NSTX-U

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

Divertor, SOL and Plasma Facing Components

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NSTX-U PAC-39
PPPL
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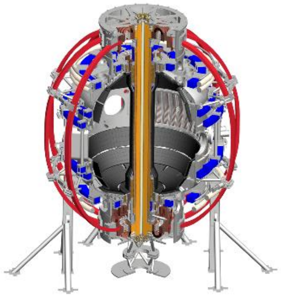
Oak Ridge National Laboratory

PPPL



Overview

- how will NSTX-U address critical issues in fusion science?
  - introduce the [2015 PMI Workshop PRDs] and show NSTX-U alignment
- what is the medium-term research vision (2020-2025)?
  - validation of heat exhaust and halo current models used in Recovery
    - enable new cryopump PFC design work and future high-Z enhancements
  - vigorous study of dissipative divertors (conventional, X-div, snowflake, etc.)
  - exploitation of the (planned) cryopump as one of multiple particle control tools
- how will NSTX-U be world leading in boundary physics in when operations resume in 2020?
  - MAST-U programmatic decisions emphasize boundary physics
  - NSTX-U provides a crucial complementary facility to confirm physics, empirical scalings and optimize core-edge integration
- briefly discuss high-Z, longer term covered by M. Jaworski

2015 PMI Workshop Priority Research Directions

- PRD-A: Identify the present limits on power and particle handling, as well as tritium control and inventory, for solid and liquid plasma facing components, and extend performance to reactor relevant conditions with new transformative solutions
- PRD-B: Understand, develop and demonstrate innovative dissipative/detached divertor solutions for power exhaust and particle control, sufficient for extrapolation to steady-state reactor conditions
- PRD-C: Understand, develop and demonstrate innovative boundary plasma solutions for main chamber wall components, including tools for controllable sustained operation, sufficient for extrapolation to steady-state reactor application
- PRD-D: Understand the science of evolving materials at reactor-relevant plasma conditions and how novel materials and manufacturing methods enable improved plasma performance
- PRD-E: Understand the mechanisms by which boundary solutions and plasma facing materials influence pedestal and core performance, and explore routes to maximize fusion performance

How does the NSTX-U facility and program align with these priorities?

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Most of this work is aspect ratio independent and a fully operational NSTX-U is another platform for testing novel PFC/materials solutions

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Physics research topics on power exhaust and particle control, including core-edge integration will be emphasized in NSTX-U program

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'Demonstrational' goals must be done on an ST facility to advance the concept, while 'Understanding' benefits the entire boundary community

Near-Term NSTX-U Activities Well Aligned with PRDs

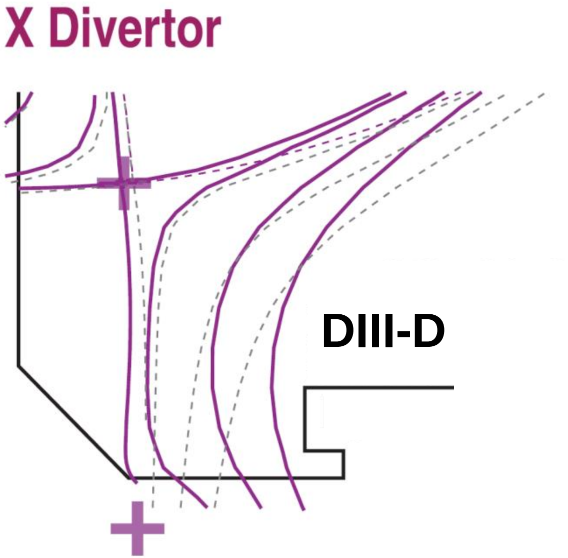
- novel castellated graphite PFCs designed at heat flux handling limit
  - graphite the right choice to validate physics and engineering basis for PFCs in STs
  - accelerate PPPL progress on non-carbon replacements
- extends the ST to high-$q_{||}$, up to 0.5 GW/m^2 at high P_{NET}/P_{TH}
  - access to highest B_p will test ST SOL physics and empirical scaling for heat flux, λ_q
  - facility to test strategies for radiative exhaust in conventional and alternative divertors
- allows multiple means of particle control in the ST to be explored
  - ELM control using 3D-field triggering, particle injection
  - direct comparison of evaporated lithium and cryopumping will clarify physics drivers
- simultaneous optimization of exhaust and pedestal solutions
  - access to high power, high triangularity configurations that maximize pedestal stability
  - explore benefits of advanced divertor configurations (snowflake, x-divertor)
  - utilization of lithium via evaporated coatings and injection (granules, droppers)

Evolution of NSTX-U PFC Heat Flux Issues

- heat exhaust previously identified as a challenge for NSTX-U, but solutions (snowflake, radiation) implied uncertainty for core, pedestal scenarios
  - DVVR/EoC process highlighted issues with PFCs meeting requirements and challenged the science basis for existing requirements
- NSTX-U established a dedicated Working Group to combine physics and engineering experts to support PFC Recovery
  - supported development of PFC Requirements based on TSG input
  - charged with to providing guidance on PFC monitoring approaches
  - year-to year Recovery-era milestones R18-1 and F18-1 guide Lab work

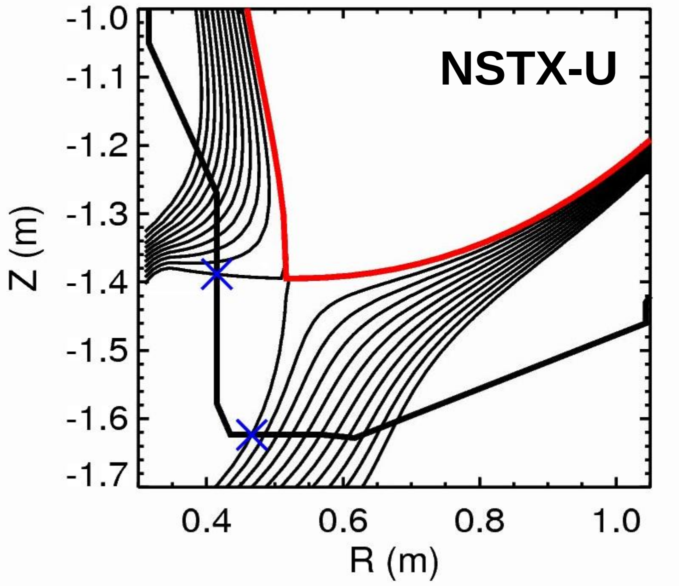
Scope of the NSTX-U Heat Exhaust Challenge

- common question: *"if Machine X were to use our model, would they predict a PFC problem?"*
  - ex: DIII-D (LSN): 27 MJ over 10 s to ODIV (floor) 1.15 < R < 1.37 ~ 1.74 m^2
  - ex: NSTX-U (DN): 14 MJ over 5 s to ODIV (IBDH) 0.45 < R < 0.60 ~ 0.50 m^2



<u>'ideal' spread evenly</u>

DIII-D: (floor)	**16 MJ/m^2** **1.6 MW/m^2**
MAST-U : (T2 tile)	**10.9 MJ/m^2** **2.2 MW/m^2**
NSTX-U: (IBDH)	**28 MJ/m^2** **5.7 MW/m^2**



ST's Have Uncertainty in Empirical λ_q Scaling

multiple estimates of heat flux width, λ_q

<u>*2 MA, 1 T, 10 MW*</u>

- **<u>Heuristic Drift Scaling [Eich, PRL 2011]:</u>**
  (7), (9-10) results in $\lambda_q \sim \mathbf{B_T}^{-7/8} q_{cyl}^{9/8}$ (used for Recovery) — **1.9 [mm]**
- <u>Eich Scaling [Eich, NF 2013]</u>:
  $\lambda_q[mm] = 1.35\varepsilon^{0.42} R_{geo}^{0.04} B_{pol,omp}^{-0.92} P_{SOL}^{-0.02}$ — 2.0 [mm]
- <u>NSTX scaling [Gray, JNM 2011]:</u>
  $\lambda_q[mm] = 9.1 I_p^{-1.6\pm0.1}$ *(impacted by Li)* — 3.0 [mm]
- <u>MAST scaling [Thornton, PPCF 2014]:</u>
  $\lambda_q[mm] = 1.84(\pm0.48) B_{pol,omp}^{-0.68(\pm0.14)} P_{SOL}^{0.18(\pm0.07)}$ — 4.1 [mm]
- <u>XGC-1 simulation [unpublished]</u> — 3.0 [mm]

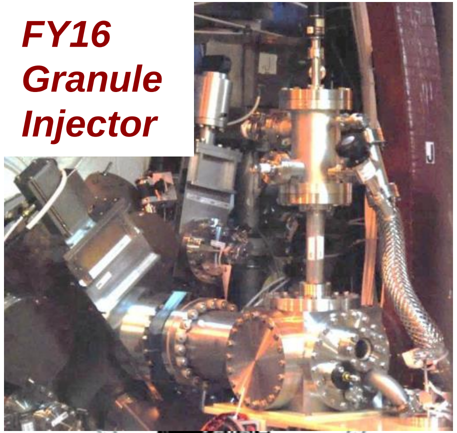
Focus of Near Term Boundary Program

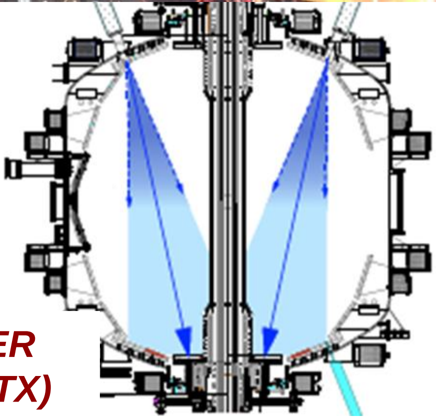
- learn to operate NSTX-U within the PFC requirements and develop skills and team to diagnose boundary plasmas
  - scenarios likely require sweeping, may need PFC monitoring
  - new boundary diagnostics, impact of altered PFC geometry, shaping
- validate PFC heat exhaust and halo current models
  - power sharing between divertors (in/out, up/down), heat flux width
  - halo current model assumptions TPF, I_{halo}/I_p, and footprint
- explore dissipation physics in conventional and alternative divertors
- investigate compatibility of power exhaust solutions w/ pedestal
  - this research has been ‘demonstrational’ in standard aspect ratio devices
  - results trigger physics studies, code validation and further experiments
- comparison of particle control techniques
  - revisit the physics and engineering requirements for the cryopump PFCs

Boundary Supports Key High Impact Program Elements

- PFCs and Div/SOL will have an operational role to support pedestal and core science mission
  - 10+ MW of P_{NBI} is available as a 'Day 1' capability while MAST-U plans to upgrade to 10 MW in early 2020's.
  - dealing with power exhaust may be rate limiting to moving to high power longer pulse length
- PFCs and Div/SOL will help to demonstrate a diverse, comprehensive set of particle control tools to help optimize advanced scenarios
  - stimulated/paced ELMs via 3D fields, granule injection
  - fueling from conventional/supersonic gas injection
  - pumping via use of evaporated lithium (LITER) and (planned) cryopump [w/ Particle Control Task Force]

FY16 Granule Injector

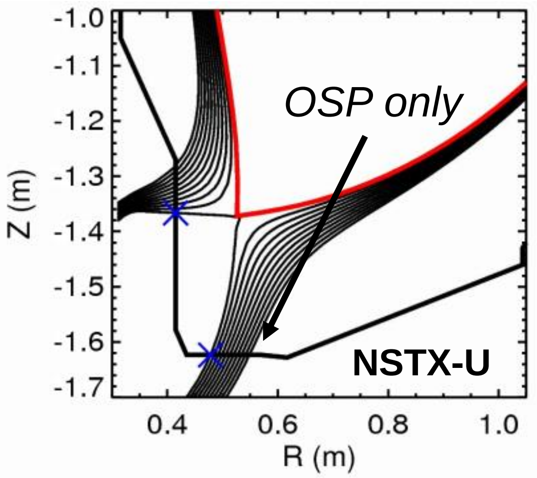


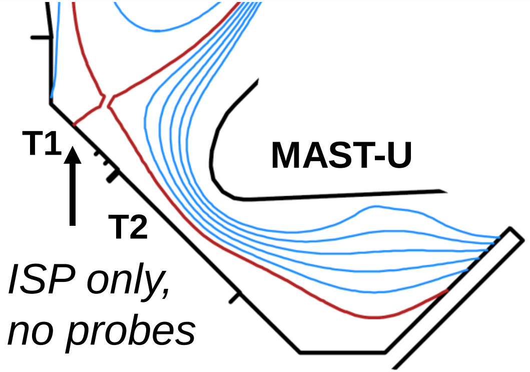


LITER (NSTX)

NSTX-U Boundary Physics Complements MAST-U

- both NSTX-U and MAST-U needed to explore simultaneous optimization of the boundary and pedestal
  - different triangularity optimization for PFCs
  - NSTX-U 'radial' off-axis beams enable more flexibility in running single null divertor geometries
- understanding existing differences in λ_q scaling and physics, requires two facilities
- MAST-U mission focuses on a wider range of boundary physics areas
  - MAST-U has ~50% of run time devoted to exhaust and the first baffled Super-X divertor
  - substantially more boundary diagnostics





Boundary Progress Enables Future High-Z Program

- ST's need to routinely access a high purity, high confinement regime
  - transport and current drive physics is impacted by dilution and high Z_{eff}
  - examples (ILW, AUG-HFSHD) of pedestal impacted by low-Z concentration
- ST's have not investigated control of high-Z impurities from PFCs
  - limited access to wave-heating actuators and reliance on NBI, high torque
  - different balance of neoclassical and turbulence ion particle transport
- NSTX-U will revisit and roadmap plans for installing high-Z PFCs
  - what type of tiles to be used (e.g. solid vs. coated)?
  - what fraction of the machine is covered and when?
  - what can be learned using near-term NSTX-U ops (high-Z gas, LBO)?
  - what can be learned from collaborations (ST-40, Globus-M2)?
- high-Z evolution linked to NSTX-U liquid metal strategy (Jaworski)

Summary

- NSTX-U will enable the research aligned with multiple Priority Research Directions identified in the 2015 PMI Workshop
  - ‘develop and demonstrate’ power exhaust and particle control in the ST configuration, move toward physics ‘understanding’
- near term program will enable a robust science mission to
  - validate PFC heat exhaust and halo current models
  - investigate the compatibility of power exhaust solutions w/ pedestal
  - evaluate and understand particle control that enable long pulse
- validation of PFC physics and engineering basis enables enhancements (cyropump, high-Z) which unlock a wider range of particle control options
- complementary programmatic decisions between MAST-U and NSTX-U highlight a joint role in advancing the ST physics basis for optimized boundary and pedestal exhaust solutions

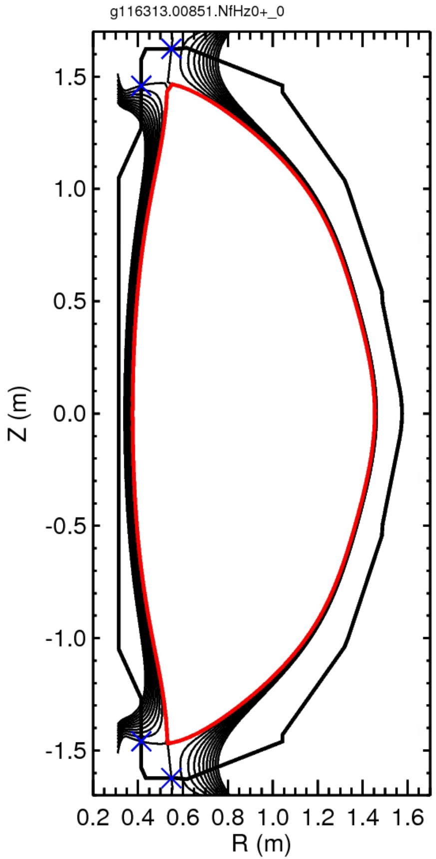
EXTRA SLIDES

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
- 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
- Developed PFC Requirements and Diagnostic Req.

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, $\vec{q} = q_{\|} \vec{B}/|B|$
- $q_{\|}$ mapped from upstream to PFC surfaces
  - $\nabla \cdot \vec{q} = 0$ results in $q_{\|}/B$ 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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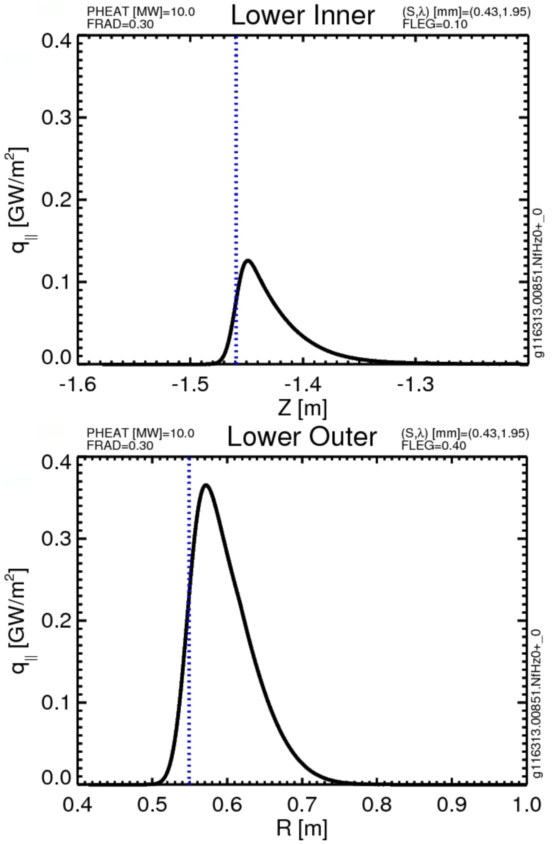

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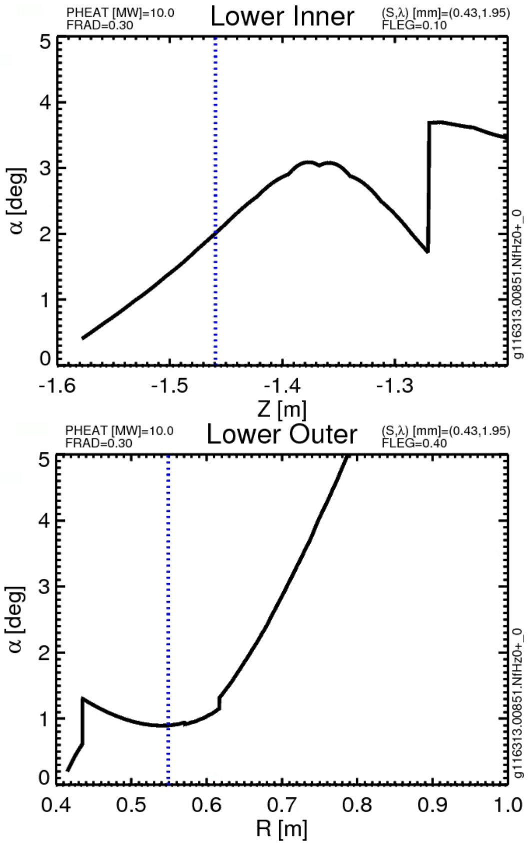

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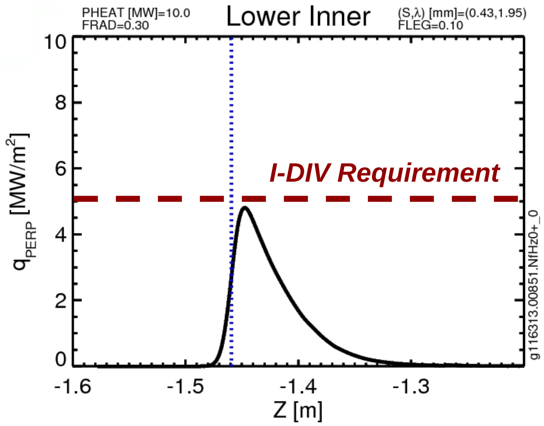
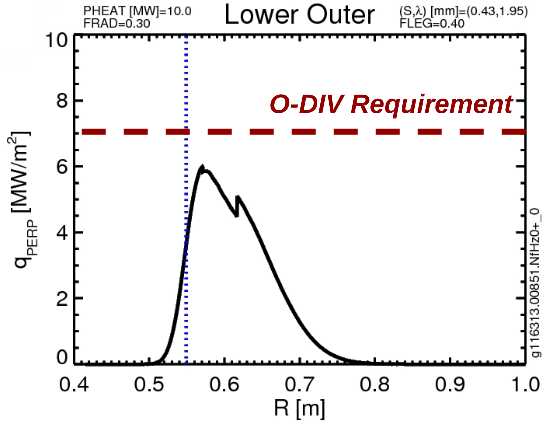
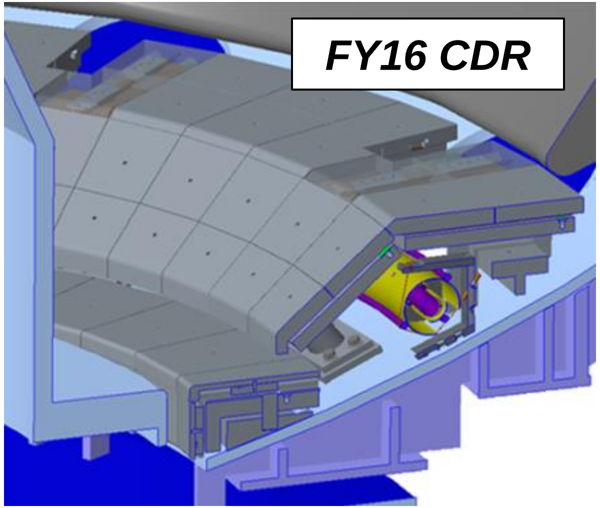




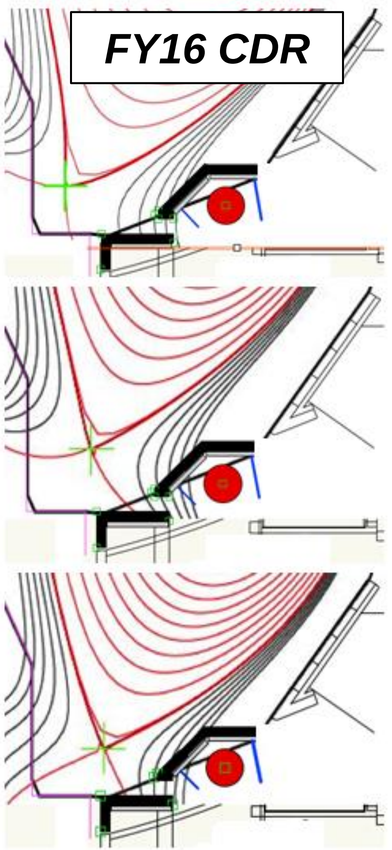
Revisit Cryopump Eng. & Physics Basis

- ‘cryo’ portion can likely be retained in part or in whole
- prior cryopump PFCs not compatible with new requirements
  - max temperature, heat flux, tile shaping, halo currents, access holes
  - lower CHI gap needs to be closed
- improved understanding of metrology use for in-vessel builds & we’ll have a better validated cost and schedule from Recovery



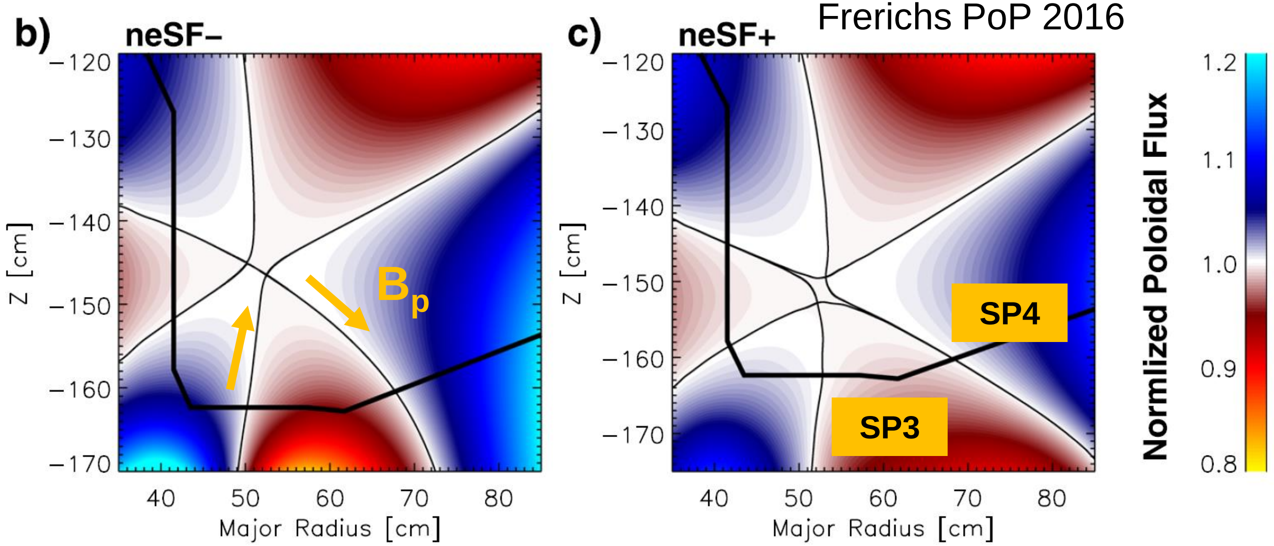
Review FY16 plans/mission for Particle Control Tasks:

- demonstrate the physics basis fluid simulations for pump design
- confirm the optimization of pump location with demonstrated range of high-impact mag. geometries
- study the correlated impacts on the inner divertor and (unchanged) upper divertor, large R_{MAJ} PFCs



Desire Flexibility to Explore Snowflake Divertor

Frerichs PoP 2016



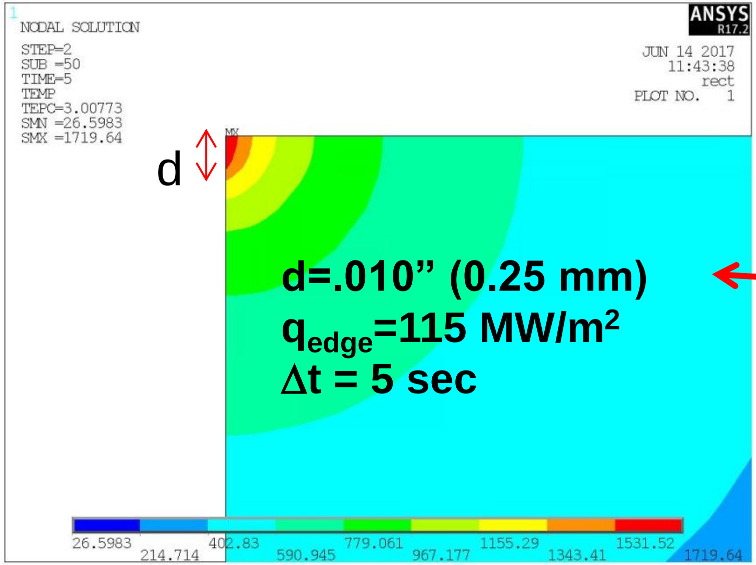
poloidal field direction switches between legs

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

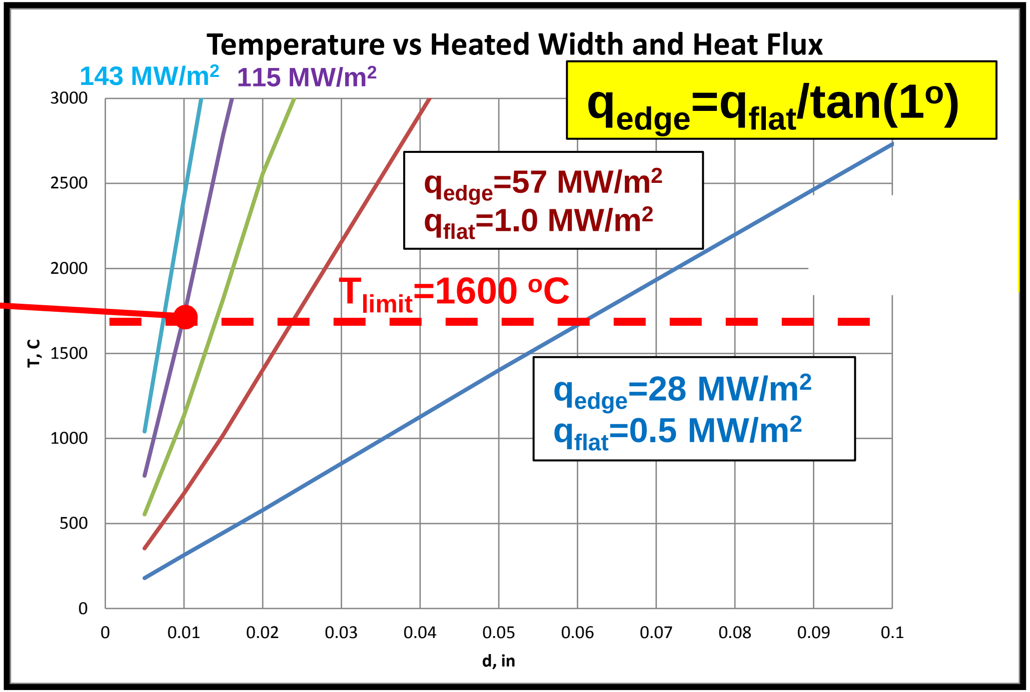
- prior experiments on NSTX, DIII-D and TCV used flat PFCs
- power sharing between strike points import
  - TCV sees ~25% of the power on SP3 on SP4 [Remierdes PPCF 2013]
  - this power approaches shaped PFCs ~ 90º making q_{surf} ~ $q_{||}$

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



Scope of the NSTX-U Heat Exhaust Challenge

- common question: *"if Machine X were to use our model, would they predict a PFC problem?"*
  - ex: MAST-U (DN): 25 MJ over 5 s to ODIV (T2) ~ 2.3 m^2 [CD/MU/01163]
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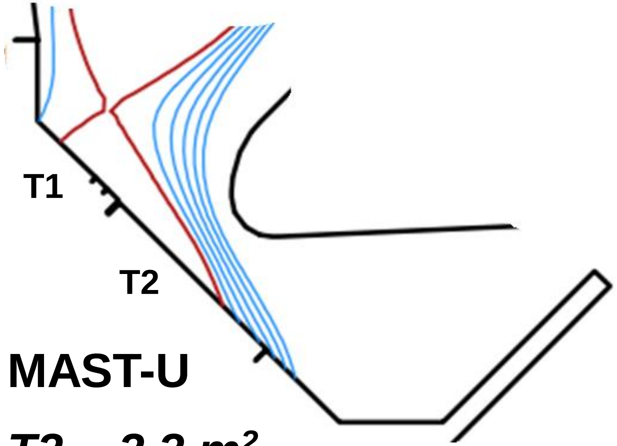
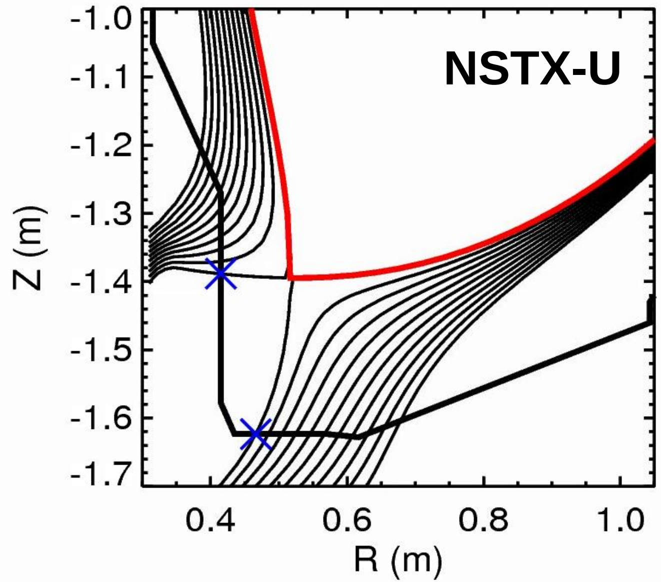


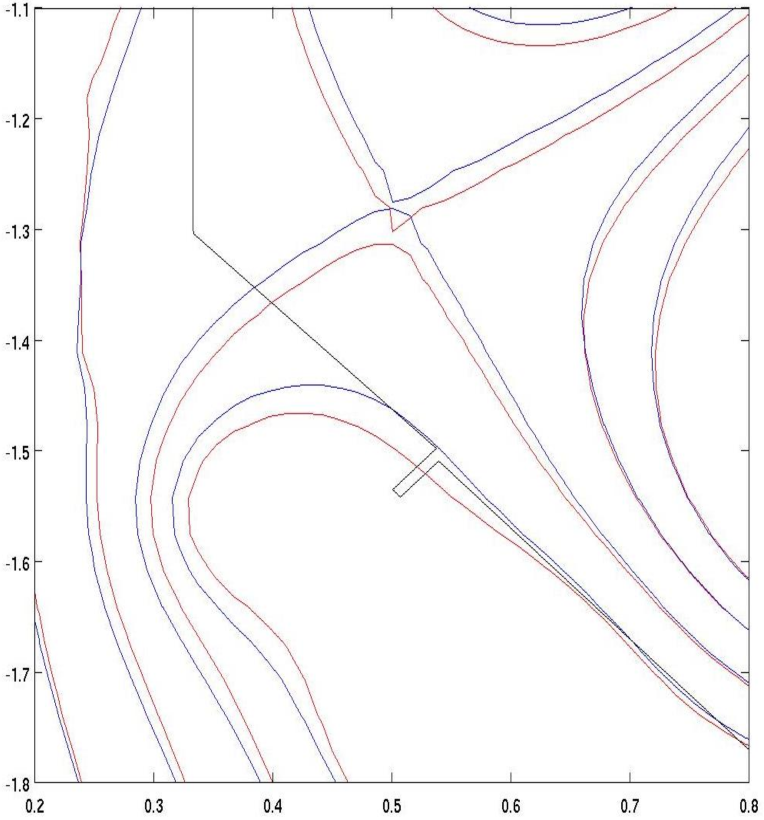
MAST-U

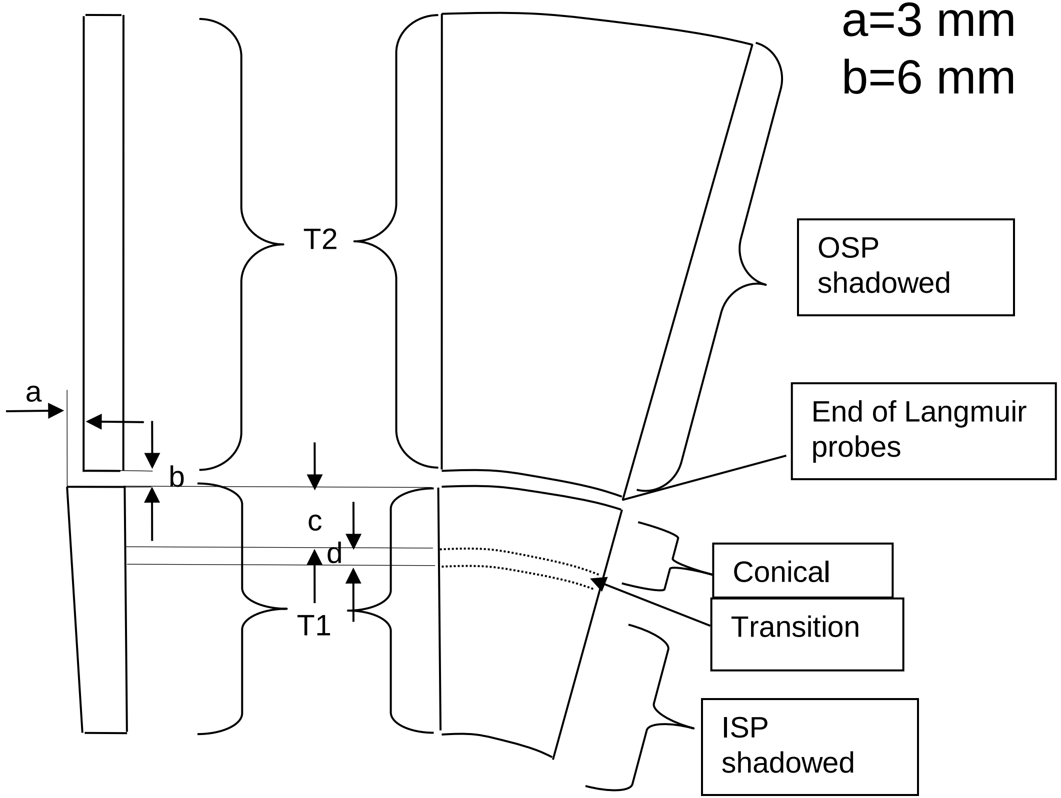
T2 ~ 2.3 m^2
T1 ~ 0.78 m^2

<u>'ideal' spread evenly</u>
MAST-U : 10.9 MJ/m^2
2.2 MW/m^2
NSTX-U: 28 MJ/m^2
5.7 MW/m^2



MAST-U Defines a ISP/OSP Transition Region





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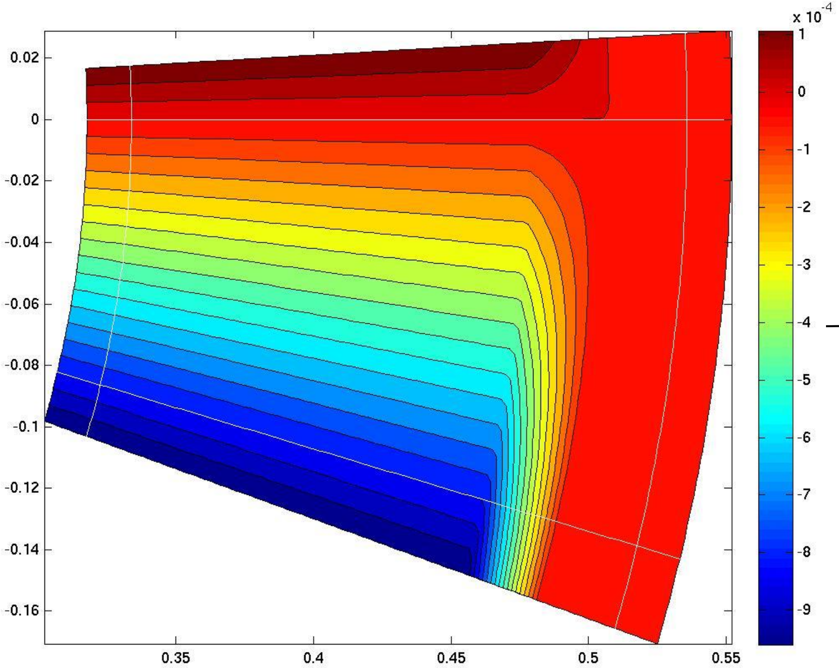
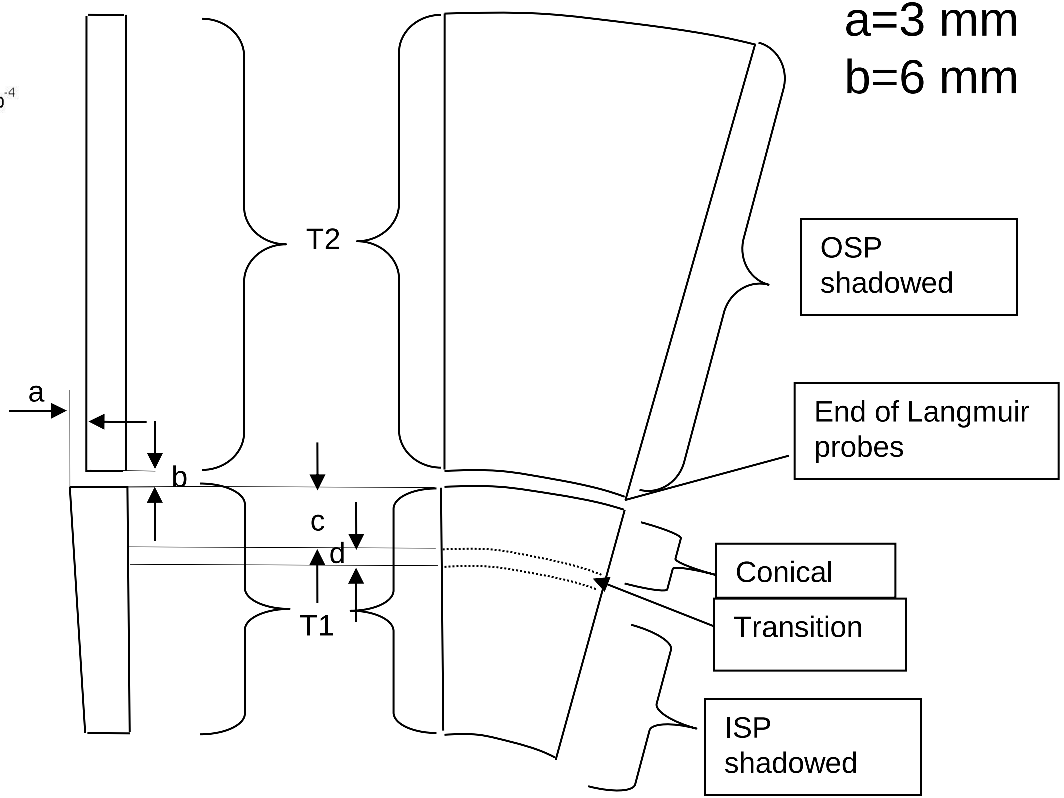
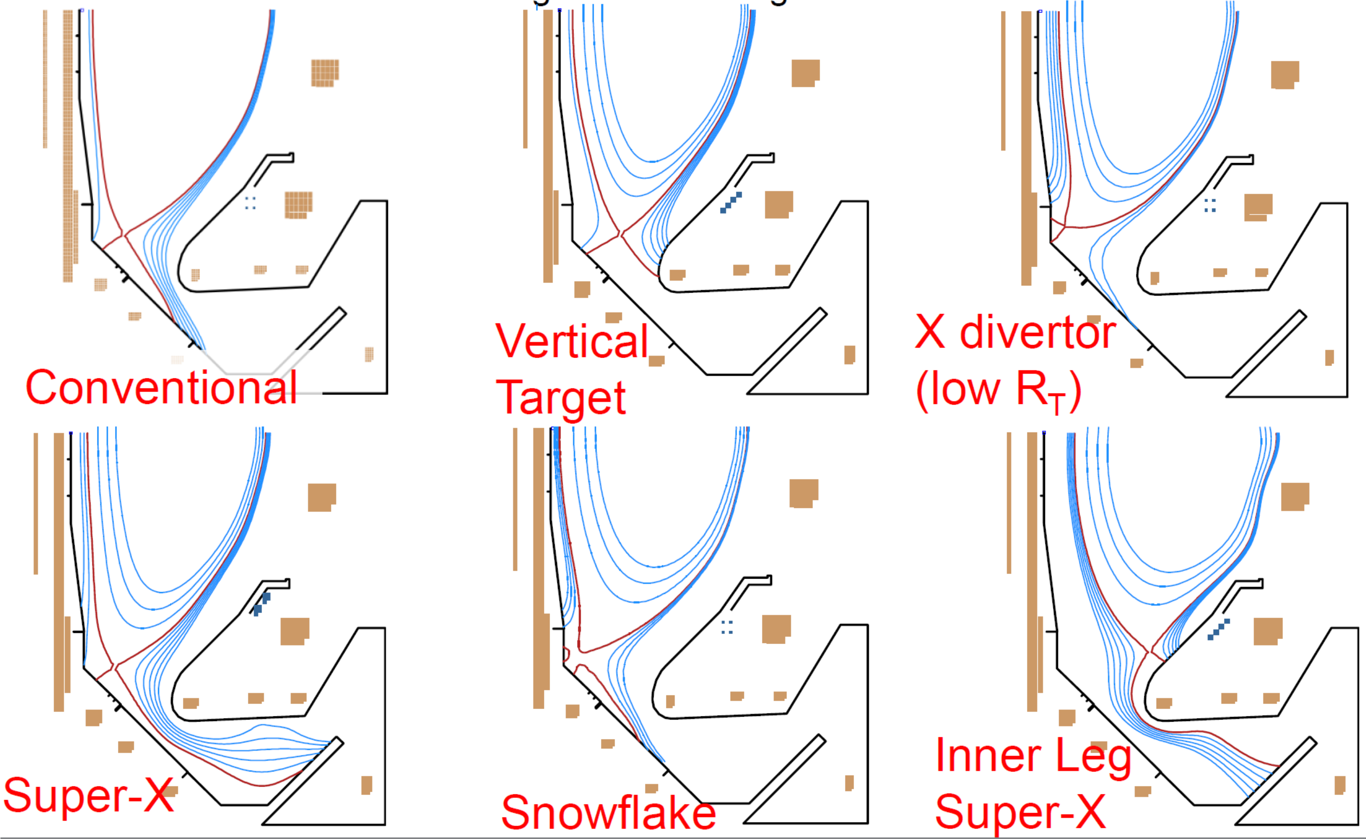




MAST Upgrade Divertor

MAST Upgrade has considerable flexibility for studying conventional and alterative divertor configurations in single and double null



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