# Overview of Strategy for Boundary Physics and Materials/PFC Programs

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**NSTX-U 5 Year Plan Review**
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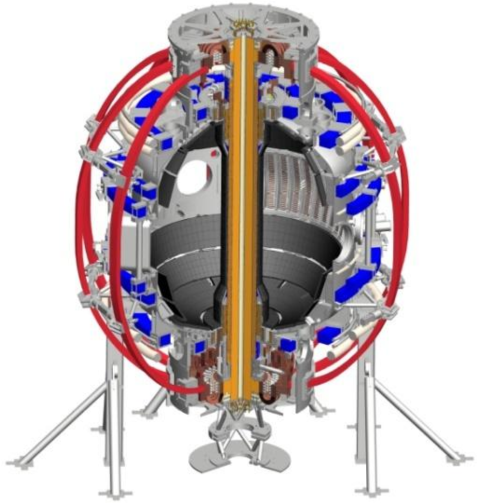


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# Introduction

- This talk precedes the Boundary Physics and Materials and PFC Topical Science Group (TSG) talks
  - Although distinct, these TSGs are intrinsically connected via plasma-surface interactions

- Goal of this talk: explain high level strategy of Plasma-Material Interface control, which includes both TSGs
  - Emphasis here is on explaining the rationale and timing of high priority upgrades in these areas

# NSTX-U edge physics program aims to answer key viability and attractiveness issues for FNSF and Demo

- Test both innovative and conventional power and particle exhaust solutions
- Develop integrated solutions with good core, pedestal, and divertor operation
  - In depth understanding in both areas will benefit ITER, as models used for ITER design will be tested on NSTX-U
- Contribute to design of a long pulse PMI facility, if needed to mitigate risks for FNSF and Demo designs
  - Also needed for full performance in NSTX-U scenarios (Gerhardt – ASC)

# Scientific elements of NSTX-U boundary program guide a staged implementation of hardware upgrades

- **Power exhaust** using conventional and innovative solutions: radiative divertor, snowflake configuration, lithium; compatibility with good core performance (Soukhanovskii)
  - High power density available at full $I_p$, $B_t$, NBI in NSTX-U
- **Particle Exhaust** using cryopump, compare with Lithium (Soukhanovskii)
- **Material migration/transport; metallic PFCs** (Jaworski)
  (a) graphite PFCs with staged transition to high-Z
  (b) lithium surface treatment vs. liquid lithium

# PMI program elements contribute to high priority NSTX-U Five Year Plan goals

- Demonstrate 100% NI sustainment at performance that extrapolates to ≥ $1MW/m^2$ neutron wall loading in FNSF
  - ✓ Controlled density and $Z_{eff}$ via cryopump and/or lithium
- Access reduced $\nu^*$ and high-$\beta$ combined with ability to vary q and rotation to extend ST physics understanding
  - ✓ Controlled density and $Z_{eff}$ via cryopump and/or lithium
- Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid

✓ Develop and utilize high-flux-expansion snowflake divertor and radiative detachment for mitigating very high heat fluxes

✓ Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

# Outline

- Power exhaust at high P/R, P/S

- High priority theory and experiments issues in power exhaust, particle exhaust, and plasma-surface interactions

- PFC and internal component staging

# Future devices target high power density, which would lead to high unmitigated divertor peak heat flux

- Technological steady heat flux removal limit $q_{limit}$ ~ 10 $MW/m^2$
  - Can decrease to 5 $MW/m^2$ if large transients considered
  - Can increase to 15 $MW/m^2$ if transients eliminated

- Reactor designs (e.g. ARIES-AT, ARIES-ST, ARIES-CS) rely on *both* high core radiated power and access to partial detachment to stay below $q_{limit}$
  - Can low impurity, high performance core be maintained?

- For projections, power balance considerations point to *P/R* and *P/S* as relevant divertor loading parameters
  - NSTX-U will have amongst the highest divertor loading compared with existing devices

# Key variables in power exhaust identified with heat flux projection from 0-D power balance

- Divertor power balance requires

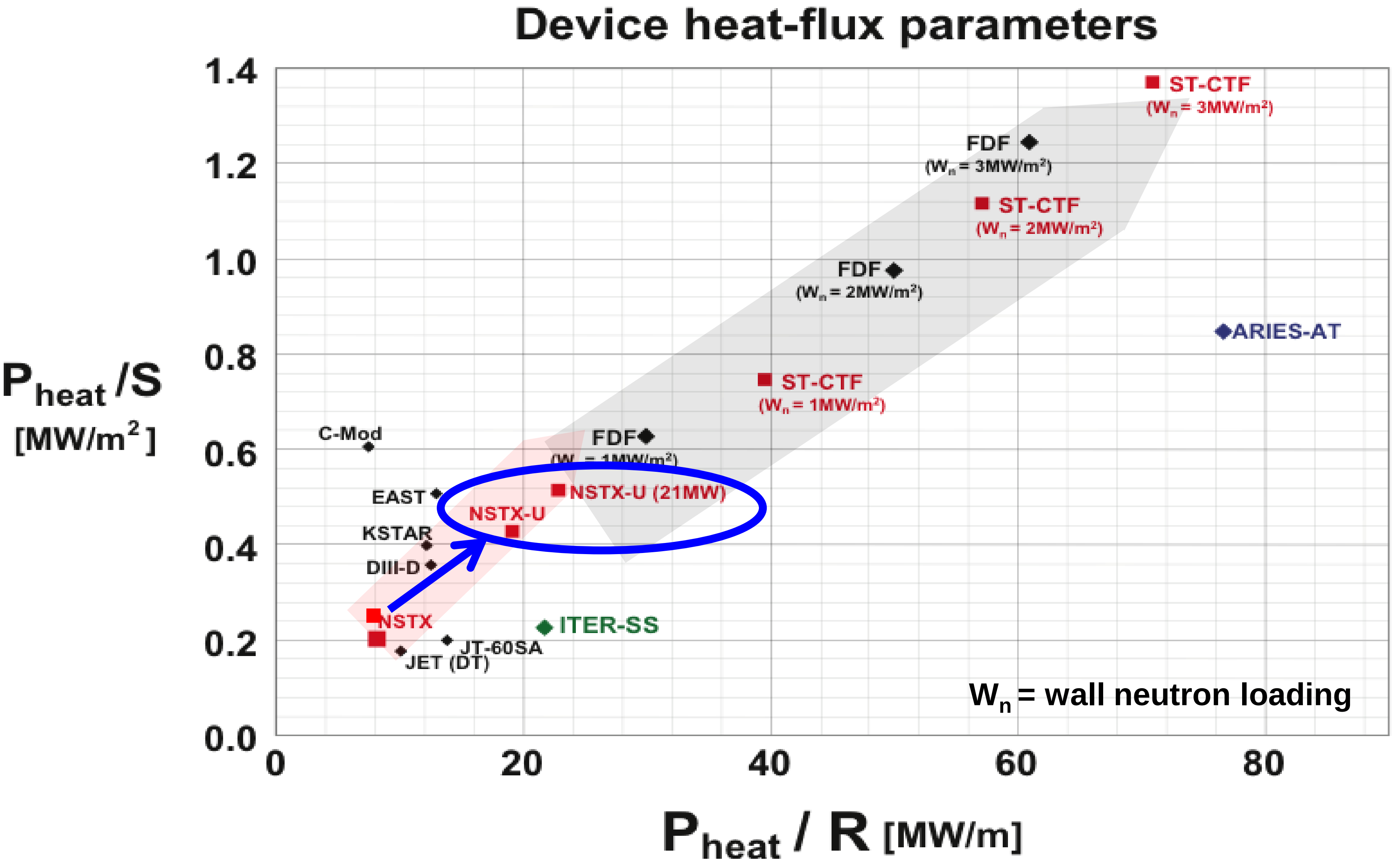
$$q_{div,peak}^{out} = f_{div} P_{loss} \Big/ \left( 2\pi R_{div}^{out} f_{\exp} \lambda_q^{mid} N_{div} \right) \text{ with } \lambda_q^{mid} = f(I_p, P_{loss}, B_t, R, a)$$

  - $f_{div}$ is the fraction of power exhausted to the outer leg
  - $f_{exp}$ is the poloidal flux expansion from midplane to divertor

$$\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{\exp} \text{ with } f_{\exp} = \frac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$$

- Data from multiple devices shows that $\lambda_q^{mid}$ independent of R (but scales with a/R) in attached plasmas: $q_{div,peak}^{out} \propto P_{loss} \big/ R_{div}^{out}$
- $P_{loss}/S$ is also relevant:
  - Wall loading and erosion increase with $P_{loss}/S$
  - For partially detached conditions, ability to spread peak heat flux (i.e. $\lambda_q^{div}$) might increase with R or a: $q_{div,part-\det}^{out} \propto P_{loss} \big/ S$

# NSTX Upgrade will extend normalized divertor and first-wall heat-loads much closer to FNSF and Demo regimes



# Outline

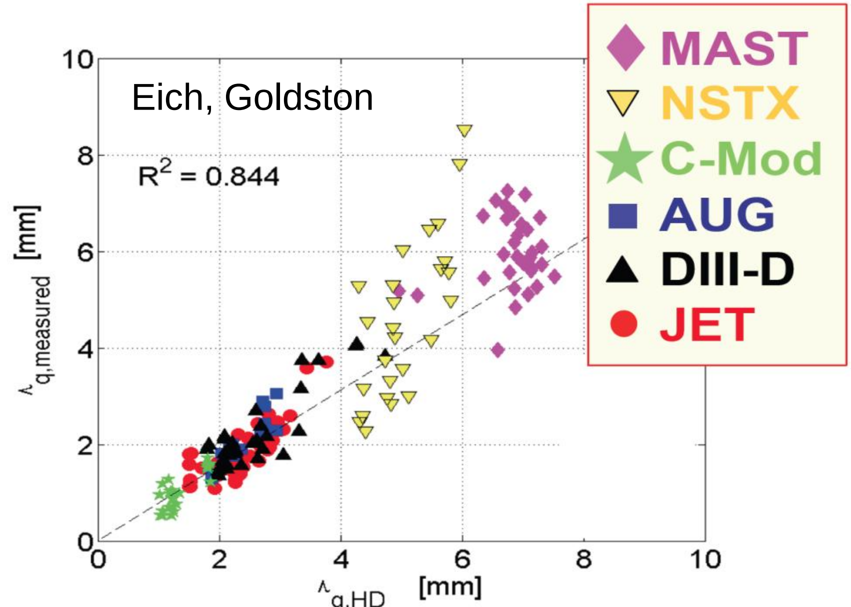
- Power exhaust at high P/R, P/S
- High priority theory and experiments issues in power exhaust, particle exhaust, and plasma-surface interactions
- PFC and internal component staging

# Theoretical and experimental challenges in power exhaust: what sets the power SOL width?

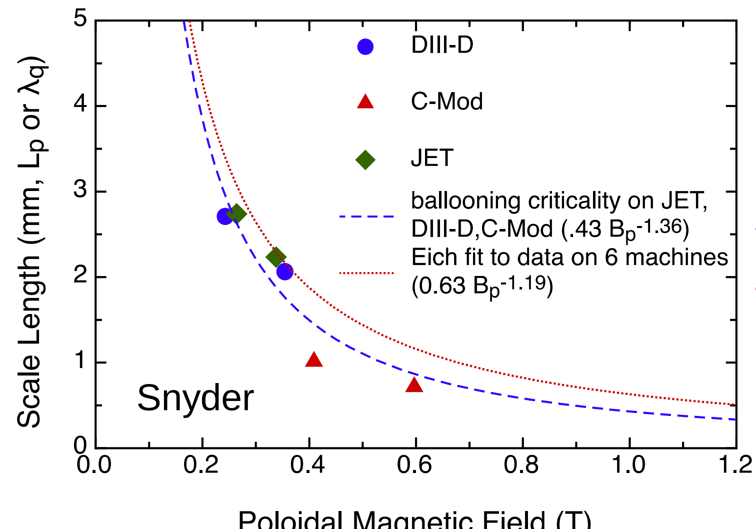
- Multi-machine scalings have identified a $1/I_p$ scaling in the divertor heat flux footprint in attached conditions
  - Measured scaling: $\lambda_q^{mid} \sim a/I_p \sim 1/B_\theta^{mid}$, in rough agreement with Goldston's heuristic drift model

- Theoretical challenge: when does P' in SOL exceed ballooning limits? What is role of resistivity?
  - ➢ Ballooning limits predicted to be higher at low R/a
  - ✓ Plan to study over range of $I_p$ with XGC, BOUT++, SOLT, 2DX

Rosner, Zinkle

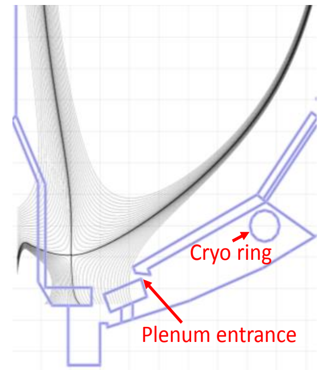



Calculated Ballooning Critical Near Separatrix Scale Length

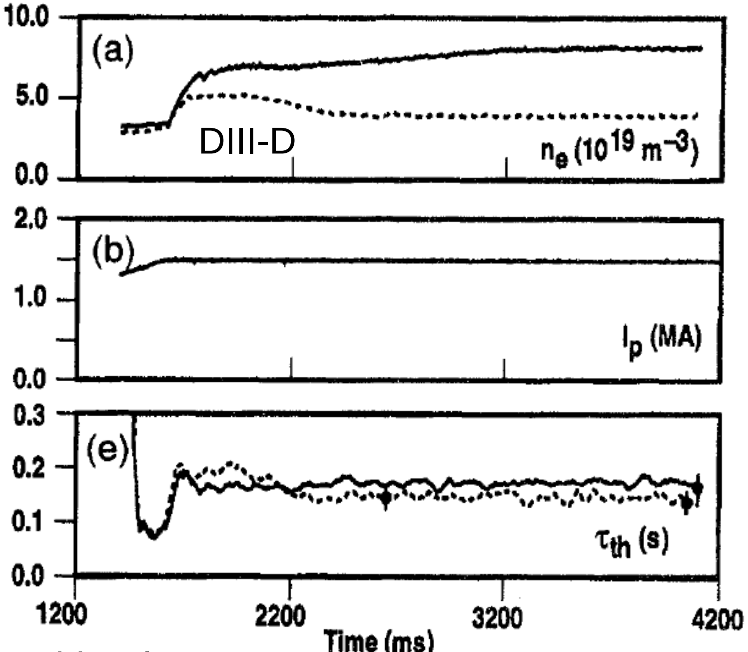


# Particle exhaust goal for NSTX-U: establish main ion and impurity control in long pulse discharges

- Main ion and impurity control achieved separately in NSTX
  - D control with Li, but discharges go ELM-free -> impurity accumulation
  - Triggered ELMs with 3D fields, fueling optimization give flat line $n_e$, but central $n_e$ ⇧, and core MHD initiated prematurely
- Central plan element: cryopump for D, Z control (*proven technology)*
  - Complements Li, ELM control with Lithium granules and NCC
- Theory: will $n_e$ control from cryo also suppress ELMs, like Li?
- Theory: Will cryopump models work for NSTX-U?

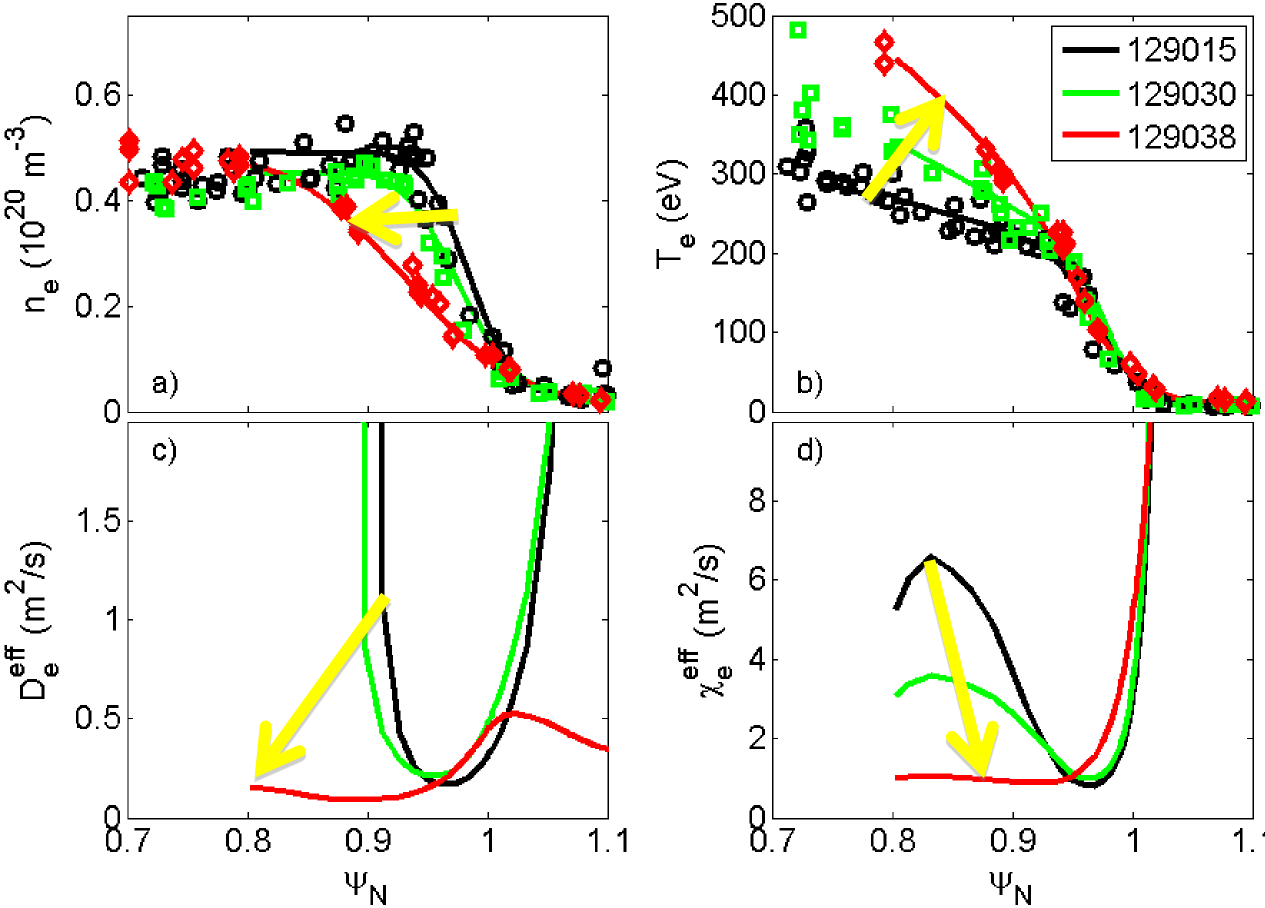



NSTX Cryopump Concept



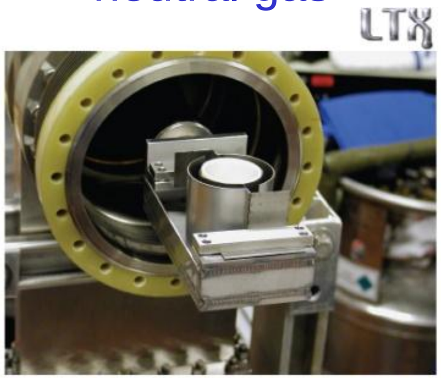

Schissel, NF 1994

# Lithium conditioning is a powerful tool to continuously control edge profiles, transport, and global confinement




- $D_e^{eff}$, $\chi_e^{eff}$ from SOLPS interpretive modeling
- Changes in $\chi_e^{eff}$ qualitatively consistent with changes in ETG and $\mu$–tearing drive, from change in $dn_e/dr$
- Theory challenge: what causes change in $D_e^{eff}$?

- Increase Li deposition coverage:
  - upward evaporation
  - evaporation into neutral gas




$Y_2O_3$ crucible, Ta heater
➢Tested to 700 °C

- Perform Li migration and vapor shielding studies

Rosner
ReNeW
T10 - PSI

# Outline

- Power exhaust at high P/R, P/S

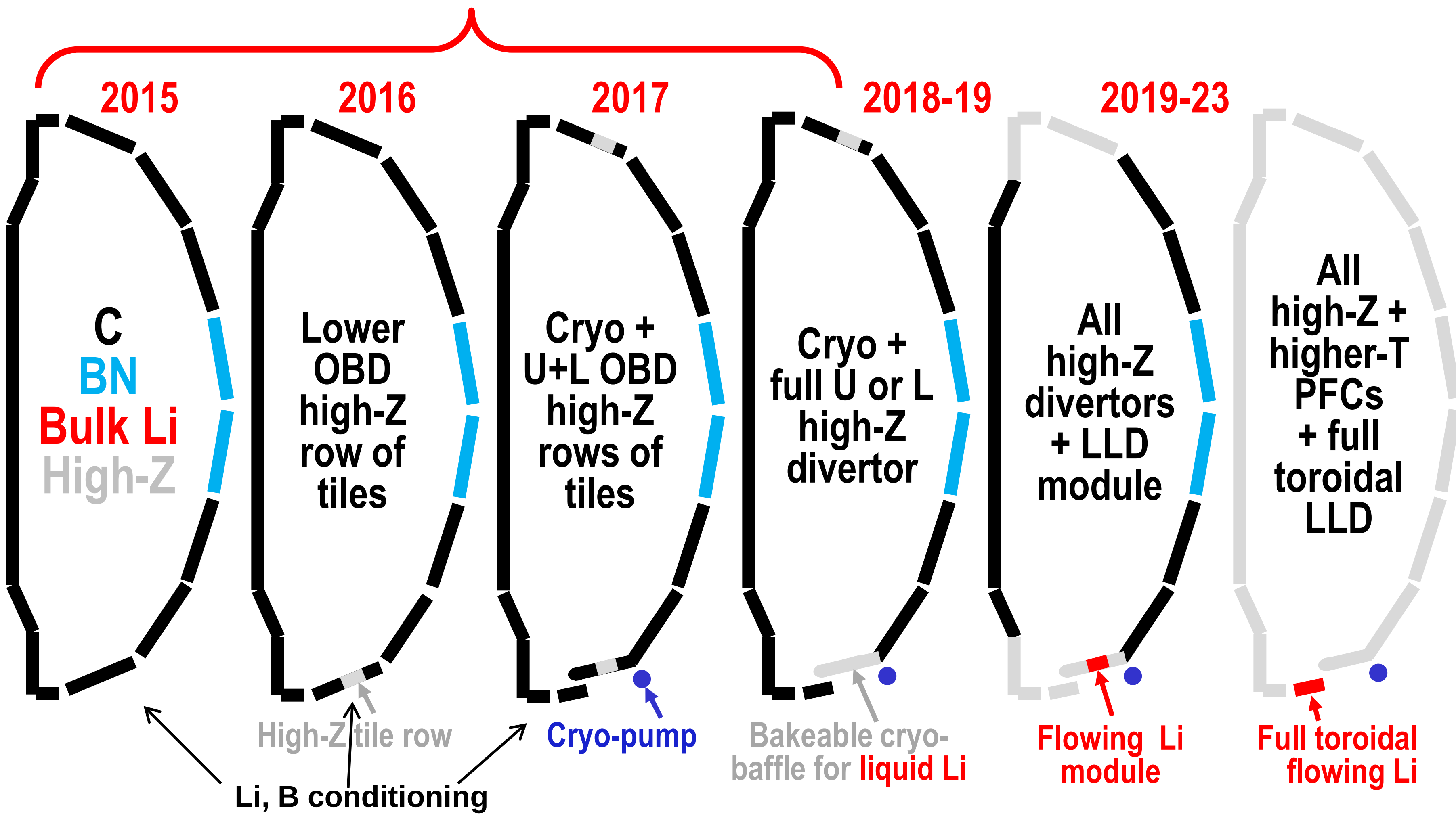
- High priority theory and experiments issues in power exhaust, particle exhaust, and plasma-surface interactions

- PFC and internal component staging: program consists of staging toward high-Z PFCs; comparison with liquid lithium

- Rosner report recommended action for ReNeW Thrust 10*: “Evaluation of the plasma-surface interactions of tungsten as a leading PFC material in appropriate plasma, thermal, and radiation damage environment; due to open questions on tungsten melting and micro-structural evolution, a parallel effort should be maintained on back-up options”*

# NSTX-U internal component baseline staging: Goal is to assess compatibility of high $\tau_E$ and $\beta$ + 100% NICD with metallic PFCs

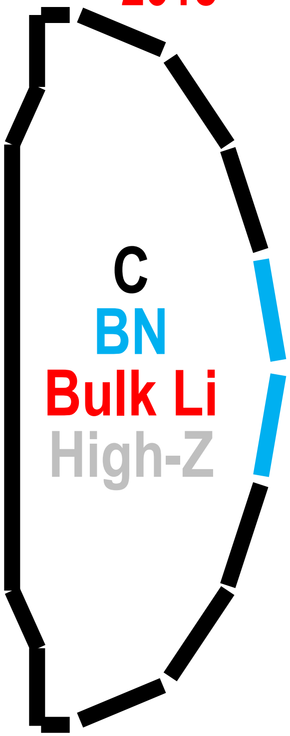
*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*



# NSTX-U internal component staging in baseline budget

*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*

**2015 | 2016 | 2017 | 2018-19 | 2019-23**

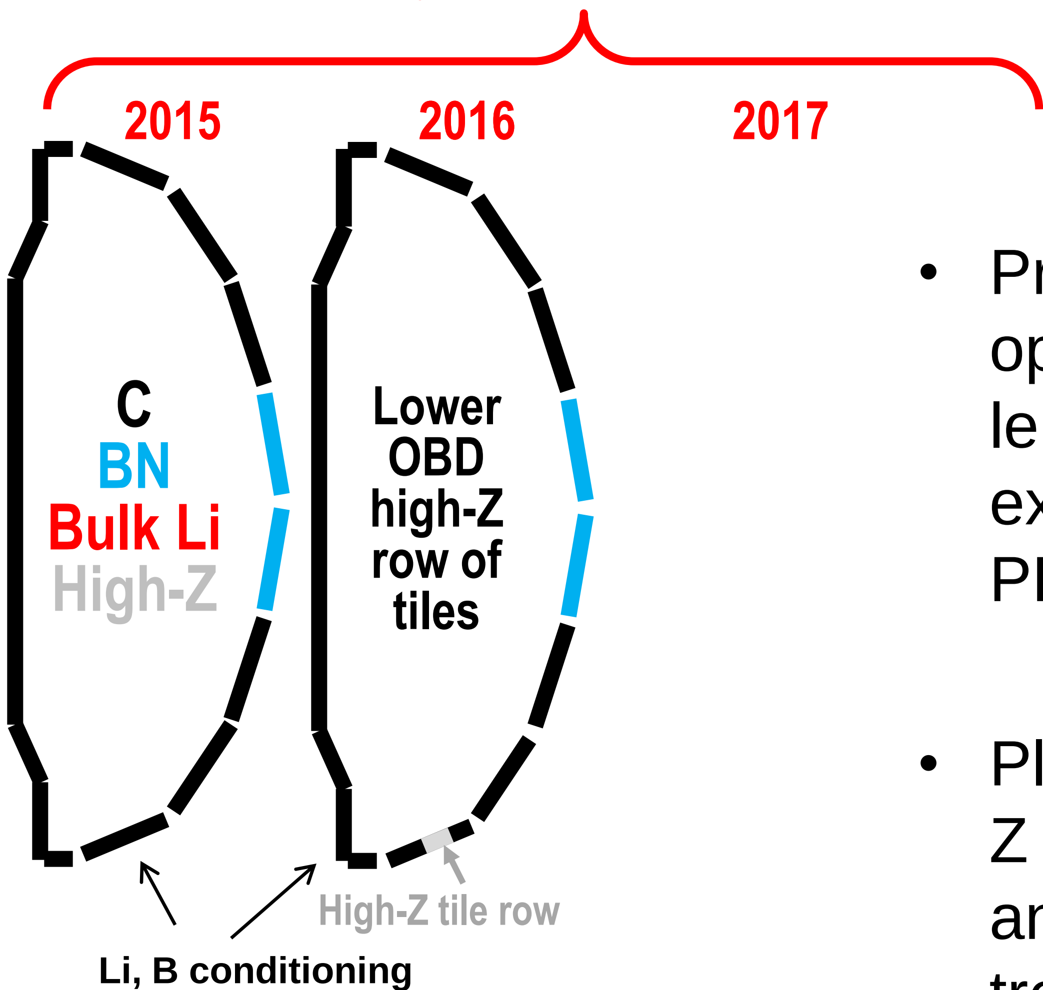



Li, B conditioning

- Priority: establish NSTX-U operating space: $I_p$, $B_t$, pulse length; develop heat flux exhaust
- Plan: Start with mainly carbon PFCs, comparing boron and lithium surface treatments

# NSTX-U internal component staging in baseline budget

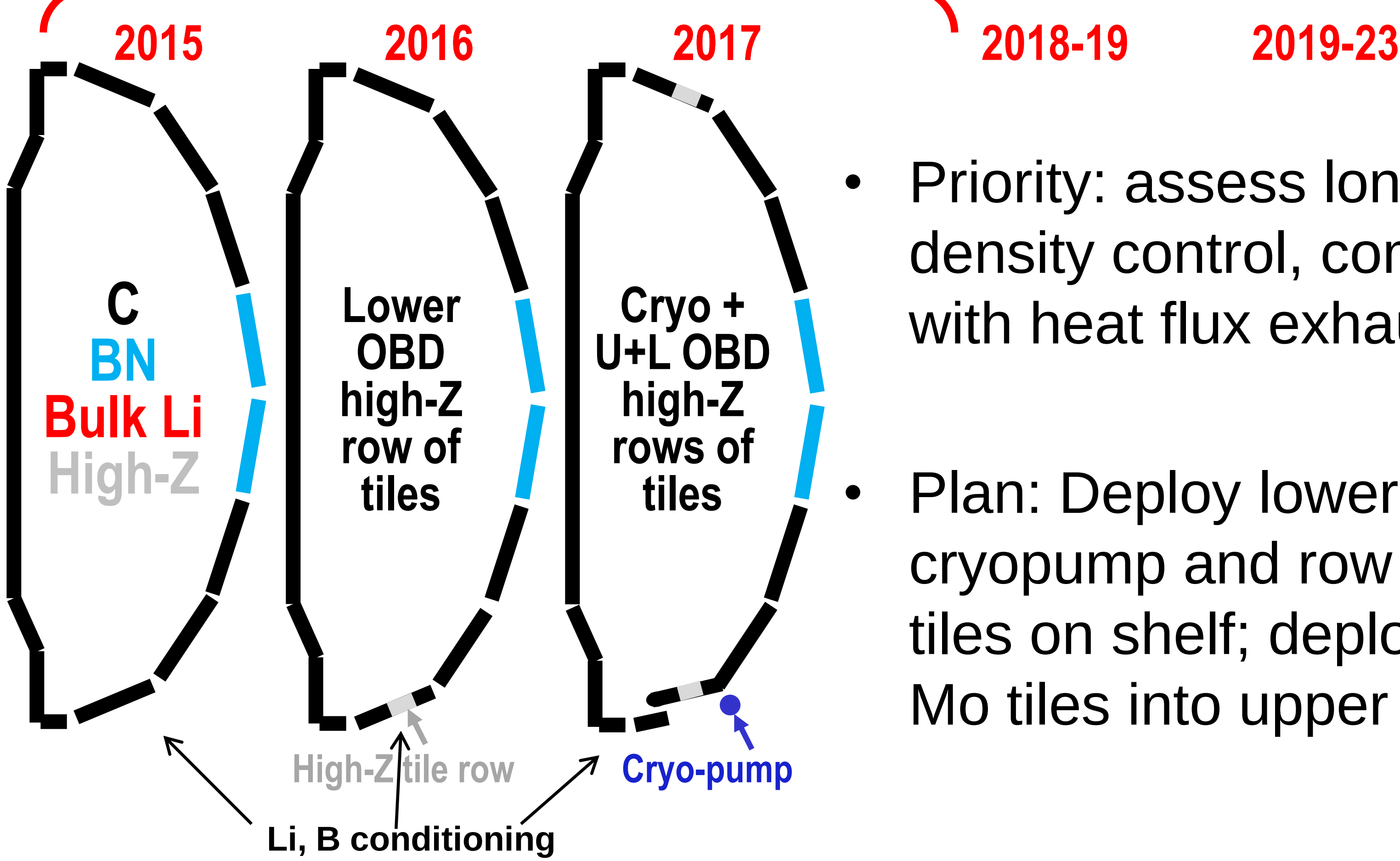
*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*




- Priority: establish NSTX-U operating space: $I_p$, $B_t$, pulse length; optimize heat flux exhaust; commence high-Z PFC assessment
- Plan: Implement row of high-Z tiles outboard of CHI gap and study erosion, surface treatments

# NSTX-U internal component staging in baseline budget

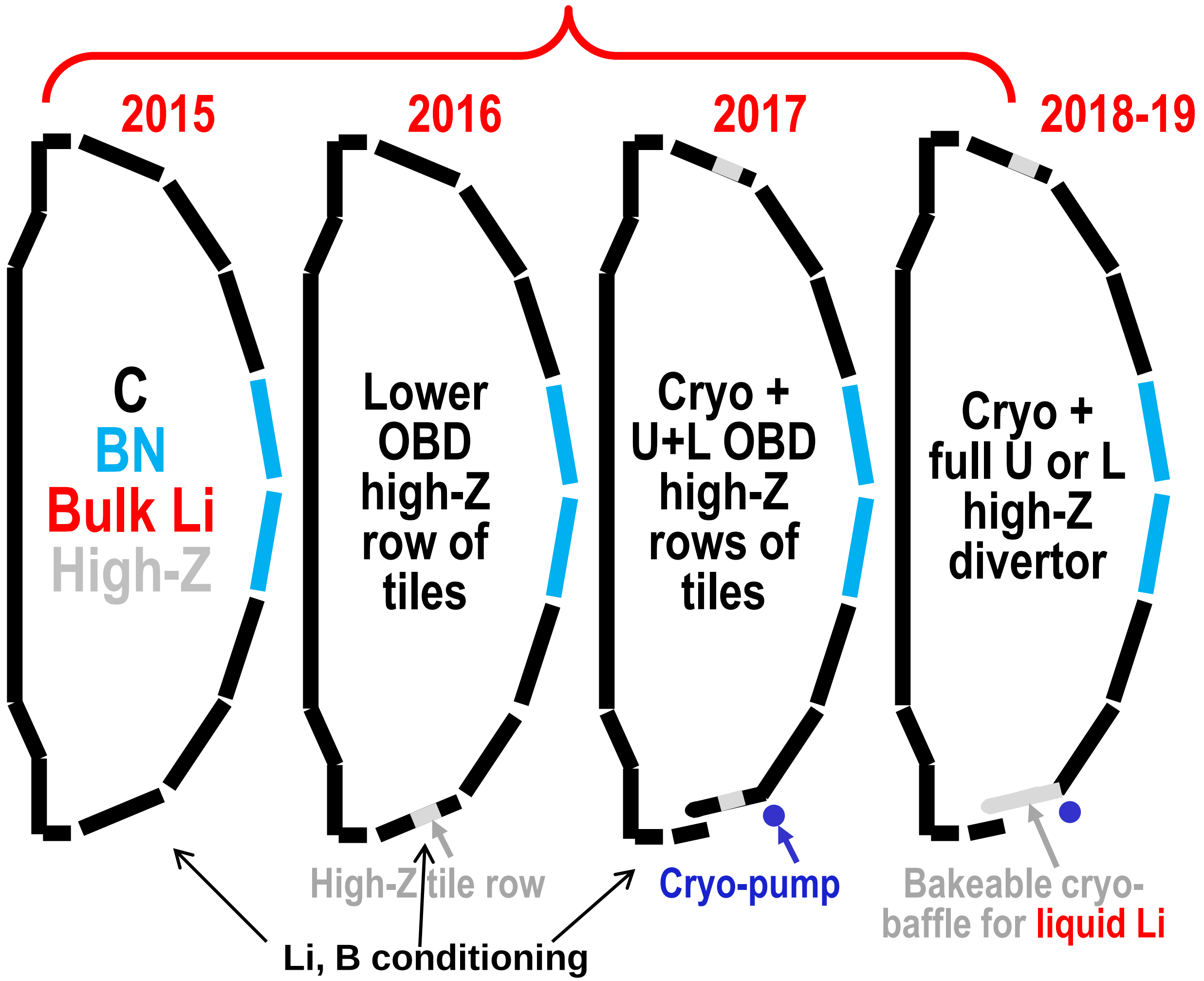
*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*




- Priority: assess long pulse density control, compatibility with heat flux exhaust
- Plan: Deploy lower divertor cryopump and row of Mo tiles on shelf; deploy lower Mo tiles into upper divertor

# NSTX-U internal component staging in baseline budget

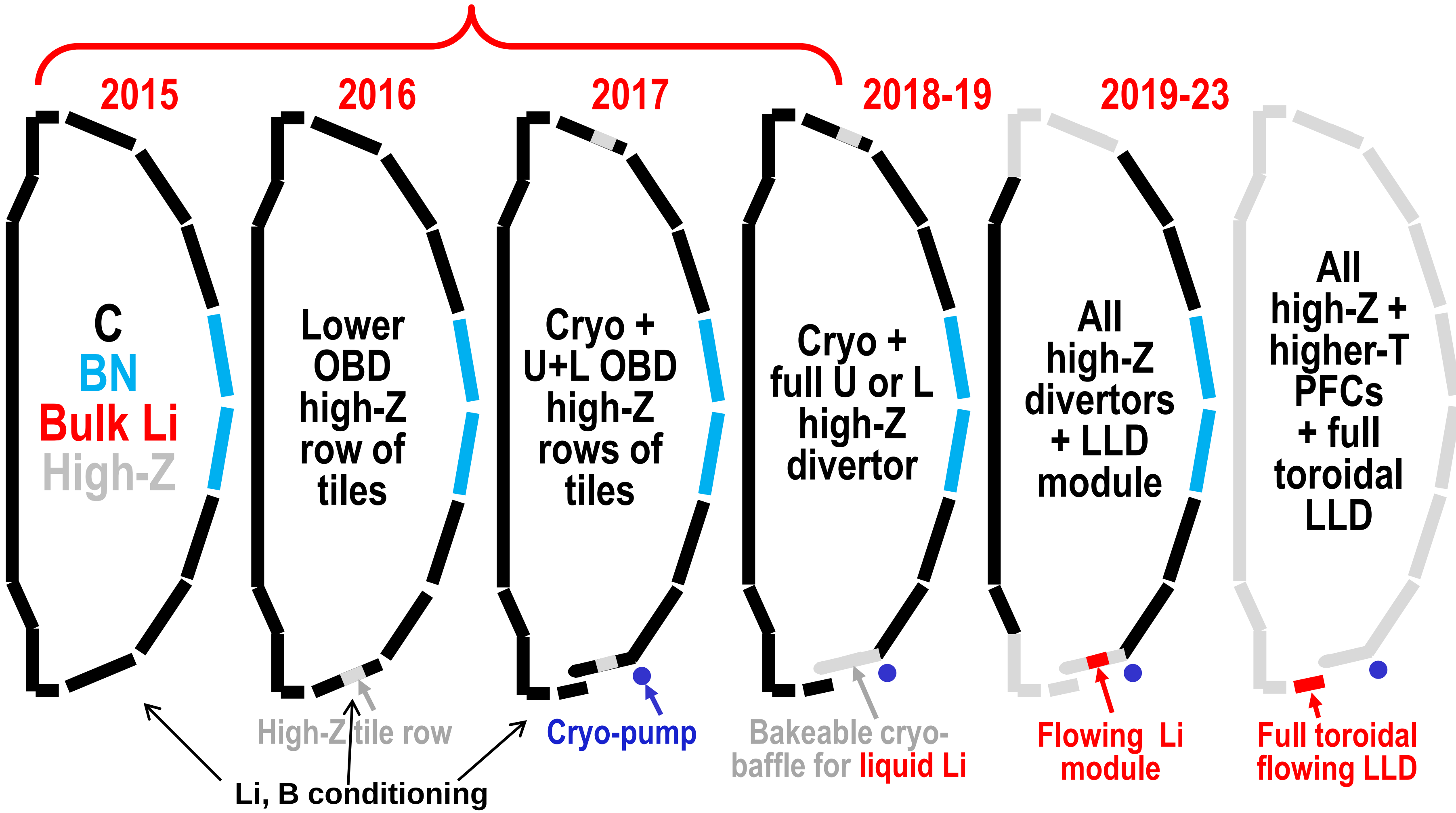
*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*



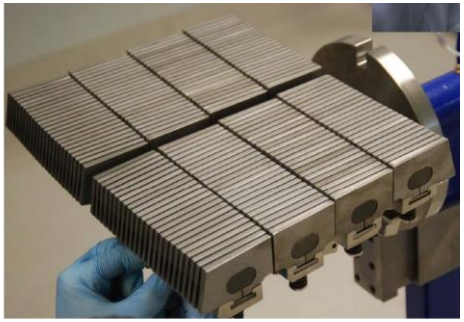

- Priority: test liquid lithium as a PFC
- Plan: Deploy lower divertor LLD on cryo shelf for 1:1 comparison with cryo

# NSTX-U internal component staging in baseline budget

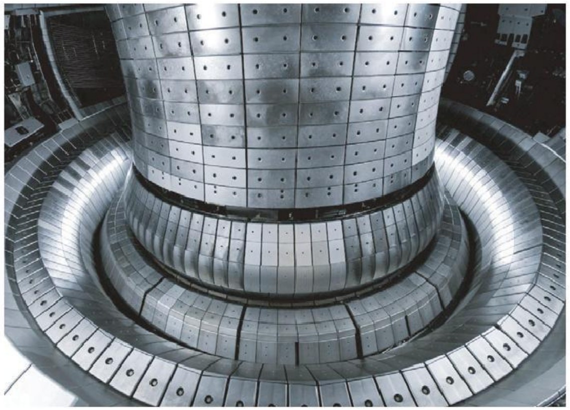
*Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD*



# Several high-Z PFC fabrication concepts will be developed in parallel w/lab studies; demonstrated readiness affects pacing



- High heat flux regions (strike-point regions)
  - TZM or W lamellae (e.g. JET)
- Intermediate heat flux regions (cryo-baffles, CS midplane)
  - TZM tiles or TZM/W lamellae
- Low heat flux regions (passive plates, CS off-midplane)
  - W-coated graphite (e.g. ASDEX-U)



# NSTX-U boundary program well aligned with highest priority ReNeW research thrusts from Rosner Panel

- Thrust 2: Control of transient events
  - ✓ Control of ELMs via density profile (lithium), 3D fields
  - ✓ *(Early detection of disruption pre-cursors; disruption mitigation)*
- Thrust 6: Development and testing of models
  - ✓ Integral component of each thrust
- Thrust 9: Unfolding physics of boundary layer plasmas
  - ✓ SOL power and particle exhaust, snowflake divertor physics
- Thrust 10: Decoding science of plasma-surface interactions
  - ✓ Lithium PSI and vapor shielding, Material migration
- Thrust 17: 3-D shaping
  - ✓ Includes optimization of tokamaks/STs with 3D fields

# NSTX-U boundary program will develop long pulse PMI solutions supporting next step design

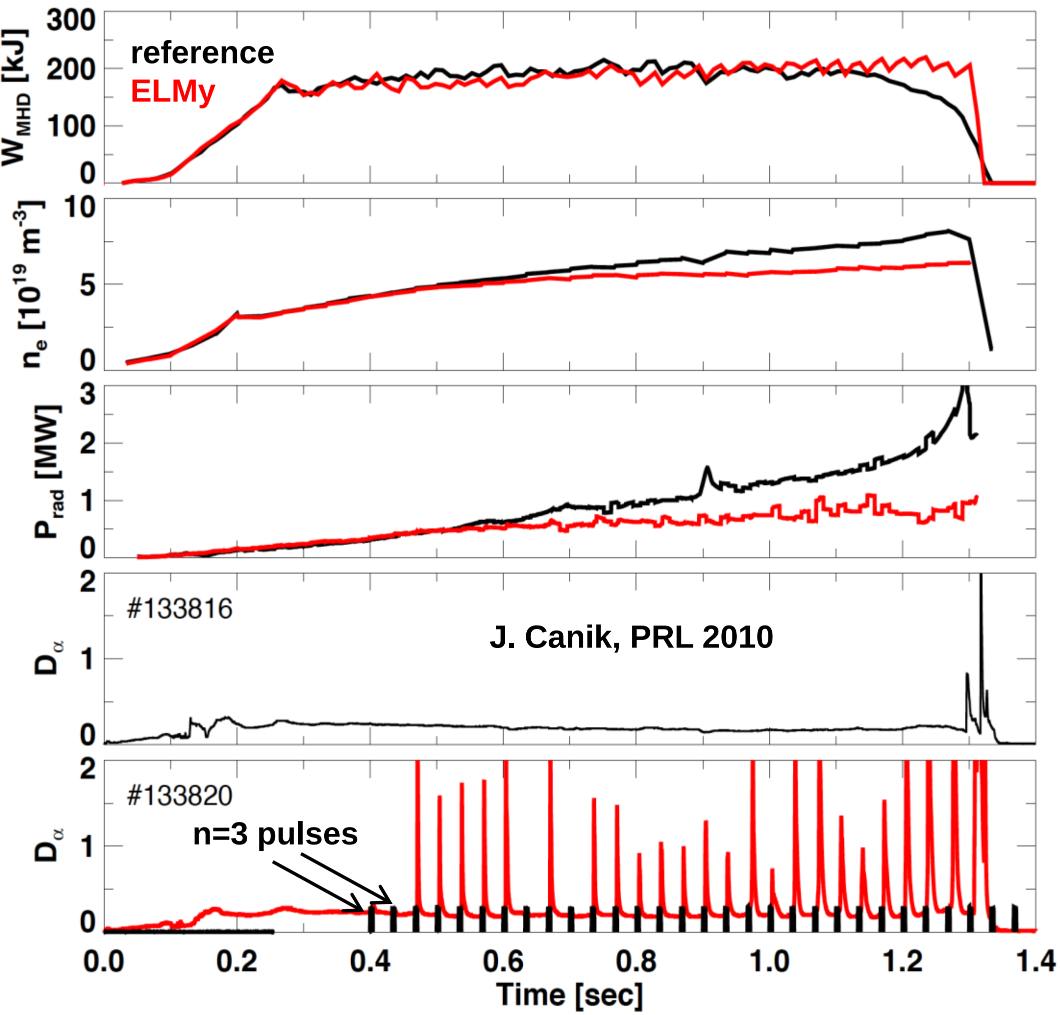
- Test both conventional and innovative power and particle exhaust solutions, compatible with high performance ST core plasmas

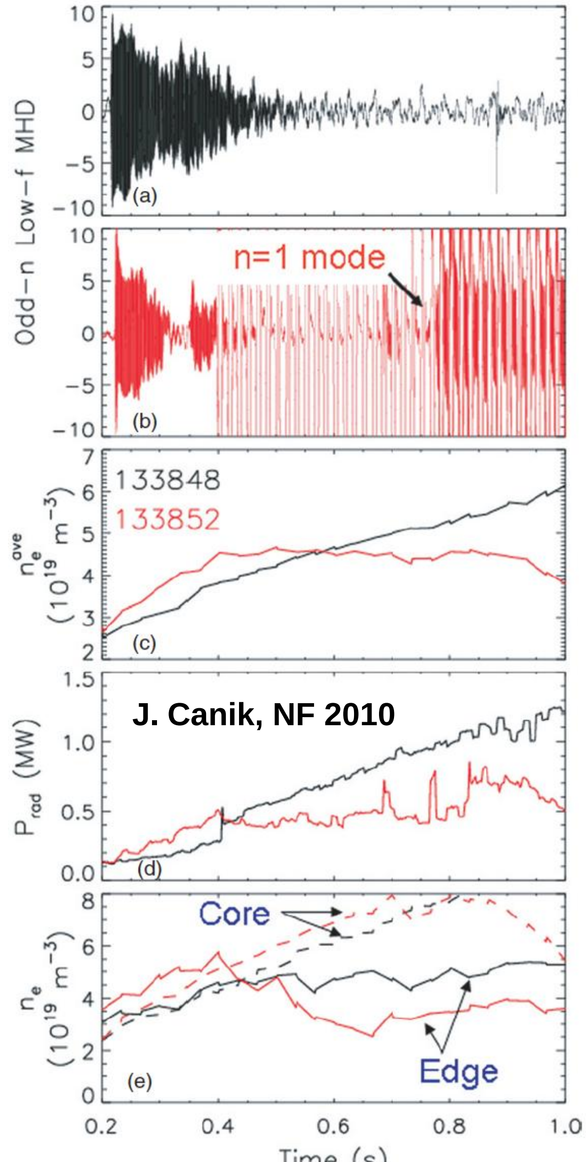
- Practical aspects of establishing operational space of NSTX-U lead to staged implementation of new capabilities
  - Near term: develop radiative and snowflake divertors
  - Mid-term: establish long pulse particle control with cryo
  - High-Z and liquid lithium PFC tests implemented in a deliberate manner that allows systematic comparisons with different stages
    - ➢ Lab studies demonstrating readiness of these PFCs paces staging

# Backup

# 3D external fields used to trigger ELMs, but core profiles still evolving and edge MHD destabilized prematurely

Type I ELMs triggered for impurity control (post-lithium, n=3)



# Boundary physics studies enabled by suite of key diagnostics

- Thomson Scattering with improved spatial resolution; CHERS, with improved data from higher $T_i^{ped}$; BES, DBS, high-k, GPI for pedestal and edge turbulence studies

- Dual-band thermography, bolometry, comprehensive spectroscopy, divertor Langmuir probes, neutral pressure for power and particle exhaust, and in-depth divertor physics
  - Coverage of upper divertor will become increasingly important
  - Divertor Thomson scattering highly desired (*incremental*)

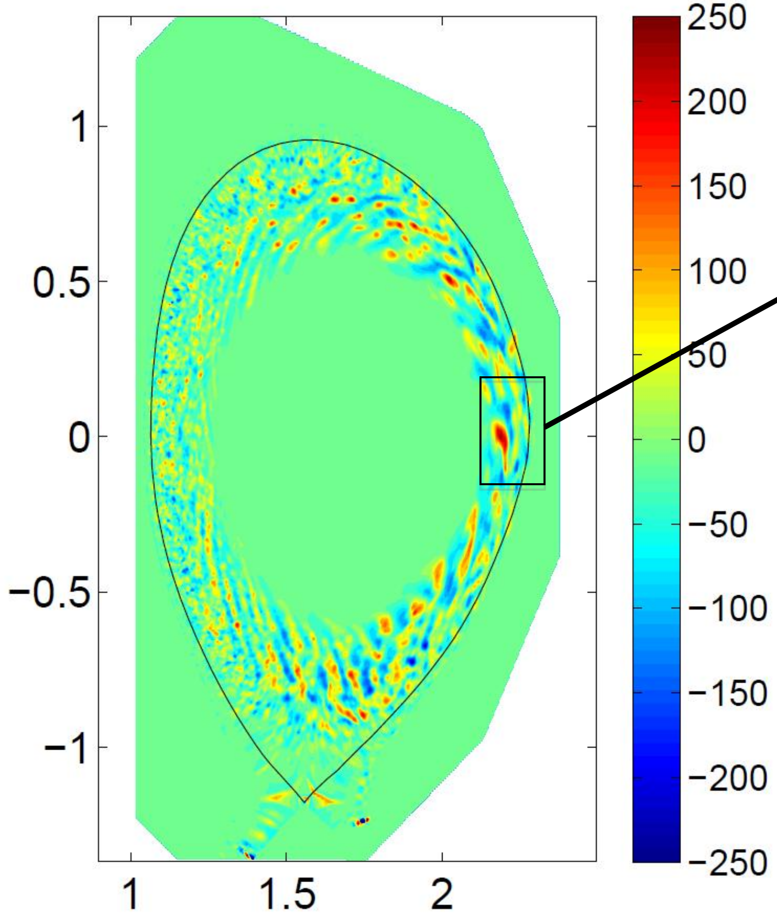
- MAPP, QCM, spectroscopy for PSI and material migration studies

# Possible NSTX-U high-Z development plan with incremental budget

- FY 13 – Perform more rigorous engineering assessment of lamellae vs. bulk-tile for NSTX-U conditions (much of this would likely require ~1 FTE engineer, ~0.5 FTE designer/drafting + some tech time per year)
  - Identify coating technology (e.g. PVD vs. VPS) for use on ATJ tiles
  - Identify heat-flux facility for cyclic testing
- FY 14 – Fabricate prototype PFC tile for thermal testing at suitable facility
  - Test small lots of coated samples
  - Test PFC prototype
- FY 15 – Determine PFC interfacing issues with existing mounting hardware – final designs, procurements
  - Begin scenario development to control PFC energy deposition
  - PFC prototype testing to failure to establish absolute limits
- FY 16 – fabrication installation
  - Complete scenario development for high-Z protection
- FY 17 – operation with all high-Z

# Flux-driven XGC1 calculations with kinetic electrons show blobs with δn/n up to ~50% in SOL

*Blobby eδΦ from XGC1 on a poloidal plane.*
*eδΦ/$T_e$ is greater than shown in scrape-off*




*eδΦ/$T_e$ blobs from XGC1 at outside midplane*