# Towards a truly predictive capability: Recent progress and next steps in core gyrokinetics

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The progress in *ab initio* simulation of MCF plasmas over the past 15 years or so has been remarkable. E.g., in the area of nonlinear gyrokinetics, we have come a long way from simplified simulations of ion temperature gradient (ITG) turbulence with adiabatic electrons in circular magnetic geometries to comprehensive simulations involving multi-mode, multi-scale turbulence with kinetic electrons and electromagnetic effects using actual profile and MHD equilibrium data in non-axisymmetric geometries. In this context, a crucial aspect has been an ongoing systematic effort in the verification and validation (V&V) of gyrokinetic codes. The ultimate goal of these efforts is to develop a truly predictive capability which can be used, e.g., to *plan* ITER discharges as well as to *guide* the design of future fusion devices like DEMO. In the present whitepaper, we would like to point out some important areas of recent progress in nonlinear gyrokinetic simulation as well as some opportunities for next steps within a timeframe of 5-10 years.

Regarding the plasma core, present-day gyrokinetic simulations of turbulent transport employing well established codes like GENE, GS2, or GYRO may be characterized as relatively mature, allowing for quantitative comparisons with measurements. Nevertheless, specific applications of such tools to actual discharges can still be challenging, raising the question of how much physics and numerical resolution is required to fully capture a given experimental situation. Some examples:

- **L-MODE OUTER CORE TRANSPORT.** Despite several successful V&V efforts involving the gyrokinetic codes mentioned above over a range of experimental conditions, gyrokinetics is trying to deal with an unexpected challenge, namely an apparent systematic underprediction of the ion heat flux in the outer core of certain cold L-mode discharges in the DIII-D device. Via careful and extensive studies with the GENE code (http://genecode.org), this challenge could be met successfully. The transport levels in DIII-D (or ASDEX Upgrade) discharges could be reproduced within the experimental error bars of the input parameters [1,2]. Such studies highlight the fact that the search for a high-enough resolution and a complete-enough set of physics effects for turbulence simulations can be highly non-trivial.

- **ELECTRON-SCALE TURBULENCE.** A large fraction of the total electron heat flux in some Alcator C-Mod discharges was recently found in GYRO studies to be caused by electron temperature gradient (ETG) turbulence on electron gyroradius scales [3]. Several earlier studies with GENE and GS2 indicate that the same may apply to a wide range of discharge conditions in present-day and future tokamaks, including transport barriers [4-6]. However, the cross-scale interaction between ion- and electron-scale turbulence is only poorly understood at this point, and quantitative predictions of the electron-scale contributions remain computationally very challenging.

- **TURBULENCE AT HIGH BETA.** In a series of gyrokinetic turbulence studies using mainly GENE, GYRO, and GS2, the nature of turbulent transport at high beta was investigated. Among other things, it was found that ITG turbulence can be strongly stabilized (far beyond linear stabilization) by nonlinear effects, leading to a greatly enhanced upshift of the critical ion temperature gradient [7-10]. At the same time, magnetic fluctuations can short-circuit zonal flows and induce a non-zonal transition [11,12]. In addition, both spherical and conventional tokamaks often exhibit microtearing modes which may exhibit an intrinsic multi-scale nature [13-15]. Their contribution to the overall electron heat transport, even if linearly stable, is a matter of ongoing research [16,17].

- **TURBULENCE AND FAST IONS.** The strongly reduced ion temperature profile stiffness observed in certain JET discharges could be traced back (via an extensive set of physically comprehensive GENE simulations) to nonlinear electromagnetic effects in the presence of a significant fast ion population [18-21]. Moreover, couplings between core and edge plasmas can further enhance this effect [22]. This discovery offers interesting new perspectives on high-performance burning plasma operation in devices like ITER, calling for theoretical and experimental follow-up studies.

- **TURBULENCE, NEOCLASSICAL TRANSPORT, AND MHD INSTABILITIES.** For many years, these three physical processes have been considered separately. However, initial studies of the nonlinear coupling between turbulence and neoclassical effects (like the neoclassical equilibrium [23,24] or the bootstrap current [25]) or MHD instabilities (like neoclassical tearing modes [26]) point to our limited understanding of these interactions, calling us to bridge subdisciplinary boundaries. While these questions can all be addressed on the firm footing of gyrokinetic theory, they involve multi-scale challenges which demand extreme-scale simulations.

- **TURBULENCE IN NON-TOKAMAK DEVICES.** An important test on the way towards a truly predictive capability is the ability to correctly describe the plasma dynamics in devices with magnetic geometries which are somewhat different from that of a conventional tokamak. This is a good way to prevent the employed simulation tools from being too focused on a relatively small corner of parameter space, potentially overlooking physical effects that become relevant only for future machines. In particular, systematic comparisons between gyrokinetic simulations and experiments for linear devices like the LAPD, stellarators like Wendelstein 7-X, or RFPs like MST offer excellent opportunities for V&V, as exploratory studies show [27-30].

As a direct consequence of these findings and considerations, any effort to do whole-device modeling needs to take into account our current understanding of various multi-scale/multi-physics coupling effects, in particular in the areas just described. This leads to the following action items:

- There needs to remain a strong effort to push towards **comprehensive nonlinear gyrokinetic simulations on peta- to exascale supercomputers**, providing a sound *ab initio* basis for core plasma modeling. A limited number of heroic simulations will remain indispensible for the development of a truly predictive capability. Grid-based gyrokinetic codes can be parallelized efficiently over the large number of grid points in the 5D phase space. E.g., GENE has demonstrated excellent scaling up to ~260,000 cores. However, close collaborations between computational plasma physicists and colleagues from applied math and computer science are needed to port such codes to future exascale platforms with millions of cores (as well as accelerators).

- Informed by such direct numerical simulations of multi-scale/multi-physics phenomena, frameworks utilizing coupled codes which are focused on various subsets of the physics need to be constantly further developed. In this context, essential building blocks are reduced, reliable models of turbulent transport. One promising new approach to reduce the cost of *ab initio* simulations is the application of well-known Large Eddy Simulation techniques to gyrokinetics [31,32]. Moreover, some significant limits of conventional quasilinear models (i.e., their inablity to address the six physics questions mentioned above) must be overcome, and new approaches (e.g., based on nonlinear dimensionality reduction techniques) should be explored. In the context of a multi-level approach to whole-device modeling, the role of **robust and reasonably accurate reduced models** cannot be overemphasized.

- All of these activities should be characterized by a **very close interaction between theory, simulation, and experiment (addressing both tokamaks and non-tokamak devices)**, involving, in particular, a continued V&V effort and a strong analytical component. **The ultimate goal is to transition from postdiction to prediction, guiding the operation and design of future fusion devices.**

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