Toward a Validated Understanding of Core Thermal Transport

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I. Physics Issues

A. Ion thermal transport

Core thermal transport in the ion channel is arguably the best understood and developed area of anomalous transport in tokamaks. There is general consensus on the identity of the underlying mechanism, i.e., turbulence from ion temperature gradient (ITG) and trapped electron mode (TEM) fluctuations. Present understanding essentially relies on 1) the output of comprehensive codes believed to accurately model the physics of the core ion gyroscale fluctuations in realistic geometry. The output shows that for parameters matching experiments, the fastest growing instabilities are combinations of ITG and TEM depending on the parameters. 2) Comparisons of computed and experimentally measured diffusivities, and on occasion other quantities such as wavenumber spectra and correlation lengths, which show agreement to varying degrees. 3) Understanding of the way these fluctuations respond to suppression mechanisms, especially flow shear, and semi quantitative agreement of these trends with experiment. Significant additional work is needed to definitively show that present understanding is complete and correct, and that models are valid, i.e., provide an accurate representation of the real world within the intended uses of the model. The goal is to be able to reliably and routinely predict, within reasonable tolerances, the transport of a discharge that has not been previously compared. Uncertainties and deficiencies in modeling and measurement, the possibility of fortuitous agreement, and the role of sensititivity in modeled quantities all pose obstacles to achieving a certified predictive capability. Verification and validation, as described elsewhere, are processes that systematically and quantitatively address these issues. If properly formulated and carried out, they offer a path toward predictive capability.

B. Electron thermal transport

For thermal transport in the electron channel there is no consensus on the identity of the underlying mechanism. In many present devices the electron loss channel is subdominant. This will not be true in burning plasmas, including ITER. Electron thermal transport is a more difficult problem than ion transport. It appears to be sensitive to physics tied to scales ranging from the ion to electron gyroradius. Depending on circumstances electron heat transport is driven by a variety of equilibrium gradients, including temperature, density, pressure, and current. It can radically change character with parameters like beta. It has not been possible to formulate a consensus understanding for a single device, much less across multiple devices where the above sensitivities are exposed to the greatest range of variations. On the basis of experience in the ion problem, and given the greater complexity of the electron problem, it is not likely that it will be understood purely on empirical grounds without significant input from theory and modeling. The additional complexity of this problem puts additional demands on experimental and modeling capabilities, as described below. However, the process by which experimental measurement, theory and modeling are brought to bear on this problem fits within the concept of validation, and therefore parallels that of the ion problem. Verification and validation can guide present activities that seek to understand underlying mechanisms and appropriately develop and assess models. As improvements are made it will provide validation of understanding and models, eventually leading to predictive capability.

C. Transport Channel Connections

While convenient for organizing presentations, it is not appropriate to think of transport as occurring in isolated channels. In burning plasmas the electron and ion heat channels are strongly coupled. Moreover, momentum and particle transport, including impurity transport, are coupled through mechanisms with diagonal and off diagonal flux-gradient elements. Diffusive transport and diffusivities represent approximations that may be unsatisfactory. Experimental measurement and modeling must seek to address these couplings and describe transport in the most comprehensive and accurate manner possible.

II. Research Requirements

The types of research activities that will lead to validated understanding of core transport can be organized in the framework of a formal validation process. Below we present the needs of experiment and modeling, as inputs to a validation process, and then address the validation process itself.

A. Experiment

Diagnostic capacity for both profile and fluctuation measurements will need to be expanded to solve the extremely demanding problems of electron thermal transport and achieving predictive capability. If validation is to lead to a satisfactory degree of predictive capability, multiple and varied diagnostics will be required on any given device, along with similar sets of diagnostics on multiple devices. Development of new diagnostics for new types of measurements is important. Gains in diagnostic performance and access, extending sensitivity, resolution, range, sampling regions and extent are also highly desirable. Particularly valuable capabilities are fluctuation measurement at high wavenumber, and measurement of fluctuations in magnetic field, velocity, density, temperature (especially T_e for electron thermal transport), and potential. The ability to independently measure and correlate two fluctuating fields responsible for a transport flux, as is done for density and potential in the heavy ion beam probe, is also highly desirable. Both fields must be measured within a correlation length and for the same wavenumber range. Such correlated measurements are very demanding and development work is needed to achieve this capability. To understand transport, fluctuation diagnostics must be accompanied by corresponding profile measurements, i.e., for flow, density, temperature, and current. Electron heating at higher power than available on existing machines is needed to access electron-loss dominated regimes.

Strides in diagnostic capability must be matched by appropriate advances in analysis technique. Visualization techniques and statistical characterization, which have both seen notable progress in recent years, must continue to be improved and expanded, and must be incorporated into quantitative measures for comparison with models. Because turbulence and transport is sensitive to classes of nonlinearly excited fluctuations that are not part of the driving instability (e.g., zonal flows and damped eigenmodes), it is important to develop diagnostics and analysis techniques that can track the relevant physics. These include wavenumber and frequency spectra, bispectral analysis for tracking energy couplings and transfer in wavenumber space, and techniques for inferring nonlinear (finite amplitude-induced) growth rate.

Current understanding suggests that key players in electron thermal transport are electron temperature gradient fluctuations, TEM, and microtearing. Means must be developed for experimentally identifying the role played by these different fluctuations, which may be present simultaneously or individually in a given discharge. These must be tracked across parameter regimes designed to vary the relative driving strengths, and from machine to machine, where the mix is also likely to be subject to variation. This involves appropriate machine cross comparisons and scans. Dimensionally similar discharges with respect to the driving physics may be achieved in certain operational regimes, with variations away from those regimes provided by scans for appropriate control parameters for instability drive (such as beta).

B. Theory and modeling

The conceptual understanding of core heat transport is still incomplete, even for the ion channel. The way in which the instabilities responsible for core transport saturate is not understood. Conventional wisdom for collisionless regimes, including the effect of zonal flow shearing, involves spectral transfer to small scales. Yet, the spectrum of ITG turbulence in gyrokinetic simulations shows essentially no spreading beyond the wavenumber range of the instability. Recent analysis suggests there are robustly damped modes in the unstable region. An improvement in the conceptual understanding of saturation, and the means to appropriately characterize it and describe it is clearly needed.

Modeling capabilities also need improvement. Even for ion transport, new code diagnostics are needed, including eigenmode solvers for comprehensive gyrokinetic codes, novel diagnostics like the nonlinear growth rate, and synthetic diagnostics. Model performance improvements also need to be aggressively sought including resolution and noise reduction. Simulations that capture multiple scale physics and driving mechanisms associated with both electrostatic type instabilities (pressure gradient) and magnetic type instability (current gradient) also need to be vigorously pursued. Validation greatly benefits from testing physics models in simpler experimental configurations, e.g., cylindrical instead of toroidal. This requires the modification of gyrokinetic models for other geometries and magnetic topologies. At all stages in the improvement process, models must undergo rigorous verification, the method by which a code is certified to properly solve the physical model it encodes. Benchmarking is a useful and instructive aspect of verification, but by no means accomplishes the whole of verification.

Computing initiatives have recently targeted the integration of different types of codes. These initiatives will fall short of desired objectives if the codes are not validated. Validation of component modules is extremely challenging; validation of integrated codes will be enormously more difficult. It is essential that integration efforts be matched by validation efforts directed at component modules, including the use of initiatives to spur the effort.

C. Validation

The linking of experiment, theory and modeling to understand core transport can be organized under the methodology of validation. This will require the use and development of tools for verification and validation. A number of verification tools have been described and should be aggressively implemented. Validation requires more development and should address needs such as sensitivity analysis and validation metrics that account for qualification, assessment of uncertainties, sensitivity, and measurement primacy. Validation scenarios need to be designed for existing devices. These determine types of measurements appropriate to device and model constraints and validation goals, and the metrics to be employed.

To rule out spurious effects, fortuitous agreement, and to sort out the effects of complexity in geometries, topologies, and physics regimes, validation should be pursued on a hierarchy of devices over which these complexities are graduated. It is not known what such a hierarchy would look like for the core transport problem, but as experience is gained with validation one should be formulated and proposed.

Synthetic diagnostics are growing in use for comparisons with experiment. While offering many advantages, synthetic diagnostics also need to undergo verification and validation. Among other things the latter involves a quantitative assessment of the theory underlying the diagnostic measurement.

III. A transport diagnostics, analysis, and modeling thrust

The above activities can be organized into a thrust for transport diagnostics, analysis and modeling. It would involve designating a suite of devices for validation, drawn from existing smaller scale devices (e.g., MST, SDSX, etc.) existing larger scale devices (DIII-D, C-Mod, and NSTX), and new devices, where the latter are chosen to provide simplified geometry or to fill a gap in physics, regime, diagnostic access, or some other aspect of validation. Identifying the appropriate suite requires analysis, modeling and careful thought. Each device would have a specific validation mission based on particular physics capabilities, regimes, overlap and complementarity with other devices. Validation would require that each device have extensive diagnostics as described in Sec. II.A above enabling comparable measurements on multiple devices.

Codes for comparison would be selected from as wide a range as possible, including codes with differing algorithms (i.e., continuum vs. discrete approaches in gyrokinetics), reduced models, etc. Where necessary the modifications would be made for differing geometries, magnetic field configurations, etc. Modeling aspects would be carried out by analysts in teams including experimentalists and theorists.