R18-1 Milestone Update

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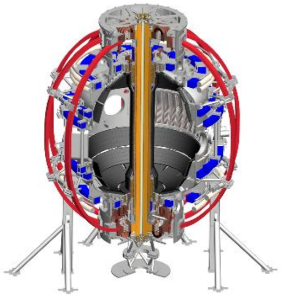
NSTX-U Milestone Update Meeting
B318
8/6/2018

UT
Oak Ridge National Laboratory
PPPL



Milestone Description

R18-1: Develop and benchmark reduced heat flux and thermo-mechanical models for PFC monitoring

The NSTX-U Recovery Project will deploy new plasma facing components (PFCs) to meet updated heat exhaust requirements driven by narrower scrape-off-layer widths, increased heating power, and longer pulse durations relative to NSTX. Inter-shot monitoring or intra-shot control of heat flux to PFCs is anticipated for a range NSTX-U operating space, necessitating reduced models that can be run between shots or even in real-time. Monitoring requires a reliable instrumentation suite which can support or contradict model predictions and confirm PFC integrity. The goals of this milestone are three-fold: (1) Develop tools for pre-shot planning and confirmation of post-shot PFC thermal observations which use reduced models to predict time-evolving heat fluxes to shaped PFCs and estimate distances from engineering limits. Assess additional effort needed for implementation of reduced models in PCS. (2) Where feasible, benchmark reduced models against boundary physics (e.g. SOLPS, UEDGE) and finite element analysis (e.g. ANSYS) tools, and validate using experimental data from relevant tokamaks and results from Facility Milestone F(18-1). (3) Evaluate examples of discrete monitoring systems that are sufficient to capture the evolution of the PFCs relative to engineering limits. Compare the ability for different techniques (e.g. thermocouples vs. imaging) and technologies (e.g. near vs. long-wave infrared cameras) to achieve NSTX-U PFC monitoring objectives.

Breakdown of R18-1 Work

- PCRF-MEMO-014 breaks out the R18-1 into three subtopics (R18-1/1, R18-1/2, R18-1/3) and develops goals and lead personnel to deliver the work (e.g R18-1/1-G1)
  - indented to be comprehensive, but no expectation of completing all work due to resource limitations, priority changes
- this presentation reviews progress and rates goals
  - *green: work satisfactorily completed or will be by 9/30*
  - *yellow: work in-progress but risk of not completing by 9/30*
  - *red: work either dropped or certain to not be completed by 9/30*
- end with discussion of life of 'R18-1/PFCR-WG' into FY19

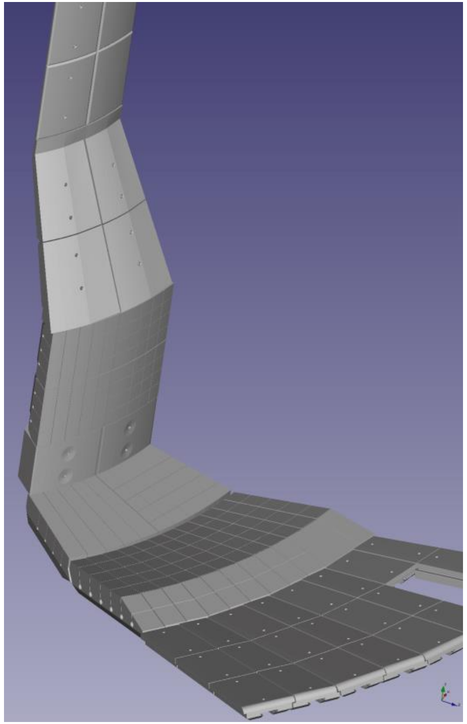
Activities Under R18-1/1

R18-1/1: Develop tools for pre-shot planning and confirmation of post-shot PFC thermal observations which use reduced models to predict time-evolving heat fluxes to shaped PFCs and estimate distances from engineering limits. Assess additional effort needed for implementation of reduced models in PCS.

- GOAL 1: Evaluate and demonstrate tools for efficiently computing heat flux from axisymmetric plasmas onto non-axisymmetric plasma facing components
- GOAL 2: Develop and test an initial ‘pre-shot’ planning tool using existing PCS infrastructure
- GOAL 3: Develop and test initial ‘post-shot’ heat flux summary tool
- GOAL 4: Determine necessary PCS enhancements for real time strike point and flux expansion control
- GOAL 5: Determine necessary PCS enhancements for doing real-time control from imaging systems

G1: Developed New Tool for 3D PFC Heat Flux

- uses of MAFOT, existing field line tracing code (guiding center approx.)
- uses 2D (GEQDSK) and 3D (M3D-C1, SIESTA, VMEC) equilibria
- uses standard CAD STL file
  - Some difficulty in automating & search for surfaces of interest from 150,000 faces
- grid generation 40s, tracing 60s/eq. and heat flux 7s (20-core CPU)
  - C++, Python 2.7 (fully parallel w/ MPI)



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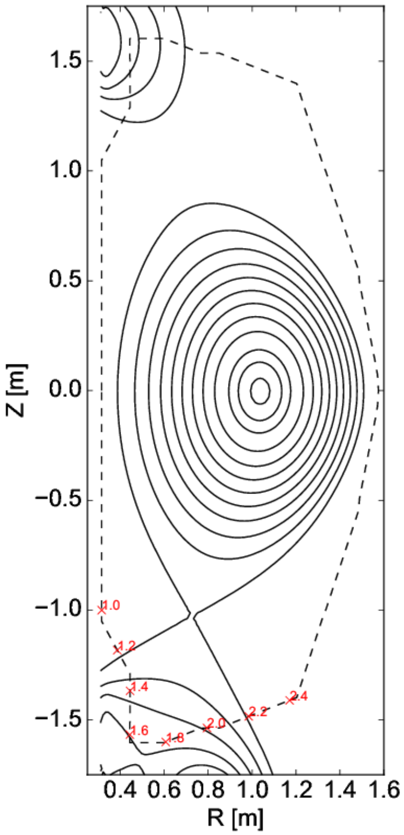
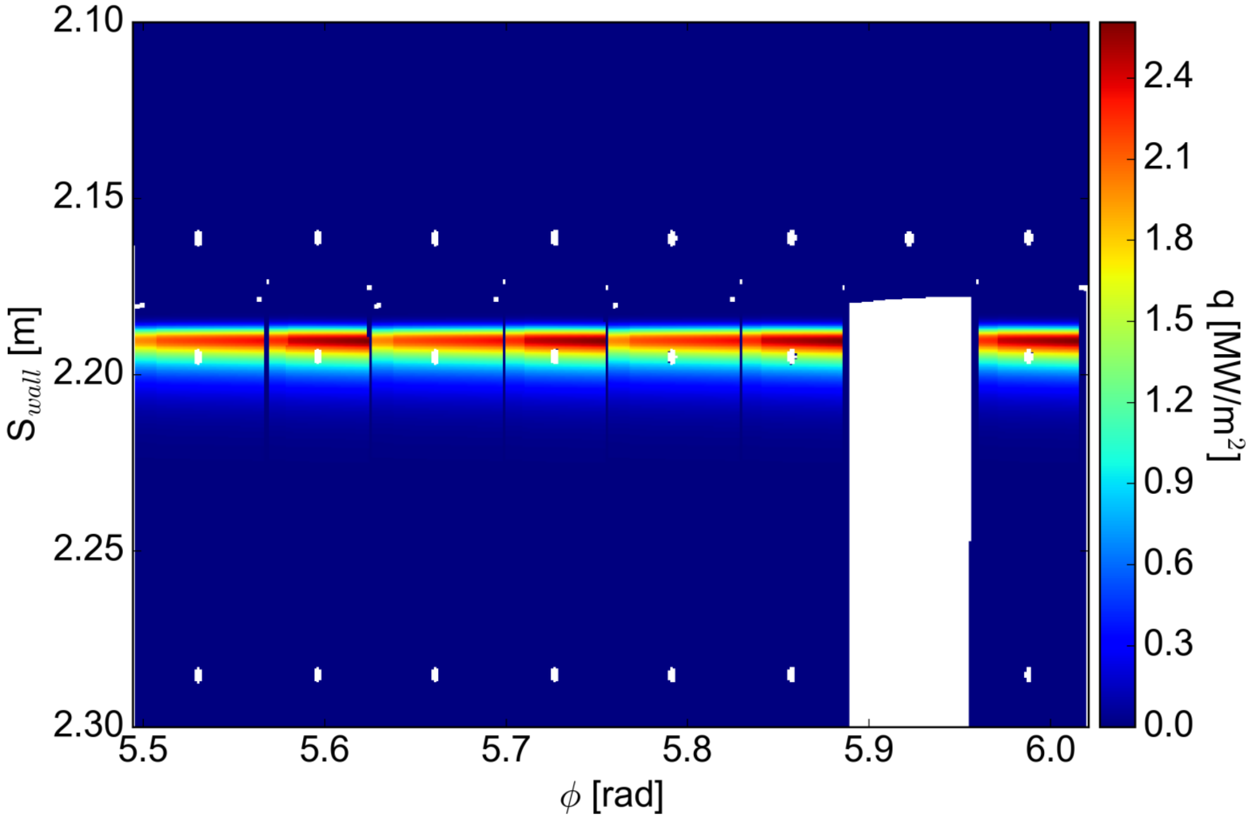
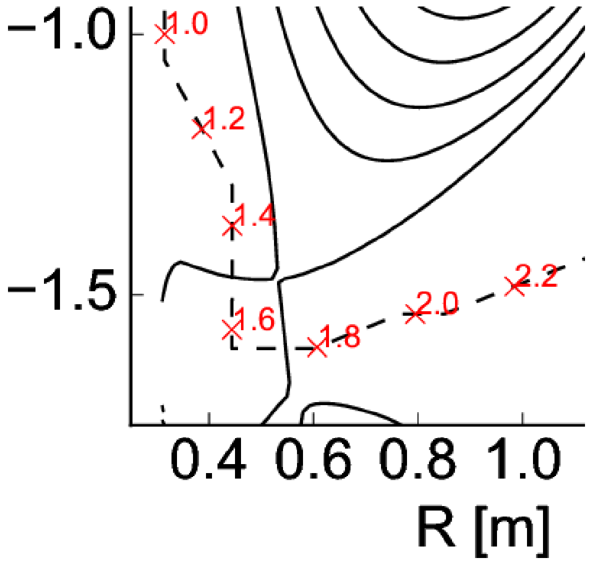
Ex: OBD345 Faceting Effect

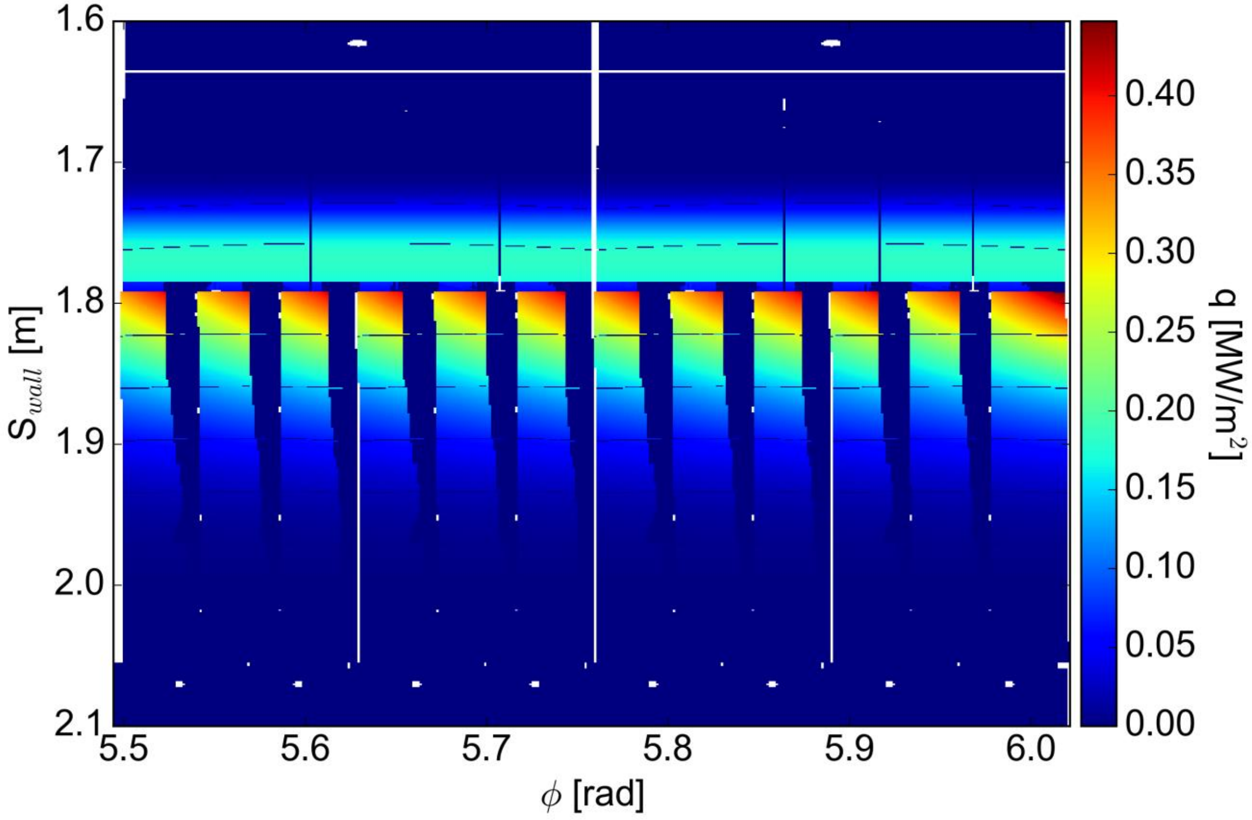




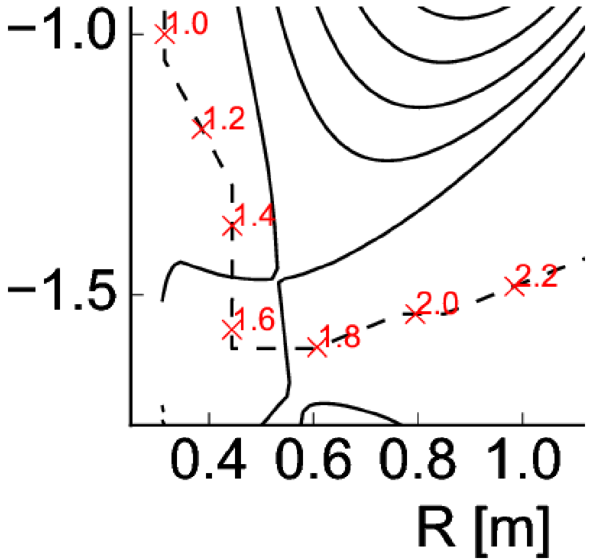
Ex: Impact of OBD12 Fishscaling



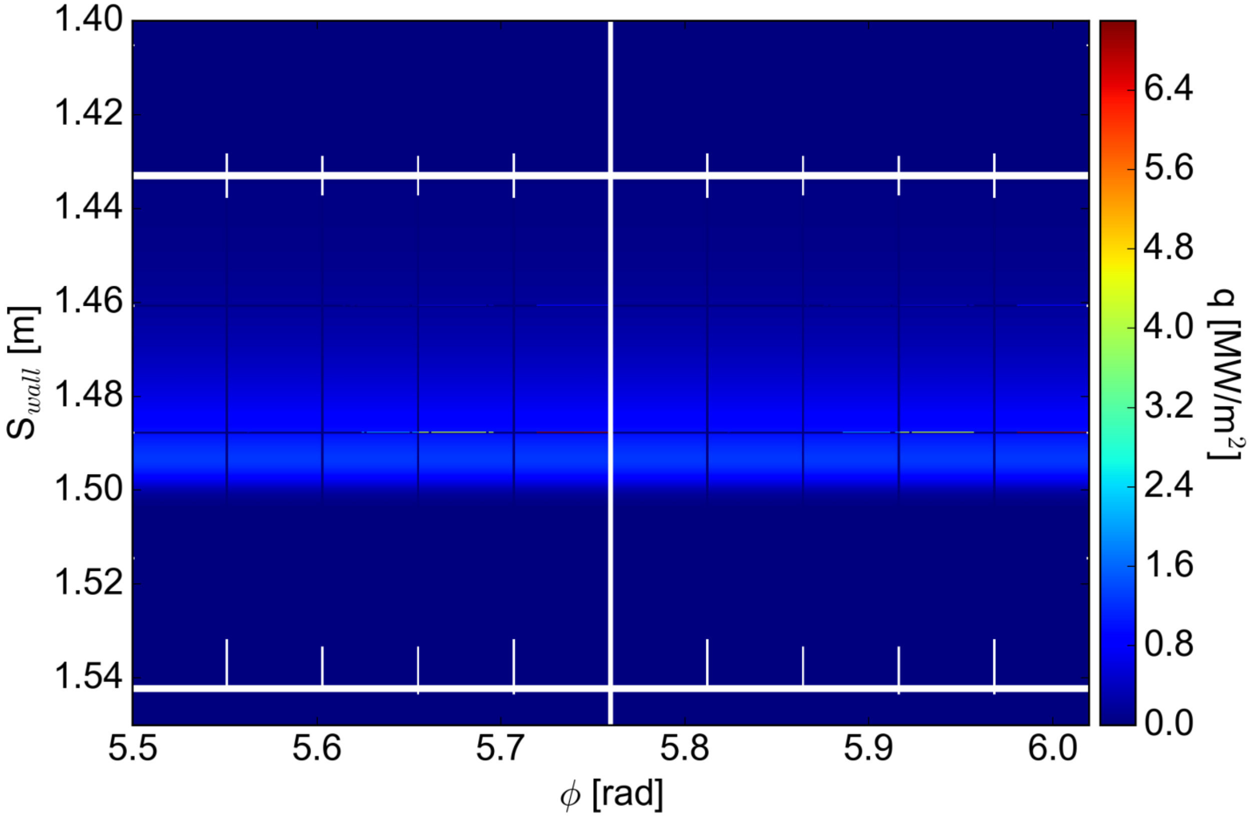
using Jan. 2018 model where IBDH not yet fishscaled



Ex: Impact of IBDV Gaps



more detailed models are needed to understand the detailed gap/edge



G4: PCS for strike point and flux expansion control

- building on TOKSYS work by Pat Vail
  - linear control about a target (EFIT, TRANSP) equilibria
- investigated algorithm needs for simultaneous strike point location (sweeping) and angle of incidence (AOI) control (PFCR-MEMO-017)
  - AOI done by controlling flux difference, but using a time-dependent request if sweeping (changing toroidal field)
- found that phase difference between inner & outer target sweeping important in maintaining I/O gaps

G5: PCS enhancements for RT control from imaging

- STEP 1: Use existing systems at other devices to understand NSTX-U needs
  - Studied all suggested material (PFCR-MEMO-021), found additional, more recent information on proposed upgrades and new systems
  - Found potential shared effort opportunity at W7-X, new monitoring system
    - We will likely contribute to a similar system for W7-X under collaboration agreement
    - There is benefit in a shared design that meets both sets of requirements
- STEP 2: Outline necessary or potential NSTX-U upgrades
  - Evaluated existing computational capacity based on other devices
    - NSTX-U resources far exceed any other implementation, including headroom for full image processing
    - Additional computer still warranted for 1) locality, 2) separation of concern, and 3) growth (GPU, AI)
  - Current RT FPDP interconnect is not well suited for pre or post processed data
    - W7-X wants to upgrade to Camera Link + µTCA, which we can and should accommodate
    - µTCA would provide a migration path away from VME, which is increasingly costly
    - Additional computer can use Dolphin, already desired for other, similar applications

R18-1/1 Remaining Work

- G1: evaluate SMARDDA for possible use for 3D heat flux (action: Reinke)
- G2: improve and link the output of TOKSYS to W_PFC (action: Reinke + Boyer)
  - improve controller (optimize gains) for high freq. sweeping
  - need to read/write set of g-files from simulations

Activities Under R18-1/2

R18-1/2: Where feasible, benchmark reduced models against boundary physics (e.g. SOLPS, UEDGE) and finite element analysis (e.g. ANSYS) tools, and validate using experimental data from relevant tokamaks and results from Facility Milestone F(18-1).

- GOAL-1: Export/Extend W_PFC to allow for comparisons to non NSTX/NSTX-U heat flux measurements
- GOAL 2: Compare W_PFC predictions to Alcator C-Mod measurements
- GOAL 3: Compare W_PFC predictions to (tokamak/ST to be determined) measurements
- GOAL 4: Extend validated high heat flux (HHF) ANSYS simulation to allow for arbitrary surface heat flux as a function of space and time#
- GOAL 5: Compare detailed ANSYS model against semi-infinite solid predictions and evaluate role of temperature dependent thermal properties#

#work to be done following PFC final design review

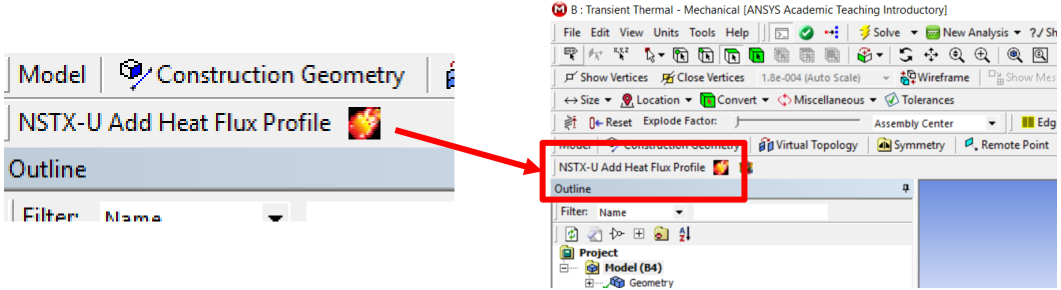
Reasons for Lack of R18-1/2 Progress

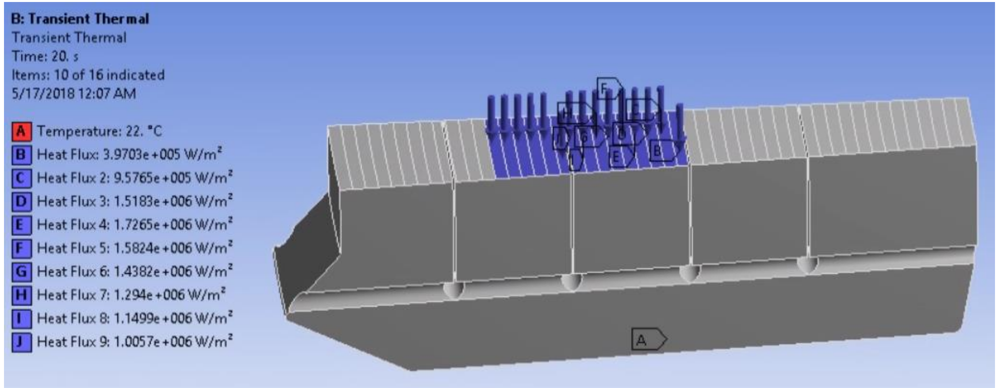
- G1-G3 work (validating/using W_PFC) dropped in priority as updated PFC Requirements became de-linked from W_PFC predictions, TSG input that used these tools
  - requirements driven by procurable material and manufacturing tolerances
  - 8 MW/m^2 for 5 seconds leads to temperature limit (1600 degC)
  - margin for ratcheting and enhancement from elimination of leading edges
    - IBDH, 5.4 MW/m^2 at 5 deg for 5 seconds, 6.5 MW/m^2 at 1 deg for 1.5 seconds
- G4-G5 work scheduled post-FDR for PFCs
  - originally scheduled (Dec 2017, Feb 201, now Sept. 2018)
  - PPPL resource limited in mechanical analysis
  - ORNL resources found, moved to help PPPL achieve Notable Outcome (PFC FDR)

Automated ANSYS Methods Demonstrated

- created autonomous ACT script to run in “batch” mode
- applies time and space-dependent heat flux to tile and solves thermal model
- not as fast as direct APDL script, but possible to do more (access to python modules) using API
- ‘one-click’ runs arbitrary number of simulations

Example: NSTX ANSYS Toolbar and Fluxes





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applied to sub-tile model (academic lic.), extend to full model post-FDR

Activities Under R18-1/3

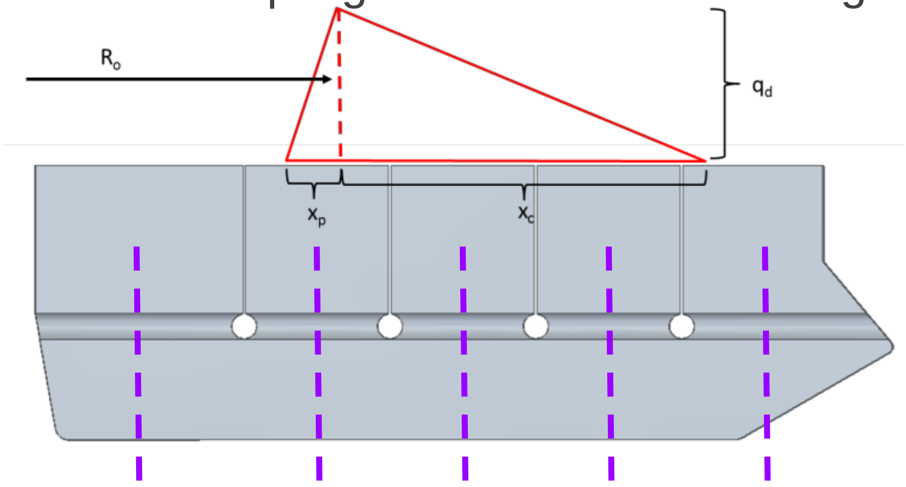
R18-1/3: Evaluate examples of discrete monitoring systems that are sufficient to capture the evolution of the PFCs relative to engineering limits. Compare the ability for different techniques (e.g. thermocouples vs. imaging) and technologies (e.g. near vs. long-wave infrared cameras) to achieve NSTX-U PFC monitoring objectives.

- GOAL-1: Describe monitoring approach that does not use optical measurements to determine if an NSTX-U discharge is approaching temperature limits
- GOAL-2: Describe monitoring approach that uses optical (NIR/IR) measurements to determine if an NSTX-U discharge is approaching temperature limits
- GOAL 3: Demonstrate pathway for sub-surface, temperature measurements to validate heat flux model

R3: Use of Sub-Surface Temp. Sensing

- UT-K (T. Looby) masters thesis project

Demonstrate how unknown heat flux model parameters can be derived with various sampling mechanisms within a given parameter space.



Simplified Eich Model:

$$x_P = S f_x$$
$$x_C = \lambda_q f_x$$
$$P_{heat} = \int_{R_o - x_p}^{R_O + x_c} q(R) 2\pi R dR$$

$$\frac{S}{\lambda_q} = C_1$$
$$\lambda_q[mm] = C_2 P_{heat}^{C_3} B_p^{C_4}$$

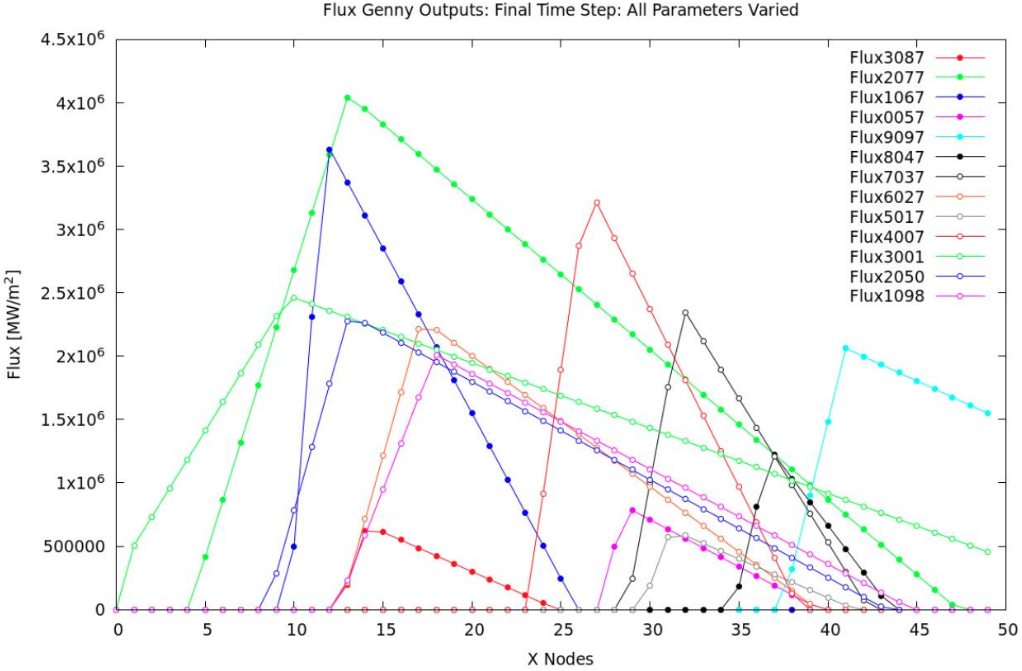
$$0.1 < C_1 < 0.3$$
$$1.0 < C_2 < 2.5$$
$$-0.1 < C_3 < 0.25$$
$$-1.2 < C_4 < -0.5$$

$$0.2 < B_p[T] < 0.6$$
$$0.5 < P_{heat}[MW] < 4.9$$
$$4 < f_x < 30$$
$$46.0 < R_o[cm] < 57.5$$
$$1 < \Delta t\ [sec] < 5$$

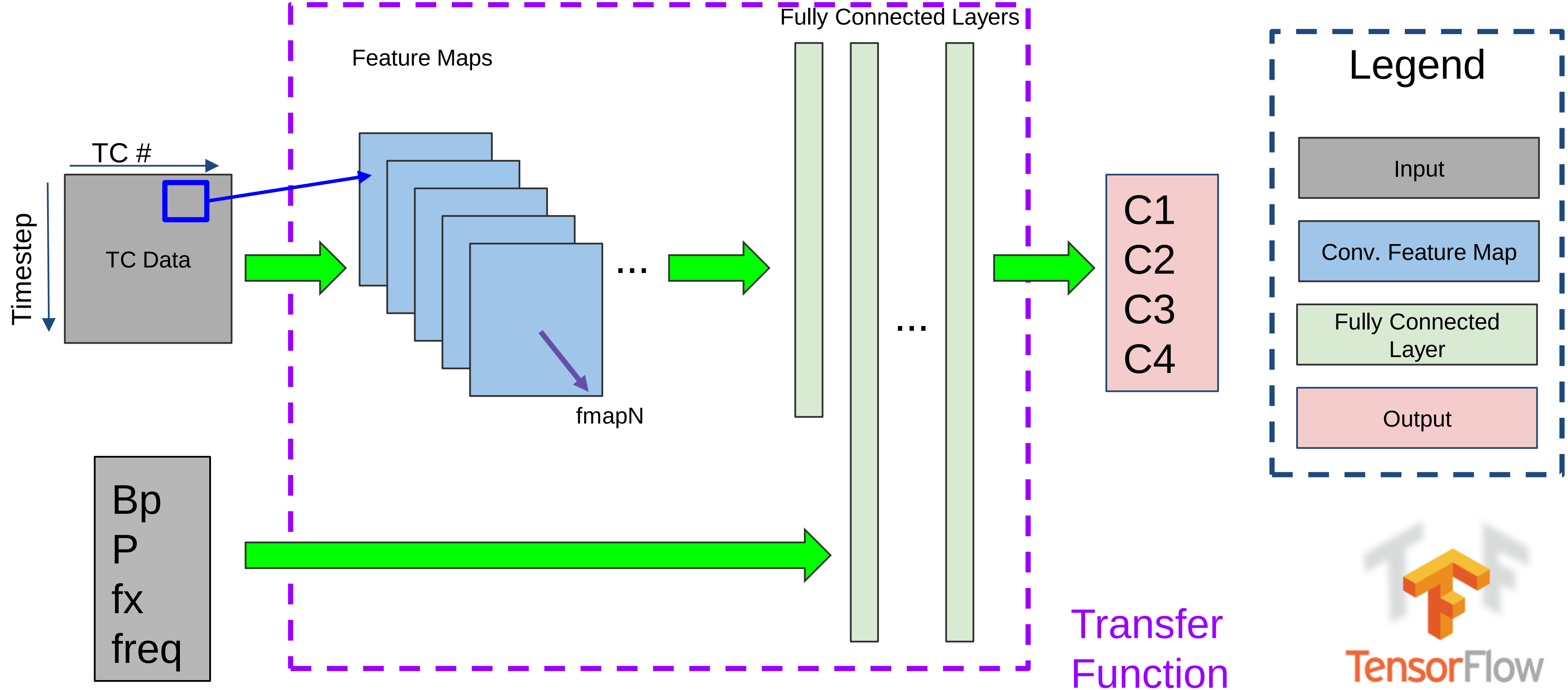
Developed Heat Flux Generator + Simulator

- Monte Carlo Style
- Pulls random deviates for each model / machine parameter (ie: Bp, C1, etc.)
- Samples entire allowable operational domain for each parameter
- Can produce arbitrary number of flux profiles
- Currently producing ~10k profiles per case

Example: Several randomly selected profiles

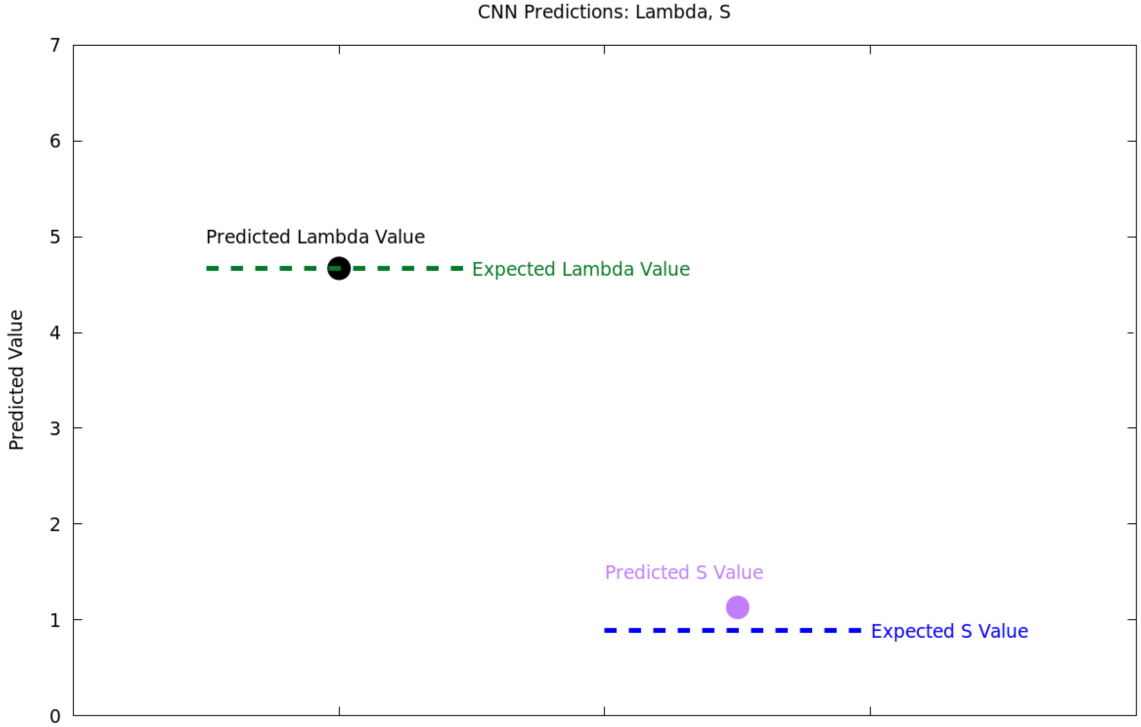


First Neural Network Attempts



Transfer Function

Recovers S and λ_q Successfully w/ 1 Shot

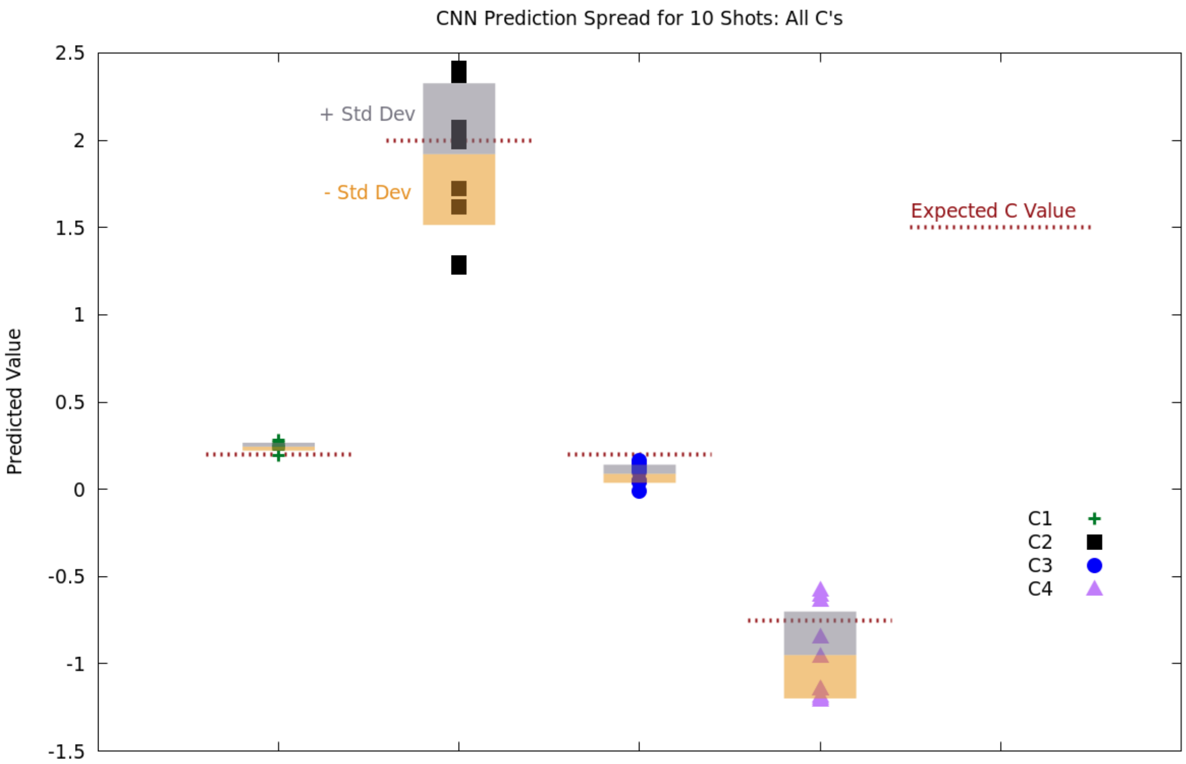


Possible ƛ Domain [mm]:
(1.0836, 25.493)

Possible S Domain [mm]:
(0.10836, 7.6479)

S and ƛ can be predicted fairly well, but these predictions overlook degeneracies in the Eich scaling parameters (the point of this research)

Degeneracy in Predicting Scaling Coefficients



-1400 training datasets trained to ~70% accuracy (no strike point sweeping)

-Need to train CNN with a minimum of three shots

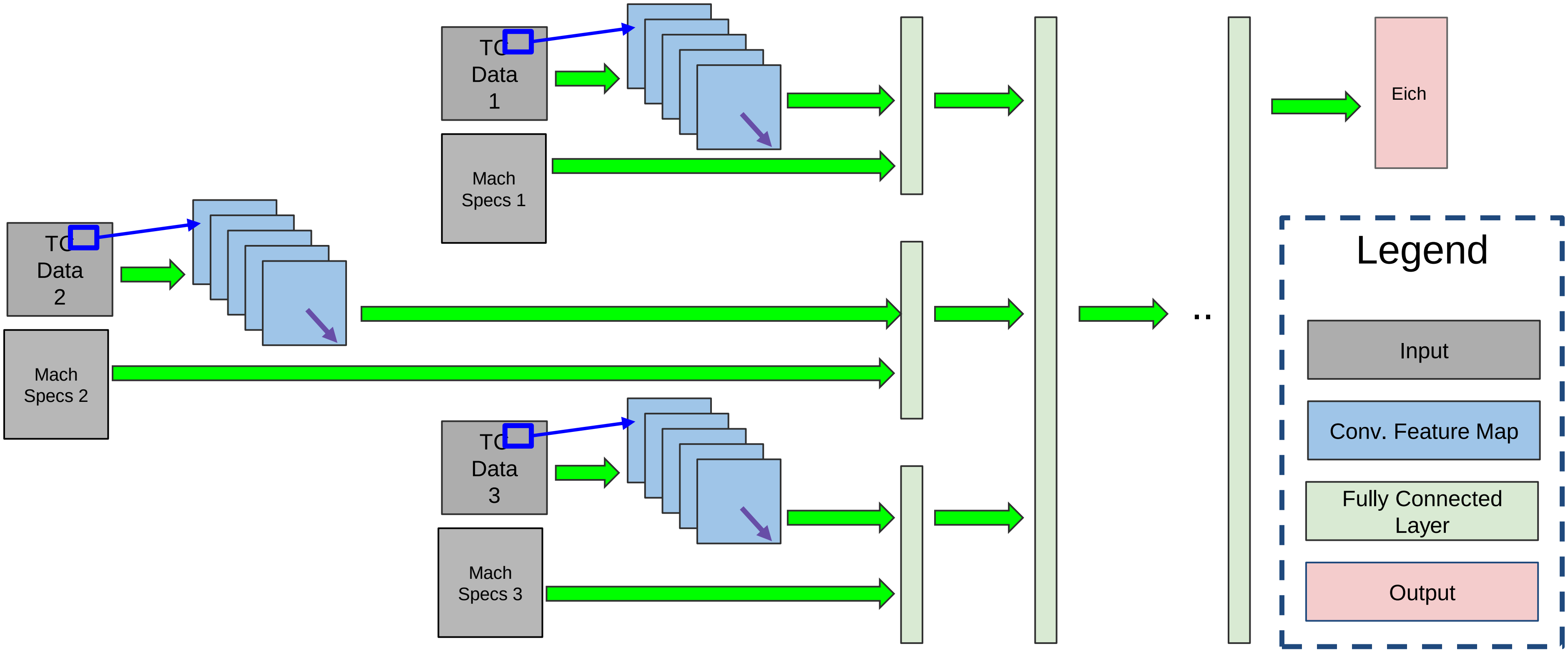
- -Constant Cs
- -Varying P and B

-Dataset is currently being generated

$$\frac{S}{\lambda_q} = C_1$$

$$\lambda_q[mm] = C_2 P_{heat}^{C_3} B_p^{C_4}$$

New ‘Triplet’ Training Method Started



Future Plans for PFCR-WG

- R18-1 Milestone organized around mission for PFC Performance and Monitoring Requirements Working Group
- leadership changes needed if WG is to continue into FY19
  - Lead: Reinke, Deputy: Mardenfeld no longer have sufficient resources
- charge 3: guidance toward operations scope needs to be PPPL driven, tied to machine performance and control
- impact of deferral scope could lessen or worsen need for WG contributions
  - short pulse durations make temperature limits a non-issue in many cases
  - stress limited OBD345 tiles may need optical monitoring approach
  - new scope on computing and observing heat loads at toroidal gaps?

Summary

- mission and goals defined for R18-1 Milestone, work being completed in three areas
  - reasonable loss of scope due to limitations and redirections of resources
- final accomplishments to be summarized in a Milestone Report after 9/30
  - scope will continue into FY19 to reach natural termination
- FY19 future of the PFCR-WG needs to be discussed