Progress Towards Control-Oriented Modeling and Model-Based Advanced Control for Long-Pulse Scenario Development in EAST

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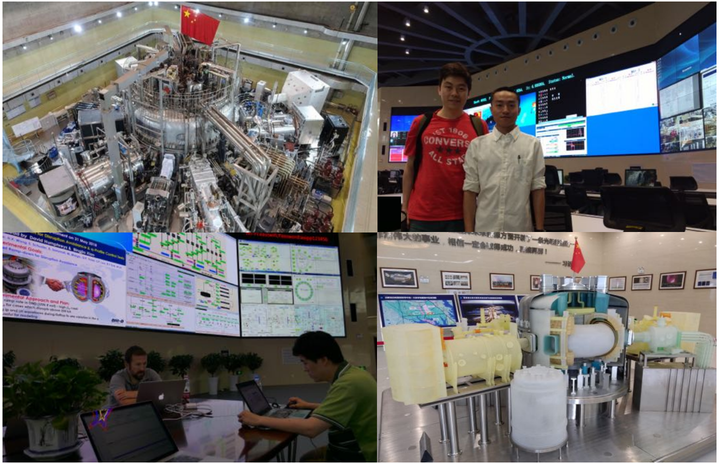

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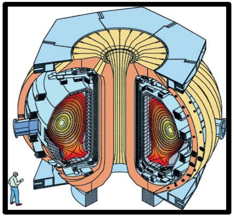
Long-Pulse High-Performance Scenarios & Control in EAST

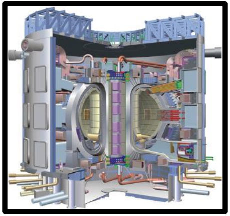
- Adapt high-performance scenarios from DIII-D to EAST
- Develop control-physics understanding to enable adaptation
- Pioneer reactor-specific scenario and control solutions



DIII-D

EAST

ITER



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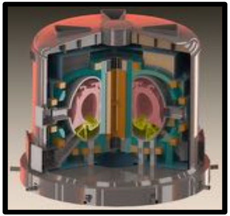


① High-Performance Steady-State Scenarios

② **Control for Long Pulse Sustainment**

③ Core-Edge Integration

④ **Simulations for Scenario Development and Control**

⑤ Diagnostics for Long Pulse Scenarios and Control

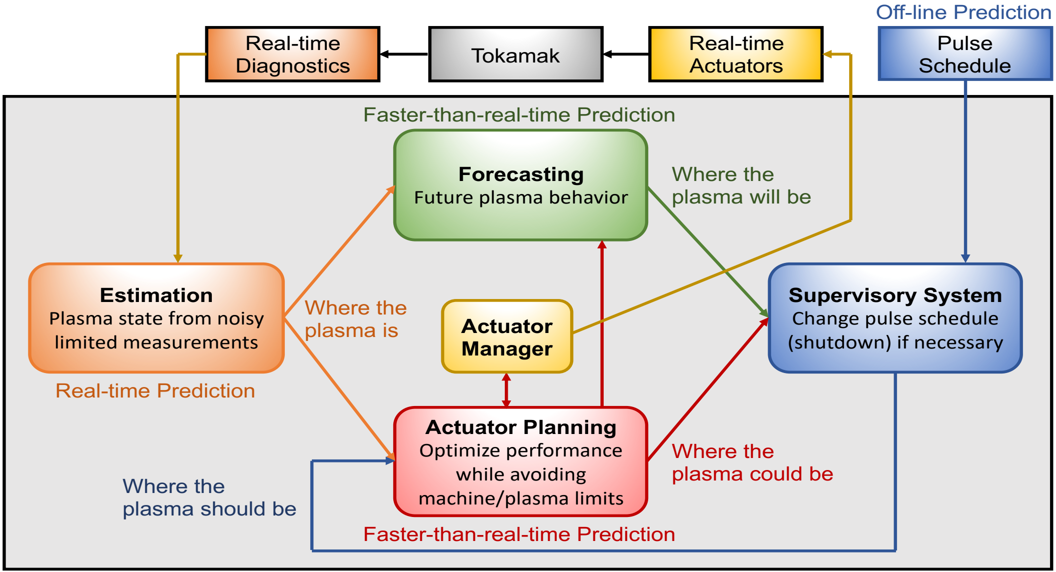
⑥ Remote Collaboration and Third Shift Operation of EAST

General Atomics
Lehigh University
Lawrence Livermore Nat Lab
Massachusetts Inst of Technology
Princeton Plasma Physics Lab
Univ of California Los Angeles
Univ of Texas Austin

Next-step Fusion Devices Will Need Smarter Real-time Algorithms

- Scenario planning based on off-line prediction+optimization (“predict first" approach) is key first step towards efficient tokamak operation but it lacks adaptation and robustness.
- **Smarter real-time control algorithms** could **increase physics output in present devices** and **safely operate future reactor-degree devices.**
- These algorithms should **optimize experiments in response to machine conditions**
  - Do we shut down if an actuator fails or if we are approaching stability limit?
  - Do we try to use alternative actuators and/or strategies to keep operating in desired scenario?
  - Do we move to a different operating point or scenario?
- These algorithms should **actively manage operation to prevent device damages**
  - Do we change control strategy if loss of control (disruption) is anticipated by following this path?
  - Do we safely terminate the discharge if alternative control strategy cannot be found?
- **These algorithms with the capability of taking decisions in real time without humans in the loop will rely heavily on fast prediction by control-oriented (reduced) models.**

Advanced Tokamak Operation Will Demand Model-based Prediction



Off-line Prediction

Real-time Diagnostics

Tokamak

Real-time Actuators

Pulse Schedule

Faster-than-real-time Prediction

Forecasting
Future plasma behavior

Where the plasma will be

Estimation
Plasma state from noisy limited measurements

Where the plasma is

Actuator Manager

Supervisory System
Change pulse schedule (shutdown) if necessary

Real-time Prediction

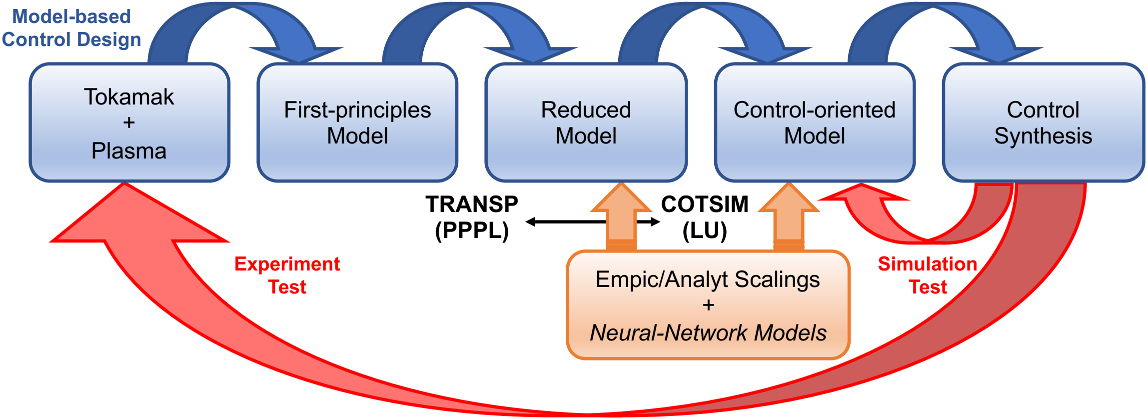
Actuator Planning
Optimize performance while avoiding machine/plasma limits

Where the plasma could be

Where the plasma should be

Faster-than-real-time Prediction

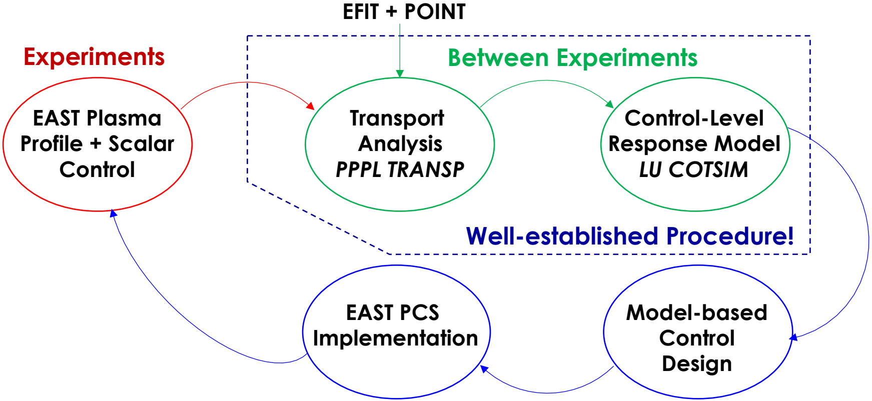
Control-oriented Modeling Enabled by TRANSP-Based Analysis



Can we develop integrated control-oriented response models (e.g., COTSIM) both fast enough and accurate enough for control applications (not for physics understanding)?

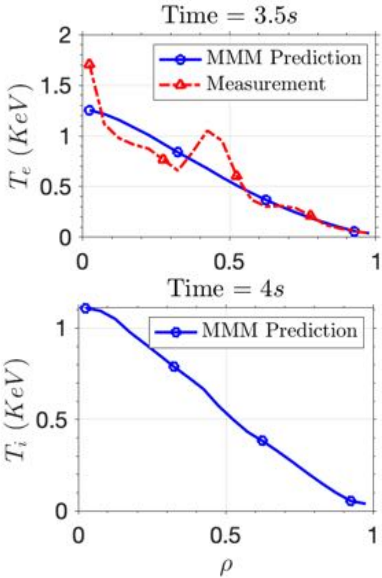
Control-oriented Modeling Enabled by TRANSP Prediction/Analysis

- Notable progress during last year towards reproducing EAST scenarios by TRANSP (PPPL).
- POINT-constrained equilibrium reconstruction (UCLA) plays critical role in modeling process.



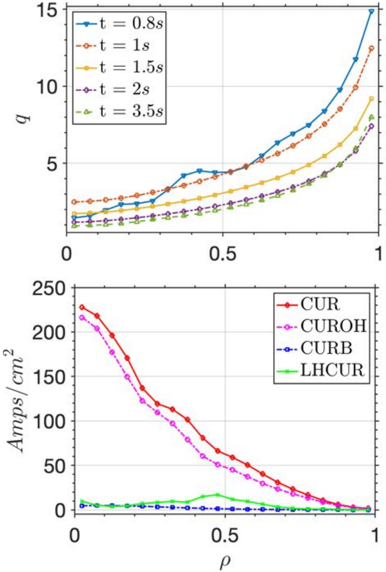
Control-oriented Modeling Enabled by TRANSP Simulations (#80208)

- TRANSP simulations are run in both interpretative and predictive modes.
- Simulations are very computationally intensive (32 processors, $\sim$ 1 week), particularly with LH, NBI.
- TRANSP calculates power deposition and current drive using experimental temperature and density profiles in interpretive simulations.
- The radial and time dependence of ion/electron power deposition, as well as total current and current drive components, are computed in interpretive simulations.
- Predicted electron temperature and q-profiles are compared to EAST experimental results. A fair prediction/measurement agreement is discovered.
- Experimental measurement of ion temperature is not available for comparison with predicted temperature.



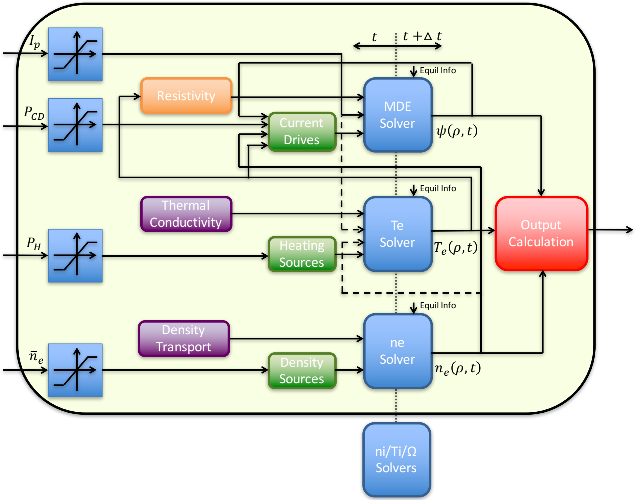
Control-oriented Modeling Enabled by TRANSP Simulations (#80208)

- Different components of heating and current density are discovered to be driven in different plasma regions.
- The LH, NBI and other contributions to total current are quantified.
- The LH and NBI heating and current drive are obtained using the GENRAY/CQL3D and NUBEAM modules, respectively.
- In addition to heating and current drive, the MMM (Multi-Mode Model) anomalous transport module is used in predictive simulations to predict plasma profiles.
- The Chang-Hinton model is used to compute neoclassical transport.
- The TEQ module is used to compute the equilibrium.



First-principles-driven Models are Engine of COTSIM

LU Control-Oriented Transport SIMulator (COTSIM)



- 1D transport code
- Matlab/Simulink-based
- Control-design friendly
- Modular configuration
- Variable physics complexity
- Closed-loop capable
- Optimizer wrappable
- Equilibrium: Prescribed → 2D Solver
- Fast (offline simulations)
- Very fast (rt control applications)

- NN models: NUBEAM, MMM
- NN model for LHCD in EAST (MIT)

Need for Advanced Long-Pulse Scenario Control in EAST

- **"Advanced Tokamak" (AT) operational goals** for **EAST** include:
  - Steady-state operation
  - High-performance operation (high β, high q_{min}, etc.)
  - MHD-stable operation

- **Active, feedback control** of the **current density profile**, as well as of other plasma kinetic profiles and scalars, can play critical role in achieving these **AT operational goals**.

$\star$ High dimensionality
$\star$ Nonlinearity
$\star$ Magnetic/kinetic coupling

} **Model-based Control Design**

- **First-principles-driven (FPD) PDE model:** Mix of **widely accepted first-principles laws** and **control-oriented models for transport/sources** by exploiting both empirical (from physical observations) and analytical scalings as well as neural-network accelerated models.

Modeling Poloidal Flux Evolution for Control Design

- **Magnetic Flux (ψ) Dynamics Modeled by 1D Diffusion Equation**

$$\frac{\partial\psi}{\partial t} = \eta(T_e)\left[\frac{1}{\mu_0\rho_b^2\hat{F}^2}\frac{1}{\hat{\rho}}\frac{\partial}{\partial\hat{\rho}}\left(\hat{\rho}\hat{F}\hat{G}\hat{H}\frac{\partial\psi}{\partial\hat{\rho}}\right) + R_0\hat{H}\frac{<\bar{j}_{NI}\cdot\bar{B}>}{B_{\phi,0}}\right], \quad \left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=0} = 0, \quad \left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=1} = -\frac{\mu_0 R_0}{2\pi\hat{G}\hat{H}}I_p(t)$$

Resistivity

Geometric Parameters

Non-inductive CD

$$\frac{\langle\bar{j}_{ni}\cdot\bar{B}\rangle}{B_{\phi,0}} = \frac{\langle\bar{j}_{bs}\cdot\bar{B}\rangle}{B_{\phi,0}} + \sum_{i=1}^{n_{lh}}\frac{\langle\bar{j}_{lh_i}\cdot\bar{B}\rangle}{B_{\phi,0}} + \sum_{i=1}^{n_{nbi}}\frac{\langle\bar{j}_{nbi_i}\cdot\bar{B}\rangle}{B_{\phi,0}}, \qquad \frac{\langle\bar{j}_i\cdot\bar{B}\rangle}{B_{\phi,0}} = j_i^{dep}(\hat{\rho})\frac{T_e(\hat{\rho},t)^{\delta}}{n_e(\hat{\rho},t)}P_{aux_i}(t)$$

Bootstrap

Auxiliary Sources

$$\Phi \triangleq \pi B_{\phi,0}\rho^2, \ \hat{\rho} \triangleq \rho/\rho_b$$

$$q = d\Phi/d\Psi = -\frac{B_{\phi,0}\rho_b^2\hat{\rho}}{\partial\psi/\partial\hat{\rho}}$$

- **Fast Evolving Kinetic Profiles Modeled by Singular Perturbation**

$$T_e(\hat{\rho},t) = T_e^{prof}(\hat{\rho})\frac{I_p(t)^{\alpha}P_{tot}(t)^{\beta}}{\bar{n}_e(t)^{\gamma}} \qquad n_e(\hat{\rho},t) = n_e^{prof}(\hat{\rho})\bar{n}_e(t)$$

Profiles Consistent with Stored Energy (W) Dynamics Modeled by 0D Power Balance

$$\frac{dW}{dt} = -\frac{W}{\tau_W} + P_{tot}(P_{tot} = P_{aux} + P_{ohm} + P_{rad}) \Rightarrow \beta_N = \frac{a(2W/3)}{I_p B_{\phi,0}/(2\mu_0)}, \ \tau_W \propto I_p^{\alpha_s}P_{tot}^{-\beta_s}\bar{n}_e^{\gamma_s}$$

Modeling Poloidal Flux Evolution for Control Design

- **Electron Temperature Profile Modeled by Heat Transport Equation**

  Assuming diffusion is dominant transport mechanism, the T_e dynamics is given by

$$\frac{3}{2}\frac{\partial}{\partial t}\left[n_e T_e\right] = \frac{1}{\rho_b^2 \hat{H}}\frac{1}{\hat{\rho}}\frac{\partial}{\partial \hat{\rho}}\left[\hat{\rho}\frac{\hat{G}\hat{H}^2}{\hat{F}}\left(\chi_e(\cdot) n_e \frac{\partial T_e}{\partial \hat{\rho}}\right)\right] + Q_e^{ohm} + Q_e^{rad} + \sum_i Q_{e_i}^{aux}$$

with boundary conditions $\frac{\partial T_e}{\partial \hat{\rho}}(0,t) = 0$, $T_e(1,t) = T_{e,bdry}$, and where $Q_{e_i}^{aux} = Q_i^{dep}(\hat{\rho}) P_{aux_i}(t)$

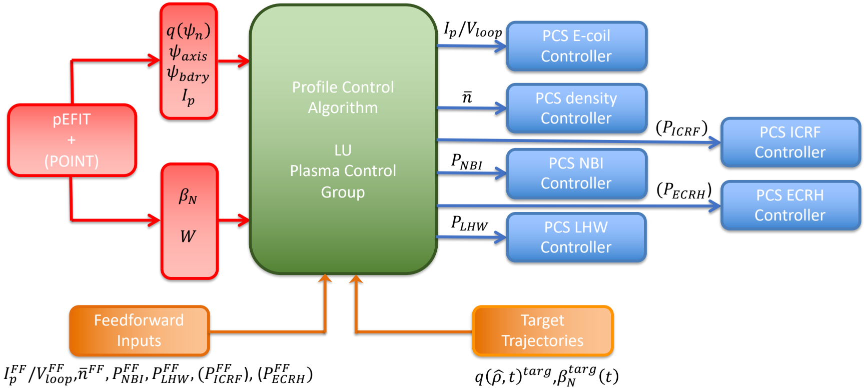
1. Thermal conductivity χ_e can be modeled as an analytical scaling law.
2. Thermal conductivity χ_e can be modeled as an empirical scaling law, e.g. $\chi_e = k_{\chi_e} T_e^{\gamma} n_e^{\nu} q^{\mu} s^{\pi}$
   - + Multi-linear regression from χ_e computed by physics models (TRANSP) to determine structure.
   - + Nonlinear optimization to determine constants:

$$\min_{\theta} J, \quad J = \int_{t_0}^{t_f} \left\{ \sum_{i=1}^{N} \alpha \left[q^{exp}(\hat{\rho}_i,t) - q(\hat{\rho}_i,t)\right]^2 + \beta \left[T_e^{exp}(\hat{\rho}_i,t) - T_e(\hat{\rho}_i,t)\right]^2 \right\} dt, \quad \theta = [k_{\chi_e}\ \gamma\ \nu\ \mu\ \pi].$$

3. Thermal conductivity χ_e can be modeled as state model, e.g. $\chi_e = f(T_e, n_e, q, s)$
   - + Machine Learning techniques → Neural Network training (NEO, TGLF, MMM, ...)

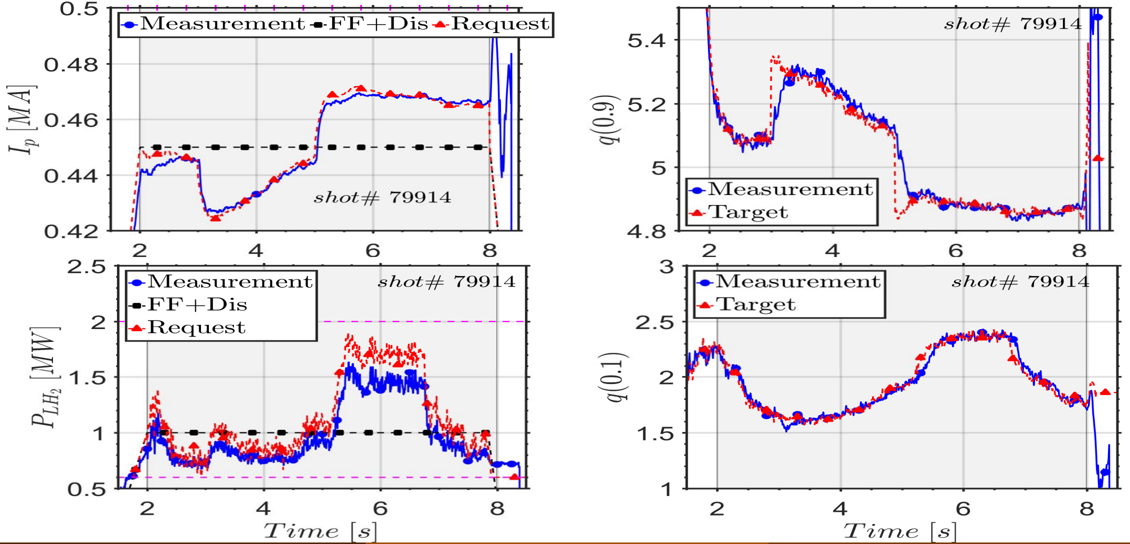
NOTE: Sources $\frac{\langle \bar{j}_i \cdot \bar{B} \rangle}{B_{\phi,0}}$ and $Q_{e_i}^{aux}$ can also be modeled using Machine Learning.

DIII-D/LU Profile Control Category Has Been Coded in EAST PCS

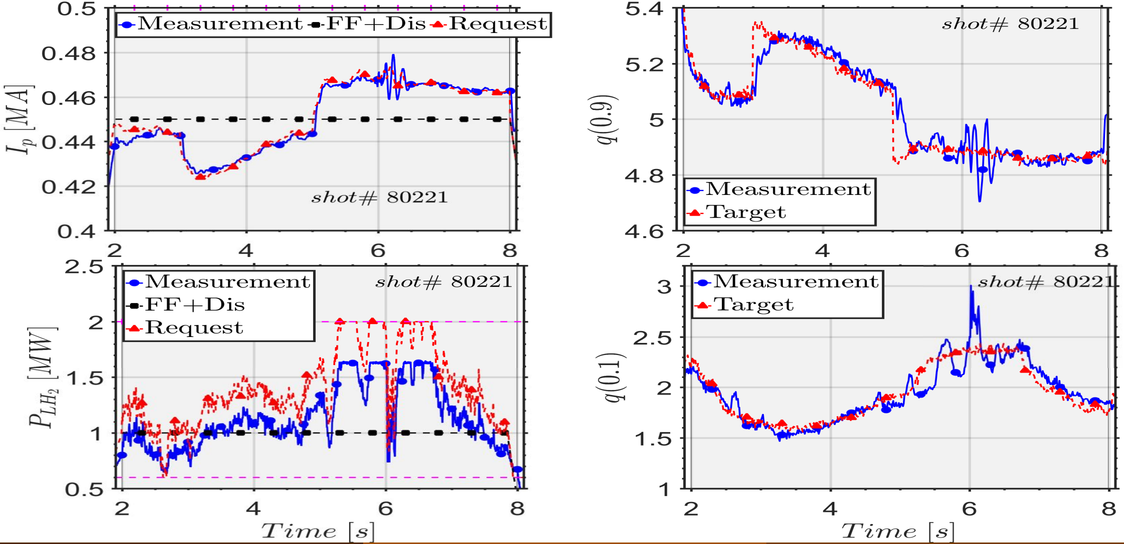


- Profile control algorithm has been coded by LU Plasma Control Group: DIII-D → EAST
- Interfaces have been coded by EAST PCS Team (Prof. Bingjia Xiao):
  - Interface with real-time pEFIT + (POINT)
  - Interface with actuators. Actuators must be under PCS.
  - Interface with user data.

Simultaneous Feedback q-profile Regulation at Edge & Core Was Demonstrated for the First Time in 2018 by Using one LH Source



New Beam Power Modulation Algorithm Implemented in 2018 for Simultaneous q-profile + β_N Control Showed Good Average Tracking



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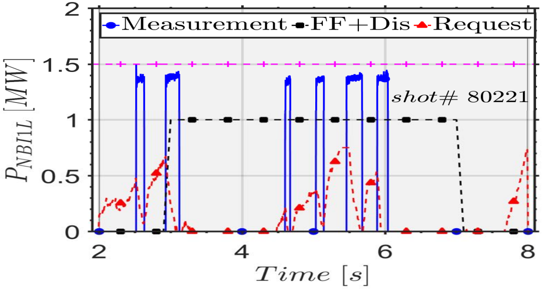
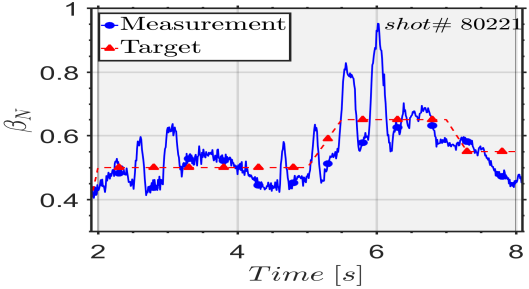
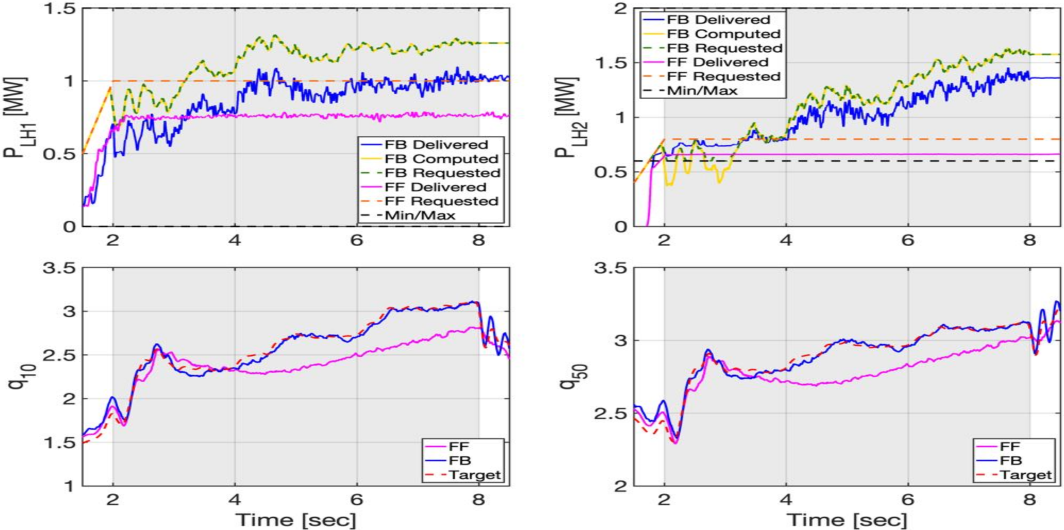




Control Objectives Achieved in 2018

- Simultaneous tracking of desired q profile at $\hat{\rho} = 0.1$ and $\hat{\rho} = 0.9$
- Tracking achieved in “average” when β_N-control is activated
- Beam power too powerful for smooth control at this β_N level

Simultaneous Feedback q-profile Regulation at Three Points Was Demonstrated for the First Time in 2020 by Using two LH Sources



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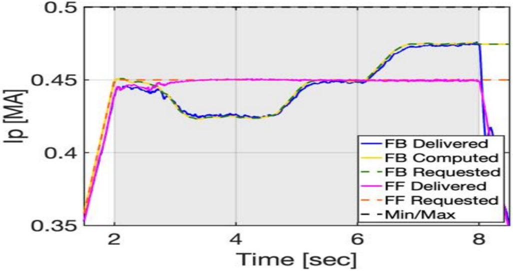

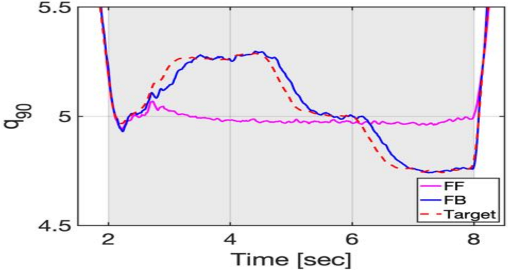

Control Objectives Achieved in 2020

- Incorporated P_{LH245} as actuator mechanism
- Increased # of simultaneously controlled variables: $q_{10}, q_{90} \rightarrow q_{10}, q_{90}, q_{50}$
- Carried out first tests of model-based offline optimal current-profile controller

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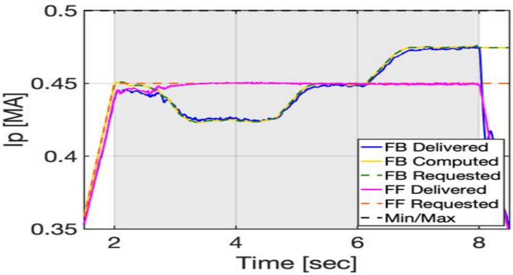

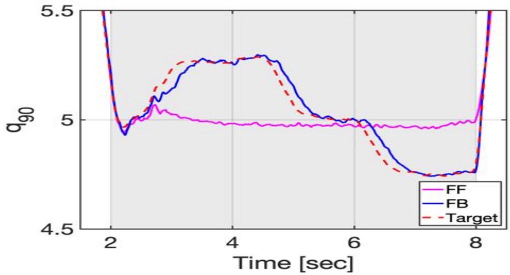

Control Objectives for Upcoming Campaigns

- POINT-constrained EFIT+TRANSP → Improved response models → control redesign
- Experimentally test model-based offline/real-time optimal current-profile controllers
- Make progress towards further control integration:
  - $q_{10}, q_{50}, q_{90} \rightarrow$ combination of $q_{10}, q_{50}, q_{90}, l_i, \beta_p, \beta_N, V_{loop}(a)$ or squared error of whole profile
- Support scenario-development experiments (LLNL)

Research and Development Tasks Needed to Further Enable Long-Pulse High-Performance Scenarios and Control in EAST

Improve Data Analysis Tools to Enable Control Physics Understanding

- **Automatically generate POINT/MSE-constrained EFIT data for all experiments**
  - POINT/MSE-constrained EFIT+TRANSP $\rightarrow$ Modeling (NBI/LHW $\rightarrow q$)
  - Enable further efforts toward LH current/power deposition modeling

Improve Diagnostics Capabilities to Enable Effective Feedback Control

- **Enable routine use of real-time POINT/MSE-constrained pEFIT**

Improve Actuation Capabilities to Allow Further Scenario Development

- **Develop new control algorithms for finer beam-power regulation**
- **Allow operation under PCS of all actuators (NBI, LHW, ICRF, ECRH)**
  - Control of multiple plasma-scenario properties and more advanced profiles