High-performance Scenario Development in NSTX-U via Physics-based Modeling and Model-based Control

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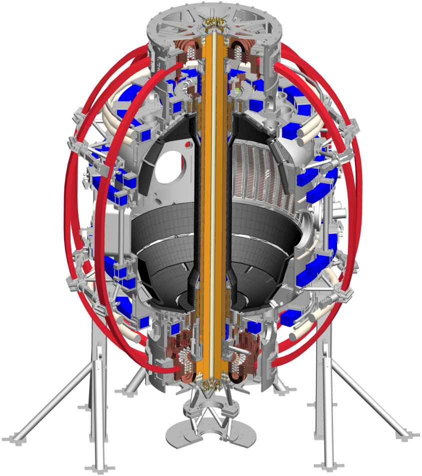

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The overall goal of this research is to impact NSTX-U by integrating physics and operation through the development of model-based approaches to scenario planning and control of MHD-stable, steady-state, high-performance plasmas at low collisionality and aspect ratio.

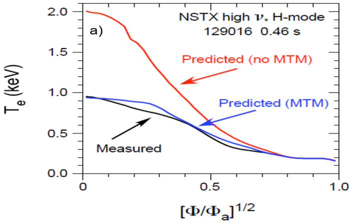
Objectives of the NSTX-U Five Year Plan Impacted by this Research:

- Objective 1 - Extend confinement and stability physics basis at low-A and high-β to lower collisionality relevant to burning plasma regimes
  - <u>Thrust 1-2</u>: Identify transport and stability mechanisms that determine core and pedestal profiles and overall performance
  - <u>Thrust 1-3</u>: Develop reduced stability and transport models required to run and validate integrated predictive simulations
- Objective 2 - Develop operation at large bootstrap fraction and advance the physics basis required for non-inductive and low-disruptivity operation of steady-state compact fusion devices
  - Thrust 2-1: Particle control / heat-flux mitigation for stationary discharges
  - Thrust 2-2: Demonstrate high-β, low-l_i discharges at low disruptivity
  - <u>Thrust 2-3</u>: Establish and optimize high non-inductive fraction operation

Research will Impact Several Physics and Operations Objectives and Thrusts of the NSTX-U Five Year Plan

Thrust 1-2:

- Identify key mechanisms impacting turbulent transport in *low-collisionality, low aspect-ratio, highly-shaped* NSTX-U plasmas via gyrokinetic studies.



Thrust 1-3:

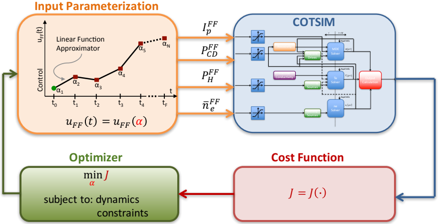
- Further development of Multi-Mode-Model (MMM) anomalous transport module. Validation against gyrokinetic codes and experimental data.
- Incorporation of enhanced version of MMM intoTRANSP, including the capability of predicting L-H transitions and temperature/density pedestals self-consistently, will enable tackling several key physics research studies:
  - Identify transport/stability mechanisms determining core/pedestal profiles and overall performance
  - Study dependence of temperature/density pedestals width and height on plasma parameters
  - Validate roles of electron/ion-scale turbulence as a function of the core density/temperature/rotation profiles

Research will Impact Several Physics and Operations Objectives and Thrusts of the NSTX-U Five Year Plan

Thrust 2-3:

- Development of control-oriented transport models to enable design and simulation of model-based profile/scalar control/estimation algorithms for realization of MHD-stable, high β_N, and high bootstrap-fraction plasmas.
  - Carry out fast model-based scenario planning (feedforward control) to optimize ramp-up (e.g. minimize ohmic-flux consumption) and flattop.
  - Design state observers to curate spatially distributed diagnostic data in real time → measurement for feedback control, initial conditions for forecasting.
  - Design current/pressure/rotation profile/scalar integrated feedback control laws to attain high-performance plasmas by exploiting actuator upgrades.

- Incorporation of control-oriented transport models, including a neural network version of MMM, into LU's Control-Oriented Transport SIMulator (COTSIM) and later into NSTX-U's Plasma Control System.



Research will Impact Several Physics and Operations Objectives and Thrusts of the NSTX-U Five Year Plan

- Coupling of plasma shape/position with scenario control (e.g., through neutral-beam efficiency) will be studied/exploited.
  - Shape/position of the plasma will be considered either as a constraint/disturbance (imposed by the shape/position controller) or as another actuation command (passed to the shape/position controller).
  - The Integrated profile and shape/position control design will be enabled by adding a free-boundary equilibrium solver for NSTX-U to COTSIM.

Thrust 2-2:

- Impact of scenario control (profile shaping) on MHD stability/steady-state operation by bootstrap-fraction enhancement will be studied/exploited.

Thrust 2-1:

- Impact of scenario control on safe divertor operation will be studied.
  - Real-time measurements of the divertor heat-flux and/or temperature can be fed into a reference governor, which will decide on the desired targets for current/pressure/rotation profiles/scalars to be tracked by scenario controller.
  - To study the interplay between core and divertor conditions, COTSIM will be coupled with reduced models of the SOL/divertor region.

LU/PPPL Collaboration on NSTX-U: On- and Off-Site Personnel, Collaborators, and Key Needs/Requirements

LU Team:

- PI: Eugenio Schuster
- Co-PI: Tariq Rafiq
- Postdoctoral researcher → PPPL
    - Cesar Clauser
- Two PhD students (more over 5-yr period)
    - Brian Leard (1st year)
    - More students coming
    - Located at PPPL after General Exam

PPPL/NSTX-U Primary Collaborators:

- Stan Kaye
- Walter Guttenfelder
- Devon Battaglia
- Francesca Poli
- Dan Boyer

- Physics & control-oriented modeling ↔ collaboration
- Actuators & diagnostics for real-time control (timeline)
- TRANSP, PCS/Simserver
- Postdoc/students space


E. Schuster


T. Rafiq


C. Clauser


B. Leard

High-performance Scenario Development in NSTX-U: *Physics-based Modeling* Tasks & Tentative Timeline

Overall Goal: Produce reliable, validated, self-consistent predictions of plasma-profile evolutions from magnetic axis to plasma edge, and from discharge start-up to shutdown by combining MMM and TRANSP

Year 1 (Ongoing):

- Identify the various modes that can contribute to anomalous transport by performing studies using the gyrokinetic code CGYRO and the current stand-alone version of the MMM.
- Initiate TRANSP simulations using MMM for a set of discharges identified by NSTX-U experimentalists representing different parameter regimes.
- Replace the present ETGM (Electron Temperature Gradient Mode) model by including missing stabilizing and destabilizing effects such as magnetic shear, flow shear, gradient density, collision and geometry.

High-performance Scenario Development in NSTX-U: *Physics-based Modeling* Tasks & Tentative Timeline

Year 2:

- Implement new ETGM model in stand-alone MMM module to explore its NSTX-U-relevant parameter dependence. The ETGM model will be verified against gyrokinetic-code predictions.
- Include an updated and verified Drift-MHD Mode model in TRANSP with the ability to predict L-H transitions and both temperature and density pedestals self-consistently.

Year 3:

- Use the new MMM anomalous thermal, particle, and momentum transport module, which will include improved MTM (Micro Tearing Mode), Drift-MHD Mode, DRIBM (Drift Resistive Inertial Ballooning Mode) models and a new ETGM model, to simulate temperature profiles in low and high collisionality discharges.
- Investigate the role of ITG (Ion Temperature Gradient), MT, TE (Trapped Electron), KB (Kinetic Ballooning), and Peeling modes on transport in both low and high collisionality discharges.

High-performance Scenario Development in NSTX-U: *Physics-based Modeling* Tasks & Tentative Timeline

Year 4:

- Identify the transport and stability mechanisms that determine the temperature and density of the pedestals.
- Examine the dependence of temperature/density pedestals height/width on current density profile, collisionality, neoclassical transport, magnetic field strength, edge density fueling strength, and plasma shape.

Year 5:

- Carry out reliable validated self-consistent MMM-TRANSP core pedestal simulations from the last closed flux surface to the magnetic axis.
- Plan, optimize and understand the new NSTX-U high-current-drive discharge scenarios.

High-performance Scenario Development in NSTX-U: *Model-based Control Design* Tasks & Tentative Timeline

Overall Goal: Develop control-oriented plasma response models by exploiting MMM+TRANSP predictions capabilities to enable model-based control design (Feedforward+Feedback Control, Estimation, Forecasting)

Year 1 (Ongoing):

- Further develop two-timescale response model (1D magnetic diffusion equation + 1/2D model for electron density and temperature) for q-profile control based on TRANSP predictive simulations → COTSIM.
- Start synthesis of improved and new q-profile and/or plasma-scalar (β_N, W, l_i, q_0, q_{95}, q_{min}, V_{loop}) FF+FB controllers based on off-line optimization by using developed two-timescale response model.
- Start development of integrated-transport response model for current, pressure, rotation profile control by using parameterized transport models.
- Start development of an MHD equilibrium solver and its coupling with two-timescale/integrated-transport response models in COTSIM.

High-performance Scenario Development in NSTX-U: *Model-based Control Design* Tasks & Tentative Timeline

Year 2:

- Start development of a neural-network (NN) model of MMM for NSTX-U. Integrate MMM/NUBEAM NN models into COTSIM.
- Start implementation of Scenario Control Category in NSTX-U PCS to enable experimental testing of q-profile and/or plasma-scalar controlllers.
- Start development of NSTX-U simserver based on both two-timescale and integrated-transport response models (PCS Debugging)
- Carry out scenario planning by off-line model-based optimization using control-oriented integrated-transport response models. Test optimal feedforward actuator trajectories in TRANSP runs, NSTX-U experiments.

Year 3:

- Experimentally test q-profile + kinetic-scalar (β_N, W) feedback controllers.
- Start development of model-based observers to estimate in real time uncertain or unmeasured plasma parameters from available diagnostics.
- Start work on the design of actuator-sharing strategies for integrated current/pressure/rotation profile/scalar control.

High-performance Scenario Development in NSTX-U: *Model-based Control Design* Tasks & Tentative Timeline

Year 4:

- Start assessment of boundaries of controllability for simultaneous q-profile, rotation-profile, and pressure-profile regulation by using control-oriented integrated-transport response model.
- Study the coupling between plasma shape/position and q-profile control.
- Couple transport equations for the plasma core in COTSIM with a reduced model for the scrape-off layer (SOL) and divertor region.
- Design governor, driven by real-time direct/indirect measurement of divertor heat flux and/or temperature, for passive divertor protection via scenario (current/pressure/rotation profile) control.

Year 5:

- Design governor, driven by real-time direct/indirect measurement of NTM/RWM amplitude and/or growth rate, for passive avoidance and stabilization via scenario (current/pressure/rotation profile) control.
- Carry out experiments on NSTX-U to test governor designs for passive NTM/RWM stabilization and divertor protection via scenario control.

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- **LU is excited to participate in the NSTX-U program and to collaborate with PPPL and all the research teams!**
- **Please contact us with any question you may have:**
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  - **Tariq Rafiq:** rafiq@lehigh.edu
  - **Eugenio Schuster:** schuster@lehigh.edu