Final technical report for DE-SC00012633
AToM (Advanced Tokamak Modeling)

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Abstract
This final report for the AToM project documents contributions from University of California, San Diego researchers over the period of 9/1/2014 – 8/31/2017. The primary focus of these efforts was on performing validation studies of core tokamak transport models using the OMFIT framework, including development of OMFIT workflow scripts. Additional work was performed to develop tools for use of the nonlinear magnetohydrodynamics code NIMROD in OMFIT, and its use in the study of runaway electron dynamics in tokamak disruptions.

I. Overview

This report summarizes research led by UCSD researchers C. Holland (PI), D. Orlov, and V. Izzo for the AToM (Advanced Tokamak Modeling) project between 9/1/204 to 8/31/2017, under support from US DOE grant number DE-SC0012633. Broadly speaking, this group was responsible for leading validation efforts in AToM, and carrying out tokamak disruption and runaway electron dynamics studies using the NIMROD code. The UCSD team lead three initiatives in AToM reflecting these responsibilities:

1. Turbulent transport modeling and validation studies of DIII-D ELMy H-mode and Alcator C-Mod I-mode plasmas,
2. Modeling responses of core DIII-D H-mode transport to changes in pedestal parameters driven by resonant magnetic perturbation (RMP) fields used to suppress ELMs,
3. Development of an OMFIT NIMROD module used to support disruption mitigation and rapid shutdown studies.

A summary of each effort is provided below. In addition to this work, UCSD researchers spent significant time supporting AToM research lead by other team members, particularly in the development of integrated core-edge transport modeling workflows, and the development and optimization of the new nonlinear gyrokinetic code CGYRO for simulations of multiscale turbulence on leadership-class high performance computing facilities.

II. Turbulent transport modeling and validation DIII-D ELMy H-mode plasmas

The largest validation activity supported by this award was extensive modeling of DIII-D ELMy H-mode plasmas using both the quasilinear gyrofluid TGLF model [Staebler:05] and nonlinear gyrokinetic simulations using the GYRO [Candy:2003] and CGYRO [Candy:2016] codes. The goal of this work is to assess the ability of these models to capture responses of core H-mode transport to variations in applied heating and torque, effectively as a measure of global transport "stiffness" [Luce:2018]. A key part of this work was the use of OMFIT's data management, organization, and analysis automation capabilities to survey model performance at multiple radii in several hundred different timeslices from different discharges, far exceeding previous validation efforts. The development of workflows to support this analysis played a significant role in informing the design and development of future uncertainty quantification tools being pursued in the 2017 AToM SciDAC effort.

The key findings of this study were that:

1. Conventional offset and RMS error metrics for self-consistent profiles predictions made with TGLF and the TGYRO transport solver were typically 20% or smaller, with largest errors arising for plasmas with significant torque injection.
2. These differences are driven by systematic discrepancies in predictions of local gradients, specifically that
    a. The normalized ion inverse temperature gradient scale length $R/L_{Ti} = -R\, d\ln(T_i)/dr$ is systematically overpredicted at larger radii ($\rho_{tor} \geq 0.7$) by up to 50%.

b. The normalized electron temperature and especially density gradient scale lengths R/L_{Te} and R/L_{ne} are systematically overpredicted at smaller radii ($\rho_{tor} \leq 0.4$).
c. At intermediate radii, the gradients are modestly underpredicted, typically 20% or less than the measured values.

3. Particularly at smaller radii, electromagnetic fluctuations and fast ion dynamics play important stabilizing roles in the transport predictions.
4. Ensemble analysis of TGLF predictions indicates sensitivity analysis performed by using variations about mean equilibrium profiles and gradients yields the same trends as the mean of an ensemble of variations about individual timeslices.
5. Gyrokinetic simulations performed with CGYRO predict local flux-matching gradients with fidelity as good as, and often better than, the TGLF results, which opens to window to improvements of the TGLF physics model that could improve its experimental fidelity. Notably, the CGYRO results also disagree with corresponding GYRO predictions in some cases. Understanding this difference will be a focus of future work.
6. Gyrokinetic simulations of the near-marginal turbulence at smaller radii exhibited significant long-term dynamics that make determination of result convergence extremely challenging and computationally expensive.

Results from this work were presented at a number of workshops, including the 2015 EU-US TTF meeting [Holland:2015], 2017 APS-DPP meeting [Holland:2017], ITPA transport & confinement working group meetings in 2015-2017, invited talks at the 2016 EPS and 2017 APS-DPP meetings given by Tim Luce (primarily experimental collaboration), and a 2018 Nuclear Fusion paper [Luce:2018] focusing primarily on the experimental data. A follow-up paper discussing the modeling results in detail is being prepared for submission in 2018.

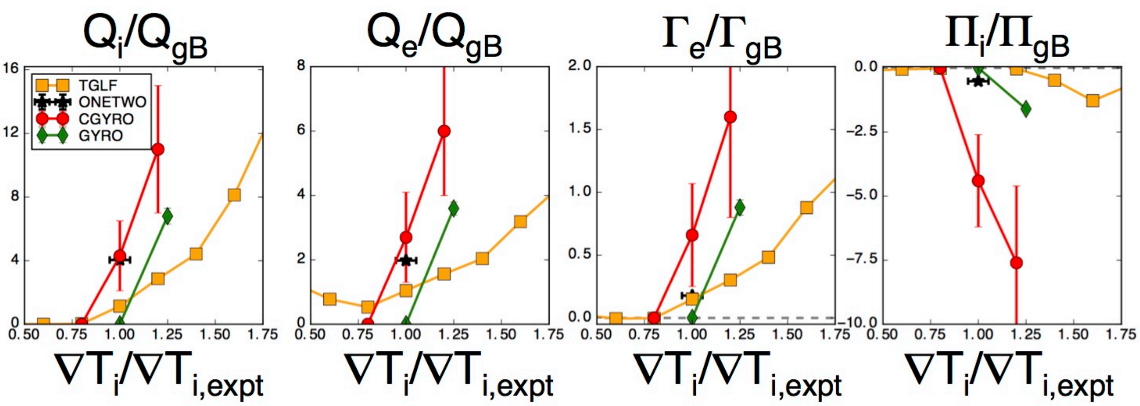

Fig. 1. Comparisons of TGLF, GYRO, and CGYRO predicted energy, particle, and momentum fluxes to power balance analysis at $\rho_{tor} = 0.7$ in a DIII-D H-mode with 7 MW neutral beam heating and 1.4 N-m of injected torque.

III. Turbulent transport modeling of Alcator C-Mod I-mode plasmas

As a complement to the DIII-D H-mode studies, similar integrated density and profile predictions of three different Alcator C-Mod I-mode plasmas were performed using

TGLF and TGYRO. The predictions exhibited a similar skill as for the DIII-D cases, with error and offset metrics typically 20% or smaller, despite the significant differences in normalized parameter space considered. The results were presented at the 2015 EU-US TTF meeting [Holland:2015].

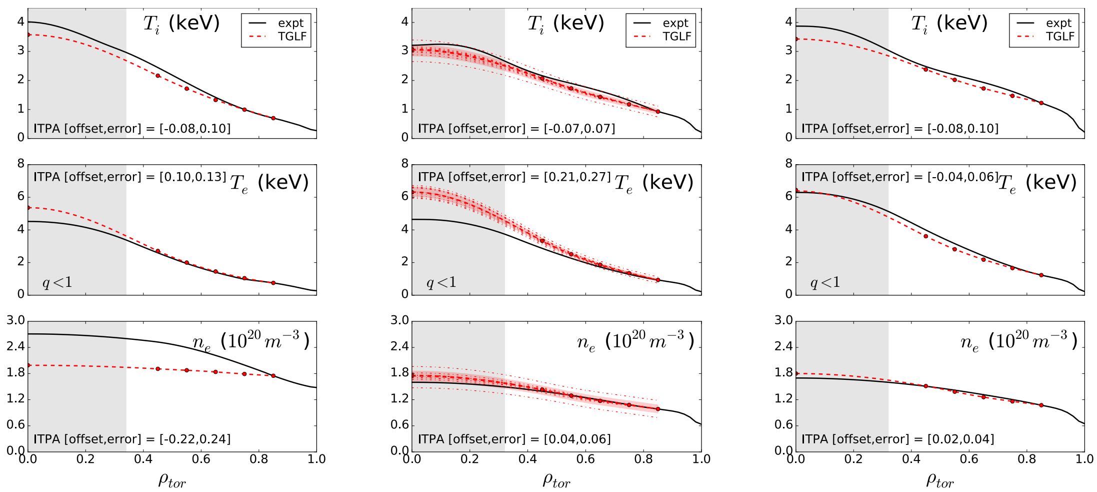

Fig. 2. Predictions of density and temperature profiles in three different Alcator C-Mod I-mode plasmas. Conventional offset and error metrics are 20% or smaller for most cases.

IV. Modeling core transport responses to RMP-driven pedestal changes

In addition to analysis of DIII-D ELMy H-mode discharges described above (Sec. II), UCSD researchers began validation studies of core transport in H-mode plasmas where the ELMs are suppressed via the use of resonant magnetic perturbations (RMPs). These studies were driven by observations of strong core profile responses to changes in plasma pedestal characteristics driven by the RMP, as well as in turbulent fluctuations responses at the pedestal top measured via beam emission spectroscopy. Predictive transport modeling of these discharges using TGLF and TGYRO exhibited systematic errors in both profiles larger than for the ELMy H-mode and I-mode cases, with the electron temperature always overpredicted and the ion temperature profile as well. The largest source of the disagreement appears to be due to TGLF's prediction of the strength of equilibrium shear suppression (Fig. 3), particularly at larger radii where local gradients and inverse scale lengths are often quite small. These initial results were presented at the 2015 TTF meeting [Orlov:2015]. Ongoing work is focused on linear and nonlinear gyrokinetic analyses of these plasmas using the CGYRO code, to contrast against the TGLF predictions. We also intend to leverage capabilities to represent static magnetic islands in CGYRO being developed by a separate award to the lead PI to investigate transport in these plasmas.

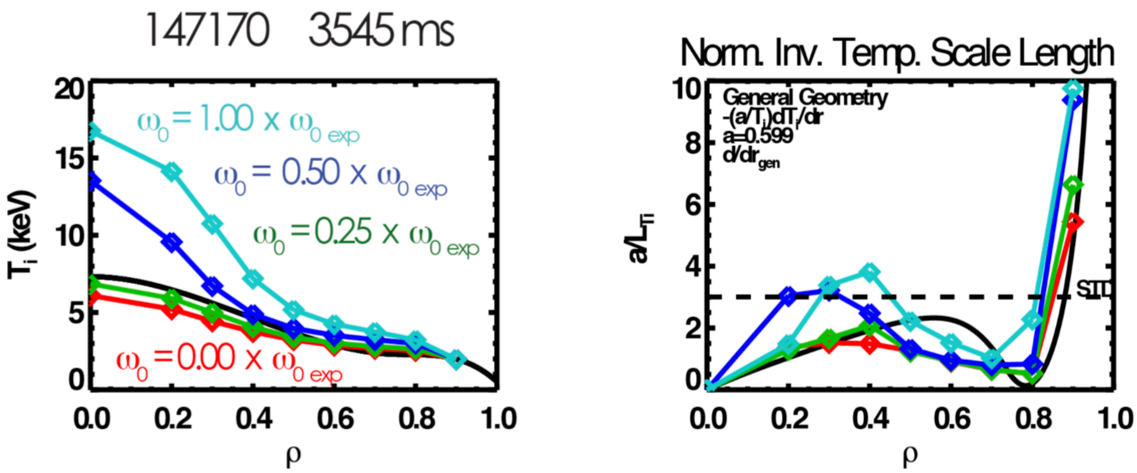

Fig. 3. Dependence of ion temperature profile predictions in a RMP ELM-suppressed discharge to variations in equilibrium rotation shear.

V. Development of OMFIT NIMROD module for disruption studies

The final research task led by UCSD was investigations of runaway electron seed generation and loss during disruption mitigation events. As a first step, a NIMROD module was developed for OMFIT, including a GUI-based front end to facilitate NIMROD setup, execution, and analysis (Fig. 4). As part of this module, the first OMFIT workflows for managing remote job execution on high-performance computing platforms such as the NERSC Hopper and Edison systems were developed, including remote data management, archiving, and retrieval tools. These tools, developed early in the AToM projected, provided the basis for a number of other remote computing workflows implemented by other OMFIT and AToM efforts.

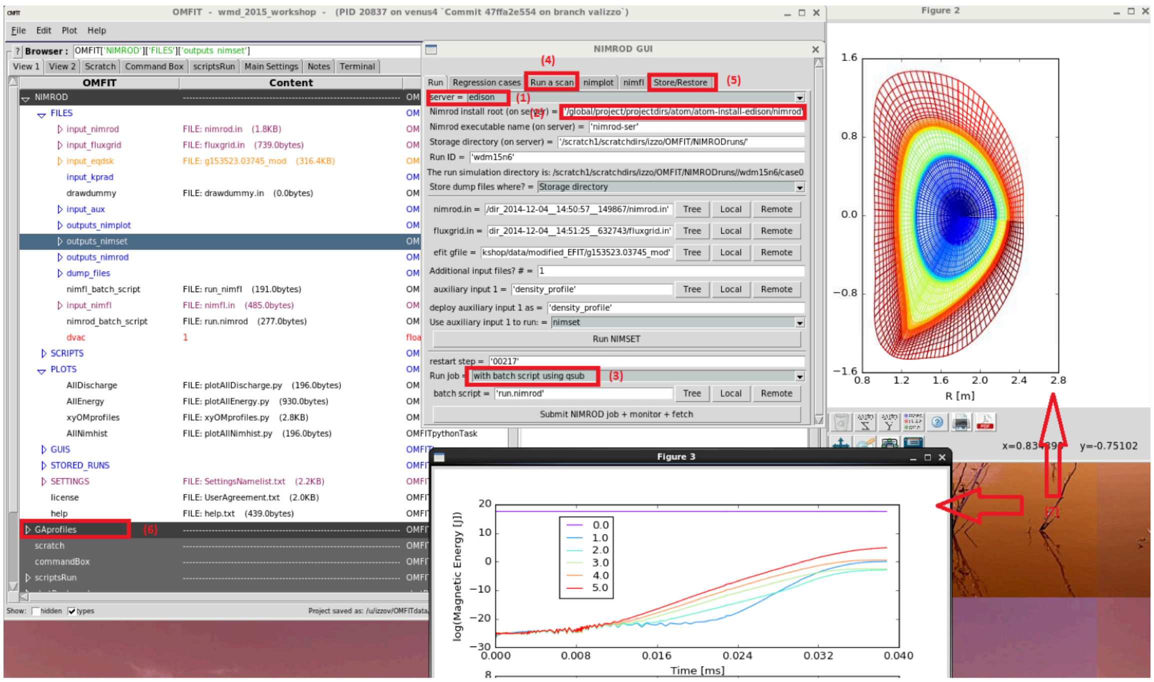

Fig. 4. OMFIT NIMROD graphical user interface.

In addition to these general NIMROD capabilities, an OMFIT workflow was developed to isolate runaway electron orbit following capability originally implemented in NIMROD, which could then be run directly in OMFIT rather than requiring a separate code. With this workflow, the user needs only to specify These tools were used to support analysis published in [Izzo:2017] and [Izzo:2018].

VI. References

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