Dynamic neutral beam injection as a mechanism for plasma control and an actuator for instability drive

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Overview

- **A novel capability has been added to the DIII-D neutral beam injection system: Simultaneous in-shot variation of beam energy and current**
  - Continuous variation of power and torque
  - Optimization of current drive, heating,
  - Control of Alfvén eigenmode activity
- **Additional flexibility is an opportunity to expand feedback control capabilities for scenario development and optimization**
  - However, these new actuators have constraints that present challenges for control design
- **First feedback algorithm to use the new actuators has been developed and experimentally tested**
  - Control of stored energy and rotation
  - Control design addresses the challenges of the new actuators

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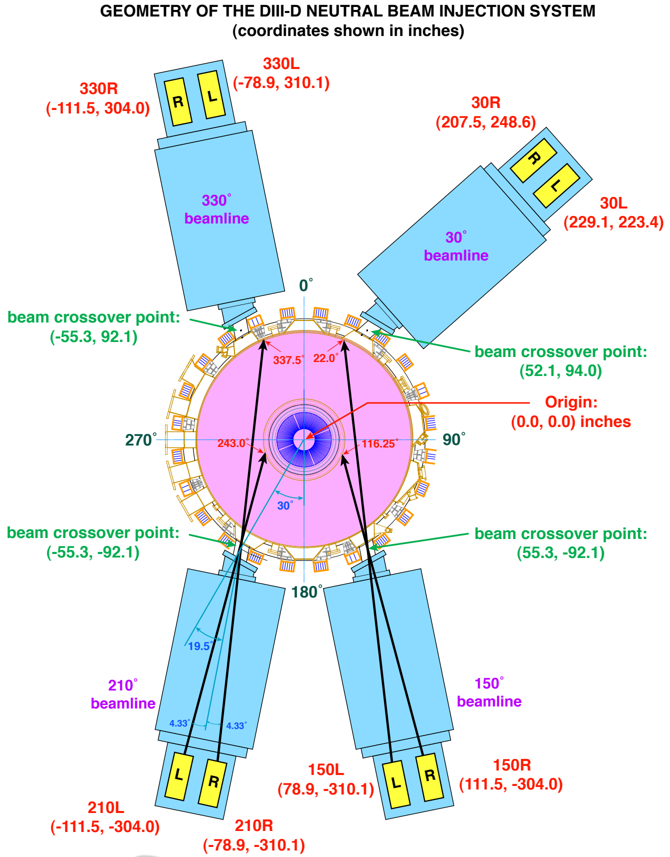
Neutral beam system provides flexibility in injection geometry and, now, current/voltage characteristics

Geometry of neutral beam system and cross section of beam injector:

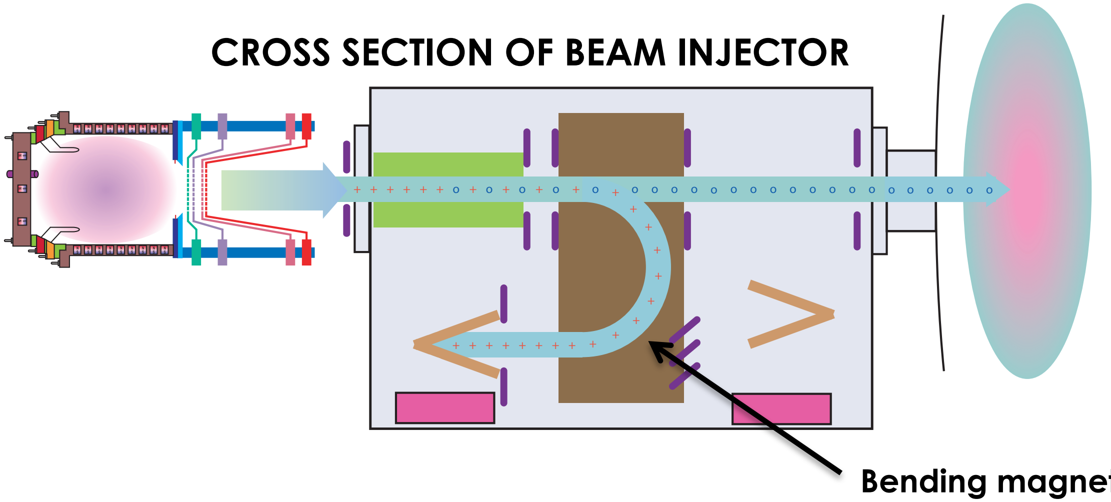
8 beams, 20MW injected
2 beams in opposite toroidal direction, i.e., counter current
7 beams have variable beam energy and perveance (VBE/VBP) capability



Perveance relates beam current and accel voltage, determines divergence of beam

$$\text{perveance} = \frac{I_{beam}}{V_{beam}^{3/2}}$$

CROSS SECTION OF BEAM INJECTOR



J. Rauch, et al., *Fus. Sci. Tech.* **72**, 500 (2017)
C.J. Pawley, et al., *Fus. Eng. Des.* **123**, 453 (2017)

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Capabilities and limitations of in-shot variation of beam energy and perveance on DIII-D

Capabilities of VBE/VBP

- **Vary V_{beam}** at constant perveance
- Vary arc density to **stay at optimum perveance**
    - Minimum beam divergence
    - **Maximum reliability**
- Vary I_{beam} at fixed V_{beam}
- Scan beam divergence
- **Decouple beam power and energy**

Limitations on VBE/VBP

- **Beam voltage** cannot be changed rapidly or too far
    - Range limited to **+/-10kV**
    - Slew rates exceeding **30-40kV/s** can cause trips
    - Voltage response has a **significant lag (50-100ms)**
- **Perveance** must remain near optimal
    - Deviating can cause arcing, blocks, eventual trips
    - **+/-15% can be done, +/-10% more reliable**

J. Rauch, et al., *Fus. Sci. Tech.* **72**, 500 (2017)
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First experimental test of feedback control using new VBE/VBP capabilities

- **Stored energy and rotation control**
  - Use PCS to **find optimal combination of voltages and perveances** (and duty cycle if desired) to track a target power and torque
  - Use **feedback on measurements of energy and rotation** to modify power and torque to track targets
  - Combinations that can be controlled:
    - (Power or Energy or β_N) and (Torque or Rotation),

- **Control challenges to be addressed in design**
  - **Many actuators** controlled simultaneously (8 beams x 3 parameters)
  - Each actuator is **constrained within a fairly small range**
  - **Voltages vary slowly** compared to confinement time, other actuators

- **Approach: Constrained optimal control at two time-scales**
  - Fast perveance changes used to compensate for slow voltage changes
  - As voltage changes, perveance can return to optimal

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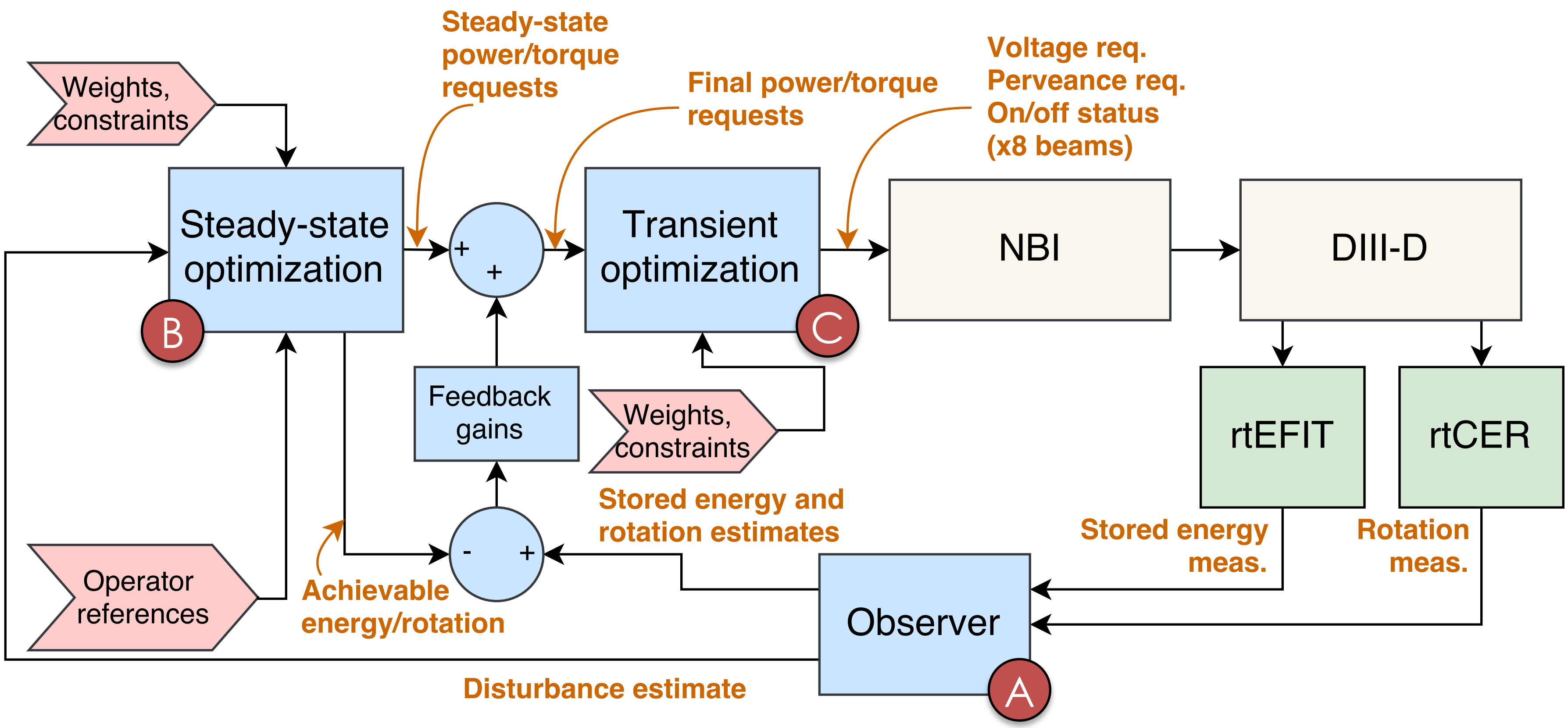
A step toward integrating feedback control of equilibrium profiles and fast ion phase space manipulation

Control algorithm design: constrained optimal control w/ two time scales



A Observer estimates stored energy, rotation, and voltages from noisy measurements + updates estimated model parameters

- 0D model, w/ power/torque calculated from voltage, perveance, and duty cycle of beams
- Observer gains chosen to ensure estimation error is driven to zero while reducing effect of noise
- Additive disturbance estimated in real-time

$$\dot{\hat{W}} = -\frac{\hat{W}}{\tau_E} + P_{inj}(V, k, f_{duty}) - L_W(\hat{W} - W_{meas}) + \hat{d}_W$$

$$\dot{\hat{d}}_W = -k_W(\hat{W} - W_{meas})$$

Benefits of using an observer

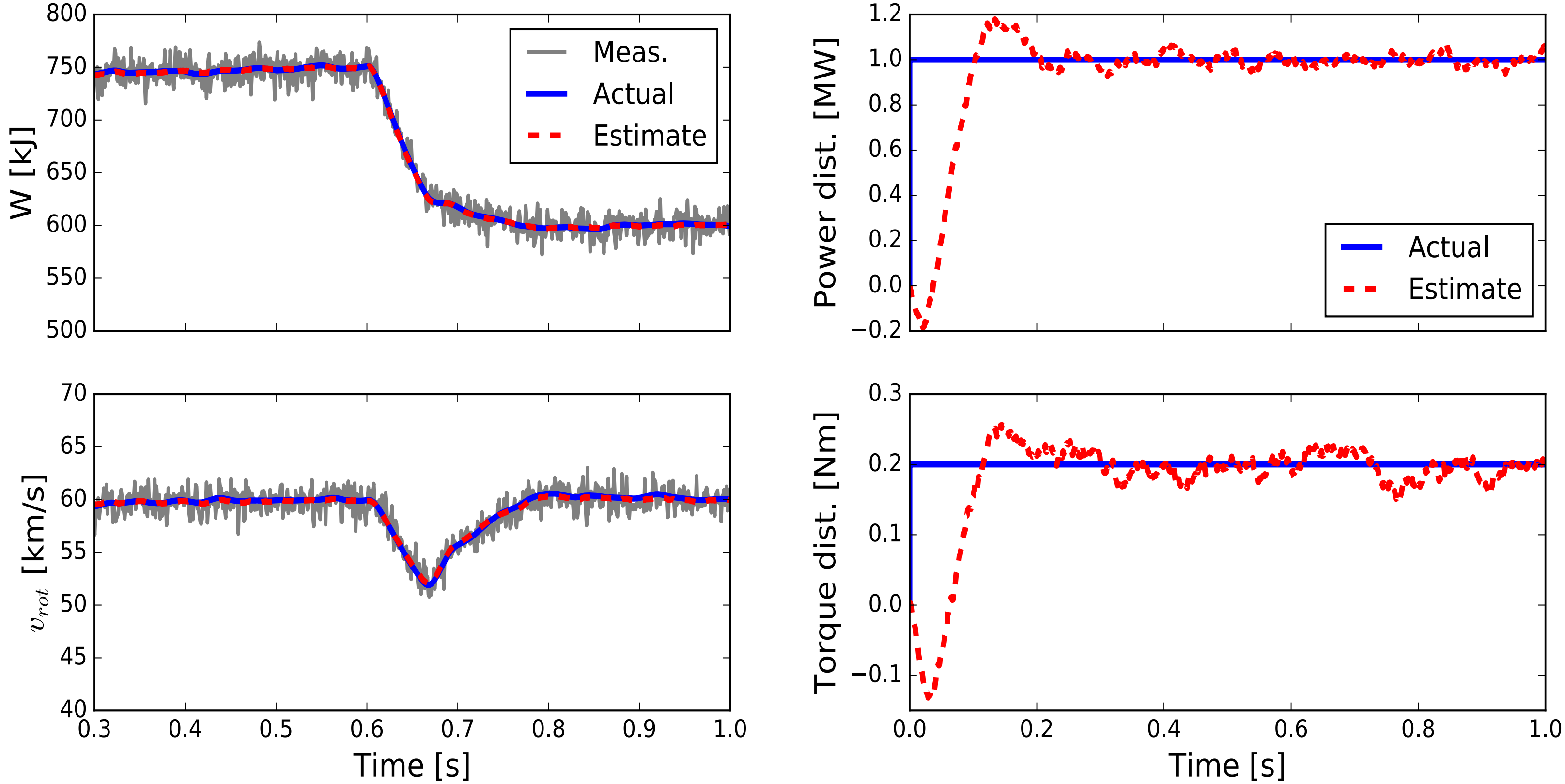
- The observer filters out noise (consistent with model and power/torque changes)
- Estimation of disturbances/parameters avoids need for integral gain in controller, avoids integrator wind-up issues.

A

Observer estimates stored energy, rotation, and voltages from noisy measurements + updates estimated model parameters

Simulation results showing benefits of using an observer

- Left: observer filters noisy measurements
- Right: Observer provides estimate of disturbances.
  - Avoids need for integral gain in controller, avoids integrator wind-up issues.



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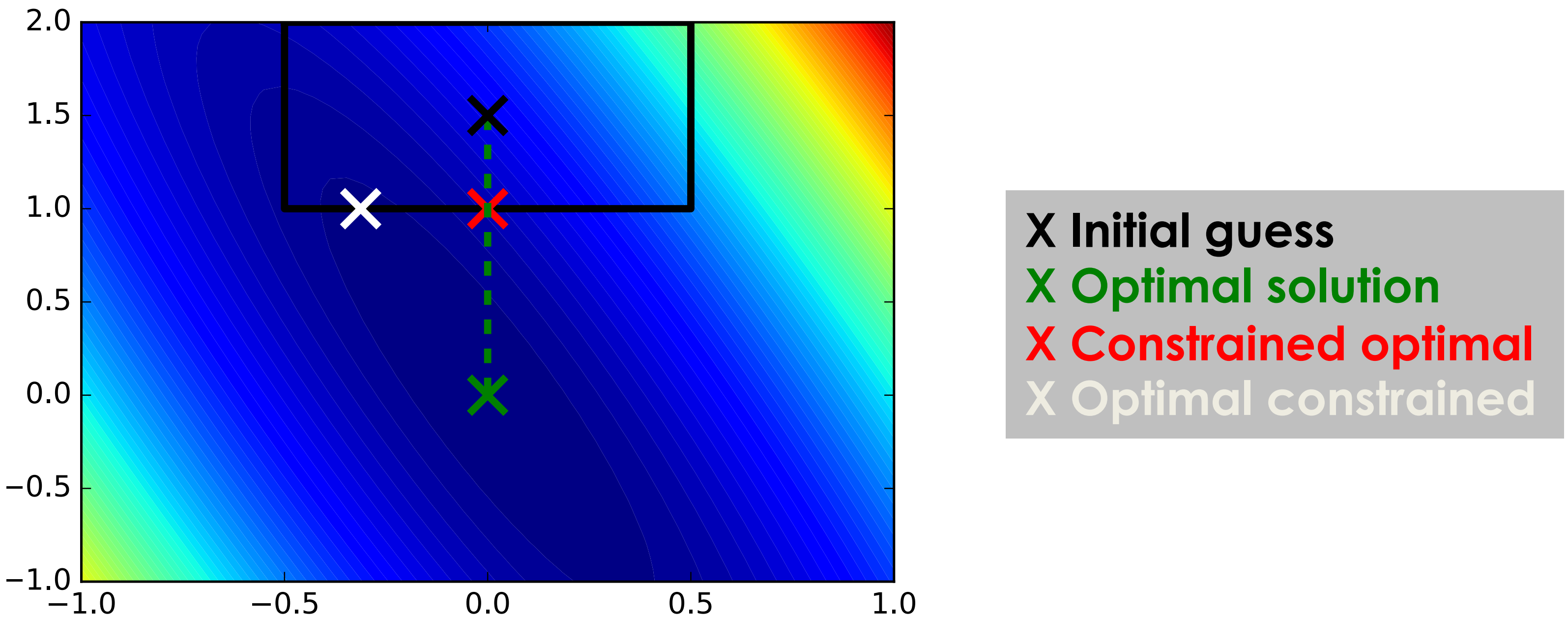
Optimal steady-state actuator requests calculated using constrained optimization algorithm

- **Steady-state linearized response model** generated at each time step
  - Local approximation of rotation, energy, power, and torque as function of voltage, perveance, and duty cycle
  - Includes disturbance estimates
- **Quadratic cost function** defined to weight **tracking error** + use of **actuators**
- Box-constrained optimization algorithm finds optimal actuator requests within allowable ranges

Constrained optimization makes best use of available actuator ranges

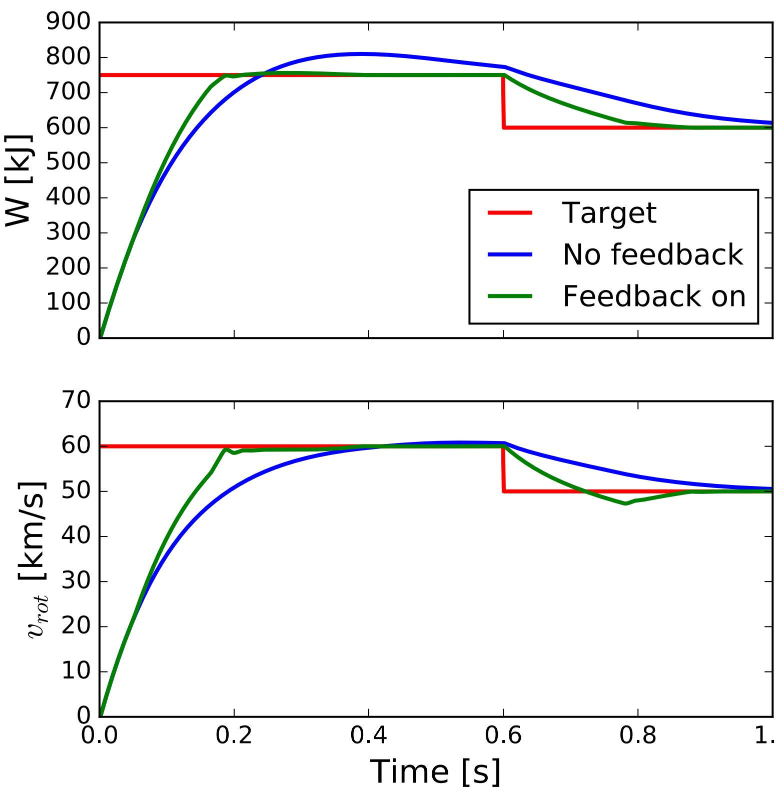
- Optimal constrained solution is different than constraining the optimal solution…

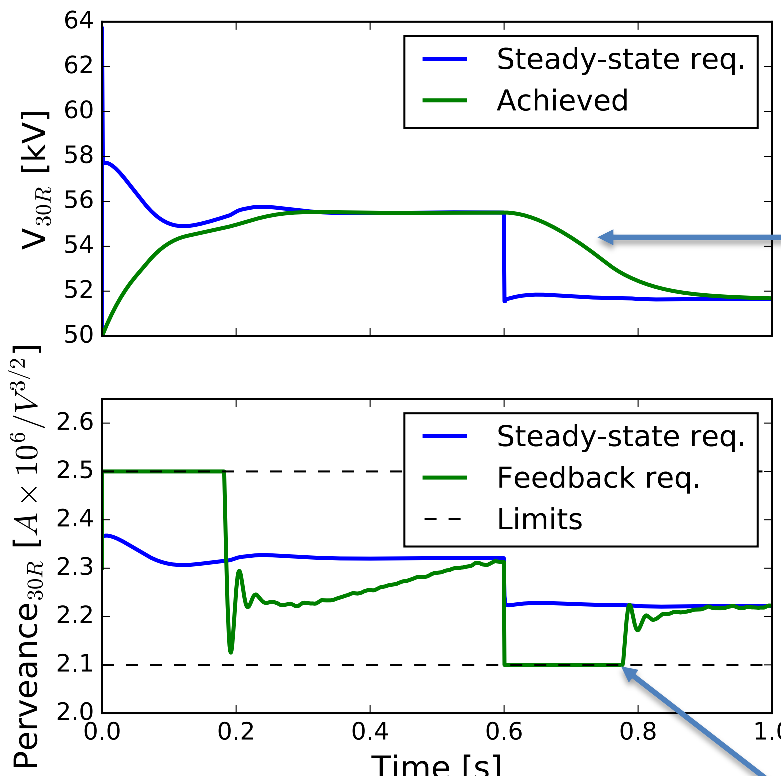


Feedback step alters perveance and/or duty cycle to speed up response, compensate for slow voltage response

Simulations comparing tracking using steady-state requests with and without the addition of feedback

- Steady-state requests alone track targets, but slowly
- Adding feedback speeds up response, compensates for slow voltage response
- Ensures perveance stays in optimal range, but this constraint limits response time



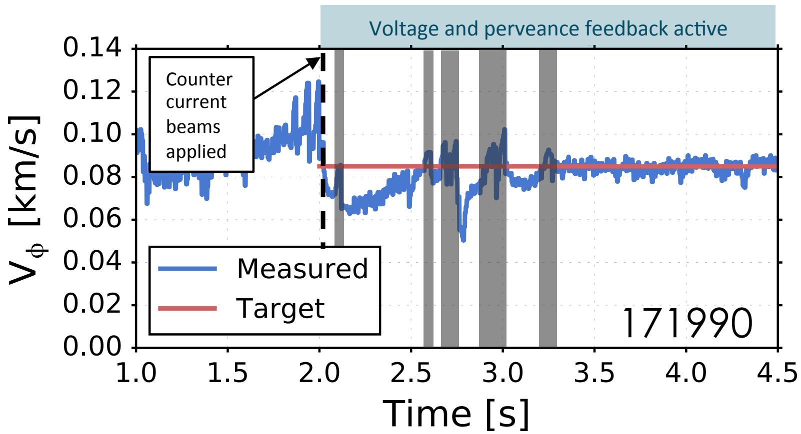


Slow voltage response

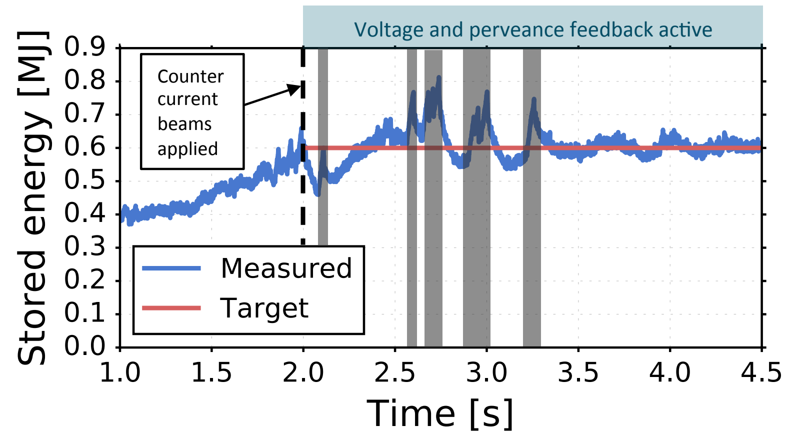
Fast perveance changes compensate for slow voltage response, but are constrained

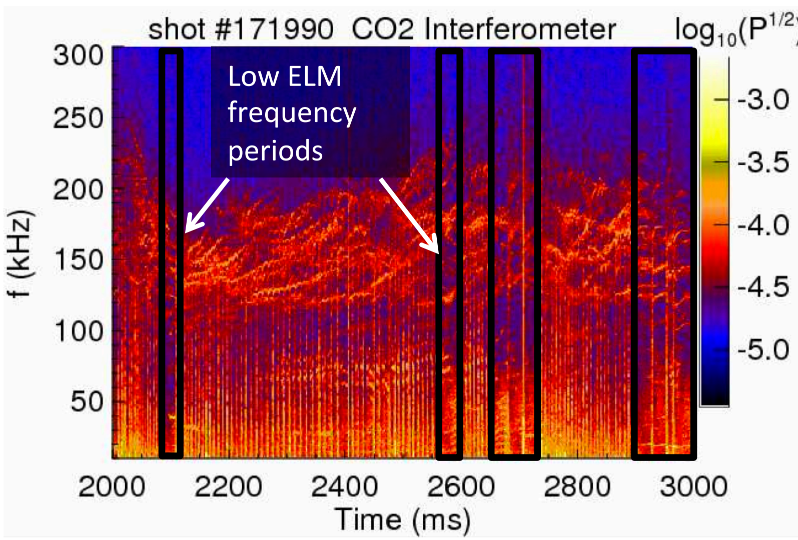
Fast perveance changes enable target tracking despite slow voltage response, however ability to reject fast disturbances was limited in initial experiments

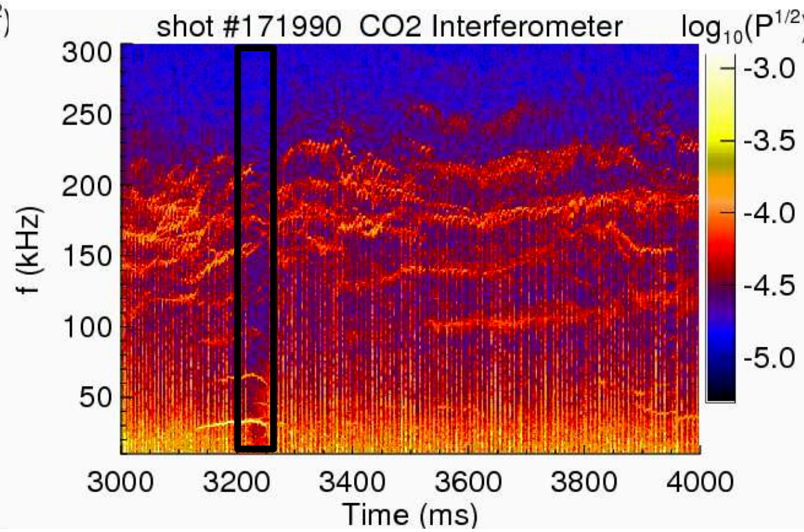
Toroidal rotation velocity



Stored energy







Periods with low ELM frequency were triggered during the shot, each associated with rapid increase in confinement and eventual crashes. Good control was achieved during intervals without these events

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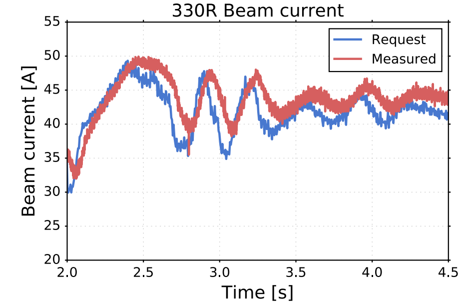
Limitation found to be due to unanticipated lag between beam current commands and achieved values. Simulations show poor performance with lag, improved performance with compensation

Beam current found to lag behind request sent from PCS

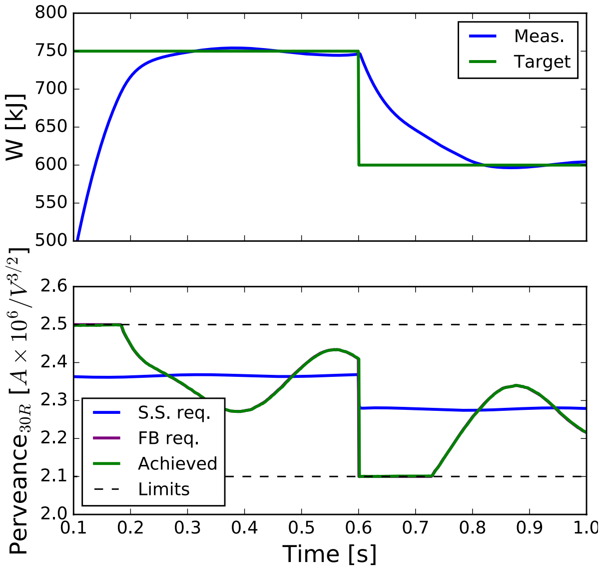
- Achieved power/torque ends up out of phase with estimated disturbance



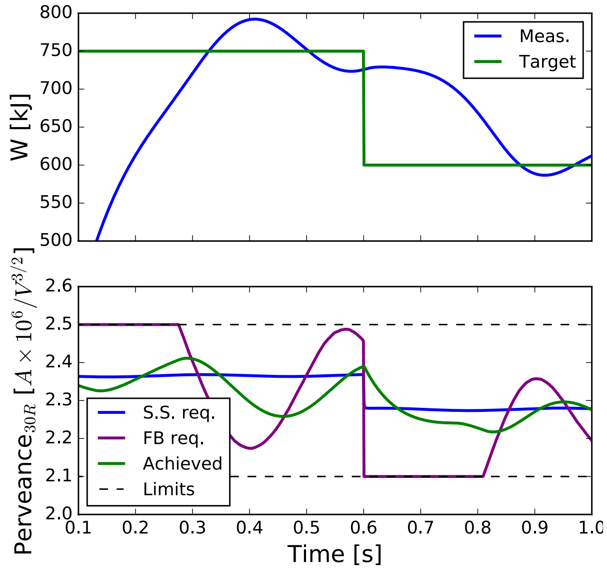
Beam current lag could be compensated to recover performance

- Adjust beam current request through feedback to quickly achieve target perveance
- Simulations with large oscillating disturbances illustrate potential improvement

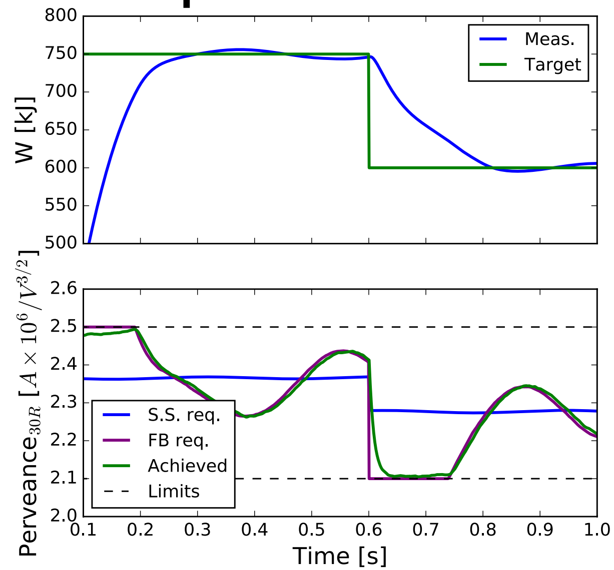
w/ fast current response



w/ slow current response

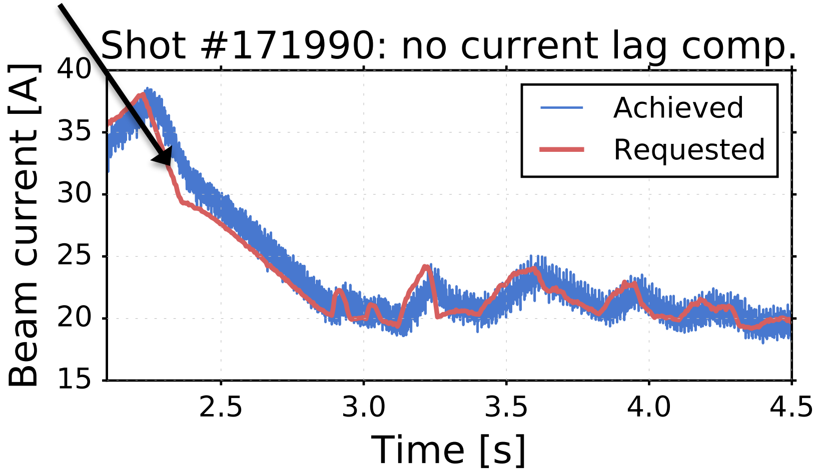


w/ slow current response + compensation

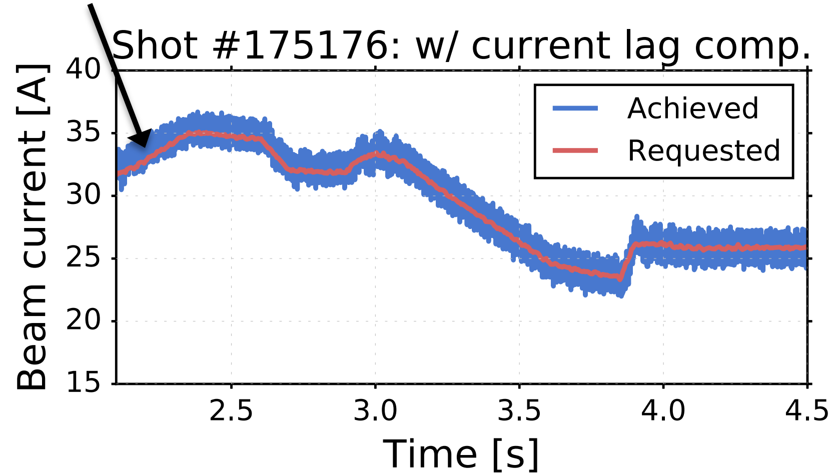


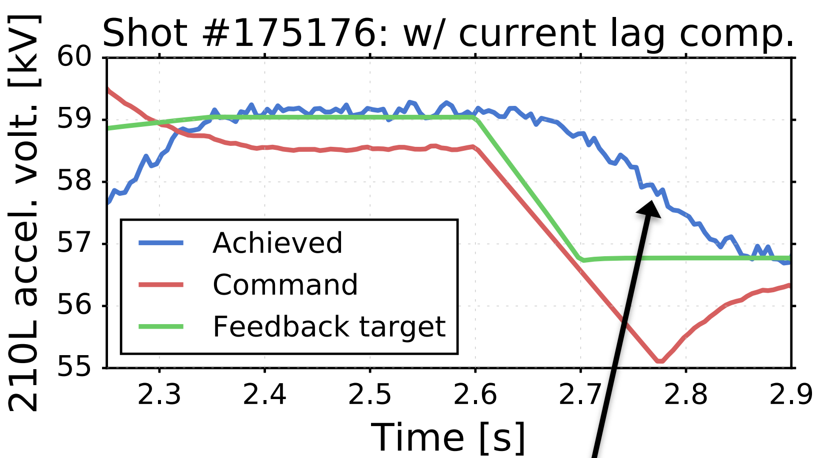
Revised algorithm compensates for lag in local beam current control system, experiment demonstrated better current tracking and improved tracking of power and torque requests

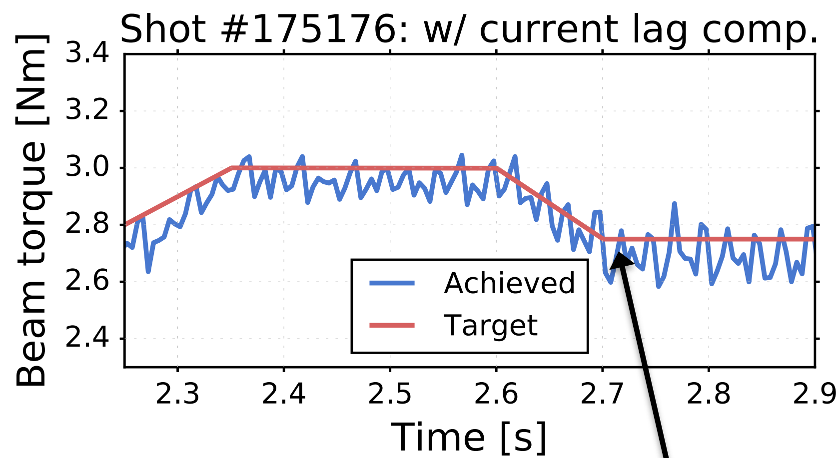
Orig. alg.: poor current tracking



Revised alg.: improved current tracking







Slow voltage response

Perveance changes enable fast torque changes

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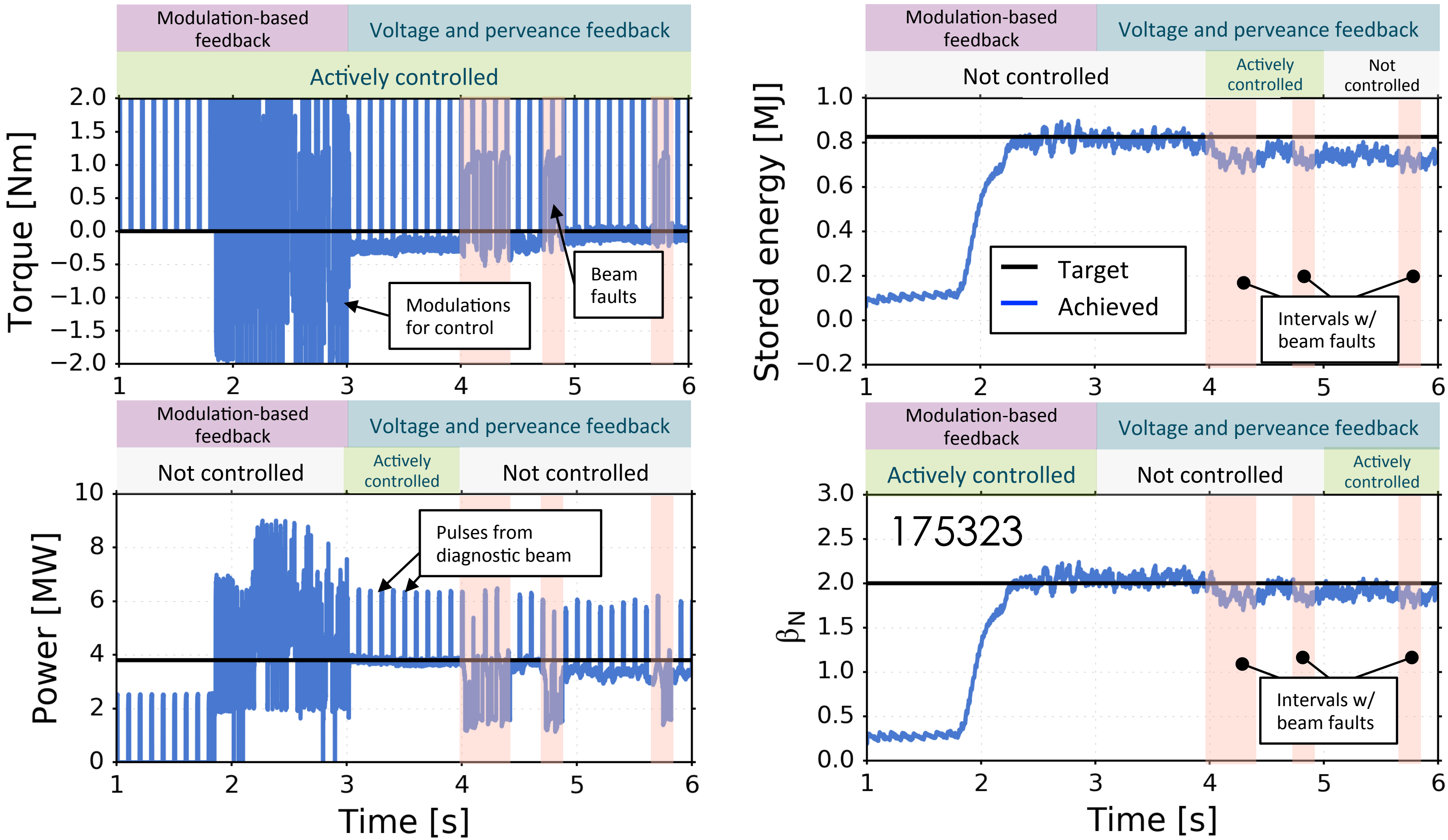
Near-zero-torque shot used to demonstrate different combinations of controlled quantities. Good tracking achieved except in intervals that had beam faults.



Although algorithm respects prescribed perveance limits, will need to establish robust perveance limit values empirically to avoid beam faults

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First experimental test of feedback using VBE/VBP capability on DIII-D: a step toward integrated control of profiles and fast ion losses

- **Equilibrium parameter + profile + AE mode control will help reproducibly achieve optimal performance in advanced scenarios**

- **New voltage and perveance variation capability on DIII-D**
  - Many potential physics and control applications

- **First experimental test of feedback control w/ new capability**
  - Control design addresses challenges:
    - Many actuators, constraints, and slow voltage response
  - Experiment demonstrated tracking
    - Identified lag in beam current response that should be correctable with an additional feedback loop or changes to local beam controllers

- **Outlook and next steps**
  - Planning to **integrate VBE/VBP** capability with **mode control** algorithms

  (W. Hu, DIII-D) and **profile control** algorithms (W. Wehner + E. Schuster, Lehigh U.)

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