U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Vertical control, real-time reconstruction, and shape control on NSTX-U

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On behalf of the ASC TSG and the NSTX-U team

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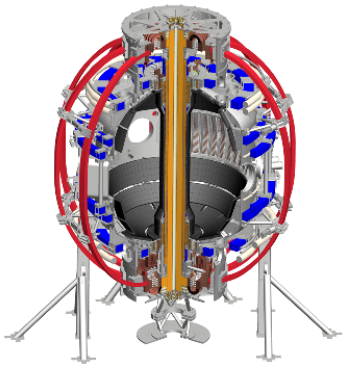
PPPL



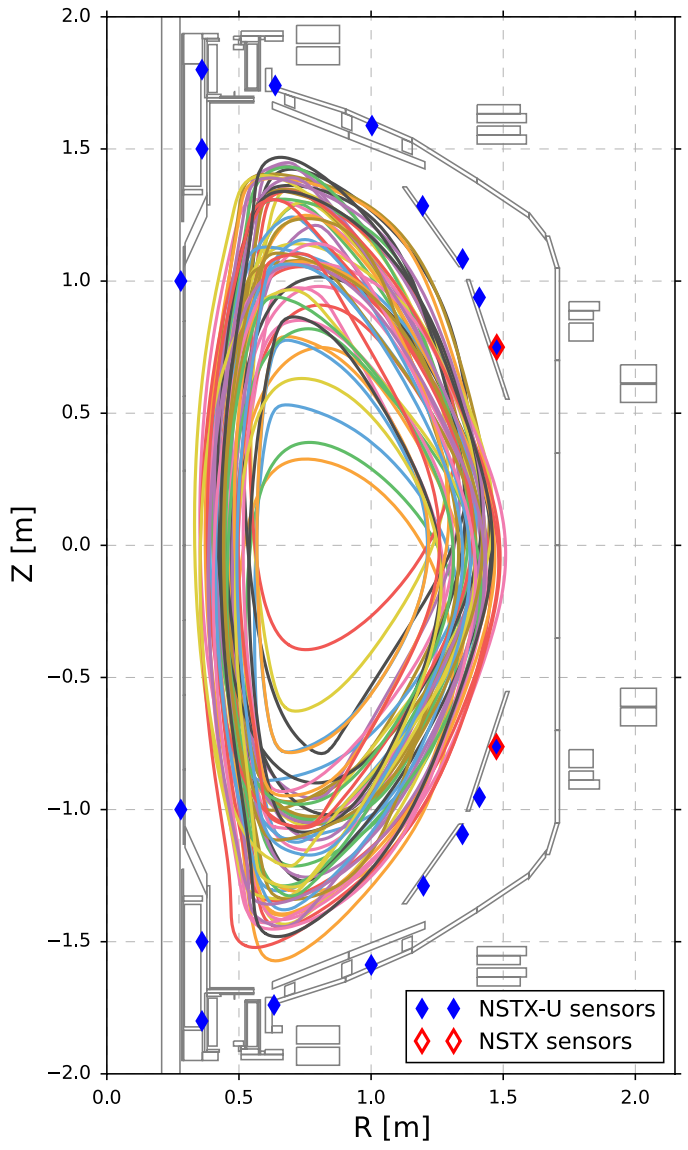
Completed 7 XMPs for upgrades and tuning of vertical control and rtEFIT/ISOFLUX

- **XMP-105:** Vertical control check-out
- **XMP-138:** Vertical control filtering
- **XMP-115:** rtEFIT, ISOFLUX
- **XMP-120:** X-point, strike point
- **XMP-147:** Improve L-mode fiducial
- **XMP-152:** New drsep control, multi-threaded rtEFIT
- **XMP-154:** Inner gap control

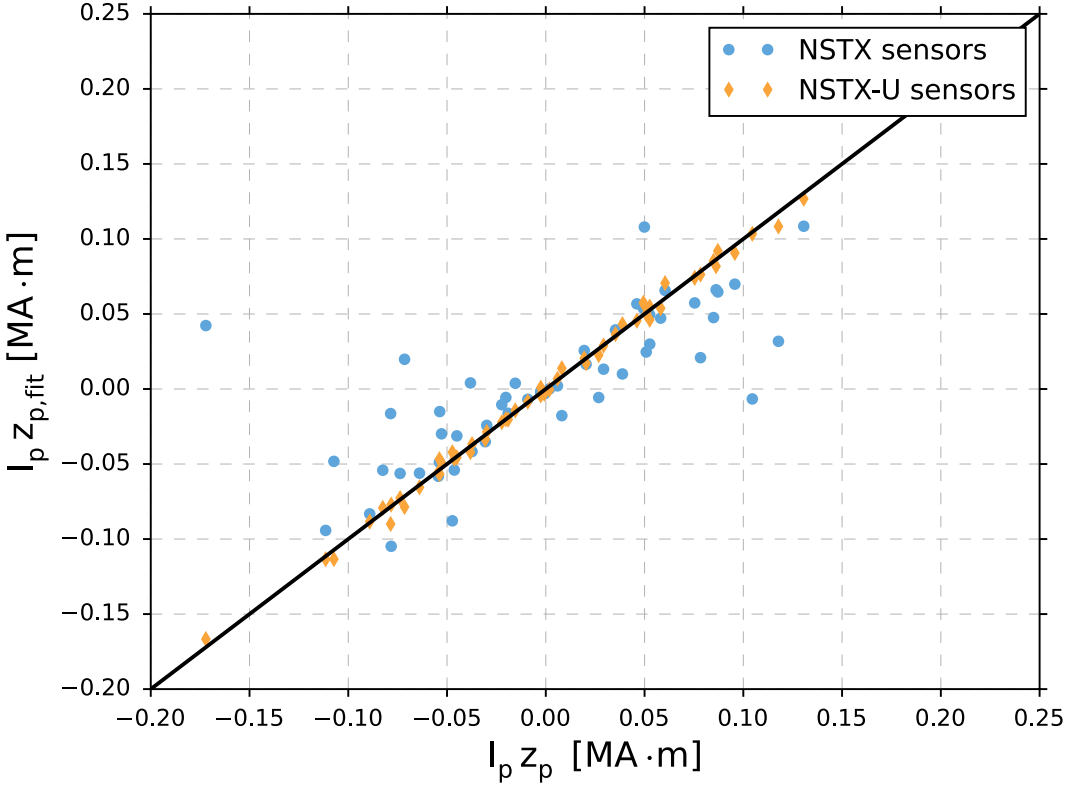
Upgraded vertical control capabilities for NSTX-U

- On NSTX:
  - Vertical control a **challenge at higher aspect ratio**
- Upgrades to PCS algorithm for NSTX-U
  - Separated **vertical control** into its own **PCS category**
    - Provides PD control when under PCC shape control
    - Provides D control when under ISOFLUX shape control
  - **Upgraded** sensing and **estimation** capabilities
  - Added ability to command **SPA currents**
  - Added ability to **signal loss-of-control**
  - **Growth-rate study** logic added

Additional flux/voltage differences improved estimation of vertical position/velocity

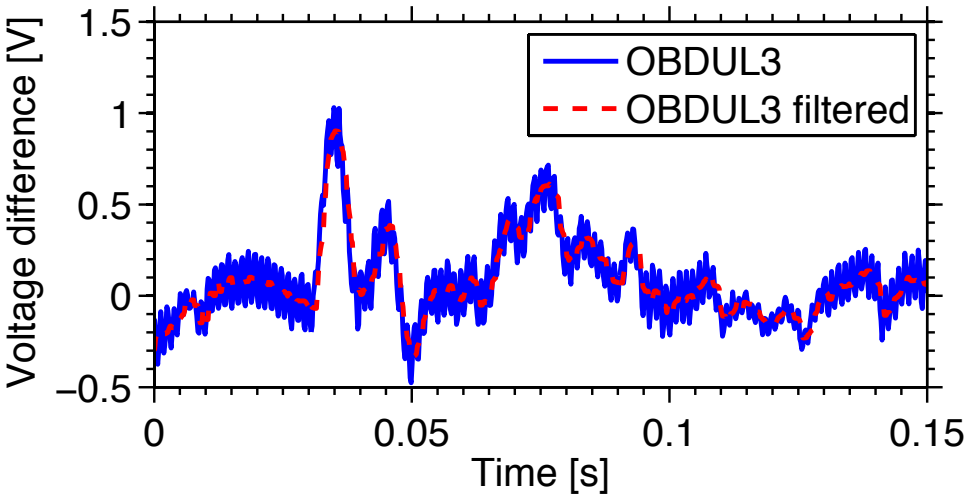


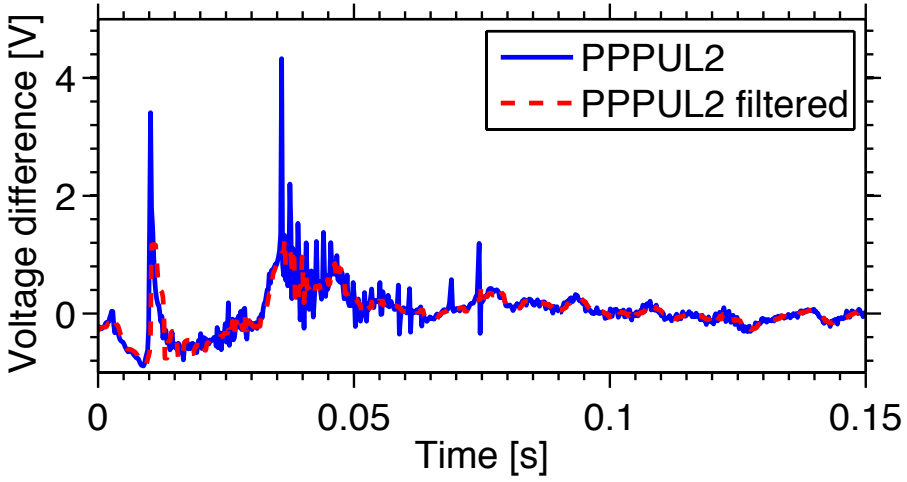
- ~60 NSTX-U equilibria generated with ISOLVER free boundary code
- Flux loop weights determined by **least squares fit to IpZp**
- Optimal weights **adjusted based on EFIT reconstructions of experimental discharges**

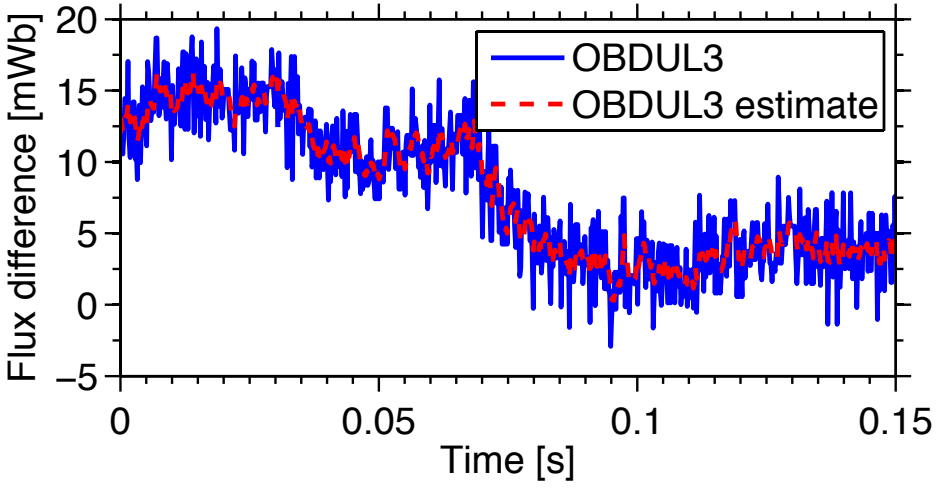


Filtering added to remove unwanted pick-up on vertical estimation sensors

- Voltage differences pick up **power supply ripple** and noise spikes due to **MHD events**
  - Too **fast** for control system response
- Flux differences subtracted in software, corrupted by **bit noise**
  - **Kalman filter** used to **estimate the flux differences** based on the noisy measurement and digital integration of the voltage difference

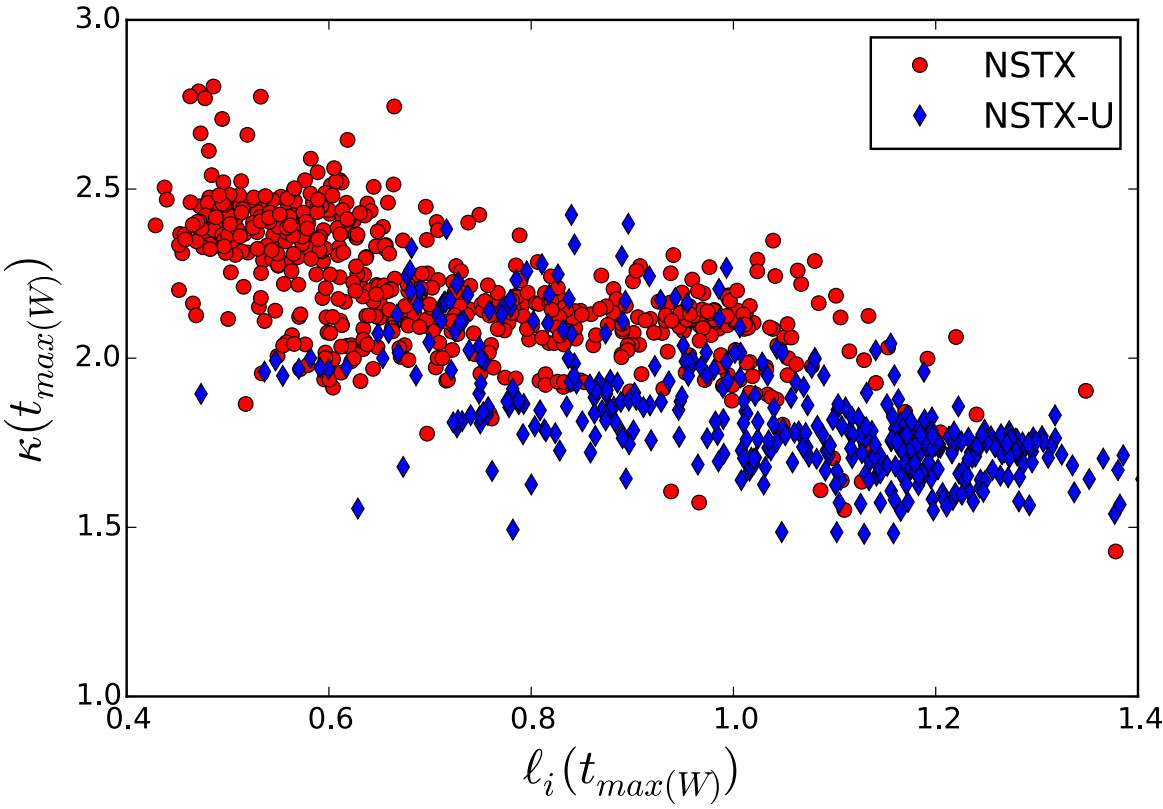






Early NSTX-U elongation limits similar to NSTX despite increased aspect ratio

- **NSTX** shots in the range **141500-142524** (the last shots of NSTX) compared with **NSTX-U** shots in the range **203800-204800**
- **NSTX** shots include many **H-mode** shots at **low-li** while **NSTX-U** shots have mostly been **high-li L-mode** shots



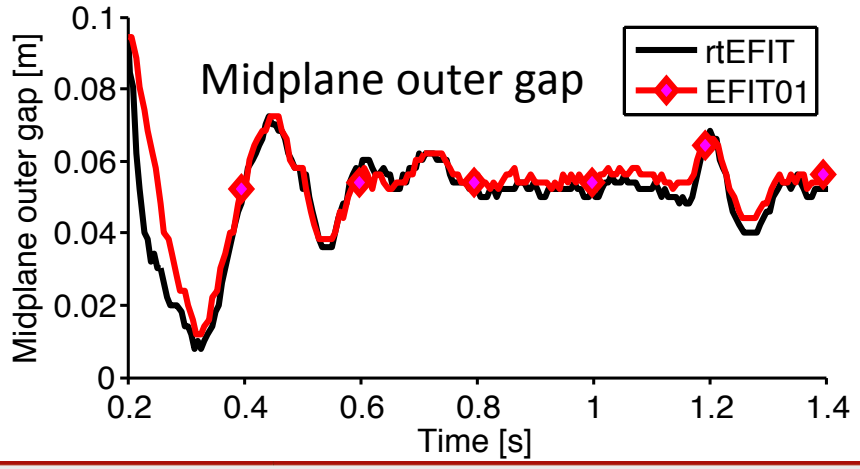
- NSTX-U vertical **control gains tuned** during **li>1** operation
- **Lower li** shots in NSTX-U are **H-modes**
  - vertical **stability limits have not yet been pushed** and **gains have not yet been optimized** for this regime

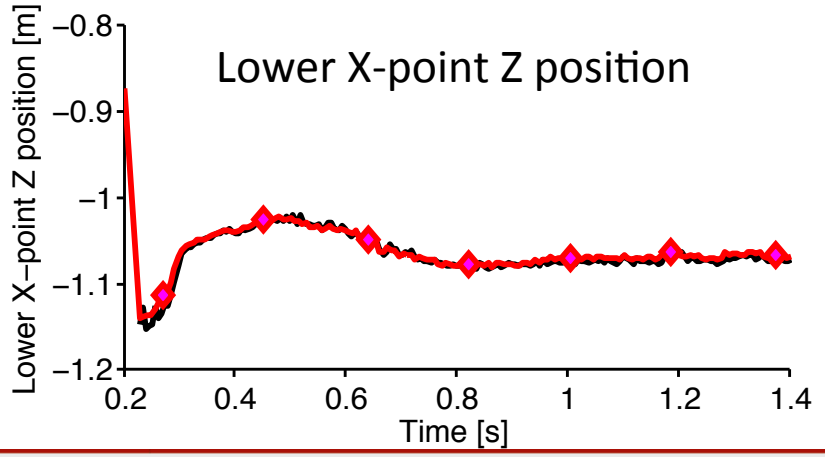
Plans for vertical control

- Push stability limits in **high-elongation H-mode scenarios**
  - Re-optimize observer **weights**
  - Adjust feedback **gains**
- Test use of **SPA currents** as a faster actuator
- Use **growth-rate study** logic to experimentally determine growth rates and maximum recoverable displacement
  - Compare result to **modeling** (see Menard's talk this afternoon)
    - Use to improve modeling and **guide future improvements to control**

Updated and improved rtEFIT for real-time reconstruction on NSTX-U

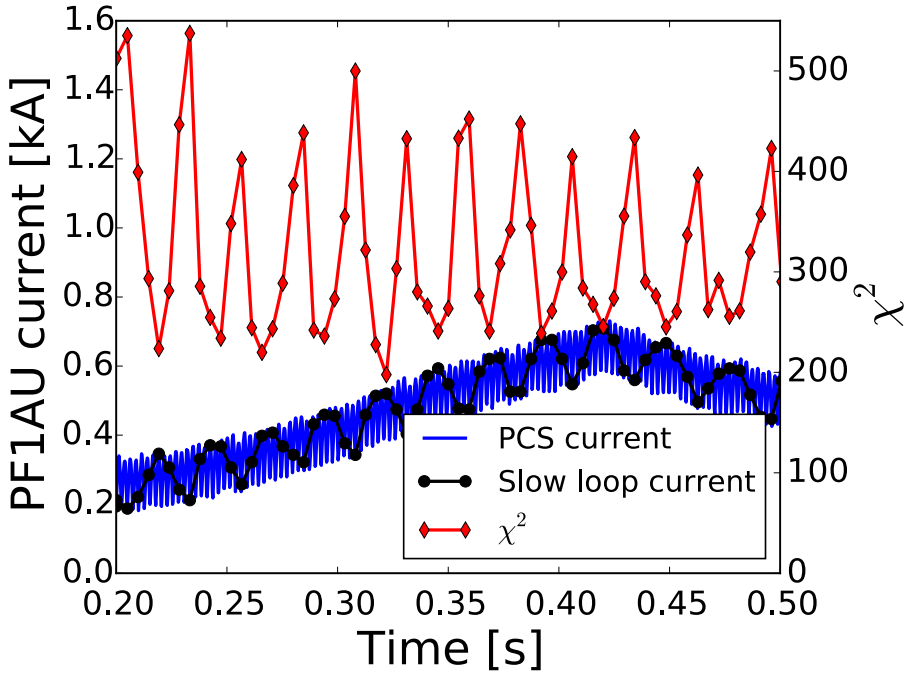
- Updated **grid size** to 65x65 (from 33x33) and vessel/coil model
- **Tested** using TRANSP data prior to run, rt4 early on
- **Multi-threading** enabled more complex calculations
  - β_N, l_i, q calculated in real-time
  - Coil and vessel currents fit instead of treated as known
- Calculated gaps and X-point positions **match closely to offline magnetics-only EFIT** (EFIT01)

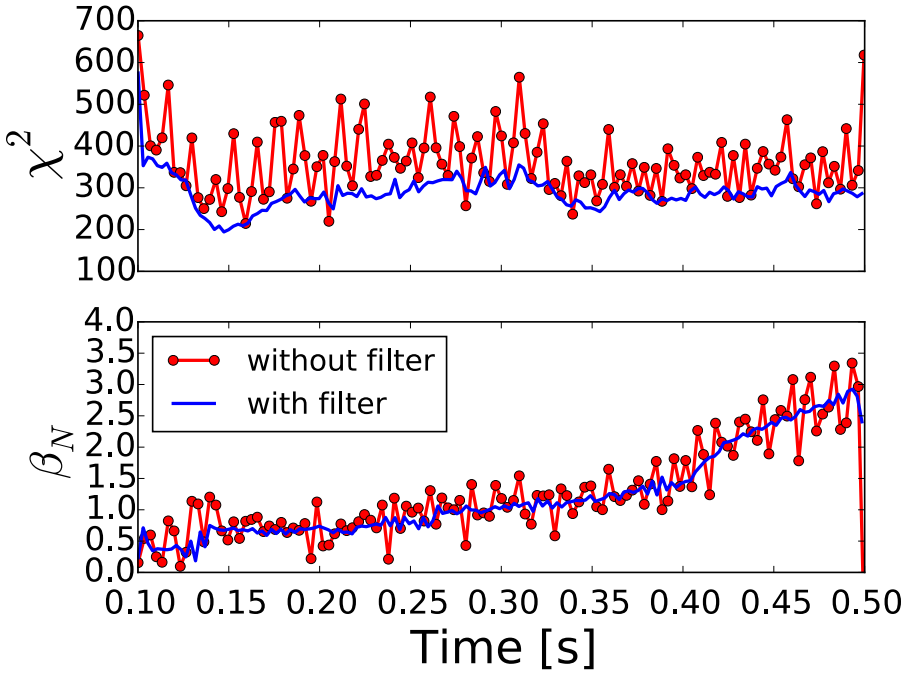




Fixed the fitting issues caused by PF1A power supply ripple with anti-aliasing filtering

- rtEFIT has a **fast loop** and **slow loop**
  - **Fast** (every PCS cycle time): determines **flux at control points** based on last reconstruction and new diagnostics
  - **Slow** (~5-25 PCS cycle times): single iteration **reconstruction**
- Aliasing of **power supply ripple** on slow loop time scale caused poor fitting, oscillations



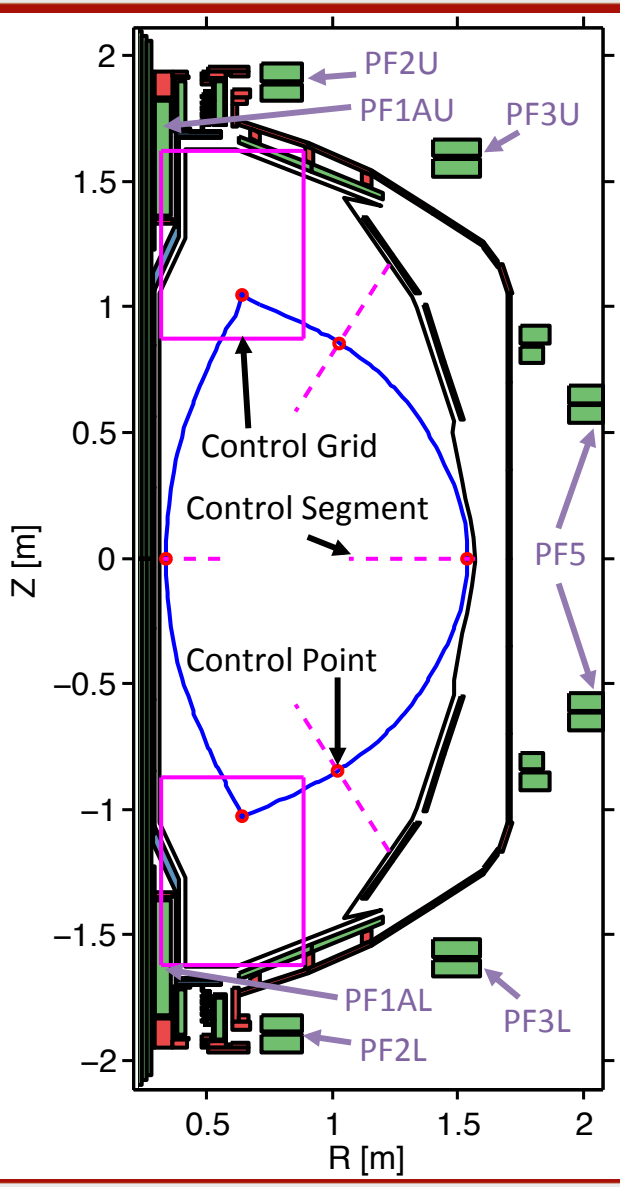


rtEFIT will be continue to be upgraded over the outage period

- Optimize **vessel current model**
- Set up to incorporate **rtMSE** to enable **q profile control**
  - Will be a separate instance of rtEFIT
- Set up to make use of **rtMPTS** and real-time **diamagnetic loop**
  - Moving towards **kinetic rtEFIT**

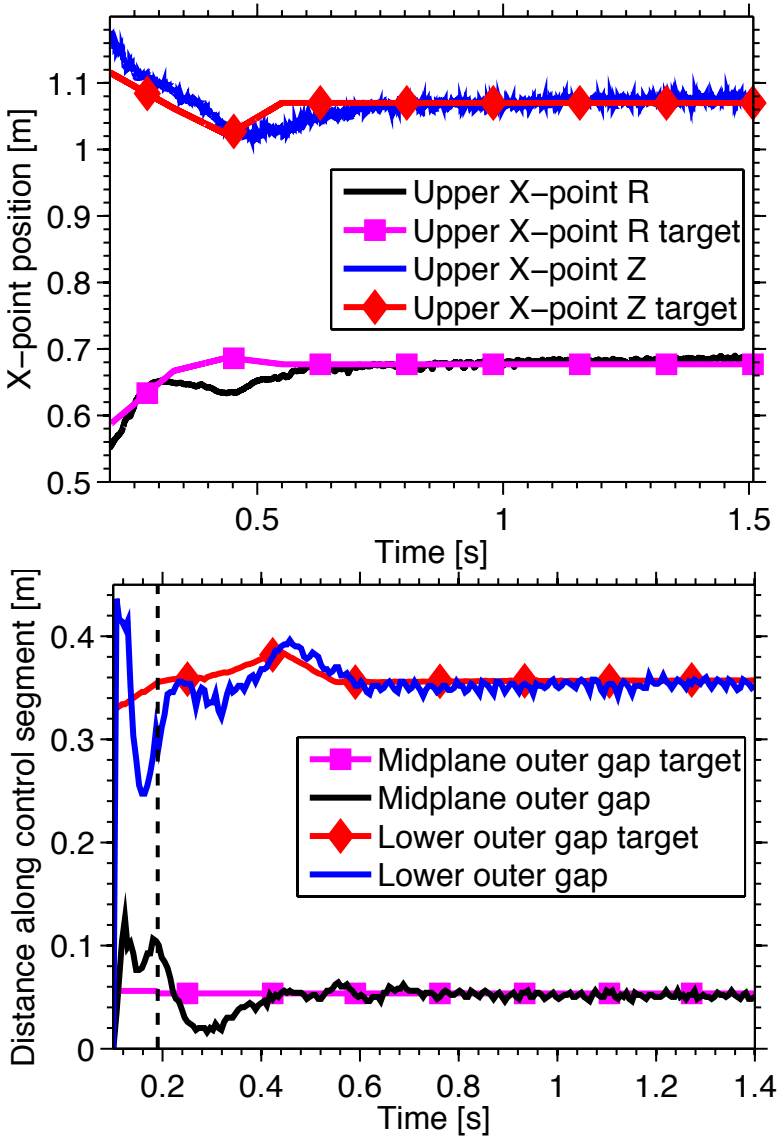
ISOFLUX shape control on NSTX-U

- **Control points** are defined as the intersection of operator selected **control segments** with the operator defined **target boundary**
- X-points are expected to be within the **control grids**
- Two main algorithms:
  - **ISOELONG** – inner wall limited discharges
  - **ISODNULL** – diverted discharges
- **Total re-write** of code by K. Erickson
  - **75% reduction in # lines of code**
  - Made changing/adding functionality much easier throughout the run



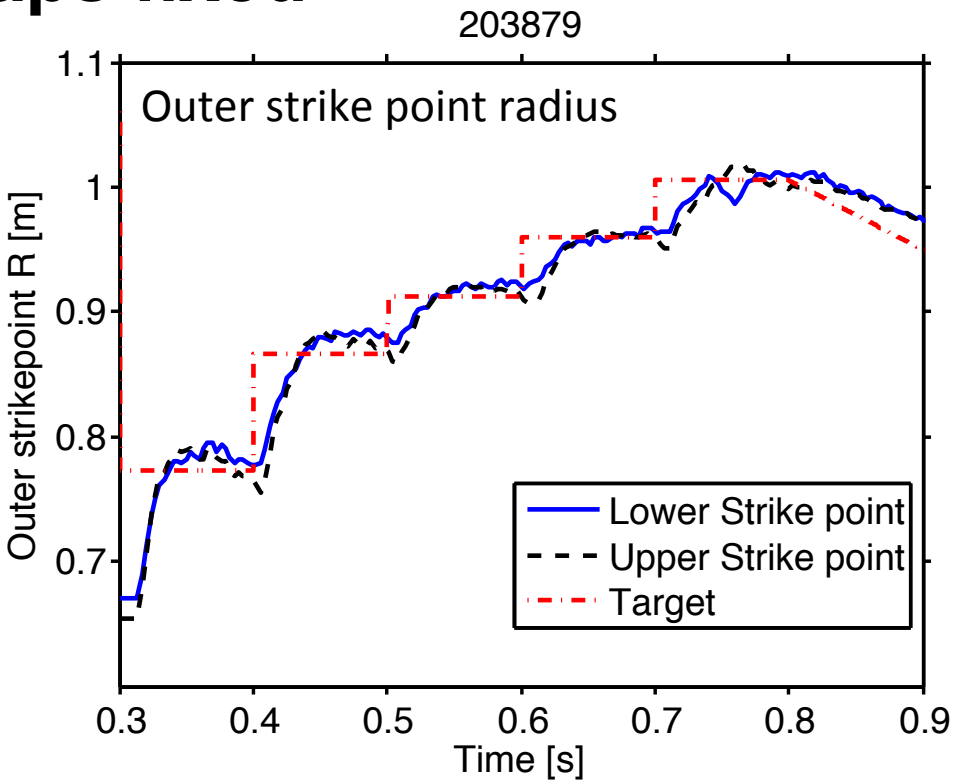
ISODNULL algorithm is used to control diverted discharges

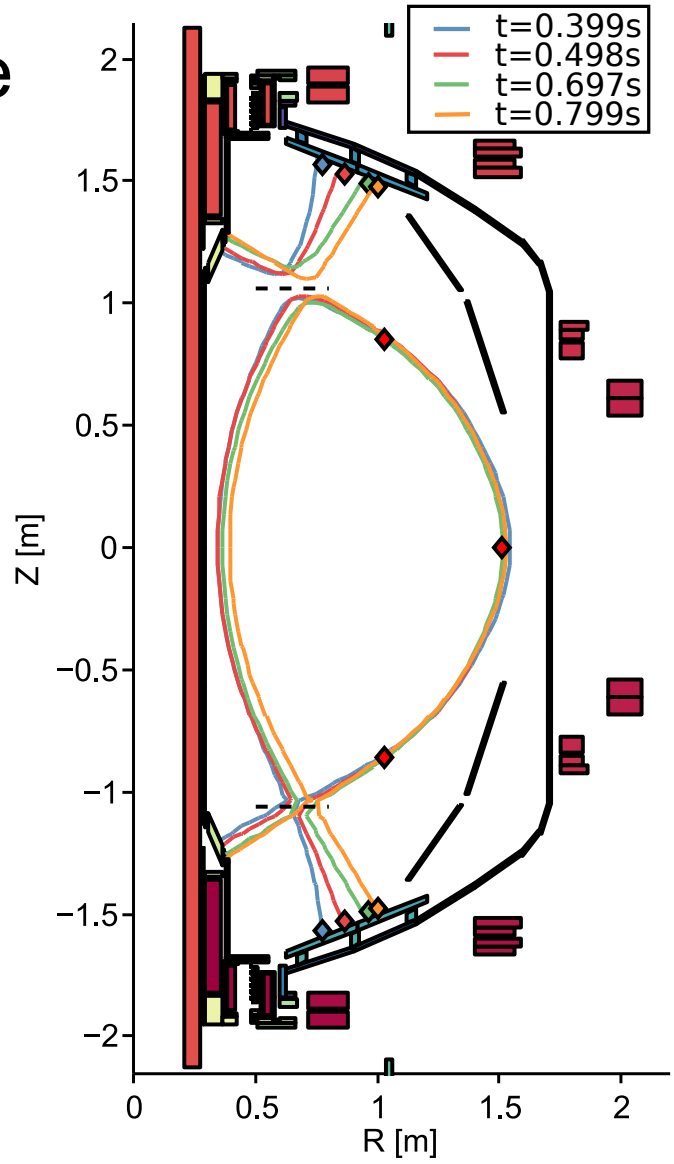
- Again, **PF5** controls **midplane outer gap**, **PF3U/L** control **upper/lower outer gaps**
- The flux at the **dominant X-point** is typically used as the **reference flux**
  - New upgrade added to **automatically switch to touch point flux if the plasma touches the center stack** during an oscillation
- **PF1A and PF2** typically used to control the **X-point locations**
  - Used **MIMO control** to account for actuator coupling



ISODNULL has also been configured to control the location of the outer strike points

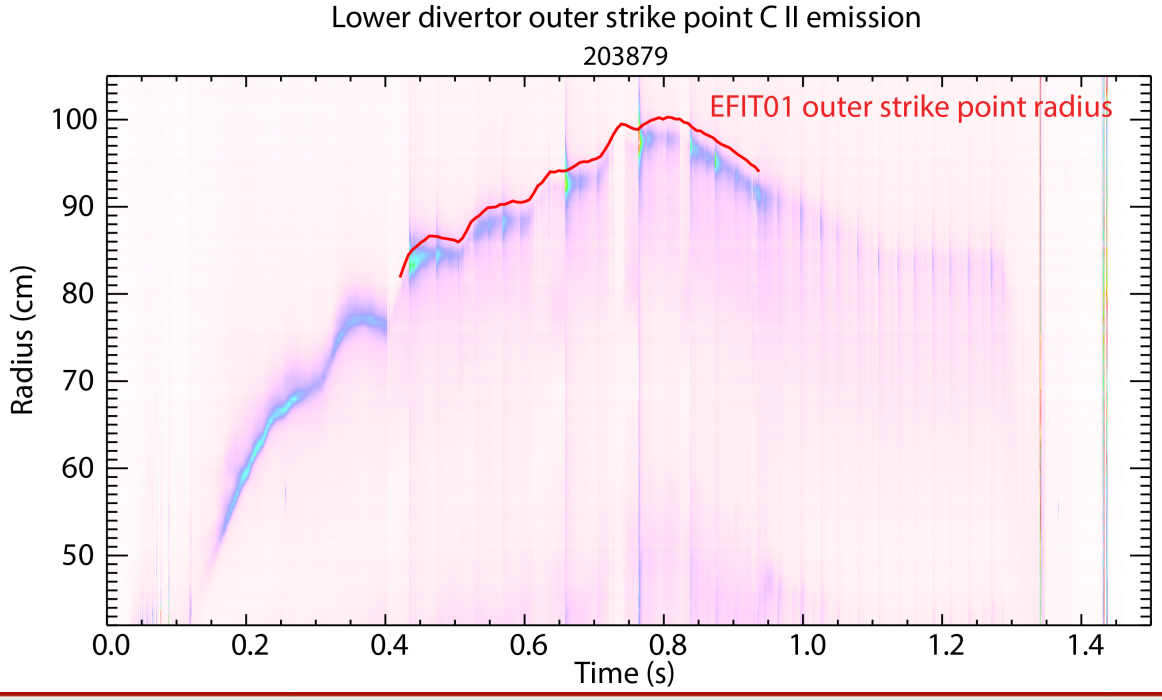
- Demonstrated ability to **scan** the **outer strike point** location with the **X-point height and outer gaps fixed**

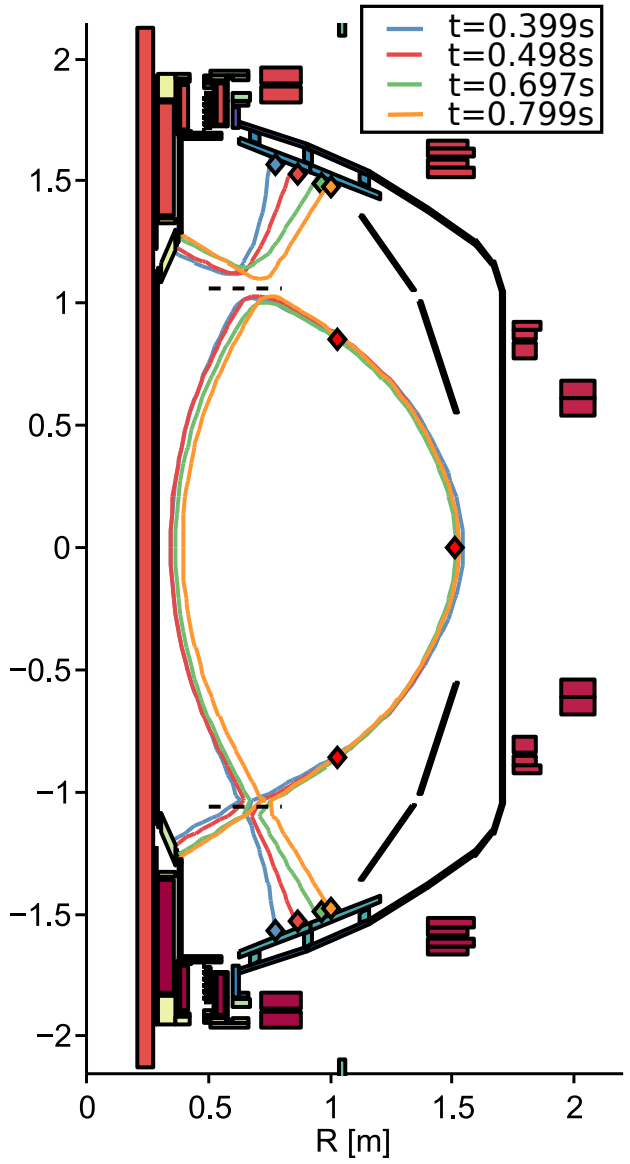




ISODNULL has also been configured to control the location of the outer strike points

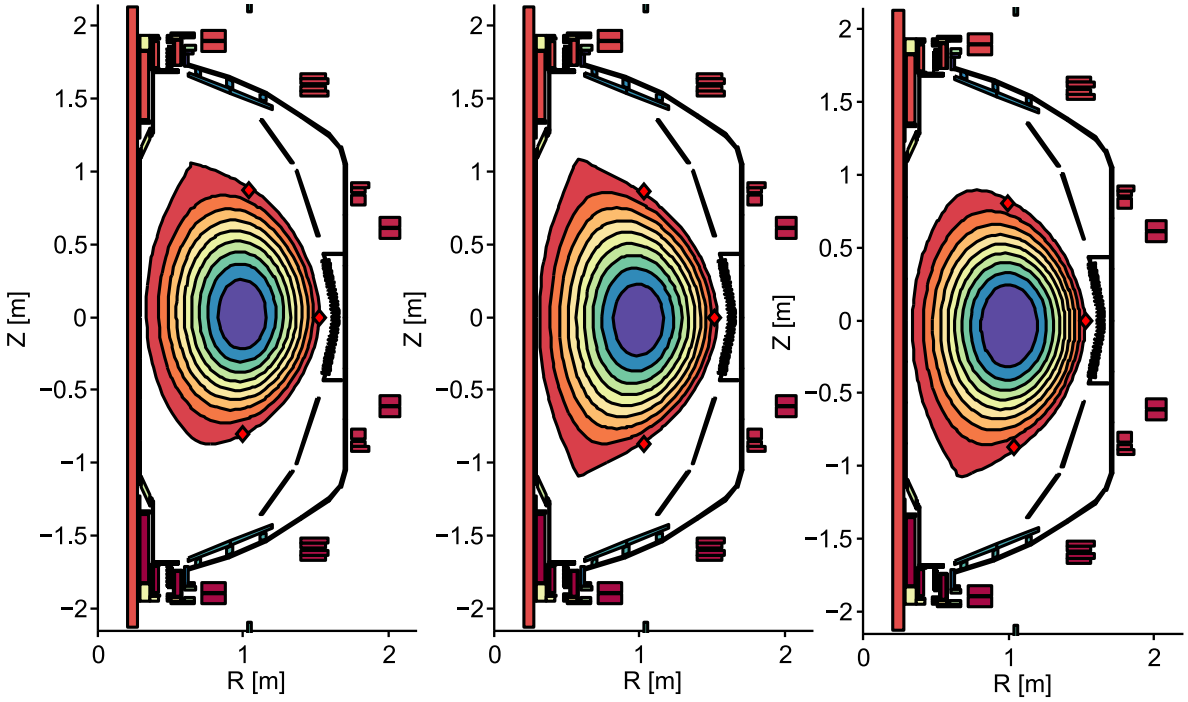
- Demonstrated ability to **scan** the **outer strike point** location with the **X-point height and outer gaps fixed**
  - Confirmed by CII emission [F. Scotti]

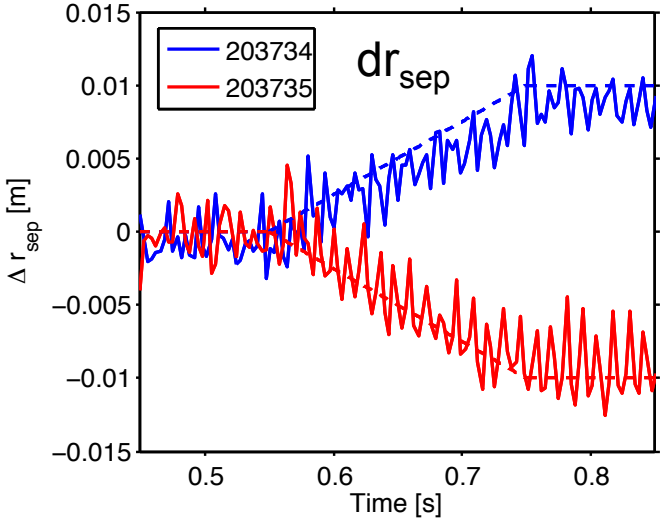




Control of dr_{sep} has been commissioned

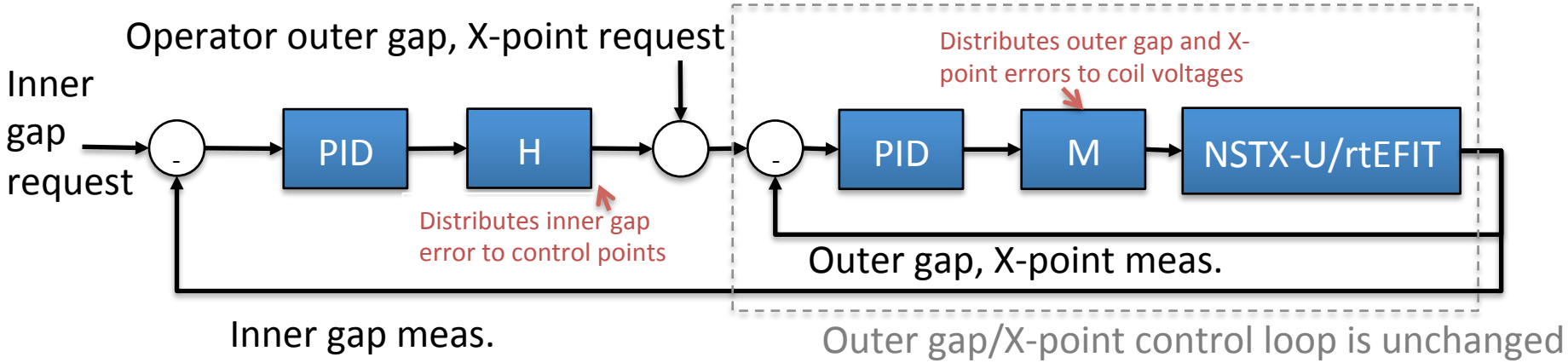
- dr_{sep} is the midplane radial distance between the upper and lower X-point separatrices
  - Used to create **balanced or upper/lower biased** discharges
- Controlled by **automatically adjusting the upper and lower outer gap** control point locations in real-time

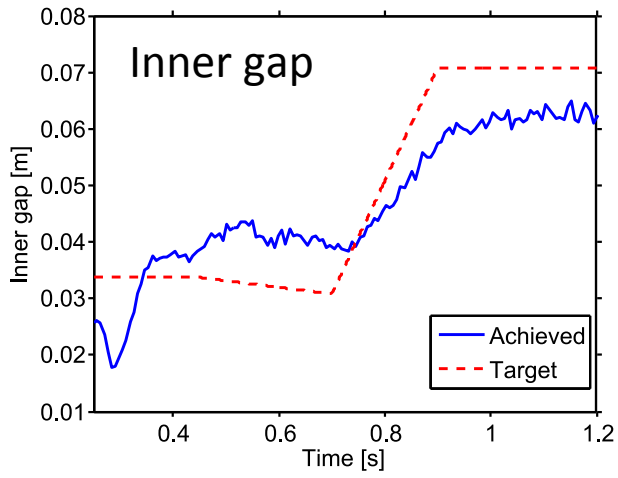


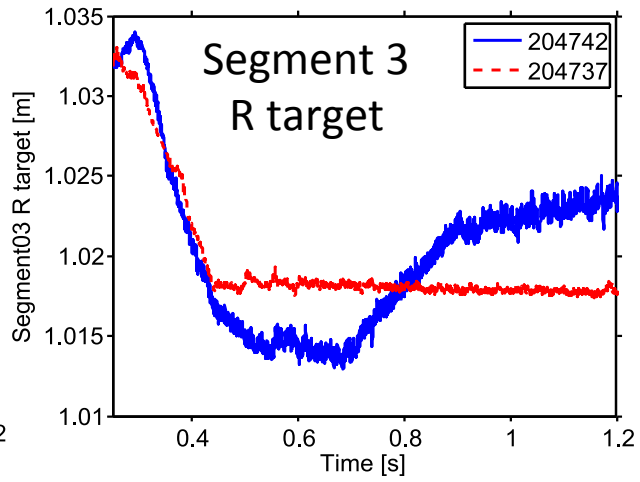


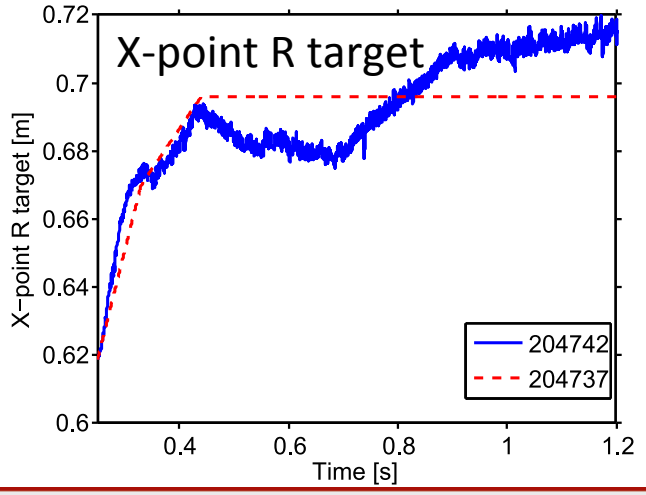
A novel method inner gap control (a challenge for ST's) has been tested

- No shaping coils on the inboard side and all coils available this campaign used for other control points
  - No way to independently control the inner gap









ISOFLUX will continue to be upgraded over the outage

- Improve **transitioning** between phases
  - Efforts made to make **voltage** transitions smooth but the **shape requests** should be made continuous as well
- Make code changes to enable **simultaneous x-point, strike point, and inner-gap control**
- Add **feedforward** control and **anti-windup**
- Look into adjustments to **account for the effect of beam modulations** on plasma position

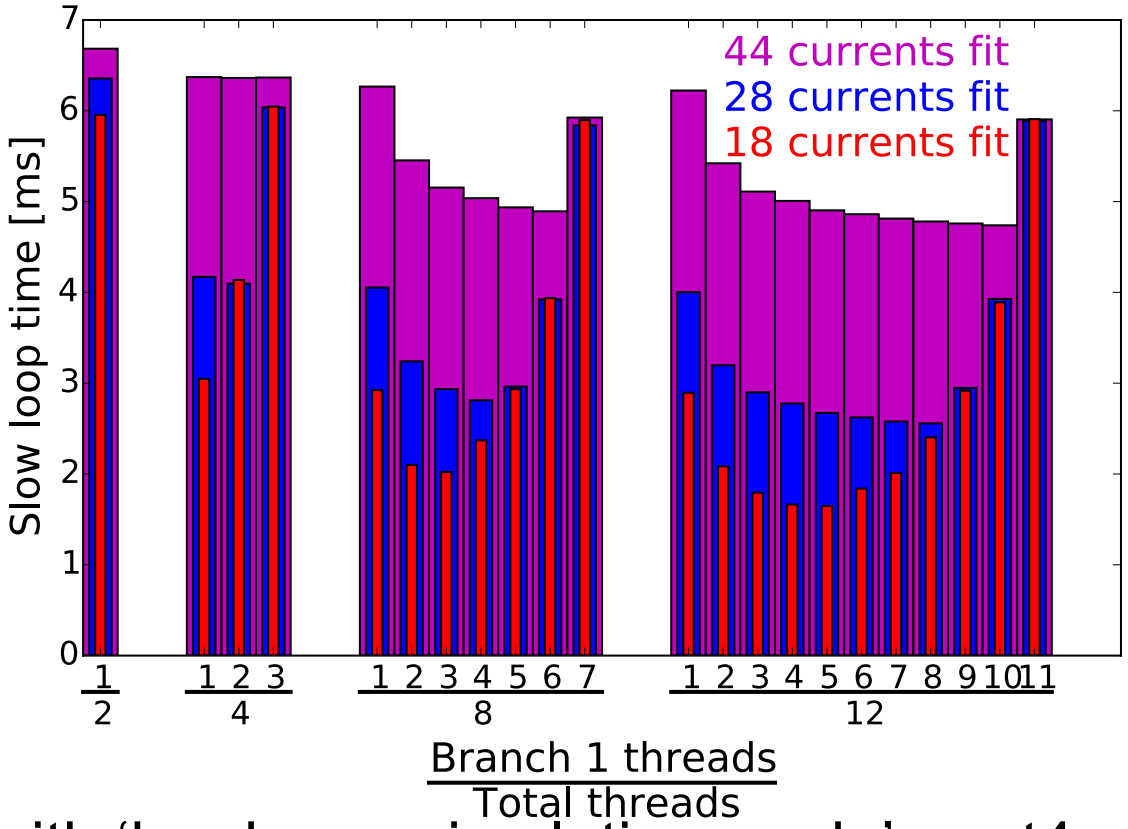
XMPs restored NSTX control capabilities + added many enhancements for NSTX-U

- Vertical control
  - Multi-sensor observer
  - Measurement filtering
  - Tuned in high-li scenarios
- rtEFIT
  - Updated model
  - Doubled plasma grid resolution to 65x65
  - Anti-aliasing for down-sampled signals
  - Vessel fitting, calculation of β_N, l_i, q, enabled by multithreading
- ISOFLUX
  - Code rewritten (75% reduction in # of lines) for maintainability
  - ISOFLUX control of limited and diverted discharges
  - X-point control, strike point control (MIMO gains)
  - dr_{sep} control (new method w/ self-consistent control points targets)
  - Inner gap control

New for NSTX-U

Multi-threading used to speed up rtEFIT allowing for more computational complexity

- **Increased complexity** due to
  - Doubled **grid size**
  - **Fitting currents, vessel model**
    - Treated measurements as ‘known’ on NSTX
  - Activated real-time calculation of β_N, l_i, **q**



- **Multi-threading** tested with ‘hardware simulation mode’ on rt4
  - Optimal **distribution of threads** determined for different # of fitted currents
- **Deployed on rt3**
  - Still need to determine **optimal # of fitted currents**

ISOELONG algorithm is used for limited discharges and initial part of diverted shots

- **PF5** controls **midplane outer gap**
- **PF3U/L** control **upper/lower outer gaps**
- **Flux at touch point** used as **reference**
- Some initial oscillation, but requested gaps are tracked within <4cm throughout control phase. (discharge 203474)