Advanced Tokamak Modeling Environment for Fusion Plasmas: Physics

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Introduction

AToM core-edge integrated workflows

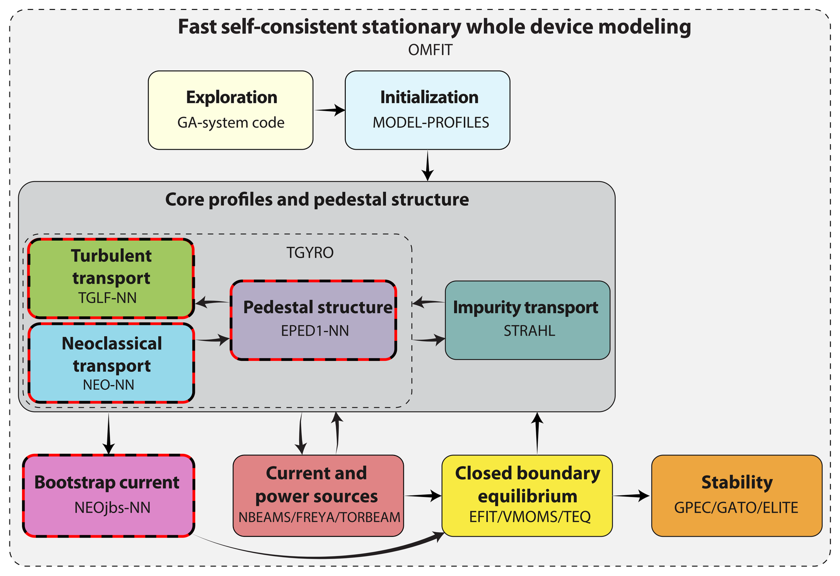
Guiding philosophy of AToM - take a bottoms-up, collaborative approach that focuses on supporting, leveraging, and integrating the wide spectrum of existing research activities throughout the US fusion community, to grow and improve a Whole Device Modeling (WDM) capability that has broad community support and buy-in. In practice, this means developing *flexible* software environment and workflows to couple existing and in-development physics component.

AToM provides two core-edge integrated workflows:

1. OMFIT-based *fast* Whole Device Modeling
2. IPS-based *High Performance Computing* Whole Device Modeling

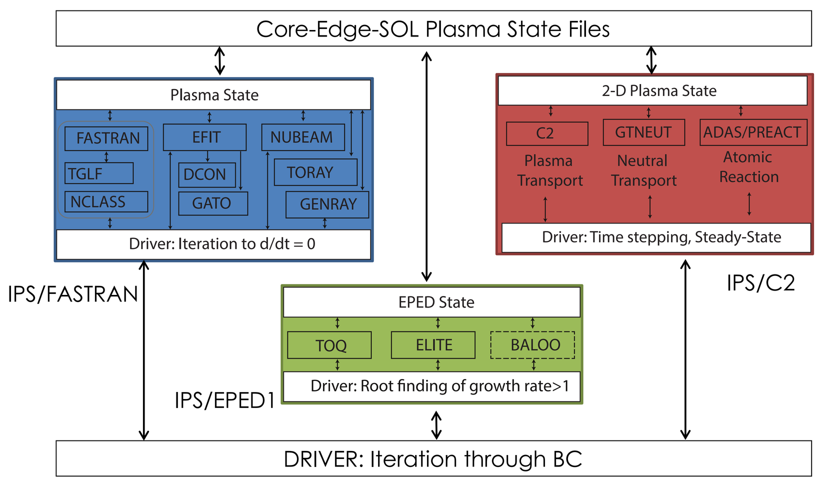
, enabling a wide range of physics studies, even *totally new*

OMFIT-based fast WDM



- Use machine learning accelerated models for EPED, NEO, and TGLF
- Transfer data between components using OMAS

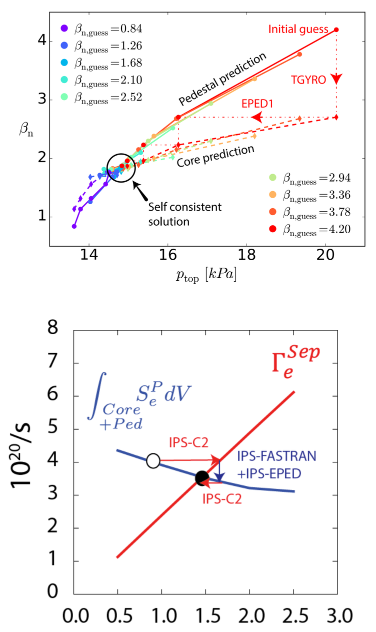
IPS-based HPC WDM

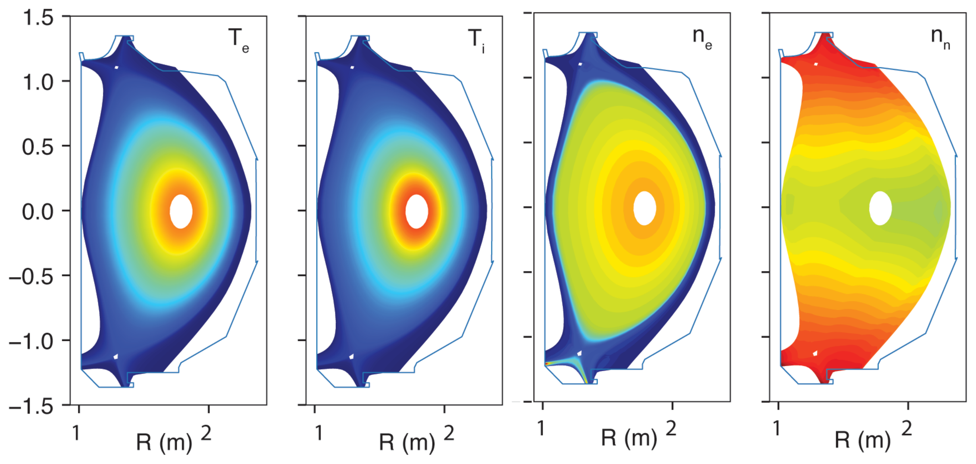


- Framework/component architecture using existing codes
- File-based communication with Plasma State for data transfer mechanism between components
- Maximal HPC resource utilization vi multi-level parallelism

One step closer toward a WDM capability

Self-consistent profile prediction from magnetic axis to wall

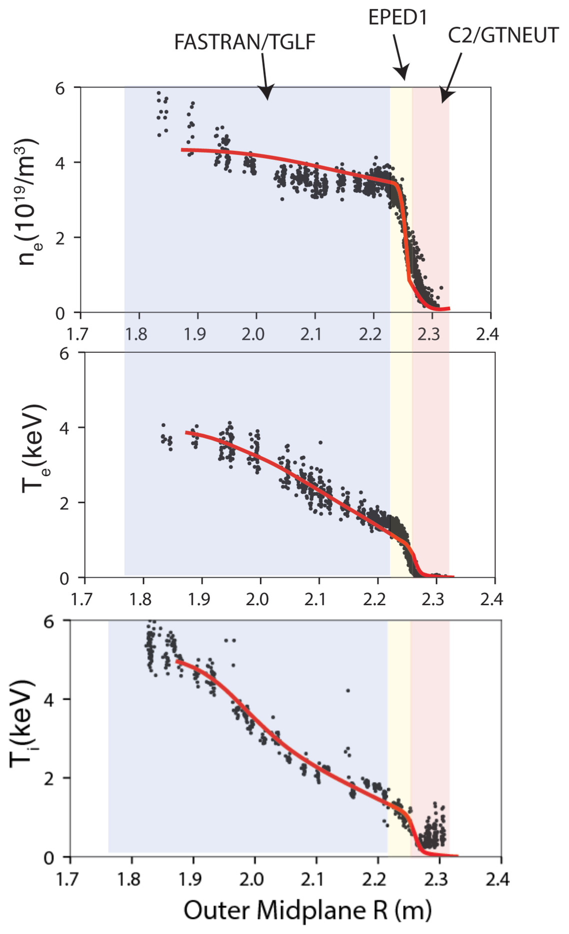




- Iterative solution procedure to match boundary conditions between the core, edge pedestal and SOL
- Self-consistent profile across the regions, especially separatrix values
- Enable study of strong interaction between the regions

DIII-D high β_N discharge simulation with 15 component codes

(FASTRAN + TGLF + NCLASS + EPED (ELITE+TOQ) + NUBEAM + TORAY + EFIT + C2 + GTNEUT + CARRE + C2MESH + CHEASE + DCON + PEST3)



First-principle model, performance, connect to AToM workflows

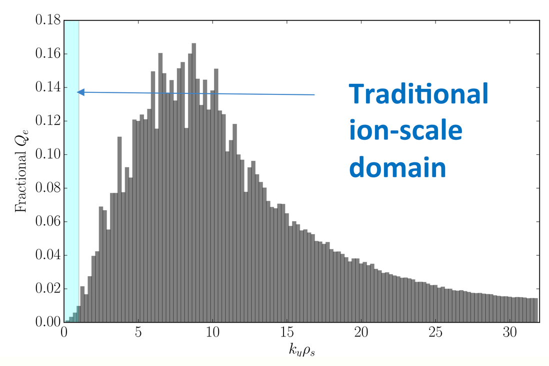
Future recalibration of TGLF with CGYRO

TGLF: the heart of AToM profile-prediction capability

- Linear gyro-Landau-fluid eigenvalue solver
- Saturated potential intensity derived from a database of nonlinear GYRO simulations
- Database resolves only long-wavelength turbulence: $k_\theta \rho_i < 1$

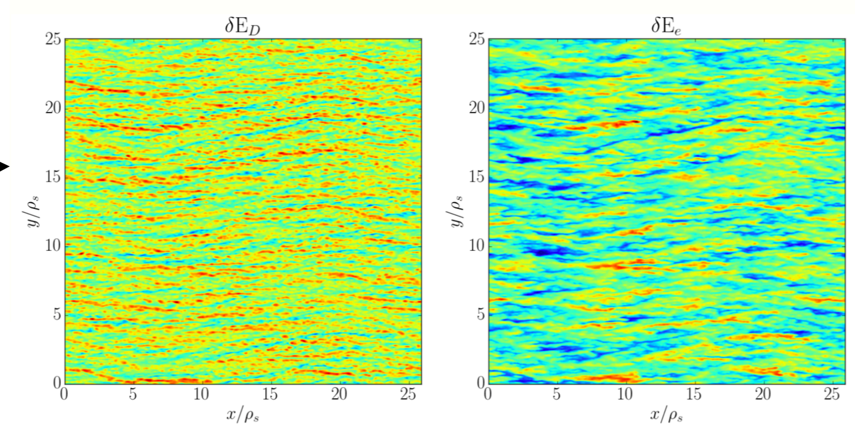
CGYRO: generate future database for TGLF calibration

- New nonlocal spectral solver for collisional edge
- Arbitrary-wavelength spectral formulation
- Designed from scratch for multiscale



CGYRO simulation: low rotation DIII-D ITER baseline discharge

- Nearly all electron flux arises from multiscale regime
- Experimental value Q_e/Q_{GB} ~ 8 accurately recovered

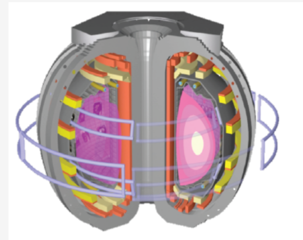


Physics and scenario exploration

From present-day experiments to ITER and beyond

Present-day experiments

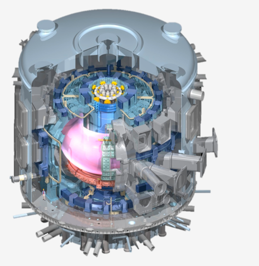
DIII-D



- Validate WDM, identify modeling gaps
- Drive new development

Support ITER

ITER

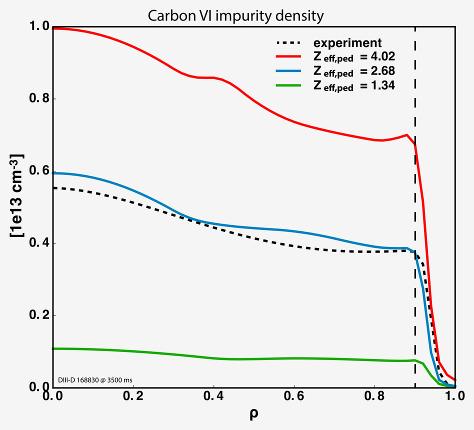


- Optimize ITER design/operation scenario
- Test WDM in reactor scale in burning plasma conditions

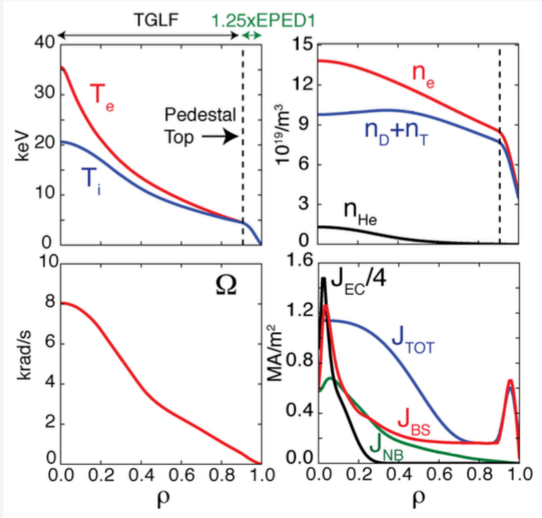
Future reactor design

DEMO

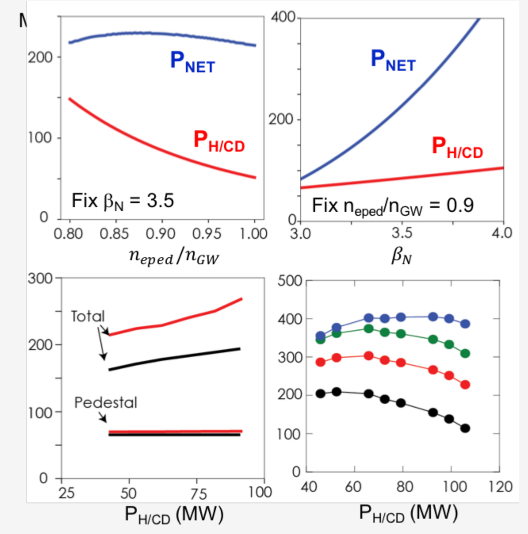
- Design next step U.S. reactor
- Develop advanced tokamak path to a future reactor



Core-pedestal Impurity profile prediction (OMFIT-based fast workflow)



ITER Steady-State Hybrid scenario (IPS-based HPC workflow)



C-AT DEMO reactor (IPS-based HPC workflow)

Optimize, find new regimes

Enabled by efficient utilization of HPC resources

Multi-dimensional parametric scan

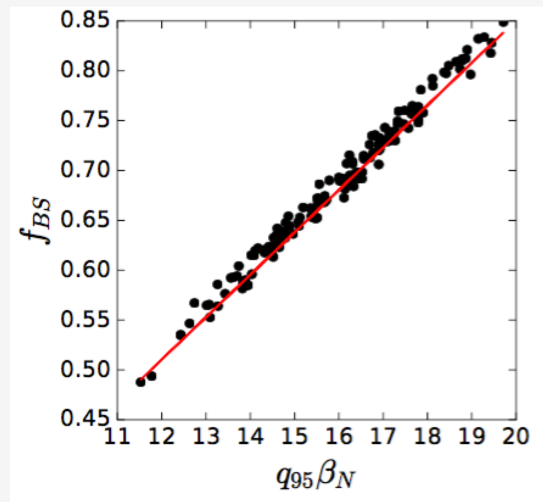
- B_T, I_p, density, P_{NB}, P_{RF}
- Monte Carlo sampling
- Each point = fully theory-based integrated modeling

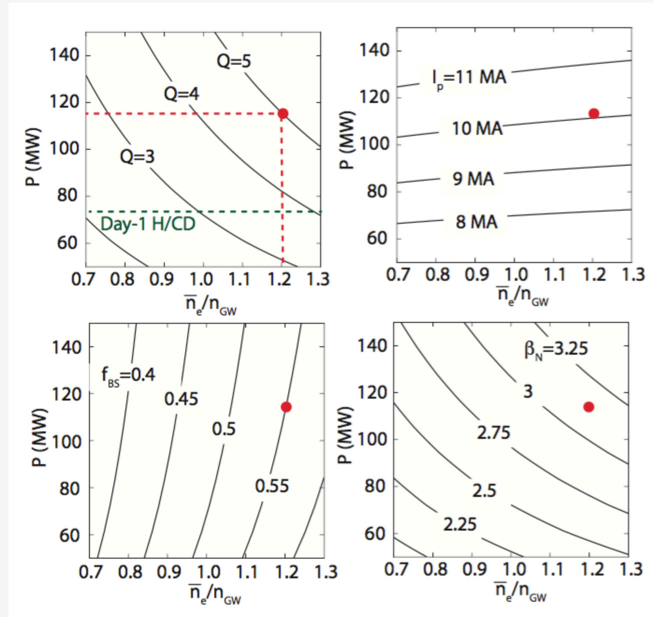
Parameterize key performance

- f_{BS} ~ $q_{95}\beta_N$
- β_N ~ $(n_e/n_{GW})^{1.35}$ $B_T^{-0.2}$ $P_{CD}^{0.2}$ $E^{0.4}$

Search optimum design/ operation point

A massive set of predictive integrated simulations → Optimize ITER scenario





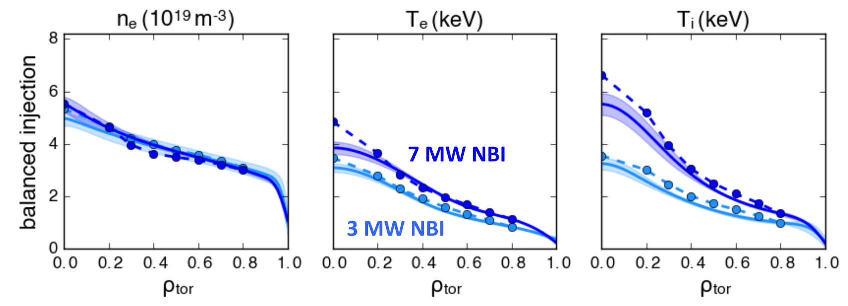
(**DAKOTAK**+IPS+FASTRAN+TGLF+EPED+NUBEAM+TORAY+GENRAY+EFIT)

Validation and uncertainty quantification

Tightly coupled to AToM workflows and physics studies

Initial focus: in-depth core transport model studies

- Ex. TGLF captures core plasma response to heating changes in low-torque H-mode plasmas



Next step: extend to multi-component modeling

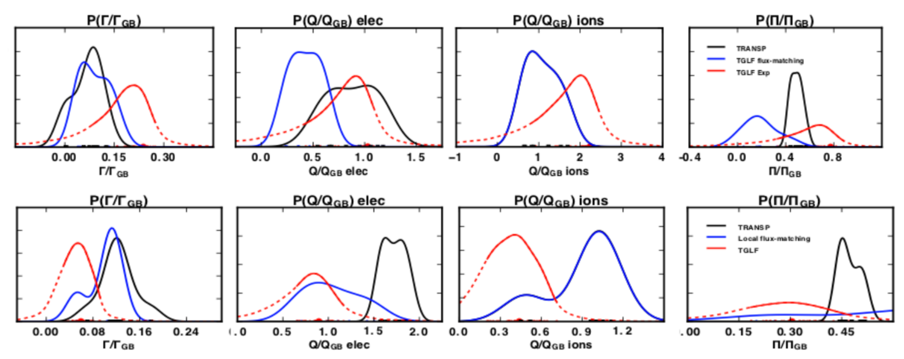
- Ex. Core-edge-impurity coupling – Can we predict response of impurities in core and pedestal to changes in RF heating?

Supports a range of focused UQ methodology studies

- Quantifying dynamics of bursty turbulence simulations
- Testing model input parameter uncertainty propagation techniques
- Inverse methods for equilibrium reconstruction, transport coefficient inference

Advanced UQ methods

- Polynomial chaos expansion methods under development for efficient probabilistic validation studies



AToM Use Cases

Entry point for collaboration with AToM

AToM validation and scenario modeling will be organized about benchmark use cases

- Well-documented datasets describing plasma discharges of interest for component and workflow validation
- Use cases provide clear way of benchmarking competing models, tracking improvements, assessing real-world performance

Each use case will include

- Magnetic equilibria and profile data in accessible format
- Relevant supporting data and analysis (power balance data, fluctuation measurements, MHD mode amplitudes)
- Provenance documentation (shots/publications/models)

Candidate use cases

1. DIII-D L-mode shortfall, ITER baseline, steady-state discharges , 2. Alcator C-Mod LOC/SOC plasmas, EDA H-ode toroidal field scan
3. ITER inductive, hybrid, and steady-state scenarios, 4. ARIES ACT-1/ACT-2 reactor scenarios, 5. ….

Research supported by USDOE grants DE-SC0017992