NSTX-U

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Overview of Strategy for Boundary Physics and PMI

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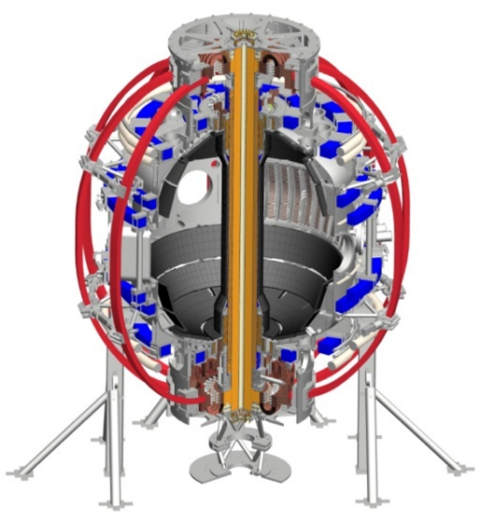
R. Maingi

NSTX-U PAC-33 Meeting
PPPL, Princeton, NJ
19-21 Feb. 2013



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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 PMI control facility, if needed to mitigate risks for FNSF and Demo designs
  - Sufficiently high input power density in NSTX-U that solutions important for full power, I_p, B_t NSTX-U scenarios

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

- **Power exhaust** using conventional and innovative solutions: radiative divertor, snowflake configuration, lithium; compatibility with good core performance (Soukhanovskii) TSG
  - Vibrant pedestal physics program not discussed here
- **Material migration and transport; metallic PFCs**: (a) graphite PFCs with staged transition to Mo or W (b) lithium surface treatment vs. liquid lithium (Jaworski) TSG
- **Particle exhaust** for long pulse density and impurity control: comparison of divertor cryopumping with lithium (Canik)
- *In FY15-16, highest priority placed on establishing and extending operational space*

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 by 50% if large transients allowed

- Reactor designs (e.g. ARIES-AT, ARIES-ST, ARIES-CS) rely on 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

- Power balance requires

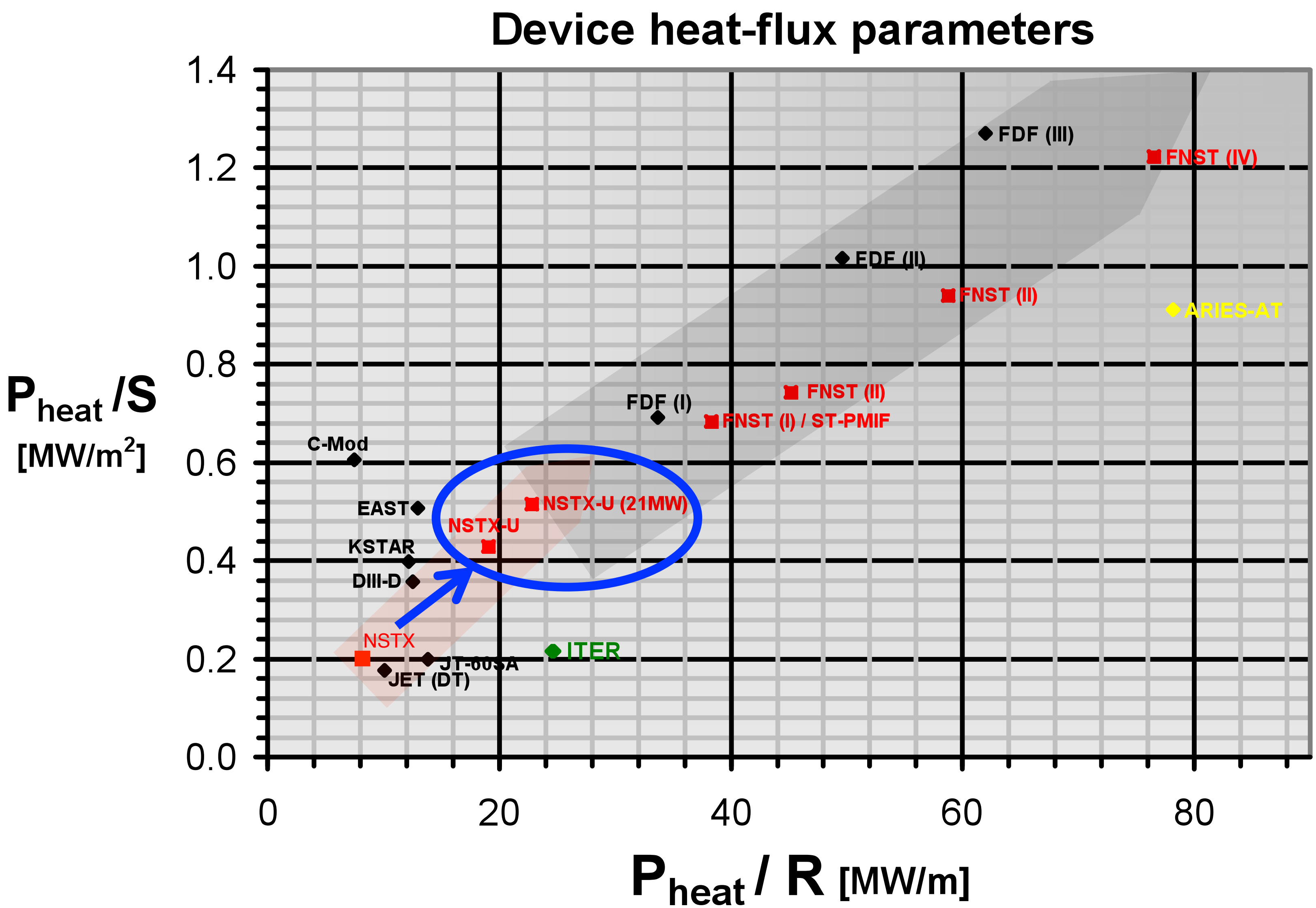
$$\boxed{q_{div,peak}^{out} = f_{div} P_{loss} \Big/ \left(2\pi R_{div}^{out} f_{\exp} \lambda_q^{mid} N_{div} \right) \ \text{with}\ \lambda_q^{mid} = f(I_p, P_{loss}, B_t, R, a)}$$

  - 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 λ_q^{mid} independent of R (but scales with a/R) in attached plasmas: $\boxed{q_{div,peak}^{out} \propto P_{loss} / R_{div}^{out}}$
- 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. λ_q^{div}) might increase with R or a: $\boxed{q_{div,part-\det}^{out} \propto P_{loss} / S}$

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



Theoretical and experimental challenges in power exhaust

- Multi-machine scalings have identified a $1/I_p$ scaling in the divertor heat flux footprint in attached conditions
  - Measured scaling: $\lambda_q^{mid} \sim a/I_p \sim 1/B_{pol}^{mid}$, in agreement with Goldston's heuristic drift model
  - Theoretical challenge: at what point do pressure gradients get so steep in SOL for ballooning modes (pedestal physics) to become unstable?
    - ➢ Ballooning limits predicted to be higher at low R/a, due to easier access to second stability, so answer in NSTX-U should be different in NSTX, as compared to higher R/a
  - Theoretical and experimental challenge: how is the footprint in detached conditions related to the attached conditions?
    - ➢ Study at high P/R and P/S in NSTX-U

✓ These studies are contained in ReNeW thrust #9: *Rosner panel priority thrust, and high level recommendation in Zinkle report*

Soukhanovskii's talk

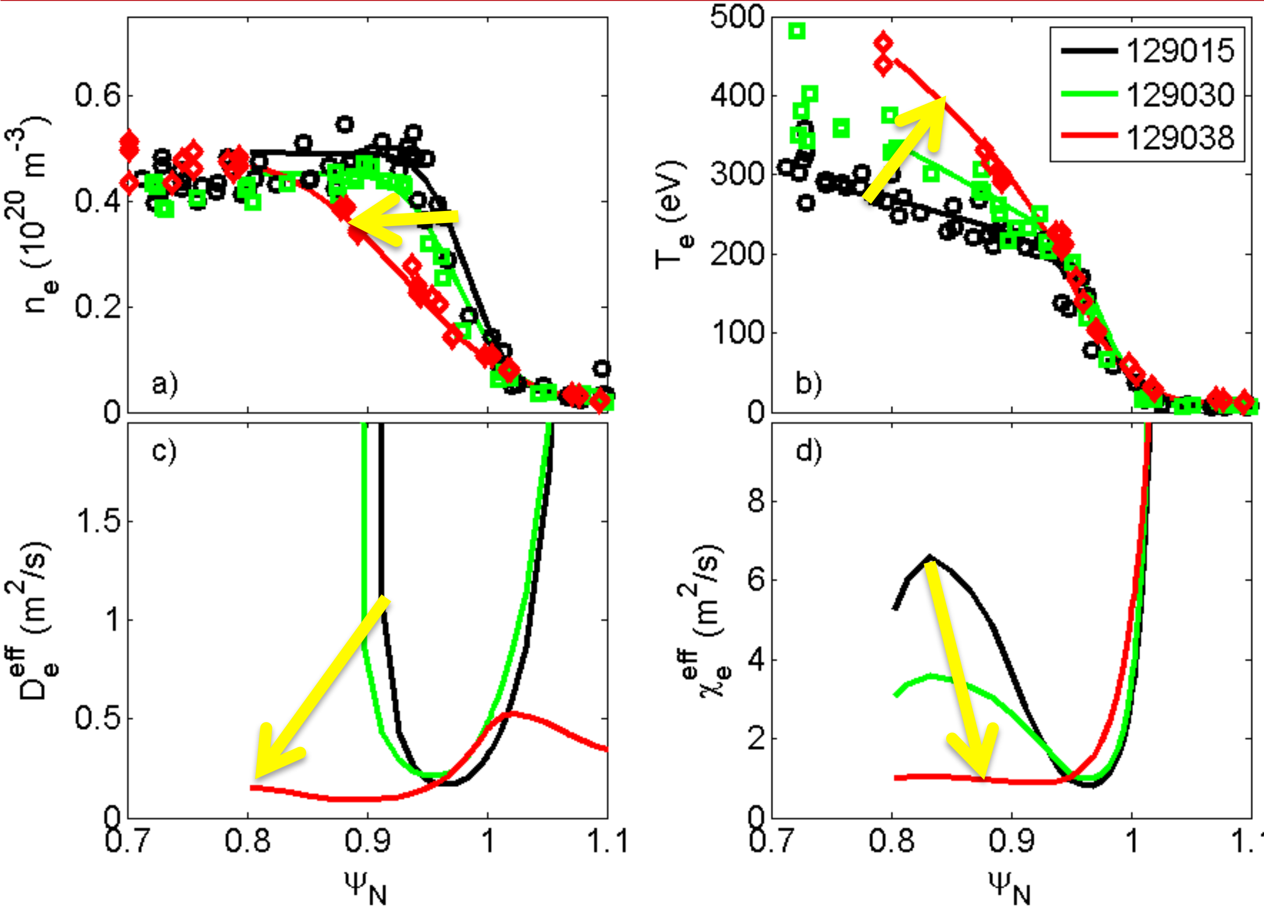
NSTX-U will use conventional radiative divertor and innovative snowflake divertor for power exhaust

- Radiative divertor demonstrated in NSTX, but MARFE sometimes forms near X-point, reducing τ_E
  - Theoretical challenge: what determines the thermal stability of the radiation front?
- Snowflake divertor (high flux expansion) demonstrated in NSTX
  - Theoretical challenges: Why does partial detachment occur at lower density? Why do ELMs (which disappear with sufficient Li) re-appear in snowflake configuration?

✓ NSTX-U particularly well-suited for studying thermal stability issues of the snowflake configuration, especially its compatibility with lithium conditioning

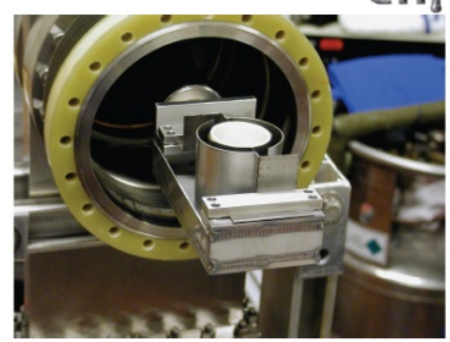
Soukhanovskii's talk

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



- Results motivate design and development of methods to increase Li coating coverage:
  - upward evaporation
  - evaporation into neutral gas

LTX



Y_2O_3 crucible, Ta heater
➢Tested to 700 °C

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

Plan elements for lithium wall conditioning studies, and material migration studies

- Lithium conditioning studies: Assess impact of more complete coverage of the PFCs by evaporated lithium using upward-facing evaporators and diffusive evaporation
  - Use Materials Analysis Particle Probe (MAPP) to identify in-situ between-shot chemical compositions of the lithium films
  - Evaluate compatibility/synergy with boronization
  - Initiate vapor shielding studies
  - Begin transition to high-Z tiles, both as substrate for Li evaporation, and as PFCs

- Material migration studies (ReNeW thrust 10): use MAPP, QCM, spectroscopy to measure erosion and re-deposition
  - Applied to both carbon and high-Z PFCs, with Li or B conditioning
  - ✓ ST geometry affords wide angle camera views for 3-D coverage

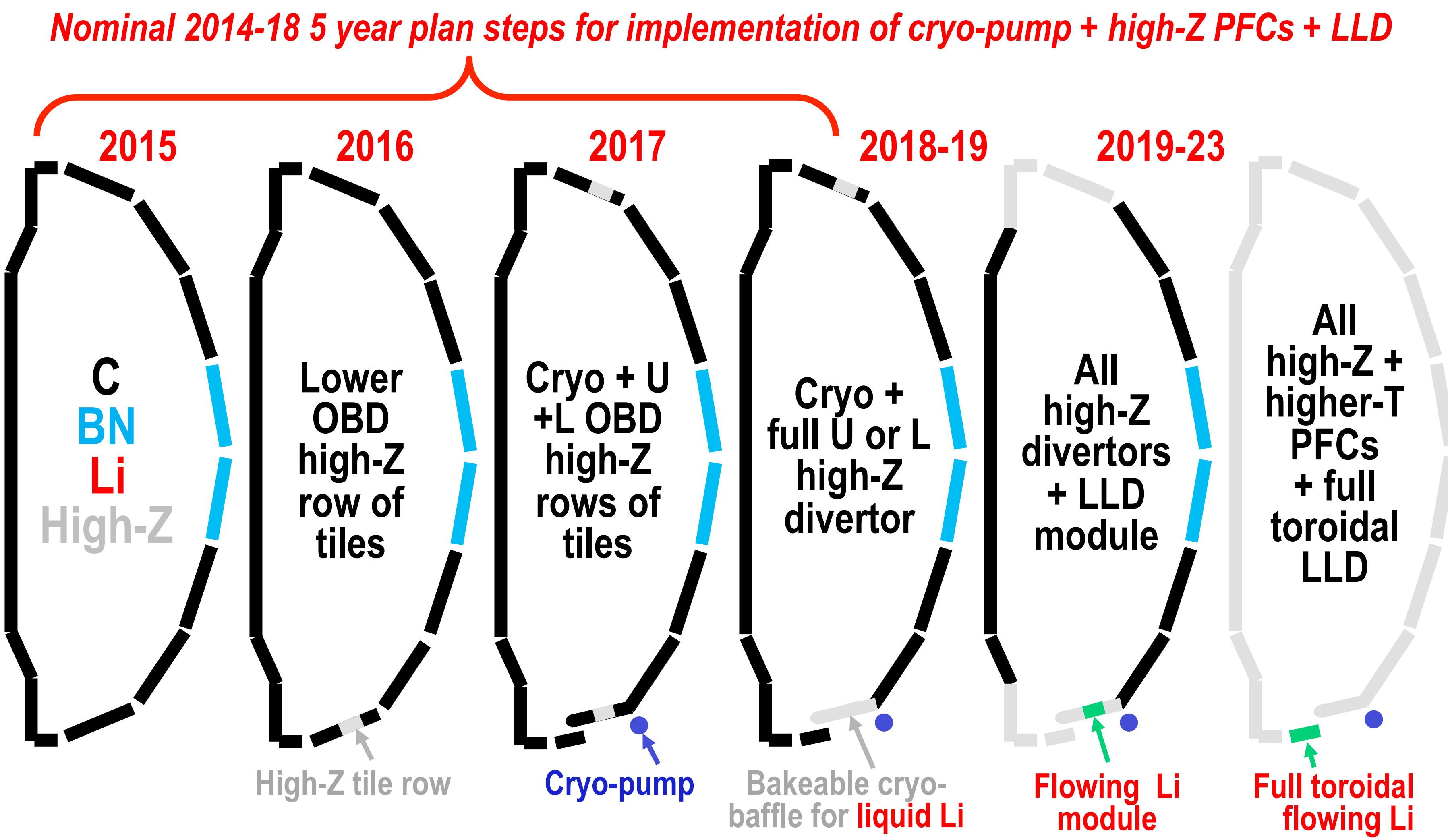
Jaworski's talk

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
  - Li enables main ion control which should extrapolate to NSTX-U pulse lengths, but discharges go ELM-free, leading to impurity accumulation
  - Best scenarios used 3-D fields for ELM triggering and gas fueling optimization, but core density increased with time, and core MHD initiated prematurely
- Plan elements for NSTX-U
  - Near term: evaluate use of boron and lithium wall treatments for long pulse particle control; evaluate ELM triggering with lithium granules
  - Mid-term: implement cryopump (*proven technology*) for comparisons with above, and compatibility with high flux expansion power exhaust solutions developed in the near term
    - Will n_e control from cryo also suppress ELMs?

Canik's talk

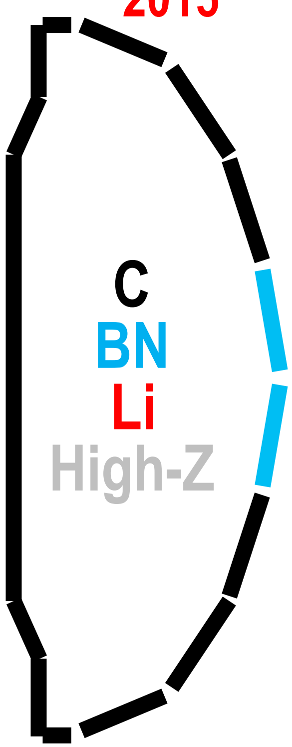
NSTX-U internal component baseline staging: Goal is to assess compatibility of high τ_E and β + 100% NICD with metallic PFCs



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**



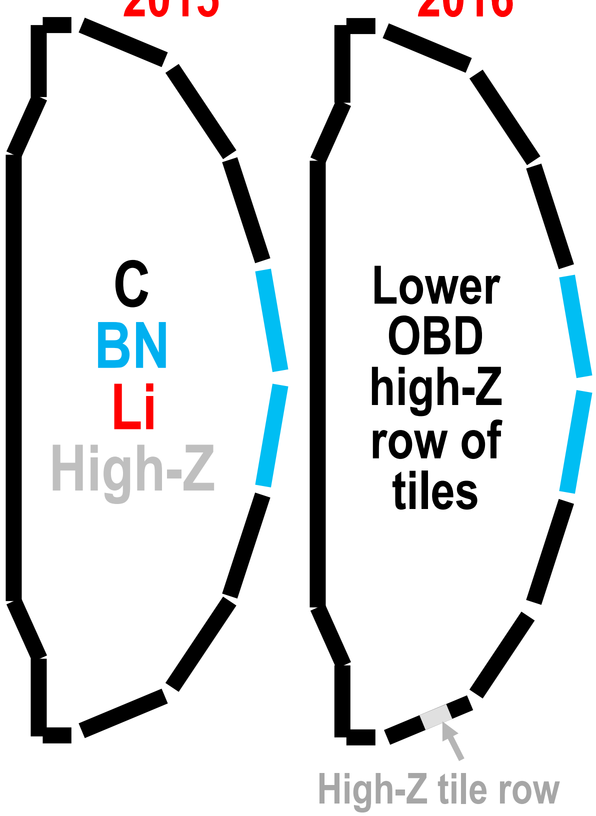
- Priority: establish NSTX-U operating space: I_p, B_t, pulse length; develop heat flux exhaust

- 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

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

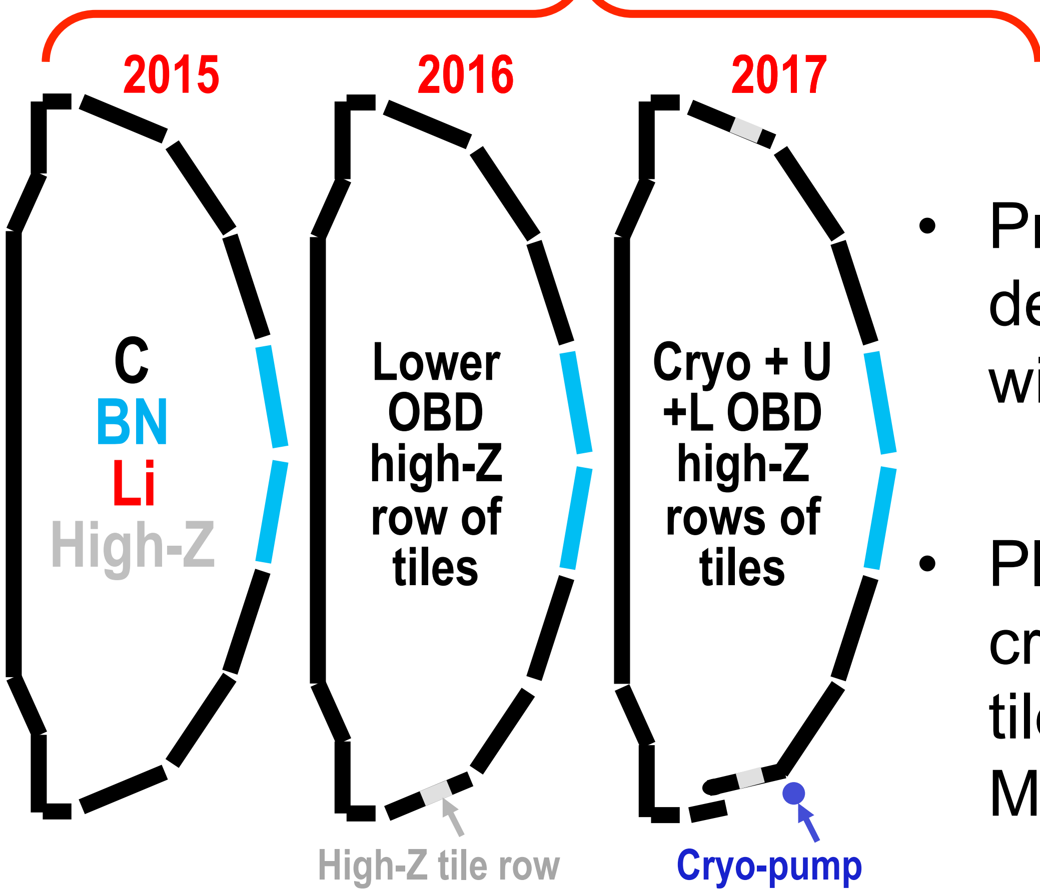


- Priority: establish NSTX-U operating space: I_p, B_t, pulse length; optimize heat flux exhaust; commence high-Z PFC assessment

- Plan: Implement row of Mo tiles outboard of CHI gap and study erosion, surface treatments

NSTX-U internal component staging in baseline budget

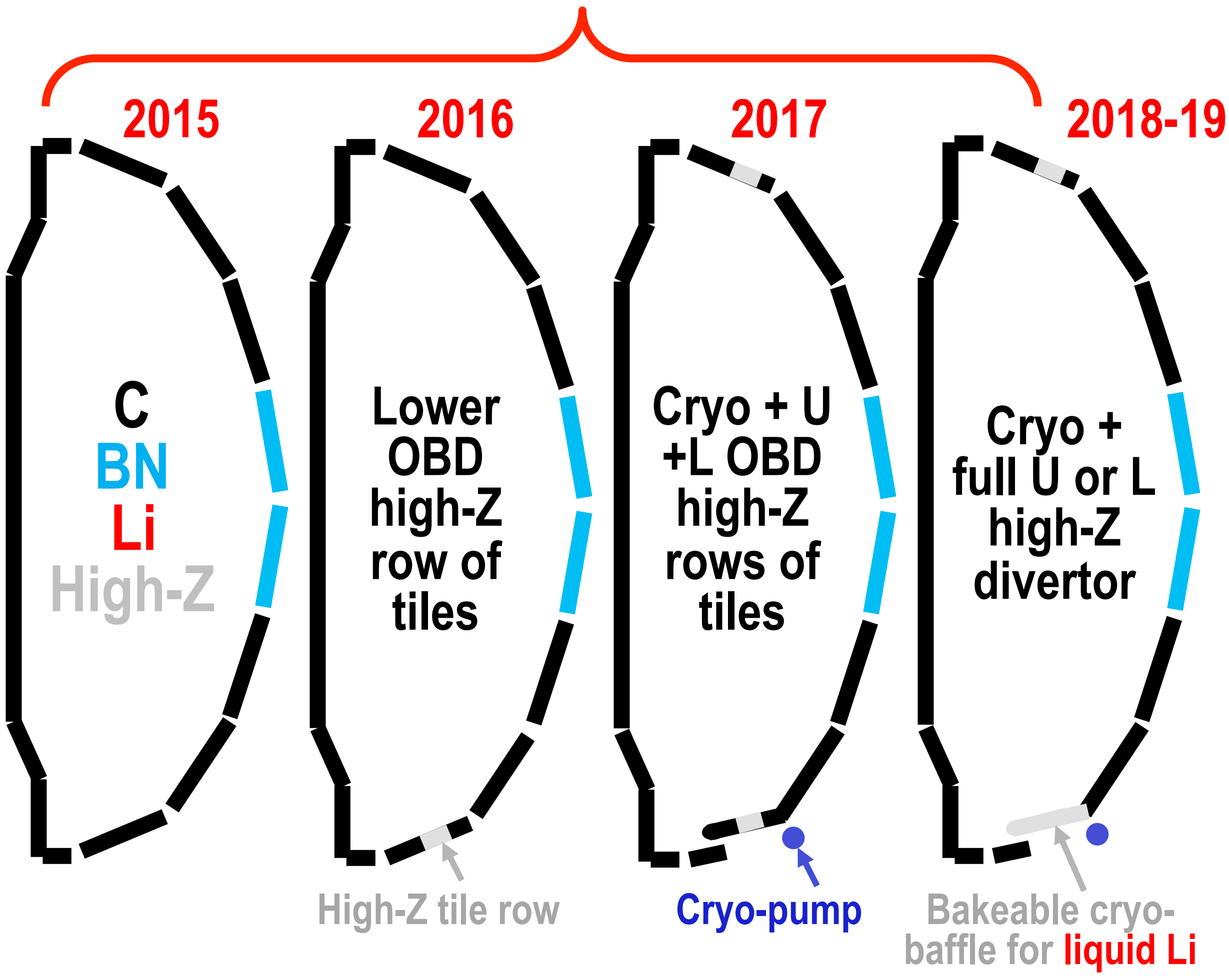
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



- 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

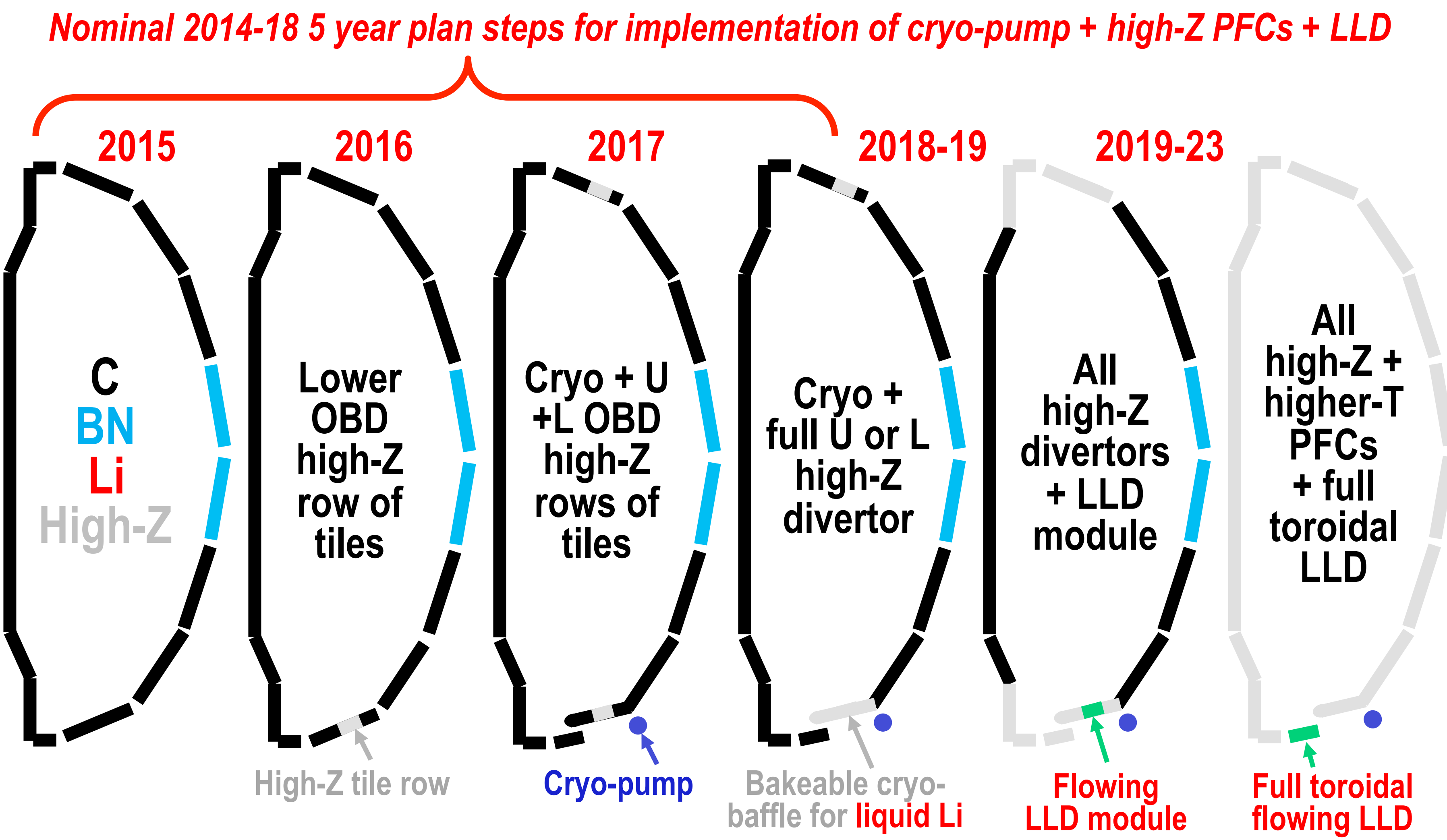
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



2019-23

- 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



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, or TZM tiles (if workable)
- 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
- Additional pulse-length extension (10-20s) at high power (~15MW) would require actively-cooled divertor PFCs

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

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

NSTX-U boundary program will develop long pulse PMI solutions, for resolving design issues for next step options

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

- Practical (manpower and budget) 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

NSXT-U boundary program is well-aligned with determined priorities from community reports (Rosner, Zinkle, ReNeW)

- Power exhaust, unfavorable I_p scaling (ReNeW T9)
- PFC erosion and material migration – pulse length, slag, elevated operating temperature (ReNeW T10)
- Control of transients (ReNeW T2)
- Core-edge compatibility (ReNeW T12); role of PFC material
- Testing and development of theories and models an integral component (ReNeW T6)
- Achieving steady state (ReNeW theme 2)
- NSTX-U supports ITER needs via ITPA divertor/SOL and pedestal groups: both pro-active and responsive to IO requests