Highlights from Sherwood 2023

SHERWOOD
Fusion Theory

Knoxville, TN - USA

May 8-10, 2023

Held at the University of Tennessee Conference Center

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Conference Program

- The program consisted of one Invited Plenary presentation, 14 Invited Speaker presentations, and 3 poster sessions.
- 103 registered participants
  - 32 Students
  - 10 postdocs
  - 61 Scientists
- 120 submitted abstracts
  - 34 invited contributions
- 3 invited talks by students

Student Poster Prizes

- 26 students eligible for poster prizes
- **William Barham**, U. Texas, Austin, “A self-consistent Hamiltonian model of the ponderomotive force and its structure preserving discretization”
- **Joseph Duff**, U. of Wisconsin-Madison, “Stellarator Turbulence Optimization Based
on Flux Surface Triangularity ”
- **Taweesak Jitsuk**, U. of Wisconsin-Madison, “Analysis of Nonlinear Selection Rules for Saturation Channels in Toroidal and Slab ITG Turbulence”
- **Richard Nies**, Princeton U. / PPPL, “Perpendicular anisotropy and critical balance
in electrostatic ITG turbulence”
- **Gregory Riggs**, West Virginia U., “Time-resolved biphase signatures of quadratic nonlinearity observed in coupled eigenmodes on the DIII-D tokamak”
- **Wenhao Wang**, UC Irvine, “A 2D simulation model for electrostatic presheath potential in FRC SOL”

Vigorous discussion at the 3 poster sessions

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Vittorio Badalassi of ORNL gave the Plenary talk “Blankets analysis & design using modeling and simulation”

ORNL Site Visit

SHERWOOD
Fusion Theory

Visited FronTier, fueling and DMS pellet lab, MPEX construction, proto-lite, RF-PIE, and other ORNL technology laboratories

A young fusion enthusiast attendee

Sherwood Fusion Theory

Sherwood Banquet

More photos can be found at:

https://drive.google.com/drive/u/1/folders/1Rm4yJP07V70PeZqEeQDJsusonMOnEVfu

Multi-Device Study of Pedestal Width Scaling Using a Gyrokinetics-Based Model

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Using a new kinetic ballooning mode (KBM) gyrokinetic threshold model, GKPED, we find the pedestal width-height scaling for multiple tokamaks. At tight aspect ratio, GKPED reproduces NSTX's experimental linear pedestal width-height scaling for ELMy H-modes [1] , overcoming previous issues with tight aspect ratio pedestal prediction [2]. At regular aspect ratio, we reproduce the square root pedestal width-height scaling for previously published DIII-D discharges [3]. Our model uses EFIT-AI [4] to calculate global equilibria with self-consistent bootstrap current, and can be applied to any H-mode equilibria. For ELMy NSTX discharges, KBM physics is needed to match the experimental data: we find that infinite-n MHD stability overpredicts pedestal pressure. For regular aspect ratio, however, we find closer agreement between ideal and kinetic ballooning mode width scalings. Combined with peeling ballooning mode (PBM) stability [5,6], our model will calculate a maximum inter-ELM pedestal width and height based on KBM and non-ideal PBM stability. GKPED also makes quasilinear predictions for turbulent pedestal transport during pedestal evolution including the effects of increasing pressure with varying temperature and density contributions. This work is an important step forward towards a unified predictive capability of pedestal stability and transport across tokamak equilibria across a range of tokamak operating space.

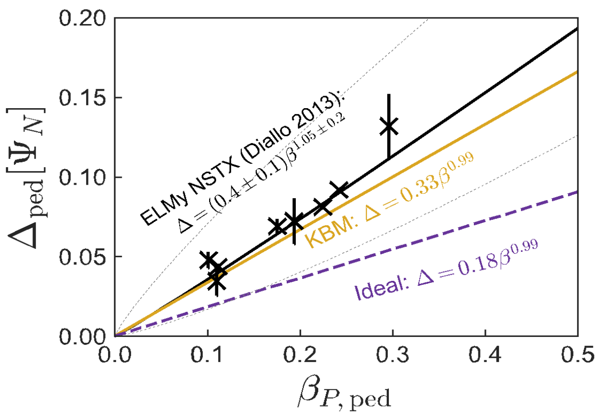

Figure 1:NSTX Δ_{ped} versus $\beta_{P.ped}$ KBM (GCP) scaling, ideal (BCP) scaling, and ELMy H-mode experimental points.

We combine linear local gyrokinetics with a self-consistent variation of pedestal width Δ_{ped} and height $\beta_{P.ped}$ to predict the critical pedestal scaling $\Delta_{ped}=C(\beta_{P.ped})^{\gamma}$ across devices [7]. Our prediction imposes the Gyrokinetic Critical Pedestal (GCP) pressure gradient constraint, obtained from KBM stability. The KBM critical gradient is always lower than the ideal mode, whose stability we calculate to produce a Ballooning Critical Pedestal (BCP) width constraint. For NSTX, the GCP gives $\Delta_{ped} =0.33(\beta_{P.ped})^{0.99}$ and the BCP $\Delta_{ped} =0.18(\beta_{P.ped})^{0.99}$, shown in Fig. 1. The maximum $\beta_{P.ped}$ at any given width also depends on how the pedestal pressure is varied, due to the bootstrap current's differential dependence on density and temperature gradients [9]. We discuss transport implications of the dependence of pedestal width on density and temperature, and show pedestal scalings for additional tokamaks. This work was supported by US Department of Energy Contract No. DE-AC02- 09CH11466.

[1] A. Diallo *et al* 2011 Nucl. Fusion 51 103031 **[2]** R.J. Groebner *et al* 2013 Nucl. Fusion 53 093024 **[3]** W. Guttenfelder *et al* 2021 Nucl. Fusion 61 056005 **[4]** A. Kleiner *et al* 2021 Nucl. Fusion 61 064002 **[5]** S. Kruger *et al* 2022, PP11.00057, APS DPP Meeting **[6]** A. Kleiner *et al* 2022 Nucl. Fusion 62 076018 **[7]** P.B. Snyder *et al* 2004 *Nucl. Fusion* 44 320 **[8]** P.B. Snyder *et al* 2009 Phys. Plasmas 16, 056118 **[9]** O.Sauter and C. Angioni 1999 Physics of Plasmas 6, 2834

Shifting and Splitting of Resonance Lines due to Dynamical Friction in Plasmas

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A quasilinear plasma transport theory that incorporates Fokker-Planck dynamical friction (drag) and pitch angle scattering is self-consistently derived from first principles for an isolated, marginally unstable mode resonating with an energetic minority species. It is found that drag fundamentally changes the structure of the wave-particle resonance, breaking its symmetry and leading to the shifting and splitting of resonance lines. In contrast, scattering broadens the resonance in a symmetric fashion. Comparison with fully nonlinear simulations shows that the proposed quasilinear system preserves the exact instability saturation amplitude and the corresponding particle redistribution of the fully nonlinear theory. Even in situations in which drag leads to a relatively small resonance shift, it still underpins major changes in the redistribution of resonant particles. This novel influence of drag is equally important in plasmas and gravitational systems. In fusion plasmas, the effects are especially pronounced for fast-ion-driven instabilities in tokamaks with low aspect ratio or negative triangularity, as evidenced by past observations. The same theory directly maps to the resonant dynamics of the rotating galactic bar and massive bodies in its orbit, providing new techniques for analyzing galactic dynamics.

This contribution is based on V. N. Duarte et al, Phys. Rev. Lett. 130, 105101 (2023);
https://doi.org/10.1103/PhysRevLett.130.105101

Neoclassical transport due to resonant magnetic perturbations in DIII-D and NSTX

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Resonant magnetic perturbations (RMPs) are applied to mitigate or suppress the instabilities present in the plasma called edge localized modes (ELMs) which arise because of the steep pressure gradient at the edge in H-mode plasmas. The RMPs often results in a decrease in the plasma density, also referred to as density pump-out, which can have deleterious effect on fusion performance. In this study, the role of neoclassical transport in density pump-out and heat flux in the presence of RMPs is investigated in DIII-D and NSTX plasmas. The drift kinetic code NEO with the enhanced capability to handle non-axisymmetric magnetic geometry is used here to evaluate the neoclassical transport properties where RMPs are applied. The magnetic field provided as an input to NEO is calculated using extended magnetohydrodynamic code M3D-C1 and includes the nonlinear resistive plasma response in realistic geometry and with realistic values of resistivity. The study [1] performed here indicates a dramatic increase of the neoclassical particle and energy fluxes for main ions in the presence of the RMPs and is on the same order as experimentally inferred fluxes, suggesting that neoclassical transport plays an important role in edge transport in such cases. The calculated neoclassical fluxes in DIII-D plasmas are found to be closely correlated with the observations of density pump-out over a range of RMP spectra. These calculations show that nonlinear MHD simulations are essential at high RMPs to satisfactorily model the perturbed magnetic geometry in the pedestal region. The transport dynamics of impurities has also been analyzed using this framework and shows that, at low collisionality the RMPs has substantial effect on neoclassical transport for impurities, but as the collisionality increases, the effect of RMPs reduces. Thus, RMPs can play a major role in reducing impurity accumulation inside the core for low Z impurities.

[1]Sinha,P et al.,Nuclear Fusion 62.12(2022):126028

SOL impurity transport and effects on H-mode pedestal in closed divertors

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Impurity seeding studies were performed for the first time in the slot divertor at DIII-D, showing that with suitable use of radiators, full detachment is possible without degradation of core confinement. First ever multi species SOLPS-ITER simulations including full cross-field drifts and neutral-neutral collisions activated in DIII-D demonstrate the importance of target shaping and plasma drifts on divertor impurity leakage. The inclusion of the drifts in the simulations enabled to study the behavior of these flows in a highly closed divertor showing the relevant role of convection on divertor asymmetry and divertor detachment in these conditions.Flow reversal is found for both main ions and impurities affecting the SOL impurity transport and explaining the dependence on strike point location of the detachment onset and impurity leakage found in the experiments. In addition to target shaping, the effect of different radiative species on power dissipation has been evaluated by replacing nitrogen with neon. The experimental results show that Ne dissipates further upstream than N as confirmed by SOLPS-ITER modeling and analytic calculations using the 2-point model [3]. The two routes for dissipation identified here lead to different pedestal responses. While Ne readily enters the pedestal, N remains compressed in the divertor without significantly affecting the profiles. This different leakage behavior is consistent with the higher ionization potential for Ne compared to N. Neon injection leads to a reduced core ion transport as supported by simulations. A self-enhancing mechanism of Ne build up has been identified as due to the increased pedestal stability and the radiative mantle. The findings of this work demonstrate that enhanced divertor dissipation and improved core-edge compatibility can be obtained by choosing appropriate radiative species for pedestal conditions, as well as by optimizing divertor geometry and tailoring drifts for particle entrainment.

BOUT++ Simulations on Turbulence Spreading in Small ELM Regimes for Divertor Heat Load Control

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Simultaneously controlling large ELMs and divertor heat loads in H-mode plasma is crucial for achieving steady-state operation of a tokamak fusion reactor. Recently, both experiments and simulations have shown that H-mode plasma regimes with small/grassy ELMs can help to reduce the ELM size and broaden the SOL width λ_q, while maintaining high plasma confinement compared to type-I ELMs. However, the physics underlying the small ELM regime is still unclear. Investigating how turbulence spreading affects the SOL width is essential for divertor heat load control.

BOUT++ turbulence simulations were conducted to investigate the effects of turbulence spreading on λ_q broadening in small ELM regimes. This study is motivated by 4 EAST discharges with 2 different poloidal magnetic field B_p in small ELMs, where the pedestal is near marginal stability and relaxes into a linearly stable state after the initial ELM crash. BOUT++ nonlinear simulations have shown that turbulence energy intensity flux Γ_ε is a crucial factor in the broadening of the SOL width λ_q. λ_q is broadened as fluctuation energy intensity flux Γ_ε at last close flux surface (LCFS) increases due to increasing pedestal ExB flow shear and local SOL turbulence, as shown in Fig.1. The transition from ELM-free to small ELM regime leads to a significant broadening of the SOL width (λ_q) due to the strong radial transport of turbulence energy. Same trend has also been found by EAST experimental database.

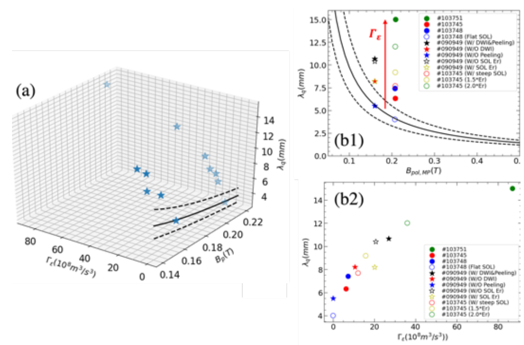

Fig. 1. (a) 3D plot of heat flux width $\lambda_q$vs poloidal magnetic field B_p and fluctuation energy intensity flux Γ_ε; 2D plot of heat flux width λ_q vs poloidal magnetic field B_p (b1) and fluctuation energy intensity flux Γ_ε (b2).

The spreading of turbulence from the pedestal to the SOL is highly dependent on the pedestal plasma parameters, as shown by Fig. 2. Here the black curves are ∇P_0 scan with low collisionality $\upsilon_{ped}^* = 0.108$ (solid curve) and high collisionality $\upsilon_{ped}^* = 1$ (dashed curve); the red curves are υ_{ped}^* scan with small $\nabla P_0 \sim 200\ kPa/m$ (solid curve) and large $\nabla P_0 \sim 200\ kPa/m$ (dashed curve). As the pedestal pressure gradient ∇P_0 increases and the pedestal collisionality υ_{ped}^* decreases, the fluctuation energy intensity flux Γ_ε increases. Turbulence spreading from pedestal to SOL depends on the radial mode structure. The low-n peeling mode induces more fluctuation energy flux Γ_ε for low collisionality as compared to the high-n ballooning mode for high collisionality, due to the wide radial mode structure for peeling mode but narrow for ballooning mode. However, strong peeling turbulence will cause a large ELM crash and large heat load on the divertor. Week peeling turbulence will be a best solution, such as small ELM regime.

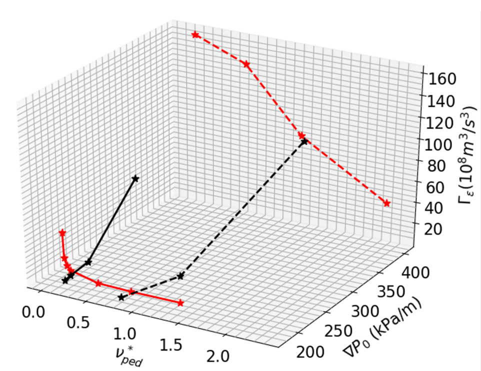

Fig. 2. 3D plot of fluctuation energy intensity flux Γ_ε vs pressure peak gradient ∇P_0 and υ_{ped}^*.

Operating in H-mode with small ELMs has tremendous potential to address two of the most critical problems for Tokamak fusion reactors: significantly reducing the ELM size and substantially broadening the SOL width.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, LLNL-ABS-845665 and by UCSD under Contract No. DE-FG02-04ER54738. This work was also supported by the National Key R&D Program of China Nos. 2017YFE0301206.

Modeling of plasma parallel transport in the Material Plasma Exposure eXperiment during radio-frequency heated discharges

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The steady state linear divertor simulator 'Material Plasma Exposure eXperiment' (MPEX) is currently under construction at Oak Ridge National Laboratory with the goal of enabling plasma-material interaction studies at future fusion reactor relevant plasma conditions. The targets in MPEX will be exposed to 10^6 seconds to achieve an ion fluence of 10^31/m^2. Ion cyclotron heating (ICH) and electron cyclotron heating (ECH) are two auxiliary heating schemes used in MPEX to independently heat ions and electrons respectively and provide fusion divertor conditions ranging from sheath-limited to fully detached divertor regimes at a material target. A new massively parallel, HPC based, quasi-neutral Particle-In-Cell code-PICOS++ is developed and applied to understand the plasma transport in MPEX during radio-frequency (RF) based ICH. PICOS++ can model plasma transport for any open magnetic field systems with (1) Coulomb collisions in Fokker-Planck framework, (2) Volumetric particle source including Neutral Beam Injection, and (3) quasi-linear RF based ICH. The code is benchmarked with the fluid code SOLPS and validated against existing data from the Proto-MPEX experiments. The experimental observation of "density-drop" at the target during ICH discharges in Proto-MPEX has been demonstrated and explained via physics-based arguments with PICOS++ modeling. In fact, the density drops at the target in Proto-MPEX/MPEX to conserve the flux and compensate for the increased parallel flow during ICH. Furthermore, the modeling suggests that the "density-drop" behavior at the target saturates for higher RF power because of the strong dominance of parallel transport over collisional transport. This further leads to a two-temperature ion distribution at the target in MPEX. Finally, a complete study on the sensitivity of various plasma parameters with respect to ICH power is performed to investigate their effect on plasma transport and particle and energy flux at the target.

Novel Stellarator Phase Space Exploration with DESC

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Stellarator optimization is the search for attractive stellarators in the huge and varied phase space of all possible 3D magnetic configurations. New ways of attacking the problem can yield novel insights and better optimized stellarators. We present innovative approaches to stellarator equilibrium and optimization in the DESC code suite that are shown to yield excellent results over conventional methods. DESC's automatic differentiation yields exact derivatives of objective functions, and also enables DESC to be the first stellarator optimization code to use only a single equilibrium solution at each iteration, which reduces the computation time by three orders of magnitude in tests compared to STELLOPT and enables exploration over a higher-dimensional parameter space. Further, a novel quasi-isodynamic (QI) metric has been developed and implemented in the code that can represent the full QI parameter space of interest. Boundary conditions constraining the near-axis behavior to match near-axis theory have been implemented in DESC and shown to result in much better optimized configurations. Constraining the Poincaré section instead of the last closed flux surface (LCFS) is also implemented and shown to recover LCFS solutions while requiring just a fraction of the variables to represent the boundary shape as compared to the LCFS. DESC has also been connected to the GX code to allow for turbulence optimization. Constrained optimization techniques implemented in DESC, such as the augmented Lagrangian approach, in tandem with these new capabilities allow for configurations with improved quasi-symmetry, quasi-isodynamicity, and turbulent transport properties to be found.

[1] Dudt, D. & Kolemen, E. Physics of Plasmas (2020).
[2] Panici, D. et al. JPP (Accepted) (2023).
[3] Conlin, R. et al. JPP (In Review) (2023).
[4] Dudt, D. et al. JPP (Accepted) (2023).

Neoclassical transport in strong gradient regions

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[3]Laboratorio Nacional de Fusión, CIEMAT, Madrid, 28040, Spain
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We present a new model to describe neoclassical transport in strong gradient regions in tokamaks such as internal transport barriers and the pedestal [1]. Previous work on neoclassical transport across transport barriers assumed large density and potential gradients but a small temperature gradient [2], or neglected the gradient of the mean parallel flow [3]. Using a large aspect ratio and low collisionality expansion, we relax these restrictive assumptions and keep gradient scale lengths that are of the size of the ion poloidal gyroradius. The poloidally varying parts of density and electric potential are included. We derive equations describing the transport of particles, parallel momentum and energy by ions in the banana regime. Studying contributions from both passing and trapped particles, we show that the resulting transport is dominated by trapped particles but includes the poloidal variations in the electric potential caused by passing particles. We find that a non-zero neoclassical particle flux requires parallel momentum input which could be provided through interaction with turbulence or impurities. The neoclassical energy flux across a transport barrier has upper and lower bounds in both temperature and density. Solutions to our transport equations are highly sensitive to the choice of sources and boundary conditions and do not always exist.

[1] S. Trinczek, F. I. Parra, P. J. Catto, I. Calvo, M. Landreman, arXiv:2301.07080 (2023)
[2] P. J. Catto, F. I. Parra, et al., Plasma Phys. Control. Fusion 55, 045009 (2013)
[3] K. C. Shaing, C. T. Hsu, Physics of Plasmas 19, 022502 (2012)

A new flexible gyro-fluid linear eigensolver

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Gyro-fluid equations are velocity space moments of the gyrokinetic equation. Special gyro-Landau-fluid closures have been developed to include the damping due to kinetic resonances by fitting to the collisionless local plasma response functions. This damping allows for accurate linear eigenmodes to be computed with a relatively low number of velocity space moments compared to gyrokinetic codes. However, none of the published gyro-Landau-fluid closure schemes preserve the Onsager symmetries of the resulting quasilinear fluxes. Onsager symmetry guarantees that the matrix of diffusivities is positive definite, an important property for the numerical stability of a transport solver. A very simple closure scheme for regularizing the gyro-fluid equations, that preserves the Onsager symmetry and is scalable to higher velocity space moments, has been developed. The new linear gyro-fluid eigensolver (GFS) is used to extend the TGLF quasilinear transport model so that it can compute the energy and momentum fluxes due to parallel magnetic fluctuations, completing the transport matrix. The GFS equations do not use a bounce average approximation. The GFS equations are fully electromagnetic, with general flux surface magnetic geometry, pitch angle scattering for electron collisions and subsonic equilibrium rotation. The TGLF transport model, with the new GFS eigensolver, can output the symmetric diffusion and convection response matrices for each species. This will be particularly helpful for multi-ion species plasmas transport studies. The TGLF fluxes for different number of velocity and parallel space moments are verified with CGYRO linear eigenmodes using the same saturation model. Prospects for future applications of quasilinear theory to new plasma transport regimes and magnetic confinement devices in addition to tokamaks are opened by the flexibility of the GFS eigensolver.

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Disruption simulation with pellet injection and runaway electrons

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The injection of a frozen impurity pellet as a disruption mitigation system (DMS) for the next generation of large tokamaks, including ITER, is a promising method for reducing the thermal and electromagnetic loads from a potential disruption without generating enough high-energy (runaway) electrons to damage the device. The effectiveness of this system has been tested on many experiments, with encouraging results. To further study its effects, we have modeled one such DMS experiment on DIII-D using the M3D-C1 nonlinear 3D extended MHD code (Jardin et al 2012 J. Comput. Sci. Discovery). Our model includes the injection and ablation of a neon pellet, impurity ionization and recombination, radiation, and the formation and evolution of runaway electrons, including both Dreicer and avalanche sources. We have found that our model provides reasonable agreement with the experimental results, in terms of the timescale of the thermal and current quench, and the magnitude of the runaway electron plateau formed during the mitigation. This provides a partial validation of the M3D-C1 DMS model, and further highlights the potential of using frozen impurity pellet injection for disruption mitigation in the next generation of large tokamaks.

This work is supported by US DE-FG02-95ER54309 DOE grant, DE-FC02-04ER54698 DIII-D, SciDAC DE-SC0016452 SCREAM and DE-SC0018109 CTTS.

Rapid assimilation of high-Z impurities along the magnetic field line from an ablated pellet

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Pellet injection is a standard technique for fueling and disruption mitigation in fusion reactors like ITER. Although the nominal goals of these two applications are similar, namely to deliver materials into the fusion core, there are important distinctions on the specifics. Particularly, for disruption mitigation of tokamak thermal quench, the primary aim is to (1) replace plasma power exhaust at the first wall with line radiation by high-Z impurities, which requires substantial amount of high-Z impurities to be assimilated into the plasma at time scale much shorter than 1 millisecond; and to (2) spread the radiation as uniformly as possible on the first wall, which requires rapid spatial transport and homogenization of high-Z radiators over a flux surface despite the initially local assimilation of the pellets. Therefore, the emphasis on post-assimilation spatial transport and mixing is a critical aspect for successful thermal quench mitigation in a tokamak reactor. Here we employ the first-principles kinetic simulations and analysis to investigate the physics underlying the high-Z impurities assimilation along the magnetic field line from an ablated pellet. We find that, the high-Z impurities' transport is limited by the cooling front, which, by definition is where the ambient hot ions meet the cold recycled ions, is formed when a fusion-grade plasma intercepts with a cooling spot (cold pellet in our case). Such cooling front among other propagating fronts significantly modify the heat flux to the pellet and hence its ablation. In contrast with a pure hydrogen pellet, it is shown that the high-Z impurities in pellet can diffusively reflect the ambient hot plasmas, which, by replenishing the distribution void, can substantially reduce the heat fluxes and hence the plasma cooling. The high-Z impurities' assimilated front in the plasma is found to be governed by the averaged charge number.

A machine learning normalizing flow surrogate model for plasma kinetic computations

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Particle-based computations play a key role in numerical simulations of plasmas in general and magnetically confined fusion plasmas in particular. These computations are time-consuming due to the multiscale dynamical processes involved and the need to follow large ensembles of initial conditions to avoid statistical sampling errors. Motivated by the need to overcome these computational challenges, we present a novel method to accelerate particle-based computations. Our approach is based on the use of Normalizing Flows, a powerful machine learning technique, to construct surrogate models for the fast integration of stochastic differential equation (SDE) corresponding to Fokker-Planck models of plasmas kinetics. In contrast to the computationally expensive standard Monte Carlo methods, the proposed method can directly generate samples of the SDE's final state bypassing the integration. In particular, the normalizing flow model can learn the conditional distribution of the state, i.e., the distribution of the final state conditioned to the initial state, such that the model only needs to be trained once and then used to handle arbitrary initial conditions. This feature provides significant computational savings when studying the dependence of the final state on the initial distribution. Two applications are presented. The first one is the simulation of the hot-tail generation of runaway electron (RE) resulting from the fast thermal quench during tokamak disruptions. Once trained, the proposed surrogate model can accurately simulate the production of RE for arbitrary initial electron distributions without the need to integrate the orbits. The second example considers transport in the ABC (Arnold-Beltrami-Childress) velocity field, a paradigmatic model of chaotic advection in 3D fluids, perturbed by Brownian noise modeling diffusion. Both applications are benchmarked and compared in terms of efficiency and accuracy with direct Monte Carlo simulations.

Effect of the NBI operational regime on the AE saturation phase in DIII-D plasma

Jacobo Varela[1], D. Spong[2], L. Garcia[1], Y. Ghai[2], D. Zarzoso[3], H. Betar[4], J. Ortiz[1], D. C. Pace[5], M. A. Van Zeeland[5], and X. Du[5]

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NBI driven Alfvén instabilities can significantly enhance fast ion transport above classical rates, leading to degraded heating efficiency and wall damage. These instabilities also lead to complex nonlinear and self-organized phenomena; the goal of this study is to analyze such effects for a range of NBI operational regimes in NBI-heated DIII-D plasmas. The analysis is done using the linear and nonlinear versions of the gyro-fluid code FAR3d [1]. A set of parametric studies is performed modifying the nonlinear simulation EP β (linked to the NBI injection power), EP energy (associated with the NBI voltage) and the radial location of the EP density profile gradient (connected to the NBI radial deposition). The analysis indicates a transition from the soft to the hard MHD regime if the simulation EP $\beta \geq 0.02$, leading to global plasma relaxation as bursting MHD activity caused by n=3 and n=6 AEs overlapping as well as a large decrease of the EP density in the inner plasma linked to an enhancement of the EP transport. In addition, shear flows and zonal current are generated that modify the flux surfaces and q profile, respectively. The evolution of the equilibrium profile in the hard MHD regime causes a decrease of the AE frequency, an effect that may explain the frequency down-shift observed for some AEs along DIII-D discharges [2]. Reducing the EP energy in the nonlinear simulations leads to a weakening of the plasma perturbation although an enhancement if the EP energy increases, consistent with DIII-D experimental observations [3]. Nonlinear simulations for off-axis NBI configurations indicate a lower plasma perturbation as the EP density gradient is located further away from the magnetic axis. In addition, the zonal currents induced by the AEs in the hard MHD regime for off-axis NBI configuration reinforce the reverse shear region, although on-axis configurations tend to reduce the deep of the reverse shear region.

Drift-Kinetic Modelling of Neoclassical Tearing Modes (NTMs) at Threshold Scale

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Neoclassical tearing modes (NTMs) are resistive MHD instabilities where magnetic islands form on toroidal flux surfaces, removing pressure gradient there. Islands amplify when their width w and the poloidal beta both exceed thresholds, thus endangering high-gain confinement. NTMs can been suppressed by reducing w below the threshold width w_c. Experimentally, w_c is comparable to the trapped ion orbit width $\rho_{bi} \sim \sqrt{\varepsilon}\, \rho_{\theta i}$, where ε is the inverse aspect ratio and $\rho_{\theta i}$ is the ion poloidal gyroradius [1]. To reliably predict w_c at finite ρ_{bi}, we must account for the drift-kinetic effects of ions, and the differing electron response. We achieve this by simplifying the drift-kinetic equation in the limit of $w/r \sim \rho_{\theta i} \ll 1$ for minor radius r, and self-consistently recalculating the electrostatic potential from quasineutrality.

We present and compare results from two drift-kinetic models of threshold scale islands ($w \sim \rho_{bi}$). Our 4D model, DK-NTM, operates in the $\varepsilon \ll 1$ limit at arbitrary collisionality [2,3,4]. We revise our earlier $w_c:\rho_{bi}$ scaling result from [4] and extend to finite island propagation frequency to identify solutions that satisfy torque balance, and quantify the ion polarization current contribution to w_c. Our 3D model, RDK-NTM, operates in general geometry in the limit of low collisionality. In the $\varepsilon \ll 1$ limit, it predicted $w_c = 2.85\rho_{bi}$ [4], consistent with the experimental data of [1]. Recent studies of plasma shaping parameters in finite ε find that higher triangularity plasmas are more NTM-prone, consistent with DIII-D observations [5], and that the scaling of w_c with poloidal beta is in agreement with EAST observations [5,6].

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