Sherwood 2021 Highlights

International Sherwood Fusion Theory Conference

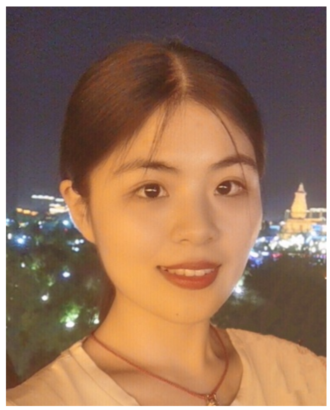
Virtual, August 16 – 18, 2021

The 2021 Sherwood Fusion Theory Conference was held via Zoom on August 16 – 18, 2021. This was the first ever Sherwood Conference held virtually. After not having a Sherwood Conference in 2020, fusion theorists were eager to meet, even virtually. The 2021 Sherwood Conference included 246 registered participants. This included a large number of student participants as well as international participation. The agenda included 12 invited talks and 94 contributed talks, including 40 talks given by students. The feedback on the virtual conference was very positive.

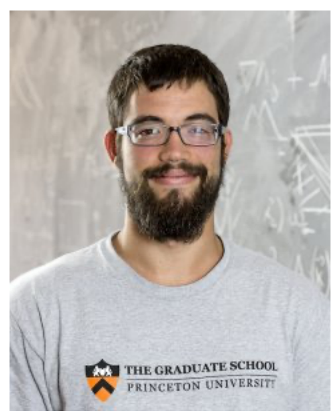
Student Presentation Awards

There were a large number of high-quality presentations from students. The selection process was very competitive. The 2021 Student Presentation Awards went to:

Toby Adkins, University of Oxford
Xiaoxue He, Dalian University of Technology
Alan Kaptanoglu, University of Washington
Joel Larakers, University of Texas, Austin
Ralf Mackenbach, Eindhoven University of Technology
Eduardo Rodriguez, Princeton University and PPPL





Electromagnetic reduction of transport and heat-flux width in gyrokinetic simulations of a helical scrape-off layer model

Noah Mandell, Gregory Hammett, Ammar Hakim, Manaure Francisquez (MIT)

We demonstrate that scrape-off layer (SOL) transport can be reduced by electromagnetic effects in high beta regimes, resulting in a reduction of the SOL heat-flux width. This conclusion is taken from electromagnetic gyrokinetic simulations of a helical SOL model that roughly models the SOL of the National Spherical Torus Experiment (NSTX). In a high-beta simulation, the heat-flux width λ_q is roughly 25% smaller when electromagnetic effects are included. We show that stabilizing effects related to magnetic-field-line bending is key to the reduction in transport, which also leads to steeper SOL pressure gradients. Field-line bending is produced by the combination of interchange dynamics near the midplane and (partial) line tying of field lines on the end plates due to conducting-plate sheath boundary conditions. The result is ballooning-like modes with parallel wavelengths of order the connection length, despite the fact that there is no favorable curvature region in the simple helical geometry that we consider.

The simulations have been performed with the Gkeyll code, which has recently demonstrated the first capability to simulation electromagnetic gyrokinetic turbulence on open magnetic field lines. Gkeyll uses a continuum full-f approach via an energy-conserving discontinuous Galerkin (DG) discretization scheme that avoids the Ampere cancellation problem, allowing electromagnetic fluctuations to be handled in a robust, stable, and efficient manner. Work is in progress to develop capabilities to examine more realistic tokamak geometries with Gkeyll, including the closed-field-line region and the X-point in diverted geometries.

[1] N. R. Mandell, et al. J. Plasma Phys. 86 (2020) 905860109
[2] A. Hakim et al. Phys. Plasmas 27 (2020) 042304
[3] N. R. Mandell, Princeton Ph.D. thesis (2021) arXiv:2103.16062

Kinetic Ballooning Mode turbulence in low-average-magnetic-shear equilibria

Ian J McKinney, M.J. Pueschel, C.C. Hegna, B.J. Faber, A. Ishizawa, P.W. Terry
(U. of Wisconsin-Madison)

Optimizing for turbulent transport in high-beta stellarators requires understanding of electromagnetic turbulence in 3D magnetic geometries. In this work, we report studies of kinetic ballooning mode (KBM) turbulence in low-average-magnetic-shear equilibria, namely HSX, Heliotron-J, and a circular tokamak. Electromagnetic flux-tube simulations of HSX using the gyrokinetic turbulence code GENE show that the onset of KBM instability at low k_y occurs at a value of normalized plasma pressure (beta_KBM) that is nearly an order of magnitude smaller than the MHD ballooning limit (beta_MHD). The beta_KBM tends to be small when the magnitude of the average magnetic shear is low, regardless of sign, and when a strong ion temperature gradient is present. Both Heliotron-J and a circular axisymmetric geometry with low average magnetic shear exhibit behavior similar to HSX with respect to beta_KBM. Regardless, saturation of nonlinear simulations of HSX with beta_KBM < beta < beta_MHD is achievable and results in lower heat fluxes than the electrostatic case. Investigations of nonlinear frequency and heat flux spectra highlight the prominent contribution of KBMs to the turbulent state. Preliminary analyses suggest that KBMs play an integral role in the nonlinear energy transfer dynamics, motivating study of the interplay between ITG and KBMs.

Towards the goal of optimizing turbulent transport in high-beta stellarators, a fluid model is introduced that extends the electrostatic model for 3D equilibria [C.C. Hegna et al., PoP 2018] to include finite-beta effects. This minimal nonlinear fluid model retains the physics of ITG-KBM saturation in stellarators, which is dominated by the transfer of energy from unstable to stable modes at similar scales via nonlinear coupling. The model will be used to build a physical understanding of the relationship between magnetic geometry and beta_KBM.

This work is supported by US DOE.

Importance of non-ideal effects for peeling-ballooning stability thresholds in spherical tokamaks*

Andreas Kleiner, N.M. Ferraro, G.P. Canal, A. Diallo, A. Kirk, L. Kogan, S.F. Smith (PPPL)

We show that non-ideal physics, particularly resistivity, can significantly alter peeling-ballooning (PB) stability thresholds in spherical torus (ST) configurations, such as NSTX and MAST. Edge-localized modes (ELMs) are typically associated with macroscopic PB modes in the edge pedestal due to strong pressure and current density gradients. PB stability thresholds calculated using ideal-MHD agree well with experiments in conventional aspect ratio devices. A long-standing problem has been the reliable modeling of such stability boundaries in STs, where ideal-MHD models often predict stability for ELMing discharges. A more accurate model is needed not only to understand pedestal physics, but also to obtain a predictive pedestal structure model for STs. Employing the state of the art extended-MHD code M3D-C1, we investigate macroscopic edge-stability in ELMing and ELM-free discharges in NSTX and MAST. In ELMing cases we find robust resistive peeling-ballooning modes well before the ideal stability threshold is met. While resistivity has a crucial impact on stability, other non-ideal effects such as finite Larmor radius effects affect the stability limits in a weaker way. With these extended-MHD models the domain of PB instability consistently expands past the experimental point in ELMing discharges. In contrast, it is found that in DIII-D ideal and resistive thresholds are similar, suggesting that resistive effects are important for STs but not for conventional aspect ratio tokamaks. We also consider ELM-free discharges in NSTX, where resistivity appears to be less destabilizing than in the ELMing H-mode cases. In this context two-fluid effects can be important. The results present a valuable basis for the development of a predictive model for ELMs in low-aspect ratio tokamaks. This is an important step towards a compact fusion power plant.

*Work supported by the U.S. Department of Energy under contracts DE-AC02-05CH11231, DE-AC02-09CH11466, DE-FC02-04ER54698

Impact of small ELMs on the divertor heat flux width scaling

Xueqiao Xu, N. M. Li, X. X. He, T. F. Tang, G. Z. Deng, X.Y. Wang, Z.Y. Li, P. B. Snyder, B. Zhu (LLNL)

The BOUT++ simulations of C-Mod, DIII-D, and EAST H-mode discharges follow the Heuristic-Drift-based (HD) empirical divertor heat flux width scaling of the inverse dependence on the poloidal magnetic field. The BOUT++ simulations for ITER and CFETR indicate that divertor heat flux width q of the future large machines may no longer follow the 1/Bpol,OMP scaling, while the HD model gives a pessimistic limit of divertor heat flux width. The simulation results show a transition from a drift dominant regime to a fluctuation dominant regime from current machines to future large machines such as ITER and CFETR for two reasons. (1) The magnetic drift-based radial transport decreases due to large CFETR and ITER machine sizes and strong magnetic field. (2) the SOL fluctuation-driven thermal diffusivity increases due to larger turbulent fluxes ejected from the pedestal into the SOL when operating in a small and grassy ELM regime.

BOUT++ turbulence simulation further shows that peeling-ballooning modes dominate in the linear stage for CFETR & ITER Fusion Power Operation (FPO) scenarios and eventually evolve into various type ELMs. (1) The divertor heat flux width broadens with fluctuations. Small/grassy ELM broadening is much more effective. Ballooning critical gradient scale length near separatrix is a good proxy for heat flux width in small ELMs. (2) micro-turbulence broadening from resistive ballooning modes and drift-Alfven instabilities is very little for ITER, CFETR, and SPARC due to their low scrape-off layer collisionality. Divertor heat flux will pose a significant challenge for compact Fusion Pilot Plant (cFPP). A proper machine design for the combination of the total magnetic field B, the poloidal magnetic Bp or the current Ip, the major radius R, and the separatrix temperature Tsep could significantly alleviate the challenge for cFPP.

Bistable turbulence in fusion plasmas with a sheared mean flow

Nicolas Christen, Michael Barnes, Michael Hardman, Alex Schekochihin (University of Oxford)

The prevailing paradigm for plasma turbulence associates a unique stationary state to given equilibrium parameters. In this talk, we report the discovery of bistable turbulence in a tokamak fusion plasma. Two distinct, stationary turbulent states, obtained with identical equilibrium parameters in local delta-f gyrokinetic simulations, have turbulent fluxes of particles, momentum and energy that differ by an order of magnitude -- with the low-transport state agreeing with experimental observations in the JET tokamak. Occurrences of the two states are regulated by the competition between an externally imposed mean flow shear and "zonal" flows generated by the plasma. With small initial turbulent amplitudes, zonal flows have little impact, and the mean flow shear causes turbulence to saturate in a low-transport state. With larger initial amplitudes, the zonal shear tends to oppose the effect of the mean flow shear, allowing the system to sustain a high-transport state. While the existence of bistability poses a new challenge for research that has so far assumed a uniquely defined turbulent state, our results lead to some remarkable consequences for turbulent transport in fusion plasmas.

The available energy of trapped electrons in a flux tube and its relation to turbulent transport

Ralf Mackenbach, J.H.E. Proll, P. Helander (Eindhoven University of Technology)

Any magnetically confined plasma possesses a certain amount of "available energy", defined as that part of the thermal energy that can be converted into instabilities, which in turn can drive turbulence. Here, I present a calculation of the available energy carried by trapped electrons in a slender non-omnigenous flux tube of plasma. This quantity is compared with gyrokinetic simulations of the non-linear saturated radial energy flux resulting from turbulence driven by collisionless trapped-electron modes in various tokamaks and stellarators. The numerical calculation of available energy is extremely fast and shows a strong correlation with the turbulent energy fluxes found in the gyrokinetic simulations. Indeed, the energy flux is found to be proportional to the available energy to the power of approximately 3/2, as one would expect from a simple phenomenological model. These results suggest that the available energy can be used as a proxy function, to find stellarators which minimize turbulent transport.

Effect of Triangularity on Ion-Temperature-Gradient Turbulence

J. M. Duff, B. J. Faber, C. C. Hegna, M. J. Pueschel, P. W. Terry (U. of Wisconsin-Madison)

In this work, we model how axisymmetric magnetic shaping affects ion-temperature-gradient-driven (ITG) turbulence. Linear and nonlinear properties of an ITG scenario with adiabatic electrons are analyzed using the gyrokinetic code GENE. Peak linear growth rates decrease with negative δ but increase in finite radial wavenumber kx with positive δ. The growth-rate spectrum broadens in kx with negative δ and significantly narrows with positive δ. The effect of δ on linear instability properties can be explained through its impact on field line bending and curvature. Nonlinear heat flux is weakly dependent on triangularity for $|\delta| \leq 0.5$, decreasing significantly with extreme δ, regardless of sign. Zonal modes play an important role in nonlinear saturation in the configurations studied, and artificially suppressing zonal modes increased nonlinear heat flux by a factor of about four for negative δ, increasing with positive δ to almost a factor of 20. Proxies for zonal-flow damping and drive suggest that zonal flows are enhanced with increasing positive δ.

An implicit, energy conserving and asymptotic preserving full-orbit time-integrator for particle-in-cell schemes*

Dr. Lee F. Ricketson and Luis Chacón (LANL)

While the gyrokinetic approximation has been extremely successful in accelerating simulations of strongly magnetized plasmas, there is increasing interest in full-orbit simulation in key contexts in which the gyrokinetic ordering may break down. Motivated by this, we present an implicit time-stepping scheme for charged particle motion that recovers the gyrokinetic limit when stepping over the gyration scale while converging to the exact, full-orbit dynamics in the small time-step limit. Such a scheme provides, for the first time, a uniform multiscale treatment of strongly and weakly magnetized regimes without the need to resolve gyration scales. The scheme is designed to function as a piece of recent implicit particle-in-cell schemes – most notably, it preserves the exact total energy conservation enjoyed by those schemes.

The development proceeds in two stages. First, the classical Crank-Nicolson scheme is modified to capture all guiding-center drift motions when stepping over the gyration scale – while still conserving energy - by introducing an effective force that induces the magnetic drift for large time-steps. Second, to capture finite Larmor radius (FLR) effects, we introduce alternating large and small time-steps to sample equispaced gyrophases in the time-stepping process. The numerical time-scales introduced by the new scheme are analyzed and resulting bounds on time-step are derived. These bounds still permit stepping over the gyration time-scale by large factors in strongly magnetized contexts.

We conclude with several numerical tests on single particle motion in complex field configurations. The ability to step over the gyration time-scale and recover correct long-time dynamics is demonstrated - even in field configurations featuring structure on the gyroradius scale - along with the scheme’s energy conservation properties.

*Prepared by LLNL under Contract DE-AC52-07NA27344.

Magnetic reconnection propulsion

Fatima Ebrahimi (PPPL and Princeton University)

A new concept for the generation of thrust for space propulsion, an Alfvenic reconnecting plasmoid thruster, is introduced (F. Ebrahimi, featured article in the Journal of Plasma Physics, Volume 86, Issue 6, December 2020). Energetic thrust is generated in the form of plasmoids (confined plasma in closed magnetic loops) when magnetic helicity is injected into an annular channel. Using a novel configuration of static electric and magnetic fields, the concept utilizes a current-sheet instability to spontaneously and continuously create plasmoids via magnetic reconnection. The magnetic reconnection process here converts magnetic energy of the applied fields to kinetic energy of the plasmoids, accelerating them to a velocity of tens to hundreds of km/s, adjustable by varying the magnetic field strength. The qualitative experimental evidence of plasmoid formation demonstrated during transient coaxial helicity injection in NSTX was first predicted by global MHD simulations (Ebrahimi & Raman Physical Review Letters 114, 205003 2015), and has inspired this thruster concept. This concept combines magnetic helicity injection with axisymmetric fast magnetic reconnection and is extensively explored via three-dimensional extended MHD NIMROD simulations. The plasmoids carry large momentum, leading to a thruster design capable of producing thrusts from tenths to tens of newtons. The Alfvenic plasmoid thruster would occupy a complementary part of parameter space with little overlap with existing thrusters and be suitable for long-distance travel with high Delta-v, including the solar system beyond the Moon and Mars.

Topological waves in magnetized cold plasma

Yichen Fu and Hong Qin (PPPL)

In the past decade, topological phases of electronic and photonic systems have become a rapidly emerging field of research, which deepened the understanding of the states of matters. One of the essential physical consequences of topological phases is the bulk-edge correspondence, which states that topologically protected edge modes will occur at the interface between topologically different matters. Recently studies have shown that these topological ideas can also be applied to continuous media, such as neutral fluids and plasmas. Here we present some recent progress [1] in the study of topological phases in magnetized cold plasma. We show that there exist ten topological phases in the parameter space of density n, magnetic field B, and parallel wavenumber k_z. The corresponding phase transitions and edge modes will also be demonstrated. This finding broadens the possible applications of these exotic excitations in space and laboratory plasmas.

[1] Fu, Y., Qin, H. Nat Commun 12, 3924 (2021). https://doi.org/10.1038/s41467-021-24189-3

Rethinking quasisymmetry

Eduardo Rodriguez and Amitava Bhattacharjee (Princeton University and PPPL)

Quasisymmetric stellarators brought about a renaissance in stellarator design by producing a concept which has the superior neoclassical performance of tokamaks, but without the liability of disruptions. However, it was soon realized that exactly quasisymmetric configurations were likely not possible. Though not rigorously proven, the overdetermination of solutions near the axis was taken as evidence of this impossibility [D. Garren, A. Boozer, Phys. Fluid B, 3, 2822 (1991)]. The reason behind this limitation was however not made clear. How fundamental is it? Is there a way around it?

To answer these questions and deepen our understanding we reformulate the notion of quasisymmetry (QS) from a single particle perspective [E. Rodriguez, et al., Phys. Plasmas, 27, 062501 (2020)]. Unlike other formulations, the new formulation makes no assumptions regarding the nature of the underlying MHD equilibrium but reduces to the standard form of QS in a static, ideal, isotropic pressure equilibrium. Generalizing the form of equilibrium to include anisotropic pressure shows that the conventional overdetermination problem of quasisymmetric fields disappears. The near-axis-expansions program with anisotropic pressure now fits the problem perfectly (same degrees of freedom as constraints) [E. Rodriguez, et al., Phys. Plasmas, 28, 012508 (2021)]. Furthermore, we formulate a variational principle with constraints that naturally produce quasisymmetric equilibria with anisotropic pressure. Numerical solutions based on expansions will be presented [E. Rodriguez, et al., arXiv:2012.02077, to appear in PRE]. This reformulation and broader view on the problem opens a new perspective and framework for QS, suggesting that there may exist solutions that are very close to QS even in ideal, static, isotropic pressure equilibrium. Additional properties such as the role of flows or the presence of current singularities and islands can now be explored from a broader perspective.

Suppression of runaway electrons in SPARC with a passive 3D coil

V.A. Izzo (Fiat Lux), RA Tinguely, DT Garnier, RS Granetz, R Sweeney (MIT-PSFC), A Sundström, O Embréus, T Fülöp, M Hoppe, I Pusztai (Chalmers University of Technology), K Särkimäki (Max Plank Institute for Plasma Physics)

Runaway electron (RE) suppression by a passively driven 3D runaway electron mitigation coil (REMC) during a SPARC [1] current quench (CQ) has been predicted using a combination of four codes to model vacuum fields, nonlinear MHD, RE transport, and RE generation and current evolution. The REMC concept, first proposed by Boozer [2], relies on the induced loop voltage associated with the CQ to drive a much larger current in an external 3D coil than could easily be produced with actively driven coils, generating large error fields that will deconfine seed REs before they can avalanche to produce a potentially damaging RE beam. Using vacuum fields for an n=1 REMC design calculated with COMSOL, NIMROD 3D MHD simulations of the CQ are carried out to calculate of destruction of flux surfaces by the coil perturbations and the nonlinear plasma response. Based on these time-dependent 3D fields, advection and diffusion coefficients for REs are calculated using the orbit-following code ASCOT5, and these coefficients are incorporated in the DREAM code to calculate the total RE current evolution including generation, avalanching and losses. The proposed n=1 REMC design is predicted to fully suppress RE formation, while n=2 and n=3 configurations also modeled are not able to fully stochasticize the core. A set of further NIMROD simulations explore the effects of the final plasma temperature, the conducting wall location, and inclusion of both thermal quench MHD and coil-driven CQ MHD fluctuations.

[1] A. Creely, M. Greenwald, S. Ballinger, et al, Journal of Plasma Physics 86 (2020) 865860502
[2] A. Boozer, Plasma Phys. Control. Fusion 53 (2011) 084002