Design and simulation of control algorithms for stored energy and plasma current in non-inductive scenarios on NSTX-U

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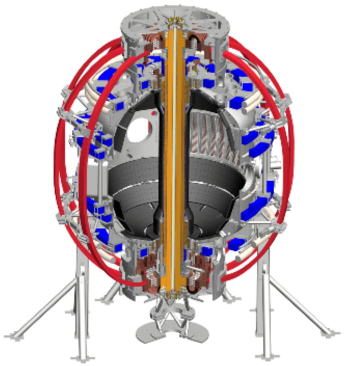

Overview

- A major goal of NSTX-U is to demonstrate **fully non-inductive operation**
- Early experiments focus on **non-inductive sustainment** and will begin with inductive start-up and ramp-up
- In this work, **TRANSP** is used to study the dynamic response of the plasma during such experiments
  - The effect of various parameter perturbations on the dynamic response is studied
- The potential for using **feedback control** of the available actuators to **improve the system response** and reject perturbations is explored
- A **framework for feedback control simulations in TRANSP** is used as a platform for assessing controller performance

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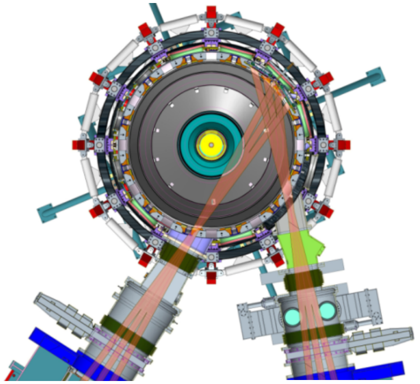
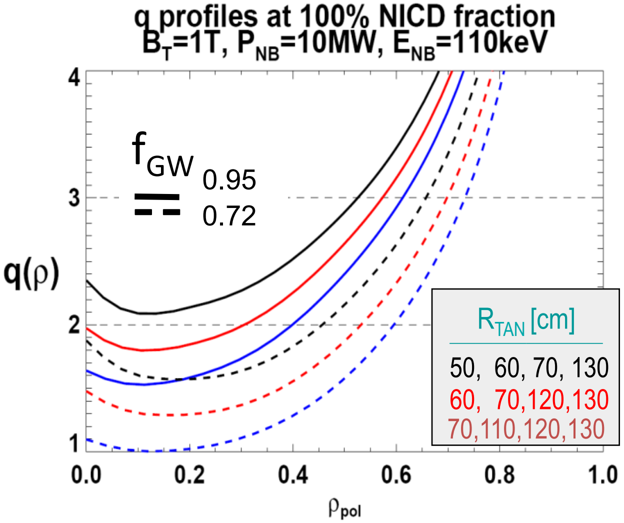
NSTX-U improves controllability and brings about new control requirements

- **New opportunities** to use feedback control to optimize performance as a result of:
  - Longer pulse length, increased toroidal field, increased heating and current drive
- **Advanced control** will be **necessary** for achieving many operational goals, e.g.,
  - Non-inductive scenarios, snowflake divertor, rotation control, current profile control



Present NBI New 2nd NBI

- ➢ 2x higher CD efficiency from larger tangency radius R_{TAN}
- ➢ 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position

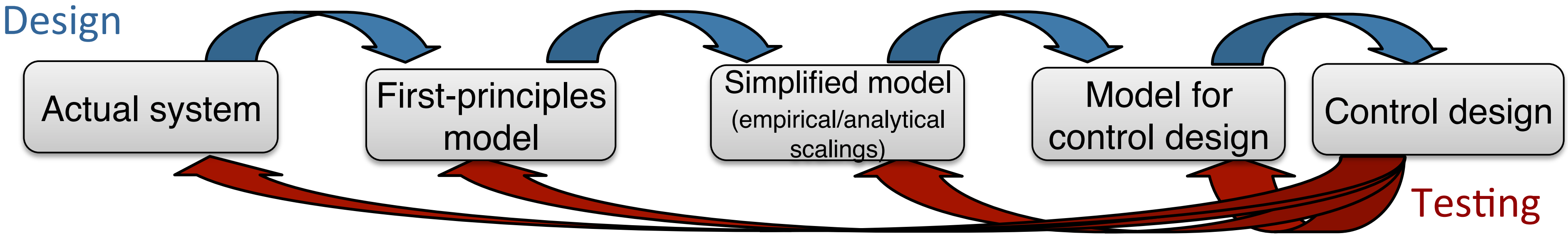


A major goal of NSTX-U is to study non-inductive operation

- A spherical torus based design may be an economical option for a **fusion nuclear science facility (FNSF)**
- However, designs have little to **no room for a central solenoid**
  - Plasma current would need to be **generated non-inductively**
- The upgrades to the device in the **NSTX-U** project will enable the **study of non-inductive scenarios**
  - Start-up, ramp-up, and flattop current sustainment
- Early experiments will look at **non-inductive current sustainment** after inductive start-up/ramp-up
  - Solenoid current will be `frozen' to **mimic solenoid-free operation**
  - Plasma current evolution determined by **coupling between kinetic and magnetic profiles**
  - Resulting dynamics may be **intolerably slow** (maybe **unstable**) and highly **sensitive to perturbations** in profiles, confinement, etc.
- Can **feedback control** with the available actuators be used to **improve response** and achieve desired conditions?

The need for high-fidelity control simulations

- Control design typically relies on **reduced modeling** to make the design problem easier

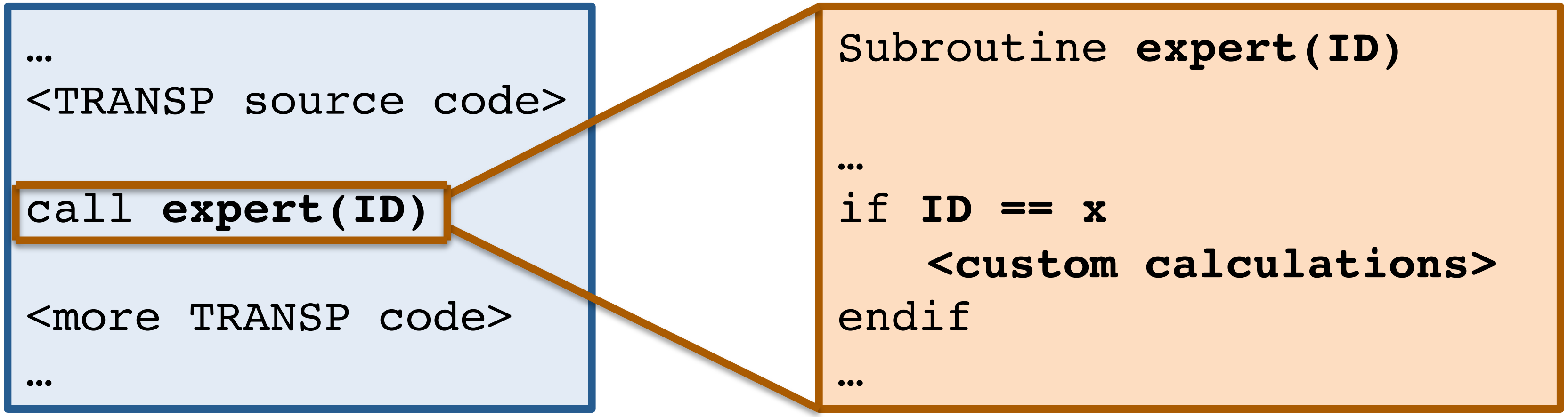


- When tested experimentally, the **nonlinearities** and **coupling** of the actual system **may degrade performance**
  - Dedicated experimental time needed for commissioning
- Testing controllers using the integrated modeling code **TRANSP** prior to implementation may:
  - Improve controller performance and **reduce time for commissioning and fine tuning**
  - Enable demonstration of **new control techniques** to justify implementation and experimental time

Approach to predictive TRANSP simulations of NSTX-U

- The computational approach used in this work has evolved from NSTX-U steady-state **scenario development studies**
  - **S. Gerhardt (*Nuclear Fusion* 2012)**
  - T_i profile predicted from Chang-Hinton model
  - MHD equilibrium calculated using **free boundary code ISOLVER**
    - ISOLVER determines coil currents that best fit the reference plasma boundary
    - Circuit equations are solved to determine induced vessel currents
    - Magnetic diffusion equation is evolved using the inductive coupling between the plasma and coils/vessel as boundary condition
  - Beam heating and current drive profiles calculated using **NUBEAM** with beam shielding calculated by Lin-Liu and Hinton model
  - Sauter model used for bootstrap current
  - Z_{eff} prescribed, used to calculate n_i assuming carbon as the only impurity

The ‘Expert file’ enables custom run-specific code to be included in a TRANSP run



```
…
<TRANSP source code>

call expert(ID)

<more TRANSP code>
…
```

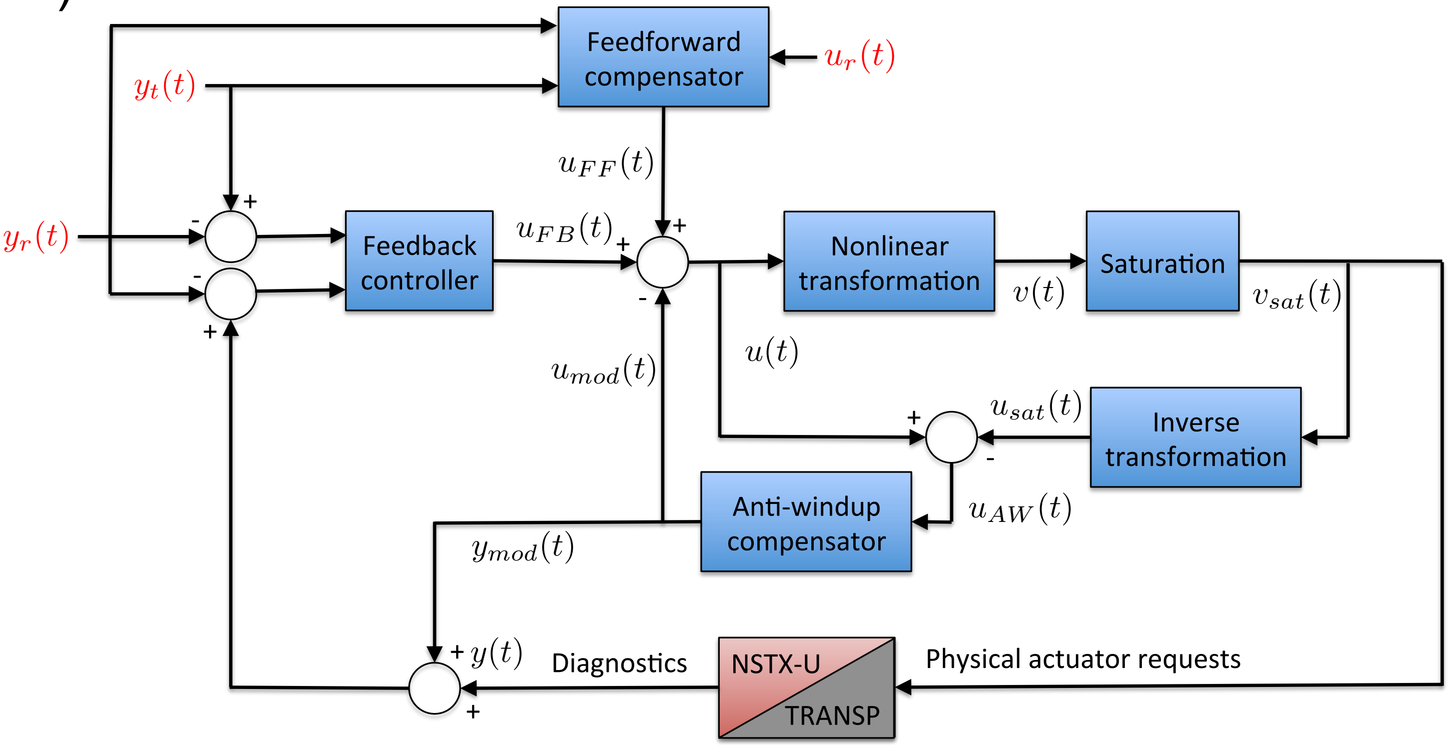
```
Subroutine expert(ID)


…
if ID == x
    <custom calculations>
endif
…
```

- Expert file modules have been developed for control simulations
  - Temperature and density profile scaling
    - Uses TRANSP calculated **power balance** and a **confinement scaling** law to evolve the stored energy
    - Evolves density to match **prescribed Greenwald fraction, line-averaged density, total particle inventory, etc.**
  - Control algorithm implementation
    - **Mimics PCS** implementation, enables ‘real-time’ actuator changes
    - User includes controller matrices and target trajectories with run

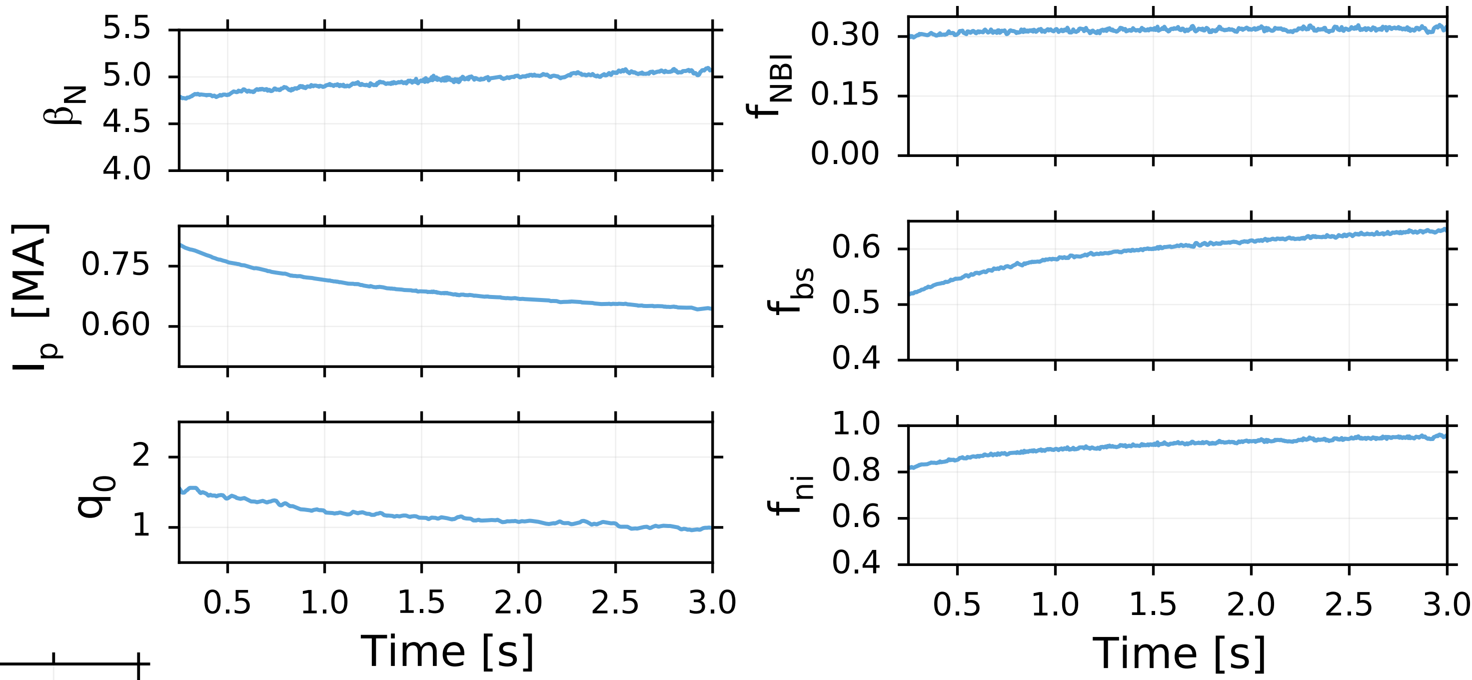
Control of stored energy, q_0, and I_p

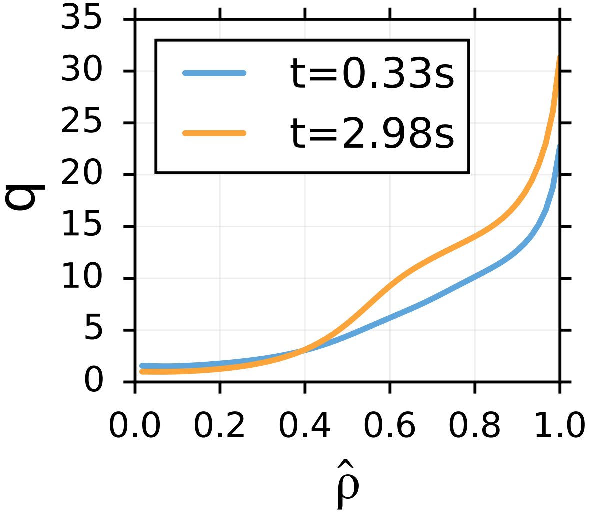
- Flexible algorithm for individually or simultaneously controlling scalar and profile parameters is planned for implementation on NSTX-U
    - Implemented in TRANSP Expert file for testing
- Multiple actuators available
    - Six beam sources, outer gap size considered in this work
- Two algorithms: PID formulation and state-space formulation (PID used in this work)



Open loop reference TRANSP simulation with fixed solenoid current

- **NB sources**: 1B, 1C, 2A, and 2B
- **Outer gap**: 14cm
- Broad **n_e, T_e profiles** from NSTX 142301
- **Particle inventory** held fixed during simulation



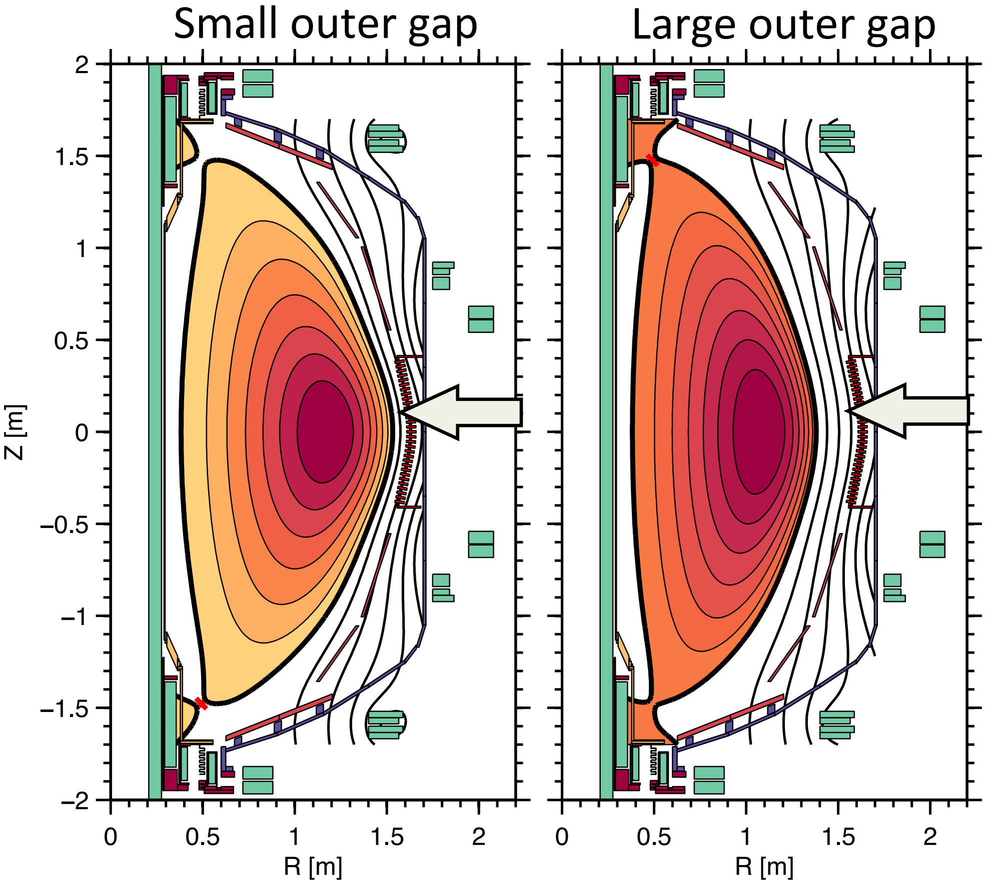


- Slow evolution to 100% non-inductive
  - How do perturbations in density, confinement, and profile shapes affect the response?
  - Can feedback control speed up response?

Mid-plane outer gap size as actuator for q_0

- Most approaches to current profile control **assume the plasma boundary to be held fixed** by a shape controller
- Boundary can have strong effect on q profile through
  - Effect on **beam deposition** profile
  - Effect on **bootstrap current** through change in elongation
- Two **reference boundaries** with different outer gap sizes were chosen, and **interpolated between** based on the feedback controller request

Reference plasma boundaries:

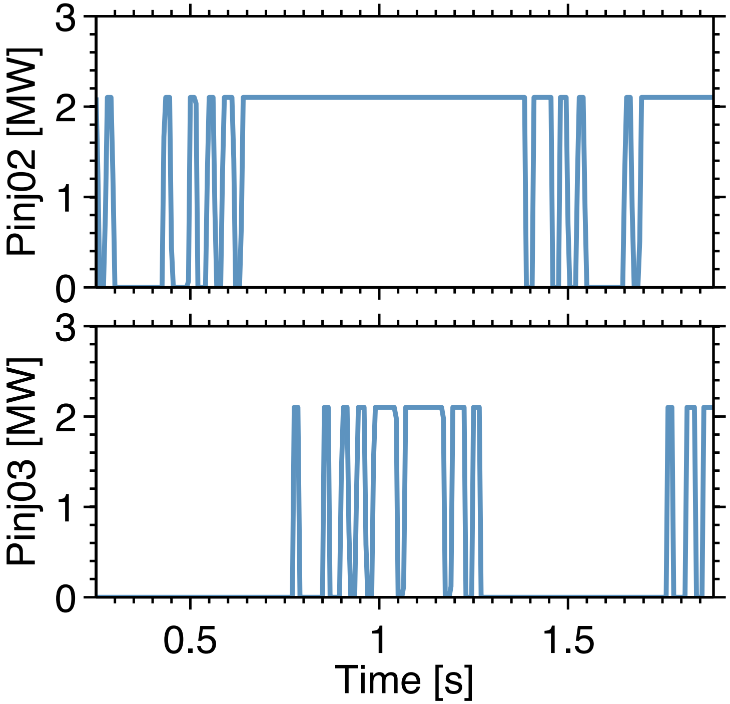


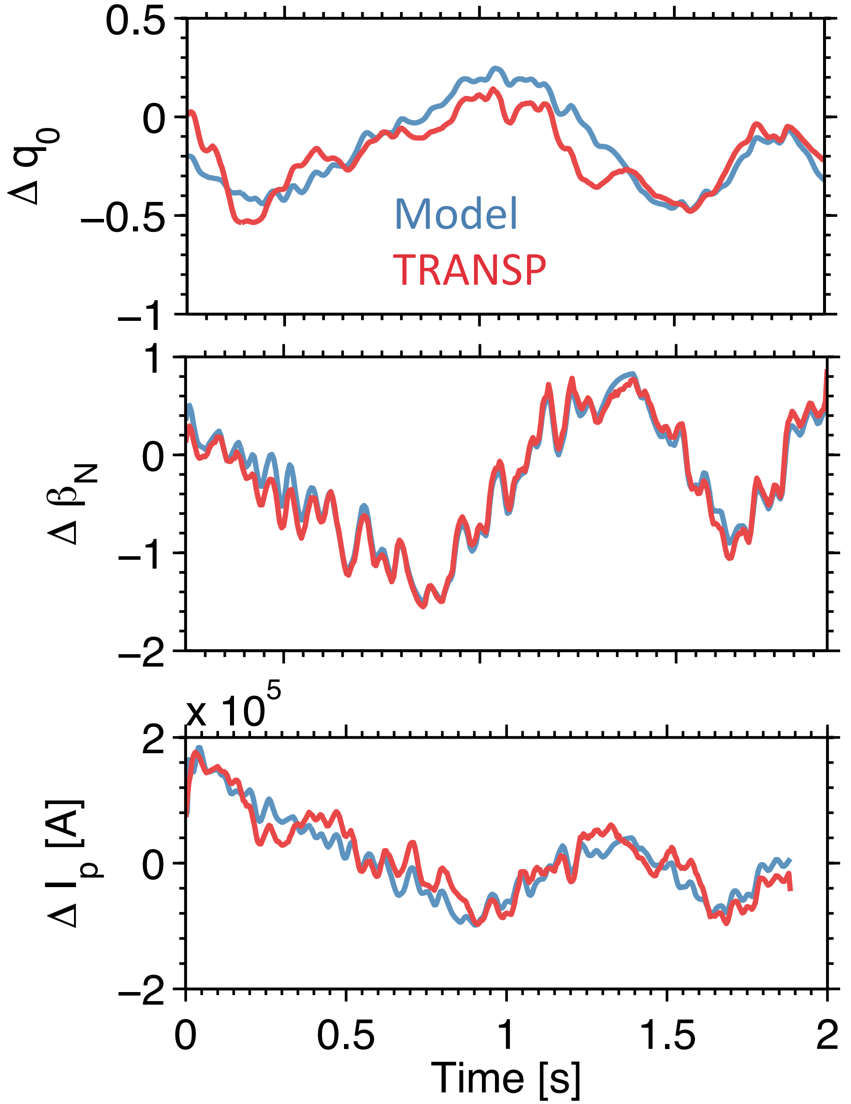
Feedback control approach

- Study ability to control $q_{0,}$ $\beta_{N,}$ I_p, or combinations of these outputs by varying beam sources and outer gap
  - Look at effect on other parameters
  - Assess difficulties and limitations
  - Guide next step design
- Initially use simple PI (proportional-integral) controllers
- Simplified model identified from TRANSP runs
  - Used for initial studies, controller tuning
  - Can be used for model-based control design
- Resulting PI control laws tested in feedback TRANSP simulations

Dynamic system ID based on modulation of beams and outer gap in TRANSP

- Open loop signals applied to each actuator
- Prediction-error method used to determine optimal model parameters for a chosen model order using part of data set (estimation set)
- Remainder of data (validation set) used to determine best model order (number of states)





Discussion and future work

- Dynamics of non-inductively sustained NSTX-U plasmas (with inductive start-up/ramp-up) may be slow and sensitive to perturbations
  - Changes in density may cause $q_0<1$ or slower response
  - Profile peaking and confinement degradation may significantly reduce achieved plasma current
- Matlab and TRANSP simulations indicate feedback control using beams and outer gap can be used to reject perturbations, and speed up response
- Strong coupling may make multi-variable control necessary
  - Specific attention to avoiding stability limits may be necessary
- Beam modulation may cause significant oscillations in $\beta_{N,}$ smaller modulations in current
  - Methods to minimize modulations will be studied

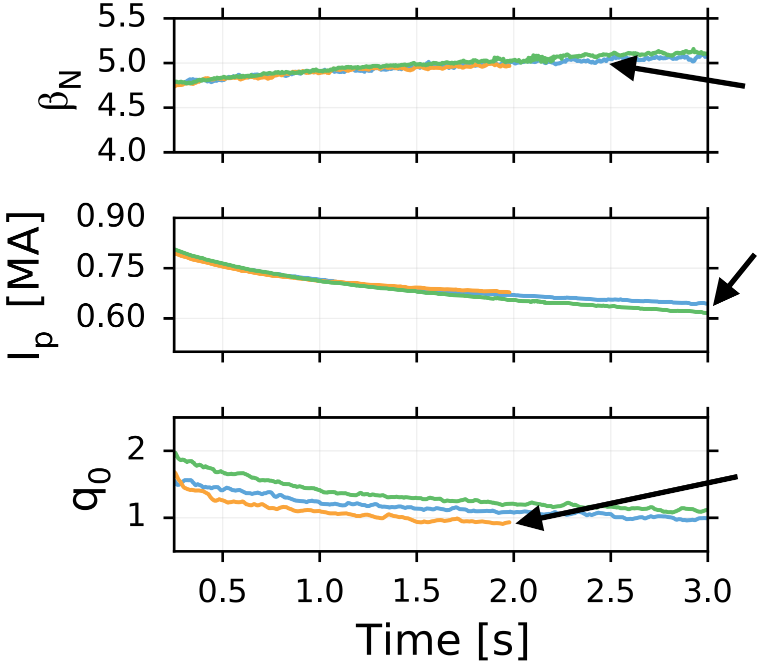
Effect of perturbations on non-inductive plasma dynamics without feedback control

- Case 1A/B: Density perturbation
  - 10% increase (A) and decrease (B) in density magnitude, fixed profile shapes

- Case 2: Confinement degradation
  - 10% decrease in confinement factor

- Case 3: Altered profile shapes
  - Broad reference profiles replaced with peaked profiles

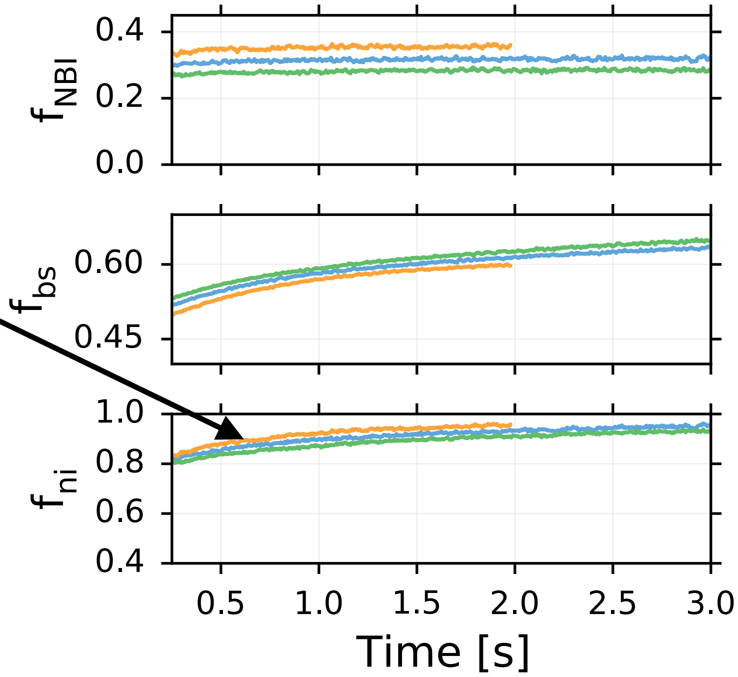
Case 1A/B: Density perturbations with fixed profile shapes

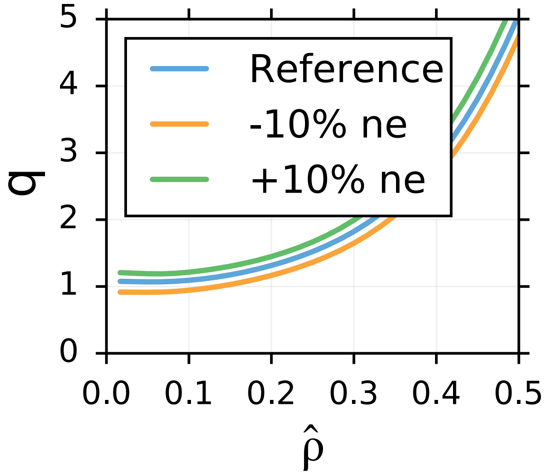


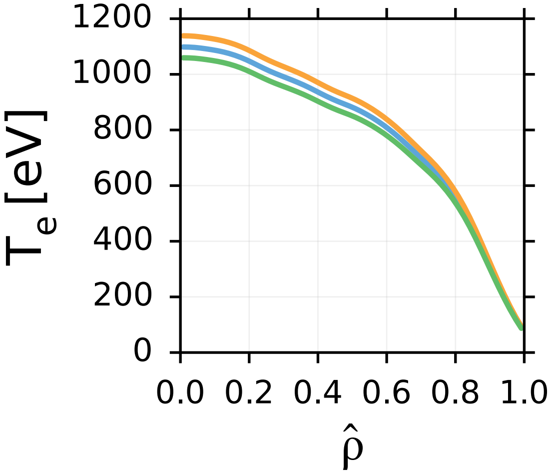
Small effect on β_N

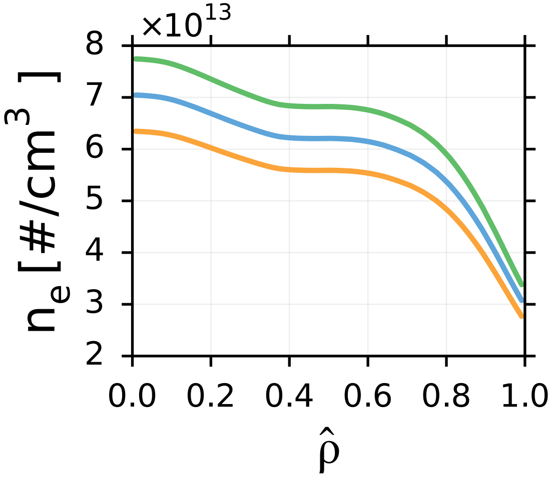
Current/f_{NI} inversely proportional to n_e

q_0 drops below 1 much sooner at lower density



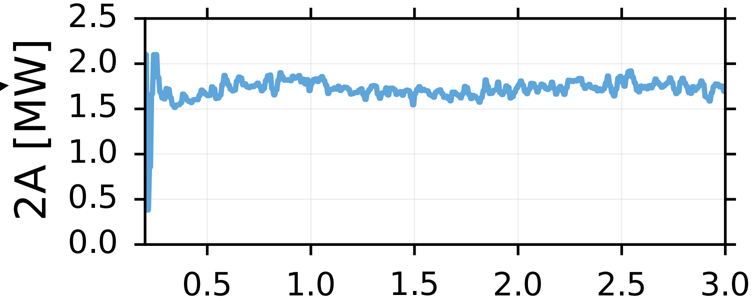


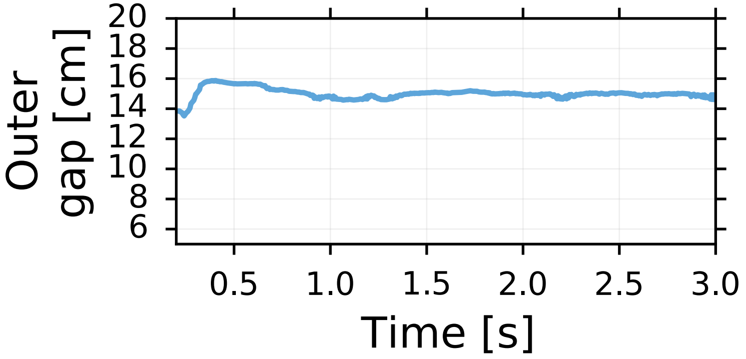


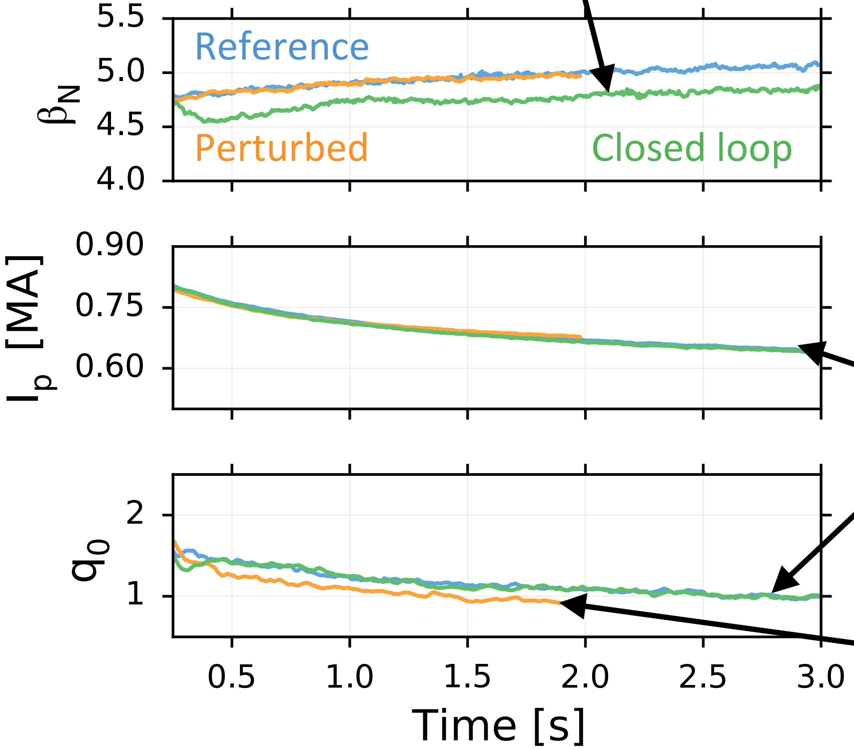


q_0 and I_p feedback control using outer gap and beam line 2 during Case 1A

- Slight adjustment to outer gap and a decrease in beam line 2 power
- Drop in heating power leads to reduction in β_N

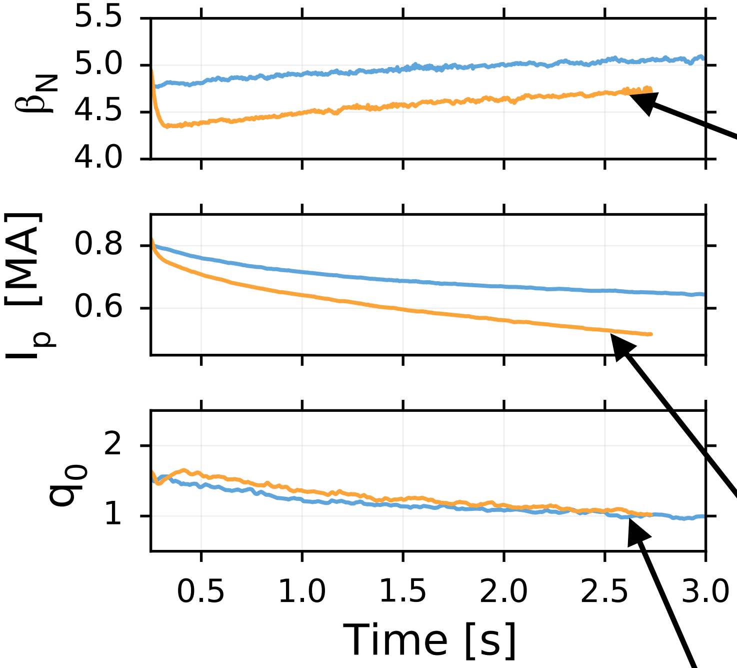






- Matches I_p and q_0 evolution from reference case
- Feedback control maintains desired I_p, q_0>1 much longer than open loop case

Case 2: Effect of energy confinement perturbation

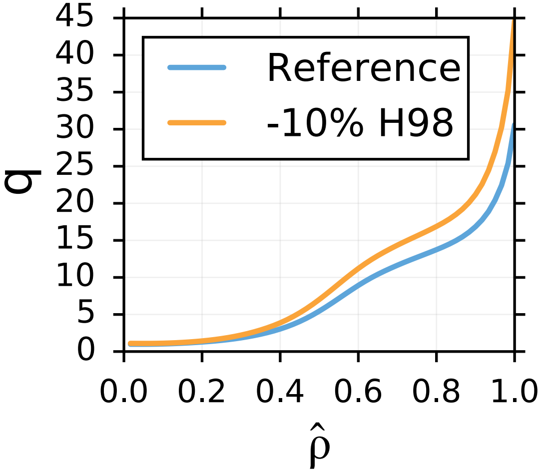


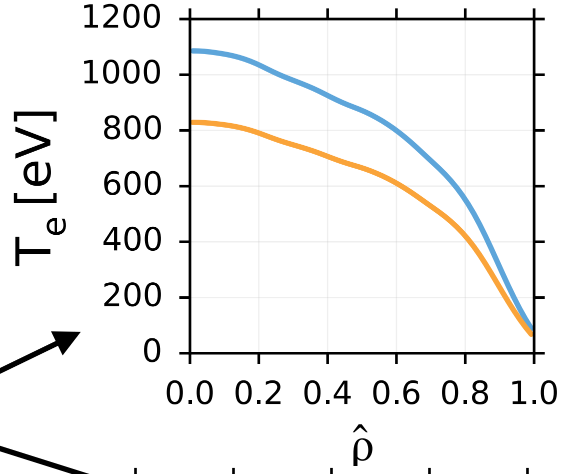
Large drop in $\beta_{N,}$ much decreased bootstrap current

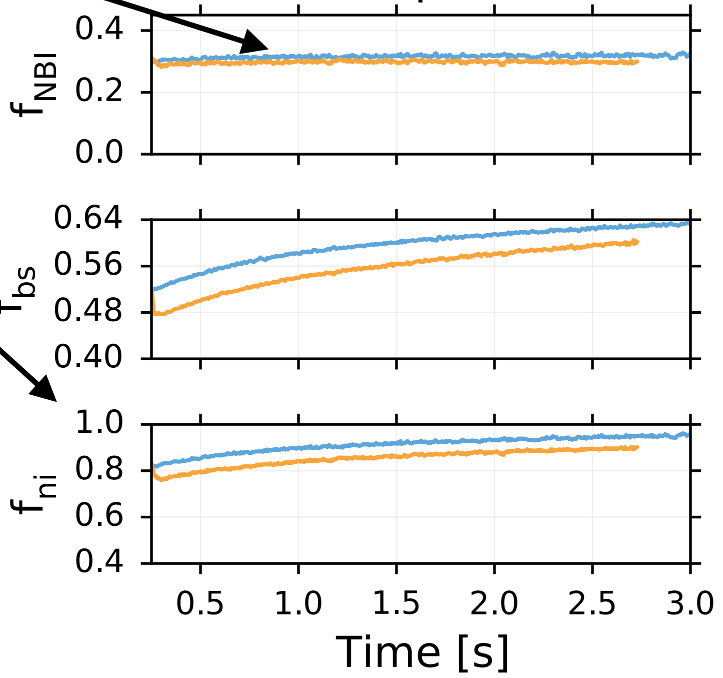
Decreased temperature leads to decreased NBCD

Drop in current/f_{NI} and decreased speed of response

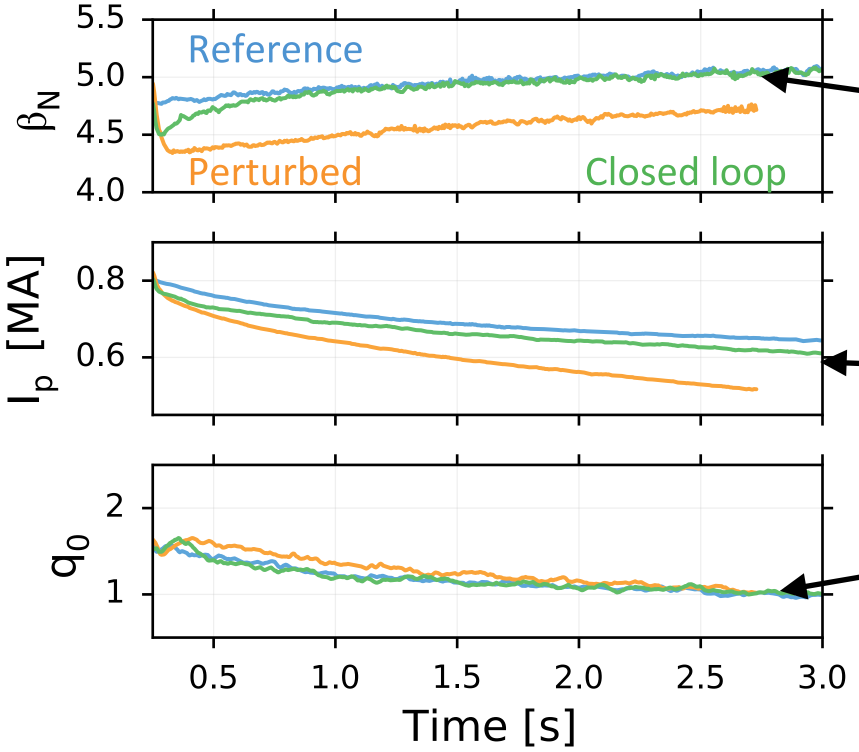
q_0 evolution similar to reference but edge q increased with lower current



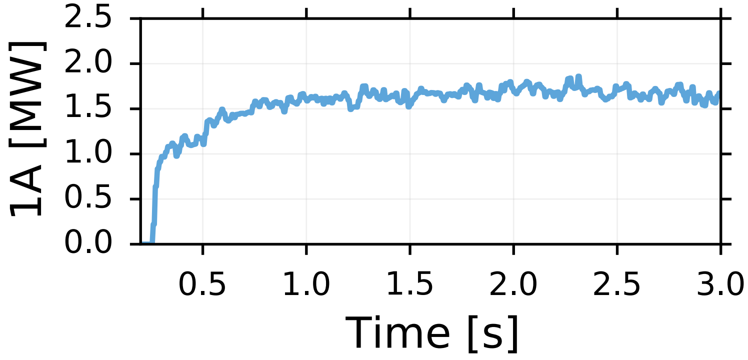


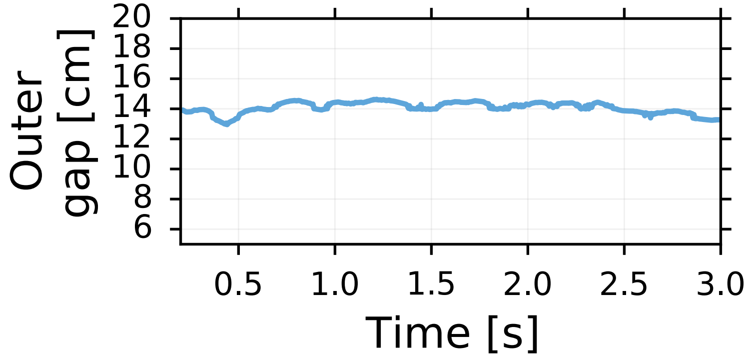


β_N and q_0 feedback using beam line 1 and outer gap control in Case 2

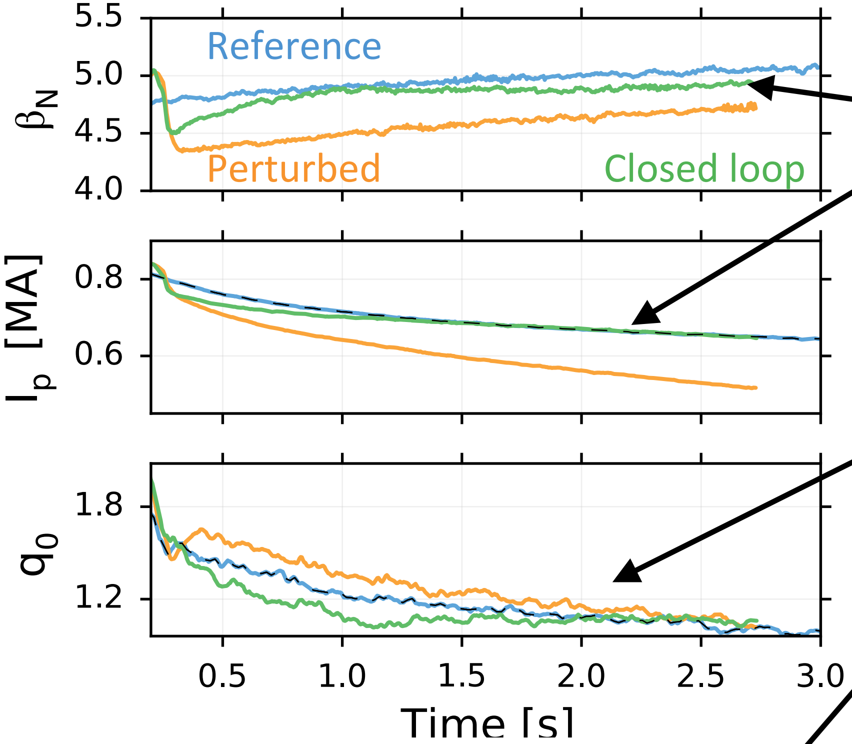


- Beam line 1 power increased to track reference β_N
- Increasing beam power and β_N leads to increased current
  - Reference current nearly recovered despite no feedback control on current
- Outer gap adjusted to maintain q_0

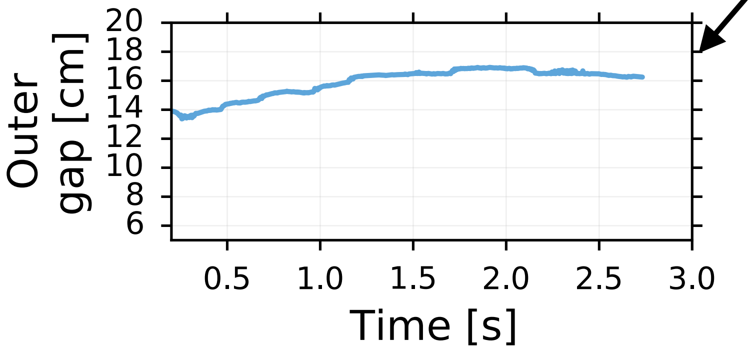


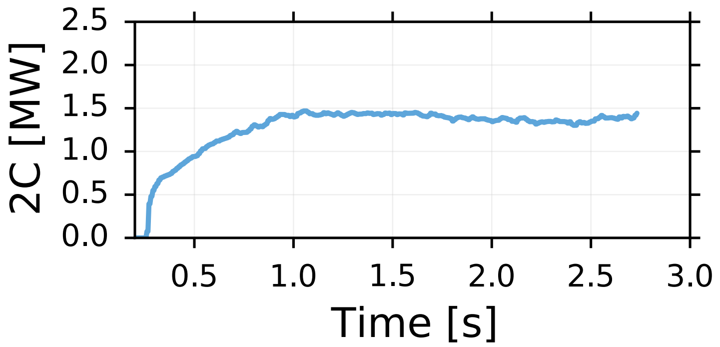


I_p and q_0 control during Case 2 using beam line 2 and gap actuation

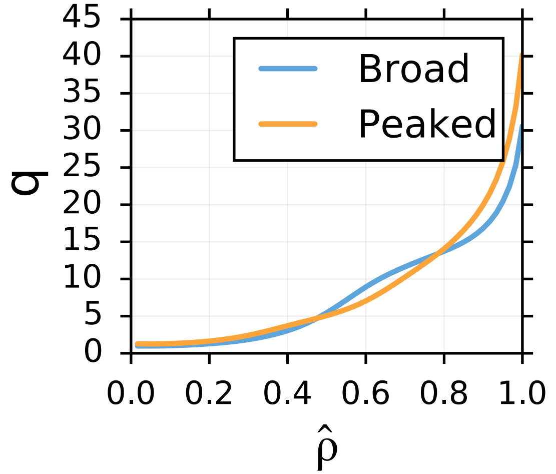


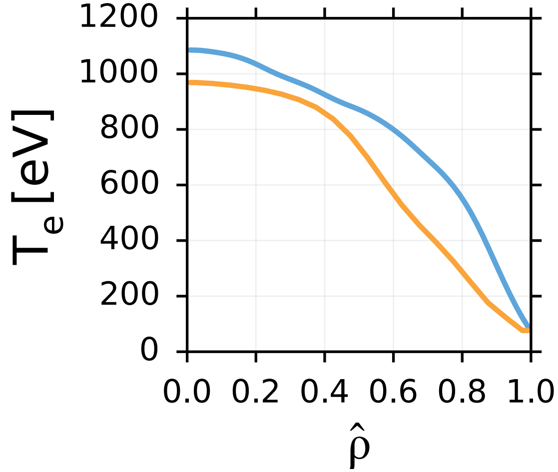
- Beam line 2 power increased to track plasma current
  - Results in β_N recovery
- Increased current drops q_0, Outer gap increased to to get back to reference value
  - May need to increase controller gain to avoid q_0<1

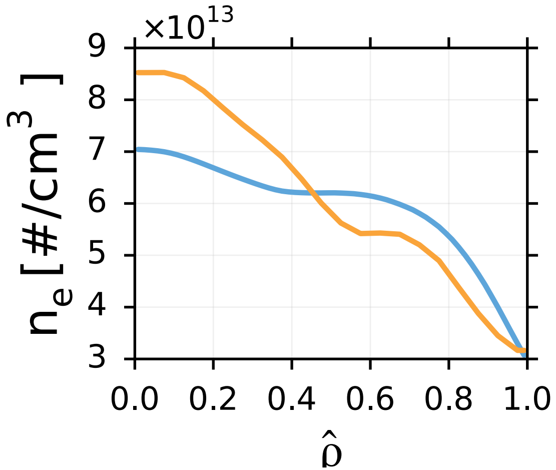


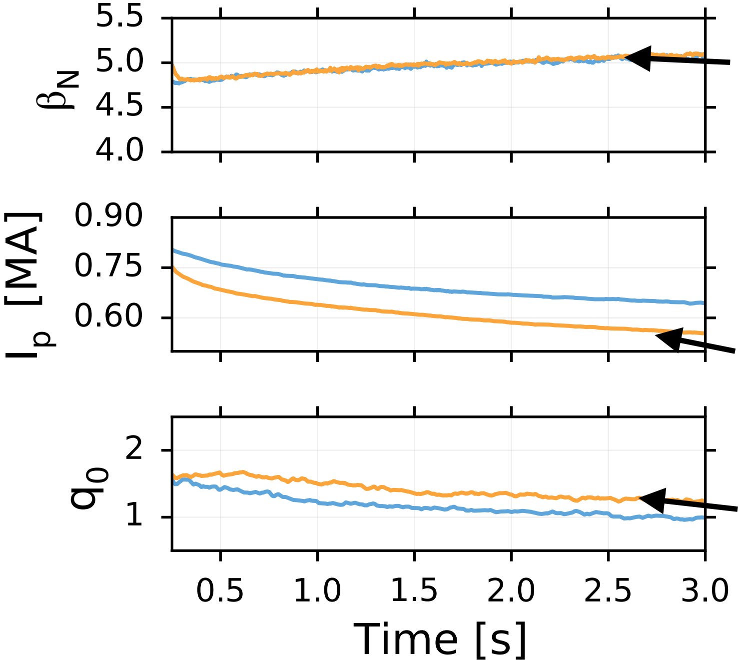


Case 3: Effect of n_e and T_e profile perturbations







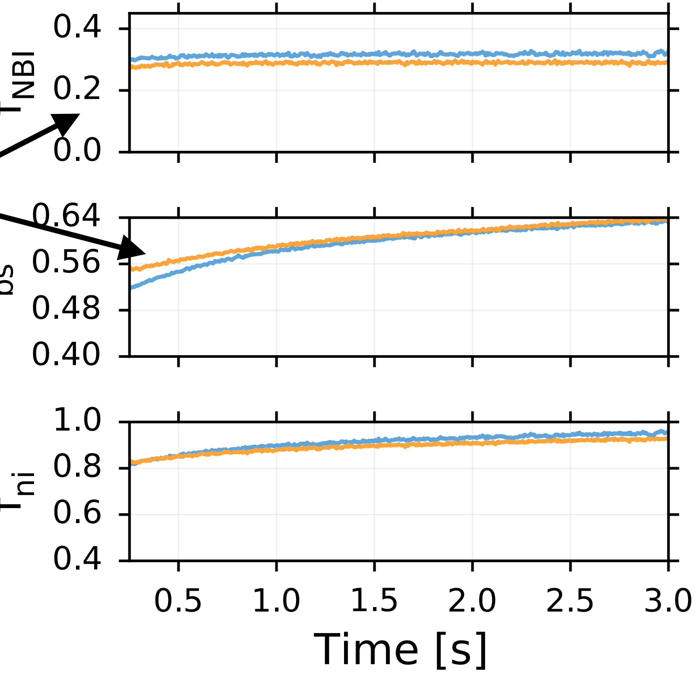


Small effect on β_N

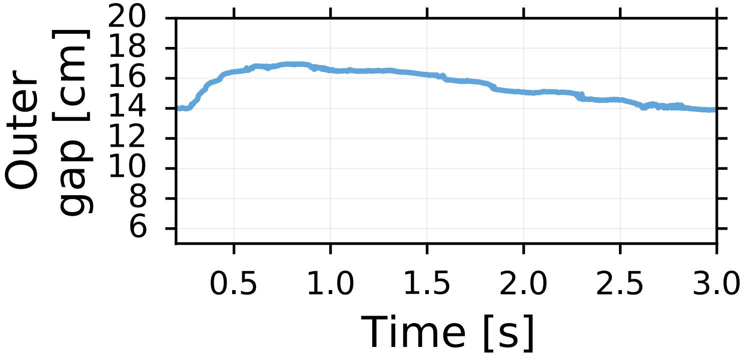
Decreased $f_{NBI,}$ similar f_{bs}

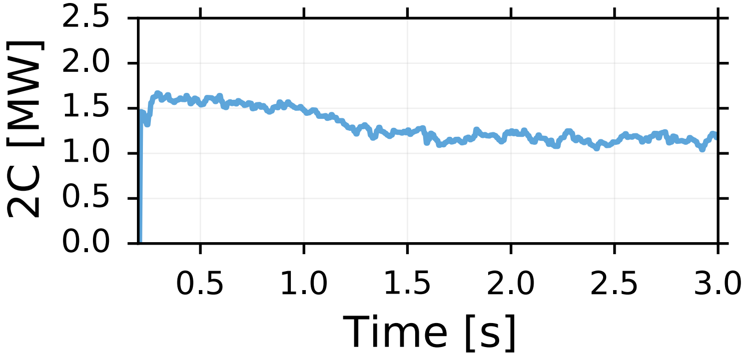
Current decreased by peaked profiles, response slowed

q_0 elevated with peaked profiles

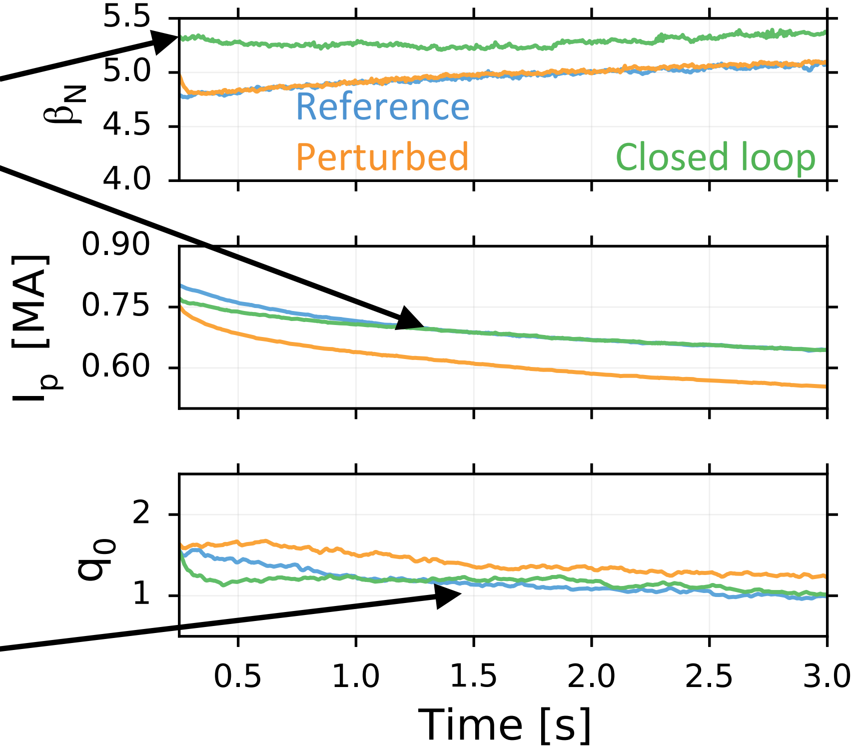


q_0 and I_p feedback control using outer gap and beam line 1 during Case 3

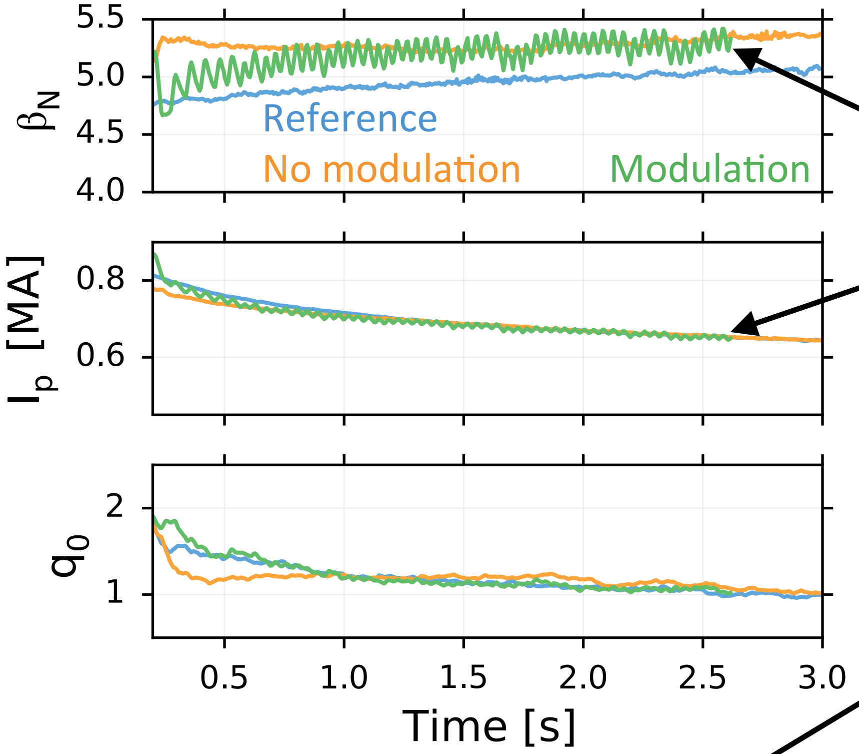




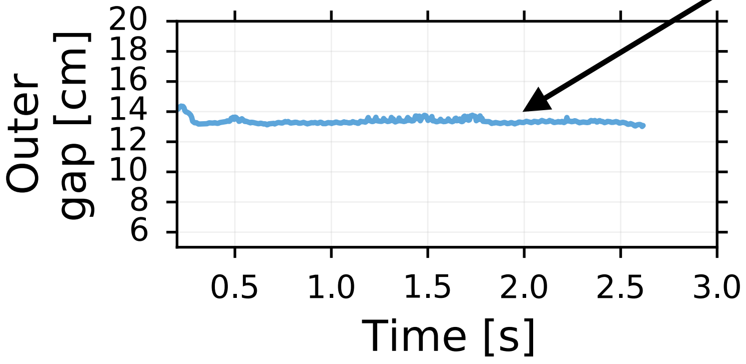
- Increase in beam power increases current to match target
  - This increases β_N as side-effect
- Outer gap adjustment reduces q_0 to match reference value

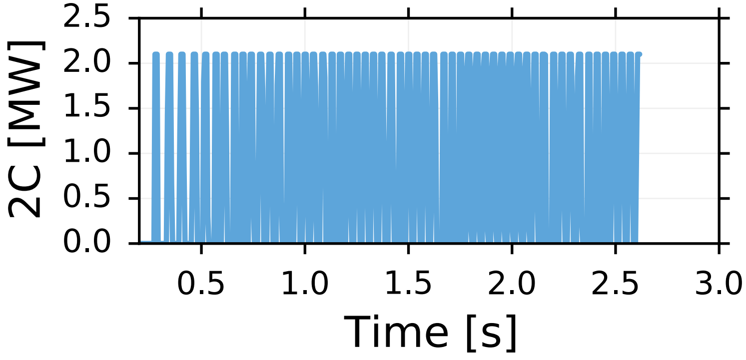


q_0 and I_p control using outer gap and beam line 2 during Case 3 **with beam modulation**



- NSTX-U beams cannot be continuously changed, so modulations will be required in experiments
- Beam modulations cause large oscillations in β_N
- Smaller oscillations in plasma current
- Good tracking, though closed loop dynamics are a bit different with modulation
- Beam modulations cause small oscillations in outer gap request

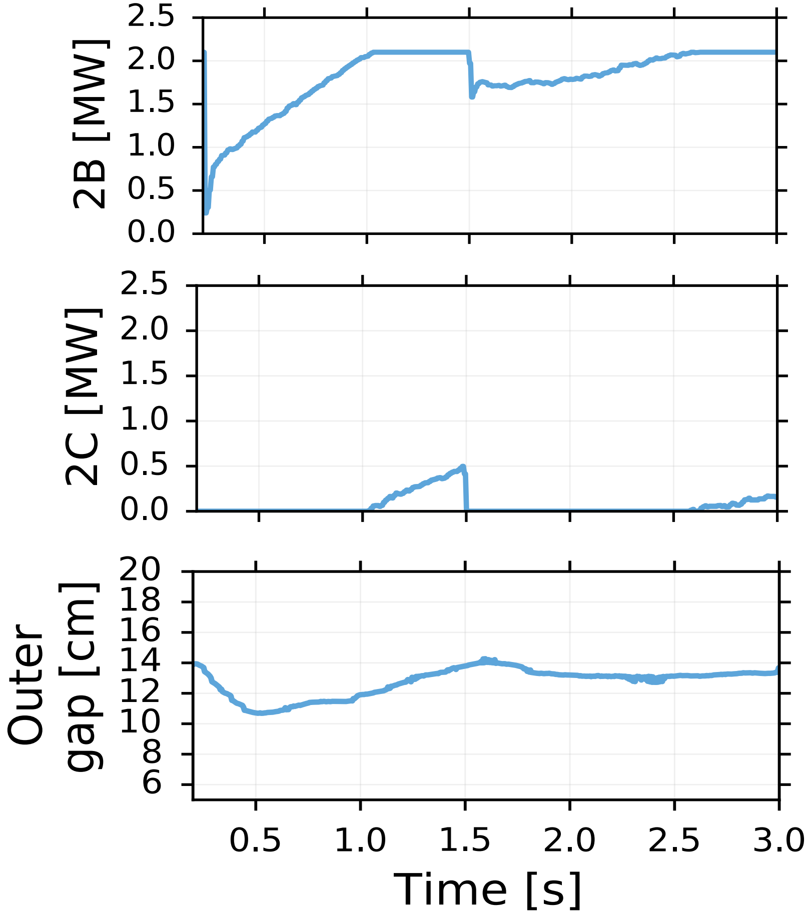


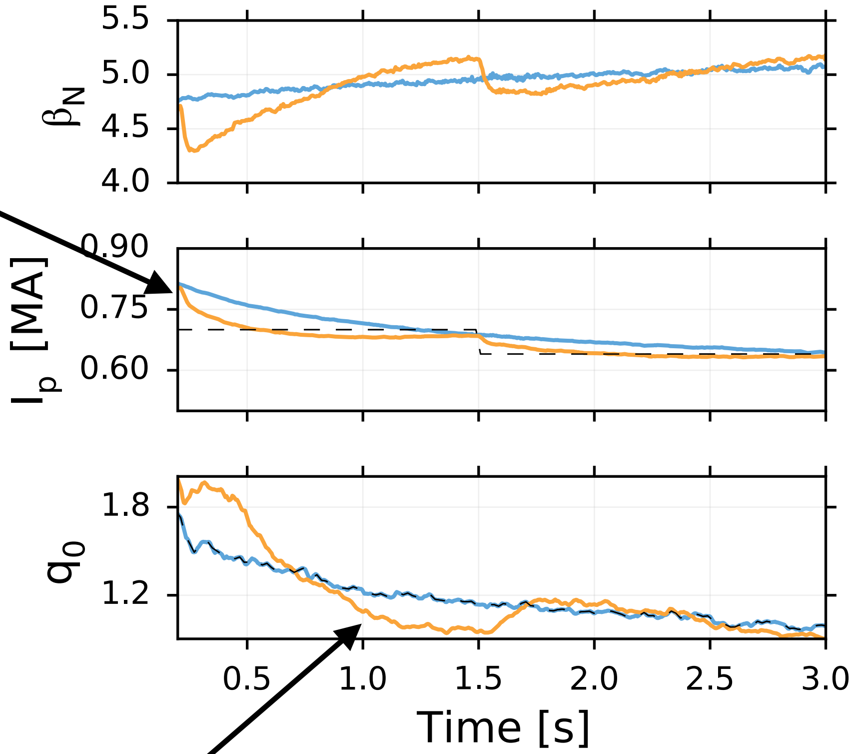


Target tracking

I_p and q_0 control with beam line 2 and outer gap

- Feedback control enables reaching steady current value more quickly

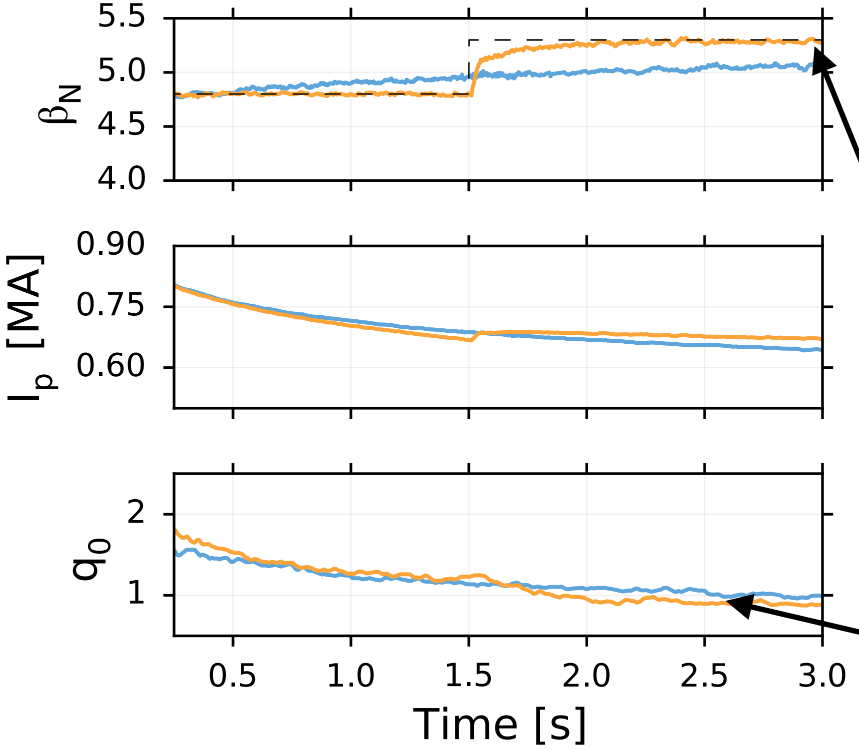




- q_0 control could be improved by increasing gain

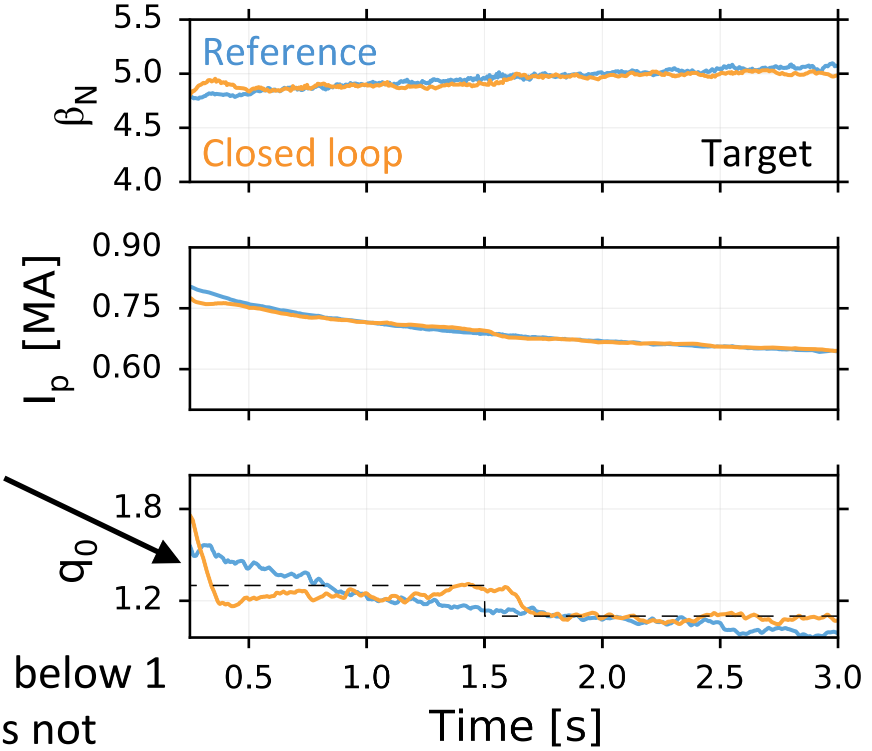
Target tracking

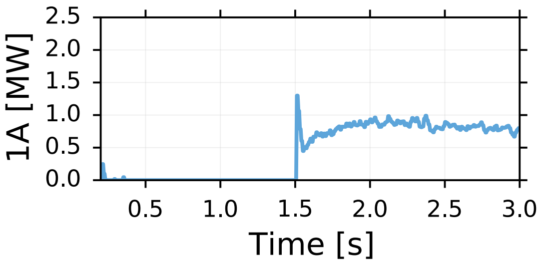
Left: β_N control w/ beam line 1
Right: q_0 control w/ outer gap

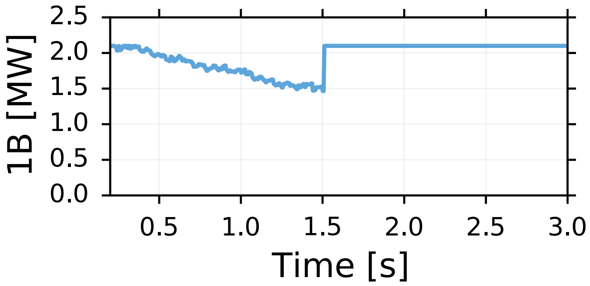


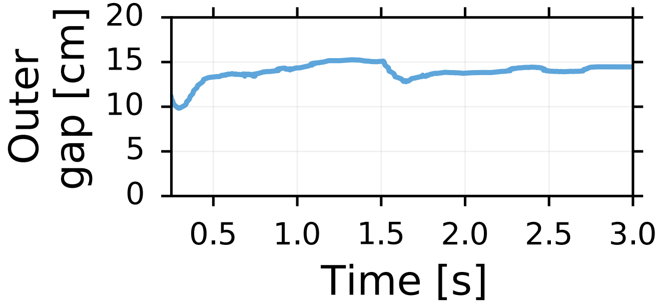
Targets tracked in both cases

q_0 drops below 1 since it is not controlled



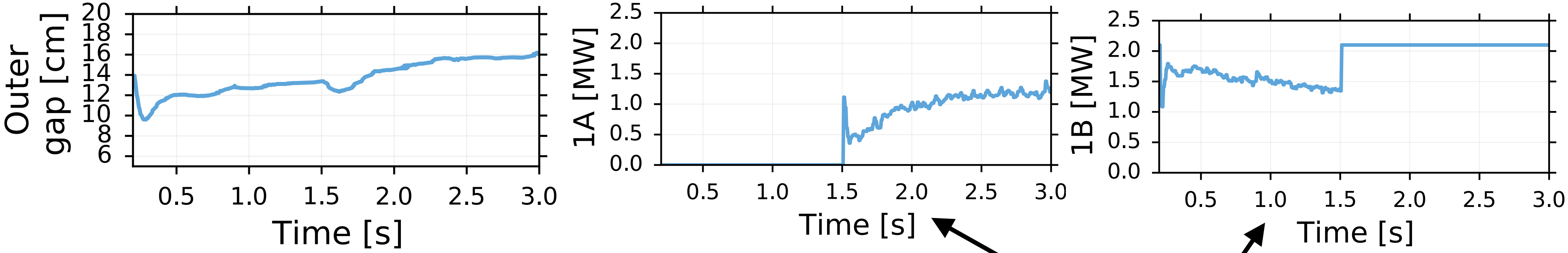


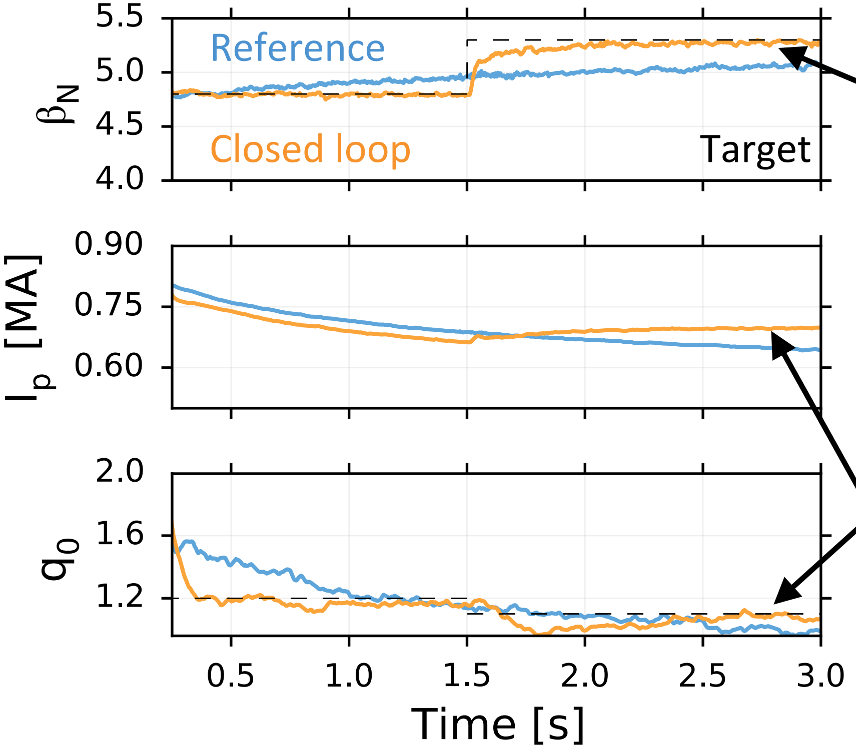




Target tracking

β_N and q_0 control with beam line 1 and outer gap





- Power reduced for first β_N target, increased for second
- Outer gap decreased to speed q_0 response, increased to maintain elevated target
  - q_0 approaches 1 after target change (could adjust target trajectories or control gains)
- Plasma current (not controlled) response varies from reference