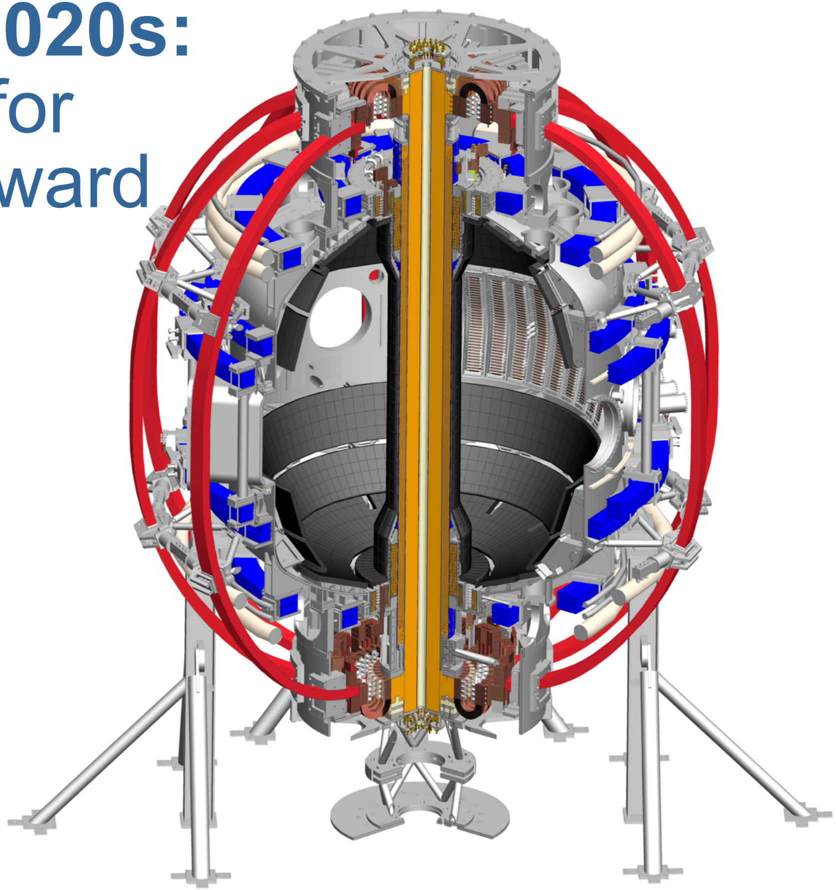
NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

The NSTX-U Facility in the 2020s:
Advancing the Physics Basis for Configuration Optimization Toward a Compact Fusion Pilot Plant

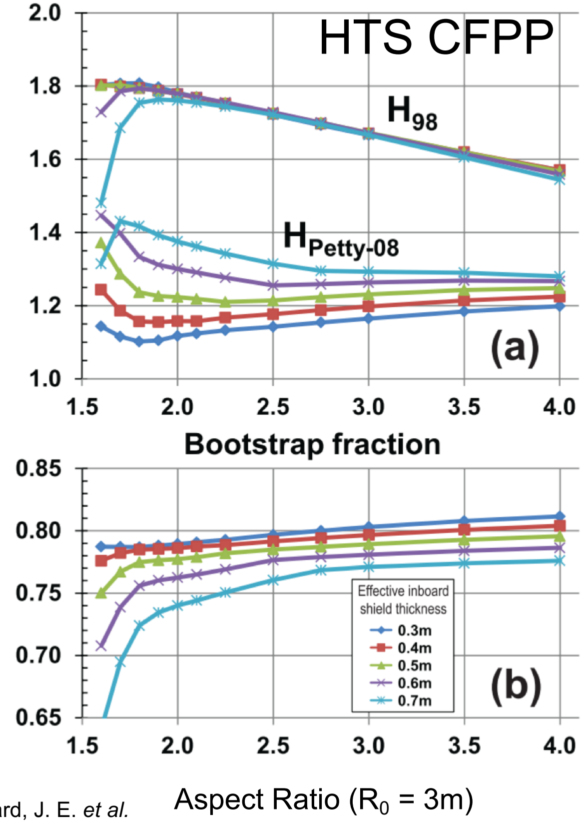


Devon Battaglia,
Mario Podesta, Walter Guttenfelder,
Stan Kaye, Steven Sabbagh

Joint Community Planning
Workshop for MFE and FM&T
Madison, WI
July 22-26, 2019

NSTX-U mission elements are well-aligned with the NAS recommendations to develop a CFPP and support ITER

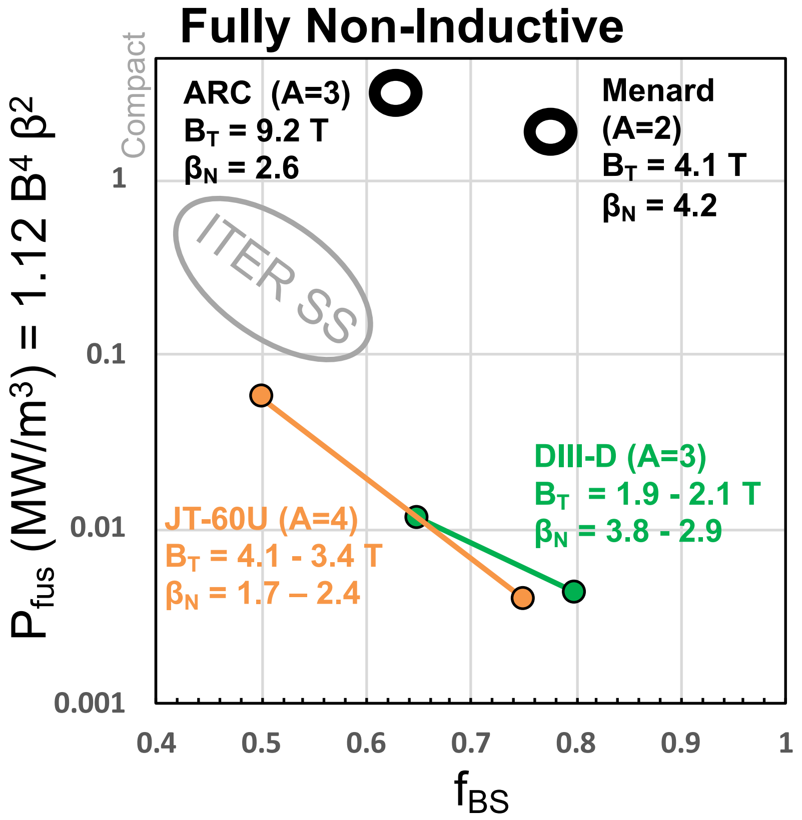
- Leverage low-A to demonstrate non-inductive scenarios at high bootstrap fraction and enhanced confinement
- Integrate non-inductive scenarios with liquid lithium PFC solutions that enable compact configurations
- Provide unique regimes to advance predictive modeling in support of ITER and the optimization of next-step devices



Menard, J. E. *et al.* *NF* **56**, 106023 (2016).

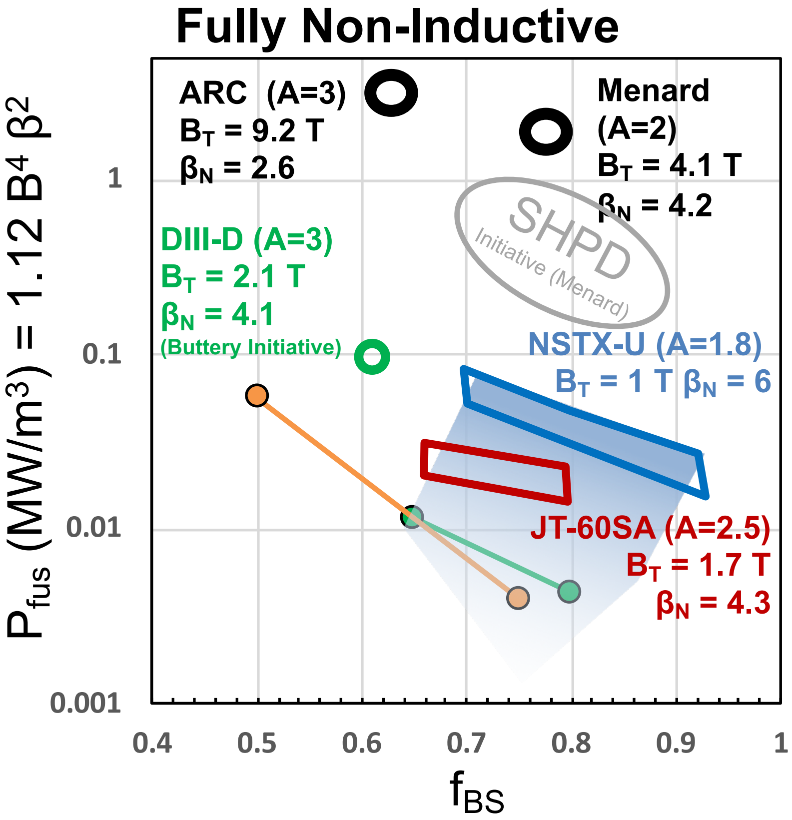
Tokamak CFPP designs require a physics basis for non-inductive regimes at high f_{BS}

- Compact tokamak pilot plants enabled by HTS + f_{BS} > 60% with $H_{98y,2}$ ~ 1.8
  - US retains global leadership in NI scenarios with high-β_N, large-H
- High-f_{BS}, large-H regimes must be extended by two orders of magnitude in P_{fus} for CFPP
  - Larger f_{BS} relaxes constraints on external current drive, but requires higher self-organization



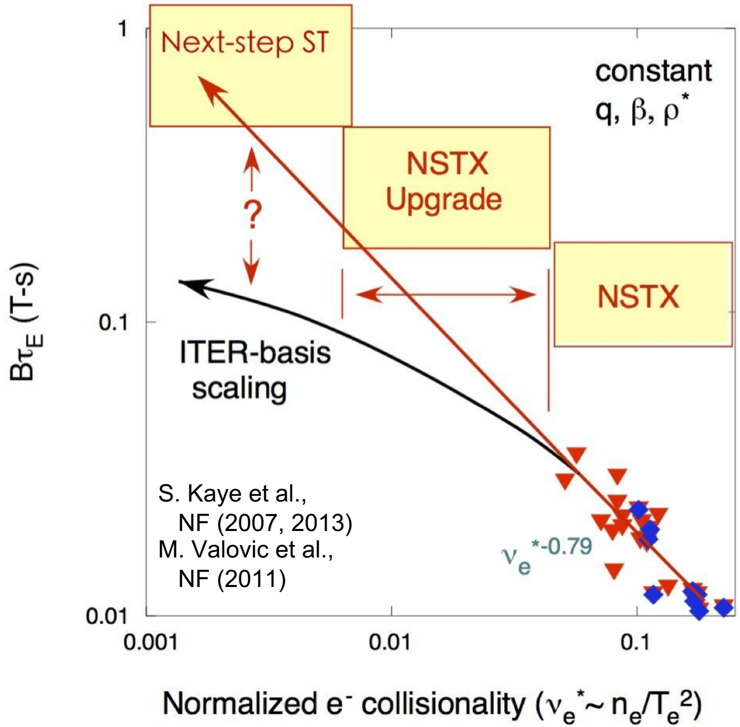
NSTX-U will provide critical data in the high-f_{BS} regime with a large degree of self-organization

- NSTX-U will leverage low-A to achieve full-NI at high f_{BS}
  - Exploit synergy of low-l_i, high-β_N with strong shaping and large edge q-shear
  - Three devices span A: critical for expanding physics basis of high-f_{BS} scenarios at larger P_{fus}
- High-β + high-B_T could be transformative for a long-pulse compact device
  - f_{BS} > 80% enables A = 2-3 HTS SHPD using 100keV positive ion NBI
  - Transport and stability at low-A have distinct differences from conventional-A



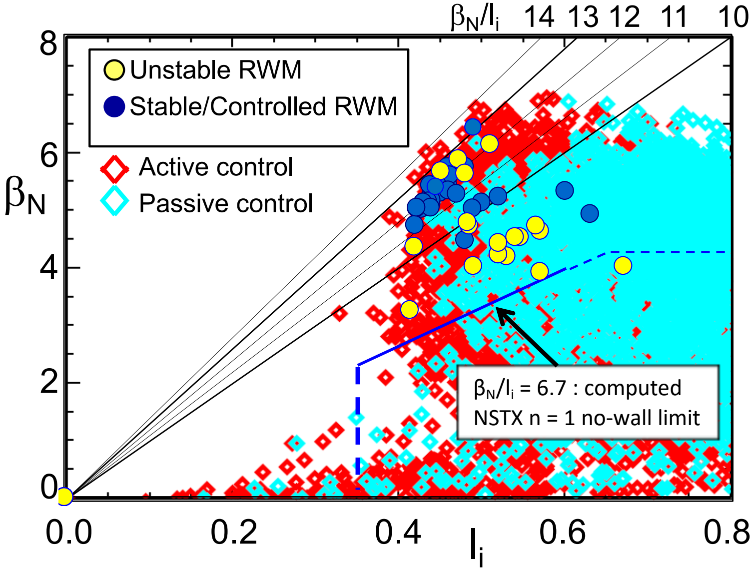
NSTX-U will test collisionality scaling of confinement at low-A, high-β

- Many features of low-A, high-β stabilize ES modes (ITG, TEM, ETG) in core transport
  - Neoclassical ion transport, EM modes (MTM, KBM) and EP modes drive electron transport
- Pedestal transport enhanced relative to KBM transport
  - Wider pedestals ($\sim \beta_\theta$) beneficial for improved confinement and ELM-free operation
  - Enhanced TEM may also drive wider SOL
- Dimensionless confinement time scales inversely with collisionality at low-A
  - Scaling extrapolates to an A=2 CFPP with H_{ST} = 0.9 equivalent to $H_{98y,2}$ = 1.75



NSTX-U will test passive and active stabilization of global MHD modes at low collisionality to achieve large β_N/l_i

- $f_{BS} \sim \beta_N/l_i$ → Broad J and P profiles
  - NSTX achieved large β_N/l_i with $\beta_N / \beta_{no\text{-}wall} > 2$
- Stability increased as β_N/l_i → 10 at critical rotation on NSTX
  - Kinetic stabilization of the RWM
  - Prediction that stabilization improves at lower collisionality will be tested on NSTX-U
- NSTX-U has expanded suite of RT control measurements and actuators
  - RT profile control using flexible NBI, density and shape actuators
  - Increased flexibility in the 3D field spectrum for EFC + rotation control

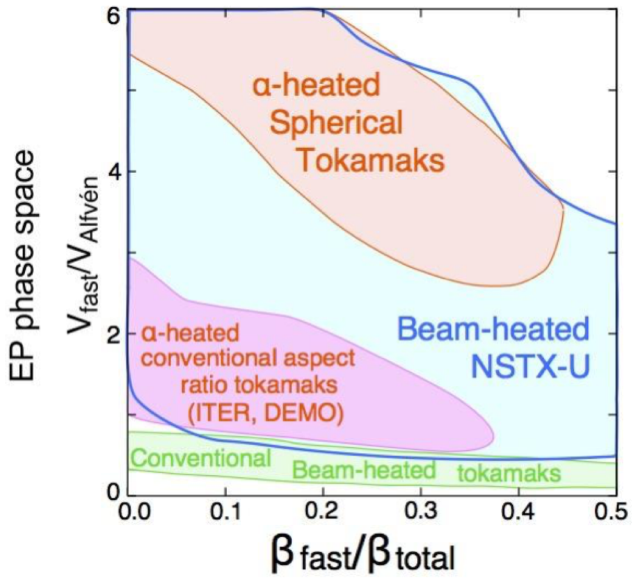


S. Sabbagh et al., Nucl. Fusion **53**, 104007 (2013)

NSTX-U will provide unique regimes for advancing prediction and optimization of burning plasma physics

- NSTX-U will access super-Alfvenic regimes over a range of $\beta_{fast}/\beta_{total}$ to advance predictive capability for ITER and next step devices
  - Includes capability to study RF interaction with super-Alfvenic fast ions

- Provides critical test for the integration of super-Alfvenic EPs in non-inductive, high-confinement regimes needed for CFPP
  - NSTX-U: modification of fast-ion distribution using new tangential NBI stabilizes EP modes
  - Prediction and control of fast-ion heating and current drive critical for realizing compact, burning plasma devices



~ (EP-instability drive)/(EP-instability damping)

NSTX-U will pursue the integration of a prototypical CFPP PFC and divertor solution with liquid lithium

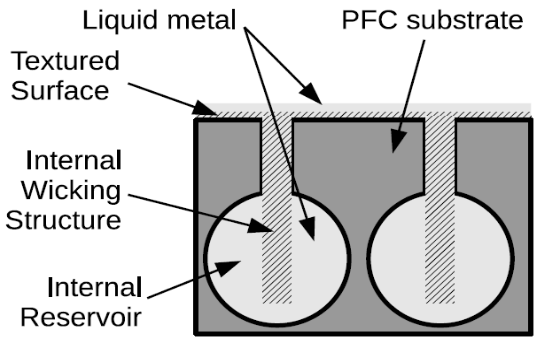
- Near-term boundary research focused on edge transport and PMI with flexible divertor magnetic topology and surface chemistry with carbon PFCs
  - Expanded DN divertor coil set, divertor fueling, boundary diagnostics and carbon wall conditioning (B, Li) capabilities
  - Heat flux projected to exceed 30 MW/m^2 in unmitigated scenarios

- Liquid lithium PFCs are a potentially transformative innovation enabling compact fusion systems (Kessel, FESS; NAS; FESAC TEC)
  - Eliminate erosion, reconstitution of PFC surfaces
  - Reduce nuclear damage compared to a solid PFC
  - Potential to provide continuous hydrogenic particle pumping
    - Edge density control shown to have beneficial impacts on confinement and ELM control

See Andruczyk Initiative; additional Initiatives by Goldston, Gray, Smolentsev, Kessel

NSTX-U in the 2020s

- Near-term research will exploit new facility capabilities to inform the configuration optimization of next-step designs
  - Commissioning in 2021, research ops begin 2021-22
- Install pre-filled heated high-Z PFCs in mid-2020s with expanded diagnostic suite
  - Examine impact of evaporative lithium surface on plasma performance



- Demonstration of prototypical core-edge solution for next-step devices with LM PFCs in late 2020s
  - Full-Z coverage + LM technology developed in concert with National program (Andruczyk Initiative)
  - Requires enhanced investment in the NSTX-U facility and broadening of technical and scientific staff with expertise in PMI and material science

High-β + high-B_T operations could be transformative for a long-pulse compact SHPD or CFPP

- NSTX-U will be the most capable ST in the world for producing non-inductive scenarios
  - Do the unique confinement and stability properties at low-A translate into an attractive regime for compact devices?
  - Critical for producing a unified physics basis with conventional-A devices

- NSTX-U will qualify liquid lithium PFCs in an integrated demonstration of CFPP-relevant scenarios
  - Complements super-X baffled divertor solution on MAST-U
  - Establish a leadership role in domestic and international program investigating liquid metal PFC solutions

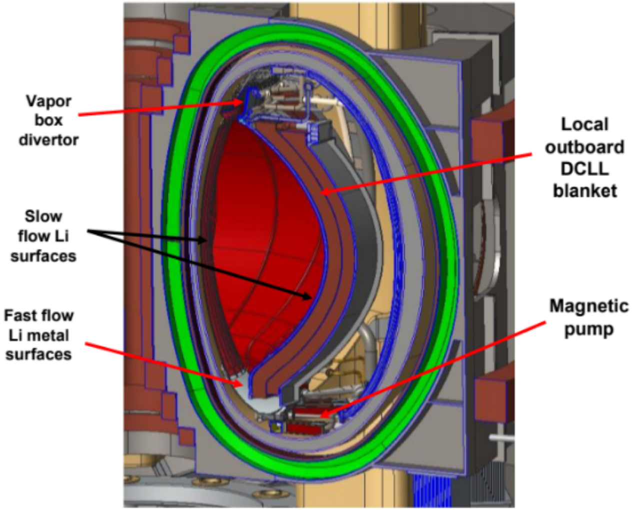


Figure 5 – Cross-sectional image of R=1m, A=2.4 SHPD concept capable of testing vapor box divertors, slow-flow LM first-walls, and fast-flow LM divertors – potentially simultaneously.

SHPD Initiative (Menard)