Development of a time-dependent transport code that can handle nonaxisymmetric magnetic fields with islands and stochastic regions, with application to disruption prediction and avoidance[1]

(a whitepaper submitted to the DOE/OFES Workshop on Integrated Simulations, April 2015)

A. H. Reiman (PPPL, reiman@pppl.gov), M. R. Dorr (LLNL CASC), L. L. LoDestro (LLNL FESP)

Submitted to sub-panel:	C
Cross-cutting topics with sub-panels:	A, D, and G
Oral presentation:	requested

The purpose of this whitepaper is to advocate the development of a “2.5D” transport code as a natural next step following the development of the ubiquitous “1.5D” transport codes (also known as “alternating dimension” or “Grad-Hogan” codes). 1.5D codes are limited to axisymmetric plasmas. A 2.5D Grad-Hogan code would be able to handle nonaxisymmetric magnetic fields; and it could handle slowly evolving magnetic islands and stochastic regions. As will be discussed below, such a code would be directly relevant to the prediction and avoidance of disruptions. Furthermore, there could be a synergy with OASCR-supported software development on the CHOMBO framework.

Grad-Hogan codes employ a formal separation of the (fast) Alfvén time scale, on which magnetohydrodynamic (MHD) equilibrium is established, and (slow) transport time scales. The radial profiles of the plasma parameters are advanced by 1D equations (which have been averaged over the equilibrium magnetic flux surfaces and include magnetic-topology coefficients) for the transport of particles, energy, *etc.*, across the surfaces. The radial profiles enter the equilibrium as source terms; the equilibrium magnetic field is updated by re-solving using updated profiles. This algorithm takes advantage of the strong anisotropy between transport parallel and perpendicular to field lines in a low-collisionality plasma confined in a toroidal magnetic field. Since their time dependence is inherently on transport scales, Grad-Hogan codes generally afford a significant speed-up over 3D initial-value extended-MHD codes; this is important when simulating low-collisionality plasmas on magnetic-flux-diffusion time scales. In addition, such codes are well structured for the inclusion of independently-developed high-fidelity models (which can include fast time scales, three spatial dimensions and two or three velocity-space dimensions) for sources and transport processes provided that the time scales of the surface-averaged quantities which enter the transport equations remain long. Each of these couplings brings in issues of ordering schemes and multi-scale coupling algorithms; and each offers the potential for significant computational savings cf. running a high-fidelity model with fast scales for the transport times as required for a whole device model. In particular, the effects of plasma microturbulence can be accurately simulated by coupling a gyrokinetic code to a Grad-Hogan code [Candy, Barnes,]. In 1.5D (*i.e.*, axisymmetry), the MHD equilibrium is given by the 2D Grad-Shafranov equation; a 2.5D code would use a 3D equilibrium solver.

Examples of 1.5D codes are TRANSP, DINA, CORSICA, ONETWO, FACETS, BALDUR, WHIST and JETTO. Some 1.5D codes under development are IMAS (ITER) and ITM (EU). The only active 2.5D code of which we are aware is TASK3D (Japan).

A 2.5D code would be ideally suited to study the long, slow, nonaxisymmetric time evolution of a tokamak plasma that precedes many disruptions. An understanding of the time evolution of the plasma during this phase will be important for the development of a capability to predict and avoid disruptions. An analysis of the 1654 unintentional disruptions in JET over the period 2000 to 2010 to determine the root-cause of the disruptions found that the largest fraction had a neoclassical tearing mode (NTM) as root

---

[1] This work was performed under the auspices of the U.S. Department of Energy by the Princeton Plasma Physics Laboratory under Contract DE-AC02-09CH11466 and by the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

cause [deVries09]. The time evolution of the NTM is determined by flux diffusion in and near the island in the presence of bootstrap current drive, with boundary conditions determined by the global 3D equilibrium solution. On JET, during the period from 2000 to 2010, the time from detection of an NTM to a disruption ranged from 100 ms to 2 seconds [deVries11]. In major disruptions, typically ½ to ⅔ of the thermal energy in the plasma is lost in the pre-disruptive phase, *before* the thermal quench [Putvinski]. One possible cause of this is the stochastization of the flux surfaces as islands grow. If we are to understand what is happening during the pre-disruptive phase, we must be able to calculate the nonaxisymmetric time evolution of the plasma over the long time scale associated with this phase. Furthermore, it is expected that turbulence will have a significant effect on the growth of islands through its effect on the ratio of parallel to perpendicular transport [Fitzpatrick]. This is a problem to which a 2.5D code coupled to a gyrokinetic code would be applicable; it would provide a high-fidelity, self-consistent calculation of the transport coefficients, including the effect of the magnetic field topology on the neoclassical and turbulent transport. An understanding of the plasma evolution during the pre-disruptive phase would help to address the question of when the plasma can be reliably shut down in a quiescent manner, and when disruption mitigation is required. If a quiescent shutdown is possible, a 2.5D code could help guide the path to such an outcome.

There would be a natural synergy between the 2.5D code development and OASCR-supported software development of the CHOMBO framework. For purposes of application to tokamak edge modeling, CHOMBO's mapped multi-block grid technology has been enhanced to allow it to handle the singular behavior near a divertor separatrix. It would be natural to extend this capability to one for handling island separatrices and O-points. Application of the CHOMBO framework in the context of 2.5D calculations with magnetic islands would provide powerful new capabilities to the 2.5D modeling, including high resolution near low-order rational surfaces, allowing accurate handling of localized currents in those regions, high-resolution grids in the interior of magnetic islands, and state-of-the-art parallelization. CHOMBO, in turn, can benefit by adapting software modules developed in the context of 3D-equilibrium software development, including a capability to construct the 2D "flux surfaces" defined by magnetic field lines, where such flux surfaces exist, and the ability to calculate "magnetic coordinates". The equation for the field-line trajectories can be written in Hamiltonian form, and magnetic coordinates correspond to action-angle variables for the magnetic-field-line Hamiltonian.

1.5D codes presently provide an important, heavily used capability to do whole-device modeling over long time scales. There has been some U.S. and Japanese 2.5D code development that assumes nested flux surfaces [Strand, Nakamura,Yokoyama], and there has been some application of the codes to stellarators, but not to tokamaks. We believe that the most compelling potential applications of a 2.5D code to tokamaks would require a capability to handle magnetic islands, and no such capability exists. The absence of 2.5D code development is a gap in the U.S. program, and the absence of 2.5D code development with islands and stochastic regions is a gap in the world program. The U.S. has historically taken the lead in the world program on 3D equilibrium code development, and it would be natural for the U.S. to take a prominent role in 2.5D code development.

Tokamak plasmas generally are nonaxisymmetric. There are field errors arising from finite tolerances in the placement of coils. There are nonaxisymmetric field-error correction coils which, while canceling the most dangerous resonant field components at low-order rational surfaces, increase the magnitude of other nonaxisymmetric components of the field. NTMs are particularly prevalent in advanced "hybrid" discharges, and, in DIII-D at least, the presence of a 3/2 NTM appears to be beneficial in these discharges [Wade]. Nonaxisymmetric magnetic fields may be imposed for the purpose of stabilizing ELMs, and ITER will have nonaxisymmetric coils for this purpose. Plasmas often go through a long slow period of nonaxisymmetric time evolution before they disrupt. The great utility of 1.5D codes suggests that 2.5D codes could also be of great utility. Such a code would be a natural component of an integrated simulation capability.

References

[Barnes] M. Barnes, I. G. Abel, W. Dorland *et al.,* Phys. Plasmas **17**, 056109 (2010); http://dx.doi.org/10.1063/1.3323082.

[Candy] J. Candy, C. Holland, R. E. Waltz *et al.*, Phys. Plasmas **16**, 060704 (2009); http://dx.doi.org/10.1063/1.3167820.

[deVries09] P.C. de Vries, M.F. Johnson, I. Segui *et al.*, Nucl. Fusion **49**, 055011 (2009).

[deVries11] P. de Vries, M. Johnson, B. Alper *et al.*, Nucl. Fusion **51**, 053018 (2011).

[Fitzpatrick] R. Fitzpatrick, Phys. Plasmas **2** (1995).

[Nakamura] Y. Nakamura, K. Watanabe, Y. Narushima *et al.*, Plasma and Fusion Research **3**, S1058 (2008).

[Putvinski] S. Putvinski, L. Baylor, D. Campbell *et al.*, in Fusion Energy IAEA meeting 2010, paper ITR/1-6.

[Strand] P. I. Strand and W. A. Houlberg, Phys. Plasmas **8**, 2782 (2001).

[Wade] M.R. Wade *et al.*, Nucl. Fusion **45**, 407 (2005).

[Yokoyama] M. Yokoyama, A. Wakasai, R. Seki *et al.*, Plasma and Fusion Research **7**, 2403011 (2012).