Elevating zero-dimensional predictions of tokamak plasmas to self-consistent theory-based simulations

by

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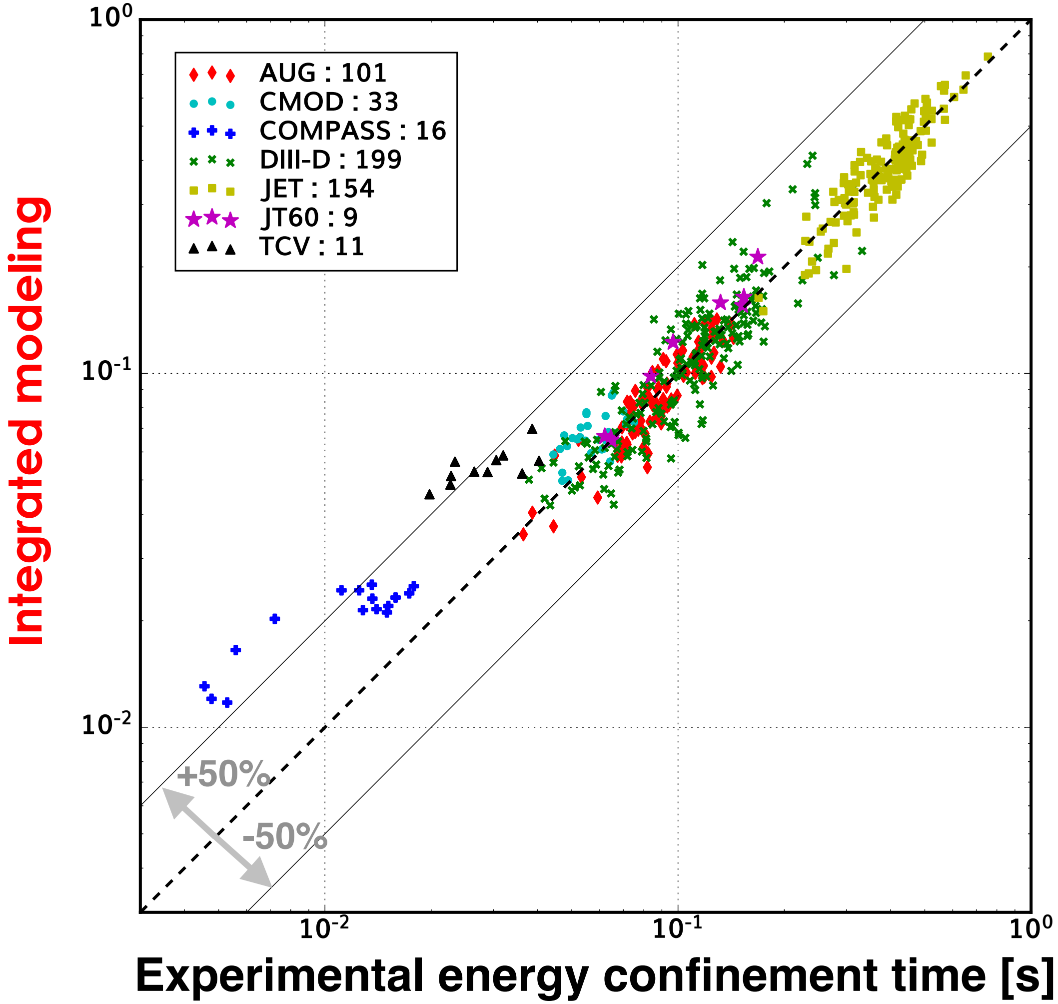


Overview

- 0D engineering parameters to a self-consistent solution

- Validation on large database spanning multiple tokamaks
- Comparing H98y2 scaling law to simulation results
- Evaluating the relative importance of pedestal and core on confinement

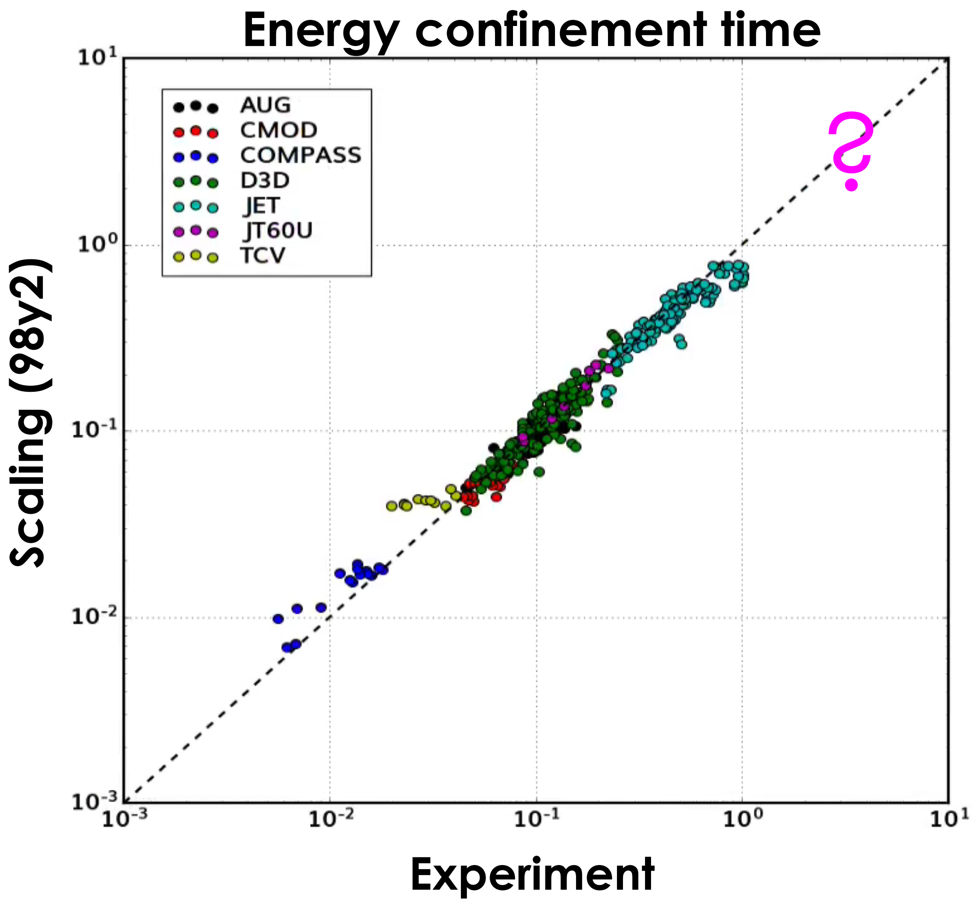
Accurate calculation of confinement is critical for future device design

- **Fusion power scales with the energy confinement time**

$$\tau_{e,th} = \frac{W_{th}}{P_{loss} - dW_{th}/dt}[s]$$

$$\tau_{e\ h98,y2} = 0.0562 I_p^{0.93} B_0^{0.15} P_{heat}^{-0.69} \kappa^{0.78} M_{eff}^{0.19} (10n_e)^{0.41} A^{-.58} R^{1.97}$$

- **Scaling laws used for prediction of $\tau_{e,h98,y2}$**
  - Based on linear regression of present tokamak experiments
- **Limitation of energy confinement scaling**
  - Not based on physics and differs by operation regime
  - Extrapolation is not recommended
- **First principle modeling to predict confinement time**



GENERAL ATOMICS

Transforming a zero-dimensional tokamak description to a starting point for theory models

0D parameters

Shape and Plasma

R, δ

B_t, I_p

$\tau_{h98,y2}$

$\dots$

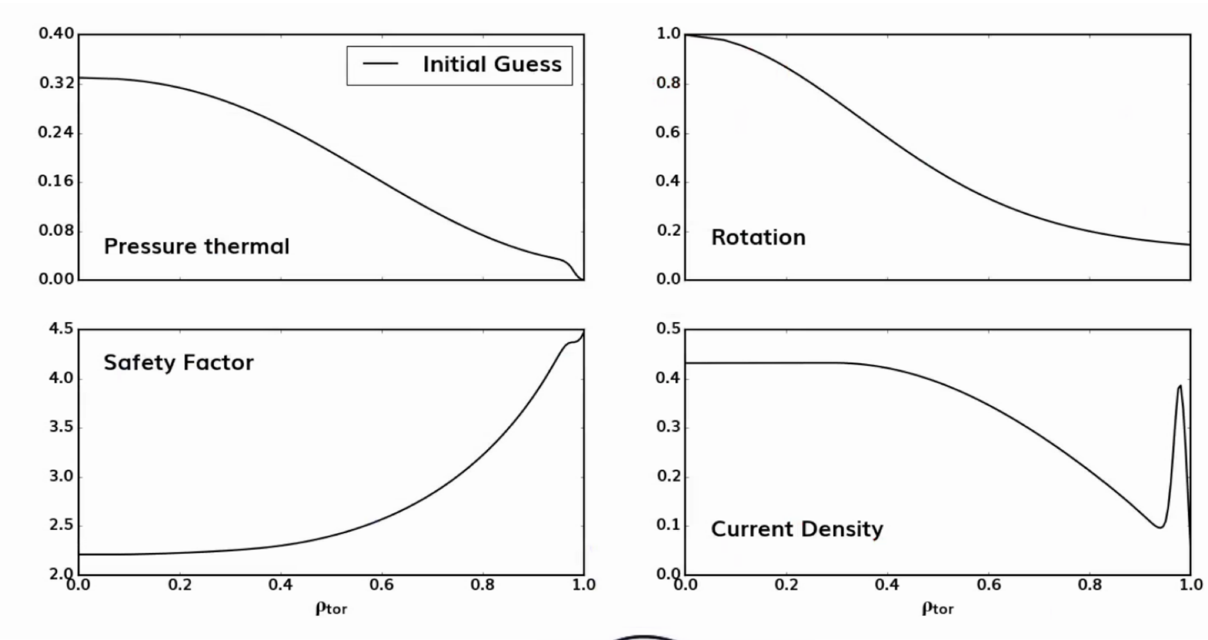
Heating and current drive

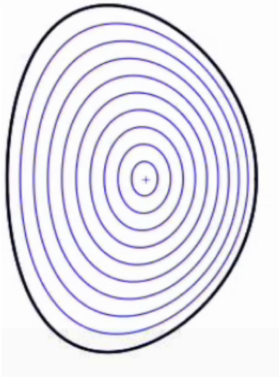
P_{NBI}, P_{IC}

$\dots$

OMFIT module:
Profiles Creator

Initial guess





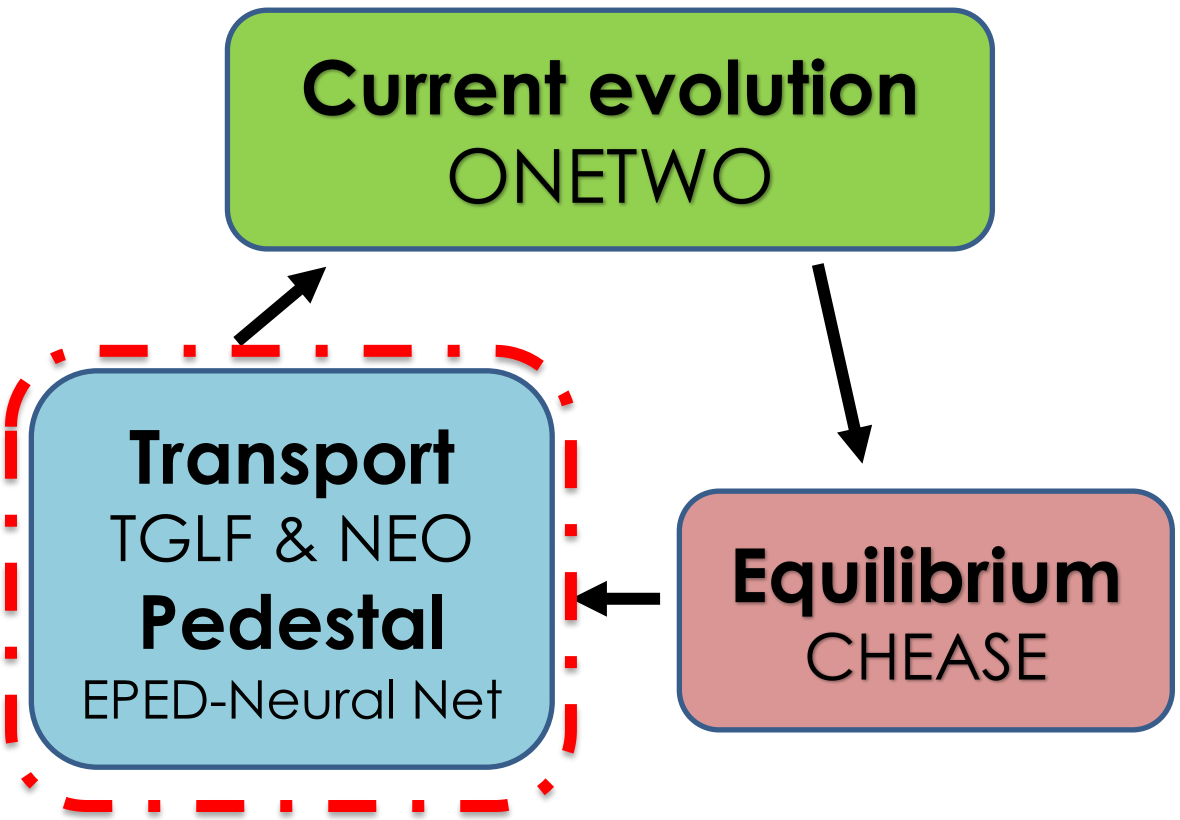
Profiles Creator (PRO-create):

- Simple analytic profiles
- Consistent equilibrium
- Heating and current drive Gaussian profiles
- Physically feasible plasma profiles
- Starting point for coupled physics models

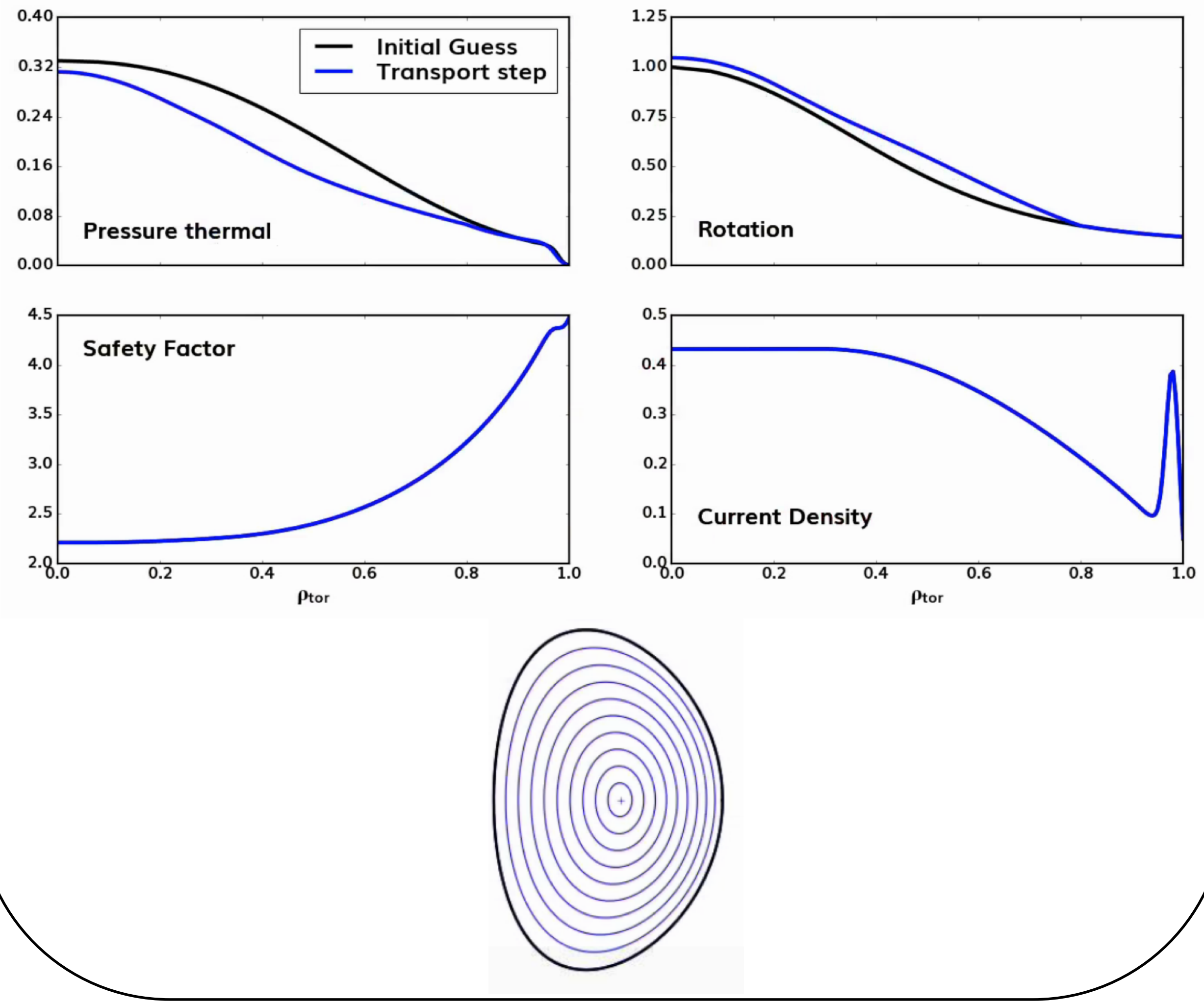
GENERAL ATOMICS

STEP Workflow to obtain self-consistent solution (Transport and Pedestal)

STEP Workflow

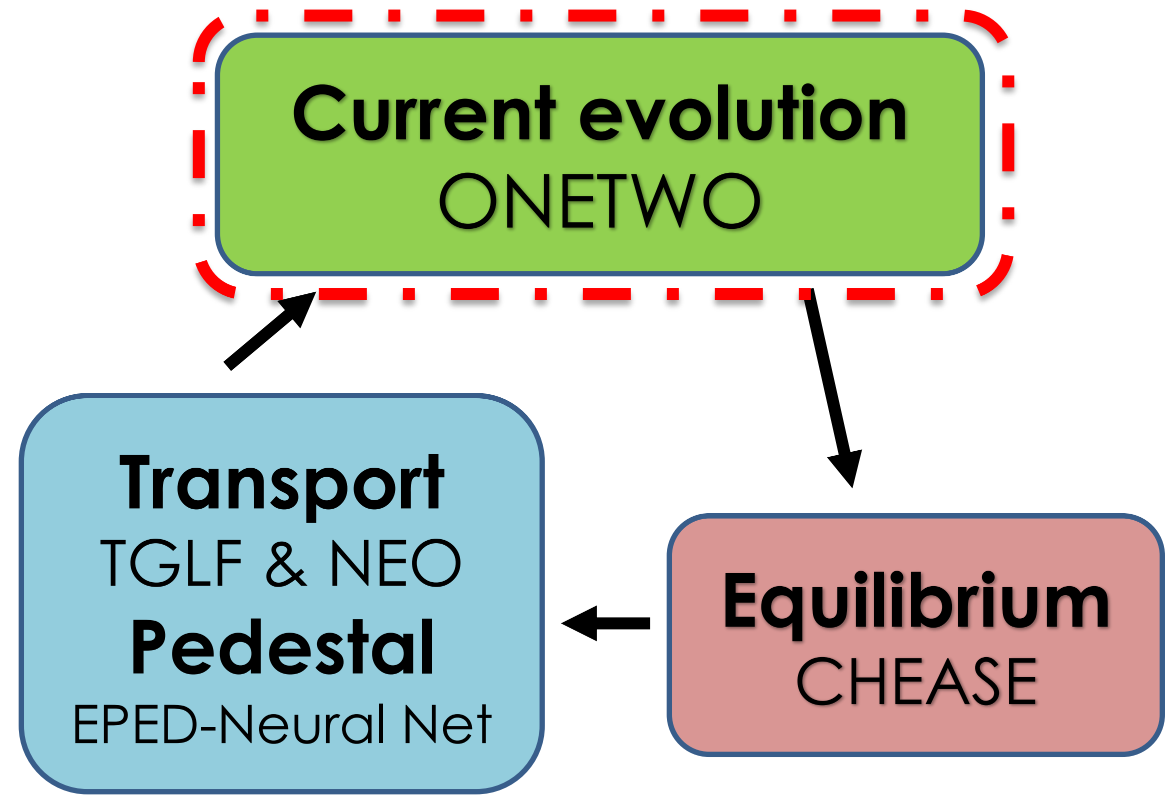


Transport & Pedestal step

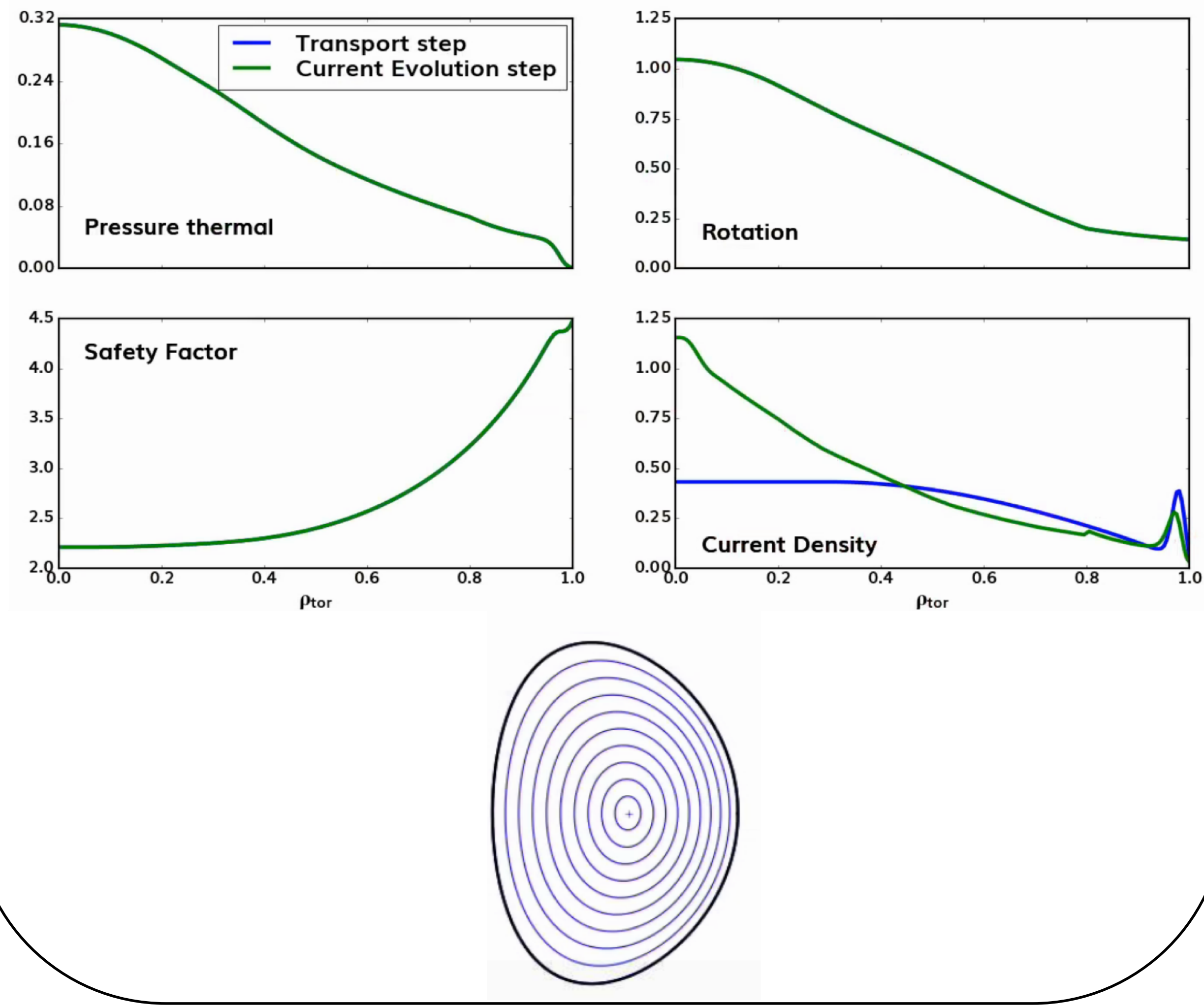


STEP Workflow to obtain self-consistent solution (Current evolution)

STEP Workflow



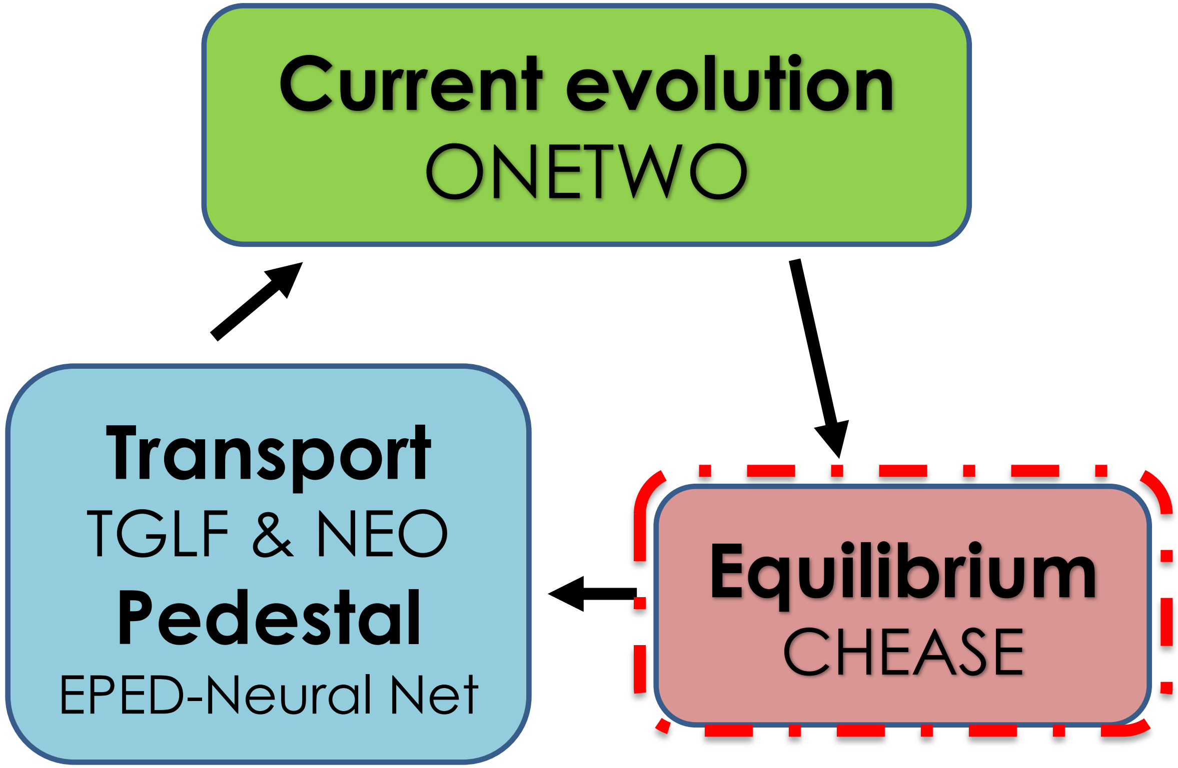
Current evolution step



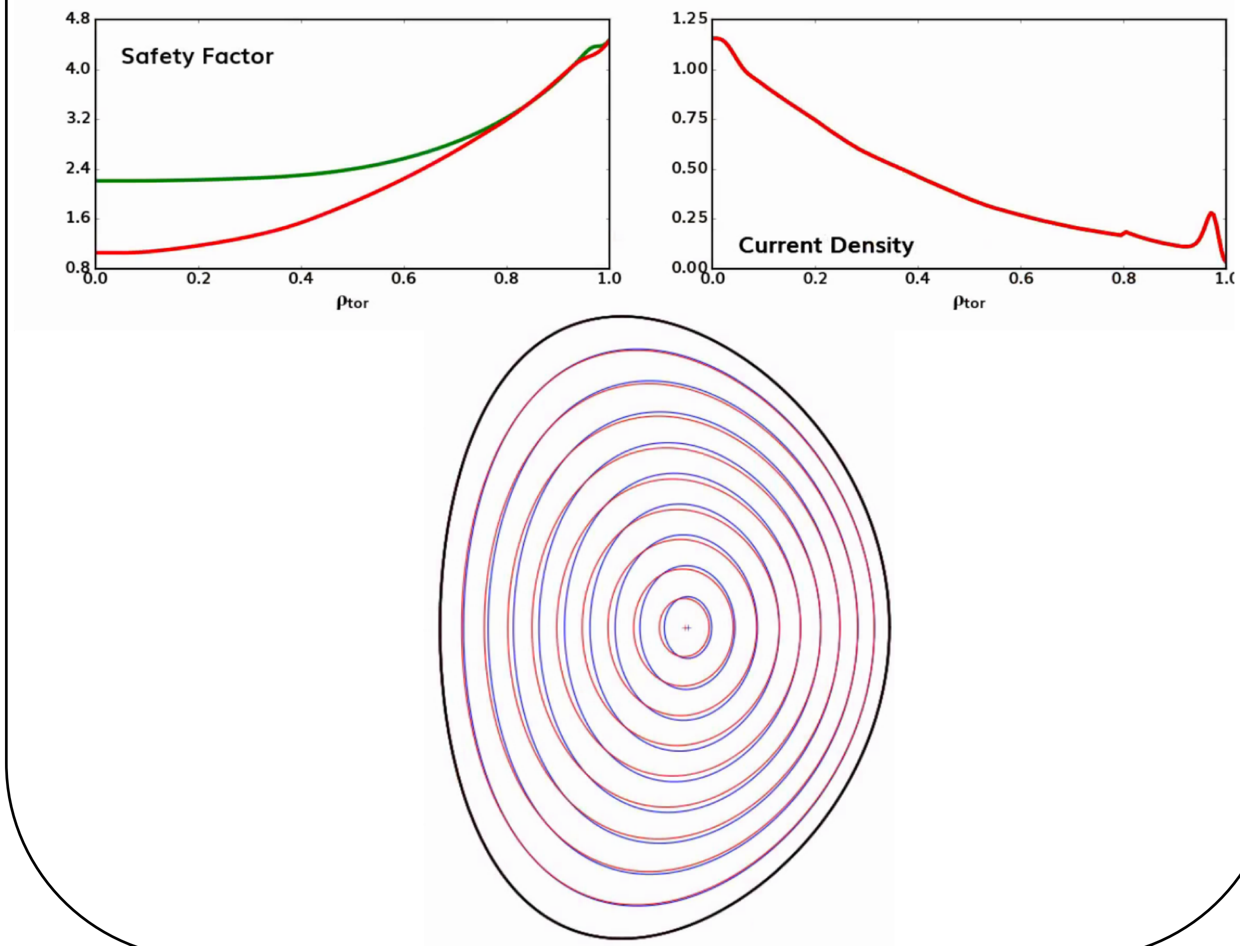
GENERAL ATOMICS

STEP Workflow to obtain self-consistent solution (Equilibrium)

STEP Workflow

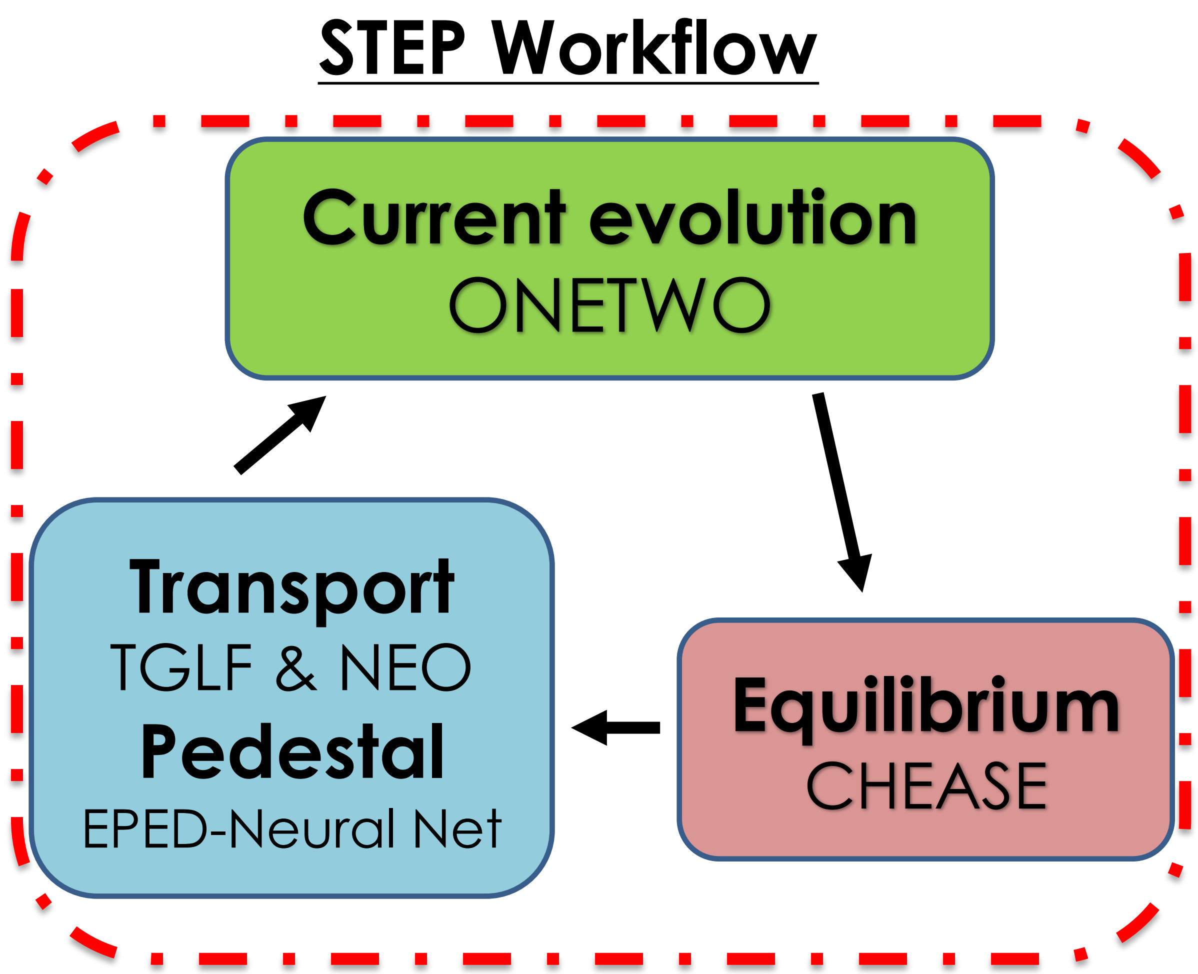


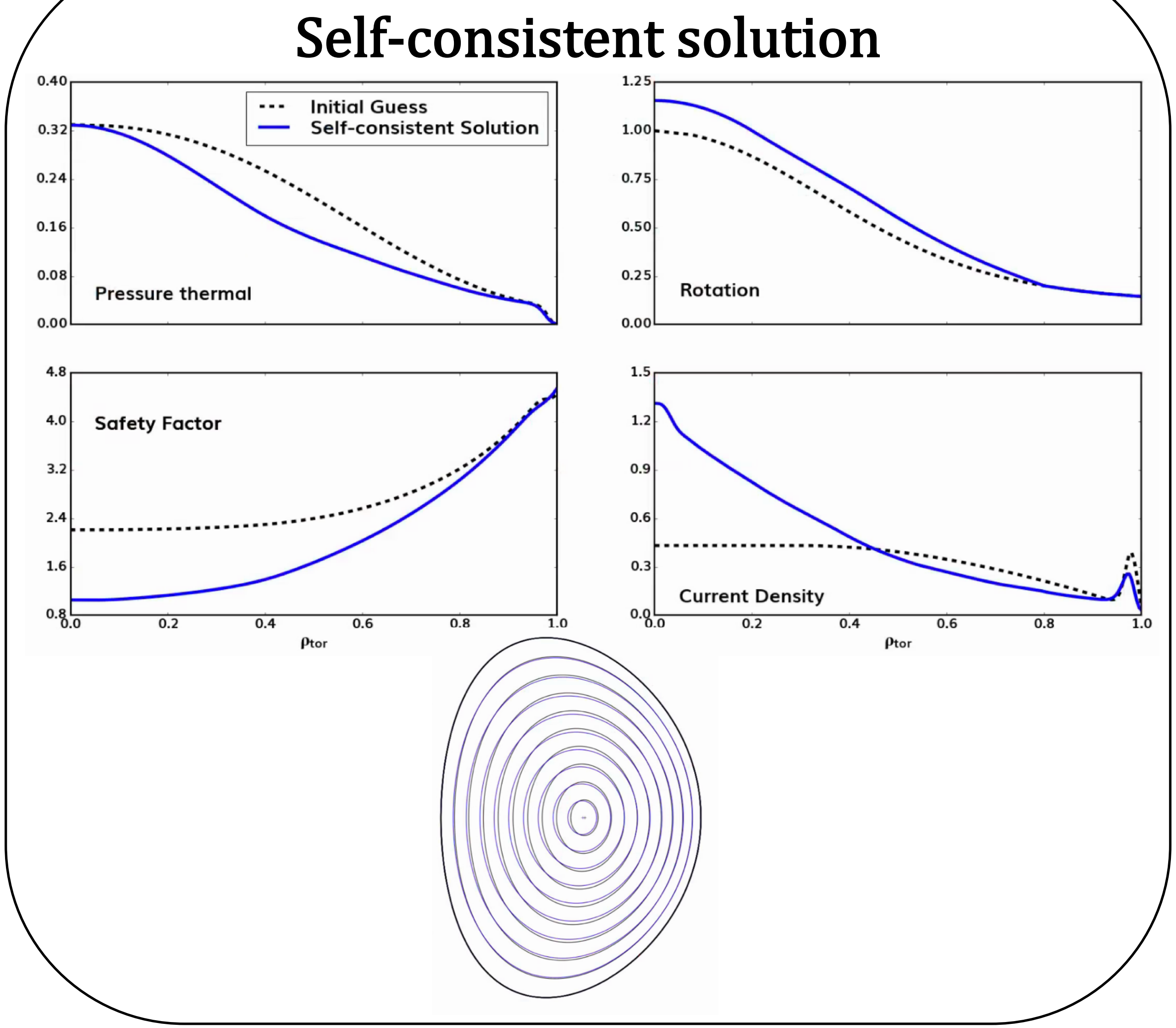
Equilibrium step



GENERAL ATOMICS

STEP Workflow to obtain self-consistent solution (final)

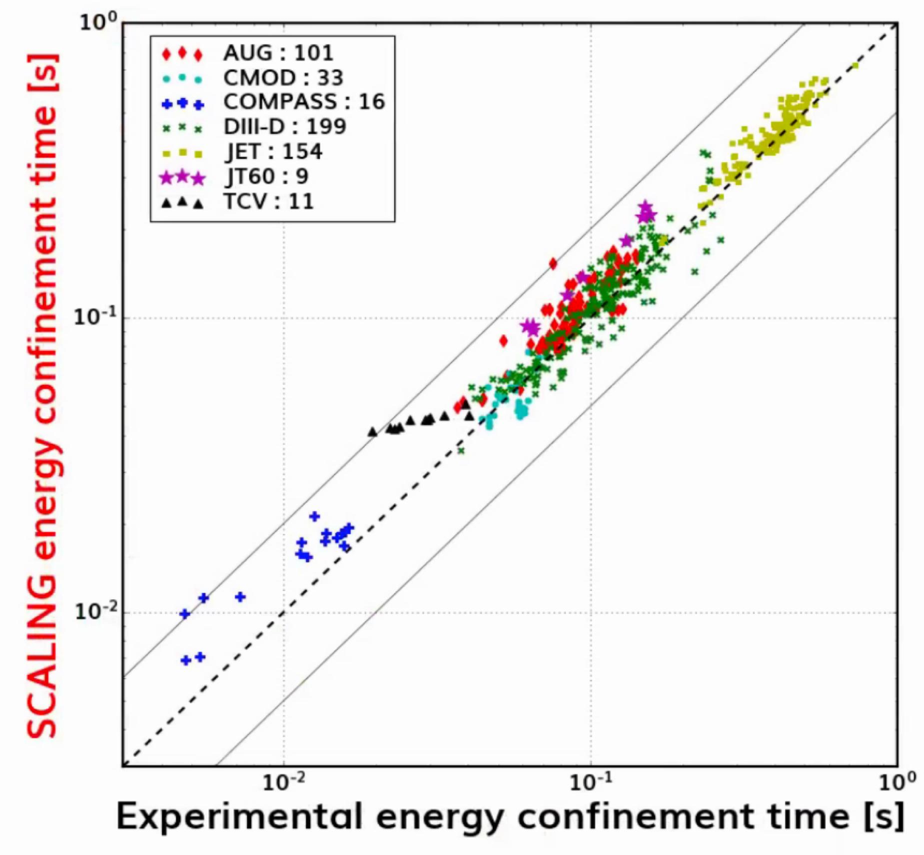




GENERAL ATOMICS

Predictive workflow validation on ITPA database

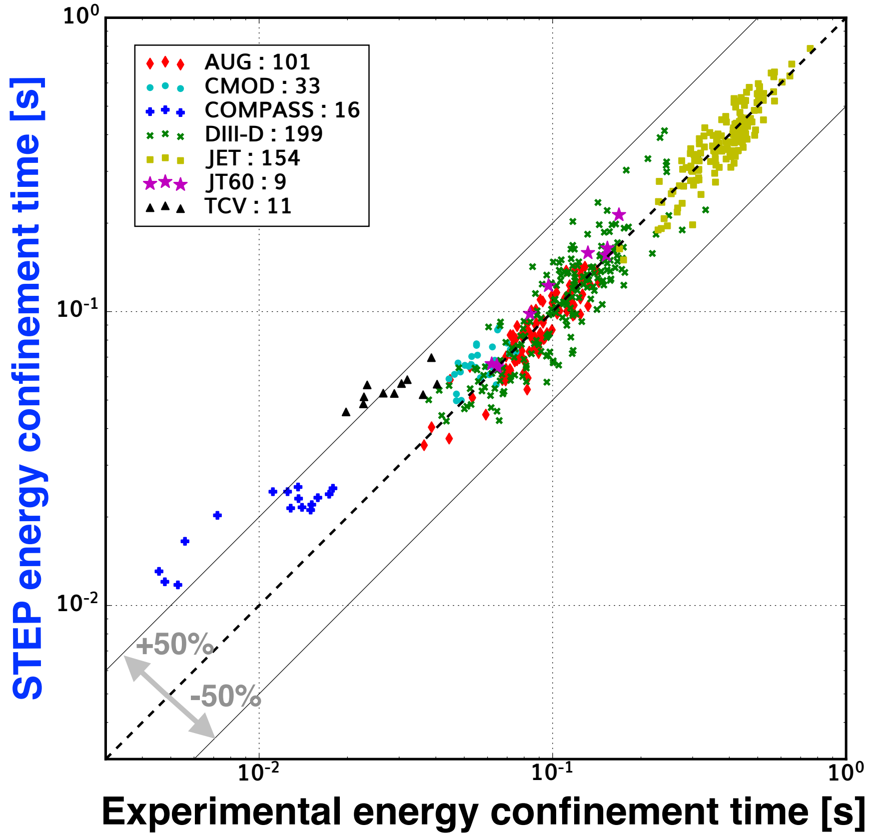
- **Validated on H-mode discharges from ITPA DB**
  - Filter
    - $\kappa < 1.3$ (EPED-nn valid domain)
    - Triangularity available
    - Keep only Deuterium plasmas
  - ~500 discharges from 7 different tokamaks
  - Carbon impurity plasmas
    - exception of CMOD (Mo treated as Ne)
  - 3 orders of magnitude in energy confinement time
- **H98,y2 scaling law is based on this dataset**

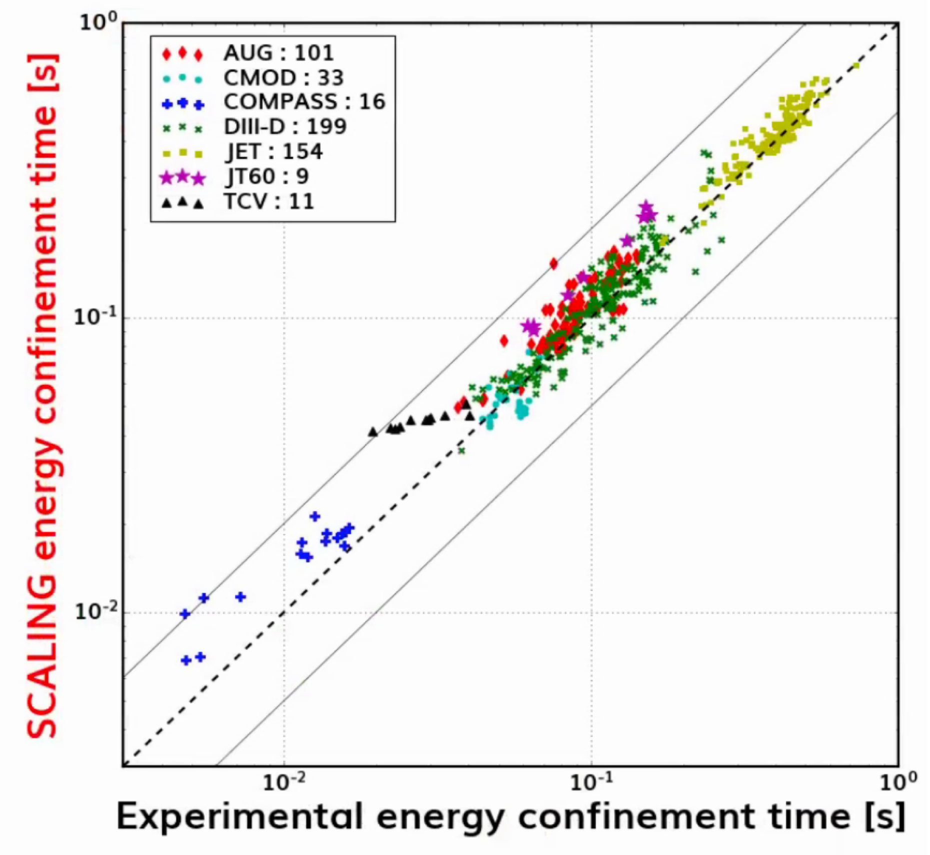


GENERAL ATOMICS

Predictive workflow successfully validated on ITPA DB5 confinement database

- **Validated on H-mode discharges from ITPA DB**
  - Mean relative error STEP 18% (including outliers)
  - For comparison Scaling law 22% mean relative error
  - Outliers ELM III discharges (COMPASS, TCV)





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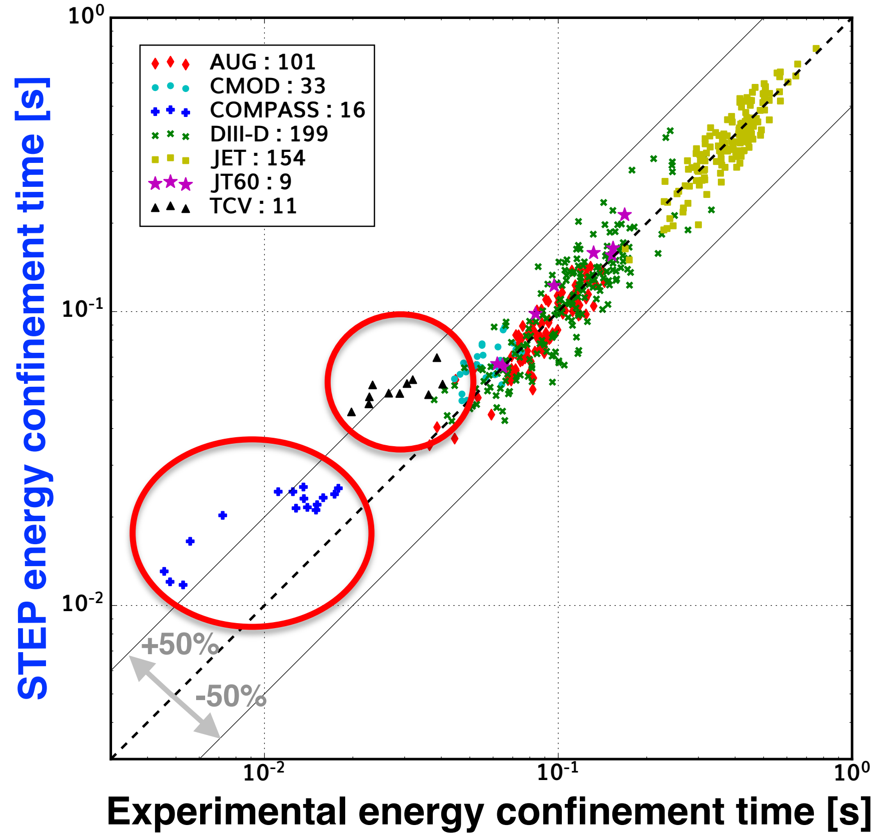
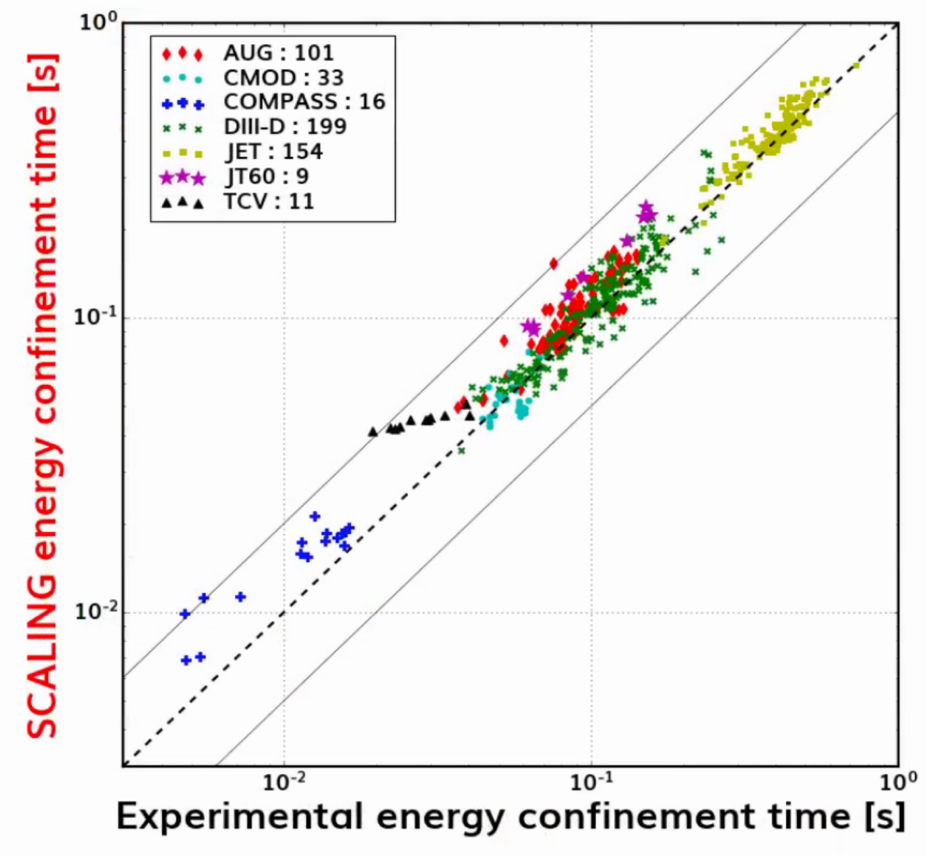
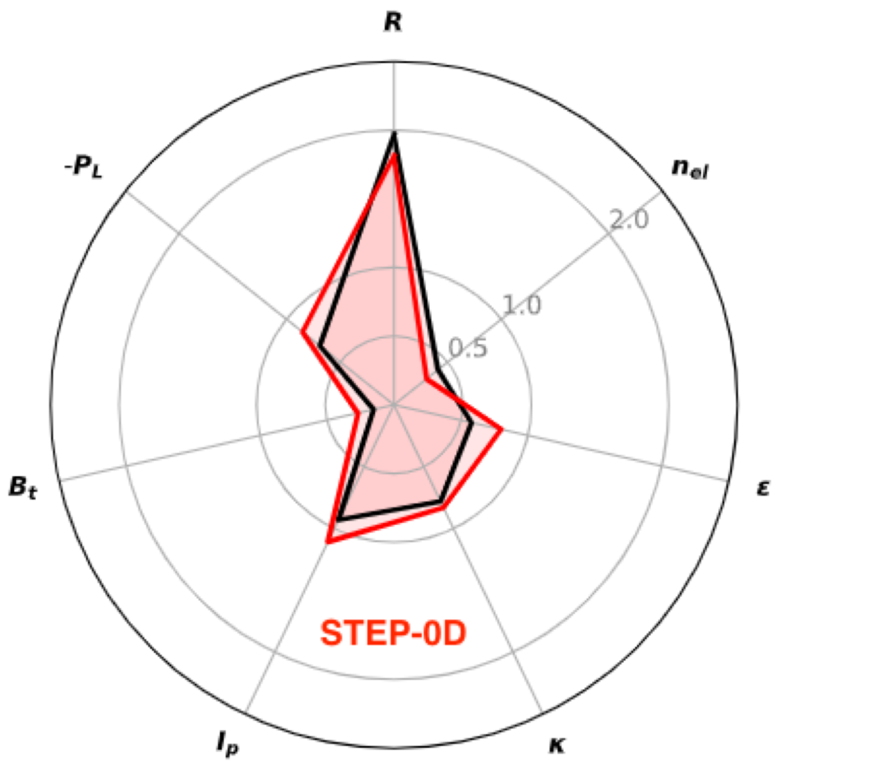




STEP workflow shows good agreement with the scaling law on the ITER-h98, y2 db

- **Weighted Linear Regression (WLS) of the STEP results and the whole database**
- **Radar plot displays power law exponents**
- **STEP reproduces the scaling law with less data**

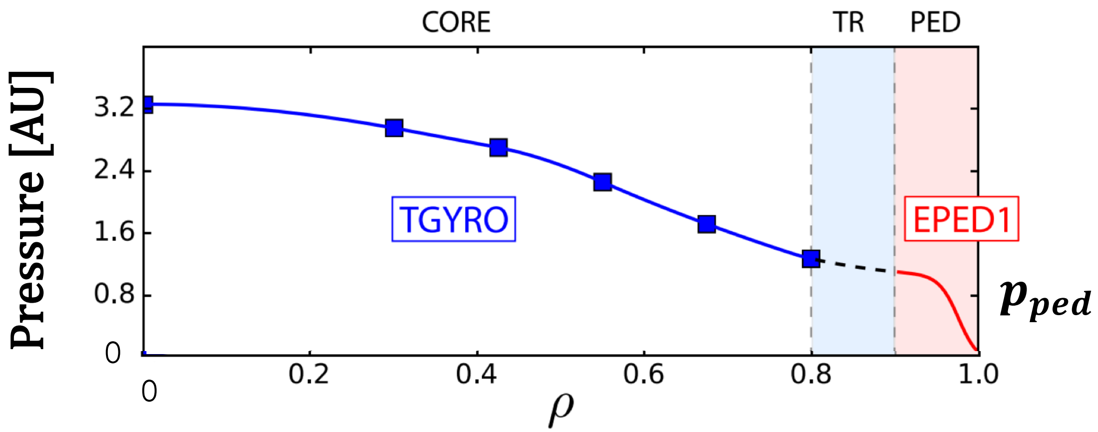


$$\tau_{e\ \mathrm{h98y2}} \propto I_p^{0.93} B_0^{0.15} P_{loss}^{-0.69} \kappa^{0.78} n_e^{0.41} A^{-0.52} R^{1.97}$$

$$\tau_{e\ \mathrm{STEP}} \propto I_p^{1.11} B_0^{0.26} P_{heat}^{-0.82} \kappa^{0.83} n_e^{0.3} A^{-0.8} R^{1.811}$$

Evaluating the relative importance of pedestal vs core on confinement

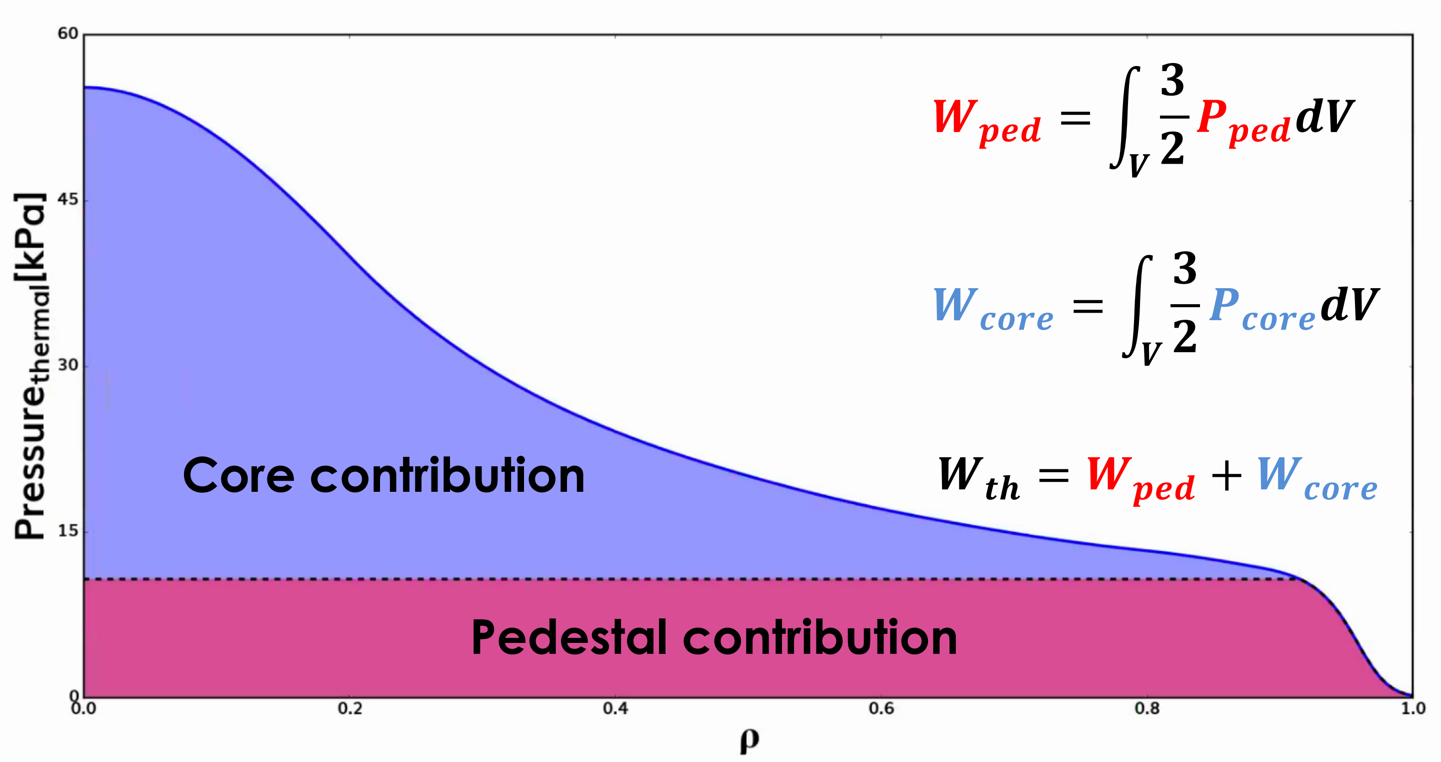
- **STEP simulations capture the physics of the pedestal (EPED) and core transport (TGYRO)**

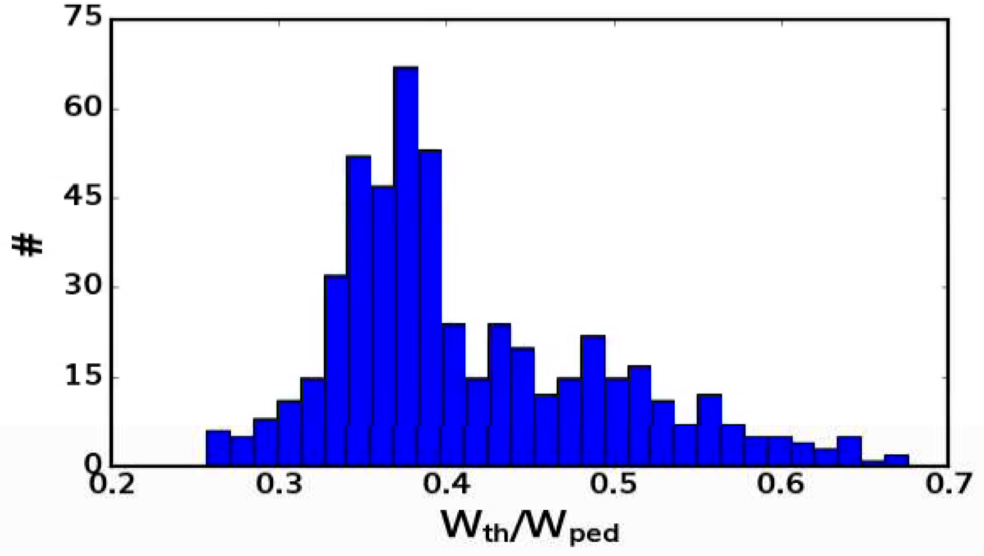


- **Comparing the pedestal and core contribution to the thermal stored energy**

Evaluating the relative importance of pedestal vs core on confinement

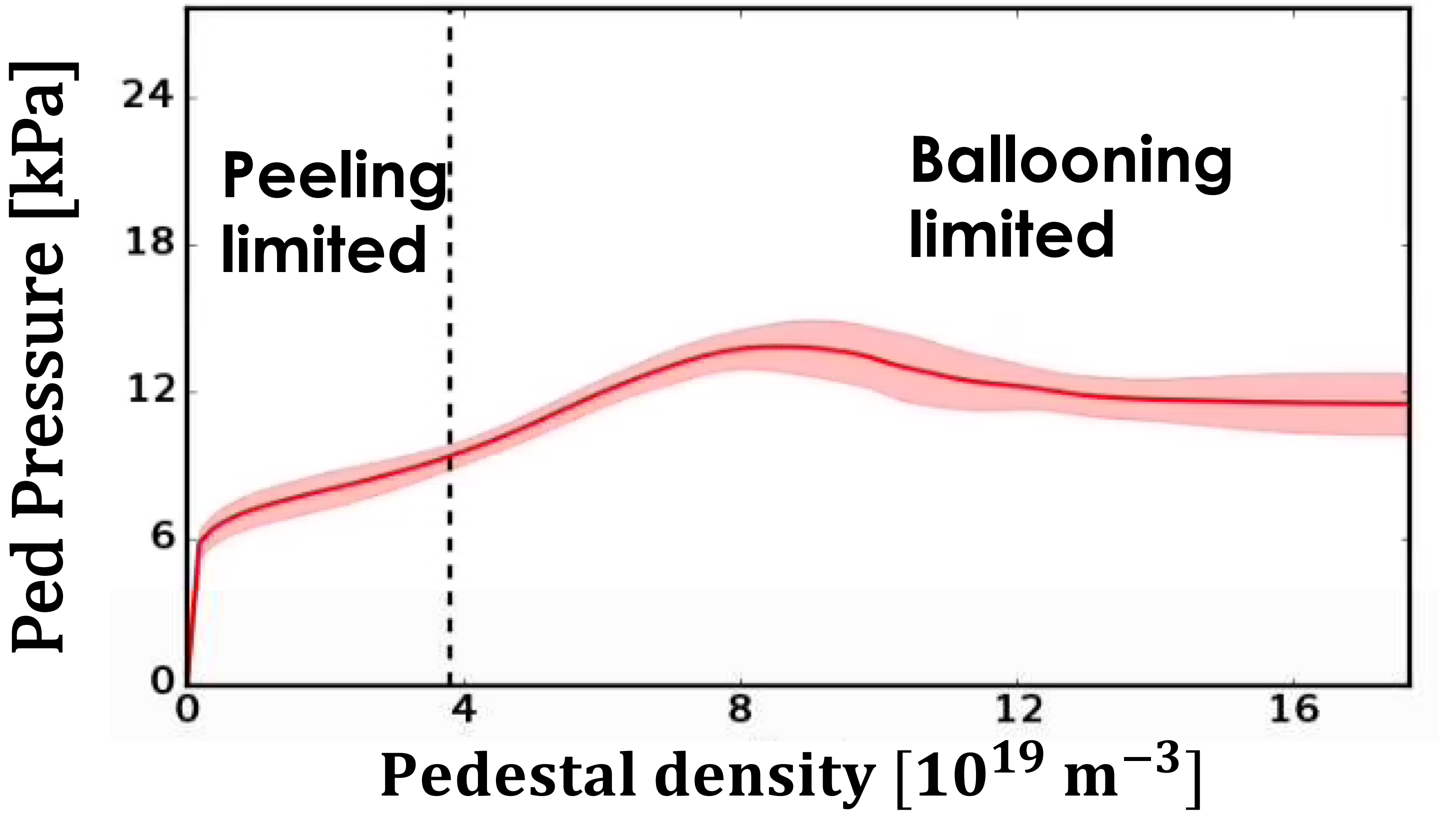
- **Pedestal and core contribution to the stored energy**





- **Pedestal contribution is large for conventional H-mode**

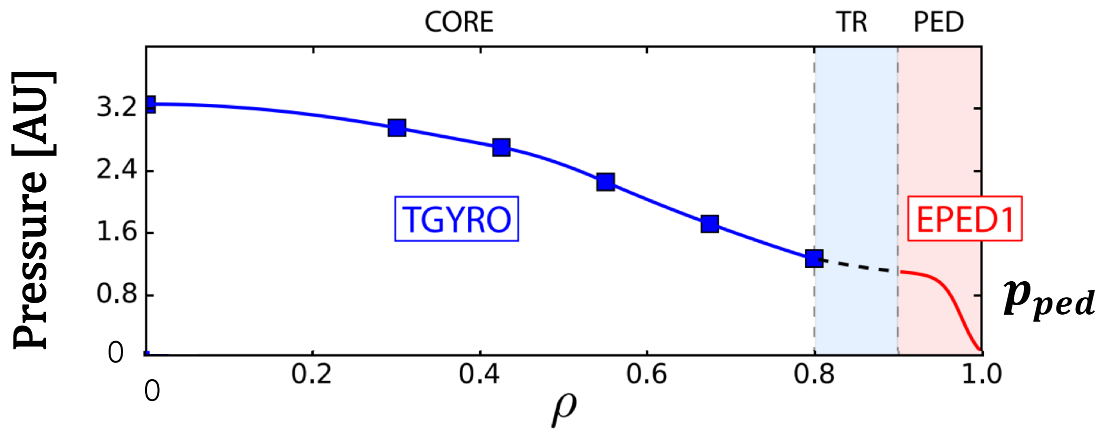
Limitation of scaling laws is that they are valid only near operation point



- Low density pedestal is peeling limited
- High density is ballooning limited
- Scaling laws miss this type of physical bifurcation
- Scaling laws have difficulty in finding ne dependence

STEP provides a framework for testing coupling of core-edge models in different regimes

- **EPED is a good model for conventional type-I ELMy H-mode regimes**



- **Unmitigated ELM type-I is troubling for reactor sized devices**
- **Edge models for other regimes are still subject to active investigation:**
  - L-mode
  - Negative Triangularity
  - RMP-suppressed plasmas
  - QH-mode
  - Grassy ELM regime

Conclusion and future work

- **New STEP workflow that predicts energy confinement time of 0D engineering parameters**
- **Validated on ~500 plasma discharges across 7 tokamak experiments**
- **Edge (pedestal) contribution is key for conventional H-mode plasmas**
- **Coupling of edge models for different regimes is an ongoing investigation**

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