ADVANCES IN PREDICTION OF TOKAMAK EXPERIMENTS WITH THEORY-BASED MODELS

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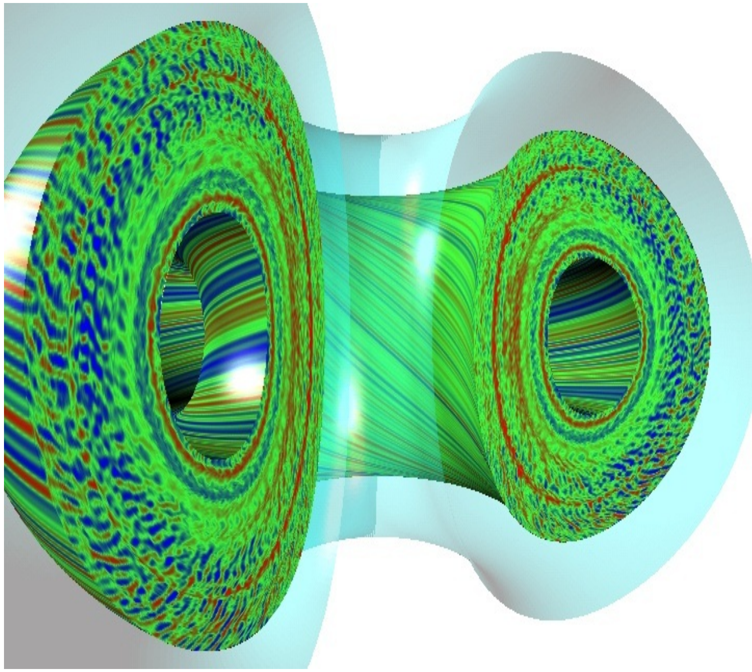

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More examples and many more references are in the OV2-5 paper

ADVANCES IN PREDICTION OF TOKAMAK EXPERIMENTS WITH THEORY-BASED MODELS

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

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

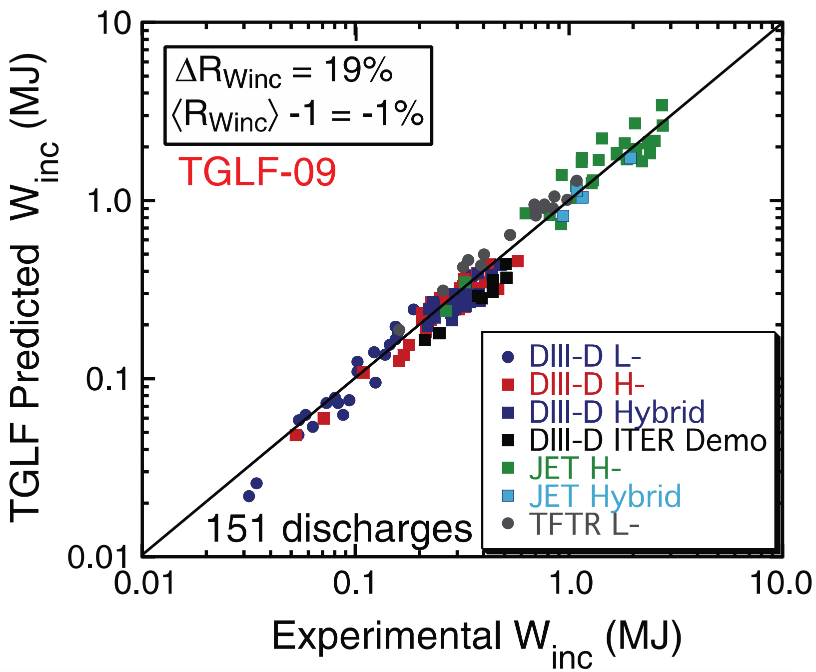
- Predictive modeling for experimental design
  - Integrated plasma modeling to plan experiments becoming routine

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

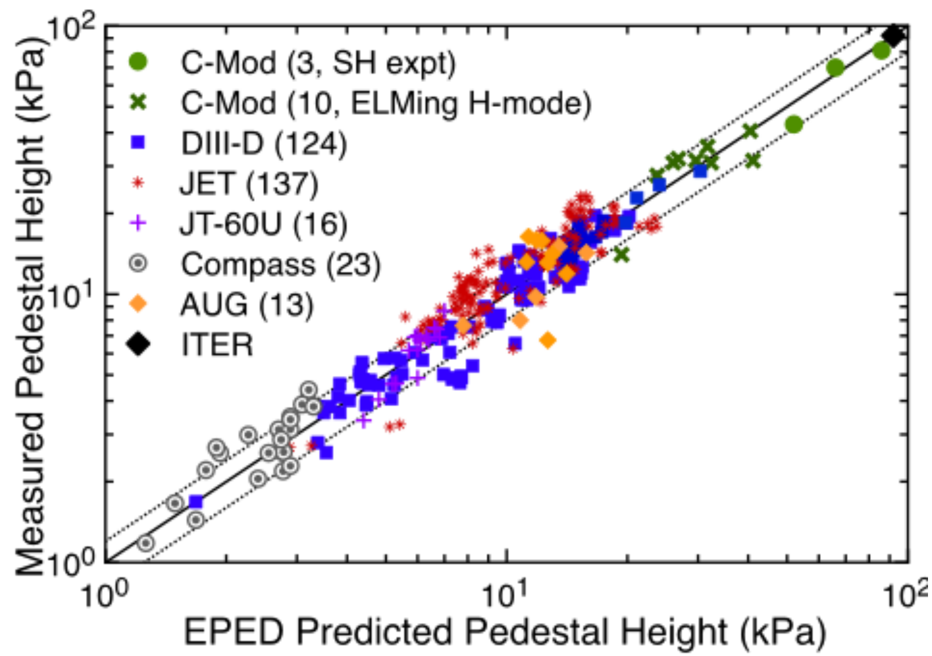
- Predict first initiative
  - Global use dataset is needed to quantify the uncertainty of prediction

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



J. Kinsey et al., Nucl. Fusion, 51, 083001 (2011)



P. Snyder et al., Nucl. Fusion, 59, 0860171 (2019)

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- A new era in predictive integrated modeling

- **Physics validation of theory-based models**

- Predictive modeling for experimental design

- Progress towards a pulse design simulator

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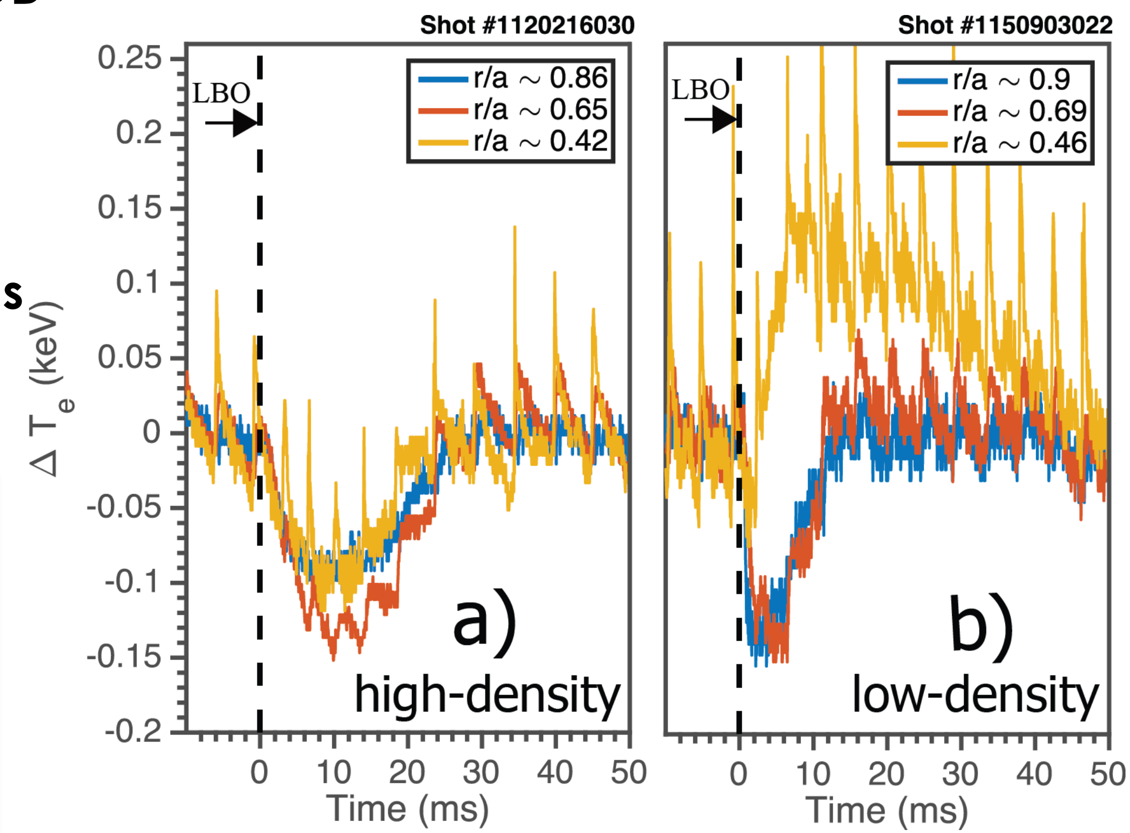
The inversion of an edge cold pulse to a core heat pulse has been a challenge for the local transport paradigm

- **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**

P. Rodriguez-Fernandez Phys. Rev. Lett., 120, 075001 (2018)



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

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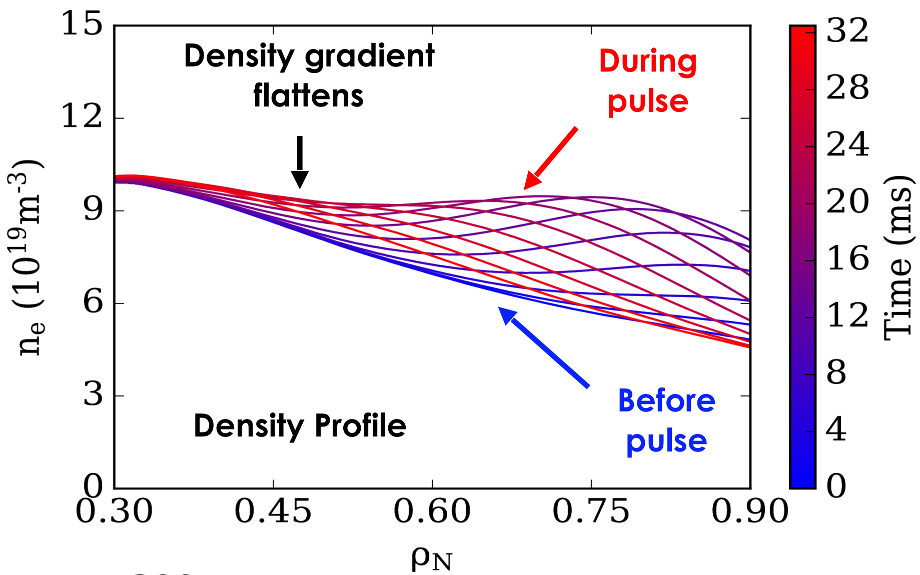
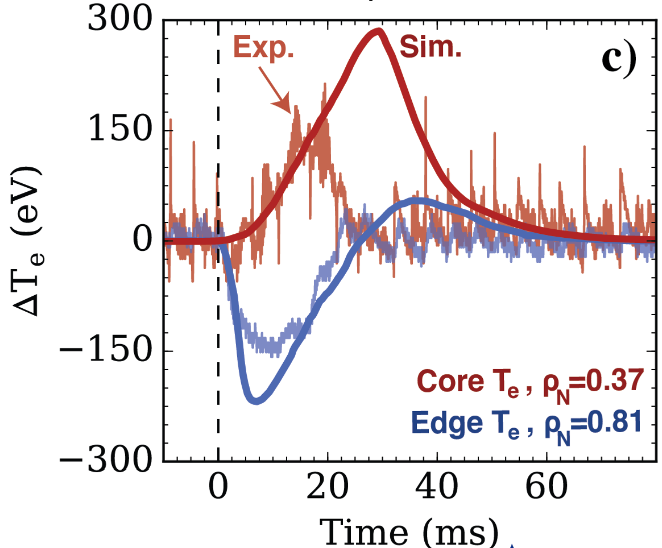
Simulation of the temperature pulse with TGLF+NCLASS captured the inversion at low density

- **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**

P. Rodriguez-Fernandez Nucl. Fusion, 59, 066017 (2019)





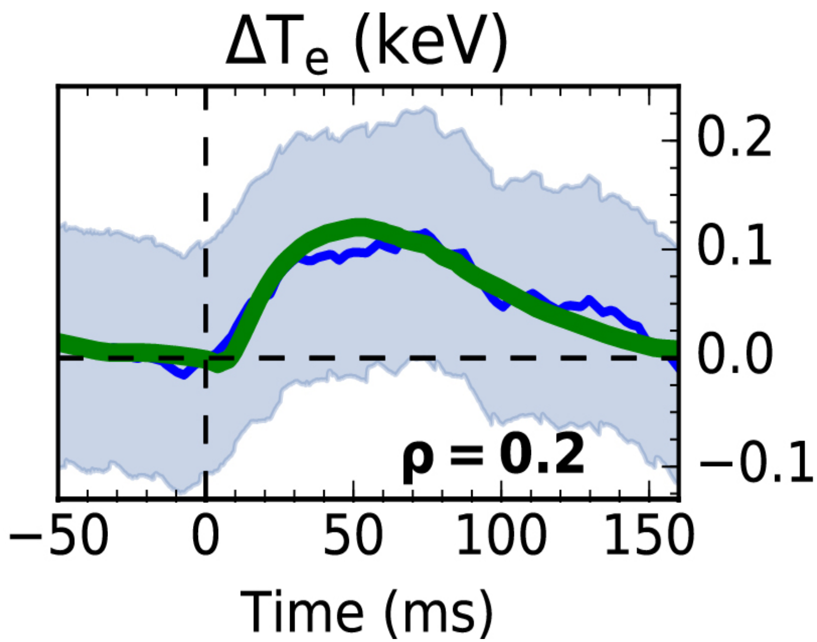
MIT PSFC

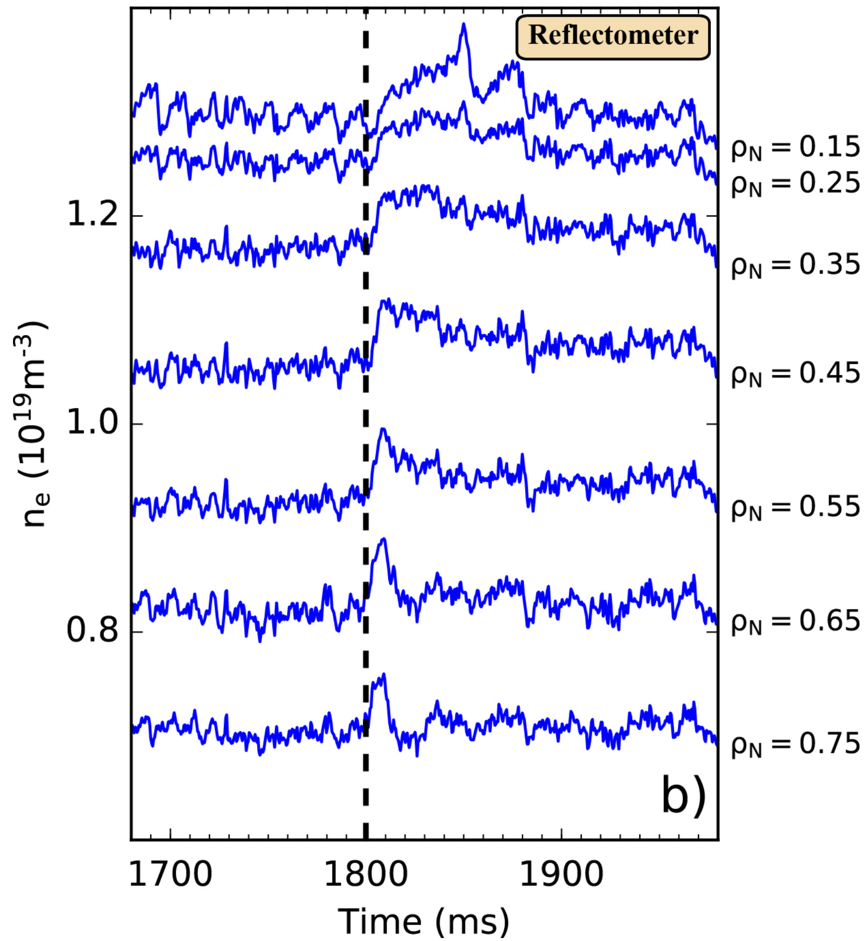
GENERAL ATOMICS

Cold pulse experiments were predicted for DIII-D

P. Rodriguez-Fernandez Phys. Plasmas, 26, 062503 (2019)

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

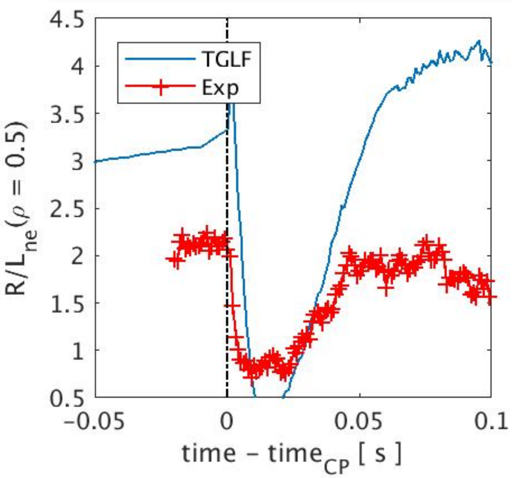


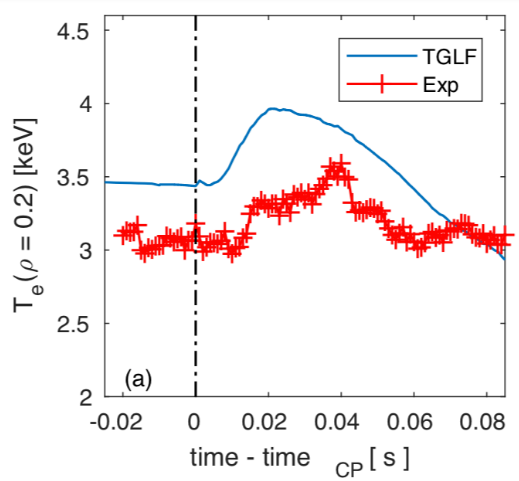


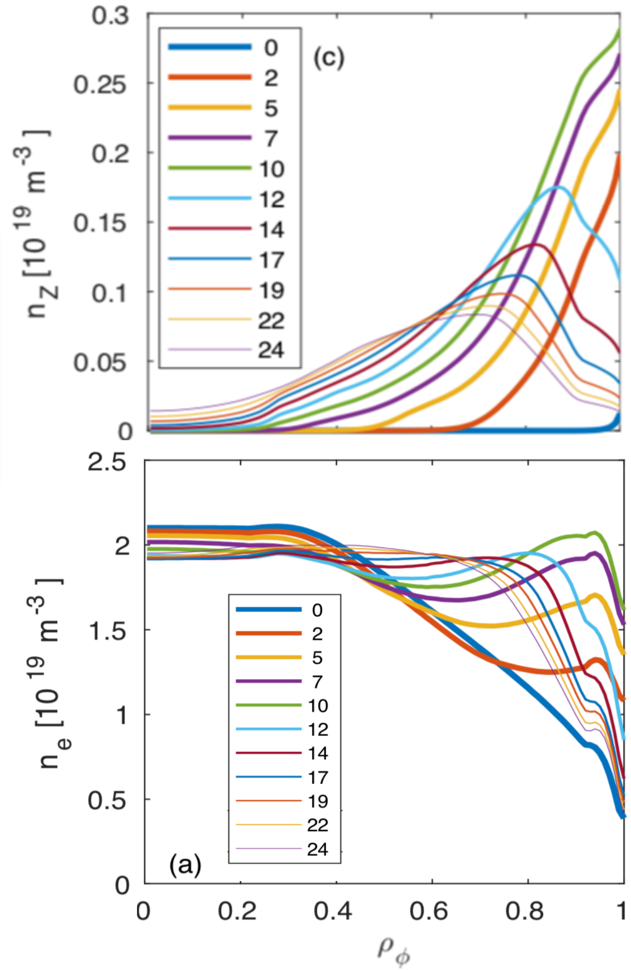
Impurity injection (STRAHL) and transport (ASTRA) on AUG

C. Angioni et. al. Nucl. Fusion, 59, 106007 (2019)

- 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**

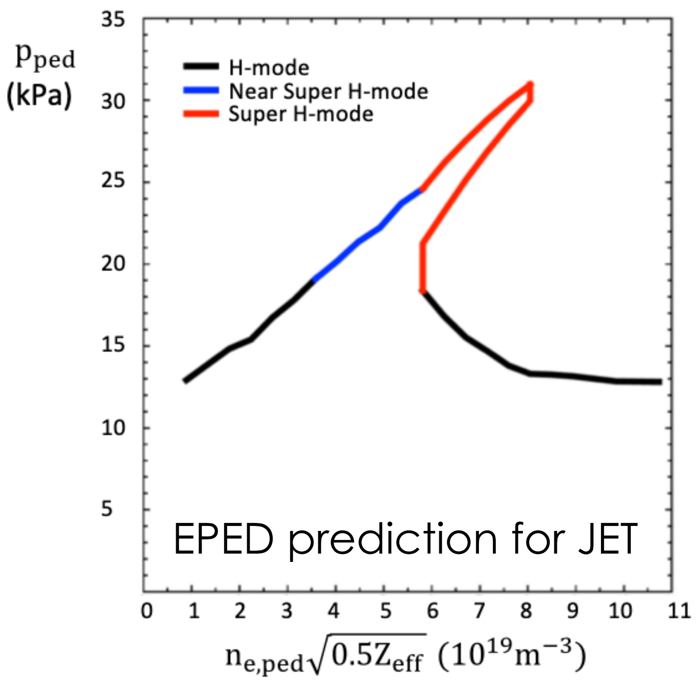


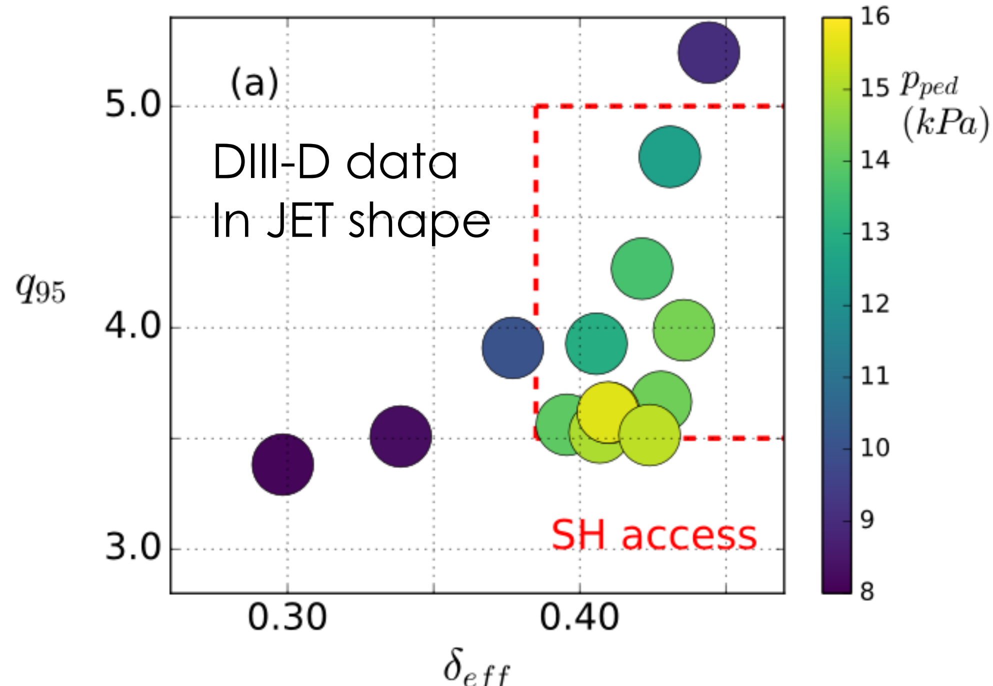




The super-H regime predicted by EPED is demonstrated on DIII-D in a JET similar discharge

- **The super-H high pedestal regimes (red) is predicted exist in JET at an achievable average triangularity** $\delta_{eff} = \frac{1}{3}\left(\delta_{lower} + 2\delta_{upper}\right) = 0.4$
- **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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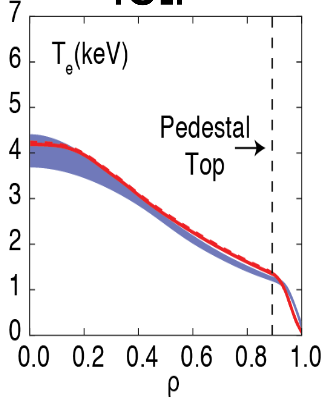
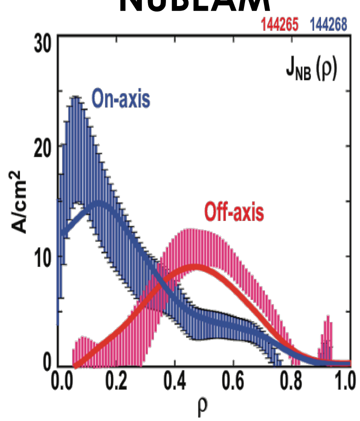
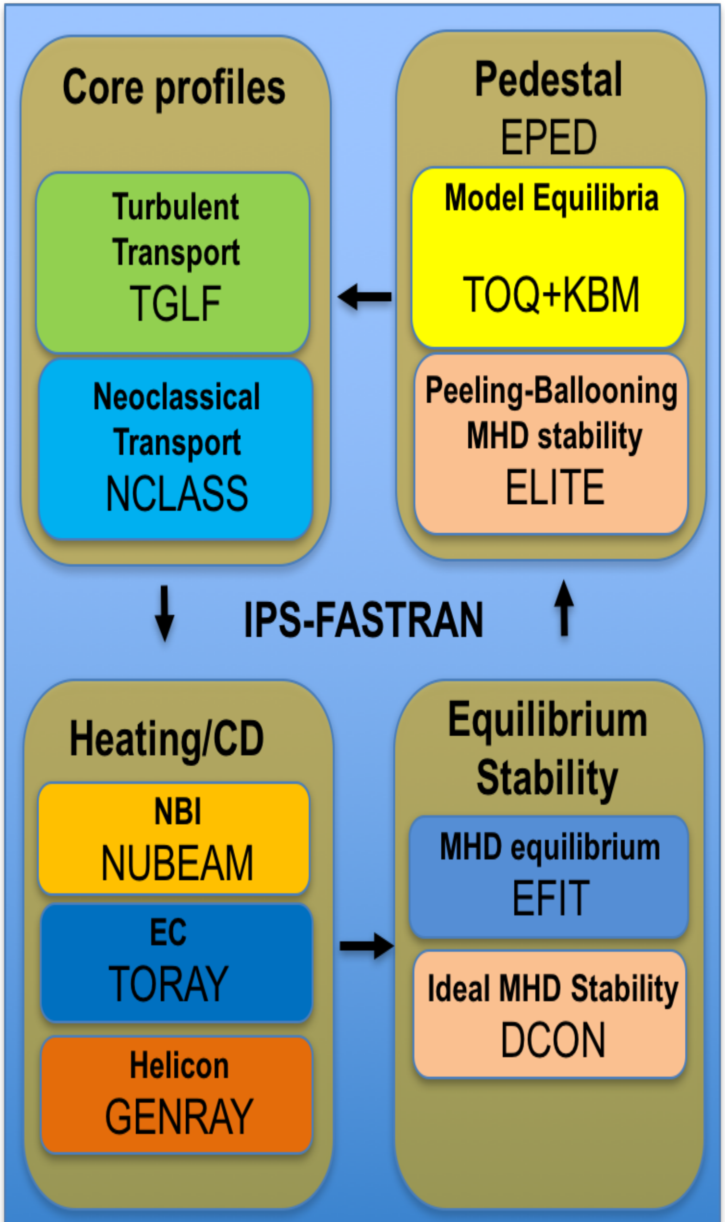
IPS-FASTRAN Integrated Simulation Suite

Turbulent Transport
TGLF

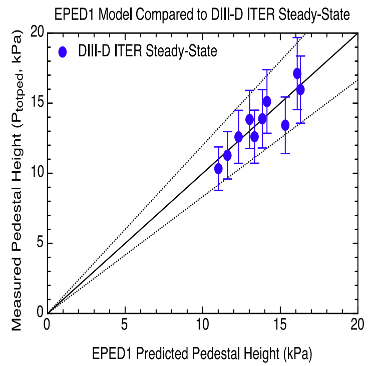


Off-axis Current Drive
NUBEAM

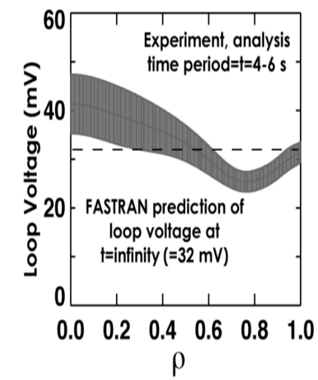




Edge Pedestal
EPED



Equilibrium/Loop Voltage
EFIT



J. M. Park Comp Phys Com 2017

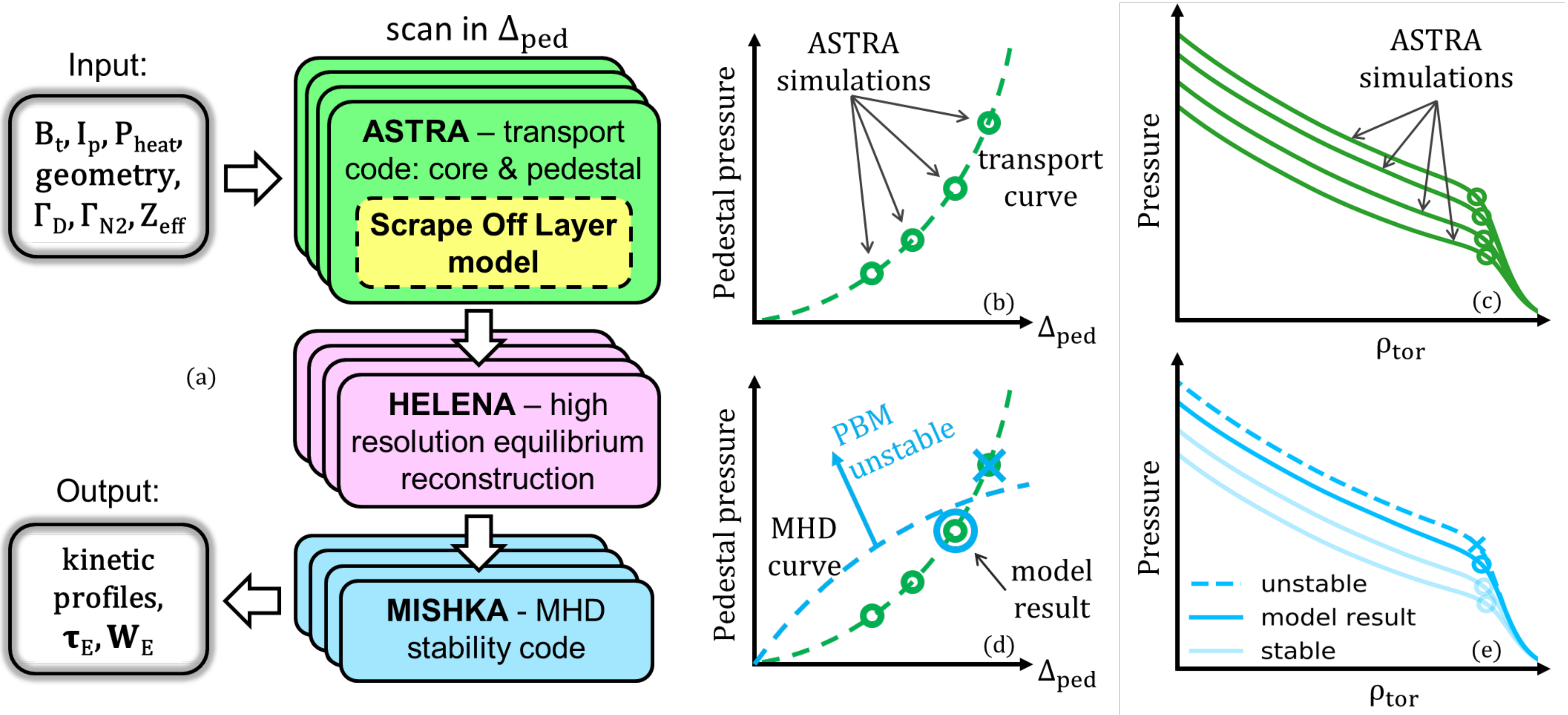
OAK RIDGE National Laboratory

GENERAL ATOMICS

IMEP-ASTRA workflow

- **Integrated Modeling base on Engineering Parameters (IMEP)**

T. Luda, Nucl. Fusion, 60, 036023 (2020)



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:

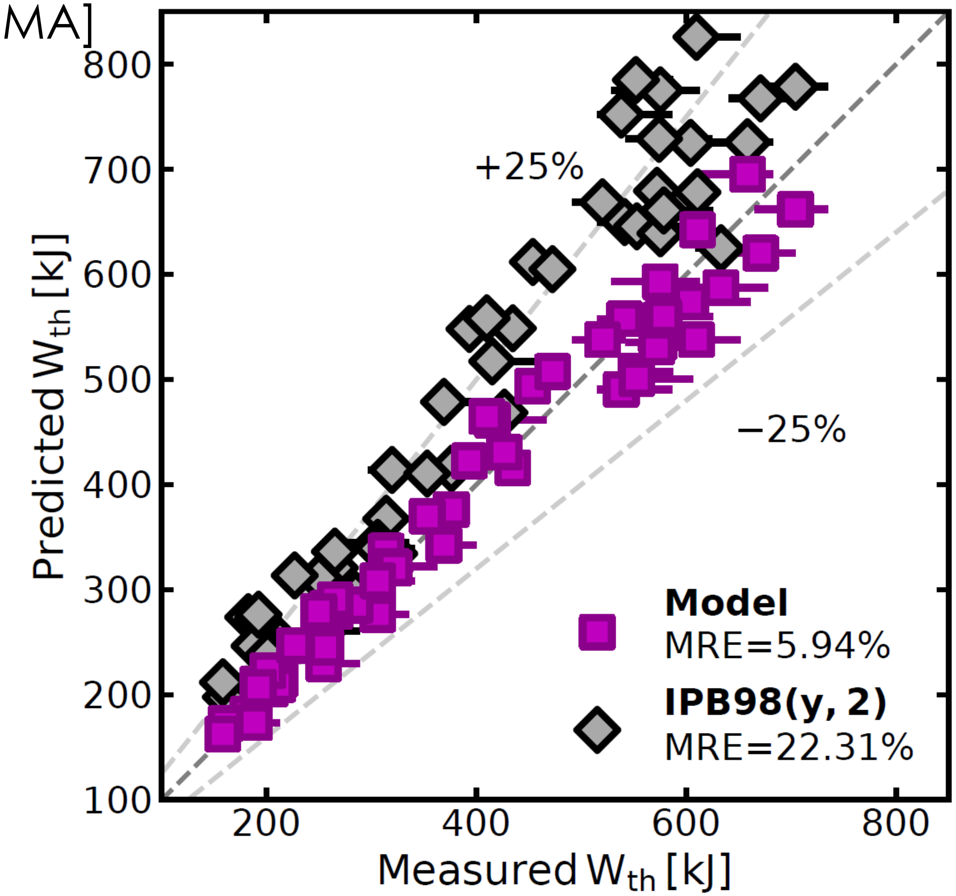
B_t = 1.5 - 2.8 [T] I_p = 0.6 – 1.2 [MA]

P_{net} = 2 – 14 [MW] q_{95} = 3 - 8

Γ_D = 0 – 8 x 10^{22} [e/s]

δ = 0.19 – 0.42

V_{NBI} = 42 - 92 [kV]

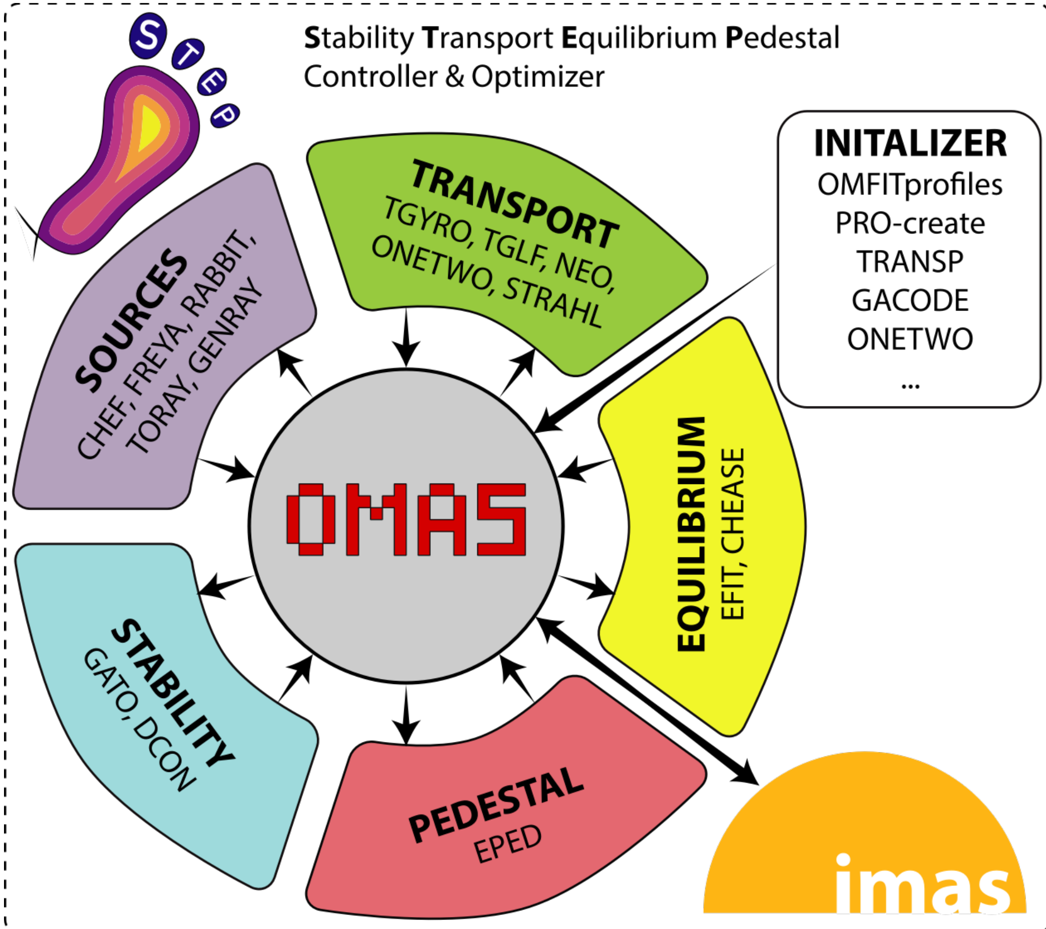


The model:

- ✓ 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

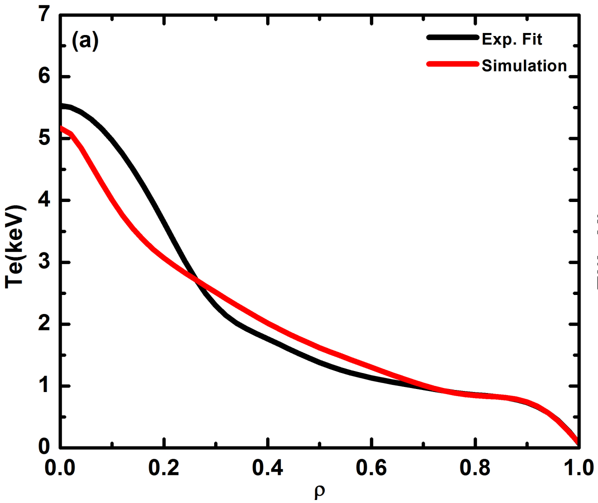
- STEP external iteration to steady state
- Python interface OMAS communicates with IMAS
- The TGYRO transport solver can verify the solution found with the quasi-linear model TGLF with CGYRO at each radial zone
- Global MHD stability
- Impurity transport

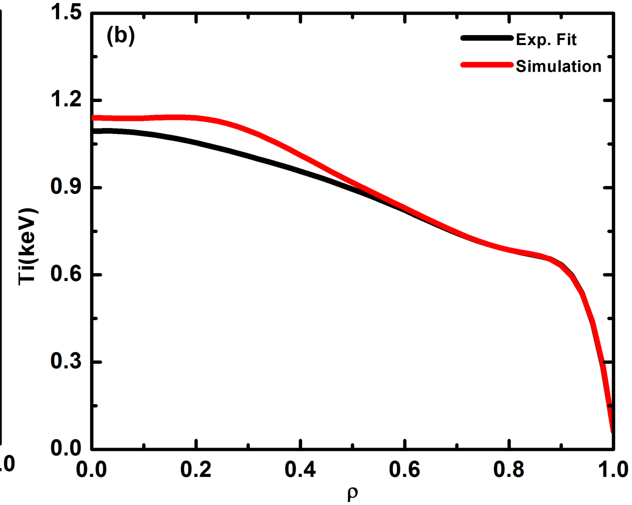


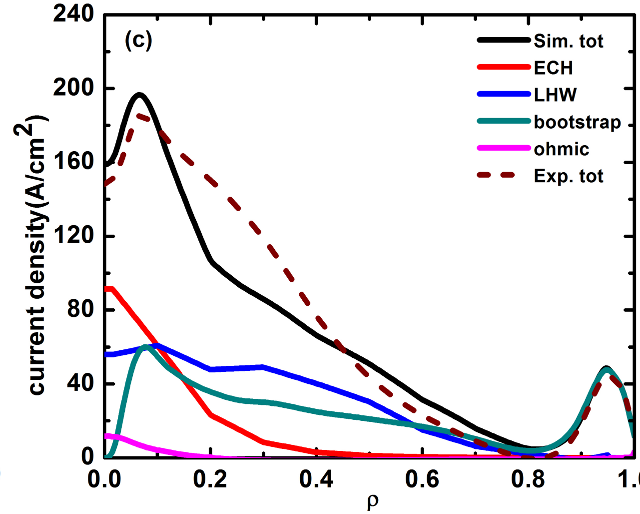
- Neural Network models are being developed: TGLF-NN, EPED-NN

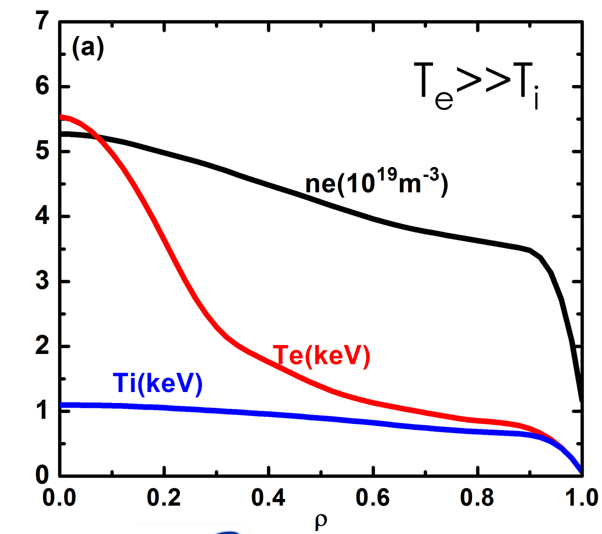
O. Meneghini et al. Nucl. Fusion, accepted (2020)

Planning experiments with STEP on the EAST tokamak high β_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 β_N ~ 1.5, β_P ~ 1.9

ECH ~ 1MW, LHW ~ 2.6MW

M.Q. Wu et al 2019 Nucl. Fusion 59 106009

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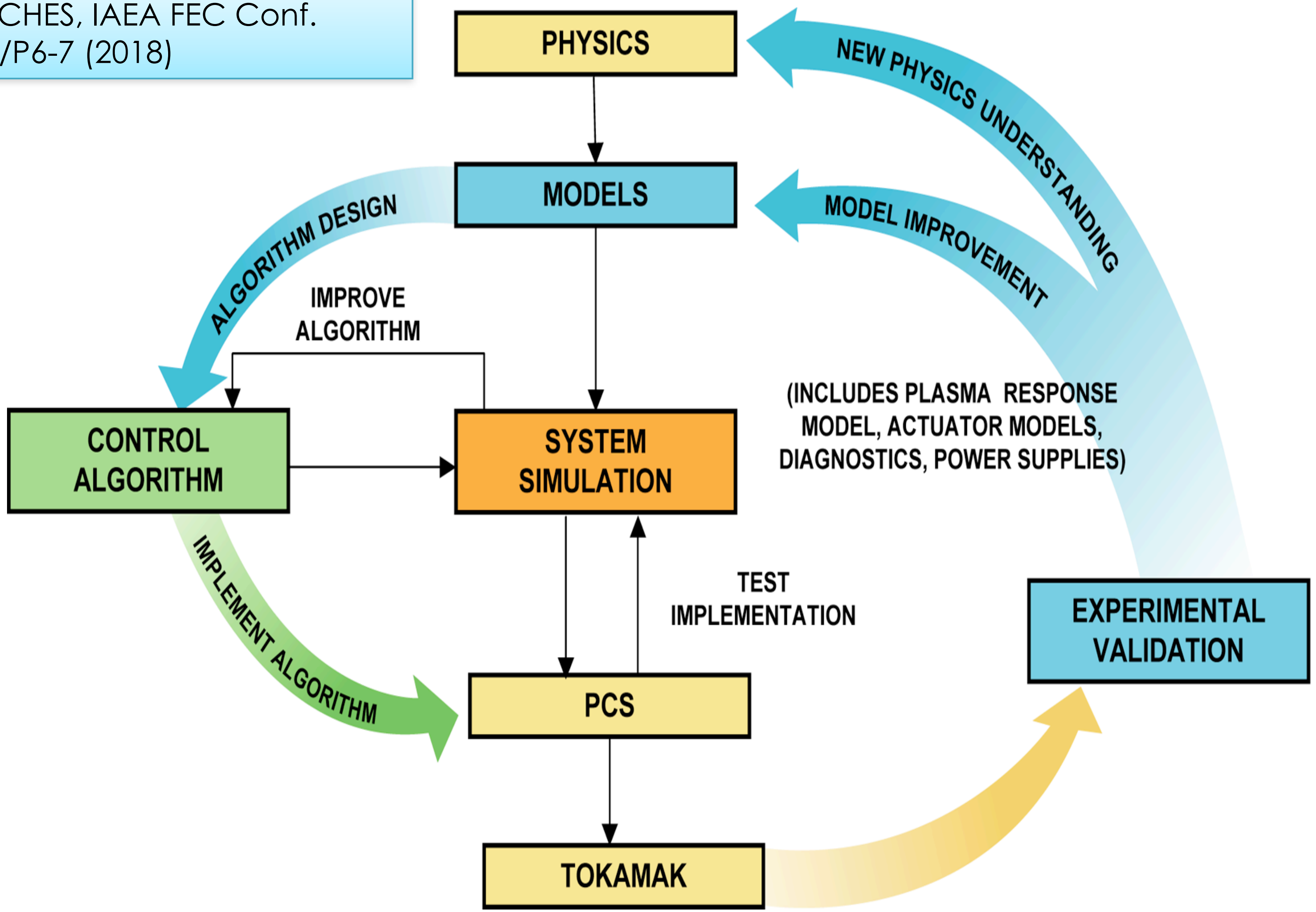
GENERAL ATOMICS

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 — K. L. Van de Plassche et al., Phys. Plasmas, 2020
  - 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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Predict-First Initiative

- **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

- **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

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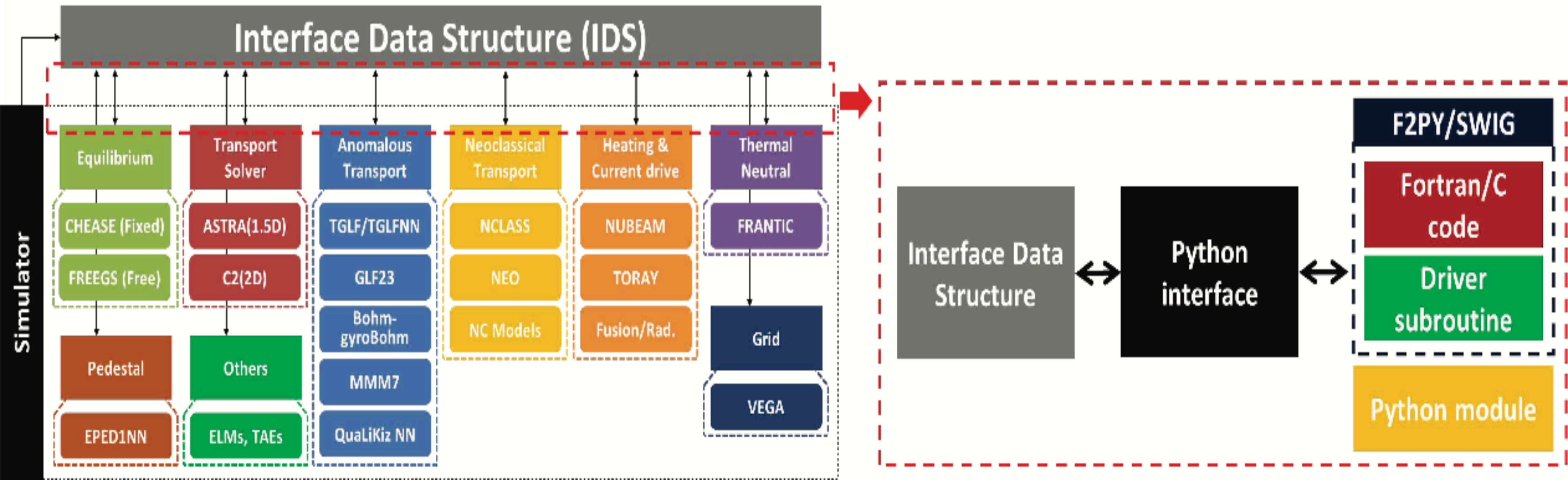
KSTAR is developing an IMAS based workflow

- 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)