Role of Analytic Theory in the US Magnetic Fusion Program

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Analytic theory has played a decisive and foundational role in the development of magnetic confinement plasma physics, as evident in numerous contributions that have become standard material in textbooks (plasma fluid theory, plasma kinetic theory, neoclassical transport theory, etc.). Fusion plasma physics has been blessed with an analytic theory tradition that, by virtue of asymptotic methods and ordering techniques, provides unusually rigorous and powerful means of treating highly complex and nonlinear systems. Moreover, analytic theory of fusion plasma physics is still developing in potent ways, including in directions prompted by simulation results. As numerical approaches increase in reach and sophistication, tackling ever more comprehensive issues, the role of analytics will be enhanced by its ability to formulate new procedures to solve problems thought to be unsolvable just a few years ago. The drive toward predictive capability, with its prima facie base in comprehensive numerical algorithms, increases the necessity for analytical theory, because both play complementary essential roles in virtually all gaps of the Greenwald Report that are addressable by theory.

Critical Capabilities of Analytic Theory include: 1) the development of hierarchies of models, from heuristic reduced models to comprehensive integrated models, to understand all aspects of physical processes operating and interacting in fusion systems [e.g., blob physics, which was first elucidated in a mechanistic analytic theory, then studied in a large variety of more complicated models, and finally described in gyrokinetic models for heat transport in the scrape off layer of tokamaks]; 2) the discovery and elucidation of fundamental properties in plasma physics processes, including symmetries, scalings, and mechanisms, and the prediction of their role in magnetic confinement [e.g., the nonlinear scaling theory of shear suppression of turbulence, which was used to discover the effect]; 3) the conceptualization of the workings of systems and the integration of their component processes, both in developing new ideas and in understanding existing systems [e.g., the conceptualization of the snowflake divertor as an exercise in analytical theory]; 4) the development of entirely new models, both for hierarchies, and for areas where existing models are missing important physics or capabilities [e.g., drift kinetic closure schemes for extended MHD codes like M3D-C1 and NIMROD]; 5) the verification and understanding of the results of numerical algorithms (codes), both in the informal sense of understanding and confirming the validity of unexpected outcomes from simulation and the formal testing of numerical algorithms as a companion exercise to validation [e.g., analytic residual flow calculations as a test for the fidelity of flow physics in gyrokinetic and gyro-Landau fluid models].

Addressing Gaps - The wide uses made of analytic theory in the above examples demonstrate its crucial capabilities in bridging gaps between the known and the unknown. Because it is a fundamental approach in physics (since at least Newton), and not simply a technique, model, or algorithm, it can be applied to all gap areas in fusion that are amenable to theory, including those of the Greenwald Report. But it is also true that analytic theory is capable of making discoveries of things we don't even know about, and that are not therefore in the Greenwald Report. These statements, which are made unassailable by history, should not lull anyone into a false sense of security. Demographic trends within the fusion workforce that will see the retirement of scientists trained exclusively in analytic theory and the allure of sophisticated simulation for younger scientists are forces that threaten to diminish and compromise the US capacity to fruitfully engage in the analytic theory required to address critical gaps. It is essential that strategies be developed within the US program to counter these trends