NSTX Upgrade: ST research to accelerate fusion development

Jon Menard (PPPL)

For the NSTX-U Research Team

FESAC Strategic Planning Panel Meeting

July 8-10, 2014

Coll of Wm & Mary
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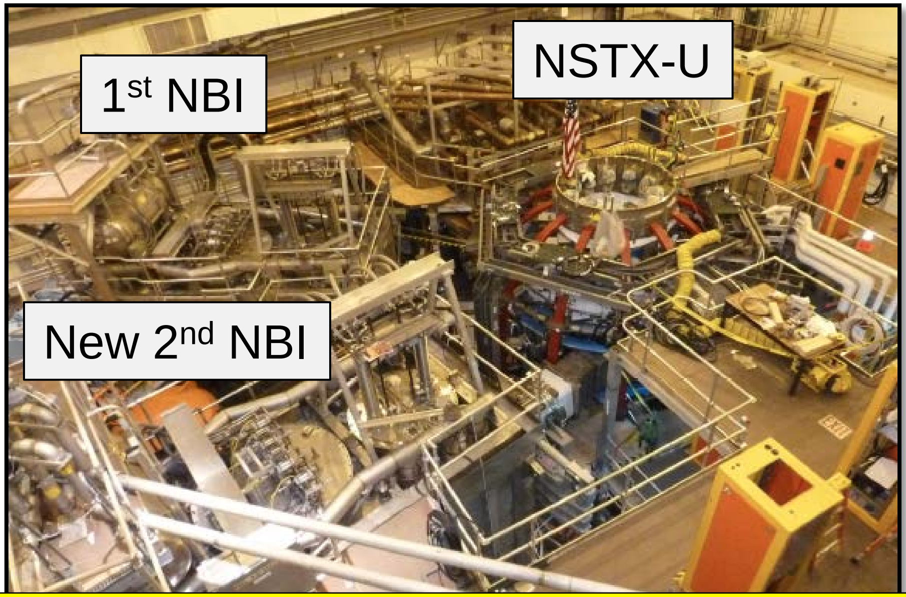
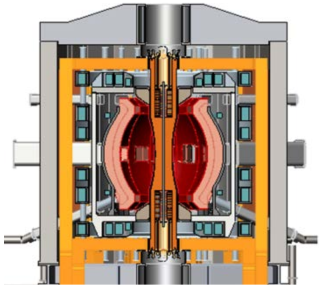


Upgrade Project: ~90% complete, 1st plasma ~Jan 2015

Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

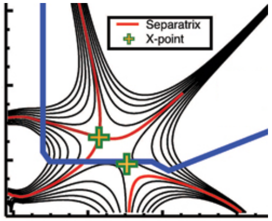
NSTX Upgrade mission elements

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)



ST-FNSF

- Develop solutions for the plasma-material interface challenge

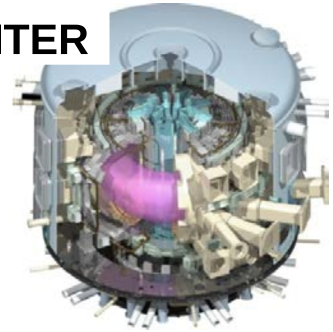


Snowflake/X

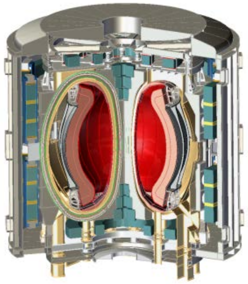
Liquid metals/Li

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

ITER



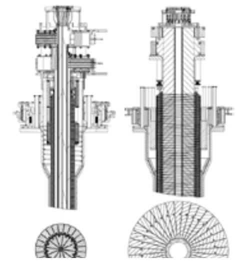
- Develop ST as fusion energy system



NSTX-U will provide world-leading research capabilities across all 5 ReNeW Themes

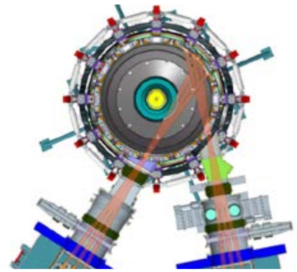
NSTX → NSTX-U performance:

- B_T = 0.5 → 1T, I_P = 1 → 2MA
- P_{NBI} = 5→10MW, t_{pulse} = 1→5s
- Full non-inductive at ~1MA

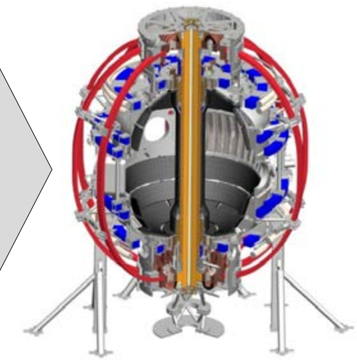


Previous New
Center-stack

+



Present New 2nd
Neutral Beam Injector (NBI)



NSTX-U contributions to ReNeW Themes:

Theme 1. Burning Plasmas in ITER
- ➢ **Access, understand, control non-linear Alfvénic instabilities**

Theme 2. Predictable, High-Performance, Steady-State Plasmas
- ➢ **Goal: 100% non-inductive operation with high-β_T ~15-20%, profile control**

Theme 3. Taming the Plasma-Material Interface
- ➢ **Leader in Li PFCs, integration: core + snowflake + detachment + high-Z + Li**

Theme 4. Harnessing Fusion Power
- ➢ **Leader in physics basis and design of low-A fusion systems**

Theme 5. Optimizing the Magnetic Configuration
- ➢ **NSTX-U most capable ST facility in world for assessing ST for FNSF**

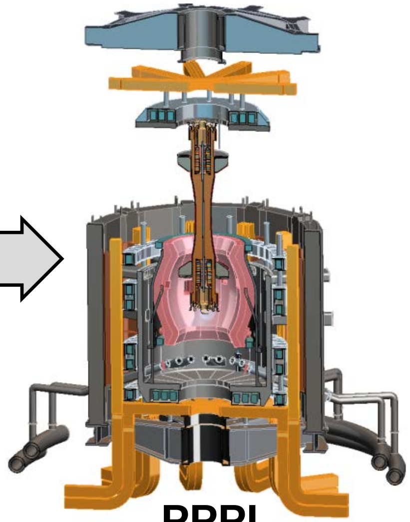
NSTX-U + DIII-D provide world-leading development of ST, AT for FNSF

Spherical Tokamak (ST) is potentially attractive as Fusion Nuclear Science Facility (FNSF)

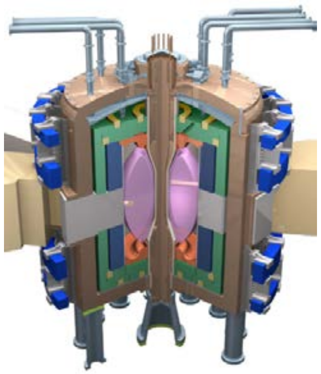
- Projected to access high neutron wall loading at moderate R_0, P_{fusion}
  - W_n ~ 1-2 MW/m^2 , P_{fus} ~ 50-200MW, R_0 ~ 0.8-1.8m
- Modular, simplified maintenance
- Tritium breeding ratio (TBR) near 1
  - Requires sufficiently large R_0, careful design

- Challenges/Gaps: (FESAC-TAP, ReNeW)
  1. Non-inductive start-up, ramp-up, sustainment
     - ➢Low-A → minimal inboard shield → no/small transformer
  2. Confinement scaling (especially electrons)
  3. Stability and steady-state control
  4. Divertor solutions for high heat flux
  5. Radiation-tolerant magnets, design (backup)

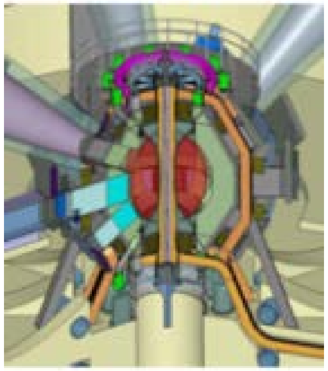
Example ST-FNSF concepts



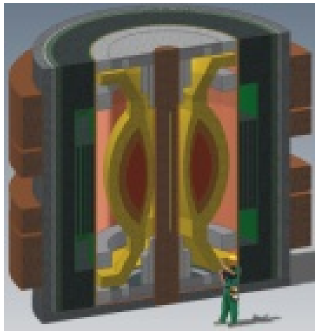
PPPL



ORNL



Culham (UK)



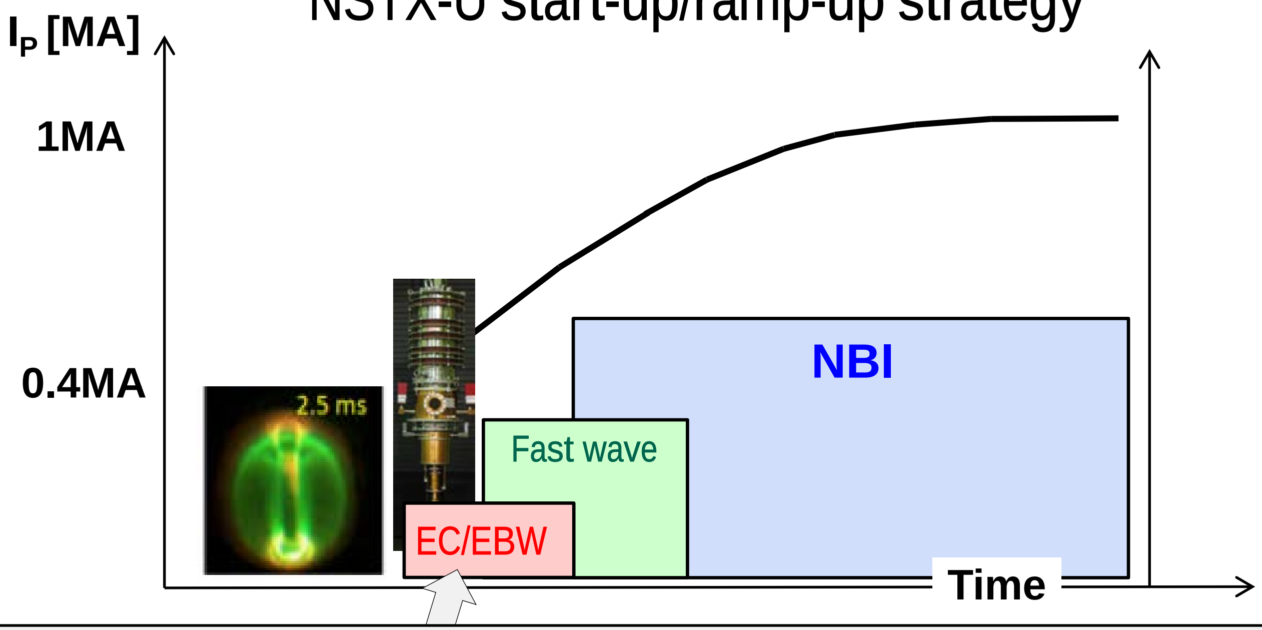
UT Austin

Gap 1: Start-up/ramp-up with small/no transformer

Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- Helicity injection (HI) start-up: 150-200kA → projects to ~0.4MA on NSTX-U
- New 2nd NBI projected to enable non-inductive ramp-up from ~0.4 → 1MA
- HI-start-up T_e, n_e too low for fast-wave, NBI coupling → need ECH to raise T_e

NSTX-U start-up/ramp-up strategy



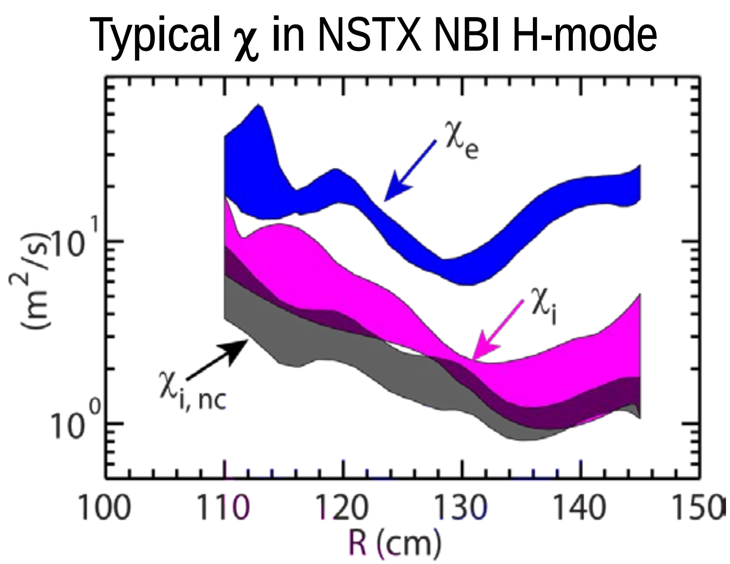
- 1 → 3MW 28GHz (with 2nd NBI) → world-leading start-up/ramp-up for ST/AT
- EBW: efficient off-axis current drive for over-dense ST/RFP/AT plasmas

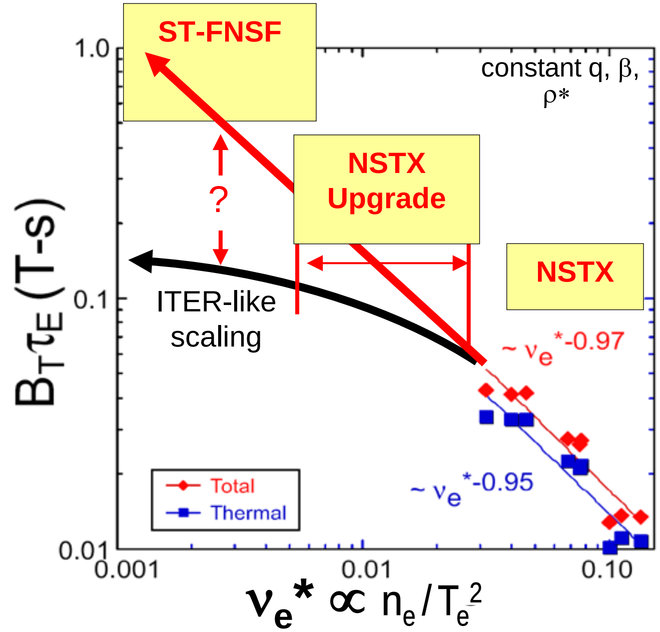
➢ See Raman Whitepaper: "Simplifying ST and AT Concepts"

Gap 2: Understand/optimize ST energy confinement

Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- Ion thermal transport ~neoclassical, electrons dominate transport ($\chi_e >> \chi_i$)
- High-β → electromagnetic turbulence (μ-tearing, Alfvénic, kinetic ballooning)
- Confinement scaling: $B\tau_E \sim \nu^{-0.9}\, \beta^{-0.2}$ differs from ITER-98y,2 $\sim \nu^{0}\, \beta^{-0.9}$





- Need to understand transport vs. β, ν^* to reliably project to FNSF (ST or AT)
  - Advanced diagnostics: beam emission spectrosc., high-$k_{r,\theta}$, polarimetry, Doppler back-/cross-polarization scattering
  - Density and ν^* control tools: lithium wall coatings, ELM pacing with Li granules and RMP, divertor cryo-pump

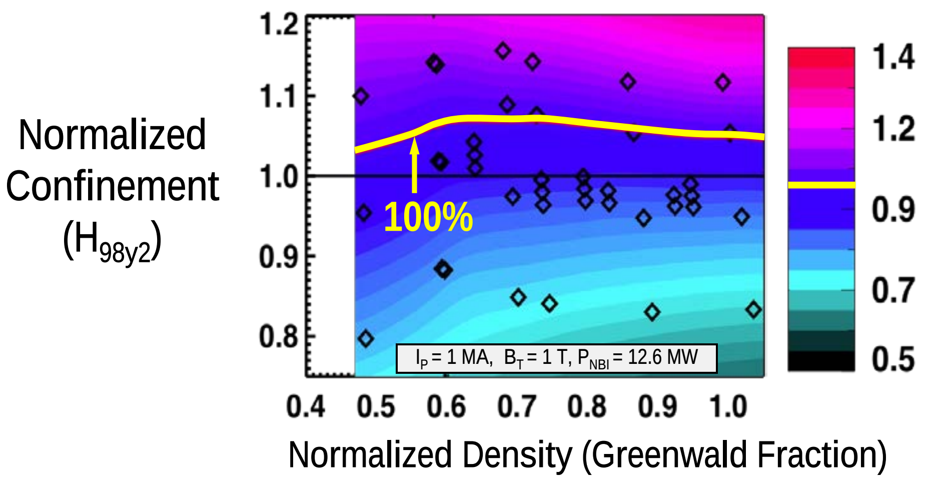
➢ See Guttenfelder/Crocker whitepaper "Validating EM turbulence/transport effects for burning plasmas", also A. White whitepaper

Gap 3: Plasma sustainment, stability, and control

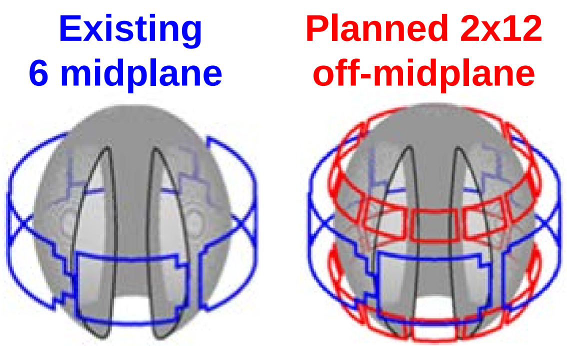
Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- NSTX achieved ~65% non-inductive current drive at FNSF-level β_T ~ 15-20%
  - TAE modes can cause redistribution/loss of NBI, higher B_T & off-axis NBI should help mitigate
- NSTX-U designed for 100% non-inductive from tangential 2nd NBI + bootstrap
- Achieved β_N ~ 6, need to integrate with full non-inductive, avoid disruptions

NSTX-U Contours of Non-Inductive Fraction



Non-axisymmetric Control Coils (NCC)



Simultaneous control of: rotation, EF, RWM, ELMs, EP/AE

- New 3D coils would greatly aid control, disruption avoidance for ITER, FNSF
- Will also test novel disruption warning, mitigation (fast MGI, EM mass injector)

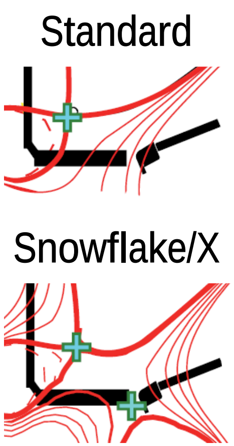
➢ See Sabbagh whitepaper on Disruption PAM, Podestá whitepaper on energetic particle/*AE control, also Strait, Buttery whitepapers

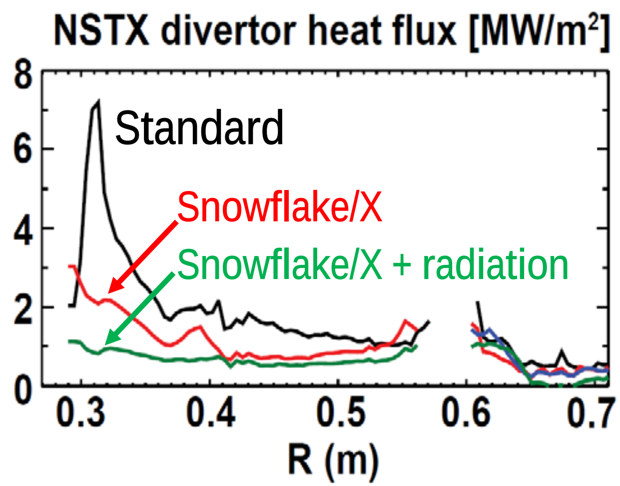
Gap 4: Divertor solutions for high heat flux
(+ core/edge integration with high-Z / liquid metal PFCs)

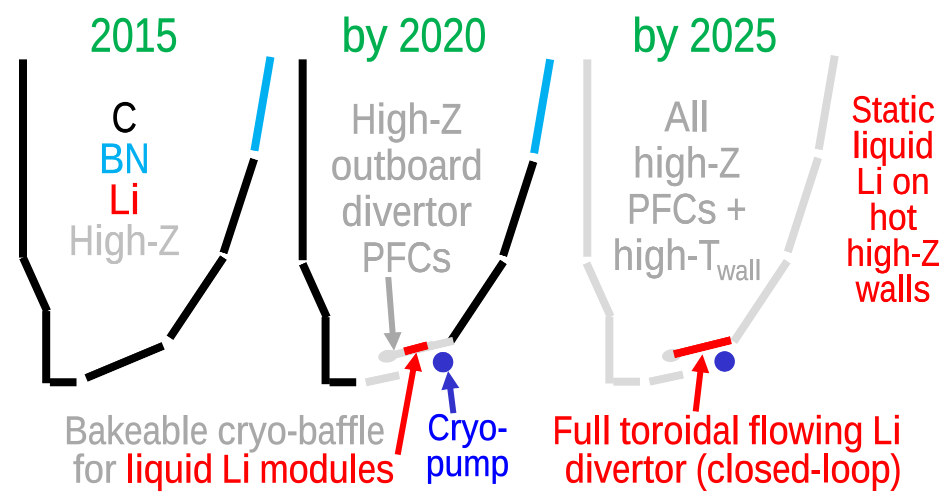
Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- High-flux-expansion snowflake/X-divertor + radiation reduce $q_{peak\text{-}div}$ up to 5×
- NSTX-U: Peak divertor heat flux ≥ 4× higher → 30-40MW/m^2 unmitigated
- Will test double-snowflake/X controllability, mitigation of very high heat fluxes

- Steady-state FNSF scenario not demonstrated in any device w/ high-Z walls
→ NSTX-U aims to integrate full non-inductive with high-Z + liquid metal PFCs

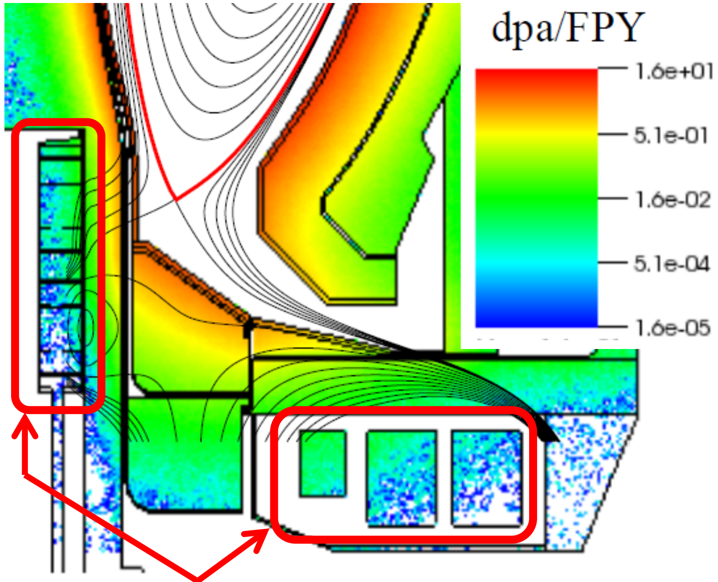


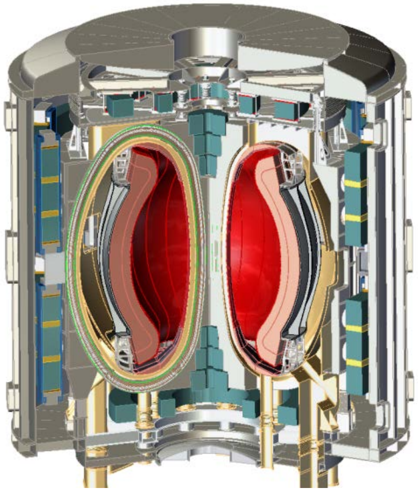




➢ See Maingi / Jaworski / Allain whitepapers on liquid metals, Hill whitepaper on FNSF PMI, ADX whitepapers

Gap 5: Radiation-tolerant magnets
(+ advanced magnet / configuration design)





- Attractive ST-FNSF configuration:
  - Ex-vessel equilibrium PF coils (6 FPY)
  - Long-leg divertor: $q_{peak\text{-}div}$ < 5MW/m^2
  - TBR = 0.95-1 for R_0 = 1.6m
- High-temp superconductor (HTS) attractive for efficient+compact ST*
- Possible missions:
  - Steady-state toroidal PMI facility
  - ST Pilot Plant (Q_{eng}~ 1), ST DEMO
- Key research need: radiation limits

**Work supported by Tokamak Energy (UK)*

- Find τ_E > 1.5× ITER H-mode needed for compact FNSF, Pilot (ST or AT)
- Recommend enhancing AT/ST FNSF design funding, include QAS, SC/HTS

➢ Endorse Majeski / LTX whitepaper for high confinement, Minervini / Whyte whitepapers on HTS R&D

5 year goal: Establish core physics/scenarios for ST-FNSF
10 year goal: Integrate high-performance core + metal walls

2015-2019	2020-2024
Establish ST physics / scenarios:	**High-performance + metal walls**
• Non-inductive start-up, ramp-up • Confinement vs. β , collisionality • Sustain high β with advanced control • Mitigate high heat fluxes • Test high-Z divertor, Li vapor shielding	• Convert all PFCs from C to high-Z • Static → flowing Li divertor module(s), full toroidal flowing Li divertor, high T_{wall} • 5s → 10-20s for PFC/LM equilibration • Assess ST with high-Z, high-Z + Li
Inform choice of FNSF configuration:	**Inform choice of FNSF / DEMO plasma facing materials:**
• Lower A or higher A? • Standard, snowflake, Super-X (MAST-U)?	• High-Z acceptable? or need high-Z + Li? • Assess for both divertor and first-wall

U.S. ST program is Accelerating fusion development

- **Advancing ST as Fusion Nuclear Science Facility**
  - Pegasus-U + NSTX-U: non-solenoidal start-up / ramp-up
  - NSTX-U: physics + scenario basis for ST-FNSF/DEMO
- **Developing solutions for plasma-material interface**
  - LTX-U + NSTX-U: liquid Li for very high confinement
  - NSTX-U: novel divertors - snowflake/X, detachment, vapor shielding
- **Exploring unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - Pegasus-U + NSTX-U: high β, toroidicity for MHD / transport validation
  - NSTX-U: non-linear Alfvénic modes, electromagnetic turbulence