Recent Progress in Integrated Simulation and Modeling of Tokamak Experiments and New Devices and Future Collaboration Opportunities

by
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Yao Huang et al. Nucl. Fusion 60 (2020) 076023 https://doi.org/10.1088/1741-4326/ab91f8
Background

- MHD and Integrated simulation and modeling are critical elements of tokamak research
  - Interpretation and planning of experiments
  - Theory/experiment validation
  - Next-step device design

This presentation:

- Recent progress in MHD and integrating simulation of tokamak experiments and future devices
- Future collaboration opportunities
  - Tokamak experimental analysis and modeling
  - 3D MHD research
  - Burning plasma and fusion reactor scenario developments
GA-PRC Integrated Modeling Collaborations Focus on Key Magnetic Fusion Topics and Contribute to US, PRC, and worldwide Tokamak Research

- Recent MHD Equilibrium collaborations focus on development of GPU-accelerated EFIT reconstruction algorithms for plasma-control applications
  - Parallel GPU based P-EFIT accurately reproduce EFIT results at a fraction of the EFIT computational cost
- MHD collaborations include extensive applications of MARS-F/K/Q codes to validate MHD physics
  - ITER ELM and RWM control and optimization, HL-2M RWM stabilization and control, DIII-D ELM ideal versus resistive response
- Productive applications of OMFIT framework to support many front-end US-PRC collaboration projects and research
  - Successful validation of EPED/REPED pedestal height and width model against DIII-D He plasmas
  - CFETR scenario developments with self-consistent core-pedestal and central pellet fueling

Kai Li et al. submitted to Nucl. Fusion (2021)
DIII-D Science Meeting J 2020
Recent MHD Equilibrium collaborations focus on development of GPU-accelerated EFIT reconstruction algorithms for plasma-control applications

- Recent MHD Equilibrium collaborations focus on development of GPU-accelerated EFIT reconstruction algorithms for plasma-control applications
  - Parallel GPU based P-EFIT accurately reproduce EFIT results at a fraction of the EFIT computational cost
- Support EAST magnetic plasma control with enhanced capability
  - Smoothed phase-transition algorithm to allow more stable phase transition
  - Locating 2nd x-point for quasi-snow-fake applications
- Successful evaluation and demonstration of accuracy and time latency of ITER equilibrium database
  - Performed benchmarks with CREATE results
  - Met ITER latency time requirements (~ 1ms)

Y. Huang et al. Nucl. Fusion 60 (2020) 076023 https://doi.org/10.1088/1741-4326/ab9118
Extensive MHD collaborative work has been carried out covering a broad range of topics

- Performed toroidal modeling study of passive and active stabilization of RWM in HL-2M [NF 59(2019)016017] SWIP
- Compared ideal versus resistive plasma response in DIII-D ELM control experiments and role of $q_{95}$ and X-point [NF 59(2019)086012], Chongqing Tech. & Business U.
- Investigated nonlinear interaction between plasma flow and edge localized internal mode [NF 59(2019)066011] SWIP
- Studied active control of RWM in ITER with control power saturation and sensor signal noise [NF 59(2019)096021], SWIP
- Performed ELM control coil optimization for various ITER scenarios [NF 59(2019)096038; NF 60(2020)016013; PoP 27(2020)042510] Donghua U.
- Investigated role of plasma parallel equilibrium flow on stability of RWM [NF 59(2019)126035] SWIP
- Investigated synergistic effects of turbulence induced plasma viscosity and plasma flow on RWM stability [PPCF 62(2020)075007] SWIP
- Carried out both numerical [PoP 27(2020)072502] and analytical [PoP 27(2020)124502] study of effects of plasma anisotropic thermal transport and Eps on RWM SWIP
- Investigated drift kinetic effects and ECCD induced local modification of magnetic shear on sawtooth activity in EU DEMO [NF 60(2020)126011] Dalian Maritime U.
- Modeled plasma core flow damping due to RMP in AUG hybrid discharge [NF 60(2020)096006] SWIP

MARS-F predicted synergistic stabilization of n=1 RWM in HL-2M, with both magnetic feedback and drift kinetic stabilization.

Guoliang Xia et al. Nucl. Fusion 59 (2019) 016017
https://doi.org/10.1088/1741-4326/aaf02c

Y.Q. Liu 2021
MARS-F Simulations Consistent with DIII-D Post-Disruption RE Experiments

- New MAR RE orbit tracing module REORBIT
- Full loss of RE beam when the resistive kink mode amplitude reaches ~ 1kG

\[ \delta B = 0 \quad \delta B = 200G \quad \delta B = 1kG \]

Y.Q. Liu Nuclear Fusion 2019

Paz-Soldan PPCF 61 (2019)
NIMROD and M3D-C1 Actively Used for DIII-D Mitigation Modeling

- NIMROD dual-injector SPI simulations demonstrate benefit of simultaneous injection
- Simulations show symmetric thermal quench and reduced mode activity
- Timing accuracy critical

NIMROD simulated SPI radiation Power consistent with DIII-D experiments, DIII-D single upper injector, V=200m/s

NIMROD DIII-D Dual-Injector Simulation

Kim, Lyons IAEA FEC 2021
**EPED/REPED** pedestal height and width model was successfully validated against DIII-D He plasmas

- **EPED/REPED model** is based on the peeling-ballooning mode and kinetic ballooning mode theory
- **DIII-D He discharge** has a lower pedestal height than the D discharge but similar width

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**EPED/REPED predicted DIII-D He pedestal heights agree well with experiments**

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<th>Shot</th>
<th>Time</th>
<th>$I_p$(MA)</th>
<th>$\langle n_e \rangle$</th>
<th>$W_{mhd}$(MJ)</th>
<th>$\beta_N$</th>
<th>$\beta_p$</th>
<th>$P_{NBI}$(MW)</th>
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<td>1.5</td>
<td>0.53</td>
<td>7.5</td>
<td>1.89</td>
</tr>
</tbody>
</table>

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**DIII-D He Pedestals**

Kai Li et al. submitted to Nucl. Fusion (2021) DIII-D Science Meeting J 2020

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MFCW 2021 MHD and Integrated Modeling Progress
A 0.5D Reduced Pellet Ablation $\nabla B$ Drift model Has Been Developed and Tested against DIII-D Pellet Fueling Experiments

- Approximate the pellet pressure distribution along the magnetic field using an average pressure with a relaxation time ~ initial ion sound time
- Drift equation solved numerically along the drift path to obtain the drift distance
- Deposition channel is taken to be a 2D Gaussian
- Model applied to simulate CFETR central pellet fueling

experiment

Simulation results


DIII-D Pellet Injectors
OMFIT STEP Module Couples Stability, Transport, Equilibrium, and Pedestal Codes to Predict Tokamak Scenarios

• Many OMFIT classes can translate between common data formats and OMAS
• Inter-changeable permitting a variety of open-loop, closed-loop, and optimization workflows

OMFIT pellet fueling workflow Integrates the PAM Pellet Ablation Module into OMFIT through the CHEF Current Heating and Fueling module for pellet fueling study

Lyons, McClanaghan, Meneghini, Saarelma, Slendebrook, Smith, Thome and the STEP Team DIII-D FSM Jan, 2021

O. Meneghini et al. Nucl. Fusion (2020)
OMFIT STEP Module Successfully tested against $H_{98-Y2}$ Database and DIII-D transport and NCS stability experiments

- Many OMFIT classes can translate between common data formats and OMAS
- Inter-changeable permitting a variety of open-loop, closed-loop, and optimization workflows

H$_{98-Y2}$ Database

DIII-D Negative Triangularity Experiments

Reasonably Predicted DIII-D Plasma Profiles with Pellet Fueling

Lyons, McClenaghan, meneghini, Saarelma, Slendebroek, Smith, Thome and the STEP Team DIII-D FSM Jan, 2021
OMFIT STEP Workflows Have Been Productively Applied to Support Many Front-end Collaboration Projects and research

- Transport analysis, interpretation, and planning of tokamak experiments
- Burning plasma and fusion reactor scenario development

EAST NBI H-Mode

HL-2M RF H-Mode

Scenario

Joseph McClanaghan et al. IAEA FEC 2021

CFETR Shattered Pellet Fueling
MHD and Integrated Simulation and Modeling Collaborations Are Productive with Many Joint Publications in Major US and international Scientific Journals

• Selected recent MHD publications

Y. Huang et al., “GPU optimized fast plasma equilibrium reconstruction in fine grids for real-time control and data analysis,” Nucl. Fusion 60 (2020) 076023. https://doi.org/10.1088/1741-4326/ab91f8


• Selected recent Integrated Simulation and Modeling publications

Many collaboration opportunities exist and Collaborations Are Welcome

- GPU accelerated and 3D equilibrium reconstructions
  - EFIT-AI multi-machine databases
  - Real-time plasma control applications
- 3D MHD simulations
  - Macroscopic MHD instabilities and operational limits
  - SPI and DSPI disruption-mitigation scenario developments
  - RE dissipation and mitigation
- OMFIT self-consistent core-pedestal workflows with impurity transport and pellet fueling
  - Central-pellet fueling
  - Open-, close-loop, and predict-first applications
  - Tokamak experiment and reactor scenario developments