Highlights from Sherwood 2025

International Sherwood Fusion Theory Conference
New Yorker Hotel
New York, NY
April 7-9, 2025



SHERWOOD
Fusion Theory

Sherwood 2025 committees

Program Committee Members

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Ben Zhu, Lawrence Livermore National Laboratory
John Van Hoorn, Networking Worlds

By the numbers

- 152 registered participants
  - 46 students
  - 17 postdocs
  - 16 international participants
- Participants enjoyed a welcome reception on Sunday evening and banquet on Tuesday evening, where the poster awards were presented









Student Poster Awards

- In 2025, the student poster award was named after Bill Dorland in honor of his contributions to the fusion theory community
- Because of the quality of posters and the increased number of student participants, 7 students received awards
    - Miguel Calvo-Carrera (MIT): “Passing alpha particle collisional transport in optimized quasisymmetric stellarators”
    - Amelia Chambliss (Columbia University): “Quadratic fux-minimizing maps for characterization of energetic particle transport mechanisms in quasihelical and quasiaxisymmetric stellarators”
    - Emma Devin (Princeton University): “Saturation of discrete driven kinetic instabilities arbitrarily near or far from marginal stability”
    - Klissman Franco (University Wisconsin-Madison): “Computations of Macroscale Dynamics in the Ultralow Safety Factor regime”
    - Lanke Fu (Princeton University): “Flexible differentiable stellarator coil proxy”
    - Jessica Li (Princeton University): “Total-f global simulations of core turbulent transport behavior in negative triangularity tokamaks”
    - Euichan Jung (Princeton University): “Orbit Confinement and Neoclassical Transport in the Collisionless Scrape-Of Layer of Tokamaks”

Columbia Reception

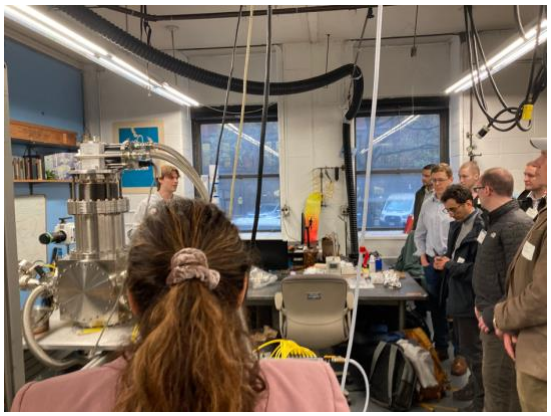
- On Monday, Sherwood participants attended a reception and tour of the Columbia Plasma Physics Laboratory
- The event celebrated the launch of the Columbia Fusion Research Center











Invited sessions

- The 2025 program included 12 invited talks, 3 presented by students



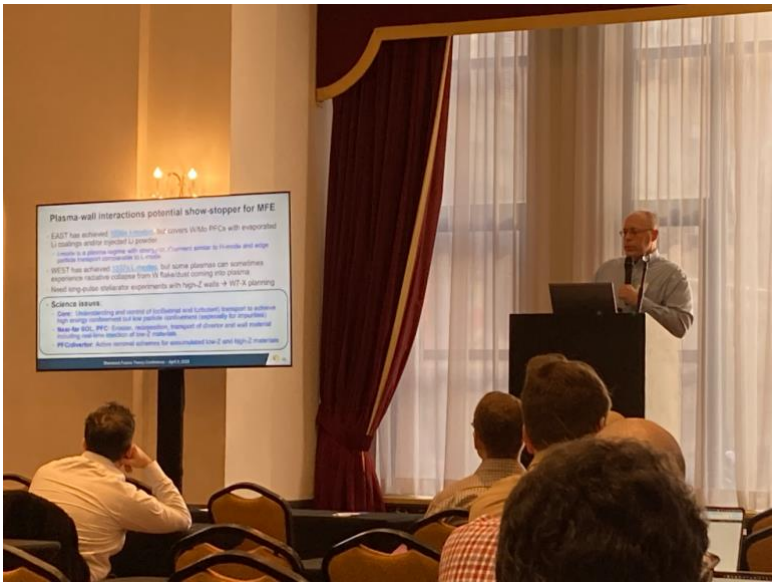




Plenary lectures

- The program included two plenary lectures:
  - Jon Menard (PPPL): “Open science issues for compact high-performance steady-state fusion pilot plants”
  - Nadir Jeevanjee (NOAA Geophysical Fluid Dynamics Laboratory): “New insights into the CO2 greenhouse effect”





Panel Discussion

- On Tuesday, a panel discussion was held on “The role of theory and computation in advancing the FPP”
- Panelists: Fatima Ebrahimi (PPPL), Sam Frank (Realta), Dave Gates (Thea), Pablo Rodriguez-Fernandez (MIT)





Poster Sessions

- 3 poster sessions were held on Monday and Tuesday, including at total of 157 posters with 49 student posters









The gyrokinetic field invariant and electromagnetic instabilities in 'good-curvature' plasmas

Toby G. Adkins, P. G. Ivanov, P. Luhadiya, A. A. Schekochihin

Princeton Plasma Physics Laboratory

Curvature-driven instabilities are ubiquitous in magnetised fusion plasmas. By analysing the conservation laws of the gyrokinetic system of equations, we demonstrate that the well-known spatial localisation of these instabilities to regions of 'bad magnetic curvature' can be explained using the conservation law for a sign-indefinite quadratic quantity that we call the 'gyrokinetic field invariant'. Its evolution equation allows us to define the local effective magnetic curvature whose sign demarcates the regions of 'good' and 'bad' curvature, which, under some additional simplifying assumptions, can be shown to correspond to the inboard (high-field) and outboard (low-field) sides of a tokamak plasma, respectively. We find that, given some reasonable assumptions, electrostatic curvature-driven modes are always localised to the regions of bad magnetic curvature, regardless of the specific character of the instability. More importantly, we also deduce that any mode that is unstable in the region of good magnetic curvature must be electromagnetic in nature. As a concrete example, we present the magnetic-drift mode, a novel good-curvature electromagnetic instability, and compare its properties with the well-known electron-temperature-gradient instability. Finally, we discuss the relevance of the magnetic-drift mode for high-beta fusion plasmas, and in particular its relationship with microtearing modes.

Leveraging Physics-Constrained Deep Learning to Accelerate Integrated Modeling of Tokamak Disruptions.

Jonathan Arnaud, X.-Z. Tang, C. J. McDevitt

University of Florida

Research on mitigating damage from tokamak disruptions is limited by the inability of experiments to access relevant plasma conditions expected in future devices. Additionally, the multi-physics nature of disruptions makes first-principles modeling computationally prohibitive for many-query analyses, which requires a self-consistent treatment of plasma power balance, magnetohydrodynamic (MHD) activity, and runaway electron (RE) formation. To this end, we present a novel path towards an efficient and high-fidelity integrated model of a tokamak disruption. This approach leverages an adjoint treatment of the relativistic Fokker-Planck equation[1] together with recent innovations in physics-constrained deep learning. While incorporating a fully kinetic description of RE formation and evolution, the adjoint formulation of the relativistic Fokker-Planck equation employed is tailored to only predict quantities of interest needed to close the coupled MHD-RE system such as RE density or current. It is shown that such an adjoint problem can be solved across a broad range of plasma conditions using a Physics-Informed Neural Network (PINN)[2]. The resulting surrogate allows for near instantaneous online predictions of RE density, while incorporating a fully kinetic description of RE physics including essential physical processes such as partial screening and radiation. As an initial application, the RE surrogate is coupled with a reduced yet fully self-consistent model of a tokamak disruption. This efficient integrated model is used to explore the high-dimensional space of potential disruption mitigation strategies, thus motivating a path towards accelerating disruption research.

[1] C. F. Karney and N. J. Fisch, The Physics of Fluids 29, 180 (1986).
[2] J. S. Arnaud, T. B. Mark, and C. J. McDevitt, Journal of Plasma Physics 90, 905900409 (2024).

Modeling Resilience of Fusion Blankets to Tokamak Disruptions

Matt Beidler, N.M. Ferraro, J.M. Park, S. Smolentsev, J.D. Lore, B. Turcksin, P. Huang, Y. Fan

Oak Ridge National Laboratory

Fusion blankets must be designed to extract energy, breed tritium, and handle the high heat loads from fusion energy reactors. However, all magnetic confinement concepts are prone to disruptions, where the current quench can induce currents in surrounding conductive structures, including the blanket. This work models disruptions in the Compact Advanced Tokamak (CAT) reactor concept [1] with different blanket concepts. We obtain estimates of the plasma equilibrium, first wall, blanket, and vacuum vessel positions using the code TokDesigner. These design features are then used in the extended-magnetohydrodynamic (MHD) code M3D-C1 [2] to simulate a disruption. In the plasma region, extended-MHD is used, and in the first wall and blanket, which are modeled as electrically conducting solids, the resistive Faraday's law is used. In this study, the effective resistivity of the blanket region is chosen to model lead-lithium and FLiBe concepts. Additionally, the effective resistivity of the blanket region can be anisotropic or isotropic to explore differences in isolated poloidal ducts and toroidally symmetric blanket configurations. An anomalous thermal quench is triggered using an unphysically large perpendicular thermal conductivity. We find that the toroidally symmetric lead-lithium (TSLL) blanket is passively stable to vertical displacement events (VDEs), as compared to dual coolant lead-lithium (DCLL) and FLiBe tank blankets. However, this passive stability comes at the cost of significantly increased static radial forces on the blanket. The toroidal currents induced in the TSLL blanket also screen out the changing poloidal field from the plasma, which has important implications for the pumping pressure needed to circulate the liquid metal through the blanket.

[1] R.J. Buttery et al., Nucl. Fusion 61, 046028 (2021).
[2] N.M. Ferraro et al., Phys. Plasmas 23, 056114 (2016).

A New Paradigm for Global Gyrokinetic Turbulence

Jeff Candy, A. Dudkovskaia, E. Belli

General Atomics

In this work we detail a new mathematical framework to carry out global gyrokinetic simulation by a suitable modification of the existing local formulation. Although global simulations have been routine for more than 20 years, systematic quantification of global corrections to the precise local limit have been lacking in both the gradient-driven and flux-driven formalisms. A key obstacle in this quantification has been the inability to remove artificial shearing generated by global Dirichlet boundary conditions and associated artificial plasma profile shapes. In the new method, global curvature corrections are introduced asymptotically via the application of a discrete radial wavenumber advection operator. This approach enables a high-precision global simulation capability without sacrificing the efficiency and spectral accuracy of local simulations. Numerical results demonstrate that there are two distinct types of global correction to the local result: (1) a shift of the local result in radius due to variation of the effective temperature and density gradient scale length, (2) a decorrelation leading to turbulence suppression, similar to the well-known ExB shear effect. Corrections (1) and (2) are fully quantified by a handful of new physics parameters which measure the profile curvature (second derivatives, and products of first derivatives). This interpretation in terms of radial shift and nontrivial decorrelation provides a simple framework for more accurate interpretation of global gyrokinetic theory.

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What Landau missed

Peter Catto

MIT Plasma Science and Fusion Center

Landau (1946) first realized that the singular behavior of the collisionless linearized kinetic equation describing weakly damped plasma waves could be resolved by Laplace transforming in time to solve a causal initial value problem. Subsequent collisionless work by Dawson (1961) and O'Neil (1965) provided additional insights into the linear and nonlinear temporal behavior of the resonant electrons. Here the focus is on steady state plasmas where weak collisions must be retained to avoid singular behavior. Such situations occur for current drive with a monochromatic applied wave, and collisional transport in an axisymmetric tokamak or quasisymmetric stellarator with a single helicity imperfection. In the weak collision limit a narrow boundary layer resolves the singular behavior, and exactly recovers the collisionless Landau results as long as the wave amplitude is small and the collision frequency finite. However, these Landau results are shown to be inappropriate once the collision frequency becomes small enough and/or wave amplitude becomes large enough, that a nonlinear treatment is required. The nonlinear solution found for a monochromatic wave retains the island structure (Hamilton et al. 2023), but Landau's results (1946) are no longer valid as the collision frequency goes to zero for a non-vanishing plasma wave amplitude. Similar behavior happens for intense current drive, and in the presence of a single helicity error field in a quasisymmetric stellarator (Catto 2025). The seemingly "collisionless" Landau (1946) limit is actually a weakly collisional plateau (or resonant plateau) regime, located between the nonlinear regime and a fully collisional plasma regime.

Supported by DOE grant DE-FG02-91ER-54109.

CATTO, P. J. 2025 Journal of Plasma Physics 91.
DAWSON, J. 1961 Phys. Fluids 4, 869.
HAMILTON, C., TOLMAN, E. A., ARZAMASSKIY, L. & DUARTE, V. N. 2023 AJ 954:12.
LANDAU, L. 1946 J. Phys. 10, 25-34. O'NEIL T. 1965 Phys. Fluids 8, 2255.

Alpha-particle orbits near rational flux surfaces in stellarators

Thomas Foster, F.I.Parra, R.B.White, J.L.Velasco

Princeton University

In modern stellarator designs, confinement of the bounce-averaged drift motion of fusion-born alpha particles is achieved by optimising the magnetic field for omnigeneity. Recently, concerns have been raised that additional optimisation may be necessary for adequate confinement of certain classes of alpha particles with unusual orbits. One such class is particles near rational flux surfaces. Simulations have shown that passing alpha particles near rational surfaces can have orbits containing islands, even when the magnetic field possesses nested toroidal flux surfaces [1,2]. Meanwhile, trapped alphas undergoing resonant motion near a rational surface can exhibit poor conservation of the second adiabatic invariant [3]. In this talk, we give a theoretical account of these unusual orbits by deriving simple, analytical expressions for the orbits of energetic particles near rational flux surfaces in a general stellarator. These orbits are determined by conservation of a 'transit adiabatic invariant' associated with the closed rational-surface field lines. To ensure accurate results even for energetic particles, we compute higher-order corrections to the transit adiabatic invariant; the resulting theory agrees extremely well with simulations conducted using the ASCOT code. We find that semi-trapped particles – trapped particles that undergo multiple toroidal transits before bouncing – do not conserve the second adiabatic invariant but do conserve the transit adiabatic invariant, which allows their orbits to be described analytically. Finally, we discuss how wide orbits, such as the islands around rational surfaces or trapped-particle orbits in an insufficiently optimised device, lead to enhanced collisional transport of alpha particles.

[1] R.White, A.Bierwage and S.Ethier, Phys. Plasmas 29, 052511 (2022)
[2] R.White, Phys. Plasmas 29, 092504 (2022)
[3] E.J.Paul, A.Bhattacharjee, M.Landreman, D.Alex, J.L.Velasco and R.Nies, Nucl. Fusion 62, 126054 (2022)

Metastable states of a rotating Z-pinch

David Hosking, S.C.Cowley

Princeton University

In this contribution, we demonstrate that a rotating Z-pinch can exist in metastable states with significantly better MHD confinement than in the static case. We solve a combinatorial problem to determine the available energy of a metastable state as a function of the plasma beta and Mach number. The ground state is reached by expulsion of an order-unity (accurately calculable) mass fraction of the plasma, leading to a similar reduction in its thermal energy. We discuss to what extent a rotating Z-pinch might constitute a minimal physical setup in which to study the nonlinear MHD dynamics of an H-mode plasma.

How does ion temperature gradient turbulence depend on magnetic geometry? Insights from data and machine learning

Matt Landreman, J Y Choi, C Alves, P Balaprakash, R M Churchill, R Conlin, G Roberg-Clark

University of Maryland

Magnetic geometry has a significant effect on turbulent transport in fusion plasmas. Here, we model and analyze this dependence using multiple machine learning methods and a dataset of > 200,000 nonlinear gyrokinetic simulations of ion-temperature-gradient turbulence in diverse non-axisymmetric geometries. At fixed gradients, the turbulent heat flux varies between geometries by several orders of magnitude. Trends are apparent among the geometries with particularly high or low heat flux. Interpretable regression and classification techniques from machine learning are then applied to extract patterns in the dataset. Due to a symmetry of the gyrokinetic equation, the heat flux and regressions thereof should be invariant to translations of the raw features in the parallel coordinate, similar to translation invariance in computer vision applications. Multiple regression models including convolutional neural networks (CNNs) and decision trees can achieve reasonable predictive power for the heat flux in held-out test configurations, with highest accuracy for the CNNs. Using Spearman correlation, sequential feature selection, and Shapley values to measure feature importance, it is consistently found that the most important geometric lever on the heat flux is the flux surface compression in regions of bad curvature. The second most important feature relates to the magnitude of geodesic curvature. These two features align remarkably with surrogates that have been proposed based on theory, while the methods here allow a natural extension to more features for increased accuracy. The dataset, openly available online, may also be used to test other proposed surrogates; we find many previously published proxies do correlate well with both the heat flux and stability boundary.

Turbulence-based predictions of core plasma performance for the Infinity Two stellarator Fusion Pilot Plant

Noah Mandell, W. Guttenfelder, G. Le Bars, L. Singh, A. Bader, K. Camacho Mata, J. M. Canik, L. Carbajal, A. Cerfon, N. M. Davila, W. D. Dorland, C. C. Hegna, C. Holland, D. P. Huet, M. Landreman, C. Lau, A. Malkus, B. Medasani, J. Morrissey, J. C. Schmitt

Type One Energy Group

As we progress down the stellarator path to a fusion pilot plant (FPP), a key need is the capability to accurately and robustly predict the equilibrium profiles (and hence fusion performance) attainable by a given FPP design configuration. In this work, we use high fidelity transport simulations to predict the energy confinement and fusion performance of Type One Energy's Infinity Two stellarator FPP concept, a high field stellarator developed using modern optimization techniques. This is accomplished using the recently-developed Trinity3D (T3D) transport modeling framework. T3D leverages multi-scale gyrokinetic theory to efficiently predict macro-scale density and temperature profiles subject to micro-scale turbulent and neoclassical losses, in addition to sources from auxiliary fueling and heating, alpha heating, radiation losses, and collisional energy exchange. For this study, the turbulent fluxes are computed from first-principles nonlinear gyrokinetic simulations using the GX code, and neoclassical fluxes are computed using the SFINCS code. A pellet fueled operating scenario is proposed that enables supporting an edge density gradient to substantially reduce ion temperature gradient turbulence. Trapped electron mode turbulence is minimized through optimization with maximum-J. We first present high-fidelity nonlinear gyrokinetic simulations to illustrate turbulence characteristics and key parametric dependencies. We then present first-principles transport predictions using the T3D+GX+SFINCS framework. A baseline operating point is predicted with deuterium-tritium fusion power of 800 MW with high fusion gain Q=40, respecting the Sudo density limit and magnetohydrodynamic stability limits. Additional higher power operating points are also predicted, including a fully ignited (Q=infinity) case producing 1.5 GW.

Universal fluctuation spectrum of Vlasov–Poisson turbulence

Michael Nastac, R. J. Ewart, J. Juno, M. Barnes, A. A. Schekochihin

University of Oxford

The thermal fluctuation spectrum of the electric field arising due to particle noise in a quiescent Vlasov–Poisson plasma was derived in the 1960s. Here, we derive the universal fluctuation spectrum of the electric field, at Debye and sub-Debye scales, for a turbulent Vlasov–Poisson plasma. This spectrum arises from what is likely to be the 'final cascade'—a universal regime to be encountered at the extreme small-scale end of any turbulent cascade in a nearly collisionless plasma. The cascaded invariant is C_2, the quadratic Casimir invariant of the particle distribution function. C_2 cascades to small scales in both position and velocity space via both linear and nonlinear phase mixing, in such a way that the time scales associated with the two processes are critically balanced at every scale. We develop a scaling theory of the spectrum of C_2 in (k, s) space—and hence of the electric field in k space—in arbitrary dimensions, where k and s are the spatial and velocity wavenumbers, respectively. The conclusions of our theory are confirmed by direct numerical simulations of 1D-1V turbulence. The cascade is ultimately terminated at the (spatial) wavenumber where the turbulent electric-field spectrum gives way to the fluctuation spectrum associated with thermal noise; this transition scale is set by the amplitude of the turbulent electric fields and the plasma parameter. The characteristic time scale for this small-scale cutoff to be reached is the dynamical time of phase-space mixing times a logarithmic factor in the plasma parameter—this is the first concrete demonstration of this property of Vlasov–Poisson turbulence, analogous to how fluid turbulence dissipates energy at a rate (nearly) independent of molecular diffusion. In the presence of the phase-space cascade—a scenario that may be ubiquitous—standard collisional plasma theory ceases to be valid. This calls for the development of new collision operators suited to such turbulent environments.

Direct optimization of the radial electric field profile in stellarators

Eduardo Lascas Neto, R. Jorge

University of Wisconsin-Madison

Recent developments in stellarator optimization have shown that optimizing stellarator reactor designs to enable electron root operation is possible [1, 2, 3]. These optimization methods tune the ion and electron neoclassical transport to increase the plasma parameter space in which a positive electric field can occur. A plasma operation regime with a core-positive electric field provides good heavy impurity and helium ash exhaust [1]. Additionally, the transition between a positive and negative electric field observed in these regimes can potentially reduce turbulence [2] and induce the formation of a transport barrier if enough ExB shear is present. In this work, we use state-of-the-art JAX-developed neoclassical transport codes to go beyond the work in Ref. [1] and, for the first time, we obtain a new quasi-isodynamic (QI) configuration with a directly optimized positive radial electric field profile. This optimization method directly targets the core positive electric field shape and root transition position, providing reactor-desired neoclassical transport properties for tungsten and helium ash while maintaining good QI properties, low bootstrap current, and achieving large ExB shear.

[1] E. Lascas Neto at al., Journal of Plasma Physics. 2025;91(1):E24. doi:10.1017/S0022377824001466
[2] P. Helander, et al., Journal of Plasma Physics. 2024;90(6):175900602. doi:10.1017/S0022377824001004
[3] B.F. Lee et al. 2024, Nucl. Fusion 64 106054

Bifurcation and hysteresis in global and local edge turbulence simulations

Ben Zhu, B.Dudson, X.Z.Tang

Lawrence Livermore National Laboratory

We report the discovery of bifurcated solutions in both flux-driven global turbulence simulations and gradient-driven local turbulence simulations. Bifurcation and hysteresis in magnetized plasmas have been observed experimentally on multiple occasions, such as the L-H transition discovered in 1982. However, theoretical and numerical studies have lagged behind due to its inherent multi-scale, multi-physics nature, which requires disentangling turbulence, background profiles, and flows across disparate spatiotemporal scales. Recent simulations using GDB, a flux-driven global edge turbulence model, confirm bifurcated quasi-stationary solutions. Under the same particle fueling and energy injection, both L-mode-like and H-mode-like edge plasma states can be attained, depending on the initial plasma conditions. These bifurcated states are closely linked to the spontaneously generated ExB flow (or edge transport barriers) near the last closed flux surface. Although difficult to attain, once generated, this flow mediates profile relaxation even when the injected power is reduced. This finding highlights the importance of self-organized structures and the critical role of edge dynamics in shaping global plasma confinement. In addition to the global system, a new bifurcated solution has been identified in the modified Hasegawa-Wakatani model, an extensively studied local turbulence model. Besides the well-known dynamic zonal flow-turbulence interaction solution, a stable, stationary pure zonal solution is uncovered by initializing the simulation with large amplitude fluctuations that are gradually ramped down. This finding reveals the existence of multiple solution manifolds, which can be accessed via alternative paths even within this minimal turbulence model. These finding are intellectually intriguing and critical for advancing our understanding of fusion plasma dynamics, providing insights that could inform the design and optimization of future fusion devices.