Development of holistic whole-device predict-first modeling of NSTX-U

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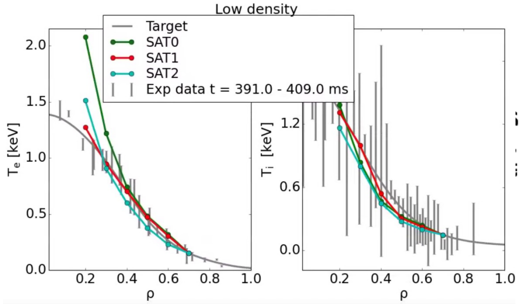

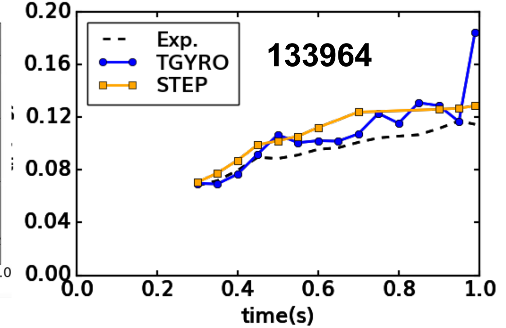

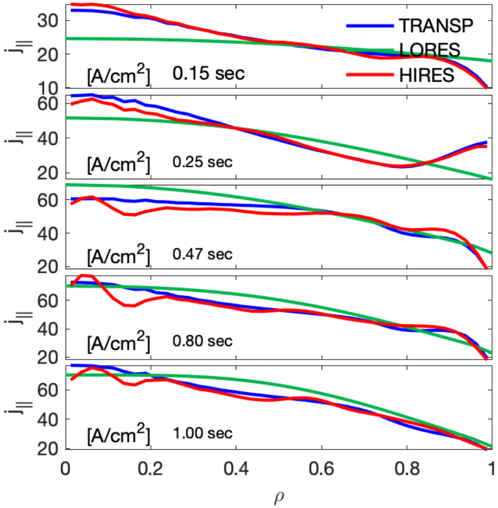

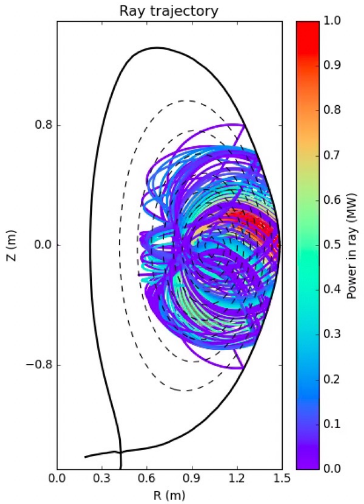

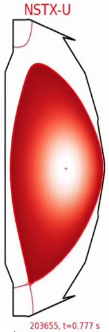

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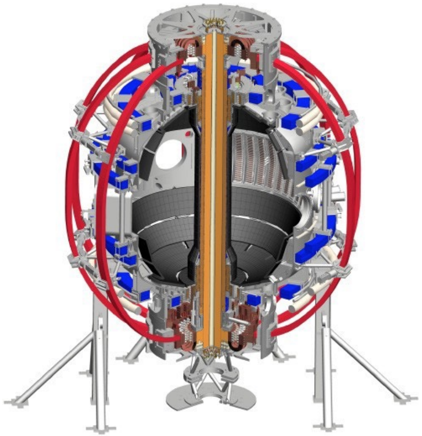
The 21st International Spherical Torus Workshop

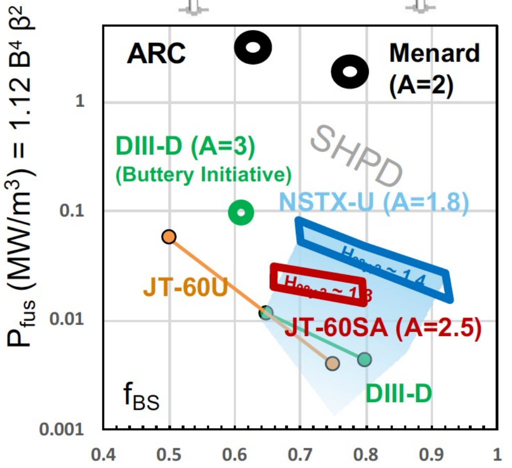
NSTX-U GENERAL ATOMICS

NSTX-U Will Explore ST Physics Towards Reactor Relevant Regimes

- **Two major upgrades while maintaining low aspect ratio A~1.7**
  - New central magnet
    - Doubling toroidal field to 1 T
    - Doubling plasma current to 2 MA
    - 5x longer pulse to 5 s
  - 2nd tangential neutral beam
    - Doubling power to 10 MW



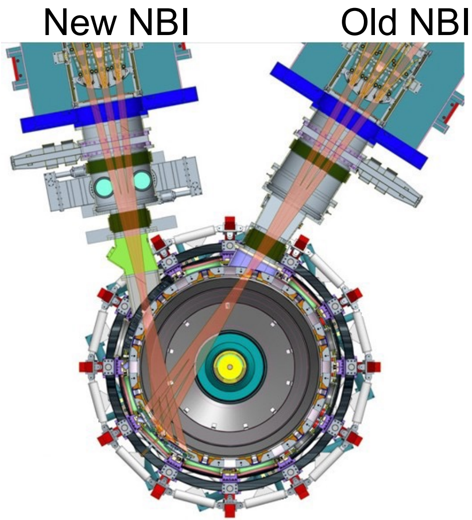
- **High $\beta_N > 5$ and strong shaping $\kappa > 2.5$ route to non-inductive operation**
  - Access to high κ enabled by operating at low-ℓ_i
  - Low ℓ_i facilitated by early L-H transition in ramp-up
  - NSTX-U will avoid core MHD that constrained operational space on NSTX



Modeling Effort Focuses on how to Create a Stationary, Noninductive Scenario with high β_T and f_{BS} on NSTX-U

- **Offline integrated predict-first modeling utilizing previous NSTX and NSTX-U data underway**
  - Provide predictions utilizing higher toroidal field and new heating and current drive tools (off-axis beams)
  - Use predominantly NSTX data to validate modeling

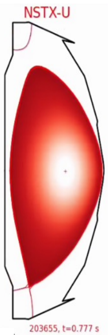
- **Three interrelated components**
  - Integrated transport modeling (task 1)
  - Heating and current drive modeling focusing on the use of the high harmonic fast wave antenna (HHFW) (task 2)
  - Whole-device simserver simulations focused on optimizing the plasma rampup (task 3)



Task 2: Characterization of Heating and Current Drive System

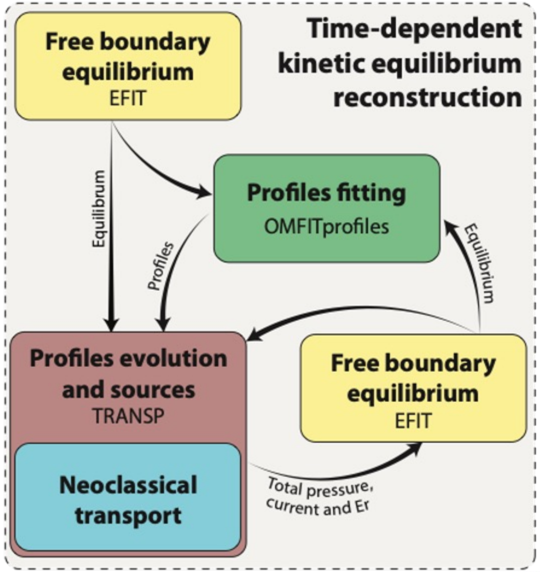
Task 1: Integrated Interpretive and Predictive Modeling

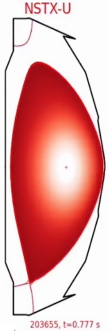
Task 3: Optimization of the Plasma Current Rampup



Progress so Far

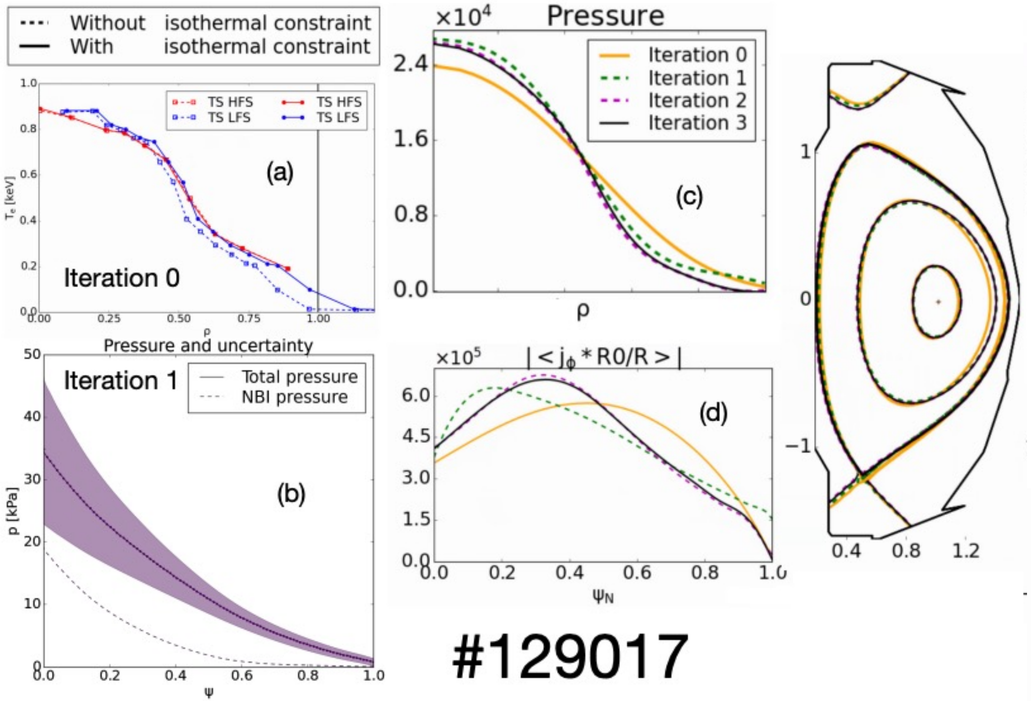
- **Integrated transport modeling (task 1)**
- Characterization of H&CD focusing on HHFW (task 2)
- Optimization of the plasma current rampup (task 3)

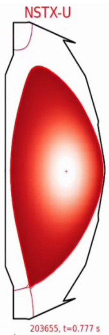




OMFIT kineticEFITtime Module Adapted for NSTX and NSTX-U

- **Full-shot kinetic equilibrium reconstructions performed by users**
  - Coupled with TRANSP for bootstrap current and fast-ion pressure
  - Iterative approach between EFIT and TRANSP
  - EFIT-AI project brings latest version of EFIT to NSTX-U
  - ST adaptations: isothermal temperature constraint, centrifugal density asymmetry, rotational pressure constraint

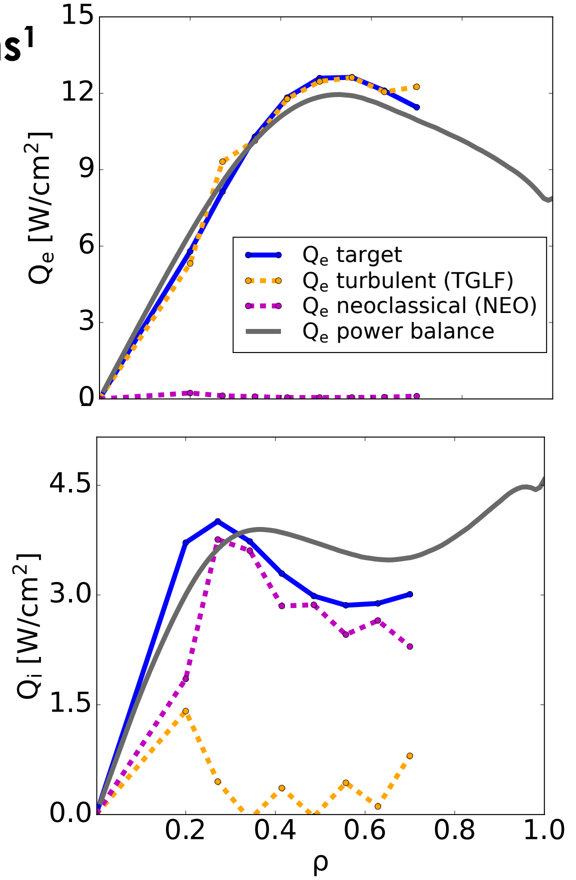




[G. Avdeeva EPS 2022: P4b.115]

OMFIT Transport Modules Adapted for NSTX and NSTX-U and Used for a Wide Range of NSTX Discharges

- **Previous transport work focused on gyrokinetic simulations[1]**
- **Predict-first modeling needs fast reduced model**
  - This work focuses on performing comprehensive TGLF study
- **Three different types of NSTX discharges studied in detail: L-mode, medium confinement H-mode and high confinement H-mode**
  - Ion transport is predominantly neoclassical
  - Electron transport is turbulent



[1]Guttenfelder et *al*., NF **62**, 042023 (2022

G. Avdeeva APS 2022: CP11.0025

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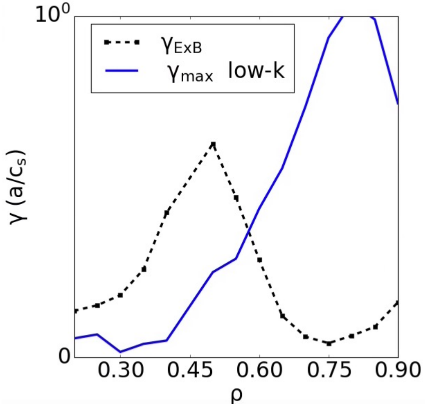
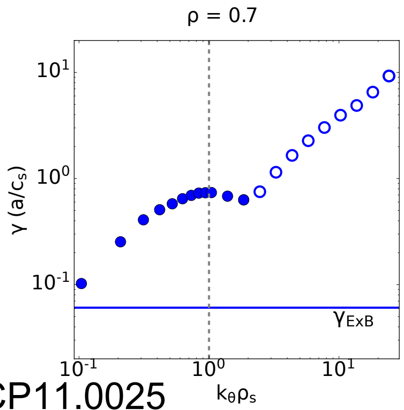
TGLF predicts low-k modes are suppressed up to the outer core





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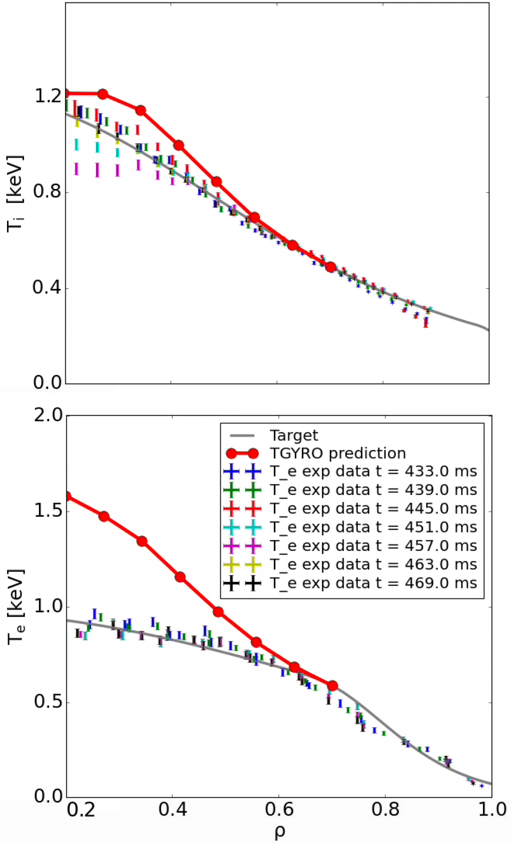
  - TGLF finds L-mode and medium confinement H-mode dominated by ETG with some ITG/TEM; TGYRO (TGLF + NEO) temperature prediction consistent with experiment
  - No unstable drift-wave modes in **high confinement H-mode** by TGLF and TGYRO overpredicts electron temperature
    - High-frequency CAE/GAEs[2], non-disruptive infernal mode[3], MTM[4]



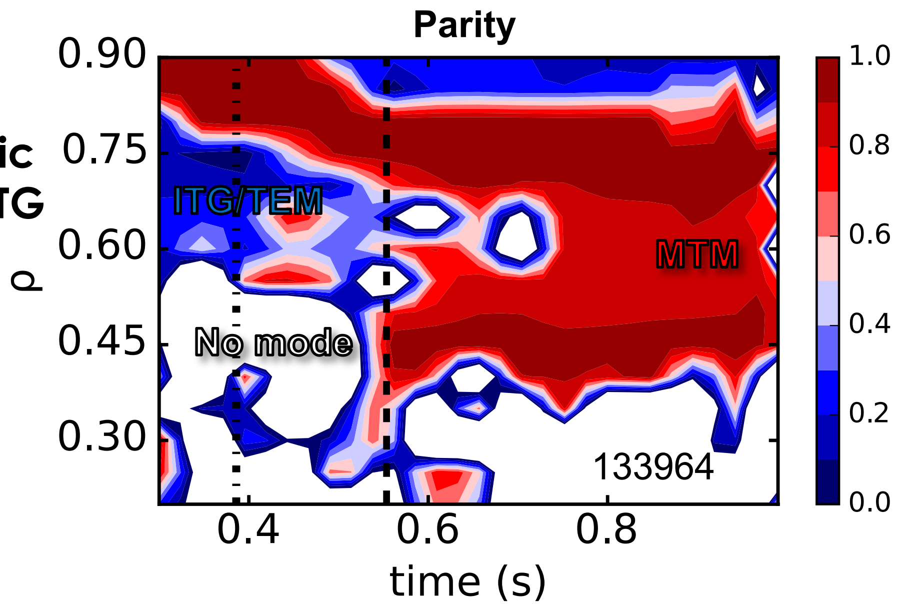
[1]Guttenfelder et *al.*, NF **62**, 042023 (2022), [2]Stutman et *al.*, PRL **102**, 115002 (2009), [3]Jardin et *al.*, PRL **128**, 245001 (2022), [4]Guttenfelder et *al.*, NF **53**, 093022 (2013)

G. Avdeeva APS 2022: CP11.0025

Microtearing Mode (MTM) the Dominant Ion-Scale Instability as Density Increases in NSTX and NSTX-U High Beta H-mode Discharges

- **MTM previously identified as possible explanation of increased core electron transport in NSTX plasmas[1]**
- **CGYRO investigation of linear gyrokinetic ion-scale modes shows transition from ITG to MTM as density increased near pedestal in DIII-D, NSTX and NSTX-U**
  - In NSTX and NSTX-U discharges, density increases with time
  - MTMs more dominant in later part of NSTX/NSTX-U discharges

CGYRO $k_y\rho_\theta$=0.3 predicted parity of electrostatic potential in ballooning space as function of time and ρ



[1] Guttenfelder et *al.*, NF **53**, 093022 (2013)

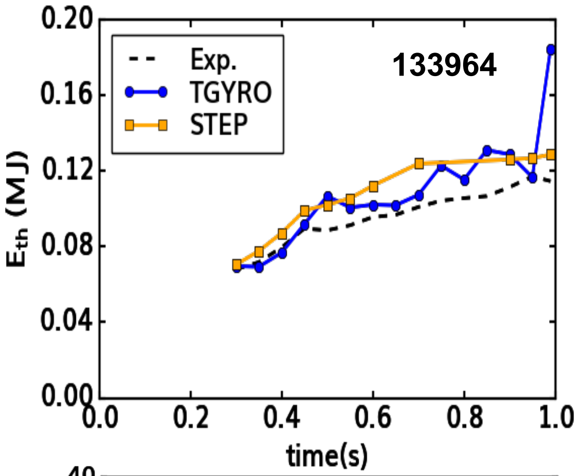
J. McClenaghan APS 2022: PP111.00088

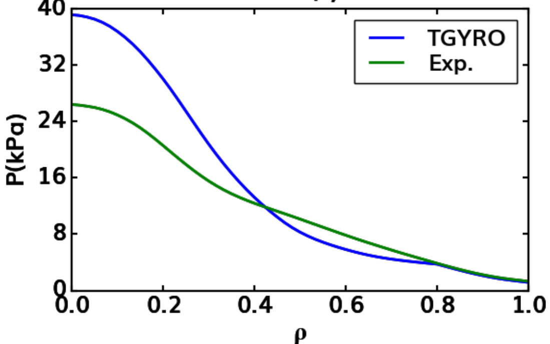
Future Integrated Modeling Work Will Improve Modeling via Workflow Upgrades, Larger Dataset and Utilization of New/Improved Models

- Continue to benchmark NSTX and NSTX-U data against TGLF + NEO and similar codes, including improved versions

- Broaden efforts to edge and incorporate pedestal modeling more fully into framework using work from NSTX-U team

Predicting high beta NSTX discharge with STEP overpredicts stored energy



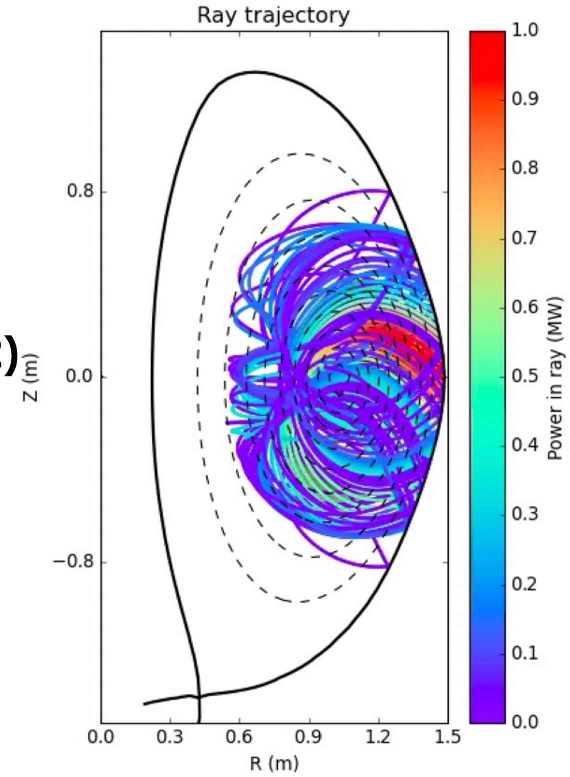


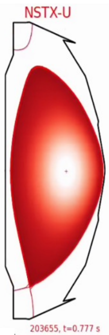
Progress so Far

- Integrated transport modeling (task 1)

- **Characterization of H&CD focusing on HHFW (task 2)**

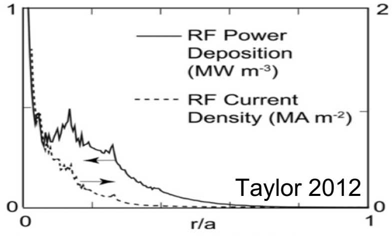
- Optimization of the plasma current rampup (task 3)

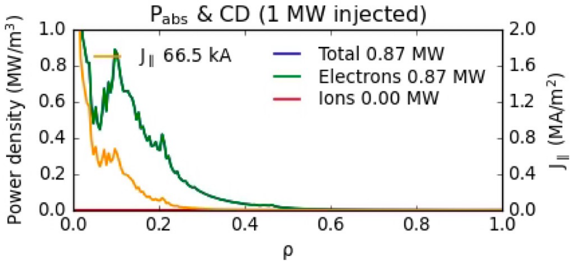


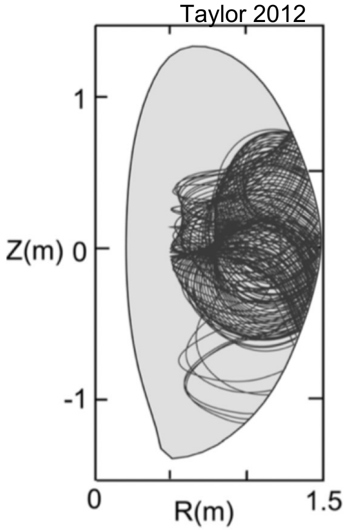


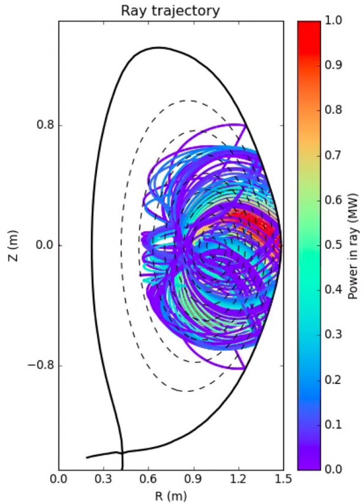
NSTX-U High Harmonic Fast Wave Heating and Current Drive (H&CD) Will be Used to Develop High Performance Scenario

- **6 MW NSTX-U HHFW antenna used for plasma rampup and flattop**
- **Need to validate models in order to incorporate HHFW into integrated modeling work**
  - Ongoing PPPL work to develop high-accuracy models[1] that takes into account pedestal → **Bertelli talk tomorrow**
- **GENRAY scoping study conducted to gauge the H&CD for a variety of NSTX-U parameters**
  - Benchmarked against NSTX shot with published predictions for HHFW H&CD using GENRAY







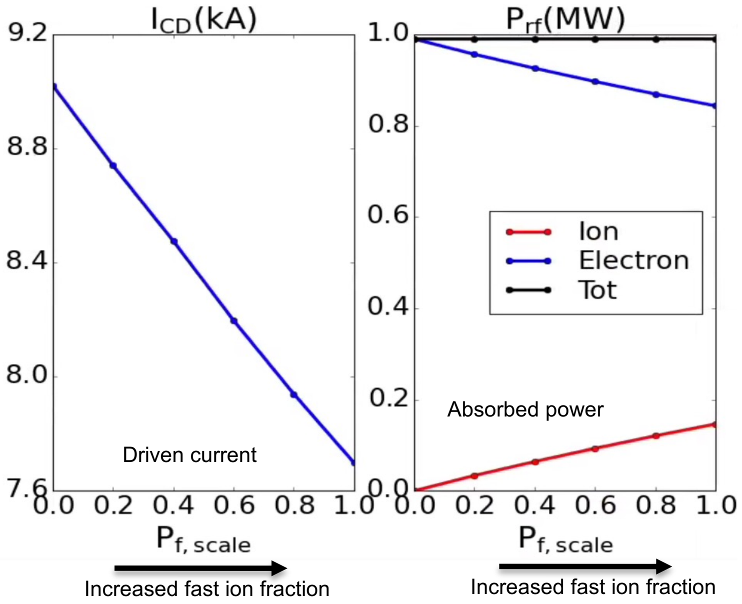


Comparison to Taylor PoP **19**, 042501 2012

[1]Tierens et *al.*, NF **62** 096011 (2022) Bertelli et *al.*, NF **59**, 086006 (2019) and references herein

Future HHFW Modeling Work will Utilize More Accurate Codes and Develop Self-Consistent Simulations with Both NBI and HHFW

- **Fast ions have potentially strong absorption, leading to less power absorbed on electrons and decrease in driven current**
- **Fast ion model in GENRAY assumes Maxwellian distribution function instead of slowing down distribution, potentially overestimating fast-ion absorption**
  - Couple GENRAY to CQL3D for a more accurate fast-ion description and TORIC
- **Optimize H&CD simulations for fully noninductive plasma**



Progress so Far

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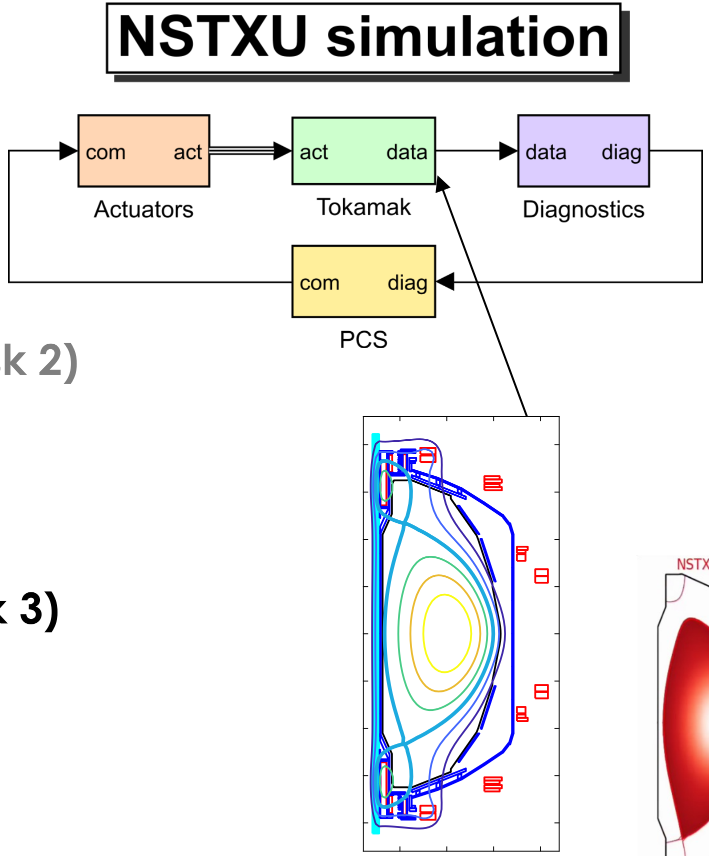
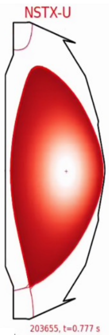
- Characterization of H&CD focusing on HHFW (task 2)
- **Optimization of the plasma current rampup (task 3)**



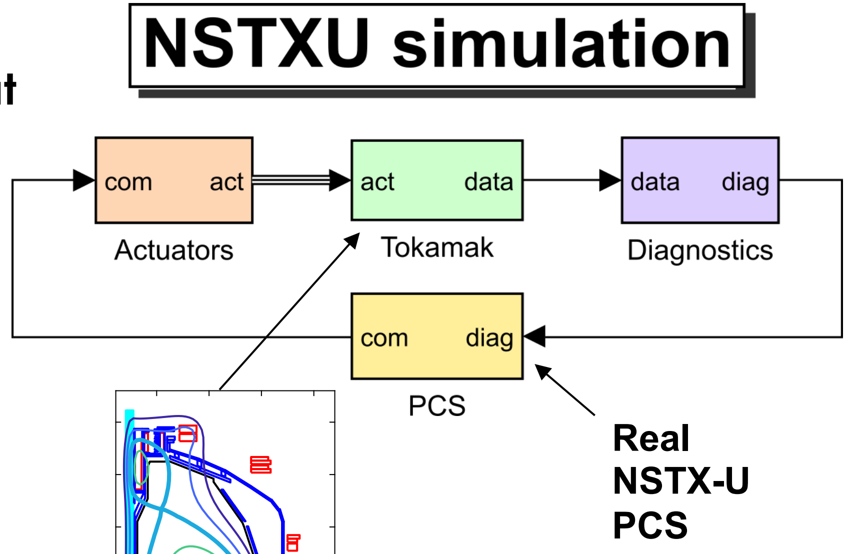


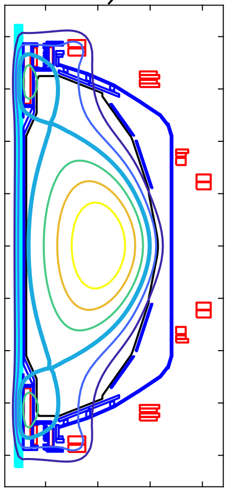
GSevolve Simulation Has Been Updated, Connected to NSTX-U Plasma Control System and Improved

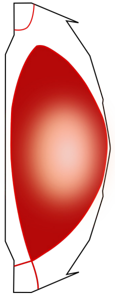
- **GSevolve is a free-boundary simulation that evolves Grad-Shafranov equilibrium including current and pressure profiles**

- **Simserver connects with same control software as experiment**

- **NSTX-U shots have been simulated successfully**

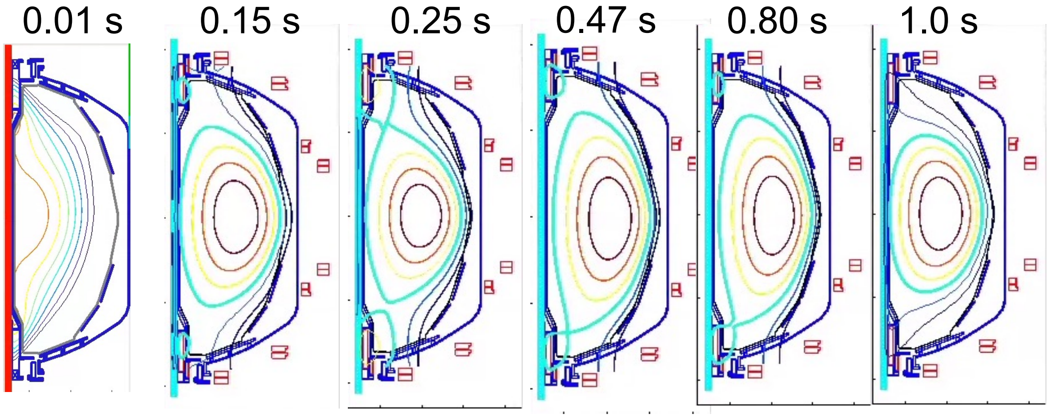


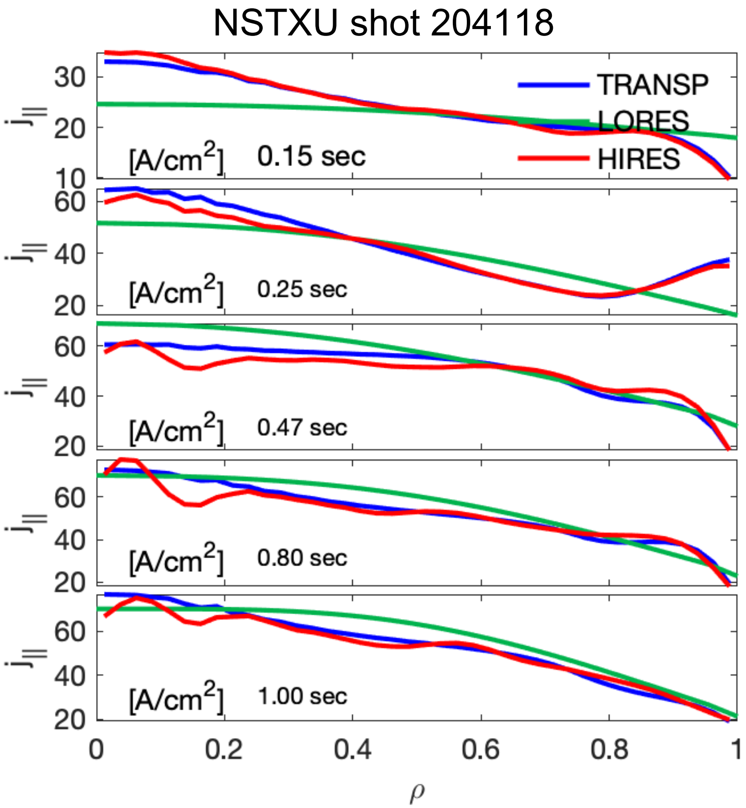




The New (HIRES) Current Profile GSevolve Simulation Improves Match to TRANSP Interpretative Run

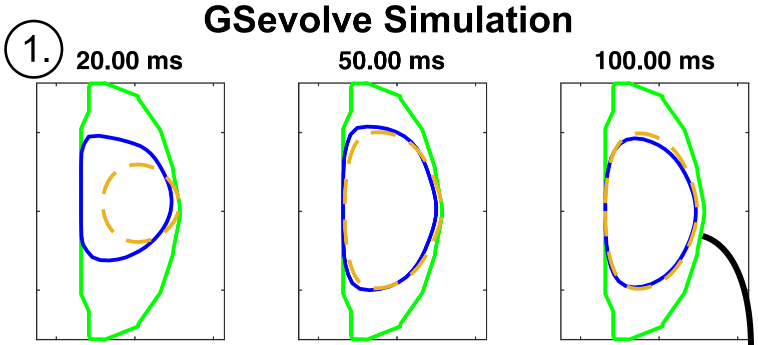
- Current density profiles for TRANSP interpretative experimental analysis, and for LORES and HIRES simulations





GSevolve and Numerical Optimal Control Can Aid Shot Development before Experiment

- **Current shot development relies largely on manual real-time control room tweaking**
- **Formulate search for feasible ramp-up solution as model-based optimal control problem**
- **Create library of solutions to account for variable conditions or hardware issues such as a beam drop out**



2.
extract Dynamics From GSevolve simulation

3.
Numerical optimal Control

minimize $J(\mathbf{x}(t), \mathbf{u}(t), t)$
$\mathbf{u}(t),\ \mathbf{x}(t),\ t_F$

subject to $\boxed{\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}, t)}$

Constraints to account for timing of LH, diverted

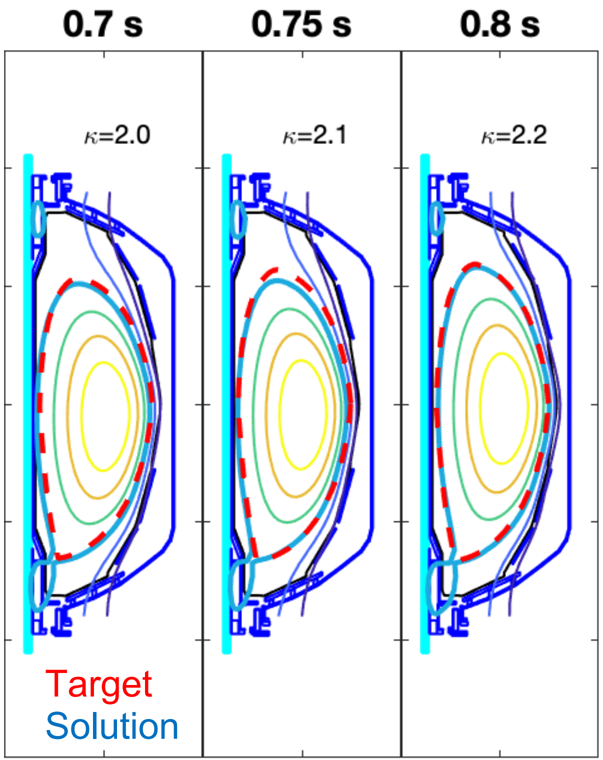
Future GSevolve Work Will Improve Models and Optimize Plasma Current Rampup

- Incorporate TRANSP with GSevolve and include HHFW model

- Utilize GSevolve simulation to improve control of previous NSTX-U discharge

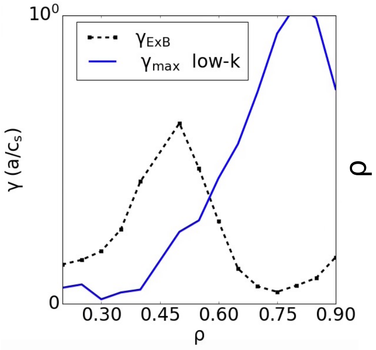
- Optimize plasma current rampup by 1) increasing elongation to lower internal inductance and 2) reduce inductive flux consumption to maximize pulse length

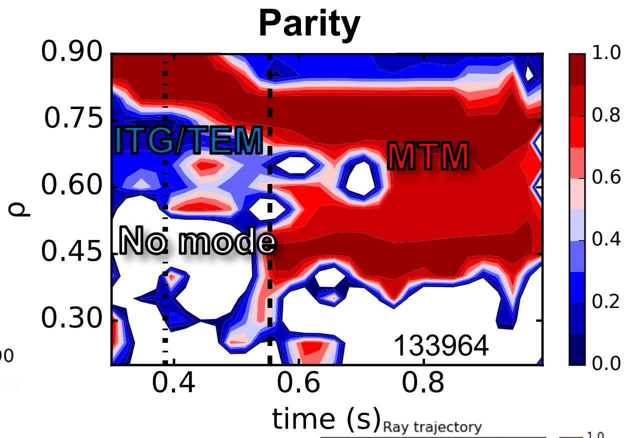
Example of NSTX-U elongation control using GSevolve



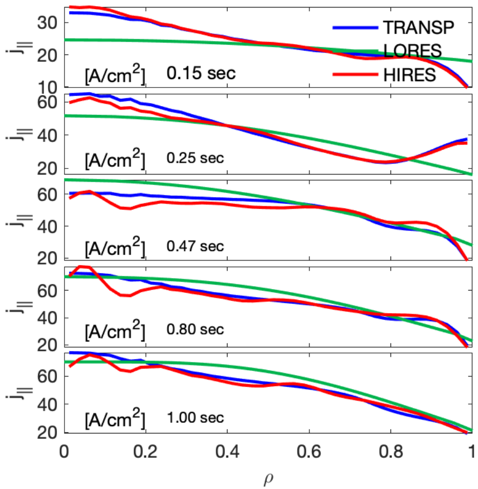
Significant Progress on Predict First Modeling of NSTX-U and Future Work will Interconnect Workflows for Full-Shot NSTX-U Simulation

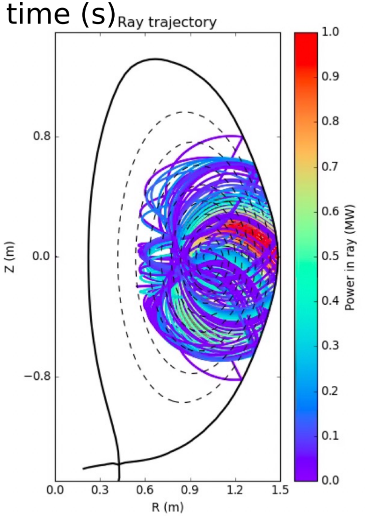
- Transport modeling utilizing TGLF, TGYRO and CGYRO conducted over range of NSTX discharges





- HHFW modeling with GENRAY indicates favorable current drive regimes





- GSevolve simulations able to reproduce NSTX-U discharges