Addressing the need for fluid plasma boundary modeling

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Motivation:

It has been widely recognized by numerous FESAC reports that the fusion energy program requires validated simulation and modeling capabilities in order to aid in interpretation and understanding of existing experiments and to make predictions that guide the design of future devices. Fluid plasma edge transport codes (2D and increasingly, 3D) play an important role in this mission, by striking a balance between extremely computationally expensive first-principles 5D-6D kinetic models and 1.5D core codes that neglect the scrape-off-layer and the full effect of recycled neutral particles. Edge fluid codes, given core (or pedestal) boundary conditions, can be used to calculate the 2D or 3D distribution of the fluid plasma moments, such as density, velocity and temperature. The models must include the effect of plasma-surface and plasma-neutral interactions in order to compute the critically important heat flux incident on material surfaces and the rate of erosion of materials through sputtering. In addition to the increased computational speed (lower computational cost) as compared to higher fidelity codes, fluid models often provide solutions that can be understood in terms of relatively straightforward concepts, such as the two-point model [1], elucidating the underlying physics and allowing the results to be extended beyond individual machines or operating points. The fluid plasma solution is additionally used to interpret diagnostic data, to provide an equilibrium and/or background edge plasma for further simulations, and in the design of divertor and pumping systems for future devices. Coupled to a core-pedestal model, fluid edge codes are also expected to be a critical component of a whole-device simulation, allowing the incorporation of open field line and neutral particle effects.

Despite the prominence and utility of these codes, it is widely recognized that the physics included is incomplete. A major need not addressed here is a physics-based model of turbulent transport. But even within the more interpretive mode where midplane profiles are fit, the codes often cannot simultaneously match the measured upstream and downstream profiles except in the sheath-limited regime, measured in-out divertor flux asymmetries are not well reproduced, and the transition to detachment is incorrect. Other areas for advancement include the equilibrium magnetic field model, particularly for tokamaks with applied 3D perturbations, and the treatment of plasma-material interactions. These examples highlight the need for investment in improving the models, which requires well-designed experiments to isolate specific physics aspects of the code, proper theory support to propose improvements, and sufficient access and familiarity with the code to advance it. While the US has played an important role in the development of boundary codes, namely the US-developed UEDGE, many leading 2D (SOLPS, B2-EIRENE, EDGE2D) and 3D (EMC3-EIRENE) codes are primarily developed in Europe, with other efforts in Japan. This relegates much of the modeling community to users, without direct access to the theory and computational staff who develop the codes. Given these needs, the program should support the application, validation, and development of existing and new boundary transport codes, specifically in the form of additional manpower.

Approach:

Targeted validation and theory support: To make meaningful progress beyond the last 10-20 years of edge modeling, modelers need to be closely coupled to and actively participate in experimental planning on the US and international fusion devices. Experiments should be designed to test specific aspects of the models and identify specifically where they breakdown and where they should be improved. Sufficient modeling support is required to apply the codes to the experiments. A critical aspect of identifying and implementing changes is strong involvement from plasma theory and computational scientists. This may take the form of updating the existing physical models, improving the numerical methods, or by incorporating reduced models that are 'calibrated' to first-principles codes.

Support of existing codes: The US plasma boundary modeling community plays a critical role in performing interpretive and predictive simulations for existing and future experiments. To maintain and improve this capability, sufficient manpower devoted to applying the codes is required. In addition, as the leading US fluid plasma transport code, UEDGE should be supported to ensure that the code is maintained and continues to advance. It is important that there is a strong user base, as well as an active development plan that allows for knowledge transfer to the next generation.

Development of a new simulation capability: The US should make high-risk high-reward investment in the development of a new fluid transport boundary code. Creating a new code has several advantages. First, the code could be developed utilizing recent advancements in parallel computation, with efficiency, modularity and scalability as guiding principles. In particular, coupling to a whole-device model should be targeted. Current fluid codes (while evolving, many originally developed 20+ years ago) despite being much faster than first-principles models, still require on the order of months to provide a steady-state solution for a typical ITER simulation when coupled to Monte Carlo neutrals [2]. Improved coupling algorithms under development would have a major impact. Second, it could target physics not captured by any existing code. For example, a 3D fluid code that robustly incorporates cross-field drifts and nonlocal kinetic closures would immediately place the US in a leadership position in edge modeling. Finally, the US edge modeling community could play an active role in the code development, instead of acting primarily as code users. Promising proposals with the potential to make significant and rapid progress should be supported at a proof-of-principle level.

Impact:

Investment in boundary plasma modeling will allow the fusion program to better address the need for efficient validated simulation capabilities for current and future fusion experiments. The program should maintain and advance our current fluid modeling capability, support targeted validation with experimental and theory support, and pursue a new simulation capability that will place the US in a leadership position in the area of boundary modeling. Specifically, investment in the form of additional manpower is required. Action in this area improves the modeling community's ability to make meaningful progress in understanding existing experiments, and increases our capability to design future devices such as FNSF and DEMO.

[1] P. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices* (2000), Bristol: IOP Publ.
[2] A.S. Kukushkin, et al., Fusion Engineering and Design 86 (2011) 2865-2873.