Morrison.

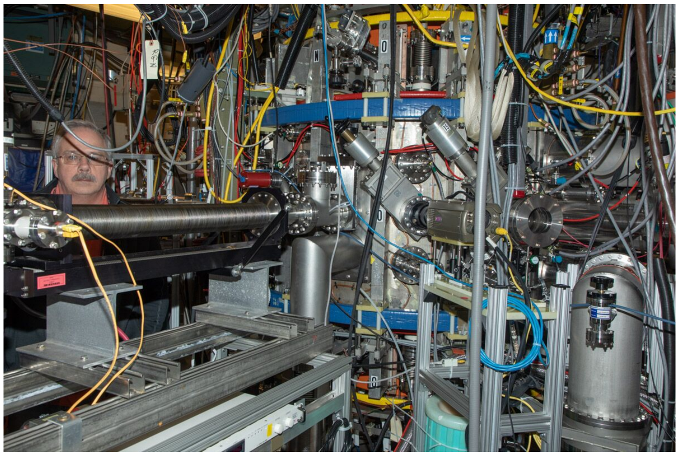


Figure 10 Alex Friedman.

Figure 11 CS Chang.

Figure 12 The Aggie contingent.

Figure 13 Hong Qin.

Figure 15 Russel Kulsrud speaks at the banquet.

Figure 14 Chris Hegna.

Figure 17 Carl Bender's talk.

Figure 16 Dr. Hammett contemplating the transformation of Gkeyll.

Figure 18 Poster session.

Invited talks are listed below:

Mode-converting wave beams can be simulated without full-wave codes

Ilya Y. Dodin (PPPL)
Co-authors: D. E. Ruiz (PPPL), K. Yanagihara (Nagoya University), Y. Zhou (PPPL), S. Kubo (Nagoya University, NIFS)

Full-wave modeling of mm waves in fusion plasmas is computationally demanding due to the small ratio of their wavelengths to the plasma size. Reduced models rooted in traditional geometrical optics (GO) are faster but do not resolve the wave-beam quasioptical structure and cannot capture mode conversion, unless they rely on semi-analytic models with limited applicability. We report a modernized version of GO, termed extended geometrical optics (XGO), which does not suffer from the said limitations. XGO allows for a general dispersion operator and expands its, using Weyl calculus in a curved ray-based metric, in the GO parameter; then, a tractable envelope equation is obtained for the coupled-mode amplitudes by a straightforward reduction. The first-order XGO predicts general fundamental corrections to the ray equations. Special cases of these corrections include spin-orbital interactions in quantum mechanics and the Hall effect of light in optics but have not been explicitly identified for classical plasma waves until recently [Ruiz and Dodin, Phys. Plasmas 24, 055704 (2017)]. The second-order XGO yields a quasioptical model of mode-converting beams. Without assuming a particular ansatz for the beam structure, this formulation leads to a parabolic PDE for a certain projection of the wave field. The number of components of this projection equals the number of the resonantly-coupled modes, so mode conversion is naturally resolved (Dodin et al, arXiv:1901.00268). A new quasioptical code PARADE (PAraxial RAy Description) has been developed based on this theory. Using this code, the dynamics of mm-wave beams in inhomogeneous plasma with and without mode conversion has been simulated, particularly in application to the Large Helical Device (Yanagihara et al, in preparation). The numerical results show good agreement of PARADE predictions with one-dimensional full-wave modeling, conventional ray tracing, and analytic formulas from Gaussian-beam optics.

Suppression of tearing modes by RF current condensation

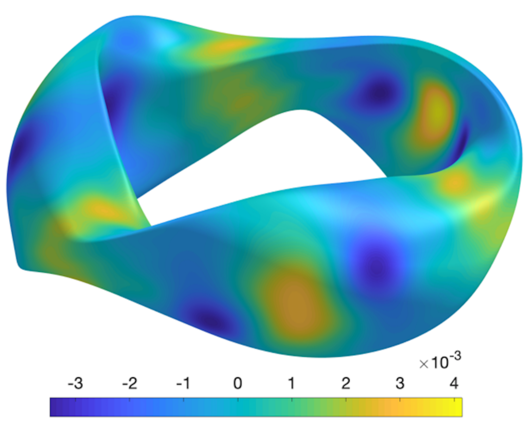
Allan H. Reiman (PPPL)
Co-author: N. J. Fisch (PPPL)

Currents driven by radio frequency waves in the interior of magnetic islands can stabilize deleterious tearing modes in tokamaks. We describe a previously unrecognized effect that can significantly facilitate that stabilization [1]. Present analyses of stabilization assume that the local power deposition and electron acceleration are unaffected by the presence of the island. This neglects the fact that the deposition is sensitive to the perturbation of the temperature, and that the deposition can significantly perturb the temperature in the island. (The temperature perturbation in the island also gives rise to an experimentally documented ohmic effect.) The nonlinear feedback on the power deposition in the island increases the temperature perturbation, and it can lead to a bifurcation of the solution to the steady-state heat diffusion equation, and a discontinuous jump in the steady-state temperature. The combination of the nonlinearly enhanced temperature perturbation with the rf current drive sensitivity to the temperature leads to an rf current condensation effect, which can increase the efficiency of rf current drive stabilization and reduce its sensitivity to radial misalignment of the ray trajectories. Taking into account depletion of the wave energy, a third root of the steady-state diffusion equation is accessed above the bifurcation point [2]. There is a hysteresis effect, with stabilized islands on the third branch shrinking to smaller widths than would otherwise be achieved. The nonlinear threshold for the current condensation effect is in a regime that has been encountered in experiments, and will likely be encountered in ITER. The effect can potentially allow the stabilization of larger islands than would otherwise be possible, and could therefore have a significant impact on disruptivity. Work supported by DOE contract DEAC02-76CH03073. [1] A. Reiman and N. Fisch, Phys. Rev. Lett. 121, 225001 (2018). [2] E. Rodriguez, Sherwood Poster, this meeting.

Adjoint methods for efficient stellarator optimization and sensitivity analysis

Elizabeth J. Paul (University of Maryland)
Co-authors: M. Landreman, I. Abel, T. Antonsen, Jr. (University of Maryland)

The design of modern stellarators often employs gradient-based optimization to navigate the high-dimensional spaces used to describe their geometry. However, computing the gradient of a target function is typically quite expensive. The adjoint method provides a means to compute gradients of a target function with respect to many design parameters at much lower computational cost and without the noise associated with numerical derivatives. This technique has been employed widely in automotive and aerodynamic engineering, and we present the first applications to stellarator design.



The shape gradient for the magnetic ripple on axis provides the local sensitivity with respect to normal perturbations of the surface. With an adjoint method, the shape gradient is computed with only two equilibrium calculations while a finite difference method requires over 6000. The calculation is performed for the NCSX stellarator.

An adjoint method has been implemented in the stellarator coil design code REGCOIL, allowing for optimization of the coil-winding surface with analytic gradients [1]. An adjoint equation has also been implemented in the SFINCS drift kinetic solver to compute gradients of moments of the distribution function, such as the bootstrap current and radial particle flux, with respect to geometric parameters. We present an adjoint method for obtaining the gradients of functions of MHD equilibria with respect to the shape of the outer plasma boundary or coil shapes, providing an order 100-1000 reduction in cost. Examples of adjoint-based optimization with these methods are presented. The derivatives obtained from the adjoint method can also be used for sensitivity analysis using the shape gradient. The shape gradient provides a means of quantifying the change in a figure of merit associated with a local perturbation, such as the normal displacement of the plasma surface or the deformation of a coil shape, providing insight into engineering tolerances [2]. For example, derivatives from REGCOIL can inform where the normal field error is most sensitive to displacements of coils. Several applications are presented. [1] E.J. Paul et al., 2018 Nucl. Fusion 58 076015. [2] M. Landreman and E.J. Paul, 2018 Nucl. Fusion 58 076023. [3] T. Antonsen, E.J. Paul, and M. Landreman, 2018 arXiv:1812.06154.

Simulations of Fast Thermal Quench Using Two-Temperature Model

Nathaniel Ferraro (PPPL)
Co-authors: B.C. Lyons (GA), C.C. Kim (SLS2 Consulting), Y.Q. Liu (GA), S.C. Jardin (PPPL)

Considerable progress has been made recently in developing our capability to model disruptions in tokamaks. Here we describe the application of a new model in the M3D-C1 extended-magnetohydrodynamic code for simulating tokamak disruptions. This model includes separate equations for ion and electron temperature evolution, and separately tracks the densities of each of the charge states of an impurity species. This type of model, which has not been used in previous simulations of disruptions, is necessary for accurately describing dynamics that are faster than the ion-electron equilibration or ion charge state equilibration timescales, which can be on the order of ten milliseconds or longer at parameters typical of a fusion plasma. Simulations of a fast thermal and current quench that are initiated by the introduction of large quantities of impurity ions are presented. It is demonstrated that, even for well-mixed impurities, the cooling of the plasma leads to the contraction of the current channel and associated magnetohydrodynamic instabilities that lead to rapid cooling of the plasma. This indicates that impurity injection may need to be highly localized near the magnetic axis in order to maintain macroscopic stability of the plasma during disruption mitigation. Simulations of fast thermal quench using two-temperature model.

Regimes of weak ITG/TEM modes for transport barriers without velicity shear in low rho* plasmas

Mike Kotschenreuther (Institute for Fusion Studies, University of Texas at Austin)
Co-authors: X. Liu, D.R. Hatch, S. M. Mahajan (IFS, UT-Austin)

Although electrostatic modes (ITG and TEM) typically dominate core transport, we show there exists a particular physical regime in which these modes are hugely weakened, enabling transport barriers without velocity shear. The passage to this regime has apparently arisen in multiple experimental contexts: high beta poloidal ITB in DIII-D, ITB in JET in pellet injection scenarios, ITB observed in the stellarator LHD, wide pedestal H-mode pedestals (and other H-modes). In all these cases the process that leads to the great weakening of linear electrostatic micro-instabilities is fundamentally similar. Through gyrokinetic simulations in model geometries and actual geometries, and simplified models, we arrive at a clear understanding of the fusion friendly regimes made possible only by the simultaneous presence of 1) geometrical effects (appropriate shaping and/or Shafranov shift) 2) the ITG class of instabilities become slab-like, i.e, parallel velocity resonances dominate; geometry is crucial for this 3) substantial density gradients. The resulting eigenmode structure, which is sometimes highly unusual, can nonetheless be explained rather well by a simple semi-analytic dispersion relation, which shows how only the confluence of geometrical effects and plasma parameters results in near stabilization. Fortunately, also, finite beta effects frequently stabilize other electromagnetic instabilities (e.g. electron modes driven by passing electrons). Performing comprehensive electrostatic and electromagnetic gyrokinetic simulations (using GENE), we find that in plasmas with the characteristics mentioned above, linear modes are weak, and the nonlinear transport can be reduced by about two orders of magnitude compared to characteristic core-like modes for "typical" conditions. We will report our explorations, and indicate how various actuators, including novel ones, might create this regime in fusion relevant conditions, including ones with low velocity shear (as in ITER).

Predictions of electron scale pedestal turbulence in DIII-D ELMy H-modes

Walter Guttenfelder (PPPL)
Co-authors: R.J. Groebner (GA), B.A. Grierson (PPPL), J.M. Canik (ORNL), E.A. Belli (GA), J. Candy (GA)

The spectral multiscale gyrokinetic code CGYRO is used to calculate theoretical nonlinear turbulent transport in the edge region of DIII-D H-mode discharges. We focus on two discharges with different divertor geometries in an attempt to clarify the role of transport vs. sources in setting the pedestal density and temperature profiles. Linear simulations predict that ion-scale instabilities dominate at the top of the pedestal where strong rotation shear (specifically parallel velocity shear) enhances the growth rates. In contrast, in the steep gradient region, ExB shearing rates are much larger than growth rates of ion scale instabilities. The electron temperature profiles closely follow the electron-scale ETG instability threshold calculated by CGYRO. Nonlinear electron-scale simulations in the sharp gradient region predict that ETG turbulence can produce significant electron heat flux, comparable to the observed heat flux, while neoclassical transport calculated by NEO provides a significant contribution to the total electron particle flux. To begin developing a theory-based ETG pedestal transport model for the sharp gradient region, nonlinear simulation scans are performed to predict the sensitivity of both electron thermal and particle transport contributions to input gradients. A pedestal-ETG transport model is derived using an analytic fit to the simulation results that follows theoretical expectations. The pedestal-ETG model is used, in addition to neoclassical fluxes from NEO, to predict both ne and Te pedestal profiles using target fluxes determined from SOLPS-ITER interpretive analysis.
This work supported by the U.S. Department of Energy under DE-AC02-09CH11466 (PPPL), DE-FC02-04ER54698 (DIII-D), DE-FG02-95ER54309 (GA Theory) and DE-AC02-05CH11231 (NERSC).

New theoretical insights on the role of ion isotope on transport and turbulence

Jeronimo Garcia (CEA)
Co-authors: A. Banon-Navarro (IPP-Garching), T. Goerler (IPP-Garching), C. Maggi (CCFE)

For more than thirty years, core transport deviations from the expected Gyro-Bohm (GB) scaling with the main ion isotope mass have puzzled the fusion community, leading to the so called isotope effect. A significant effort towards a better understanding has been carried out with the GENE code by performing non-linear gyrokinetic simulations on a large variety of JET plasma conditions in H and D [1] (both in L and H-modes) and ITER extrapolations. A continuous transition from GB scaling for the ion heat flux to strong deviations has been obtained depending on a variety of effects such as increased collisionality, adiabatic or kinetic electrons or external ExB shearing. An important aspect is the stronger coupling with zonal flows with increasing mass, which is additionally boosted through electromagnetic effects. These elements point out to especial plasma conditions where core isotope effects on transport could be clearly identified, i.e. plasmas at high input power (and beta) and significant torque [2]. Gyrokinetic simulations performed for ITER DT extrapolated high beta plasmas show that isotope effects could be very strong due to the relatively closeness of such plasmas to turbulence threshold. Furthermore, the presence of a significant population of fast ions from the DT reactions lead to even stronger isotope effects, with ion fluxes in DT three times lower than in DD. Such studies are helping to understand and guide the JET operation, as one of its main goals is the understating of the isotope effect physics. For that purpose, several campaigns in H, D and T are scheduled for the period 2019-2020 and a strong link between experiment and 14oppler14 /theory has been established. The final goal is to perform a dedicated and successful DT campaign in 2020 with the aim of addressing ITER DT physics [3].

[1] MAGGI C. F. et al Plasma Phys. Control. Fusion 60 (2018) 014045
[2] GARCIA J et al Nucl. Fusion 57 (2017)
[3] JOFFRIN E. et al submitted to Nucl. Fusion.

Plasma theory connections to quantum information science

Scott E Parker (University of Colorado, Boulder)
Co-authors: Alexander Engel (UC Boulder), Chen Tang (UC Boulder), Graeme Smith (UC Boulder), John Bollinger (UC Boulder), Dominic Meiser (UC Boulder)

The potential impact of quantum information science (QIS) on large-scale computing is tantalizing due to the capability to manipulate 2^N complex numbers where N is the number of qubits. Even for N=60, one approaches exascale. Additionally, Moore's law scaling, nearing 5 nm scale, is approaching physical limits. Present day experimental quantum computers are very modest in terms of size and general capability. Whether they may be useful someday for large-scale computation is unknown due to fundamental constraints. Efficient operations are linear. Copying data is approximate. Measurement, or obtaining output is expensive. Here we present two research areas where QIS and plasma theory overlap in interesting ways: 1) quantum algorithms solving the Vlasov equation, and 2) direct numerical simulation of ultra-cold non-neutral ion plasmas used in QIS. We have developed a quantum algorithm that time evolves the linear Vlasov equation with an exponential speed up, thereby, directly addressing the computational demands of the 6D phase space. Progress is being made on developing strategies for the nonlinear problem. A series expansion with good convergence properties using the Homotopy Analysis method (HAM)[1] allows formulation of the nonlinear problem as a large number of matrix multiplies suitable for an efficient quantum algorithm. Additionally, we will discuss how plasma theory can help support QIS via many-particle simulation of ultra-cold non-neutral ion plasmas. A Penning trap is being used to study 100's of interacting quantum spins using an ultracold 2D crystal of singly-ionized Beryllium ions[2]. The simulation obtains excellent agreement with linear eigenmode analysis and includes a fairly detailed laser 15oppler cooling model that allows prediction of the ultracold plasma steady state, and shows agreement with experimentally observed temperatures.

[1] S. Liao, J. of Non. Mech. 34 759 (1999)
[2] J. Bohnet, et al., Science 352 1297 (2016)

Particle transport induced by energetic geodesic acoustic modes

David Zarzoso (CNRS)
Co-author: D. del Castillo Negrete (ORNL)

Energetic particles are ubiquitous in fusion plasmas and need to be well-confined in order to transfer their energy to thermal particles and thus achieve self-sustained fusion reactions. However, energetic particles excite modes that tend to de-confine the particles themselves. This is the reason why understanding and controlling energetic particle modes is of prime importance. In this presentation we focus on a special class of modes, called energetic geodesic acoustic modes (EGAMs) [1, 2]. Because these modes are axisymmetric, they have been assumed to play little role on transport. However, experiments in DIII-D provided puzzling and, so far, unexplained evidence that particles can be de-confined in the presence of EGAMs [1]. In this presentation we elucidate the underlying transport mechanism and show that even if the EGAM potential is axisymmetric and not turbulent, a chaotic channel from the inner region to the edge of the tokamak is created [3]. To support this idea, we present full-f gyro-kinetic simulations with the state-of-the-art multi-species GYSELA code where EGAMs are excited [4, 5] and show that transport results from a complex 3D interaction of resonances that make the particle trajectories chaotic. Our gyro-kinetic results are complemented by a reduced model that exhibits novel aspects of particle transport in the presence of EGAMs including fractal behavior and trapping-induced anomalous diffusion.

[1] R. Nazikian et al, Phys. Rev. Lett. 101,185001 (2008)
[2] G. Fu, Phys. Rev. Lett. 101, 185002 (2008)
[3] D. Zarzoso et al., Nucl. Fusion 58 106030 (2018)
[4] D. Zarzoso et al, Phys Rev Lett 110, 125002 (2013)
[5] D. Zarzoso et al., Phys. Plasmas 19, 022102 (2012).

Cross scale interaction mechanisms in coupled electron and ion scale turbulence

Michael R. Hardman (University of Oxford)
Co-authors: M.Barnes (University of Oxford), C.M.Roach (CCFE), and F.I.Parra (University of Oxford)

Turbulence in magnetic confinement fusion devices has a multi-scale character, due to the smallness of the electron-to-ion mass ratio, and the distinct micro-instabilities driven at the scales of the electron and ion gyroradii. Multi-scale gyrokinetic simulations show the effect of cross-scale interactions [1,2], which can significantly change the character and saturated level of the turbulent transport in multi-scale simulations compared to single scale simulations. We obtain a model of multi-scale turbulence by expanding the gyrokinetic equation in mass ratio [3]. We find gyrokinetic equations describing coupled, scale-separated ion and electron scale turbulence. The cross-scale terms in our equations provide scale-separated mechanisms for cross-scale interactions seen in multi-scale simulations. Our model is solved in a system of coupled flux tubes, making simulations of multi-scale turbulence possible at reduced cost. We present a study exploring the effect of ion scale turbulence on electron scale physics using the flux tube code GS2. We find that electron scale turbulence can be strongly modified in the presence of both weakly and strongly driven ion scale turbulence. We discuss the dominant interaction mechanisms in our model. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/P012450/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors acknowledge EUROfusion, the EUROfusion High Performance Computer (Marconi-Fusion), and the use of ARCHER through the Plasma HEC Consortium EPSRC grant number EP/L000237/1 under the projects e281-gs2.

[1] Howard et al. Nucl. Fusion 56:014004 (2016)
[2] Maeyama et al. Nucl. Fusion 57:066036 (2017)
[3] M. R. Hardman et al. PPCF 61:065025 ArXiv 1901.07062 (2019).

Role of stable modes in the saturation and transport properties of shear flow turbulence

Adrian E. Fraser (University of Wisconsin-Madison)
Co-authors: M.J.Pueschel (IFS-University of Texas at Austin), P.W.Terry (University of Wisconsin-Madison), E.G.Zweibel (University of Wisconsin-Madison)

Reduced transport models are of interest in shear-flow turbulence, particularly for quick predictive characterization of discharges where strongly sheared zonal flows may become unstable. Here, we present a series of investigations into how shear-flow instabilities saturate and drive turbulence. Particularly, we show that large-scale, linearly stable (damped) modes play an important role, and that properly accounting for them can significantly improve reduced transport models. Unlike previous work in systems that were gyroradius-scale or quasi-homogeneous, this work is an investigation into stable modes in a macroscopic, fully inhomogenous instability. Like other systems, stable modes in shear flows decay in the linear regime – and thus are generally neglected in reduced models – but can be shown to be nonlinearly driven to large amplitudes in the saturated state [Fraser et al. PoP (2017)]. Here, the modes are inviscid, and the linear decay corresponds to reversible energy transfer to the mean flow, reflected in their significant modifications to the Reynolds stress. These findings are consistent with gyrokinetic simulations of a driven, shear-unstable flow, where the amplitudes of stable and unstable modes are nearly equal in the turbulent state [Fraser et al. PoP (2018)]. The relative amplitudes can be controlled by a large-scale damping term that is observed to preferentially suppress stable modes over unstable ones. By comparing regimes with and without significant stable mode activity, it is shown that stable modes are a crucial ingredient in reduced models of Reynolds stress when they are present. Ongoing work towards modeling a shear layer with a flow-aligned magnetic field, where stable mode activity is expected to depend on the equilibrium field, will also be presented.

Gyrokinetic continuum simulations of plasma turbulence in the Texas Helimak

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Co-authors: E.L. Shi (PPPL), K. Gentle (UT-Austin), A. Hakim (PPPL), G.W. Hammett (PPPL), T. Stoltzfus-Dueck (PPPL), E.I. Taylor (UT-Austin)

Simple magnetized torus (SMT) experiments, such as the Texas Helimak, use vertical and toroidal field coils to create open, helical magnetic-field-line configurations with curvature and shear. With dimensionless parameters and magnetic geometry similar to the SOL, these devices can be used to compare analytic and numerical models of SOL turbulence to experimental data. Prior to this work, only fluid simulations had been performed of the Helimak. Building on work by Shi et. al.[1-3] using the computational plasma physics framework Gkeyll, we present the first continuum gyrokinetic simulations of plasma turbulence in the Texas Helimak[4]. The device has features similar to the scrape-off layer region of tokamaks, such as bad-curvature-driven instabilities and sheath boundary conditions on the end plates, which are included in our model. A bias voltage can be applied across conducting plates to drive ExB flow and study the effect of velocity shear on turbulence suppression. We performed simulations of grounded and limiter-biased scenarios. Comparisons between simulations and measurements from the experiment show good qualitative similarities, including equilibrium profiles and fluctuation amplitudes that approach experimental values, but also some important quantitative differences. We discuss how including additional physical and geometric effects in our model, such as real ion-to-electron mass ratio and vertical ExB flow could improve agreement with experiment. Both experimental and simulation results exhibit turbulence statistics that are characteristic of blob transport, and, overall, results demonstrate good progress towards modeling turbulence on helical, open-field lines in tokamak SOL-like conditions with gyrokinetic equations.
[1] E. Shi, et. al. J. Plasma Phys (2017).
[2] E. Shi, Ph.D. thesis, Princeton University (2017).
[3] E. Shi, et. al. Phys. Plasmas (2019). [4] T. Bernard, et. al. Phys. Plasmas, in review. arXiv:1812.05703

Cooling the target plasma to a sub-eV detachment temperature using thermionic electrons

Michael D Campanell (Lawrence Livermore National Laboratory)
Co-authors: G.R. Johnson (LLNL), M.V. Umansky (LLNL)

Conventional theoretical models of tokamak scrape-off layer plasmas set boundary conditions assuming the surfaces are below the plasma potential. Recently, our studies found that when emission is sufficiently strong, the plasma-surface interaction switches to an inverse sheath regime where the surface is above the plasma potential and ions are confined [1]. Inverse regimes may have several important consequences in magnetic fusion. Inverse sheath theory explains why emissive probes often float above plasma potential in experiments [2]. Simulation studies [3] suggest that inverse sheaths cause formation of ion-ion plasmas in negative ion sources, an important issue for the design of ITER neutral beams. In a new study, we showed that if an inverse sheath forms at a divertor plate, it will cool the target plasma to a sub-eV temperature, even if the upstream plasma is tens of eV or hotter [4]. This extreme cooling effect was not predicted by other studies of thermionic emission in divertors [5] because the sheath was assumed to be space-charge limited (SCL). Under SCL theory, the target plasma can remain arbitrarily hot relative to the thermionic temperature. Our work shows that an inverse sheath is more stable and it constrains the nearby plasma to the tenths-of-eV thermionic temperature. It follows that use of thermionic divertor plates with inverse sheaths may offer an alternative method of inducing radiative detachment, avoiding the usual need to inject impurities that can contaminate the core plasma.

[1] M. D. Campanell and M. V. Umansky, PoP 24, 057101 (2017) and PRL 116, 085003 (2016)
[2] B. F. Kraus and Y. Raitses, PoP 25, 030701 (2018)
[3] Z. Zhang et al., PSST 27, 06LT01 (2018)
[4] M. D. Campanell and G. R. Johnson, PRL 122, 015003 (2019)
[5] M. Komm et al., PPCF 59, 094002 (2017)

Kinetic model of grazing-angle magnetic presheaths

Alessandro Geraldini (University of Maryland)
Co-authors: F. I. Parra (Oxford), F. Militello (CCFE)

The magnetic presheath is a plasma-wall boundary layer whose thickness is comparable to the ion gyroradius. This layer arises when the magnetic field impinges on the wall making an oblique angle, so that the gyromotion of the ions is distorted by the electric field near the wall. Of particular interest is the fusion-relevant situation of a magnetic field at grazing angle with the wall. In this case, an asymptotic expansion of the ion trajectories in the small angle leads to a gyrokinetic-like model for closed ion orbits. To account for the ions lost to the wall during their last gyration, the gyrokinetic model is complemented by a treatment of open orbits. There are a small number of ions in open orbits, but these are important because the number of ions in closed orbits drops to zero at the wall. The kinetic model allows the analytical derivation of the local condition at the collisionless magnetic presheath entrance (generalizing the Chodura condition), and an efficient numerical solution of the quasineutrality equation (assuming Boltzmann electrons) in the collisionless magnetic presheath. The ion distribution function satisfies the kinetic Bohm condition at the Debye sheath entrance, and is predicted to become thinner at smaller values of the angle and at smaller electron temperature. The potential implications on main ion and impurity sputtering are discussed.

Gyrokinetics of thermalisation of turbulent energy in astrophysical plasmas: a fusion-astro synergy success story

Alexander Schekochihin (Oxford)
Co-authors: Y. Kawazura (Tohoku University), M. Barnes (Oxford), W. Dorland (Maryland), S. Balbus (Oxford)

Perhaps the most popular and most productive route by which the theoretical machinery of fusion science has been ported to astrophysical plasmas (and, on a few notable occasions, brought back, conceptually enhanced, to bear on fusion problems) was the application of gyrokinetic theory to the problem of collisionless plasma turbulence in accretion flows and in the heliosphere, in particular to the question of how energy is partitioned between species (ions and electrons) when this turbulence is thermalised. After many years of promising, but perhaps not entirely conclusive advances in this area, the latest news is that we finally have some quantitative grasp on the answer: GK turbulence promotes disequilibration of species: at high beta, ions are preferentially heated; at low beta, electrons are. This conclusion is supported by GK simulations, which are finally able to give us a heating vs. beta and Ti/Te curve [Kawazura et al. 2019, PNAS 116, 771] and, in the case of low beta, also by relatively rigorous theory [Schekochihin et al. 2019, JPP in press/arXiv:1812.09792]. I will review this progress, spell out caveats (of course there are caveats), describe the next steps (some of which may have been made by April), including some theoretical progress on the high-beta regime, and muse about ways in which ideas that have crystallised in this astrophysical context might be of some use to those of us who would also like to think of turbulence in fusion devices.

PT Symmetry: Physics in the Complex Domain

Carl M. Bender (Washington University in St. Louis)

Complex-variable theory provides insight into the nature of physical theories. For example, it provides a simple and beautiful picture of quantization and it explains the underlying reason for the divergence of perturbation theory. By using complex-variable methods one can generalize conventional Hermitian quantum theories into the complex domain. The result is an exciting new class of parity-time-symmetric (PT-symmetric) theories whose remarkable physical properties are currently under intense study by theorists and experimentalists. Many theoretical predictions have been verified in recent laboratory experiments.