NSTX-U modeling and control

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0. RT-MPTS Diagnostics (E. Kolemen, F. Laggner, G. Tchilinguirian, R. Rozenblat A. Diallo, B. LeBlanc)

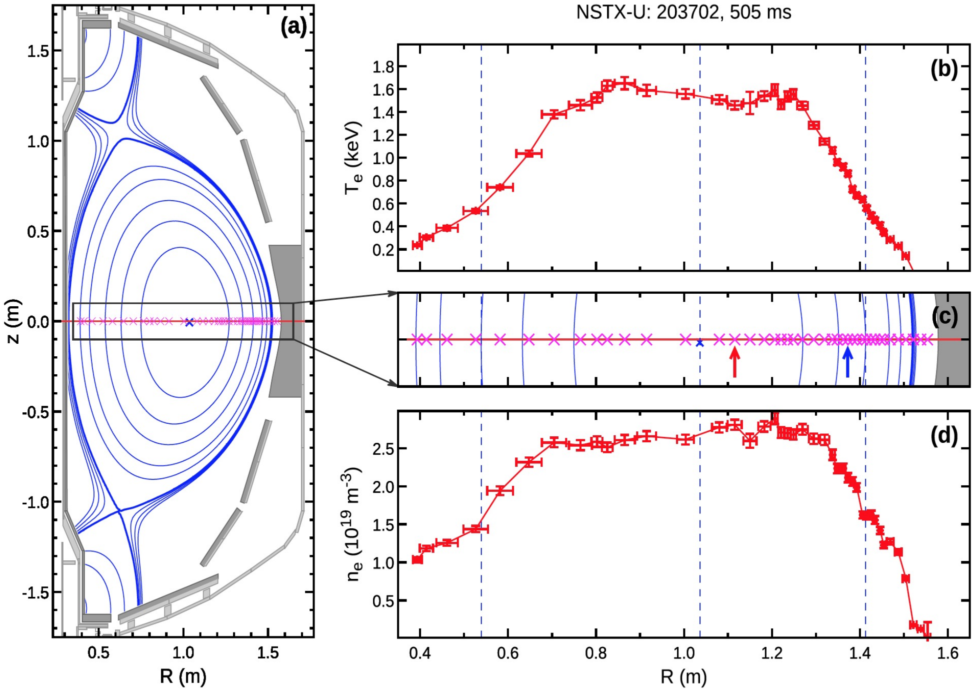
F.M. Laggner (postdoc), D. Eldon (postdoc), A.O. Nelson (grad student), C. Paz-Soldan, A. Bortolon, T.E. Evans, M.E. Fenstermacher, B.A. Grierson, Q. Hu (partial postdoc), D.A. Humphreys, A. Hyatt, R. Nazikian, O. Meneghini, P.B. Snyder, E.A. Unterberg, and E. Kolemen, “Real-time pedestal optimization and ELM control with 3D fields and gas flows on DIII-D”, Nuclear Fusion 60 076004 (2020)

F.M. Laggner (postdoc), A. Diallo, M. Cavedon, and E. Kolemen, “Inter-ELM pedestal localized fluctuations in tokamaks: Summary of multi-machine observations”, Nuclear Materials and Energy, Vol. 19, pp. 479-486 (2019)

F.M. Laggner (postdoc), A. Diallo, B.P. LeBlanc, R. Rozenblat, G. Tchilinguirian, and E. Kolemen, “A scalable real-time framework for Thomson scattering analysis: Application to NSTX-U”, Review of Scientific Instruments 90, 043501 (2019)

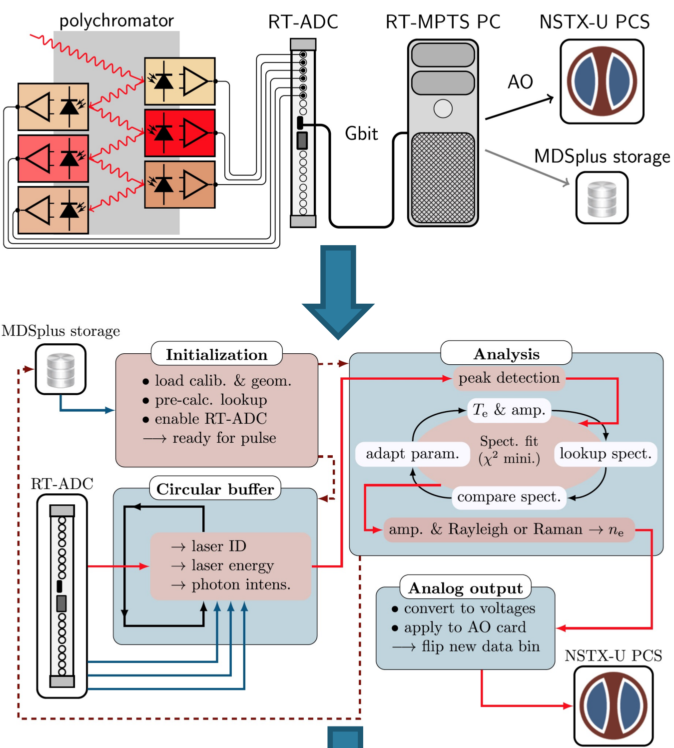
R. Rozenblat, E. Kolemen, F. M. Laggner (postdoc), C. Freeman, G. Tchilinguirian, P. Sichta, and G. Zimmer, “Development of Real-Time Software for Thomson Scattering Analysis at NSTX-U”, Fusion Science and Technology, DOI: 10.1080/15361055.2019.1658037 (2019)

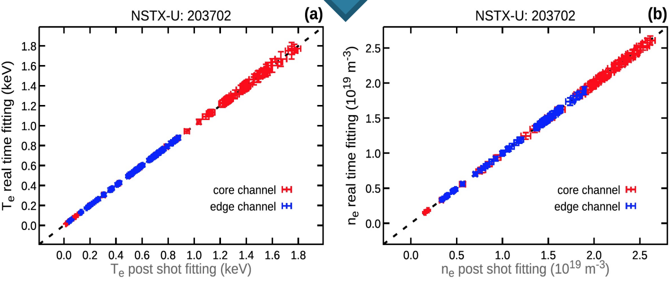
NSTX-U RT-MPTS System



rt-MPTS to enable rt T_e n_e calculations, better EFIT and control

Rt-MPTS for Control and Rt-Kinetic-EFIT





Project Objectives:

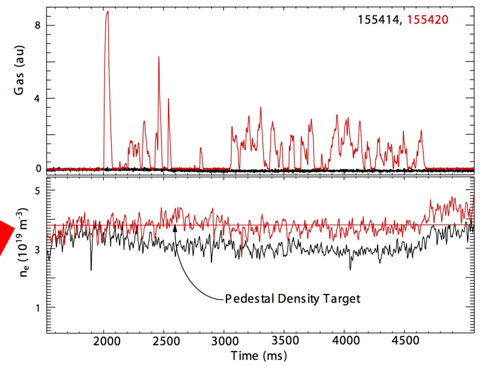
a) Compute n_e and T_e profiles in real-time (2021)

b) Share this information with PCS (2021)

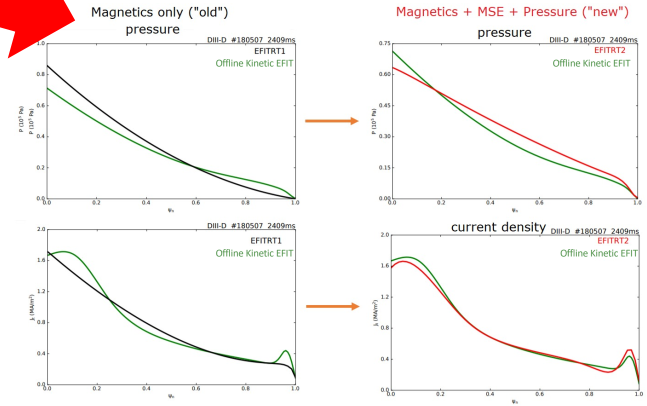
c) Enhance rt-EFIT with rt-MPTS data (2022)

d) Develop control algorithms to achieve and stabilize scenarios with prescribed edge and core structures (2022-2023)

e) Improved disruption avoidance (2023-2025)



Control Example: Pedestal Density (DIII-D)



Rt-Kinetic EFIT (DIII-D)

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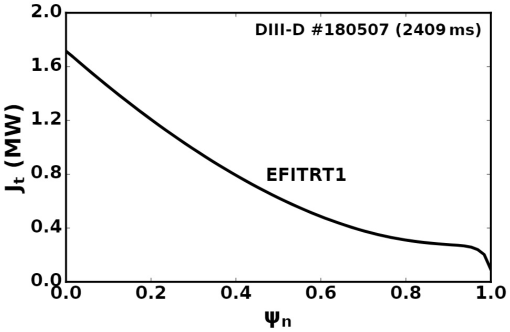
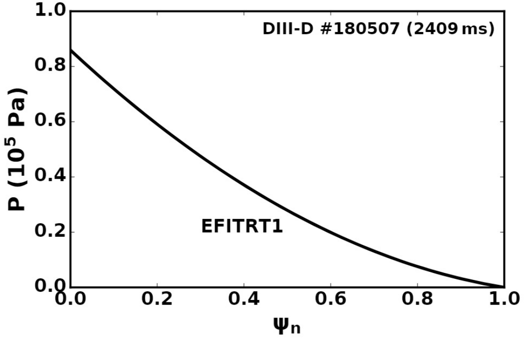
Egemen Kolemen

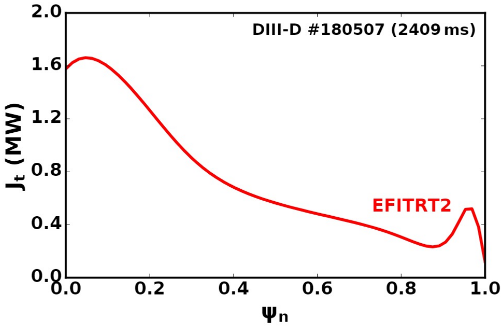
Real-time Kinetic EFIT with new rt-MPTS

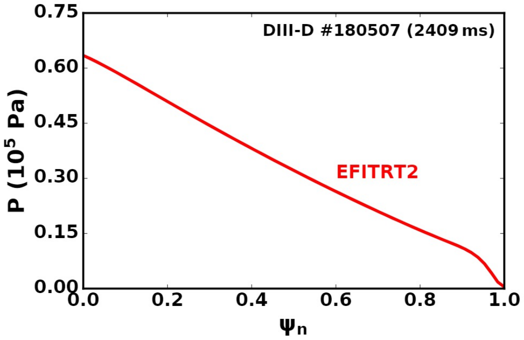
EFITRT1





New Real-time MSE+CER+ Thomson EFITRT2 at DIII-D





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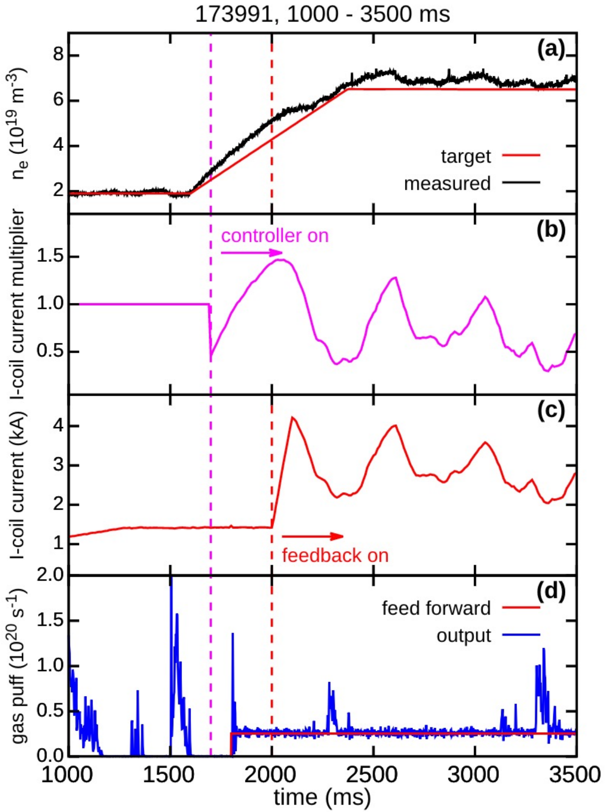
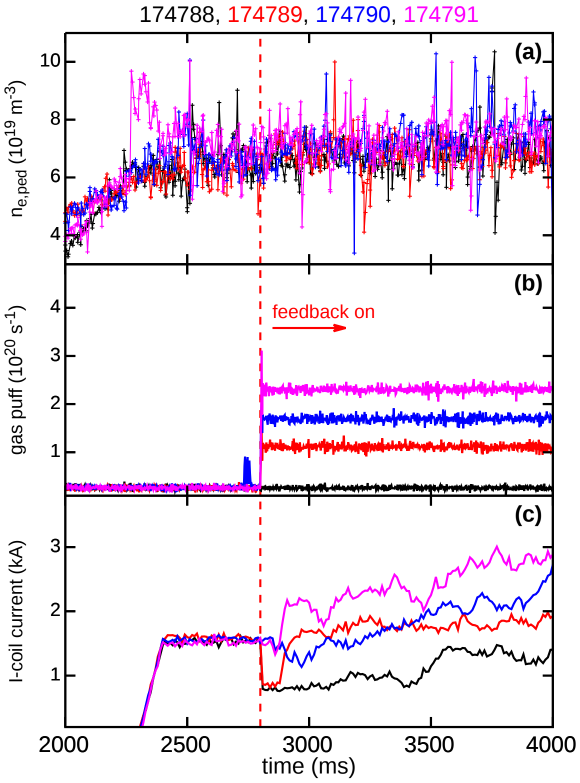
R. Shousha with K. Erickson
F. Laggner, Z. Xing, J. Ferron

Advanced Pedestal Control Enables Physics

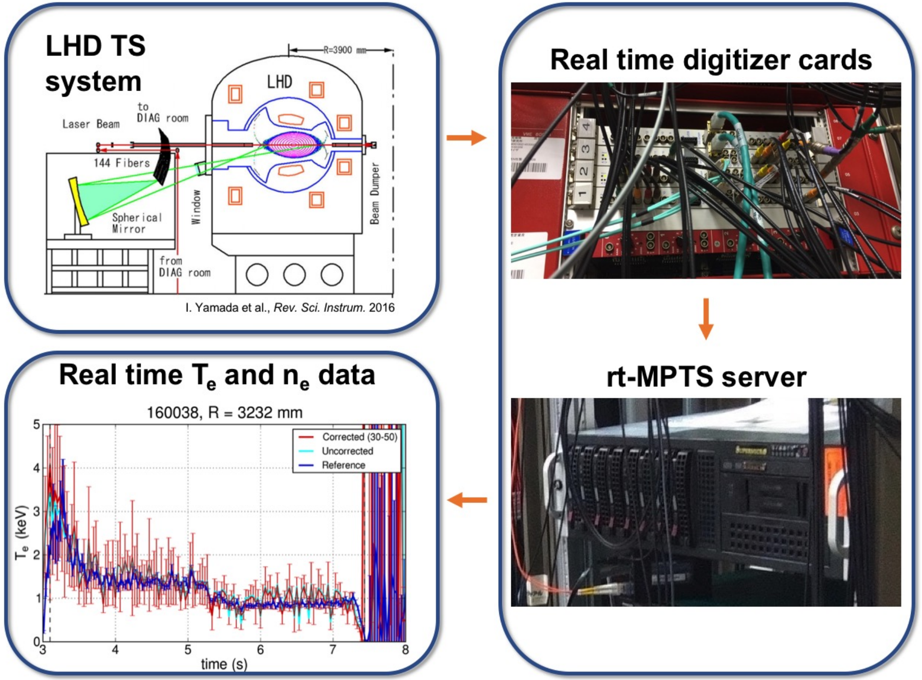


- Developed at Tested Pedestal Control (density, pressure at pedestal top) using **3D Coils + Gas puffing**
- Enable desired pedestal with minimal perturbations
- **Allowed achieving Super-H mode under different fueling regimes with same pedestal density.**



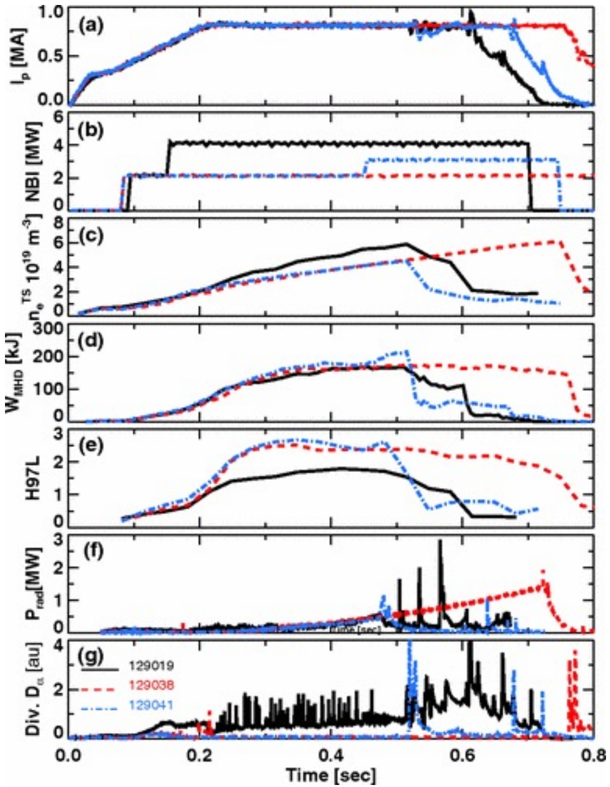
Laggner NF 2020

NSTX-U RT-MPTS Copy Running at LHD System

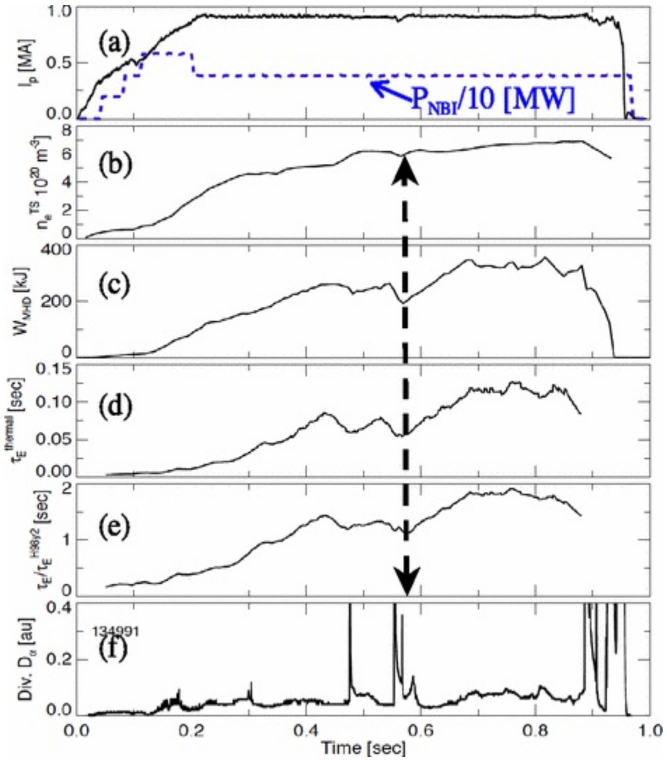


The digitizer cards and the real time server (right) as implemented at LHD. The rt-MPTS T_e result is compared with the offline TS system (bottom left), with the rt-MPTS system in red and reference in blue.

NSTX-U RT-Thomson: Help Advanced Scenarios



Comparison of pre-lithium ELMy discharge (black), and two post-lithium discharges with different NBI power (blue, red)



Time evolution of discharge with transition to the enhanced pedestal H mode

Schedule for RT-MPTS System

- **Hardware is manufactured now**
- **We will install the system in 2021**
- **2022 test of the rt-MPTS on NSTX-U with plasma**
- **2023 test of control with rt-MPTS**
- **RT-efit development with Te/ne constraints is being tested on DIII-D in 2021/2022. Hopefully will be applied on NSTX-U in 2022/2023.**

Control/Physics Overview

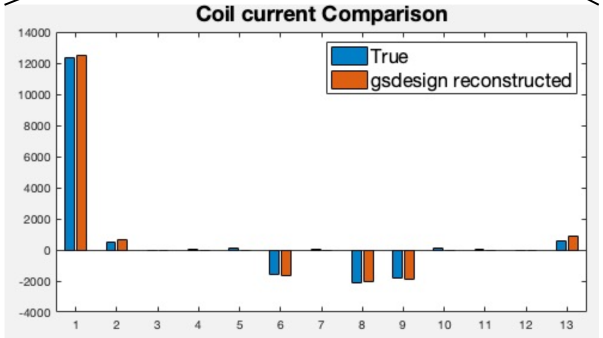
1. Snowflake divertor (SFD) feedback control
2. Optimization of SFD power and particle exhaust
3. Improving SFD reconstruction via infrared thermography
4. Shape control model validation
5. Optimization of rampup feedforward trajectories
6. Neural networks for fast shape reconstruction and modeling

5. Optimization of rampup feedforward trajectories (Wai, Boyer)

Optimization of feedforward trajectories -

Iterative time slice algorithm:

User inputs a few target equilibria at times (either shaping parameters or flux maps) → Flux map is used to obtain equilibrium currents (e.g. via NN GS solver) → Solve an optimization problem to identify coil current trajectories → Identify vessel currents and update the target equilibria to include these → Use a neural net to ***quickly*** find equilibria from simulated coil currents



Optimization to find feedforward trajectories

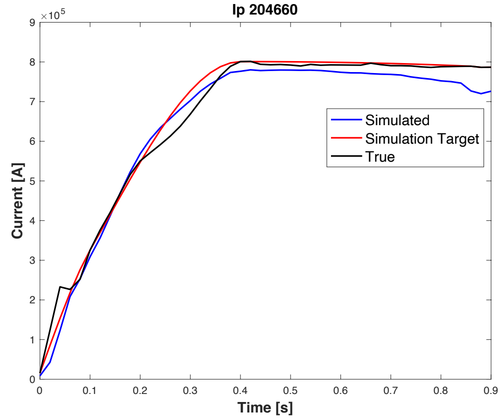
- Define a cost function of the form

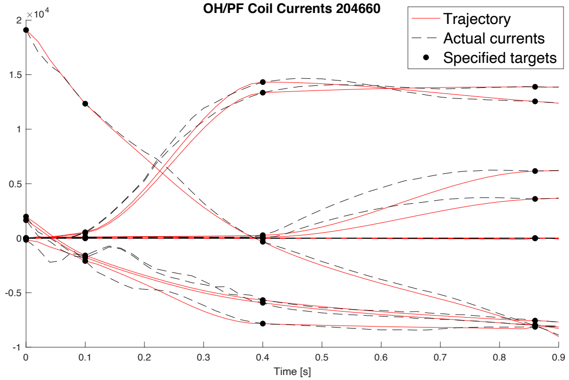
$$J = \sum_{i=1}^{N} (I_{k+i} - r_{k+i})^T Q (I_{k+i} - r_{k+i}) + \Delta I_{k+i}^T Q_v \Delta I_{k+i}$$

Subject to: (dynamics constraint)

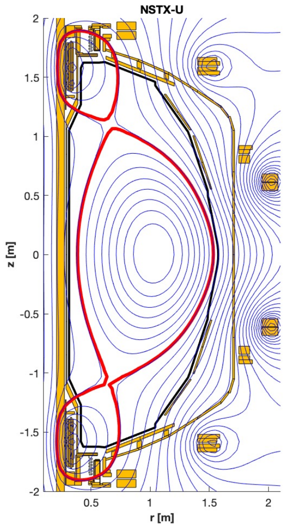
$$\dot{I} = A(t)I + B(t)v$$

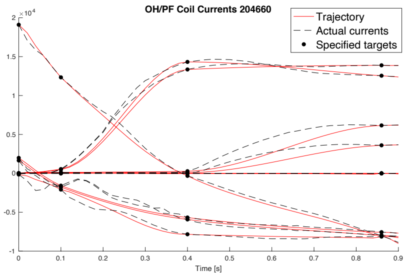
- The reference trajectory r depends on vessel currents, and A(t)/B(t) depend on the equilibrium, so this problem should be solved iteratively.





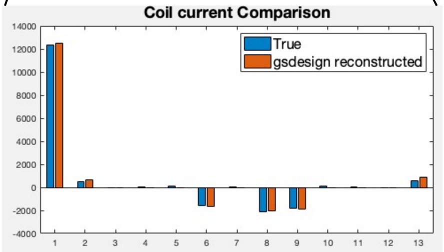
Coilnet: Optimizing coil current trajectories for magnetic equilibrium shaping





User inputs a few target equilibria at times (either shaping parameters or flux maps)

Coilnet: Flux map is used to obtain equilibrium currents (e.g. via gsdesign or with NN)



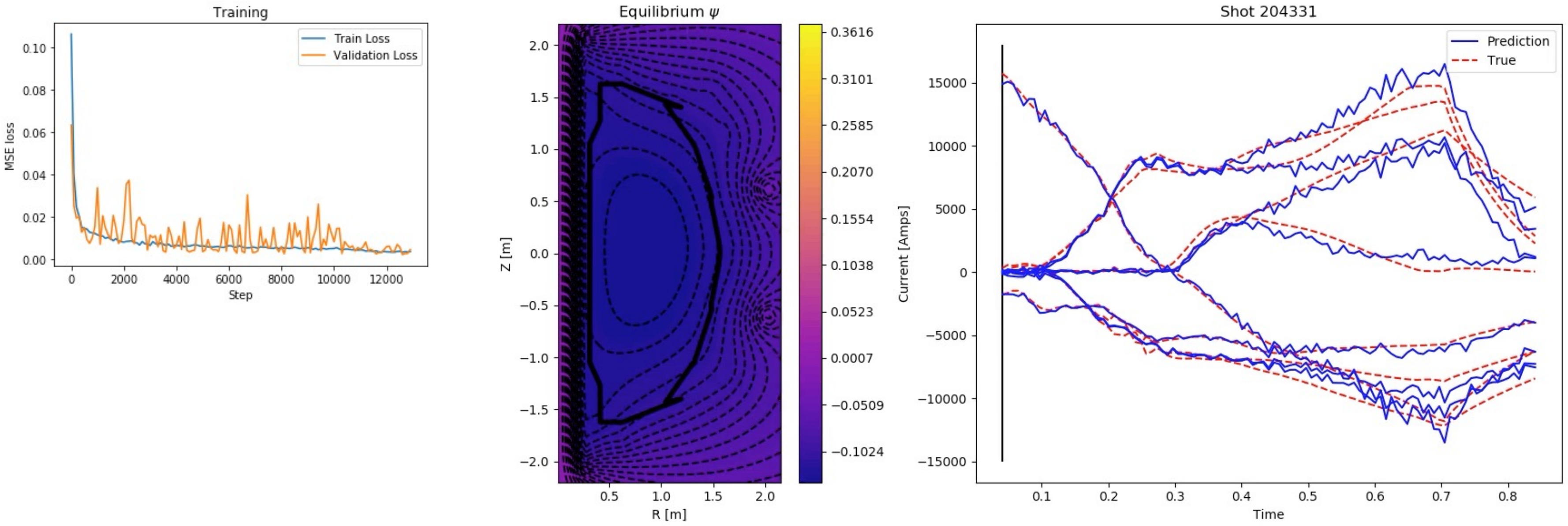
Pertnet: Include estimate of nonlinear dynamics, for vertical instability.

Solve an optimization problem to identify coil current trajectories

Identify vessel currents and update the target equilibria to include these

Eqnet: Use a neural net to ***quickly*** find equilibria from simulated coil currents

Coilnet: Flux map is used to obtain equilibrium currents



Validation dataset:
100.0% of samples are within 20% (Full Scale) of the true coil currents.
99.1% of samples are within 10% (Full Scale) of the true coil currents.
94.9% of samples are within 5% (Full Scale) of the true coil currents.
43.3% of samples are within 1% (Full Scale) of the true coil currents.

NN architecture based on AlexNet

Pertnet: Estimating the plasma-modified mutual inductance matrix

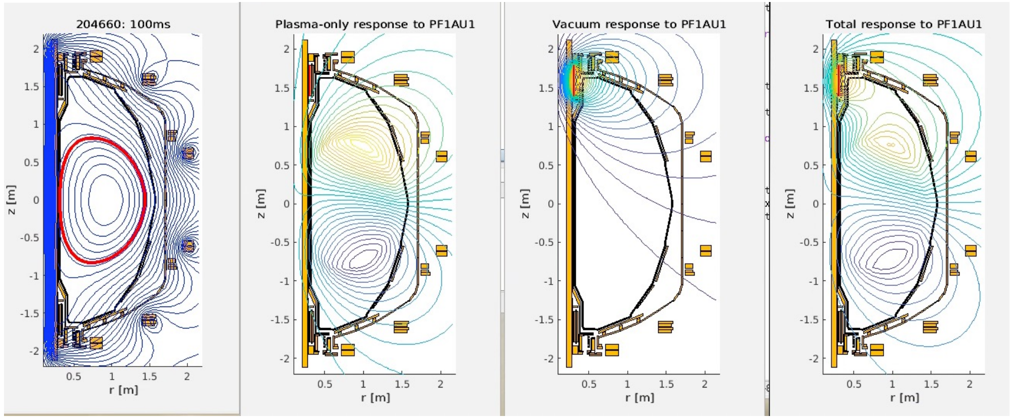
$$v_s = R_s I_s + M_{ss}\dot{I}_s + \dot{\Psi}_{ss,plasma}$$

$$\dot{\Psi}_{ss,plasma} = \frac{\partial \Psi_{s,plasma}}{\partial I_s}\dot{I}_s$$

$$\dot{I} = A(t)I + B(t)v$$

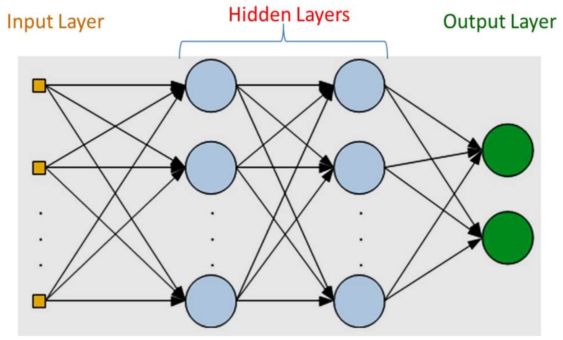
- Related to a perturbed solutions to the Grad-Shafranov equation

$$\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \psi}{\partial r}\right) + \frac{1}{r}\frac{\partial^2 \psi}{\partial z^2} = -\mu_0 r^2 \frac{dp}{d\psi} - rB_\phi \frac{d(rB_\phi)}{d\psi}$$

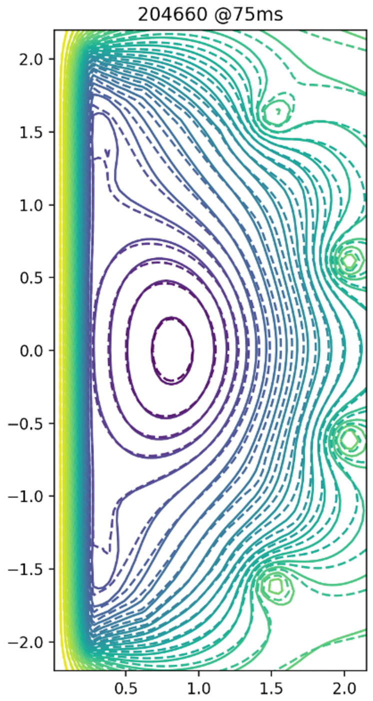


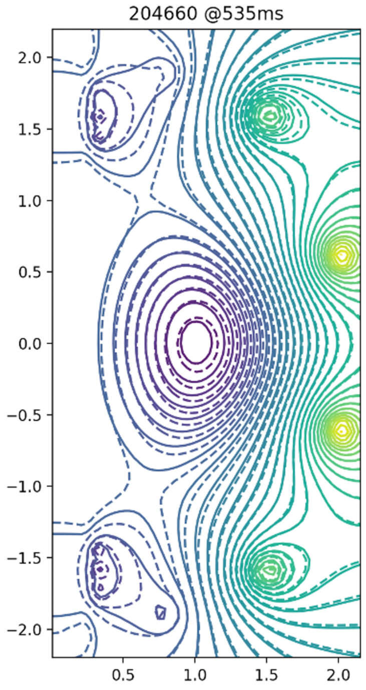
Eqnet used an MLP to estimate flux surfaces from coil currents

- ***Pertnet*** Goal: perform similar calculation with MLP except with gspert targets
- Perturbed response has higher dimensionality. x48 (1 response per coil)



MLP



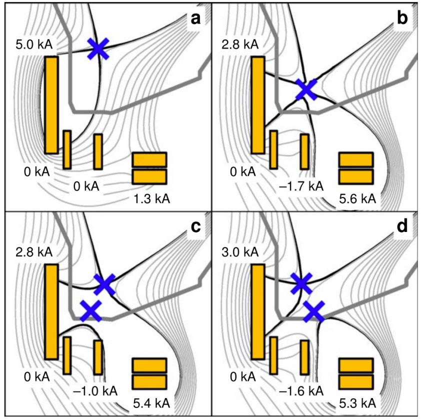


1. Snowflake divertor feedback control

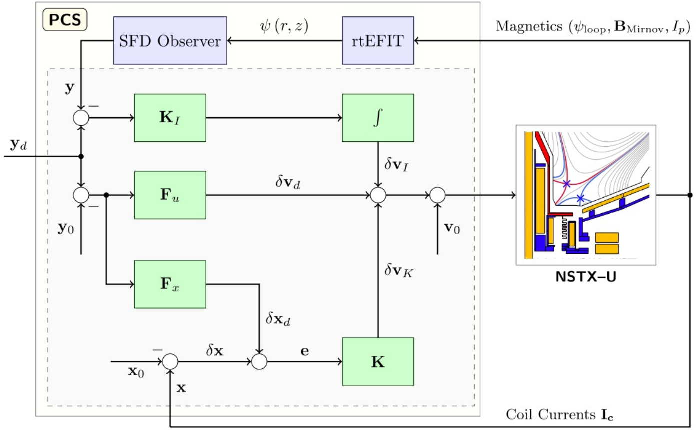
Snowflake divertor control – (Vail)

- *Snowflake divertor:*
  - *Second order null*
  - *High flux expansion, heat flux splitting phenomenon, detachment access*
- *Control algorithm:*
  - *Proportional control for isoflux shape targets*
  - *LQI for snowflake targets (dr, dϴ)*

https://doi.org/10.1088/1361-6587/aaf94a

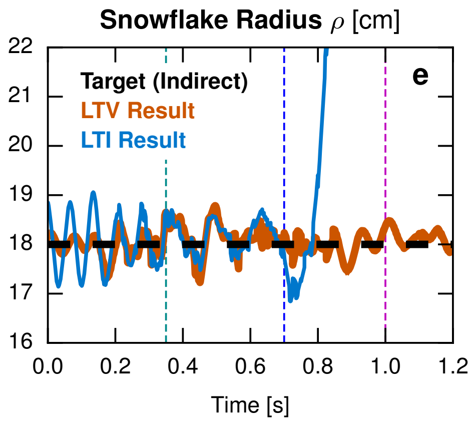


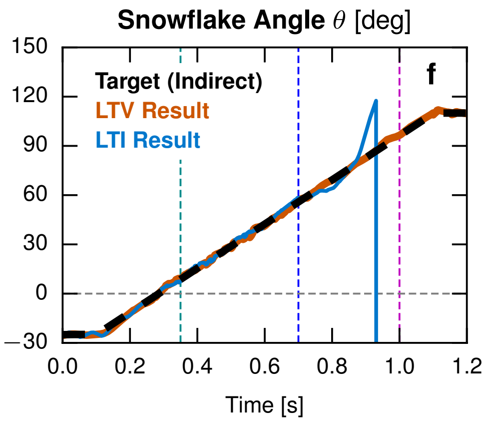
a. Standard divertor
b. Perfect snowflake
c. Snowflake plus
d. Snowflake Minus

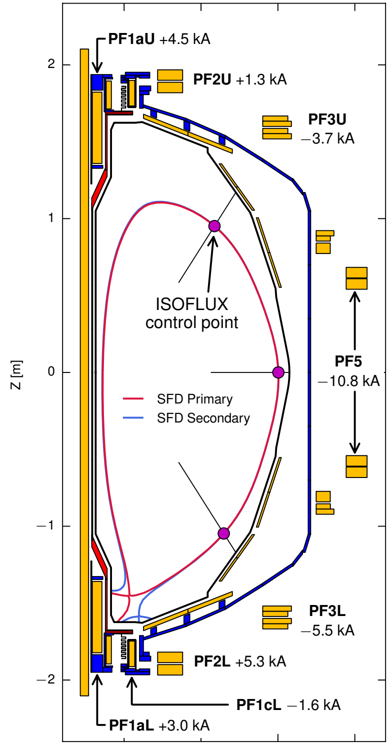


High-fidelity closed loop simulation indicates need for time-varying model in control

- *Developed and tested with nonlinear closed loop simulation environment.*
- *Linear time-invariant (LTI) system insufficient for moderate-large changes. Must use time-varying (LTV) model*



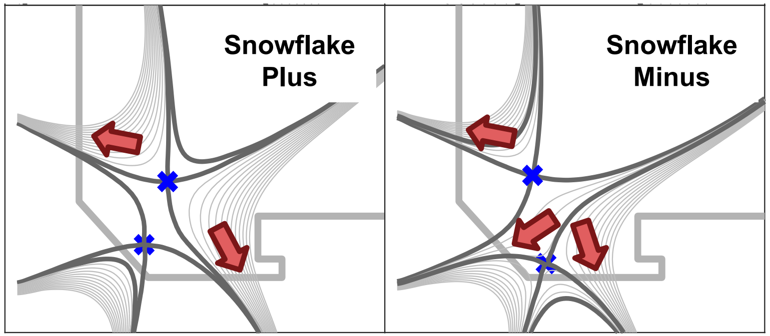


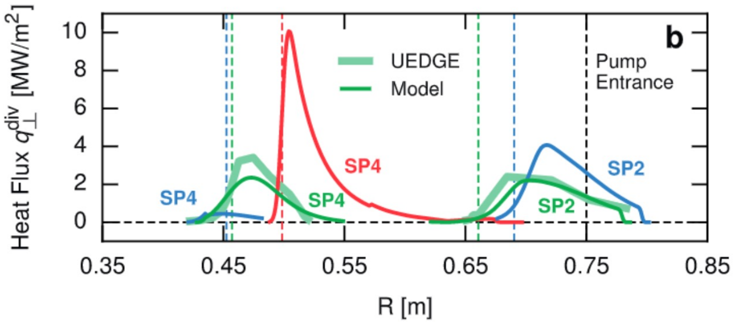


2. Optimization of SFD power and particle exhaust (Vail, Izacard)

Snowflake divertor heat exhaust

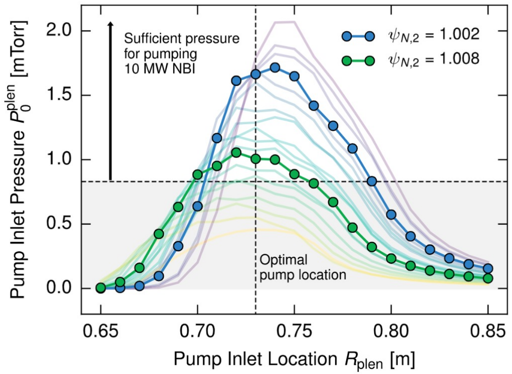
- *Study of power and particle exhaust capabilities using in NSTXU using cryopump + snowflake*
- *Develop simple, fast heat flux diffusion model [Vail, NME] and validated with UEDGE*
  - *Heat flux diffuses across ψ but in separate domains for SFD-minus*

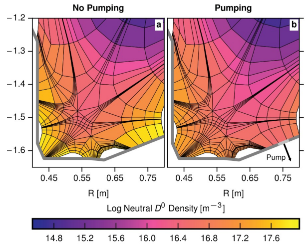




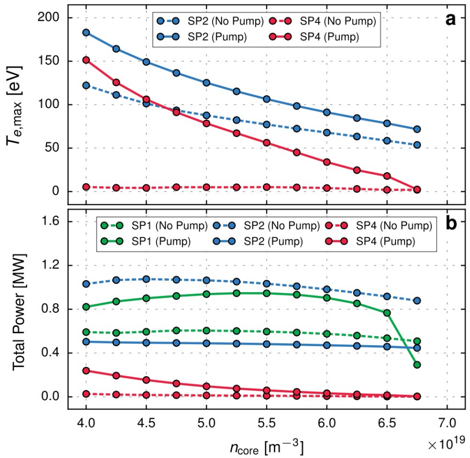
SFD power exhaust with cryopumping

- *To pump 10MW NBI power, need P > 0.83 mTorr at pump inlet [Vail, NME]*
  - *Assume 24 kL/s volumetric pump rate for liquid helium cooled cryopump*
- *At pump optimal location, 83% of SFD equilibria in database meet this condition.*
- *UEDGE simulation: with pumping*
  - *Te rises at strike points due to reduced collisionality*
  - *SOL power is redistributed among strike points ➔ changes the ideal 'power balanced' SFD configuration*





UEDGE grid generation



3. Improving SFD reconstruction via infrared thermography (Wai, NME, 2020)

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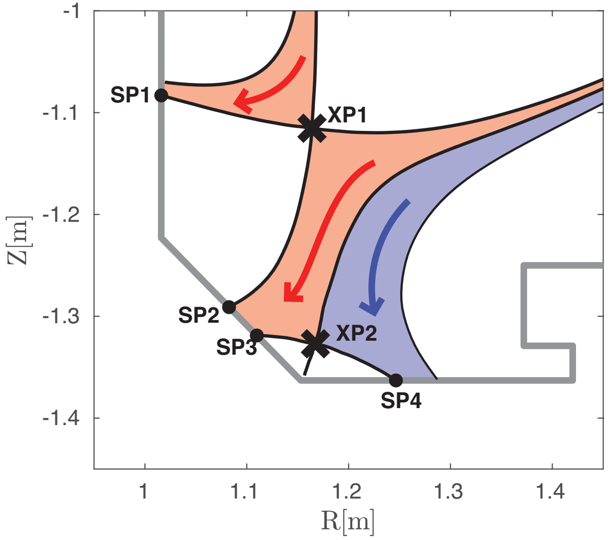
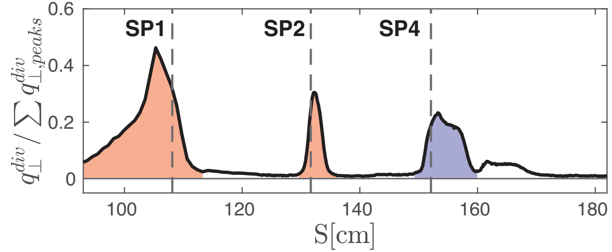
Infrared thermography (IRTV) for SFD reconstruction

- ***Snowflake plus:*** *secondary x-point lies in the private flux region. Scrape-off layer (SOL) fieldlines directly intersect divertor in 2 locations ⇒ 2 heat flux peaks.*
- ***Snowflake minus:*** *secondary x-point lies in the SOL. Fieldlines directly intersect divertor in 3 locations ⇒ 3 heat flux peaks.*
- *Equilibrium vs. IRTV inconsistencies*
  - *Strike point location mismatch*
  - *Occasionally, incorrect # of heat flux peaks for the snowflake type*
  - *IRTV used to improve equilibrium*
  - *Useful for control (feedback on x-point locations [Kolemen, 2018])*
  - *Geometry sensitive to unmeasured divertor currents. Potential use as diagnostic for bootstrap current.*





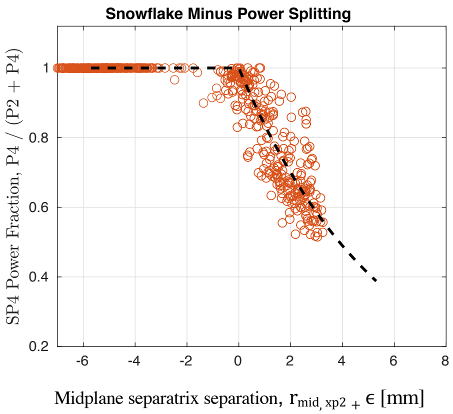
Heat flux power fraction in the SFD

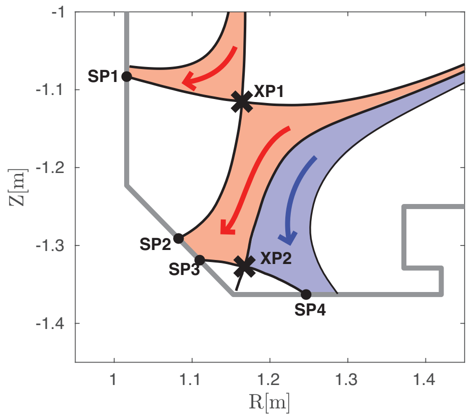
- Power fraction f_{sp4} measured from the divertor heat flux profile. At each peak, $P_{pk} = \int 2\pi R(s) q_\perp(s) ds$
- Secondary separatrix position $r_{mid,\,xp2}$ measured from EFIT equilibrium.
- Data is selected from subset of shots that have wide range of x-point separation and fit to:

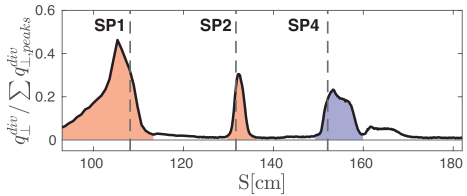
$$f_{sp4} := \frac{P_4}{P_2 + P_4}$$

$$= \frac{\int_{r_{mid,xp2}}^{\infty} q_\perp^{mid,peak} e^{-r/\lambda_q^{eff}} dr}{\int_0^\infty q_\perp^{mid,peak} e^{-r/\lambda_q^{eff}} dr}$$

$$= e^{-r_{mid,xp2}/\lambda_q^{eff}}$$

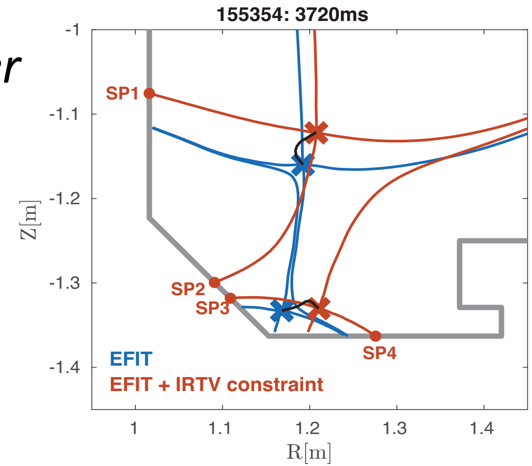


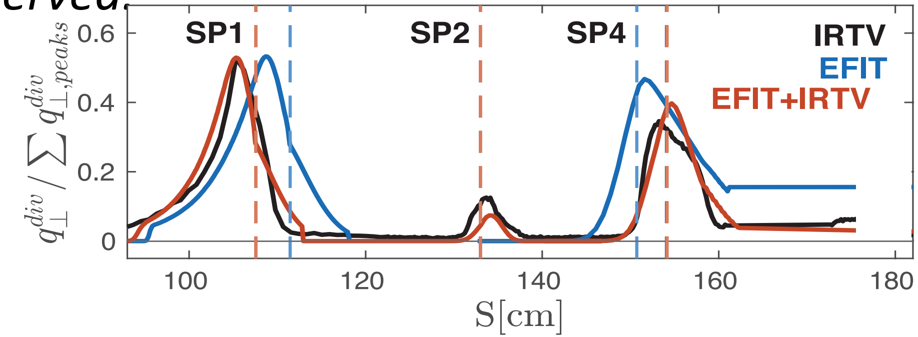




IRTV used to constrain strike points, x-points

- *Strike points and outboard power fraction are mapped to x-point locations [?].*
- *Final heat flux profiles match consistently.*
- *Modification to edge current observed.*





Measure mismatch

Use IRTV to measure strike points and ψ_{xp2}. Compare to equilibrium (from EFIT).

Identify x-points

Use algorithm to update the x-point spatial positions.

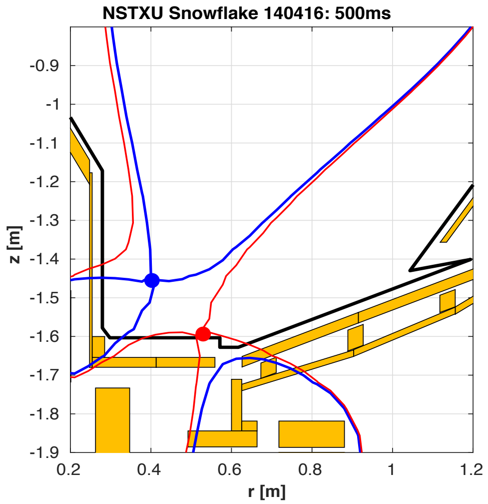
Solve for new equilibrium

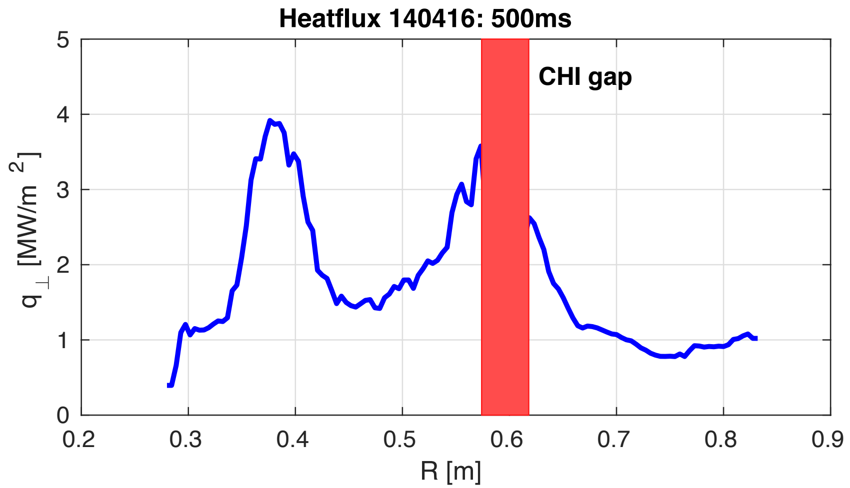
Solve free boundary Grad-Shafranov equation (using Toksys [Walker, 2015]) with hard constraints on x-point positions.

~4-5 iterations to converge

Extension to NSTXU

- Technique was developed with DIII-D but principles can extend to NSTXU
  - Fewer constraints available to lack of visibility on inner wall, CHI gap





The 2 observable LFS heat flux peaks. Inner peak not observed, and outermost peak obscured by CHI gap.

4. Shape control model validation (Wai, Boyer)

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Model validation for shaping feedforward control

- Shape control based on the toroidal circuit equation which can be transformed to time-varying state-space system.

$$v_s = R_s I_s + M_{ss}\dot{I}_s + \dot{\Psi}_{ss,plasma}$$

$$\dot{\Psi}_{ss,plasma} = \frac{\partial \Psi_{s,plasma}}{\partial I_s}\dot{I}_s$$

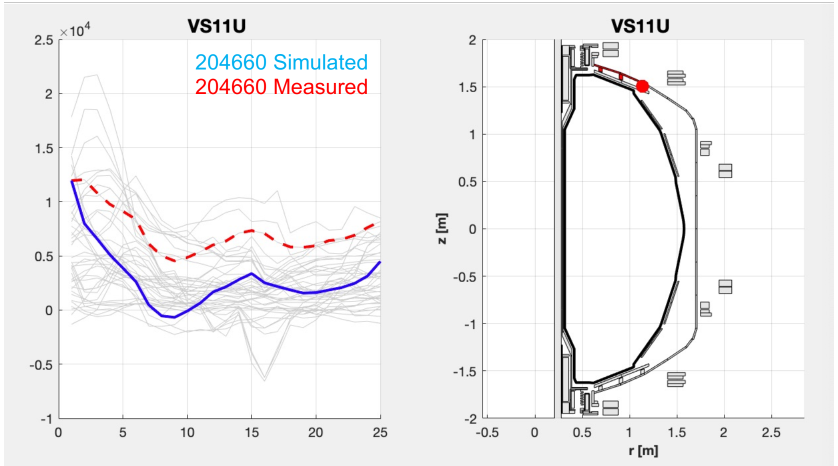
→

$$\dot{I} = A(t)I + B(t)v$$

- *Shape control algorithm relies entirely on PID feedback with no feedforward.*
- *Large shape errors at startup, and small errors during flattop lead to poor performance.*
- *A **design tool that translates a target shape evolution into approximate feedforward current evolution** is needed*

Model validation

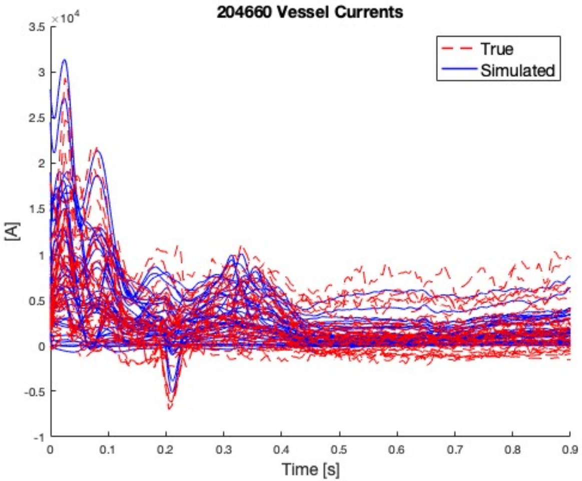
- First step is to validate the model versus experiment, so that current evolution can be simulated.
  - Vessel currents play a strong role on equilibrium, especially with NSTXU short pulse length
- Use a greybox fitting procedure to identify: coil power supply internal inductances, vacuum vessel resistances, plasma resistance Rp(t).

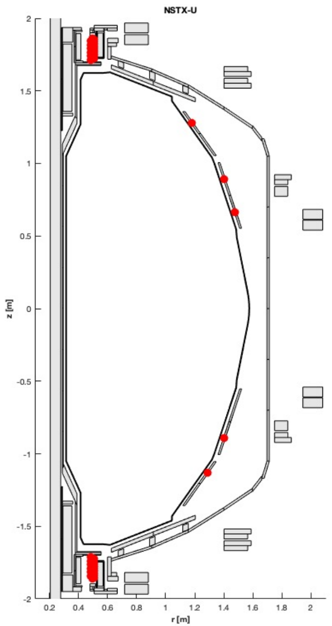


Vacuum vessel currents show inconsistency with measured.

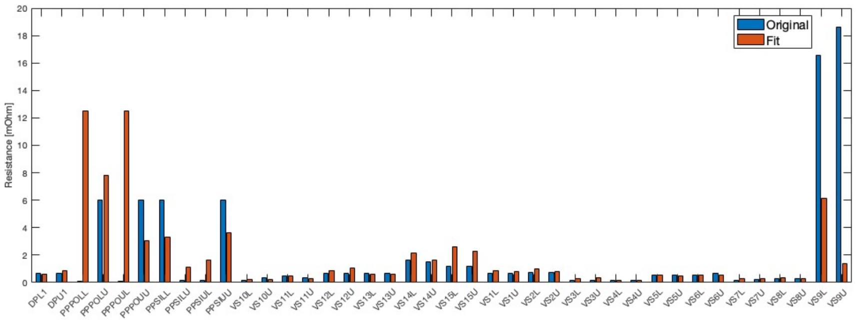
Vessel fitting results modify resistance in bellows, passive plates

- Fitted model parameters give much better match to vessel currents, plasma current.
- Resistances that changed the most with fitting are consistent with expectations
  - Bellows
  - Passive plates, ‘effective’ resistances difficult to measure because of nontoroidal eddy currents





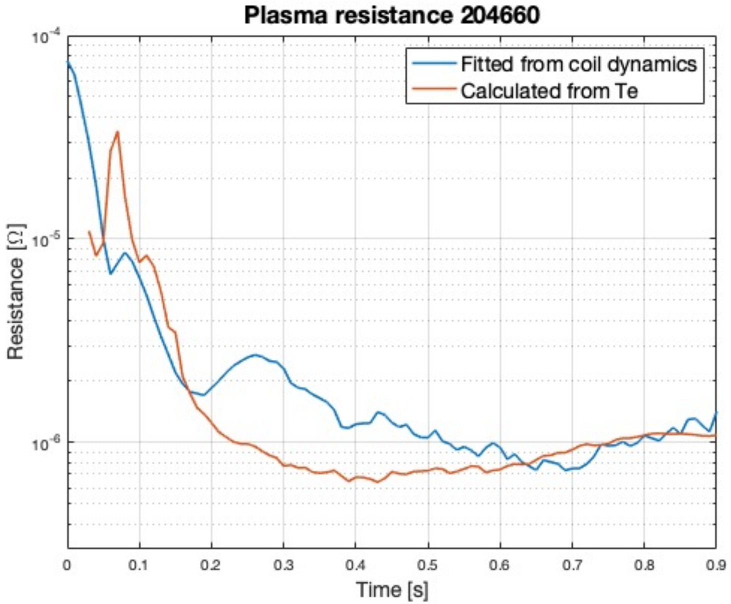
Bellows and passive plate locations



Identify plasma resistance Rp(t)

- Plasma resistance an important time-varying parameter to identify
- Sets the trajectory for OH coil
- Currently, using values fit from the dynamics model.
  - In future, could couple with evolution predictors (Nubeam net, current profile evolution, Te/ne modelling)
  - Fitted values not far from simple Te modeling with Spitzer resistivity

$$Res = \frac{2\pi R_0 \eta}{\pi \kappa a^2} \qquad \eta \approx \frac{\pi e^2 m^{1/2}}{(4\pi\epsilon_0)^2 (KT_e)^{3/2}} \ln \Lambda$$

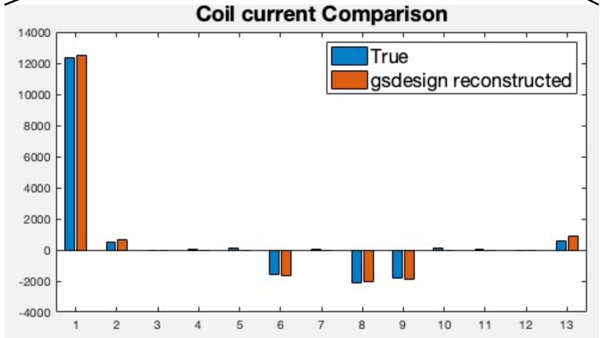


5. Optimization of rampup feedforward trajectories (Wai, Boyer)

Optimization of feedforward trajectories -

Iterative time slice algorithm:

User inputs a few target equilibria at times (either shaping parameters or flux maps) → Flux map is used to obtain equilibrium currents (e.g. via gsdesign) → Solve an optimization problem to identify coil current trajectories → Identify vessel currents and update the target equilibria to include these → Use a neural net to ***quickly*** find equilibria from simulated coil currents



Optimization to find feedforward trajectories

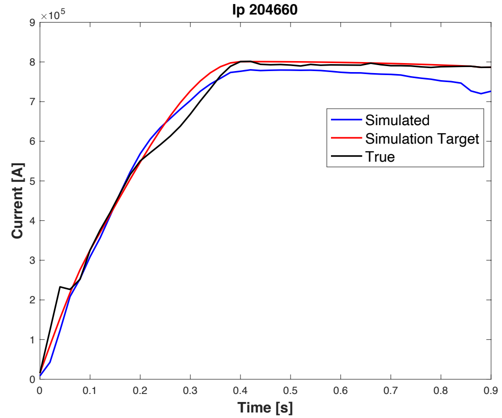
- Define a cost function of the form

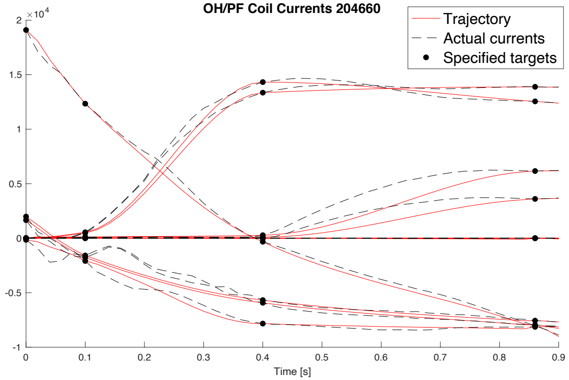
$$J = \sum_{i=1}^{N} (I_{k+i} - r_{k+i})^T Q (I_{k+i} - r_{k+i}) + \Delta I_{k+i}^T Q_v \Delta I_{k+i}$$

Subject to: (dynamics constraint)

$$\dot{I} = A(t)I + B(t)v$$

- The reference trajectory r depends on vessel currents, and A(t)/B(t) depend on the equilibrium, so this problem should be solved iteratively.





6. Neural networks for fast shape reconstruction and modeling (Boyer, Wai)

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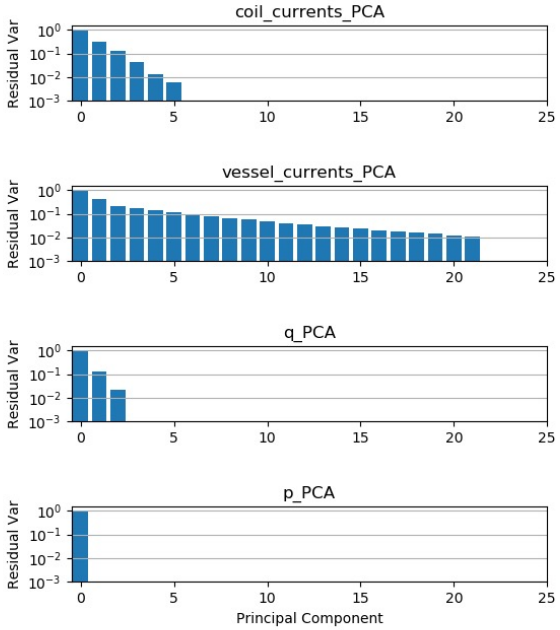
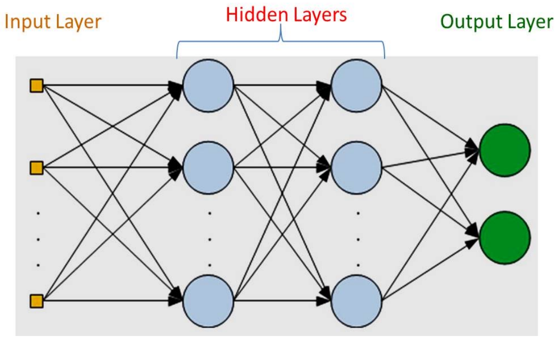
Eqnet finds equilibrium from coil currents

- Feedforward trajectory planner could be useful as an operator tool, especially if results can be obtained quickly! ~1 min
- Several steps currently in optimization take ~1hour
  - Free boundary GS solutions for all equilibria timeslices
  - Identify plasma flux response for all times
- **Eqnet:** finds approximate flux map based on coil currents, vessel currents, q and p profiles.
  - Use PCA reduction of inputs, n_components selected for 99% explained variance

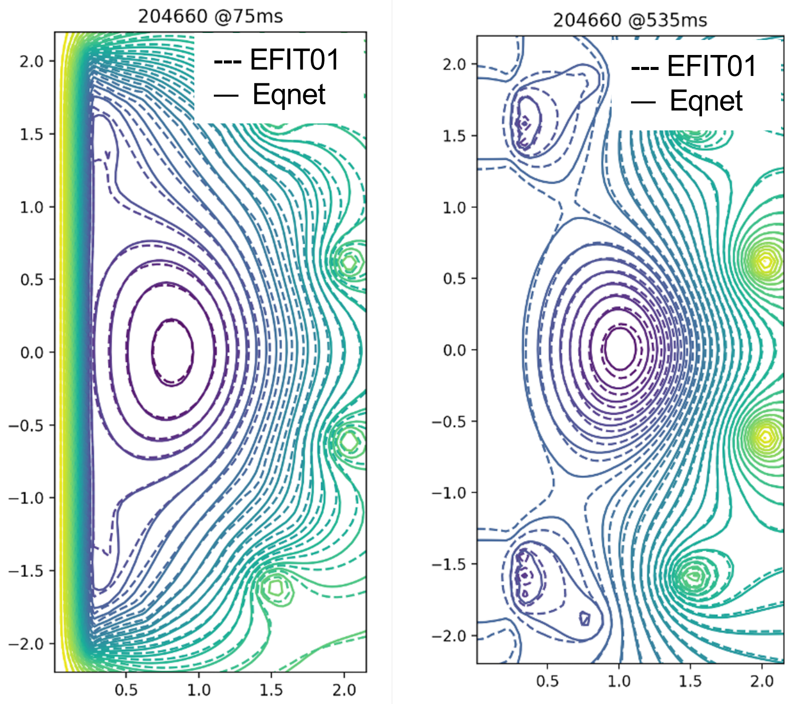


Eqnet

- Uses separate PCA components for rampup and flattop
  - Allows accurate for accurate estimation during rampup (~ t < 300ms) since rampup samples under-represented in database
- Eqnet has standard multi-layer perceptron (MLP) framework.

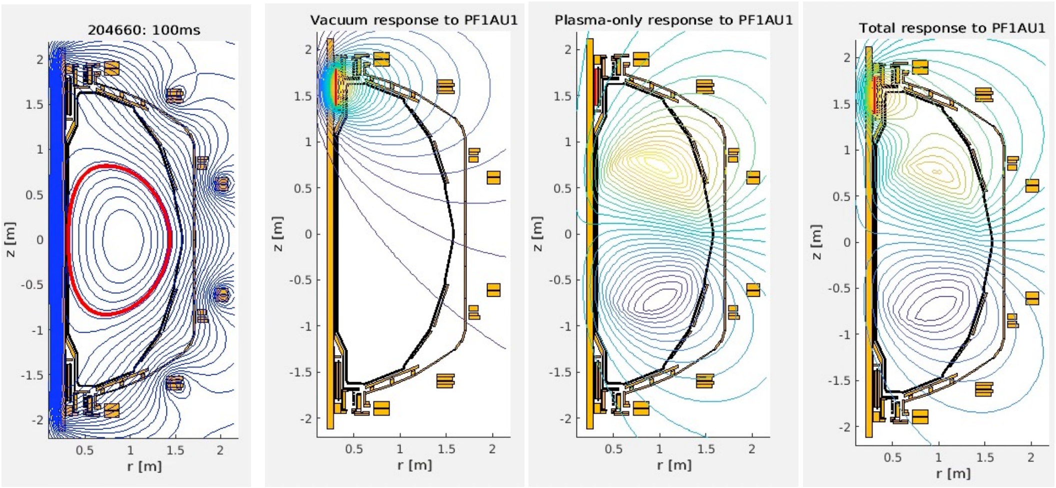


Generic MLP network



Future extensions to include estimation of response

- Future extension
  - Train NN to identify the plasma response
  - In theory, identifying plasma response does not require much more representation capacity than estimating the equilibrium
  - Targets could be identified from code (gspert) or from actual data (derivative of the equilibrium wrt time, minus the vacuum response)



Plasma response calculated from the gspert code

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