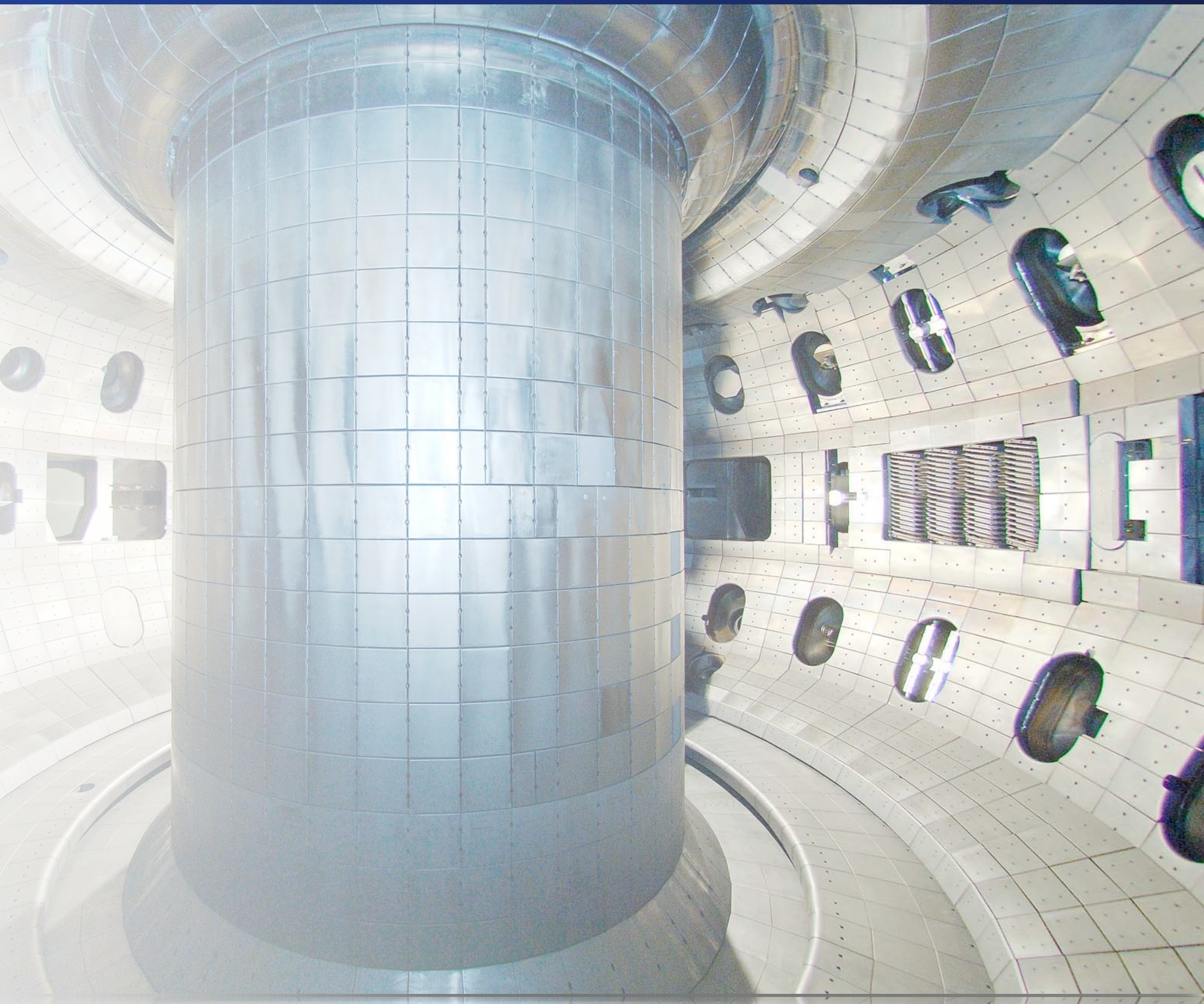
TRANSP Usage at DIII-D and TRANSP For Predictive Capability / Model Validation

by

B.A. Grierson

PPPL

Thanks to CPPG!



Presented at the TRANSP Users Meeting

Princeton Plasma Physics Laboratory
Princeton, NJ

March 24, 2015

DIII-D
NATIONAL FUSION FACILITY

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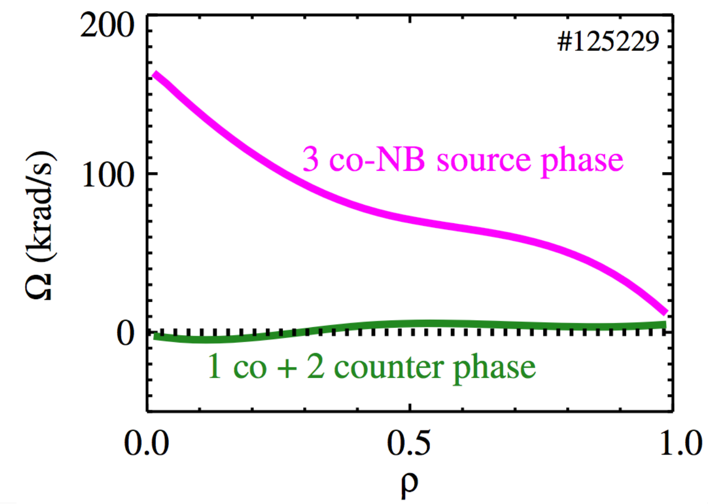
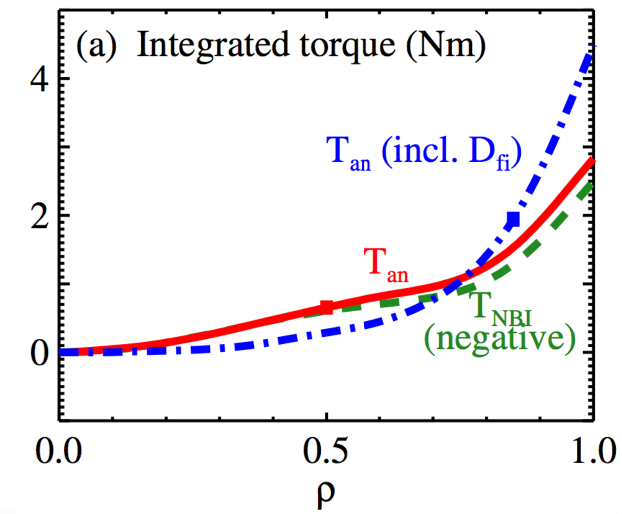
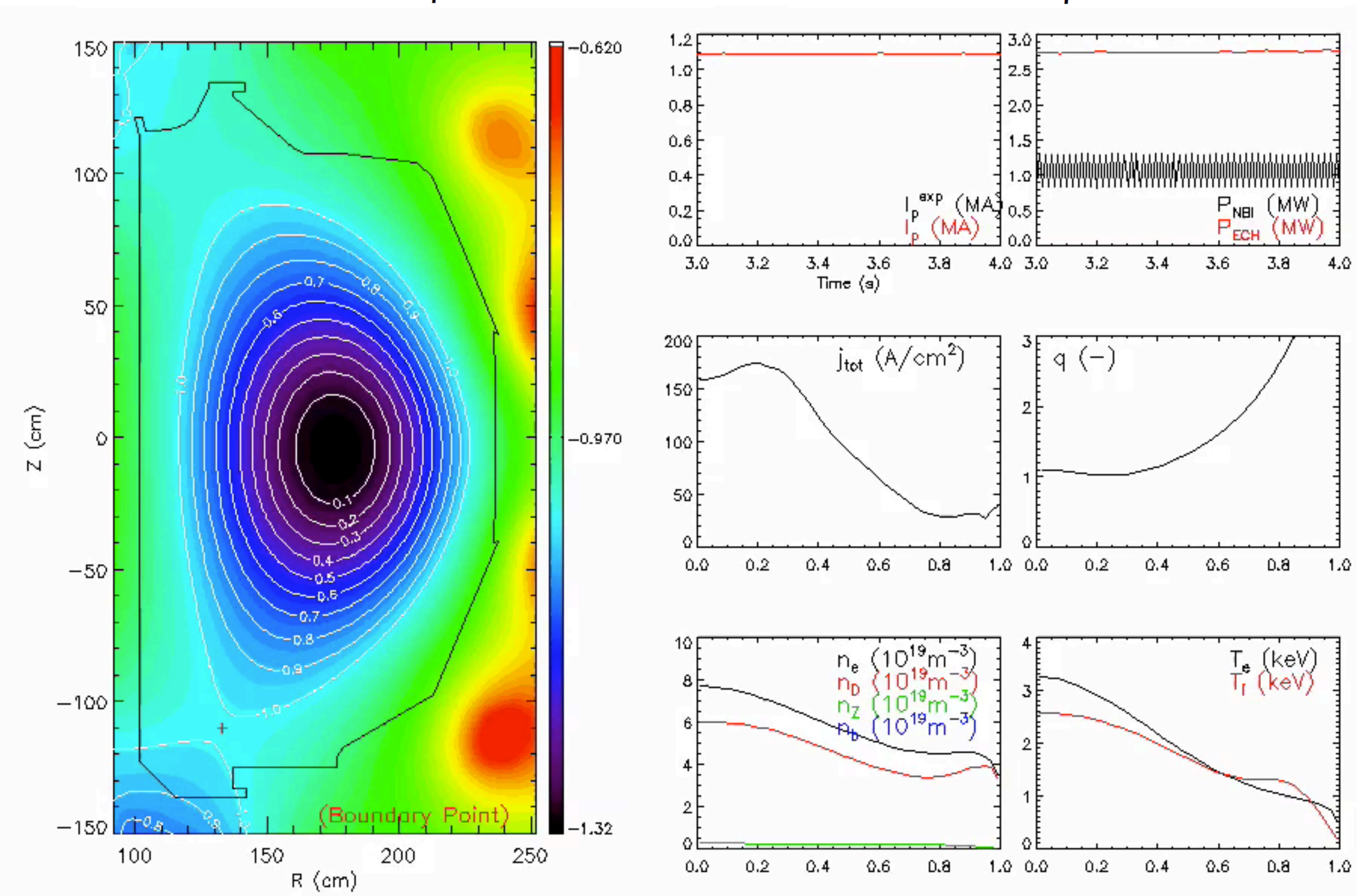
Overview

- **TRANSP Usage at DIII-D**
  - Interpretative
- **Expanding TRANSP usage**
  - Predictive core transport and equilibrium







Free-boundary simulation of DIII-D ITER Baseline with sawteeth*

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*movie

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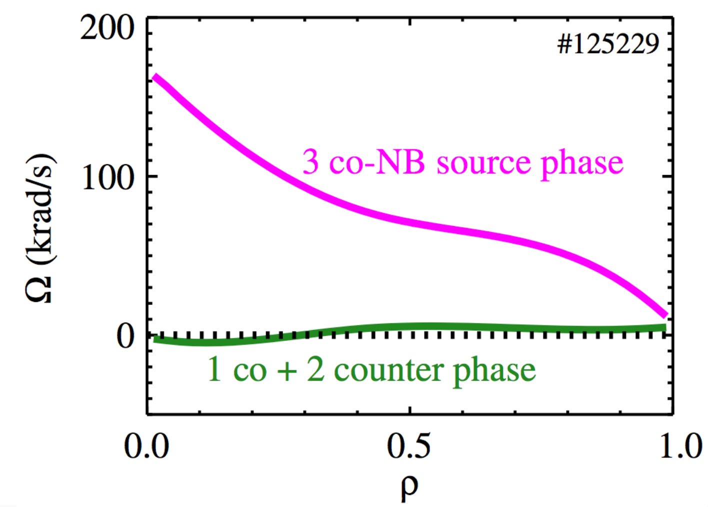

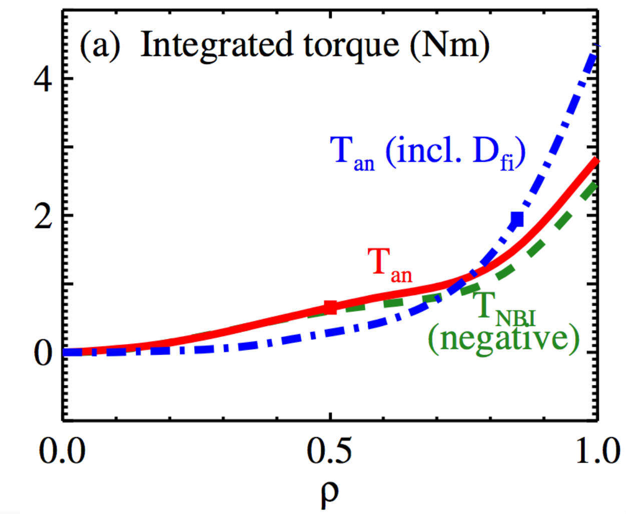

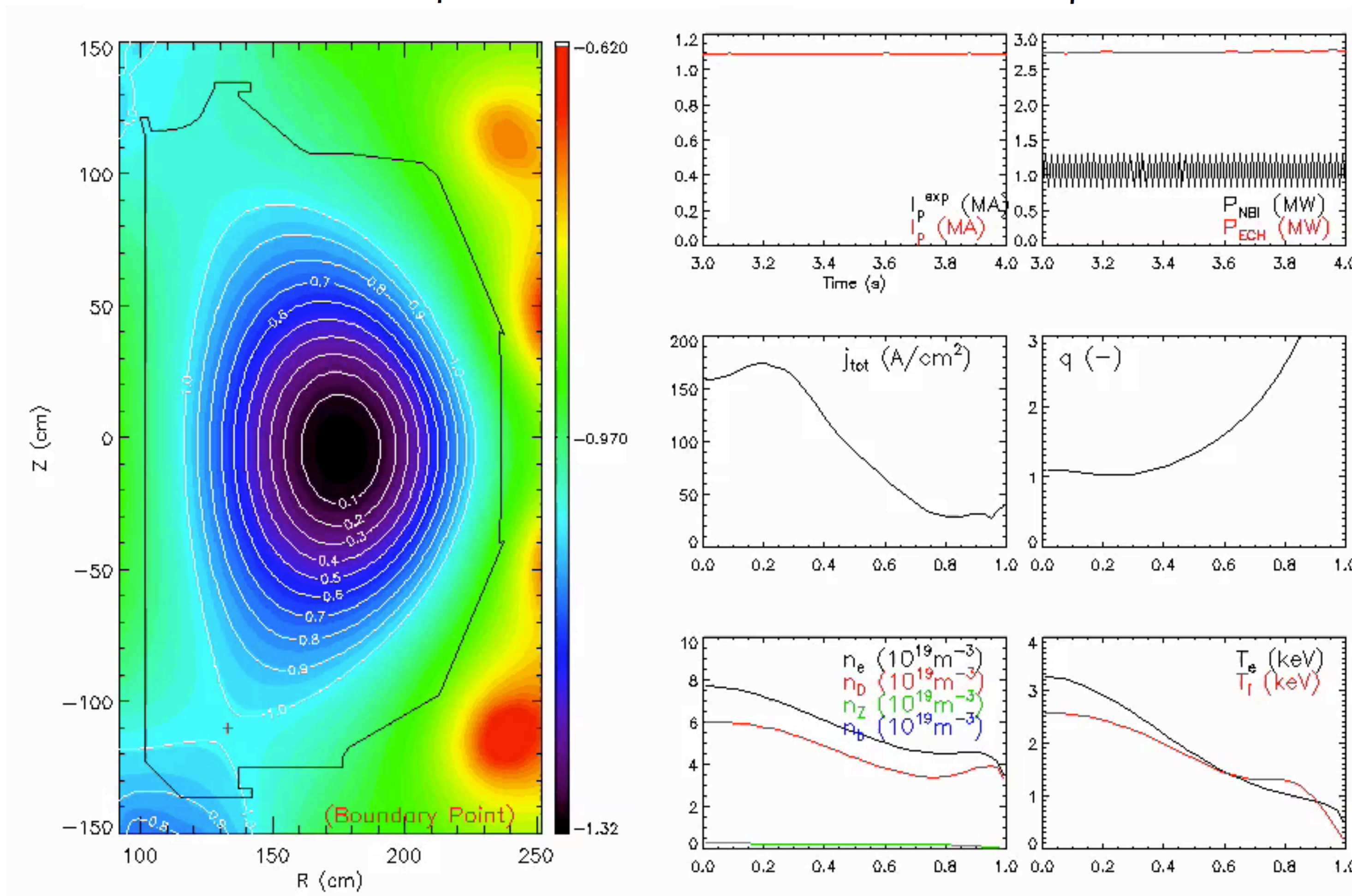

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TRANSP Users at DIII-D*

- **Early TRANSP implementation by Chuck Greenfield: AUTOTRANSP**
  - UFILE preparation for 1D histories, 2D profiles from user or automatic profile fits, MDSPlus EFITs, default namelist
  - `profiles_dir/IDL>autotransp` → GUI Driven TRANSP Submission
- **Long time users:**
  - Budny, Ernst, Heidbrink, Murakami, Park, Petty, Solomon, van Zeeland
- **Recent Additions:**
  - Grierson, Pace, Lanctot, Hanson, Tobias, Meneghini, Bardoczi, Chrystal, Logan, Haskey, Holland recent users
- **Many off-site users**

***All users are experimental plasma physicists**

Diverse Set of Workflow use TRANSP as Critical Component for Plasma Physics: TRANSP is a "Production Code"

- **EP Physics use TRANSP for kEFIT, neutrons, fast-ion distribution FIDAsim**
  - Synthetic diagnostics

  $f(\xi,E,R,Z), P_b, S_n, n_b^{(j)}$

- **Stability physics uses TRANSP for fast-ion distribution in kinetic calculations**
  - Sources for first-principles models

  $f(\xi,E,R,Z),\ P_b$

- **Rotation physics uses TRANSP for torque balance and intrinsic rotation studies**
  - Intrinsic torque, momentum transport coefficients

  $T_{inj},\ \Pi(\varrho)$

- **Turbulence and transport uses TRANSP for power balance fluxes as input to GK simulations (HPC)**
  - Sources for first-principles gyrokinetic models

  $Q,\ \Gamma,\ \Pi$

- **Turbulence and transport use TRANSP for transport model validation and predictive equilibrium+transport modeling**
  - Validation of reduced transport models (TGLF, GLF23, MMM, RLW)

  $Q,\ \Gamma,\ \Pi$
  $\eta,\ j^{BS}, \gamma^{MSE}$

- **Scenarios use TRANSP for both time-dependent and steady-state modeling**
  - Predictive modeling of coupled transport+equilibrium evolution

  $Q,\ \Gamma,\ \Pi$
  $I_p,\ V_{sur}, \eta,\ j^{BS}, j^{aux}$

What I mean by “TRANSP”

- **TRANSP at its core evaluates the time dependent transport equations on an equilibrium grid incorporating sources and sinks**

- **Interpretive TRANSP provides fluxes and uses experimental profiles to determine transport coefficients**
- **Input equilibrium and sources**
- **Output η, χ, D, etc… to compare to transport models**
- **Output for post-processing of diagnostics (MSE γ, FIDA, etc…)**

- **Predictive TRANSP uses fluxes and transport models to determine profiles**
  - Compare experimental profiles to model-based profiles
- **Equilibrium and sources from experiment *or* prescribed for study**
  - Distinguishes from “model validation” or “prediction” workflow

What I mean by "TRANSP"

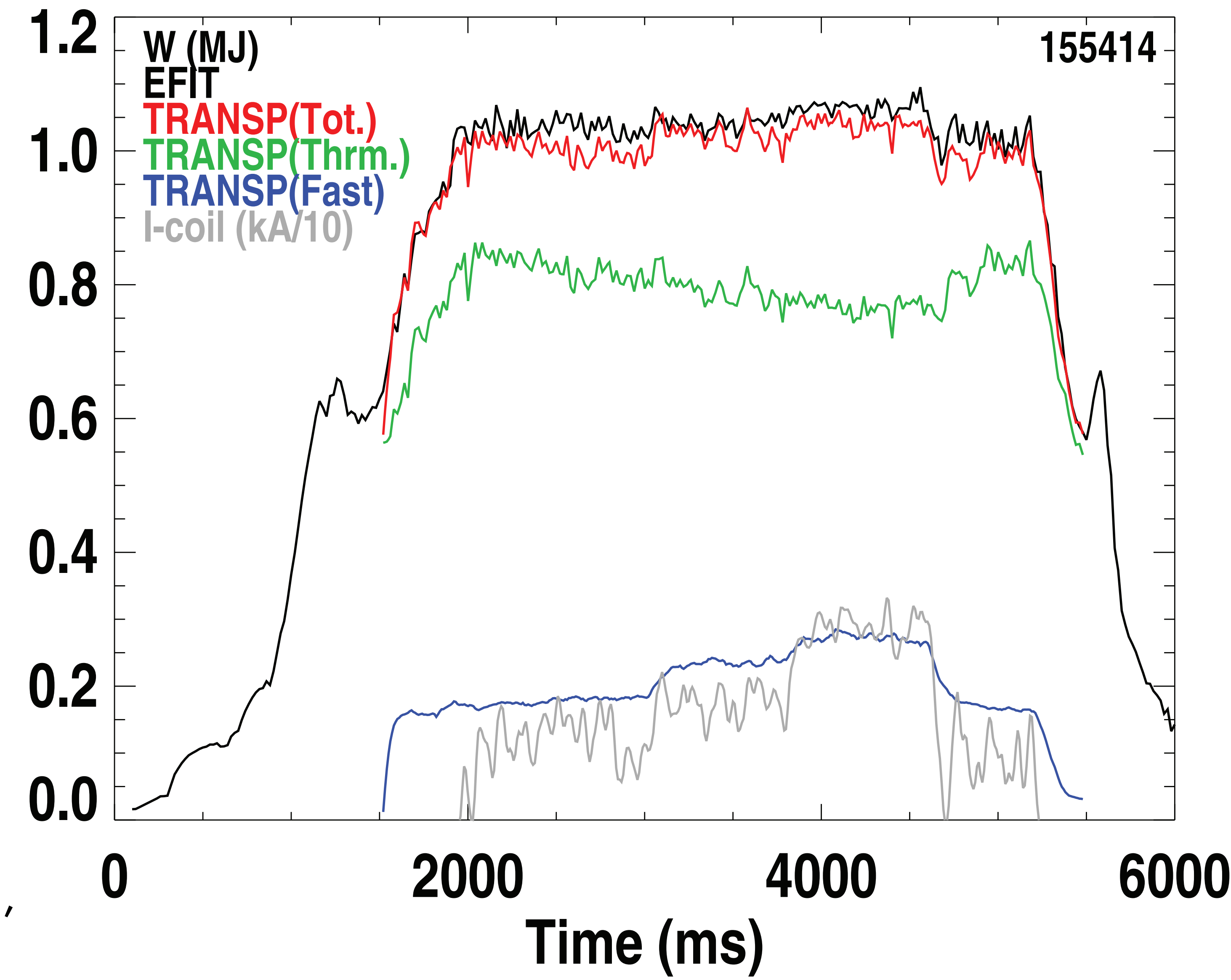
- **TRANSP at its core evaluates the time dependent transport equations on an equilibrium grid incorporating sources and sinks**

- Sources
  - NUBEAM (MPI)
  - LSC, TORAY, CURAY, GENRAY,
- Equilibrium options
  - Prescribed (EFIT)
  - Grad-Shafranov with fixed boundary (TEQ)
  - Free boundary with experimental coil currents (ISOLVER)
  - Free boundary predicting coil currents (ISOLVER)
- Transport model options
  - Use predictive transport solver PT_SOLVER
  - Neoclassical Chang-Hinton, NCLASS
  - Serial turbulent models GLF23, MMM, parallel TGLF
- MHD instabilities
  - Porcelli/Kadomtsev sawteeth
  - Ad-hoc options for NTM, ELMs

Interchangeable via simple namelist

Contrasting Interpretive vs. Predictive TRANSP

- **"Interpretative transport"**
  - Components of W
  - Power balance χ, D
  - Prescribed equilibrium
- **"Predictive Simulation"**
  - Fluid variables T_e, T_i, n_e, Ω from transport model
  - Chang-Hinton, NCLASS
  - GLF23 (serial), MMM (serial), TGLF (parallel)
  - Equilibrium from experiment (EFIT) or current diffusion with prescribed flux-surfaces, TEQ, or free-boundary ISOLVER



DIII-D I-Coils regulate thermal stored energy as "burn control" actuator Hawryluk, *et. al. NF* (2015)

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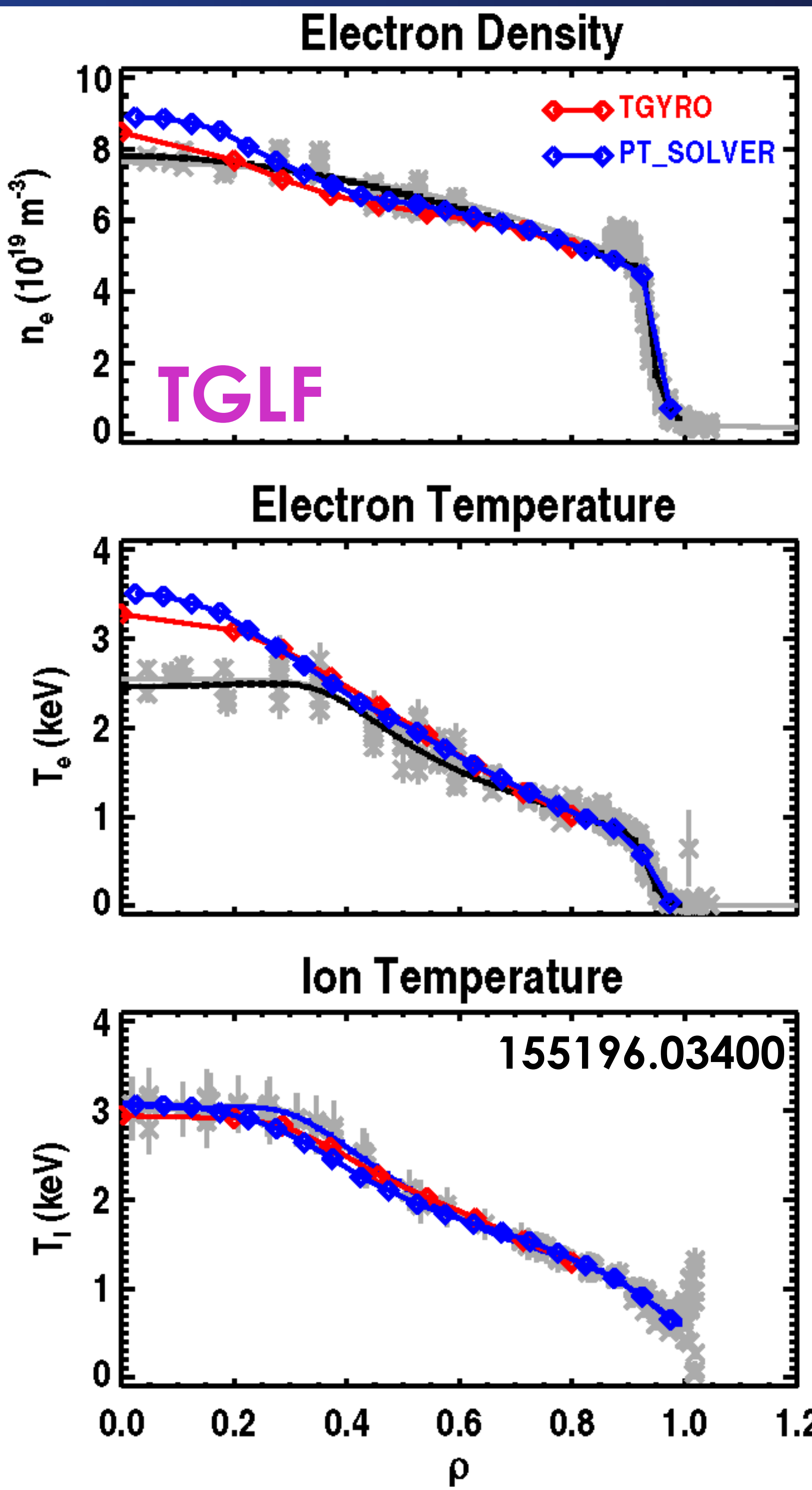
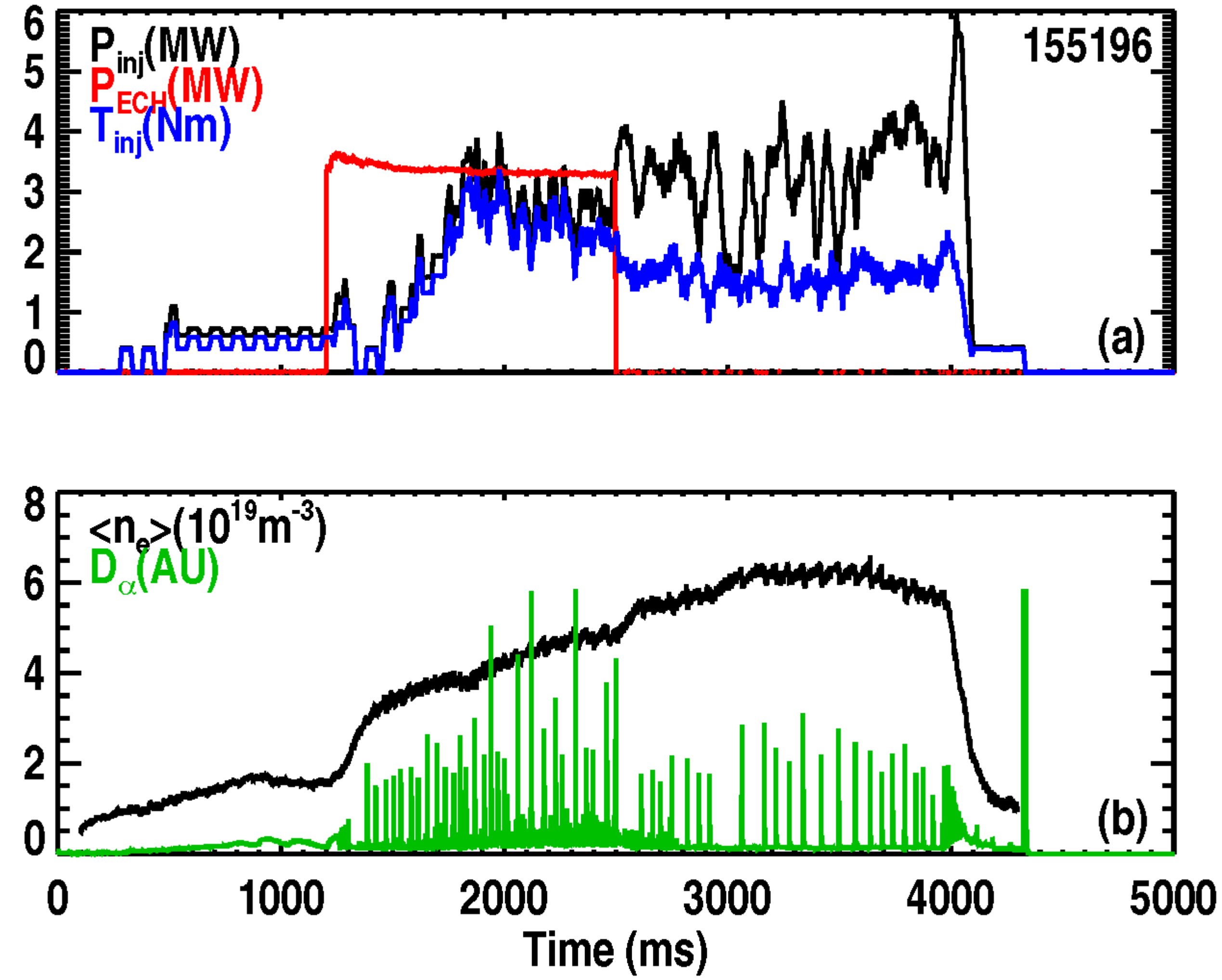
PT_SOLVER verified in steady-state by comparing to TGYRO



Time-Dependent Predictive Capabilities in TRANSP Enable Efficient and Streamlined Model Validation Studies

- **Snapshot analysis is used for first-principles GK simulations (HPC)**
  - Often same workflow used for reduced models
  - *but* Reduced models fast enough to be used in time-dependent simulations
- **Can evaluate model fidelity as actuators and equilibrium evolves**
- **Convenient and familiar storage of output enables entire TRANSP runs to be directly compared for arbitrary 1D and 2D quantities (T_e, T_i, n_e, q, j^{BS}, etc…)**



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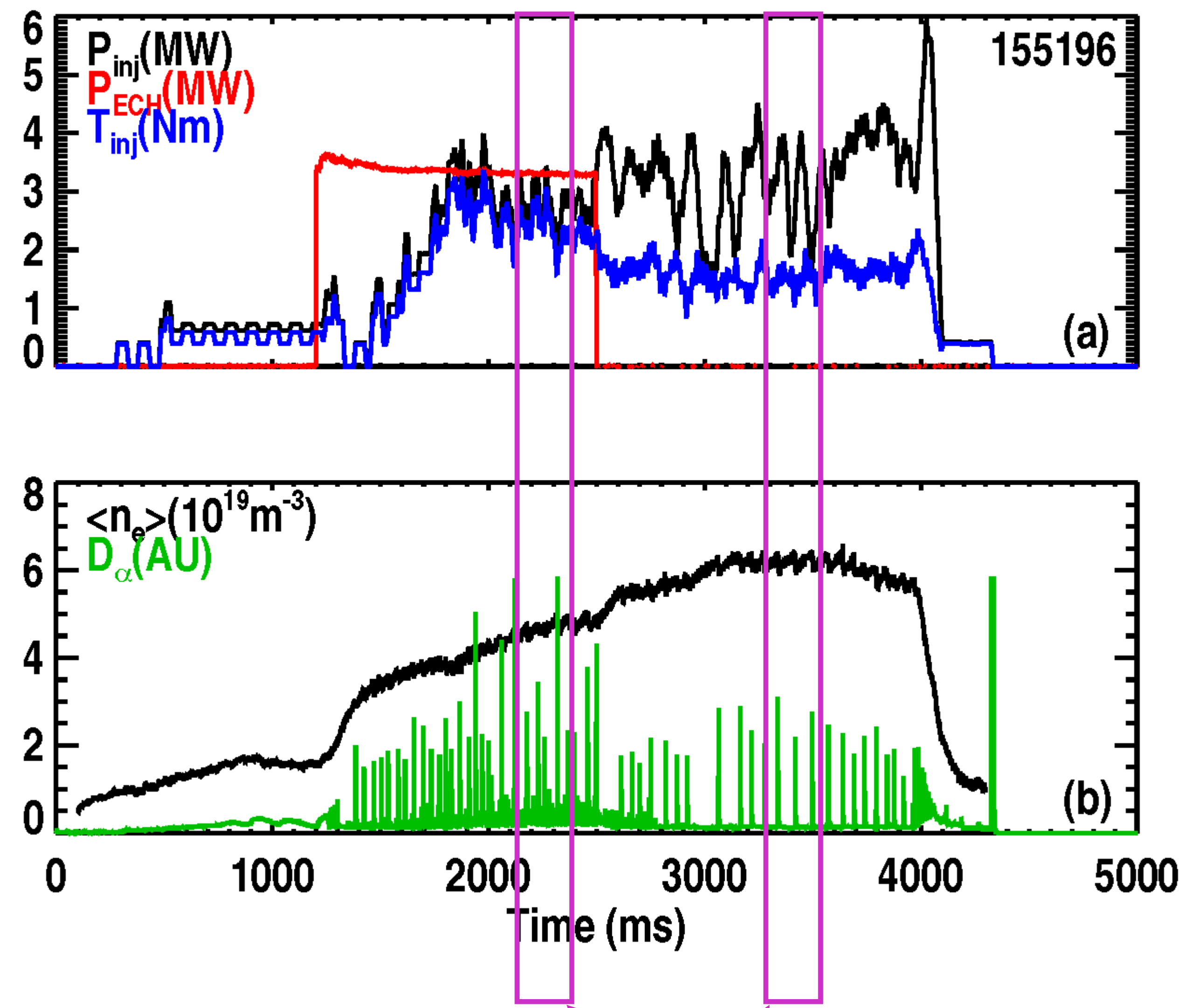


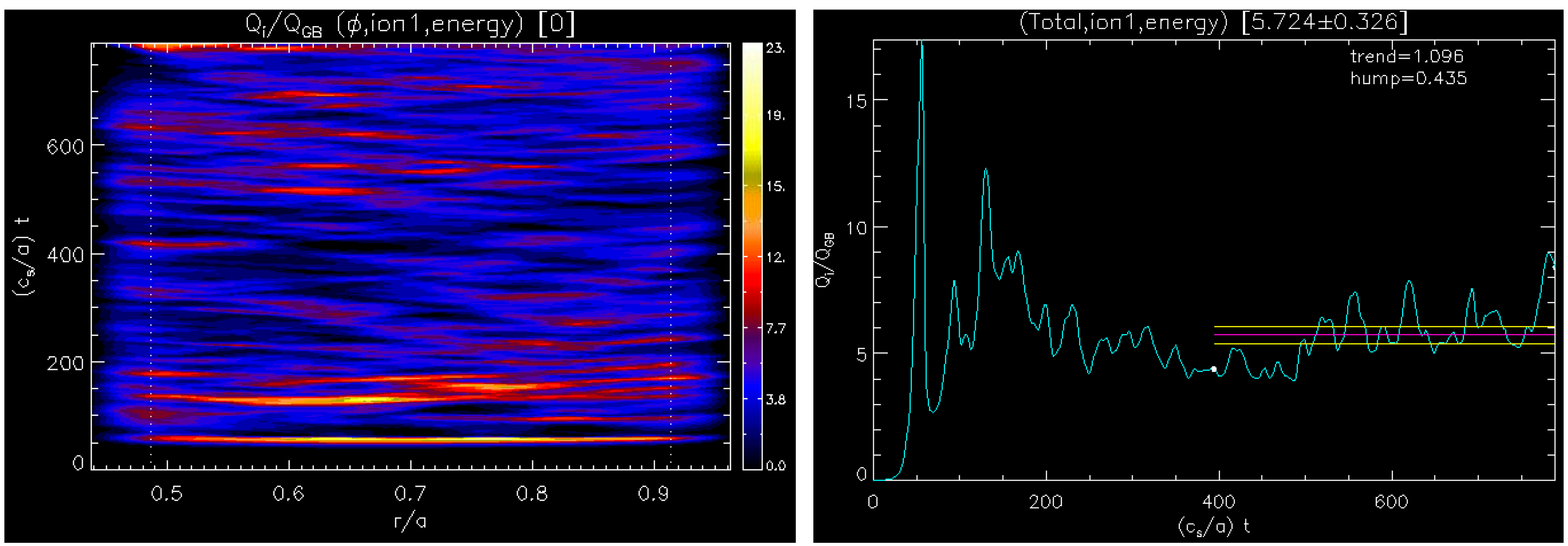
Do snapshot analysis here
GYRO, TGYRO, MMM, PT_SOLVER

Looks "good"? Run time-dependent simulation for entire H-mode phase for available transport models

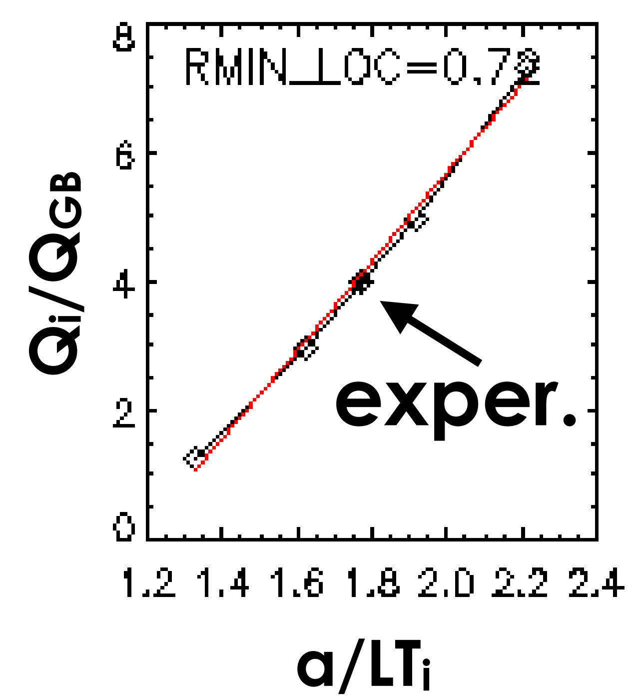
TRANSP Output Used for Reduced Model Verification Prior to Time-dependent Simulations

- **GYRO, TGLF, NEO and TGYRO all run for snapshots using TRANSP equilibrium, profiles and fluxes**
- **Verification that TGLF is capturing first-principles model determined by a/L_X scans**
  - $Q^{TGLF} \approx Q^{GYRO}$ locally
  - Quantification of expected stiffness

Nonlinear flux-tube GYRO at r/a=0.7

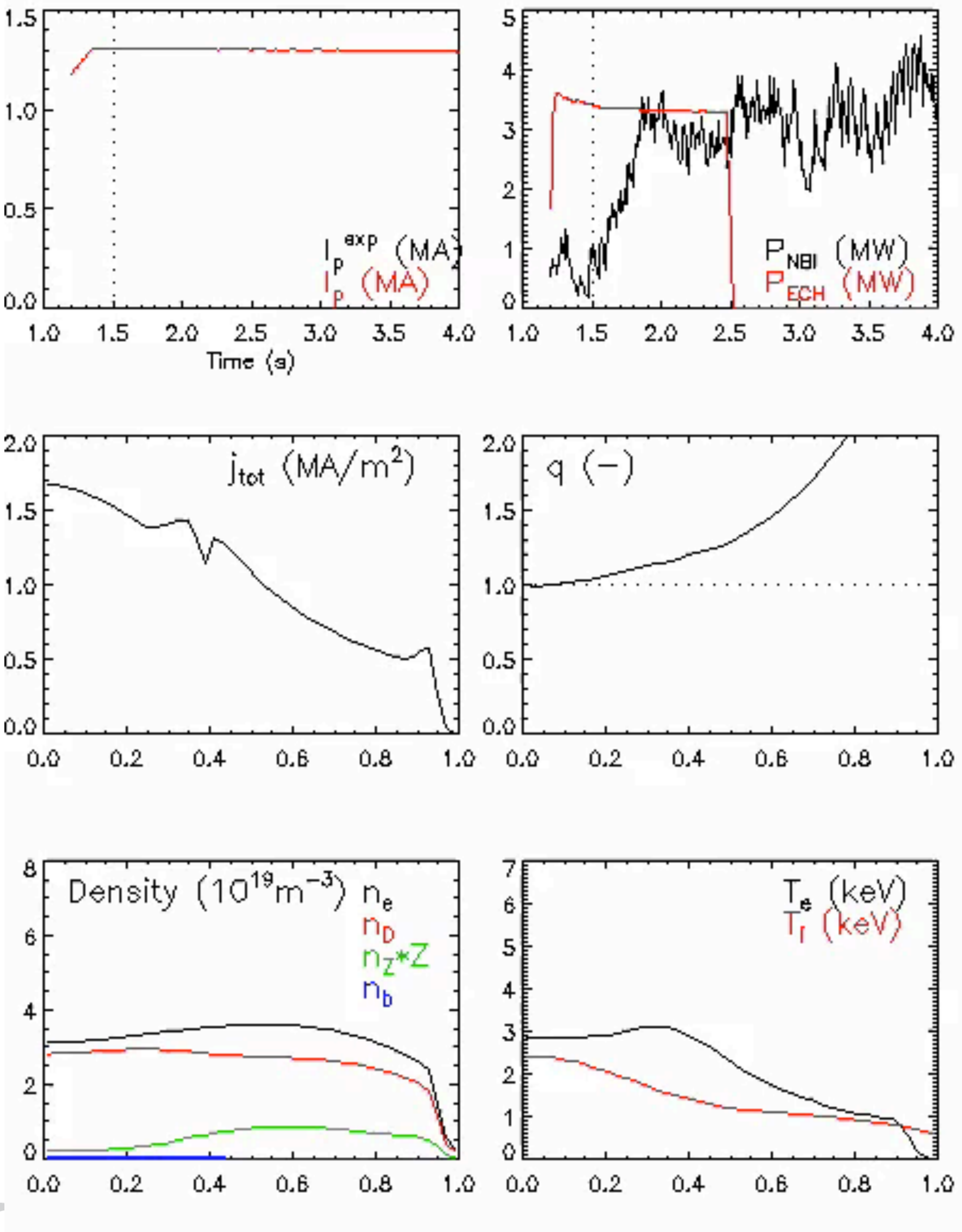


TGLF

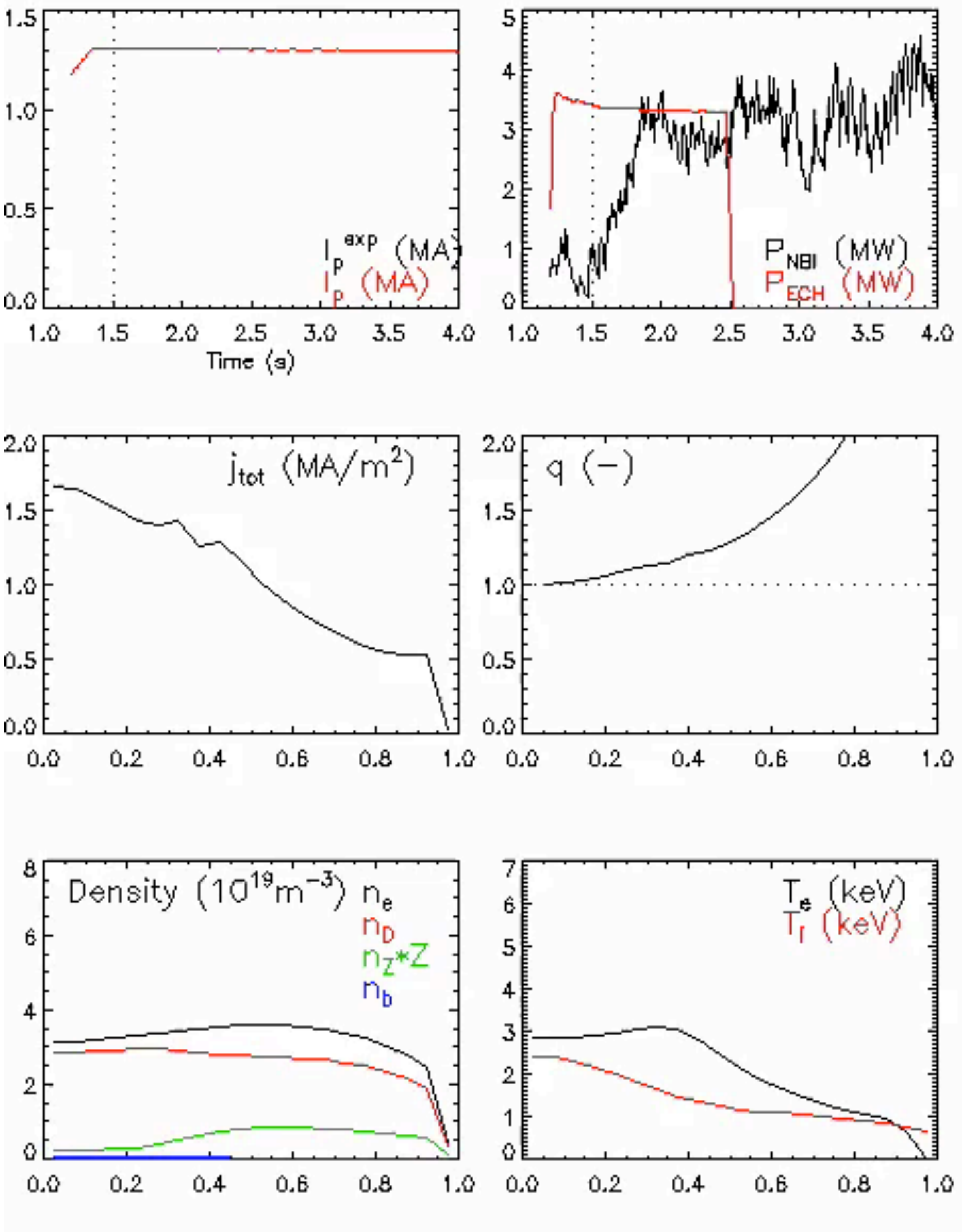


Simulations Are Executed using Various Models by Increasing Level of Complexity to Assess Sensitivities as Inter-dependencies are Identified

Simulation with GLF23*



Simulation with TGLF*



*movie

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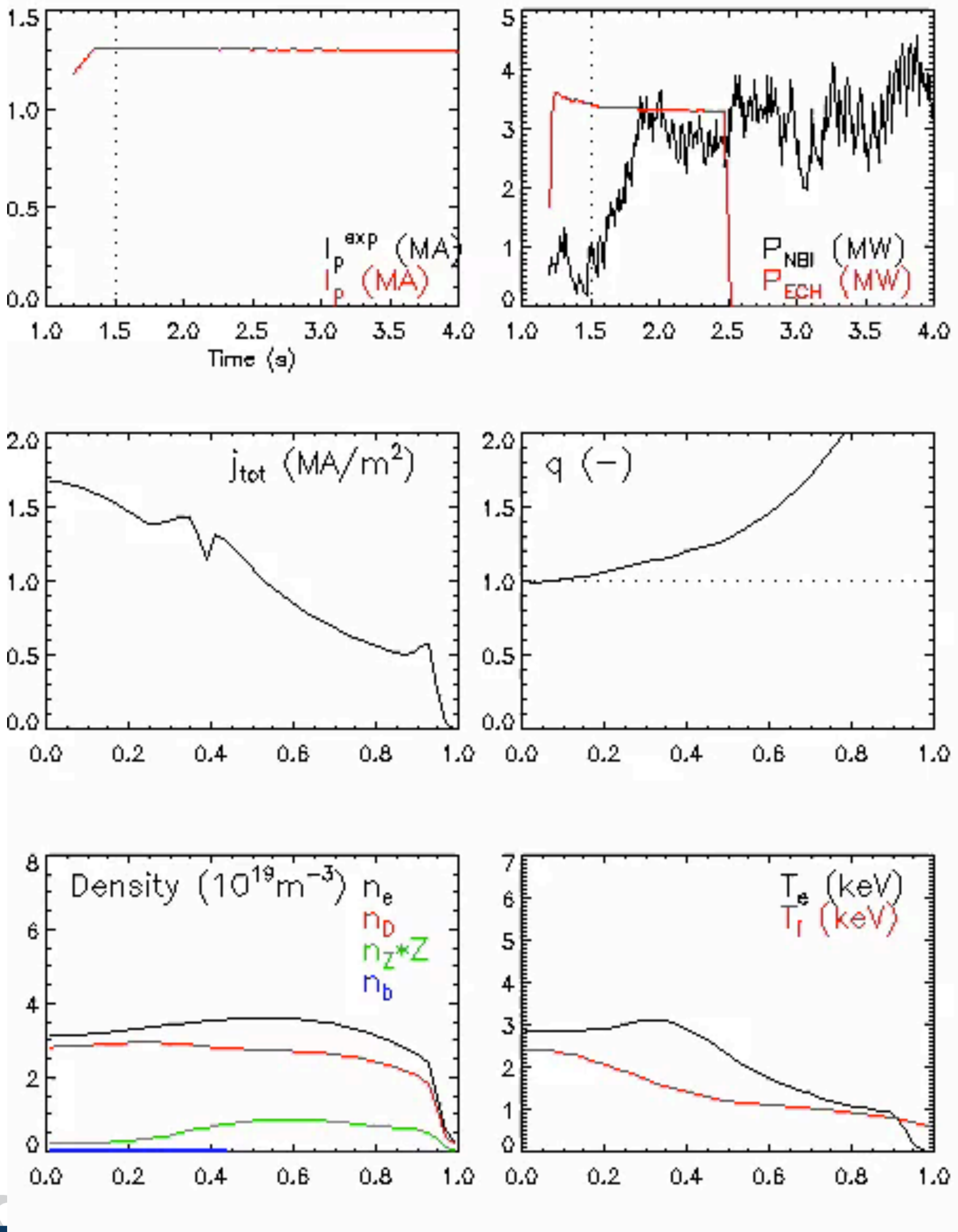
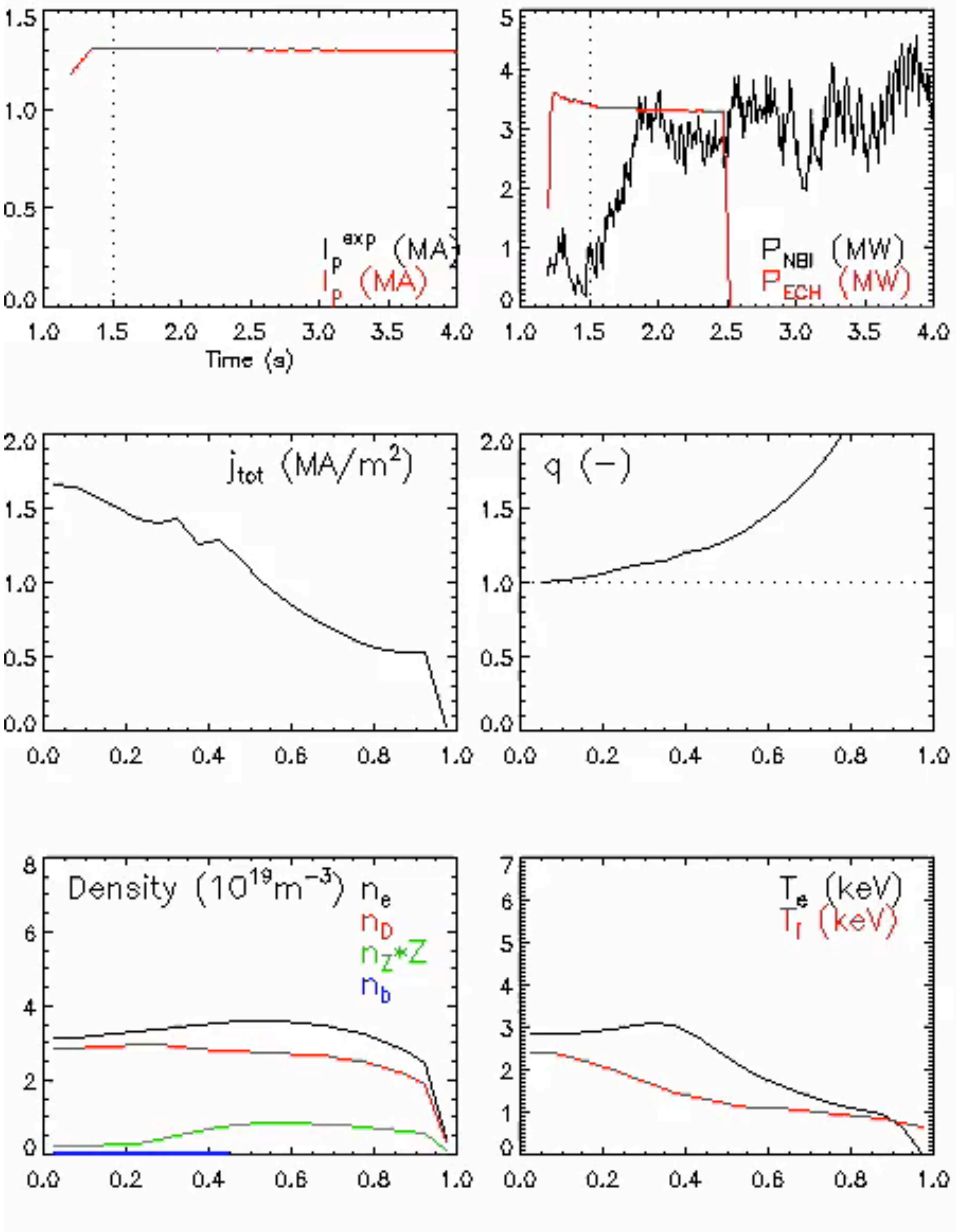


Simulation with TGLF*



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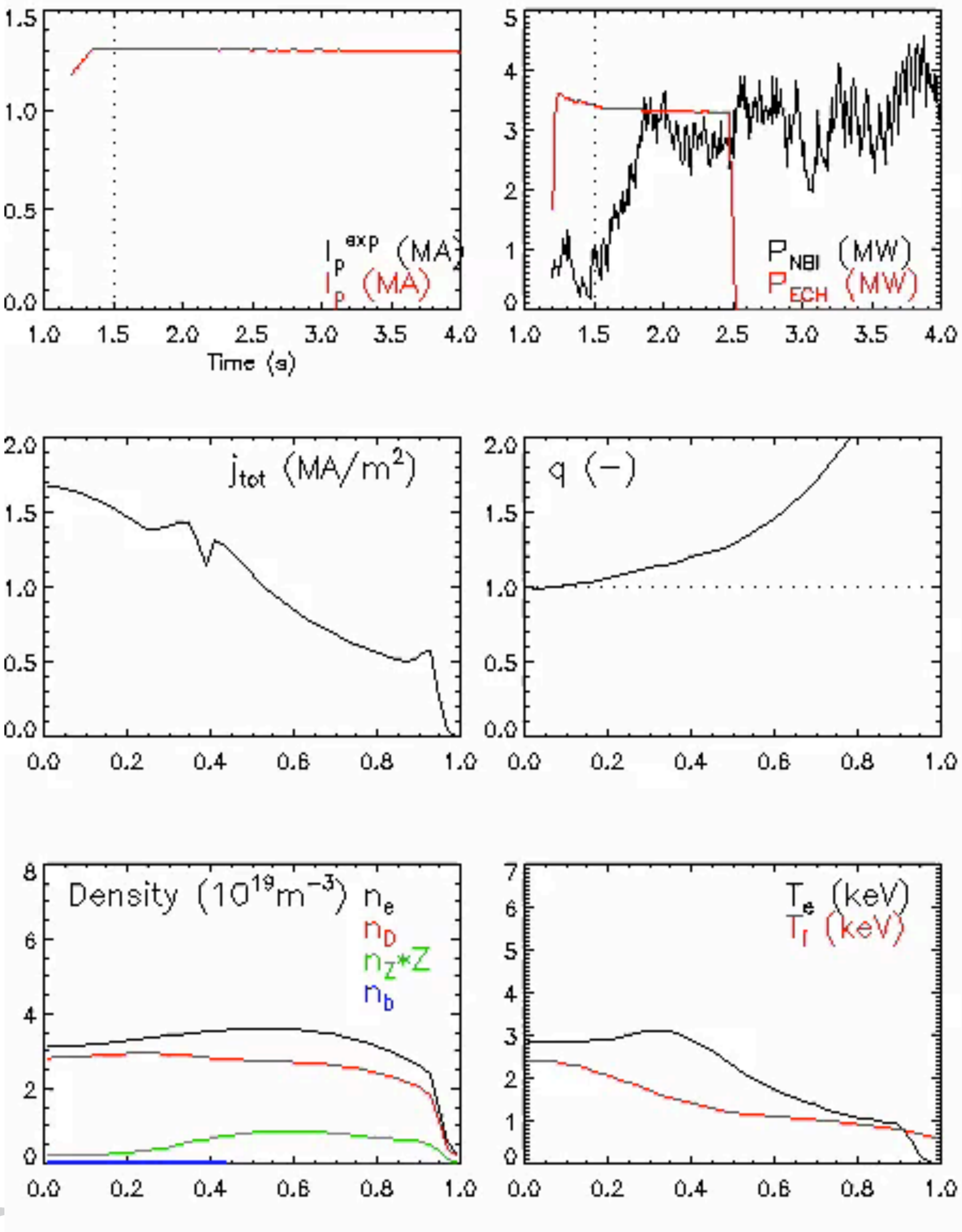
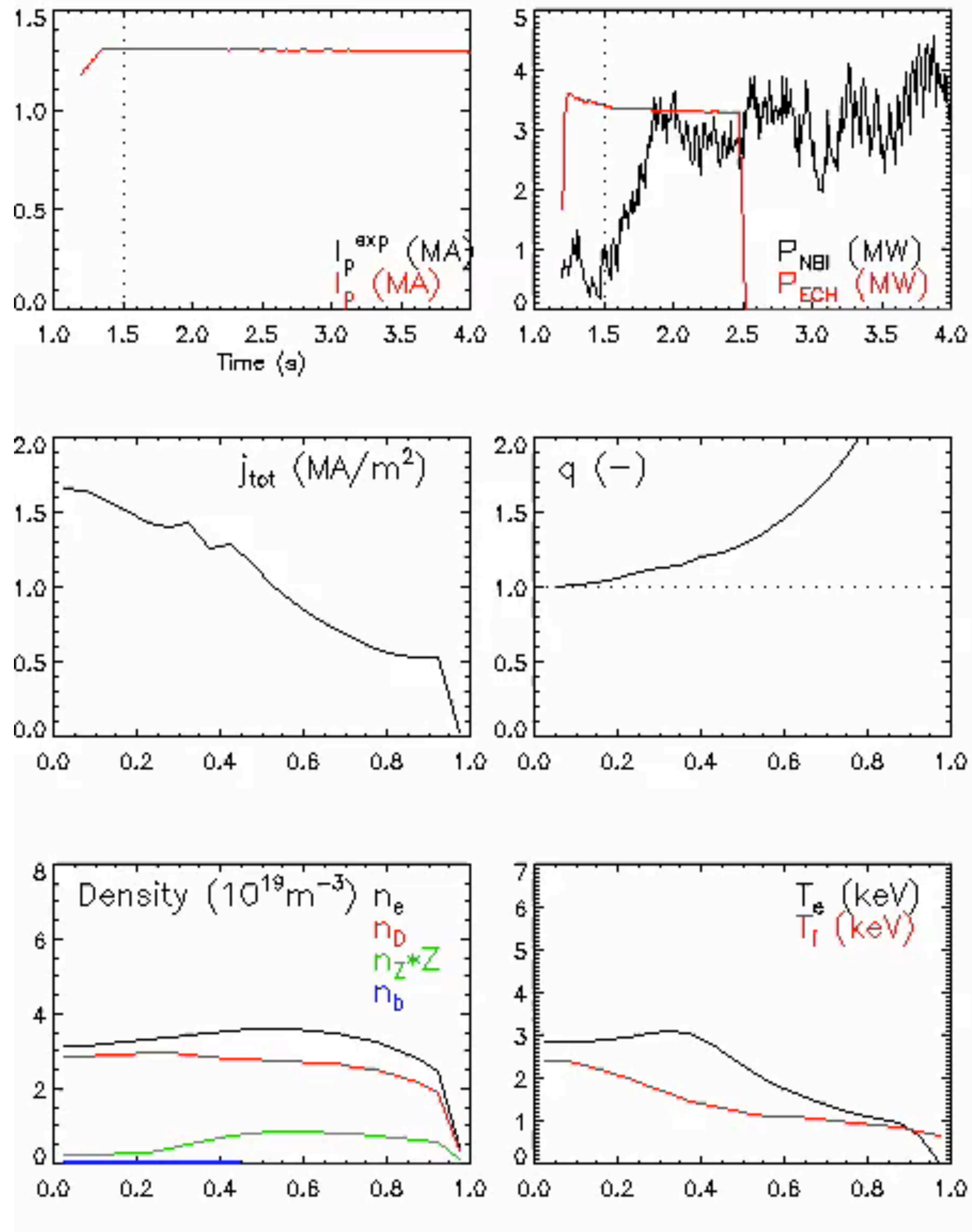


Simulation with TGLF*



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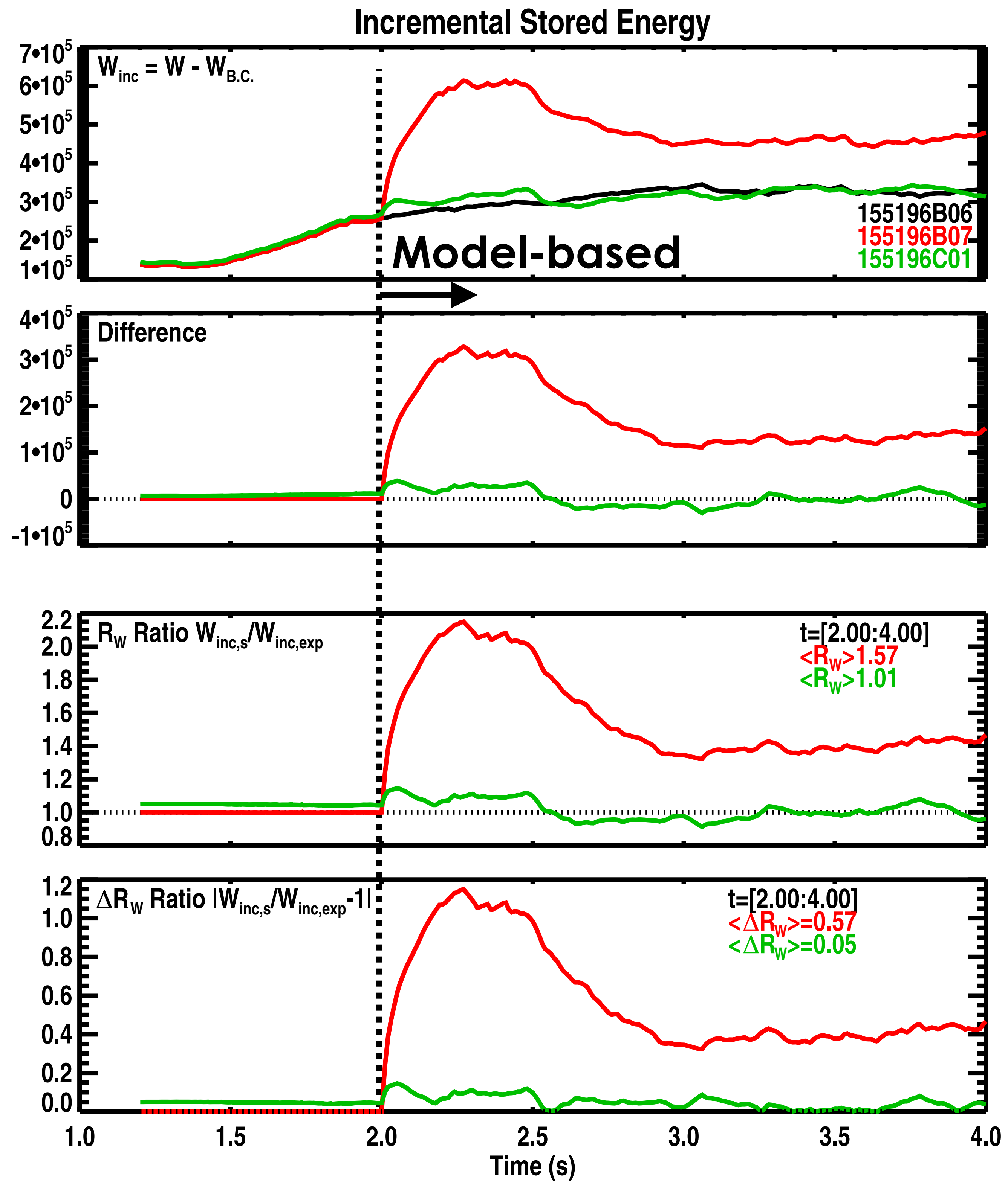
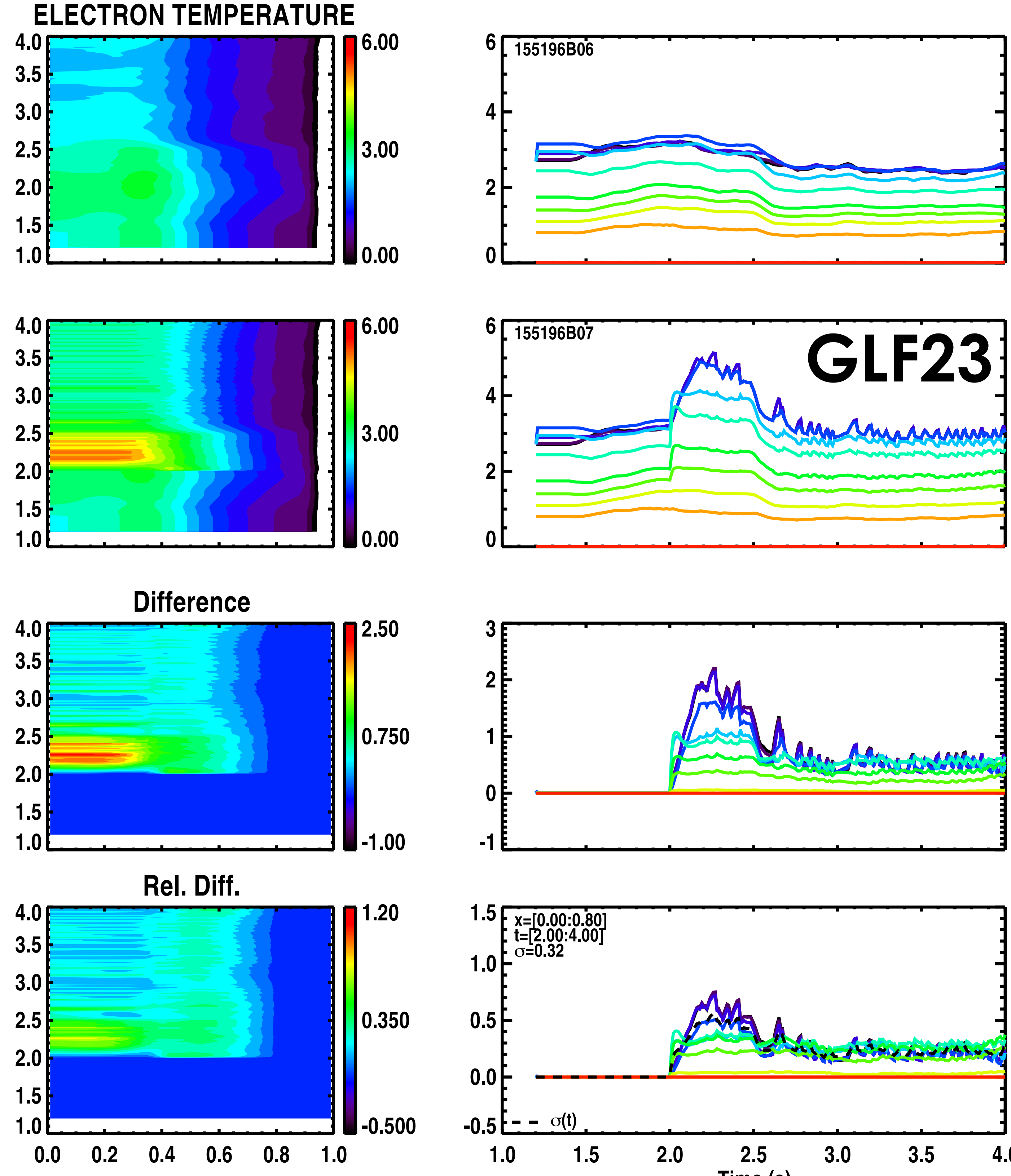
Global Quantities Evaluated With Straightforward Loop over TRANSP Run IDs: Clear TGLF is a More Accurate Transport Model for ITER Baseline w/ Electron Heating

- Thermal stored energy W_{inc} compared to experimental value has been used as a core transport model metric
- Experimental, GLF23 and TGLF TRANSP runs used to define model "validity"
- Global confinement metrics indicated TGLF is more accurate ($\langle\Delta R_W\rangle$=57%, $\langle\Delta R_W\rangle$=5%) for global stored energy
- Clear that direct electron heating (ECH) causes large discrepancy from experiment



Computing Validation Metrics of Individual Profiles (and gradients) in Spatio-Temporal Space Indicates where Model Inaccuracies are Largest

- **Global metrics do not distinguish if a model is off "a little everywhere" or "a lot somewhere"**
- **Time dependent modeling with predictive TRANSP provides efficient post-processing of validation metrics**
- **Simple visualization of profile differences and relative differences**



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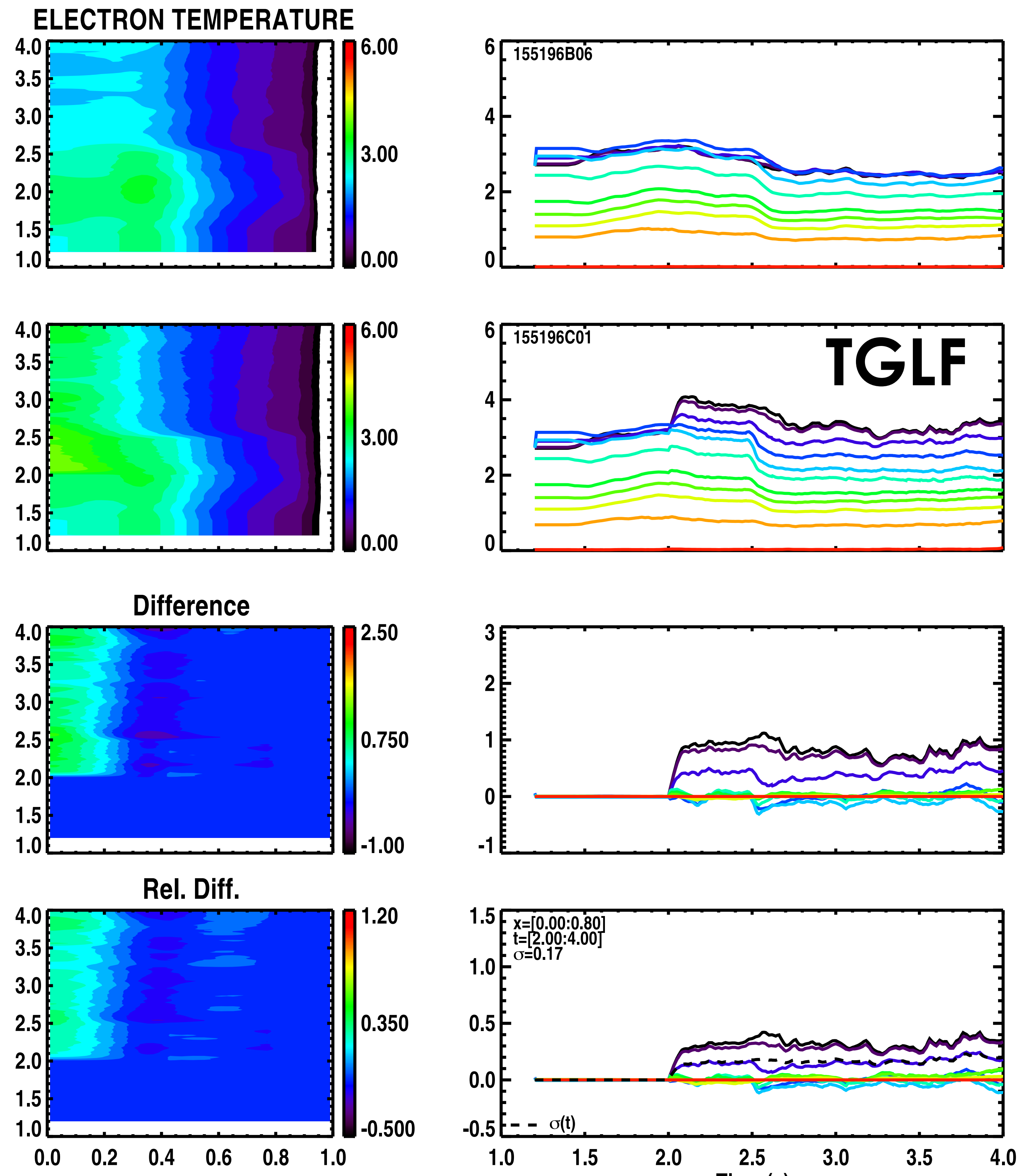

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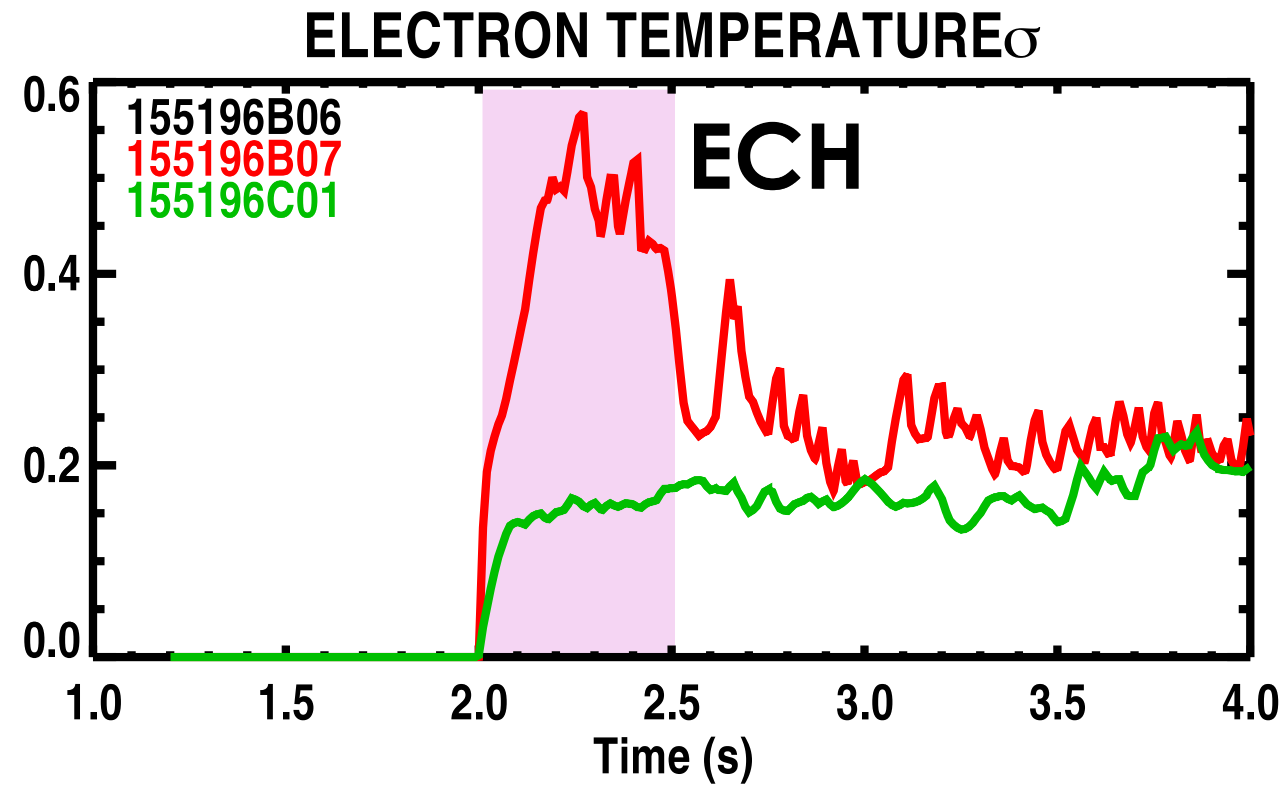
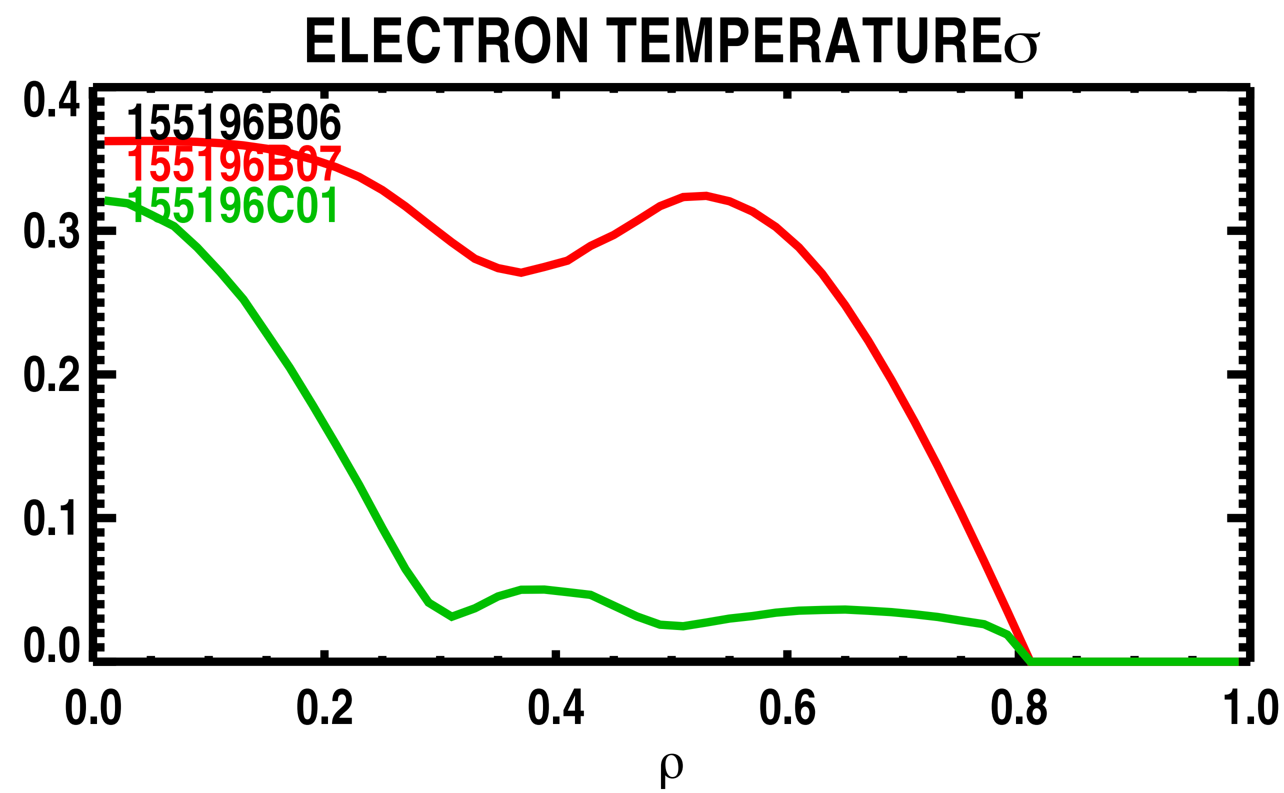
Validation Metrics In Time and Space (t,ρ) Expose Where the Model is Inaccurate (large σ)

- **Experimental, GLF23 and TGLF TRANSP predictive simulations show that:**
  - GLF23 is more inaccurate with direct electron heating
  - TGLF is equally accurate with electron **or** ion heating
  - TGLF inaccuracy is limited to near-axis
- **TGLF evaluation of Q inside of q=1 is well-know to be optimistic for confinement**
- **Inclusion of clean sawteeth brings electrons into agreement**





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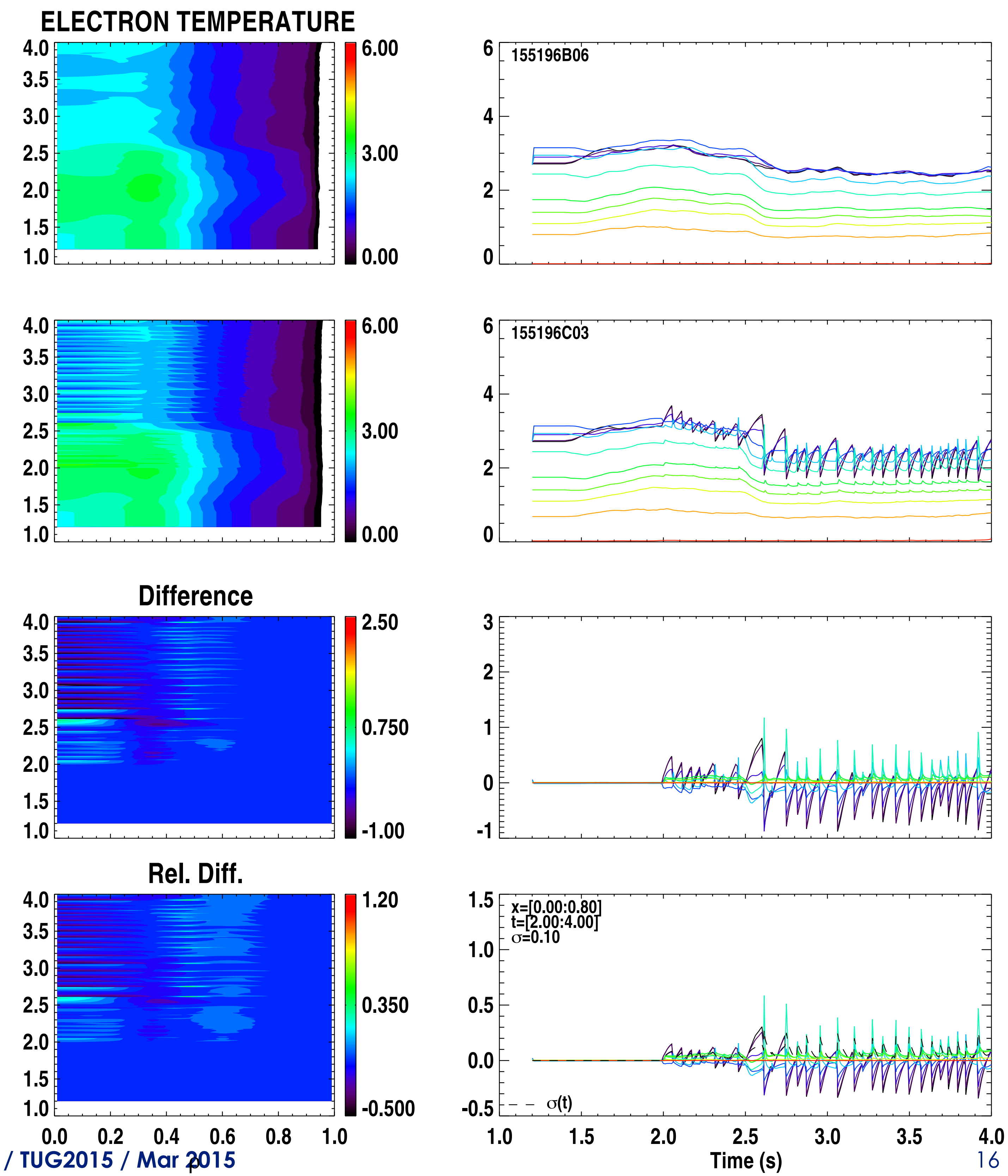
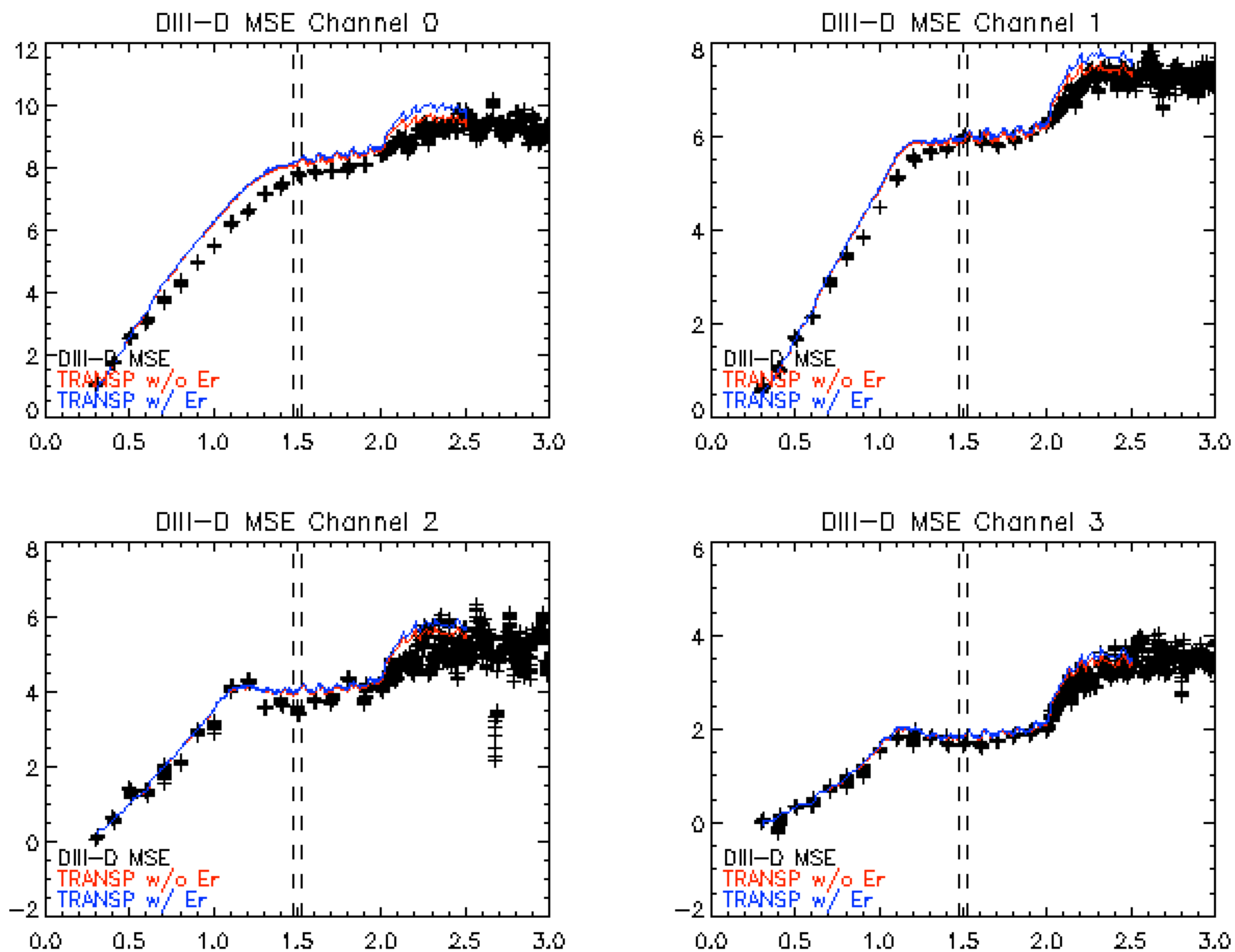


Critical Requirement of Any Predictive Modeling Code/Framework/Workflow Is Validation

- **Demonstration of *verified* module communication is required for accurate software engineering, but not physics**
  - Getting codes to run, proof-of-principle examples, overplots, etc…
- **Meaningful validation studies require direct comparison to experimental measurements with *uncertainties, synthetic diagnostics***
- **Validation requires interchangeable experimental or model-based quantity (T_e, T_i, q, j, Ω) to expose gaps in models**
  - How does model-based steady-state j^{BS} depend on choosing experimental or model-based n_e, T_e, Z_{eff}?
- **Meaningful validation studies require:**
  - Error Propagation or ensemble Monte-Carlo based statistics (how does the Porcelli sawtooth trigger frequency depend on the uncertainty in my Thomson scattering system?)
- **Synthetic Diagnostics**
  - Do the MSE pitch-angles match the q evolution from Porcelli?

Validation Metrics For Core Transport Are Reasonably Defined for Global Histories, Profiles: What are Metrics for Equilibrium?

- **Pitch angles and l_i are well defined**
- **What is metric for flux consumption?**
- **What is shape metric for δ, ϰ, plasma-wall or divertor X-point distance?**
- **Power supply coil currents (including vessel) should be metric?**



DIII-D 150840
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L_SAWTOOTH(32)=1
C_SAWTOOTH(2)=0.5
C_SAWTOOTH(26)=0.4
FPORCELLI=0.8
```

TRANSP Continues to be a Critical Component for Plasma Physics Research for DIII-D

- **Interpretive transport essential for characterizing discharges**
  - What are the power/particle/momentum balance fluxes?
    → Compare to first-principles models (HPC)
  - Are my diagnostics and/or heating sources mis-calibrated? $W_k \neq W_{MHD}$, $S_n \neq S_n^{NUBEAM}$?
    → Data consistency for international databases
- **Predictive modeling for core transport, equilibrium, MHD instabilities and control solutions**
  - Validation studies of reduced models
  - Self-consistent modeling of transport and equilibrium