Highlights from Sherwood 2022

International Sherwood Fusion Theory Conference

April 4-6, Santa Rosa, CA

Hosted by the Scientific Program Organizing Committee

Held at Hyatt Regency Sonoma Wine Country Hotel

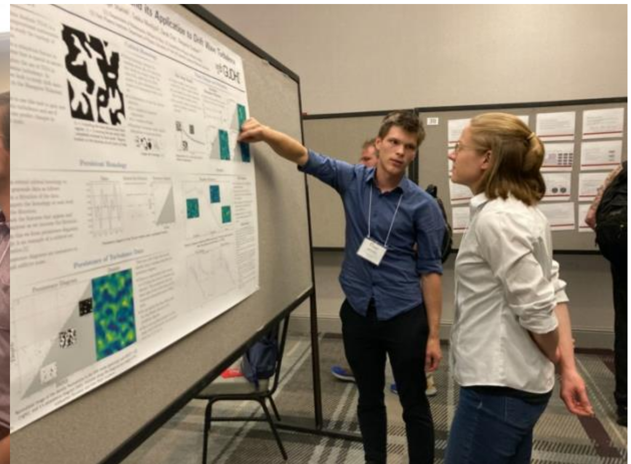
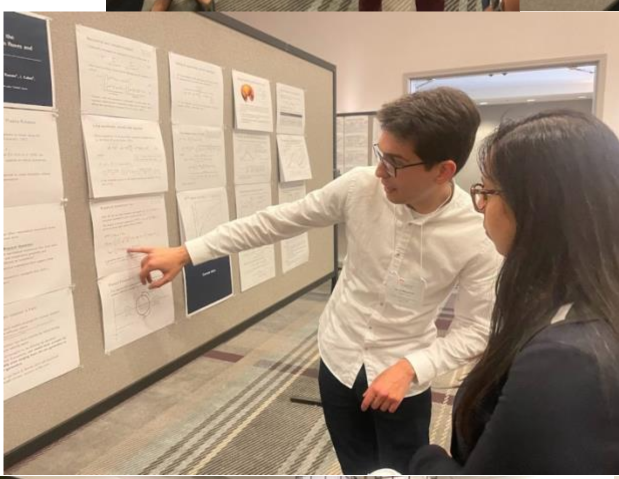
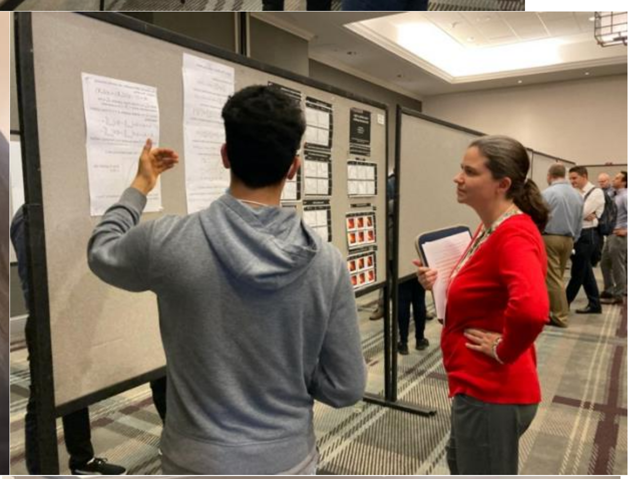
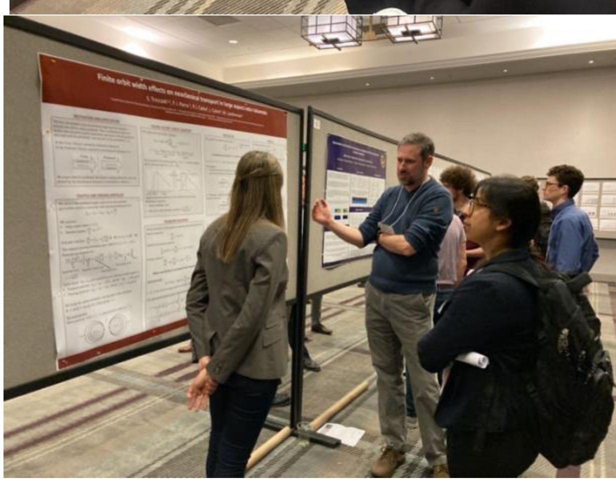
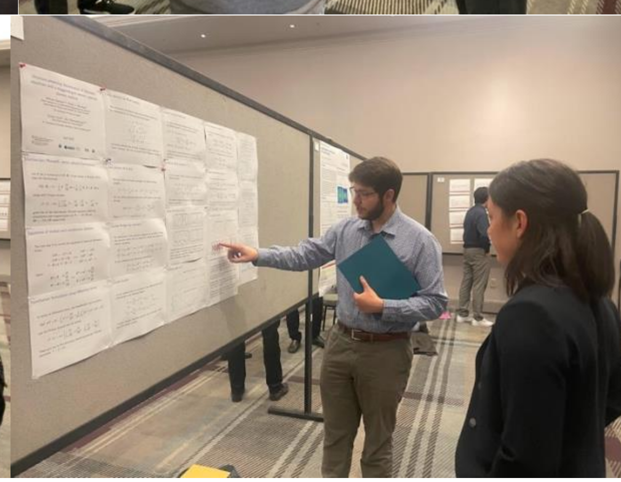
Co-located with US-EU Joint Transport Task Force Workshop

After the 2020 meeting was cancelled and the 2021 meeting was held virtually due to Covid-19, Sherwood returned to its in-person format for 2022. The conference had about 110 in-person attendees, with about 30 students in attendance. The 2.5 day program featured one plenary talk and 13 invited talks. Two joint invited sessions were held with the TTF workshop. Invited talk abstracts are provided at the end of the document.

Wednesday morning, Phil Snyder gave the plenary talk with the title “Physics of the tokamak pedestal, and implications for a fusion pilot plant”

Sherwood and TTF attendees enjoyed coffee breaks in the Santa Rosa sun

99 posters were presented during sessions on Monday and Tuesday afternoon, with 27 student presentations

Six poster awards were given to the following students:

Alistair Arnold (Max Planck Institute for Plasma Physics) – "Parallel expansion of a pellet plasmoid"
Urvashi Gupta (Univ. of Wisconsin-Madison) – "Pressure driven dynamics and global energy transport in finite-beta RFP computations"
Patrick Kim (IREAP) – "Prospects for Efficient Calculation of 3D Plasma Response to RMPs Using Equilibrium Principles"
Silvia Trinczek (Univ. of Oxford) – "Finite orbit width effects on neoclassical transport in large aspect ratio tokamaks"
Bindesh Tripathi (Univ. of Wisconsin-Madison) – "Transport reduction in forced shear layers due to stable modes"
Javier Maurino (Univ. of Oxford) – "Effect of turbulence on the neoclassical momentum fluxes and current drive"

From left to right: Alistair Arnold, Urvashi Gupta, Patrick Kim, Silvia Trinczek, Bindesh Tripathi, Javier Maurino, Valerie Izzo (chair of Program Committee)

Valerie Izzo presents award to Alistair Arnold

Achieving energetic particle confinement in stellarators with precise quasisymmetry

Matt Landreman, Stefan Buller, Antoine Cerfon, Michael Drevlak, Andrew Giuliani, Elizabeth Paul, Georg Stadler, Florian Wechsung

University of Maryland

While stellarators are free from disruptions and the Greenwald density limit, are intrinsically steady-state, and do not require recirculated power for current drive, confinement of energetic particles in stellarators has long been a significant concern. Quasisymmetry is a property of some stellarator magnetic fields that can resolve this confinement challenge. Using improved optimization procedures, here we present several new stellarator configurations [1] that possess quasisymmetry throughout a volume to significantly higher precision than demonstrated previously. As a result, losses of fusion-produced alpha particles can be reduced significantly below levels for previous stellarators, and neoclassical transport can be suppressed by orders of magnitude. In at least some cases, these levels of confinement can be achieved with as few as 16 modular coils. A new method is also presented for including the bootstrap current self-consistently in the optimizations.

[1] Landreman & Paul, Physical Review Letters 128, 035001 (2022)

Exploring stellarator beta-limits with nonlinear MHD modelling

Adelle Wright, Nate Ferraro

Princeton Plasma Physics Laboratory

We present the first results from a parametric exploration of beta-limits in a 10-field period heliotron, showcasing the M3D-C1 code's new capability to perform extended-MHD simulations in stellarator geometry. We examine the effect of heating power and transport on MHD dynamics and nonlinear stability, observing low-n core mode activity that is broadly consistent with experimental observations on the Large Helical Device (LHD). This paves the way for quantitative validation with LHD experiments.

We capture the self-consistent evolution of both the magnetic field and pressure gradients using sources and anisotropic thermal transport. Importantly, we impose no assumptions or constraints on the magnetic field topology (such as the existence of magnetic surfaces) or the plasma shape.

Understanding nonlinear MHD stability is important for fusion. Clarifying the role of 3D effects is critical for determining when macroscopic instabilities are benign or have the potential to become disruptive. Like tokamaks, stellarators can be susceptible to (sometimes disruptive) pressure and current-driven instabilities; soft linear stability limits, corresponding to benign core-MHD activity, and disruptions, have both been observed experimentally.

The extended-MHD, initial value-code, M3D-C1, was recently extended to accommodate stellarator geometry, providing a unique capability to explore nonlinear MHD and the effect of 3D transport in stellarators.

Exploration of Quantum Computing for Fusion Energy Science Applications*

Ilon Joseph, Alessandro R. Castelli, Vasily I. Geyko, Frank R. Graziani, Stephen B. Libby, Jeffrey B. Parker, Max D. Porter, Yaniv J. Rosen, Yuan Shi, Jonathan L. DuBois

Lawrence Livermore National Lab

Quantum computing promises to deliver large gains in computational power that can potentially have a beneficial impact on a number of Fusion Energy Science (FES) application areas that rely on either intrinsically classical or intrinsically quantum calculations. This work presents an overview of our recent efforts to develop and extend quantum algorithms to perform FES-relevant calculations and perform concrete examples of quantum computations on present day quantum computing hardware platforms. We have developed quantum algorithms that can: (1) exactly simulate the Liouville equation [1], even for nonlinear non-Hamiltonian, e.g. dissipative, classical dynamics; (2) perform efficient eigenvalue estimation for generalized eigenvalue problems common in plasma physics and MHD theory [2]; (3) efficiently implement nonlinear wave-wave interactions [3]; and (4) efficiently explore chaotic quantum and classical dynamics [4].

Simplified versions of these quantum algorithms have been implemented on state-of-the art cloud-based superconducting architectures such as the IBM-Quantum Experience and Rigetti Quantum Cloud Services platforms in order to test the fidelity of emerging quantum hardware capabilities. We have also implemented some of these algorithms on the LLNL Quantum Design and Integration Testbed (QuDIT), which has novel capabilities such as the ability to work with more than two energy levels per transmon and the ability to synthesize arbitrary unitary gates (for small qubit numbers) using optimized control pulses. These hardware platforms have been used to simulate a nonlinear three-wave interaction problem [3] and a three-level Grover's search algorithm. We have also explored the ability of the IBM-Q platform to simulate chaotic dynamics through the quantum sawtooth map [4], as well as a number of the building blocks of the quantum variational eigensolver algorithm. The fidelity of the experimental results matches noise models that include decay and dephasing processes and highlights key differences between state-of-the art approaches to quantum computing hardware platforms.

*LLNL-ABS-833451 was prepared by LLNL for U.S. DOE under Contract DE-AC52-07NA27344 and was supported by the U.S. DOE Office of Fusion Energy Sciences "Quantum Leap for Fusion Energy Sciences" project (SCW1680) and by LLNL Laboratory Directed Research and Development project 19-FS-072.

References

[1] I. Joseph, "Koopman-von Neumann approach to quantum simulation of nonlinear classical dynamics," arXiv:2003.09980, Phys. Rev. Research **2**, 043102 (2020)
[2] J. B. Parker, I. Joseph. "Quantum phase estimation for a class of generalized eigenvalue problems," arXiv:2002.08497, Phys. Rev. A **102**, 022422 (2020),
[3] Y. Shi, A. R. Castelli, X. Wu, I. Joseph, V. Geyko, F. R. Graziani, S. B. Libby, J. B. Parker, Y. J. Rosen, L. A. Martinez, and J. L. DuBois, "Quantum computation of three-wave interactions with engineered cubic couplings," arXiv:2004.06885, Phys. Rev. A **103**, 062608 (2021).

[4] M. D. Porter, I. Joseph, "Observability of fidelity decay at the the Lyapunov rate in few-qubit quantum simulations," arXiv:2110.07767, submitted to Quantum (2021).

A conservative multi-scale hybrid scheme with full-orbit ions and fluid-electrons

Adam Stanier, L. Chacon

Los Alamos National Laboratory

Hybrid kinetic-fluid models have long been used to model magnetized plasma experiments. Full-orbit versions can be complementary to the gyrokinetic (GK) model, due to their extended validity in regimes where GK ordering parameters may not be small. This can include strong gradient regions such as the tokamak pedestal, or fast occurring phenomena such as reconnection in a sawtooth crash or a tokamak disruption.

We will describe a novel implicit, electromagnetic particle-based scheme for this model [1]. It uniquely conserves mass and energy for general curvilinear meshes [2], as well as momentum for a subset of adaptive (packed) tensor-product meshes. The use of implicit time-stepping, along with exact conservation, lends favorable stability properties to the scheme. The basic algorithm is extended to treat multi-scale problems by using adaptive sub-stepping and orbit averaging of the full-orbit ions, to integrate their orbits accurately and reduce noise. Physics-based preconditioning, using a low-order fluid model to accelerate the high-order kinetic scheme, yields a significant performance gain when taking large timesteps. We will demonstrate the utility of the scheme for several numerical examples, including an m=1 kink mode in helical geometry.

Finally, we will comment on the mitigation of a previously unidentified cancellation issue [3] that arises from the hybrid discretization (with ions treated as particles and electrons on a mesh), and is common to all hybrid-kinetic schemes of this type.

[1] Stanier, A., Chacón, L., & Chen, G. (2019). J. Comp. Phys., 376, 597-616.

[2] Stanier, A., & Chacon, L. (2021). arXiv preprint arXiv:2110.03886.

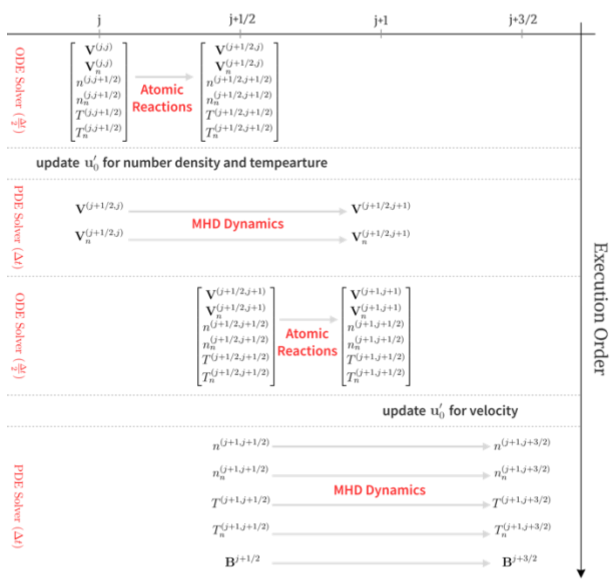
[3] Stanier, A., Chacon, L., & Le, A. (2020). J. Comp. Phys., 420, 109705.

A time-split approach to atomic and multiple species physics within the semi-implicit leapfrog method and development for next-generation hardware

Jacob R King, Sina Taheri, Eric Howell, Brian Cornille

Tech-X Corp

Incorporation of atomic physics associated with multiple species is required to study next-generation fusion device topics such as integration of MHD modeling of resonant magnetic perturbations or edge-harmonic oscillations with advanced edge solutions. The semi-implicit leapfrog time-discretization is a workhorse for initial-value MHD codes such as NIMROD and M3D-C1. By exploiting the functional structure of the MHD equations, the advances each field can be staggered or solved sequentially resulting in a smaller algebraic system during each separated field advance relative to the full system size. The inclusion of nonlinear atomic interactions breaks the functional structure of the MHD equations that is exploited by the leapfrog. We present an operator-splitting formulation of the atomic interactions using a Strang-splitting technique to naturally break equations into constituent ODE and PDE parts and preserve the structure exploited by the semi-implicit leapfrog. By testing on a battery of cases, we show that a second-order-in-time Douglas-Rachford inspired coupling between the ODE and PDE advances is effective in reducing the time-discretization error to be comparable to that of Crank-Nicholson with Newton iteration of the nonlinear terms. Since all of the nonlinear atomic interaction is handled by a local ODE solver using an Adams-Bashforth method, no nonlinear iteration is required and each spatial point can be treated independently and in parallel. This parallelism is advantageous for exploiting GPUs. We use OpenACC with a modern Fortran implementation using a continuous-integration development cycle to port NIMROD algorithms to the GPU architecture. The performance of the ported finite-element and matrix preconditioning kernels is reported. Finally, we show that for systems with multiple charged species the momentum equations can be transformed into a form with the charge-density-weighted terms from the center of mass equation and ODE coupling terms.



Bohm criterion of plasma sheaths away from asymptotic limits

Li Yuzhi, B.Srinivasan, Y.Zhang, X.Z.Tang

Virginia Tech

Sheath theory has a central place in plasma physics as its original formulation coincided with the recognition of plasma physics as a sub-field in physics and it applies to any plasma bounded by a material boundary. One of the most celebrated findings in sheath theory is the so-called Bohm criterion that predicts a threshold, the so-called Bohm speed, which would provide a lower bound for the plasma exit flow speed at the sheath entrance. The Bohm speed regulates the plasma particle and power exhaust fluxes to the wall, and it is commonly deployed as a boundary condition to exclude the sheath region in quasi-neutral plasma modeling. Traditionally, evaluation of Bohm speed from the Bohm criterion invokes drastic simplification of plasma transport that ignores the transport physics in the plasma-sheath transition problem. These and even more sophisticated kinetic Bohm criterion analysis are all performed in the asymptotic limit of vanishing Debye length, and hence their applicability becomes suspect in a realistic plasma. Here, we drive an expression for the Bohm speed from a set of anisotropic plasma transport equations. The thermal force, temperature isotropization and heat flux enter into the evaluation of the Bohm speed. Away from the asymptotic limit, it is shown from the simulation results that there exists a plasma-sheath transition region, where the quasi neutrality is weakly perturbed, rather than a single sheath entrance in the asymptotic limit, so a Bohm speed is predicted for the entire transition region. By comparison with kinetic simulation results, the Bohm speed model in our work is shown to be accurate in the sheath transition region over a broad range of collisionality. This, to our knowledge, is the first time that a predictive formula for Bohm speed has been shown to be quantitatively accurate in the intermediate plasma regime, which is away from the known limiting cases and the asymptotic limit.

Ref: Y. Li et al PRL 128, 085002 (2022)

Tokamak Disruption Event Characterization and Forecasting Research and Expansion to Real-Time Application

S.A. Sabbagh[1], J.W. Berkery[1], Y.S. Park[1], J.M. Bialek[1], J. Butt[1], Y. Jiang[1], V. Klevarova[1], J.D. Riquezes[1], M. Tobin[1], J.G. Bak[2], M.D. Boyer[3], K. Erickson[3], A.H. Glasser[4], C. Ham[5], J. Hollocombe[5], J. Kim[2], A. Kirk[5], J. Ko[2], W.H. Ko[2], L. Kogan[5], J.H. Lee[2], J.W. Lee[2], A. Piccione[6], M. Podesta[3], D. Ryan[5], A. Thornton[5], Y. Andreopoulos[6], S.W. Yoon[2], Z.R. Wang[3]

[1]Dept. of Applied Physics and Applied Mathematics, Columbia U., New York, NY, USA
[2]Korea Institute for Fusion Energy, Daejeon, Republic of Korea
[3]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[4]Fusion Theory and Computation, Inc., Kingston, WA, USA
[5]Culham Centre for Fusion Energy, UKAEA, Abingdon, UK
[6]University College London, London, UK

Disruption prediction and avoidance is critical for ITER and reactor-scale tokamaks to maintain steady plasma operation and to avoid damage to device components. Physics-based disruption event characterization and forecasting (DECAF) research determines the relation of events leading to disruption, and forecasts event onset. The analysis has access to data from multiple tokamaks to best understand, validate, and extrapolate models. Recent code improvements allow fully automated analysis spanning an entire device run campaign or even the entire device database. Significant new hardware and software for real-time data acquisition and DECAF analysis are being installed on the KSTAR superconducting tokamak. Real-time magnetics, electron temperature, T_e, profiles from electron cyclotron emission (ECE), 2D T_e fluctuation data from ECE imaging, and velocity and T_i profiles show excellent agreement with offline data/analysis. An MHD mode locking forecaster has been developed for off-line and real-time use using a torque balance model of the rotating mode. Early warning forecasts on transport timescales potentially allow active profile control to avoid the mode lock. Mode stability alteration by ECCD is examined and recent experiments have shown the ability to avoid mode lock-induced disruption by applying rotating 3D fields. Innovative counterfactual machine learning is used to examine hypothetical RWM stabilization scenarios with rotating MHD. An ELM identification event module includes the ability to distinguish localized and global MHD events. Fully non-inductive current scenarios in KSTAR are examined by “predict-first” analysis of already highly (~75%) non-inductive plasmas. Resistive stability analysis including Δ' computed by DCON is evaluated with comparison to experiment examining sensitivity to localized variations of kinetic equilibrium reconstructions of the *q* profile using MSE magnetic pitch angle data.

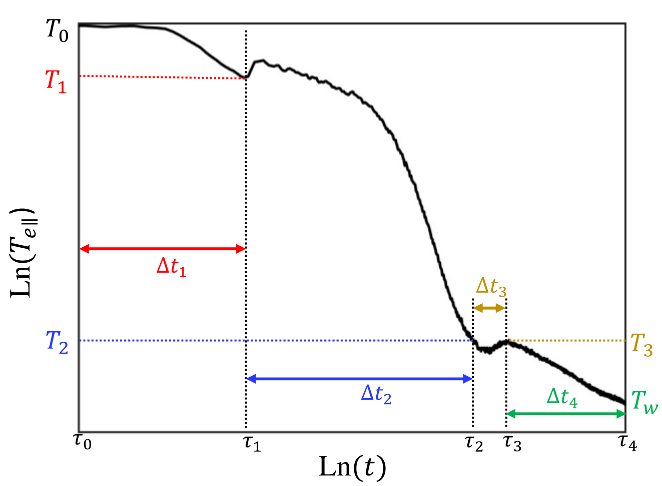
Supported by US DOE Grants DE-SC0016614 and DE-SC0018623.

Cooling flow regime of a plasma thermal quench

Yanzeng Zhang, Jun Li, Xianzhu Tang

Los Alamos National Laboratory

ITER's standard approach of mitigating the thermal load of an incoming thermal quench in the event of a major disruption is to inject neon pellets and force a core thermal collapse through radiation. This is conceptually similar to structure formation in clusters of galaxies in which local accumulation of gas produces a radiative cooling spot for the surrounding intra-cluster hot gas. An even more striking similarity is that both plasmas are nearly collisionless, so the plasma cooling due to the presence of a radiative cooling spot is in an exotic regime in which one would normally assume that electron thermal conduction, even with free-streaming flux limiting, is the dominant mechanism for the thermal quench. In the aforementioned astrophysics problem, one instead observes a robust cooling flow into the radiative cooling spot. Ways to inhibit thermal conduction, for example, by tangled magnetic field lines in the transverse direction, have been an active area of research for the astrophysics community. Here we use first-principles kinetic simulation and analytical theory to show that for a nearly collisionless plasma, its thermal collapse due to the interaction with a radiative cooling spot is not conduction-dominated, but instead relies on convective energy transport for cooling. As the result, there is a robust cooling flow towards the radiative cooling spot. The fundamental physics is the constraint of ambipolar transport, which in the case of a nearly collisionless plasma, enforces a particularly simple and robust form of electron energy transport that favors convection over conduction. The thermal collapse now takes the form of four propagating fronts that originate from the radiative cooling spot, along the magnetic field in the case of a tokamak. The slowest one, which is responsible for deep cooling, is a shock front. Similar physics can occur for an unmitigated thermal quench where 3D field lines connect the core plasma directly to the first wall.



Cooling history of core parallel electron temperature, where the propagating fronts turn the core TQ into four different phases

Electromagnetic total-f simulation of diverted edge plasma in the gyrokinetic particle-in-cell code XGC

Robert Hager, S. Ku, A. Y. Sharma, C. S. Chang, M. Churchill, the XGC Team

Princeton Plasma Physics Laboratory

A total-f electromagnetic gyrokinetic algorithm has been implemented in the particle-in-cell code XGC, which, for the first time, can simulate electromagnetic turbulence in tokamak boundary plasma in realistic divertor geometry together with neutral particle recycling and neoclassical physics. The generalization of XGC's total-f method to the electromagnetic regime is based on the reduced delta-f mixed-variable/pullback algorithm [1,2] implemented in XGC and verified by M. Cole et al.[3] The new electromagnetic XGC now combines the traditional strengths of its total-f algorithm such as realistic tokamak geometry from the magnetic axis to the material wall, combined neoclassical and turbulence physics, neutral particle recycling, a nonlinear Fokker-Planck collision operator, and efficient, GPU-accelerated parallelization, with the numerical stability of the mixed-variable/pullback formulation that mitigates the "cancellation problem" and allows for relatively large time steps. We will present an overview of the electromagnetic total-f algorithm with all its major building blocks. A pair of simulations in a DIII-D-like H-mode boundary plasma comparing the electrostatic and electromagnetic total-f method will be discussed. These results show that electromagnetic simulation is necessary for a higher fidelity understanding of particle and heat transport even at the low values of beta at the pedestal foot around the separatrix. We will also present results from electromagnetic simulations of the divertor heat-load in a present-day tokamak and ITER (fusion power operation).

[1] R. Kleiber et al., Phys. Plasmas 23, 032501 (2016)

[2] A. Mishchenko et al., Phys. Plasmas 21, 052113 and 092110 (2014)

[3] Michael Cole et al., Phys. Plasmas 28, 034501 (2021)

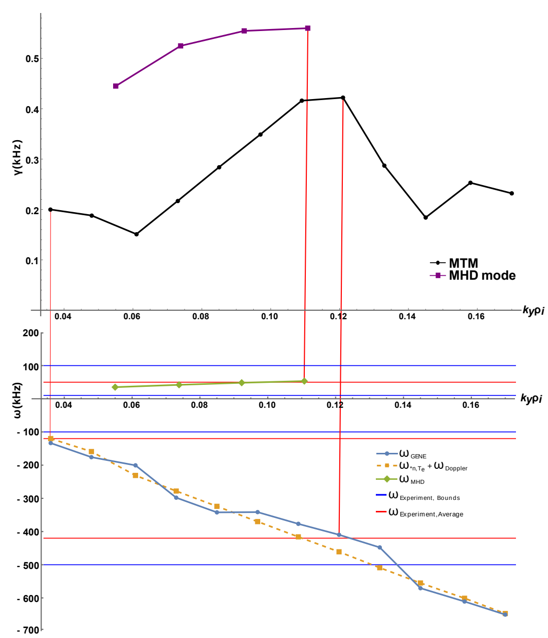
Supported by the U.S. Department of Energy via the SciDAC program and by the INCITE program at leadership computing facilities.

Analysis of gyrokinetic microinstabilities driving anomalous losses in DIII-D pedestal region

Michael R Halfmoon, D. Hatch, M. Kotschenreuther, S. Mahajan, A. Nelson, E. Kolemen, F. Laggner, A. Diallo, E. Hassan, M. Curie, and R. Groebner

University of Texas at Austin

There remain multiple candidate mechanisms accounting for transport across the H-mode pedestal, including microtearing modes (MTM), ion temperature gradient modes / trapped electron modes (ITG/TEM), electron temperature gradient (ETG) modes, and kinetic ballooning modes (KBM). In this study, gyrokinetic simulations are performed for DIII-D discharge 174082 using the GENE code with inputs from equilibrium profiles reconstructed from experimental data. Local nonlinear simulations have shown that electron heat flux has contributions from ETG-driven transport, but not at the level required to fully satisfy power balance, even with variations to the background profiles. MTMs are identified in both linear gyrokinetic simulations and magnetic fluctuation data, providing an additional mechanism to account for electron heat transport. Neoclassical transport is investigated to account for the remaining observed energy losses in the ion channel. The MTM instabilities found in simulations of a DIII-D discharge are consistent with observed magnetic fluctuations, having frequencies in the electron diamagnetic direction and in the expected range as calculated from equilibrium gradients. Modifying the equilibrium βe can result in MHD-like modes becoming the most unstable linear global mode, with ”fingerprints” that are distinct from MTM’s. We investigate magnetic field and density fluctuations for both MHD-like modes and MTMs in an effort to establish a useful ”fingerprint” for distinguishing these two modes in both simulations and experiments. We investigate the structure and underlying physics of this MHD-like instability. Cross-code comparisons between simulation fingerprints are performed for each set of instabilities. Work supported by US DOE under DE-FC02-04ER54698, DE-FG02-97ER54415, and DE-AC02-09CH11466.



Dimits transition in three-dimensional ion-temperature-gradient turbulence

Plamen G. Ivanov, A.A.Schekochihin, W.Dorland

University of Oxford

We present analytical and numerical results on the nonlinear saturation of ion-scale electrostatic turbulence driven by ion-temperature-gradient (ITG) instabilities in slab geometry with constant magnetic curvature. Our work is based on a 3D extension of our 2D, long-wavelength, cold-ion fluid model. We identify two qualitatively distinct routes to saturation: a Dimits state dominated by strong zonal flows (ZFs), and a strongly turbulent state whose saturation is aided by `parasitic' small-scale ITG modes.

The 3D Dimits state is governed by the same underlying physics as that in the 2D model. Turbulence is suppressed by a quasi-static zonal-staircase arrangement of the ZFs and zonal temperature. This structure is reminiscent of the ExB staircase observed in global GK simulations. The zonal staircase consists of interleaved regions of strong zonal shear that suppresses the ITG turbulence in those regions, and localised turbulent patches at the turning points of the ZF velocity.

The distinctive feature of 3D cold-ion ITG turbulence, as opposed to its 2D counterpart, is the existence of a `parasitic' small-scale slab-ITG instability driven predominantly by the gradients of large-scale perturbations, rather than by the equilibrium gradients. We demonstrate analytically and numerically that the parasitic modes extract energy from the large-scale perturbations and provide an effective enhancement of large-scale thermal diffusion, thus aiding the energy transfer from large injection scales to small dissipative ones. Furthermore, these modes always favour a ZF-dominated state. In fact, a Dimits state with a zonal staircase is achieved regardless of the strength of the linear drive provided the system is sufficiently extended along the magnetic field and sufficient parallel resolution is provided. If a Dimits state cannot be maintained, the system enters a strongly turbulent regime where energy transport from large to small scales is dominated by the parasitic instability.

Acceleration of SOLPS-ITER Simulations with Data-Driven Projective Integration

Sebastian De Pascuale, D. L. Green, J. D. Lore, and K. Allen

Oak Ridge National Laboratory

In this talk, we present a data-driven approach for extracting steady-state dynamics latent around an operating point of SOLPS-ITER simulations. We adapt the projective integration framework to accelerate the prediction of key variables in the tokamak plasma boundary. Linear time advance operators constructed via dynamic mode decomposition (DMD) are used to project profiles of the divertor target density and temperature with stable large time steps and robust error convergence. We show that these operators can be analyzed in terms of spectral components that allow for the identification of advantageous time step stability constraints and the separation of fast and slow timescales for integration. By selectively choosing subset time intervals in the ongoing SOLPS-ITER simulation for stable projection, we demonstrate that the error incurred by this approach increases linearly with speedup factor. We show that these operators can achieve up to an 8x acceleration of the target quantities with an average relative error on the order of 10%. For the SOLPS-ITER simulations considered here, these results are found to be robust to the level of numerical noise. We also address one of the limitations of DMD due to the poor scaling of the SVD on systems with higher degrees of freedom by investigating an alternative low-rank approximation scheme. The algorithm we have applied to SOLPS-ITER data is shown to be at least two orders of magnitude faster than the SVD and capable of data compression down to 1% with a total relative error on the order of 10^-4. These findings encourage further development of data-driven projective integration to overcome the weeks to months wall-clock time of SOLPS-ITER at full fidelity and to extend this work towards more challenging multiscale problems such as those captured by gyrokinetic simulation.

Coupled UEDGE/Vorpal modeling of RF-induced ponderomotive effects on edge and SOL transport

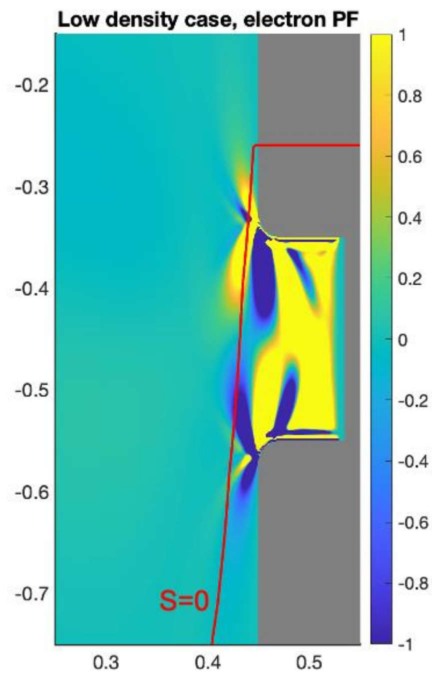
Thomas G. Jenkins[1], David N. Smithe[1], Maxim V. Umansky[2], Andris M. Dimits[2], Thomas D. Rognlien[2]

[1]Tech-X Corporation, Boulder, Colorado, USA, tgjenkins@txcorp.com, smithe@txcorp.com
[2]Lawrence Livermore National Laboratory, Livermore, CA, USA, umansky1@llnl.gov, dimits1@llnl.gov, rognlien1@llnl.gov

Large-amplitude EM fields driven by RF antennas in the tokamak plasma edge induce perturbed charge and current densities on fast RF timescales as power is injected to heat the core plasma. However, these fields, charges, and currents also give rise to slow (transport-timescale) ponderomotive effects, since the time-average of products of fast quantities is nonzero on these longer timescales. Together with the conventional grad(E^2) ponderomotive force associated with nonuniform EM energy density, additional force terms dependent on density gradients, species charge signs, collisionality, and incident wave polarization arise, and these terms introduce new vorticity, energy, and parallel momentum sources to the edge and SOL transport. We have coupled the Vorpal (FDTD EM+plasma solver) and UEDGE (2D edge plasma transport) codes in a manner enabling numerical study of these ponderomotive terms and their effects on edge/SOL transport. In NSTX-adjacent scenarios with experimentally realistic plasma profiles and antenna parameters, we observe that the ponderomotive contribution to parallel electron momentum is significant (comparable to or larger than other edge transport processes) for representative RF input power fluxes. We demonstrate that this parallel momentum source drives the transport of density away from the region immediately in front of the RF antenna. Further, as the density is reduced, we show that the polarization, propagation, and absorption of incident RF waves is accordingly modified, often in detrimental (for antenna efficiency and core power coupling) and potentially self-reinforcing ways.

Because ponderomotive effects scale in magnitude with the antenna input power flux, they become increasingly relevant for large, high-RF-power experiments such as ITER (input power flux ~1 MW/m^2). We consider the implications of these results for ITER antenna operation.

This work is supported by the U.S. Department of Energy's Office of Fusion Energy Sciences in connection with the SciDAC Center for Integrated Simulation of Fusion Relevant RF Actuators (rf-SciDAC), under contracts DE-AC52-07NA27344 (LLNL), FWP-2017-LLNL-SCW1619 (LLNL), and DE-SC0018319 (Tech-X).



Near an RF antenna, the magnitude and spatial localization of ponderomotive forces parallel to the background magnetic field can vary significantly, depending on the positioning of the lower hybrid resonant layer (S=0) relative to the antenna aperture. The ensuing (and sometimes self-reinforcing) local density reduction/enhancement can significantly affect the coupling of injected RF power to the plasma core.