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Requirements, Designs and Plans for NSTX-U High Heat Flux Plasma Facing Components

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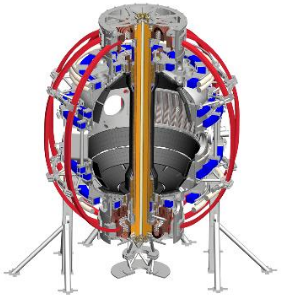
19th International Spherical Torus Workshop
Seoul National University
9/20/2017

Oak Ridge National Laboratory

PPPL



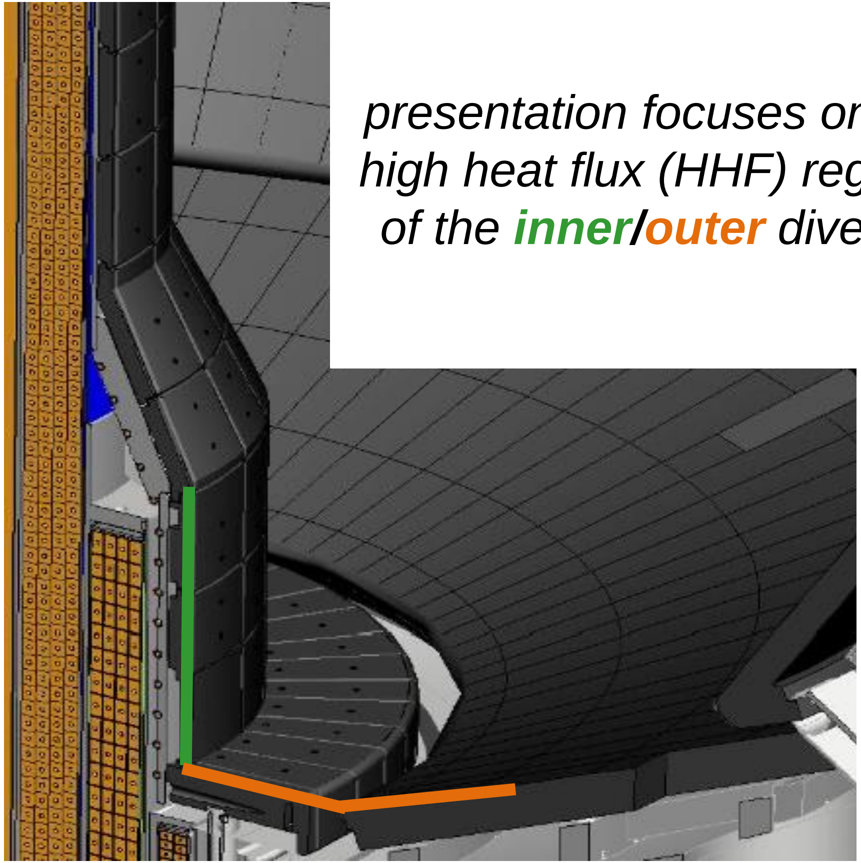
Background

- following a series of events in FY16, NSTX-U were instructed to:

  "Complete an extensive extent-of-condition review of NSTX-U to identify all design, construction, and operational issues."

- process revealed concerns w/ existing plasma facing components
  - could not meet combined halo current and heat flux requirements
  - concern that these requirements did not reflect present physics understanding
- heat exhaust previously identified as a challenge for NSTX-U [Menard NF 2012], but solutions (snowflake, radiation) had uncertainty
- NSTX-U established a dedicated Working Group to combine physics and engineering experts to support PFC design activities

Background



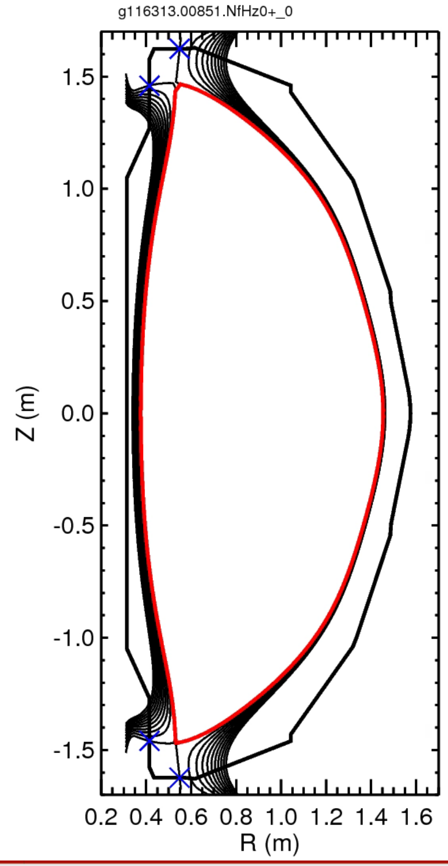
*presentation focuses on the high heat flux (HHF) regions of the **inner**/**outer** divertor*

Overview of Presentation

- simulation workflow to quantify the PFC heat flux
- methods to mitigate high heat flux
  - poloidal flux expansion and strike point sweeping
- design of tiles to support high performance scenarios and broad physics program
  - stress analysis in chosen castellated tile design
  - impact of PFC surface shaping to hide leading edges

Example of Workflow

- compute equilibrium (I_p, B_T, P_{NBI})
- radiated power fraction and power sharing between divertors assumed
- λ_q assumed, defines upstream parallel heat flux, $\vec{q} = q_{\parallel} \vec{B}/|B|$
- $q_{\parallel}$ mapped from upstream to PFC surfaces
  - $\nabla \cdot \vec{q} = 0$ results in $q_{\parallel}/B$ constant
- diffusive spreading (S) into PFR (Eich model)
- find impact angle $\sin\alpha = \vec{B} \cdot \vec{n}$
- compute surface heat flux, q_{perp}



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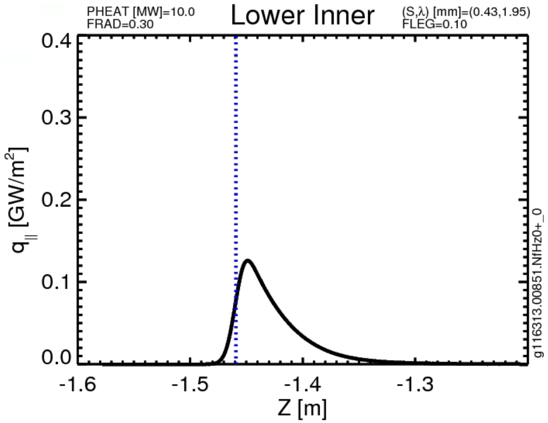

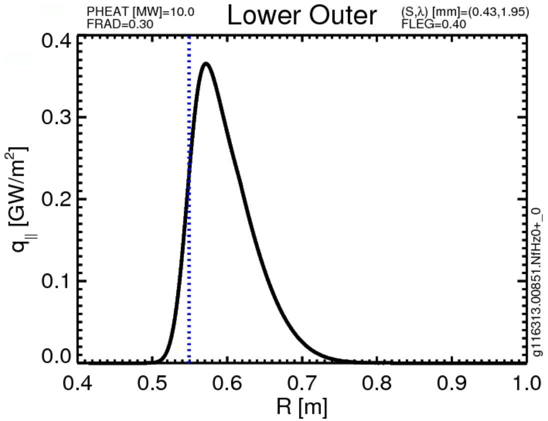

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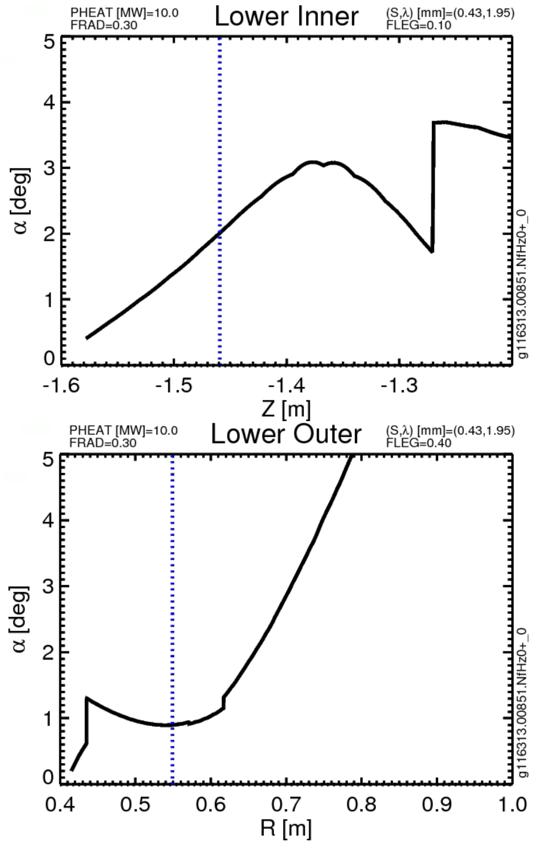

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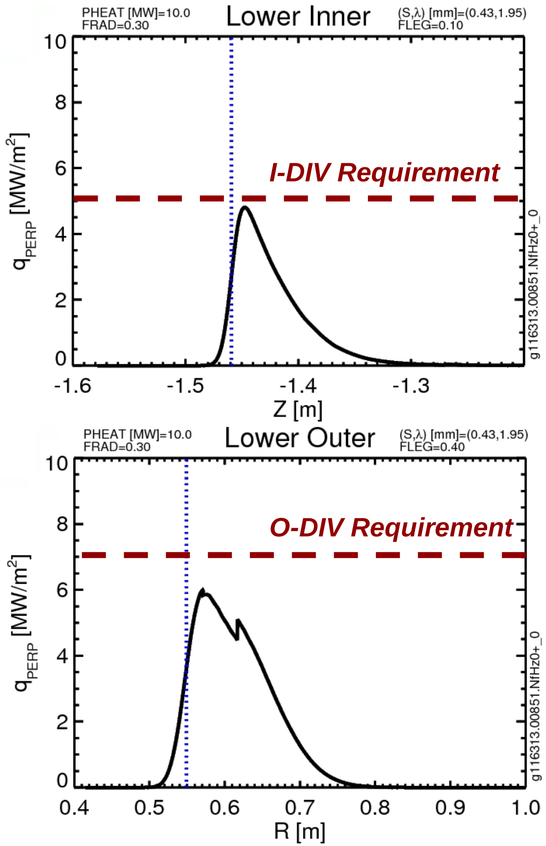


Use Conservative Approach: Assume Narrow λ_q

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

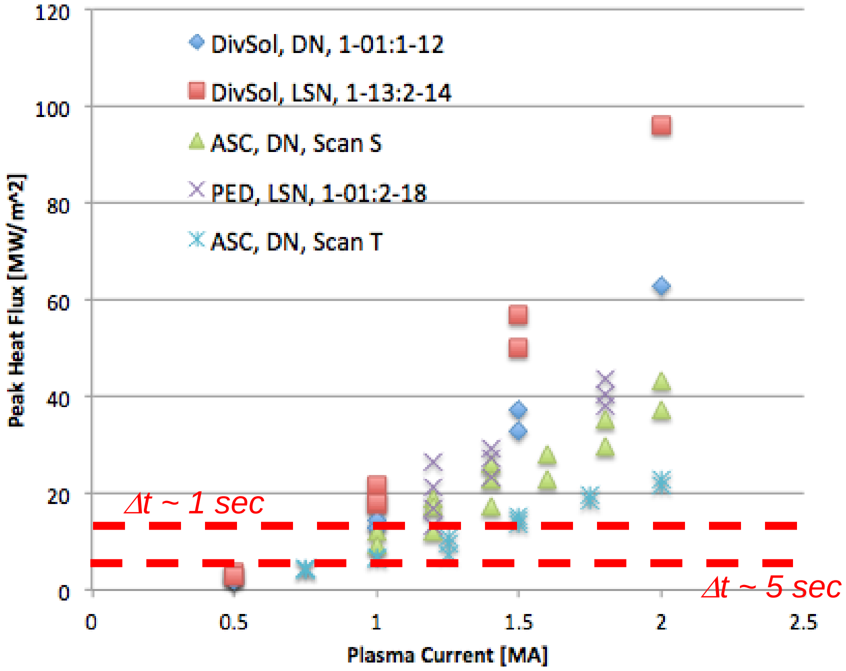
- **Heuristic Drift Scaling [Eich, PRL 2011]:** **1.9 [mm]**
  (7), (9-10) results in $\boldsymbol{\lambda_q \sim B_T^{-7/8} q_{cyl}^{9/8}}$
- MAST scaling [Thornton, PPCF 2014]: 4.1 [mm]
  $\lambda_q[mm] = 1.84(\pm 0.48) B_{pol,omp}^{-0.68(\pm 0.14)} P_{SOL}^{0.18(\pm 0.07)}$
- Eich Scaling [Eich, NF 2013]: 3.0 [mm]
  $\lambda_q[mm] = 1.35 \varepsilon^{0.42} R_{geo}^{0.04} B_{pol,omp}^{-0.92} P_{SOL}^{-0.02}$

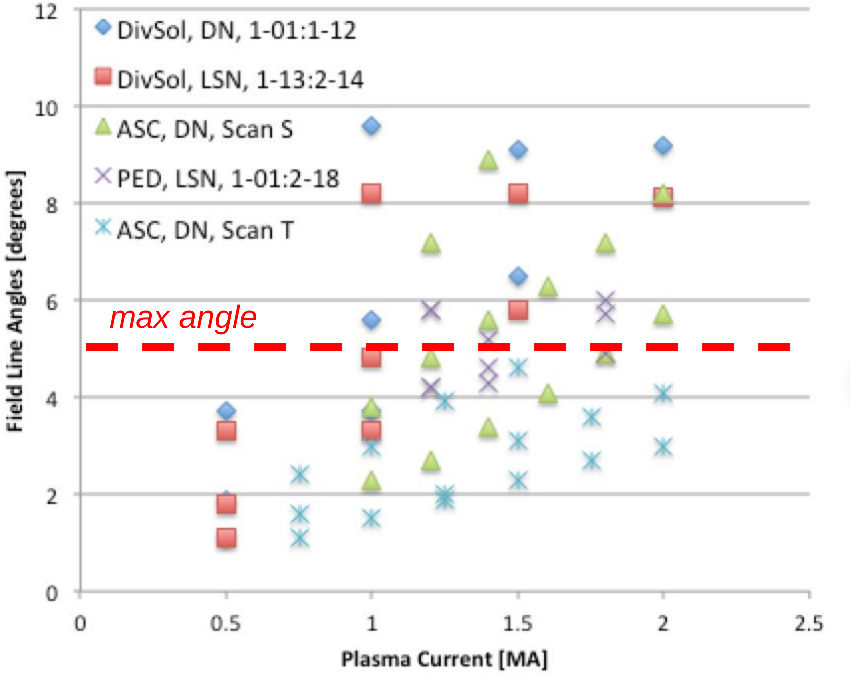
NSTX-U PFC Requirements developed assuming Heuristic Drift Scaling

2 MA, 1 T, 10 MW Scenario

Stationary Horizontal Target Heat Fluxes

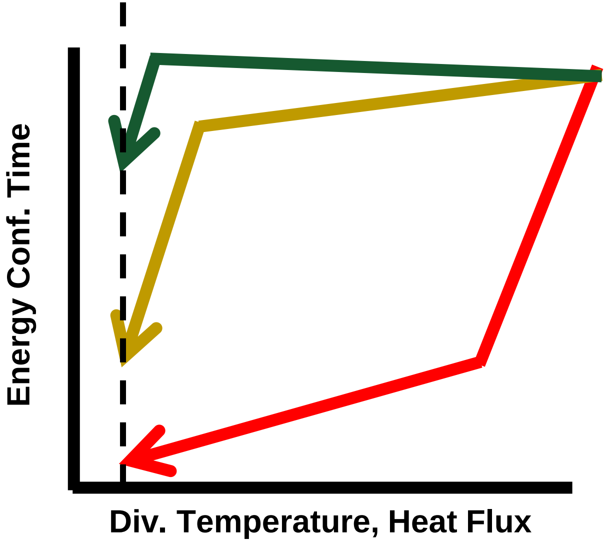
- many stationary LSN cases will not be possible even at short pulse w/o some kind of further mitigation





Strategies for Mitigating Heat Fluxes

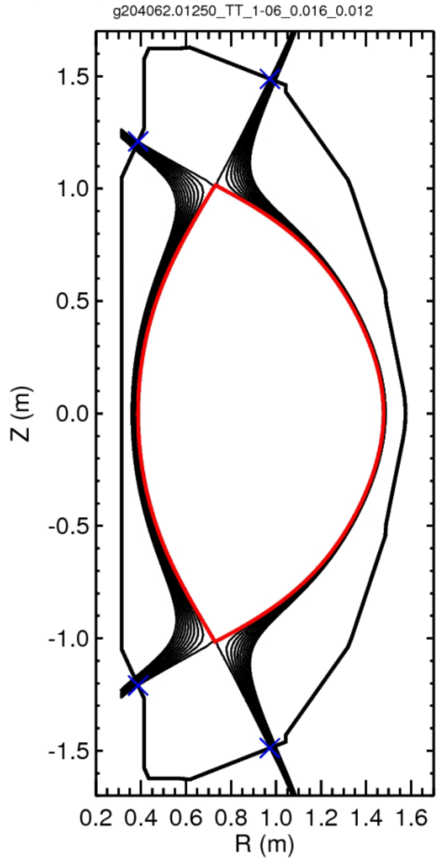
- increase poloidal flux expansion
  - changes the amount of wetted area on divertor, but also makes for shallow angles
- strikepoint sweeping in time
  - use PF coils to move the strike point back and forth across the surface
- increase radiation fraction *(30% assumed in models)*
  - contingency due to uncertainty of compatibility w/ physics goals
  - adding new divertor fueling locations to help us exploit radiative exhaust



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

Elongation Impacts Use of Poloidal Flux Expansion

- low-κ shapes have x-point far from PFCs have useful scientific value (Fri. Guttenfelder)
  - I_p = 1 MA, P_{NBI} = 3 MW L-mode
  - flux expansion < 3, field line angles > 10 deg
  - high stationary heat flux (> 6 MW/m^2)



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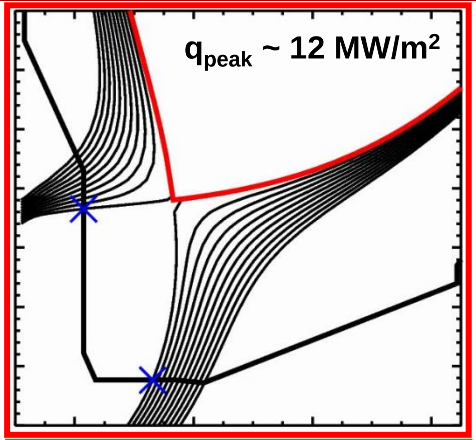
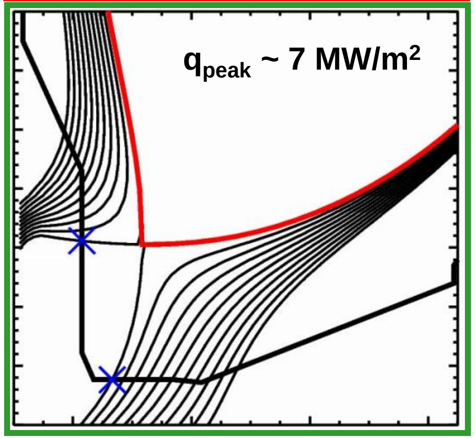
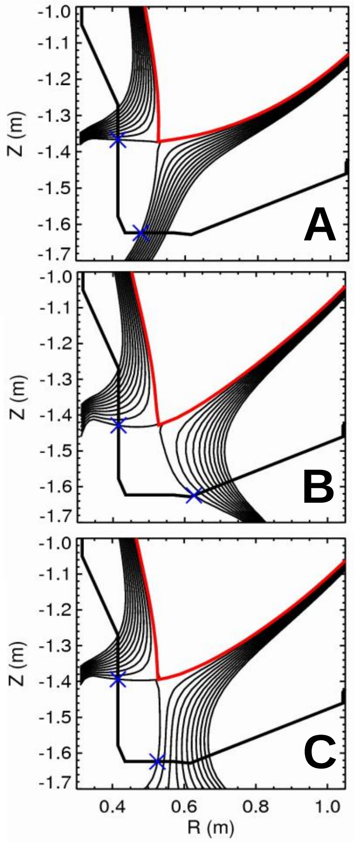
  - flux expansion < 3, field line angles > 10 deg
  - high stationary heat flux (> 6 MW/m^2)
- increasing kappa and moving x-point closer to targets can mean higher I_p, P_{NBI} are 'easier'
  - I_P=1.00 MA, B_T=0.75 T, 7.5 MW: q_{peak} ~ 12 MW/m^2
  - I_P=1.25 MA, B_T=0.75 T, 8.0 MW: q_{peak} ~ 7 MW/m^2
- shape/heat flux coupling stronger in STs

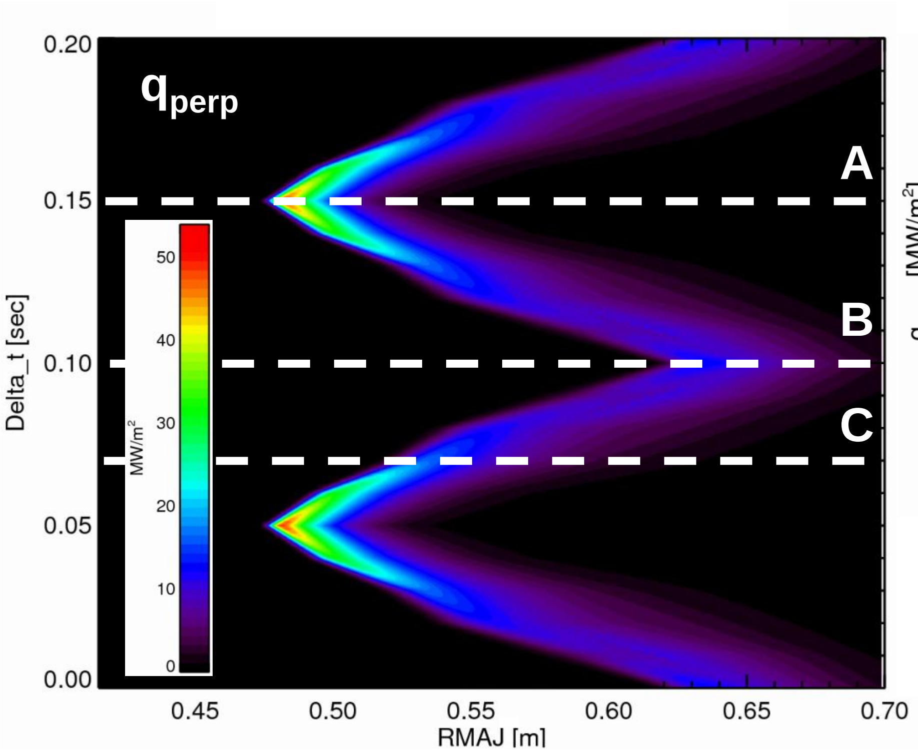


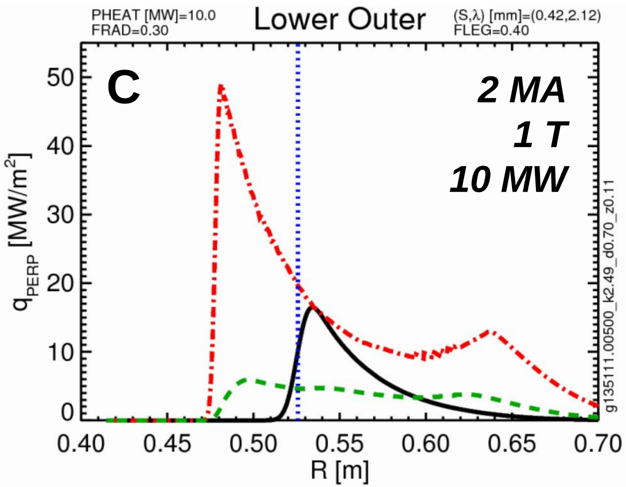


Initial Modeling of Sweeping Shows Benefits

assemble individual equilibria and interpolate







Single Equilibrium
Peak Across Scan
Time Averaged

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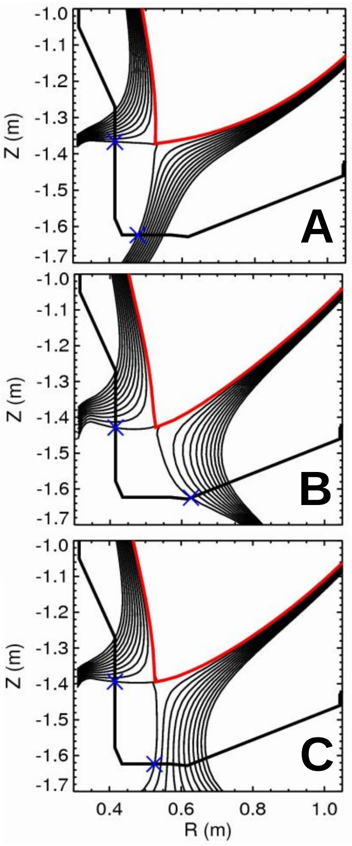

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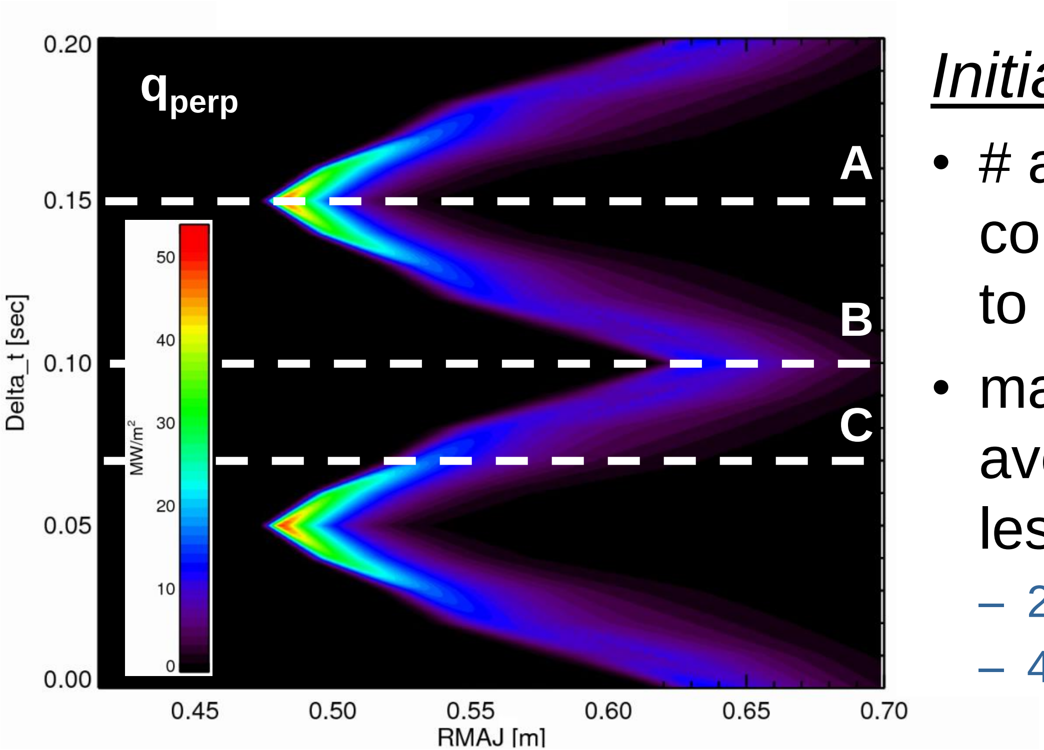
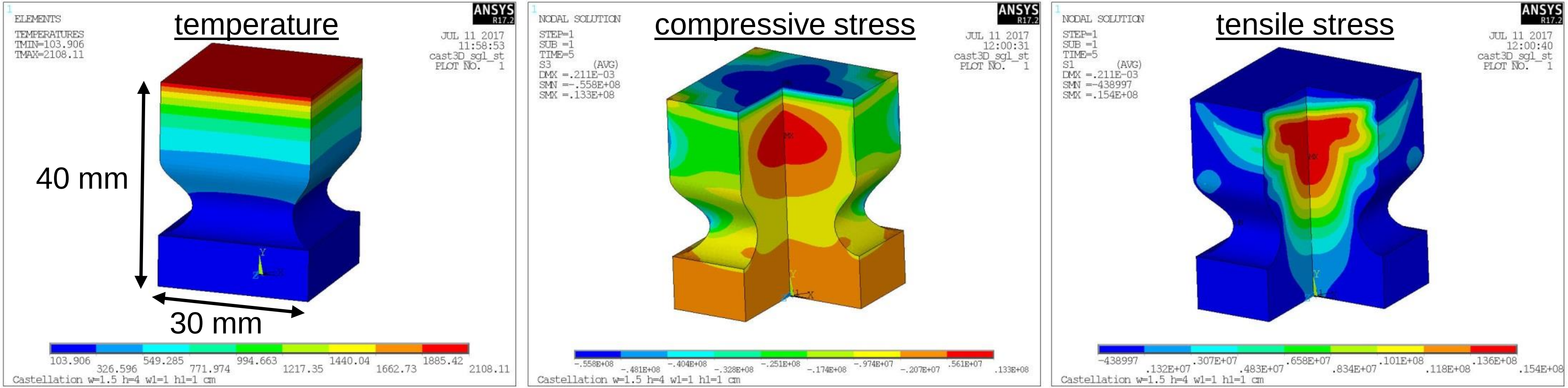


<u>Initial Findings</u>

- # and location of coils impacts ability to smoothly sweep
- maximum time-averaged heat flux less impacted by λ_q
  - 2.1 mm, q_{ave} ~ 4.5 MW
  - 4.3 mm, q_{ave} ~ 3.5 MW

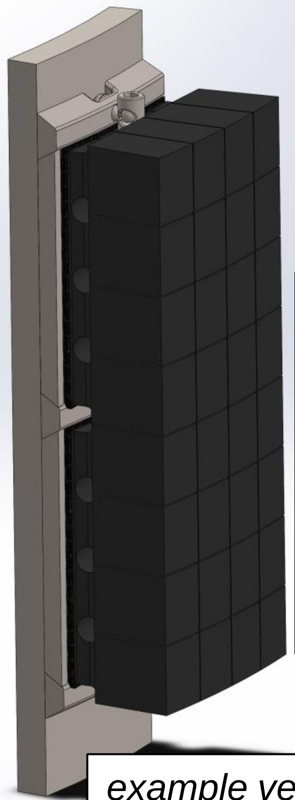
HHF Tile Designs Converged to 'Small Cubes'

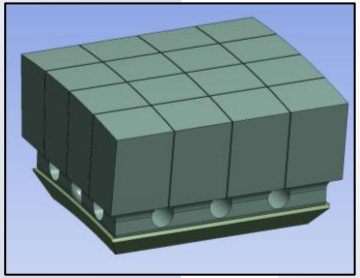


ANSYS simulation of 10 MW/m² for 5 sec onto isotropic graphite at normal incidence

- larger tiles 'bow', enhancing stress, small cubes relieve this by 'mushrooming'
- design criteria using T_{limit} ~ 1600 ^{o}C, and allowable stresses of 50% material limit
- scoping simulation show T_{max} = 2100 ^{o}C, max compressive stress of 55.8 MPa (86% of allowable) and max tensile stress of15.4 MPa (51% of allowable)
  - example of design that is 'temperature limited' and not 'stress limited'

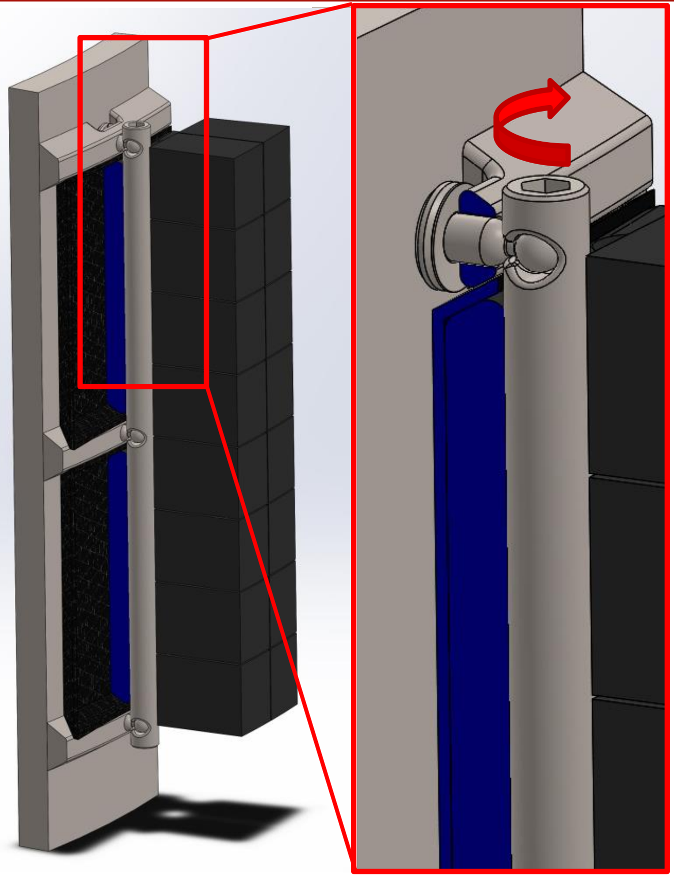
Developing Designs Using Castellated Tiles





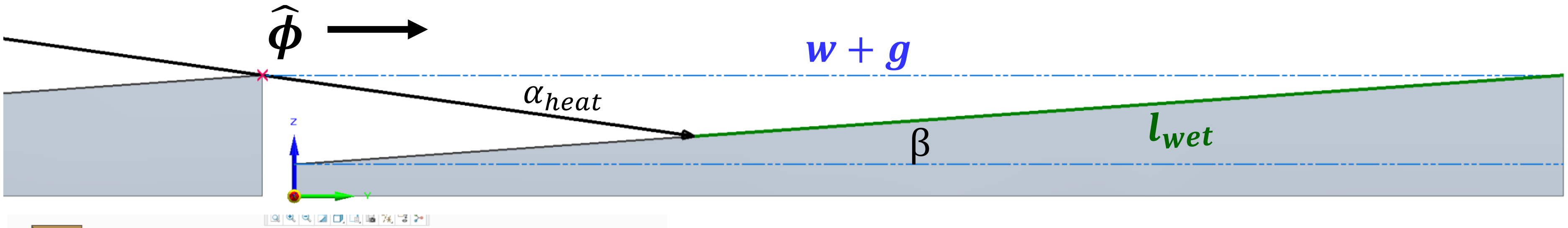
cover HHF surfaces using 100 mm x 100 mm tiles made of 4 x 4 castellated 'small cubes'

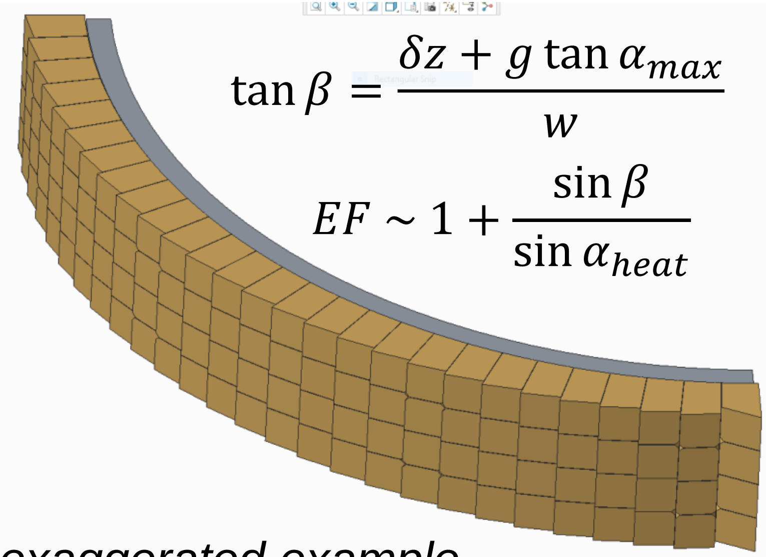
example vertical divertor



- designs working to avoid front-surface holes in HHF regions
- side-access through removing low-heat flux tiles w/ front surface holes
- ex: **cam-like action** secures tiles against mounting plate/vessel
- beginning designs for inter/intra-tile diagnostics

Tile Shaping Used to Avoid Leading Edges





$$\tan\beta = \frac{\delta z + g\tan\alpha_{max}}{w}$$

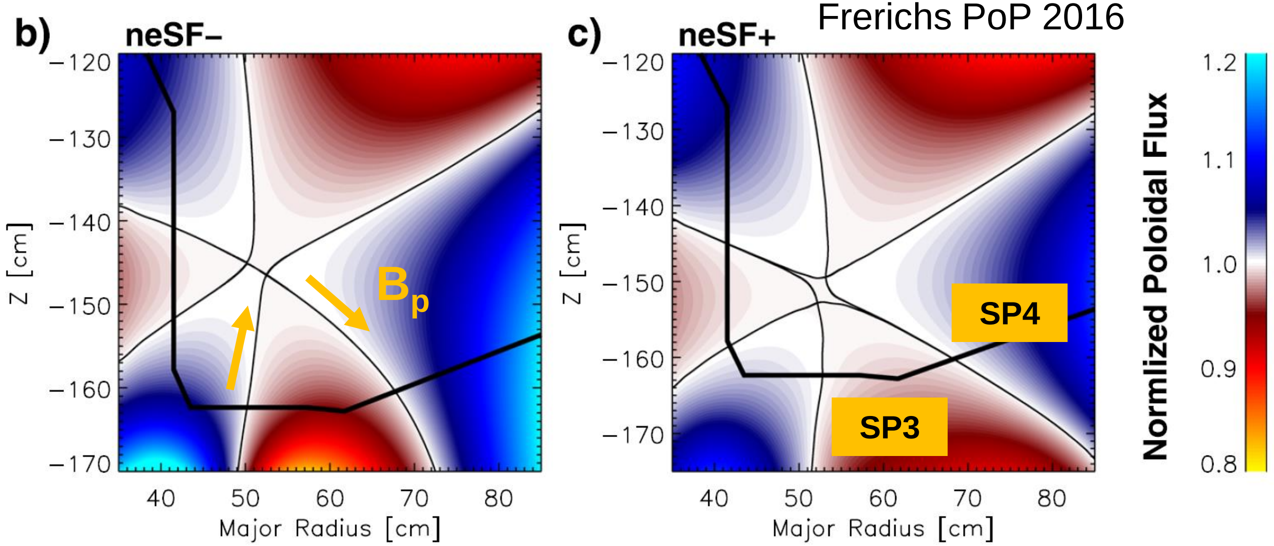
$$EF \sim 1 + \frac{\sin\beta}{\sin\alpha_{heat}}$$

exaggerated example

- small ramp toroidally, $\beta \sim 1^o$
  - driven by max field line expected, α_{max}
  - impacted by alignment uncertainty, δz
- this reduces wetted area (increases $\vec{B}\cdot\hat{n}$) : 'enhancement factor (EF)'
- large pol. expansion leads to shallow attack angles, $\alpha_{heat} \sim 1^o$

Desire Flexibility to Explore Snowflake Divertor

Frerichs PoP 2016



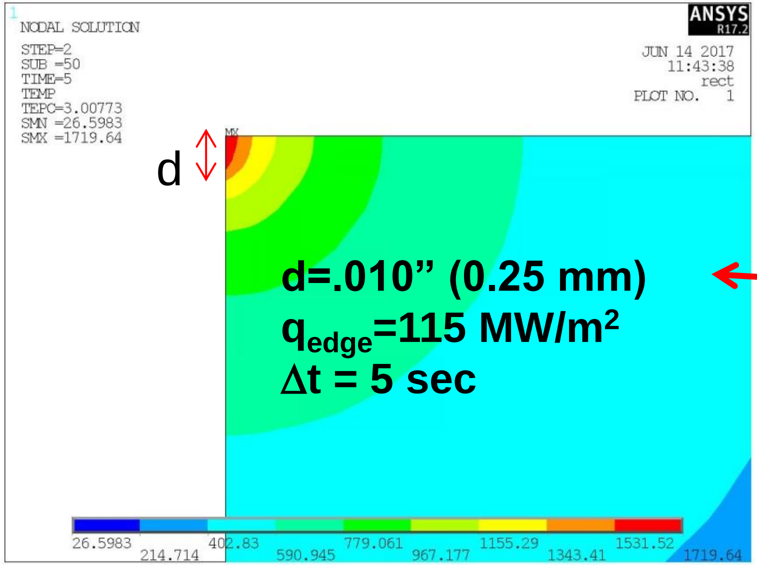
poloidal field direction switches between legs

SP4 = 'outer leg'
SP3 = 'inner leg'

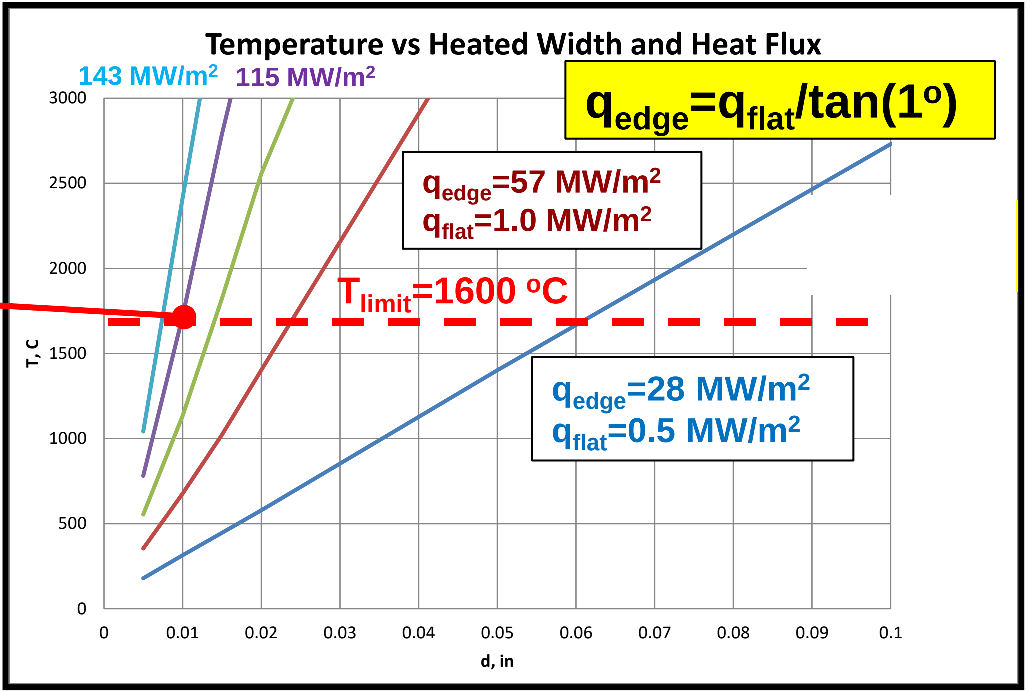
- prior experiments on NSTX, DIII-D and TCV used flat PFCs
- power sharing between strike points import
  - TCV sees ~25% of the power on SP3 on SP4 [Remierdes PPCF 2013]
  - this power approaches shaped PFCs ~ 90º making $q_{surf} \sim q_{||}$

Analysis Shows PFCs May Tolerate 'Snowflake Like' Cases

thermal analysis shows heat conducted into PFC bulk allows substantial edge heating over small edges, allowing heat loads in 'unfavorable' directions



'd' constrained by field line angle and tile size



Summary

- new designs for NSTX-U high heat flux plasma facing components expected to support operations at full performance (2 MA, 1 T, 10 MW, 5 sec.)
  - updated halo current and heat flux specifications developed
- scenarios using poloidal flux expansion and strike point sweeping have been analyzed
  - enhanced radiated power will be used as contingency
- PFC designs based on ‘small cubes’ designs are expected to be ‘temperature limited’ instead of ‘stress-limited’
  - PFC shaping being used to avoid leading edge heating

EXTRA SLIDES

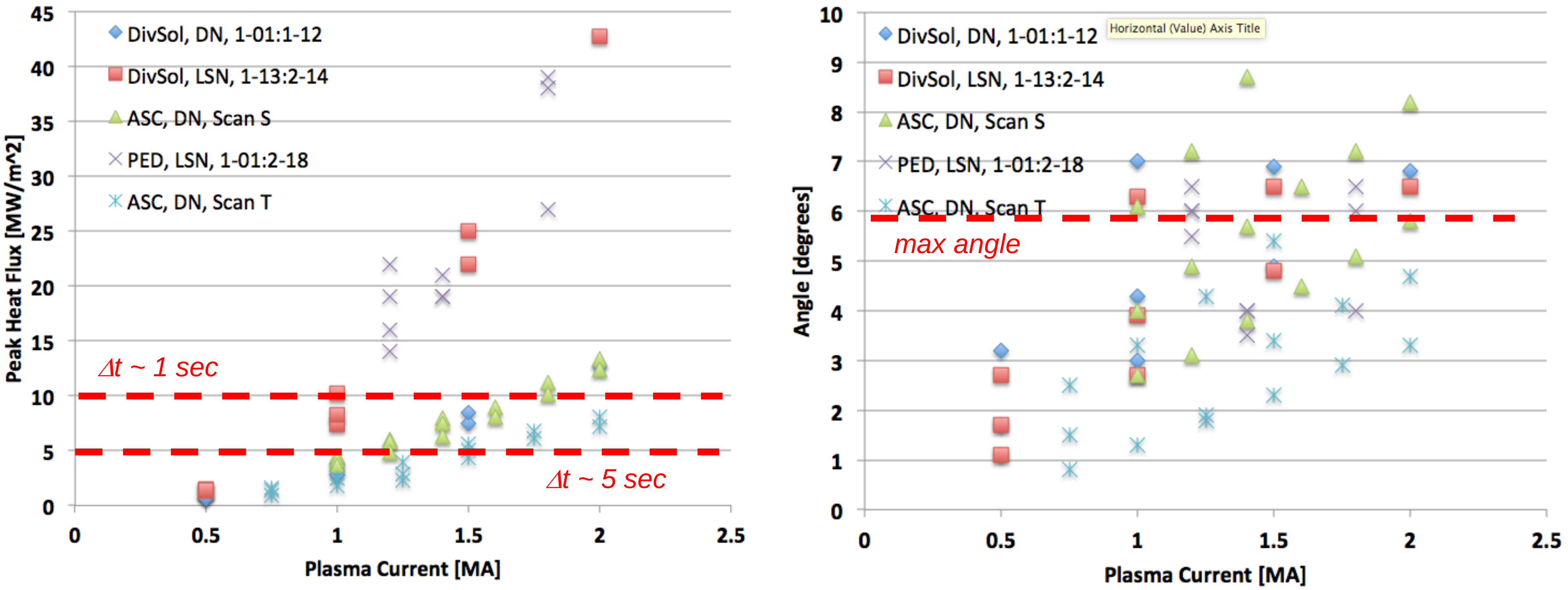
PFC Requirements Derived from Science Team Input

<u>**IBDH**</u>	**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*

Stationary Vertical Target Heat Fluxes

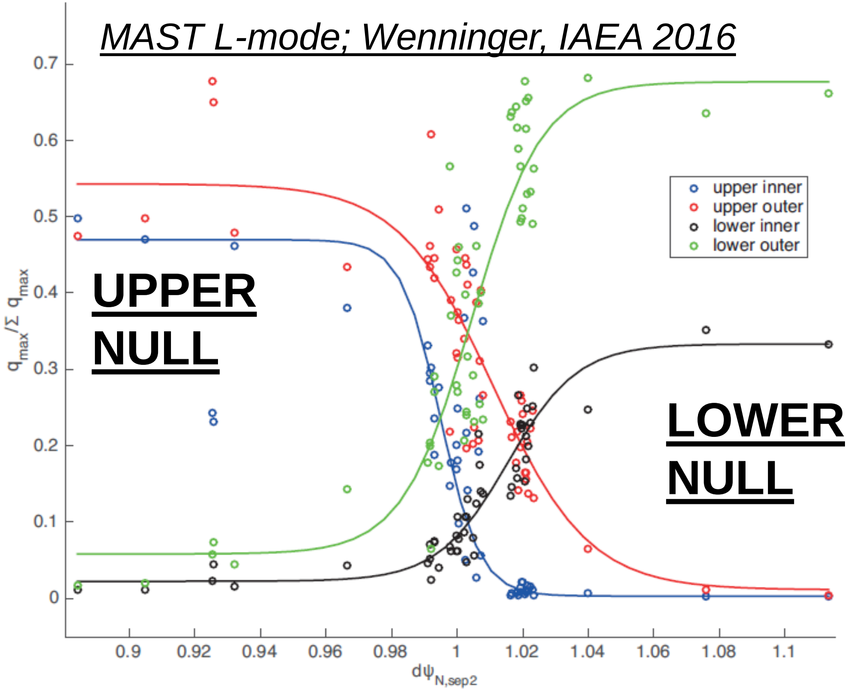
- developed multiple scenarios based on input from NSTX-U topical science groups on desired I_p, B_t, P_{NBI}, shape, pulse duration



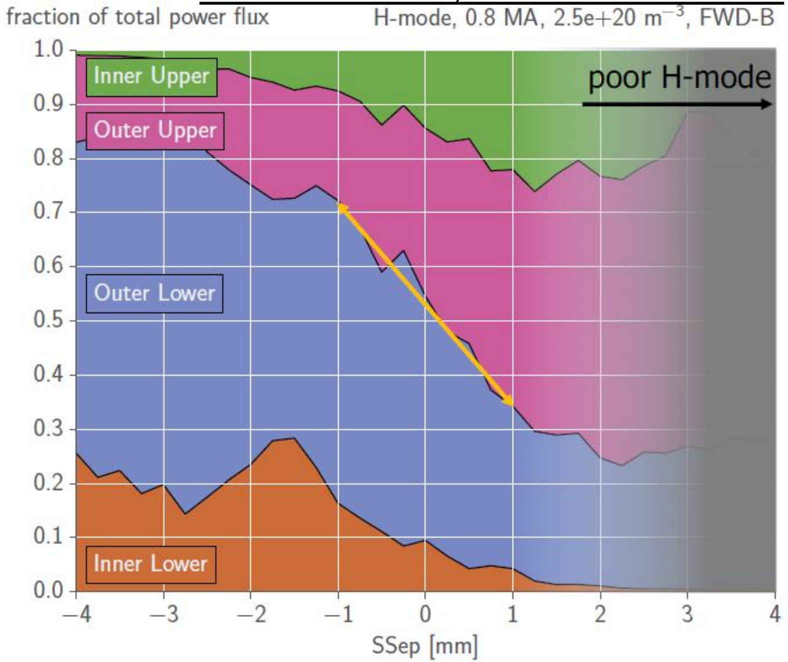
Empirically Motivated Divertor Power Sharing

- 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

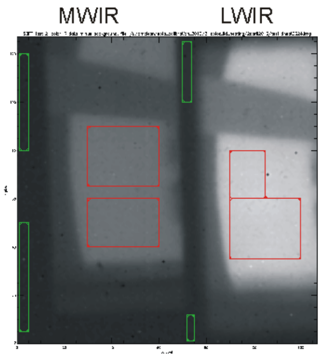


C-Mod H-mode; Brunner APS 2016

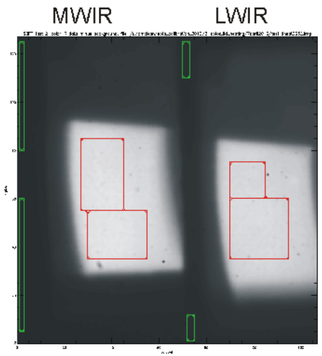


PFC Monitoring Challenges

ex: from NSTX LLD



April 2, 2010 12:46.06 PM
Both LLD plates at ~60°C, ratio=2.2



April 7, 2010 3:25.26 PM
K-H LLD plate at ~320°C, ratio=1.0

- mixed-material environment w/ time varying surface emissivity
- characterizing the total P_{RAD}
  - new NSTX-U diagnostics needed
- real-time versus inter-shot?