Commissioning upgrades to the NSTX-U Plasma Control System

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The upgrade to the National Spherical Torus eXperiment (NSTX-U) [1, 2] included a larger center-stack, enabling higher toroidal field and longer pulse duration, and three new tangentially aimed neutral beam sources, which increase heating and current drive, and allow for flexibility in shaping deposition profiles. To meet the high-performance goals of NSTX-U, major upgrades to the Plasma Control System (PCS) hardware [3] and software have been made. Several control algorithms, including those used for vertical control, real-time equilibrium reconstruction, and shape control, have been upgraded to improve and extend control capabilities. The shape controller has been tuned to control inner-wall limited and diverted discharges and has been used with the vertical position controller to produce repeatable discharge evolutions, contributing to achieving 1MA, 0.65T scenarios on NSTX-U with 2s pulse length.

Vertical position stabilization

On NSTX, vertical stabilization was provided by modifying the PF3 upper and lower voltage requests based on the vertical position and velocity of the magnetic axis of the plasma, as estimated by the difference in flux and voltage, respectively, between a pair of up-down symmetric flux loops near the primary passive plates. Attempts to create NSTX-U relevant higher aspect ratio plasma shapes in NSTX were often terminated due to vertical instability at fairly low values of ℓ_i, motivating improvements to the vertical position estimation and feedback control [4]. To improve estimation, eight additional flux loop pairs were added to the real-time control system [5], providing back-up for sensor failure and the opportunity to use weighted combinations of sensors to improve estimation. Fig. 1 compares κ vs ℓ_i at the time of maximum stored energy for

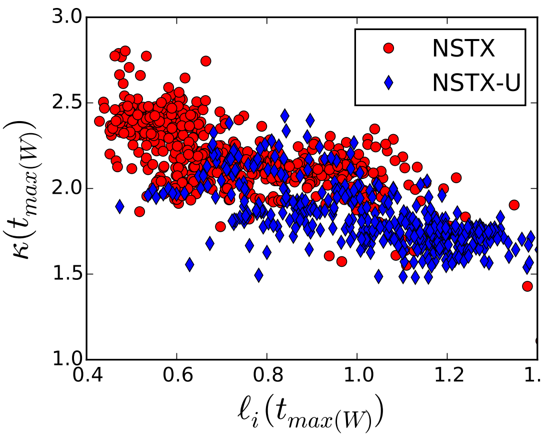

Figure 1: κ *vs* ℓ_i *at time of maximum stored energy in shots between 141525 and 142525 (final shots of NSTX) and between 203742 and 204742 (NSTX-U).*

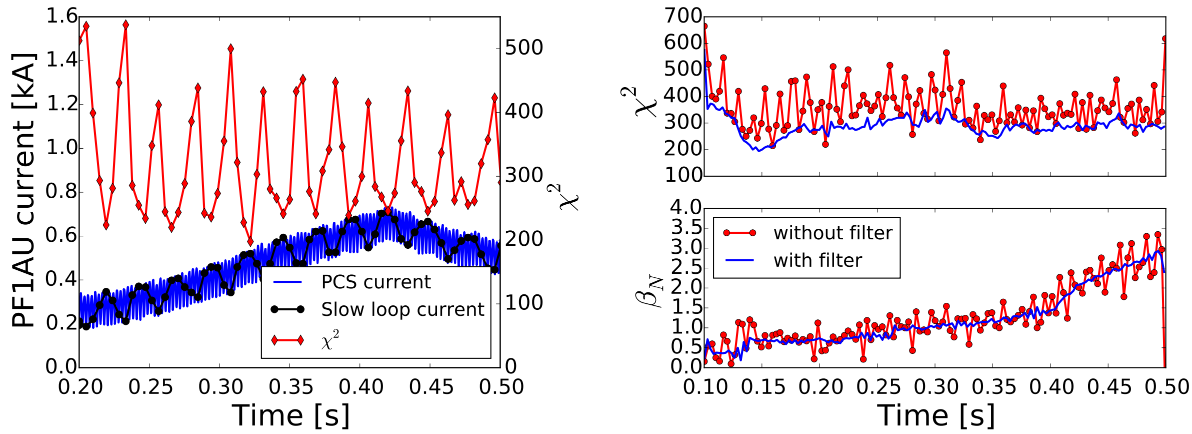

Figure 2: *Aliasing of PF1A currents at rtEFIT sample time and corresponding χ^2 oscillations (left) and reduction of χ^2 and improvement in estimation of β_N with filtering applied (right).*

NSTX shots between 141525 and 142525 to NSTX-U shots between 203742 and 204742. Since the NSTX-U commissioning has mostly studied L-mode discharges, many discharges have had very high ℓ_i in the range of 1.0-1.6. Elongation limits in this high-ℓ_i operating space have been explored, confirming the trends established at moderate ℓ_i in NSTX. The achievable elongation has increased at lower values of ℓ_i in H-mode discharges, however, the limits of vertical control have not yet been pushed and gains have not been re-optimized for the lower ℓ_i operating space. Nonetheless, it appears that achievable elongation trends for NSTX-U in the range of ℓ_i studied are not significantly different from those on NSTX, even at increased aspect ratio.

Real-time equilibrium reconstruction

The rtEFIT algorithm [6] was used for real-time equilibrium reconstruction for several years on NSTX [7]. For NSTX-U, the coil and vessel model was updated for the new device and the diagnostic response was calculated for the increased number of magnetic sensors [5]. The spatial grid used to discretize the plasma current model was increased from 33x33 to 65x65, matching the resolution of the offline EFIT code used for NSTX-U [8, 9]. While the PCS hardware improvements enabled 3.4ms 'slow loop' times (the time it takes to complete an iteration of the equilibrium reconstruction; the rtEFIT 'fast loop' updates the errors used by the shape controller on a 200μs time scale [6]) at the higher resolution, the calculation time became unacceptably slow when fitting the vessel currents and calculating β_N, ℓ_i, and the q profile in real-time. To overcome this, the system was set up to use the multi-threading capabilities of rtEFIT, enabling fitting of all vessel currents and calculation of the extra real-time quantities with a slow loop time <6ms. Early operations showed that ripple from the rectifiers was aliased into low frequency oscillations in the reconstructions (although signals entering the real-time system are anti-alias filtered based on the data acquisition rate, the slow loop of rtEFIT runs at a reduced rate). This effect was removed by implementing a digital multi-pole filter for the inputs to the slow loop, significantly improving the fit to the magnetic measurements as shown in Fig. 2.

Plasma boundary shape control

NSTX used the isoflux control approach to control the plasma boundary shape [7] with separate feedback algorithms for inner-wall limited and diverted discharges. Early in NSTX-U discharges, the inner-wall limited algorithm adjusts the PF3 upper/lower and PF5 coil voltage requests to match the flux at three control points on the outer boundary to the flux at the limiter touch point, while the PF1A and PF2 coils are under current-control to bring X-points into the vessel. Once the plasma nears diverting, the system is switched to the diverted algorithm, using the PF3 and PF5 coils to match the flux at the three boundary points to the X-point flux, and the PF1A and PF2 coils to control the X-point radial and vertical positions or the X-point height and the radius of the outer strike point. While the NSTX X-point and strike point control scheme linked each quantity to a single coil [10], the X-point and strike point control for NSTX-U accounts for the interaction of the coils in the control law. Use of the feedback controller to track different outer strike point positions with fixed X-point heights and outer boundary location during a single shot is shown in Fig. 3. Control of the parameter Δr_{sep}, the distance between the radial position of the two points on the outer mid-plane with the same flux as the upper and lower X-points, has been commissioned to produce double null, lower-, and upper-biased discharges. The Δr_{sep} control method has been updated to adjust the boundary control point targets in response to the measured Δr_{sep} to bias the target shape to track the Δr_{sep} target. Finally, a novel method for controlling the inner gap (the mid-plane gap between the plasma and the center-stack) has also been commissioned.

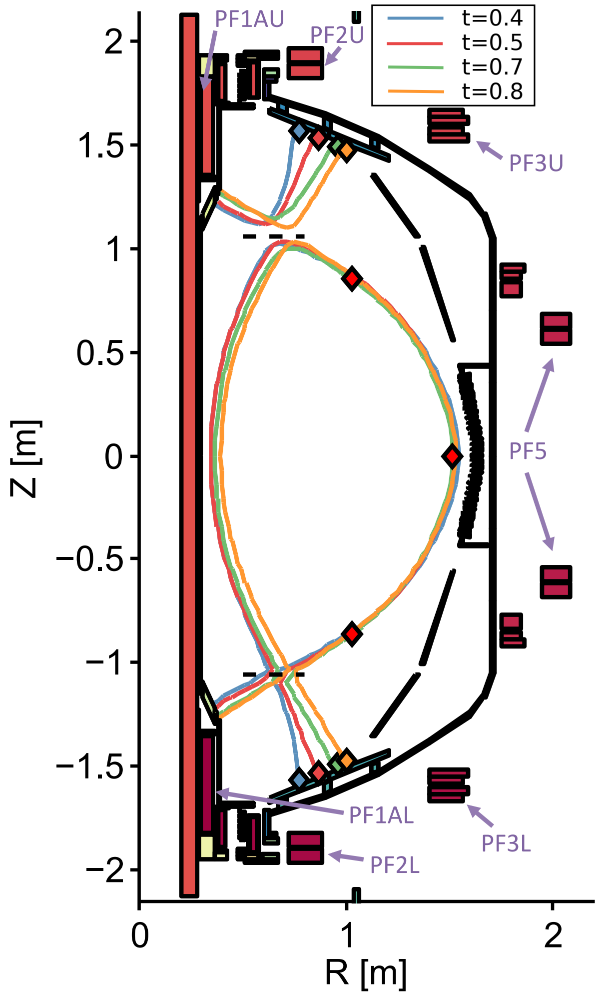

Figure 3: *Strike point target tracking (colored diamonds on outboard divertor) during 203879 while maintaining outer gap targets (red diamonds) and the height of the X-points (dashed black lines).*

Because there are no coils on the in-board side of the machine and each of the active shaping coils is currently mapped to controlling other points, the inner gap cannot be independently controlled. In the approach taken, the target locations of each control point are modified away from the pre-programmed values in real-time by the output of a PID operator on the inner gap error. Adjustable gains for each control point allow the operator to chose from shot to shot how the plasma shape should be changed in real-time to track the inner gap target.

Discussion

Rapid progress has been made in commissioning the upgrades to the NSTX-U Plasma Control System, primarily in the areas of vertical control, real-time reconstruction, and boundary shape control. Improved estimation of the vertical position and velocity have been used to explore vertical stability limits. The resolution of real-time equilibrium reconstructions has been improved from what was used in NSTX, and fitting of the coil and vessel currents in real-time has been activated. The plasma shape control algorithms have been updated and retuned for the new device, enabling accurate control of the plasma boundary, X-points, strike-points, and Δr_{sep}. Next steps will involve commissioning feedback control of the plasma stored energy, current profile, rotation profile, and the 'snowflake' divertor configuration.

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