White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	9 June 2015

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• Turbulence and transport	P
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• Plasma self-organization	S
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Title:	Coarse-Grained Modeling and Simulation of Turbulent Plasma Flows
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Coarse-Grained Modeling and Simulation of Turbulent Plasma Flows

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- ***Research frontier:***

Plasma flows are inherently multi-scale in which various physical phenomena are associated with characteristic temporal and spatial extents (e.g. from charge dynamics within a Debye length to advective processes within the spatial domain size). In particular, turbulent plasma flows, found in diverse contexts, both natural (e.g. astrophysical jets, supernovae, accretion disks, solar flares, lightning) and technological (e.g. confined fusion, planetary entry, fuel reforming, processing of materials), present the largest range of scales. The computational exploration of these flows is extremely challenging due to the large range of scales and physical process involved, yet would lead to greater fundamental scientific understanding and to diverse impacts in modern technology.

Turbulence modeling and simulation methods are classified according to their degree of approximation into (Fig. 1): Direct Numerical Simulation (DNS), which resolves all the scales of the flow, and is therefore the most accurate methodology; Large-Eddy Simulation (LES), which resolves the large scales and models only the small scales; and Reynolds-Averaged Navier-Stokes (RANS), which models all scales (not depicted in Fig. 1). The intractable computational demands of DNS has led LES, which is typically orders of magnitude less computationally expensive than DNS, as the de facto standard for the exploration of most turbulent flows.

The vast majority of LES techniques rely on two basic assumptions: (1) the suitability of spatial filters to separate scales into large and small, and (2) the adequacy of the use of an eddy viscosity to model the redistribution of momentum from the small scales. The effects of anisotropy and non-linearity, as well as the interaction of different physical transport processes, ubiquitous in plasma flows (e.g., thermodynamic non-equilibrium, chemical reactions, magnetization, charge transport) invalidate those assumptions. Therefore, approaches are needed for the consistent (the solution should approach a DNS for increasingly finer discretizations) and complete (no empirical parameters), coarse-grained modeling and simulation of turbulent plasma flows.

The challenges associated to coarse-grained turbulent plasma flow modeling has limited the computational investigation of these flows to within the extent allowable by DNS, and therefore to flows with a relatively small range of scales and within simple geometries. In this regard, the turbulent plasma modeling and simulation literature is dominated by the use of MHD flow models for astrophysical and space weather problems [3-5] and fully ionized plasma models (i.e., no neutral species) for fusion research [6]. Nevertheless, very recently, there have been efforts to formulate coarse-grained modeling and simulation methodologies for plasmas, such as the work reported in [7] for astrophysical plasmas and the work in [8] for confined fusion plasmas. Such efforts need to be fomented and expanded, as they have the potential to bring to Plasma Physics the same level of predictive capabilities achieved by turbulence modeling and simulation in other disciplines.

- ***Approach to advancing the frontier:***

Some characteristics of ideal coarse-grained modeling and simulation approaches are: they would be general enough such to allow their application to different types of plasma flow models (e.g., magnetized, multi-fluid, non-neutral, resistive and Hall MHD); they are likely to circumvent the need for spatial-temporal filters; would not require the calibration of model parameters; would be capable to capture laminar-to-turbulent transitions; would allow the seamless handling of wall-bounded flows (e.g. near

electrodes or solid surface); would allow the consistent coupling to diverse intervening phenomena (e.g. radiation transport, particle formation and dynamics, multi-phase interactions); as well as would allow the handling of complex geometries, as required for the analysis of diverse industrial plasma applications. The Variational Multiscale (VMS) framework developed by Hughes and collaborators [9] for the modeling of incompressible flows is a promising approach that fulfills some of the above characteristics. Initial steps towards applying a VMS formulation to the modeling of plasma flows is reported in [10].

In additional to the development of numerical and computational approaches, software tools for turbulence plasma flow simulation need to be devised and made available to the Plasma Science and Engineering community. Such software tools have to be capable for massively-parallel simulations using current and future-generation high performance computing resources (e.g. heterogeneous infrastructures, multi-core/multi-tread, GPU/accelerators, low latency synchronization). The tools should be capable to interface other plasma modeling and simulation software tools (e.g. Boltzmann solvers, global kinetics codes, radiation transport solvers) to ensure the continuous progress towards more comprehensive physical models.

- ***Impact on plasma science and potential societal benefits:***

The availability of coarse-grained modeling and simulation approaches for turbulent plasma flows would enable greater understanding of instability phenomena, transition to turbulence, and turbulence through a wide range of plasma types and operating regimes. Such understanding can lead to increases in the scalability and economic viability of current plasma processes and applications (e.g. from materials processing, chemical and particle synthesis, and fuel reforming, to combustion enhancement, environmental remediation, and medicine); to the fundamental scientific understanding of unexplored phenomena (e.g. current distribution in coherent, long-lived, flow structures), flow regimes (e.g. highly-turbulent non-equilibrium plasmas); and potentially to the development of novel technologies (e.g. high electron flux atmospheric-pressure plasma sources).

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Figures

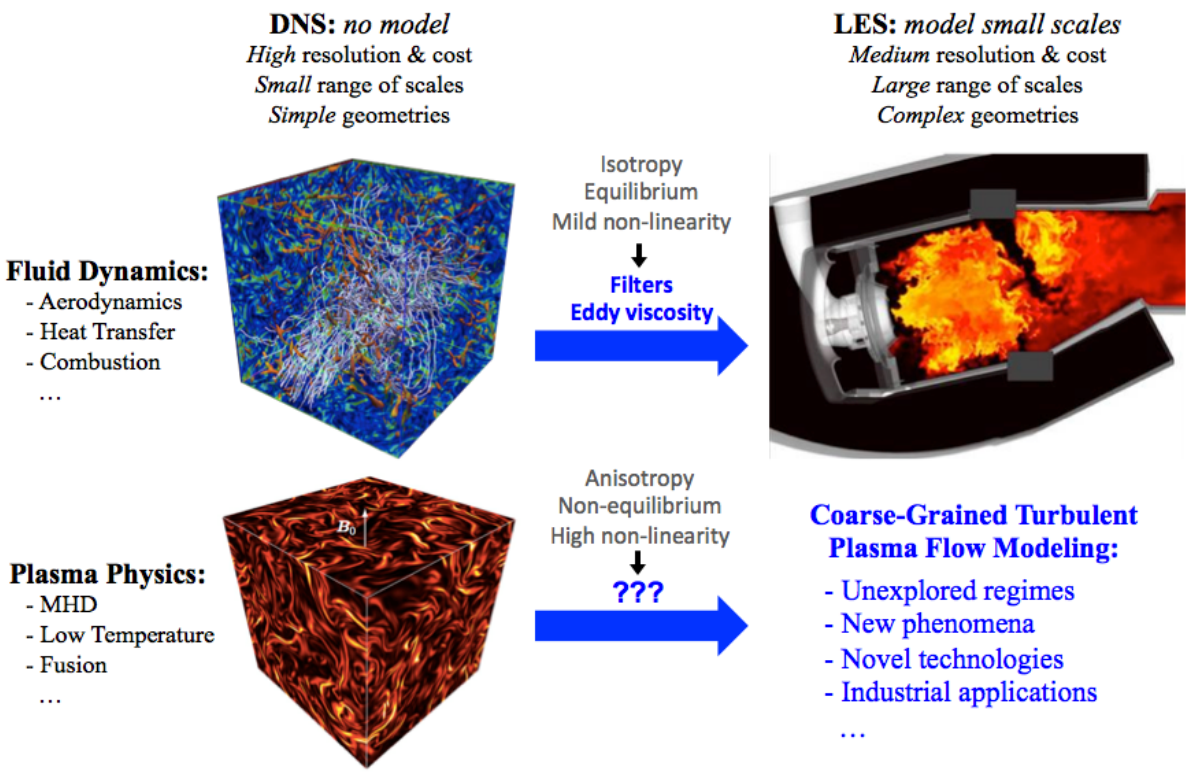

Figure 1 – Direct Numerical Simulation (DNS), which does not rely on any approximation of the flow, requires high-fidelity numerical methods and exceedingly large computational resources, limiting their use to relatively simple turbulent flows; in contrast, the coarse-grained strategy known as Large Eddy Simulation (LES), by modeling only the smallest scales, which potentially display universal characteristics, is suitable for the modeling of more complex flows. Coarse-grained modeling and simulation methodologies, counterpart to LES, are needed for the modeling of turbulent plasma flows in a wide range of applications and flow regimes. Such formulations would have the potential to bring to Plasma Physics the same level of predictive capabilities achieved by other fields, such as Aerodynamics, Heat Transfer, and Combustion. (Images: *top-left* – DNS of isotropic turbulence [1], *bottom-left* – DNS of isotropic MHD turbulence [2], and *top-right* – LES of the flow in gas turbine combustor [3].)