NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

XP: Optimization of vertical control algorithm

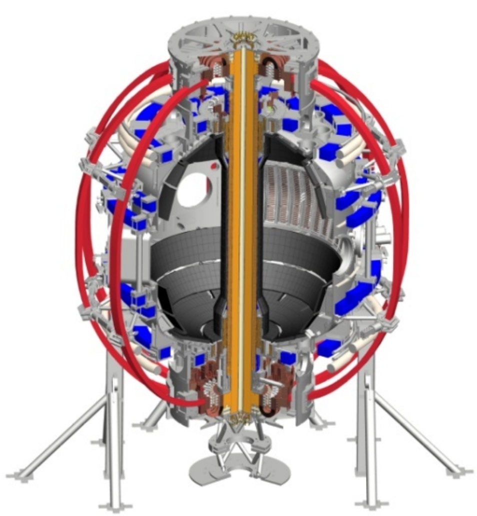
Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

Dan Boyer

S. Gerhardt, D. A. Gates, S. A. Sabbagh[1], E. Kolemen[2]

[1]Columbia University
[2]Princeton University

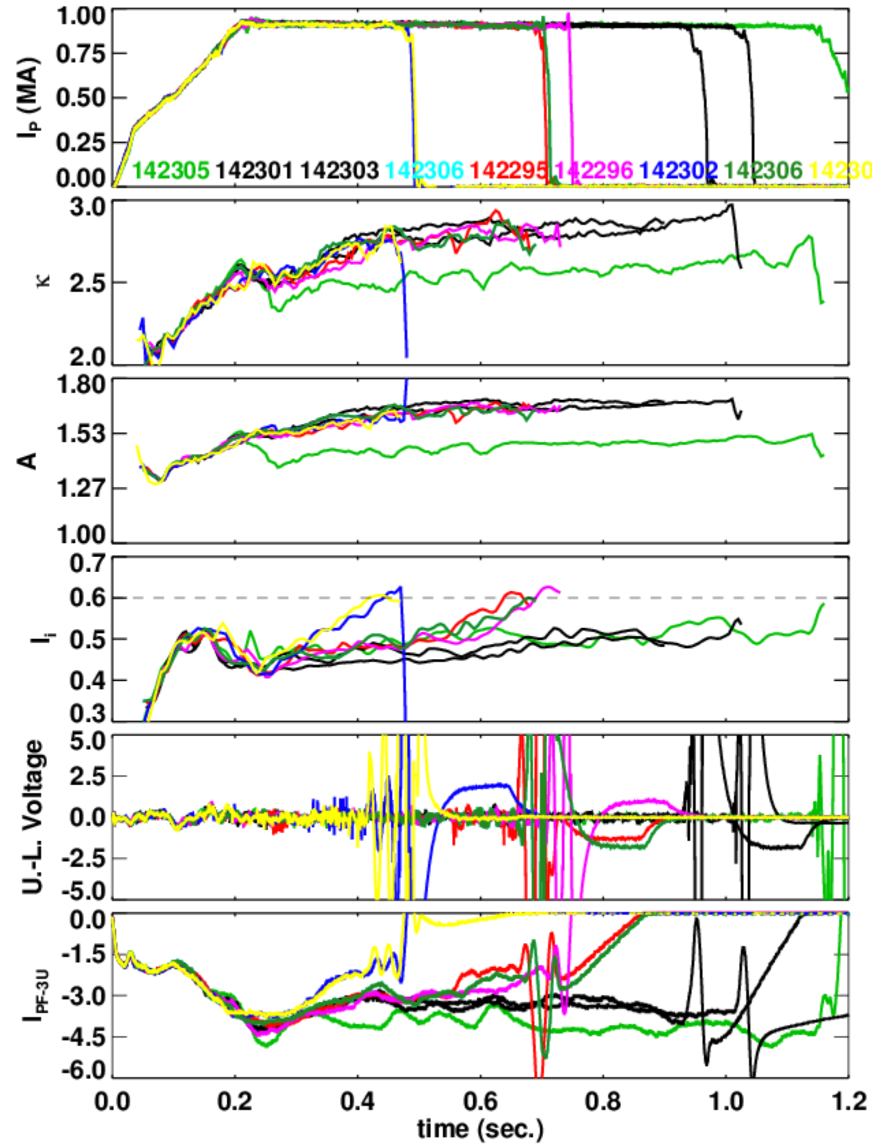
2015 Research Forum
2/24/2015



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

XPs in NSTX showed that vertical position control can be lost at higher aspect ratio

- Fiducial (green) and 8 shots at **higher aspect ratio**
  - Black cases: no VDE
  - Colored cases: VDEs
- VDE triggered when l_i=0.6
  - Not particularly high
  - **Many upgrade scenarios with central NBCD have l_i>0.6**
- Motivates studies to **understand limitations** and implement **improvements to the vertical position controller**



There are several potential causes of loss of control, and many solutions to explore…

- Potential limitations
  - Poor detection of vertical motion
    - Need to respond to instability quickly, so it is important to be able to detect small motion (need accuracy and high signal to noise ratio)
  - Growth rate changes with plasma parameters
    - Linear controller may only be stabilizing in small region
  - Fast growth rates
    - Response of coils may not be fast enough
    - Latency is also an issue
- Potential solutions
  - Improve “dZ/dt observer”
  - Improve controller gains or modify control law
  - Explore use of faster actuators
  - Reduce latency

Vertical Position Controller is a PD Controller Using Loop Voltages for dZ/dt Measurement

- Proportional controller is simply the Isoflux shape control algorithm:

$$V_{PF-3,P} = M \times PID(\text{segment error})$$

- Fast derivative controller is based on the up-down loop voltage difference.

$$V_{PF-3,D} = D \times \left(\dot{\psi}_{Upper-Loop} - \dot{\psi}_{Lower-Loop}\right)$$

- The underlying assumption is that the plasma vertical position can be measured by only 2 loops:

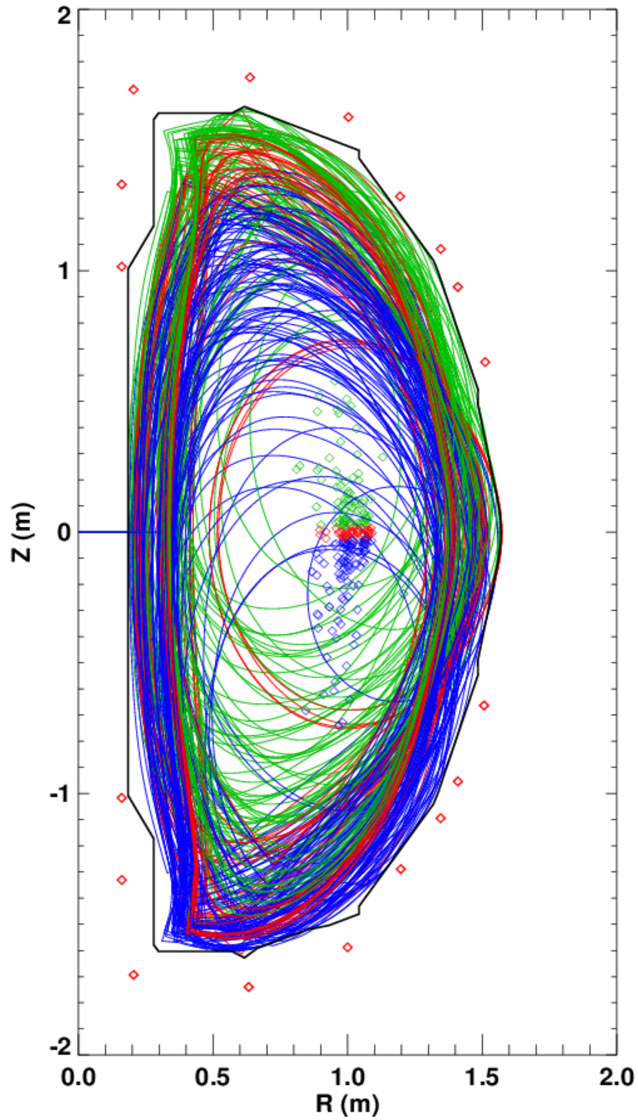
$$I_P Z_P = C \times \left(\psi_{Upper-Loop} - \psi_{Lower-Loop}\right)$$

- Thesis: Using more loops will lead to a better estimation of the plasma position.
  - Eliminate n=1 pickup from random loop orientation problems.
  - More information for shapes that are distorted.

Numerical Tests Have Found That More Loops Are Better (I)

- Constructed ~220 NSTX equilibria.
  - Shift them off the axis, change the divertor coils, change I_P.
- Computed the flux at the various flux loop locations.
- Fit the magnetic axis location to a function:

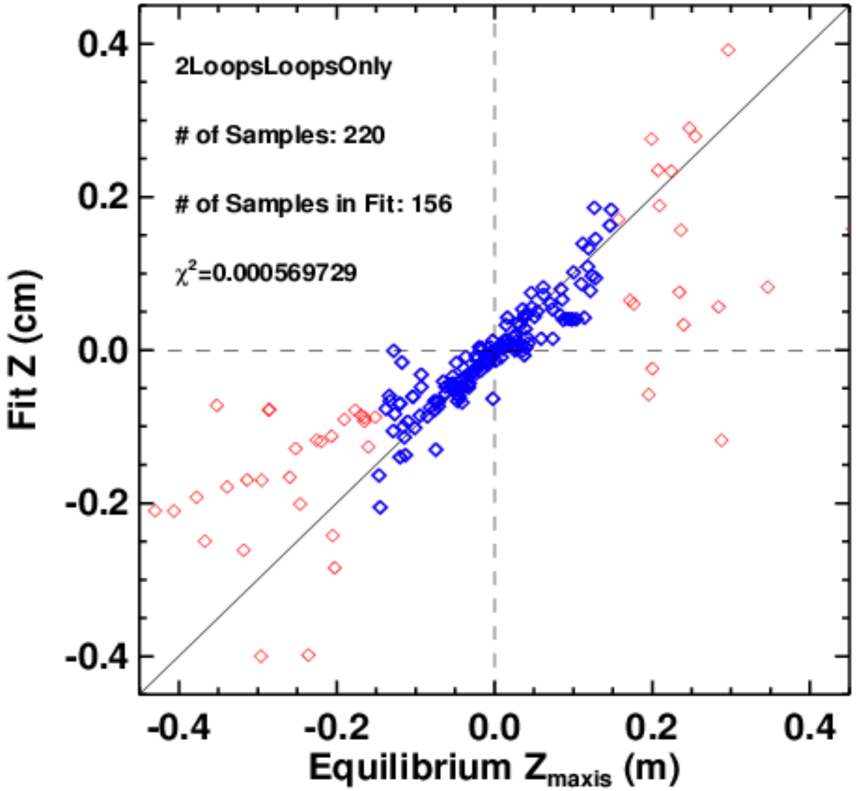
$$I_P Z_P = \sum_{i=1}^{NumLoopPairs} C_i \times \left(\psi_{Upper-Loop,i} - \psi_{Lower-Loop,i}\right)$$



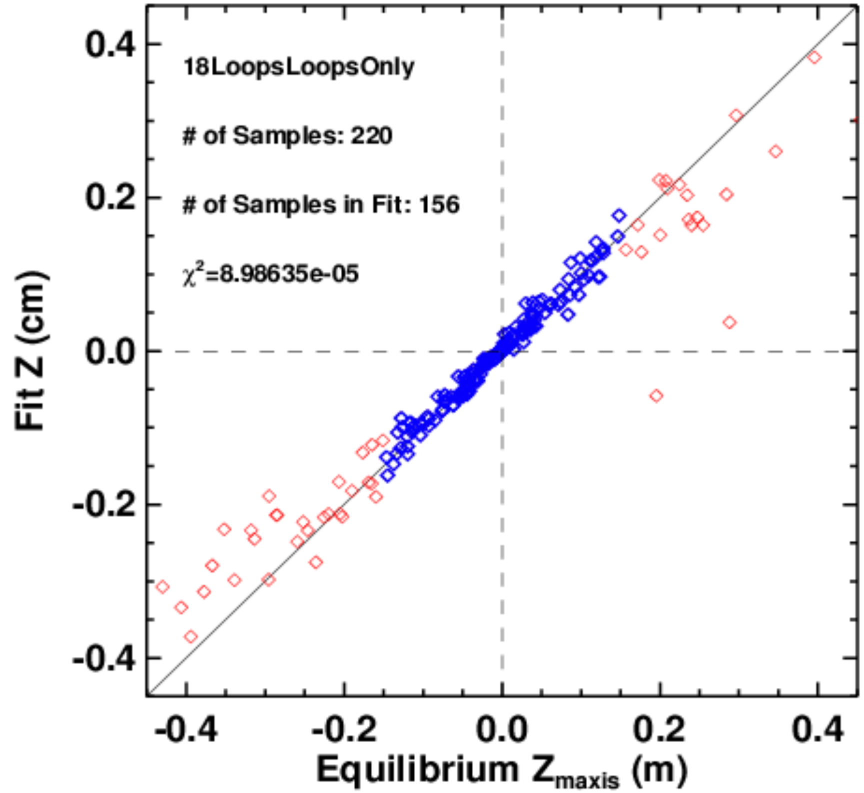
Numerical Tests Have Found That More Loops Are Better (II)

- Use only blue points in the fits ($|Z_{maxis}|<15$ cm)

1 Pair of Loops (On Primary Passive Plates)



9 Pair of Loops (6 Cat. 4, 3 Cat. 3)

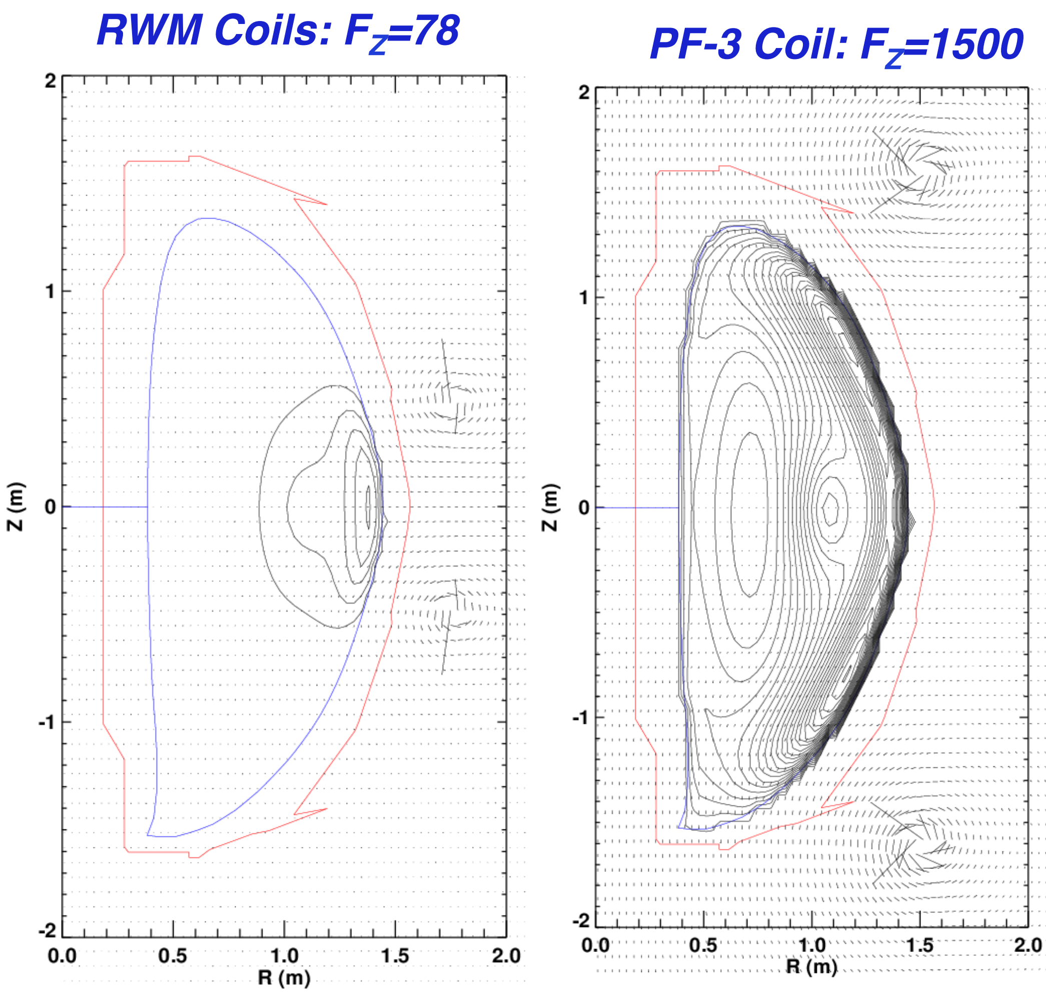


Potential improvements to controller

- Growth rate depends on plasma parameters
  - Changes could cause control gains to no longer be stabilizing
  - Could retune controller for different shapes, parameters
    - Use relay feedback as a quick way of adjusting gains
  - Could employ a nonlinear control law in which gains depend on plasma parameters
    - Use model based control
    - Test designs with TOKSYS (PCS-in-the-loop simulation)
- Latency forces controller to act on old information
  - Could use model-based predictive control to account for latency

Vertical Position Control May Be Possible With the RWM Coils

Calculate force assuming 1 amp of power supply currents $$F_Z = \sum J_\phi B_R$$



RWM Coils make far less force for the same power supply current.

(ratio is not as bad for lower-elongation plasmas)

However….

1) SPA are very fast (to 3 kA in 1-2 msec)

2) RWM coil field may not couple as strongly to the passive plates.

Use this as a last resort if we have insufficient vertical control margin after other things are tried.

Run Plan

- Implement and test new observer [0.5 days]
  - Use offline testing (ISOLVER, preliminary experimental data) to determine best parameters
  - Assess maximum stable elongation as a function of li
  - Retune controller as needed to try to extend stable region
    - Test use of relay feedback

- Implement and test control improvements [0.5-1.0 days]
  - If previous shots show that optimal controller gains are a strong function of elongation and/or li, implement scheduled or nonlinear control law
  - Study the improvement gained by including RWM coils
    - Spot check maximum stable elongation as a function of li
  - Implement controller that accounts for latency

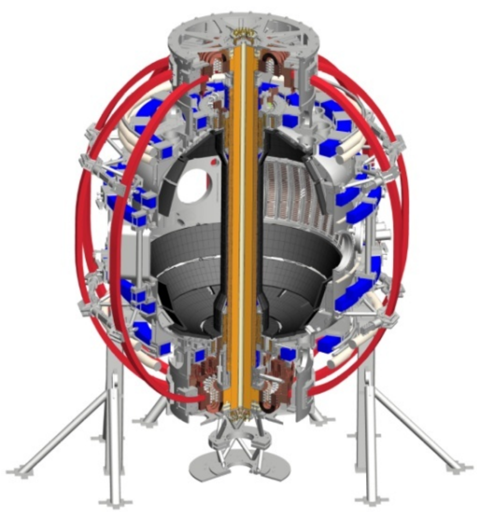
XP: Current profile controllability scoping study

Dan Boyer

S. Gerhardt, D. A. Gates,
S. A. Sabbagh[1], E. Kolemen[2],
D. Mueller, D. Battaglia, E. Schuster[3], Z. Ilhan[3]

[1]Columbia University, [2]Princeton University, [3]Lehigh University

2015 Research Forum
2/24/2015

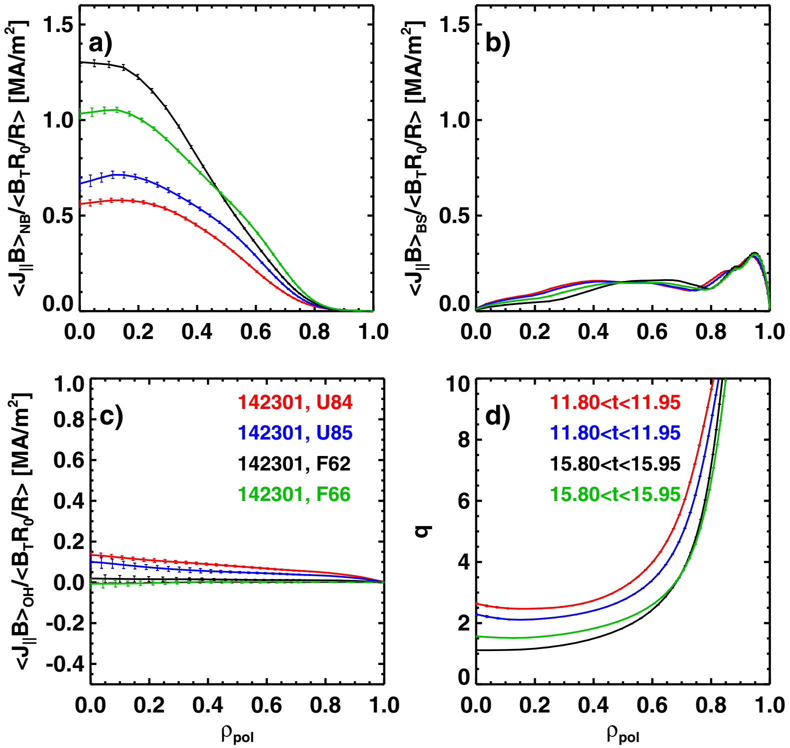


XP is motivated by FY15 milestones, JRT-15, and plans for feedback control of the current profile

- Motivation:
  - MHD stability, confinement, and non-inductive current drive strongly coupled to shape of the current profile (JRT-15)
  - Desirable to avoid stability limits, reproducibly track targets for q0, qmin, shear, li, etc. (15-3)
  - 2nd beam line adds more flexibility in shaping current drive profile (15-2)
    - Additional flexibility can come from the mid-plane outer gap size
    - Eventual particle control will add still more flexibility
- Goals
  - Identify candidate scenarios for initial current profile control studies
    - Those with leverage from the beams and long MHD free periods
  - Validate predictive TRANSP simulations
    - TRANSP is planned for use as a test-bed for controller design, need to make sure it captures the dynamics we're interested in
  - Tune and validate control-oriented models (w/ Lehigh U)
    - Models will be used for actuator planning and feedback control design

Predictive TRANSP runs show that changing mix of beams can change the current profile

- Stefan's study of NSTX-U equilibrium operating space
  - Similar scan for outer gap size
  - Assumptions made on profile shapes, density
- Ability to achieve these scenarios will depend on
  - Machine capabilities during campaign
  - Density and profile peakedness
  - Restrictions on beams due to diagnostics (MSE, CHERS)
  - Requirements on outer gap
    - vertical stability, MPTS



All: E_{inj}=90 kV, P_{inj}=8.4 MW, I_P=800 kA, B_T=1.0 T, $H_{98y,2}$=1, f_{GW}=0.72

R_{tan}=[50,60, 70, 130] cm, q_{min}=2.47, f_{NI}=0.87

R_{tan}=[50,60, 120,130] cm, q_{min}=2.11, f_{NI}=0.92

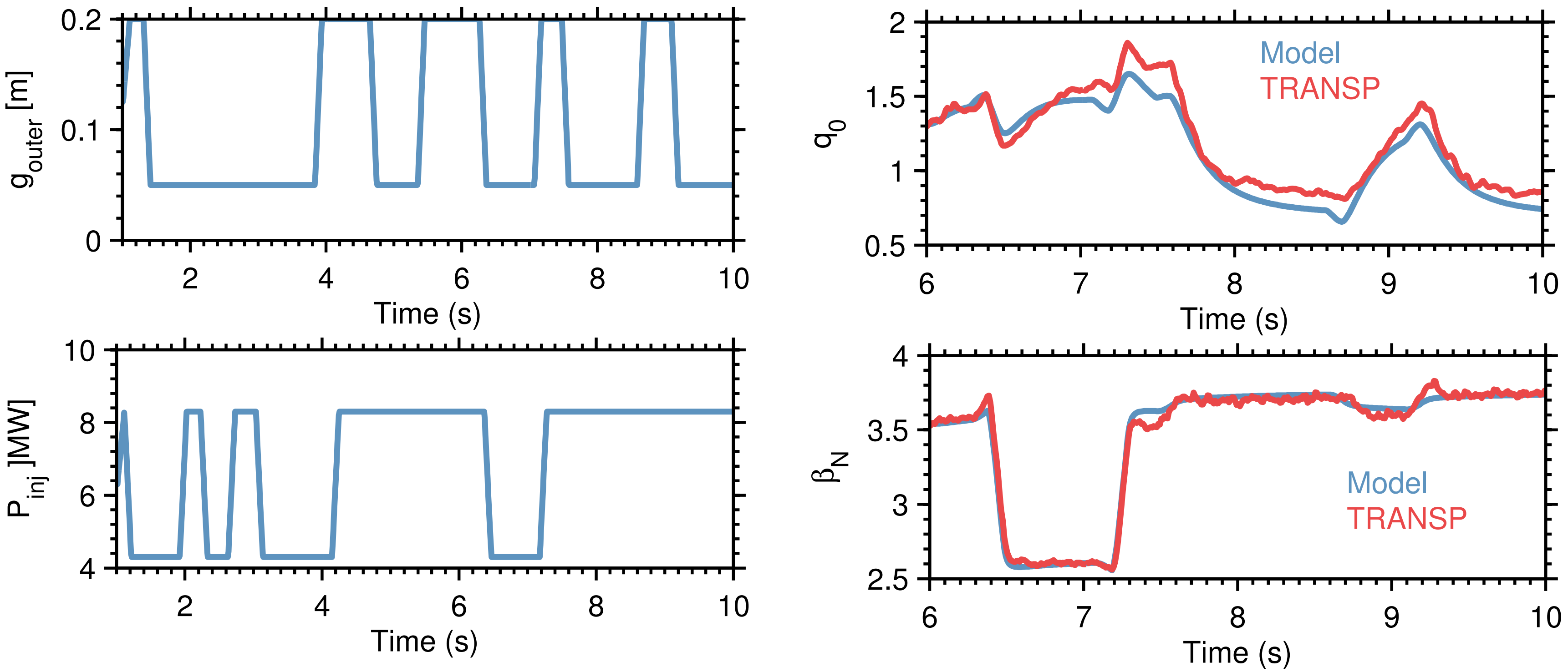
R_{tan}=[60,70, 110,120] cm, q_{min}=1.11, f_{NI}=0.98

R_{tan}=[70,110,120,130] cm, q_{min}=1.51, f_{NI}=0.99

S. Gerhardt NF 2012

Data from shots in which actuators are modulated can be used to develop control-oriented models

- Example: modulation data used to identify a linearized model of the response of q_0 and β_N to changes in outer gap and total injected power
  - Resulting model is in a form that can be used with a variety of model-based control design tools



Experimental plan

- Scan $B_T/I_p/f_{GW}$/outer gap to identify scenarios [0.5 days]
  - Guided by TRANSP scans, considering restrictions on beams for diagnostics
  - Ties in with broader 2nd NBI characterization efforts
    - Will be a refinement of the broader scan in promising regions
- Modulation for control-oriented modeling [0.5 days]
  - Modulate actuators (individually and/or simultaneously) during flat-top
    - Individual beams
    - Plasma current
    - Density
    - Outer gap
  - Repeat during ramp-up
    - Model and control approach may differ in ramp-up phase

NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

XP: Combined β_N and l_i feedback control

Dan Boyer

S. Gerhardt, D. A. Gates,

S. A. Sabbagh[1], E. Kolemen[2],

D. Mueller, D. Battaglia

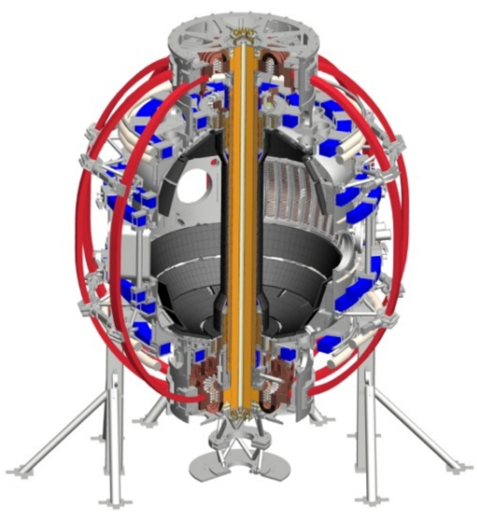
[1]Columbia University

[2]Princeton University

2015 Research Forum

2/24/2015

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Combined β_N and l_i feedback control

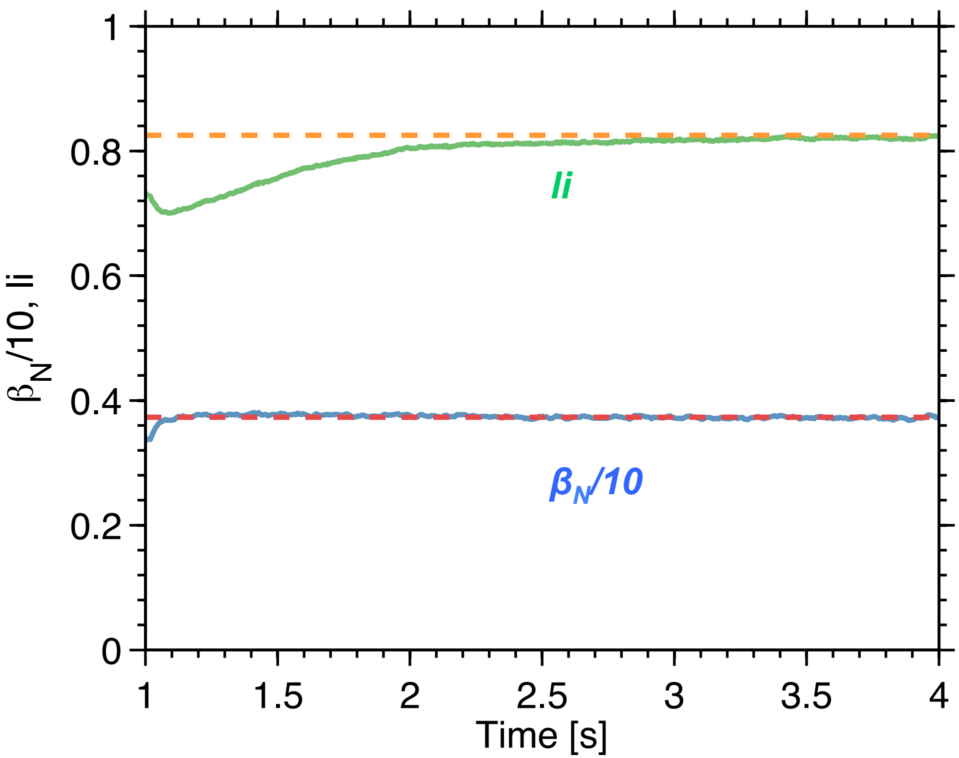
- Motivation:
  - Want to be able to **operate safely near stability boundaries**
    - **β limit**, **vertical instability** caused by li getting to high
  - Want to be able to **conduct controlled experiments** where other parameters are varied at fixed β_N and/or li
- Goals:
  - Demonstrate ability to **reproduce β_N and li** despite introduction of disturbances (variation in pre-programmed heating, or plasma current ramp rate)
  - Demonstrate feedback **modification of li by modifying distribution of power among beams** (and possibly other actuators) during flat-top
  - Demonstrate ability to **scan li at fixed β_N (and vice versa)** using flat-top and/or ramp-up feedback control

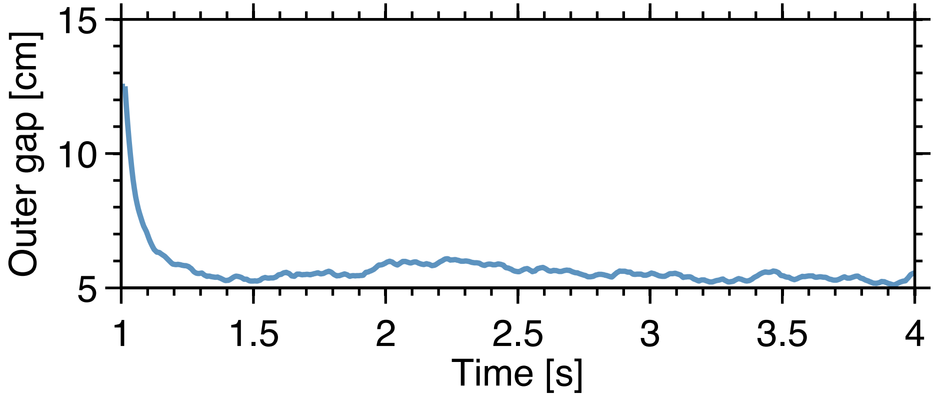
Status of tools

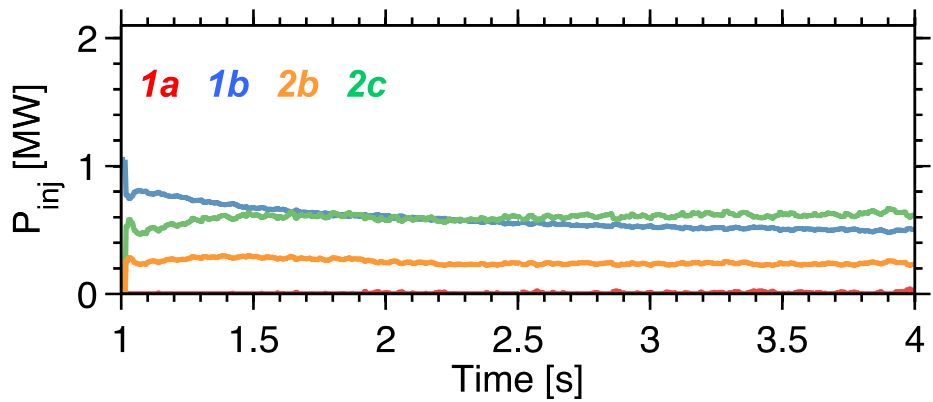
- Beam control algorithms coded, being tested
- General control algorithms specified
  - PID
    - For simple, hand-tunable control designs
  - MIMO
    - more flexibility for implementing model-based control laws
  - Code needs to be written and debugged
    - Simserver testing will be used for offline testing of code
- Offline simulation of feedback control laws can now be performed with TRANSP
  - Capability to implement **feedback control of beams, plasma current, density, and boundary shape**
  - Will be used for initial **tuning of control laws**, **comparison of different approaches**, and to **assess robustness** of control laws to changes in scenarios

TRANSP simulations of feedback controllers can be used to guide design

Example: Outer gap and individual beams used for feedback







f_{GW}=0.6
B_T=1T
I_p=600kA

1c and 2a fixed at 2.1MW

Experimental plan

- Initial test
  - Establish a reference shot
  - Modify pre-programmed heating during ramp-up/flat-top, turn on feedback to correct for change
  - Modify pre-programmed plasma current ramp-rate, turn on feedback to correct for change
- Further testing
  - Change target li for fixed β_N
  - Change target β_N for fixed li
- Several potential feedback actuator combinations to explore
  - 2 beams (or groups of beams)
  - Individual beams
  - Total beam power + outer-gap size
  - Total beam power + plasma current (during ramp-up)