Development and Implementation of Integrated q-profile+β_N Feedback Control Strategies for Advanced Scenarios in EAST

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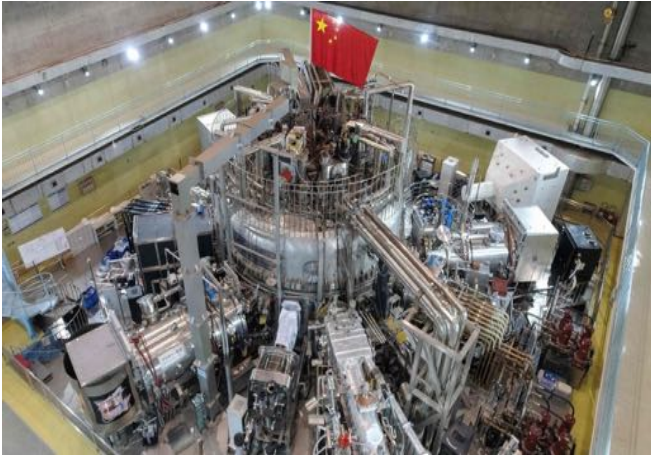

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Need for Advanced Long-Pulse Scenario Control in EAST

- **"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**.

> ⋆ High dimensionality
> ⋆ Nonlinearity
> ⋆ 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+Energy Evolution for Control Design

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

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

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**

$$T_e(\hat{\rho},t)=T_e^{prof}(\hat{\rho})\frac{I_p(t)^{\alpha}P_{tot}(t)^{\beta}}{\bar{n}_e(t)^{\gamma}}\qquad n_e(\hat{\rho},t)=n_e^{prof}(\hat{\rho})\bar{n}_e(t) \tag{2}$$

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

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

Modeling Poloidal-Flux+Energy 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

$$\frac{3}{2}\frac{\partial}{\partial t}\left[n_e T_e\right] = \frac{1}{\rho_b^2 \hat{H}}\frac{1}{\hat{\rho}}\frac{\partial}{\partial \hat{\rho}}\left[\hat{\rho}\frac{\hat{G}\hat{H}^2}{\hat{F}}\left(\chi_e(\cdot) n_e \frac{\partial T_e}{\partial \hat{\rho}}\right)\right] + Q_e^{ohm} + Q_e^{rad} + \sum_i Q_{e_i}^{aux} \quad (4)$$

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:

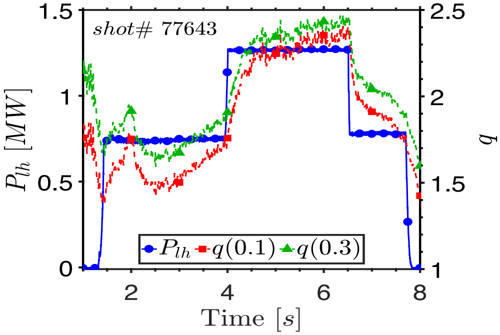
$$\min_{\theta} J, \quad J = \int_{t_0}^{t_f} \left\{ \sum_{i=1}^{N} \alpha \left[q^{exp}(\hat{\rho}_i,t) - q(\hat{\rho}_i,t)\right]^2 + \beta \left[T_e^{exp}(\hat{\rho}_i,t) - T_e(\hat{\rho}_i,t)\right]^2 \right\} dt, \quad \theta = [k_{\chi_e}\ \gamma\ \nu\ \mu\ \pi].$$

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 $\rightarrow$ 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.

Plasma Response Characterization Experiments for Model Tailoring

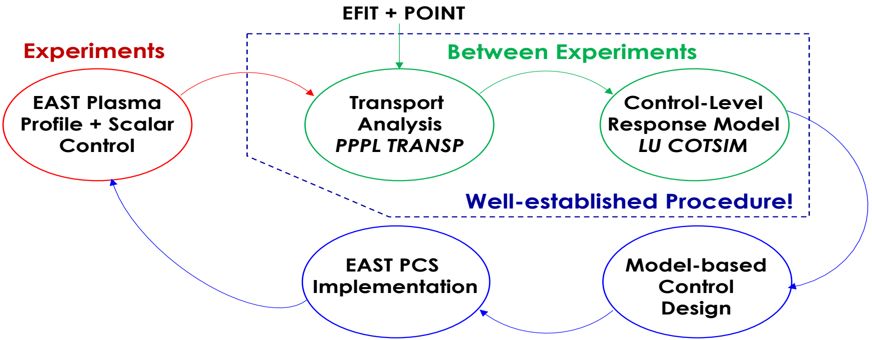
- Several plasma-response characterization experiments were conducted before the q-profile+β_N feedback-control experiments.
- Plasma-response data was generated by exciting the plasma through different available actuators.
- Figure shows typical response of q profile at two spatial locations ($\hat{\rho} \in [0.05, 0.3]$) in response to open-loop excitation of P_{LH2} (4.60 GHz LHW source power) during flattop in shot #77643.
- This data was used to tailor the control-oriented model (1)-(3) to the EAST scenario of interest.



This tailored control-oriented model was used in this work to optimize the gains of the employed fixed-structure controller and to test the PCS implementation of the control algorithm in closed-loop Simserver simulations before experiments

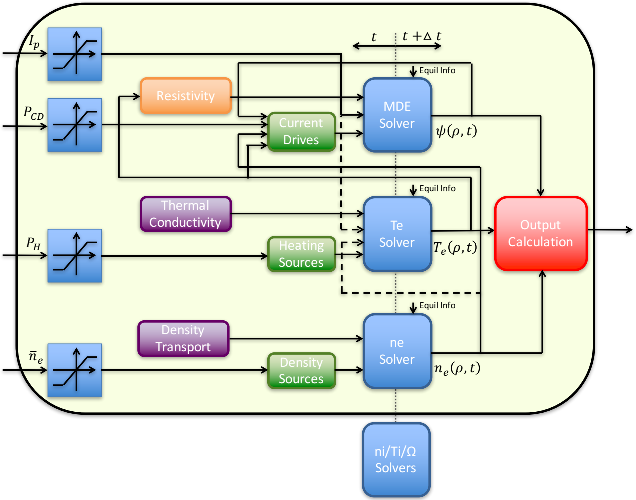
Control-oriented Modeling Enabled by TRANSP Prediction/Analysis

- TRANSP simulations are run in both interpretative and predictive modes to produce plasma response data for the development of lower-complexity, faster, control-oriented models.
- Equilibrium reconstruction constrained by POlarimeter-INTerferometer (POINT) plays critical role in comparing model-predicted q-profile+β_N evolutions with experimental data.



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 (real-time control)

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

Fixed-structure PID-type Feedback Control Algorithm

- The feedback (FB) control algorithms use a proportional-integral-derivative (PID) structure, i.e.

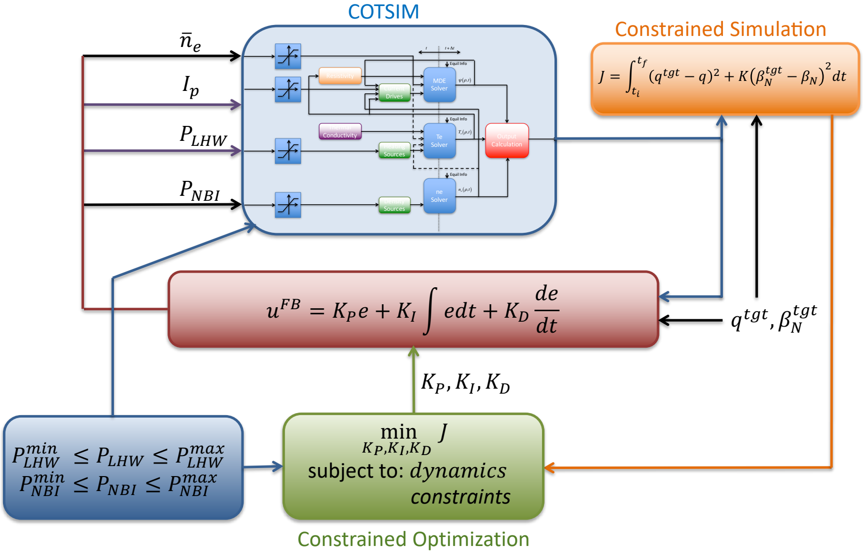
$$u^{FB}(t) = K_P e(t) + K_I \int_o^t e(t) + K_D \frac{de(t)}{dt} \tag{5}$$

where the input/output vectors are defined as

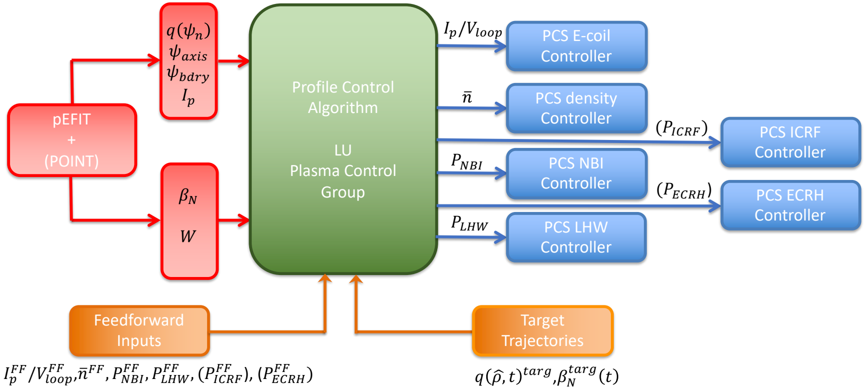
$$u^{FB} = [I_p^{FB} \;\; P_{LH1}^{FB} \;\; P_{LH2}^{FB} \;\; P_{NBI1}^{FB} \;\; P_{NBI2}^{FB} \;\; P_{NBI3}^{FB} \;\; P_{NBI4}^{FB}]^T, \qquad e = \begin{bmatrix} q(0.1) - q^{tgt}(0.1) \\ q(0.5) - q^{tgt}(0.5) \\ q(0.9) - q^{tgt}(0.9) \\ \beta_N - \beta_N^{tgt} \end{bmatrix}. \tag{6}$$

- Actuators considered in this work: total plasma current I_p, 2.45 GHz LWH source power P_{LH1}, 4.6 GHz LHW source power P_{LH2}, individual co-current NBI powers (P_{NBI1} (NBI1L), P_{NBI2} (NBI1R)), and individual counter-current NBI powers (P_{NBI3} (NBI2L), P_{NBI4} (NBI2R)).
- K_P, K_I, K_D are gain matrices optimized in simulations based on control-oriented model (1)-(3).
- The superscript tgt denotes target values for the to-be-controlled plasma properties.

Model-based PID Gain Optimization Before Experimental Testing

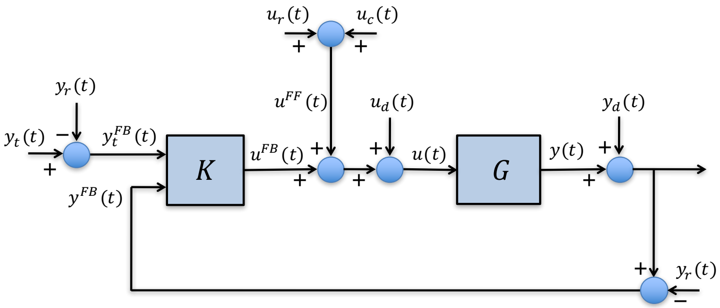


DIII-D/LU Profile Control Category Has Been Coded in EAST PCS



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

Profile/Scalar Control Configuration in Profile Control Category



Overall input for plant G (EAST):

$$u = u^{FF} + u^{FB} + u_d + (s), \qquad (7)$$

Overall input for Controller K:

$$y^{FB} = y + y_d - y_r. \qquad (8)$$

To-be-tracked target:

$$y_t^{FB} = y_t - y_r. \qquad (9)$$

- u^{FF}: feedforward control, u^{FB}: feedback control (output of controller K), u_d: input disturbance.
- $u^{FF} = u_r + u_c$, u_r: input reference, u_c: output of feedforward compensator.
- s: output of an optional anti-windup (AW) compensator (signal added only when AW is on).
- y: overall plant output, y_d: output disturbance, y_r: output reference (associated with u_r).
- y_t^{FB}: reference-modified output target (linearized-model-based controllers), y_t: output target.

Profile/Scalar Control Configuration in Profile Control Category

- One controller implemented in Profile Control category has linear state-space representation:

$$x_{k+1} = Ax_k + B \begin{bmatrix} y_t - y_r \\ y + y_d - y_r \end{bmatrix}_k, \qquad u_k^{FB} = Cx_k + D \begin{bmatrix} y_t - y_r \\ y + y_d - y_r \end{bmatrix}_k, \tag{10}$$

- **IMPORTANT: After time discretization, proposed controller** (5) **can be implemented in the Profile Category by using this linear discrete-time state-space representation.**
- Controller (10) is complemented by an anti-windup compensator in discrete-time state-space form:

$$x_{k+1}^{aw} = A_{aw}x_k^{aw} + B_{aw}\left[sat(u) - u\right]_k, \qquad s_{k+1} = C_{aw}x_k^{aw} + D_{aw}\left[sat(u) - u\right]_k, \tag{11}$$

- The saturation function is defined as

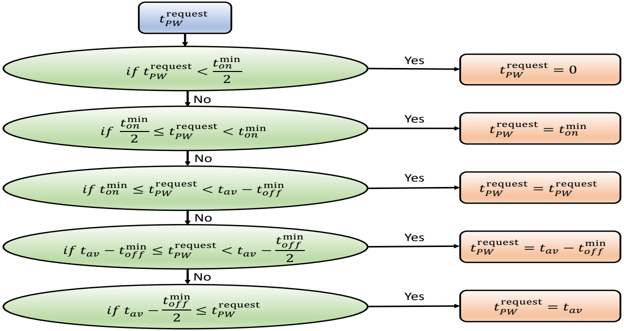
$$sat(\cdot) = \begin{cases} (\cdot)^{min} & \text{if } (\cdot) < (\cdot)^{min} \\ (\cdot) & \text{if } (\cdot)^{min} \leq (\cdot) \leq (\cdot)^{max} \\ (\cdot)^{max} & \text{if } (\cdot) > (\cdot)^{max} \end{cases}$$

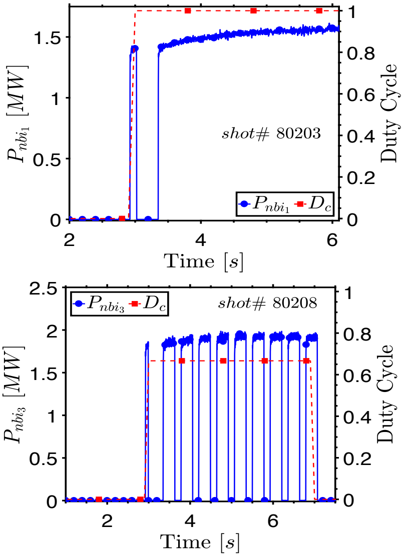
Pulse Width Modulation for the Command of NBI Power

A pulse width request $t_{PW}^{request}$ is first defined based on a chosen averaging time interval t_{av} and a given duty cycle D_c defined by the requested/maximum NBI power ratio, i.e.

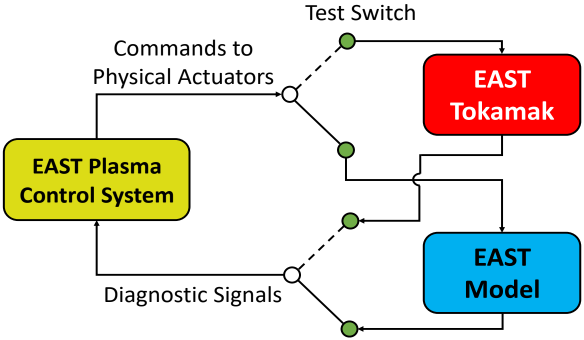
$$t_{PW}^{request} = D_c t_{av}, \qquad D_c = \frac{P_{NBI}}{P_{NBI}^{max}}. \qquad (12)$$

Algorithm below guarantees fulfillment of minimum on/off times:





Simserver Simulations Enable Debugging Before Experiments



- Connection is built between response model (1)-(3) ($\psi, W \rightarrow q, \beta_N$ dynamics) and PCS
- Enables debugging of the algorithm implementation in the Profile Control category
- Validates real-time computations carried out by the implemented control algorithm
  - Uses model-based predicted diagnostic data before experimental testing

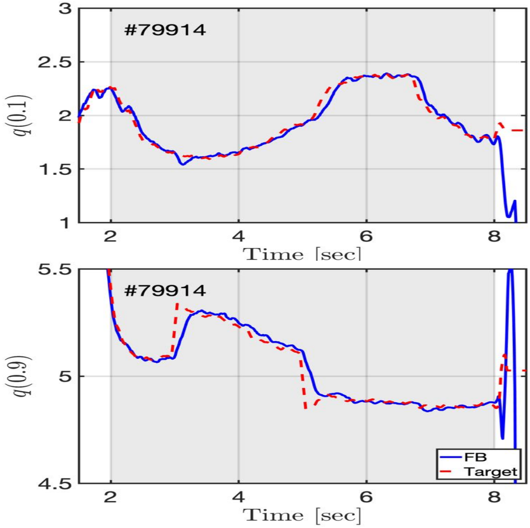
Simultaneous Feedback q-profile Regulation at Edge & Core Was Demonstrated for the First Time by Using 4.60 GHz LHW Source

- Tracking of desired q profile at $\hat{\rho} = 0.1$ and $\hat{\rho} = 0.9$ is achieved by using I_p and P_{LH2} actuation.

- Feedback control (FB) is turned on for $2s < t < 8s$ (indicated by light-gray background in figures).

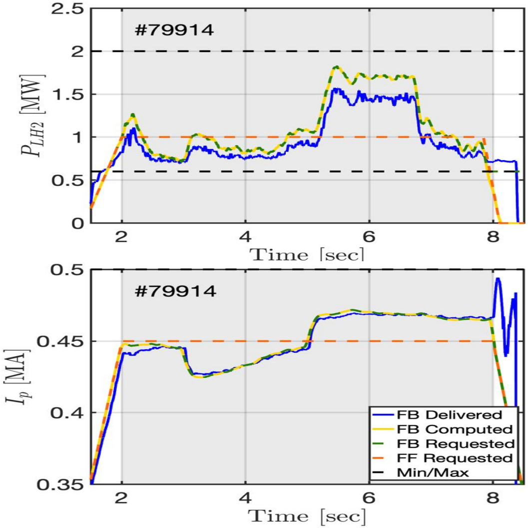
- Feedforward-control components are modified by feedback controller so that actual evolutions (solid-blue) track targets (dashed-red).

- Target evolutions for the q profile at these 2 points were obtained from actual shot to ensure feasibility.

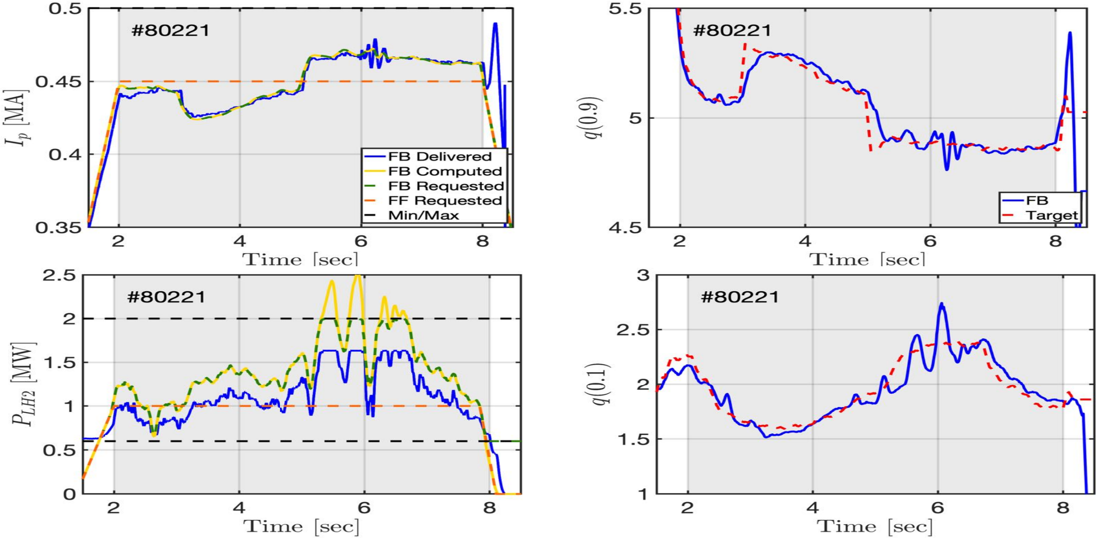


Simultaneous Feedback q-profile Regulation at Edge & Core Was Demonstrated for the First Time by Using 4.60 GHz LHW Source

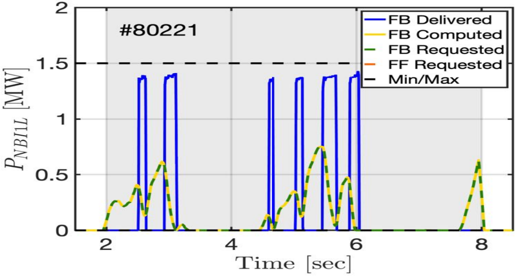
- Feedforward (FF) control (dashed- orange lines) is corrected by feedback (FB) controller to produce requested actuation (dashed-green lines).
- There is a bias between requested (dashed-green lines) and delivered (solid-blue lines) LHW power due to the way this actuator is controlled.
- In spite of bias, the FB controller is capable of tracking targets due to presence of integral action.
- The requested actuation (dashed-green lines) is the result of constraining the actuation computed by the FB controller (solid-yellow lines) by the physical limits associated to the different actuators.
- These saturation limits (dashed-black lines) were not active in this discharge.

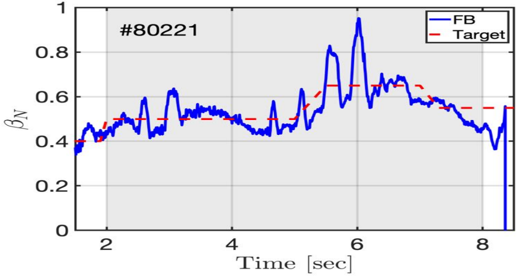


New Beam Power Modulation Algorithm Implemented in PCS for Simultaneous q-profile $+\beta_N$ Control Showed Good Average Tracking



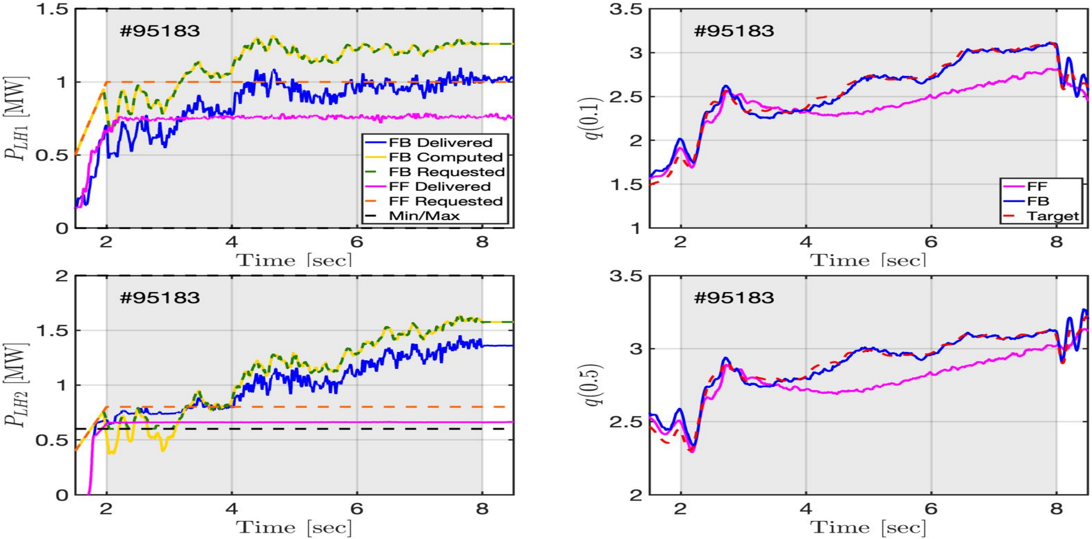
New Beam Power Modulation Algorithm Implemented in 2018 for Simultaneous q-profile + β_N Control Showed Good Average Tracking





- Tracking of desired q profile at $\hat{\rho} = 0.1$, $\hat{\rho} = 0.9$ and β_N is achieved by using I_p, P_{LH2} and P_{NBI1} actuation
- PWM algorithm (12) was used with mixed results to command the NBI1L source ($P_{NBI1} = P_{NBI1L}$)
- The targets are tracked in average but the PWM algorithm introduces significant perturbations due to:
  + Minimum on/off time constraints significantly impacting this relatively low-β_N plasma
  + Detected implementation issues: i- FF control set to zero, ii- time delay introduced by PWM algorithm

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



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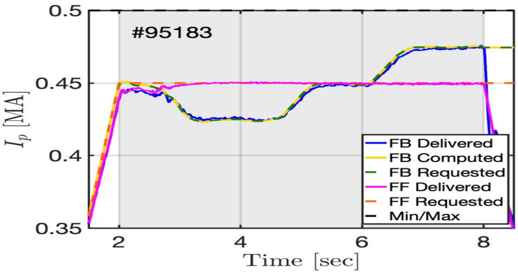
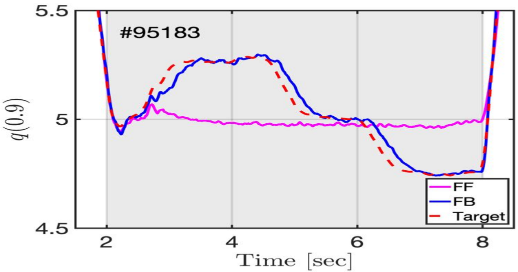
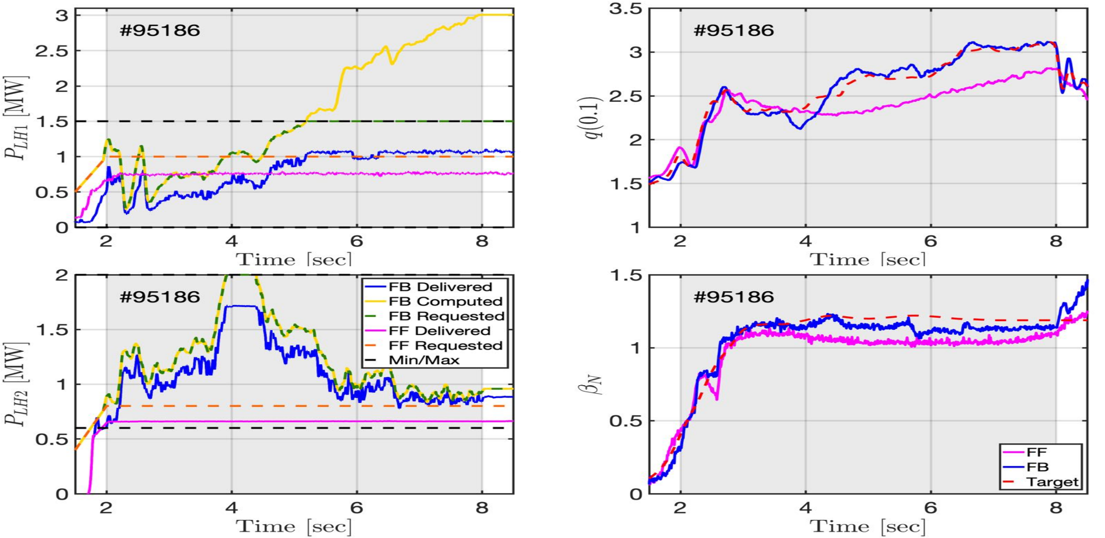




- Tracking of desired q profile at $\hat{\rho} = 0.1$, $\hat{\rho} = 0.5$, $\hat{\rho} = 0.9$ is achieved by using I_p, P_{LH1}, and P_{LH2} actuation
- Solid-magenta lines show q-profile evolutions at these points for feedforward-only EAST shot #95176.
- FF control needs to be modified by FB control for actual (solid-blue) profile to track target (dashed-red)
- Saturation in the 4.60 GHz LWH power (P_{LH2}) is briefly observed at the beginning of FB-on window.
- Around 1MW of ECRF H&CD power was used in this and subsequent shots to keep plasma in H-mode.

Simultaneous Feedback Regulation of Two Points of the q Profile and β_N Was Experimentally Tested by Using two LHW Sources



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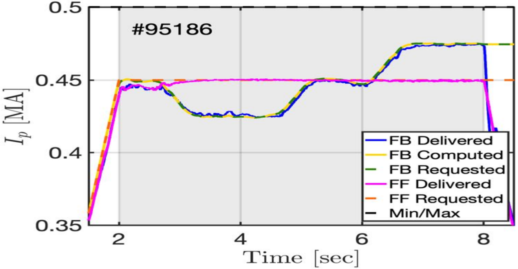
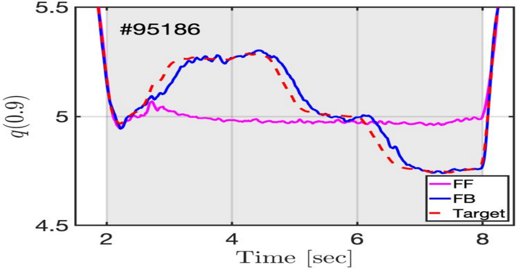
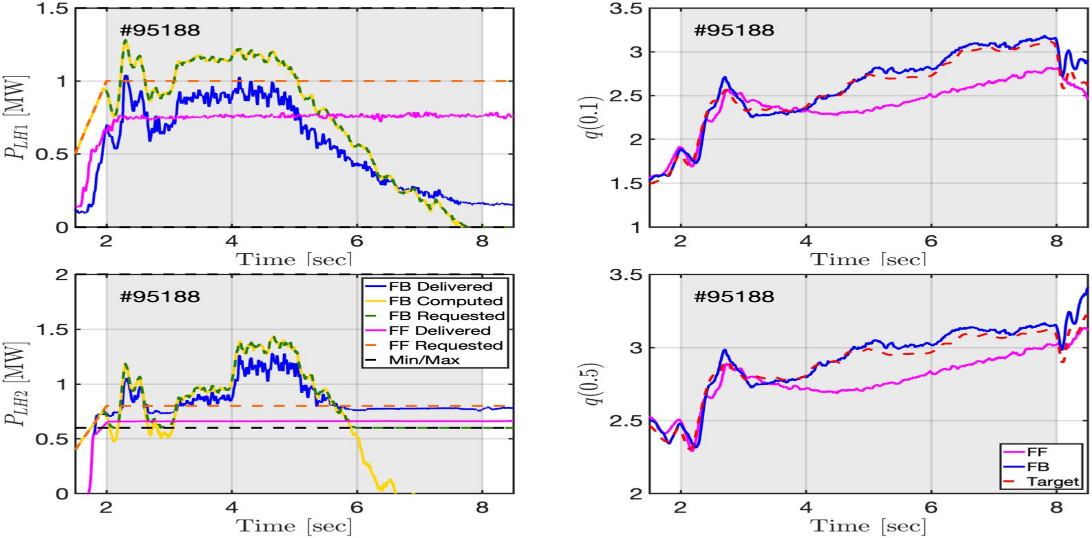




- Tracking of desired q profile at $\hat{\rho} = 0.1$, $\hat{\rho} = 0.9$ and β_N is achieved by using I_p, P_{LH1}, and P_{LH2} actuation
- Solid-magenta lines show q-profile evolutions at these points for feedforward-only EAST shot #95176.
- FF control needs to be modified by FB control for actual (solid-blue) profile to track target (dashed-red)
- Saturation in the 2.45 GHz LWH power (P_{LH1}) is observed after around 5 sec. as the combined q-profile+β_N controllers tries to track the β_N target more closely while controlling q at $\hat{\rho} = 0.1$, $\hat{\rho} = 0.9$.

Simultaneous Feedback q-profile Regulation at Three Points Was Demonstrated Even Under the Presence of Input Disturbances



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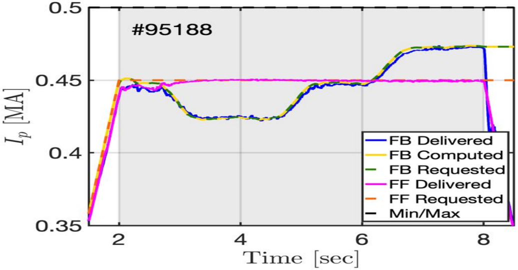

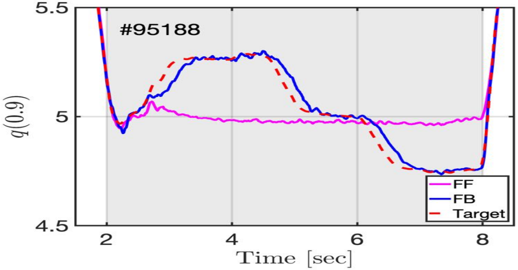

- Tracking of desired q profile at $\hat{\rho} = 0.1$, $\hat{\rho} = 0.5$, $\hat{\rho} = 0.9$ is achieved by using I_p, P_{LH1}, and P_{LH2} actuation
- Solid-magenta lines show q-profile evolutions at these points for feedforward-only EAST shot #95176.
- FF control needs to be modified by FB control for actual (solid-blue) profile to track target (dashed-red)
- Shot similar to #95183 but introducing 0.3 MW perturbation in the 4.60 GHz LWH power (P_{LH2}) for $t \in [4, 6]$.
- FB controller starts reducing request of LHW power after actual (solid-blue line) q values at $\hat{\rho} = 0.1$ and $\hat{\rho} = 0.5$ exceed targets. Tracking improvement is limited by lower-limit saturation of P_{LH2} after 6 sec.

Development and Implementation of Integrated q-profile+β_N Feedback Control Strategies for Advanced Scenarios in EAST

- Successful q-profile+β_N control was demonstrated for the first time in EAST
- Task 1: Number of actuators under the Profile Category in the PCS should be increased by:
  - Enhancing the NBI PWM algorithm and testing it in H-mode plasmas
  - Incorporating the command of ECRF and ICRF H&CDs
- Task 2: The quality of the real-time reconstruction of the q profile needs to be improved by constraining pEFIT with POINT measurements
- Task 3: The accuracy of the control-level models used for control design should be enhanced by further developing control-physics understanding and continuing validation efforts
- Completion of these tasks will further augment capability of tightly regulating q-profile and β_N to routinely enable access to long-pulse, disruption-free, high-performance operation in EAST
- It is anticipated that this augmented control capability will be achieved by employing more sophisticated, model-based, optimal, control algorithms.