National Spherical Torus eXperiment Upgrade

NSTX-U Research Program Update

NSTX-U PAC-40 – Sept. 11, 2019

S.M. Kaye
NSTX-U Interim Director of Research

NSTX-U PAC-40 Charge

- The NSTX-U Research Program requests advice from PAC-40 in three areas:
  1. Please comment on the quality and importance of recent research results, including collaborative activities, and how they advanced the NSTX-U Mission and Milestones
  2. How well the FY20 and 21 Research Milestones address issues critical to the ST and fusion as well as the preparation for operations of NSTX-U, and the suitability of expertise and resources needed to achieve these milestones successfully.
  3. **The role, uniqueness and importance of NSTX-U in developing a national fusion strategy and to contribute to the design of a next-step tokamak device. In particular, is the proposed R&D program well-positioned to close gaps needed for a compact pilot plant as outlined in the recent NAS and FESAC TEC studies?**

Presentations (2:20 + 1:10 hour)

I. Research Program Update – S. Kaye (30 + 15 min)
   I. Will address Charge 3, PAC-30 recommendations
II. Status of NSTX-U Recovery – S. Gerhardt (20 + 10 min)
   I. Successful Independent Project Review (Aug. 27-29, 2019)
III. NSTX-U researcher activities
   I. R19-21/22 Milestone research [Battaglia (30+15)] – Charge 1 & 2
   II. Non-Milestone research results that can impact NSTX-U, ITER research; collaborations/public-private partnerships [A. Diallo (30 + 15 min)] – Charge 1
IV. Liquid Metal program – R. Maingi (30 + 15 min) – Charge 3
   I. How to accelerate the LM NSTX-U program

Outline of Research Program Update

- Programmatic events since PAC-39
  - Summary of FES Office of Project Assessment (OPA) Mission Review (3-18)
- Developments in domestic fusion program (NAS Study, FESAC TEC)
  - How does NSTX-U fit in? How has the NSTX-U Mission changed?
  - 10 year mission and research goals (more from Maingi)
- Response to PAC-39 recommendations (Kaye, Maingi)
  - State of NSTX-U Science Team and plans for its reconstitution

Outline of Research Program Update

- Programmatic events since PAC-39
  - Summary of FES Office of Project Assessment (OPA) Mission Review (3-18)
- Developments in domestic fusion program (NAS Study, FESAC TEC)
  - How does NSTX-U fit in? How has the NSTX-U Mission changed?
  - 10 year mission and research goals (more from Maingi)
- Response to PAC-39 recommendations (Kaye, Maingi)
  - State of NSTX-U Science Team and plans for its reconstitution

Major OPA Review of NSTX-U Science Mission March 2018

- Follows review of NSTX-U Recovery Project conducted in Feb. 2018
- Review lasted 2 ½ days
- Review Committee: J. van Dam called it the "A Team" of reviewers, OPA the "gold standard" of reviews
  - Ray Ohrbach (Chair)
  - Dave Campbell (ITER-retired)
  - Norbert Holtkamp (SLAC, Stanford U.)
  - Thomas Klinger (W7-X, Germany)
  - Paul Thomas (Tokamak Energy, Ltd. UK, formerly JET)
  - Anne White (MIT)
- Talks given by McComas (PU perspective), Hawryluk (PPPL perspective), **Menard (Scientific Relevance), Kaye (Transport/Turbulence and EP), Sabbagh (Macrostability and Integrated Scenarios), Maingi (Boundary)**

Link to talks: OPA Science Mission Presentations

Major OPA Review of NSTX-U Science Mission in March 2018
(Charge questions and committee responses)

1. What is the committee's assessment of continued scientific relevance of spherical torus research and the NSTX-U Facility's contributions to that area of research? Does the facility address critical issues for fusion science?
   - NSTX-U has maintained its relevance; enhanced capabilities important for improving physics basis for ST and ITER; research program wide-ranging and challenging, provides potential for significant advances
2. Are there advances in plasma physics, or tokamak core technologies, since the NSTX-U project was designed and constructed that may impact the timeliness or relevance of proposed research at the NSTX-U Facility?
   - NSTX-U well-positioned to make significant contributions in validating new computing and software methods from well-characterized devices; lithium as an advanced wall material will be world-leading
3. If the NSTX-U Facility resumes operations in 2020, what is the Committee's opinion regarding the status and capabilities of other domestic and international spherical torus facilities?
   - NSTX-U bigger and more fusion relevant than most; will be world leader in chosen domains of exploration (high-β, low-collisionality core, lithium research)

The NSTX-U Program thanks the PAC for their useful input that led to a successful FES OPA Mission review

Outline of Research Program Update

- Programmatic events since PAC-39
  - Summary of FES Office of Project Assessment (OPA) Mission Review (3-18)
- Developments in domestic fusion program (NAS Study, FESAC TEC)
  - How does NSTX-U fit in? How has the NSTX-U Mission changed?
  - 10 year mission and research goals (more from Maingi)
- Response to PAC-39 recommendations (Kaye, Maingi)
  - State of NSTX-U Science Team and plans for its reconstitution

NAS Strategic Plan Provides a Vision for the Fusion Program

- Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research" (2019)
- Two main recommendations:
  - (1) The United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.
  - (2) The United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.

NAS Study Identified Science and Technology Challenges

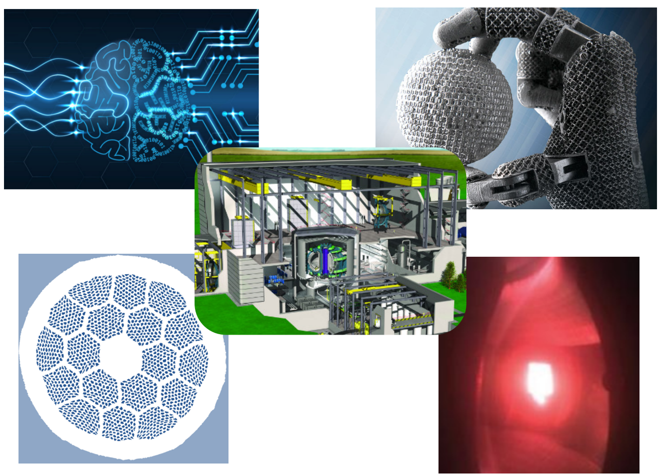
- No surprises in challenges/gaps – identified previously; they include:
  - Heating and sustainment
    - Transport and confinement
    - Energetic particles
    - Transients
    - Steady-state operation
  - Boundary and divertor physics
    - Power handling
- Challenges formed basis for the agenda of first APS-DPP Community Planning Activity (Madison, WI, July 2019)
  - Good representation by NSTX-U researchers and collaborators
    - **CPP leadership**: N. Ferraro, W. Guttenfelder, M. Reinke
    - **Presentations**: Battaglia (Program relevance), Ono (Integrated RF program), Sabbagh (Disruption prediction/avoidance, Raman (CHI), Menard (SHPD Mission), Andruczyk (LM), Gray (LM), Goldston (LM/Vapor Box) + other participants

FESAC TEC Report Identifies Liquid Metal PFCs as a Potential "Game-Changer"

FUSION ENERGY SCIENCES ADVISORY COMMITTEE REPORT

R. Maingi, co-chair

Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy



Feb. 2018

U.S. DEPARTMENT OF ENERGY | Office of Science *Fusion Energy Sciences*

- **Charge**: Identify promising Transformative Enabling Capabilities that could promote efficient advance toward fusion energy, building on burning plasma science and technology
- (Fast) **flowing liquid metal PFCs** may prove to be an attractive alternative to handle both high steady-state and transient plasma heat flux

The NAS and FESAC TEC recommendations elevate the importance of the NSTX-U mission

- NSTX-U will provide critical results required to optimize the geometry, including aspect ratio. of next-step compact devices

- NSTX-U will provide unique regimes for studying burning plasma-related physics and improve predictive capabilities

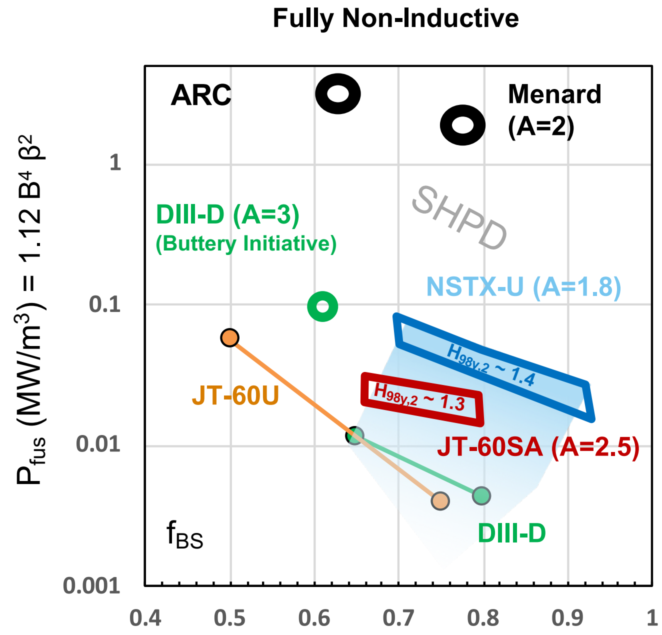
- NSTX-U will evaluate integrated operations with liquid metal PFCs that would enable compact systems

NSTX-U will provide unique regimes in the initial years of operations required to **optimize the geometry (R/a, κ, δ) of next-step devices**

- Elements of "near-term" program address core/boundary performance
  - Demonstrate **high-performance steady-state non-inductively sustained regimes** at large bootstrap fraction (f_{BS} > 0.7), large Greenwald density fraction (f_{GW} > 0.7) and β_N values surpassing typical conventional-A scenarios with sufficient stability margin for low disruptivity
  - Investigate if a **strong scaling of confinement and stability improvement with reduced collisionality** in regimes dominated by electron thermal transport at high-β and low-A persists at lower collisionality
  - Burning plasma (i.e., **ITER**)-related physics issues
  - **Unify predictive modeling of transport, stability and fast ion physics** at low-A, low-ν_e* and high-β_N with conventional-A tokamaks to improve confidence in projections to next-step fusion devices, including ITER and a CPP

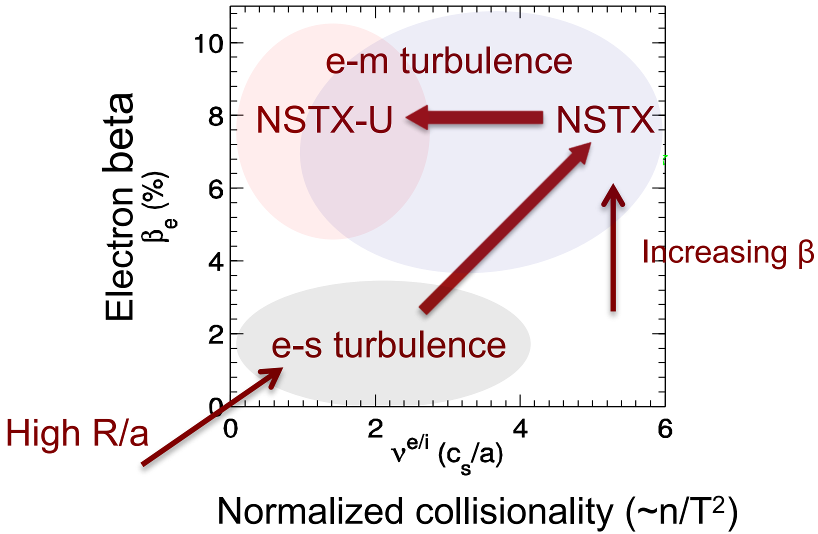
Compact Fusion PP physics basis requires non-inductive regime at high f_{bs}

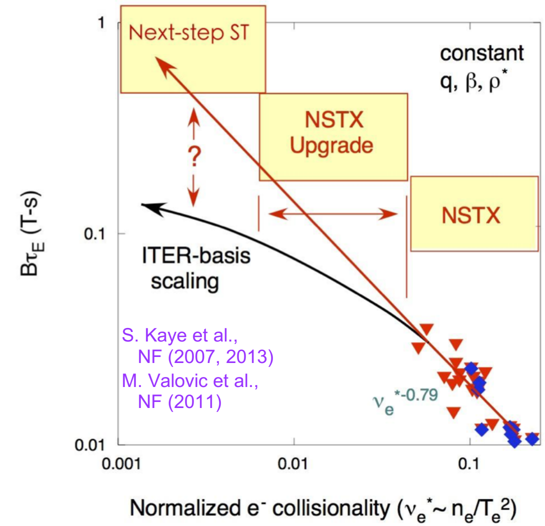
- Tokamak HTS CPP concepts: f_{BS} > 60% and $H_{98y,2}$ = 1.5 – 2
  - Fully non-inductive without impurity and He ash accumulation
  - Scenario must be compatible with divertor solution for heat flux
- NSTX-U will explore the high-β_n (>5) and strong shaping (κ>2.5) route to high bootstrap current fractions
  - Synergy with broad current profiles and large edge q-shear
  - Provides possible transformative route when coupled with enhanced transport and stability properties at low-A



Transport at low-A is fundamentally different than transport at conventional-A

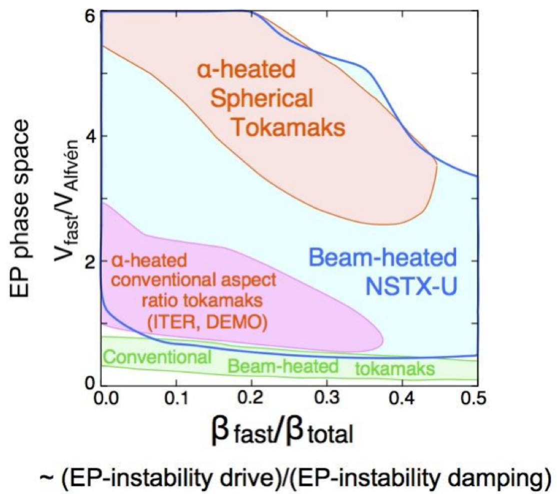
- Many features of low-A, high-β stabilize ES modes (ITG, TEM, ETG) in core
  - Neoclassical ion transport, MTM, KBM and EP modes drive electron transport
- Dimensionless confinement time scales inversely with collisionality at low-A ($\Omega_{ci}\tau_E \sim \nu_*^{-0.8}$)
  - Scaling extrapolates to an A=2 CPP with H_{ST} = 0.9 equivalent to $H_{98y,2}$ = 1.75
  - NSTX-U will operate at up to a factor of six lower ν_* than NSTX

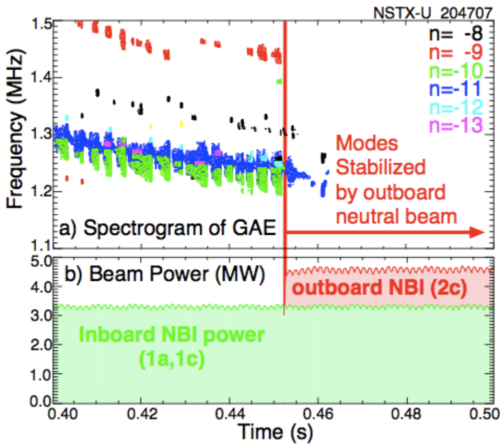




NSTX-U will access unique regimes in fast particle physics critical for prediction and optimization

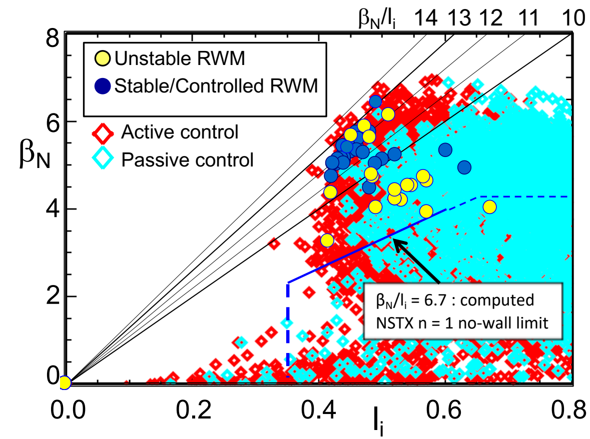
- NSTX-U will produce and study EP modes relevant to alpha driven instabilities expected at both high- and low- aspect ratio
  - Characterizing fast ion interaction with RF (see Diallo talk)
  - Important for ITER and CPP
- Modification of fast-ion distribution using tangential NBI can stabilize EP modes that enhance transport
  - Study and develop techniques to suppress alpha-driven modes through phase-space engineering





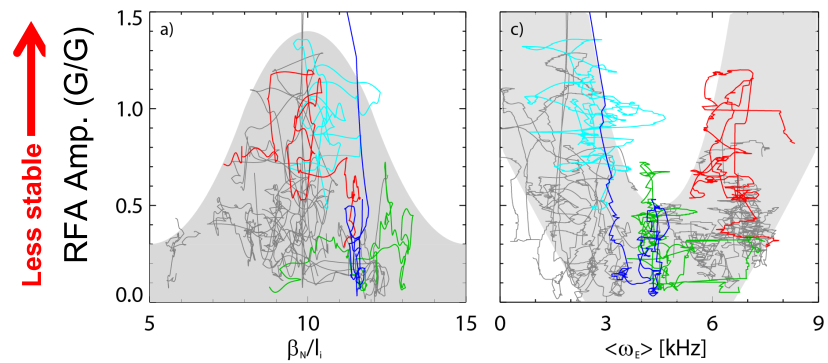
Stability at large β_N/l_i is a strong lever for a compact device

- $f_{BS} \sim \beta_N/l_i$ → Broad current and pressure 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
  - Kinetic stabilization of the RWM
  - Prediction that stabilization improves at lower collisionality will be tested on NSTX-U



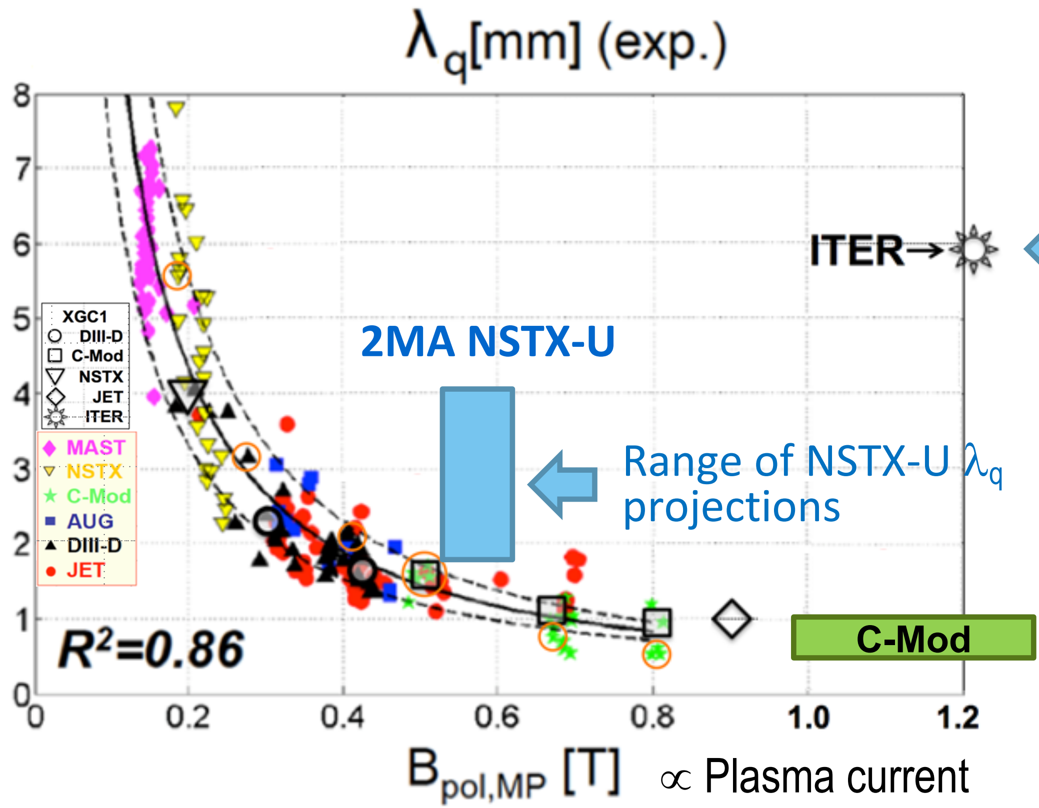
S. Sabbagh et al., Nucl. Fusion **53**, 104007 (2013)

- NSTX-U has expanded suite of real-time control measurements and actuators
  - RT profile control using tangential NBI, density and shape actuators
  - Increased flexibility in the 3D field spectrum for EFC + rotation control



J.W. Berkery, et al., PoP **21** (2014) 156112,
J.W. Berkery, et al., Phys. Rev. Lett. **106** (2011) 075004

NSTX-U will play important role in understanding how power exhaust width extrapolates to future devices



XGC1 simulations predict turbulence will widen edge heat flux in ITER

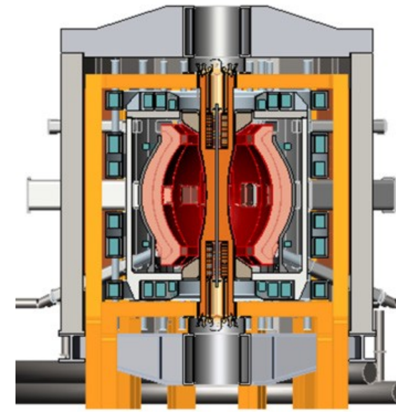
C.S. Chang et al 2017 Nucl. Fusion **57** 116023

XGC1 studies of NSTX-U indicate enhanced TEM transport in the low ν^*, 2 MA NSTX-U pedestal, similar to mode expected for ITER

Recovery includes divertor tile improvements to access high current, power, shaping

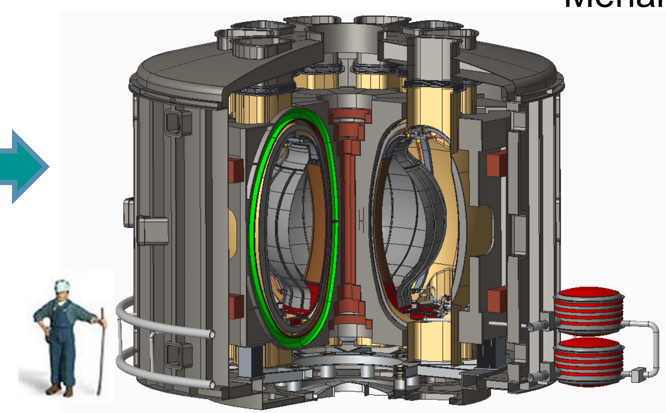
Has the NSTX-U mission changed over the past few years?

- Components of the short-term (1-3 yrs) research plan remain the same, and can benefit domestic strategy that is presently being developed by CPP
- NSTX-U Science mission can address critical issues for:
  - ST-based FNSF
  - **Optimizing geometry (e.g., κ, δ, aspect ratio) of next step "compact" devices**
    - CPP Initiative to develop **national** design team
  - ITER
- De-emphasize non-solenoidal startup; reassess if Urania successful
- LM divertor path instead of cryopump



Menard (2016)

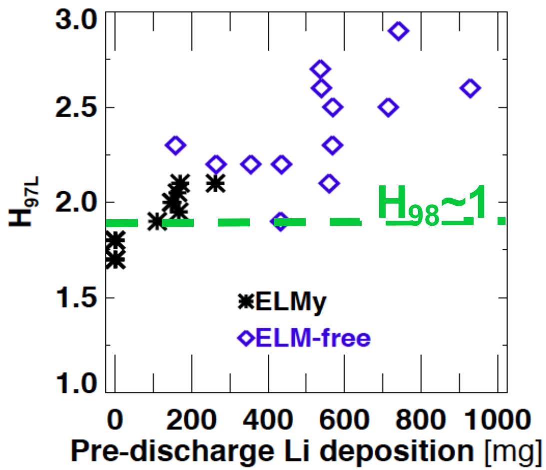
Menard, Brown



R=1.0m, A=2.4

The longer-term (5-10 yrs) mission has directed its focus on testing Liquid Metal PFCs (Maingi presentation)

NSTX: Higher lithium deposition → higher confinement



<u>NSTX-U near-term</u>: Double Li deposition, effect on confinement (carbon tiles)

<u>Long-term</u>: Test liquid metals as transformative wall solution:

- Phase I: prefilled high-Z tiles/LM modules
- Phase II: complete toroidal coverage (LM/Vapor Box)

Could begin design and fabrication in 2020 with appropriate support as Engineers roll off Recovery

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

NSTX-U:	Construction	1st campaign Carbon	Phase I high-Z	Phase II - All metal/Liq. Lithium/VB
	Design & Fab. of Phase I, II (?)	Li evap (top & bottom)	Pre-filled high-Z tiles /liquid Li modules	Fully toroidal/VB option

Outline of Research Program Update

- Programmatic events since PAC-39
  - Summary of FES Office of Project Assessment (OPA) Mission Review (3-18)
- Developments in domestic fusion program (NAS Study, FESAC TEC)
  - How does NSTX-U fit in? How has the NSTX-U Mission changed?
  - 10 year mission and research goals (more from Maingi)
- Response to PAC-39 recommendations (Kaye, Maingi)
  - State of NSTX-U Science Team and plans for its reconstitution

Response to PAC-39 concerns and recommendations

- Liquid metal research to be covered in Maingi presentation
- "It is recommended that the NSTX-U national facility adopt an integrated scientific management of the facility"
  - "NSTX-U program appeared to divide the team between PPPL and non-PPPL participants, applying different work structures and metrics to them"

    -MISCONCEPTION-

  - During ops and planning for ops, there is no distinction between PPPL and non-PPPL participants
    - Team fully integrated in both research and management
    - Non-PPPL held scientific leadership roles, had input in developing research program
    - NSTX-U management sensitive to collaborators' goals to satisfy their funded objectives, and made accommodation for them

Most NSTX-U Team members (PPPL & non-PPPL) involved in collaborative research during Recovery

- Areas that could impact NSTX-U research (Diallo presentation)
  - Wall conditioning on domestic and international devices (Maingi presentation)
  - ST-related research on MAST Upgrade, ST40 (public-private partnership), QUEST, Pegasus/Urania
- Funding for non-PPPL researchers mostly shifted to non-NSTX-U projects
  - Targeted Recovery, JRT tasks
  - Need to achieve research goals "outside" NSTX-U purview
    - Future NSTX-U could capitalize on this work
- Present funding for PPPL researcher activities minimized and capped (to benefit Recovery funding)

NSTX-U has lost a number of Team members critical to even initial operations

- Retirement, outside opportunities, other (both PPPL and non-PPPL researchers)
  - Machine ops Magnetics Neutronics and fast ion physics
  - Boundary physics and engineering (including Li systems)
  - RF physics and engineering MSE, SXR
- Because of Recovery demands, cannot replace or add PPPL researchers
  - Pulled back 5 reqs for post-doc/Jr. staff (transport analysis, scenario development, RF physics, LM PFCs, neutronics/fast ions), 5-8 other reqs for ops prep on hold
  - Cut back Theory partnership by >1 FTE (20%)
  - Remaining (PPPL) researchers split efforts between NSTX-U and collaborations
    - Much work common between NSTX-U and collaborations (e.g., real-time control)
    - Employing junior staff would help achieve goals in both
- Attempt to maintain cohesiveness through weekly research meetings
  - Should expand with start of MAST Upgrade, ST40 physics program (Spring 2020)

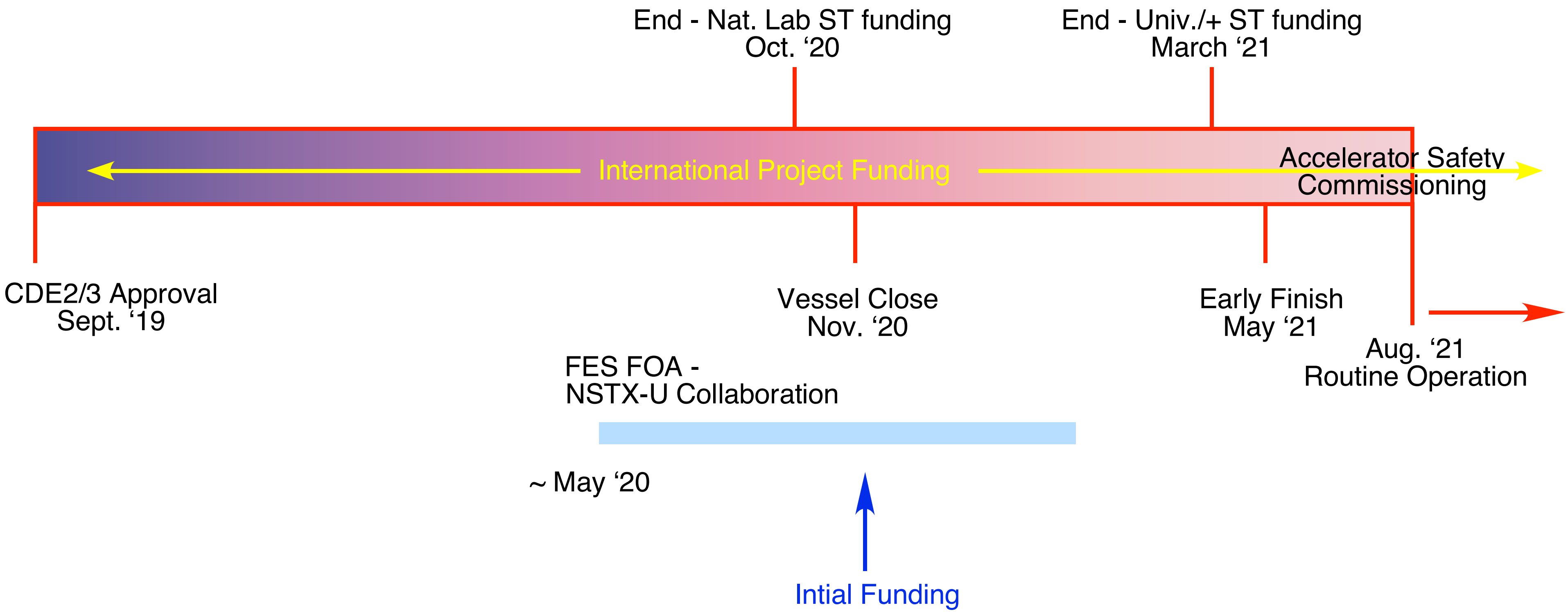
We are developing a plan to reconstitute the Research team in advance of NSTX-U restart

- Early start: May ‘21 (Late – March ‘22): First Plasma
  - Vessel closed ~7 months prior to First Plasma (Nov. ‘20 if Early start)
- Recognize need to assemble initial research team, diagnostics and any related in-vessel work, and have experimental plan in place well before to First Plasma
  - Plan for success (i.e., Early start)
- Developing list of high-level research objectives as well as necessary diagnostics and theory/modeling tools for first 1 to 3 years through “informal” discussions
  - Will guide needs for personnel, resources
  - Detailed research plan to be developed through Research Forum once Team assembled
- Revisit science program governance (mission driven vs science user facility)

Pre- and experimental-operation planning has to be coupled to discussions with Recovery Project and FES

- Cannot impact Recovery schedule
  - Take advantage of pre-2 shift Recovery work for in-vessel tasks?
- Plan to hold discussions with FES to develop timeline for PPPL personnel funding, call for collaboration proposals once Project once CDE2/3 approval given (end Sept. 2019)
  - Need to dovetail NSTX-U funding growth with other commitments (ST, International-funding grants)
    - NSTX-U will have to compete with these other projects for resources
  - **Funding can be phased in, but need to ensure ready for operation and experiments leading to substantive scientific results when restart occurs - even if Early!**

Notional timeline for funding



It is most likely that Restart will be at least several months after May ‘21

Diagnostics are one key to being able to do science

Day 1 diagnostic set is minimum set and is sufficient only for commissioning activities

Magnetics for equilibrium reconstruction	PPPL
PFC thermocouples	PPPL
PFC Langmuir probes	PPPL
Multi-Pulse Thomson Scattering (MPTS)	PPPL
Toroidal CHERS	PPPL
Fission chamber neutron detectors	PPPL
Plasma TV cameras	PPPL
Filterscopes	LLNL
Extreme Ultraviolet (EUV) spectrometers	LLNL

Has to be funded through Maintenance & Run Prep budget
- In process of assessing available resources for this

Many other diagnostics that were available in 2016 are essentially "ready to go"

- In most cases, would require incremental funds to make available
  - Large return for small investment
  - Would allow for comprehensive physics studies shortly after restart

e.g., EP physics studies would require:

fast Mirnovs (high–f magnetic fluctuations), reflectometer (fluctuation amplitudes)
FIDA, ssNPA (fast ion distribution function)
MSE (current profile to assess NBCD)

Aside from funding issue, have to work with Recovery to ensure not draining their technician resources or impacting their schedule

Responses to other PAC comments

S&MHD-1	List of objectives for a research plan to demonstrate non-inductive ops on NSTX-U – Milestones and steps of how to achieve within in first five years	See following vugraphs
S&MHD-2	Emphasize in plan to achieve non-inductive ops that it is at higher field and density compared to NSTX, MAST-U	Reported in OPA Mission review
S&MHD-3	Highlight world-class, real-time measurement and control capabilities upon restart and results from collaborations.	Reported in OPA Mission review, see following vugraphs
S&MHD-4	Focus on ramp-up and not plasma formation; study role of fast ion transport in achieving sufficient current drive	See slides on R19-2, R19-4
S&NHD-5	Detail research milestones for macroscopic stability and disruption detection/avoidance for first five years	Not yet done
Core-1	Investigate low- and high-Z impurity transport properties in prep for high-Z wall operations	Will conduct research on restart
Core-2	Explore turbulent transport and stability at reactor relevant rotation	Some done in Ruiz et al. (2019), Ren et al. (2019); more to be done with HHFW on restart
Core-3	Broaden EP to included active control of fast ion distributions combined with predictive model testing for stabilization of AEs	R19-4, R20-4 (also see note in R19-2) slides, in the research plan
Core-4	Specify EP physics questions that are important for ST, and a clear list of objectives to achieve in first five years	See following vugraphs
Core-5	Maintain, if not improve, HHFW system	System being maintained, dummy load tested on a regular basis. Some improvements to control electronics made. Fully employing system will require additional staff (physics and technical)

Responses to other PAC comments

Ped-1	Pedestal research should be organized around potential impact on NSTX-U and PP operational scenarios.	Scenarios with optimum core-edge coupling for high performance will be consider as part of research operation planning in FY20/21
Ped-2	More tightly couple pedestal to core research. Leverage increasing sophistication of core transport models to the pedestal	See above and R20-1
Ped-3	Exploit use of lithium to examine role of pedestal fueling from edge on pedestal density transport and edge density profile. Identify any additional diagnostic and modeling needs.	Baseline covered by JRT-19. Objective for initial ops after restart. Starting process to identify additional diagnostic needs and detailed research approach.
Ped-4	Highlight ELM-control strategies, especially at lower collisionality and higher pedestal pressure, and how ELM control can impact pedestals and scenario performance	Assessment being done through collaborative research (AUG, EAST, DIII-D, KSTAR)
Div-1	Leverage XGC results to identifying diagnostics and experimental scans necessary to validate heat flux width predictions	Will be done as part of research operation planning in FY20/21
Div-2	Integrate divertor with pedestal research to understand divertor compatibility with high performance ST core	Will be done as part of research operation planning in FY20/21 and on restart(divertor detachment, impurity transport)
Div-3	Develop boundary solutions for PFC heat flux and erosion control	Program is putting more emphasis and immediacy on liquid metal wall solutions to the boundary heat flux issue.

Near-term objectives for non-inductive operation research program

- Year 1: Demonstrate $f_{NI} > 90\%$, $\tau_{pulse} \sim \tau_{CR}$ at $B_T = 0.65 - 0.85T$
  - Test and refine predictions for fully NI scenarios at $I_p < 0.9$ MA
  - Scan NBI mix and parameters at fixed shape, $I_{p,}$ strive for constant f_{GW}
  - Test and refine models used for ramp-up optimization
- Year 2: Demonstrate $f_{NI} \sim 100\%$, $\tau_{pulse} > \tau_{CR}$ at $B_T = 0.85 - 1T$
  - Ramp-up and RT control optimization to achieve strong shaping
  - Demonstrate fully NI scenarios at $B_T = 1T$ over range of NBI voltage, f_{GW}
  - Begin integrating heat flux mitigation into higher I_p (1 MA) scenarios
- Year 3: Extend pulse length of $f_{NI} \sim 100\%$ scenarios to multiple τ_{CR}
  - Integrate heat flux mitigation into high-I_p scenarios
  - Density and RT profile control to achieve steady-state q-profile
  - Integrate HHFW heating into ramp-up to reduce OH flux consumption

Real-time control capabilities on NSTX-U

Control target	**Real-time measurement** (Ready, near term, long-term)	**Actuator**	**Status**
B_T, I_p, Separatrix position, X-point/strikepoint	rtEFIT with Magnetics + wall model $P = P_e + P_i + P_{fast}$ (rtMPTS, rtCHERS, reduced model + rt neutrons) q-profile (rtMSE)	Coil voltages	65x65, multi-threaded rtEFIT (as low 1ms slow-loop) Magnetics only rtEFIT ready
Multiple X-point control (snowflake/X-divertor)	Magnetics	Divertor coil voltages	Ready.
Vertical position	Up-down flux difference	PF3 voltages, offset current in RWM coils	Ready.
Plasma density	rtMPTS, rtFIR interferometer	LFS fueling, supersonic gas injector	Feed-forward control ready.
Divertor radiation, divertor heat flux	AXUV diodes, divertor neutral pressure, EUV spectroscopy, IR thermography, SOL currents	Strikepoint location/sweep, divertor fueling	Feed-forward control ready.
Volumetric radiation	AXUV diodes, bolometry	LFS impurity fueling	Feed-forward control ready.

Real-time control capabilities on NSTX-U

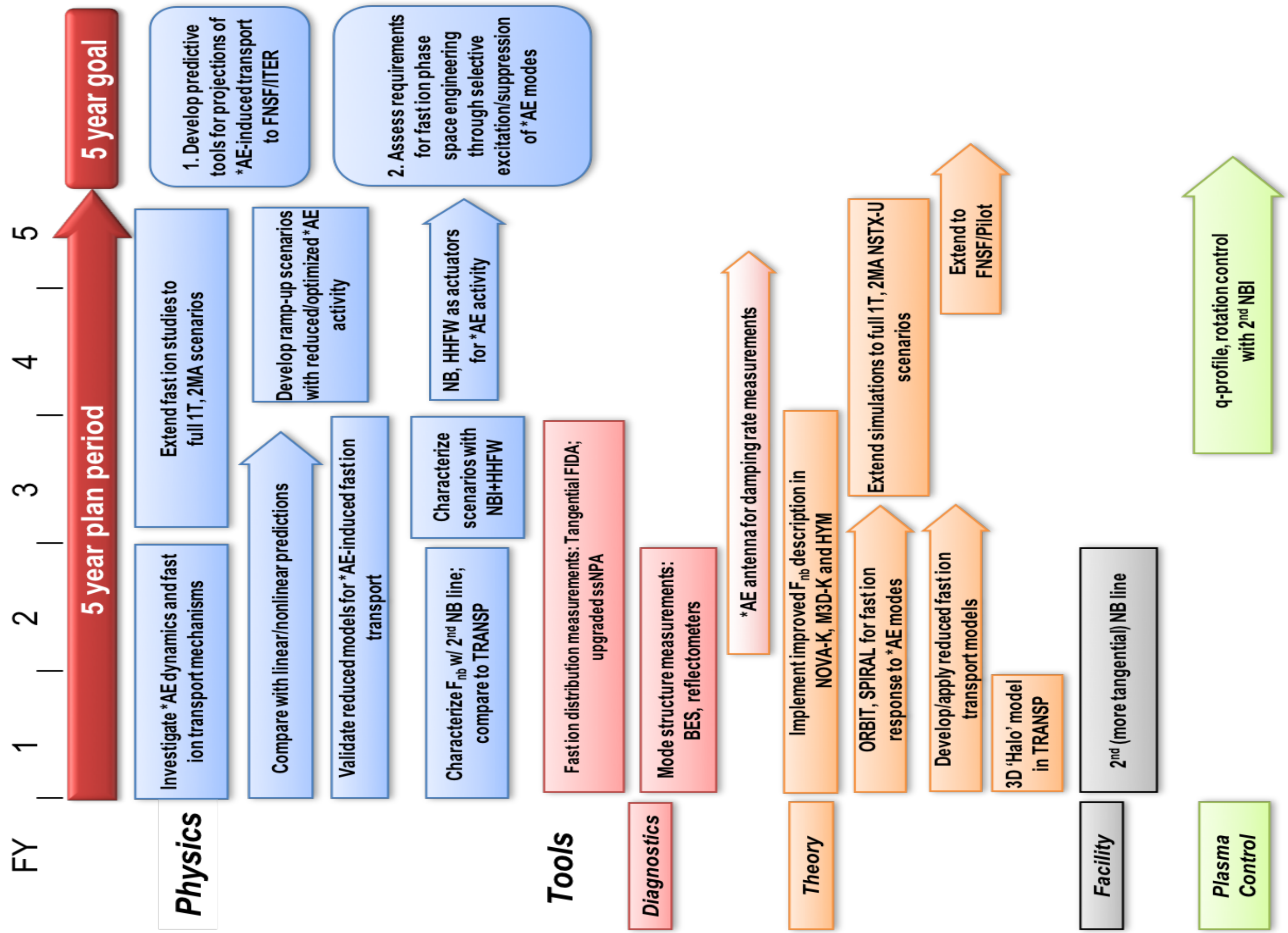
Control target	Measurements	Actuators	Status
q_{min}, q-profile	rtEFIT (rtMSE essential)	NBI, outer gap, density, HHFW	rtMSE needed.
Toroidal rotation	rtCHERS	NBI, 3D field, outer gap, density, HHFW	Planned for restart.
β_N	rtEFIT (rtMPTS, rtCHERS, P_{fast} model + neutrons important)	NBI	Ready with magnetics only rtEFIT.

Control capability	Goal	Status
Active feedback on RWM	Detect RWM, apply 3D field to maintain plasma rotation	Ready
Disruption avoidance	Avoid disruption by altering plasma state and/or triggering controlled ramp down	Initial tests completed, research program
Controlled ramp-down	Terminate discharge without a disruption	Initial tests completed, research program

EP Physics Questions/Milestones

- Core-4: "…specifying the energetic particle physics questions that are important for STs and a clear list of objectives that NSTX-U plans to achieve in the first five years…"
- The two main Thrusts for EP research after NSTX-U operations restart are:
  - Develop predictive tools for projections of AE-induced fast ion transport (extended to other types of instabilities)
  - Assess requirements for *fast-ion phase space engineering* techniques, aimed at controlling/mitigating instabilities and improve plasma performance (e.g. through optimization of the NB driven current profile)

Energetic Particle research timeline



Summary

- NSTX-U research is critical to retain a world-leading ST science capability
  - High-level research goal emphasis revisited to align well with the NAS and FESAC TEC report recommendations, as well as with PAC-39 recommendations
  - Vital for developing predictive capability for fusion science, next-step designs

- We need to start the process of reconstituting the Research Team now to be prepared upon restart to perform science critical to the ST concept and fusion energy development

Backup

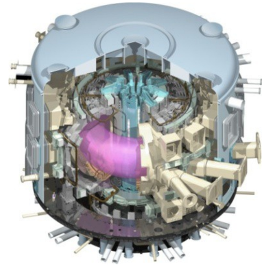
NSTX-U Mission Elements Support the NAS Vision

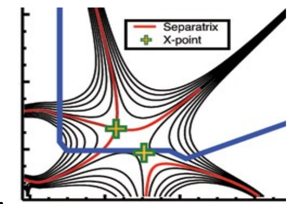
- Exploit unique Spherical Tokamak (ST) parameter regimes to advance predictive capability - for ITER and beyond

- Develop solutions for plasma-material interface (PMI) challenge

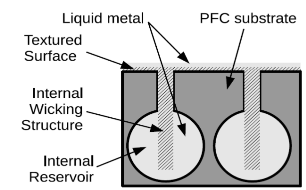
- Explore ST physics towards reactor relevant regimes (Fusion Nuclear Science Facility, low-A Pilot Plant)

ITER



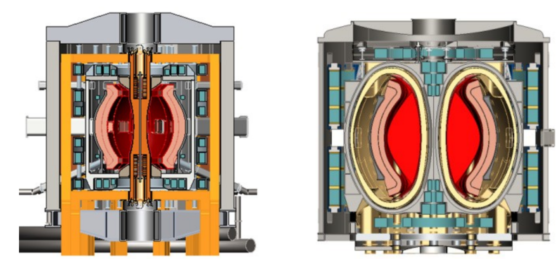


Advanced divertors



Liquid metals

ST-FNSF / Pilot-Plant



NSTX-U vital for addressing key ST / fusion questions

Highest normalized pressure at high T

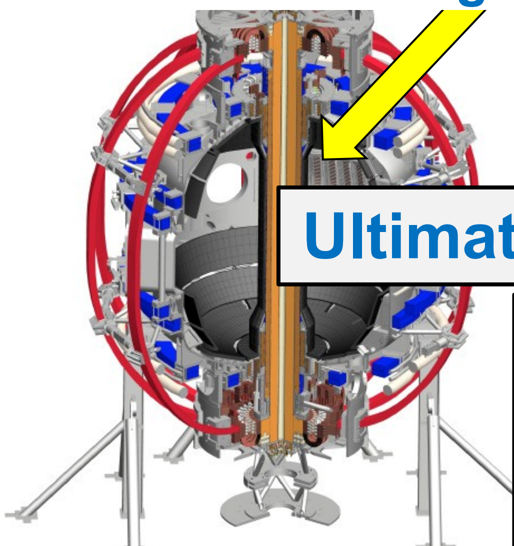
Unique regime, study new transport and stability physics

Sustain steady-state plasma

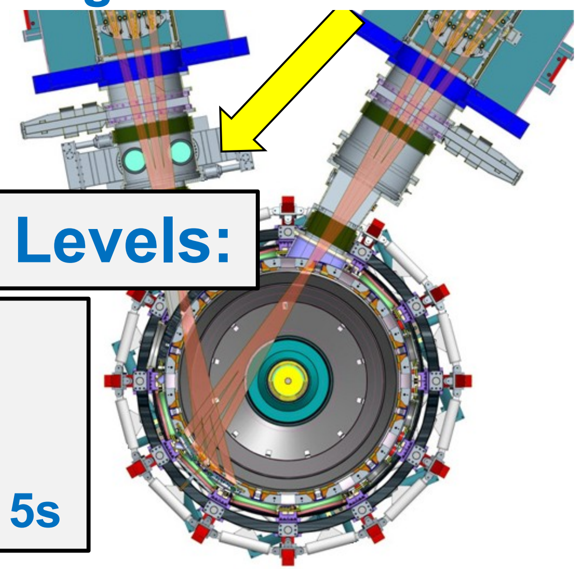
Not yet achieved at high-β_T, low ν^*

Two new tools:

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Ultimate Performance Levels:

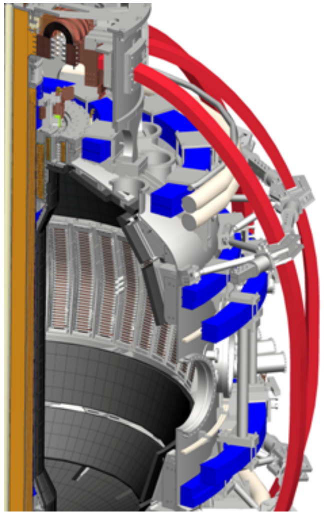
B_t =1T
I_p = 2 MA
P_{NB} = 10 MW
Flat top duration = 5s

NSTX-U has many unique aspects relative to MAST-U

- NSTX-U is unique when compared with MAST-U for addressing key goals:
- Higher pressure and field (enabling the key goal of assessing ST confinement)
- Longer pulse (enabling the key goal of developing sustained high beta scenarios)
- Close-fitting wall (enabling the key goal of developing sustained high beta scenarios)
- Higher density non-inductive scenario (enabling key goal of sustained high beta scenarios)
- HHFW (enabling the key goal of developing sustained high beta scenarios)
- Wall conditioning with lithium, wider pedestals and a path to lithium-wall.
- Wide shaping flexibility when applying full beam power (whereas MAST-U is limited by vertically-displaced beam geometry)
- Larger $q_{||}$ for short pulse to assess divertor scalings in STs
- More flexible beam injection tangency allowing studies of fast ion physics, momentum transport etc in wider range of scenarios as well as for current ramp-up development
- NSTX-U will benefit from strong collaboration with MAST-U to exploit complementary capabilities
- NSTX-U also has leading capabilities that contribute to mainline program

NSTX-U and MAST-U are the most capable devices in a world-wide ST research program

NSTX-U



Similar features:

- Major radius R = 0.8-1m
- Plasma current up to 2MA
- Pulse durations 1s → up to 5s
- Strong neutral beam heating

Having both NSTX-U and MAST-U important to confirm unique ST results

Complementary Research:

MAST-U (UK)

Core emphasis

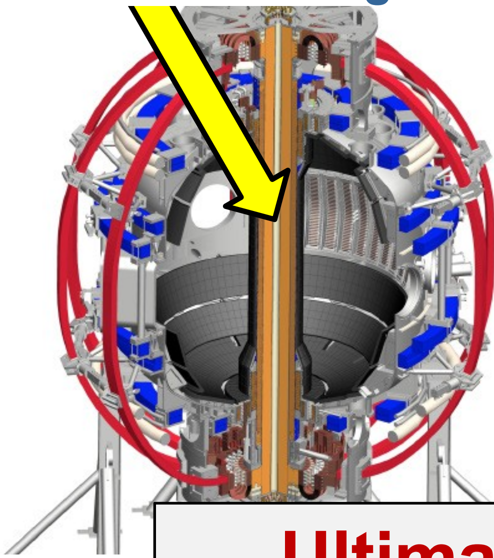
- Highest magnetic field, pressure
- Highest plasma beta in large ST
- 2× higher max power (NBI+RF) and edge heat fluxes
- 2× higher self-driven current
- Only large ST with RF heating

Boundary emphasis

- Highly-flexible "long-leg" divertor for power exhaust research
- Only large ST with off-midplane 3D magnetic field coils for edge instability control

NSTX-U targeting major performance increase to explore new physics regimes

1. New Central Magnet



2. Tangential 2nd Neutral Beam

Ultimate Performance Goals:

- ➢2× toroidal field (0.5 ➔ 1T)
- ➢2× plasma current (1 ➔ 2MA)
- ➢5× longer pulse (1 ➔ 5s)
- ➢2× heating power (5 ➔ 10MW for 5s)
  - Tangential NBI ➔ 2× current drive efficiency
  - Up to 15MW NBI + 4MW RF for 1-2s
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)
- ➢4× divertor heat flux (➔ ITER levels)

NSTX-U vital for addressing key ST / fusion questions

Will access new physics with 2 new tools:

Highest normalized pressure at high T

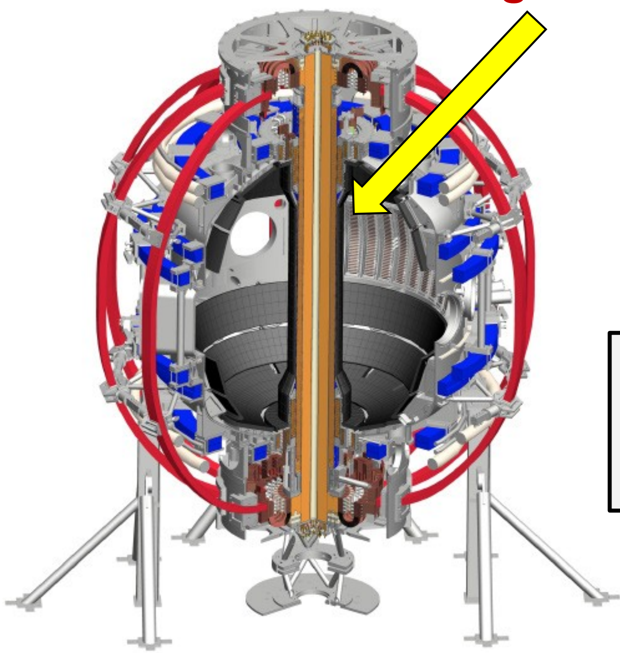
➔ Unique regime, study new transport and stability physics

Sustain plasma without transformer

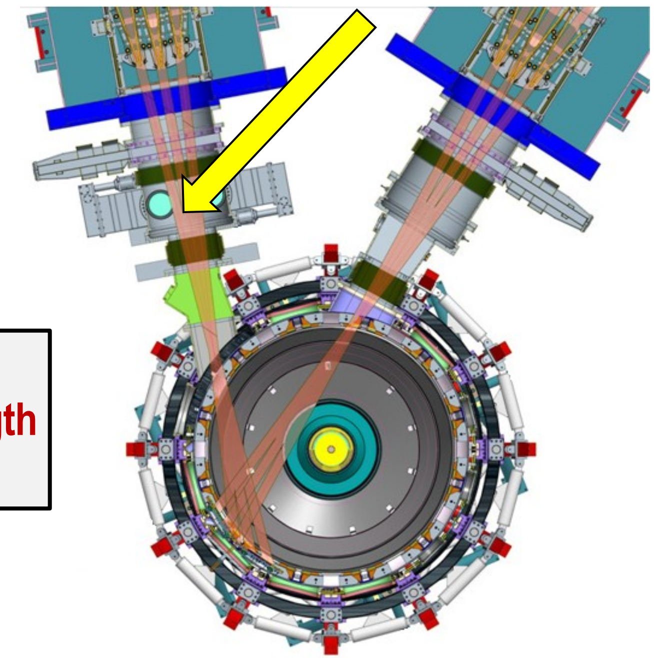
➔ Not yet achieved at high-β_T, low ν^*

Essential for any future steady-state ST

1. New Central Magnet



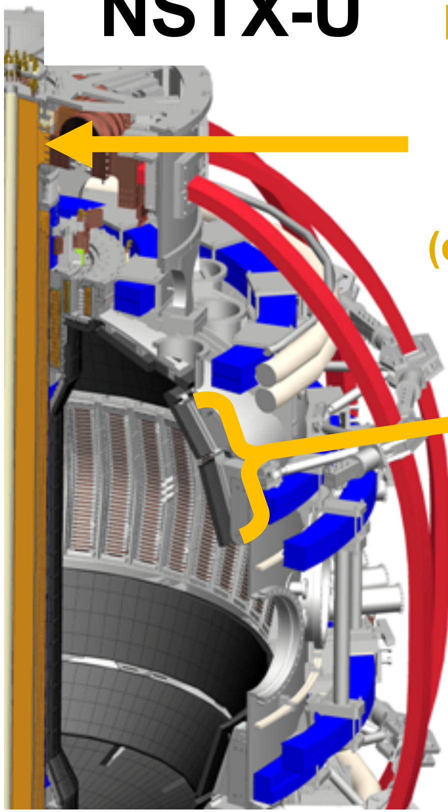
2. Tangential 2nd Neutral Beam



2× field, current, power
4× heat flux, 5× pulse length
Up to 10× higher $nT\tau_E$

NSTX-U design enables access to 2-3× higher plasma pressure, temperature than MAST-U

NSTX-U



NSTX-U central magnet provides 1.5× higher toroidal field current

→ ~1.5 - 2× higher B_T^2

(depending on plasma shape)

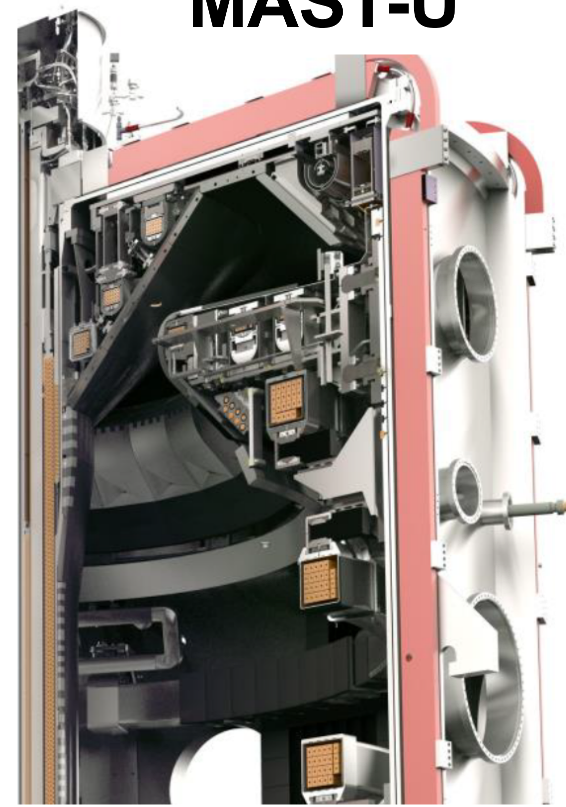
Conducting plates can suppress global kink instabilities,

~1.5× higher β_T

$$p \propto \beta_T B_T^2$$

2-3× higher

MAST-U

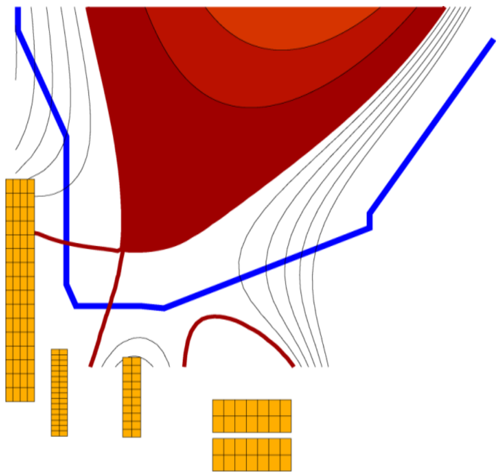


- Expect ~2× higher edge "pedestal" pressure due to higher B, shaping

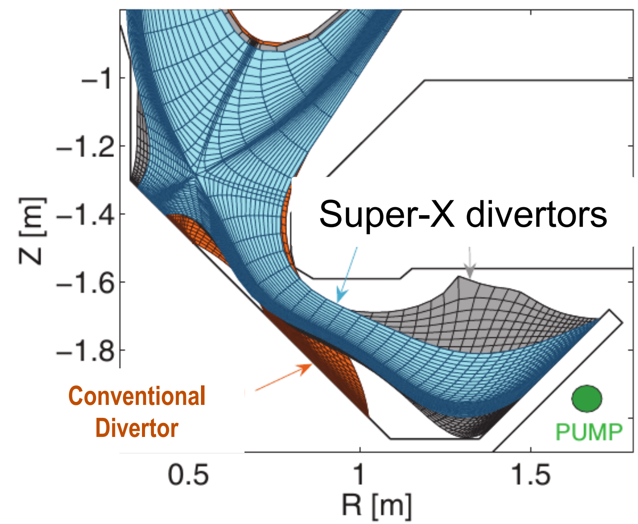
STs will provide leading contributions to development and understanding of advanced divertors

NSTX-U: Short-leg flared divertor + radiation to mitigate heat flux

MAST-U: World-leading pumped long-leg + flexible flaring, radiation



New PF1 magnets for flaring control, highest shaping, highest ST edge parallel heat flux



E. Havlickova, et al., Plasma Phys. Control. Fusion ***56*** *(2014) 075008*

Together provide science basis to integrate high performance ST core with advanced power exhaust