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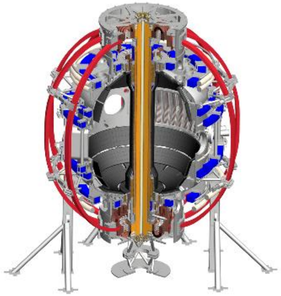
Fusion Energy Sciences

Update on Activities and Action Items for PFCR Working Group

M.L. Reinke and S. Gerhardt

PFCR-WG Update Meeting
B-252
8/9/17



Goals of the Meeting

- discuss important open ACTIONS & MEMOs
  - MEMOs and ACTION ITEMS
  - impact of gyro orbits and the limitation of shaping (URGENT)
  - approach for initial contributions to Charge 3 on PFC Monitoring (October/November)

- examination of PFC compatible requests from TSGs
  - outline example PFC-compatible paths to high B_T, I_p, P_{INJ}

Heat Flux Modeling Connected to Science Mission

- April/May: Menard charges the TSGs to discuss how polar region changes impacted goals (use 5 year plan, XPs)
- asked to document NSTX-U configurations necessary
  - plasma shape, B_T, I_p, powers, durations, etc.
  - done in a manner agnostic to possible changes in the PFCs
- each TSG held a meeting to discuss impacts and produced a memo to document needs (summary memo)
- June/July: Gerhardt/Reinke developed simulation data and modeling tools to turn TSG requests into heat fluxes

Work Aligned With PFCR-WG Charges

1. define which (additional) parameters need to be specified in an updated requirements document for the NSTX-U PFCs
2. facilitate generation of updated requirements utilizing:
   a) available reduced models, empirical scalings, boundary simulations
   b) ultimately, a validated model for specifying heat loads to all plasma facing components for arbitrary NSTX-U scenarios
3. in preparation for operations, develop:
   a) instrumentation plan for intra and inter-shot PFC monitoring
   b) a reduced model for heat loading for pre-shot planning
   c) guidance on how to best integrate monitoring with operations
   d) control, diagnostic requirements for real-time heat-flux control
4. work closely with engineers and analysts to develop and implement requirements

http://nstx-u.pppl.gov/program/working-groups/pfc-requirements-working-group

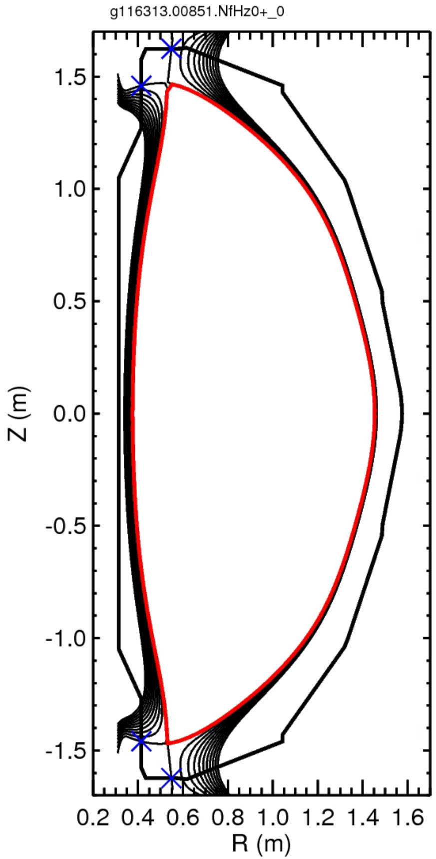
Quantifying PFC Heat Fluxes

- need radiated power fraction and impact on core
  - radiation from impurities: C from PFCs, metals at 10^{-3} levels
  - balance of sources and transport; no robust predictions
- need the distribution of power between divertors
  - drifts lead to inner/outer divertor different, as is top/bottom
- scaling of the heat flux width, λ_q with eng. parameters
  - limited, conflicting information of how λ_q scales with I_p in STs

NSTX-U attention to PFC heat flux is a sign that we're joining a class of machines that are working to understand and solve a key problem for fusion energy science

Example of Workflow

- compute equilibrium (I_p, B_T, P_{NBI})
- radiated power fraction and power sharing between divertors assumed
- (S, λ_q) assumed, defines upstream parallel heat flux, $q_{||}$
- $q_{||}$ mapped to PFC surfaces
- find impact angle $\sin\alpha = \vec{B} \cdot \vec{n}$
- compute surface heat flux, q_{perp}
  – complicated by tile shaping (CDR)



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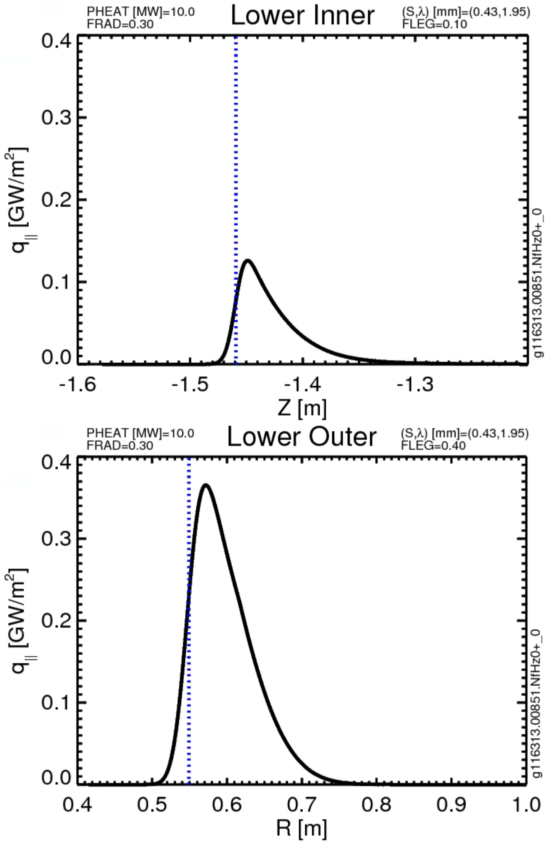

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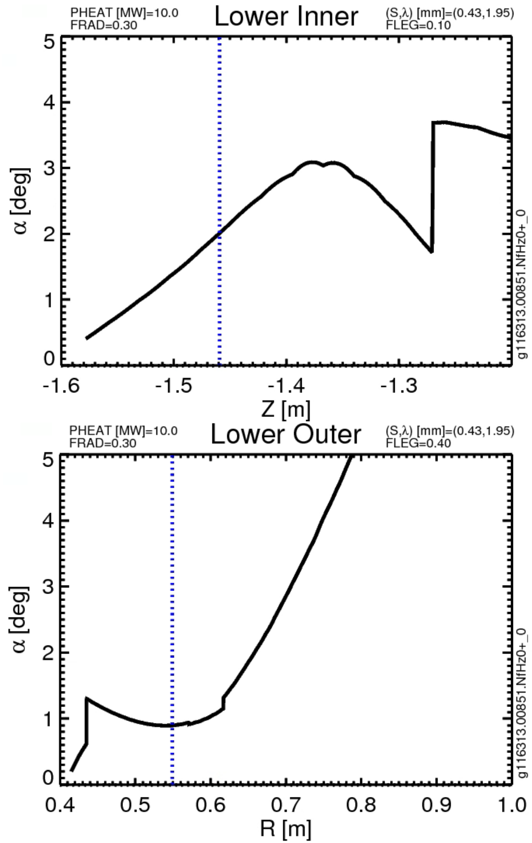

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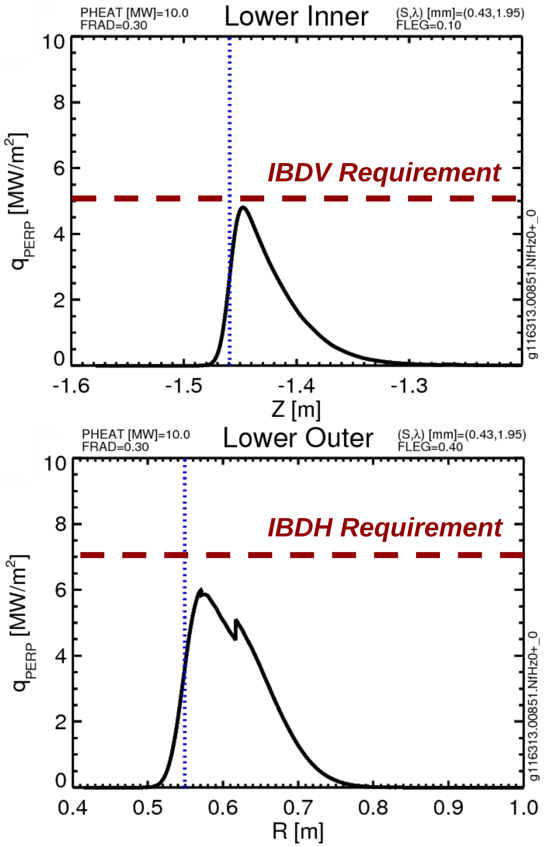
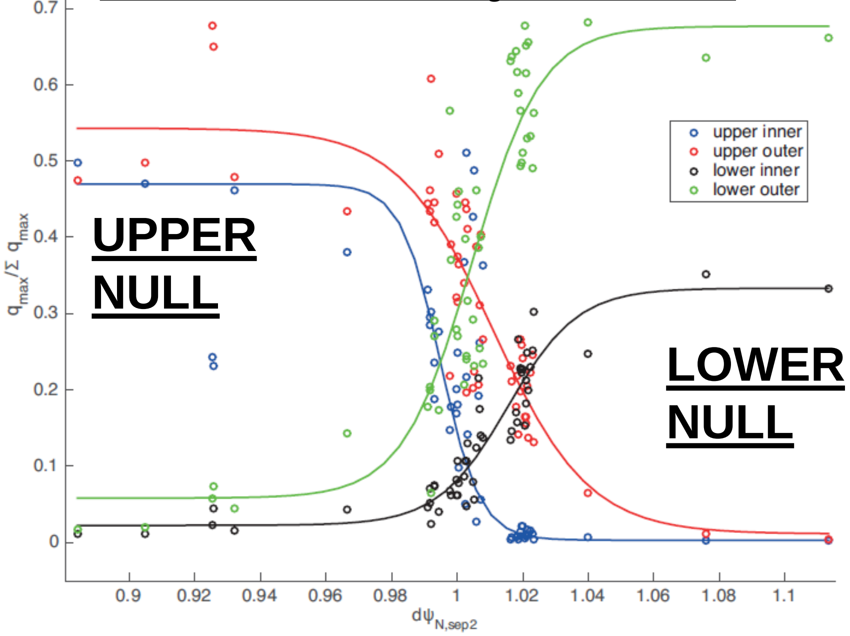
  – complicated by tile shaping (see CDR)



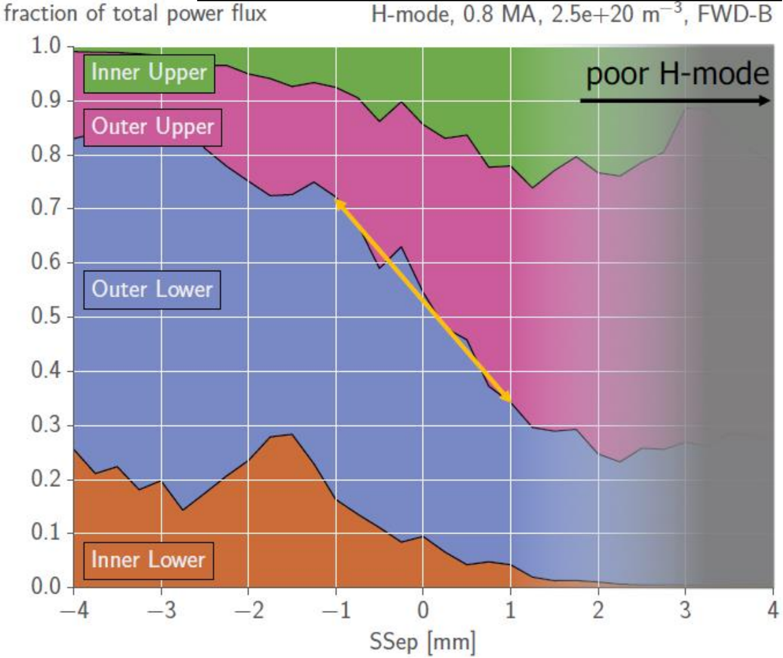
Empirically Motivated Divertor Power Sharing

- NSTX only measured the outer, lower divertor heat flux
  - model uses inner/outer split of 70/30 LSN and 55/45 USN, smooth transition in-between

MAST L-mode; Wenninger, IAEA 2016

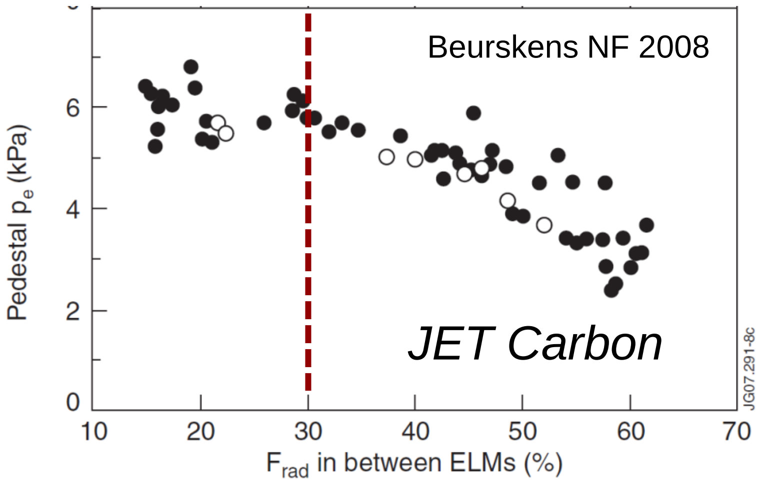


C-Mod H-mode; Brunner APS 2016



Use Conservative Approach: Assume Low P_{RAD}

- no solid basis for ST P_{RAD} fractions
  - NSTX never fielded relevant sensors
  - MAST had limited coverage & resolution
- non-ST carbon machines (ex: JET)
  - intrinsic minimum level is >10%
  - above 30% energy confinement drops
- if you assume high P_{RAD} means you need to deliver that
  - operations critical measurement and auxiliary system requirement



PFC Requirements developed assuming 30% radiated power fraction

Use Conservative Approach: Assume Narrow λ_q

three scalings of heat flux width, λ_q, with eng. parameters

- **Heuristic Drift Scaling [Eich, PRL 2011]: (7), (9-10) results in $\lambda_q \sim B_T^{-7/8} q_{cyl}^{9/8}$** — **1.95 [mm]**
- MAST scaling [Thornton, PPCF 2014]: $\lambda_q[mm] = 1.84(\pm 0.48) B_{pol,omp}^{-0.68(\pm 0.14)} P_{SOL}^{0.18(\pm 0.07)}$ — 4.09 [mm]
- Eich Scaling [Eich, NF 2013]: $\lambda_q[mm] = 1.35 \varepsilon^{0.42} R_{geo}^{0.04} B_{pol,omp}^{-0.92} P_{SOL}^{-0.02}$ — 2.96 [mm]

PFC Requirements developed assuming Heuristic Drift Scaling

2 MA, 1 T, 10 MW Scenario

PFC Requirements Derived from TSG Requests

- PFCR-MEMO's developed for each divertor PFC region
  - PFCR-MEMO-008: Centerstack Angled Surface and Far OBD
  - PFCR-MEMO-009: Inboard Divertor Vertical Surface
  - PFCR-MEMO-010: Inboard Divertor Horizontal and Near OBD
  - under review by PFCR-WG, drafts distributed for CDR
- MEMOs explore how TSG requests map to PFC areas
  - unrealistic, low-priority requests are filtered out
  - high-priority scenarios collected to form the requirements
    - many medium/lower priority are satisfied by these constraints
    - identify non-critical scenarios which will be informed by early operations

Example PFC Requirements Derived from TSG Input

IBDH	Case # ->	1	2	3	4	5
Range of Application	m	0.48 < R < 0.6			R < 0.6	R < 0.48
Max Angle	degrees	1.0	5.0	3.6	-1	4.0
Min Angle	degrees	1.0	1.5	3.6	-5	1.0
Heat Flux	MW/m^2	7.0	5.5	14	1	3.5
Duration	sec	5	5	1	1	5
Reference Scenario	---	Stationary High Ip/Bt w/ large poloidal flux expansion (Table 5.1)	High Ip/Bt Long Pulse Swept Case (Table 6.1)	Stationary High Power Short Pulse (Table 4.1.1)	Reversed Helicity Requirement (Section 7)	Spill Over From HHF Regions (Section 8)

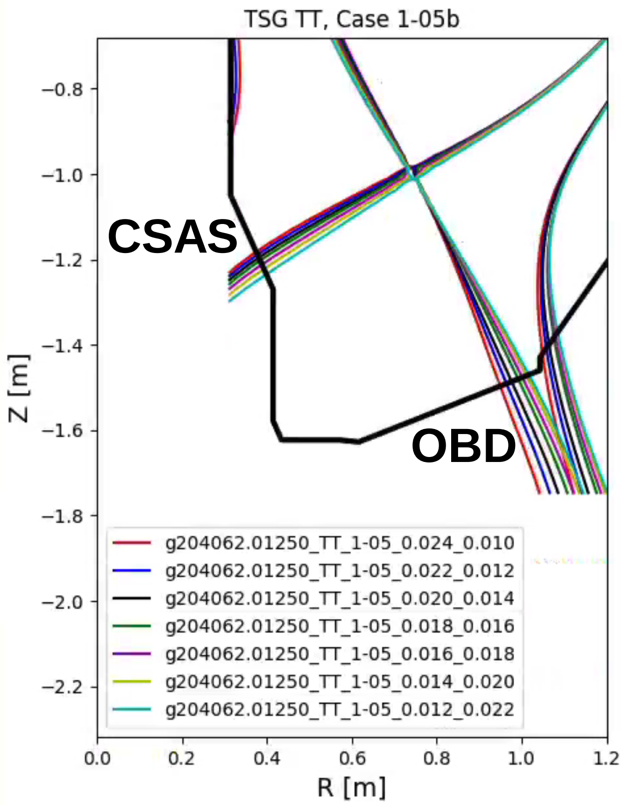
***Table 2.1**: Suggested heat flux requirements for the IBDH*

Where You Can Find Data

- PFCR-MEMO-008 describes the process in detail
- GEQDSK files, organized by TSG
  - /p/nstxusr/nstx-users/sgerhard/PFCs/NSTXU_Recovery_Requirements/TSG_geqdsk
- IDL setup and savefiles for use with W_PFC
  - *.info in /u/sgerhard/PFCGUIInput/
  - *.sav in /u/sgerhard/PFCGUIInput/sav/

TSG Implications: L-mode

- T&T, EP wanted to have use L-modes at highest available NBI power
- this drives requirements for the CSAS and far OBD
  - low κ, high angle of incidence (> 10°)
  - stationary peak heat fluxes > 4 MW, making sweeping mandatory
    - likely to happen due to solenoid flux swing



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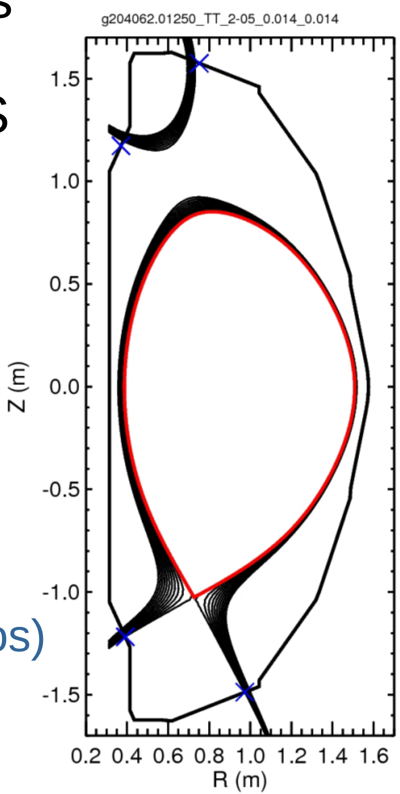
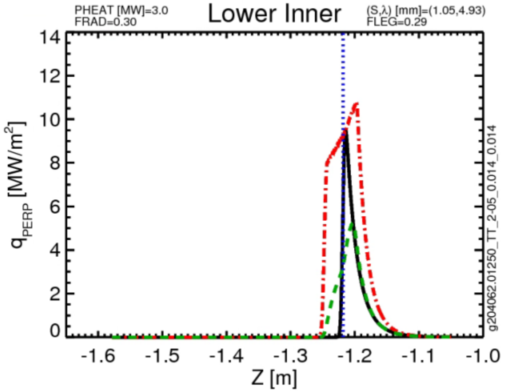
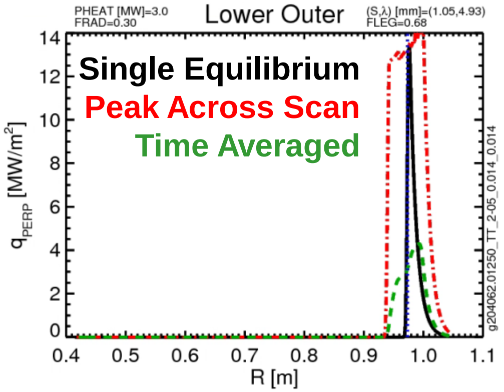
- this drives requirements for the CSAS and far OBD
  - low κ, high angle of incidence (> 10°)
  - stationary peak heat fluxes > 4 MW, making sweeping mandatory
    - likely to happen due to solenoid flux swing
- LSN L-modes chosen to drive requirements for CSAS, far OBD
  - Case #1: 5.2 MW/m² on CSAS and 4.3 MW/m² on OBD R4/5 for 2.0 seconds
  - Case #2 & #3 bracket angles (I_p/B_t combos)
  - duration of USN L-modes will need to be judged based on final design & commissioning, accuracy of q_{perp} model







Far OBD Requirements Also Includes MAPP

OBD-R4/5	**Case # ->**	**1**	**2**	**3**	**4**
Max Angle	degrees	14	8.2	16.5	10
Min Angle	degrees	9.2	4.8	13.5	8.5
Heat Flux	MW/m^2	4.3	1.8	3.0	3.0
Duration	sec	2.0	2.0	2.0	5.0
Reference Scenario		High I_P/B_T LSN Swept L-Mode	Low I_P/B_T LSN Swept L-Mode	High I_P/B_T LSN Swept L-Mode	MPFC Far-OBD MAPP Scan

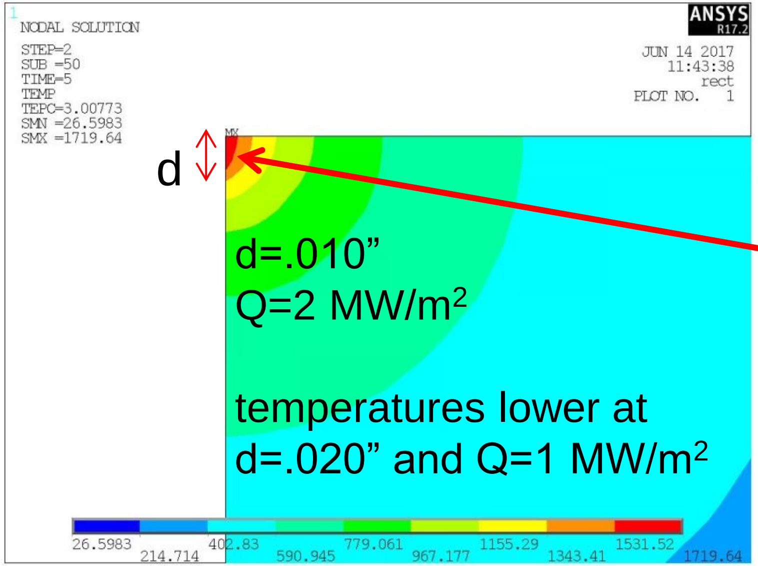
Table 2.3*: Suggested heat flux requirements for OBD-R4 and OBD-R5 (R > 0.92).*

IBDV/IBDH Include Reversed Helicity for Snowflake & Operations

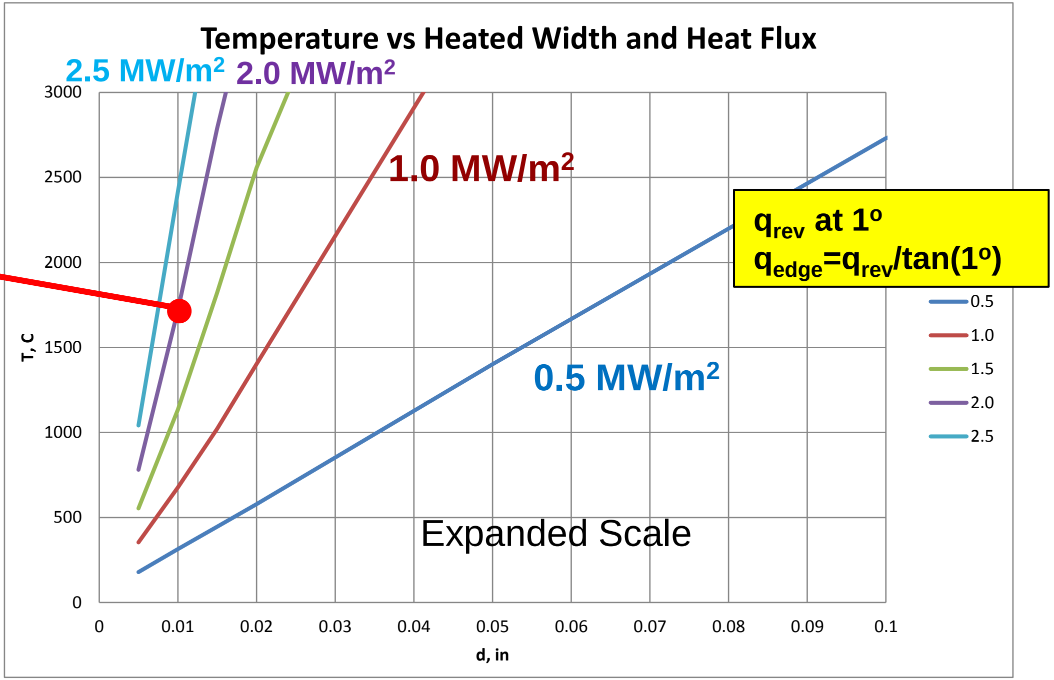
IBDV	Case# ->	1	2	3	4
Range of Application	m	1.27< |Z| < 1.5	1.27< |Z| < 1.5	|Z|>1.5	|Z| > 1.27
Max Angle	degrees	5.5	6.0	4.0	-1
Min Angle	degrees	2.0	2.0	1.0	-5
Heat Flux	MW/m^2	5.0	10	3.5	1
Duration	s	5	1	5	1
Reference		High I_p and B_T DN w/ Sweeping (Table 5.6)	LSN Sweeping (Table 5.5)	Spill Over from Scans in HHF region	Reversed Helicity Requirement (Section 6)

***Table 2.1**: Suggested heat flux requirements for IBDV surface*

Edge Loading Can Handle Low, Transient Power



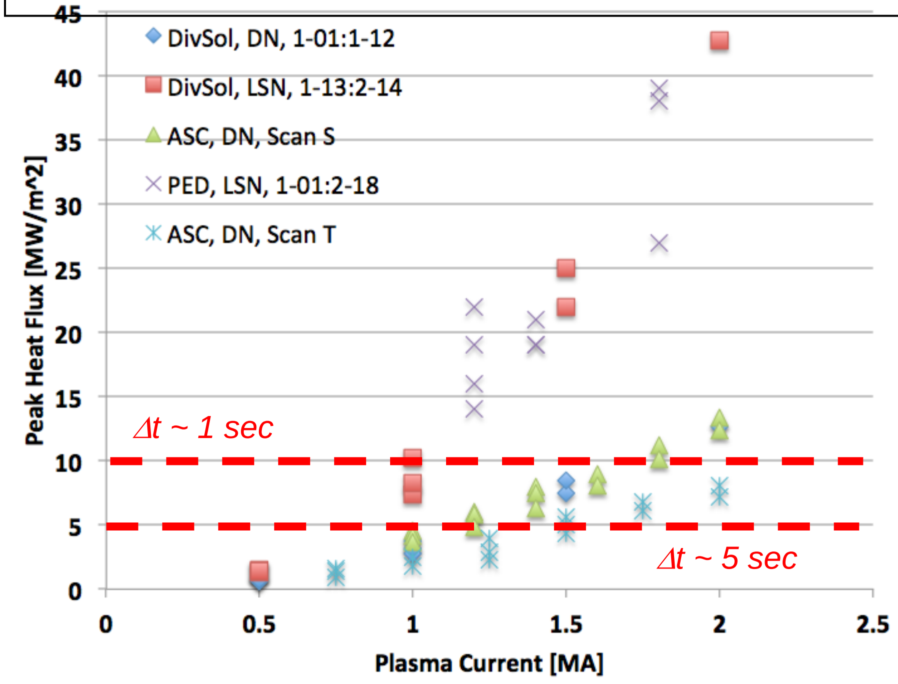
from: Art Brooks

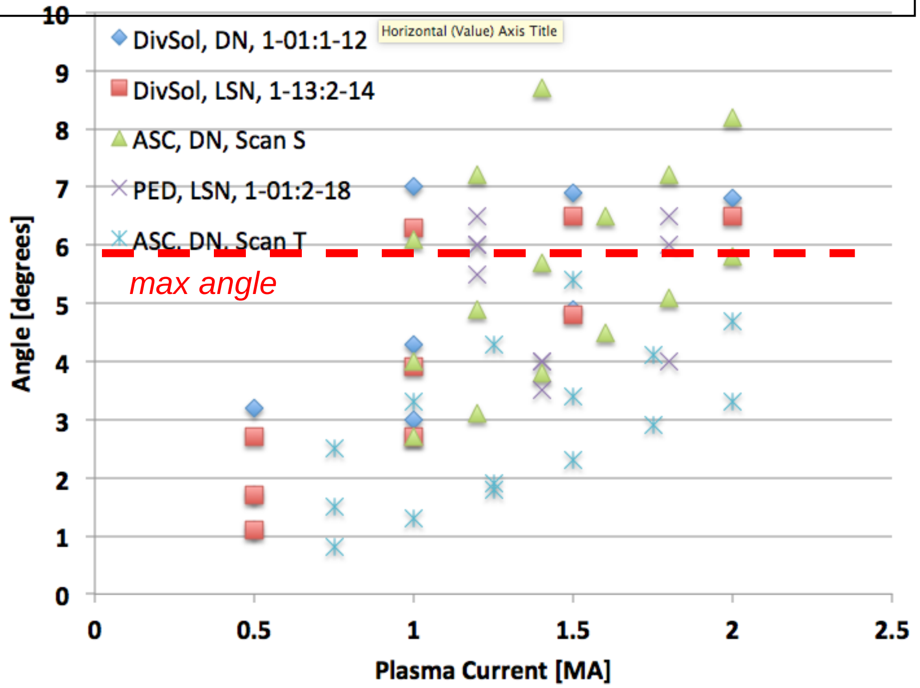


thermal analysis shows 'enhancement factor' analysis is inaccurate when loading small parts of the tile, so uni-directional shaped tiles can take low reversed heat flux

Stationary Vertical Target Heat Fluxes

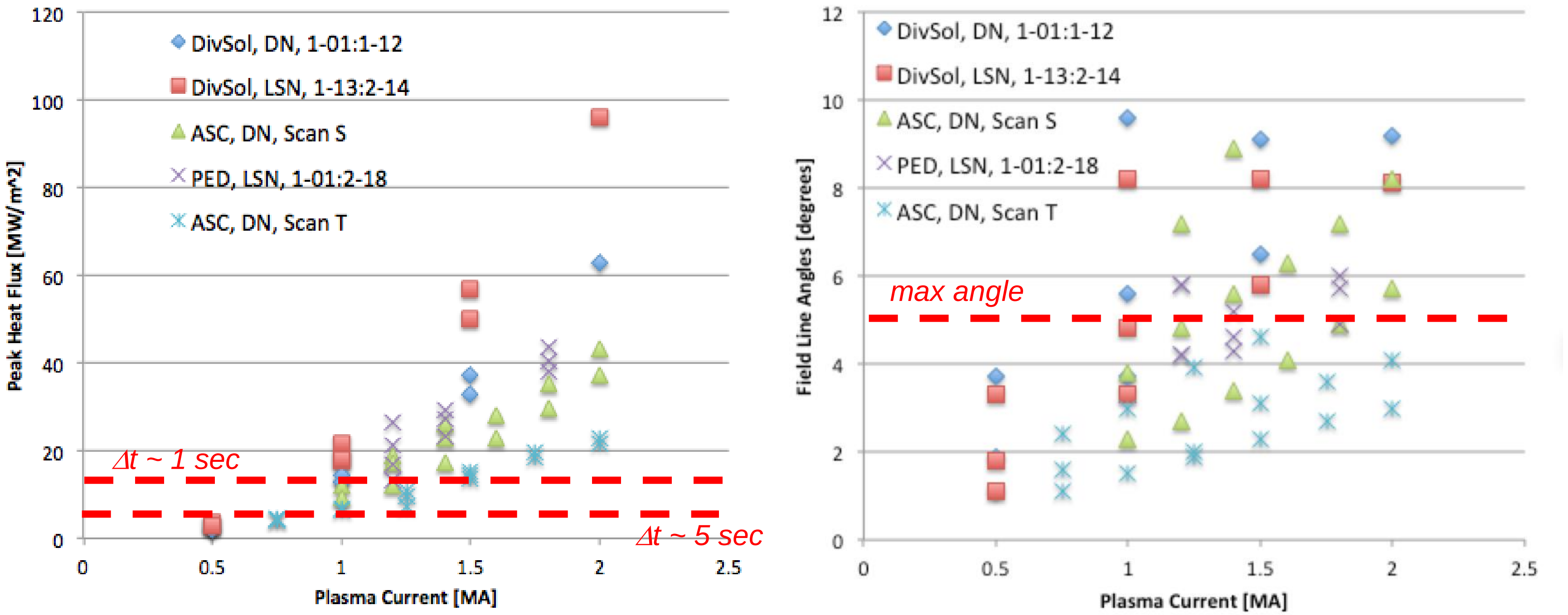
- many stationary LSN cases will not be possible <u>even at short pulse</u> w/o some kind of further mitigation (P_{RAD} or sweeping)





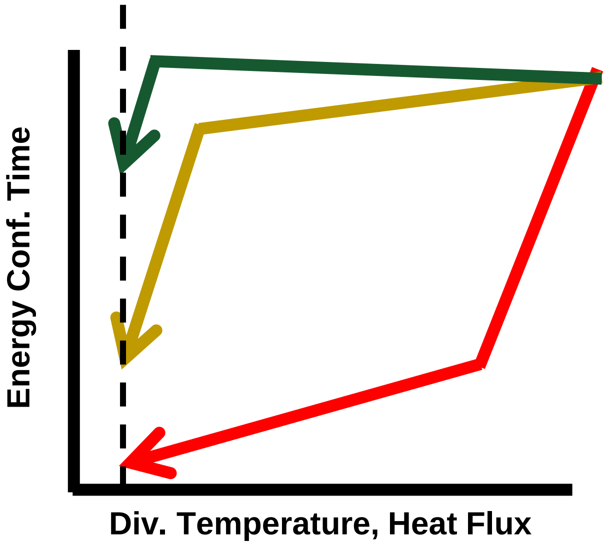
Stationary Horizontal Target Heat Fluxes

- many stationary LSN cases will not be possible even at short pulse w/o some kind of further mitigation (P_{RAD} sweeping or poloidal flux expansion)



Strategies for Mitigating Heat Fluxes

- increase poloidal flux expansion
  - changes the amount of wetted area on divertor, but also makes for shallow angles
- strikepoint sweeping in time
  - use PF coils to move the strike point back and forth across the surface
- increase radiation fraction
  - contingency due to uncertainty of compatibility w/ physics goals
  - PFC requirements add new divertor fueling locations to help us exploit this

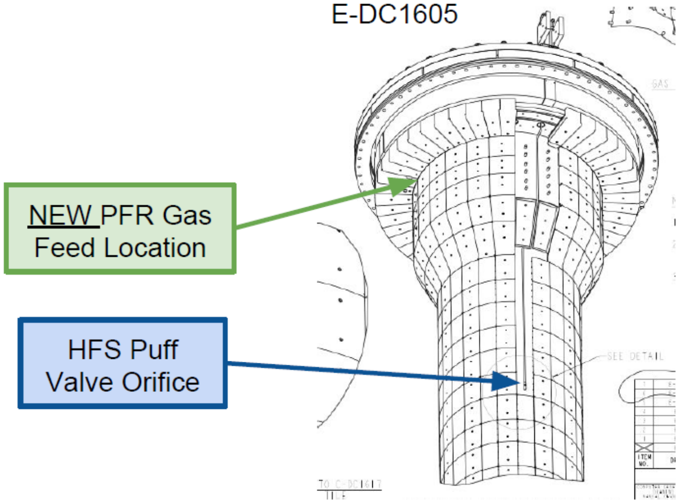


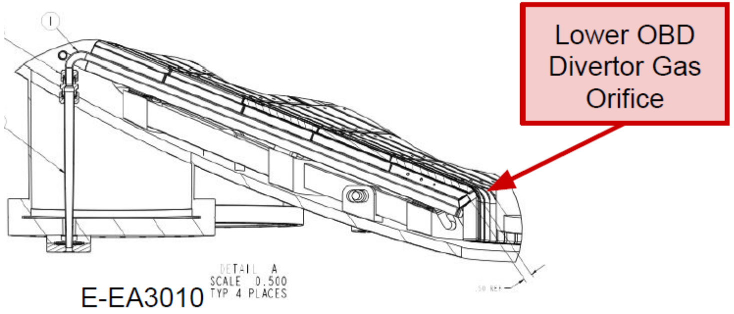
how we move on this plot is a research focus of the fusion program worldwide

General Requirements- Gas Fueling

- Must preserve four high field side puff valves as per NSTX-U.
- Must preserve the divertor gas feeds on the lower divertor.
- Must **add** private flux region feeds on each of top and bottom of CS.

plans for how to optimize radiative exhaust will need to be made





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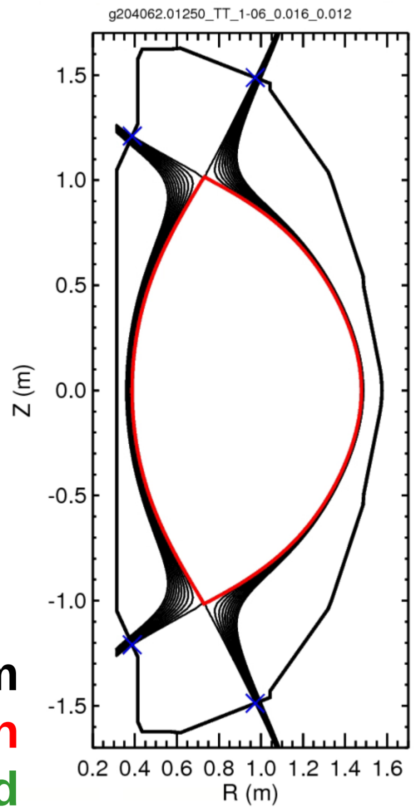
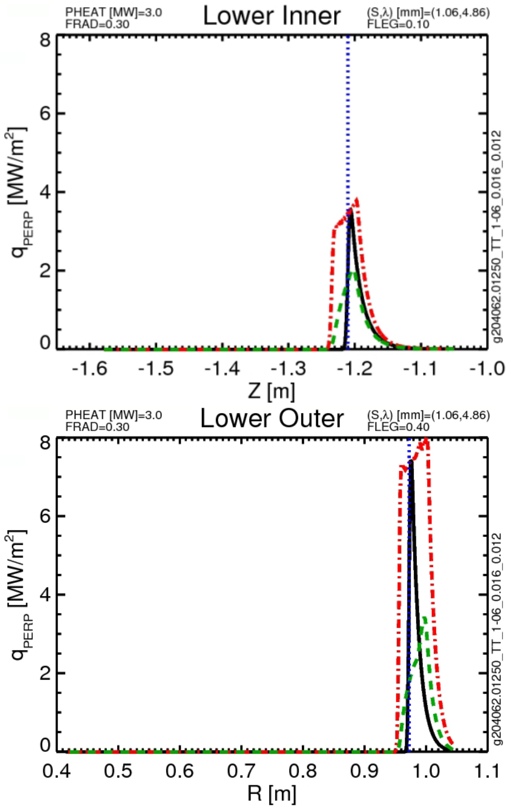
Flux Expansion Path to High B_T, I_p, and P_{INJ}

- (TT_1-06a) L-mode plasmas low current and power (sweeping)
  - I_P=1 MA, B_T=1 T, 3 MW, Δt=2 sec

Single Equilibrium
Peak Across Scan
Time Averaged





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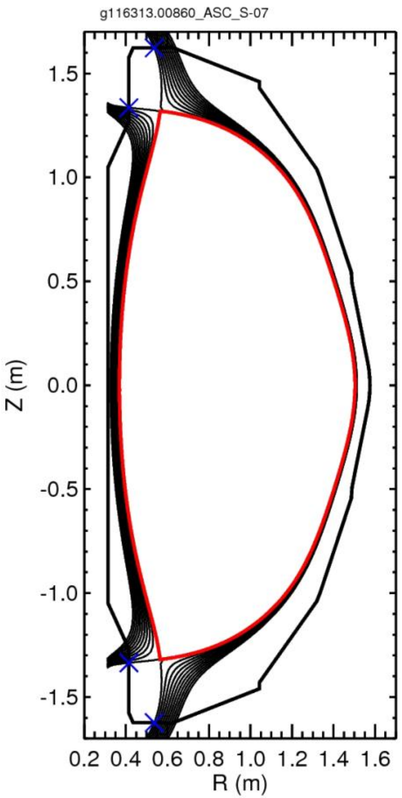
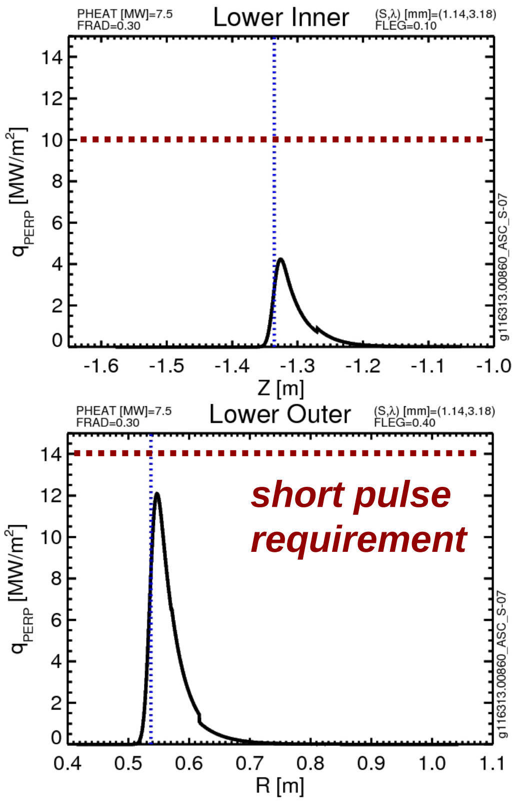
- (ASC_S-07) H-mode, low elongation, low current
  - I_P=1 MA, B_T=0.75 T, 7.5 MW, Δt=1 sec





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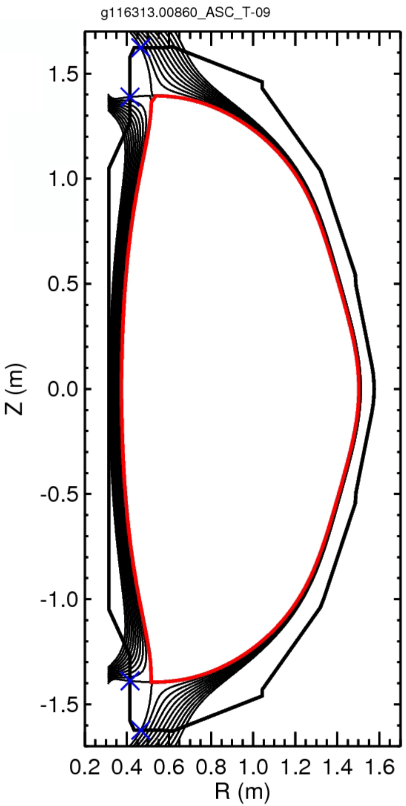
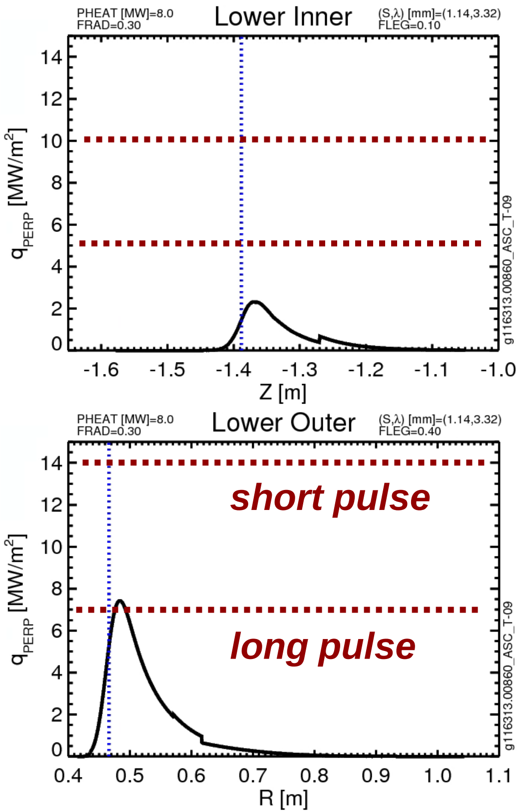
- (ASC_S-07) H-mode, low elongation, low current
  - I_P=1 MA, B_T=0.75 T, 7.5 MW, Δt=1 sec
- (ASC_T-09) H-mode, higher elongation, higher current
  - I_P=1.25 MA, B_T=0.75 T, 8 MW, Δt > 1 sec





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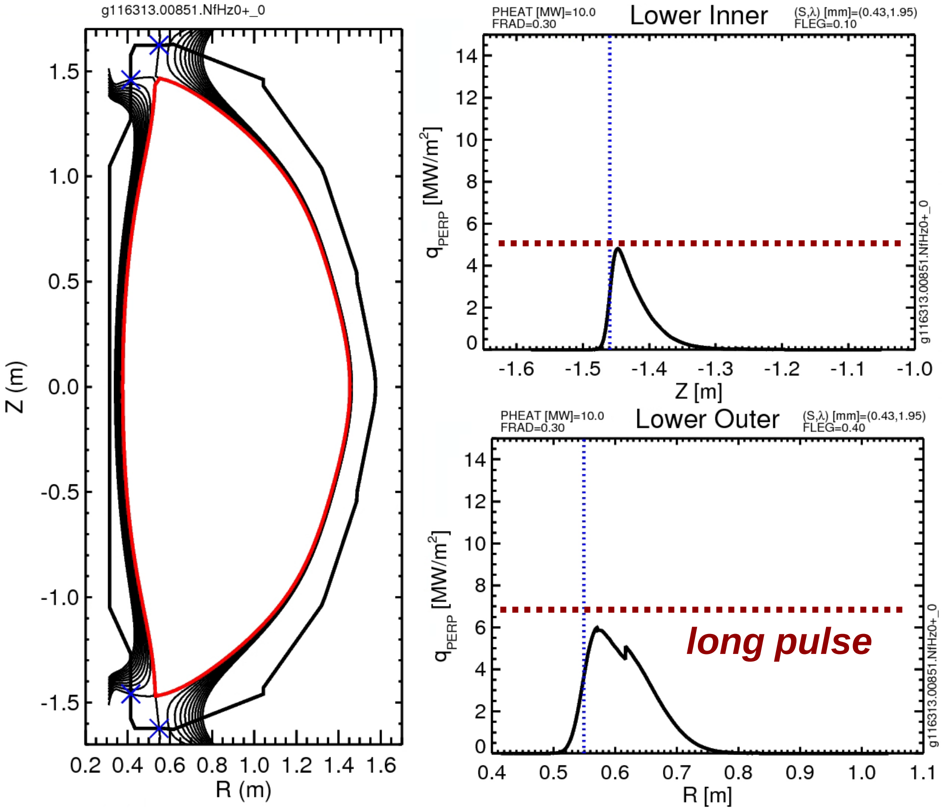
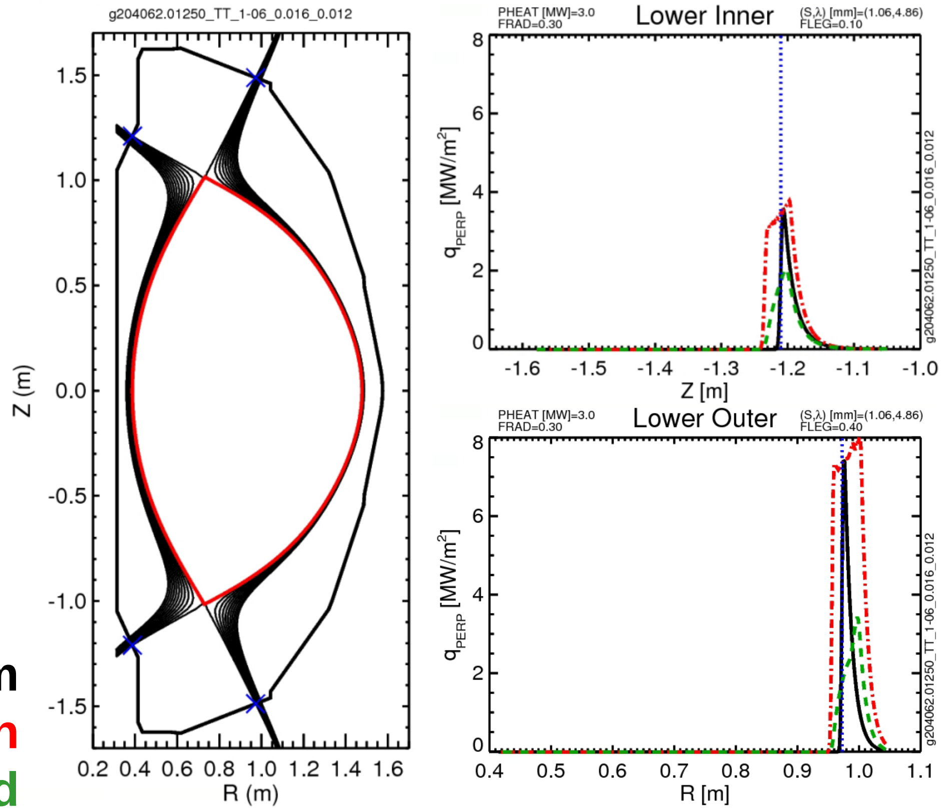
- (ASC_T-09) H-mode, higher elongation, higher current
  - I_P=1.25 MA, B_T=0.75 T, 8 MW, Δt > 1 sec
- (…likely need another step…)
- (NfHz0+_0) H-mode, full spec
  - I_P=2 MA, B_T=1 T, 10 MW, Δt = 5 sec



Sweeping Path to High B_T, I_p, and P_{INJ}

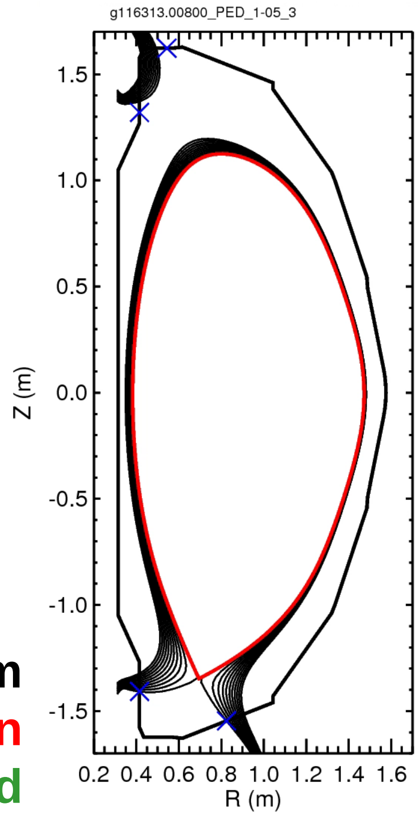
- (TT_1-06a) L-mode plasmas low current and power (sweeping)
  - I_P=1 MA, B_T=1 T, 3 MW, Δt=2 sec

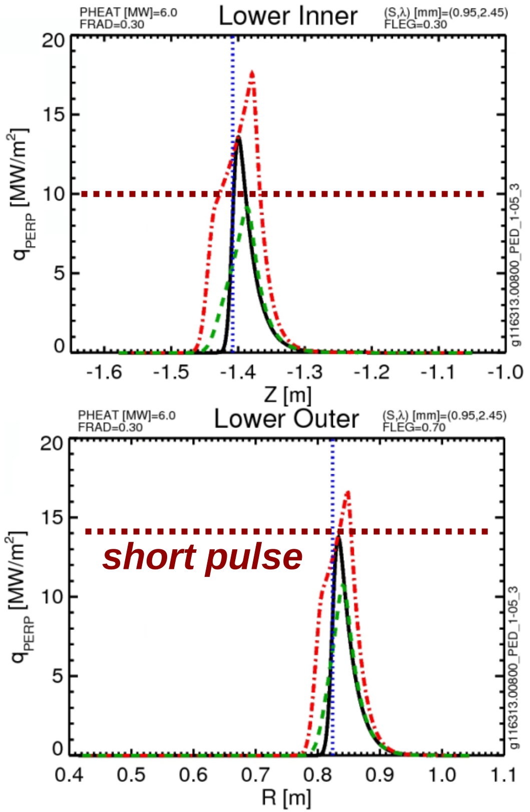
Single Equilibrium
Peak Across Scan
Time Averaged



Sweeping Path to High B_T, I_p, and P_{INJ}

- (TT_1-06a) L-mode plasmas low current and power (sweeping)
  – I_P=1 MA, B_T=1 T, 3 MW, Δt=2 sec
- (PED_1-05) H-mode, low triangularity, low current
  – I_P=1.2 MA, B_T=0.65 T, 6 MW, Δt=1 sec





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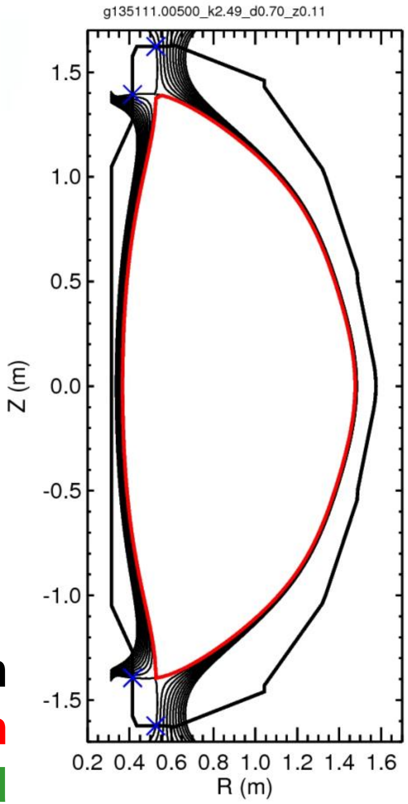
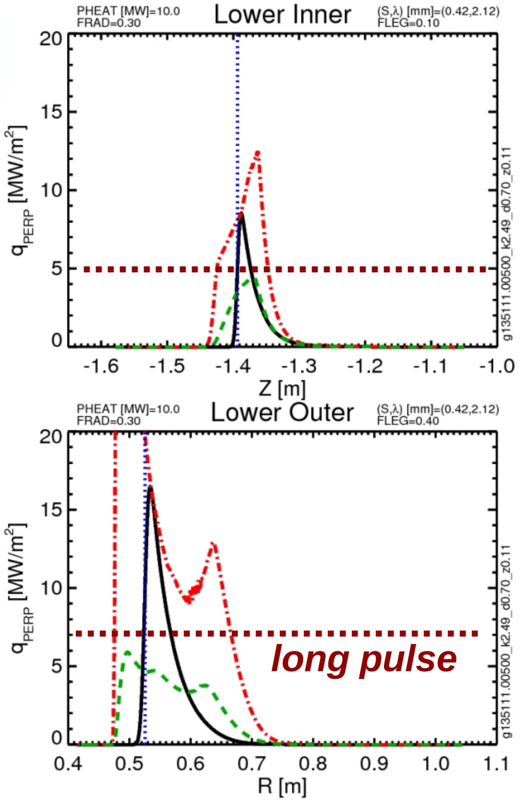
  – I_P=1.2 MA, B_T=0.65 T, 6 MW, Δt=1 sec
- (…need more steps…)
- (C2/S4) H-mode, full spec
  – I_P=2 MA, B_T=1 T, 10 MW, Δt = 5 sec





Single Equilibrium
Peak Across Scan
Time Averaged

Maintaining Requirements Expected to be Iterative

- Section 3.0 of Draft PFC Requirements:

If PFC designs are shown to not meet these requirements, relaxation may be granted. First, more accurate profiles of field directions and heat flux magnitudes along the divertor surface can be made available, by contacting the Head of the PFC Requirements Working Group and/or the Head of NSTX-U Research Operations. If necessary, reduction of the ultimate parameters may be feasible, but the impact on NSTX-U operational space must be taken into consideration, and modifications to these requirements be done in coordination with the Head of NSTX-U Research Operations and the NSTX-U Research Director.

- physics attends weekly PFC meetings, and engineering contributes to the PFCR Working Group (ex: OBD faceting)
  - physics catches unanticipated design issues early
  - engineering gives feedback on requirements which drive design complexity

FY18 Milestones Continue and Extend this Work

- PPPL and Lab collaborators likely to be contributing to:
  - R(18-1): Develop and benchmark reduced heat flux and thermo-mechanical models for PFC monitoring
    - paraphrase Rich: if we imposed our model on someone else would we come up with a conclusion that they shouldn't run their machine (e.g. DIII-D)?
  - F(18-1): Evaluate PFC operational limits and develop integrated diagnostic plans for operations
  - FY18 milestones targeted towards developing capabilities and starting long-lead activities preparing for post-Recovery PFC monitoring needs
- benefit from better demonstrations of a broad mission space while also maintaining a path to get to the high B_T, I_p & P_{NBI}
  - true time-evolving simulations of sweeping equilibria
  - some framework of evolution from low power, elongation shot-to-shot

Summary

- draft PFC Requirements for CDR developed through contributions from the PFCR-MEMO-008, 009 and 010 (needs review by WG)
- traceable, maintainable science and physics basis
  - science mission derived from TSG requests and programmatic objectives
  - heat fluxes to various PFC regions documented in an extensive set of MEMOs (under WG review, drafts available for CDR)
- conservative estimates being used to derive heat fluxes
  - use 30% radiated power fraction, narrowest λ_q
- two routes to 2 MA, 1 T and 10 MW: stationary, high poloidal flux expansion and inner/outer strikepoint sweeing
  - enhanced radiated power left in contingency