NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

NSTX-U Milestone R18-2: Develop simulation framework for ST breakdown and current ramp-up

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FY2018 Q3 Research Milestone Status
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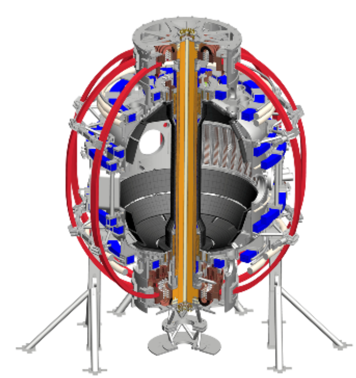


PPPL

R18-2: Develop simulation framework for ST breakdown and current ramp-up

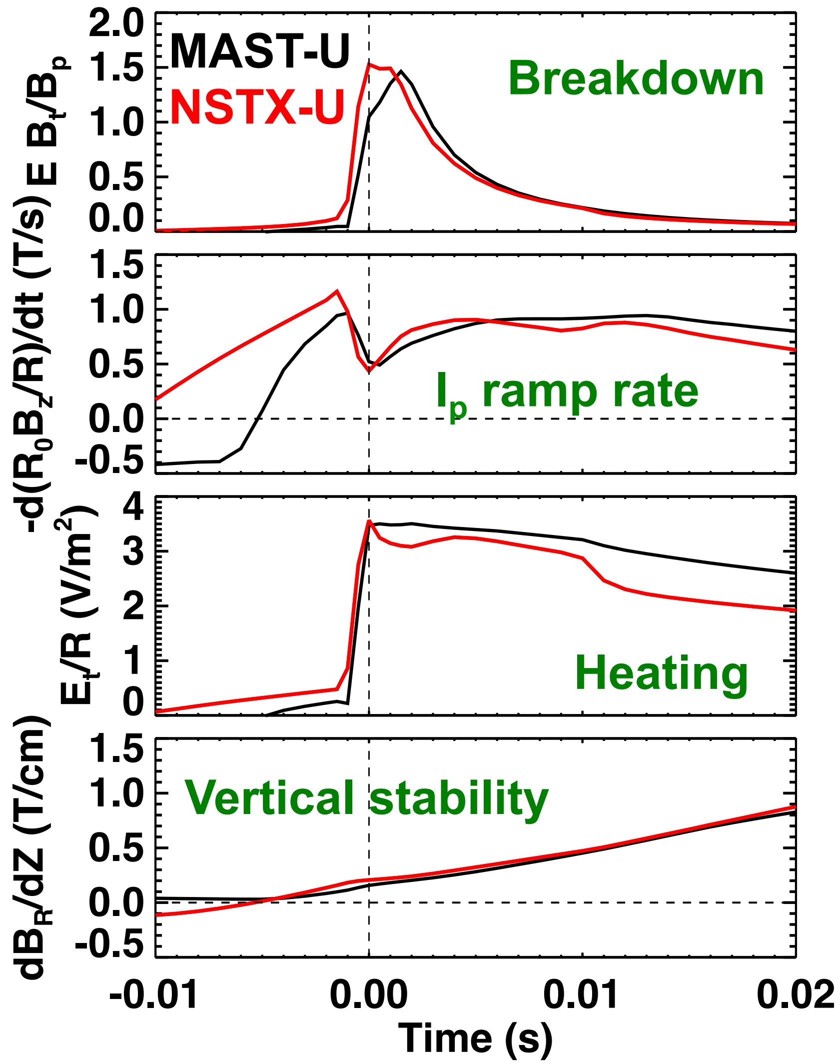
- Inductive startup calculations using LRDFIT
  - Develop predictive vacuum field simulation capability for NSTX-U and MAST-U
  - Establish metrics for comparing and optimizing startup scenarios

- Control modeling focusing on IWL → DN transition
  - Establish framework for closed-loop simulations with PCS code and "mirrored" control algorithms in SIMULINK
  - Develop power supply, conductor and plasma models suitable for time-dependent NSTX-U rampup calculations

- TRANSP calculations for heating and current drive
  - Evaluate models within TRANSP for NSTX and NSTX-U ramp-up
  - Demonstrate the capability for predictive time-dependent calculations for the ramp-up period

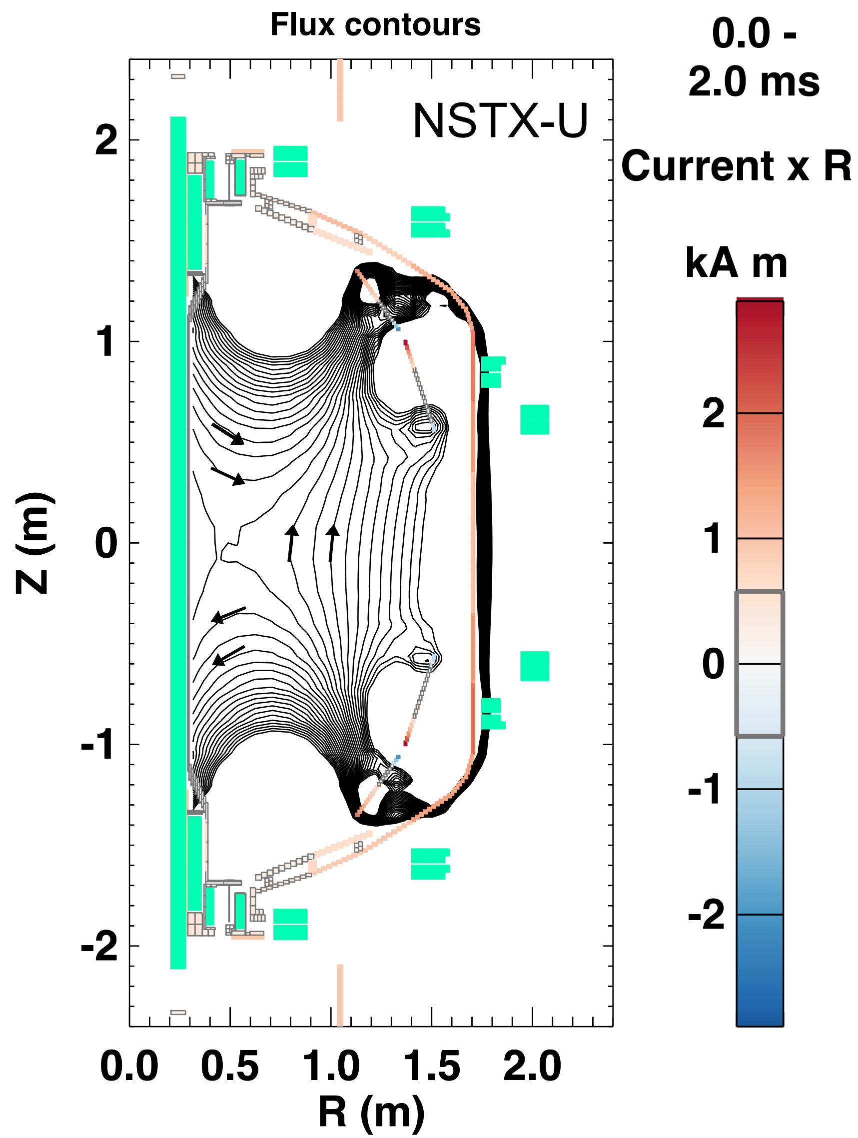
Developed 1-D metrics for startup calculations (LRDFIT)

- Assume fixed boundary shape, zero-beta and force-free ($J \sim B_\phi \sim 1/R$)
  - Breakdown: $E\ B_\phi/B_\theta \sim E/(RB_\theta)$
    - Cross-section averaged EB_ϕ/B_θ
    - Assume 10G NA field
  - Radial force balance: $I^2/R_0 \sim JB_Z$
    - I_p ramp rate: $d(I_p)/dt \sim d(B_Z R_0/R)/dt$
    - Cross-section averaged
  - Heating: $JE \sim E/R$
    - Cross-section averaged V_{loop}/R^2
  - Vertical stability: $dF/dZ \sim d(JRB_R)/dZ$
    - Boundary averaged dB_R/dZ
    - Positive is stable

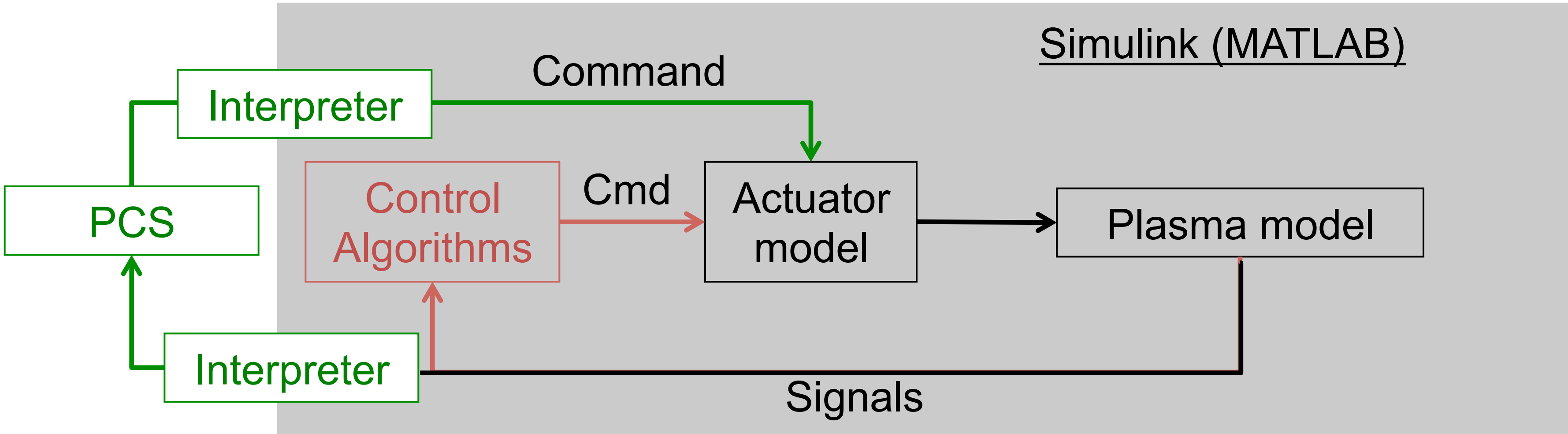


Startup modeling efforts in Q4

- Calculations supporting MAST-U operating procedures
- Size of null (breakdown) versus vertical stability
  - Use divertor coils to increase null size at the expense of vertical stability
- Limits to B_Z/dt after breakdown
  - Power supply voltage, current drive (heating) and vertical stability

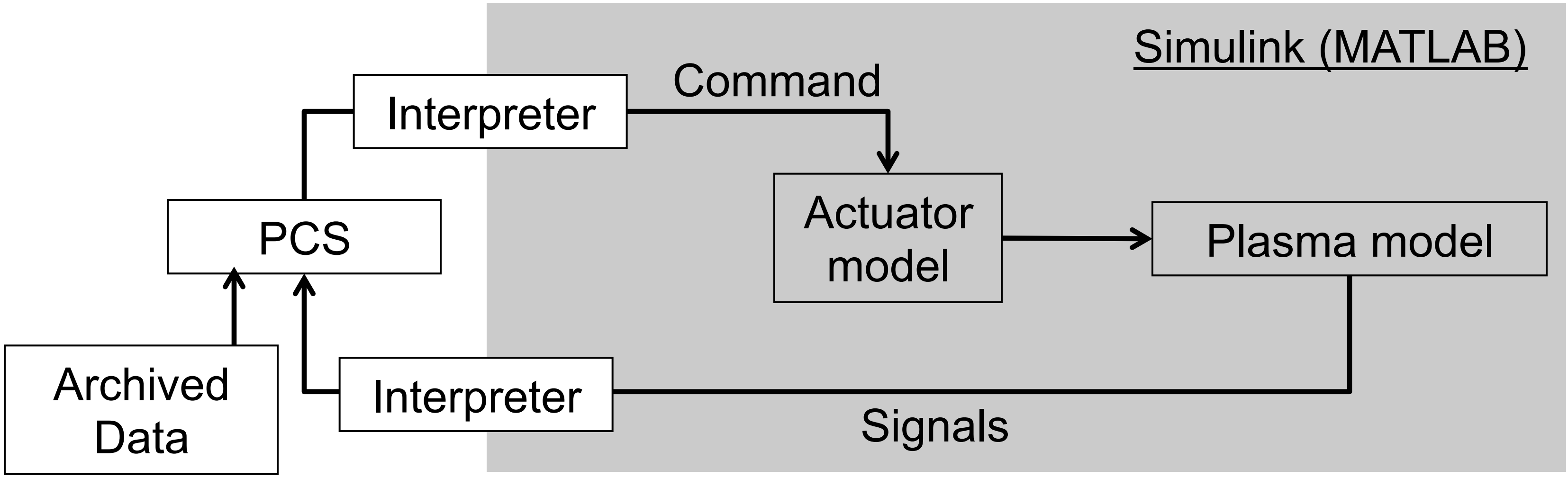


Update on Ramp-up control modeling framework using SIMULINK + TOKSYS



- Connect PCS for a "flight simulator" or test control algorithms in SIMULINK environment
- Plasma model could be
  - TOKSYS
    - Reduced models for fast calculations
    - Different models for computing plasma equilibrium
  - TRANSP
    - More complete physics

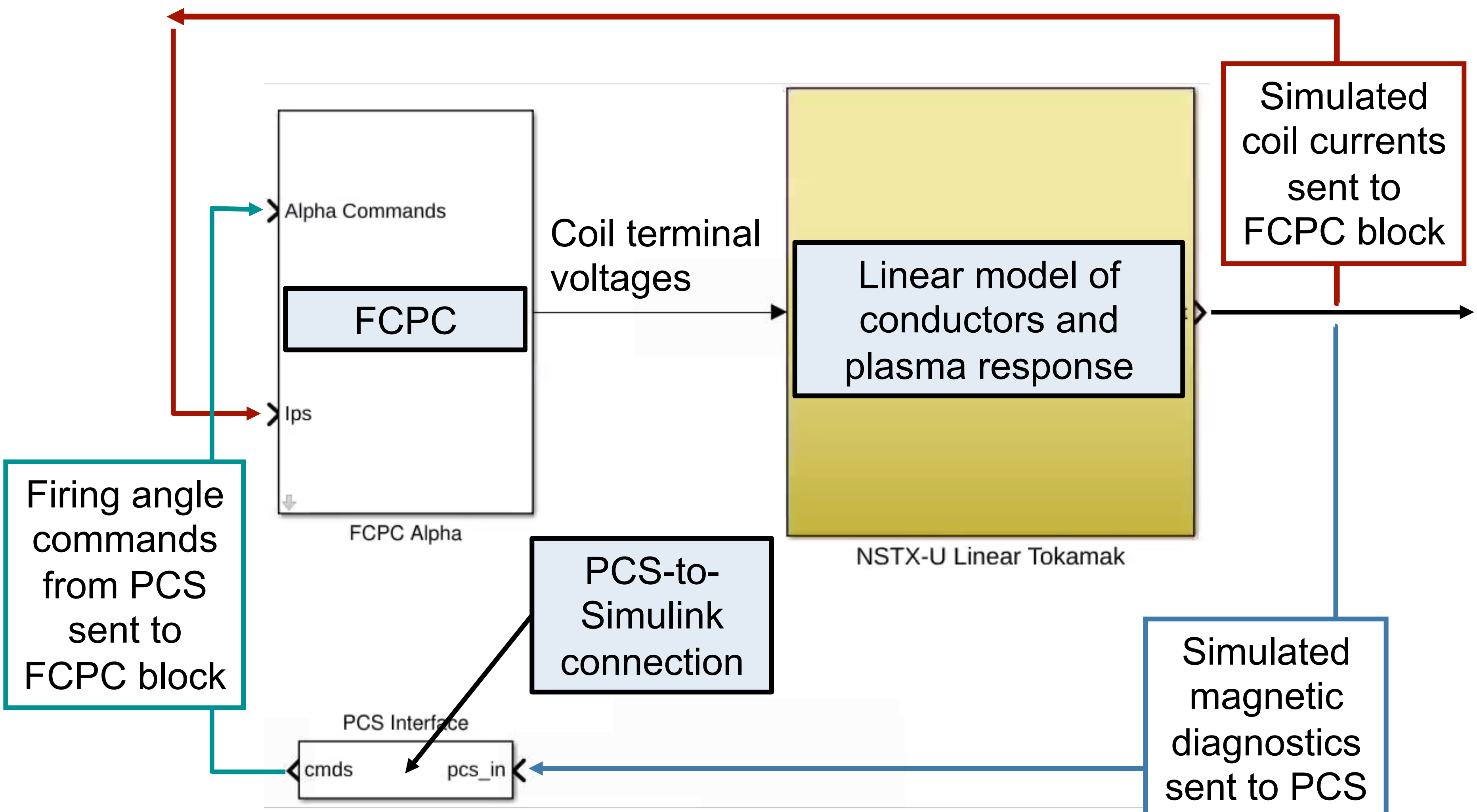
Update on closed-loop calculations with PCS



- [Q2-3] PCS feed-forward demonstration
  - Archived data provides input to PCS
  - Power supply commands communicated to SIMULINK
  - PCS commands converted to coil voltage to drive plasma model

- [Q4] Format SIMULINK output for input into PCS to complete closed-loop framework

Closed-loop simulation between PCS and Simulink connects previously developed and validated models



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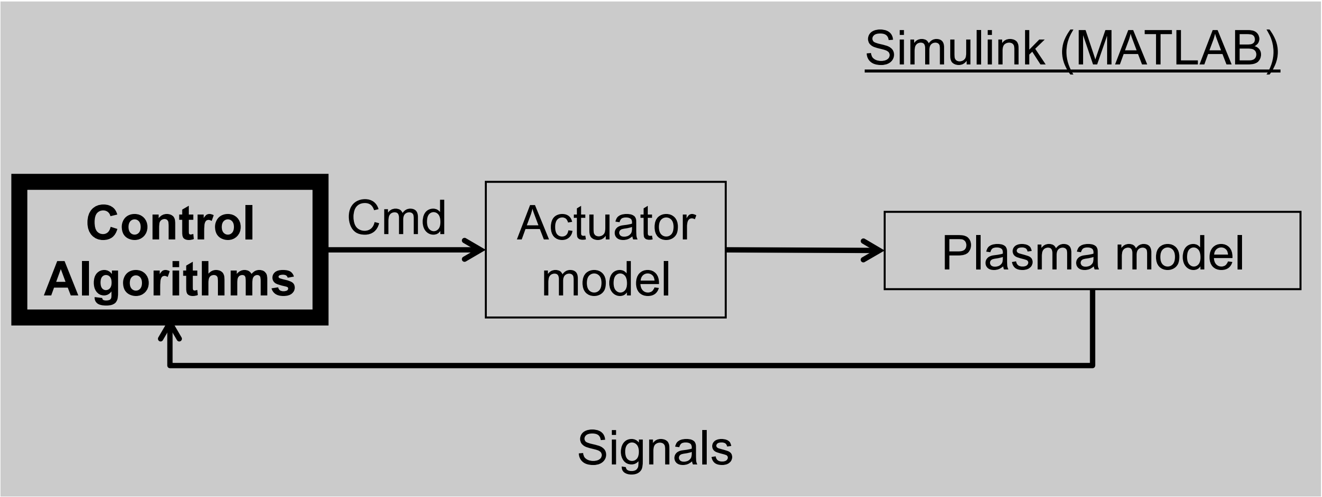
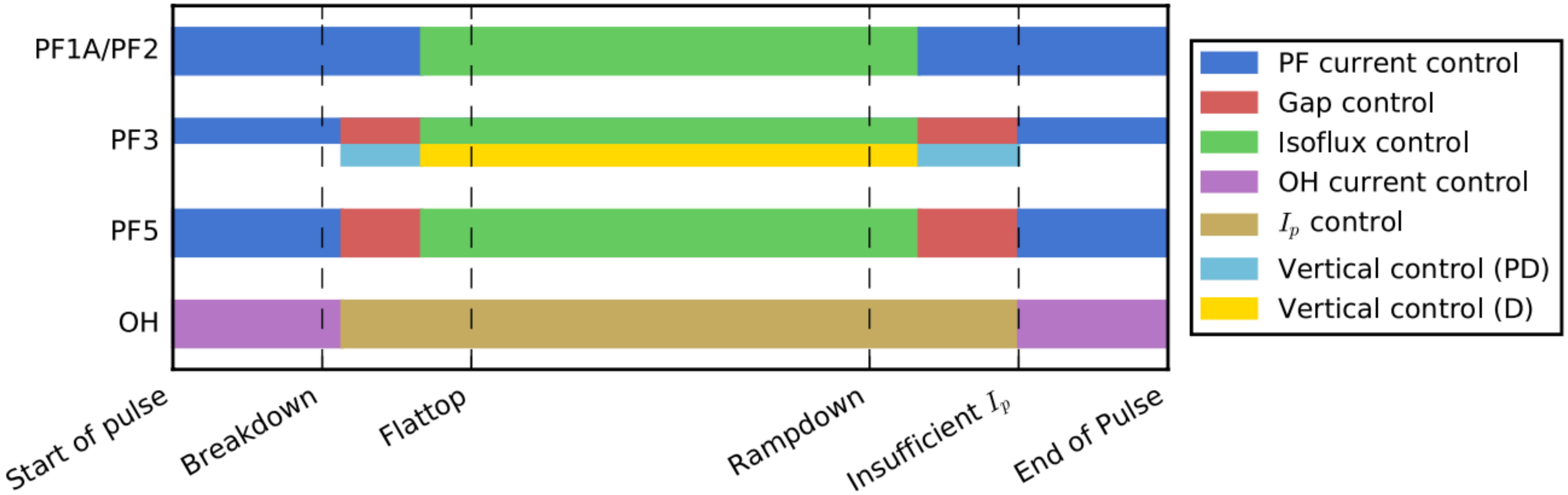


- [Q3-4] Demonstrated closed-loop SIMULINK framework with TRANSP and TOKSYS
  – Reproduce shape & beta feedback algorithms in SIMULINK
  – Includes inner gap, drsep and strikepoint control algorithms
    - Supports PFC working group
  – Currently adding algorithm transitions to control algorithms

Update on Ramp-up control modeling framework using SIMULINK + TOKSYS



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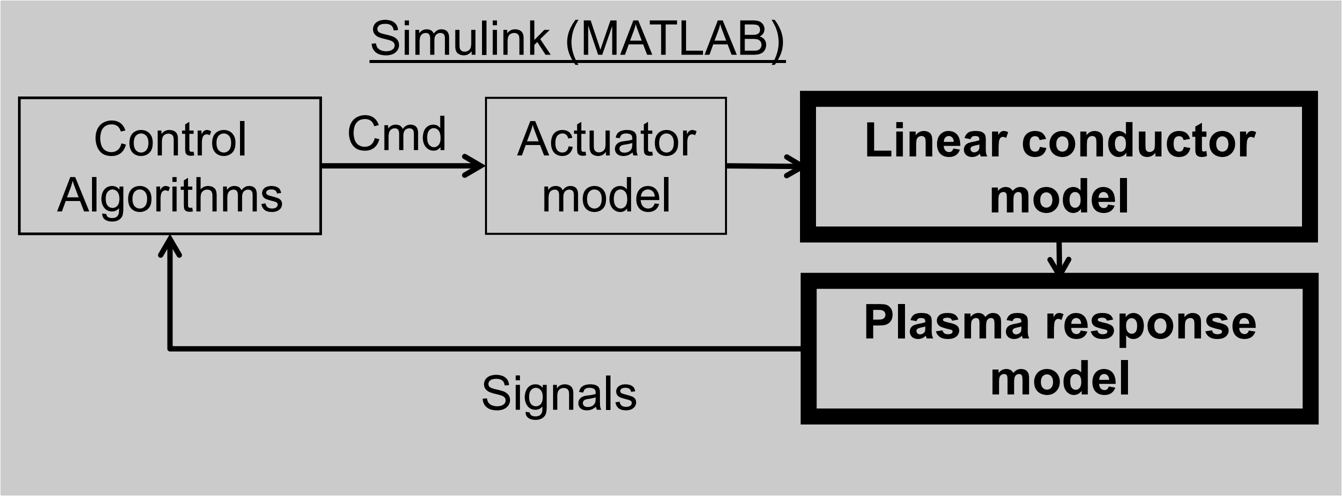
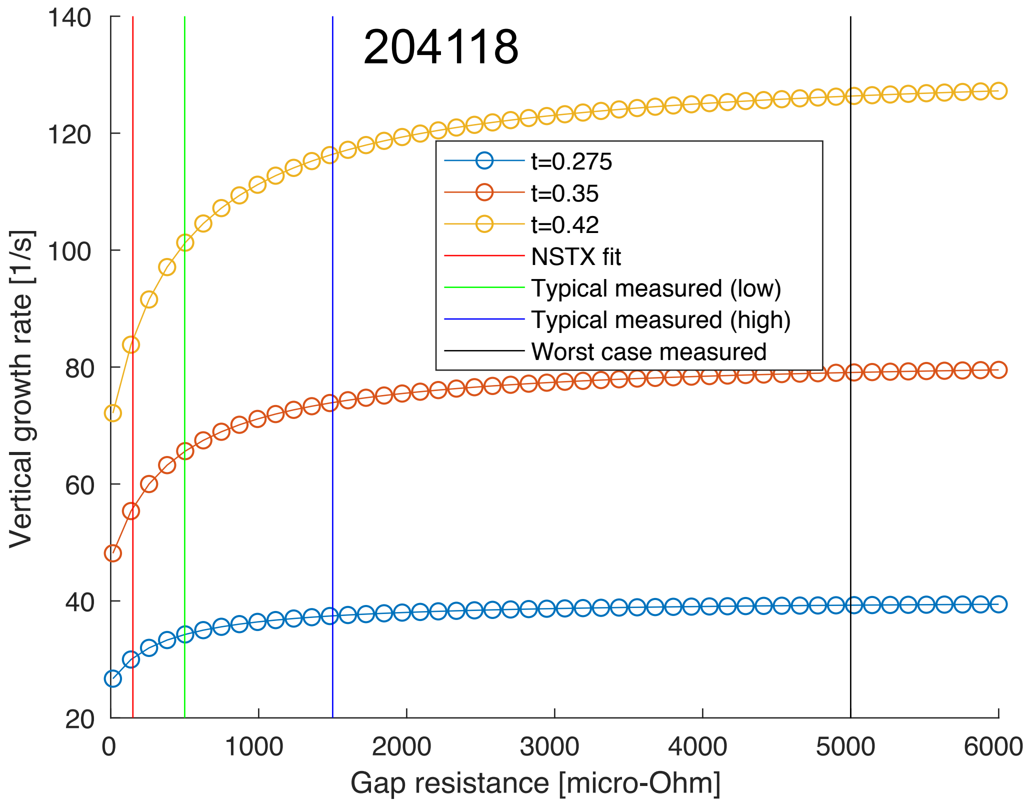


- Linear "conductor model" computes induced wall current

- Options for computing diagnostic signals including plasma response
  - Linear models use a constant plasma response (~1 minute)
    - Derived from existing equilibrium, assumes boundary is fixed, or rigid
    - Linear model must change as equilibrium evolves
  - Nonlinear model solves the free-boundary GS equation (~1 hour)
    - Inputs: Coil and vessel currents, target values for I_p, β_p, and l_i.
    - Output: Flux on grid and updated plasma boundary.

Treatment of the passive plate currents was improved in the conductor model

- [Q3] Induced current in PPs modeled as two circuits
  - Eddy current loop + winding toroidal path through mounting brackets

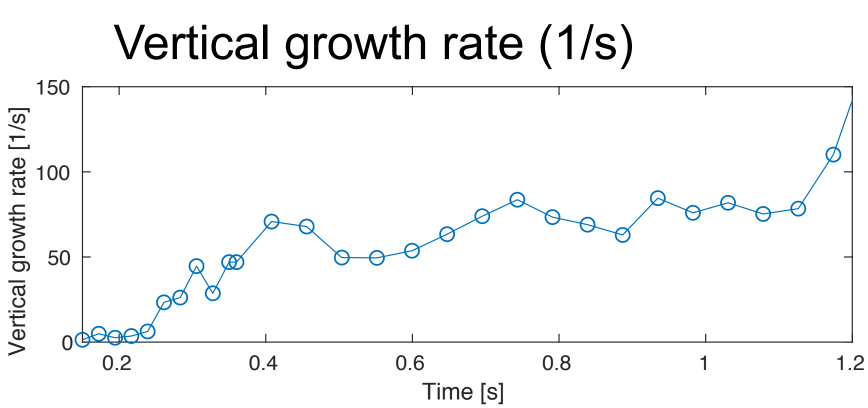


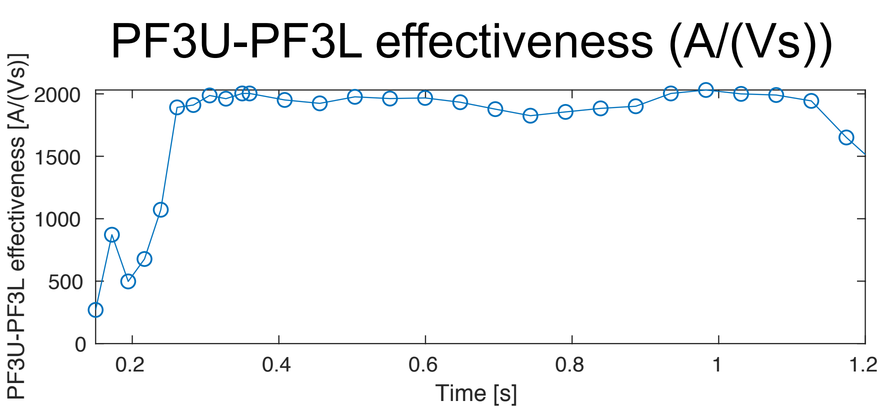
Evaluate VDE growth rate at different times in a discharge as a function of the passive plate mounting bracket resistance

Smaller vertical growth rate is better

Capability added to interpolate linear models for ramp-up simulations

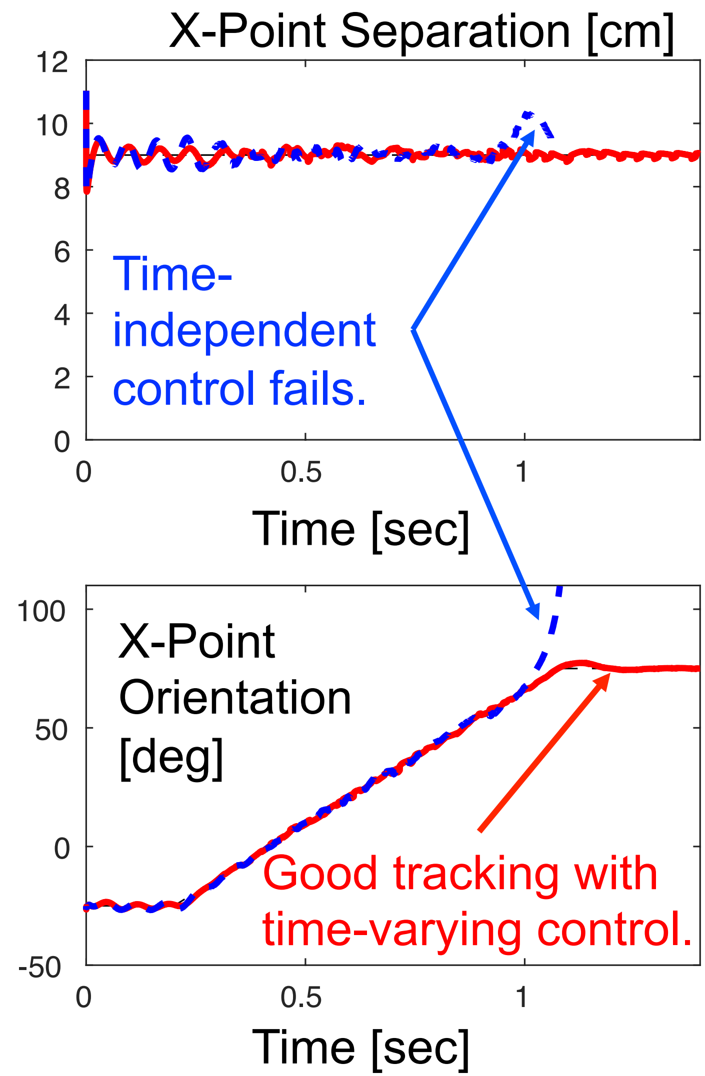
- [Q3] Demonstrated linearized models changing in time
  - Important for ramp-up where equilibrium has considerable differences
    - L-H transition, limited to diverting transition, etc.
  - Reworked parts of SIMULINK model for matrix interpolation
  - Provides more realistic simulation capability
    - For example, evolving vertical growth rate, coil effectiveness





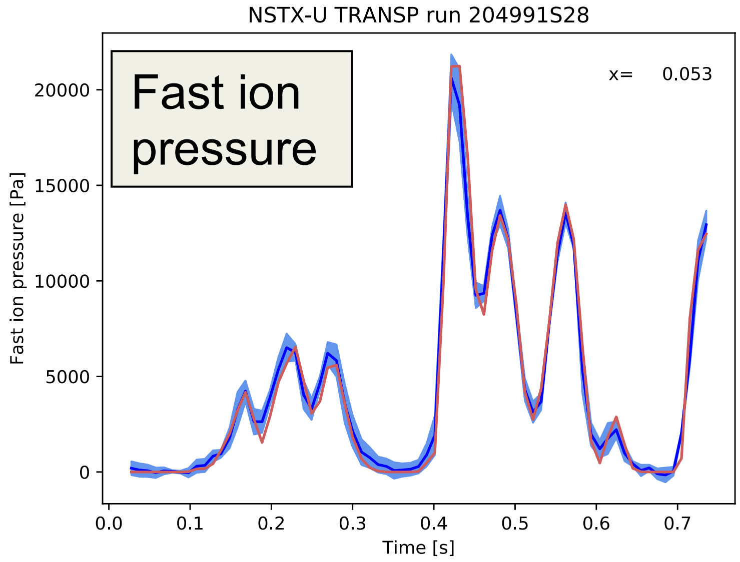
Closed-loop simulator with free-boundary solution was used to develop new snowflake control algorithm

- Nonlinear simulation <u>required</u> for some control development such as snowflake divertor
- Time-independent control algorithm performs well with simulations using a linear equilibrium model
  - However, this control fails in a simulation using free-boundary solution
- Motivated development of time-varying snowflake controller algorithm
- Equilibrium models of different fidelity now available for NSTX-U simulations
  - Linear reduced models (including NN)
  - Non-linear equilibrium
  - Transport driven models (TRANSP)

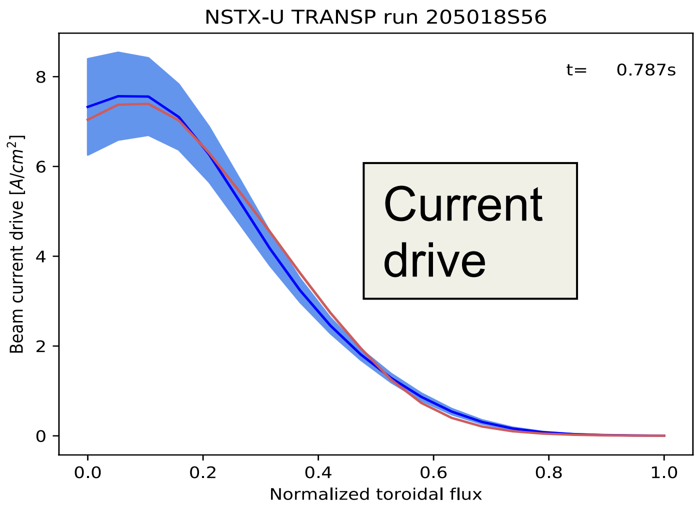


Neural net development for NUBEAM, to be used for scenario optimization and control

- [Q3] Completed higher fidelity NUBEAM runs and added beam modulations to dataset
  - Helps reduce uncertainty when using beams that weren't used much in FY16 experiments



- [Q3] Implemented NUBEAM NN calculations on NSTX-U real-time computer
  - Demonstrated execution times well within 200us NSTX-U PCS control cycle time
  - Need to interface with diagnostics



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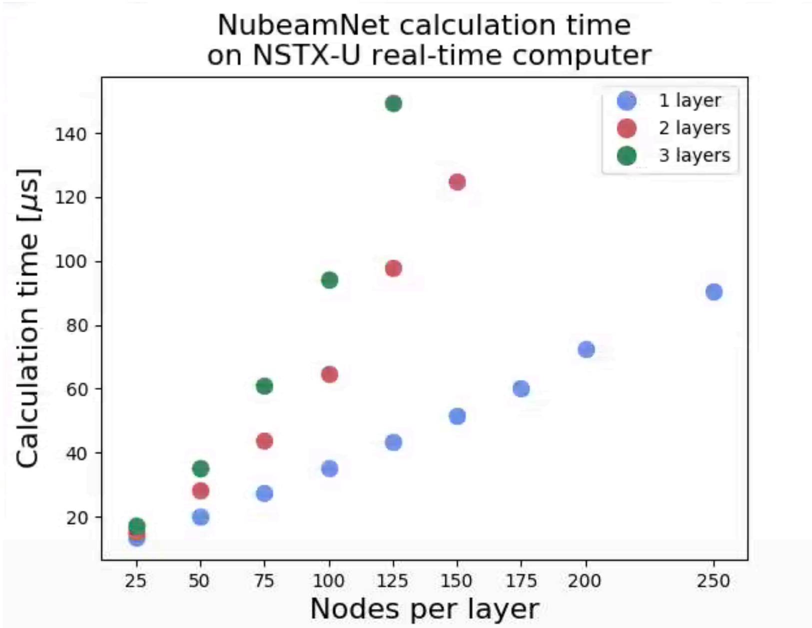
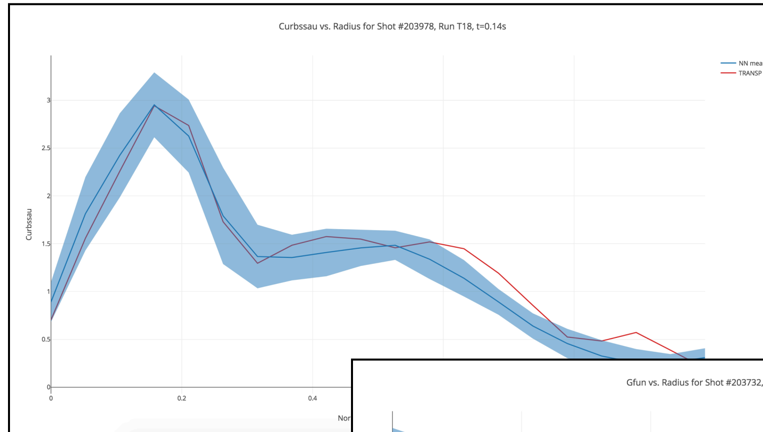


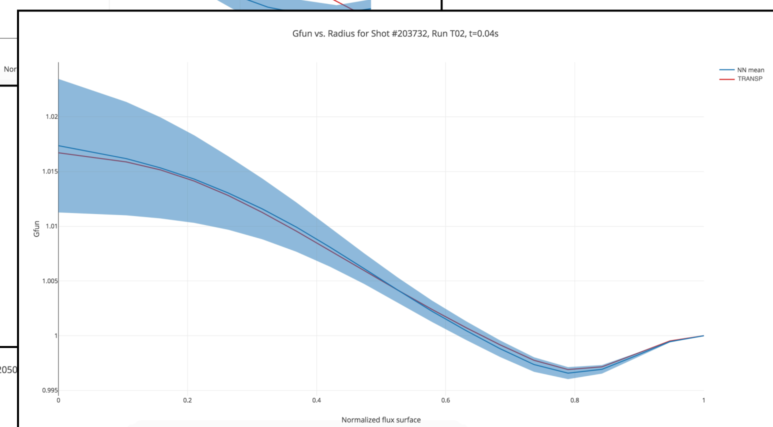
Additional neural network models for current diffusion

- [Q3-4] NN bootstrap current, resistivity, and geometric flux surface averages for current diffusion equation
  - SULI student Vaish Gajaraj

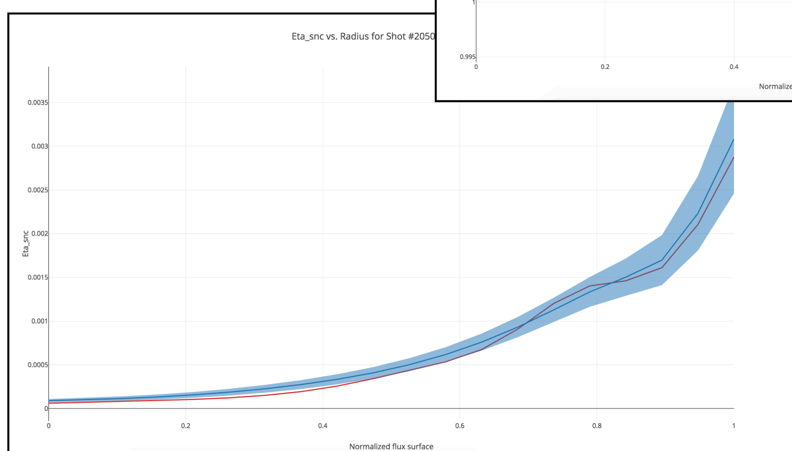
- Plans for developing NN for transport coefficients in FY19



Bootstrap current



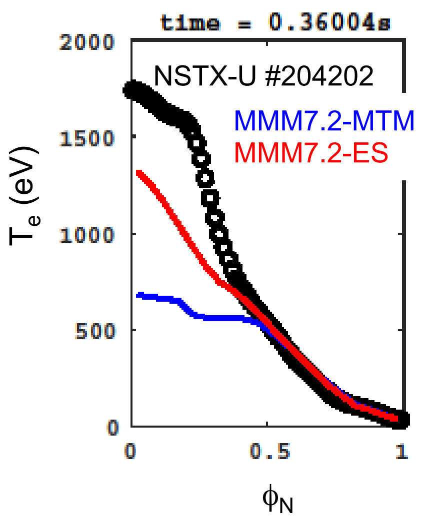
Para/diamagnetism

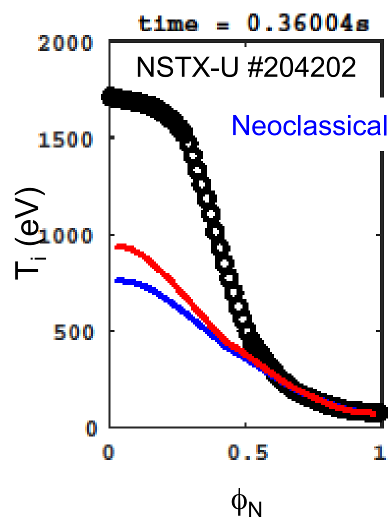


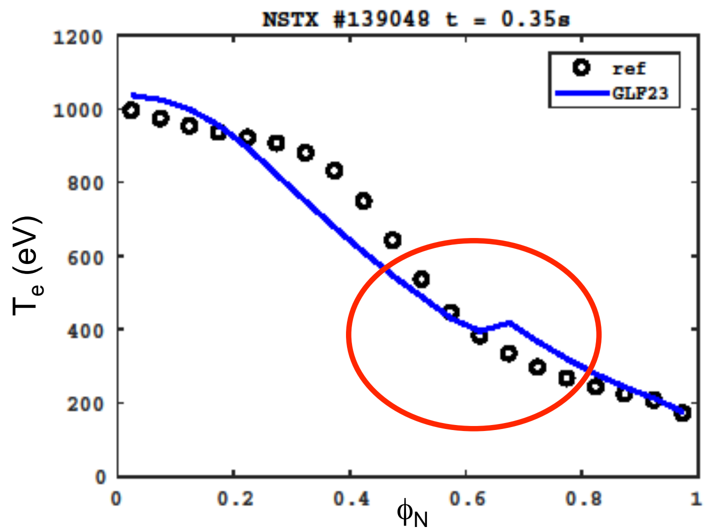
Resistivity

Updates on evaluating TRANSP simulations of NSTX-U ramp-up

- [Q3] Fidelity of predictive models in TRANSP for current diffusion and thermal transport in ramp-up in NSTX and NSTX-U completed
  - Core electron thermal transport: MMM7.2 (no microtearing)
    - GLF23 has numerical problems at around 2/3 of the minor radius (not clear)
  - Core Ion thermal transport: neoclassical
  - Current diffusion: TEQ fixed boundary equilibrium



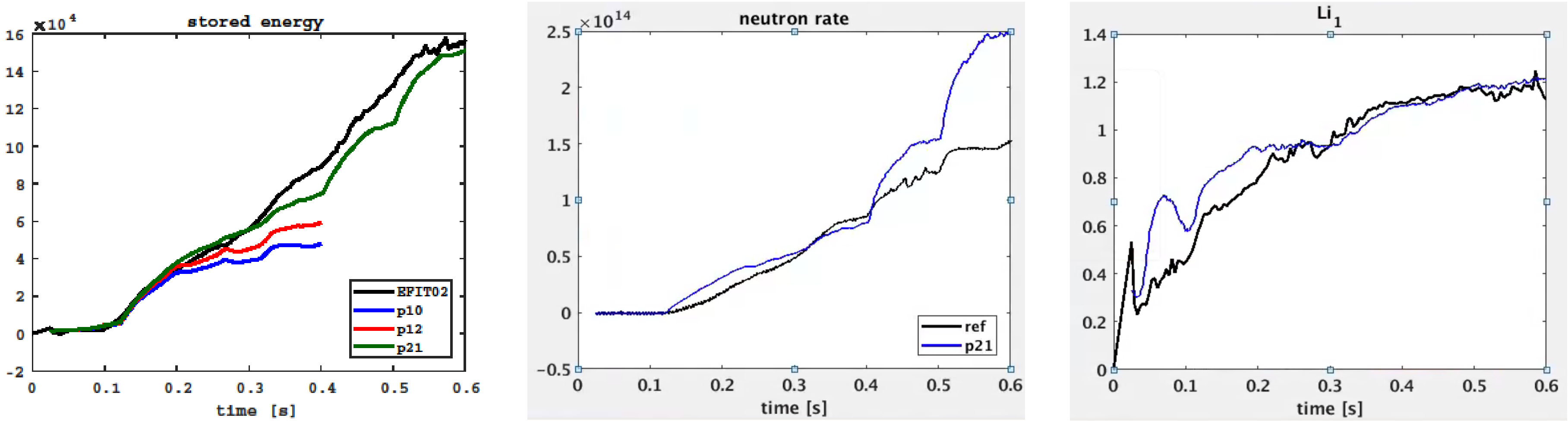




Good prediction of global parameters

- Good reproducibility of the stored energy and internal inductance when kick model is used.
- Overestimate of neutron rate after 0.40s to be investigated

204202 L-mode using only beamline 1



Summary of Q3-4 work

- Metrics established for evaluating breakdown scenario calculations
  - Applied to the development of the MAST-U startup procedures
- PCS feed-forward SIMULINK simulation completed
  - Working to “close the loop” by feeding diagnostic signals from SIMULINK into PCS
- Closed-loop time-dependent simulations with control algorithms in SIMULINK completed
  - Developed ability to interpolate linear matrices
  - Demonstrated non-linear equilibrium GS solver for NSTX-U

Summary of Q3-4 work

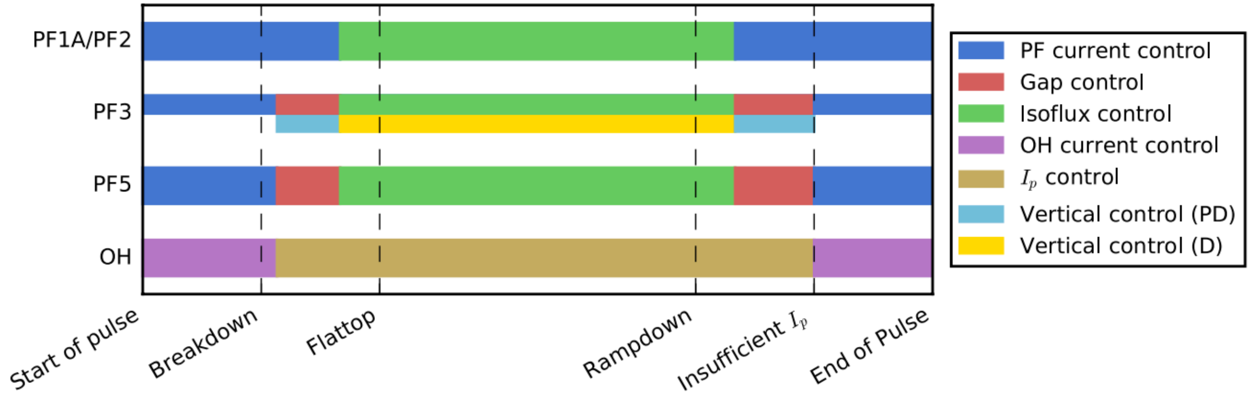
- Improved PP model to assist in evaluating impact of bracket resistance on vertical stability
- Increased fidelity of NUBEAM NN and implemented NN model in PCS code
  - NN for current drive under development
- Transport model options within TRANSP were evaluated for ramp-up phase on NSTX-U

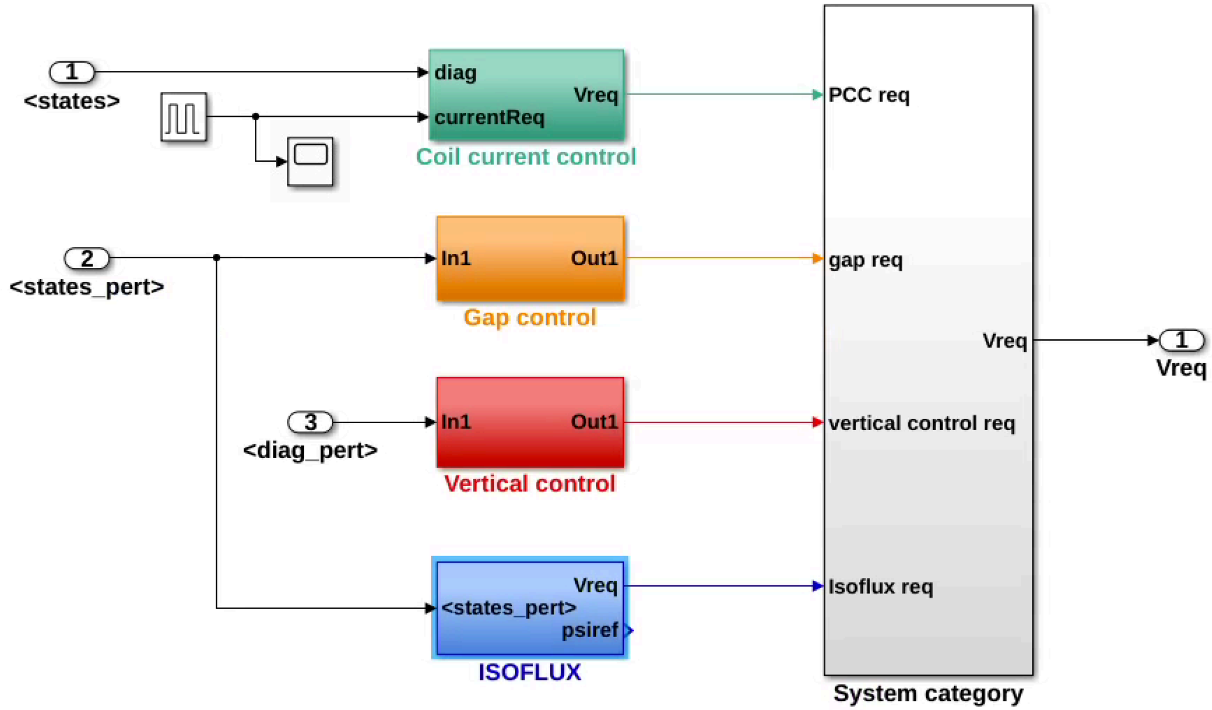
R19-2: Demonstrate optimized ramp-up

- Extend linearized TOKSYS models to include current drive, heating and transport models
- Extend evaluation and development of transport models within TRANSP required for time-dependent ramp-up simulations
  - For example, neutral fueling model for density evolution
- Leverage models to evaluate stability (VDE, MHD, fast-ion) and resiliency of ramp-up scenarios aimed at low-l_i, high shaping
  - Accelerate the realization of high-performance discharges on NSTX-U and MAST-U

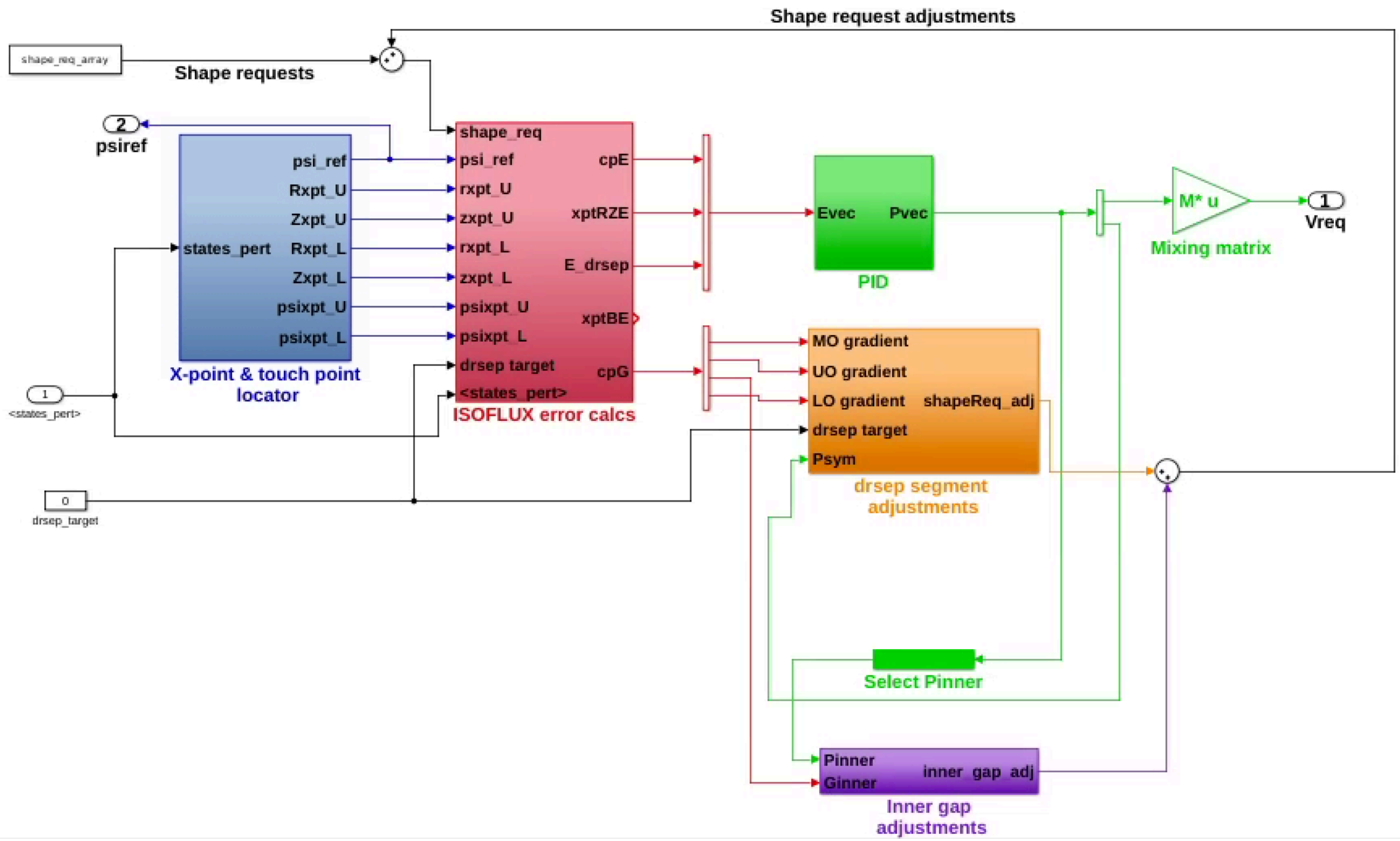
Backup

Implemented coil control algorithms in Simulink for testing and development





Implemented ISOFLUX in Simulink for testing and development



Status of TRANSP calculations

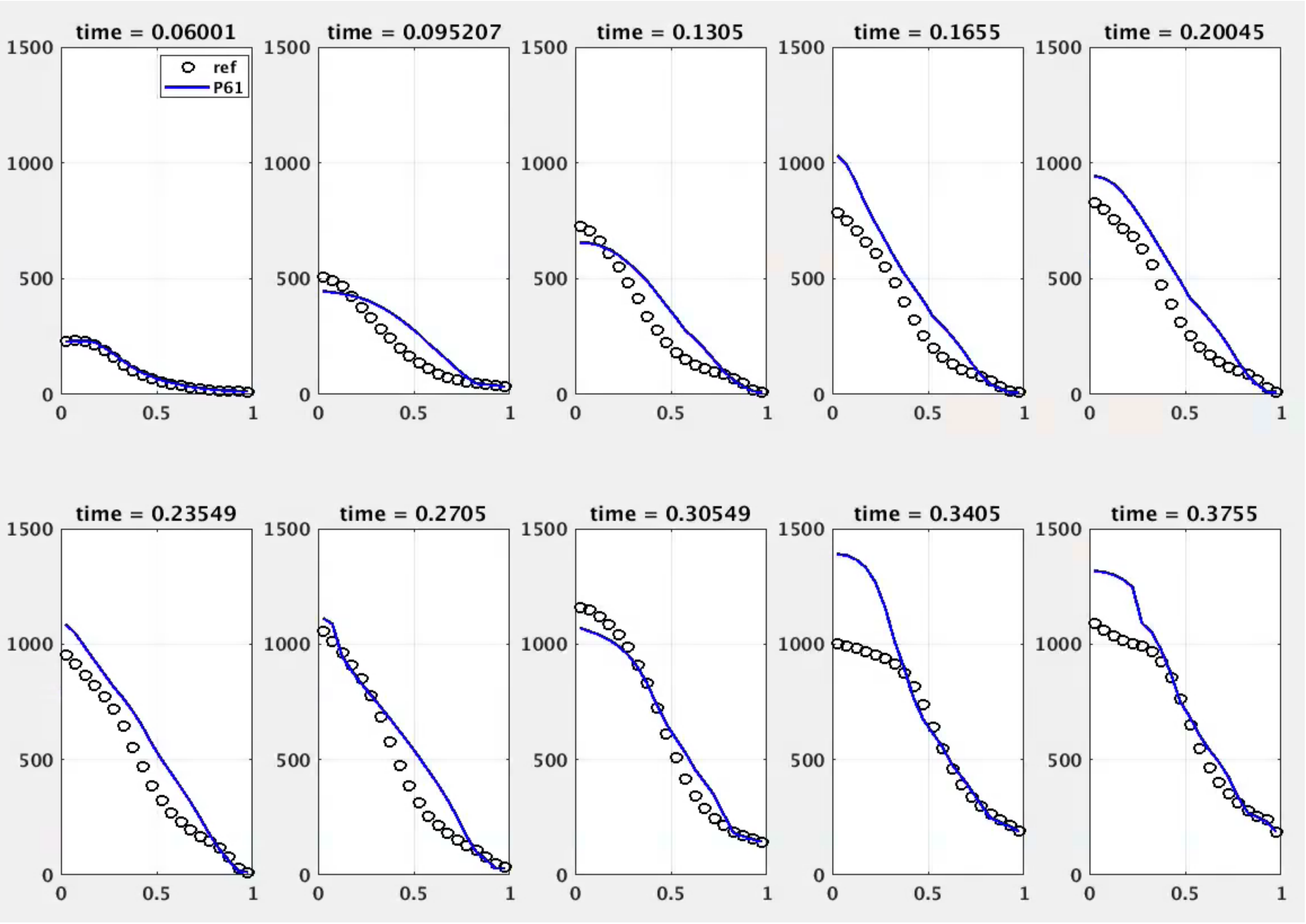
- [Q2-3] Validation of TRANSP model for ramp-up period (Doohyun, Francesca)
  - NSTX w/ MSE (139048)
    - See attached slides
  - NSTX-U w/ CHERs (204202)
    - See attached slides
  - NSTX-U early H-mode development (202946, 203679, 204112) using NBI #2
    - Underway
  - Evaluate ability of flux-driven transport models to capture evolution of discharge in L- and H-mode ramp-up

- [Q3-4] Free-boundary predictions for NSTX-U
  - Start with validated predictive model of an NSTX-U rampup
  - Examine impact of NBI, outer gap, density, dIp/dt, κ, and/or timing of L-H transition on l_i
    - Need to provide target shapes for NSTX-U cases
    - First try an NSTX-U ramp-up where everything happens earlier and faster

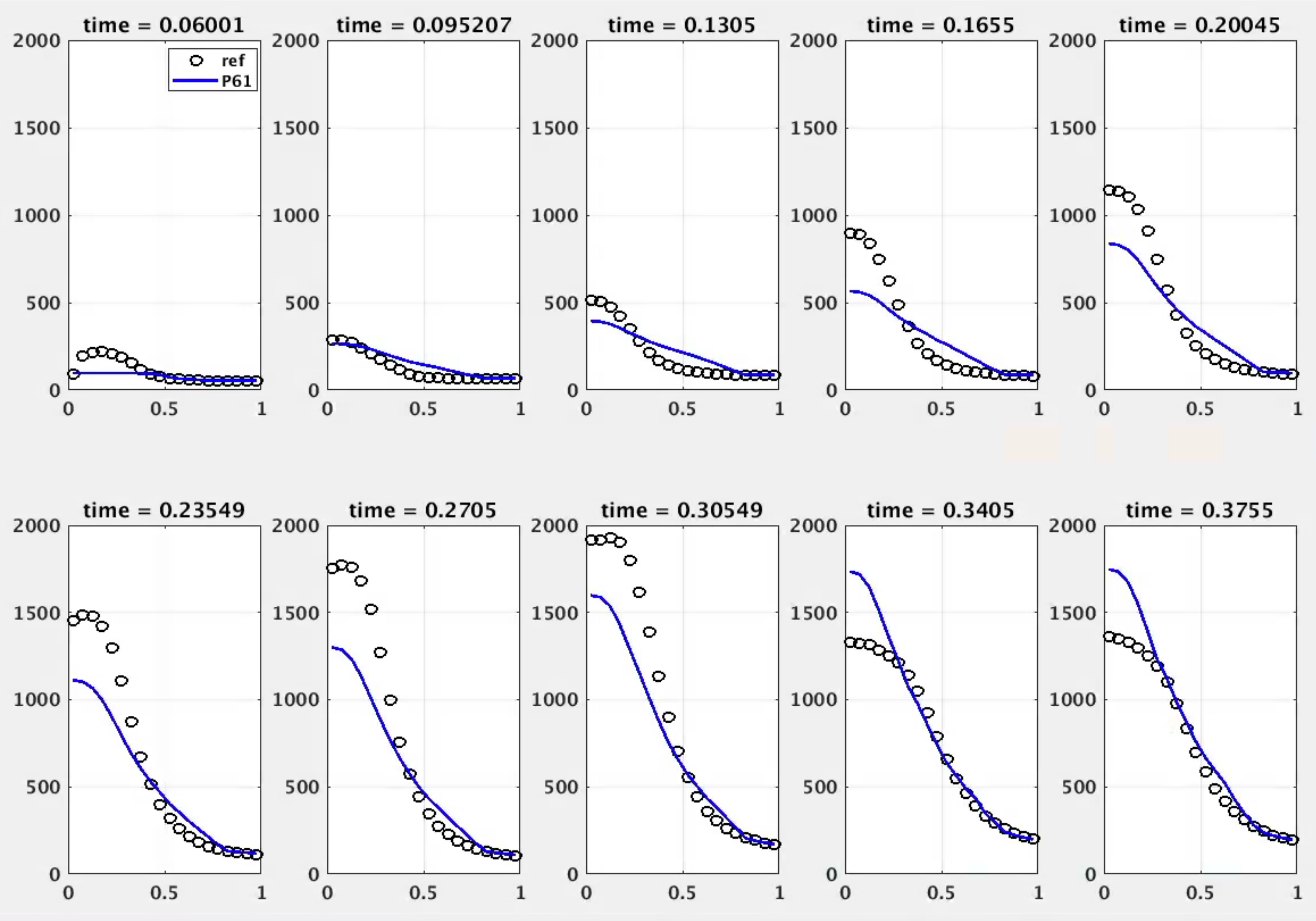
Te/Ti prediction initial test for NSTX/NSTX-U

- Transport
  - NSTX case (139048P61)
    - transport: turbulence (MMM), NC (NEOCH), ExB (TRANSPEXB)
      - MMM: Weiland (e/i), MTM (e), ETG (e)
  - NSTX-U case (204202P16)
    - Electron transport: turbulence (MMM), NC (NEOCH), ExB (TRANSPEXB)
      - MMM: Weiland, MTM, ETG
    - Ion transport: Neoclassical only (NEOCH)
  - Calculation boundary
    - Central (rho = 0 – 0.2), core (0.2 – 0.8), edge (0.8 – 1.0)
    - Te/Ti calculation in central and core regions
- Equilibrium / poloidal field diffusion
  - TEQ (fixed boundary)
  - Fixed total plasma current (ufile), calculated vloop
  - Default resistivity
- Anomalous Fast Ion Diffusion
  - Constant across minor radius (1e4)
- More test will be done for NSTX-U using 204202P16 setting

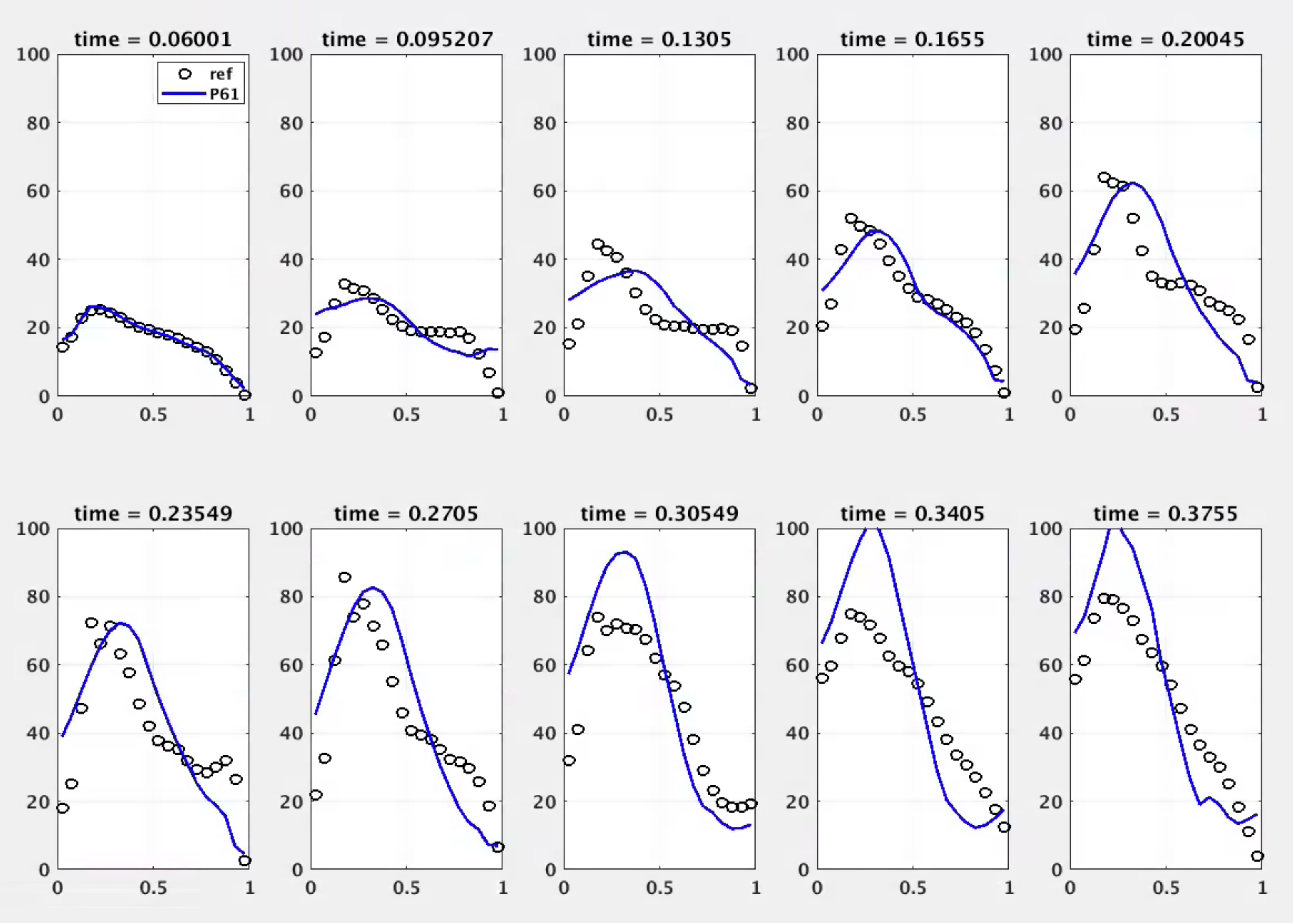
Te profiles - NSTX



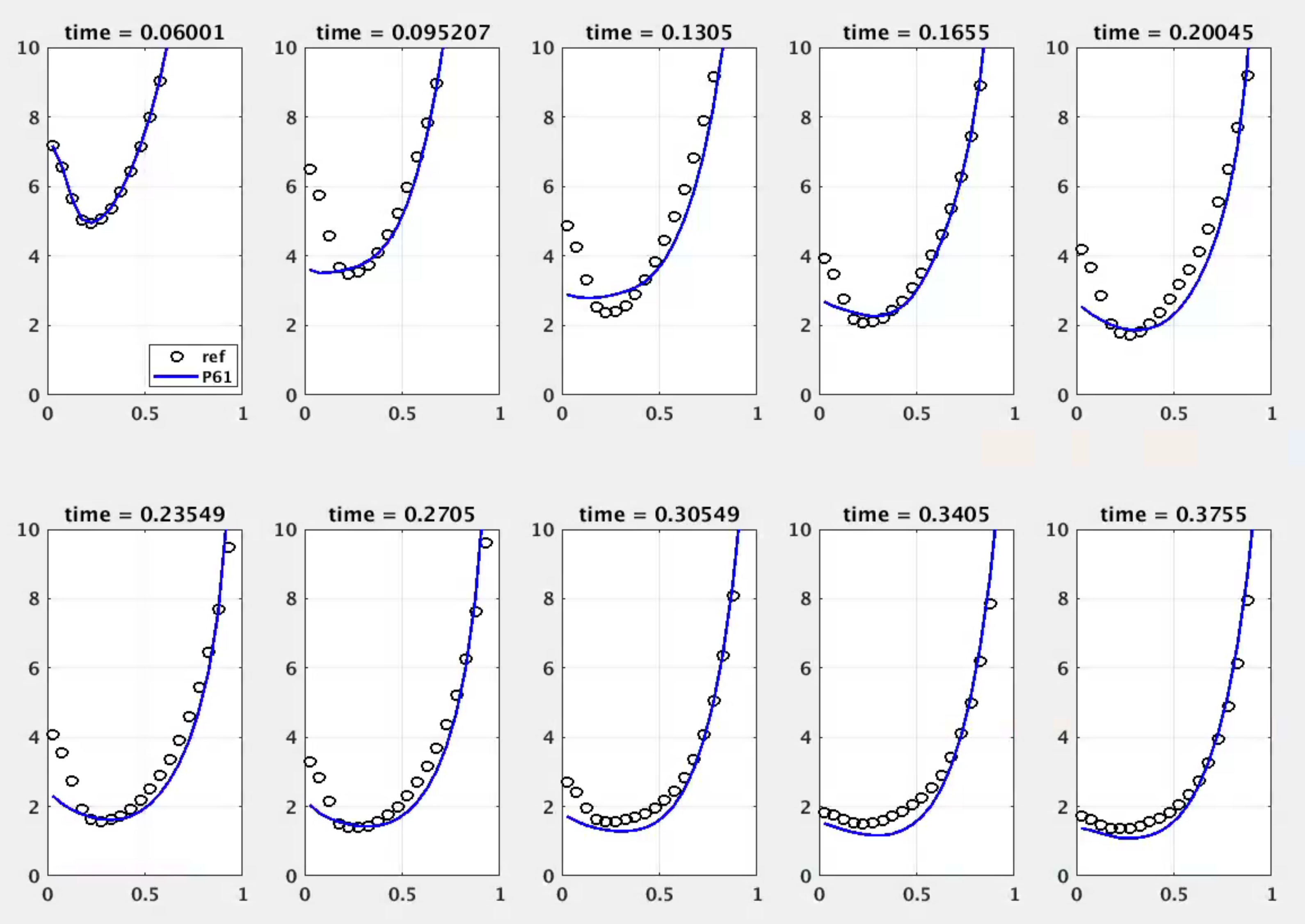
Ti profiles - NSTX



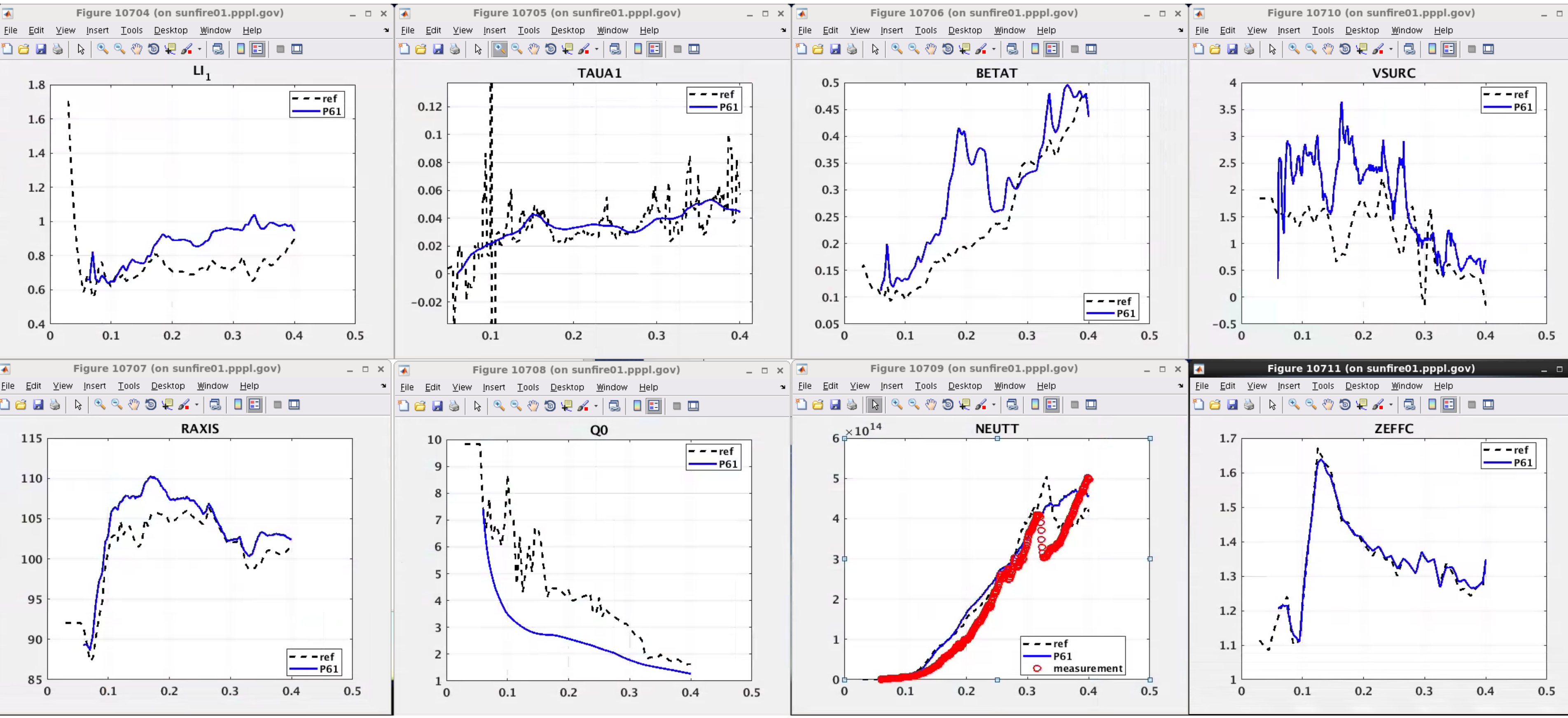
Total current profiles - NSTX



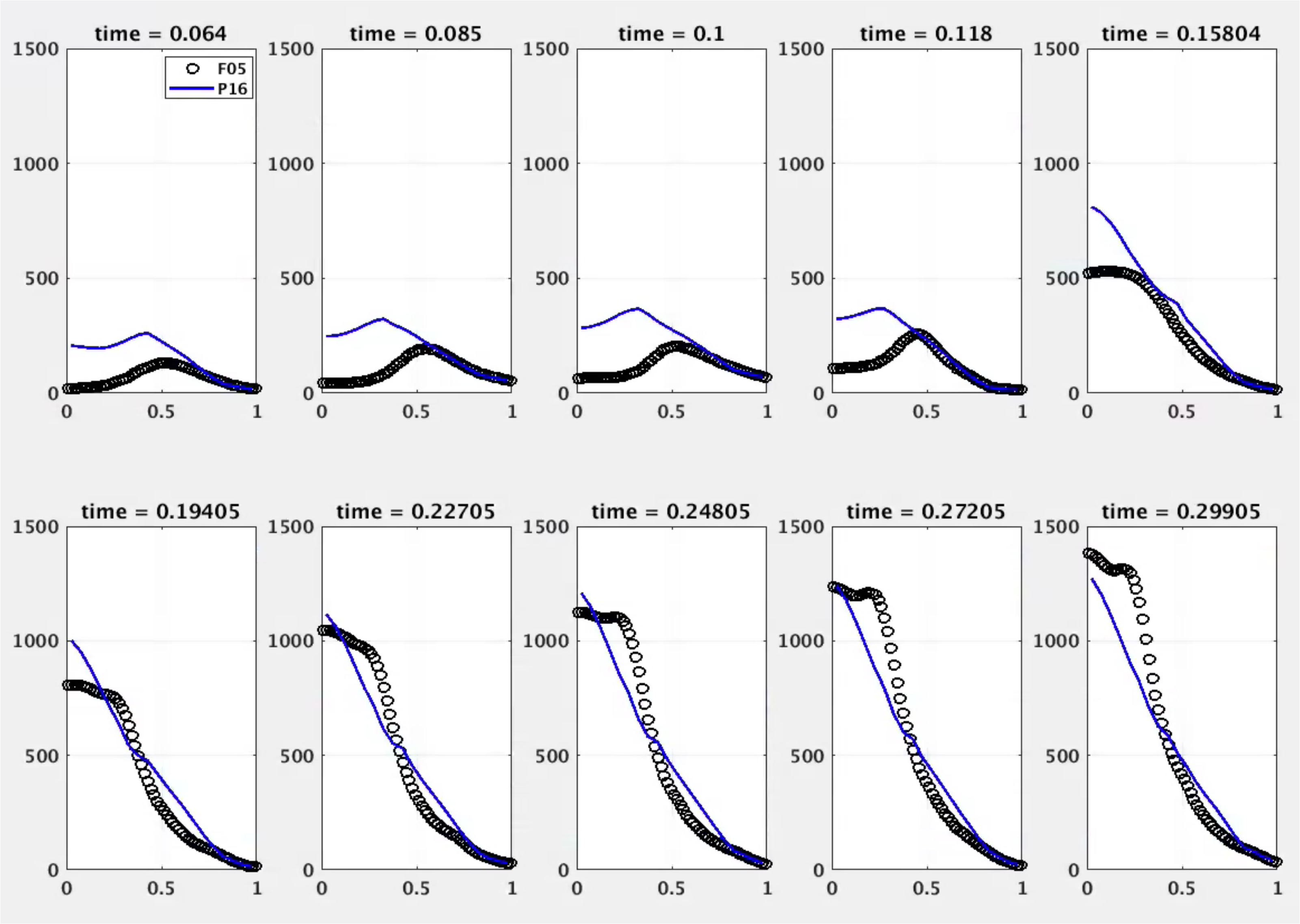
q profiles - NSTX



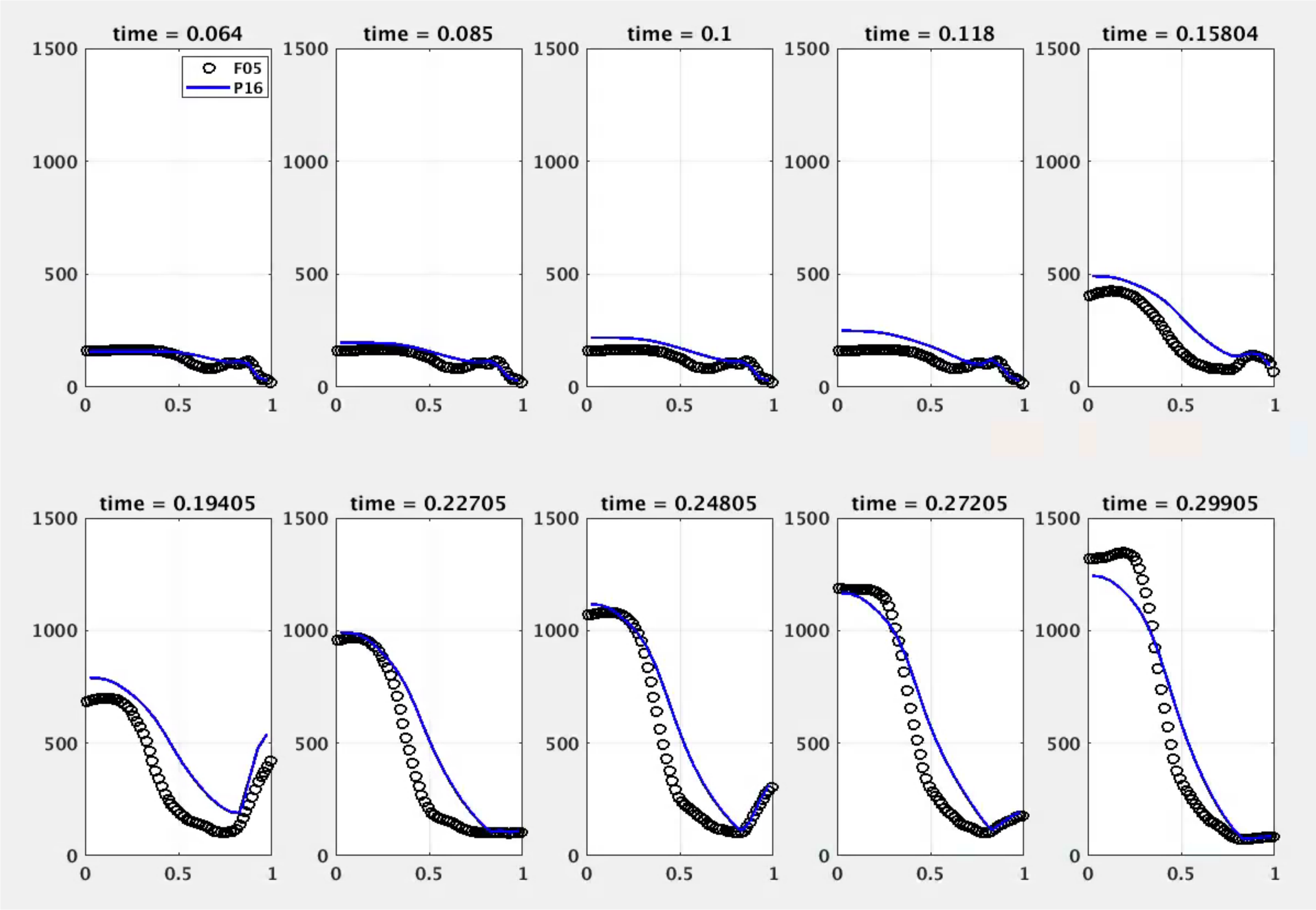
0-D parameters - NSTX



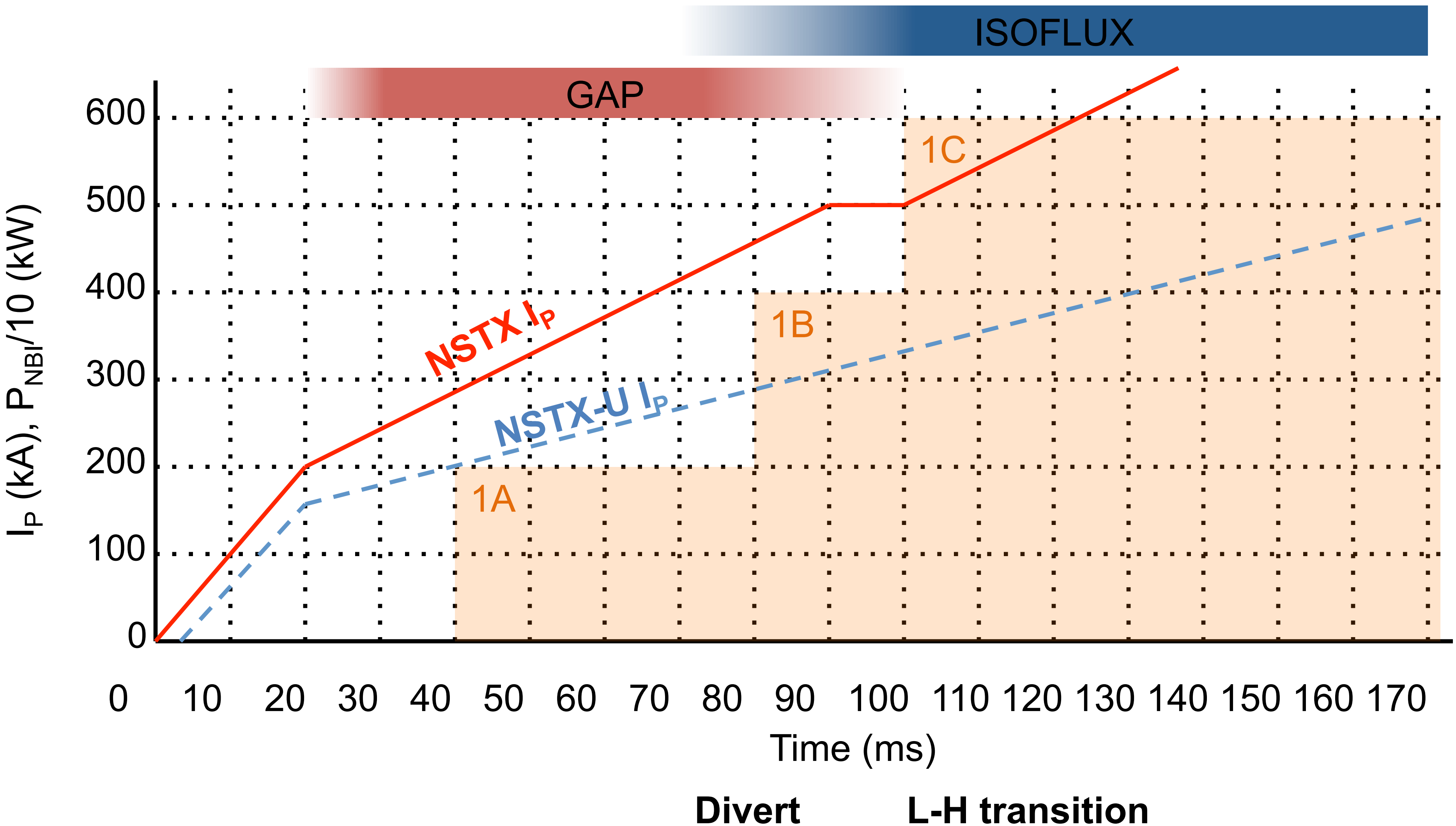
Te profiles – NSTX-U



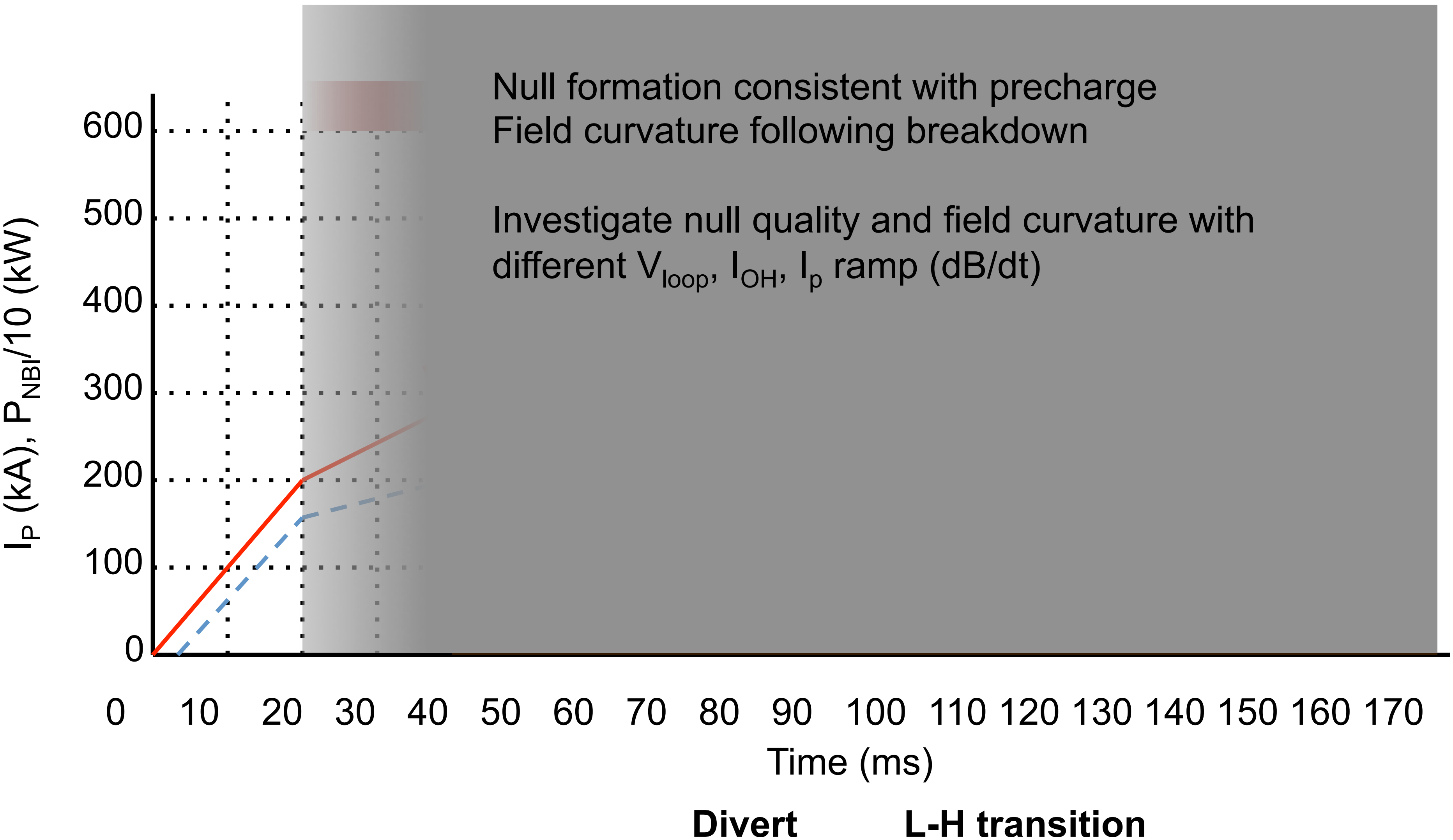
Ti profiles – NSTX-U



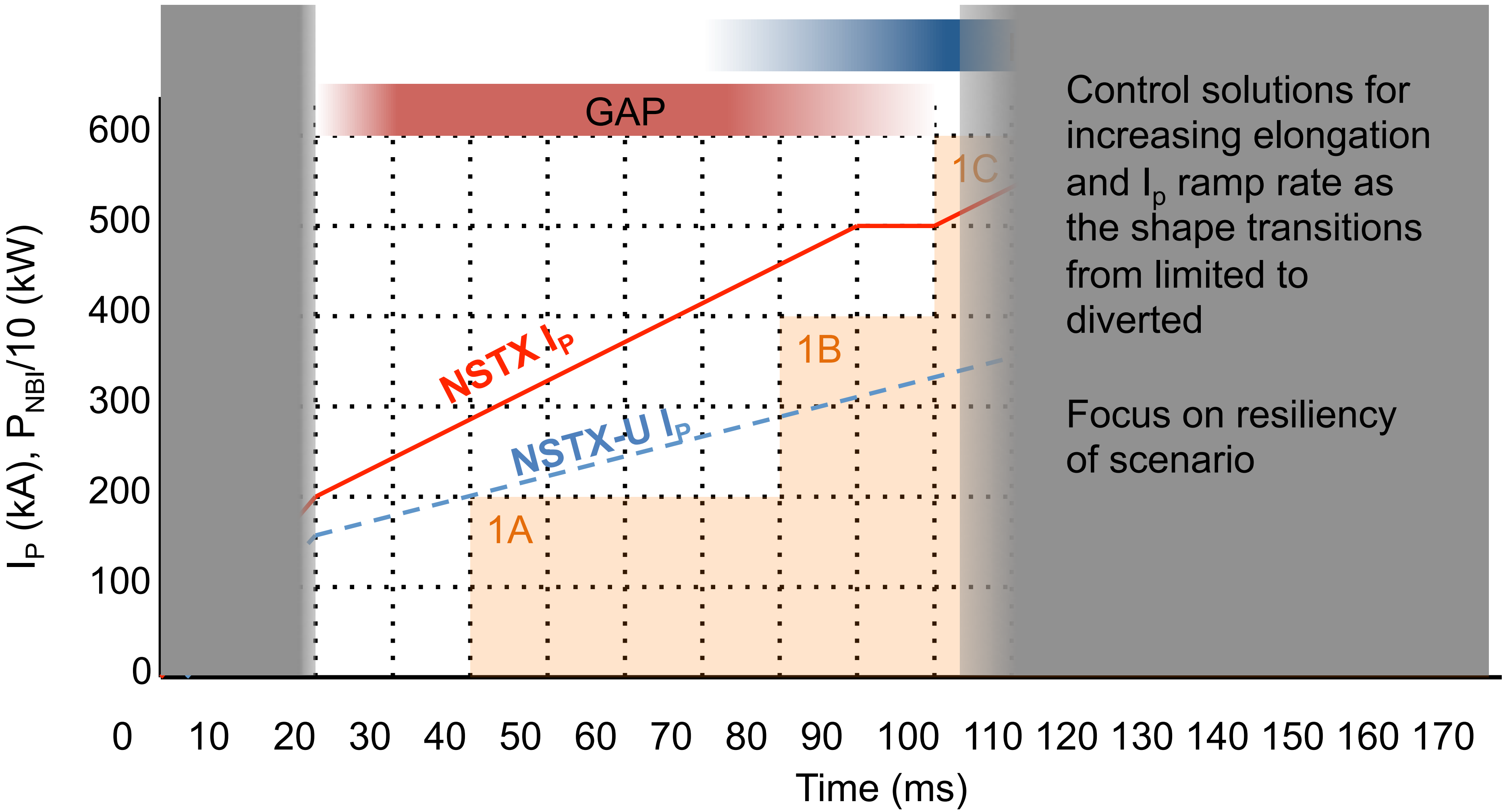
Typical NSTX ramp-up



LRDFIT modeling focus



TOKSYS modeling focus



Control solutions for increasing elongation and I_p ramp rate as the shape transitions from limited to diverted

Focus on resiliency of scenario

Divert **L-H transition**

TRANSP modeling focus