NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Discussion of PFC/particle/lithium plans for NSTX-U

J. Menard

for the NSTX Research Team

NSTX Physics Meeting
PPPL – B318
Monday, January 30, 2012

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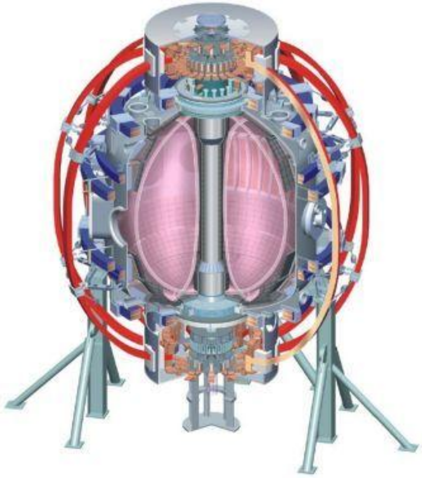

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Overview

- This presentation is meant to provide strawman plans and ideas, and motivate discussion

- **It is up to TSG groups and the NSTX-U team to modify, improve, formulate the PMI plan**

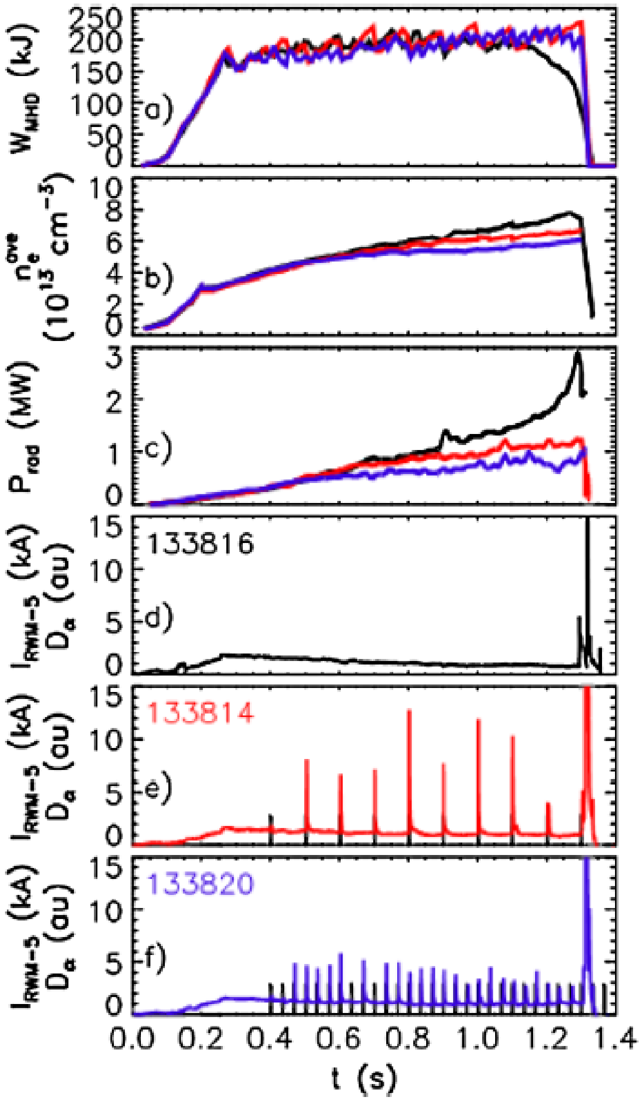
Common questions:

- How will NSTX-U control particle inventory (main ion, impurities) for long pulse lengths?

- How will NSTX-U handle very high heat fluxes at high current and heating power?

- How will NSTX-U research contribute to the development of PMI solutions for FNSF/Demo?

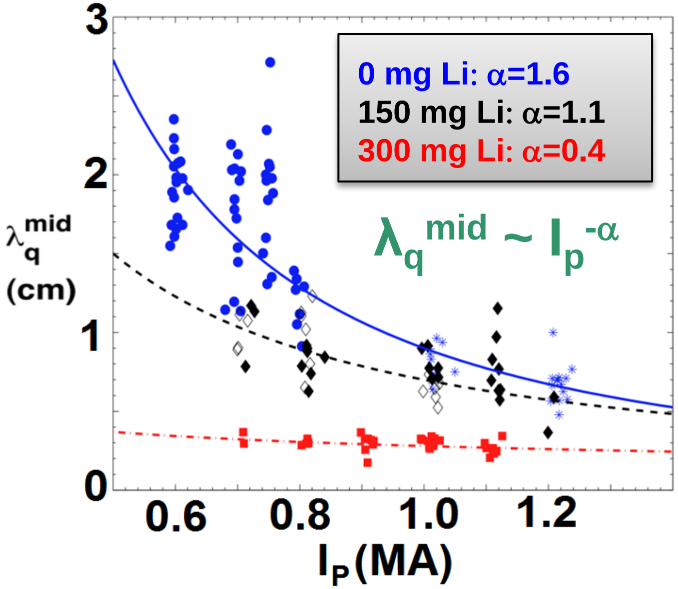
Scenarios exist which trend toward stationary D and C inventory – but how do they extrapolate?



J. Canik - PRL 104, 045001 (2010)

- Li coatings + triggered ELMs come closest to achieving stationary D inventory and Z_{eff}
- How do these results project to NSTX-U parameters?
  - Up to 5x longer pulse
  - Up to 2x higher NBI fueling
- How persistent is D pumping by Li?
  - Can we use run days where large lithium evaporation was only performed in morning, or at beginning of week, to inform the pumping persistence question?
- This issue will begin to be addressed in FY2012 BP+LR research milestone

NSTX-U scenarios with high current and power are projected to challenge passive cooling limits of graphite divertor PFCs



- High I_P scenarios projected to have narrow λ_q^{mid} → ~3mm
  - At high power, peak heat flux ≥ 9MW/m^2 even with high flux expansion ~60 with U/L snowflake
  - Numbers shown ignore radiation, plate tilt, strike-point sweeping

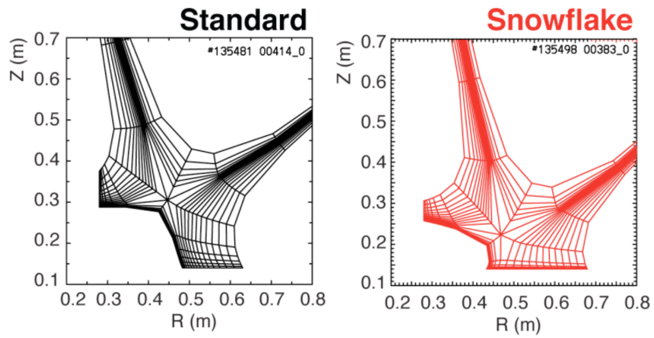
NSTX Upgrade Scenarios

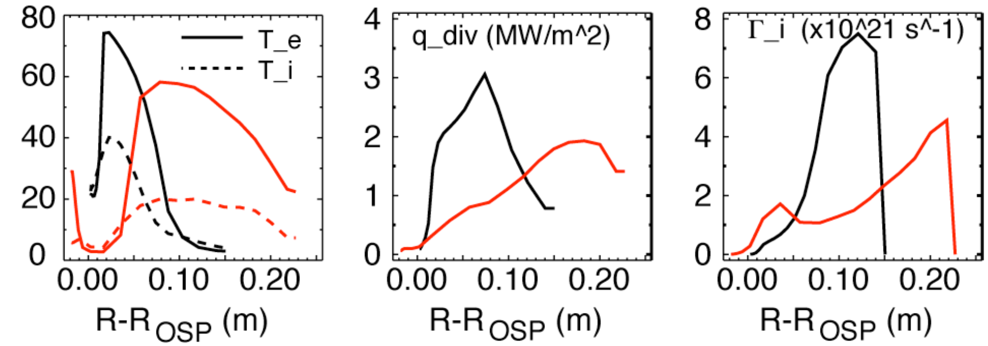
Device and scenario	NSTX-U 100% NICD		NSTX-U Long-pulse		NSTX-U Max I_P		NSTX-U Max I_P, P_{heat}		NSTX-U 100% NICD		NSTX-U Max I_P		NSTX-U High f_{BS}	
Confinement scaling	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	ST	ST	ST	ST	ST	ST
I_P [MA]	1.10	1.02	0.90	0.90	2.00	2.00	2.00	2.00	1.50	1.46	2.00	2.00	1.11	1.16
B_T [Tesla]	1.00	1.00	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Aspect ratio A	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
R_0 [m]	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Elongation κ	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
P_{NBI} [MW]	10.0	10.0	5.0	5.0	10.0	10.0	15.0	15.0	6.0	6.0	6.0	6.0	2.0	2.0
P_{RF} [MW]	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0	2.0	2.0
P_{ind} [MW]	0.00	0.00	0.05	0.08	0.23	0.37	0.10	0.18	0.00	0.00	0.10	0.21	0.00	0.00
P_{heat} [MW]	10.0	10.0	5.05	5.08	10.2	10.4	19.1	19.2	6.00	6.00	6.10	6.21	4.00	4.00
Greenwald fraction	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00
n_e-bar [$10^{20}m^{-3}$]	0.54	1.00	0.44	0.88	0.98	1.96	0.98	1.96	0.73	1.43	0.98	1.96	0.59	1.23
I_P flat-top time [s]	5.0	5.0	10.0	10.0	5.0	5.0	0.3	0.3	5.0	5.0	5.0	5.0	5.0	5.0
$\tau_{current\text{-}redistribution}$ [s]	1.04	0.57	0.65	0.37	1.37	0.79	1.83	1.05	2.41	1.13	2.23	1.05	1.76	0.81
# redistribution times	4.8	8.7	15	27	3.6	6.3	0.2	0.3	2.1	4.4	2.2	4.8	2.8	6.2
Stored energy [MJ]	0.68	0.54	0.36	0.33	0.96	1.08	1.35	1.37	1.04	1.00	1.20	1.26	0.65	0.70
β_N [%mT/MA]	5.4	4.6	4.7	4.2	4.2	4.7	5.9	5.9	6.0	6.0	5.2	5.5	4.9	5.0
β_T [%]	10.3	8.2	9.8	8.8	14.7	16.4	20.5	20.8	15.8	15.3	18.3	19.1	9.9	10.7
q*	6.8	7.3	6.2	6.2	3.7	3.7	3.7	3.7	5.0	5.1	3.7	3.7	6.2	5.9
Power fraction to divertor	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
$R_{strike\text{-}point}$ [m]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
SOL heat-flux width [mm]	7.9	8.9	10.9	10.9	3.0	3.0	3.0	3.0	4.8	5.0	3.0	3.0	7.8	7.3
Poloidal flux expansion	22	22	22	22	62	62	62	62	22	22	38	38	22	22
Peak heat flux [MW/m^2]	9.1	8.1	3.4	3.4	8.7	8.8	16.2	16.2	9.0	8.6	8.4	8.6	3.7	4.0
Time to T_{PFC} = 1200°C [s]	6.1	7.6	44	44	6.7	6.5	1.9	1.9	6.1	6.7	7.1	6.8	36	31
Fraction of T_{PFC} limit	0.96	0.76	0.24	0.24	0.97	1.00	0.94	0.95	1.00	0.91	0.92	0.96	0.16	0.19

- **Passive cooling ok for low-I_P scenarios**
- **Long-pulse + high I_P and power may ultimately require active divertor cooling**

Major goal of NSTX-U PMI research will be investigating high flux expansion snowflake + detachment for large heat-flux reduction

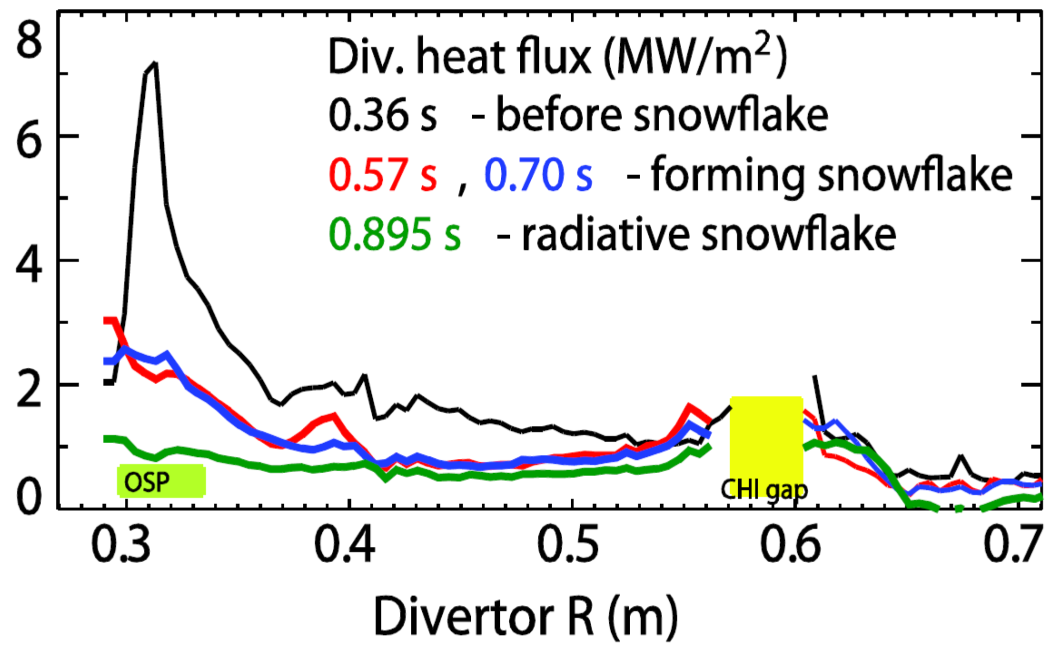
- UEDGE modeling performed comparing conventional divertor to snowflake





V. Soukhanovskii (LLNL) – EPS 2011

- Snowflake synergistic with detachment/radiative divertor
  - 5-10x peak heat flux reduction
- What are predictions for NSTX-U regimes? And for FNSF/Demo?
- Is this configuration compatible with cryo-pumping and/or lithium pumping?



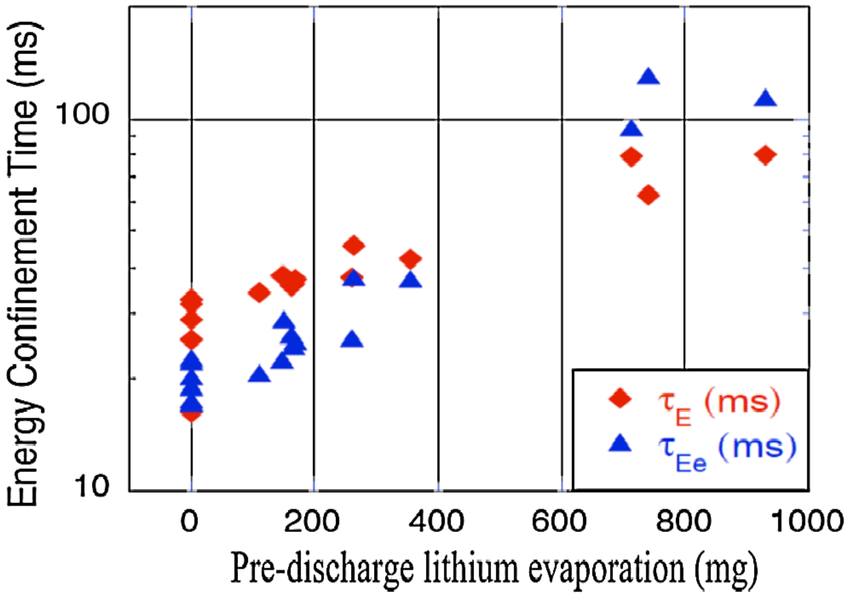
NSTX-U aims to address a wide range of PFC/PMI issues

(baseline/initial NSTX-U, *long-range goal*)

- D pumping method
  - Li coatings
  - *Cryo-pumping, flowing liquid lithium*
- Recycling, fueling techniques
  - High recycling (R_P~0.98), edge fueling
  - Intermediate/*low recycling* (R_P~0.90-0.98/*0.5-0.9*), *core fueling*
- Heat flux mitigation methods
  - High flux expansion, partial detachment/radiative divertor
  - *Flowing liquid metal, CPS/evaporative cooling, lithium radiation*
- Plasma facing component material
  - Graphite
  - *Molybdenum, tungsten*
- PFC cooling and heating
  - Passive cooling of divertor PFCs, room-temperature first-wall
  - *Active cooling/heating of divertor/first-wall (long-pulse ops/retention & diffusion)*

Lithium coatings will continue to be an important research tool for NSTX-U

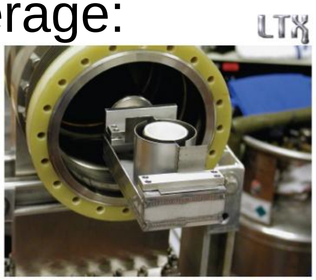
R. Maingi, et al., PRL 107, 145004 (2011)



- Energy confinement increases continuously with increased Li evaporation in NSTX
- High confinement very important for FNSF and other next-steps

what is τ_E upper bound?

- Work with LTX to understand Li chemistry, impact of wall temperature, Li coating thickness
- Assess D pumping vs. surface conditions (MAPP), lab-based surface studies, PFC spectroscopy
- Design/develop methods to increase Li coating coverage:
  - upward evaporation
  - evap into neutral gas
  - Li paint sprayer



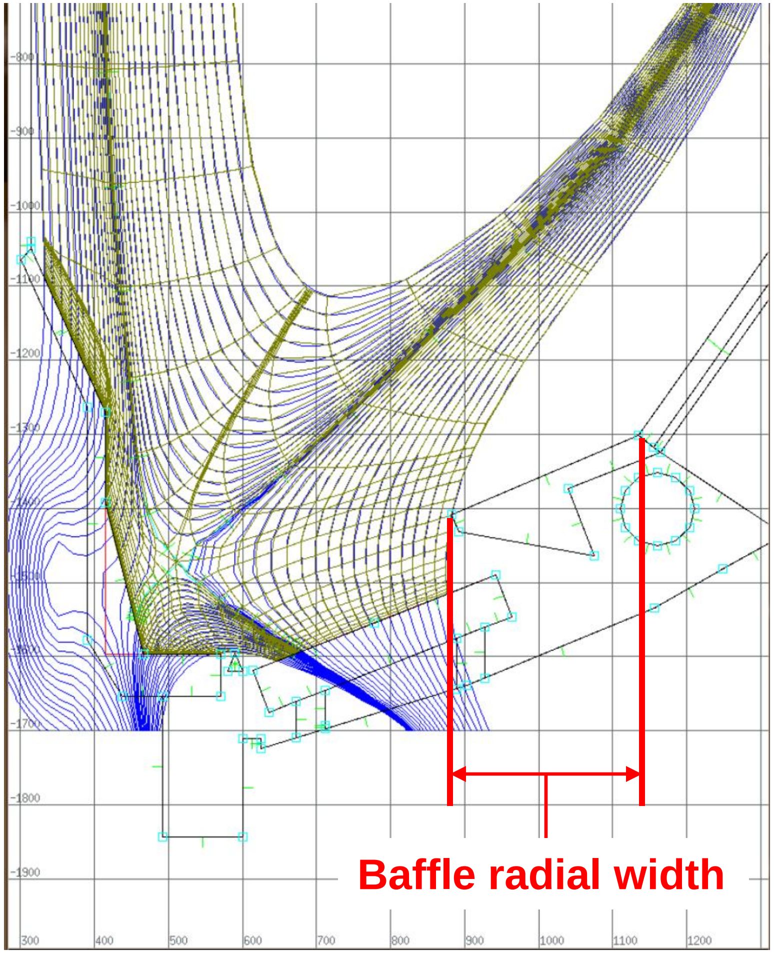
Y_2O_3 crucible, Ta heater
➢Tested to 700 °C

- Assess impact of full wall coverage on pumping, confinement
- Test Li coatings for pumping longer τ_{pulse} NSTX-U plasmas

Divertor cryo-pumping being analyzed for D particle control

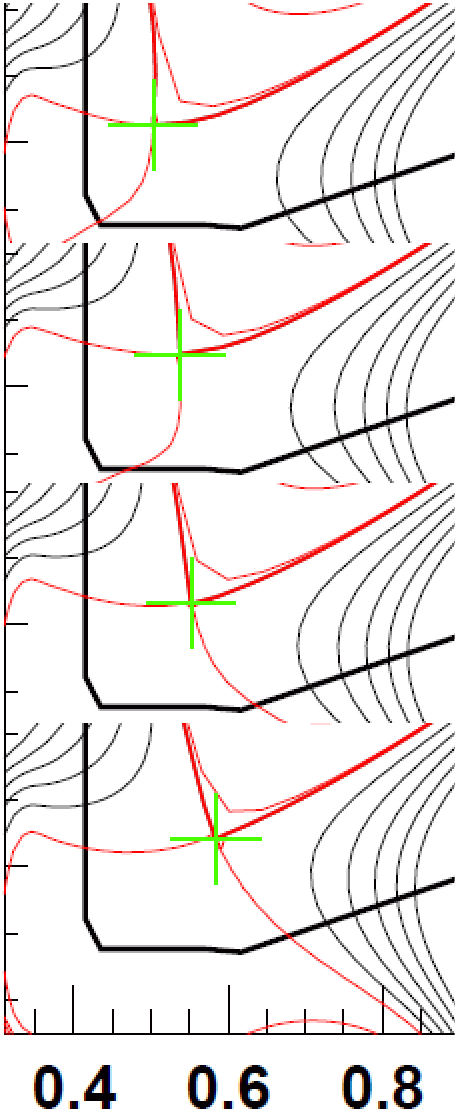
- The persistence of Li coatings for D pumping presently not well characterized
  - Unknown if Li coating will pump 5s NSTX-U
  - May be possible to extrapolate to NSTX-U using time-depdendent SOLPS analysis of NSTX discharges with Li coatings
  - Cryo-pumping and Li-coating R_P evolution to be addressed in FY12 BP milestone

- Cryo-pumping is being assessed for compatibility with NSTX-U geometry, in-vessel components, and boundary shapes desired for NSTX Upgrade operations
  - Attempting to identify designs that do not modify passive plates or supports
  - Assume divertor region will be modified
  - Length of baffle, details of pump entrance will be critical parameters to optimize



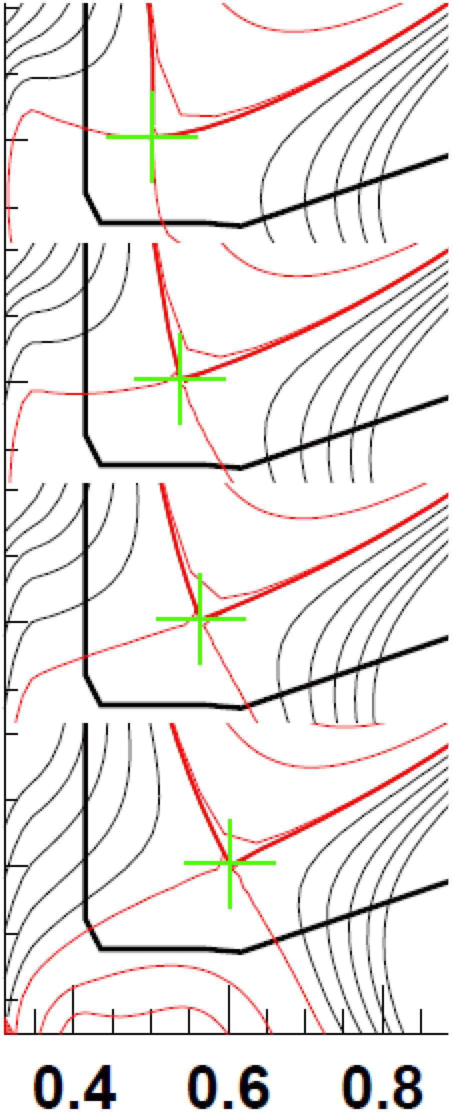
J. Canik (ORNL), D. Stotler

Divertor designs should aim to be compatible with boundary shapes most likely to be utilized in NSTX-U



Snowflake divertors ⇦

Standard divertors ⇨



- What is optimal radius for entrance to cryo-pump?
  - Estimate: R_{ent} = 0.7 to 0.85m
  - Being assessed with SOLPS
- LLD on OBD could have large surface area for particle & power exhaust
  - Potentially less sensitive to strike-point radius

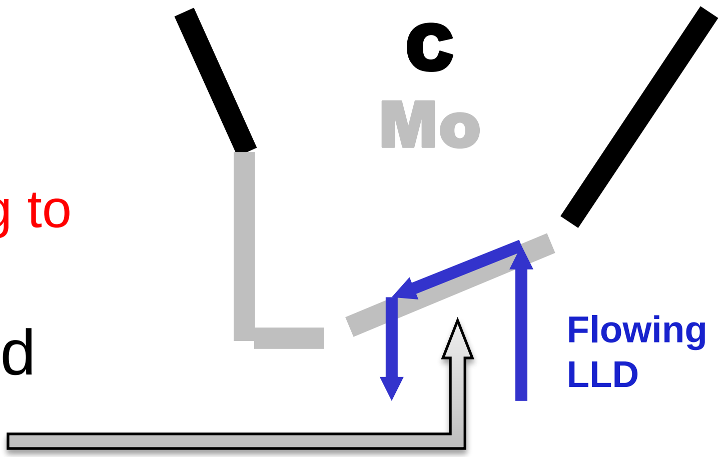
Flowing LLD development should be studied as alternative means of particle and power exhaust, access to low recycling

- LLD, LTX → liquid Li required to achieve pumping persistence
  - Flowing Li required to remove by-products of reactions with background gases
- Substantial R&D needed for flowing Li
- Need to identify optimal choice of concept for pumping, power handling:
  - Slow-flowing thin film (FLiLi)
  - Capillary porous system (CPS)
  - Lithium infused trenches (LiMIT)

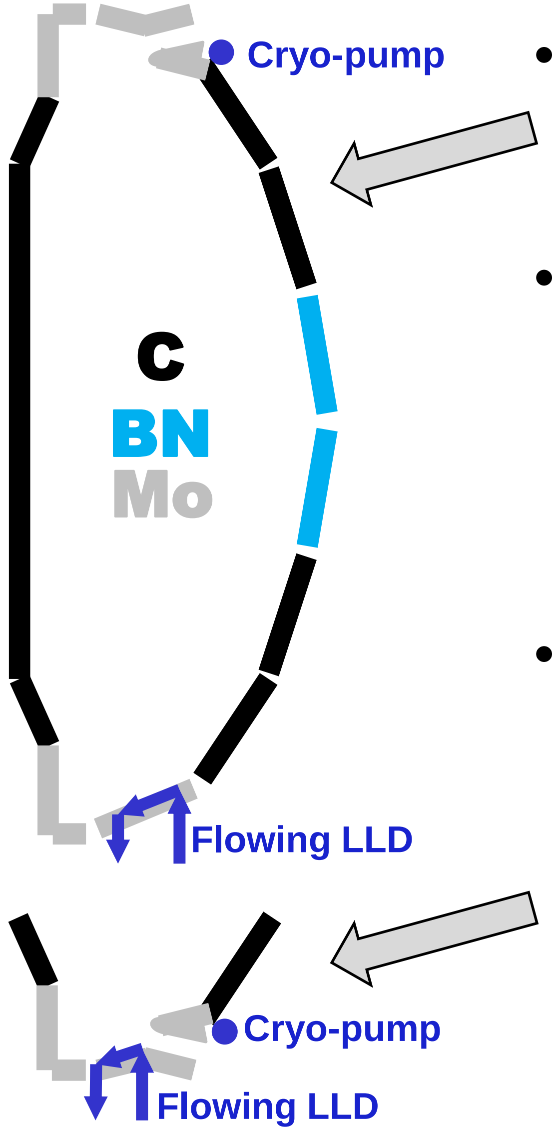
    All systems above require active cooling to mitigate highest heat fluxes of NSTX-U
- Elimination of C from divertor needed for “clean” test of LLD D pumping
  - May need to remove all C PFCs?

Possible approach:

- Dedicate 1-2 toroidal sectors (30-60° each) to LLD testing (and/or integrate with RDM?)
- Test several concepts simultaneously
- Full toroidal coverage after best concept is identified



Direct comparison of particle control from cryo-pumping and flowing LLD would greatly aid development of FNSF divertor



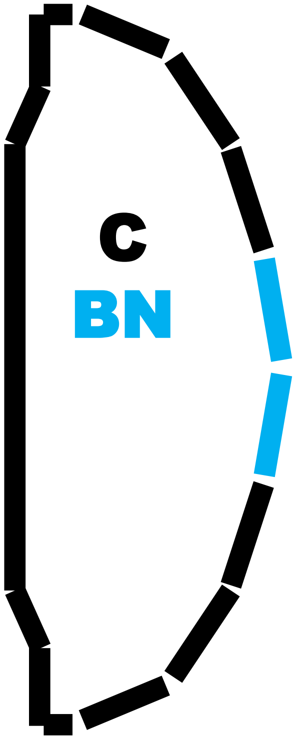
- Could dedicate upper divertor to cryo-pumping and lower divertor to flowing Li
- IF this is the preferred long-term approach, it argues for converting lower divertor to Mo tiles first to avoid re-doing upper divertor PFCs for cryo.
- If flowing LLD region is sufficiently narrow radially, it could (maybe) be combined with cryo-pumping in the same divertor:
  - Utilize cryo for D pumping?
  - Utilize flowing Li + evaporative and/or radiative cooling for power exhaust?
  - Can Li pump D while taking power exhaust?

Fueling

- Existing/baseline systems
  - LFS gas puffing, high-field-side (will have faster turn-off in Upgrade)
  - Supersonic Gas Injection (SGI) – 2-3x higher efficiency than LFS fueling
    - Not yet integrated into PCS control
  - NBI for core fueling
    - Cannot decouple from heating
    - Fueling will double at high power
- 5 year plan goals
  - Need to demonstrate particle pumping (any flavor), density stationarity
  - Need real-time density signal, algorithm, and actuator(s)
- Longer term possibilities, especially for low recycling regimes
  - Molecular cluster
  - Pellet fueling
  - CT injection
  - Plasma jets
  - Should these be part of upcoming 5 year plan?

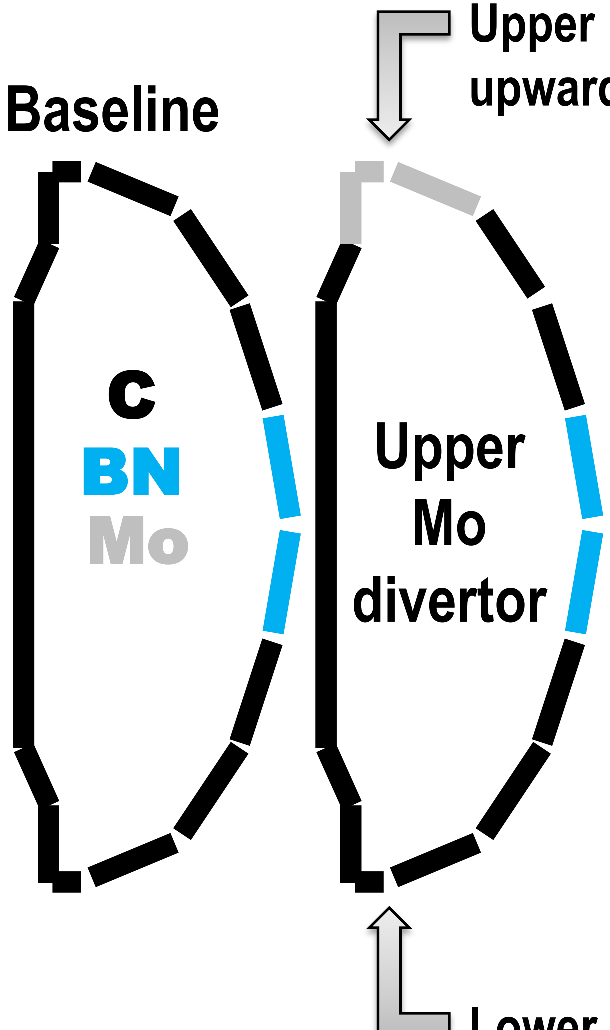
Possible progression of PFC materials in NSTX-U

Baseline NSTX-U PFCs are all C (and BN) to minimize risk and cost



- C is widely accepted to be unviable for FNSF/Demo applications due to erosion and re-deposition, retention, and neutron damage issues
- W is viewed as most viable fusion material
- Mo (TZM) has similar thermal/PMI properties to W, but is easier to fabricate and machine
- One scientific limitation of the above baseline approach is that tests of high-Z PFCs – by themselves, and with lithium – are deferred/delayed

Possible progression of PFC materials in NSTX-U

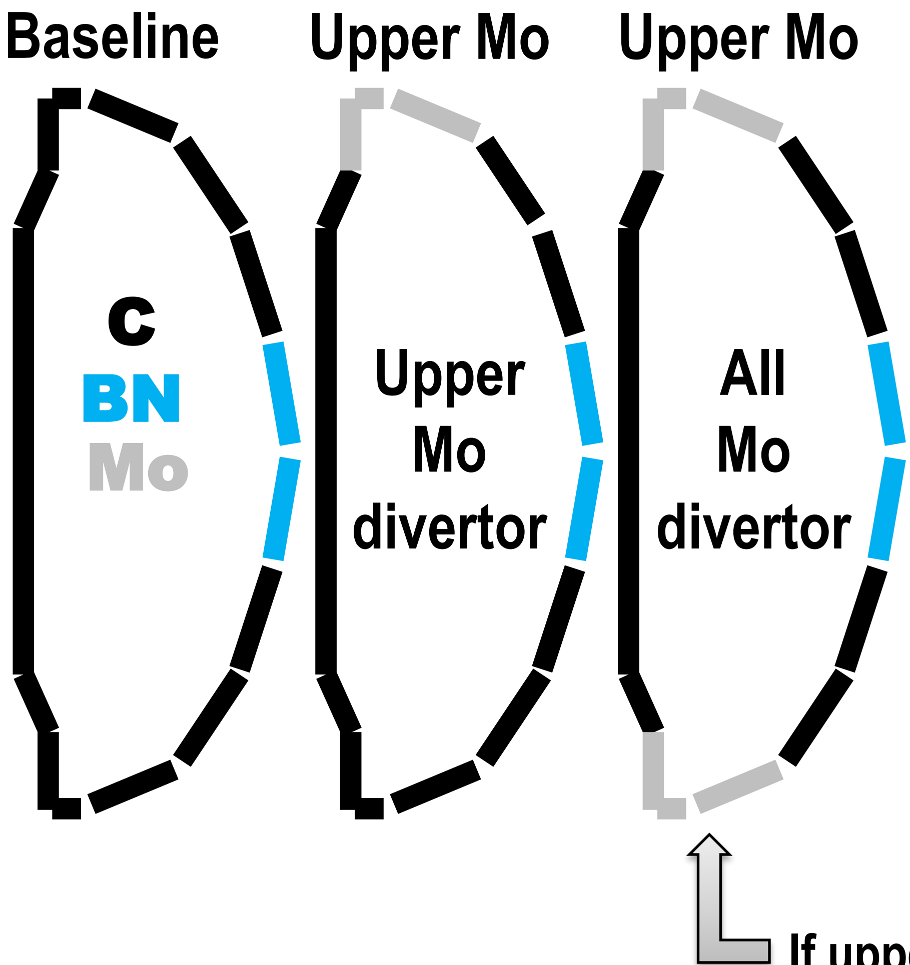


Upper Mo divertor to test Mo as PFC, Li on all Mo - requires upward Li evaporator and upper divertor diagnostics

- Having at least one divertor be all Mo (with Li coating capability) would:
  - Enable comparisons of Mo vs. C
  - Continue research planned for 2011-12, i.e. test effects of Li on Mo PFCs w.r.t. impurity production, possible temperature clamping
  - Inform/accelerate decisions for metal PFCs

Lower C divertor enables comparison to NSTX results, reduces risk of high-Z PFCs for initial physics/long-pulse ops goals

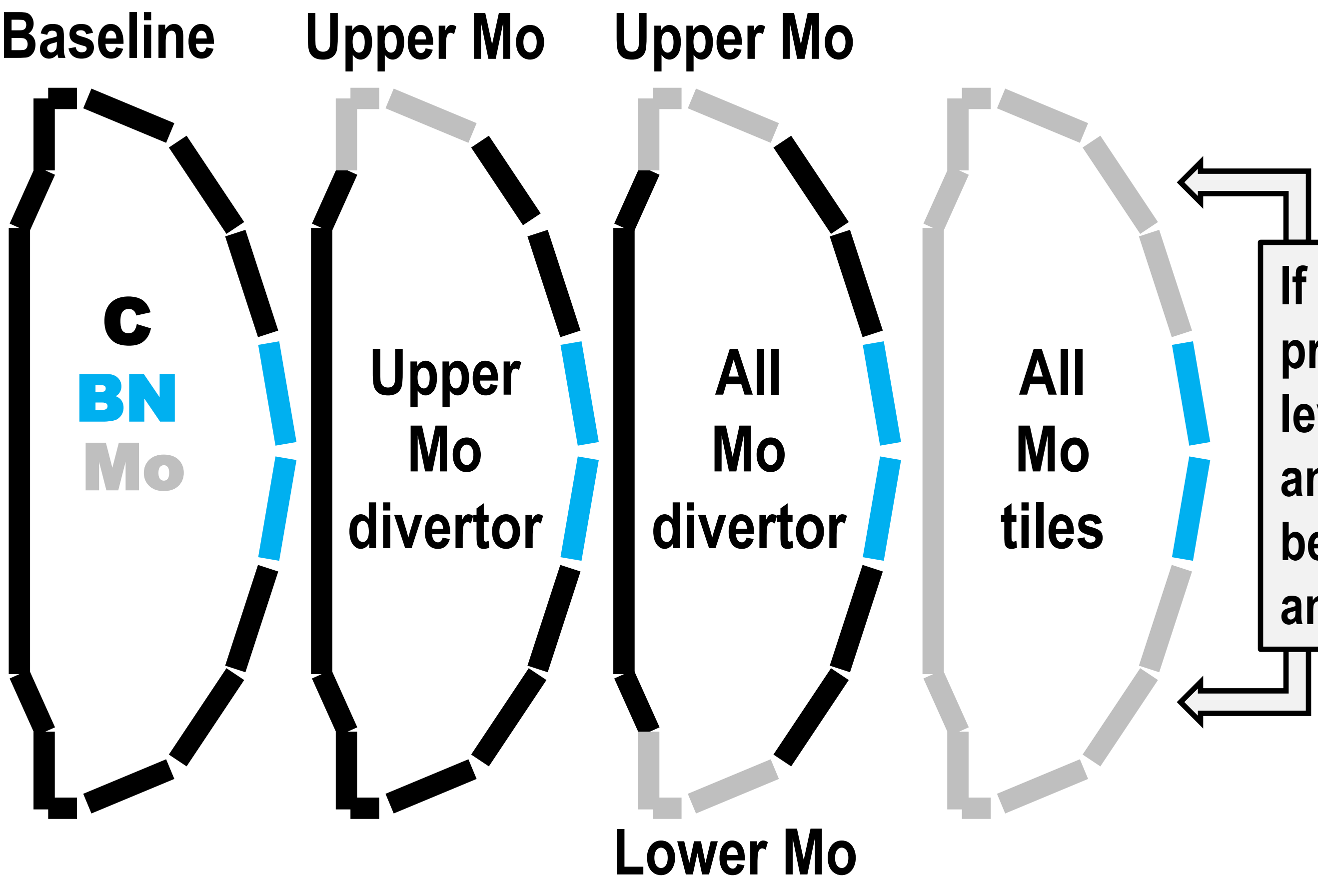
Possible progression of PFC materials in NSTX-U



- Upper and lower Mo divertor enables double-null ops on similar high-Z PFCs for comparison to all C and/or upper-only Mo divertor

If upper Mo divertor performed well, could then implement lower divertor Mo tiles

Possible progression of PFC materials in NSTX-U



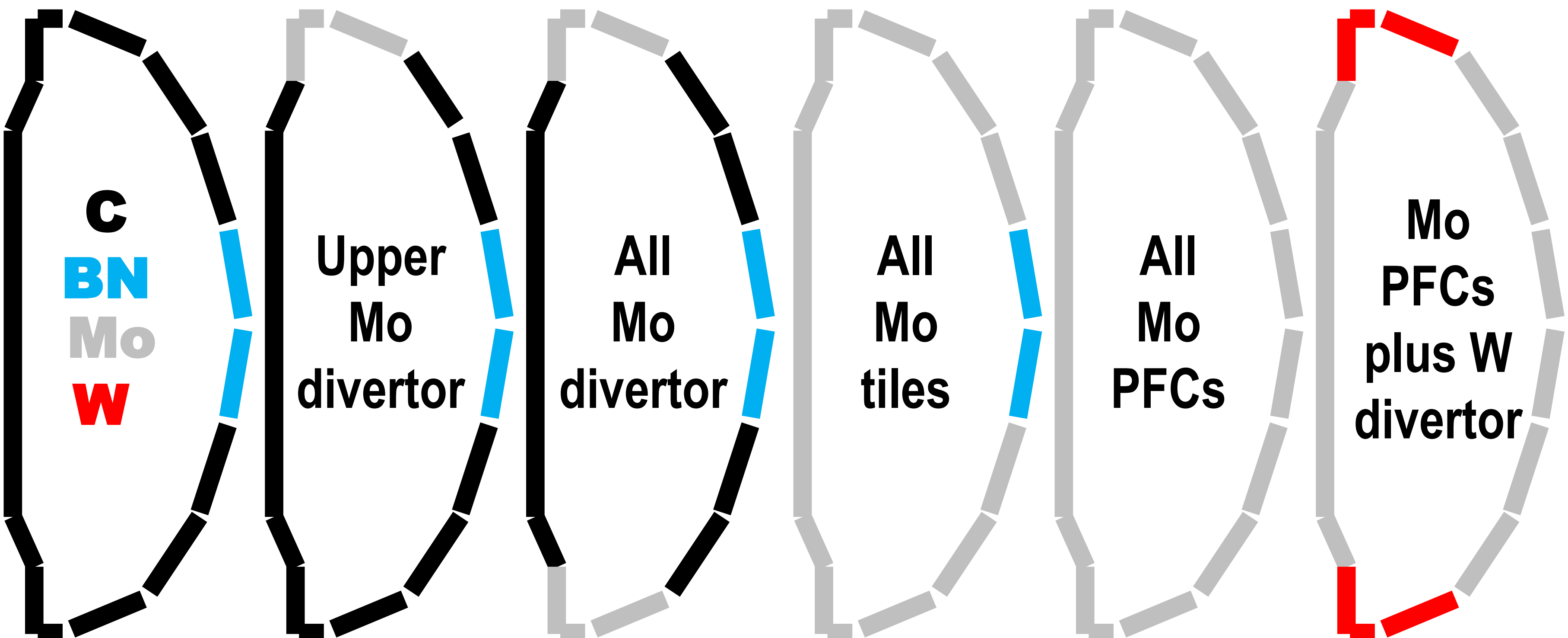
If C plasma impurities are present at unacceptable levels, all metal tiles and/or tile coatings may be needed for the CS and/or passive plates

Possible progression of PFC materials in NSTX-U

NSTX-U should ultimately progress to (nearly) complete wall coverage with metallic PFCs

Many possible progressions exist!

Baseline



All metal PFCs (especially W in divertor) are most representative of what will be used in FNSF/Demo

Beginning of 5 yr plan → **End of 5 yr plan**

Active PFC cooling and heating

- Active divertor cooling – if needed – would likely be implemented near end of 5 year plan period
  - Very little discussion of this so far…
- PFC (first-wall) heating could be useful for:
  - Study retention/diffusion of hydrogenic species (needs high T_{wall})
  - Liquid Li films over large surface areas (after changing to Mo/W PFCs)
  - Consider using bake-out systems for accessing 200-350˚C
  - Possible to go to higher temperature for FNSF/Demo relevance?
  - Unclear if this can be implemented during upcoming 5 year plan – maybe implement in subsequent 5 year plan

Summary

- Urge TSG/team discussion of these issues, as they will impact NSTX-U operation, operating space, other upgrade ideas
  - What is missing or should be modified/deleted?
- Have not yet addressed other lab-based R&D studies and proposals (such as FES materials solicitation) that could influence the NSTX-U plans and decisions
  - Such studies/proposals should be incorporated into the overall plans and work-scope for 5 year planning purposes.
    - Surface studies– collaboration with FOM/DIFFER
    - B. Koel laboratory work on Li chemistry
    - NSTX-U researcher collaborations on other fusion facilities…
    - Other?
- Once the proposed PMI plan is decided, can assess cost and schedule estimates, assign dates to the various elements