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

by

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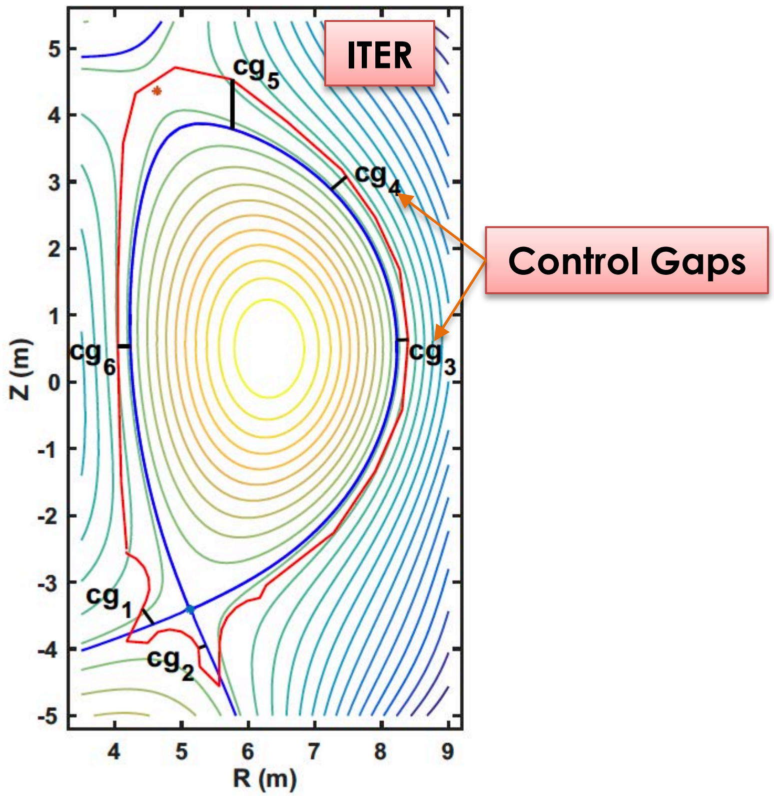
High Spatial-Resolution ITER Shape Control with GPU-Based *P-EFIT*



Control Gaps

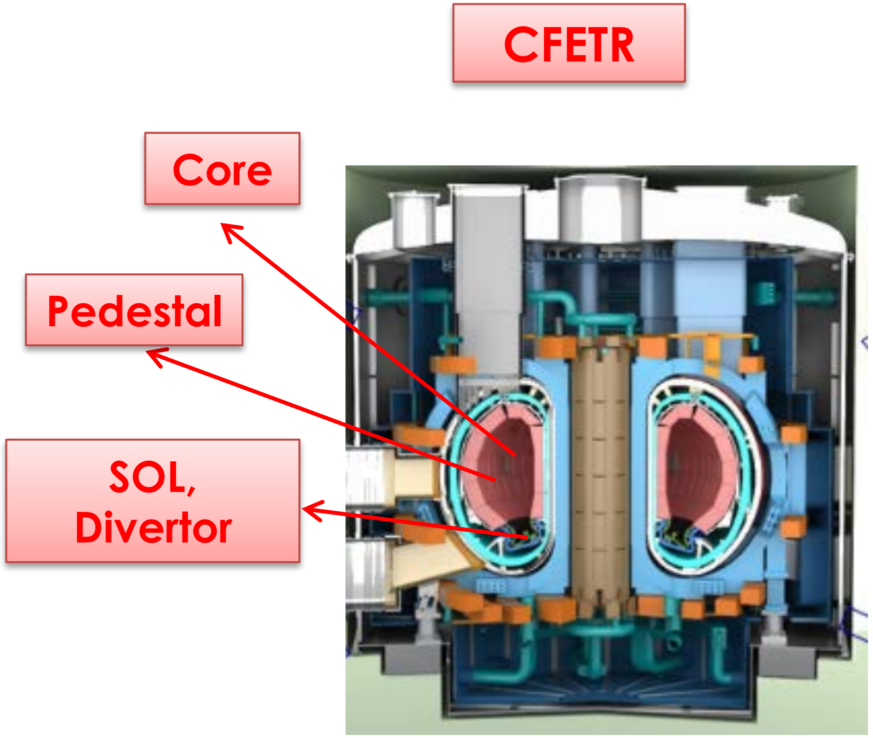
Yao Huang et al. Nucl. Fusion 60 (2020) 076023 https://doi.org/10.1088/1741-4326/ab91f8

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:

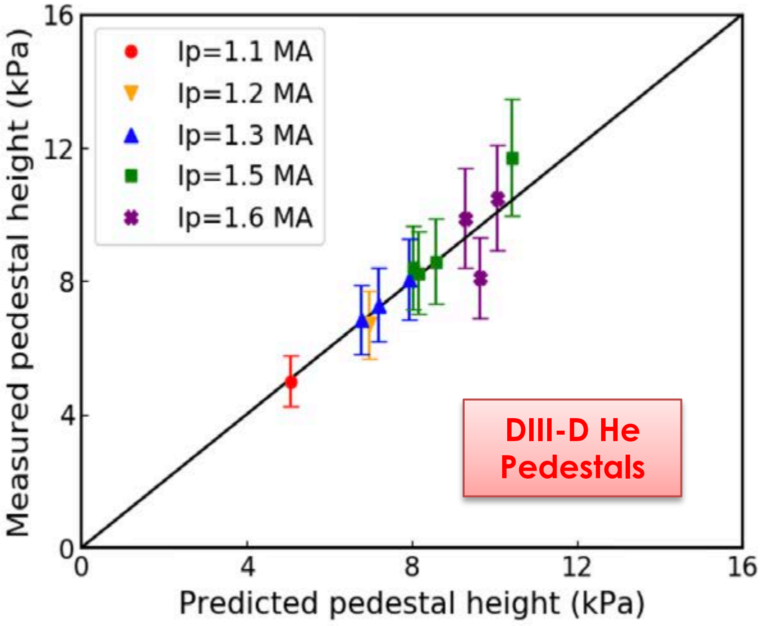
- Recent progress in MHD and integrating simulation of tokamak experiments and future devices
- Future collaboration opportunities
  - Tokamak experimental analysis and modeling
  - 3D MHD research
  - Burning plasma and fusion reactor scenario developments



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**

EPED/REPED predicted DIII-D He pedestal heights agree well with experimental values



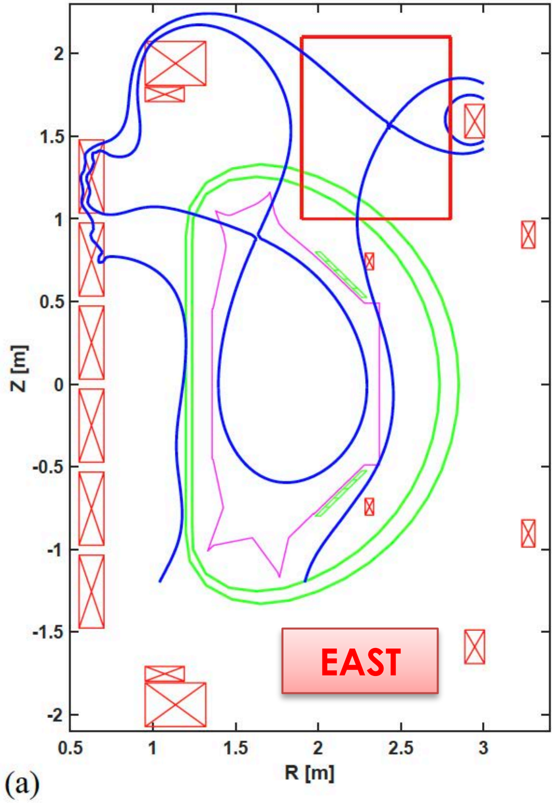
DIII-D He Pedestals

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)

EAST Quasi-Snow-Fake Reconstruction and Control

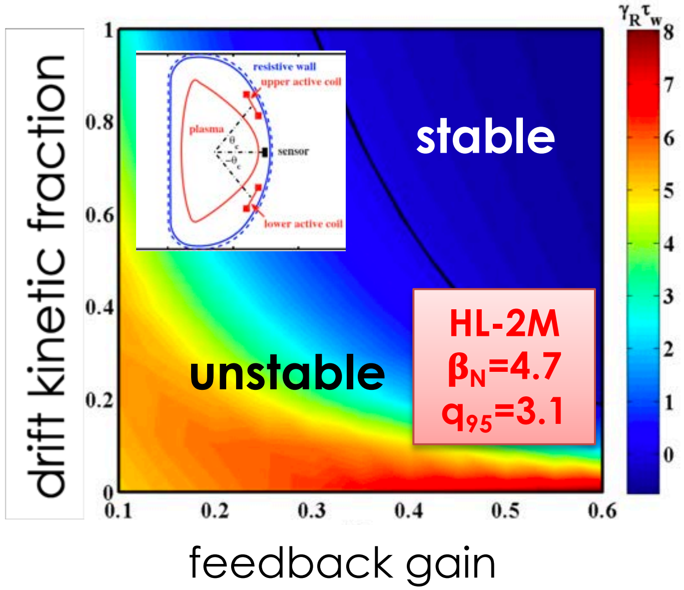


Y. Huang et al. Nucl. Fusion 60 (2020) 076023 https://doi.org/10.1088/1741-4326/ab91f8

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 infernal 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
- Studied influence of plasma flow shear and drift kinetic effects from thermal particles on internal kink stability [PoP 26(2019)102102] Dalian U. Tech.
- 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.

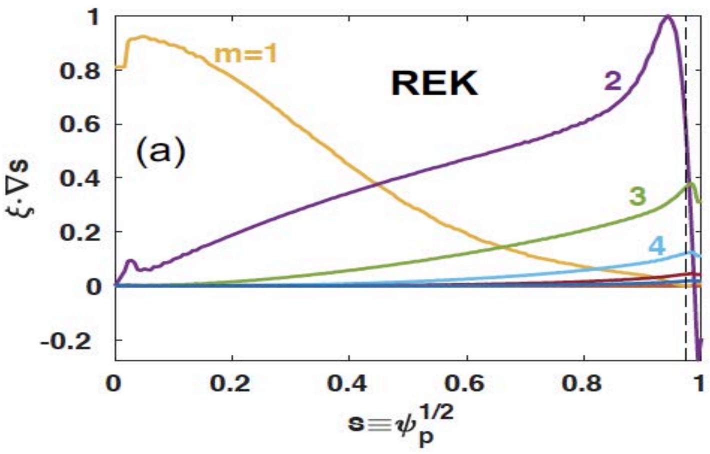


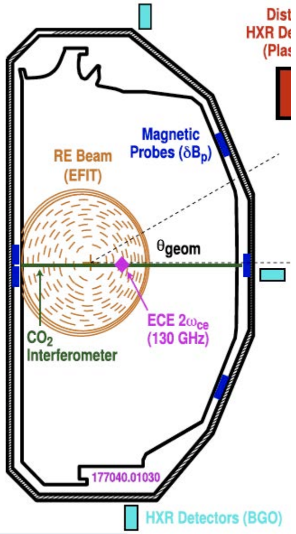
Guoliang Xia et al. Nucl. Fusion 59 (2019) 016017 https://doi.org/10.1088/1741-4326/aaf02c

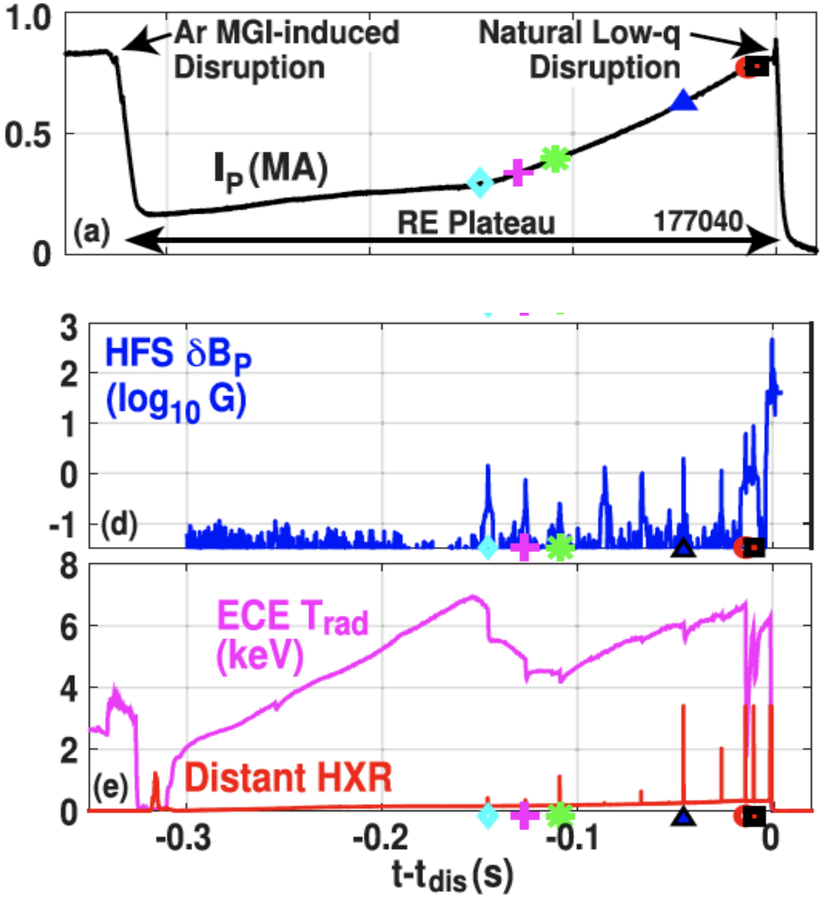
Y.Q. Liu 2021

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**



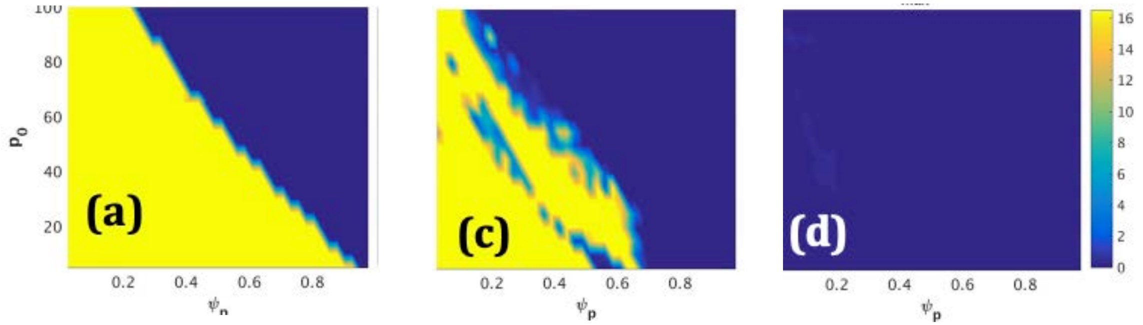




δB= 0

δB= 200G

δB= 1kG

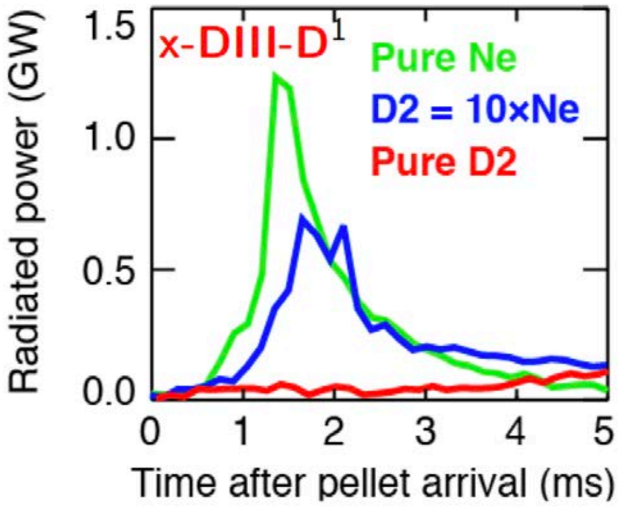


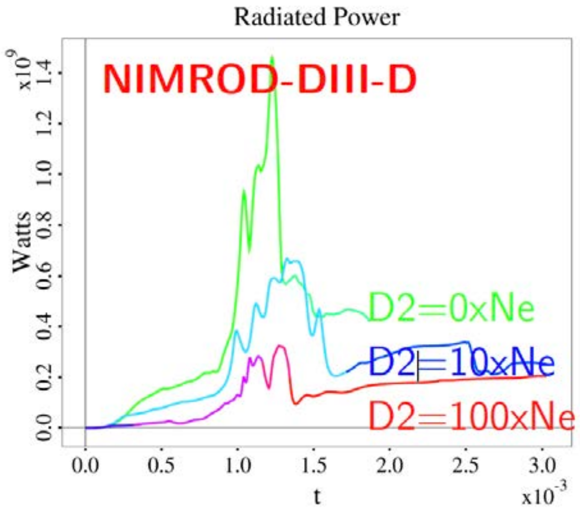
Y.Q. Liu Nuclear Fusion 2019

Paz-Soldan PPCF **61** (2019)

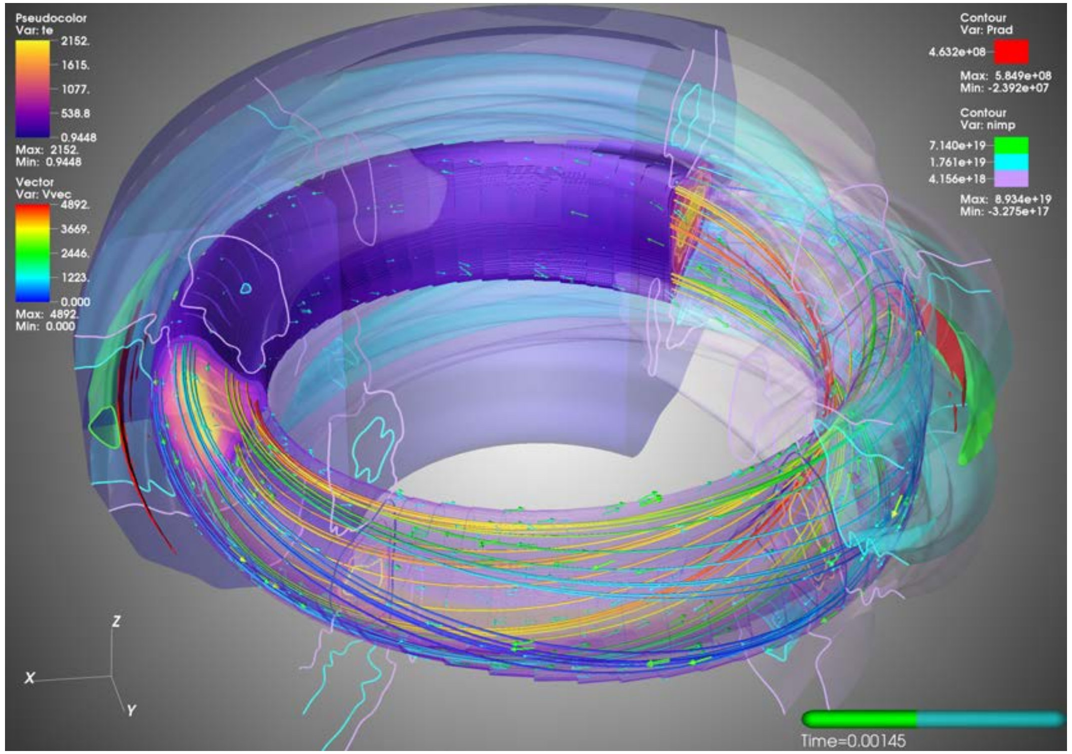
NIMROD and *M3D-C1* Actively Used for DIII-D Mitigation Modeling

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





NIMROD DIII-D Dual-Injector Simulation



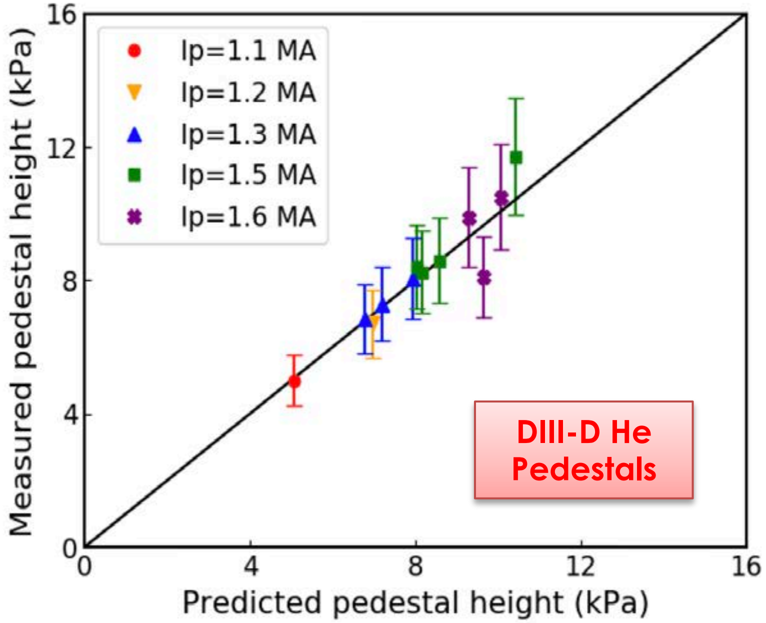
- ***NIMROD*** **dual-injector SPI simulations demonstrate benefit of simultaneous injection**
- **Simulations show symmetric thermal quench and reduced mode activity**
- **Timing accuracy critical**

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**

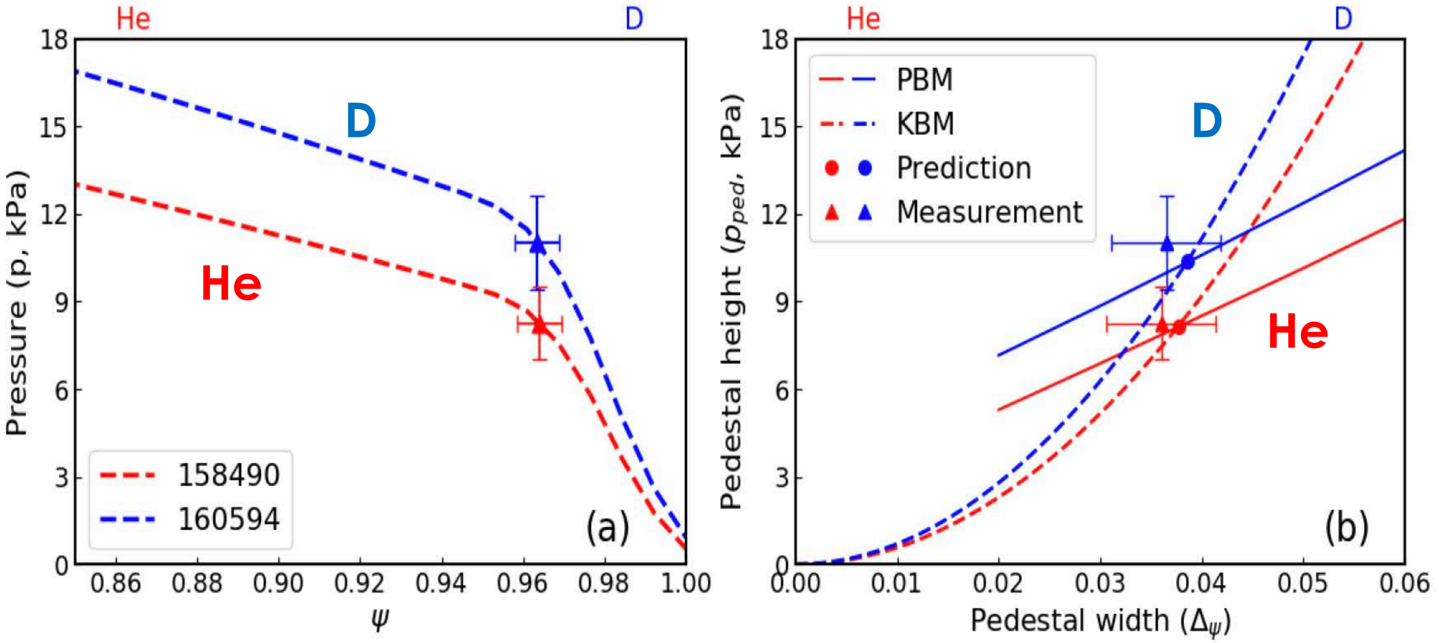
EPED/REPED predicted DIII-D He pedestal heights agree well with experiments



DIII-D He Pedestals

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

Shot	Time	I_p(MA)	$\langle n_e \rangle$	W_{mhd}(MJ)	β_N	β_p	P_{NBI}(MW)	B_T
158490	1540	1.54	5.13	0.65	1.1	0.44	8.6	1.96
160594	3520	1.59	4.37	0.83	1.5	0.53	7.5	1.89

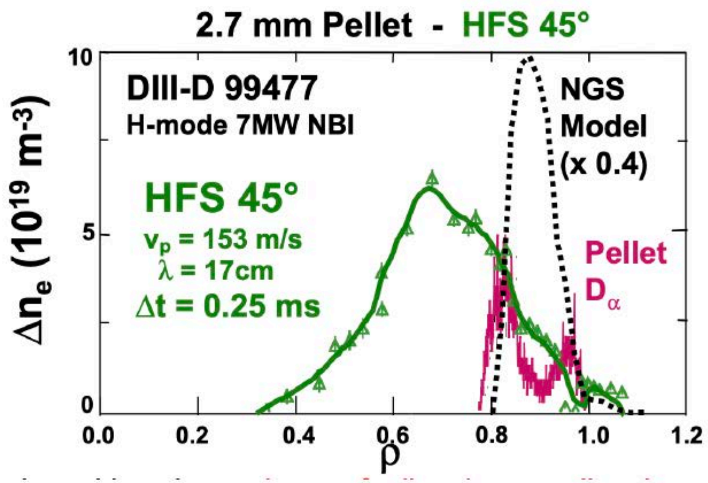


ASIPP

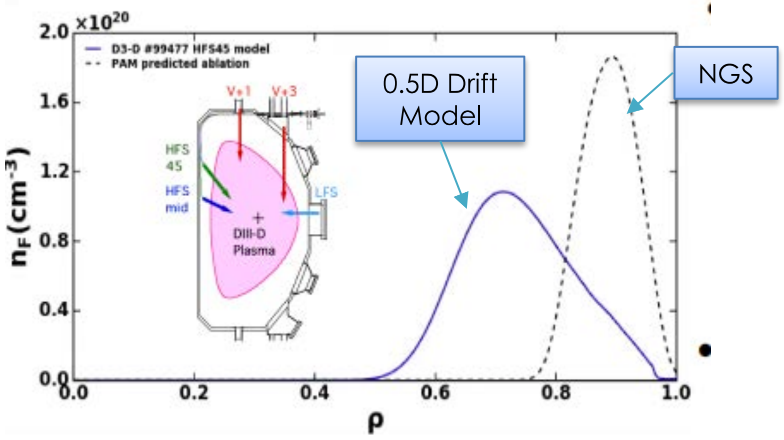
A 0.5D Reduced Pellet Ablation ∇B Drift model Has Been Developed and Tested against DIII-D Pellet Fueling Experiments

- **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**

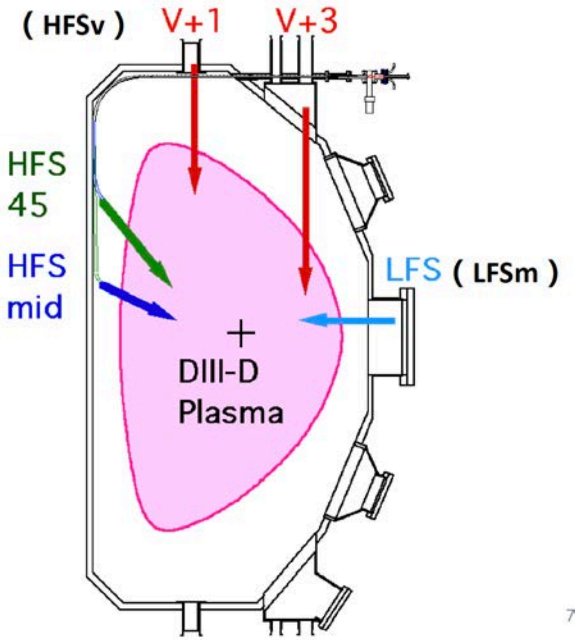
experiment



Simulation results



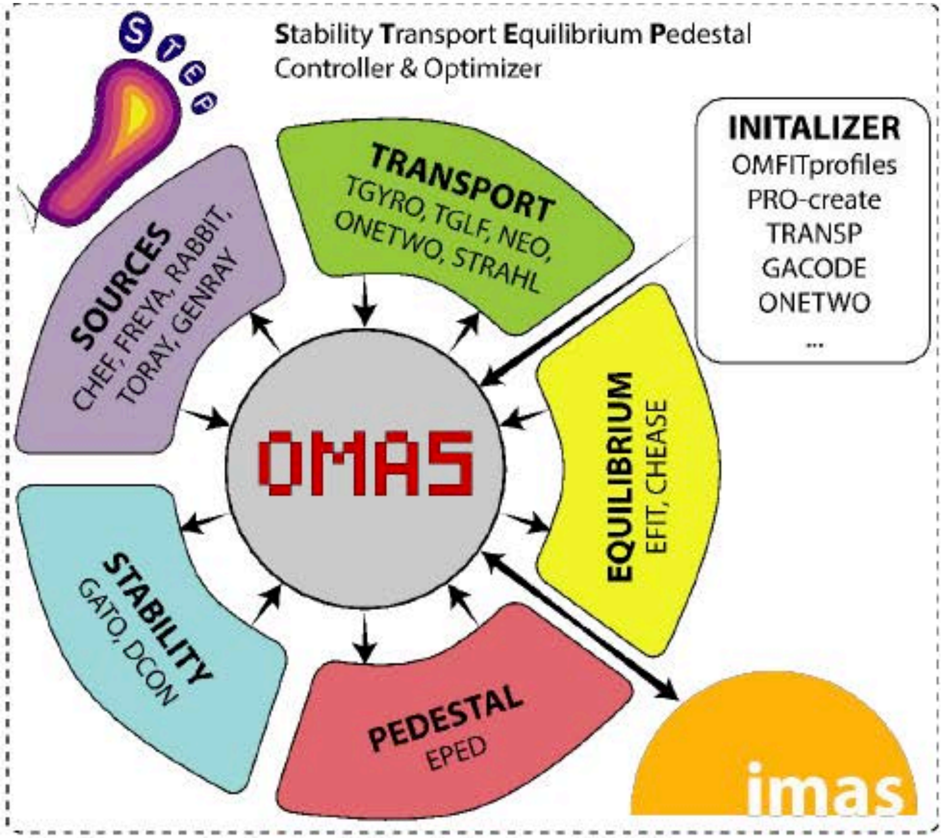
DIII-D Pellet Injectors



Zhang FSM Dec , 2020,

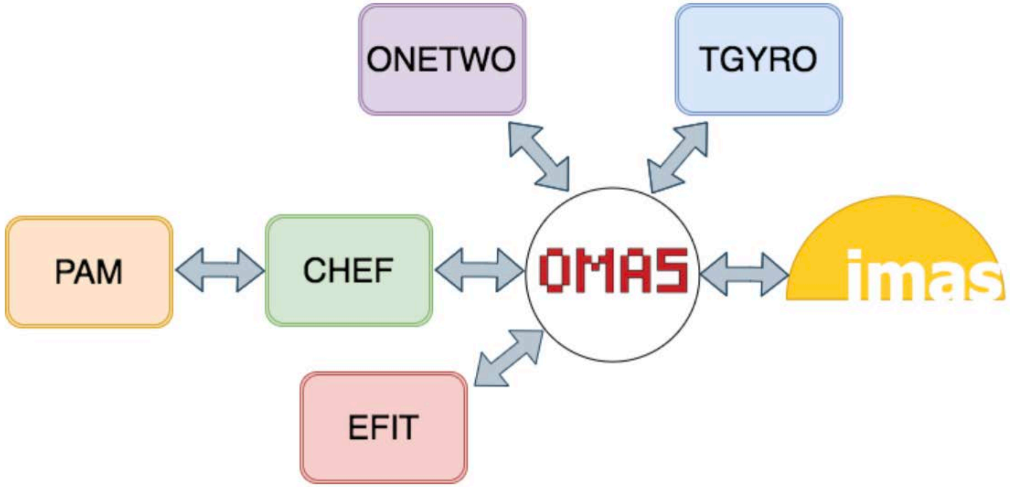
OMFIT STEP Module Couples Stability, Transport, Equilibrium, and Pedestal Codes to Predict Tokamak Scenarios

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



O. Meneghini et al. Nucl. Fusion (2020)

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

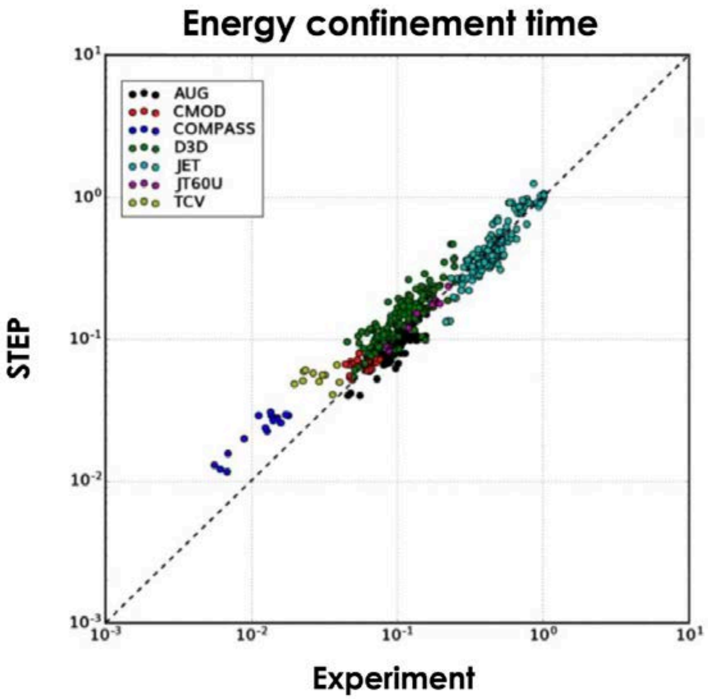


Lyons, McClenaghan, meneghini, Saarelma, Slendebroek, Smith, Thome and the STEP Team DIII-D FSM Jan, 2021

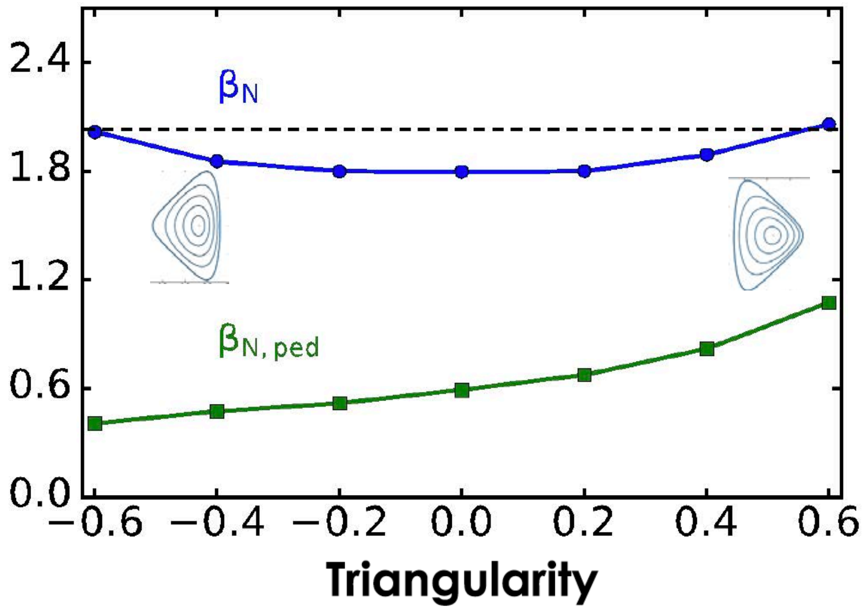
OMFIT STEP Module Successfully tested against $H_{98\text{-}Y2}$ Database and DIII-D transport and NCS stability experiments

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

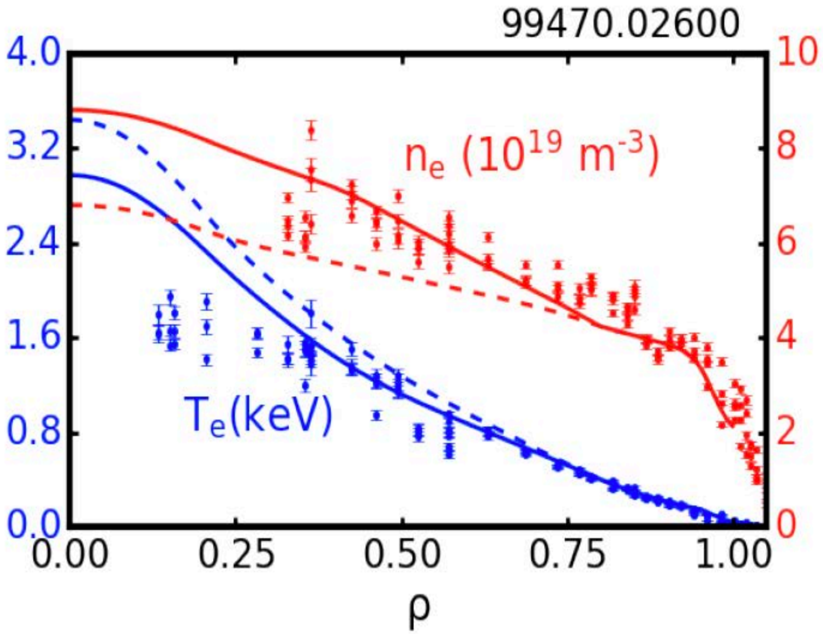
$H_{98\text{-}Y2}$ Database



DIII-D Negative Triangularity Experiments



Reasonably Predicted DIII-D Plasma Profiles with Pellet Fueling

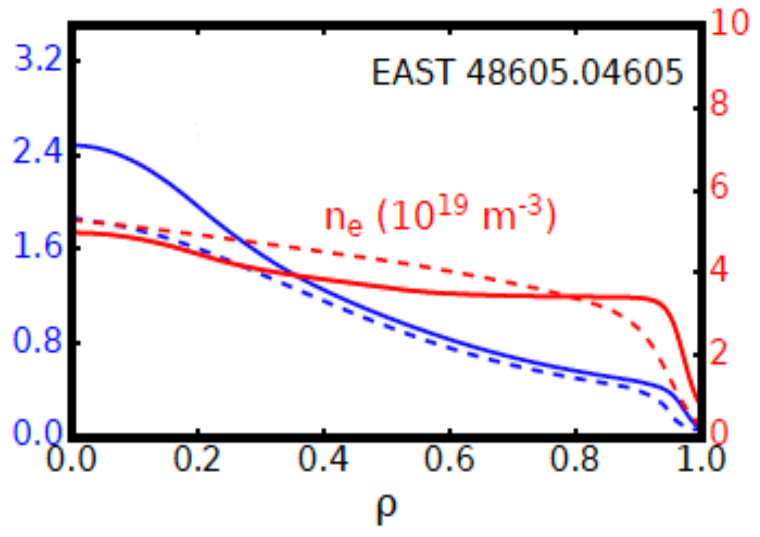


Lyons, McClenaghan, meneghini, Saarelma, Slendebroek, Smith, Thome and the STEP Team DIII-D FSM Jan, 2021

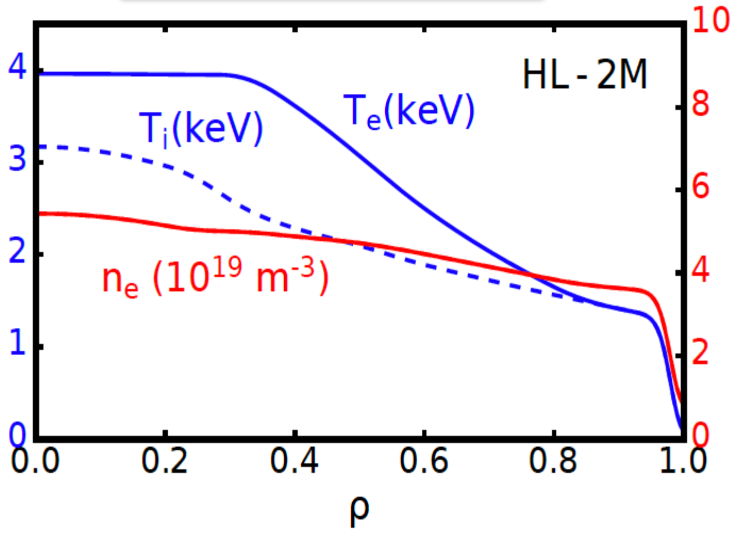
OMFIT STEP Workflows Have Been Productively Applied to Support Many Front-end Collaboration Projects and research

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

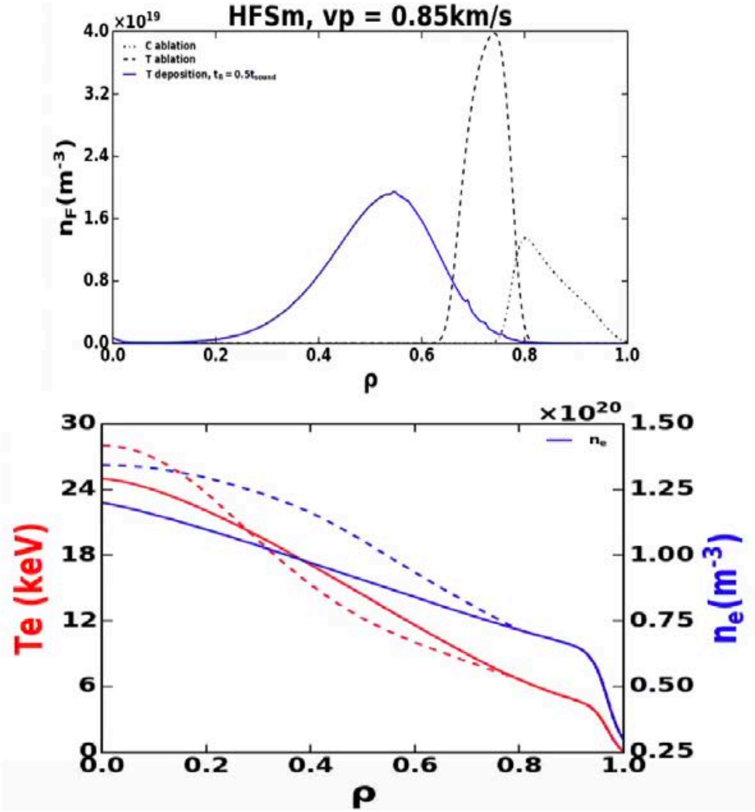
EAST NBI H-Mode



HL-2M RF H-Mode Scenario



CFETR Shattered Pellet Fueling



Joseph McClenaghan et al. IAEA FEC 2021

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

L. Li, Y.Q. Liu et al. , "ELM control optimization for various ITER scenarios based on linear and quasi-linear figures of merits," Phys. Plasmas 27 (2020) 042510. https://doi.org/10.1063/1.5139890

Xue Bai, Yueqiang Liu, and Guangzhou Hao, "Analytic investigation of combined effects of anisotropic thermal transport and energetic particles on stability of resistive plasma resistive wall mode," Phys. Plasmas 27(2020) 124502. https://doi.org/10.1063/5.0031261

Ze-Yu Li, V.S. Chan et al. , "Ideal MHD stability and characteristics of edge localized modes on CFETR," Nucl. Fusion 58 (2017) 016018. https://doi.org/10.1088/1741-4326/aa9149

J.P. Qian, L.L. Lao et al., "EAST equilibrium current profile reconstruction using polarimeter-interferometer internal measurement constraints," Nuc. Fusion 57 (2017) 036008. https://doi.org/10.1088/1741-4326/aa4e58

- **Selected recent Integrated Simulation and Modeling publications**

J. McClehaghan, L.L. Lao et al., "Self-consistent integrated modeling and investigation of density fueling needs on ITER and CFETR," IAEA FEC 2021.

K. Li et al. , "Study of H-mode pedestal model for helium plasmas in DIII-D," submitted to Nucl. Fusion (2021).

J. Zhang and P.B. Parks, "Analytical Formula for Pellet Fuel Source Density in Toroidal Plasma Configurations Based on an Areal Deposition Model," Nucl. Fusion 60 (2020) 066027. https://doi.org/10.1088/1741-4326/ab868e

J. McClenaghan, A.M. Garofalo, L.L. Lao et al., "Transport at High β_P and Development of Candidate Steady State Scenarios for ITER", Nucl. Fusion 60, (2020) 046025. https://doi.org/10.1088/1741-4326/ab74a0

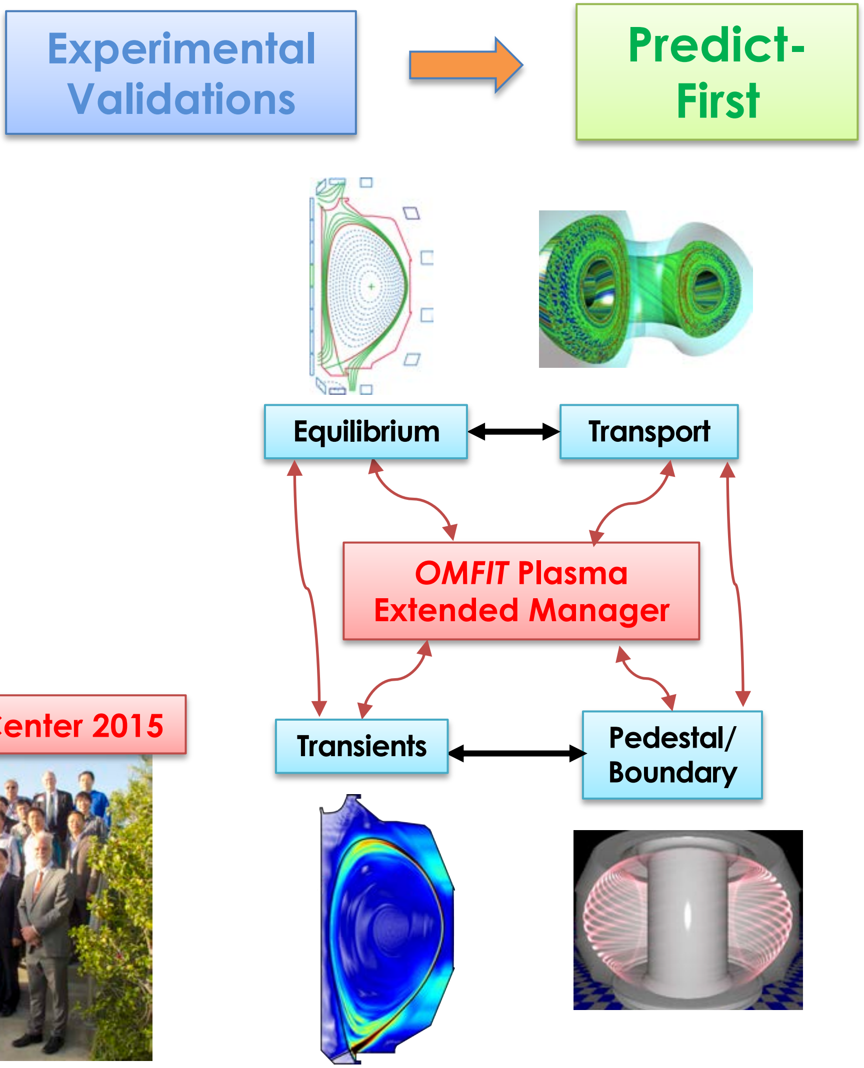
G.M. Staebler et al., "Transport barriers in bootstrap-driven tokamaks," Phys. Plasmas 25 (2018) 056113. https://doi.org/10.1063/1.5019282

C. Pan, G.M. Staebler, L.L. Lao et al., "Investigation of transport in DIII-D High-β_P EAST-demonstration discharges with the TGLF turbulent and NEO neoclassical transport models," Nucl. Fusion 57, (2017) 036018. https://doi.org/10.1088/1741-4326/aa4ff8

Q.L. Ren et al., "Progress toward steady-state tokamak operation exploiting the high bootstrap current fraction regime," Phys. Plasmas 23 (2016) 062511. http://dx.doi.org/10.1063/1.4948724

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



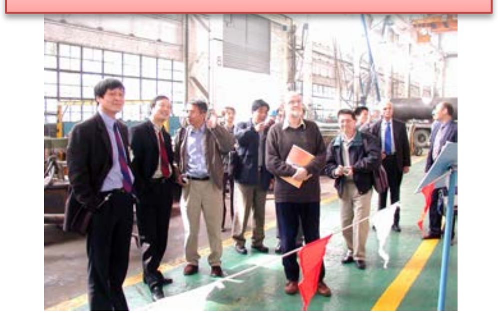
Experimental Validations → Predict-First

Equilibrium ↔ Transport

OMFIT Plasma Extended Manager

Transients ↔ Pedestal/ Boundary

ASIPP-Hefei 1st MFCW 2002



Ren, Lao , Li APS 2007

GA-ASIPP Fusion Center 2015

ASIPP