Development and Validation of a Self-Consistent Core, Pedestal, and Equilibrium Model

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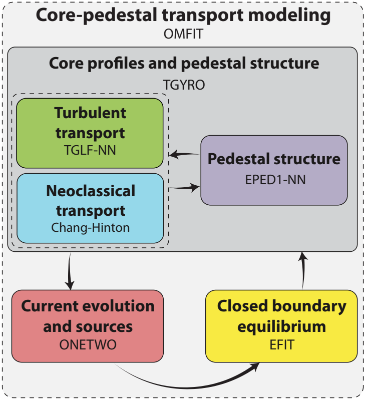


Core-pedestal transport modeling
OMFIT

Core profiles and pedestal structure
TGYRO

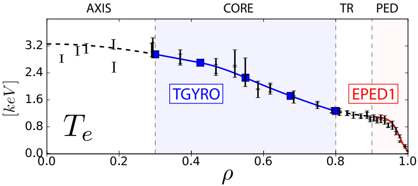
Turbulent transport
TGLF-NN

Neoclassical transport
Chang-Hinton

Pedestal structure
EPED1-NN

Current evolution and sources
ONETWO

Closed boundary equilibrium
EFIT

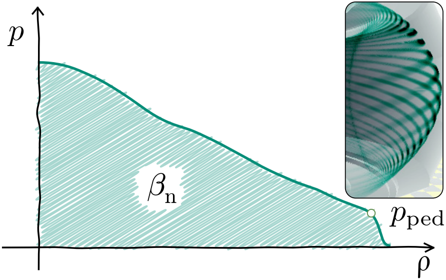


A self-consistent core, pedestal and equilibrium model is needed for reliable prediction of fusion performance

Core and pedestal regions of the plasma are **strongly coupled** to one another:

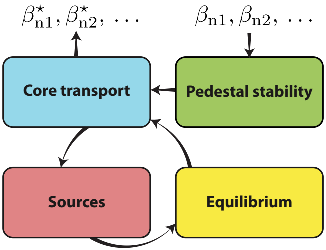
- **Pedestal $\Longrightarrow$ Core**
  Pedestal affects core pressure via the boundary condition

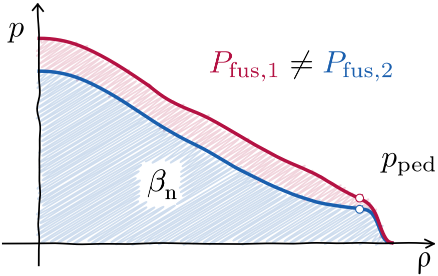
- **Core $\Longrightarrow$ Pedestal**
  Core pressure affects the pedestal via the Shafranov shift of the equilibrium, which improves stabilization of edge MHD instabilities



$$P_{\mathrm{fus}} \propto \beta_{\mathrm{n}}^2 \Leftrightarrow p_{\mathrm{ped}}^2$$

Typical core transport studies assume that the pedestal structure is given and is fixed

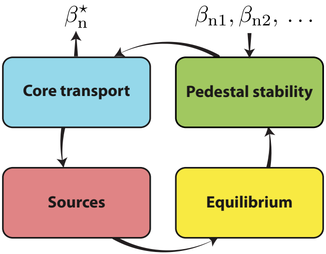


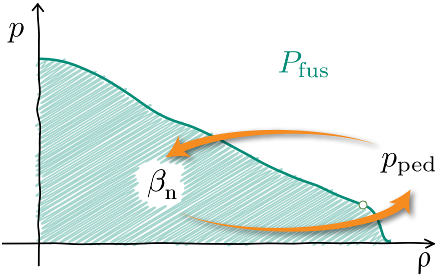


- **Pedestal held fixed** while only core, sources, and equilibrium are iterated to self-consistency
- Can be highly inaccurate for poor initial assumptions about the pedestal

- **Inconsistency** between predicted $\beta^\star_{\mathrm{n}}$ and initially assumed β_{n}
- **Different predictions** depending on initial assumptions of β_{n}

In this work we self-consistently account for the core-pedestal interaction





- Pedestal, core, sources and equilibrium are **all iterated to consistency**
- Starting β_n is not a fixed assumption, but rather the **initial guess** to a non-linear root-finding problem

- A **unique solution** with self-consistent core and pedestal predictions
- Final solution **independent of initial guess** for β_n

Outline

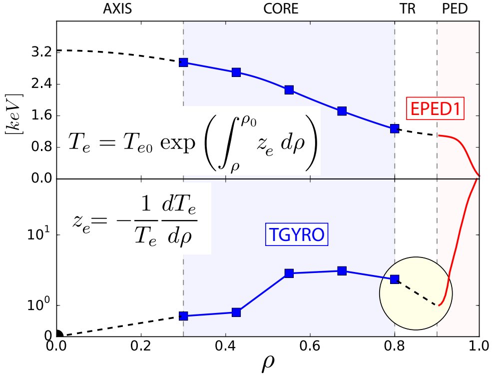
1. Iterative workflow and coupling scheme to robustly find self-consistent solution

2. Self-consistent optimization of fusion power for ITER baseline scenario

3. Accelerated core-pedestal predictions with neural-network based models

Technique used to couple core-pedestal models based on expectation that profiles should be continuous and smooth

Four radial zones based on the dominant H-mode physics:



$$T_e = T_{e0} \exp\left(\int_{\rho}^{\rho_0} z_e \, d\rho\right)$$

$$z_e = -\frac{1}{T_e}\frac{dT_e}{d\rho}$$

Smooth profiles are obtained by integrating piece-wise linear z

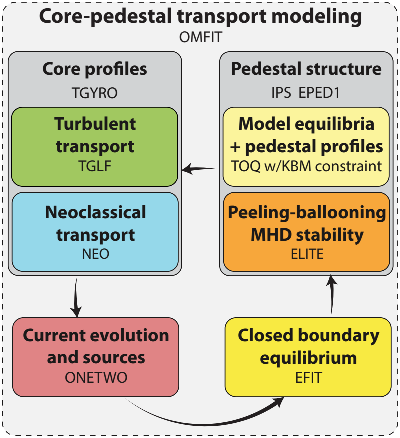
EPED1 model finds H-mode **pedestal** profile with maximum stable height and width

TGYRO finds z for which fluxes balance sources in the **core**

z is zero on **axis**

Transition region adapts z consistent with core transport, to the one that is consistent with MHD stability in the pedestal

Iterative workflow robustly and efficiently finds the self-consistent steady-state coupled solution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IPS EPED1

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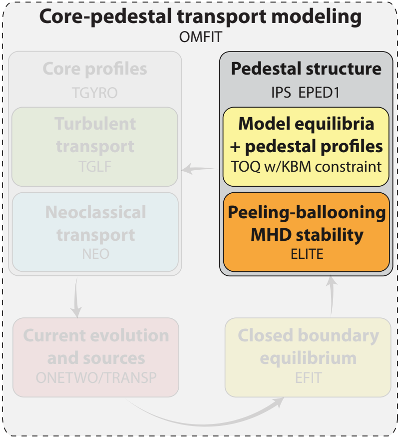
Physics inputs to the workflow:

- Pedestal model
  - Plasma shape, B_t and I_p
  - $n_{e,\mathrm{ped}}$ and $Z_{\mathrm{eff},\mathrm{ped}}$
  - Initial guess for β_n
- Transport code
  - Configuration of particle, heat, current and momentum sources

Illustrative example: DIII-D ITER baseline scenario discharge with low torque and electron heating

Start with EPED1 to obtain an initial equilibrium and profiles $\beta_{\mathrm{n,guess}} = 75\%\, \beta_{\mathrm{n,exp}} = 1.3$



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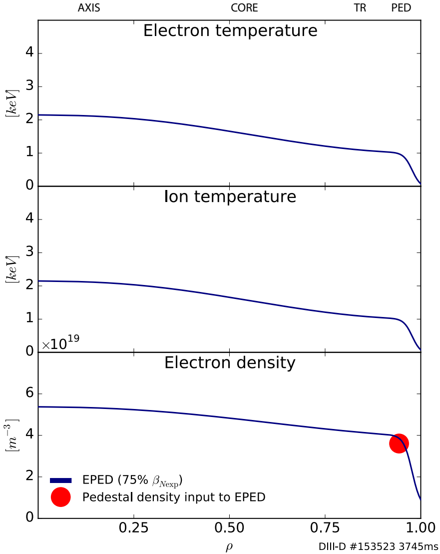
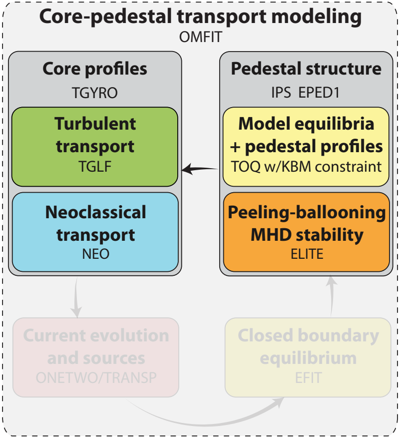


DIII-D #153523 3745ms

TGYRO evolves core with pedestal as boundary condition



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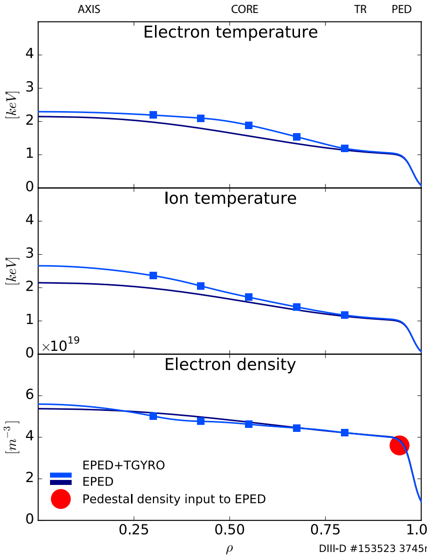
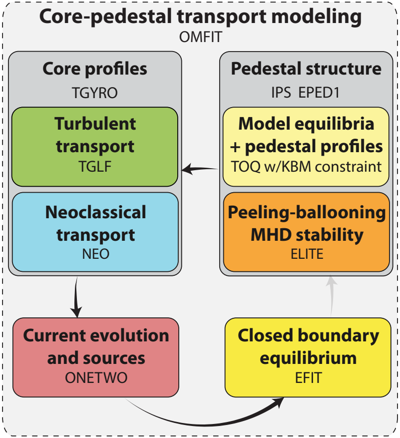


DIII-D #153523 3745ms

Update sources, current profile and equilibrium → new β_n



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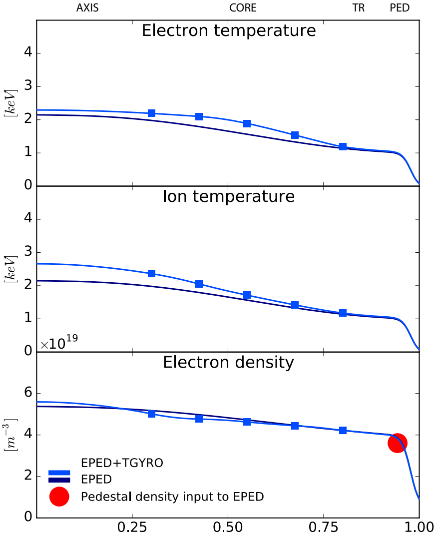
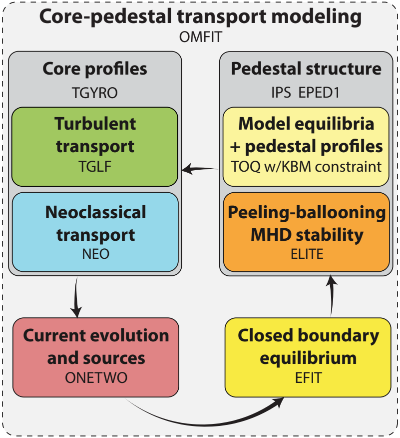


DIII-D #153523 3745ms

Pedestal calculation is updated based on the new value of global pressure β_n, and loop is iterated until convergence



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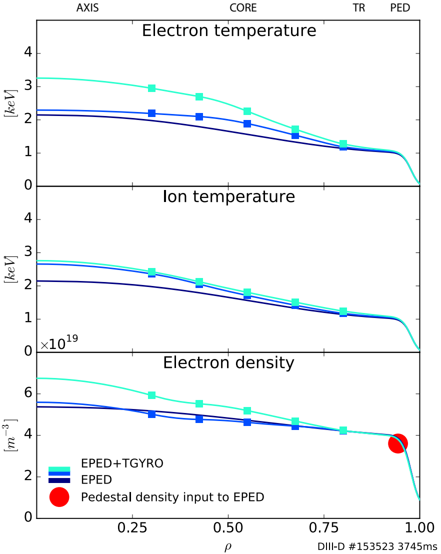

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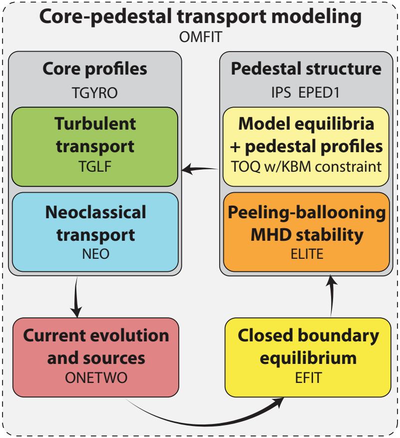

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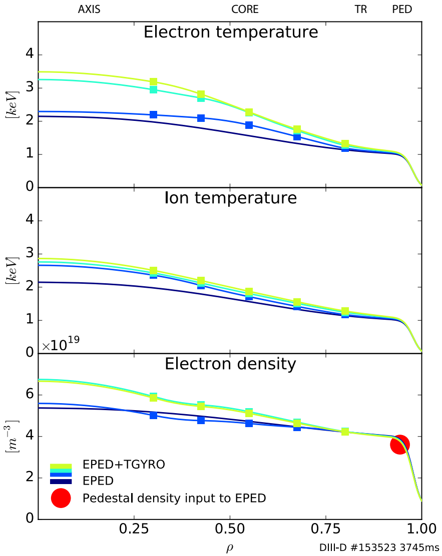
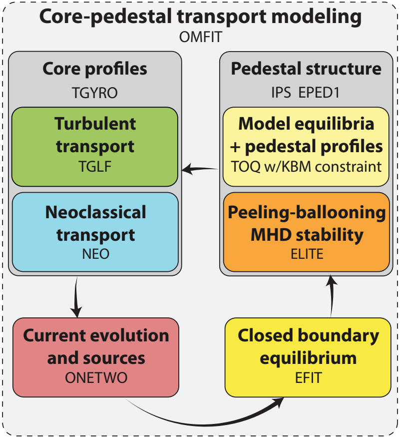


DIII-D #153523 3745ms

GENERAL ATOMICS

Pedestal calculation is updated based on the new value of global pressure β_n, and loop is iterated until convergence



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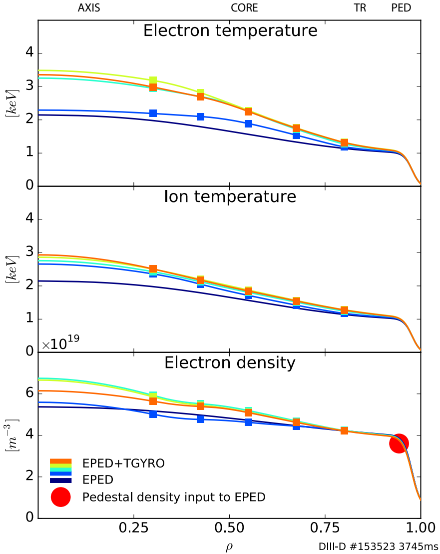

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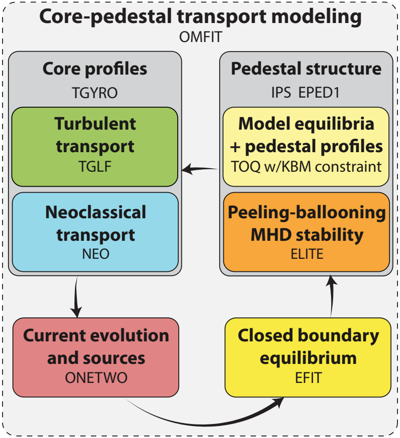

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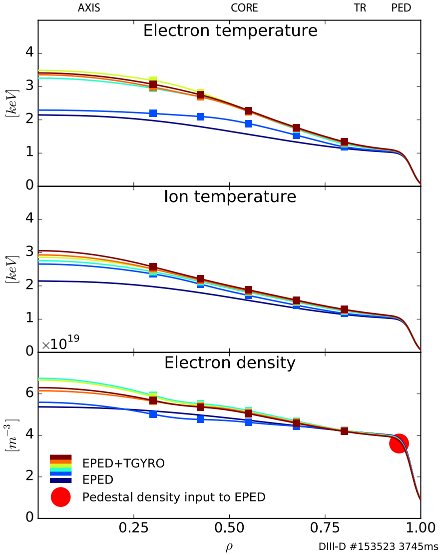
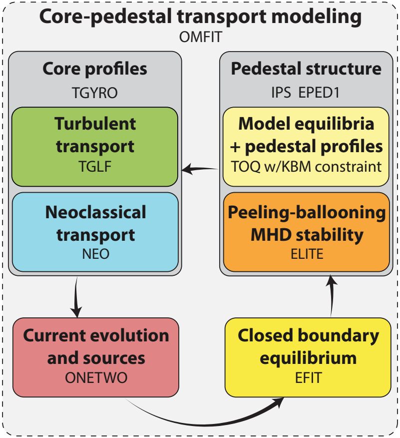


DIII-D #153523 3745ms

Converged solution compares very well with measurements across the whole plasma



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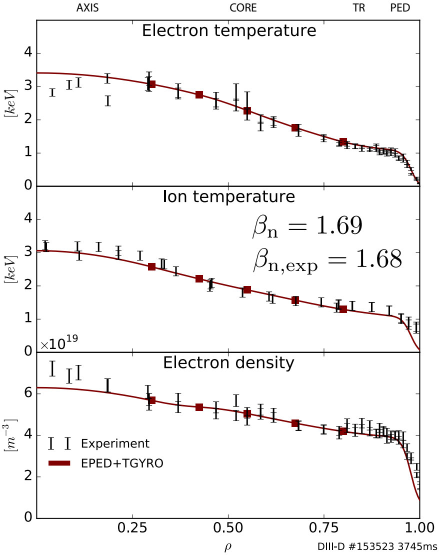
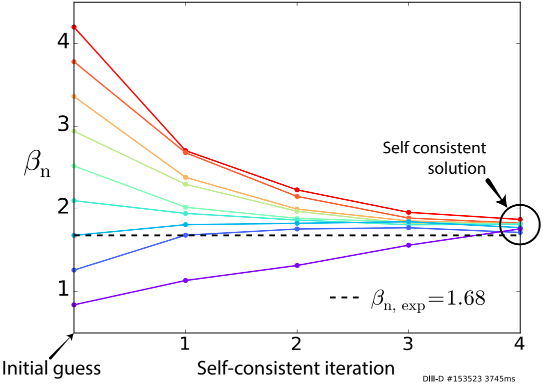


DIII-D #153523 3745ms

Converged solution is insensitive to the initial guess of global pressure $\beta_{\mathrm{n,guess}}$

- Workflow converges to the same solution for a broad range of initial $\beta_{\mathrm{n,guess}}$
- $\beta_{\mathrm{n,guess}}$ is the initial guess to a non-linear root-finding problem
- Faster convergence for $\beta_{\mathrm{n,guess}} \sim \beta_{\mathrm{n,solution}}$

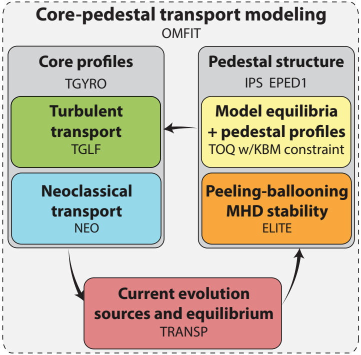


Self-consistent core-pedestal optimization of ITER baseline scenario with $n_{\mathrm{e,ped}}$ and $Z_{\mathrm{eff,ped}}$ as actuators

1 Iterative workflow and coupling scheme to robustly find self-consistent solution

2 Self-consistent optimization of fusion power for ITER baseline scenario

3 Accelerated core-pedestal predictions with neural-network based models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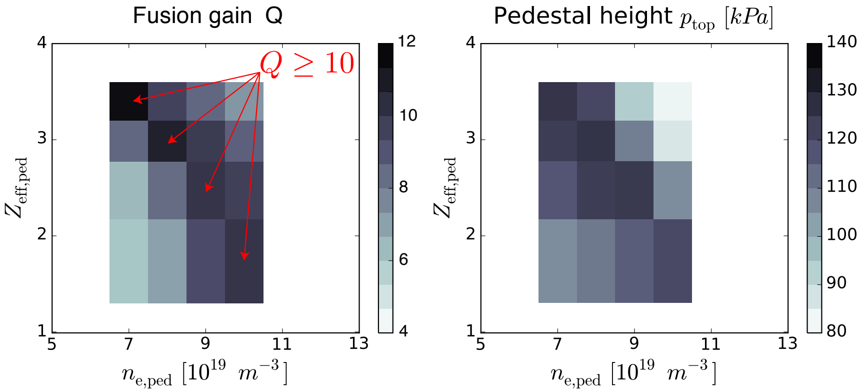
Initial conditions based on:

Budny,R.V. (2009) Nuclear Fusion **49** 115
Comparisons of predicted plasma performance in ITER H-mode plasmas

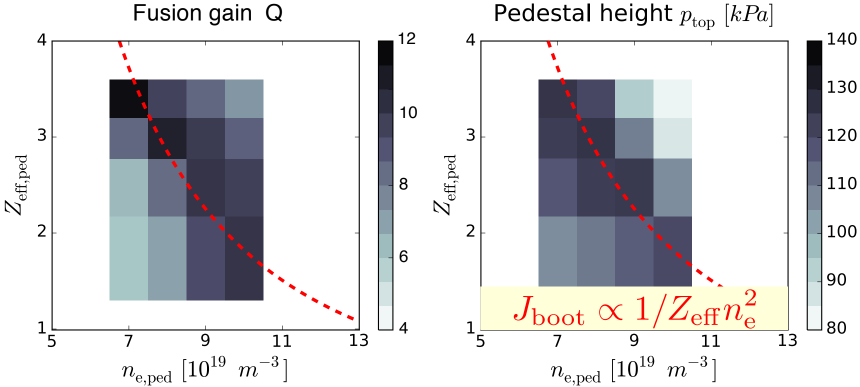
2D scan in n_e, Z_eff identifies a family of self-consistent solutions which satisfy ITER baseline $\mathrm{Q} \geq 10$ target



High fusion performance:

- for different values of n_e and Z_eff

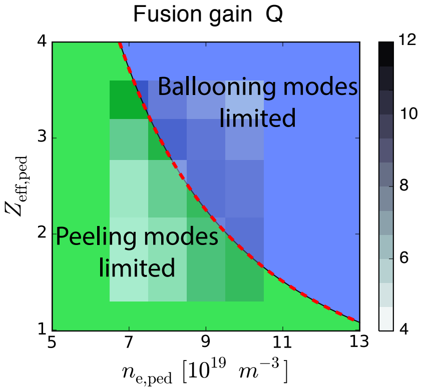
High fusion performance cases share similar values of pedestal pressure and bootstrap current

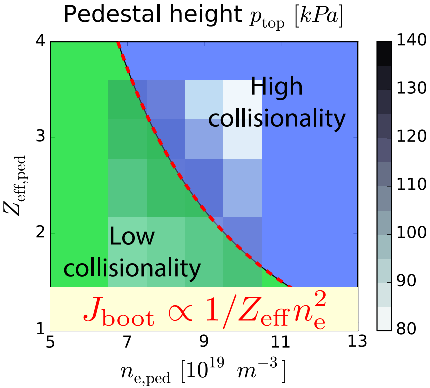


High fusion performance:

- for different values of n_{e} and Z_{eff}
- but similar values of pedestal pressure and bootstrap current

Lower fusion power conditions due to peeling or ballooning modes depending on pedestal collisionality





High fusion performance:

- for different values of n_{e} and Z_{eff}
- but similar values of pedestal pressure and bootstrap current
- where pedestal height is peeling-ballooning limited

First-principles core-pedestal transport simulation are computationally demanding and still require supervision

These self-consistent coupled core-pedestal simulations

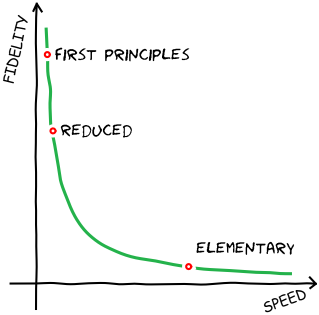
First Principles Models → **Reduced Models** → Elementary Models

Standalone → **Loose Coupling Integration** → Tight Coupling Integration

Days/**Hours** → **Minutes**/Seconds → Milliseconds

One of a Kind → **Supervised** → Automatic

Physics Validation → Planning & Engineering → Control



1+ hour for each self-consistent iteration (at least 5+ iterations)

- **EPED1** ∼ 20 mins on HPC with hundreds of cores
- **TGLF** ∼ secs but transport solution requires 1000's of evaluations

Elementary models faster, but at the cost of reduced physics fidelity

⇒ **need to break traditional modeling speed-vs-fidelity tradeoff** ⇐

Neural Network paradigm can provide the missing link towards functional whole device modeling simulations

Self-consistent core-pedestal coupled simulations **with NN**

First Principles Models → Reduced Models → **Neural Network Models**

Standalone → Loose Coupling Integration → **Tight Coupling Integration**

Days/Hours → Minutes/**Seconds** → **Milliseconds**

One of a Kind → Supervised → **Automatic**

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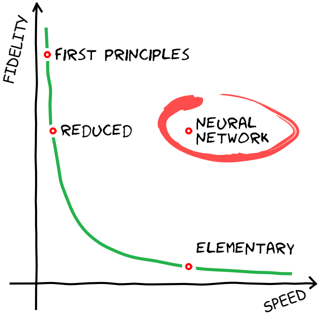

Neural networks can be used to produce a non-linear multidimensional regression to a database of high fidelity calculations

- NN models are fast and yet retain fidelity of training simulations
- Regularization techniques used to obtain smooth NN output

Accelerated EPED1 and TGLF models with neural networks to enable routine coupled core-pedestal transport studies

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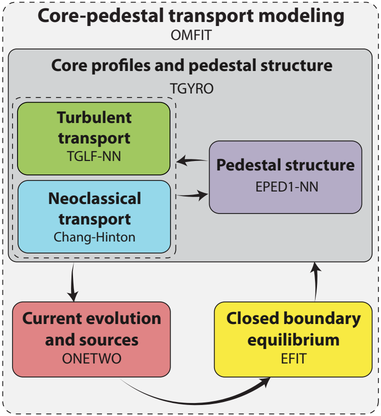

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TGYRO simulations with coupled core-pedestal NN models run in few seconds

EPED1-NN model closely reproduces EPED1 predictions Trained across input parameter range of multiple devices

10 EPED input parameters to predict p_{ped}, w_{ped}

Trained on database of ∼20,000 EPED1 runs (2 million CPU hours)

DIII-D: 3,000 runs

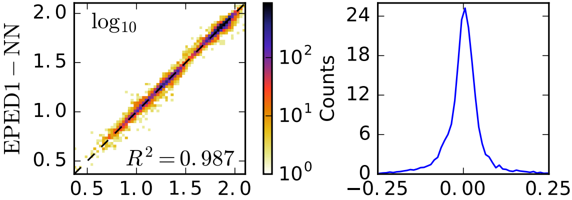
KSTAR: 700 runs

JET: 200 runs

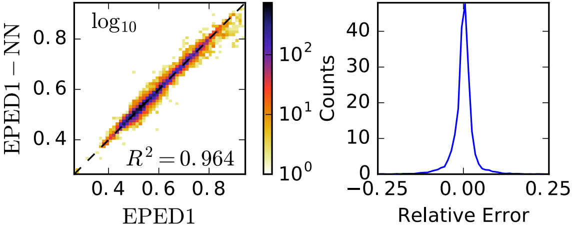
ITER: 15,000 runs

$\times 10^9$ **speedup**

Pedestal height p_{ped} [kPa]



Pedestal width w_{ped} [$\Delta\%\psi$]

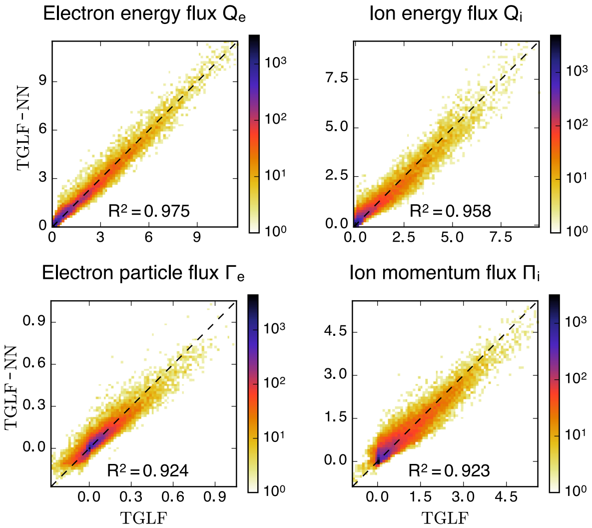


TGLF-NN model closely reproduces TGLF predictions
Trained on ion energy transport DIII-D experiments

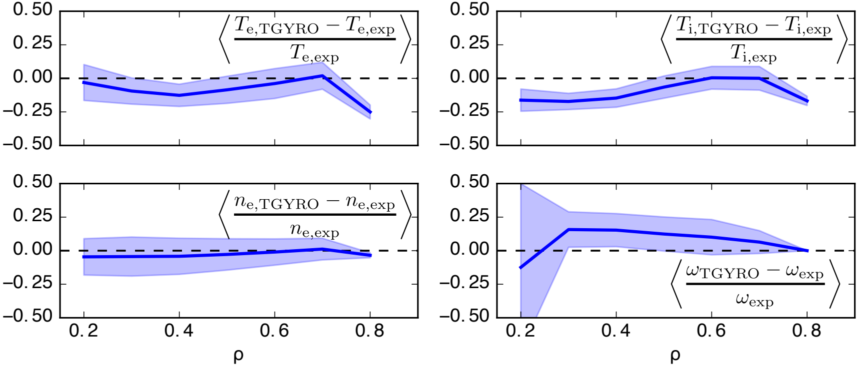
23 TGLF input parameters to predict gyro-Bohm fluxes $Q_e, Q_i, \Gamma_e, \Pi_i$

Trained on database of 32,000 TGLF runs based on DIII-D experiments aimed at probing ion energy transport (power and torque scans)

$\times 10^6$ **speedup**



Validated TGYRO simulations with coupled NN models against 200 time slices from DIII-D ion transport experiments



- For this dataset on average β_n converges to $\sim 90\%\ \beta_{n,exp}$
- Robust NN models → convergence does not require supervision

Conclusion: enabling core-pedestal coupled workflow, and increasing speed by millions with neural networks

❶ Iterative workflow robustly finds self-consistent solution without pedestal height/width as free parameters

❷ Scan in $n_{\mathrm{e,ped}}$ as well as $Z_{\mathrm{eff,ped}}$ has identified a family of self-consistent solutions for which $Q \geq 10$ ITER baseline target can be achieved

❸ TGLF-NN and EPED1-NN accelerate core/pedestal calculations and provide the missing link for functional WDM simulations and control

Next step: core ⇔ pedestal ⇔ SOL coupling