

Use of TRANSP for feedback control algorithm development

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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**

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

Complexity of the control problems motivates the use of model-based control design techniques

- **Spatially distributed** systems with **nonlinearities** and **coupling**
	- Multiple actuators and measurements
- Need to balance **competing goals** to achieve optimal performance
	- Need to respect **constraints** to avoid MHD instabilities or machine limits
- Need to consider **actuator limitations**
- **Noisy**, possibly **limited real-time measurements**
- **By incorporating dynamic models in the design process, control algorithms can be made to handle all of these issues**

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

TRANSP has been used previously for NSTX-U predictive simulations (open loop)

- The computational approach used in this work is based on NSTX-U steady-state **scenario development**
	- **S. Gerhardt (***Nuclear Fusion* **2012)**
	- T_i profile predicted from Chang-Hinton model
	- MHD equilibrium calculated using **free boundary code ISOLVER**
	- 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
	- $-$ T_e, n_e profile shapes and scale factors **prescribed prior to simulation** runs
		- Scale factors **scanned during several runs** to achieve desired H98 and Greenwald fraction
	- Z_{eff} prescribed, used to calculate n_i assuming carbon as the only impurity

Modifications to the previous approach are necessary to perform control simulations

- 1. Ability to change actuators in `real-time', i.e., based on feedback control
- 2. Electron temperature and density no longer *a priori* inputs
	- Interested in transient behavior unlike previous scans of steady state
	- Temperature should change based on confinement as beam powers are modified
- 3. An analog to the plasma control system (PCS) is needed
	- To perform control calculations, allow targets and gain waveforms to be loaded, etc.
	- To mimic the beam modulation algorithms used to modify heating power in the actual experiment

Modifications have been implemented using external code: the Expert file ounications nave been implemented using external cod
fhe Expert file TRANSP is being developed and the contract of the contract of

- Expert subroutine called at many places throughout TRANSP production code
- \bullet ni calculated based \bullet • An identifier is passed along with the call
- different snippets of code can be run at different points during the **Modern Framework needed** simulation framework needed to simulation framework needed
- 1. Specify **density** based on **controller request** or desired **Greenwald fraction** • Custom run-specific code can be run at each call to manipulate certain variables (which would typically be input ahead of time) based on the state of the simulation

1. Ability to change actuators in `real-time', i.e., based on feedback control

- Focus has been on actuators used for current/rotation profile control so far, but others will be added in the future
- Hooks added to TRANSP code and appropriate code added to expert file to overwrite U-file data for:
	- Beam powers,
	- Density,
	- Total plasma current,
	- NTV torque (I. Goumiri, Princeton U.),
	- Plasma boundary shape request

2. Temperature is set based on stored energy predicted by EXAMPLE CONFINEMENT SCALING EXPRESSIONS *Te,*⁰ = **2. Temperature is set based on stored energy predicted by** 2. Temperature is set based on stored energy predicted b m, and is the inverse aspect ratio, and is inverse aspect ratio, and is in the elongation. The loss power ρ MW and is defined in [7] as total input heating power less *dW/dt* and fast ion losses inconfilement scaling expressions at the Expert file confinement scaling expressions

At the beginning of each transport step (*t* = *ta*), the value of the thermal stored

• At each TRANSP step (from time t_a to t_b), stored energy predicted by Δt each $TDMMCD$ chain (fine is these the $\pm \lambda$ statistical experiments) appropriate time time time other that the density information at a time of the second that $\frac{1}{a}$ to $\frac{1}{b}$, stored the second that $\frac{1}{a}$ or *t^b* during a particular transport step) and replaces the TRANSP internal variable for through charge-exchange-exchange-exchange, $\frac{1}{2}$ or $\frac{1}{2}$ interpreted from a user-supplied wavefully wavefully wavefully supplied wavefully a user-supplied wavefully supp Because Transp typically obtained the electron temperature from an input file, and including the electron temperature file, and including the electron temperature from an input file, and including the electron temperature **t** and *t* and *t* and *t* and *t* and *t***_{***r***} and** *t***_{***f***} and** *t***_{**} $\overline{\text{C}}$

energy *Wth* for the appropriate time based on *Wth,a* and *Wth,b*, the predicted values at

$$
W_{th,b} = W_{th,a} + (t_b - t_a) \left(-\frac{W_{th,a}}{\tau_E} + P_{net} \right),
$$

- Confinement based on scaling (either ITER98 or ST scaling)
− P , and scaling law parameters from TRANSP internal variables
- P_{net} and scaling law parameters from TRANSP internal variables *t*_{net} and scaling law parameters from TRANSP internal variables *x* g l *d*⇢ˆ*,* (9)
	- Electron temperature assumed to be of the form $\frac{1}{2}$ assumptions. The first is the *H*98*y,*² scaling expression [52], given by • Electron temperature assumed to be E **F**
 $\frac{1}{4}$ \cdot Electron temperature assumed to be

$$
T_e(\hat{\rho}, t) = T_{e,0}(t) T_e^{ref}(\hat{\rho})
$$

where *Tref* and using the volume \sim Scale factor calcul $-$ Scale factor calcul

$$
T_{e,0} = \frac{\frac{2}{3} \langle E_{th} \rangle - \langle n_i T_i \rangle}{\langle n_e T_e^{ref} \rangle}
$$

$$
\langle E_{th} \rangle = \frac{W_{th}}{V} = \frac{3}{2} \left[T_{e,0} \langle n_e T_e^{ref} \rangle + \langle n_i T_i \rangle \right].
$$

$$
\underbrace{\qquad \qquad}_{0} \underbrace{\qquad \qquad}_{0} \underbrace{\qquad \qquad}_{0.2} = 1.6 \text{MA}}_{0.4}
$$

2. Line-averaged electron density or Greenwald fraction *n***_e(***t***) =** *n***^e(***t***) =** *n***^e(***t***) =** *n***²), (***t***) =** *n***²),** ϵ raged electron density or Green ϵ *y*(*t*) *ymod*(*t*) *^f*(*uk*) = (*y*(*t*) *ymod*(*t*) *^f*(*uk*) = (*ymod*(*t*) *^f*(*uk*) = (*u^k k* = 1*,...,* 4

3.1. Electron density specificiation

• Density assumed to be of the form *N*_{*r*} and defined as a function of the specified as $\left(\begin{array}{cc} a & b \end{array}\right)$ and $\left(\begin{array}{cc} a & b \end{array}\right)$ *^f* ¹(*vsat*) = (*v*_{*s*} $\frac{1}{2}$ $\frac{1}{2}$ 200*aµ*⁰ $f(r) = \frac{f(r)}{r}$ *vsat,k k* = 1*,...,* 4

u^k k = 1*,...,* 4

where *nref*

 $a_{e}(\rho, v) = a_{e,0}(v) a_{e}$ (*P*) $n_e(\hat{\rho}, t) = n_{e,0}(t) n_e^{ref}(\hat{\rho})$ $e^{ref}(\hat{\rho})$

u^k k = 1*,...,* 4

• A simple model is used to evolve the electron inventory N at each TRANSP transport time step (from time t_a to t_b) $\frac{N}{\sqrt{N}}$ and $\frac{N}{\sqrt{N}}$ of $\frac{N}{\sqrt{N}}$ and $\frac{N}{\sqrt{N}}$ and *I* RANSP transport time step (from time t_a to t_b) nple model is used to evolve the electron inventory N at λ *P* Ipoth (from time t_a to t_h) \overline{a} \overline{b} *I*ventory iv at *ⁿ*¯ Line-averaged density # ⇥ ¹⁰¹⁹*/m*³ Density

 $N_b = N_a + (t_b - t_a)(N^{req} - N_a)/\tau_N$ $\Delta v_b - \Delta v_a + (v_b - v_a)(\Delta v - \Delta v_a)/T N$ $N_b = N_a + (t_b - t_a)(N^{req} - N_a)/\tau_N$ $-t_a$)($N^{eq} - N_a$)/ τ_N

• N^{req} prescribed by controller or calculated from requested line-averaged density or Greenwald fraction f_{GW} : for fueling sources and recycling. veraged density or Greenwald fraction f_{GW}: *ⁿ*¯ Line-averaged density # ⇥ ¹⁰¹⁹*/m*³ Density prescribed by controller or calculated from reque *Pⁿ* Individual power for beam *n* MW NBI *gouter* outer-gap size m ISOFLUX *Pr* or calculated from requested *P* is a power of the power of the power P and P is a model of the P **I**^T F_{**T**} $\frac{1}{2}$ F_T $\frac{1}{2}$ F_T^{$\frac{1}{2}$} F_T^{$\frac{1}{2}$} FT^{$\frac{1}{2}$} *Ptot* Total beam power MW NBI *IT F* Toroidal field current MA TF *Nreq* = *y^c*

• Profile scale factor calculated from the predicted inventory as le factor calculated from suitable for this work, (2) could be replaced by a conservation equation that accounts for fueling sources and recycling. For a particular inventory, *N*, the scale factor *ne,*⁰ is calculated from ۔
R ale file scale $\overline{\text{m}}$ *s* $\overline{\text{b}}$ *o* $\overline{\text{c}}$ *l* $\overline{\text{c}}$ *n*
Iated from tl

$$
n_{e,0}=\frac{N}{\int_0^1 n_e^{ref} \frac{\partial V}{\partial \hat{\rho}} d\hat{\rho}}.
$$

. (3)

2. The added capabilities can be used to constrain simulations to match a desired time-varying f_{GW} and H₉₈

- Greenwald fraction request decreased at 0.75s
	- TRANSP modifies the density (on an appropriate time scale for density changes) to achieve the request
- H98 request ramped down until 1.0s, step at 1.0s
- Stored energy prediction responds to f_{GW} and h_{98}
	- drops slowly as H_{98} ramps down (0.0-0.75s), and faster as the density is decreased
	- Step change in H_{98} causes a large drop in stored energy

3. A general controller structure has been implemented within the Expert file

3. Beam power modulation algorithms planned for NSTX-U have been implemented in TRANSP simulations

- Enables assessment of modulation's effect on performance
	- Beams modulated to achieve requested average power, respecting minimum on/off times and maximum modulations per shot.
	- Results can help determine optimal modulation parameters (minimum on/off times) and control gains to achieve desired levels of performance

Several on-going projects using TRANSP feedback control framework

- Stored energy, q₀/li control on NSTX-U
	- M. D. Boyer, PPPL
- **Rotation profile control on NSTX-U**
	- I. Goumiri, Princeton U.
- Current profile control on NSTX-U
	- Z. Ilhan, Lehigh U.
- Rotation profile control on DIII-D
	- W. Wehner, Lehigh U.
- Shape control on NSTX-U
	- M. D. Boyer, PPPL

TRANSP testing of simultaneous q₀ and β_N control via beam power and outer gap size

- 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

Central safety factor and ^N control on NSTX-U 9 *Reference plasma boundaries:*

 $\mathbf{H} \mathbf{D}$. Consequently, $\mathbf{H} \mathbf{D}$ consequently the two references comparing the two reference MHD equilibria with (left) *gouter* = 0*.*05m and (right) *gouter* = 0*.*20m. *M.D. Boyer, NF 2015*

State-space system identification for simultaneous q₀ and β_N control $\boldsymbol{\mathsf{D}}$

- 101 \ldots \ldots 0 • Open loop signals applied to each actuator
- parameters for a particular model order using first part of • Prediction-error method used to determine optimal model data set (estimation set)
- model order (number of states) \overline{C} • Remainder of data (validation set) used to determine best Figure 2: Actuator requests used in the system in the

LQG servo controller designed for identified system a comparison of the output of the output of output of α the validation of the value of α and α and α and α and α **a** servo controller designed for identified system *IT F* Toroidal field current MA TF *Nreq* = *y^c*

the validation data is shown in Figure 3, showing good agreement in *q*⁰ and excellent

The identified model was then used to design a linear-quadratic-Gaussian servo

• Solves the **optimal control problem** of minimizing the cost function roo tho opening oome of prowidites a minimize $\sqrt{ }$ $\left| \right|$ $\sqrt{ }$ $\sqrt{2}$ *x*˜ 3 1 \mathcal{L} \vert *,* (24) \int $\frac{1}{2}$ \int 0 >>< $\begin{bmatrix} \tilde{x} \\ \tilde{x} \end{bmatrix}$ olem of mi $\left($ $\left\{ dt \right\}$ າເzing the co >>= *n*^e *p*otimal *c* $\left[\tilde{x}^T, u^T_{\alpha}\right]$ dt ⁰ *n*^o
*i*s the optimal $\int_0^\tau \left[\int_{0}^{\tau} x^T u \right]$ $dt\Big\}$. *Pⁿ* Individual power for beam *n* MW NBI *I IT To IT F* Toroidal field current MA TF *Nreq* = *y^c*

 $J = E$ \downarrow $\lim_{\tau \to \infty} \int_0^{\tau}$ $\left[\tilde{x}^T, u_{fb}^T\right] Q_{xu}$ $\begin{matrix} \end{matrix}$ *ufb* $\overline{}$ $+ x_i^T Q_i x_i$ CCA *dt* \int $, i$ $\left(\begin{array}{ccc} \lambda & \lambda & \lambda \\ \lambda & \lambda & \lambda \end{array} \right)$ $E\left\{\lim_{\tau\to\infty}\right\}$ 3*IpB^T V* Q_{xu} $\begin{array}{c} \tilde{x} \ u_{\epsilon} \end{array}$ u_f $+ x_i^T Q_i x_i$ $J = E \left\{ \lim_{\tau \to \infty} \int_0^{\tau} \left[\left[\tilde{x}^T, u_{fb}^T \right] Q_{xu} \right] \left[\begin{array}{c} \tilde{x} \\ u_{fb} \end{array} \right] + x_i^T Q_i x_i \right\} ,$ \int **P** \int **P** \int **P** \int **P** \int $\Big] Q_{xu} \Bigg| \Bigg|$ $\lfloor n \rfloor$ $+\left(x_i^T Q_i x_i\right)$ $\left\{\right\}$ ^{*n*} $\left\{$ *n*_{*n*} $\left\{$ *n*_{*n*}

for the system $\dot{\tilde{x}} = A\tilde{x} + B\tilde{x} + d\tilde{y}$

Nreq = *y^c*

n¯*ref*

n¯*ref*

$$
\dot{\tilde{x}} = A\tilde{x} + Bu_{fb} + w,
$$

$$
\tilde{y} = C\tilde{x} + Du_{fb} + v,
$$

where Q_{xu} is a weight matrix for the states and inputs, $y^{\prime} = c_0 + b_1 + c_2$

and Q_i weights the integral of the output tracking error according to the weights in *Qxu*, which are free design parameters, and also ensure with the integral of the cutput treaking error x agrite the integral of the output traesing enor x_i $\overline{\mathbf{a}}$ *xi* Q_i weights the integral of the output tracking error x_i

• Since the states of the identified model are not measured, they are estimated by a Kalman filter *d* and unmated by a **indifferent state on the measurements** $\boldsymbol{\mu}$ parameters in *Qi*. A Kalman filter is embedded in the resulting control law, which optimally estimates the unmeasured states *x*˜ based on the measurements *y*˜, taking into *Qxu Qi Qxu*

 $-$ Tuned based on expected process and measurement noise (w, v)

• **Integral action** ensures steady-state error is driven to zero in the presence of disturbances or target tracking using Simulink in order to tune the free design parameters to achieve a desired system grai a simulation framework. Time-dependent results of the closed loop simulation of the using Simulink in order to tune the free design parameters to achieve a desired system *v* response. The controller was the controller was the proposed in a TRANSP simulation using the proposed in

Ptot Total beam power MW NBI

Ptot Total beam power MW NBI

Optimal controller achieves good target tracking performance in TRANSP simulation testing and *NST* 2

 J ap batara ϵ $\overline{}$ $^+$ 3004 • Outer gap saturated at 4s, but performance is still good

(d) \mathbb{Z} \overline{C} • Small change in non-inductive fraction, line-average density Figure 4: Results of closed loop simulation of the MIMO control law: (a) *q*⁰ result increased due to decrease in volume at fixed particle inventory outer gap, (e) injected power, and (f) electron density.

Profiles and coil currents during optimal controller simulation

ID \overline{NSTX} -U **Interferent coil currents during the MIMO coil currents during control algorithm development, Dan Boyer, 3/24/2015**

Rotation profile control in NSTX [I. Goumiri]

• For design, a simplified form of toroidal momentum equation is assumed, with model profiles derived from TRANSP

$$
\sum_{i} n_{i} m_{i} \langle R^{2} \rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_{i} n_{i} m_{i} \chi_{\phi} \langle R^{2} (\nabla \rho)^{2} \rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}
$$

Rotation profile control in NSTX [I. Goumiri]

• For design, a simplified form of toroidal momentum equation 1 is assumed, with model profiles derived from TRANSP 20 $\overline{\text{fr}}$ 1 ,

Modeling and control of plasma rotation using NTV and NBI 5

*NSTX-U Use of TRANSP for feedback control algorithm development***, Dan Boyer, 3/24/2015** (c) 5x 10[−]⁷ Use of TRANSP for feedback control algorithm development, Dan Boyer, 3/24/2015

Figure 2. The momentum di↵usivity coecient is calculated through predictive

Simplified models assumed for NBI and NTV torque [I. Goumiri]

Figure 6. Model representation of the Neoclassical Toroidal Viscosity (NTV) coils

Simplified model predictions compare very well to TRANSP simulations [I. Goumiri]

Modeling and control of plasma rotation using NTV and NBI 12

 \mathcal{L}_max and red dots (o) (simplified model) respectively. The blue dashed model model \mathcal{L}_max

TRANSP simulation of rotation profile controller [I. Goumiri]

Future plans for feedback control simulations in TRANSP

- Extend framework to other machines
- Extend to include additional actuators and control loops
	- Coil voltages for shape control in TRANSP (mostly finished)
		- For testing control laws
		- Or for ensuring that predictive simulations mimic experiments
	- RF for heating, current profile control, NTM control, etc.
		- Will need hooks for modifying RF input parameters in `real-time'
- Use transport models for $T_{\rm e}$, density
	- Add puffing/pellets/pumping as feedback actuators
	- May want a simplified transport model to speed of simulations
		- Neural networks? O. Meneghini
- 1. Add confinement and Greenwald fraction constraints to production code
	- These have been useful for several users already
- 2. Enable external programs to `steer' TRANSP through a socket connection:

