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

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Abstract:

This paper examines a method for real-time control of non-inductively sustained scenarios in NSTX-U by using TRANSP, a time-dependent integrated modeling code for prediction and interpretive analysis of tokamak experimental data, as a simulator. The actuators considered for control in this work are the six neutral beam sources and the plasma boundary shape. To understand the response of the plasma current, stored energy, and central safety factor to these actuators and to enable systematic design of control algorithms, simulations were run in which the actuators were modulated and a linearized dynamic response model was generated. A multi-variable model-based control scheme that accounts for the coupling and slow dynamics of the system while mitigating the effect of actuator limitations was designed and simulated. Simulations show that modest changes in the outer gap and heating power can improve the response time of the system, reject perturbations, and track target values of the controlled values, however, the actuator limits constrain the range of achievable targets.

1 Introduction

The National Spherical Torus eXperiment Upgrade facility (NSTX-U) [1], which recently completed its first campaign of plasma operation, looks to span the gap between earlier spherical torus devices, like NSTX [2] or the Mega-Ampere Spherical Tokamak (MAST) [3], and potential future facilities intended to study nuclear components [4] or production of fusion power [5]. NSTX-U will explore several issues for such future devices, including the scaling of electron transport with field and current [6, 7], the physics of fast particles [8, 9], and the achievement and sustainment of non-inductive, high-β scenarios [10, 11, 12]. The latter point is especially critical for spherical torus based designs because their compact size combined with the need for tritium breeding blankets and neutron shielding in such facilities leaves little to no room for a central solenoid to induce plasma current. The recently completed and commissioned upgrades to NSTX-U will enable the study of non-inductive scenarios, including start-up, ramp-up, and flattop current sustainment. One of the primary components of the upgrade project was the replacement of the 'center stack' (which contains the inner-leg of the toroidal field (TF) coils, the Ohmic heating

(OH) solenoid, and some divertor coils) to enable fields up to 1.0T and to provide more Ohmic flux for longer inductive discharges. The other major upgrade was the addition of a second neutral beam injector with three neutral beam sources aimed more tangentially, which significantly increases the auxiliary heating power and current drive and adds flexibility in shaping the spatial deposition of these quantities in the plasma.

Advanced plasma control will be an important tool for achieving the research goals of the NSTX-U program. Ongoing development (e.g., [13, 14]) aims to enable current and rotation profile control, power and particles exhaust control, and edge transport barrier control, building on the successful advances made during NSTX operations [15, 16, 17]. This paper extends this development by examining potential approaches to active real-time control during non-inductive scenarios using a framework for feedback control simulations in the integrated modeling code TRANSP [13]. Active control schemes will be necessary in such scenarios to tailor the response time of the discharge evolution, to enable reproducible discharges in the presence of disturbances to enable controlled scans of plasma parameters, and for active avoidance of plasma instabilities.

2 Predictive simulation approach

TRANSP[18, 19, 20] is a time-dependent integrated modeling code for tokamak discharge prediction and interpretive analysis of experimental data. Its predictive mode has been used for scenario development on NSTX-U to explore the potential equilibrium operating space, including fully non-inductive scenarios [21], and has been used to explore non-inductive plasma current ramp up [22]. Recently, the ability to include feedback control algorithms in TRANSP simulations has been developed to study control algorithms for stored energy and plasma profiles in inductive scenarios [13, 14]. The framework for feedback simulations in TRANSP uses the NUBEAM[23] module for calculating neutral beam heating and current drive, and the ISOLVER free-boundary equilibrium solver [24, 25] to evolve the discharge shape and current distribution. In this work, ISOLVER is used in a mode that chooses the coil current evolution to match a prescribed target plasma boundary shape in a least-squares sense. The Chang-Hinton model is used to predict the ion temperature profile evolution, and the ITER-98 confinement scaling expression is used to constrain the electron temperature based on the TRANSP predicted volume-averaged power balance. The electron temperature profile shape is prescribed ahead of time for each simulation. The electron density is modified throughout the simulation to match a prescribed trajectory for the particle inventory, with the shape of the density profile prescribed *a priori*. The ion density is calculated assuming a flat Zeff=2 profile and Carbon as the only impurity. While experimental studies of non-inductive start-up and ramp-up are planned, the earliest non-inductive scenario development studies on NSTX-U will likely start with an inductively formed plasma and, at some point during the shot, clamp the Ohmic coil current to observe the plasma behavior as it relaxes to a fully non-inductive state. This approach is mimicked in TRANSP by beginning with an inductively formed plasma and fixing the Ohmic coil current throughout the simulation starting at $t = 0.1s$. An open loop (no feedback control) simulation was performed for

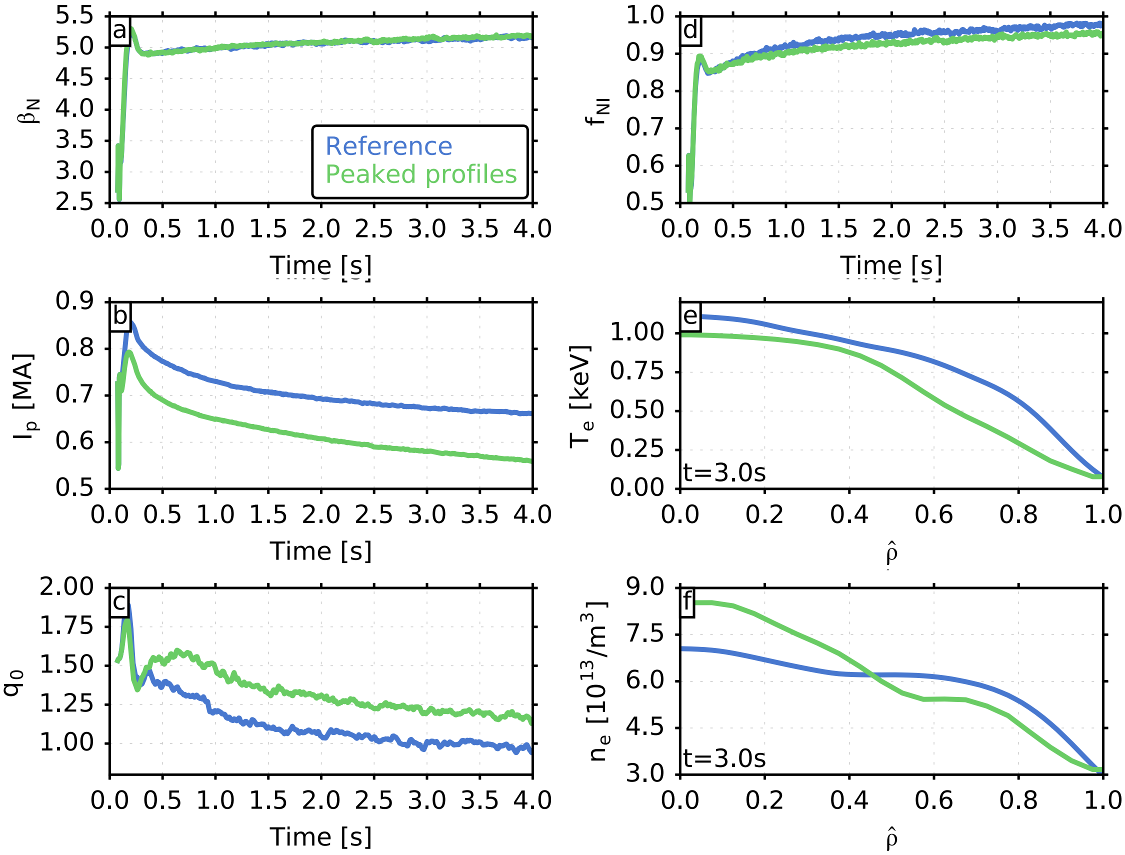

FIG. 1: Comparison of (a) β_N, (b) plasma current, (c) central safety factor, (d) non-inductive fraction, (e) electron temperature profile, and (f) electron density profile during the reference simulation and the simulation with more peaked profiles.

use as a reference throughout the rest of the study. The profile shapes used throughout the simulation were broad profiles taken from NSTX discharge 142301. Beam sources 1A, 1B, 2A, and 2B were on throughout the simulation, the boundary shape was held fixed with a mid-plane outer gap of 15cm, and the electron inventory was held fixed at 6.65×10^{20} ($f_{GW} \approx 0.7$). Results of the reference case are shown in FIG. 1. During the reference simulation, the plasma slowly settles to a steady state with $\beta_N \approx 5.1$ and $I_p \approx 660kA$ (see FIG. 1a and 1b), taking roughly 4s to fully relax (as indicated by reaching 100% non-inductive fraction). On the same time scale, the safety factor on axis relaxes to close to 1.0, which could potentially lead to discharge-ending MHD activity. The current redistribution time for these discharges is $\tau_{CR} \approx 1.4\frac{a^2\kappa T_e[keV]^{3/2}}{Z_{eff}} \approx 0.65s$ while the energy confinement time is $\tau_E \approx$ 0.03s, indicating that the coupling of kinetic and magnetic profile dynamics results in a slowed plasma response in this scenario.

To test the sensitivity of the scenario to changes in parameters, simulations were run with disturbances, including changes in electron temperature and density profile shapes,

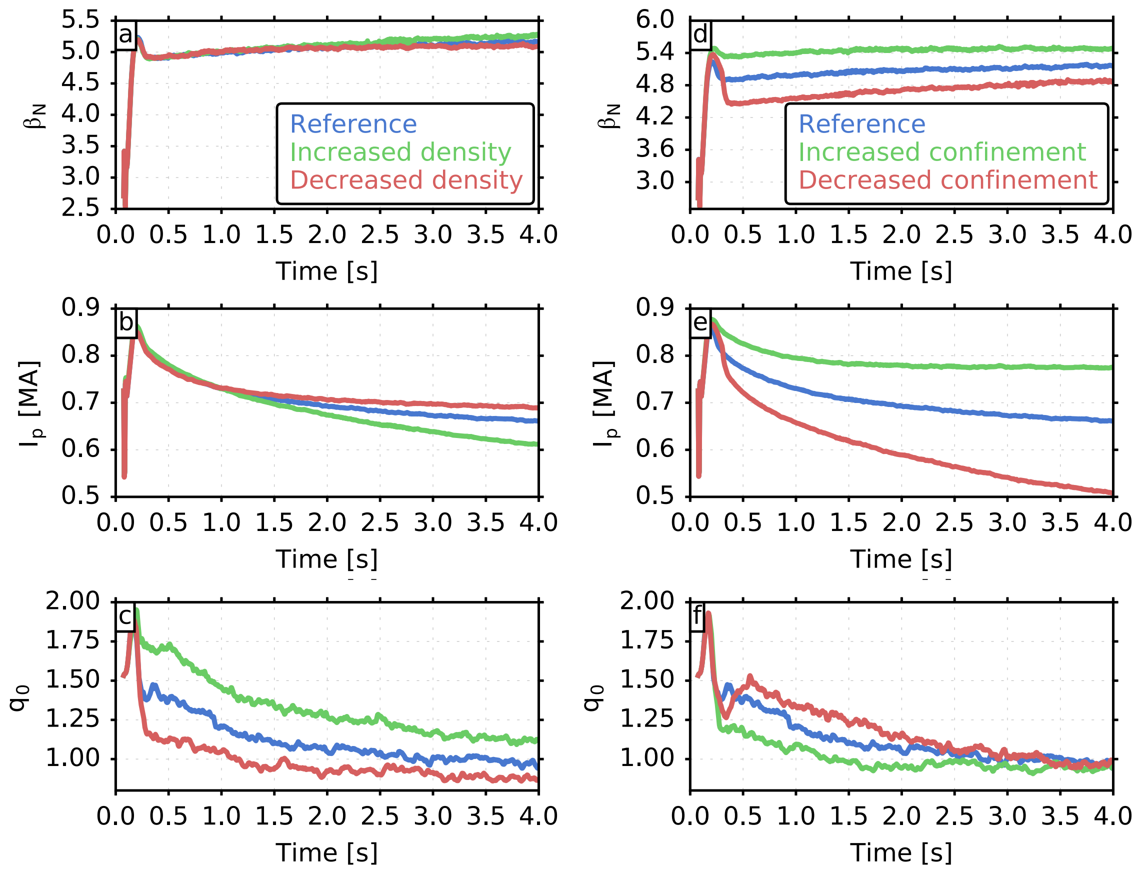

FIG. 2: Comparison of β_N, plasma current, and central safety factor during density disturbances (a,b, and c) and confinement disturbances (d,e, and f).

density magnitude, and confinement quality. FIG. 1 shows that more peaked profiles led to reduced plasma current with a slightly slower response time, higher central safety factor, and a nearly identical β_N evolution. FIG.s 2a-c show that the final value of β_N varied (slightly) proportionally to the applied density perturbations of $+15\%$ and -10%, while the current was reduced as the density increased. The central safety factor elevated with increased density, but dropped below 1.0 around 2 seconds faster than the reference case with reduced density. FIG.s 2d-f show that the applied confinement increase $(+10\%)$ led to increased β_N and I_p and a faster settling time. The final value of q_0 was nearly unaffected, however, it settled much more quickly with increased confinement. Decreased confinement (-10%) resulted in lower β_N and I_p, a slower response time, and no effect on the final value of q_0. These simulations indicate that, given a desired scenario, disturbances could lead to significant changes in performance or MHD-shortened discharges. This motivates development of feedback control algorithms to reject such disturbances and recover, as closely as possible, the reference evolution. Because the open-loop response time of the discharge is comparable to the discharge limit dictated by coil heating or limits

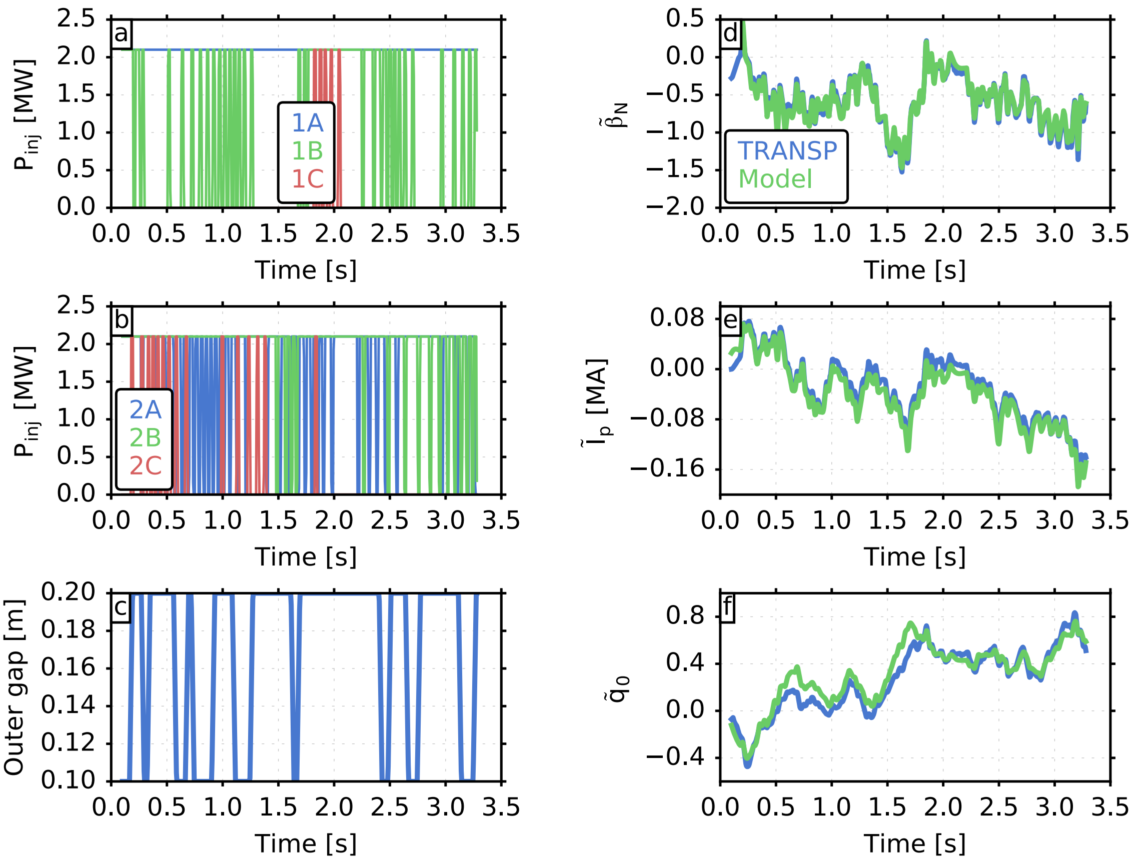

FIG. 3: Modulations of beam line 1 source powers (a), beam line 2 source powers (c), and the mid-plane outer gap (e) during simulation for validating identified model. Comparison of deviation from the reference values of (b) β_N, (d) plasma current, and (f) central safety factor during TRANSP simulation to the predictions of the identified linear model.

on neutral beam pulse length, the ability of feedback to improve the response time and track requested target scenarios will be important for efficient use of experimental time.

3 Feedback 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 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 was considered in this work was the mid-plane outer gap. Two target boundaries, one with a small outer gap and the other with a large outer gap, were chosen as references. Based on the requested outer gap from the feedback controller, the target boundary used by ISOLVER to determine the coils currents was interpolated between the two reference boundaries. Increasing the size of the outer gap changes shaping parameters in such a way that bootstrap current is increased and moves the neutral beam deposition further off-axis, resulting in an increase in the central safety factor. Due to the strong coupling between kinetic and magnetic profile dynamics in non-inductive scenarios, varying any of these actuators during the discharge can alter the plasma current, stored energy, and central safety factor, which are chosen as the to-be-controlled variables in this work.

To understand the response of these variables to the actuators and enable the systematic design of real-time control laws, TRANSP simulations were done in which the actuators were modulated around the values used in the reference simulation, and a linear dynamic response model was fit to the resulting data. The modulation pattern was formed by switching the actuators between their minimum and maximum allowed values at randomized times to create an information-rich dataset for identification. The order of the identified model (the number of states of the system) was chosen by comparing the prediction error of models of different orders on a separate validation simulation (i.e., one not used in the fitting procedure). FIG.s 3a-c show the beam modulations and outer gap modulations used in one of the validation simulations, while FIG.s 3d-f compare the deviation of the TRANSP outputs during the modulated simulation from those obtained in the reference simulation, and the prediction of these deviations based on the identified linear model with 13 states. Evidently, the simplified model captures the dominant dynamics of the system well enough for use in control design and initial testing of algorithms.

The control design approach proposed in this work is a model-based multi-variable scheme that embeds the identified dynamics of the system in the control law to account for the coupling and multiple time scales, while also mitigating the effects of actuator saturation on the performance of the closed-loop system. The proposed scheme includes four main parts: 1) a dynamic observer to estimate the unmeasured states of the identified model as well as unmodeled disturbances (assumed to be constant for the purpose of design), 2) a feedforward compensator to calculate adjustments to a reference actuator trajectory to track the operator-provided target values of the plasma parameters as closely as possible, taking the limits of the actuators and the disturbances estimated by the observer into consideration (targets are assumed to be constant offsets from the reference trajectory for the purpose of design), 3) a state-feedback control law designed using the linear-quadratic-regulator approach to improve the response time of the system, and 4) an anti-windup scheme to limit the effect of actuator saturation on the feedback portion of the controller. While more complex than an empirical PID-based approach, tuning the proposed approach is expected to be more intuitive for operators, as they must only provide a reference shot, target outputs, and relative weights determining importance of tracking each quantity, as well as the weights penalizing the use of each actuator.

4 Feedback control simulation results

Initial closed loop (controlled) simulations were performed using the identified state-space plasma response model to test the system response tune output and actuator weightings. The resulting controller was then tested in TRANSP simulations to assess its robustness to the increased complexity of the model. Although in the experiment the neutral beam sources can only be switched on or off and variations in power must be obtained through pulse-width-modulation, preliminary simulations approximated the source behavior with continuous power requests. Simulations like the one shown in FIG. 4 showed that modest changes of outer gap and heating power can improve the response time of the system and track requested targets. During testing, actuator constraints were found to limit the possible controllable range of plasma parameters when weighting all output quantities roughly equally, however, the optimal control strategy proposed makes it possible to easily adjust output weighting to ensure that a particular quantity that is most critical to a particular experiment can be most tightly controlled, even when actuator saturation occurs. FIG. 4 shows successful tracking of a step changing q_0 target while I_p is maintained steady above the value achieved in the reference simulation and β_N is kept close to its reference value. Initial closed loop simulations including pulse-width-modulation of the beam sources were also performed and found to exhibit small oscillations in current but significant oscillations in stored energy. Methods for reducing beam modulations and their effect on closed loop performance will therefore be explored in future testing.

Acknowledgements

This work was supported by the US Department of Energy Grant under contract number DE-AC02-09CH11466.

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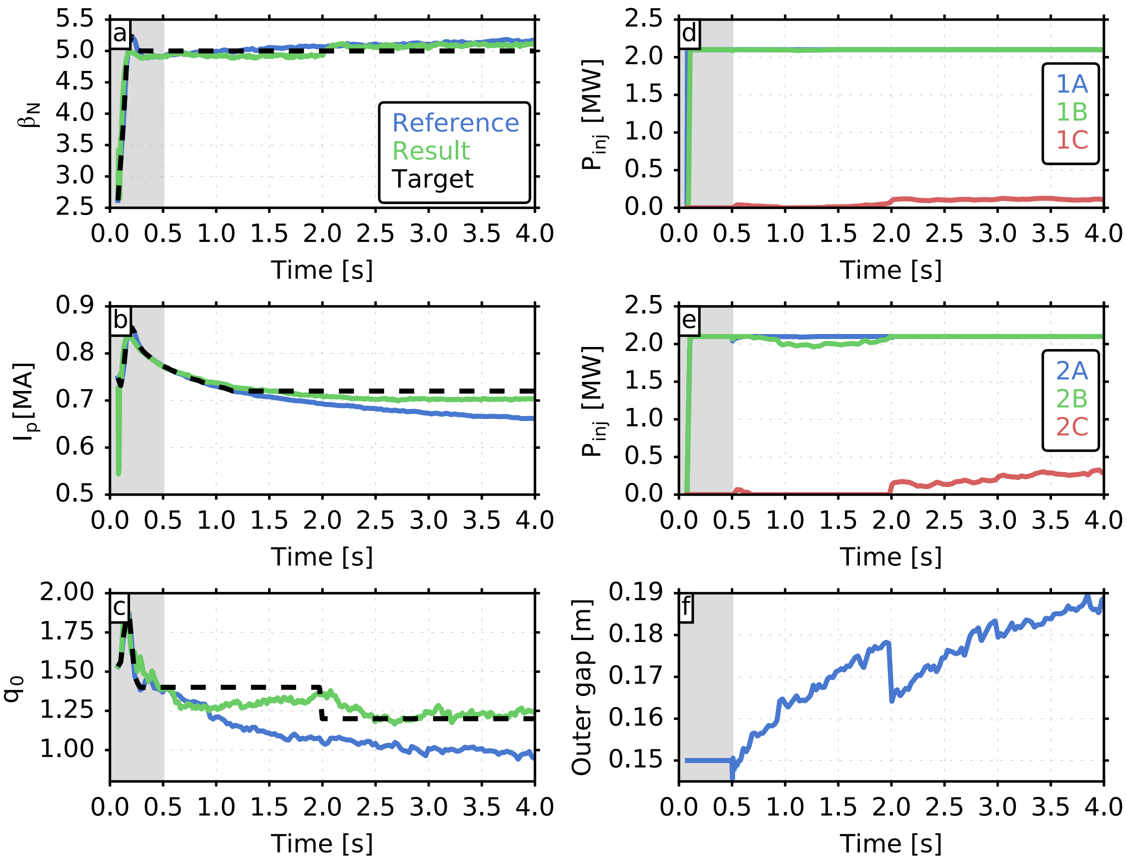

FIG. 4: Feedback controlled evolution of a) β_N, (b) I_p, c) q_0. Requested source powers for d) beam line 1 and e) beam line 2, along with f) requested outer gap. Feedback control was activated after 0.5s.

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