Integrated Physics Advances in Simulation of Wave Interactions with Extended MHD Phenomena

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Abstract: The broad scientific objectives of the SWIM (Simulation of Wave Interaction with MHD) project are: (A) To improve our understanding of interactions that both 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 (B) To develop an integrated computational system for treating multi-physics phenomena with the required flexibility and extensibility to serve as a prototype for the Fusion Simulation Project (FSP).

1. Introduction

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 using extended magnetohydrodynamics (MHD). 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. Figure 1 shows measurements on the JET tokamak [1] of two different applications of RF power in the ion cyclotron frequency range and which affect an important type of plasma macro-instability called a sawtooth oscillation.

![Figure 1](image)

**Figure 1.** The central electron temperature in a JET discharge (top trace) shows the development of large amplitude, long period sawtooth oscillations produced by ion cyclotron waves having +90° antenna phasing (bottom trace). An additional wave source with -90° antenna phasing applied later modifies the plasma profiles to produce reduce the amplitude and period of the sawtooth oscillations.

The sawtooth cycle consists of two distinct phases: (1) The slow sawtooth ramp phase; a quiescent period during which the plasma density and temperature increase approximately linearly with time in the plasma core due to plasma heating and the plasma remains largely...
axisymmetric and, (2) a rapid crash phase in which a 3D disturbance develops, causing the
density and temperature within the $q = 1$ surface to flatten, resulting in a return of the plasma to
an axisymmetric state. This sequence is usually repetitive with the ramp phase typically being
much longer than the crash time. The crash results in an outward transport of energy and
energetic particles that can affect the fusion burn in an ignited device such as ITER.

Clearly the capability to understand and predict the effects of RF waves on plasma stability will
be of significant scientific and economic benefit in the development of fusion energy. The center
for Simulation of Wave Interactions with Magnetohydrodynamics (SWIM) is creating a new
capability for modeling the interactions between high-power electromagnetic waves and MHD
stability, by building an end-to-end computational system that integrates emerging mathematical
methods, software component and data management systems, and several of the world's most
accurate and capable fusion energy codes.

2. Structure of the SWIM project

The broad scientific objectives of the SWIM project are: to improve our understanding of
interactions that both RF wave and particle sources have on extended-MHD phenomena thereby
improving our capability for predicting and optimizing the performance of burning plasmas in
devices such as ITER; and to develop an integrated computational system for treating multi-
physics phenomena with the required flexibility and extensibility to serve as a prototype for the
FSP. 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.

2. Design and Implementation of the Integrated Plasma Simulator

The IPS is based on a component/framework approach but does not employ a formal component-
based architecture such as CCA for the first implementation. The components are being
implemented using existing, well-tested codes that are wrapped with adapter code to provide the
component generic interfaces. The use of separate executables is intended for the fast MHD
campaign, where the coupling between components is fairly light-weight in size of data and most
of the high performance computing required is within each component. To ensure that the IPS
has the flexibility for extension multiple codes are being employed for each required
functionality. For the campaign dealing with slowly growing modes, the physics models must be
more tightly coupled and it is likely that subroutine access to the codes will be required.
The various required physics functionalities have been abstracted at a high level and formal interfaces defined such that the components can be implemented by any code that provides the required functionality, so that multiple code implementations can be used. 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 layered over the existing software, 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 for distributed computing such as for the TRANSP and TSC, and is in routine use in TSC/TRANSP free boundary hybrid simulations.

The typical physics component consists of a wrapper script in PYTHON that provides the generic interface to the SWIM framework and that launches a series of fortran executables that 1) extract the required input data from the Plasma State and prepare it in the form required by the specific physics code, 2) launches a massively parallel run of the code itself, and 3) processes the code output into the form required by the Plasma State and loads the resulting back into the plasma state. The component script also provides the interface to the framework that actually handles the file movement and parallel job launch.

The framework is written in Python for flexibility and portability. Its main functions are to assemble and instantiate the components required for the specific simulation and to provide a set of services to the components. The services include mechanisms for managing data, job launch, resources and events. The data manager does all of the data staging and archiving of the plasma state and other input and output files for the components. The job launch manager launches the component codes on a set of computer resources and monitors their status. The resource manager keeps track of what resources are available and determines what resources are given to a particular job. The event handler receives and publishes events from the codes, and eventually a fault tolerant back plane will allow modification of the workflow accordingly.

There is a distinguished Driver component that uses framework services, to set up the working directory structure, initialize the other components, start the physics time stepping loop, archive the plasma state and code output files at the end of each successful time step, and calls the component finalize functions at the end of the simulation. The time stepping loop of the driver is intended as a ‘physicist accessible’ layer that will allow great flexibility in how the user constructs the workflow of the simulation. Presently it consists of a simple explicit series of time-steps advancing the components sequentially, but a more elaborate time stepping scheme has been designed.
3. Technical progress

The framework and Plasma State service are fully implemented and tested, and several Driver components have been developed. Available 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. It also is planned to develop a Fokker Planck/neutral beam component based on NUBEAM although NUBEAM can already be used in SWIM simulations through the direct coupling between TSC and TRANSP. The linear MHD component will contain 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 will extract data from the simulation data structure and present it in a form for runtime monitoring using the ELVIS system.

Figure 3 shows a preliminary simulation of an ITER discharge using the IPS. In this case a single physics component was employed, and Equilibrium and Profile Advance (EPA) based on the TSC code. However TSC makes a connection by means of the Plasma State to the TRANSP code which incorporates RF and neutral beam energy source modules. Figure 1a shows the time evolution of the central electron and ion temperatures as the various heating sources are brought into operation an the heating from fusion alpha particles ramp up, Figure 1b.
There have also been two significant code-porting efforts. For development and testing purposes all relevant codes were ported to the PPPL Altix 350 cluster. Also to prepare for production runs requiring leadership scale computing porting and optimization studies of other major community MPP codes were carried out on Jaguar. M3D has been ported to both the Phoenix and Jaguar machines at NCCS and scaling studies up to 5,120 nodes on Jaguar were performed with up to 80% efficiency using the Hypre algebraic multigrid solver within PETSc. NIMROD has also been ported to Jaguar and production runs are beginning. The CQL3D and ORBIT–RF Fokker Planck solvers were also ported to Jaguar.

The primary effort in physics analysis has been to address how RF waves modify the MHD equations and how to include RF effects in the fluid closure as required by the Slow MHD campaign. A multi-level approach for has been developed for simulating the interaction of an RF source with magnetic islands in toroidal plasmas. This involves three levels of sophistication that can be pursued somewhat in parallel. The first approach is a computational effort to model the interaction RF with magnetic island evolution by inserting an analytically chosen form for a source term in the Ohm’s law. In the second approach, a phenomenological evolution equation will be used to describe the temporal and spatial structure of the source term. In the third approach, a more rigorous analytic problem will be solved where the inclusion of RF effects are treated as closure problems. The modified equations can then be implemented in numerical simulations. In the second and third approaches direct interfaces with the RF codes are required.

**Future plans**

The immediate objective of the project is to provide a stable, easily useable public release of the IPS and to transition the IPS to the Jaguar computer system. Within the next year we plan to perform an initial sawtooth simulation with the IPS, demonstrating the computational flow from a 2D (axisymmetric) state calculated by the IPS to 3D nonlinear MHD code, M3D and/or NIMROD, complete a sawtooth event and return the re-symmetrized state back to the IPS. We also expect to obtain preliminary results on the slow MHD campaign, in particular to study the effects or RF on classical tearing modes with NIMROD coupled to an RF code for electron cyclotron current drive.

**References**

[1] L.-G Ericksson et al, Phys Rev. Lett., 92, 235004-1, 2004