# Advanced PFC 5-Year Research Plan
# Lithium Research Topical Science Group

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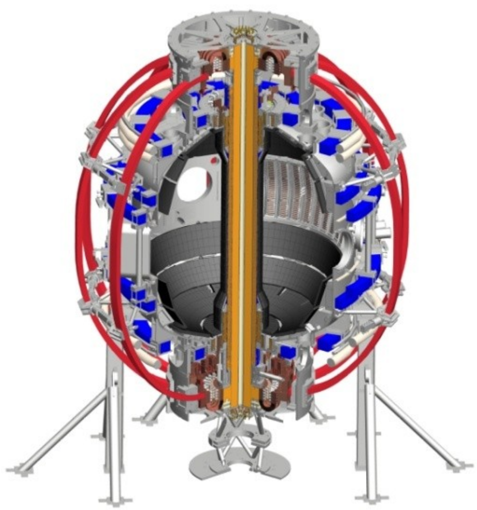
**MA Jaworski**
*C Skinner, D Stotler*

*and the NSTX Research Team*

**5-year plan planning meeting**
**B318**
**July 26, 2012**



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# Work backwards from FNSF needs, use Pilot-ST as baseline (Menard, NF 2011)

- Needs H98 ~1.35 for break-even at lowest power-plant thermal efficiency
  - Reduces auxiliary heating requirement and overall size
  - Could relax confinement requirement with larger reactor
- Needs to operate for 30% availability: robust PFCs
  - Cannot be subjected to excessive down-times
  - Are non-stationary walls even feasible in a reactor?
- Requires SOL radiated fraction of 70% and high flux-expansion divertor: heat-flux mitigation+handling by the PFC
  - Reduce divertor heat loaded
  - Develop PFCs capable of handling heat and particle load

# Extend lithium efficacy to long-pulse

- Lithium has demonstrated confinement improvements in NSTX and previous machines (e.g. TFTR, CDX-U)
  - H97L~3 recently shown by Maingi (H98,Elmy~1.4)
  - Improvement observed with increased lithium usage
  - No saturation yet found
- Solid coatings have limited lifetime due to erosion and gettering of hydrogen and impurities
  - LITER used to replenish on a shot-by-shot basis
  - NSTX-U will help establish coating life in 5s discharges (with Magnum-PSI, LTX and EAST data)
  - Must extrapolate to 30% duty factor = 9e6s for FNSF (Boron has the same issue)
- Flowing system provides means of creating "stationary conditions" on the PFCs to extend lithium efficacy

# Magnitude and location of PFC erosion problem

**Table 1**
Rough estimate of net erosion rate of main walls based on assumptions in text. Assumes 100% wall coverage by Be, B, C or W.

| Device | $P_{heat}$ (MW) | $\tau_{annual}$ (s/yr) | $E_{load}^{year}$ (TJ/yr) | Beryllium net wall erosion rate (kg/yr) | Boron net wall erosion rate (kg/yr) | Carbon net wall erosion rate (kg/yr) | Tungsten net wall erosion rate (kg/yr) |
|---|---|---|---|---|---|---|---|
| DIII-D | 20 | $10^4$ | 0.2 | 0.13 | 0.11 | 0.08 | 0.16 |
| JT 60SA | 34 | $10^4$ | 0.34 | 0.22 | 0.19 | 0.15 | 0.27 |
| EAST | 24 | $10^5$ | 2.4 | 1.6 | 1.2 | 0.82 | 1.8 |
| ITER | 100 | $10^6$ | 100 | 77 (29)[a] | 64 | 44 (53)[a] | 92 (41)[a] |
| FDF | 100 | $10^7$ | 1000 | 610 | 500 | 340 | 740 |
| Reactor | 400 | $2.5 \times 10^7$ | 10,000 | 6500 (21,000)[b] | 5300 | 3700 | 7900 (5000)[b] |

*P.C. Stangeby, et al., JNM 415 (2011) S278.*

- CX in plasma edge results in high-energy particles (~300eV) impinging wall causing sputter erosion
- Little prompt redeposition expected because of diffuse plasma present in far-SOL at the wall
- Likely to redeposit where the plasma is coolest (e.g. detached divertor targets, behind baffles)
- How the “slag”/redeposited layers affect PFC operation is unknown

# Improve component lifetime by eliminating net erosion/redeposition effects

- Estimates made of wall erosion in ST-pilot based on Stangeby methodology
  - Pheat = 253MW, 30% of year → 1800 kg/yr eroded tungsten
  - Surface area of wall ~ 260m2
  - Wall erosion rate: 0.4mm/yr @ 30% duty cycle
  - Wall area / divertor area ~ 45
  - 100% redep on divertor → 17mm/yr growth
- If 5mm net is criteria before replacement, divertor will last ~4 mos.
- Exact fate of eroded material needs more study as these are only simple estimates
- Liquid metal PFC can replenish (remove) net eroded (deposited) materials eliminating continual component evolution
- Effect of transient melting of a solid PFC eliminated
- Estimates of per-shot erosion/redeposition indicate single NSTX-U 15MW, 5s discharge should be quantifiable with QMB systems

# Reduce scrape-off layer heat flux to target

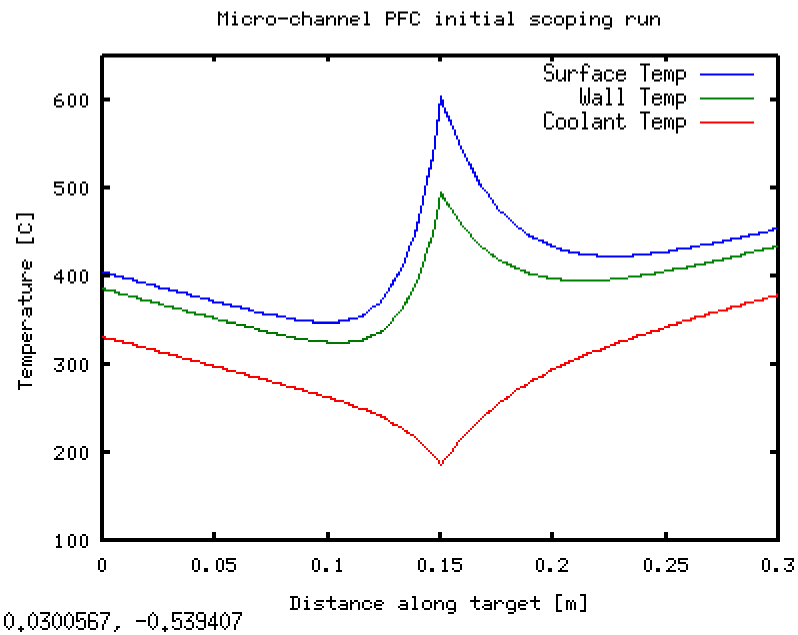
- Experiments have indicated lithium is able to radiate significant power in the SOL
  - Modeling by Rognlien and Mirnov indicated ~1keV/ion*
  - FTU, T11-M show reduced limiter heat fluxes
  - NSTX has similar indications of reduced heat fluxes
- Steady-state power loading in the divertor leads to significant surface temperatures
  - 550-600C for 10-12MW/m2 peak incident heat fluxes with advanced cooling scheme/PFC design
  - Some modeling indicates this should not be stable (Brooks, Rognlien), but FTU operates in this regime
  - Evaporation alone removes 2.6 g/m2/s at strike point, gross erosion acts on >11 g/m2/s, nominal 300mg LITER deposition is 0.15g/m2
- Liquid flow to strike-point would maintain sufficient lithium in this area for a continuous supply of low-Z radiator material into the SOL

**Debated results*

# Unique operating regime likely for liquid lithium PFCs

- Divertor heat fluxes likely to result in >400C temperatures for any PFC
  - At right, 10MW/m2 exponential + 2MW/m2 radiative heating background
  - Temperature peaks at 600C
  - Other regions will be cooler and could still absorb incident fluxes
- Sputtering enhancement and significant evaporation expected at these temperatures
- Most machines and codes look at minority-impurity quantities

**Strong evaporation/erosion will be new regime unique to liquid lithium PFCs**




***PPPL LDRD activity R035 – next-step actively wetted/actively cooled LM-PFC development***

# NSTX-U studies to determine LM-PFC viability for FNSF-ST/Pilot-ST (Extension to long-pulse)

- Extend lithium efficacy with additional evaporator coverage and laboratory R&D to field LM-PFCs
  - Continue confinement/collisionality studies with coatings
  - Determine requirements for lithium efficacy through laboratory R&D
  - Optimize LM-PFC design for long-pulse, sustained high performance discharges
- Improve component lifetime with LM-PFC usage
  - Measure wall fluxes and assess local and machine-wide migration of solid coatings in preparation for LM-PFC deployment
  - Demonstrate LM-PFC robustness against SOL plasma bombardment before going to full toroidal coverage
- Sustained lithium presence in divertor for frad>=0.7
  - Begin studies with coatings to understand existing lithium effects on SOL power balance
  - Improve modeling/plasma description in minority impurity plasmas and extend models to significant impurity fractions
  - Test models against LM target (thick coatings, flowing PFC) to extrapolate to FNSF

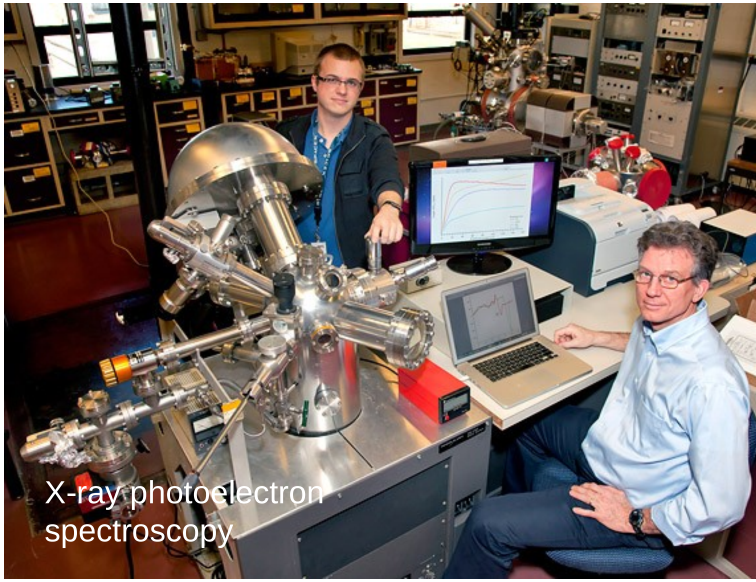
# Liquid metal surface science

To date:

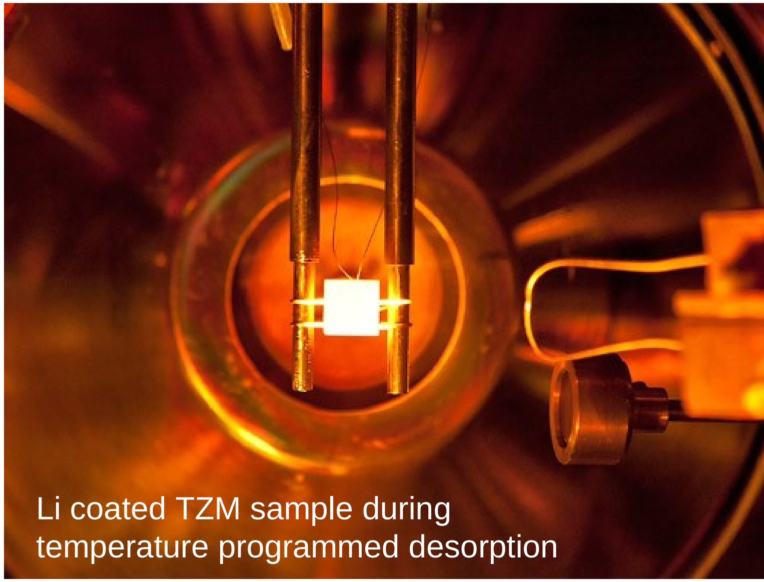
- Oxidation times for Li and Li-coated TZM surfaces exposed to tokamak residual gases measured (J. Nucl. Mater., submitted).

Plan

- Oxidation of Li-coated single crystal Mo
- Measurement of $D_2$, $D^0$, $D^+$ uptake of solid and liquid Li-coated Mo, TZM, C films using new ECR plasma source, before and after surface oxidation by residual gas.
- Investigation of surface coverage (wetting) vs. temperature and oxide contamination using the 30-nm resolution and elemental discrimination  of scanning Auger microscope.
- Extend to oxidation and wetting of Ga and Sn.
- Help provide a design basis for developing advanced liquid metal PFCs for NSTX-U.



X-ray photoelectron spectroscopy

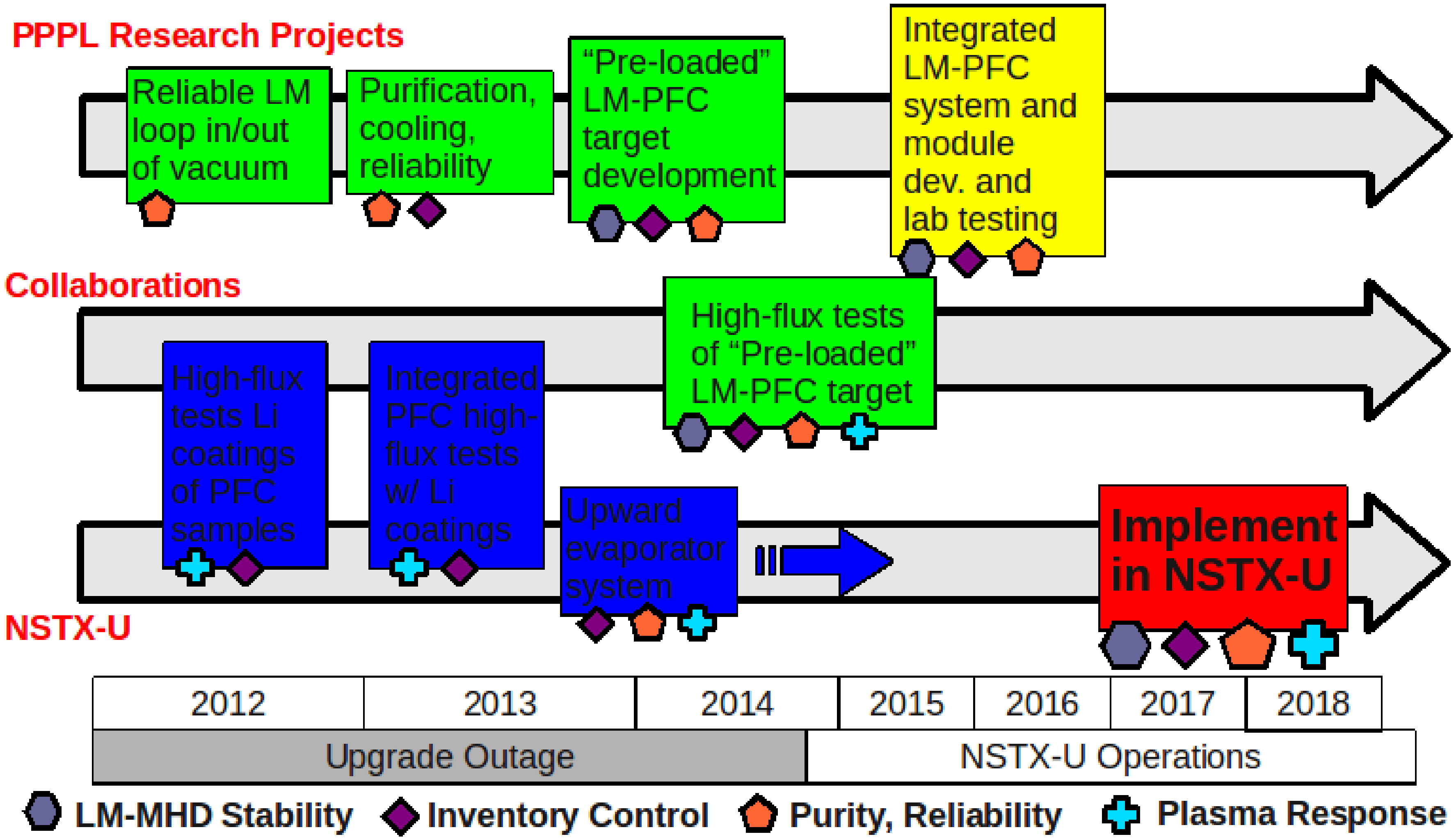


Li coated TZM sample during temperature programmed desorption

# Main Research Needs for Implementing Liquid Metal Plasma Facing Components

- **Need 1:** Demonstrate stability of the LM surface
  - Design against ejection events and substrate exposure.
  - **Near-term strategy: Emphasize capillary-restrained schemes**
- **Need 2:** Establish control over the in-vessel inventory of liquid metal
  - Control evaporation and condensing surface locations and material collection
  - **Near-term strategy: Leverage existing active cooling technologies for thermal control while developing next-step schemes**
- **Need 3:** Develop adequate means of maintaining the liquid metal
  - Perform efficient purification and establish robust operation and maintenance
  - **Near-term strategy: Learn from IFMIF and develop robust, maintainable systems from day 1**
- **Need 4:** Understand plasma response and physics of LM-PFC
  - Develop descriptive and prescriptive models for the SOL/PMI of LM-PFCs
  - **Near-term strategy: Validate fluid and kinetic codes and databases against available linear-machine data as well as tokamak database**
- **Develops engineered, LM-PFC modules to a significant technology maturity for implementation in NSTX-U or other devices**

# Near-Term Development Path to Address Research Needs and Implement in NSTX-U



# Backups

# High-Z PFC development as parallel track with LM-PFC development

- LM-PFCs still require a substrate material that will likely be a high-Z metal
- Erosion/redeposition can equally be studied for solids as for liquids with the same diagnostic tools
- Removal of high-Z substrate impurities after lithium coating/flow important marker indicating success of LM approach (i.e. protection of substrate materials)
- FNSF/Pilot-ST still places goals for power handling and confinement/performance whether the PFC is LM or solid

# Solid PFCs may not extrapolate to a reactor, neither may liquids

- Solid PFCs (tungsten) is the leading candidate but may not extrapolate to an attractive power reactor
  - Well studied - many years of solid PFC work
  - Neutron damage may introduce new failure modes
  - Net erosion/deposition difficult to predict and control
  - Transients can melt and permanently deform PFC
- Liquid PFCs (Li, Sn, Ga) may solve many problems for solids but are not technically advanced enough to know for sure
  - Net erosion/deposition is replaceable by liquid flow
  - Thermal stress, neutron damage non-existent
  - Flowing systems not implemented on a large scale divertor
  - Large-area, high-temperature lithium compatibility with good core performance has not been experimentally demonstrated
- Interestingly, liquid flow over tungsten substrate may be unique way to eliminate net erosion and flaking to help make tungsten work
- **Significant uncertainties in both approaches makes it difficult to defend down-selection at this time**

# Movable mid-plane limiter for initial implementation

- Nominal year 3-5 goal is to test flowing Li-PFC toroidal sector in NSTX-U, possible full toroidal coverage
  - Represents significant leap in current technology to go straight to LLDT (liquid lithium divertor target)
  - Offline testing is a must. Degree of integrated testing on a test-stand depends on funding/support
- Staged integration into the tokamak with mid-plane limiter poses the least risk to operation
  - Divertor targets are critical to operation, RDM requires significant vessel alteration or multiple degrees of freedom (DOF)
  - Mid-plane limiter can be retracted if there's a problem
  - Could test solid-based PFCs with inter-changeable target
- Provides additional diagnostic opportunities
  - e.g. Far-SOL particle fluxes (LPs), material migration and net erosion (QMBs)

# Liquid metal PFCs should be pursued to mitigate risk of tungsten not extrapolating to fusion reactor.

*PAC-31 Slide*

- Recent FESAC report: "The uncertainty in establishing PFC solutions is high, as the environment is severe and the requirements for long lifetime are challenging."
  - Tungsten is leading candidate but has issues with neutron damage, erosion, melting, brittleness, thermal fatigue.
- ReNeW highlighted that DEMO PFCs are much more challenging than ITER's.
  - advocated substantial program to assess new ideas, incl. liquid metals (Li, Sn, Ga).
  - No neutron damage, erosion, thermal fatigue in liquids – but technical base less mature.
- Importantly, liquid flow over tungsten substrate may be unique way to eliminate net erosion and flaking to help make tungsten work
- **Liquid PFCs have potential to relieve over-constrained problem: they do not need to *simultaneously* satisfy plasma and nuclear loading constraints.**
- Significant uncertainties in both approaches suggest both W and liquids should be investigated
- ReNeW recommended: "*Liquid surface PFC operation in a tokamak environment…*"

# Pursuing multidisciplinary approach to developing liquid metal PFCs for NSTX-U, FNSF and beyond

PAC29-5c

PAC29-18

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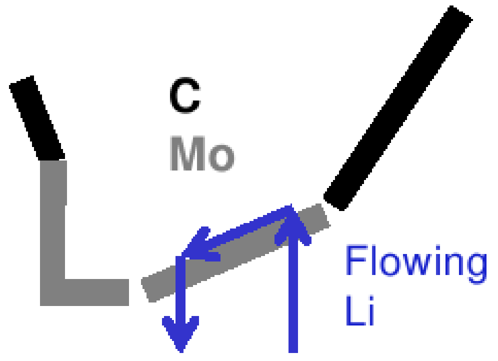
Issues: Li surface reactivity, saturation & diffusion of D in Li, impurity segregation, wetting, replenishment of Li, graphite/Mo PFC substrates, heat flux limits with passive/active cooling, recovery after vents, reliability…

Multi-scale R&D approach from atoms to PFCs,

1. Understand impact of lithium on core and edge transport and stability.
2. Assess D pumping vs. surface conditions:
   - Atomistic MD modeling (ORNL)
   - Lab expt. on ideal systems e.g. single xtal Mo + monolayer Li + $D^0$, $D^+$ beam. detailed surface analysis via XPS, AES, TPD, SAM… (Purdue / PPPL Labs)

2. Assess Heat Flux handling in linear plasma facility:
   - PFC prototype tests with high power plasmas in Magnum PSI

3. Tokamak integration:
   - XGC Kinetic modeling, non-equilibrium Li radiation
   - LTX liquid Li studies, MAPP -> LTX then NSTX-U
   - Li granule injector tests on EAST, then NSTX-U
   - Divertor Li-PFC design, then testing in NSTX-U.



# NSTX-U Plan for Years 1-5 of operation:

PAC29-5c

PAC29-18

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- Year 1-2:
  - Test Li evaporation for pumping longer pulse duration NSTX-U plasmas.
  - Test Li evaporation to upper vessel by evaporator/injector, He diffusion, electrostatic sprayer.
  - Assess impact of full wall Li coverage on pumping, confinement
  - Test ELM control by midplane Li granule injector
  - Test Li-PFC prototypes on Magnum PSI and possibly LTX or EAST
- Year 2:
  - Down select to best flowing Li-PFC concepts
  - Test on Magnum PSI and LTX or EAST
- Year 3-5:
  - Test flowing Li-PFC on at least one toroidal sector of NSTX-U, possibly full toroidal coverage system, pending lab-based tests and modelling

# Summary:

PAC-31 Slide

- Li PFCs have demonstrated promise for
  - Superior plasma performance
  - High heat flux handling
  - May solve PFC neutron damage and erosion issues in FNSF and demo.
- High confidence implementation requires R&D on:
  - Surface chemistry
  - Off-line heat flux tests of PFC prototypes
  - Tokamak integration
- Staged approach in place from atomistic simulations & lab experiments to test stands, LTX, EAST collaborations, leading to Li-PFC implementation in NSTX-U