First-principles simulations and reduced models for core turbulent transport

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DOE Workshop on Integrated Simulations for Magnetic Fusion Energy
Primary sub-topic C: Whole device modeling
NO oral requested

One sentence summary

The magnetic fusion energy community must continue to pursue both first-principles simulations *and* reduced modeling for core transport physics relevant to regimes and operating scenarios of present-day tokamaks, spherical tokamaks, ITER and future burning plasmas.

Motivation

Profiles of plasma density (electron, ion, impurity, fast ions/fusion products), temperatures and rotation are all required to determine the tokamak plasma state (MHD equilibrium and stability, non-inductive fraction, energetic particle stability, fusion power/gain, etc…). Whole device integrated simulations attempting to predict the time-dependent plasma state will therefore always demand a model capable of reproducing the appropriate core transport physics.

Due to computational expense, it is unlikely that first-principles simulations of core transport processes (especially turbulence) can be routinely utilized alone within integrated whole-device modeling to predict the time-dependent plasma state. Even if this does become possible, the number of such simulations will be very limited, making it unrealistic to test the sensitivity of integrated simulations to variations in initial conditions, boundary conditions, and various model assumptions. Such tests are critical in determining the utility and robustness of integrated simulations in which many strongly nonlinear modules are coupled. Reduced transport models (that can run $>10^6$ faster than first-principles codes) must therefore continue to be developed with evolving accuracy to reproduce the relevant physics uncovered in first principles simulations.

Approach

There must be continued efforts to validate both first principles turbulence simulations (e.g. gyrokinetic codes like GEM, GENE, GKW, GS2, GTC, GTS, GYRO, ORB5, XGC) and reduced turbulence transport models (e.g. typically through fluid or gyrofluid approaches like MMM, QuaLiKiz, TGLF) using experimental transport and turbulence measurements in present day devices. This includes:

- Significant efforts to run, analyze and benchmark first-principles codes
- Testing the sensitivity of simulations and models within the context of experimental results and uncertainties, including transport analysis and turbulence measurements. This inherently requires first principles simulations that are capable of being run many times per test case, as single-point comparisons are often misleading.
- Continued development and improvement of first-principles codes (numerical algorithms, HPC performance), as well as increasing availability of cpu time at appropriate HPC facilities

As first-principles codes provide the foundation for development and testing of reduced models, there must be continued emphasis on benchmarking the fidelity of different approaches (continuum vs. PIC), numerical algorithms and corresponding resolution requirements, especially as physical realism is improved, e.g.:

- Including multiple species (D, T, low-Z and high-Z impurities, fast particle distributions from NBI, RF, and fusion products)
- Including finite beta electromagnetic effects (synergistic stabilizing effect with fast ions as the magnetic axis is approached; challenges when approaching ideal/kinetic ballooning mode limits in the core of high-performance plasmas or in the H-mode pedestal; development of microtearing instabilities at high beta; influence of compressional perturbations at high beta in spherical tokamaks)
- Investigating finite rotation and rotation shear beyond traditional E×B shear suppression (residual stress from E×B shear; influence of sheared equilibrium parallel flow in driving instability; influence of centrifugal effects on impurity and momentum transport; extrapolating from present devices to ITER/burning plasma regimes where rotation is likely reduced)
- Moving towards more reactor relevant regimes and scenarios (strongly electron heated scenarios with reduced rotation; presence of D, T, He ash)
- Testing non-local (finite-ρ_*) effects in a uniform way to benchmark fidelity and accuracy of appropriate codes (potentially important for core-edge coupling and boundary research; residual stress contributions; interaction between turbulence and low-n MHD/NTMs) -- demands communication, cooperation and coordination among different code developers and users

Reduced modeling must continue to evolve to include with sufficient accuracy the relevant effects uncovered in first-principles simulations (such as examples listed above)

- Should strive to use most recent experimentally-based first-principles simulations (as they become available) to quantify limits and uncertainties, and ultimately improve, reduced models
- Ideally would coordinate effort between analysts/code runners and model developers
- Different approaches for reduced models should be investigated and benchmarked

Validation of both first principles simulations and reduced models should take advantage of all domestic tokamaks:

- DIII-D provides large variation in operating scenarios and significant turbulence diagnostics
- Alcator C-Mod provides zero torque ICRF heated plasmas at high field with high-Z plasma facing components, very similar to ITER conditions
- NSTX-U provides a strong test of models at reduced aspect ratio, high beta and larger ρ_*
- Collaboration with international experiments, simulation codes and modelers must also continue, as has been done historically through ITPA workshops

Impact

Allow US to maintain leadership in development and validation of core transport physics and models necessary for integrated simulations.