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

E. Schuster[1], H. Wang[1], Z. Wang[1], Y. Huang[2], Z. Luo[2], B. Xiao[2], Q. Yuan[2], J. Barr[3], D.A. Humphreys[3], A.W. Hyatt[3], M.L. Walker[3], W.P. Wehner[3]

[1] Lehigh University, Bethlehem, Pennsylvania 18015, USA, [2] Institute of Plasma Physics (CAS), Hefei, P. R. of China, [3] General Atomics, San Diego, California, USA
E-mail: schuster@lehigh.edu

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**

$$\underbrace{\frac{\partial\psi}{\partial t}=\eta(T_e)}_{\text{Resistivity}}\left[\underbrace{\frac{1}{\mu_0\rho_b^2\hat{F}^2}\frac{1}{\hat{\rho}}\frac{\partial}{\partial\hat{\rho}}\left(\hat{\rho}\hat{F}\hat{G}\hat{H}\frac{\partial\psi}{\partial\hat{\rho}}\right)}_{\text{Geometric Parameters}}+\underbrace{R_0\hat{H}\frac{<\bar{j}_{NI}\cdot\bar{B}>}{B_{\phi,0}}}_{\text{Non-inductive CD}}\right],\quad \left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=0}=0,\quad \left.\frac{\partial\psi}{\partial\hat{\rho}}\right|_{\hat{\rho}=1}=-\frac{\mu_0R_0}{2\pi\hat{G}\hat{H}}I_p(t) \qquad (1)$$

$$\frac{\langle\bar{j}_{NI}\cdot\bar{B}\rangle}{B_{\phi,0}}=\underbrace{\frac{\langle\bar{j}_{BS}\cdot\bar{B}\rangle}{B_{\phi,0}}}_{\text{Bootstrap}}+\underbrace{\sum_{i=1}^{n_{lh}}\frac{\langle\bar{j}_{LH_i}\cdot\bar{B}\rangle}{B_{\phi,0}}+\sum_{i=1}^{n_{nbi}}\frac{\langle\bar{j}_{NBI_i}\cdot\bar{B}\rangle}{B_{\phi,0}}}_{\text{Auxiliary Sources}},\qquad \frac{\langle\bar{j}_i\cdot\bar{B}\rangle}{B_{\phi,0}}=j_i^{dep}(\hat{\rho})\frac{T_e(\hat{\rho},t)^{\delta}}{n_e(\hat{\rho},t)}P_{aux_i}(t)$$

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

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

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

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

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

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

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

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:

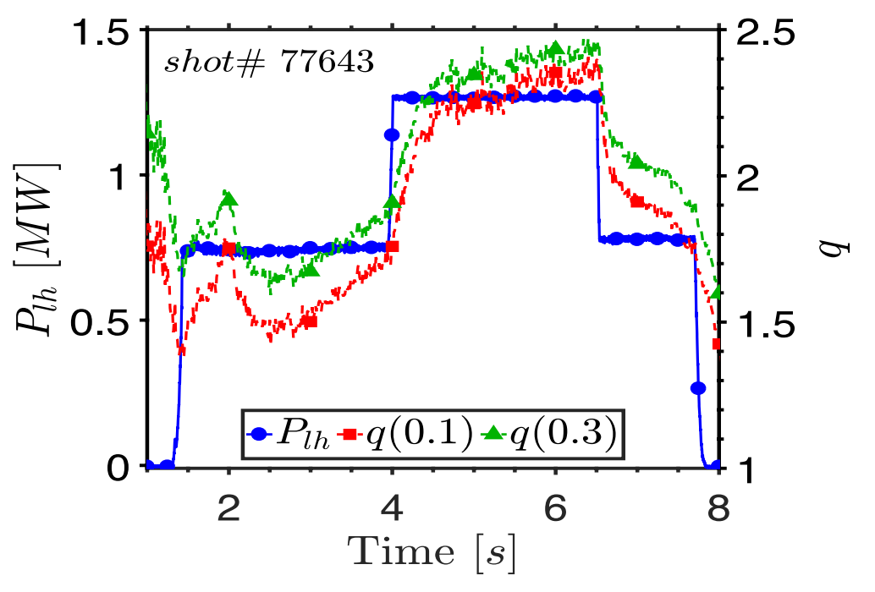
$$\min_{\theta} J,\quad J=\int_{t_0}^{t_f}\left\{\sum_{i=1}^{N}\alpha\left[q^{exp}(\hat{\rho}_i,t)-q(\hat{\rho}_i,t)\right]^2+\beta\left[T_e^{exp}(\hat{\rho}_i,t)-T_e(\hat{\rho}_i,t)\right]^2\right\}dt,\quad \theta=[k_{\chi_e}\ \gamma\ \nu\ \mu\ \pi].$$

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 → 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

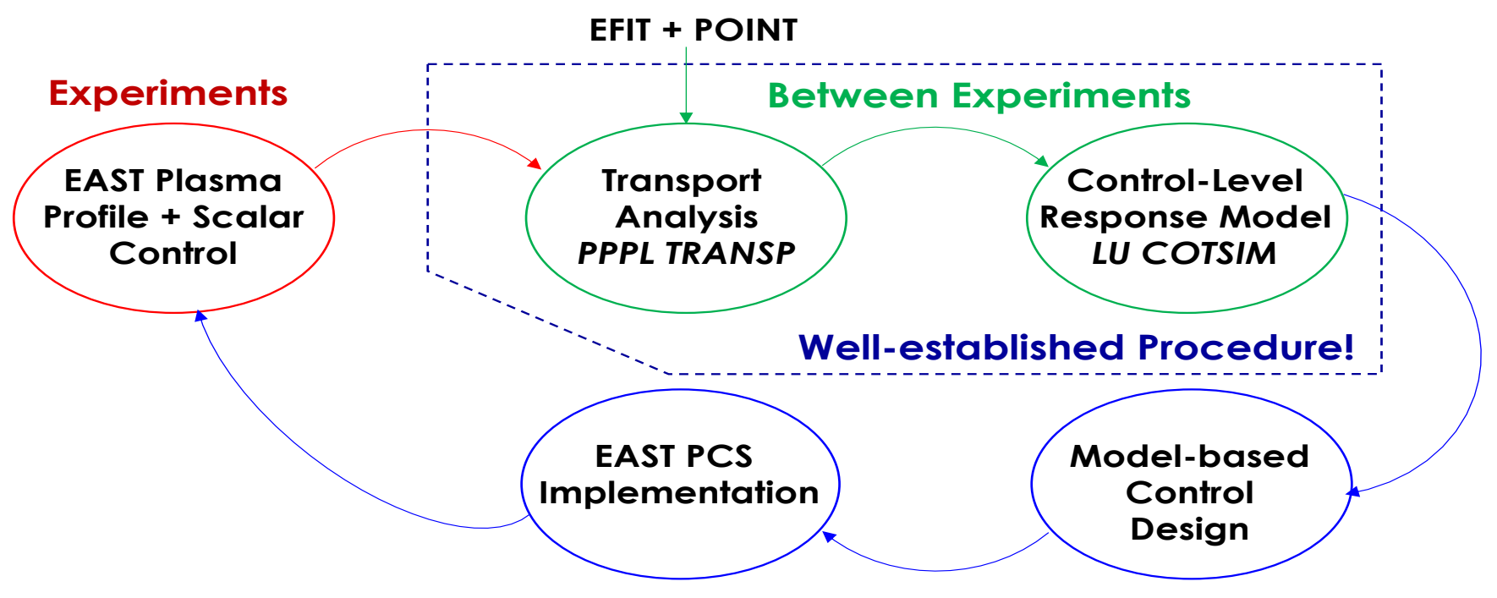
- Several plasma-response characterization experiments were conducted before the q-profile+β_N feedback-control experiments.
- Plasma-response data was generated by exciting the plasma through different available actuators.
- Figure shows typical response of q profile at two spatial locations ($\hat{\rho}\in[0.05,0.3]$) 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

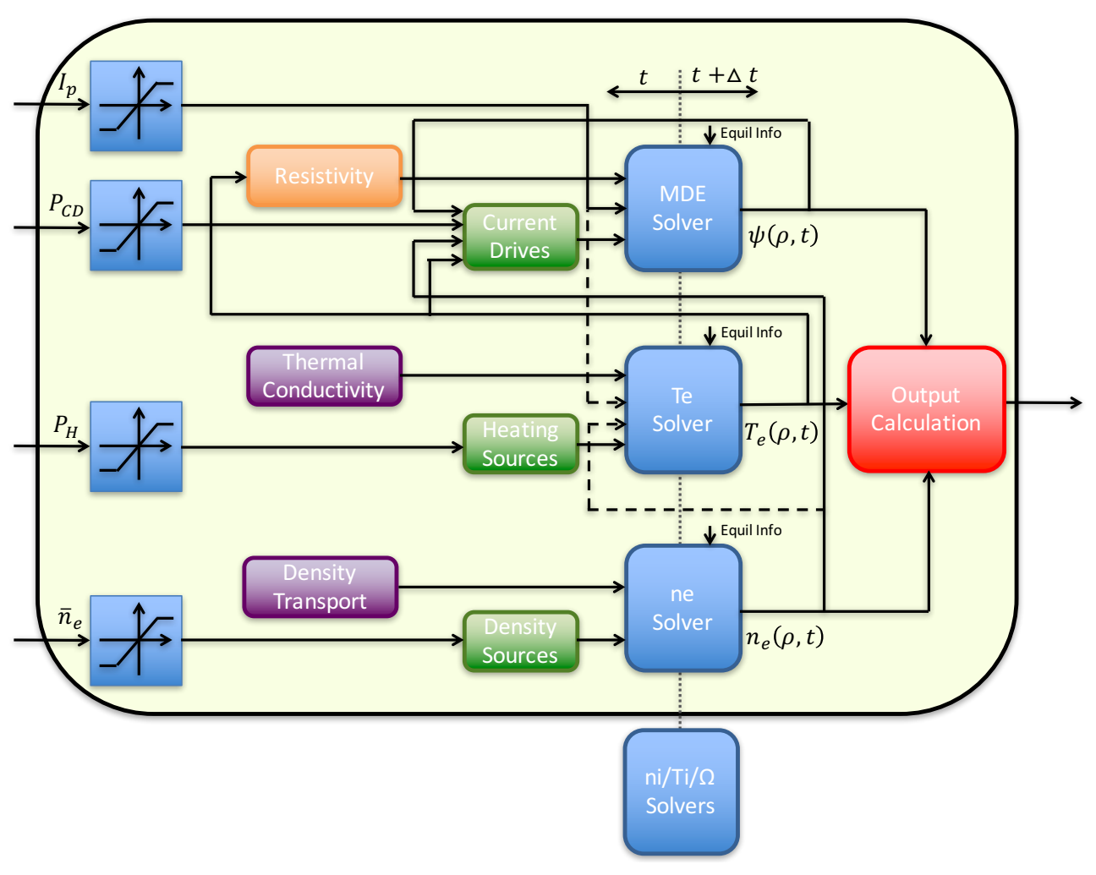
Control-oriented Modeling Enabled by TRANSP Prediction/Analysis

- 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.

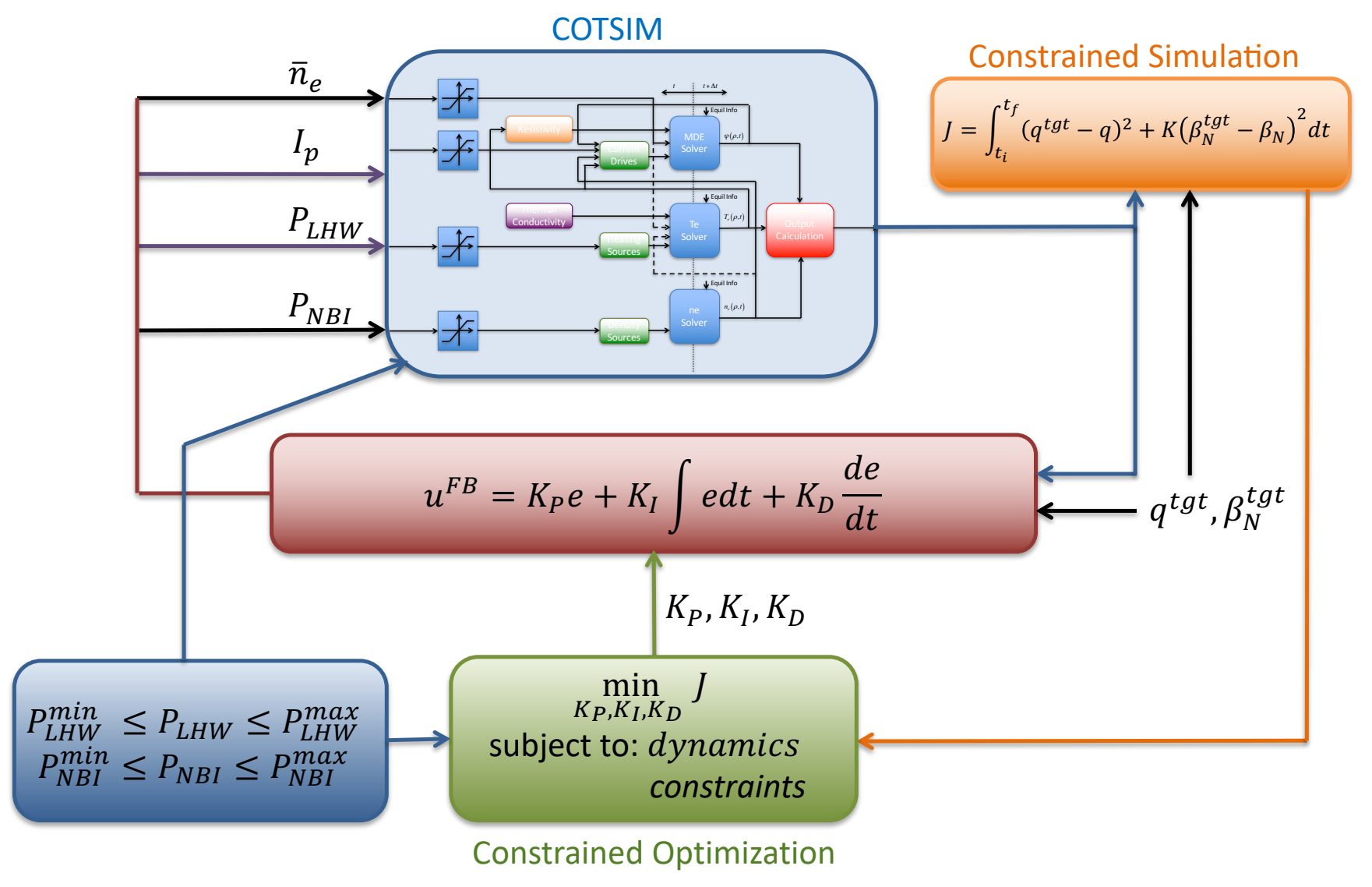
$$u^{FB}(t)=K_Pe(t)+K_I\int_o^t e(t)+K_D\frac{de(t)}{dt} \qquad (5)$$

where the input/output vectors are defined as

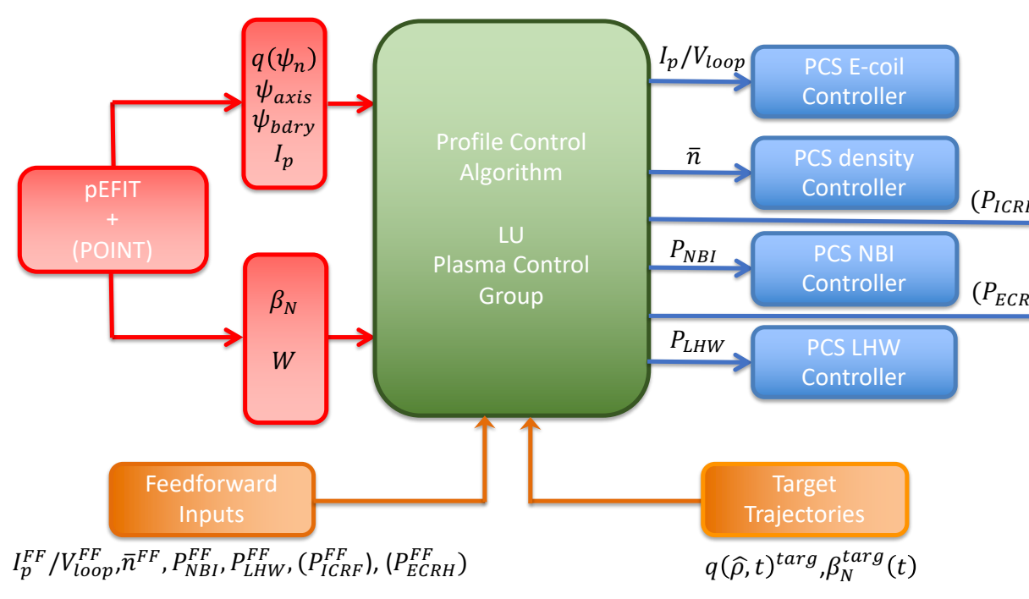
$$u^{FB}=[I_p^{FB}\ P_{LH1}^{FB}\ P_{LH2}^{FB}\ P_{NBI1}^{FB}\ P_{NBI2}^{FB}\ P_{NBI3}^{FB}\ P_{NBI4}^{FB}]^T,\qquad e=\begin{bmatrix}q(0.1)-q^{tgt}(0.1)\\ q(0.5)-q^{tgt}(0.5)\\ q(0.9)-q^{tgt}(0.9)\\ \beta_N-\beta_N^{tgt}\end{bmatrix}. \qquad (6)$$

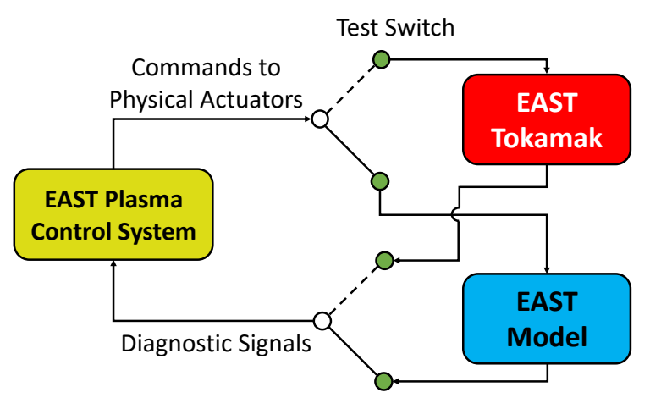
- Actuators considered in this work: total plasma current I_p, 2.45 GHz LWH source power P_{LH1}, 4.6 GHz LHW source power P_{LH2}, individual co-current NBI powers (P_{NBI1} (NBI1L), P_{NBI2} (NBI1R)), and individual counter-current NBI powers (P_{NBI3} (NBI2L), P_{NBI4} (NBI2R)).
- K_P, K_I, K_D are 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

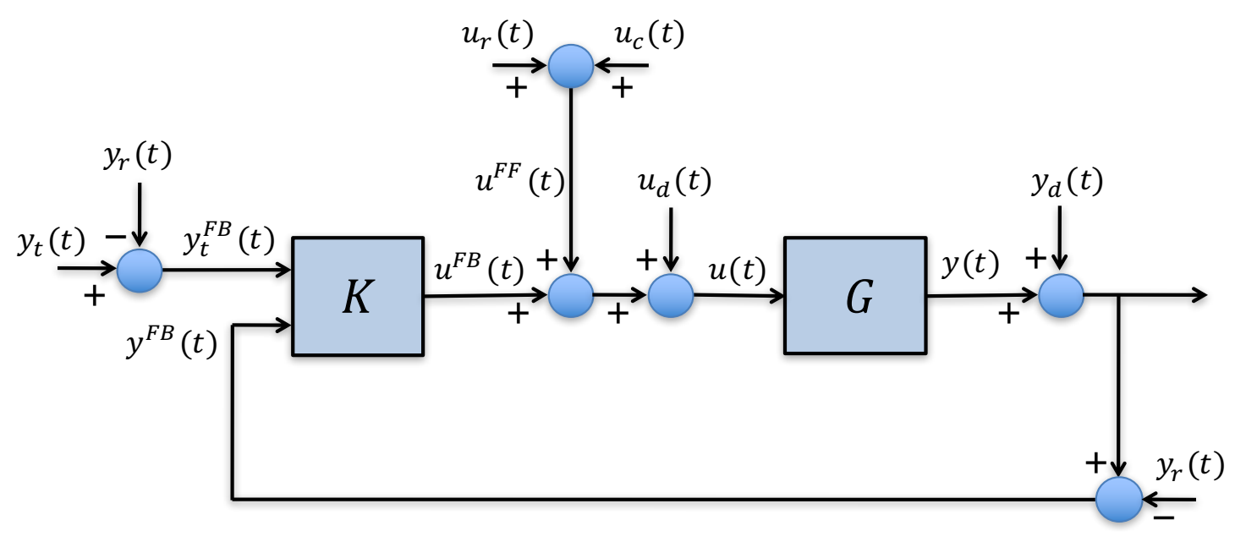




Connection between response model (1)-(3) and PCS enables debugging before experiments

- 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:

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

- **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:

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

- The saturation function is defined as

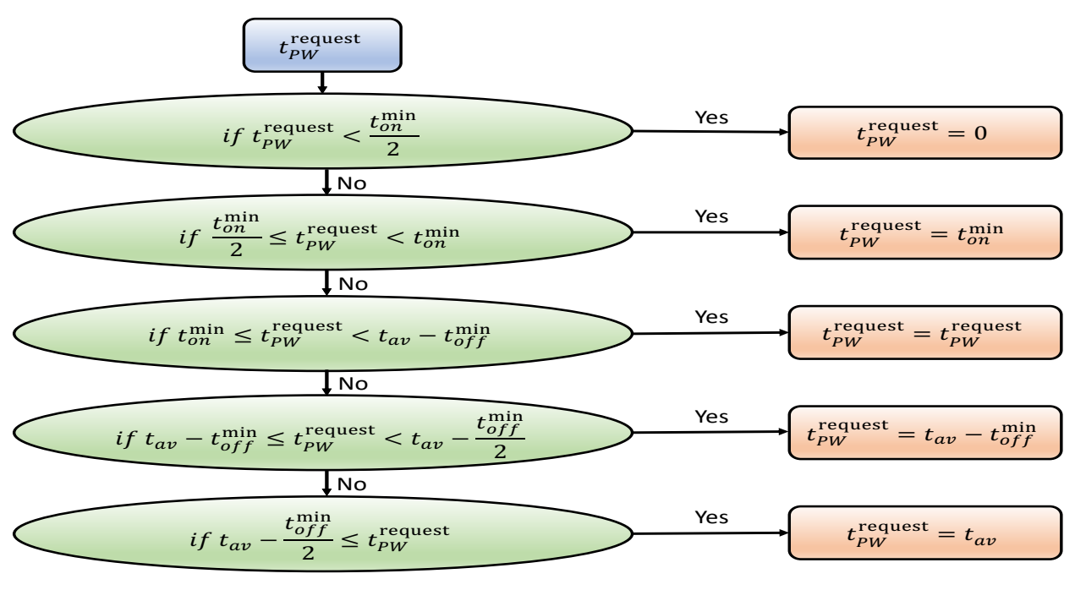
$$sat(\cdot)=\begin{cases}(\cdot)^{min} & \text{if } (\cdot)<(\cdot)^{min}\\ (\cdot) & \text{if } (\cdot)^{min}\le(\cdot)\le(\cdot)^{max}\\ (\cdot)^{max} & \text{if } (\cdot)>(\cdot)^{max}\end{cases}$$

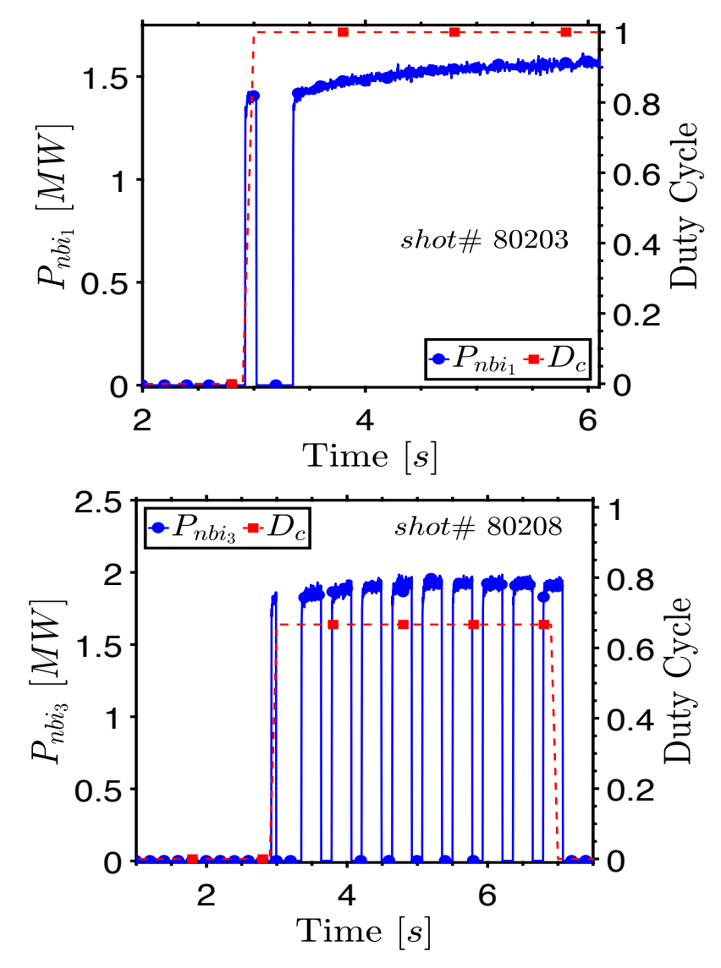
Pulse Width Modulation for the Command of NBI Power

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.

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

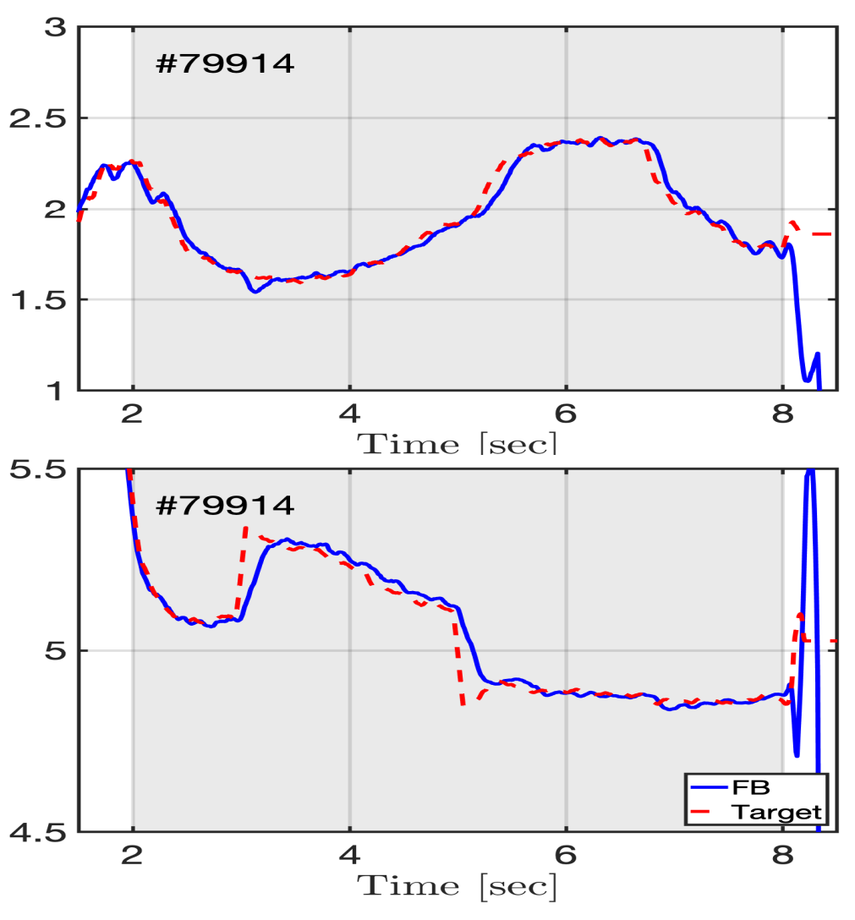
Algorithm below guarantees fulfillment of minimum on/off times:





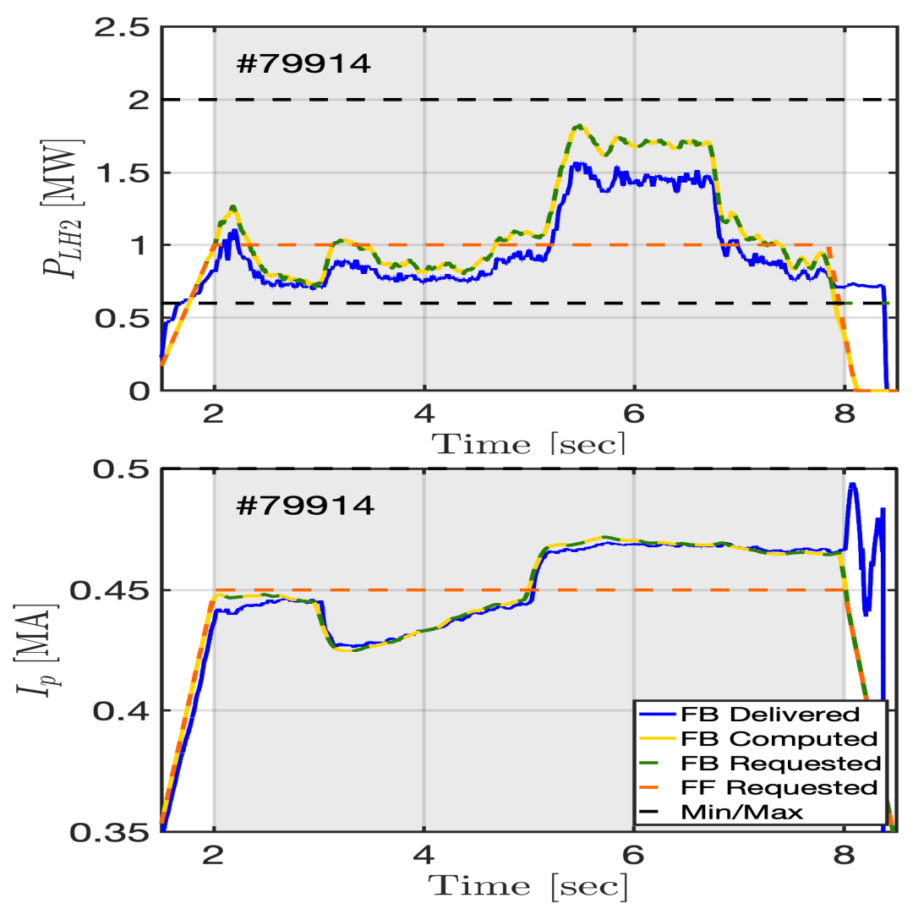
Simultaneous Feedback q-profile Regulation at Edge & Core Was Demonstrated for the First Time by Using 4.60 GHz LHW Source

- 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.

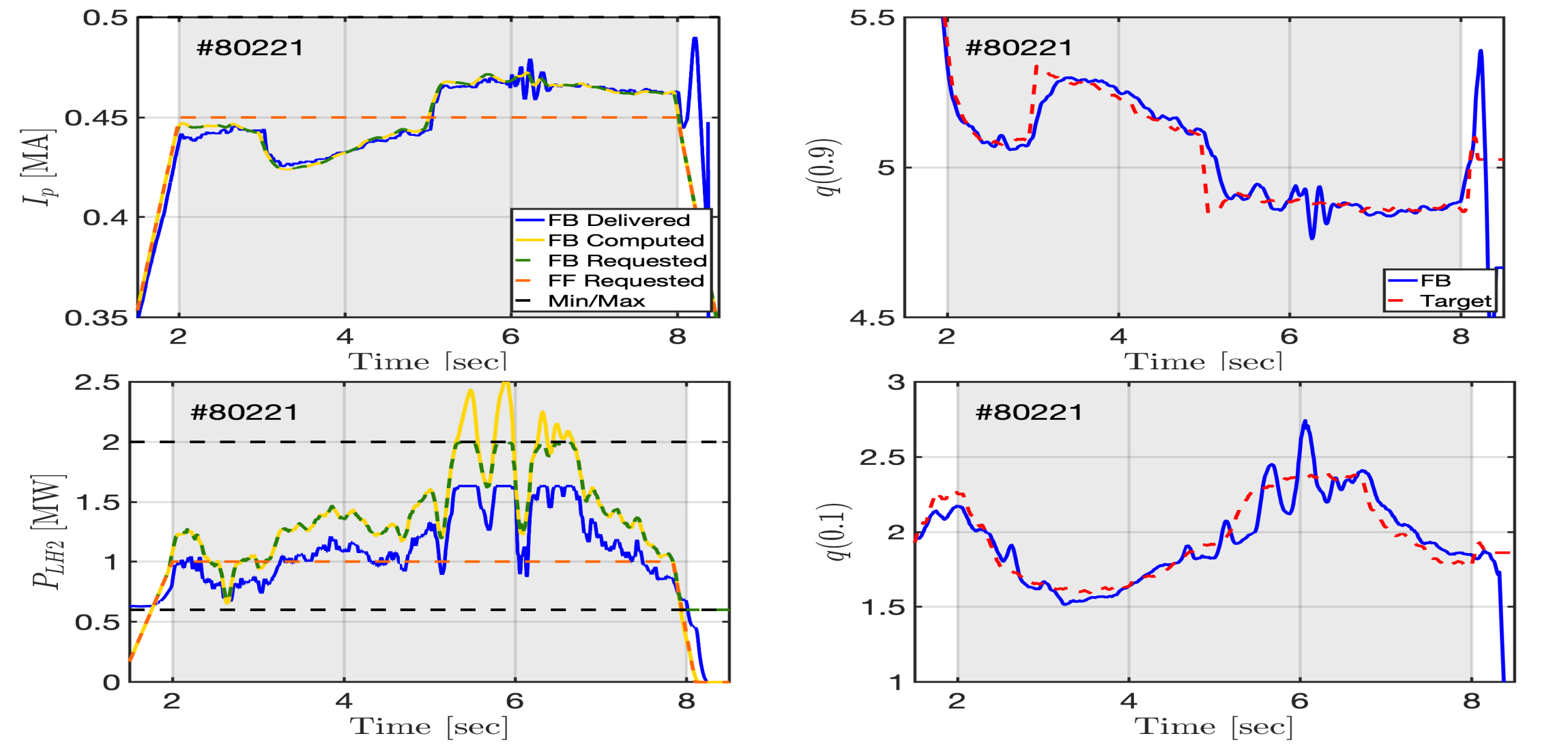


Simultaneous Feedback q-profile Regulation at Edge & Core Was Demonstrated for the First Time by Using 4.60 GHz LHW Source

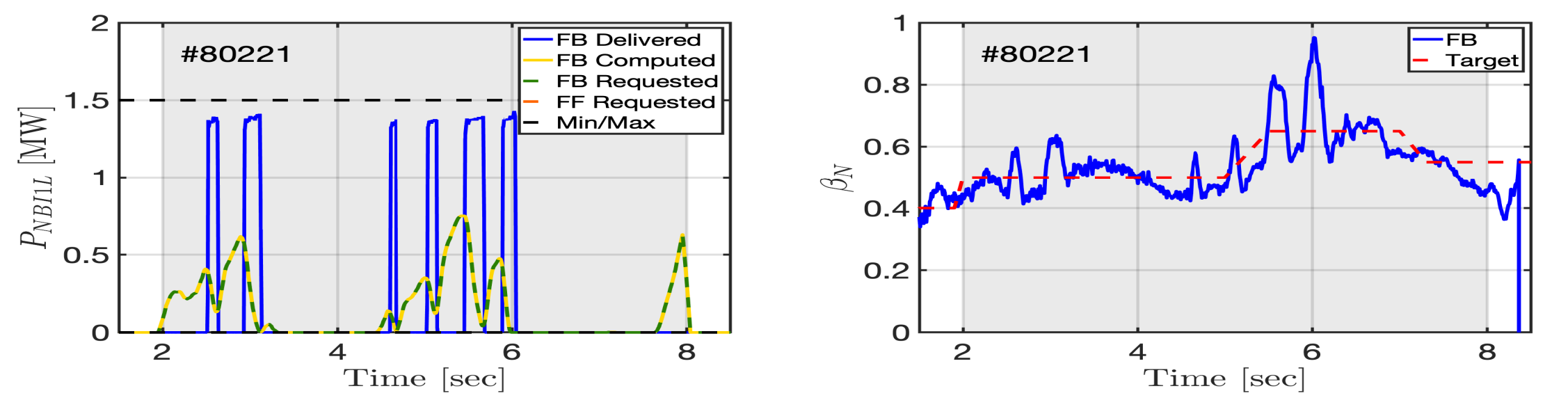
- Feedforward (FF) control (dashed- orange lines) is corrected by feedback (FB) controller to produce requested actuation (dashed-green lines).
- There is a bias between requested (dashed-green lines) and delivered (solid-blue lines) LHW power due to the way this actuator is controlled.
- In spite of 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 +β_N Control Showed Good Average Tracking

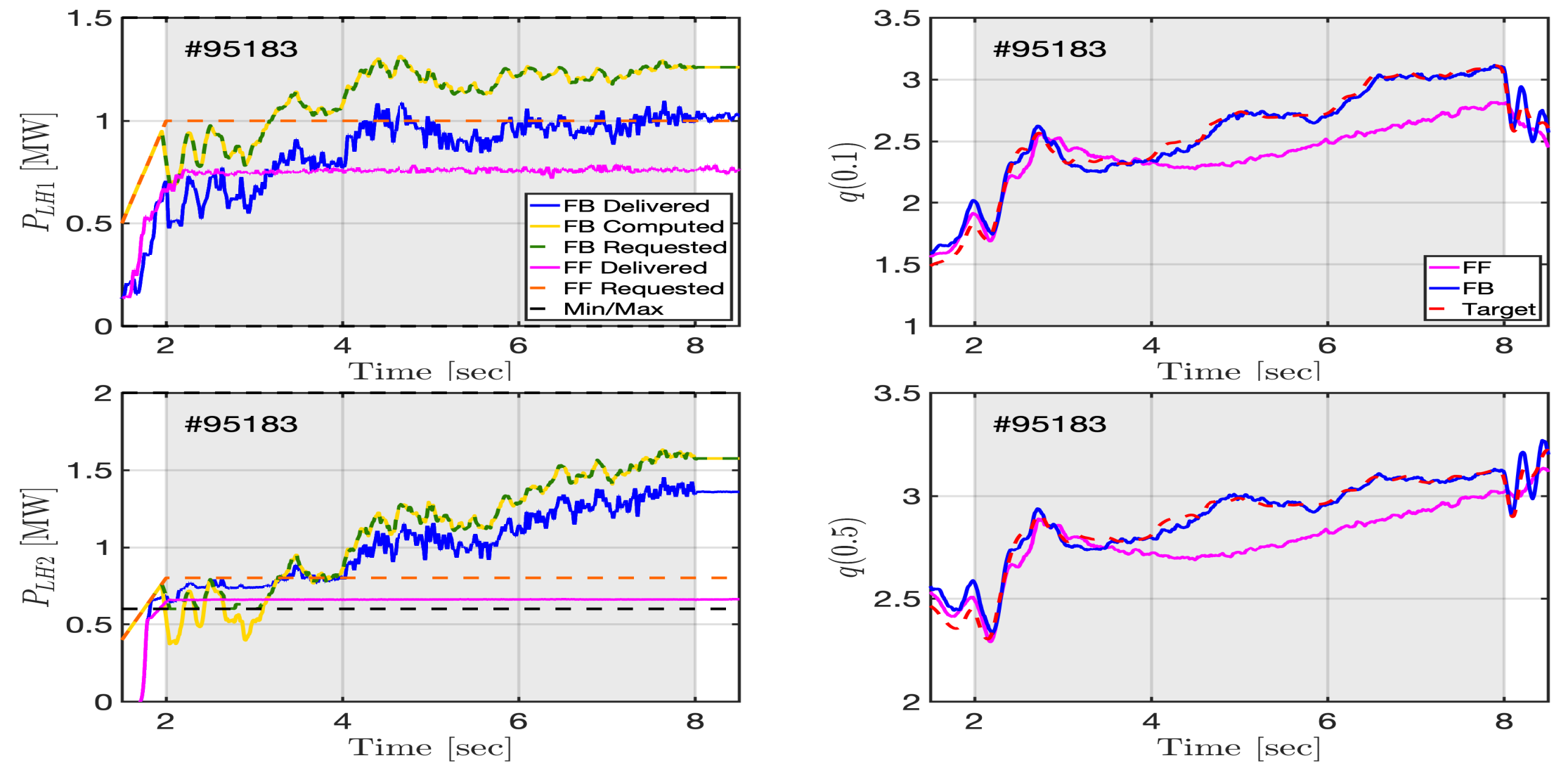


New Beam Power Modulation Algorithm Implemented in 2018 for Simultaneous q-profile + β_N Control Showed Good Average Tracking

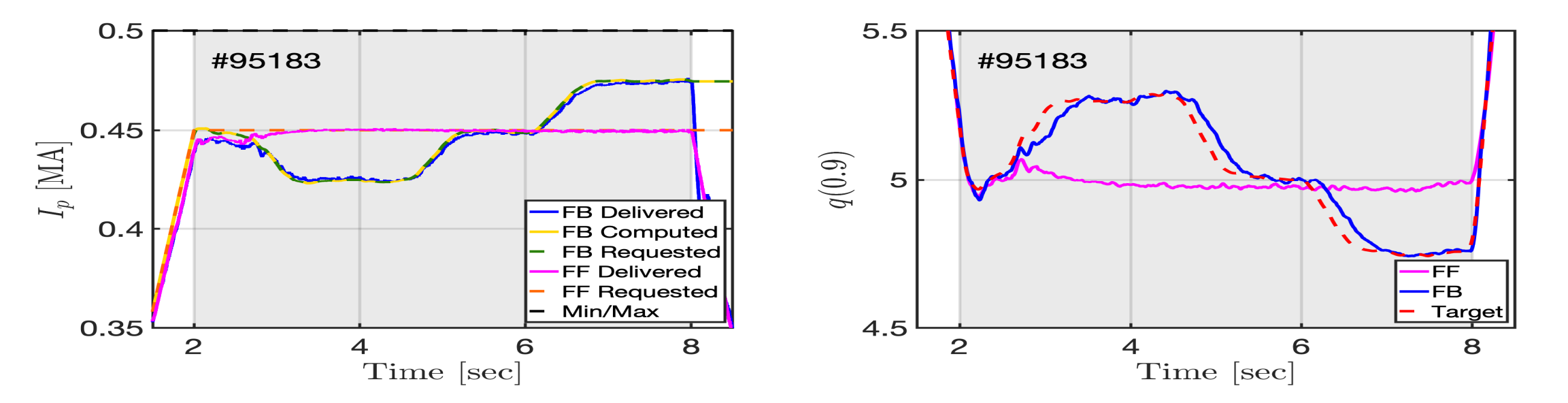


- Tracking of desired q profile at $\hat{\rho}=0.1$, $\hat{\rho}=0.9$ and β_N is achieved by using I_p, P_{LH2} and P_{NBI1} actuation
- PWM algorithm (12) was used with mixed results to command the NBI1L source ($P_{NBI1}=P_{NBI1L}$)
- The targets are tracked in average but the PWM algorithm introduces 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

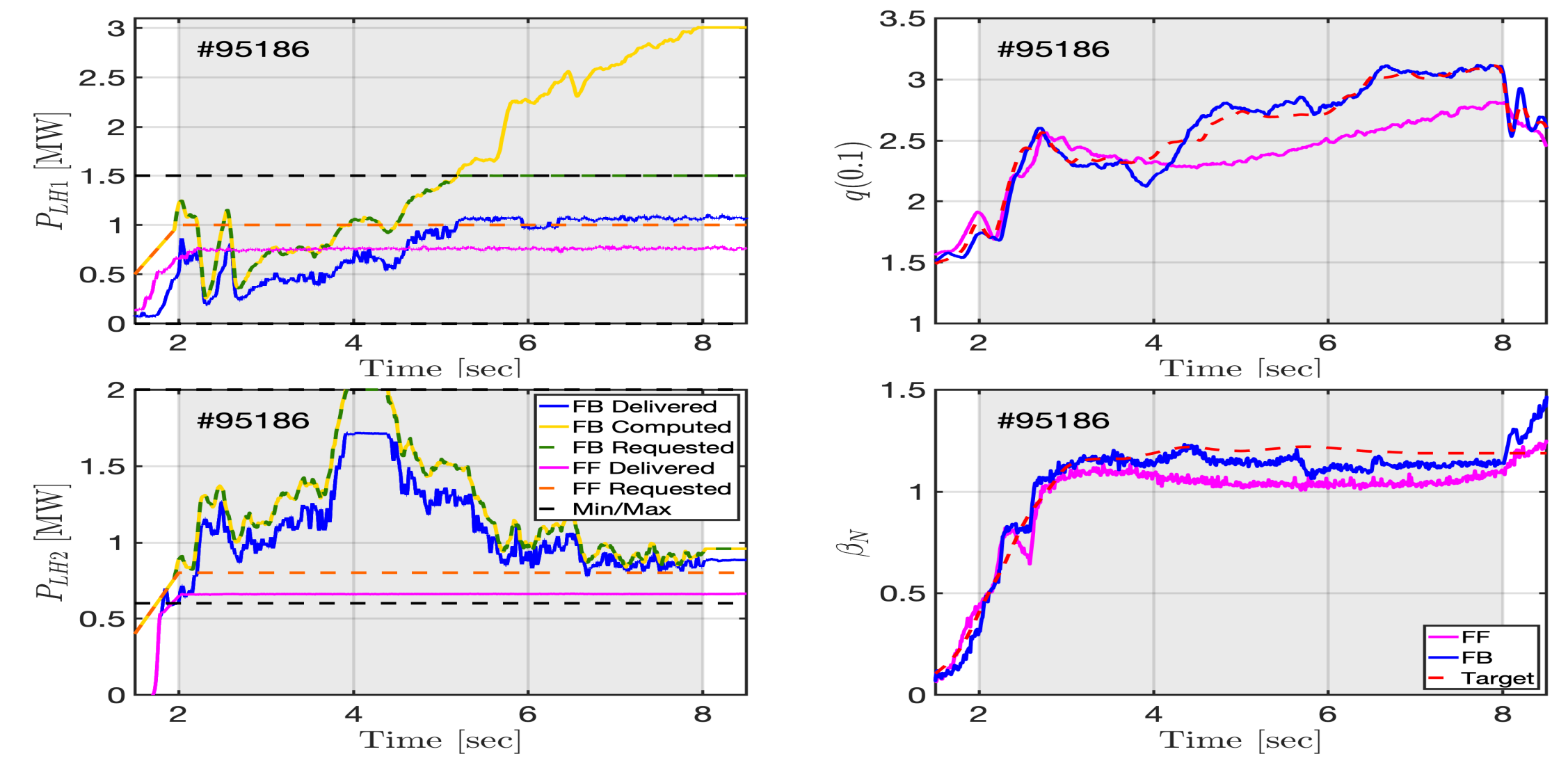


Simultaneous Feedback q-profile Regulation at Three Points Was Demonstrated for the First Time by Using two LHW Sources

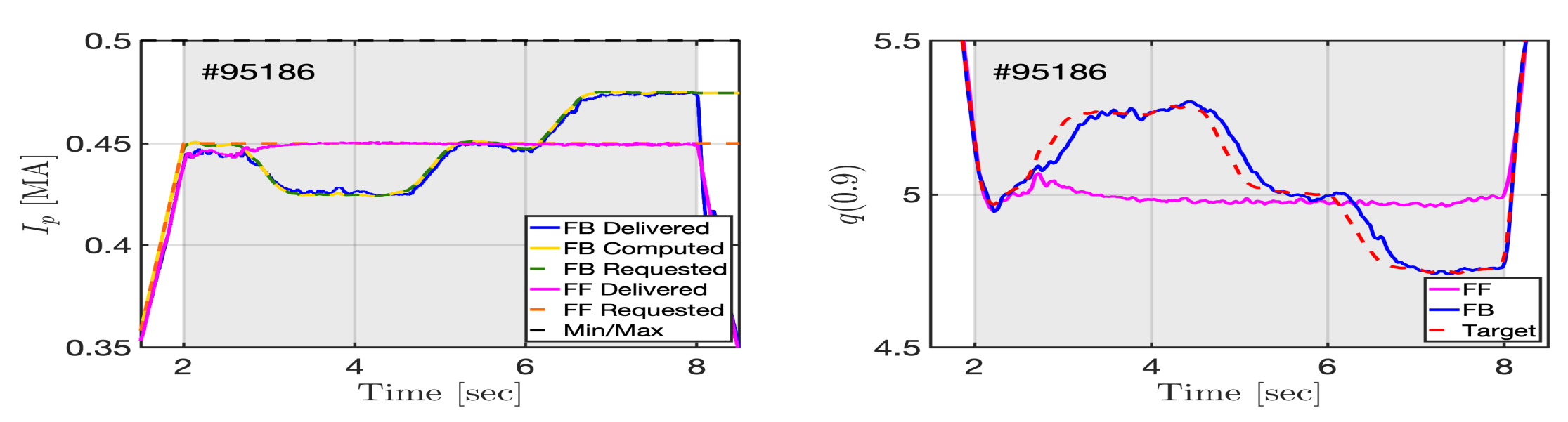


- Tracking of desired q profile at $\hat{\rho}=0.1$, $\hat{\rho}=0.5$, $\hat{\rho}=0.9$ is achieved by using I_p, P_{LH1}, and P_{LH2} actuation
- Solid-magenta lines show q-profile evolutions at these points for feedforward-only EAST shot #95176.
- FF control needs to be modified by FB control for actual (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



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



- 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 $\hat{\rho}=0.1$, $\hat{\rho}=0.9$.

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.