ADVANCES IN PREDICTION OF TOKAMAK EXPERIMENTS WITH THEORY-BASED MODELS

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More examples and many more references are in the OV2-5 paper
ADVANCES IN PREDICTION OF TOKAMAK EXPERIMENTS WITH THEORY-BASED MODELS

• A new era in predictive integrated modeling
  –准确传输和脚点模型的准确性和预测性启动了整合模型的复兴

• Physics validation of theory-based models
  –极度详尽的物理验证和预测执行

• Predictive modeling for experimental design
  –集成等离子体建模计划实验成为常态

• Progress towards a pulse design simulator
  –等离子体控制系统已准备好与等离子体模型耦合

• Predict first initiative
  –全球使用数据集可用于量化预测的不确定性
Advances in turbulent transport and pedestal structure model accuracy makes integration attractive

- Gradual improvement of quasi-linear turbulent transport model accuracy to below 20% error in incremental stored energy
  - Validates gyrokinetic turbulence theory
- EPED model can predict pedestal pressure height to 22%
  - Validates theory that pedestals are limited by combination of peeling and kinetic ballooning mode thresholds

\[ \Delta R_{W_{\text{inc}}} = 19\% \]
\[ \langle R_{W_{\text{inc}}} \rangle - 1 = -1\% \]

J. Kinsey et al., Nucl. Fusion, 51, 083001 (2011)
P. Snyder et al., Nucl. Fusion, 59, 0860171 (2019)
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The inversion of an edge cold pulse to a core heat pulse has been a challenge for the local transport paradigm.

- Laser blow-off impurity injection on Alcator C-MOD shows an electron temperature pulse inversion at low density.
- At higher density the temperature pulse remains a cold pulse in the core.

- The density below which this inversion occurs is close to the change from linear to saturated Ohmic confinement.

Simulation of the temperature pulse with TGLF+NCLASS captured the inversion at low density

- Electron and ion temperatures were evolved
  - An electron density pulse was imposed
  - TEM is dominant in the core at low density

- $T_e$ pulse inversion was caused by the flattening of density gradients stabilizing TEM turbulence in the core

Cold pulse experiments were predicted for DIII-D

- Fast electron density measurements on DIII-D confirmed the density pulse modeling
  - Could the density pulse be predicted?

\[ \Delta T_e \text{ (keV)} \]

\[ \rho = 0.2 \]

\[ n_e \text{ (10}^{19} \text{m}^{-3}) \]

Laser blow-off experiments on AUG were predicted evolving $T_e$, $T_i$, $N_z$, $N_e$.

The cold pulse prediction agreed with data for several heating methods.

The destabilization of the edge ITG by the hollow impurity density accelerated the electron density pulse matching the experiment.
The super-H regime predicted by EPED is demonstrated on DIII-D in a JET similar discharge

- The super-H high pedestal regimes (red) is predicted exist in JET at an achievable average triangularity $\delta_{\text{eff}} = \frac{1}{3}(\delta_{\text{lower}} + 2\delta_{\text{upper}}) = 0.4$
- DIII-D running JET shape and aspect ratio mapped out the SH access. The highest pedestal pressure (yellow) was achieved for lower safety factor and average triangularity near the JET limit

M. Knolker Phys. Plasmas, 27, 102506 (2020)
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IPS-FASTRAN Integrated Simulation Suite

- Turbulent Transport: TGLF
- Neoclassical Transport: NCLASS
- Off-axis Current Drive: NUBEAM
- Heating/CD: NUBEAM, TORAY, Helicon
- Equilibrium Stability: MHD equilibrium, EFIT, Ideal MHD Stability, DCON
- Pedestal Equilibria: TOQ+KBM, Peeling-Ballooning, MHD stability, ELITE
- Core profiles: TGLF, NCLASS

Graphs and charts illustrating various simulation and modeling outputs.
**IMEP-ASTRA workflow**

- **Integrated Modeling base on Engineering Parameters (IMEP)**
  
  T. Luda, Nucl. Fusion, 60, 036023 (2020)

**Input:**

- $B_t$, $I_p$, $P_{\text{heat}}$, geometry, $\Gamma_D$, $\Gamma_{N2}$, $Z_{\text{eff}}$

**Output:**

- kinetic profiles, $\tau_E$, $W_E$

**Scrape Off Layer model**

**HELENA** – high resolution equilibrium reconstruction

**ASTRA** – transport code: core & pedestal

**MISHKA** - MHD stability code

**Pressure**

- $\rho_{\text{tor}}$
- $\Delta_{\text{ped}}$

**Pedestal pressure**

- $\rho_{\text{tor}}$
- $\Delta_{\text{ped}}$

**ASTRA simulations**

- Transport curve

**Pressure**

- $\rho_{\text{tor}}$

**Pedestal pressure**

- $\Delta_{\text{ped}}$

**Figure (a)**

**Figure (b)**

**Figure (c)**

**Figure (d)**

**Figure (e)**
IMEP-ASTRA predicts H-mode plasmas without data

This modeling workflow is tested by simulating 50 H-mode stationary phases from ASDEX Upgrade discharges covering wide variations in:

- $B_t = 1.5 - 2.8$ [T]
- $I_p = 0.6 - 1.2$ [MA]
- $P_{\text{net}} = 2 - 14$ [MW]
- $q_{95} = 3 - 8$
- $\Gamma_D = 0 - 8 \times 10^{22}$ [e/s]
- $\delta = 0.19 - 0.42$
- $V_{\text{NBI}} = 42 - 92$ [kV]

The model:

✓ is more accurate than the IPB98(y,2) scaling law

✓ can accurately capture the effect of the different operational parameters
Stability Transport Equilibrium Pedestal: STEP workflow

- STEP external iteration to steady state
- Python interface OMAS communicates with IMAS
- The TGYRO transport solver can verify the solution found with the quasi-linear model TGLF with CGYRO at each radial zone
- Global MHD stability
- Impurity transport

- Neural Network models are being developed: TGLF-NN, EPED-NN

O. Meneghini et al. Nucl. Fusion, accepted (2020)
Planning experiments with STEP on the EAST tokamak high $\beta_p$ fully non-inductive regime

- Experimental: $f_{bs}$ ~47%, $f_{LHW}$ ~44%, $f_{ECH}$ ~ 9%.
- Prediction: $f_{bs}$ ~50%, $f_{LHW}$ ~41%, $f_{ECH}$ ~ 9%.
- “Steady-state” energy transport and current evolution using integrated modeling (STEP)

EAST#81481 $\beta_N$ ~ 1.5, $\beta_P$ ~ 1.9
ECH ~ 1MW, LHW ~ 2.6MW

M.Q. Wu et al 2019 Nucl. Fusion 59 106009
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Integrated Plasma Prediction and Control Pulsed Design Simulator (PDS*) Concept

* S. D. PINCHES, IAEA FEC Conf. paper TH/P6-7 (2018)

D. Humphreys, 2010
Integration of the Plasma Control System (PCS)

• ITER PCS simulation platform standard has been adopted
  M. Walker et al., SOFT-28, 2015

• FENNIX “flight simulator” (ASTRA-SPIDER) is being used to run pulse designs prior to experiments to validate the PCS simulation platform model of ASDEX-Upgrade
  F. Janky et al., SOFT-30, 2019

• Only simple empirical plasma transport models have coupled to PCS simulations to date
  – Next step: Fast neural networks
  – QuaLiKiz
  – TGLF, EPED
    O, Meneghini, et al., NF, 2020

• A Pulse Design Simulator (PDS) that integrates theory-based models for transport, pedestal, MHD equilibrium, sources and plasma boundary with PCS simulators is technically within reach
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It is time for the fusion community to make a commitment to a “Predict-first Initiative” in order to have a validated PDS for ITER

- Run PDS predictions of discharges prior to experiments
- Collect use data on the accuracy of the predictions (UQ)
- Reduce the number of failed pulse designs (control or plasma)
- Benefit to experimental run time efficiency as the PDS is evolved

Uncertainty quantification (UQ) of a PDS system requires experience using it on present tokamaks to build up a use database

- Determination of model accuracy requirements
- Field testing of methodologies and control algorithms
- Quality engineering of the PDS architecture
- Exceed operational limits to test mitigation methods
ADVANCES IN PREDICTION OF TOKAMAK EXPERIMENTS WITH THEORY-BASED MODELS

- A new era in predictive integrated modeling
  - Accurate transport and pedestal models launch integration revival

- Physics validation of theory-based models
  - Exquisitely detailed physics validation and prediction executed

- Predictive modeling for experimental design
  - Integrated plasma modeling to plan experiments becoming routine

- Progress towards a pulse design simulator
  - Plasma control systems are ready to be coupled to plasma models

- Predict first initiative
  - Global use dataset is needed to quantify the uncertainty of prediction
KSTAR is developing an IMAS based workflow

- Tokamak Reactor Integrated Automated Suite for Simulation and Computation: TRIASSIC
- Architecture is similar to STEP: plug and play library of modules
- Communication with IMAS Interface Data Structure
- TRIASSIC is being used to find current profiles with high energy confinement in fully non-inductive KSTAR discharges

Y. Lee  this conference
There Are Many Actuators And Sensors On A Tokamak For Guidance And Control

Real Time Feedback Controlled (Actuator, Sensor)

- Pressure profile (ITB, Te): ECH, ECCD, ECE
- Current Profile: ECCD, ECH, MSE
- Edge Stability: I-coil, Counter NBI
- $T_e$: ECH, ECE
- NTM: ECCD, magnetics
- Disruption: Gas jet, magnetics, bolometers
- NBI
- Plasma $\beta$: $P_{aux}$, RTEFIT
- RWM: C-Coil, I-Coil, magnetics
- Equilibrium: PF-Coils, RTEFIT
- Density: Pellet/Cryopumps/Gas valves, CO$_2$ Interferometers