Predicting Performance and Stability of Tokamak Plasmas Using Flexible, Integrated Modeling

by

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November 10th, 2021

GENERAL ATOMICS

DIII-D
NATIONAL FUSION FACILITY

Acknowledgements and Disclaimers

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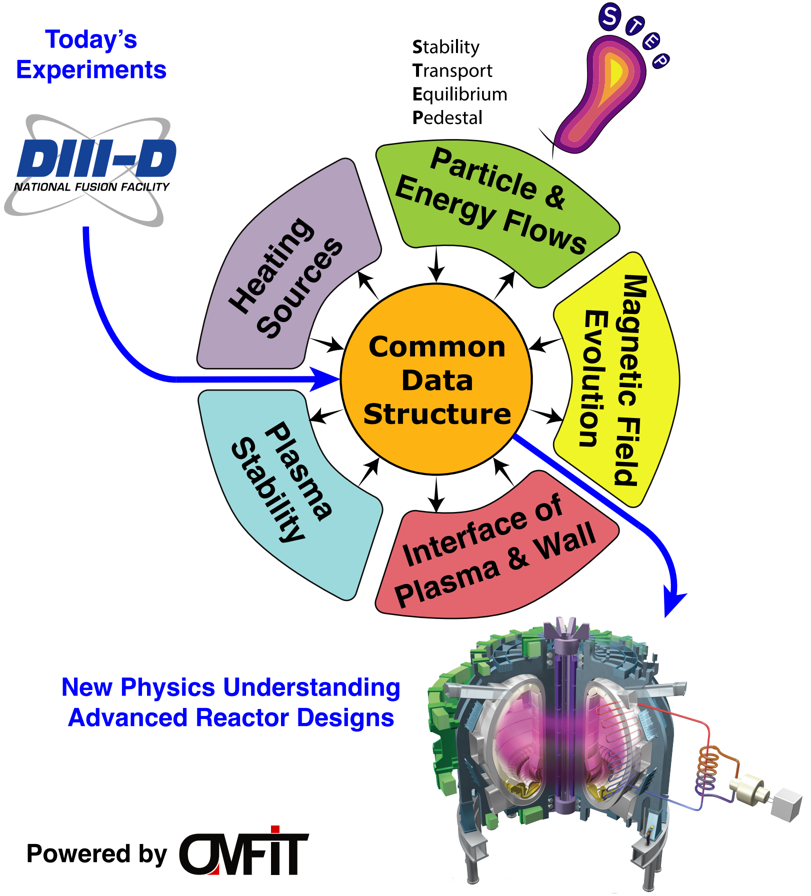
- This study is supported by General Atomics corporate funding.
- Contributions from O. Sauter were supported by the Swiss National Science Foundation.

STEP Developed to Predict Stable Tokamak Equilibria Self-Consistently With Core-Transport & Pedestal Calculations

- **Couples theory-based codes for different physics to analyze experiments and predict reactors**
- **Uses centralized data structure for communication**
  - Highly flexible workflow development
  - Easily swap between high-fidelity and reduced models (including neural nets)
- **Created in OMFIT for user-friendliness and wide access**



Today's Experiments

DIII-D NATIONAL FUSION FACILITY

Stability
Transport
Equilibrium
Pedestal

Particle & Energy Flows

Heating Sources

Common Data Structure

Magnetic Field Evolution

Plasma Stability

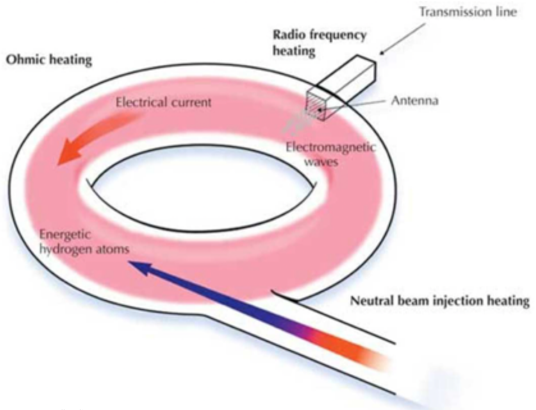
Interface of Plasma & Wall

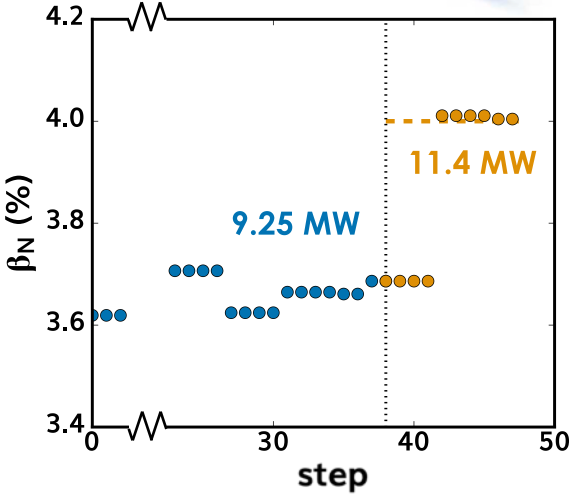
New Physics Understanding
Advanced Reactor Designs

Powered by OMFIT

Tokamak Reactor Designs Must Answer Critical, Coupled Questions

- **How much and what kind of heating & current drive is needed to achieve a desired fusion gain?**
- What scenario optimizes performance?
- Can I avoid or mitigate disruptions in high-performance scenarios?





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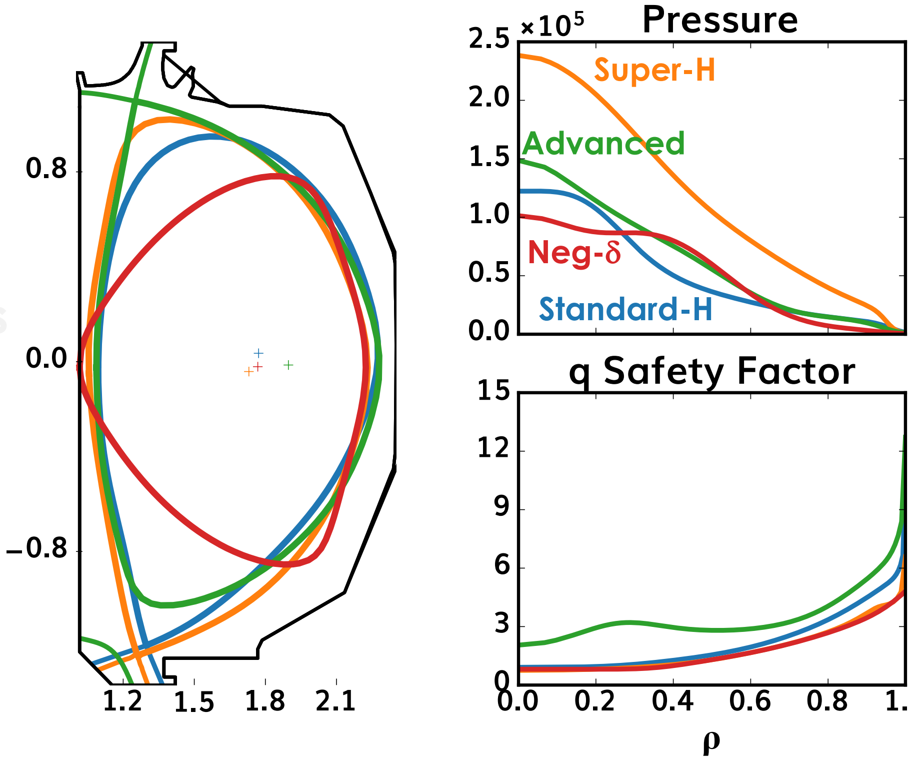

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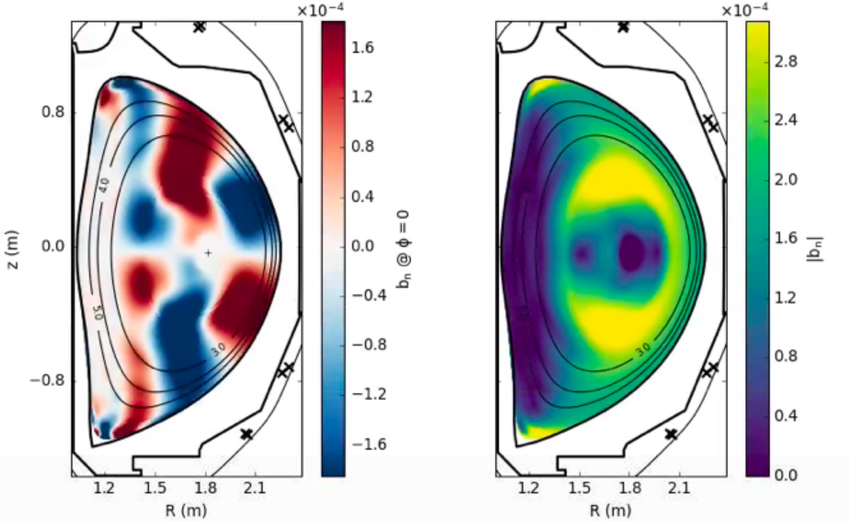

Ideal external kink instability from DCON

Tokamak Reactor Designs Must Answer Critical, Coupled Questions

- **How much and what kind of heating & current drive is needed to achieve a desired fusion gain?**
- **What scenario optimizes performance?**
- **Can I avoid or mitigate disruptions in high-performance scenarios?**

- **And so many others…**
  - Can my scenario avoid, mitigate, or suppress edge-localized modes?
  - How do I avoid radiative collapse from excess impurities in the core?
  - Does my divertor solution preserve core performance?
  - Can my materials handle the steady-state and transient heat flux?

First-Principle Codes and Reduced Models Typically Focus on a Subset of Relevant Physics

Stability

NIMROD M3D-C1
GATO DCON

Transport

XGC (C)GYRO
TGLF(-NN)

Equilibrium

EFIT CHEASE

Pedestal

EPED(-NN)

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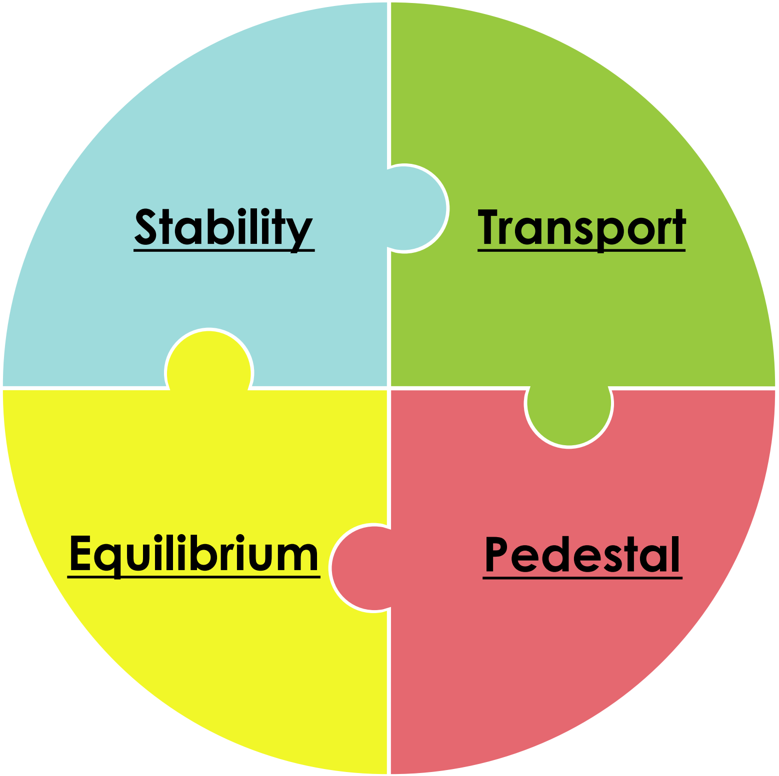
Predictive Modeling of a Tokamak Reactor Requires an Integration of All These Physics



Stability

Transport

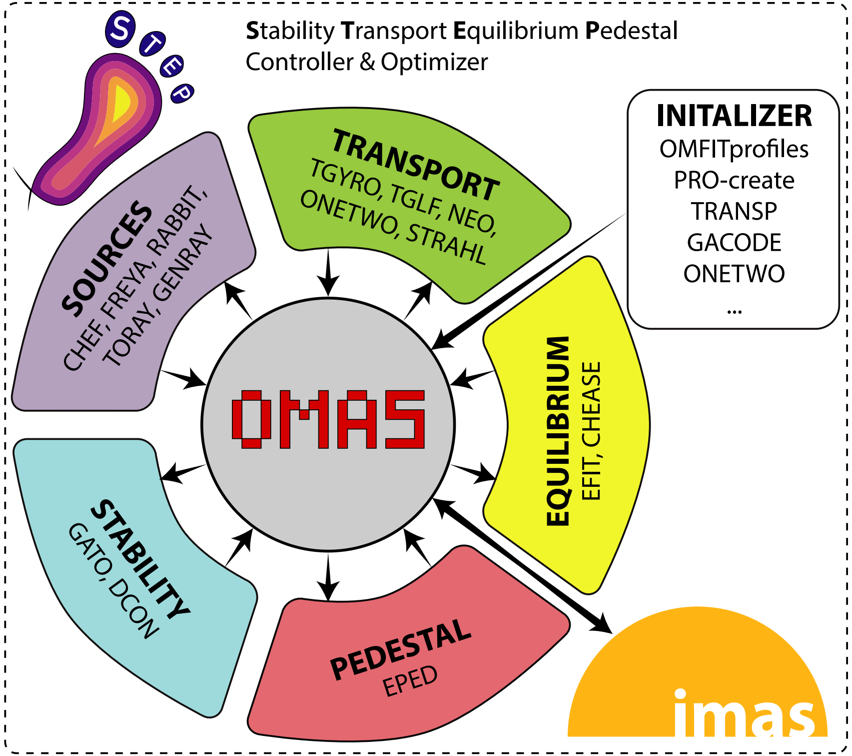
Equilibrium

Pedestal

Introduction to STEP Integrated-Modeling Workflow

STEP Module in OMFIT Couples Stability, Transport, Equilibrium, & Pedestal Codes to Predict Tokamak Scenarios

- **Each physics code is wrapped into a "step" that reads from & writes to centralized data structure**
- **Steps are interchangeable, permitting a variety of workflows**
  - **Open-loop:** given these parameters, what does my plasma look like?
  - **Closed-loop:** given a desired plasma, what parameters do I need?
  - **Optimization:** what parameters maximize a desired plasma metric?
- **Initialize simulations from:**
  - Experimental data
  - Existing simulations
  - 0D parameters (via PRO_create)
  - Data in ITER IMAS format



Stability **T**ransport **E**quilibrium **P**edestal
Controller & Optimizer

INITALIZER
OMFITprofiles
PRO-create
TRANSP
GACODE
ONETWO
...

TRANSPORT
TGYRO, TGLF, NEO, ONETWO, STRAHL

SOURCES
CHEF, FREYA, RABBIT, TORAY, GENRAY

EQUILIBRIUM
EFIT, CHEASE

STABILITY
GATO, DCON

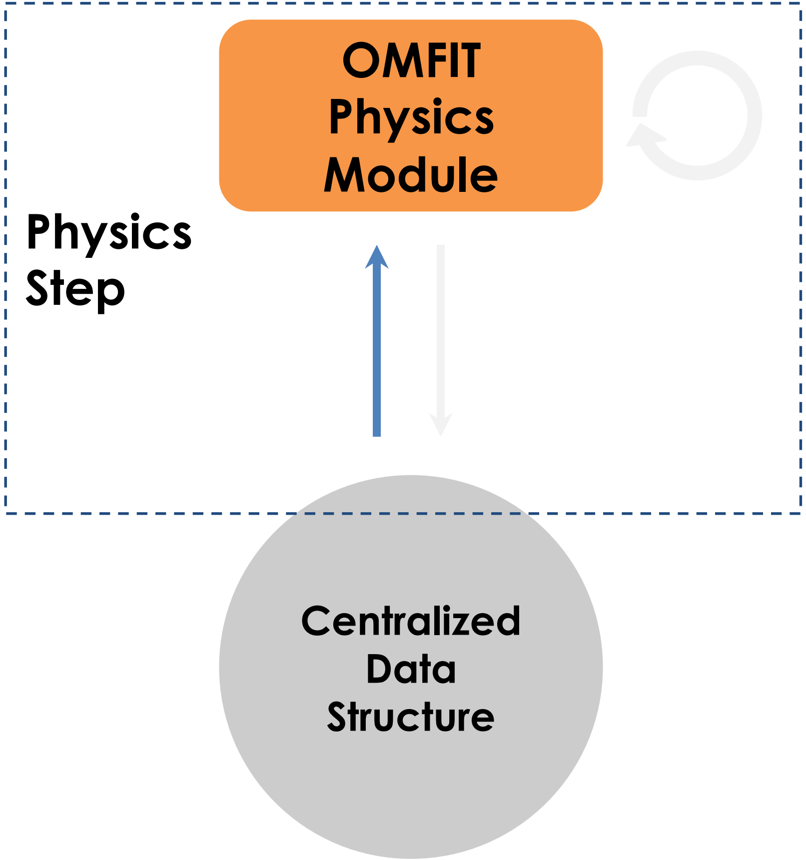
PEDESTAL
EPED

O. Meneghini et al. Nucl. Fusion **61**, 026006 *(2021)*

STEP Wraps Other OMFIT Modules Into Individual “Steps”

Each step:

- **Reads data from a centralized data structure**
- **Automatically executes code**
  - Robust default settings
  - Opportunity for detailed control and customization
- **Write results to centralized data structure**



OMFIT Physics Module

Physics Step

Centralized Data Structure

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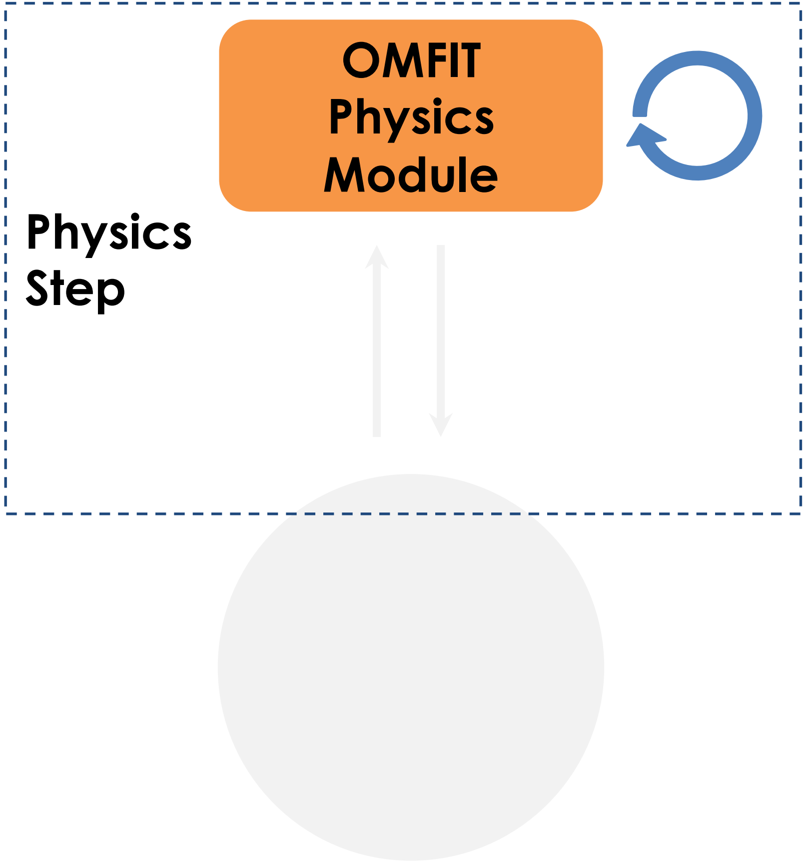

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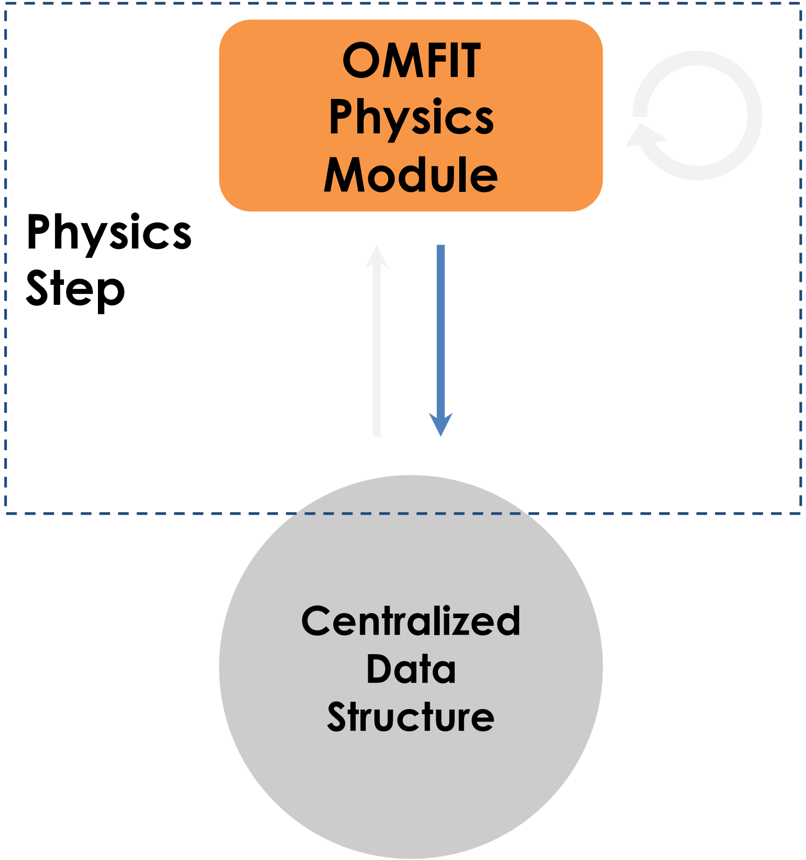


Many Physics Steps Already Available

Stability

- DCON – Ideal MHD
- GATO – Ideal MHD

Equilibrium

- EFIT – Free-boundary
- CHEASE – Fixed-boundary

Pedestal

- EPED – Balances stability and transport

Transport

- TGLF – Quasilinear gyro-Landau-fluid model
- NEO – Neoclassical drift-kinetic solver
- TGYRO – Runs multiple instances of TGLF & NEO to balance fluxes
- ONETWO – Current evolution
- STRAHL – Impurity transport

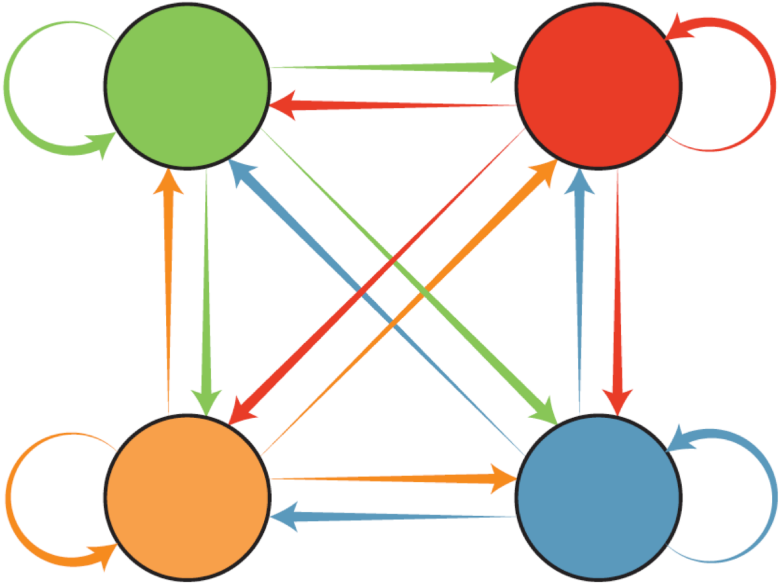
Sources

- CHEF – Runs NBI, RF, and fueling models
- FREYA & RABBIT – NBI heating & current drive
- TORAY & GENRAY – RF heating & current drive

STEP's Use of Centralized Data Exchange Greatly Facilitates Development of Flexible, Integrated Modeling Workflows

- **If we have N codes, each speaking a different language, then arbitrary coupling requires N^2 translators**
- In practice, we end up creating static workflows
- Centralized data structures
  - Simplify addition of new codes (2 N translators: each code from and to data structure)
  - Permit arbitrary execution order

Free-form data communication (in theory)



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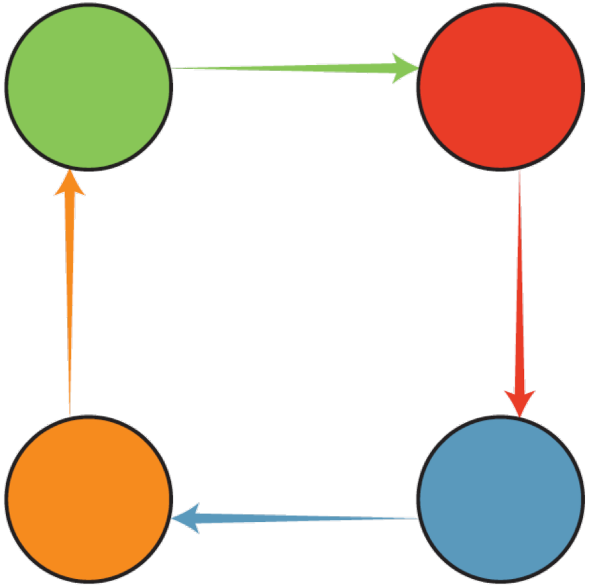
“Free-form” data communication (in practice)



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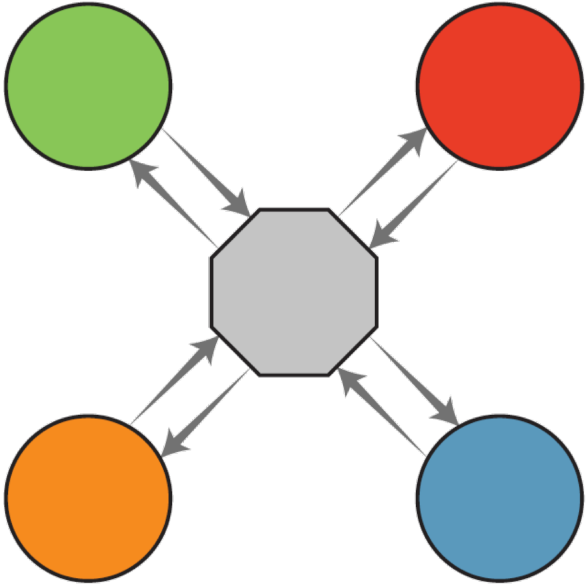
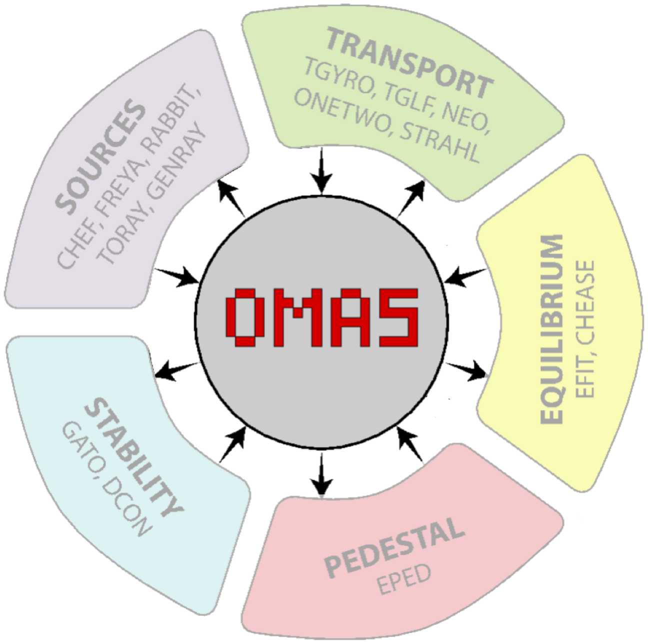
Standardized data communication

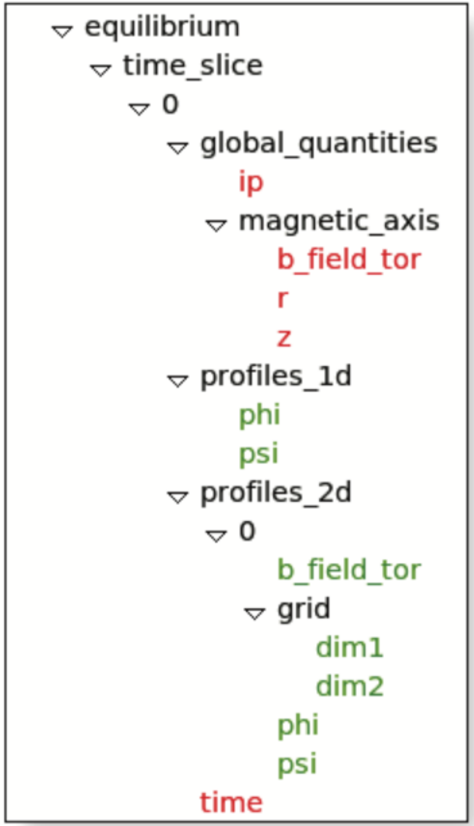


OMAS Ordered Multidimensional Array Structure Provides Centralized Data Structure Within OMFIT (and STEP)



- **Adheres to ITER IMAS data schema, providing standardization for both experimental data and simulation results**
- **Interface Data Structures (IDSs) organize data hierarchically**
  - **68 IDSs, sorted by physics areas, e.g.,**
    - `equilibrium`
    - `core_profiles`
    - `core_sources`

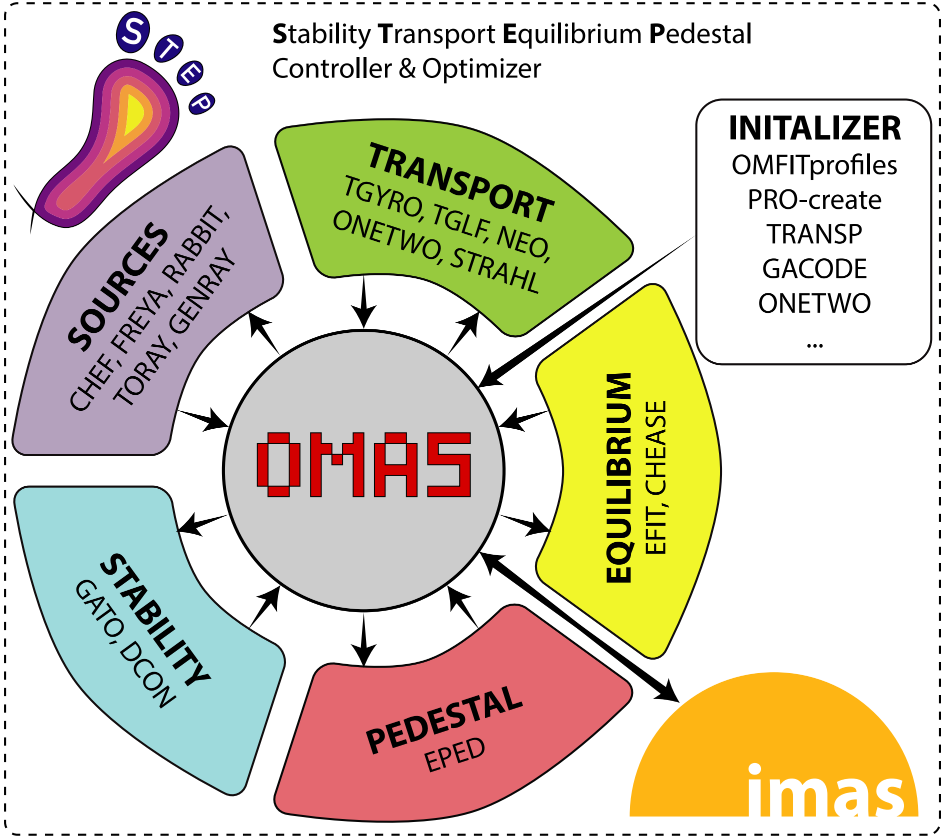
See Meneghini's poster Thursday PM, UP11.00090



```
equilibrium
  time_slice
    0
      global_quantities
        ip
        magnetic_axis
          b_field_tor
          r
          z
      profiles_1d
        phi
        psi
      profiles_2d
        0
          b_field_tor
          grid
            dim1
            dim2
          phi
          psi
    time
```

That's STEP! What Can We Do With It?

- Design your own workflow based on physics need
- *Manually* iterate through codes
- Define custom convergence conditions
- Define custom actuators and targets



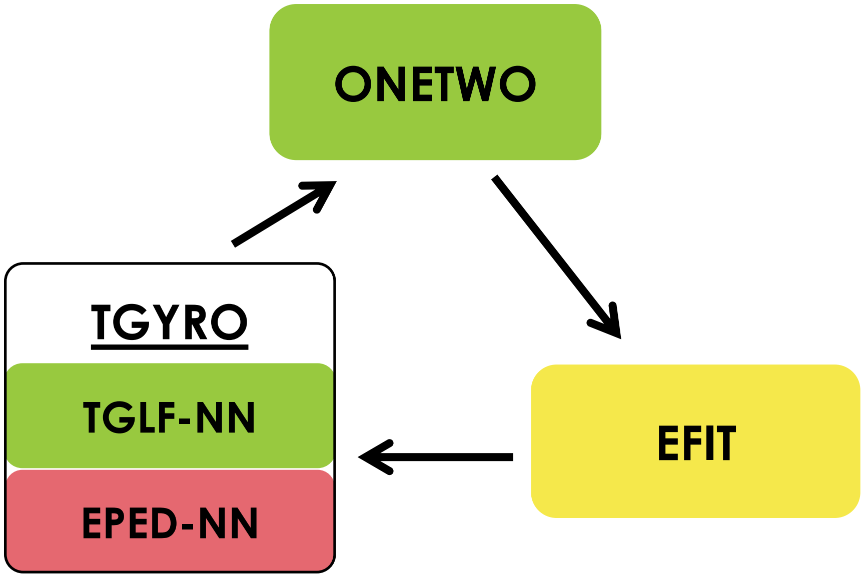
Stability **T**ransport **E**quilibrium **P**edestal Controller & Optimizer

GENERAL ATOMICS

STEP Open-Loop, Self-Consistent Workflow Allows Prediction of Stationary Tokamak Plasmas

- **In general, for open-loop predictions we use:**
  - ONETWO for sources & current evolution
  - EFIT for equilibrium calculations
  - TGYRO (with neural nets)
    - TGLF for steady-state transport
    - EPED for pedestal height/width
- **Many variations are possible**
  - CHEASE for fixed-boundary equilibria (e.g., for future devices)
  - Full codes when neural nets not applicable
    - TGLF+NEO
    - EPED
  - CHEF for additional or increased control over sources

Standard Self-Consistent Workflow



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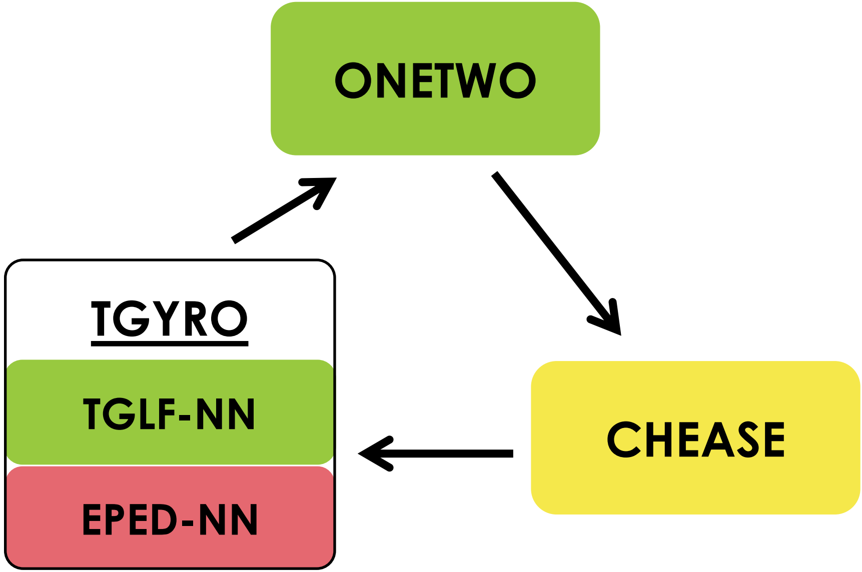

ONETWO

CHEASE

TGYRO

TGLF-NN

EPED-NN

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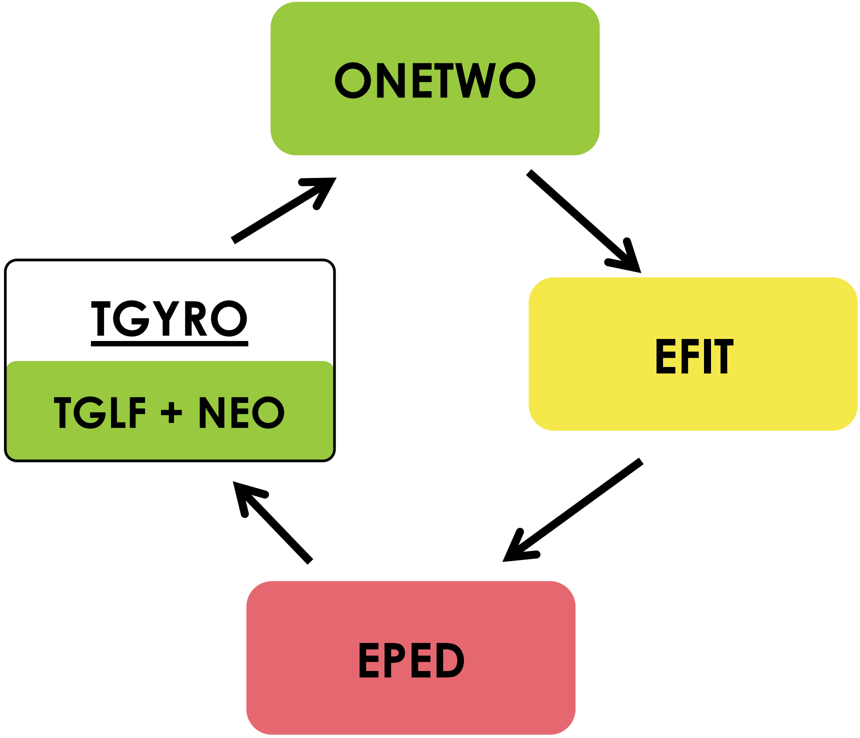

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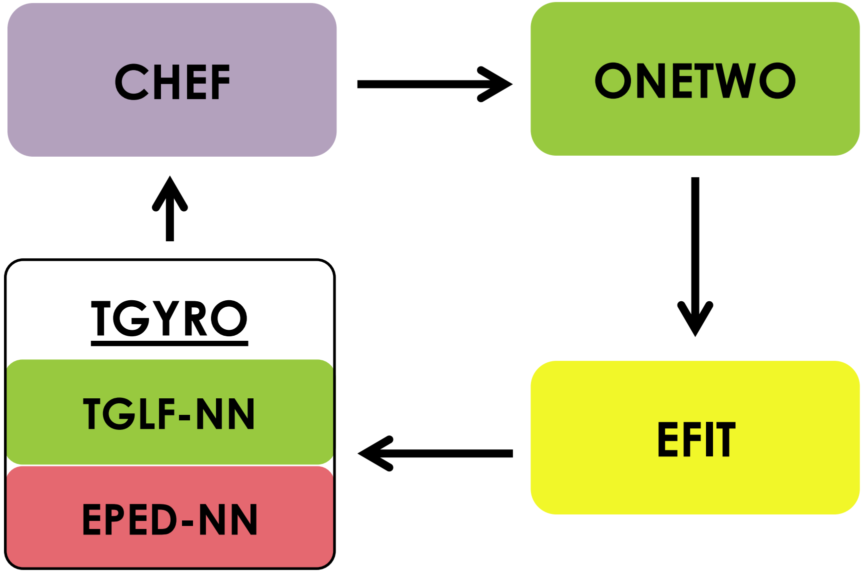
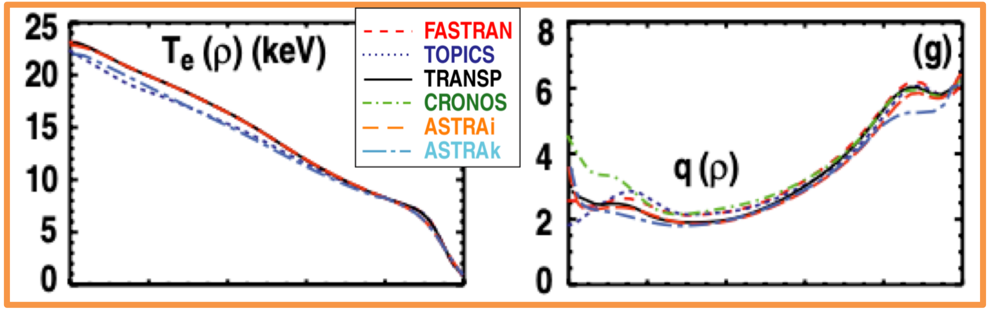


STEP Verified Against Integrated-Modeling Benchmark

- **Variety of integrated models used to simulate ITER weak-shear, steady-state scenario** (*Murakami et al. 2011 Nucl. Fusion 51 103006*)
- Simulation profiles setup from ONETWO/FASTRAN simulations
- Standard, self-consistent STEP workflow with GLF23 used as transport model
- Differences from FASTRAN within benchmark uncertainties



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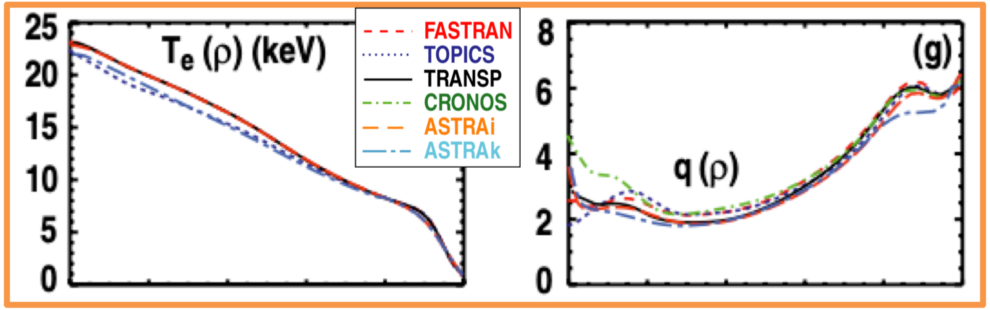
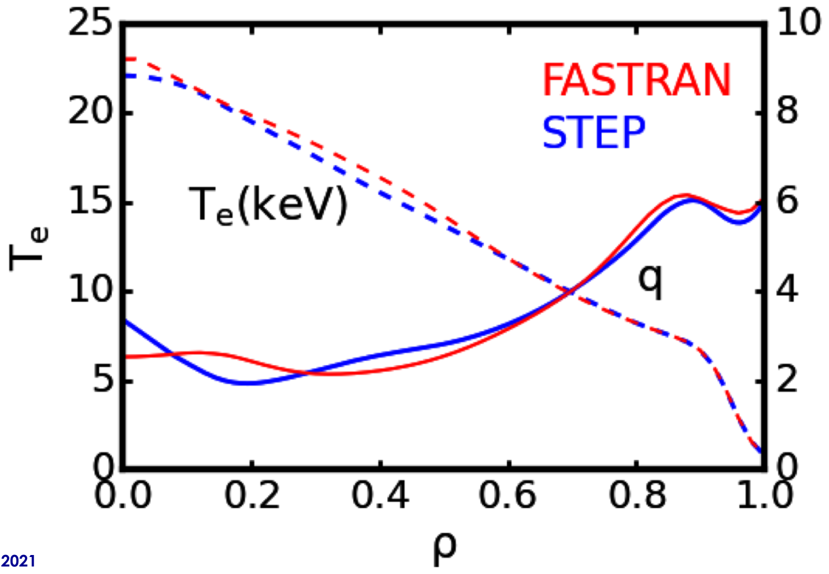


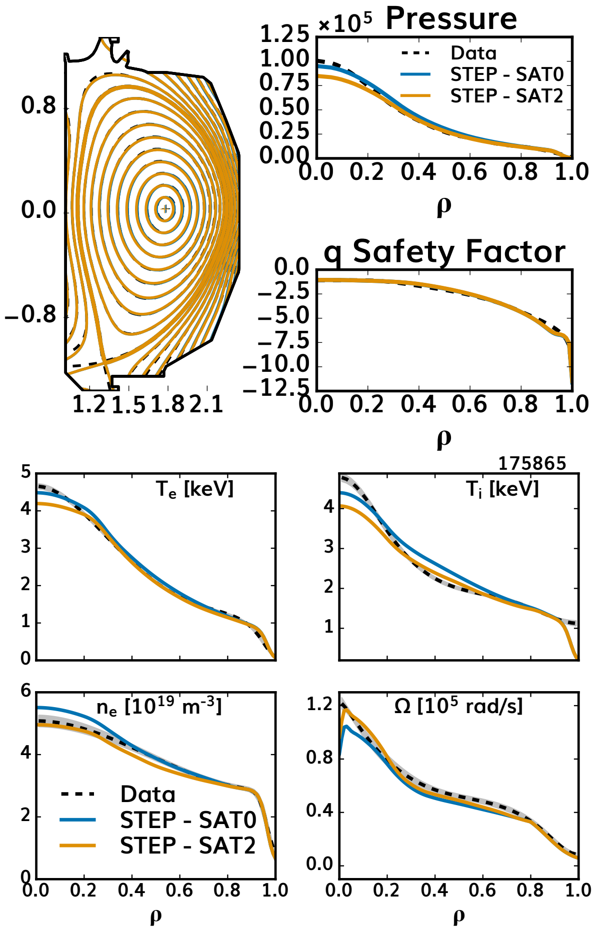


STEP in Standard H-mode

T. Slendebroek

STEP Accurately Reproduces Standard H-modes in DIII-D

- **STEP initialized with experimental equilibrium and profiles from DIII-D standard H-mode**
  - 175865 @ 2100 ms
  - High-torque phase of torque-scan experiment
- **Self-consistent workflow to steady-state given experimental sources**
  - Full TGLF & NEO with EPED-NN
  - Predicts equilibrium and profiles with high accuracy

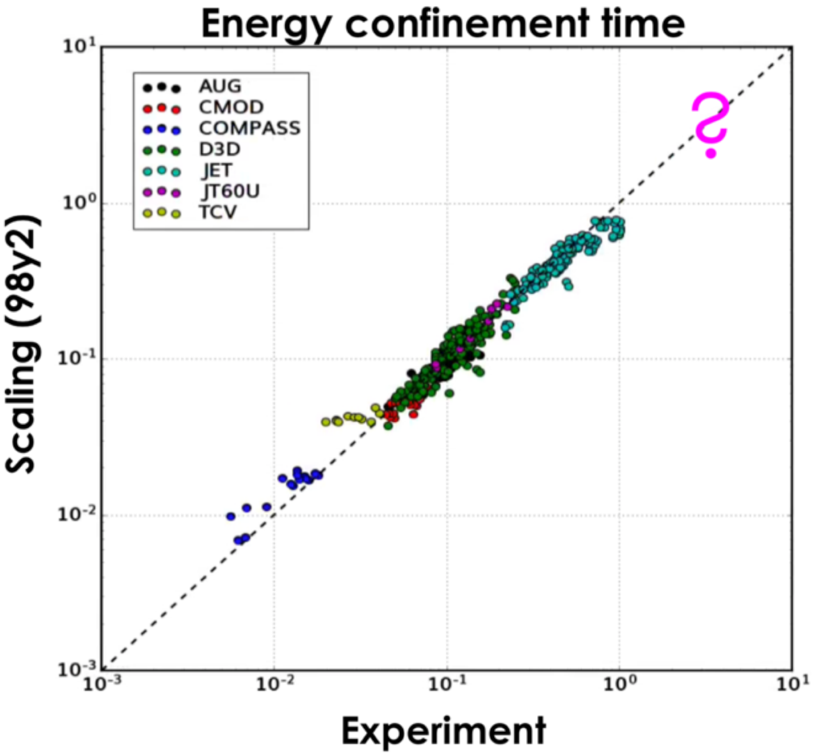


Confinement Scaling Provides Validative and Predictive Test for STEP Modeling of Standard H-mode

- Prediction of energy confinement in future devices often based on $H_{98,y2}$ experimental scaling

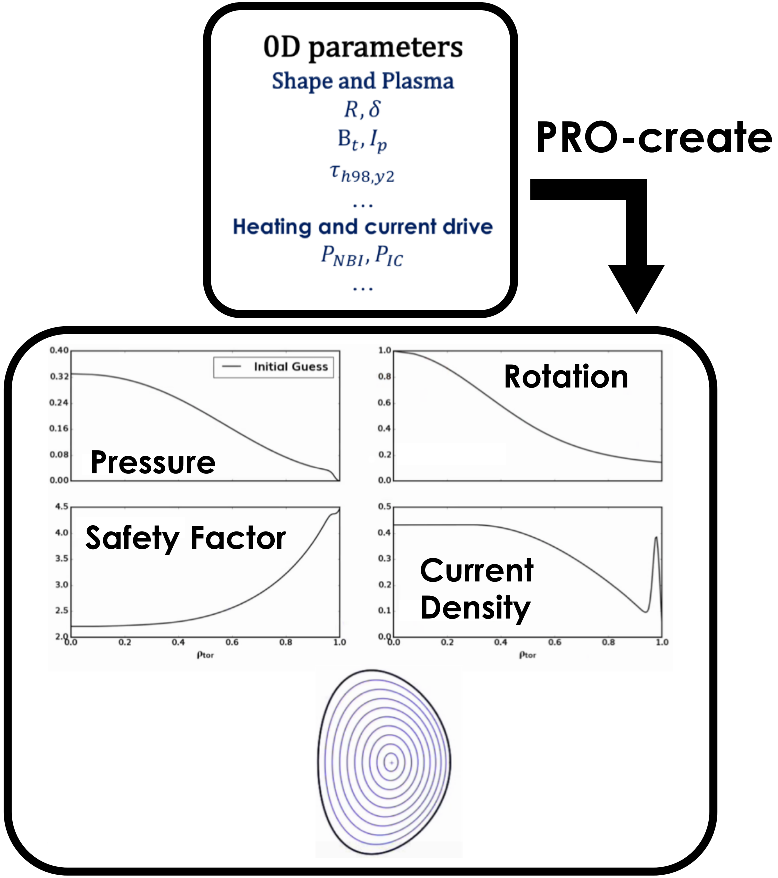
$$\tau_{e\,h98,y2} = 0.0562 I_p^{0.93} B_0^{0.15} P_{heat}^{-0.69} \kappa^{0.78} M_{eff}^{0.19} (10 n_e)^{0.41} A^{-.58} R^{1.97}$$

- Such extrapolation of linear regression is not based on physics
- STEP can be validated against past experiments and then make physics-based predictions for future devices



STEP Generates Self-Consistent, 1.5D Stationary Solution Starting from Zero-Dimensional Parameters

- **Profiles Creator (PRO-create) creates starting point from 0D parameters**
  - Physically feasible plasma conditions
  - Simple analytic profiles
  - Self-consistent equilibrium
- STEP standard workflow iterated to steady-state



0D parameters

Shape and Plasma

R, δ

B_t, I_p

$\tau_{h98,y2}$

…

Heating and current drive

P_{NBI}, P_{IC}

…

PRO-create

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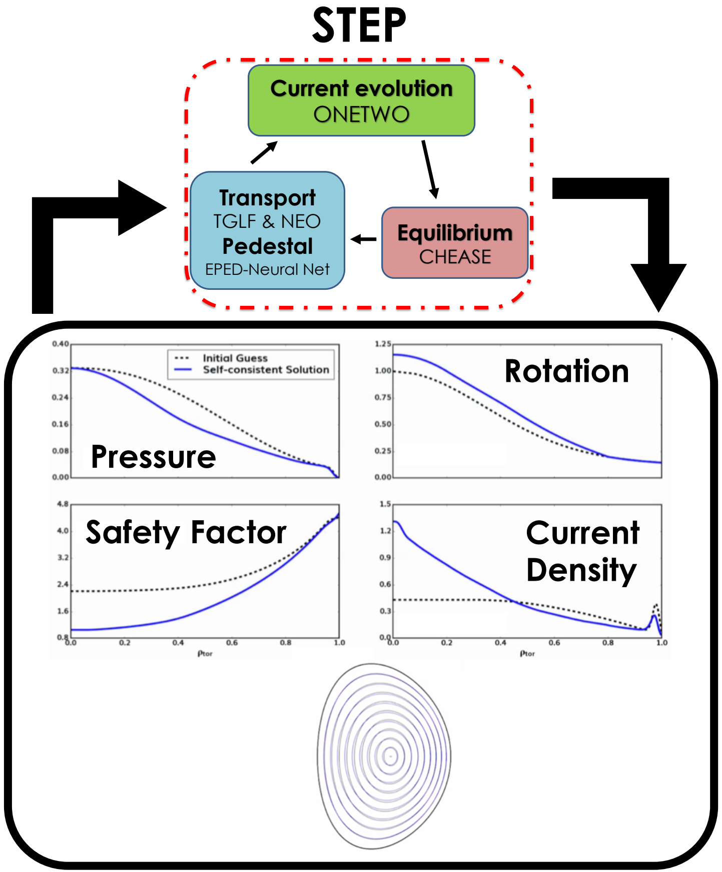
See Slendebroek's oral Thursday 4:48 PM, UO07.00014



STEP

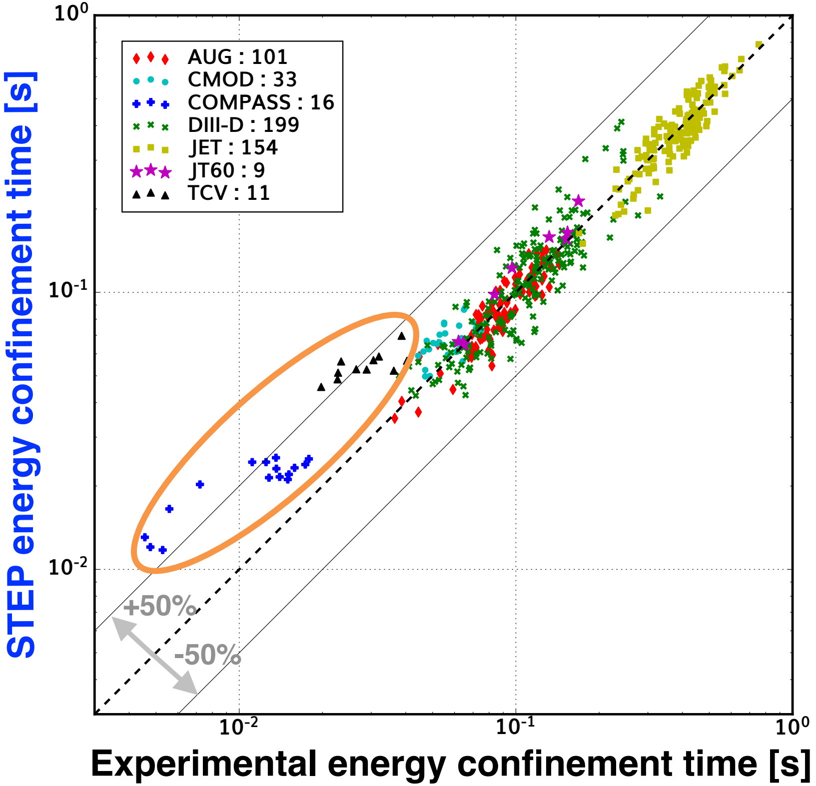
Current evolution
ONETWO

Transport
TGLF & NEO
Pedestal
EPED-Neural Net

Equilibrium
CHEASE

STEP Calculations of Confinement Times in Good Agreement with Experiment and Scaling

- **PRO-create + STEP simulations performed for ~500 discharges from 7 tokamaks in $H_{98,y2}$ database**
  - Span three orders of magnitude in confinement time
  - Conservative and identical assumptions for all discharges
  - No tuning of free-parameters
- **Excellent agreement with experiment**
  - Mean relative error 18% (versus 22% for $H_{98,y2}$ regression)
  - Includes outliers (COMPASS, TCV) due to type-III ELMing discharges



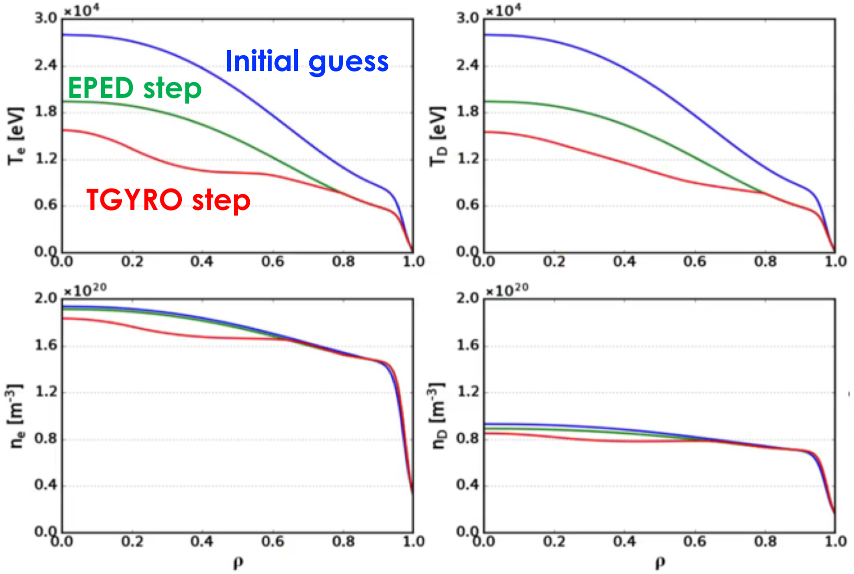
GENERAL ATOMICS

STEP Shows Limitations of Scaling Law Approach for Future Reactors

- **0D reactor design[1] considered large-aspect-ratio, ignited tokamak**

$$B_{\text{coil max}} = 17.6\ [\text{T}] \qquad H_{98} = 1$$
$$R_0/a = 7.66 \qquad P_{\text{fusion}} = 1800\ [\text{MW}]$$

- **STEP predicts reduced fusion power (323 MW) due to collapse of pedestal**
- **STEP H-factor ~60% higher due to reduced heating power from fusion**
- **Lowering aspect ratio improves performance by restoring pedestal**



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[1] Freidberg, Mangiarotti, & Minervini, Phys. Plasmas 22, 070901 (2015)

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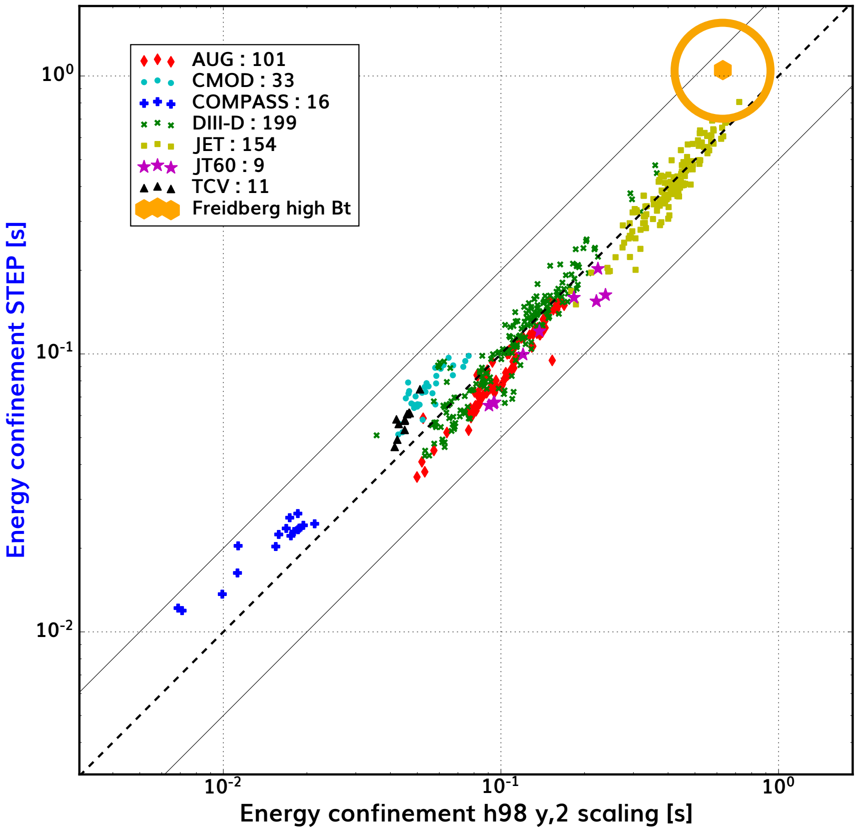

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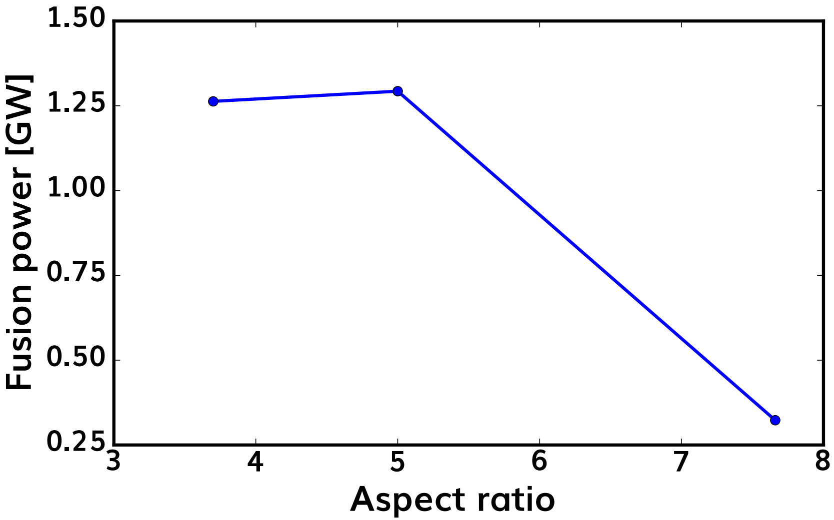


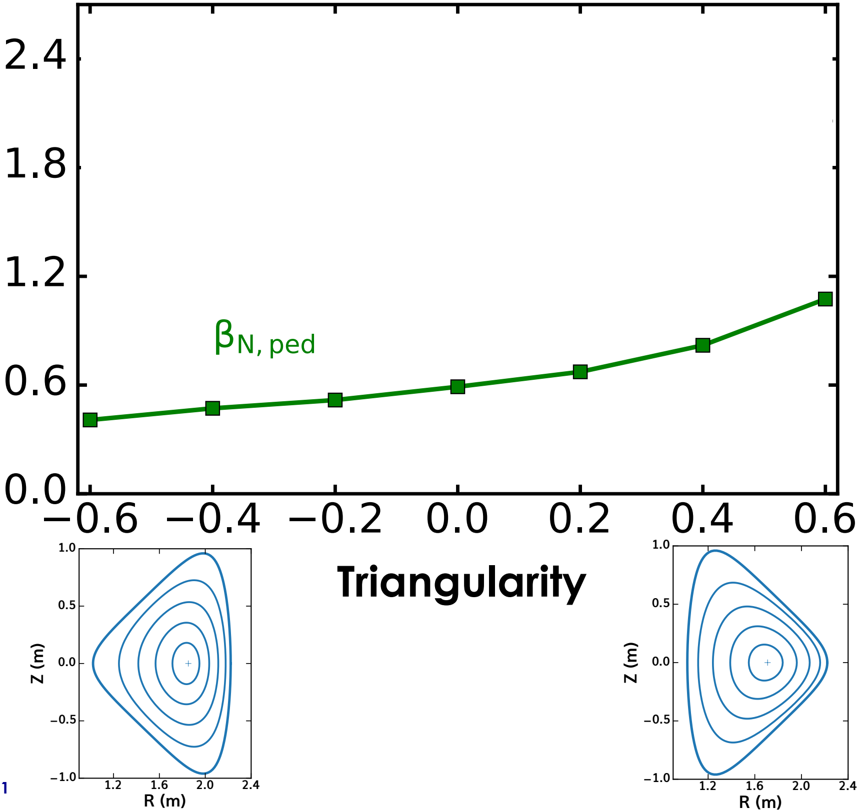
Assessing Performance in Negative Triangularity

J. McClenaghan

EPED Analysis of Negative Triangularity Predicts Significantly Reduced Pedestal Heights

- **Full EPED model has been run for a range of triangularities**
  - DIII-D conditions
  - Fixed β, pedestal density, elongation, magnetic field, and plasma current
- **Pedestal β in negative δ is 50% lower than positive δ**
- **Negative-δ H-mode rarely observed[1], but this provides reduced edge-confinement without bias from different edge models**

J. McClenaghan et al., forthcoming



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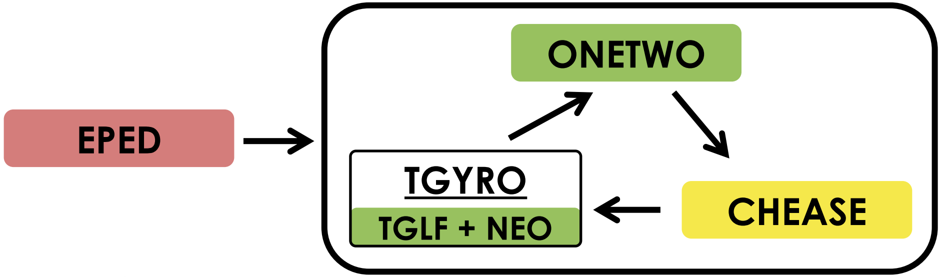
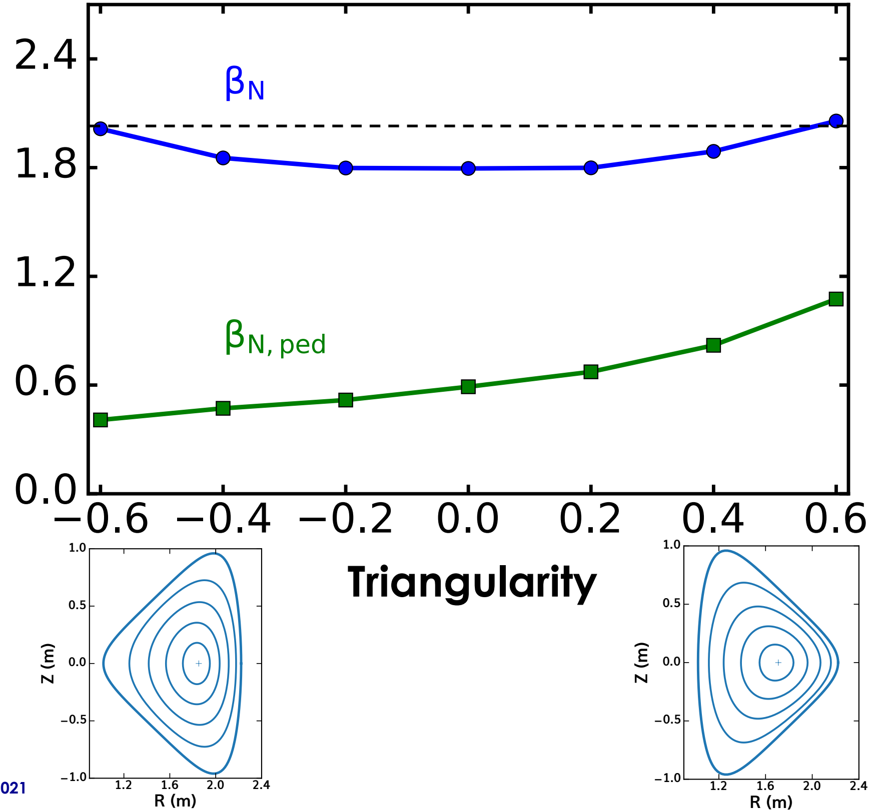
[1] A .Pochelon et al., Plasma and Fusion Research, 7:2502148 (2012)

STEP Shows Negative Triangularity has Similar Performance to Positive Triangularity Despite Lower Pedestals

- **STEP calculations performed using pre-computed EPED pedestals**
  - Work done before full EPED available in STEP
  - Pedestal height not expected to vary much in fully coupled modeling
- **U-shaped dependence of normalized β**
- **Suppression of core turbulence offsets decreased pedestal height in negative δ**
- **Consistent with observations on TCV & DIII-D and worthy of future investigation**



J. McClenaghan et al., to be submitted

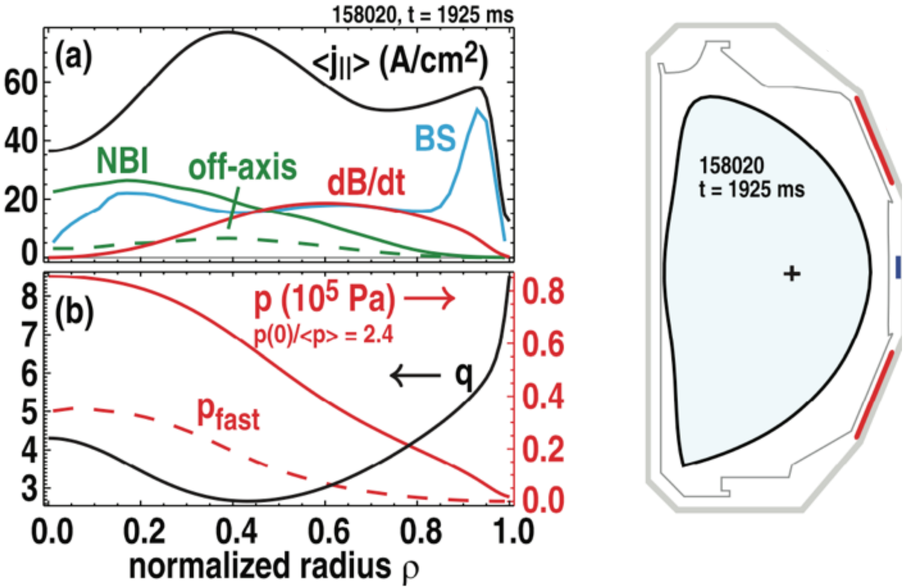


Toward Performance Optimization with MHD Stability Constraints

B.C. Lyons

Negative Central Shear (NCS) is an Advanced Tokamak (AT) Scenario with Improved MHD Stability

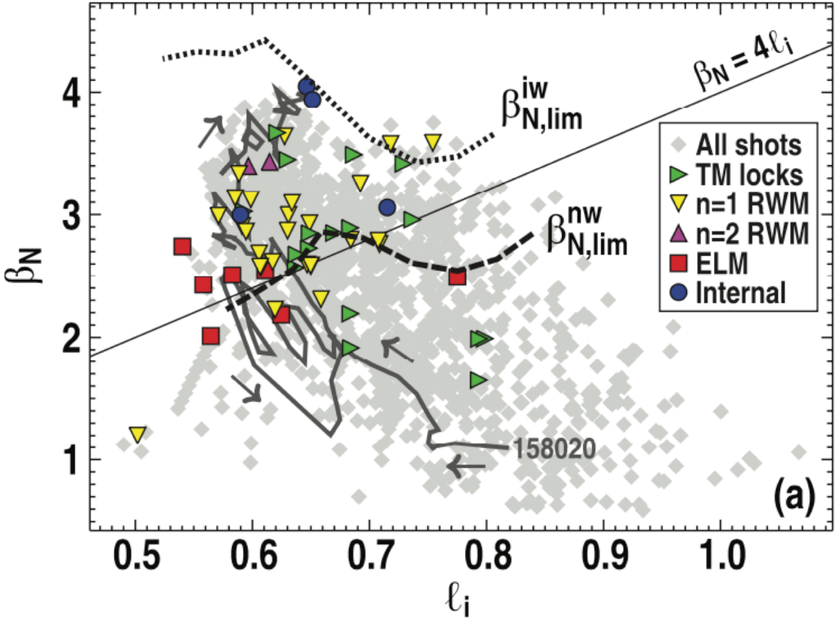
- **ATs often considered for steady-state reactors**
  - High bootstrap fraction
  - High beta
  - Can often be MHD unstable
- **NCS improves passive stability**
  - q>2 everywhere eliminate low-order rational surfaces (e.g., 2/1, 3/2)
  - Large magnetic shear throughout most of plasma
- **NCS plasma can have core transport barriers leading to improved confinement**



J.M. Hanson et al., Nucl. Fusion 57, 056009 (2017)

NCS Plasmas are Limited by Ideal-Wall Beta Limits

- **NCS plasmas achieved a wide range of normalized β and internal inductance**
- **Typically limited by an MHD event, not transport**
- Highest achievable β_N consistent with ideal-wall limit
- Excellent test-case for stability modeling in STEP
  - Open-loop: reproduce single equilibrium in exotic scenario
  - Closed-loop: β_N scan by varying NBI power



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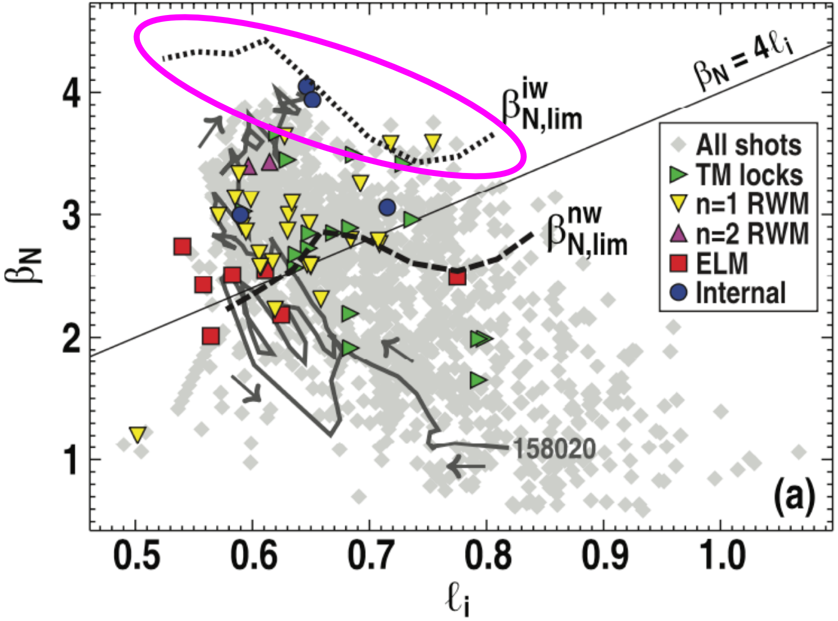

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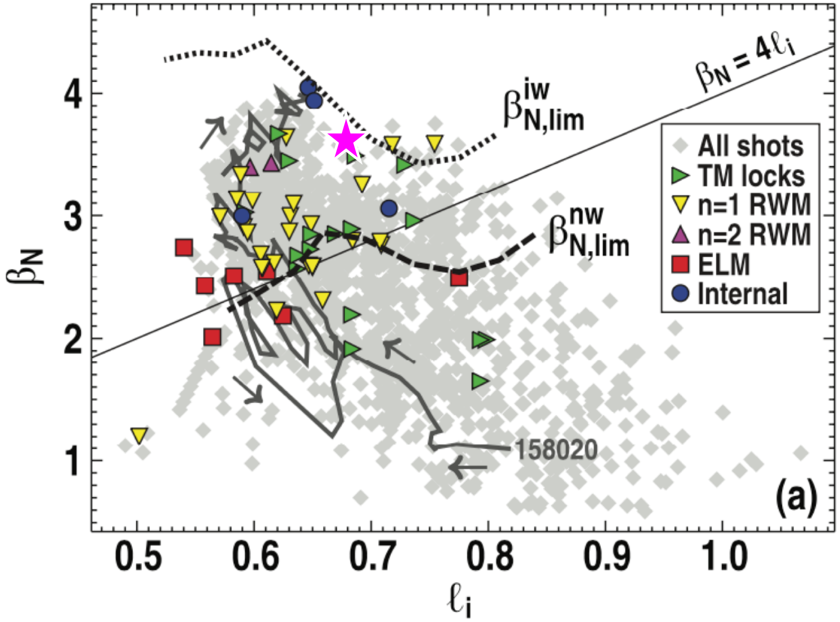

J.M. Hanson et al., Nucl. Fusion 57, 056009 (2017)

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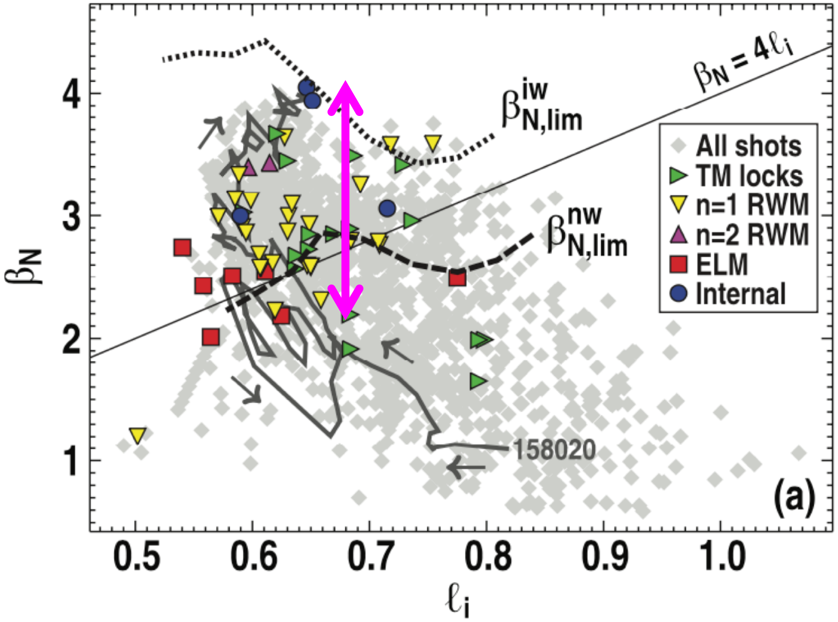
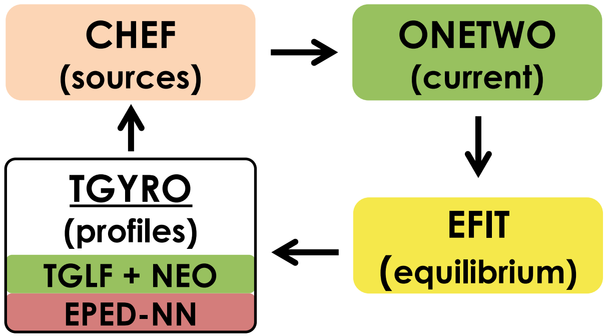


J.M. Hanson et al., *Nucl. Fusion 57, 056009 (2017)*

Open-Loop STEP Workflow with Enhancements Accurately Reproduces Negative-Central-Shear Plasmas

- **Required implementation of off-axis current drive from toroidal field ramp**
- **Open-loop workflow converges to stationary solution**
- **Despite exotic scenario, STEP can reasonably predict NCS plasma conditions**

Open-Loop Workflow

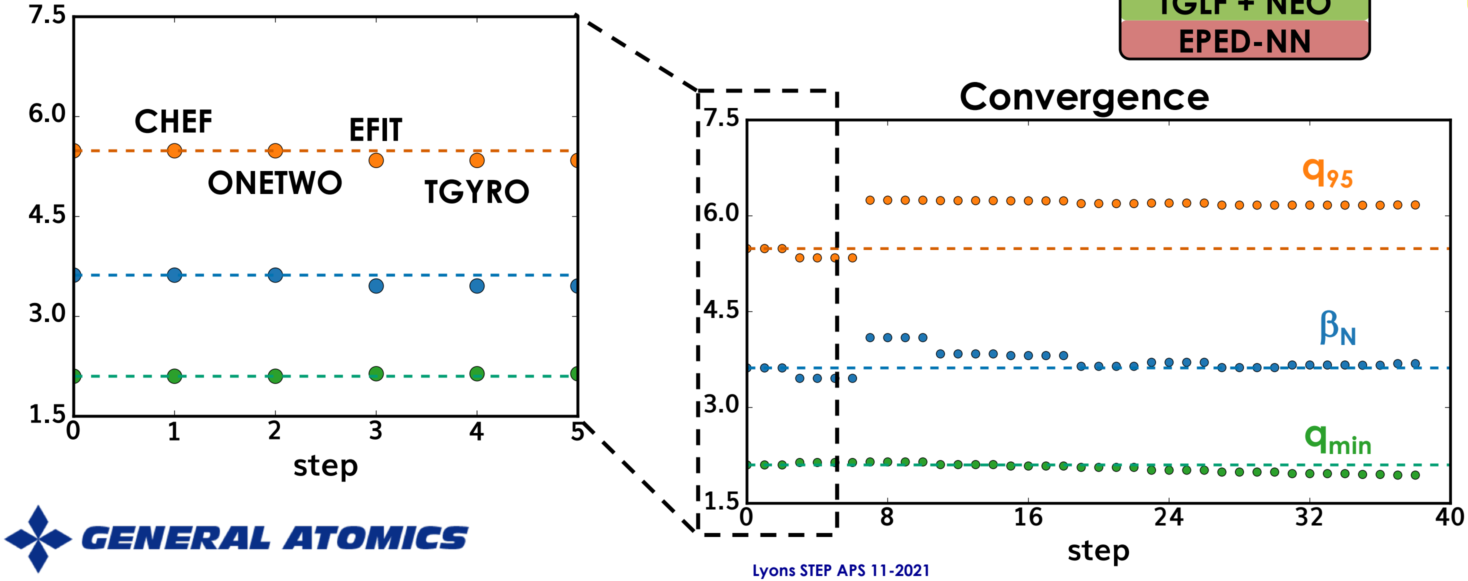


CHEF
(sources)

ONETWO
(current)

EFIT
(equilibrium)

TGYRO
(profiles)
TGLF + NEO
EPED-NN



Convergence

Open-Loop STEP Workflow with Enhancements Accurately Reproduces Negative-Central-Shear Plasmas

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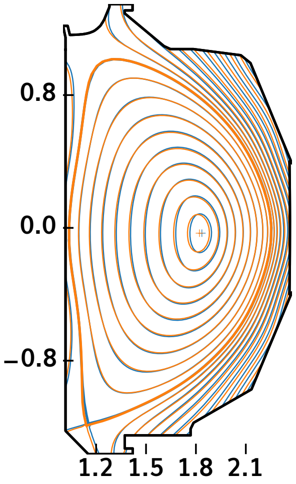
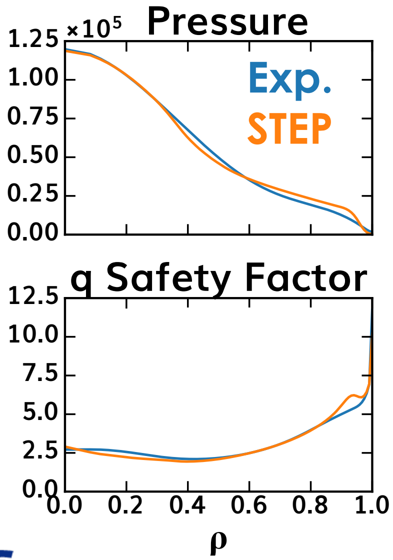
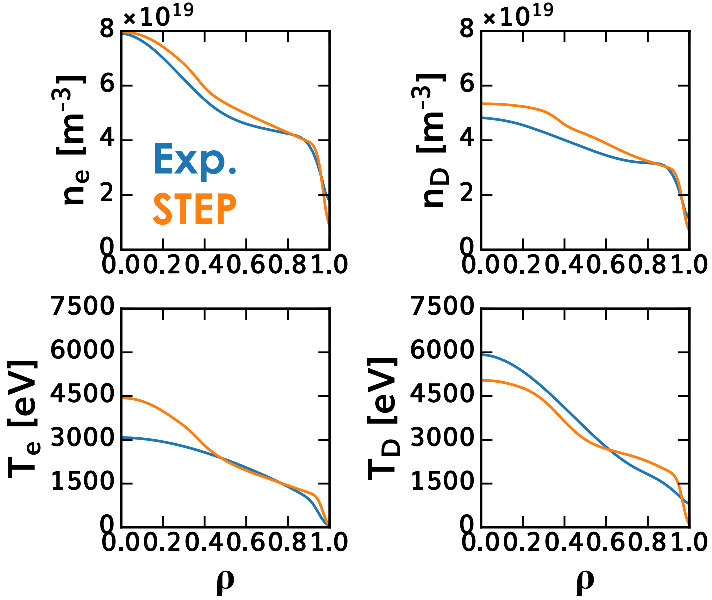
Further refinement possible by varying fast-ion diffusion and transport model

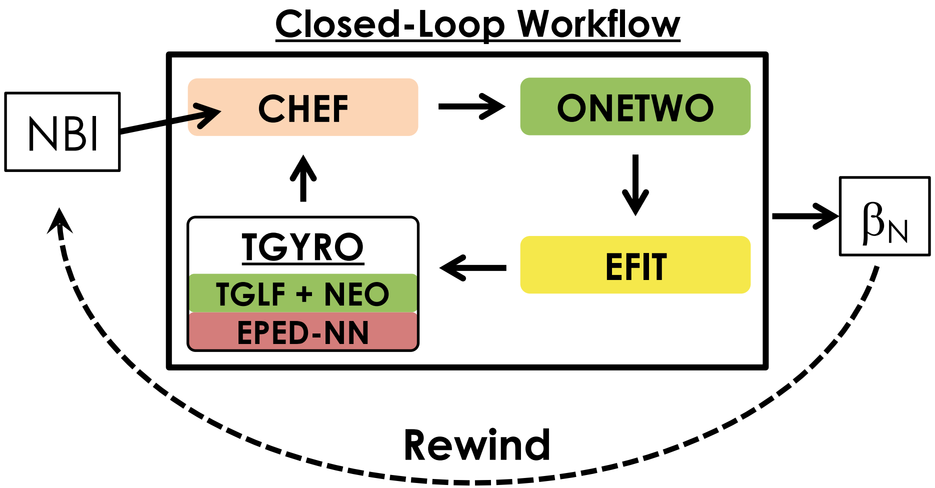






Closed-Loop STEP Workflow will Allow Prediction of Ideal Stability Boundaries

- **STEP allows the tuning of actuators to achieve defined targets using root-finding algorithm**
  - Set actuator (e.g., NBI power)
  - Run workflow to convergence
  - Compare solution to target (e.g., β_N)
  - Rewind and iterate
- **STEP finds NBI power necessary to achieve desired β_N**
- **Ongoing work**
  - Scan β_N and internal inductance
  - Assess ideal stability
  - Compare to published/ experimental limits



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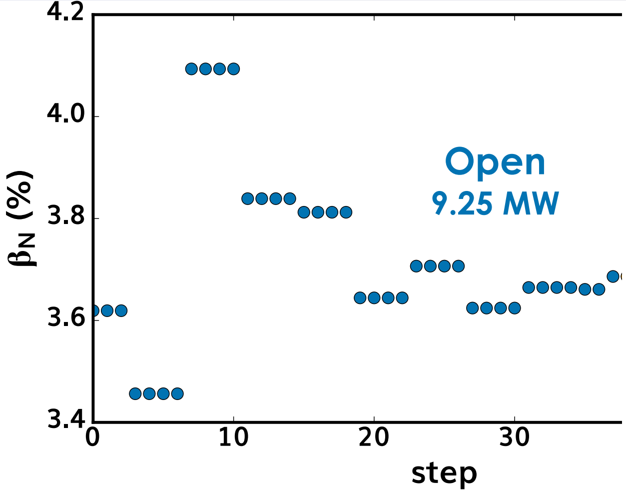

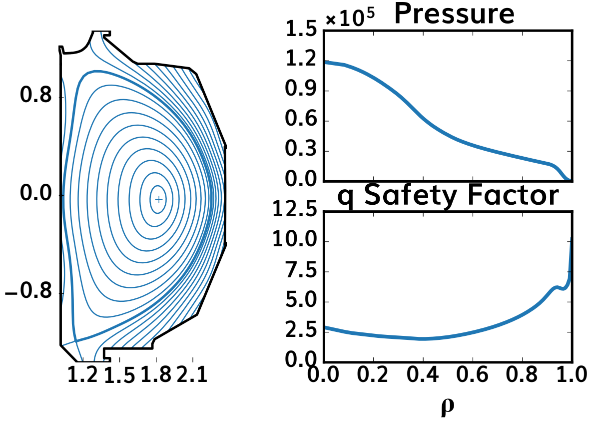

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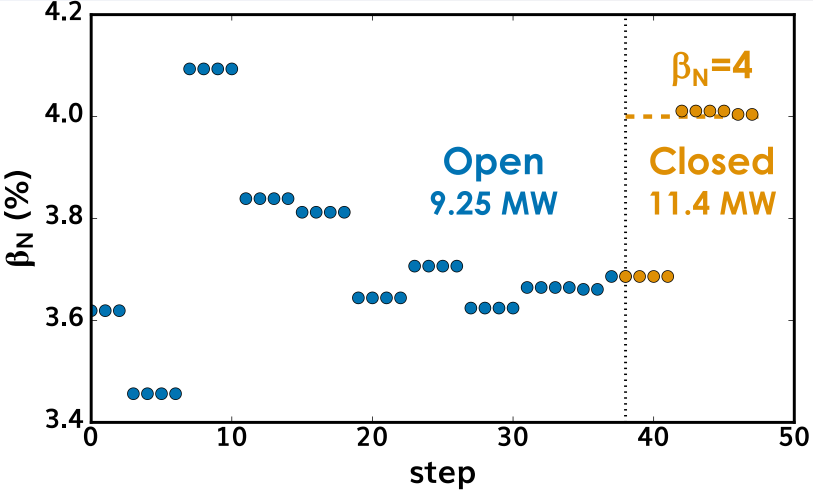

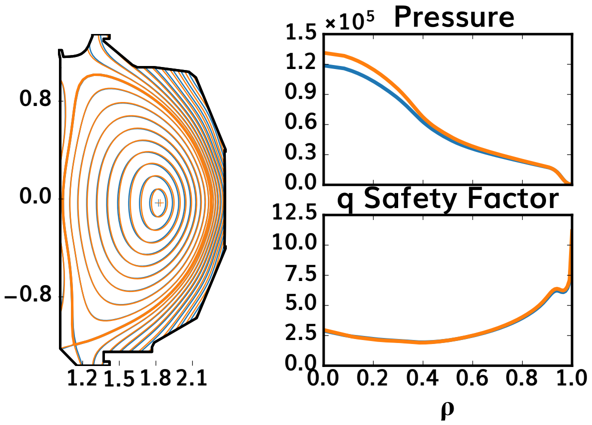

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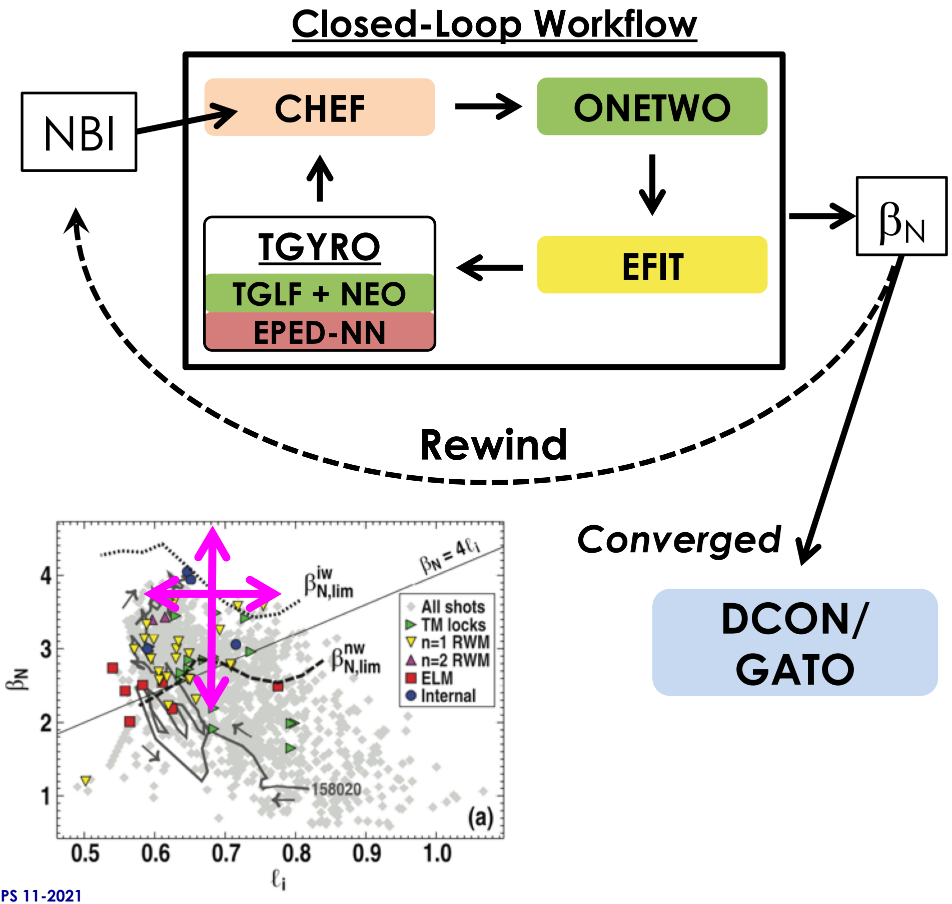


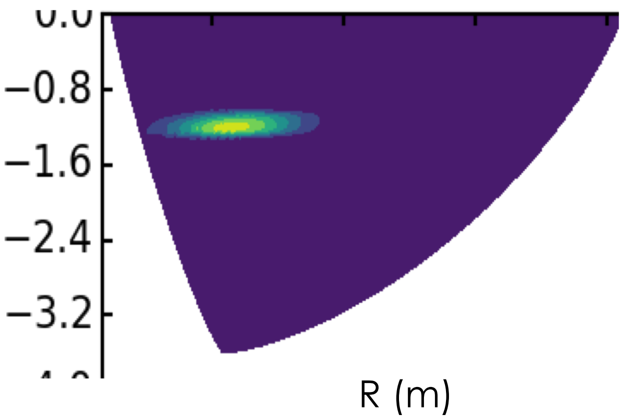
Predicting Performance in Future Tokamaks

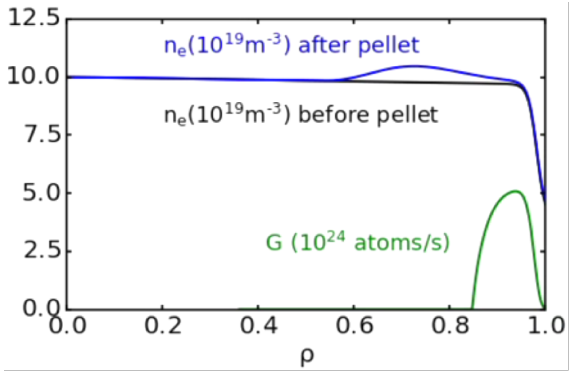
J. McClenaghan

STEP Modeling with Pellet Fueling Predicts Improved Performance of Super-H-mode in ITER Baseline Scenario

- **Previous results, optimizing only pedestal n_e and $Z_{eff,ped}$, predicted that the ITER baseline goal Q=10 would be narrowly met**
  - Solomon et al., NF 2014
  - Meneghini et al. PoP 2017
- **STEP allows for pellet-fueling studies through CHEF's Pellet Ablation Module (PAM)**
- **With 6-Hz pellet fueling, Q=13 predicted for super-H-mode profiles without significant optimization**

High-Field-Side ITER Fueling





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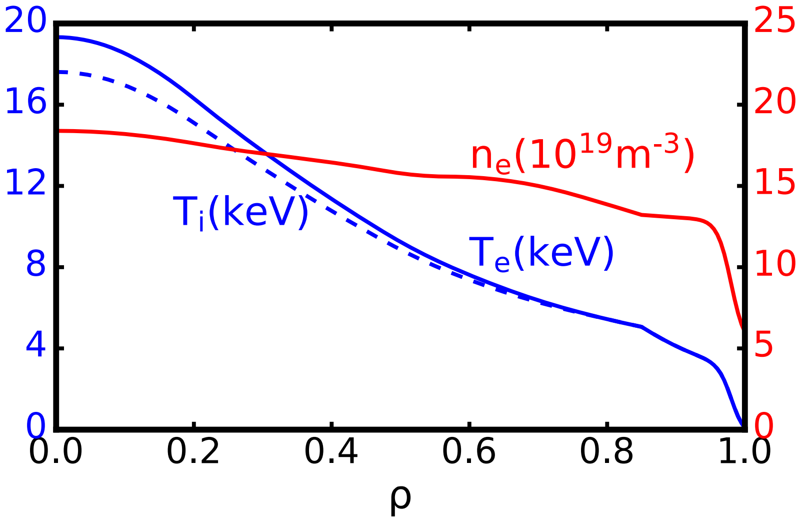
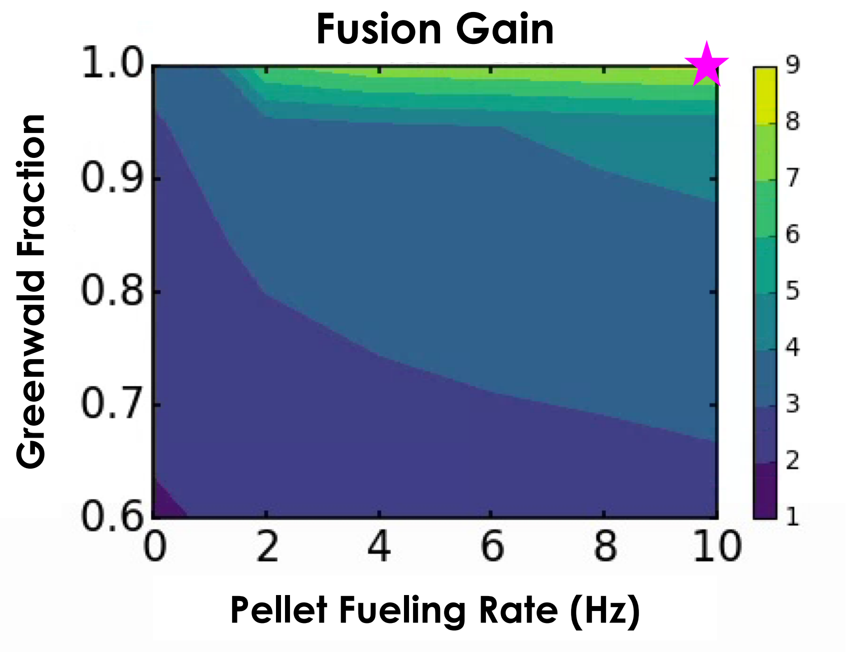
Profiles for Q=13 plasma ITER Baseline Super H-mode



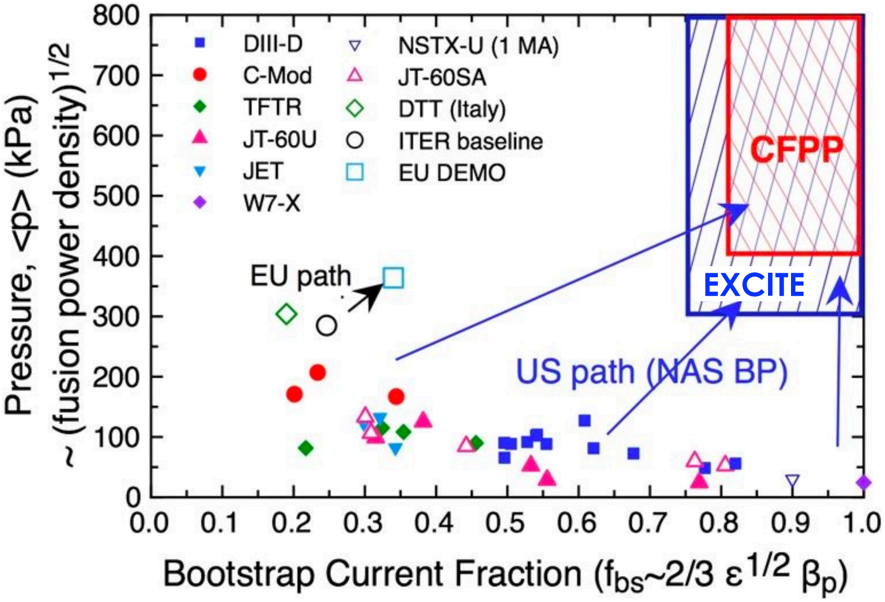
Pellet Fueling Improves Predicted Performance in ITER Advanced-Inductive Scenario

- **STEP modeling performed for 12 MA advanced-inductive scenario**
  - Improves performance by pushing stability limits over 15 MA baseline
  - Variety of pedestal densities and core fueling rates
- **Q=9 predicted for pedestal density at Greenwald limit and rapid pellet fueling**



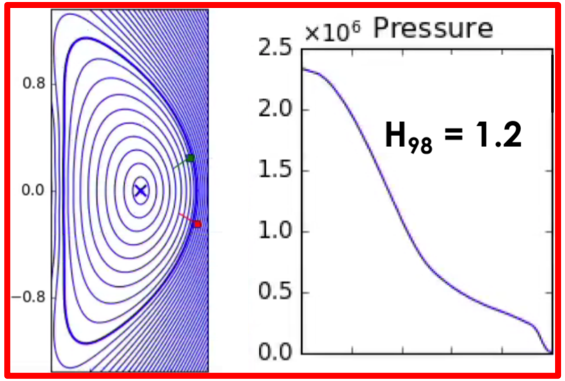
STEP Predicts Promising Scenarios for EXCITE High-Pressure Operation

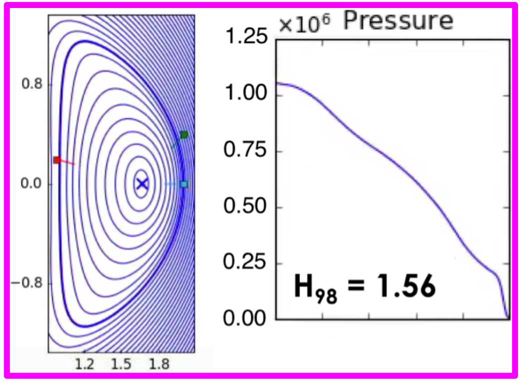
- **EXCITE is the next-generation tokamak experiment proposed by NAS/FESAC community planning**
- **Meant to test core-edge integration at reactor-relevant conditions**

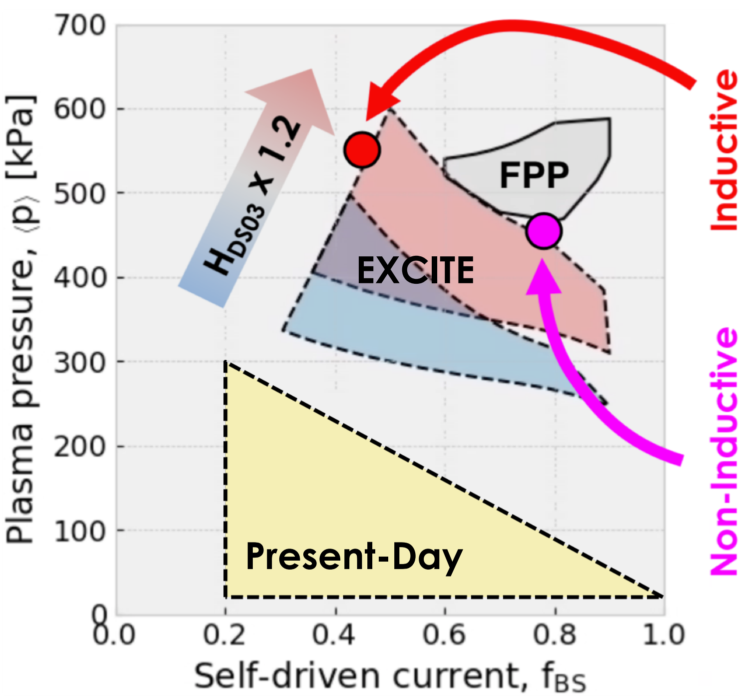


Inductive and Noninductive Scenarios Computed by STEP to Meet EXCITE Mission

- **Inductive (High Pressure Only)**
  - I_p=5 MA, β_N = 2.8, $n_{e,ped}$=4×10^{20} m^{-3}
  - 50 MW auxiliary power (helicon & ICRF)
- **Noninductive (High Pressure & Bootstrap)**
  - I_p~3.7MA, β_N = 3.0, $n_{e,ped}$=2.7×10^{20} m^{-3}
  - 40 MW auxiliary power (NBI, helicon, & ICRF)

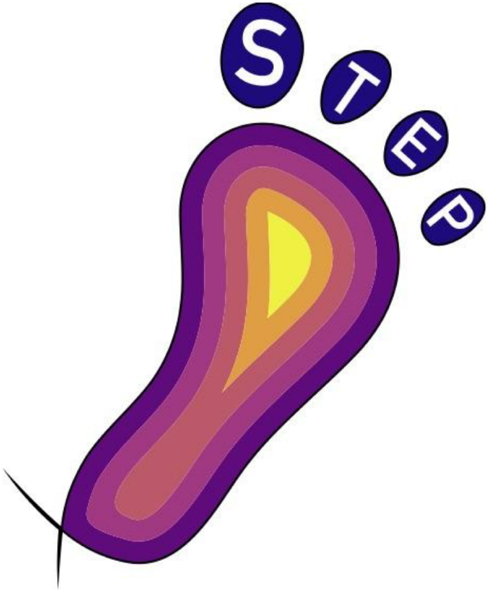






Conclusions

- **STEP (<u>S</u>tability, <u>T</u>ransport, <u>E</u>quilibrium, & <u>P</u>edestal) provides a flexible tool for theory-based, predictive, integrated modeling**
- **STEP is being used to analyze present experiments and to predict future tokamaks (ITER & EXCITE)**
- **Other devices can and will be considered**
  - Potential DIII-D upgrades (e.g. higher B_T)
  - NSTX-U
  - SPARC, DTT, STEP reactor, BEST/CFETR...
  - U.S. FPP



What Would You Like STEP to Do?

Contact:
Brendan Lyons
lyonsbc@fusion.gat.com

STEP-Related Talks at APS

- **Weisberg – EXCITE Design**
  JO07.00015, Tuesday 4:48 PM
- **Holland – Compact Reactor Design**
  TP11.00103, Poster Thursday AM
- **Slendebroek – Confinement Predictions**
  UO07.00014, Thursday 4:48 PM
- **Meneghini – OMAS**
  UP11.00090, Poster Thursday PM