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Simulation of wave interactions with MHD

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Abstract. The broad scientific objectives of the SWIM (Simulation of Wave Interaction with MHD) project are twofold: (1) improve our understanding of interactions that both radio frequency (RF) wave and particle sources have on extended-MHD phenomena, and to substantially improve our capability for predicting and optimizing the performance of burning plasmas in devices such as ITER: and (2) develop an integrated computational system for treating multiphysics phenomena with the required flexibility and extensibility to serve as a prototype for the Fusion Simulation Project. The Integrated Plasma Simulator (IPS) has been implemented. Presented here are initial physics results on RF effects on MHD instabilities in tokamaks as well as simulation results for tokamak discharge evolution using the IPS.

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1. Introduction

Comprehensive plasma simulations are essential to the development of fusion energy. Not only does simulation serve to advance science by allowing us to evaluate and test basic theory through comparison with experiments, it also has a direct economic benefit by maximizing the productivity of experimental facilities and by supporting design decisions for new facilities. For a device like ITER, such decisions can have large financial consequences. The Center for Simulation of Wave Interactions with Magnetohydrodynamics (SWIM) was begun in 2005 with the scientific objectives of improving our understanding of interactions that both RF wave and particle sources have on extended-magnetohydrodynamics (MHD) phenomena; improving our capability for predicting and optimizing the performance of burning plasmas; developing an integrated computational system for treating multiphysics phenomena with the required flexibility and extensibility to serve as a prototype for the Fusion Simulation Project; addressing mathematics issues related to the multiscale, coupled physics of RF waves and extended MHD; and optimizing the integrated system on high performance computers.

The scientific rationale of the SWIM project is relatively simple. One of the most fundamental observations in fusion devices is that performance is often limited by the appearance of unstable plasma motions that can degrade plasma containment or even terminate the plasma discharge, with the potential for damage to the containment device. These instabilities can be modeled by using extended magnetohydrodynamics. A second observation is that high-power radio frequency

(RF) electromagnetic waves can be used to influence plasma stability—sometimes producing instability and sometimes reducing or eliminating instability. A capability to understand and predict the effects of RF waves on plasma stability is of significant scientific and economic benefit.

2. Structure of the SWIM project

The SWIM Center consists of three elements:

(1) Development of a computational platform, referred to as the Integrated Plasma Simulator (IPS), that will allow efficient coupling of the full range of required fusion codes or modules.

(2) A physics campaign addressing long timescale discharge evolution in the presence of sporadic fast MHD events. This involves interfacing the IPS to both linear and 3D non-linear extended MHD codes and carrying out a program of research related to use of RF and other driving sources to study and control fast time-scale MHD phenomena such as optimizing burning plasma scenarios and improving the understanding of how RF can be employed to achieve long-time MHD stable discharges and control sawtooth events.

(3) A physics campaign for modeling the direct interaction of RF and extended MHD for slowly growing modes. This requires development of new approaches to closure for the fluid equations and the interfacing of RF modules directly with the extended MHD codes and with code modules that implement the fluid closures. The primary physics focus of this campaign is to improve the understanding of how RF can be employed to control neoclassical tearing modes.

3. Design and implementation of the Integrated Plasma Simulator

The computational core of the SWIM project is the Integrated Plasma Simulator (figure 1), a software framework designed and developed not only to support the coupled simulations required by the SWIM science plan but also to explore issues associated with integrated fusion simulation at an even larger scale for future efforts such as the proposed Fusion Simulation Project (FSP). The IPS environment brings together a variety of well-established physics codes and a Plasma State component to manage the exchange of key simulation data, under a SWIM-specific framework written in Python that provides a uniform execution environment, services for data and resource management, and integration with a web portal to facilitate tracking the progress of simulations. It also provides a convenient facility for testing mathematical issues related to multiphysics coupling and time-stepping algorithms.

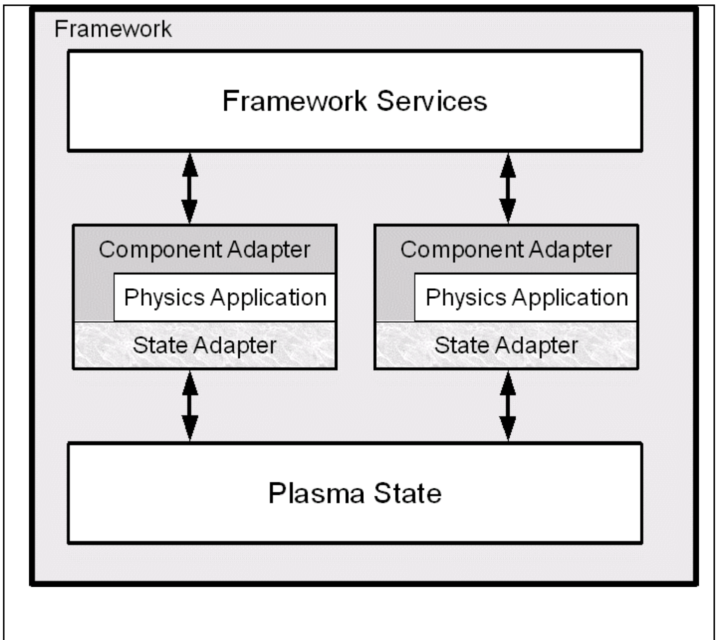

Figure 1. Schematic architecture of the Integrated Plasma Simulator environment (from W. Elwasif 2007).

The physics codes of interest have their own input and output files and formats, so we use small "helper" programs within the component wrapper script to serve as adapters between the Plasma State and the physics code's own input and output files.

The design anticipates the need to shift from file-based to in-memory data exchange eventually, as SWIM's science plan moves to simulations with tighter couplings and exchanging larger volumes of data. The IPS has been designed to accommodate multiple implementations of individual physics components, even within the same simulation run. The framework design imposes few restrictions on the types of simulations that can be carried out, allowing the IPS to be used for studies outside SWIM's physics principle targets of RF interactions with MHD.

An important feature of the IPS is the exchange of simulation data between components using an intermediate Plasma State service that has a simple user interface and a standardized data format. It also provides services to map between different grids when the grid required by the components differs from that on which it is stored in the state. It is implemented as a Fortran 90 module, thus permitting multiple time-step instances to be in memory at once. The Plasma State code is automatically generated from a plasma state specification file allowing for ease and accuracy of modification and extensibility. The SWIM Plasma State service has been adopted by other fusion computing projects as their communication mechanism.

3.1 IPS development and implementation

The framework and Plasma State service are fully implemented and tested on the Jaguar computer at ORNL and on the SGI cluster at PPPL, and several driver components have been developed. Physics components include Equilibrium and Profile Advance (EPA), RF solver, Fokker-Planck solver, MHD Stability, and Visualization. The main EPA component is based on the TSC code. Two RF Ion Cyclotron components based on the TORIC and AORSA codes give us flexibility for comparison and for a wide range of RF physics capabilities. A Fokker Planck solver components based on the CQL3D continuum code and a Monte Carlo RF Fokker Planck solver based on ORBIT–RF from are nearing completion. A Fokker Planck/neutral beam component based on NUBEAM is nearly complete, although NUBEAM can already be used in SWIM simulations through the direct coupling between TSC and TRANSP. The linear MHD component contains the capabilities of equilibrium refinement, flux surface mapping, ballooning stability evaluation using BALLOON, and low-n stability evaluation using DCON, PEST-1, or PEST-2. It will be extended in the near future to include the energetic particle code NOVA-K and ultimately to the nonlinear codes M3D and NIMROD. The Visualization component extracts data from the simulation data structure and presents it in a form for run-time monitoring using the ELVIS system.

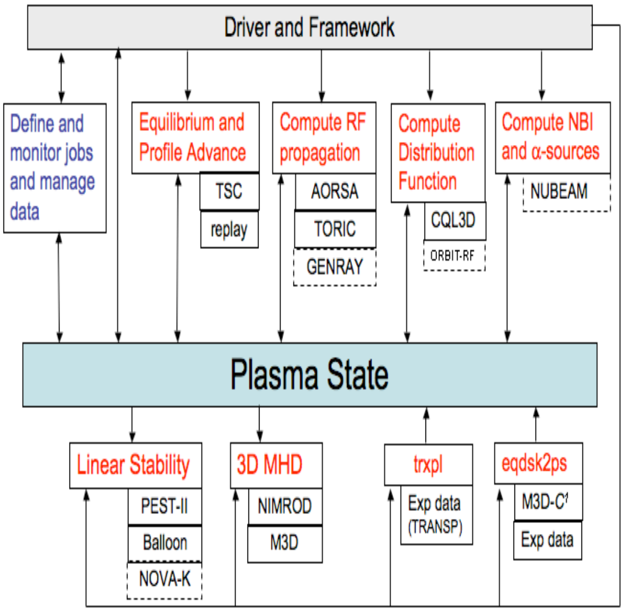

Figure 2. IPS physics components.

3.2 Fast MHD campaign and IPS applications

We have begun using the SWIM framework to simulate the time-dependent evolution of the fast ion distribution during hydrogen minority heating in the Alcator C-Mod device. These simulations will allow us to validate the predictive capability of the RF and MHD components, a prerequisite to investigating sawtooth modification in the presence of energetic particles. The TSC EPA component is being used to advance the plasma profiles and equilibrium for a specific C-Mod discharge, and both the AORSA and CQL3D codes are being used to self-consistently calculate the 3D (r, $v_\perp$, $v_{//}$) fast ion distribution during ICRF minority heating. The simulation is programmed to adjust the OH-coil and other PF coil currents (and thus the loop voltage) to give the experimental values of the plasma current and plasma major radius vs time as well as the line-averaged density and the Z_{eff}.

The simulation used the standard TSC thermal conductivity model, which normally provides a good model for L-mode transport at low power, and the Porcelli sawtooth model was used for sawtooth evolution. Model source terms were used for the electron and ion heating associated with the collisional slowing down of the minority ion tail. We are comparing with the experimental values of sawtooth amplitude and crash time, the loop voltage, the plasma shape, and the variation in the electron temperature during different phases in the heating and sawtooth cycles. As can be seen from figure 3, the overall comparison between the TSC simulation and the experiment is very good.

Using the RF component (AORSA-CQL3D), we have also performed a standalone simulation of the time evolution of the minority tail energy at a time corresponding to 0.91 sec. in the C-Mod discharge simulation of figure 3. Figure 4 compares the minority tail energy from this simulation with the measurement of charge exchange count rate due to energetic minority ions, as detected by a compact neutral particle analyzer (CNPA) diagnostic on C-Mod. The simulated turn-on time of the fast ion tail energy follows the rise time of the CNPA signal quite well for the vertical diagnostic channel viewing at R = 69 cm, corresponding to $\rho \approx 0.1$. The decay time of the energetic tail in the simulation is noticeably longer than the fall time of the CNPA signal, however. This difference may be attributed to the fact that no spatial losses were turned on in the Fokker Planck simulation. Also, the simulation assumed a constant electron and deuteron temperature in time, whereas in reality the background temperatures were evolving during the 60 msec. simulation time, due to the ICRF heating and sawtooth cycle. These latter effects will be captured properly when the model ICRF heating sources used in the TSC simulation are coupled with the AORSA-CQL3D results.

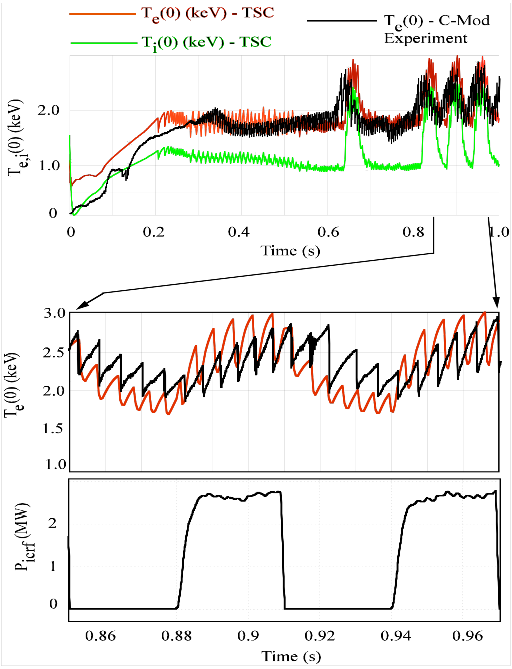

Figure 3. Comparison of experimental central electron temperature (black traces) with TSC simulation. Central electron (ion) temperatures from the simulation are shown in red (green). The bottom graph shows an expanded time period with associated ICRF power pulse.

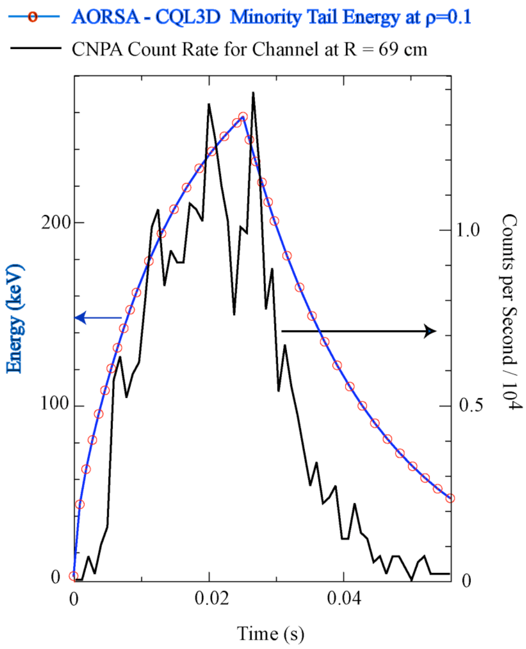

Figure 4. Comparison of minority hydrogen tail temperature (keV) versus time (s) from an AORSA-CQL3D simulation with CNPA diagnostic count rate versus time for a channel at R=69 cm. Plasma parameters correspond to the TSC simulation at 0.91 sec.

3.3 Slow MHD campaign

In the Slow MHD campaign a theoretical approach for including the effects of RF in the fluid closure has been developed, a computational approach to coupling MHD with RF has been developed, and initial numerical studies with reduced models have begun. Figure 5 illustrates the effect of the RF current source on the evolution of a resistive magnetic island. The equilibrium is unstable to a 2/1 tearing mode that is allowed to grow and saturate. An externally specified, axisymmetric RF current source added to the Ohm's law equation in the NIMROD 3D nonlinear MHD code. The current is then gradually in time increased from small amplitude. Comparing the subsequent evolution of the magnetic island with and without the RF current source, we find that the island shrinks in response to the current perturbation. The relative sizes of the magnetic islands in the presence and absence of RF are shown in figure 5. More detailed comparisons are ongoing.

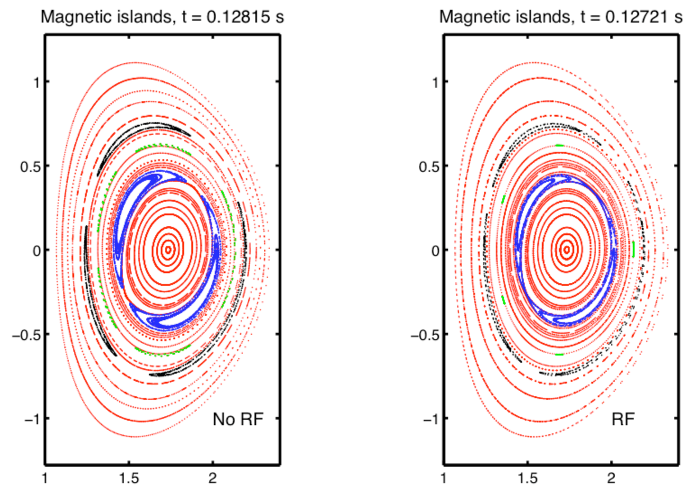

Figure 5. Size of the 2/1 magnetic island near the end of the simulations without (left) and with (right) RF current source.