Feedback control design for non-inductively sustained scenarios in NSTX-U using TRANSP

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The spherical torus is being considered as an option for facilities designed to study fusion nuclear science [1] or to generate fusion power [2]. Such designs have little to no room for a central solenoid, and require the plasma current, which is necessary for confinement, to be generated non-inductively. Recently completed upgrades to NSTX-U will enable the study of non-inductive scenarios, including start-up, ramp-up, and flattop current sustainment. This paper examines approaches to active control of such scenarios using TRANSP simulations of NSTX-U.

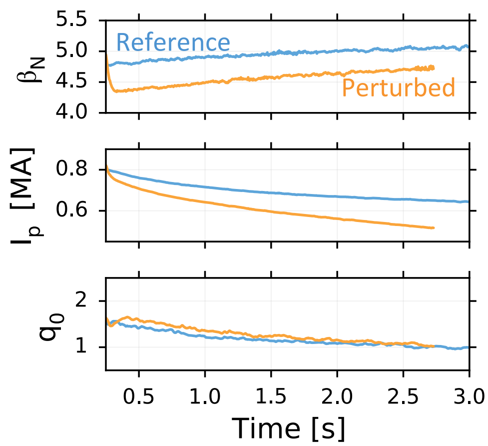

Figure 2: Results of reference simulation compared to a case with a -10% confinement perturbation.

Simulation Approach: TRANSP is a time-dependent integrated modeling code for discharge prediction and interpretive analysis of tokamak experimental data. Its predictive mode has been used for scenario development on NSTX-U to explore the potential operating space, including fully non-inductive scenarios [3], and has been used to explore approaches to non-inductive plasma current ramp up [4]. Recently, the ability to include feedback control algorithms in predictive TRANSP simulations has been developed [5]. The framework uses the NUBEAM module for calculating neutral beam heating and current drive, and the ISOLVER free-boundary equilibrium solver to evolve the discharge shape and current distribution. The Chang-Hinton model is used to predict ion temperature, and the ITER-98 confinement scaling expression is used to constrain the electron temperature with profile shapes prescribed for each simulation. To mimic the earliest planned non-inductive scenario studies on NSTX-U, the simulations begin with an inductively produced plasma and the Ohmic coil current is fixed throughout the simulation. An open loop (uncontrolled) reference simulation was done, which shows that the plasma slowly settles to a steady state over time (see Fig. 1). Additional simulations show that the evolution of the scenario is sensitive to disturbances, including changes in density, profile shapes, and confinement.

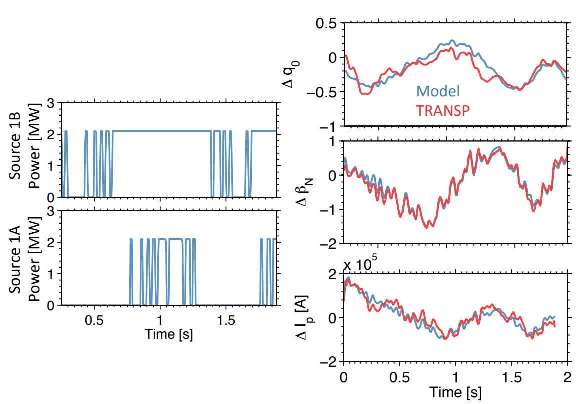

Figure 1: Beam modulations used during model comparison (left) and comparison of linear model to TRANSP results (right).

Control Approach: The actuators considered for control in this work are the six neutral beam sources and the plasma boundary shape. The neutral beam sources, three of

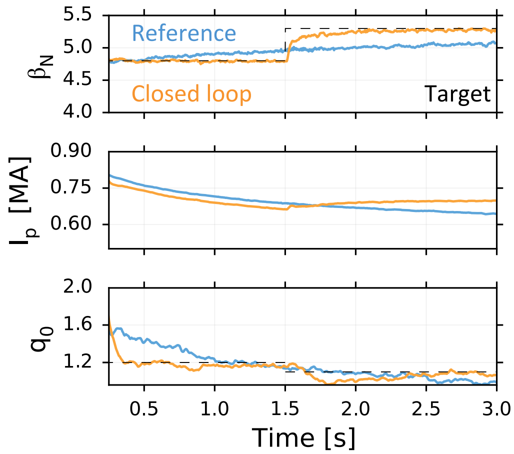

Figure 3: Comparison of closed loop tracking with reference simulation.

which are new for NSTX-U, allow the current drive deposition and heating to be tailored in real-time. The primary plasma boundary shape parameter that is considered in this work is the mid-plane outer gap. Increasing this gap size leads to increased bootstrap current and moves the neutral beam deposition further off-axis, which tends to increase the central safety factor. Varying these actuators during a non-inductively sustained discharge can alter the plasma current, stored energy, and central safety factor. To understand the response of the system to these actuators and to enable the systematic design of control algorithms, a series of TRANSP simulations were run in which the actuators were modulated around the reference values and a linear dynamic response model was fit to the resulting data. Fig. 2 shows a comparison of the linear model prediction to the TRANSP results, showing that the simplified model captures the dominant dynamics of the system. The simplified model was then used to design several PID control laws using different combinations of actuators and measurements. While a more complex state-space controller that considers all of the actuators and measurements simultaneously could be designed using the identified model, simple PID control laws were used here as a first step to explore the effectiveness and limitations of the actuators. These results will then be used to guide the more complete control algorithm design.

Control Simulations: A series of closed loop (controlled) simulations was done to test the system response using various controllers in reference tracking scenarios and in the presence of disturbances. Simulations show that modest changes in the outer gap and heating power can improve the response time of the system and reject perturbations. Fig. 3 shows successful tracking of β_N and q_0 references using beam power to control β_N and outer gap to control q_0. Closed loop simulations including beam modulations, like those used in experimental shots to approximate analog power requests, show small oscillations in current but significant oscillations in stored energy (see Fig. 4). This indicates that methods for reducing beam modulations should be explored. In general, simulations show a strong coupling between the controlled quantities, which will make multi-variable control design an important next step.

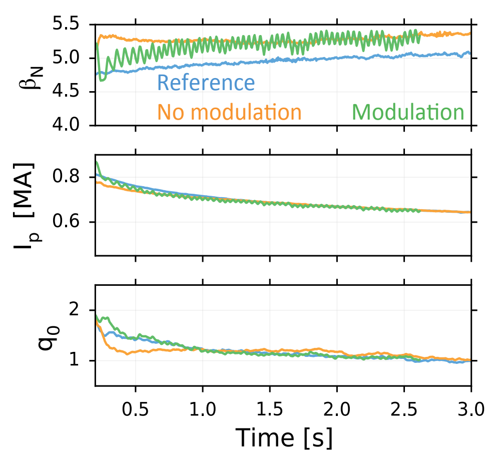

Figure 4: Comparison of closed loop simulations with and without beam modulation.

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