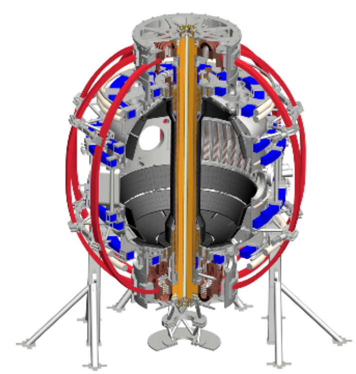
Boundary Science Group: Progress and Plans

R. Maingi, C.S. Chang
with input from NSTX-U Boundary TSG leaders

NSTX-U Program Advisory Committee Meeting
Princeton, NJ
26-28 January 2016



Outline

- Introduction and topics in Boundary Science Group
- Mission elements and research thrusts
- Priorities within each TSG, and relation to thrusts and near term milestones
- Relation to 2015 Community Workshop Reports
- Summary

This talk will provide input on several of the PAC charges

- Please assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign - are there any major missing elements, or new opportunities?
- Please assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs.
- Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support "integrated predictive capability".
- Please comment on the present team prioritization of planned facility enhancements including: divertor cryo-pump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research.

Boundary Science Group talk covers three TSGs and one task force

Boundary Science Group
R. Maingi, C.-S. Chang (deputy)

Pedestal Structure and Control
A. Diallo, R. Maingi
Theory/Modelling: J. Canik[1]
University Rep: D. Smith[2]

Divertor and Scrape-Off-Layer
V. Soukhanovskii[3], J.-W. Ahn[1]
Theory/Modelling: D. Stotler
University Rep: O. Schmitz[2]

Materials and PFCs
M. Jaworski, C. Skinner
Theory/Modelling: B. Wirth[4]
University Rep: J.-P. Allain[5]

Core Science Group
S. Kaye, S. Sabbagh[6] (deputy)

Macroscopic Stability
J. Berkery[6], J.-K. Park
Theory/Modelling: S. Jardin
University Rep: D. Brennan[7]

Transport and Turbulence
W. Guttenfelder, Y. Ren
Theory/Modelling: W. Wang
University Rep: K. Tritz[8]

Energetic Particles
M. Podestá, D. Liu[9]
Theory/Modelling: N. Gorelenkov
University Rep: N. Crocker[10]

Integrated Scenarios Group
S. Gerhardt, R. Raman[11] (deputy)

Advanced Scenarios and Control
D. Battaglia, S. Gerhardt
Theory/Modelling: F. Poli
University Rep: E. Kolemen[7]

Solenoid-free Start-up & Ramp-up
D. Mueller, R. Raman[11]
Theory/Modelling: F. Ebrahimi[7]

Wave Heating and Current Drive
R. Perkins, J. Hosea
Theory/Modelling: N. Bertelli
University Rep: P. Bonoli[12]

Particle Control Task Force (FY2016-17)
Leader: J. Canik[1], **Deputy:** R. Maingi

Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

NSTX-U Scientific Organization – August 2015

Boundary Science Group talk covers three TSGs and one task force

- Pedestal structure topical science group
  - Objective: Control and optimize the H-mode pedestal and ELMs

- SOL/divertor topical science group
  - Objective: Test both innovative and conventional power and particle exhaust solutions, and develop integrated solutions with good core, pedestal, and divertor operation

- Materials & PFC topical science group
  - Objective: Perform comparative assessment of high-Z and liquid metal PFCs

- *Particle Control Task Force (2016-2017)*
  - Goal: develop pumping and fueling tools, operating scenarios, and control systems for impurity density control and long pulse

Good balance between PPPL and non-PPPL leaders reflects strong collaborative nature of the SG effort and activity

- Pedestal structure topical science group
  - Leader: A. Diallo, Deputy: R. Maingi, Theory/Modelling: J. Canik, University: D. Smith

- SOL/divertor topical science group
  - Leader: V. Soukhanovskii, Deputy: J-W. Ahn, Theory/Modelling: D. Stotler, University: O. Schmitz

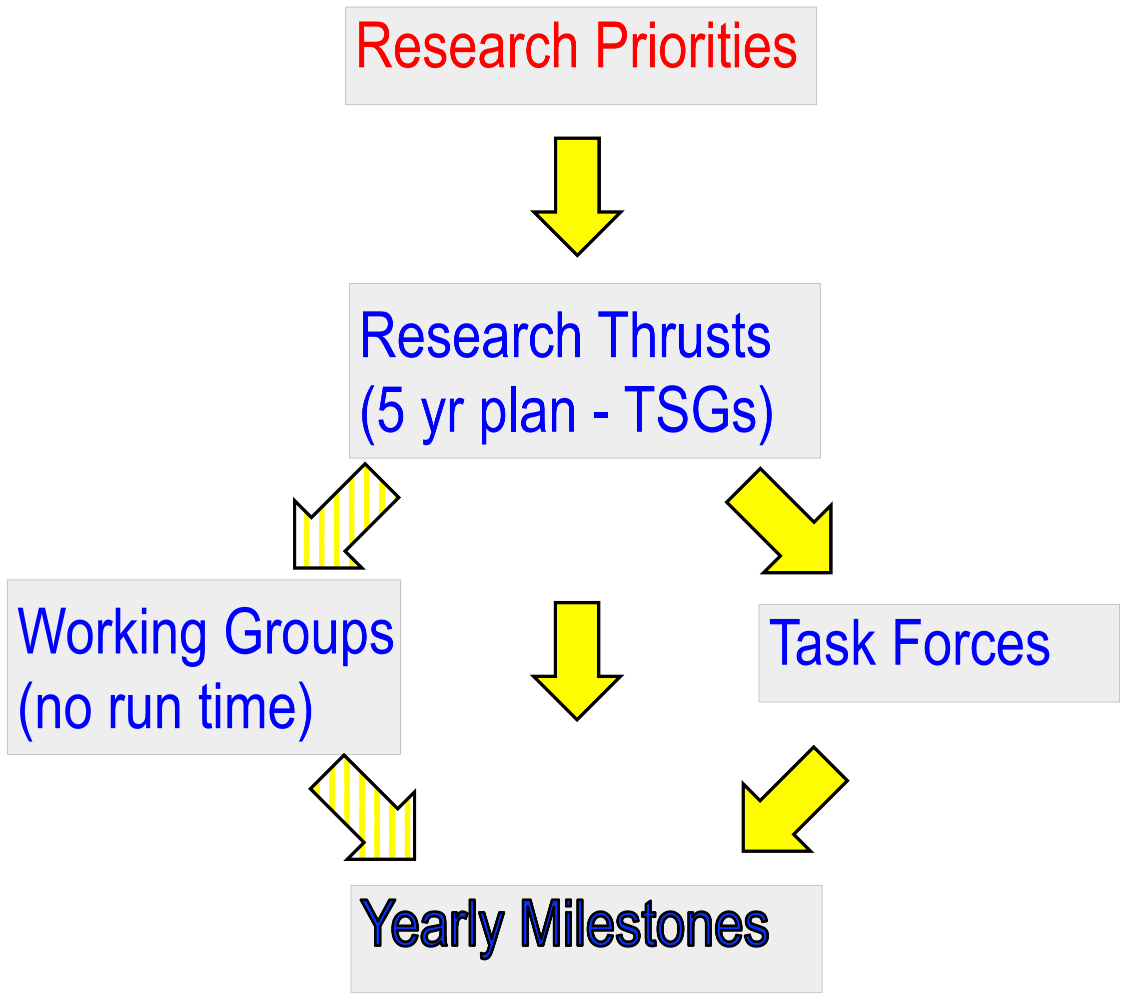
- Materials & PFC topical science group
  - Leader: M. Jaworski, Deputy: C. Skinner, Theory/Modelling: B. Wirth, University: J.P. Allain

- *Particle Control Task Force (2016-2017)*
  - Leader: J. Canik, Deputy: R. Maingi
  - Goal: develop pumping and fueling tools, operating scenarios, and control systems for impurity density control and long pulse

NSTX-U Mission Elements and the five High Level Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

High Level Research Priorities Map to Research Thrusts within each Topical Science Group



Six thrusts in the boundary science group contribute to three of the top five mission elements

Research Priorities

- Understand confinement and stability at high beta and low collisionality
- Dissipate high edge heat loads using expanded magnetic fields + radiation
- Compare performance of solid vs. liquid metal plasma facing components

Thrusts

– BP-1: Assess and control pedestal structure, edge transport and stability (pedestal)

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– BP-2: Assess and control divertor heat and particle fluxes (SOL/Div)

– MP-1: Establish the science of continuous vapor-shielding (M&P)

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- MP-2: Understand lithium surface-science for long-pulse PFCs (M&P)
- MP-3: Unravel physics of tokamak-induced mat. migration and evolution (M&P)

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– BP-3: Establish and compare long-pulse particle control methods (SOL/div, PC-TF)

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NSTX-U Milestone Schedule for FY2016-18

	FY2016	FY2017	FY2018
Run Weeks: (Incremental)	18	16 (Incremental: 18)	12 (Incremental: 16)
Boundary Science + Particle Control	R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2: Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1: Assess impurity sources and edge and core impurity transport IR18-1: Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3: Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	IR18-2: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for major facility enhancement(s) sometime during FY2018
Integrated Scenarios	R16-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1: Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4: Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2: Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3: Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT: Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT: *Examine effect of configuration on operating space for dissipative divertors*	NSTX-U leads JRT: TBD

Near term milestones prioritize elements in six boundary science group thrusts

- BP-1: Assess and control pedestal structure, edge transport and stability (pedestal)
  - R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}
- BP-2: Assess and control divertor heat and particle fluxes (SOL/Div)
  - R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}
  - R17-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density
  - JRT17: Examine effect of configuration on operating space for dissipative divertors
  - IR 18-1:Investigation of power and momentum balance for high density and impurity fraction divertor operation
- MP-1: Establish the science of continuous vapor-shielding (M&P)
  - IR 18-1:Investigation of power and momentum balance for high density and impurity fraction divertor operation
- MP-2: Understand lithium surface-science for long-pulse PFCs (M&P)
  - Long term PFC program evolution
- MP-3: Unravel physics of tokamak-induced material migration and evolution (M&P)
  - R17-2: Assess high-Z divertor PFC performance and impact on operating scenarios
  - R18-1: Assess impurity sources and edge and core impurity transport
- BP-3: Establish and compare long-pulse particle control methods (SOL/div, PC-TF)
  - Cryopump, liquid lithium

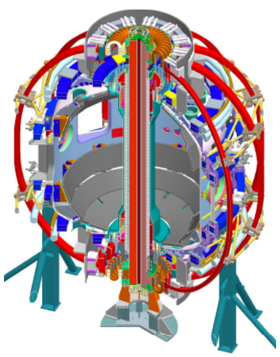
Five Year Facility Enhancement Plan (green – ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

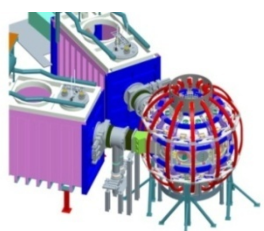
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack

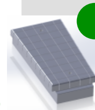


2nd NBI

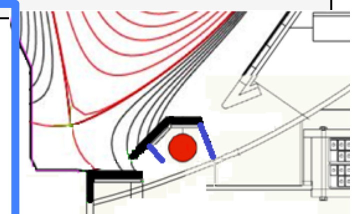


Boundary Science + Particle Control

Pulse-burst MPTS
High-Z PFC diagnostics
Boronization
Li granule injector
MAPP
Upward LiTER
High-Z tile row on lower OBD

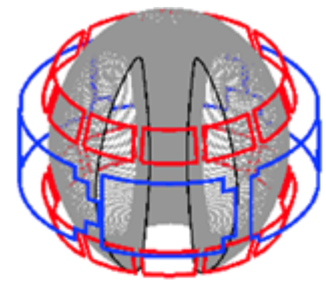


Lower divertor cryo-pump
Enhanced High-Z PFC diagnostics
LLD using bakeable cryo-baffle



Core Science

MGI disruption mitigation
Upgraded halo sensors
Laser blow-off
42 ch MPTS
48 ch BES
MSE/LIF
High k_θ
Charged fusion product
4 coil AE antenna
δB diag. - incremental
Off-midplane 3D coils (NCC)
Enhanced MHD sensors
DBS, PCI, or other intermediate-k
Neutron collimator



Integrated Scenarios

Establish control of:
Snowflake
FIReTIP
Rotation
$\bar{n}_e$
q_{min}
Divertor P_{rad}
1 MW ECH/EBW
Upgraded CHI for ~0.5MA
0.5-1 MA CHI
HHFW limiter upgrade
up to 1 MA plasma gun

Pedestal TSG Plans

Research Priorities

- Understand confinement and stability at high beta and low collisionality
- Dissipate high edge heat loads using expanded magnetic fields + radiation
- Compare performance of solid vs. liquid metal plasma facing components

Thrusts

- BP-1: Assess and control pedestal structure, edge transport and stability (pedestal)
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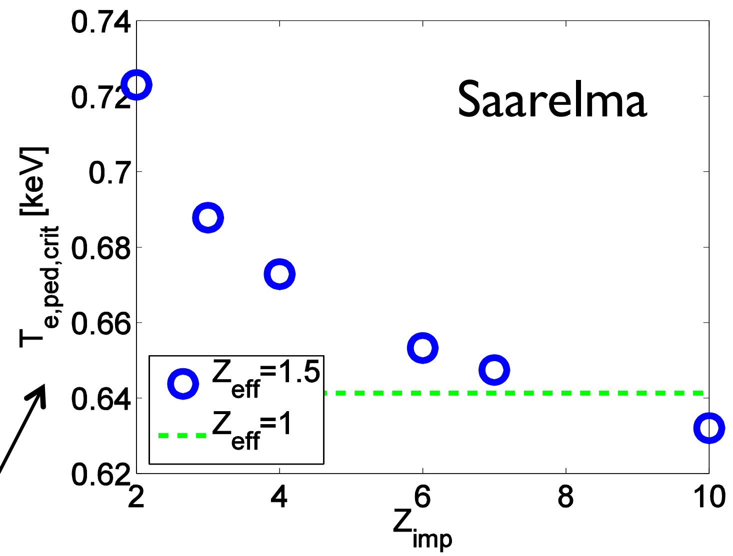
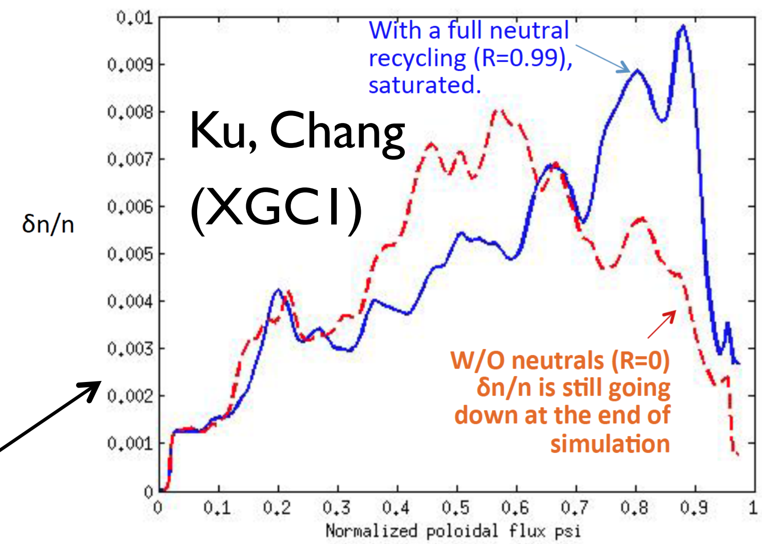
- BP-3: Establish and compare long-pulse particle control methods (SOL/div, PC-TF)

Pedestal TSG will examine role of higher Ip, Bt available in NSTX-U on pedestal, as well as low-Z impurities

Thrust BP-1

- Pedestal structure in NSTX-U (XP1512 Diallo) R16-1
  - First measurements in NSTX-U; I_p, B_t, and P_{NBI} variations
  - Builds on data from (XP1520 Kaye) and (XP1523 Podesta)
- Effect of impurities and neutrals on pedestal (XP1537 Osborne)
  - Compare low-Z impurity injection, e.g. Ne, N with lithiated discharges
  - Direct connection to ITPA PEP JEX#37
  - Vary neutral density via fueling to gauge effect on turbulence

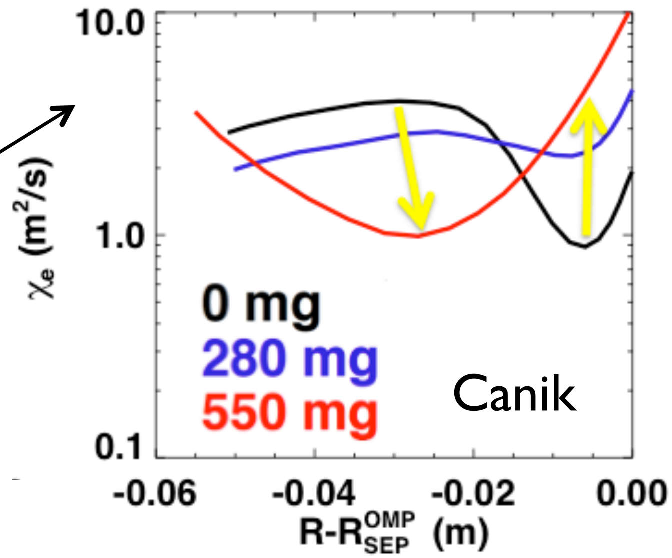




Pedestal group also focused on B-Li transition, 3-D field effects, and L-H transition physics

Thrust BP-1

- Effect of B-> Li transition on pedestal structure (XP1529 Maingi)
  - Lithium dose scanned; compare with boronization and NSTX high δ scan
  - Assess effect on λ_q, local recycling



- Effect of 3-D fields on pedestal structure (XP1536 Lore)
  - ELM mitigation/suppression with midplane coils; impact on profiles
  - ELM frequency vs. q95 – resonant behavior, as in JET?
- L-H transition comparison with Pegasus (XP1511 Bongard)
  - Also comparison with NBI tangency radius (PB on XP1523 Podesta)
  - Also investigation of anomalous transport at L-H and H-L transitions

Pedestal group: Priority 2

Thrust BP-1

- Pedestal rotation shear enhancement (*highest priority*)
  - Use high-n NTV plus second NBI
  - De facto an attempt to trigger Enhanced Pedestal H-mode
- ELM stability physics
  - Peeling ballooning along ballooning boundary (low δ)
  - Non-linear ELM dynamics with Beam Emission Spectroscopy
- Generating an Edge Harmonic Oscillation
  - QH-mode search; counter I_p as proposed
- I-mode search
  - Delayed to full field, since high B_t values seem to widen the I-mode operating window

SOLdiv TSG Plans

Research Priorities

- Understand confinement and stability at high beta and low collisionality
- Dissipate high edge heat loads using expanded magnetic fields + radiation
- Compare performance of solid vs. liquid metal plasma facing components

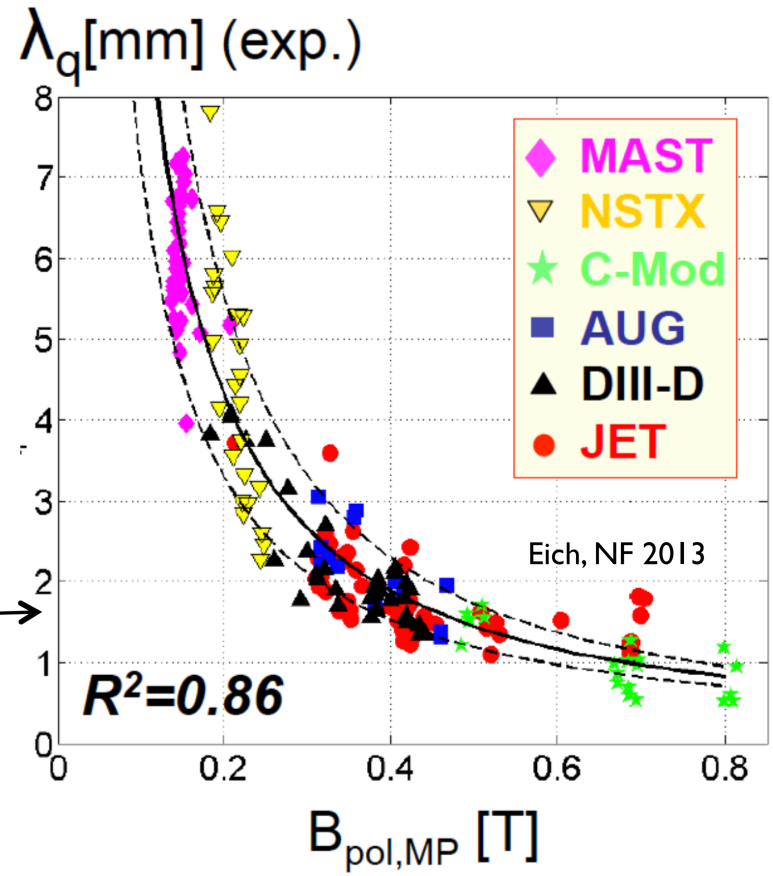
Thrusts

- BP-1: Assess and control pedestal structure, edge transport and stability (pedestal)
- BP-2: Assess and control divertor heat and particle fluxes (SOL/Div)
- MP-1: Establish the science of continuous vapor-shielding (M&P)
- MP-2: Understand lithium surface-science for long-pulse PFCs (M&P)
- MP-3: Unravel physics of tokamak-induced mat. migration and evolution (M&P)
- BP-3: Establish and compare long-pulse particle control methods (SOL/div, PC-TF)

SOLdiv group neat term emphasis on power exhaust footprint and disipation

Thrust BP-2

- SOL widths, transport and turbulence (XP1514 Gray) R16-1
  - Connect measured λ_q with
    - GPI measurements and SOLT modeling
    - Effect of Li
  - Characterize heat flux spreading into the private flux region
  - Differentiate between NSTX scaling ($\sim I_p^{-1.6}$) and Eich ($\sim I_p^{-1}$), by extending to $B_{pol,MP} \sim 0.5$ in NSTX-U
  - Builds on data from (XP1520 Kaye) and (XP1523 Podesta)



- Radiative divertor studies (XP1538 Soukhanovskii) JRT17
  - Baseline radiative divertor studies; 3-D asymmetry from gas injection

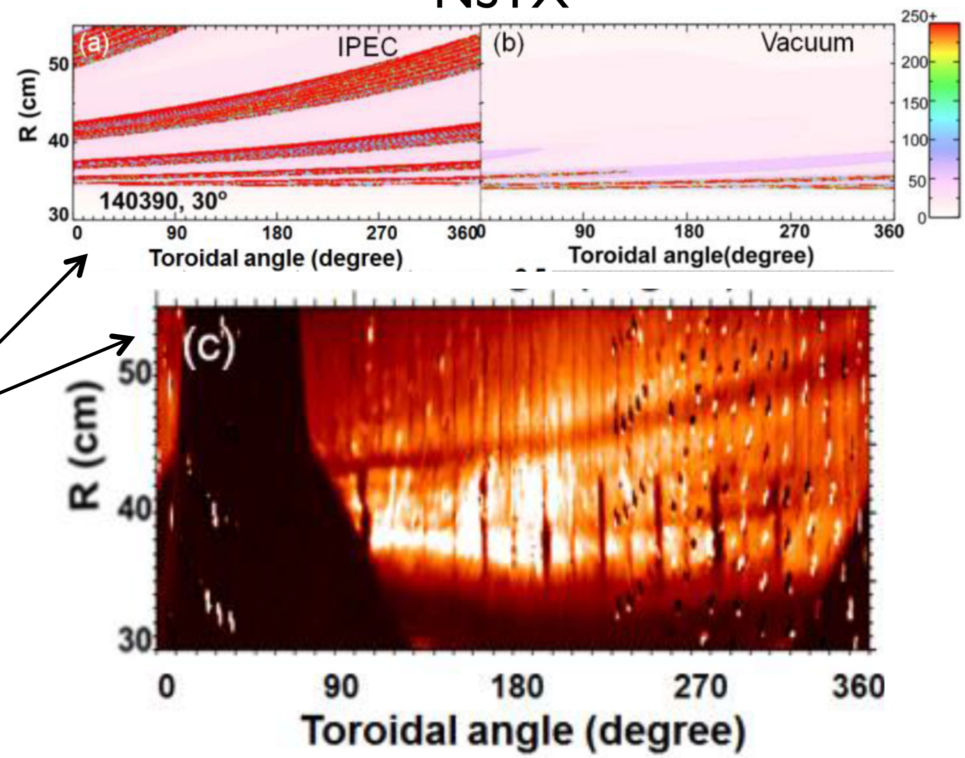
SOLdiv group also examines effectes of 3-D fields, and snowflake divertor studies

Thrust BP-2

- Snowflake divertor studies (XP1539 Soukhanovskii) R17-1
  - Emphasis on configuration variations
  - Also effect of 3-D fields, and detachment comparison with standard

- Effect of 3-D fields on heat flux profiles (XP1557 Ahn)
  - Includes high recycling, emphasis on partially detached to understand differences between NSTX and DIII-D observations
  - Try to separate (cross-field) transport from topology, and role of plasma response

NSTX



Ahn, Scotti

SOLdiv group: Priority 2

Thrust BP-2

- Advanced divertors to compare with snowflake configuration (*highest priority*)
  - X-divertor
  - Long-leg divertor
  - Cusp-like divertor

- Standardized configuration optimized for boundary diagnostics
  - Detailed model validation

- Neutral density profiles using Edge Neutral Density diagnostic or 2-D lithium emission pattern

- Low-Z and high-Z dust transport

Materials and PFCs TSG Plans

Research Priorities

- Understand confinement and stability at high beta and low collisionality
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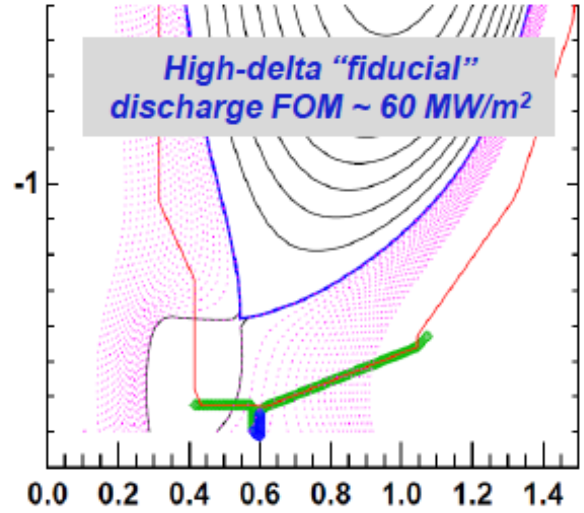
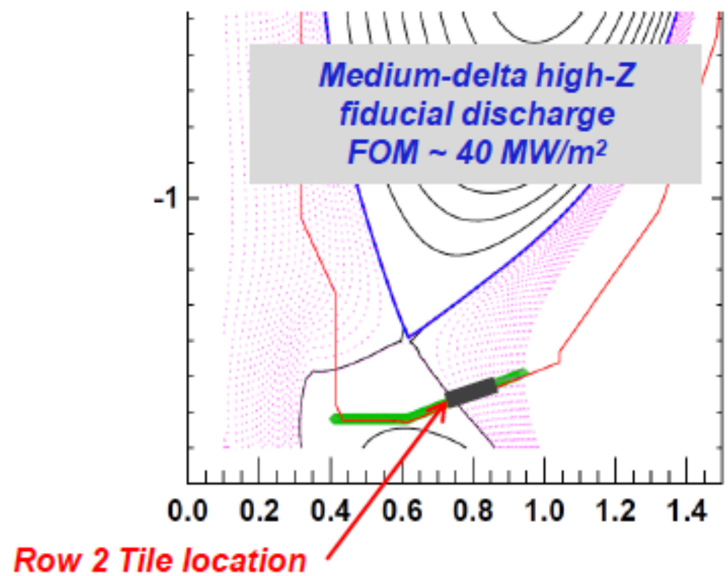
M&P group charactering baseline graphite PFCs before high-Z tile installation, and on boronization optimization studies

- Divertor heat transport in low-δ discharge shapes with the strike point on the planned high-Z tile ring (XP1526 Jaworski) R17-2
  - Assess leading edge effects
  - See talk by Jaworski with many more details on high-Z PFC program



- Boronization optimization (XP1505 Skinner)
  - Three boron inlet lines in NSTX-U (up, mid, down); only mid in NSTX
  - Test different GDC pressure and d-TMB injection locations
  - Use of MAPP for evaluation of PFC surface



M&P priority 1 experiments have additional emphasis on understanding PFC surface evolution

- Standardized configuration optimized for boundary diagnostics (XP1561 Soukhanovskii) Thrust MP-3
  - Also supports material migration study part of Ph.D.
- Longevity of lithium pumping (XP1540 Scotti) Thrust MP-2
  - Vary Li deposition, heating power, and divertor gas puffing
  - Make use of MAPP for evaluation of surface
- Interest for ex-situ analysis of in-vessel samples Thrust MP-2
  - Both local (PU) and afar (MIT, UIUC)

M&P group: Priority 2

- Behavior of high-Z impurities (*highest priority*) R18-2
  - Better to wait till laser blowoff available?

- Effect of ELMs on material migration Thrust MP-3
  - Possible part of a Ph.D. thesis

- Testing of a textured Mo surface as a PFC Thrust MP-2
  - Possible XMP?

Particle Control Task Force Plans

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Particle Control Task Force uses expertise from multiple TSGs, with specific goals and finite duration

- Confirm physics design calculations of the cryopump plenum geometry

- Deploy a number of long pulse particle control techniques
  - Impurity Granule Injector (IGI) for ELM pacing
  - LiTERs (downward + new upward in 2017)
  - Snowflake divertor and gas puffing
  - 3-D fields for ELM pacing

- Coordinate effort for density feedback implementation with cryo

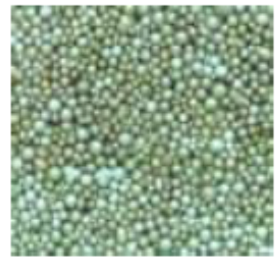
Particle Control group experiments focus on cryopump physics validation and control techniques

Thrust BP-3

- Validate assumptions used to design cryopump (XP1528 Canik)
  - Specific strike point range with IR, Langmuir probe data, D_{α} profiles
  - Do this with boronized conditions and lithiated conditions
- ELM pacing via granules and 3-D fields (XP 1527 Lunsford)
  - Possibility for Li, B4C, vitreous carbon with granule injector
  - Compare with DIII-D, EAST: overlapping teams working on all of these devices!
  - Granule ablation and ELM destabilization: M3Dc1 model
  - Use 3-D fields in same discharges for ELM pacing, direct comparison

B_4C

Li



Mansfield NF 53 (2013)

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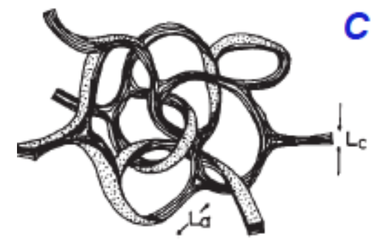
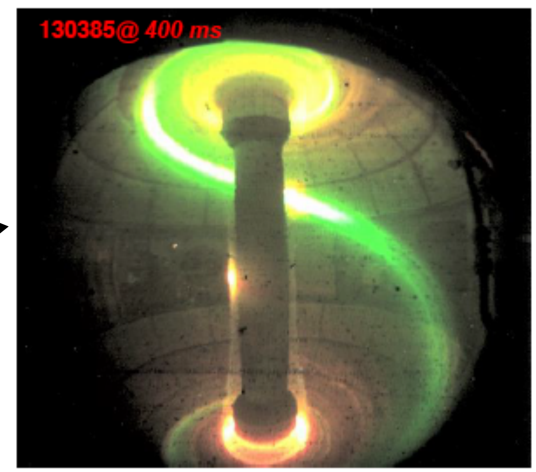


Fig. 3 Structural model for the network of ribbon stacks in glassy carbon.



Injection of low velocity (~5m/s) lithium clumps (~2mm) into NSTX (2008)

Particle Control experiments also contribute to impurity control via gas injection, and low fueling

Thrust BP-3

- Divertor gas inj. for impurity reduction (XP1542 Soukhanovskii)
- Gas fueling optimization for low n_e H-mode (XP1562 Battaglia)
- Combine two most promising techniques (XP1541 Lore)
  - Initial focus on 3D fields or LGI + divertor gas injection, but snowflake configuration a possibility

Particle Control group: Priority 2

Thrust BP-3

- Optimization of helium-dispersed Li evaporation
  - Similar to helium dispersed boronization for more uniform coating

- Development of naturally occurring small ELM regimes
  - Type II or Type V ELMy H-mode in long pulse?

- Scoping study to search for and stimulate Edge Harmonic Oscillation for particle control
  - Use RF antenna?

Summary of priority 1 experiments

- Milestone R16-1: Wide I_p, B_t range
- Effects of neutrals and impurities (IO, ITPA)
- 3-D field effects (ITPA)
- L-H threshold (multi-machine collaboration)
- SOL transport and turbulence, heat flux (R16-1)
- Radiative divertor (R17-1)
- 3D fields, likely emphasizing detachment (ITER/ITPA)
- Snowflake divertor physics (R17-1)
- Power exhaust and heat flux with large strike point radius (R17-2)
- Boundary diagnostic optimized plasmas; material migration
- Understanding Li pumping longevity
- Boronization optimization
- Cryopump assumption validation, low n_e H-mode development
- LGI + 3-D fields
- Divertor gas puff for impurity reduction
- Combination of ELM/impurity control techniques

Ped

SOLdiv

M&P

PC-TF

- B -> Li transition studies (impacts all 4 group)

Outline

- Introduction and topics in Boundary Science Group
- Mission elements and research thrusts
- Priorities within each TSG, and relation to thrusts and near term milestones
- Relation to 2015 Community Workshop Reports
- Summary

NSTX-U boundary science group activities well aligned with 2015 PMI community workshop report recommendations

- Five Priority Research Directions were identified (*not prioritized*)
  - Advanced Divertor Science & Solutions
  - Main-Chamber Science & Solutions
  - Plasma-Materials Interactions Science & Solutions
  - Power & Particle Exhaust Science & Technologies
  - Divertor/PMI/ Pedestal/Core Integration Science
- Four Cross-cutting Research Opportunities were highlighted (*not prioritized*)
  - Enhance exploitation of existing machines
  - Examine long pulse PMI science issues
  - Understand the science of liquid surfaces
  - Integrated PMI on Divertor Test Tokamak

✓ NSTX-U clearly contributes to all five PRDs in the 'Enhancements to Existing Facilities' and 'Model Validation' area

✓ NSTX-U will strongly contribute to 'liquid PFCs'

NSTX-U boundary science group activities aligned with 2015 Transients (ELM control) workshop report recommendations

Recommendation #1 Develop validated physics based models and multi-scale plasma simulations required for predicting the access requirements for high performance ELM stable and ELM mitigated plasmas at reactor scale.

- *Validated multi-scale physics models of long wavelength MHD and 3D magnetic field interactions with edge plasma microturbulence and transport*
- *Validated models of natural & mitigated ELMs, incl. reduced models and advanced simulations, to predict mode structure, 3D heat and particle pulse*
- *Validated models of the first wall and divertor erosion with ELMs and in the mitigated and suppressed ELM states.*
- *Whole device modeling, with reduced models of the pedestal, actuators, and core transport, to predict & optimize plasma performance and control*

Recommendation #2 Expand research on current facilities, with additional run time and staffing, to determine the optimal use of the ITER ELM control systems for accessing:

→*RMP ELM suppressed H-mode, QH-mode and I-mode regimes*

→*ELM mitigated operation with pellet pacing*

NSTX-U boundary science group activities aligned with 2015 Transients (ELM control) workshop report recommendations

Recommendation #1 Develop validated physics based models and multi-scale plasma simulations required for predicting the access requirements for high performance ELM stable and ELM mitigated plasmas at reactor scale.

see also Bhattacharjee's talk

- *Validated multi-scale physics models of long wavelength MHD and 3D magnetic field interactions with edge plasma microturbulence and transport*

Pedestal TSG

- *Validated models of natural & mitigated ELMs, incl. reduced models and advanced simulations, to predict mode structure, 3D heat and particle pulse*
- *Validated models of the first wall and divertor erosion with ELMs and in the mitigated and suppressed ELM states.*

Granule injector,
M3Dc1, JOREK

- *Whole device modeling, with reduced models of the pedestal, actuators, and core transport, to predict & optimize plasma performance and control*

XGC1

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→ *ELM mitigated operation with pellet pacing*

Pedestal TSG, NCC
Granule injector

NSTX-U boundary science group activities well aligned with 2015 Integrated Modeling report recommendations

- [PRD-Boundary-1] Develop a high-fidelity simulation capability and predictive understanding of the coupled pedestal/SOL system and its structure and evolution in the presence of microturbulence and collisional transport
- [PRD-Boundary-2] Incorporate the dynamics of transients, particularly intermittent edge-localized mode events that eject bursts of particles and energy into the SOL, leading to large transient heat loads on the walls
- [PRD-Boundary-3] Develop a simulation capability that integrates the moderately collisional midplane SOL plasma with the highly collisional divertor plasma
- [PRD-Boundary-4] Integrate RF antenna/plasma-absorption simulations with SOL/pedestal plasma transport simulations, filling a notable gap in present capability
- [PRD-Boundary-5] Develop an enhanced capability to couple wall response models to plasma models. A related activity is to examine advanced divertor concepts, including alternate magnetic-geometry divertors and liquid walls

NSTX-U boundary science group activities well aligned with 2015 Integrated Modeling report recommendations

- [PRD-Boundary-1] Develop a high-fidelity simulation capability and predictive understanding of the coupled pedestal/SOL system and its structure and evolution in the presence of microturbulence and collisional transport

  see also Bhattacharjee's talk

  XGC1

- [PRD-Boundary-2] Incorporate the dynamics of transients, particularly intermittent edge-localized mode events that eject bursts of particles and energy into the SOL, leading to large transient heat loads on the walls

  Granule injector plus M3DC1, JOREK

- [PRD-Boundary-3] Develop a simulation capability that integrates the moderately collisional midplane SOL plasma with the highly collisional divertor plasma

  XGC1

- [PRD-Boundary-4] Integrate RF antenna/plasma-absorption simulations with SOL/pedestal plasma transport simulations, filling a notable gap in present capability

  AORSA

- [PRD-Boundary-5] Develop an enhanced capability to couple wall response models to plasma models. A related activity is to examine advanced divertor concepts, including alternate magnetic geometry divertors and liquid walls

  Wirth SciDAC, couple to NSTX-U

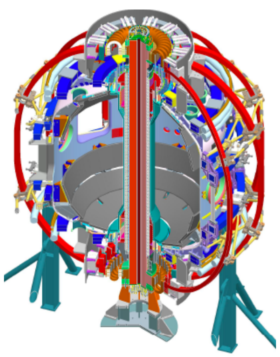
Five Year Facility Enhancement Plan (green – ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

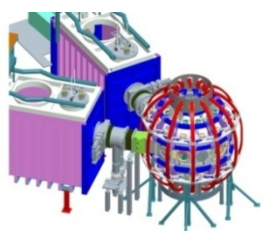
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack

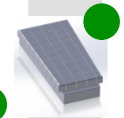


2nd NBI

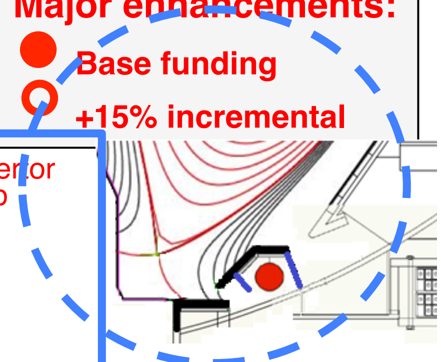


Boundary Science + Particle Control

- Pulse-burst MPTS
- High-Z PFC diagnostics
- Boronization
- Li granule injector
- MAPP
- High-Z tile row on lower OBD

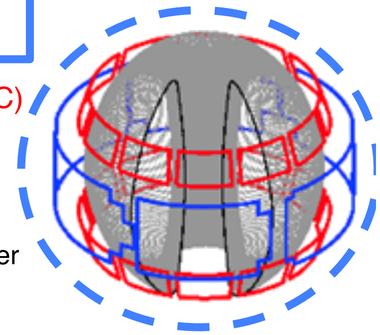


- Upward LiTER
- Lower divertor cryo-pump
- Enhanced High-Z PFC diagnostics
- LLD using bakeable cryo-baffle



Core Science

- MGI disruption mitigation
- Upgraded halo sensors
- Laser blow-off
- 42 ch MPTS
- 48 ch BES
- MSE/LIF
- High k_θ
- Charged fusion product
- 4 coil AE antenna
- δB diag. - incremental
- Off-midplane 3D coils (NCC)
- Enhanced MHD sensors
- DBS, PCI, or other intermediate-k
- Neutron collimator



Integrated Scenarios

- Establish control of: *Rotation*, q_{min}, $\overline{n}_e$, Divertor P_{rad}
- Snowflake
- FIReTIP
- 1 MW ECH/EBW
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- HHFW limiter upgrade
- up to 1 MA plasma gun

Proposed NSTX-U facility enhancements are needed to optimize boundary SG contributions to mission elements

- Cryopump (also Canik, PAC-33)
  - Allows comparison of conventional particle control with lithium
  - Enables study of compatibility with high flux expansion divertors, e.g. snowflake
  - Enables steady density for controlled collisionality scans

- High-Z PFCs and liquid metals research (Jaworski, next talk)
  - Needed for high level mission – steady effort required
  - Ability to field systems depends on parallel R&D, including collaborative work on e.g. EAST

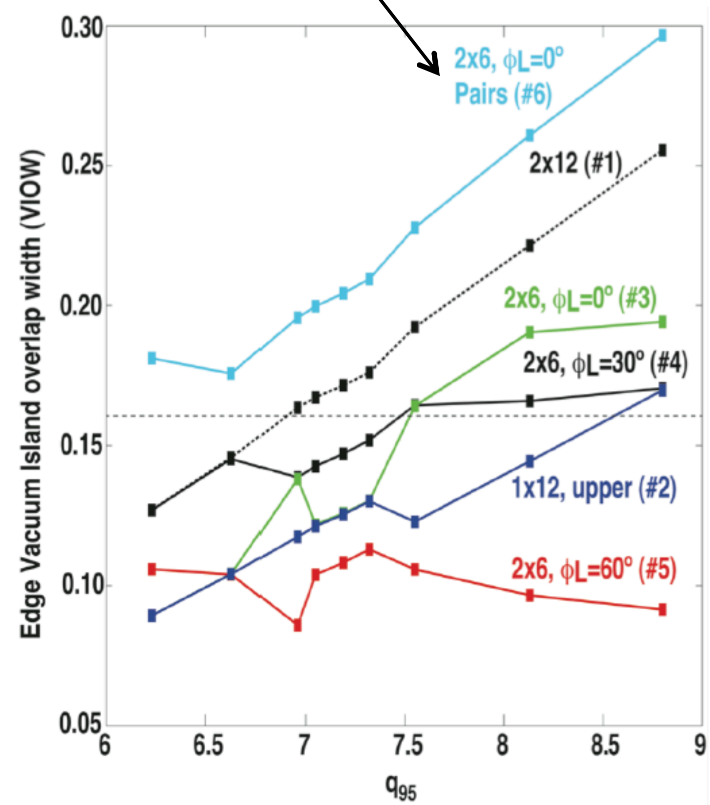
- NCC upgrade (also J.K. Park, PAC-33, Berkery PAC-35)
  - Broader range of poloidal field spectra for ELM mitigation and ELM suppression studies (see next slide)

Study of RMP characteristics with NCC extended with TRIP3D (T. Evans) – 2x12 NCC (and 2x7) favorable for RMP

- Vacuum Island Overlap Width (VIOW) analysis shows full NCC 1kAt can produce sufficient VIOW in a wide range of q_{95}, but partial NCC needs more currents with low q_{95} targets
  - Also shows 2x7, with "one" more additional array upon partial NCC can provide the greater VIOW by toroidal coupling (n=2,4,9)

NCC Configurations Used for the plots Shown in Figures 1 and 2

#	Description, Color	NCC Configuration Layout
1	2x12 **dashed black line**	[+] [+] [-] [-] [+] [+] [-] [-] [+] [+] [-] [-] [+] [+] [-] [-] [+] [+] [-] [-] [+] [+] [-] [-]
2	1x12, upper **solid blue line**	[+] [+] [-] [-] [+] [+] [-] [-] [+] [+] [-] [-] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]
3	2x6, ϕ_L=0° **solid green line**	[+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ]
4	2x6, ϕ_L=30° **solid black line**	[+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-]
5	2x6, ϕ_L=60° **dashed red line**	[+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ] [-] [ ] [+] [ ]
6	2x7, ϕ_L=0° Pairs **solid light blue line**	[+] [ ] [-] [ ] [+] [-] [ ] [+] [ ] [-] [ ] [ ] [-] [ ] [+] [ ] [-] [+] [ ] [-] [ ] [+] [ ] [ ]



Boundary Science Group poised and eager to commence research program!

- H-mode routinely obtained, meaning the machine is nearing readiness to support high quality experiments
  - Need to bring actuators and diagnostics online quickly

Charge questions

✓ Boundary SG has prioritized research via connection to mission elements, research thrusts, and near term milestones

✓ Boundary SG is well-aligned with goals and the FESAC / FES initiatives as reflected by 2015 community workshops, and ITER urgent research needs in targeted areas

- Please comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support "integrated predictive capability"

✓ Boundary SG contributions to mission elements are strongly enhanced by divertor cryo-pump, conversion to all high-Z PFCs and liquid metals research, and NCC

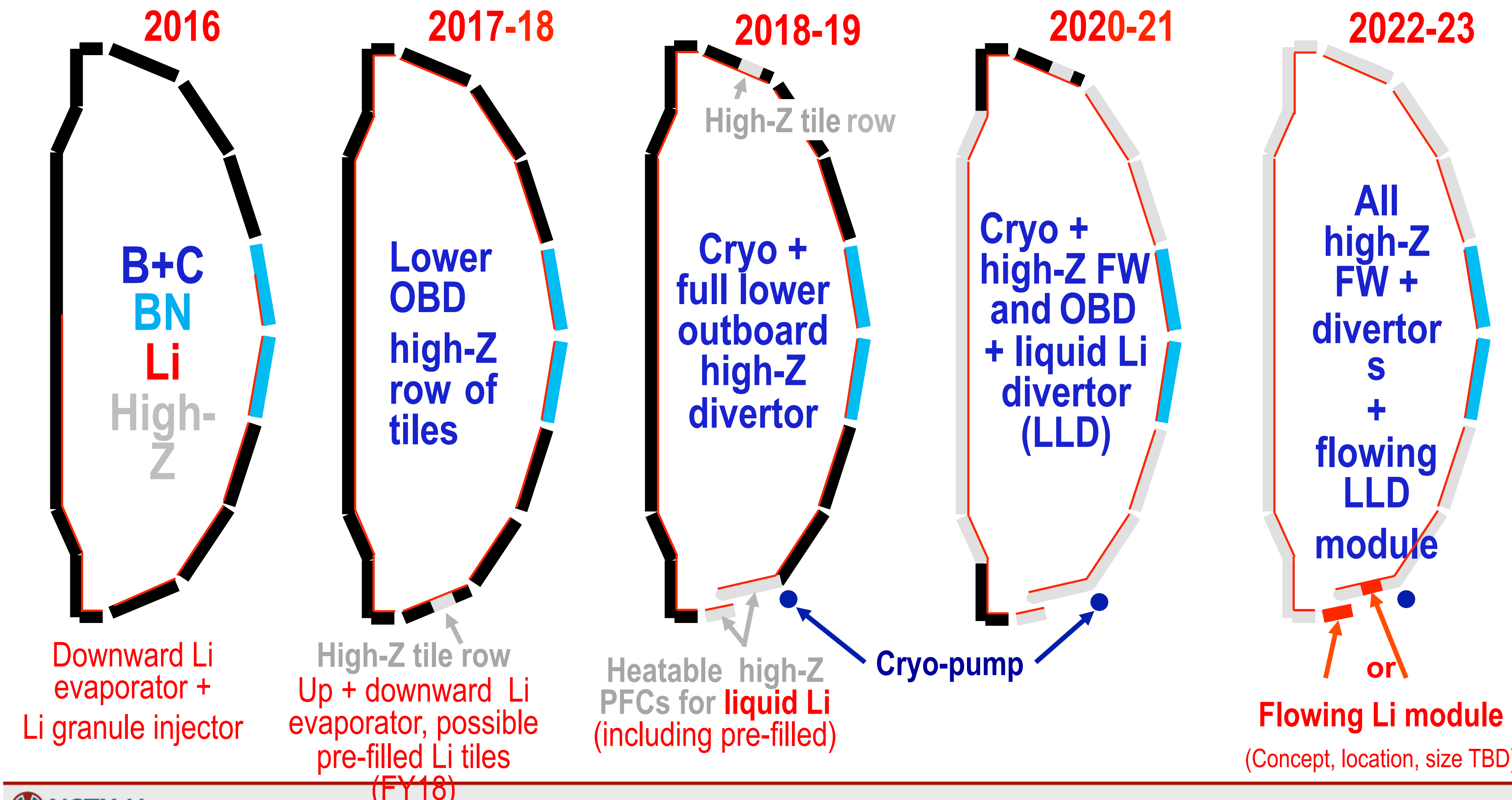
Backup

Boundary related research thrusts in the NSTX-U five year plan are being carried out in the Topical Science Groups

- Pedestal structure topical science group
  - Assess and control pedestal structure, edge transport and stability
- SOL/divertor topical science group
  - Assess and control divertor heat and particle fluxes
- Materials & PFC topical science group
  - Understand lithium surface-science for long-pulse PFCs
  - Unravel the physics of tokamak-induced material migration and evolution
  - Establish the science of continuous vapor-shielding
- Particle Control Task Force (2016-2017)
  - Establish and compare long-pulse particle control methods

NSTX-U boundary / PFC plan: add divertor cryo-pump, transition to high-Z wall, study flowing liquid metal PFCs

- 5yr goal: Integrate high τ_E and β_T with 100% non-inductive
- 10yr goal: Assess compatibility with high-Z & liquid lithium PFCs



Five Priority Research Directions were identified in the 2015 PMI community report

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

Four crosscutting research opportunities identified

- **Enhanced exploitation of existing machines for PMI issues**
  - Leverage existing investments with new PMI diagnostics, targeted upgrades, enhanced PMI dedicated run time; new staff expertise, enhanced modeling and simulation (SOL, etc.)
  - Opportunity to integrate boundary plasma and plasma materials R&D
- **Examine long pulse PMI science issues under reactor-relevant conditions of high accumulated plasma and neutron fluxes**
  - Long pulse toroidal (international collaboration) and linear plasma devices (upgrades/new build)
- **Understand the science of liquid surfaces at reactor-relevant plasma conditions and examine the feasibility of liquid PFC solutions**
- **Develop integrated plasma-material solutions in a purpose-built Divertor Test Tokamak**
  - Provide experimental test bed to develop and test models and divertor + PFC solutions for reactor-relevant conditions

FY2017 Joint Research Target wording

Conduct research to examine the effect of configuration on operating space for dissipative divertors

- Handling plasma power and particle exhaust in the divertor region is a critical issue for future burning plasma devices, including ITER
- The very narrow edge power exhaust channel projected for tokamak devices that operate at high poloidal magnetic field is of particular concern
- Increased and controlled divertor radiation, coupled with optimization of the divertor configuration, are envisioned as the leading approaches to reducing peak heat flux on the divertor targets and increasing the operating window for dissipative divertors
- Data obtained from DIII-D and NSTX-U and archived from Alcator C-Mod will be used to assess the impact of edge magnetic configurations and divertor geometries on dissipative regimes, as well as their effect on the width of the power exhaust channel, thus providing essential data to test and validate leading boundary plasma models