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

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

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

$$P_{\text{fus}} \propto \beta_n^2 \Leftrightarrow p_{\text{ped}}^2$$
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 $\beta_n^*$ and initially assumed $\beta_n$
- **Different predictions** depending on initial assumptions of $\beta_n$
In this work we self-consistently account for the core-pedestal interaction

- Pedestal, core, sources and equilibrium are all iterated to consistency
- Starting $\beta_n$ 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 $\beta_n$
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:

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

Smooth profiles are obtained by integrating piece-wise linear $z$
Iterative workflow robustly and efficiently finds the self-consistent steady-state coupled solution.

Physics inputs to the workflow:

- **Pedestal model**
  - Plasma shape, $B_t$ and $I_p$
  - $n_{e,\text{ped}}$ and $Z_{\text{eff,ped}}$
  - Initial guess for $\beta_n$

- **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 
\[ \beta_{n,\text{guess}} = 75\% \beta_{n,\text{exp}} = 1.3 \]

Core-pedestal transport modeling
OMFIT

- Core profiles
  - TGYRO
- Turbulent transport
  - TGLF
- Neoclassical transport
  - NEO
- Pedestal structure
  - IPS EPED1
- Model equilibria + pedestal profiles
  - TOQ w/KBM constraint
- Peeling-ballooning
  - MHD stability
    - ELITE
- Closed boundary equilibrium
  - EFIT

Current evolution and sources
ONETWO/TRANSP

Electron temperature

Ion temperature

Electron density

EPED (75\% \beta_{\text{exp}})
Pedestal density input to EPED

O. Meneghini - 2016 IAEA FEC Kyoto
TGYRO evolves core with pedestal as boundary condition

Core-pedestal transport modeling
OMFIT

Core profiles
TGYRO

Pedestal structure
IPS EPED1

Model equilibria + pedestal profiles
TOQ w/KBM constraint

Peeling-ballooning
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Turbulent transport
TGLF

Neoclassical transport
NEO

Current evolution and sources
ONETWO/TRANSP

Closed boundary equilibrium
EFIT

Electron temperature

Ion temperature

Electron density

EPED+TGYRO
EPED
Pedestal density input to EPED

DIII-D #153523 3745ms

O. Meneghini - 2016 IAEA FEC Kyoto
Update sources, current profile and equilibrium → new $\beta_n$

Core-pedestal transport modeling
OMFIT

Core profiles
TGYRO

Pedestal structure
IPS EPED1

Model equilibria + pedestal profiles
TOQ w/KBM constraint

Peeling-ballooning
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Closed boundary
equilibrium
EFIT

Current evolution and sources
ONETWO

Turbulent transport
TGLF

Neoclassical transport
NEO

Electron temperature
Ion temperature
Electron density

Electron density

$10^{19}$

EPED+TGYRO
EPED
Pedestal density input to EPED

DIII-D #153523 3745ms

O. Meneghini - 2016 IAEA FEC Kyoto
Pedestal calculation is updated based on the new value of global pressure $\beta_n$, and loop is iterated until convergence.
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**Core-pedestal transport modeling**

- Core profiles: TGYRO
- Turbulent transport: TGLF
- Neoclassical transport: NEO
- Current evolution and sources: ONETWO
- Pedestal structure: IPS EPED1
- Model equilibria + pedestal profiles: TOQ w/KBM constraint
- Peeling-ballooning: MHD stability
- Closed boundary equilibrium: EFIT

**Graphs:**
- Electron temperature
- Ion temperature
- Electron density
- EPED+TGYRO
- EPED
- Pedestal density input to EPED

O. Meneghini - 2016 IAEA FEC Kyoto
Pedestal calculation is updated based on the new value of global pressure $\beta_n$, and loop is iterated until convergence.
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**Core-pedestal transport modeling**

- **Core profiles**
  - TGYRO
- **Pedestal structure**
  - IPS EPED1
- **Model equilibria + pedestal profiles**
  - TOQ w/KBM constraint
- **Peeling-ballooning**
  - MHD stability
  - ELITE
- **Neoclassical transport**
  - NEO
- **Closed boundary equilibrium**
  - EFIT
- **Current evolution and sources**
  - ONETWO

**Graphs**

- **Electron temperature**
- **Ion temperature**
- **Electron density**

**Legend**

- EPED+TGYRO
- EPED
- Pedestal density input to EPED

O. Meneghini - 2016 IAEA FEC Kyoto
Converged solution compares very well with measurements across the whole plasma.

**Core-pedestal transport modeling**

- **OMFIT**
  - **Core profiles**
    - TGYRO
  - **Pedestal structure**
    - IPS EPED1
  - **Model equilibria + pedestal profiles**
    - TOQ w/KBM constraint
  - **Peeling-ballooning MHD stability**
    - ELITE
  - **Closed boundary equilibrium**
    - EFIT

**Graphs:**

- **Electron temperature**
- **Ion temperature**
  - $\beta_n = 1.69$
  - $\beta_{n,\text{exp}} = 1.68$
- **Electron density**

*General Atomics*
Converged solution is insensitive to the initial guess of global pressure $\beta_{n,\text{guess}}$

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

![Graph showing self-consistent solution](image)
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

Initial conditions based on:
Comparisons of predicted plasma performance in ITER H-mode plasmas
2D scan in $n_e, Z_{\text{eff}}$ identifies a family of self-consistent solutions which satisfy ITER baseline $Q \geq 10$ target

High fusion performance:

- for different values of $n_e$ and $Z_{\text{eff}}$

![Fusion gain $Q$](image1)

![Pedestal height $p_{\text{top}} [kPa]$](image2)
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

\[ J_{boot} \propto \frac{1}{Z_{eff} n_e^2} \]
Lower fusion power conditions due to peeling or ballooning modes depending on pedestal collisionality.

High fusion performance:

- for different values of $n_e$ and $Z_{\text{eff}}$
- 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.

1+ hour for each self-consistent iteration (at least 5+ iterations)
- **EPED1** $\sim$ 20 mins on HPC with hundreds of cores
- **TGLF** $\sim$ secs but transport solution requires 1000’s of evaluations

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

$\Rightarrow$ need to break traditional modeling speed-vs-fidelity tradeoff
Neural network paradigm can provide the missing link towards functional whole device modeling simulations.

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
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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 $p_{\text{ped}}, w_{\text{ped}}$

Trained on database of $\sim 20,000$ 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
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 $\beta_n$ converges to $\sim 90\% \beta_{n,exp}$
- Robust NN models $\rightarrow$ convergence does not require supervision
Conclusion: enabling core-pedestal coupled workflow, and increasing speed by millions with neural networks

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

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

3. 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