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PPPL-4124 PPPL-4124

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October 2005

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

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# Integrated Modeling for Burning Plasmas

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*abstract*

This is a summary of the session by this name that was held at the Workshop (W60) on "Burning Plasma Physics and Simulation" held on 4-5 July 2005 at the University Campus, Tarragona, Spain under the auspices of the IEA Large Tokamak Implementing Agreement. We discuss where we now are in our ability to perform integrated modeling of burning plasmas, where we want to go, and how best to get there.

## Introduction

The term "Integrated Modeling" is used to denote all modeling and simulation activities that combine one or more of the traditionally separate disciplines of plasma stability, plasma transport, heating and current drive physics, and edge plasma physics. There were a number of presentations addressing different forms of integration, and showing results of integrated simulations of ITER where the integration led to increased self-consistency of the different effects, including self heating by the alpha particles. The near-term plans of the different parties in this area were also discussed.

## Where are we?

Mature 1½ D transport-timescale evolution code packages presently exist within each of the major parties. In Japan, as part of the Burning Plasma Simulation Initiative (BPSI) there are the TASK (Transport Analyzing System for Tokamak) and the TOPICS (Tokamak Prediction and Interpretation Code) projects. In the European Union, there is a newly formed Integrated Tokamak Modeling Task Force and the JET initiative, which includes the ASTRA, CRONOS, JETTO, and RITM codes. In addition, there is a project to couple the DINA and CRONOS codes to provide a free boundary evolution code with advanced source models. In the US, there is a new PTRANSP (predictive TRANSP) initiative that is building on the NTCC (National Transport Code Collaboration) structure, a project to couple the TSC and TRANSP codes (similar to DINA/CRONOS above), and several additional transport timescale codes including BALDUR, ONTEWO and CORSICA.

The 1½ D integrated modeling codes provide a reduced description of the evolution of the plasma in a tokamak. They each consist of a number of modules that describe the relevant transport processes, MHD instabilities and particle, momentum, and energy sources. These modules are normally not the most advanced models available but are chosen as a tradeoff between physics content and computational speed. There is a need for improved reduced modules in most areas. Turbulent transport models need to be improved, and their regions of validity need to be better quantified. Extended MHD and energetic particle modules need to be improved. There is a need for better particle and impurity transport models.,and a general need for better benchmarking of all modules.

More fundamental physics models than what are used in the transport codes exist in most areas, in particular in the areas of 5D Gyrokinetics, nonlinear extended MHD with energetic particle effects, full wave RF codes coupled with Fokker-Plank solvers, and in edge/PSI (Plasma Surface Interaction) codes. These compute-intensive codes seek to describe isolated phenomena at a more fundamental level. All have had some success, but they are still under development and will be for some time. Also, the computer requirements in each of these areas for a full ITER simulation are beyond present capability, even for isolated phenomena.

Extended MHD and energetic particle codes need to be further developed and validated on existing experiments. Full 3D nonlinear sawtooth simulations are now possible for small tokamaks, but not yet for ITER. Good reduced semi-analytical models are available (Porcelli model), but the regime of validity needs to be better quantified. There has been some recent progress on ELM modeling (BOUT-Snyder, JOREK-Huysmans, NIMROD-Brennan, M3D-Strauss), but there is not yet a full 3D ELM simulation for even small tokamaks. Semi-analytical models of ELMs are being developed. (including ideal-MHD/Enhanced transport model with MARG2D in TOPICS). There is not yet a full 3D neoclassical tearing mode (NTM) simulation. The modified Rutherford equation (semi-analytical) model is widely used to model NTMs, but it neglects mode coupling effects that can sometimes be very important. (for example, in the FIR regime). There is not yet a full 3D nonlinear model of the resistive wall mode (RWM) or for the locked mode threshold. For the toroidal Alfven eigenmode (TAE), 3D hybrid particle/fluid simulation models are possible for modeling short times and weakly nonlinear behavior, but full nonlinear integration with thermal particles is not yet possible. In the area of disruption modeling, axisymmetric modeling is in fairly good shape, but full 3D modeling is just beginning.

In the area of fundamental turbulence simulations, the focus is presently on core turbulence: ITG, ETG, ITG/ETG coupling, finite β effects, transition from Bohm to gyro-Bohm, and turbulence spreading. There is a need to develop a long-time (transport timescale) predictive simulation capability, to calculate particle diffusivities from transport simulations and to calculate impurities and helium ash transport, to integrate turbulence and neoclassical simulations, to better understand and be able to predict mechanisms for transport barrier formation, and to better integrate pedestal region and core-edge simulations. Also, we need to understand how best to couple turbulence calculations with the 1 ½ D transport timescale codes

In the area of edge-plasma integrated modeling, we note that a full 3D predictive edge model is lacking. However, numerous edge codes exist to provide qualitative understanding and quantitative results for specific phenomena. For edge transport, there are the CSD, SONIC, UEDGE, SOLPS (B2-Eirene), EDGE2D-NIMBUS codes. For kinetic edge turbulence, there are the PARASOL, DALF codes. For collisional edge turbulence, there is the BOUT code. There are also local codes for erosion/deposition such as ERO, and ccoupled Core-Edge codes: COCONUT:JETTO-SANCO-EDGE2D-NIMBUS. SOLPS is beginning to target disruptions and ELMs. There is a semi-analytical/empirical NTCC PEDESTAL module suitable for incorporating in 1 ½ D codes. Dynamic models for pedestal formation and ELM cycles are used in the JETTO and ASTRA codes. There is now increasing evidence that ELMs are triggered by current-driven MHD modes. In order to calculate this quantitatively, the MARG2D ELM model has been incorporated into TOPICS. In the U.S, several Fusion Simulation Projects have been proposed to study integrated edge-plasma. However, many issues remain in this area: a fundamental description of the L-H transition and pedestal physics; nonlinear ELM crash, transport, and pedestal recovery; density limit and impurity transport; material erosion including redeposition and dust formation (there is work in progress to integrate plasma and plate (SOLPS5-B2)—need to characterize mixed materials. To truly calculate integrated phenomena, there is a need to move physics from edge transport codes into edge turbulence codes, and also a need to include drifts into edge transport codes, and to move to a 1D neoclassical description where appropriate.

In the area of RF, NBI, α-particle, and fueling sources, we note the following: Comprehensive suites of RF and neutral beam codes exist and are being used in integrated modeling calculations. Integrated computations between full-wave ICRF and Fokker-Plank (FP) solvers are underway, but not yet in routine use. Integrated modeling that combines advanced ICRF antenna modules with full-wave solvers are underway. RF and NB source modules have been combined with 1 ½ D transport timescale codes, but generally not the most advanced RF packages. RF/FP Codes need to be coupled to MHD codes in order to simulate instability control Modeling of mode conversion physics in ITER scale plasma is not yet possible. There is a need to incorporate all RF and NB systems together with FP for ions and electrons self-consistently, and with energetic particle MHD. There has been a coupling of SPOT (for α-particles) and DELPHINE (for LH wave propagation and absorption and calculation of the electron distribution function) within the CRONOS framework.

## Where do we want to go?

In the foreseeable future, we want to continue to have a hierarchy of codes with a range of compute speeds and physics accuracy. There will continue to be a need for reliable validated transport-timescale code packages with improved modules for all processes *with reliable ranges of validity*. By this, we mean that we want to use reduced models to interpolate between regimes in which more fundamental model results exist, and not to extrapolate into parameter regimes for which more fundamental results are lacking.

This implies that we also need to have improved fundamental "first principles" nonlinear models that can quantitatively reproduce existing experimental results and future regimes. These are needed in the areas of turbulent transport, extended MHD, RF full-wave RF physics, and plasma edge modeling discussed above.

In addition to these more fundamental first principles models, we need to begin to develop *coupled* fundamental models to examine strongly interacting physics issues. Examples of these are the RF stabilization of MHD, turbulence effects on MHD modes, and core/edge/materials coupling.

As these integrated modeling codes become more mature, they will be called upon to perform a number of tasks needed to effectively operate a large burning plasma experiment such as ITER. They will be used extensively in experimental preparation. It is unlikely that any experimental proposal will be prepared unless there are extensive modeling results to support them.

Post-discharge analysis will also be a very big application. Running the codes in an interpretive mode will be a major high-level diagnostic that will allow physicists to understand what physical processes were active in a particular discharge.

In addition to these "traditional" uses for integrated modeling codes, there is a potential need for very fast codes for real time forecasting and control. These codes will be used in ways that are now not possible, improved equilibrium and discharge reconstruction, real-time profile control, and disruption prediction and mitigation.

## How do we get there?

Each of the major parties has self-organized to some extent and is developing integrated modeling frameworks and projects. We encourage each of the parties to continue their modeling projects, and at the same time to begin interacting more with the other parties.

Since these projects involve a large number of people and will span many years, it is important to utilize modern software practices in the development of these large integrated modeling packages. It is essential that the projects have good documentation and conform to agreed upon standards. There is a great benefit to be had from interacting with the Computer Science and math communities. This is one way to transfer the experience from other communities to the fusion community.

International collaboration could take the form of periodic workshops devoted to comparative modeling. For example, having each team look at certain specified discharges in depth, and comparing results is a good way of finding areas of agreement and disagreement, allowing participants to focus on the underlying reasons for the latter. These periodic workshops would also be a good place to develop international standards that would facilitate software exchange between parties. The standards might start out to be relatively non-controversial things such as a fusion-specific international standard for physical units or certain types of file formats, but could develop into more fusion-specific items.

In order to develop meaningful integrated modeling packages, there needs to be increased emphasis on verification and validation at all levels. This applies to the individual physics modules, to the entire “reduced model” code predictions, and to the “first principles” codes predictions. There are a variety of methods for accomplishing this, but it needs to be the dominant focus of the integrated modeling activities for many years into the future. The standardized discharges for comparative analysis will play an important role in this activity. It has been suggested that we make use of the ITPA profile database for this activity.

Finally, we note that developing large integrated modeling packages will require continued support and recognition by funding agencies in the different parties. To ensure this, we encourage all parties to maintain visibility by highlighting their accomplishments at appropriate conferences and other venues, and to ensure that their software products are of the quality and usefulness that lead to a growing user base.

## Acknowledgments:

Other members of the session that contributed to this summary were: N. Fisch, H. Takenaga, T. Hellsten, W. Lee, C. Kessel, D. Coster, A. Kritz, T. Ozeki, M. Schneider, and R. Budny. This work was supported by US DOE contract DE-AC02-76CH03073.

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05/16/05

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