Research Thrust to Establish Predictive Simulation Capability for Fusion Nuclear Science

S. Diem[1], D. Batchelor[1], V. Chan[2], A. Garofalo[2], Y.K. Peng[1], D. Spong[1], A. Sontag[1]
[1]Oak Ridge National Laboratory, Oak Ridge, TN, [2]General Atomics, San Diego, CA

1. Mission and Scope Summary

The ITER-era goal for the U.S. Spherical Torus (ST) Program identified in the TAP report [1] is to:

> *Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component test facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*

A fusion component test facility (CTF) has been suggested as a device [2] that can provide a full fusion nuclear environment and will be an essential tool to test components that are needed by a fusion demonstration power plant (DEMO). The scientific exploration phase of the CTF has the potential to enable the R&D critical to closing the gaps in knowledge base identified in the FESAC "Priorities,….." report [3]. Discovery and understanding of the underpinning physical properties of components in such an environment will enable DEMO-capable components for subsequent engineering and technology demonstration testing.

Predictive plasma simulations are essential to the development of fusion energy and in particular to the development and design of a fusion nuclear science facility (FNSF), as the first phase of a CTF. The area of theory and simulation was identified in the TAP report [1] as being one of the two uniquely urgent needs for the ST. The highly reliable plasmas required of a CTF will need predictive simulation capabilities covering start-up and ramp-up, first-wall heat flux, and electron energy transport.

2. Closing a Research Gap to the ST ITER era goal

Data from existing and upgraded experiments, including tokamaks, will be used to validate predictive models. This will allow these models to be used in the design of CTF. Predictive simulations will be needed to address several of the high priority issues (Tier -1) identified in the TAP [1] and FESAC 'Priorities, …" [2] report for the ST:

Start-Up and Ramp-Up. Simulations will be required to investigate whether it is possible to start-up and ramp-up the plasma current to multi-MA (8-10 MA) levels with minimal or no use of a central solenoid. Ramp-up currents of 0.5 MA are projected on MAST and NSTX through RF injection. The plasma current ramp-up technique suggested for a CTF will consist of neutral beam (NBI) current drive supplemented by RF heating. Upgrades to existing devices will overcome limitations that currently prevent tests of experimental ramp-up with NBI. This new capability will allow validation of NBI start-up and ramp-up method physics, study of the affects of fast-particle induced MHD on NBI current drive efficiency, and plasma equilibrium evolution. EC assist during the breakdown and burn-through phases can greatly improve the robustness of the FNSF startup scenario. With EC assist in DIII-D, breakdown was reproducible and burn-through of low Z impurity radiation was rapid. The Corsica free- boundary equilibrium code can be used for FNSF ramp-up simulations. In addition Corsica can simulate the FNSF control system, including models of power supplies and coil systems; an essential requirement for ramp-up optimization. Modeling of initial electron heating and current drive will benefit with improved models of RF wave propagation from the antenna to the plasma edge to enable more accurate estimates of RF antenna loading. Time-dependent modeling will be needed to account for the projected confinement and stability to extrapolate between 0.5 MA to ~8-10 MA.

First-Wall Heat Flux. Due to the small major radius of the ST, peak heat fluxes of up to ~10 MW/m^2 occurs in current STs, much higher than in tokamaks. The predicted heat load for an unmitigated CTF device is ~ 40 MW/m^2. Alternative divertor geometries, such as the Super X-divertor, may reduce the peak heat flux by a factor of 5. Simulations of proposed divertor designs using 2-D edge fluid transport codes SOLPS and UEDGE are required to quantitatively model the variety of divertor geometries aim at reducing the peak heat flux in CTF. The various divertor geometries can be incorporated in upgraded STs and will provide a benchmark for simulations. The coupling of the edge code to core transport remains an open research issue. Additionally, detailed edge models will need to be incorporated in the simulations to accurately predict the peak first-wall heat flux.

Electron Energy Transport. Turbulence and transport occur on a wide range of space (from 10^{-5} m to meters) and time scales (10^{-7} s to 10^{3} s). Predictive simulations must be developed to predict phenomena on both microscopic and macroscopic length and time scales. In particular, in the ST the electron transport scaling and modeling occurs at a T_e 10x higher and at lower collisionality than with conventional tokamaks. *The role of magnetic geometry on confinement is an active area of research that promises a unified means to improve both stability and transport, especially electron heat transport.* An effective research program will require flexibility in plasma shaping and current profile control to create desirable magnetic configurations. Simulation codes will have to treat realistic geometries. Due to a great commonality in the underlying confinement physics between the ST and the tokamak, understanding the electron energy transport is expected to equally benefit the Tier-1 research gap for the ST ITER era goal.

Several Tier-2 issues will benefit from advances in predictive modeling: integration, disruptions, RF heating and current drive, 3D fields, ion scale transport, and fast particle instabilities. These issues will require improved predictive capability for confinement, disruption avoidance, ELM avoidance and mitigation, rotational stabilization of the RWM, and momentum and fast ion transport. Data obtained in upgraded STs can be combined with predictive simulations in order to bridge the gap of understanding between present day experiments and DEMO. These advancements will require the development of 3D equilibrium and time dependent modeling as well as detailed diagnostics to benchmark codes.

Predictive simulations that can simulate the behavior of a high temperature, fusion grade plasma on all important time and space scales and account for the interactions of all relevant processes will be necessary to address the high priorities identified for the ST. The Center for Simulation of Wave Interactions with Magnetohydrodynamics (SWIM) is developing an end-to-end computational system that allows existing physics codes to be able to function together. This is a modular approach that allows one to incorporate new codes as they are developed. The SWIM code system provides a tool to understand and predict the effects of RF waves on plasma MHD stability. This tool provides a capability to address the start-up and ramp-up ST priority using RF techniques. To address the other priorities, 3D equilibrium codes will need to be developed. These issues include alpha particle transport, energetic particle losses to plasma facing components, 3D modifications in the magnetic field and magnetic island formation in the plasma edge. Codes such as VMEC and SIESTA will be useful for this purpose, but will need further improvement to treat free-boundary equilibria in the presence of field ripple, blanket modules and other ferritic steel structures that can introduce 3D perturbations into the equilibrium. Predicting alpha particle losses and associated sputtering will require improved models for alpha particle induced turbulence and Monte Carlo slowing down models that can follow large numbers of alpha particles from birth to either thermalization or loss at the wall.

Despite the low-aspect ratio and low toroidal field of the ST, a growing international database has shown that there is a great commonality of underlying physics between the ST and the tokamak. Therefore, any advances in predictive simulations that occur with studying the ST may be applicable to tokamaks such as ITER.

3. Elements of the Research Thrust

As stated in [3], two gaps in predictive modeling are verification and validation. The source code and a database of detailed results of newly developed codes should be available to interested scientists for code verification. Another significant task is code validation. This process requires benchmarking of current and future codes to insure the codes exhibit the same phenomena over a corresponding range of plasma parameters. Code validation requires an active collaboration between the code development groups, experimentalists, and theorists. Benchmarking of codes will also require new, detailed diagnostics to provide detailed measurements to compare between code results and experiments. Many codes have been written for tokamak geometry and may require modifications for an accurate treatment of low-A plasmas. Efforts are currently underway through fusion SciDAC projects in extended MHD (CEMM) and energetic particle transport (GSEP, PEPSC) to develop computational tools for MHD and energetic particle instabilities. In their final form, these codes should all be applicable to arbitrary aspect ratio systems. However, working versions of some of these codes (HGMC, GYRO, GTC) are based on either large aspect ratio or circular cross section equilibrium models; these are currently being upgraded. Also, reduced MHD and/or perturbative assumptions are built into some of the energetic particle instability models (NOVA-K, TAEFL). Low-aspect ratio systems will need full MHD and non-perturbative versions of these models to be developed. Work in this direction is currently underway through more advanced hybrid fluid-particle (M3D) and full particle/gyrokinetic (GYRO, GTC) models.

[1] "Report of the FESAC Toroidal Alternates Panel", Nov. (2008).
[2] Y.K.M. Peng, et al., "Extensive handling and conservative plasma conditions to enable fusion nuclear science R&D using a component testing facility", IAEA FEC 2008 Conference Proceedings, Geneva, Switzerland (2008).
[3] "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy", FESAC Report, Oct. 2007.