NSTX-U

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

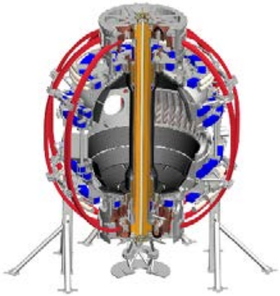
NSTX-U PAC-39 Program Overview

J. Menard

For the NSTX-U Research and Recovery Teams

PPPL

January 9, 2018



PPPL

Outline

- PAC Members and charge questions
- ST and NSTX-U research goals
- Program impacts from extended outage
- Key questions addressed by NSTX-U
- World-leading ST capabilities during initial ops
- Summary

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Thank you to PAC-39 members

	Cary Forest	University of Wisconsin — PAC chair
new	Richard Buttery	General Atomics
Remote	Ian Chapman	Culham Center for Fusion Energy
	Jerry Hughes	Massachusetts Institute of Technology
	Tony Leonard	General Atomics
new	Yijun Lin	Massachusetts Institute of Technology
Unavailable	Piero Martin	Eurofusion and Consorzio RFX, University of Padua, Italy
new	Rachael McDermott	IPP Garching
Unavailable	Kouji Shinohara	National Institutes for Quantum and Radiological Science and Technology
	George Sips	EFDA Close Support Unit, Culham Science Centre, UK
	Ezekial Unterberg	Oak Ridge National Laboratory
	Xueqiao Xu	Lawrence Livermore National Laboratory
	Dennis Youchison	Oak Ridge National Laboratory
	Phil Efthimion	Princeton Plasma Physics Laboratory

Process for this PAC

- We request "real-time" PAC assistance in helping our team put forward the most compelling arguments for NSTX-U – the mission, program, facility / Recovery
  – We encourage the PAC to request improved arguments and slide content homework - overnight especially, longer-term
  – It would be most valuable to have any PAC consensus and endorsement of NSTX-U major strengths in the PPT debrief
- Technical discussions should focus on the charges
- Keep questions until end of talks to help stay on time

PAC-39 Charge Questions

The NSTX-U research program requests PAC-39 comments and recommendations on:

1. Quality and importance of recent NSTX / NSTX-U research results
2. Uniqueness / timeliness of important questions NSTX-U will answer for fusion science
3. How / whether NSTX-U will be world-leading when operation resumes in 2020
4. Important scientific and technological findings since:
   - Original physics design of NSTX-U (2009)
   - And/or since the last 5 year plan was written (2014)

   And how such findings influence the impact of medium-term research on NSTX-U (2020-2025) and the long-term NSTX-U vision (2025-2030).

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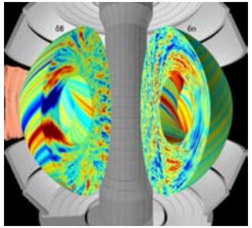
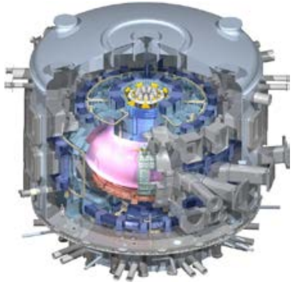
Low aspect ratio “Spherical Torus / Tokamak” (ST) vital for predictive capability for toroidal science and fusion energy

- ST accesses unique regime of high normalized *p*
  - Fundamental changes in nature of turbulence, MHD stability → Enhanced electromagnetic and super-Alfvénic effects
  - STs can more easily study electron-scale turbulence at high temperature → Important for all toroidal configurations
  - Neutral beam fast-ions in present STs mimic ITER DT fusion products → Study burning plasma science

Electromagnetic turbulence

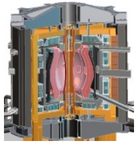


ITER

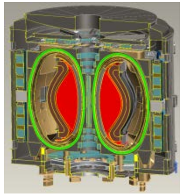


- If physics results favorable, STs could provide more economical fusion development & energy systems
  - Potentially reduced magnet and device size and cost

FNSF / CTF



Pilot Plant

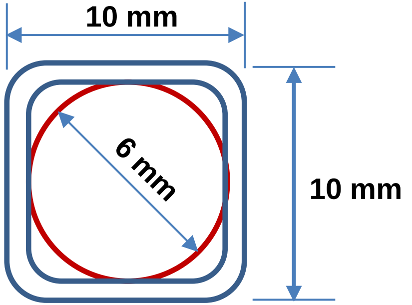


High-current-density rare earth barium copper oxide (REBCO) superconductors motivate consideration of low-A pilot plants

Conductor on Round Core Cables (CORC): High winding pack current density at high magnetic field

J_{WP} ~ 70MA/m^2 at 19T

Higher current densities, B likely possible…

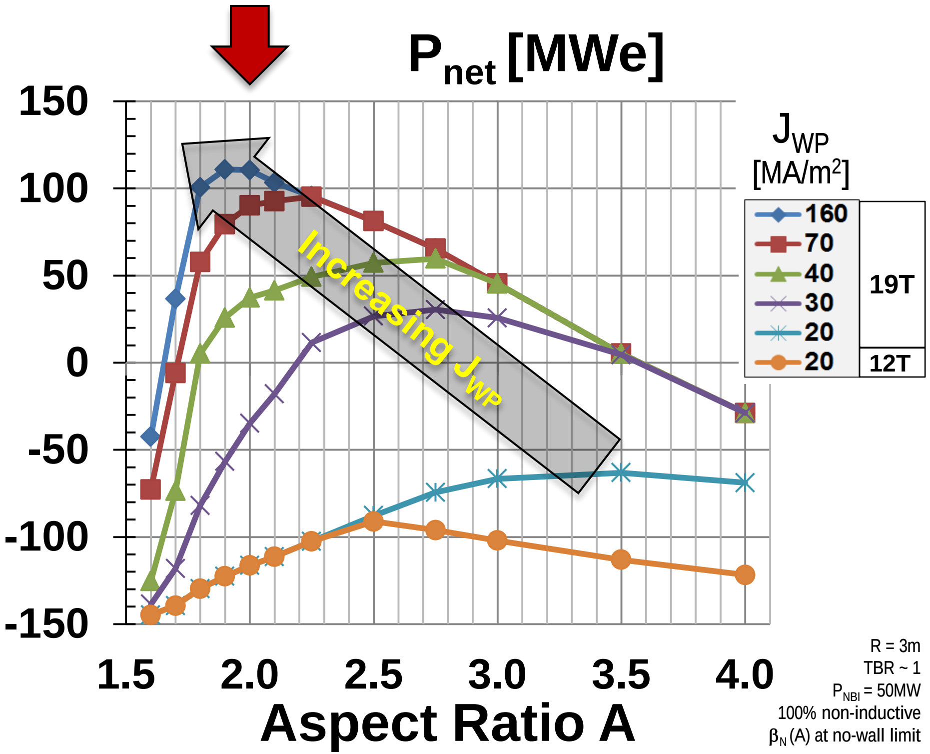


7 kA CORC (4.2K, 19 T) cable

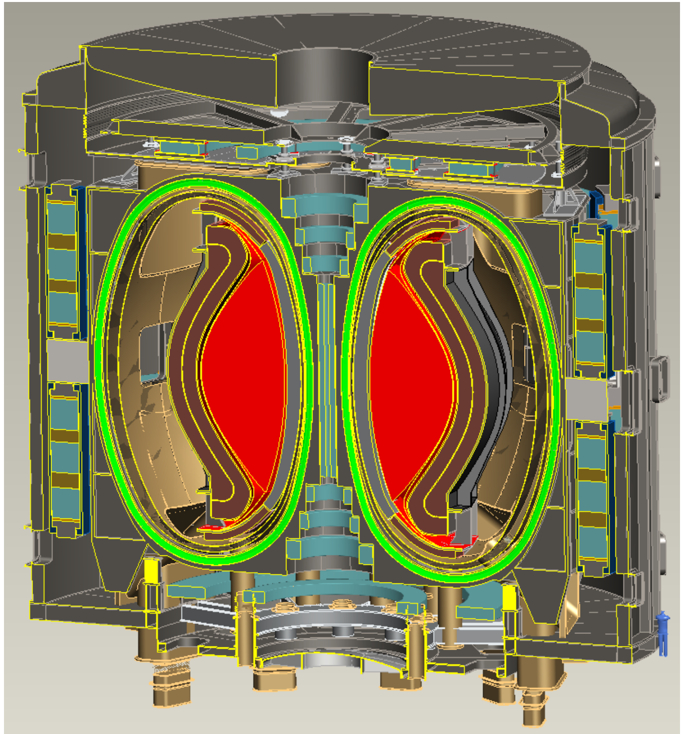
Base cable: 50 tapes YBCO Tapes with 38 μm substrate

(Van Der Laan, HTS4Fusion, 2015)

A ~ 2 attractive at high J_{WP}



Example: A=2, R_0 = 3m HTS-TF Pilot Plant



Cryostat volume ~ 1/3 of ITER

B_T = 4T, I_P = 12.5MA

$\kappa = 2.5$, $\delta = 0.55$

β_N=4.2, β_T=9%, f_{gw}=0.8

H_{98} = 1.75, $H_{Petty\text{-}08}$ = 1.3

H_{ST} = 0.7-0.9

f_{NI} = 100%, f_{BS} = 0.76

Startup I_P (OH)~2MA

J_{WP} = 70MA/m^2

$B_{T\text{-}max}$ = 17.5T

No joints in TF

Vertical maintenance

P_{fusion} = 520 MW

ST confinement scaling uncertain, but potentially favorable

ST non-inductive sustainment at high performance remains to be demonstrated

Peak n-fluence: 7MWy/m^2

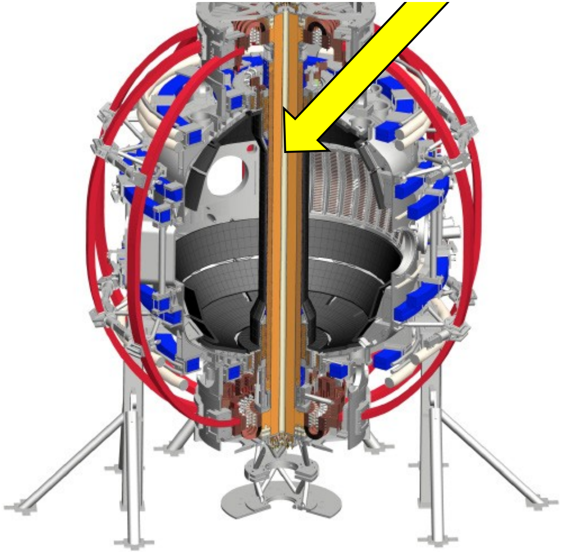
TBR ≥ 1

J. Menard, et al., Nucl. Fusion 56 (2016) 106023

NSTX-U vital for predictive capability, fusion science

Will access new physics with 2 new tools:

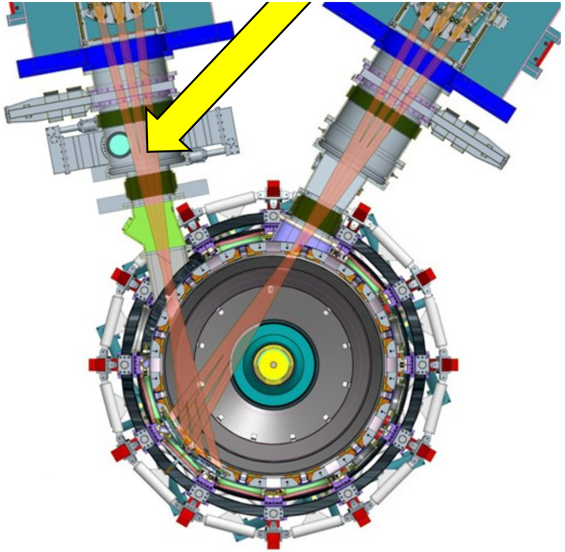
1. New Central Magnet



High normalized pressure at high T

→ Unique regime, study new transport and stability physics

2. Tangential 2nd Neutral Beam



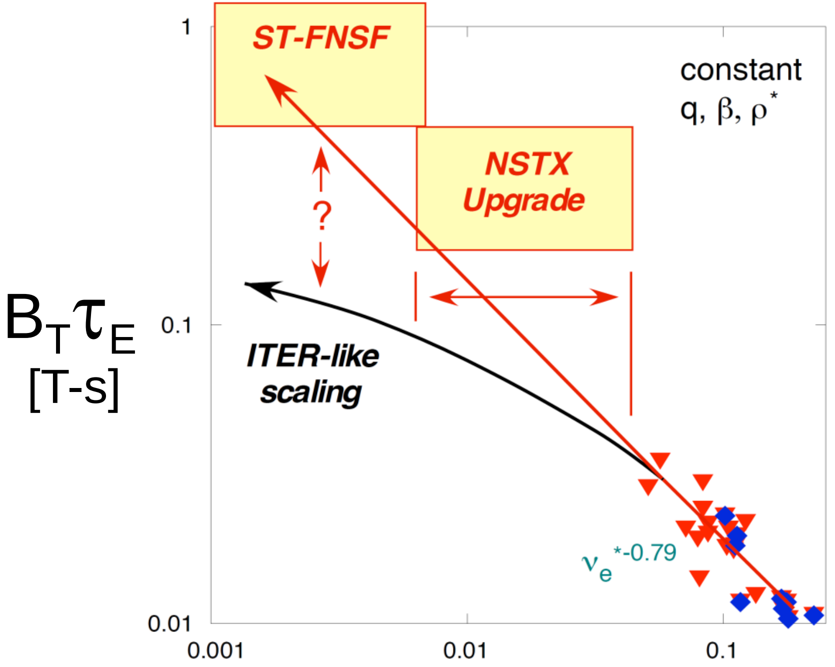
Sustain plasma without transformer

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

Essential for any future steady-state ST

NSTX / MAST confinement increased at higher T_e

Will confinement trend continue, or look like conventional A?



Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

ST scaling: $\tau_{E,\,th} \propto \nu_{*e}^{-0.8}\ \beta^{-0.0}$

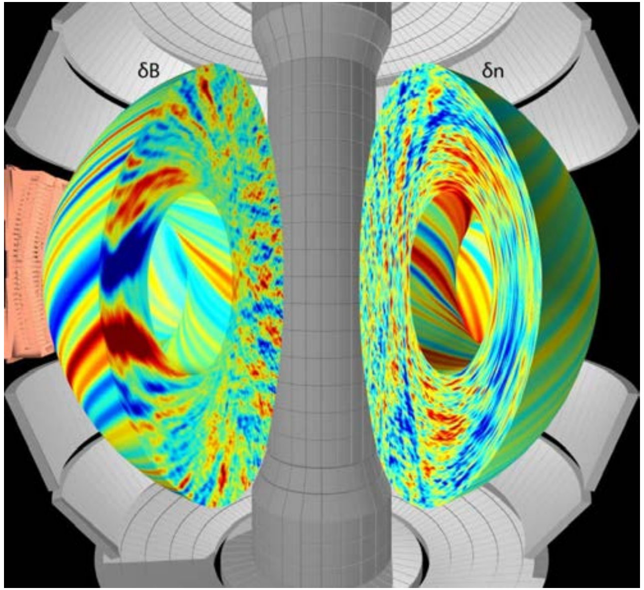
ITER 98y,2: $\tau_{E,\,th} \propto \nu_{*e}^{-0.1}\ \beta^{-0.9}$

Continued favorable confinement trends could lead to more compact ST reactors

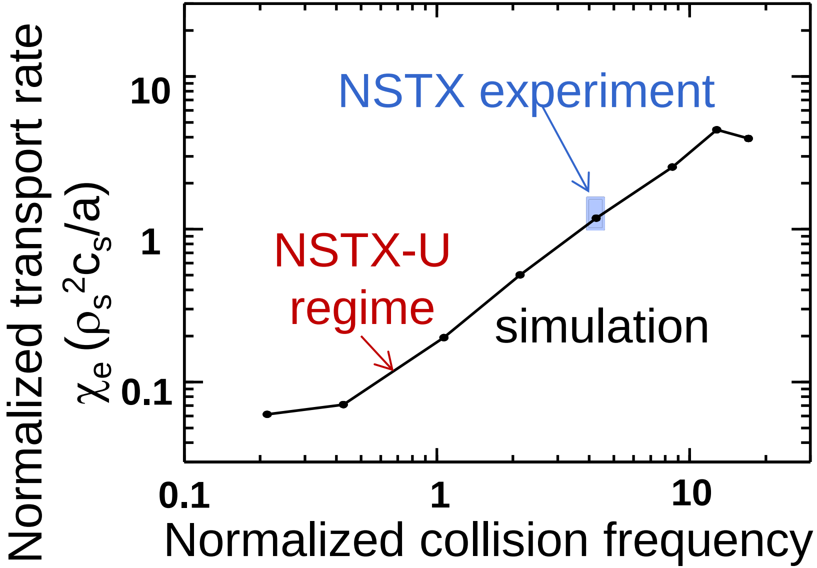
Low ν* → need higher plasma current, toroidal field, heating power, density control

NSTX-U will access and measure novel regimes of electron turbulent transport driven by high beta

- Energy confinement scaling from "micro-tearing" modes simulated to be similar to NSTX results



Visualization courtesy F. Scotti (LLNL)

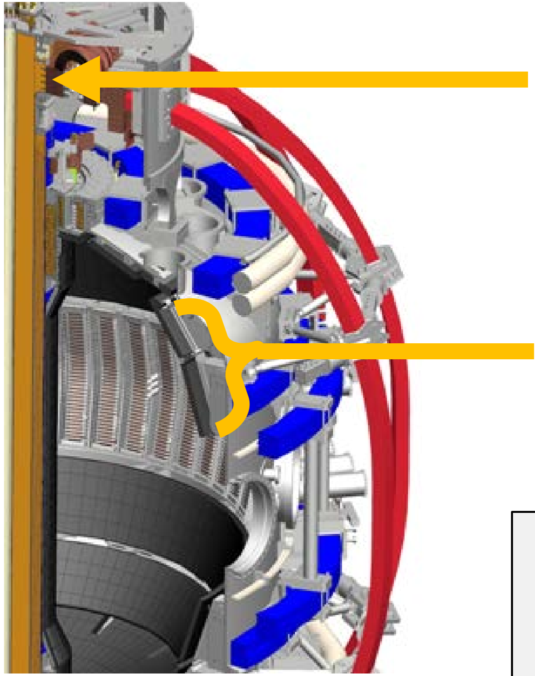


Guttenfelder, PRL (2011), PoP (2012)

Dissipative trapped electron modes (DTEM) → similar scaling

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

NSTX-U



NSTX-U design provides 1.4× higher B_T and

2× higher B_T^2

Conducting plates suppress kink instabilities,

1.5× higher β_N, β_T

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

3× higher

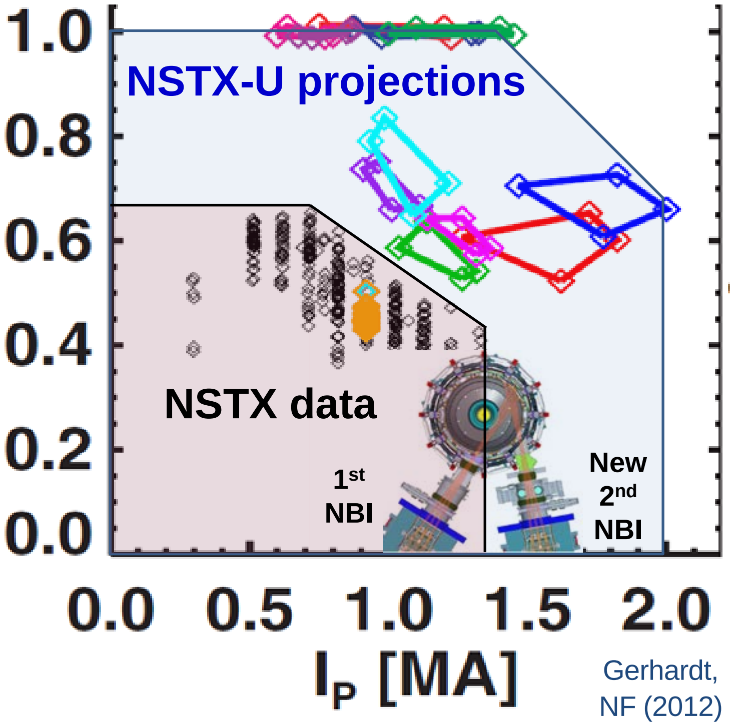
MAST-U

NSTX-U will test whether high-performance STs can be sustained for future fusion applications

NSTX-U greatly expands plasma current operating space:
100% non-inductive at ~1MA, 5s
Plasma current up to 2MA for 5s

NSTX ≤ 65% non-inductive
I_P = 1MA for ~1s, 1.3MA for 0.2s

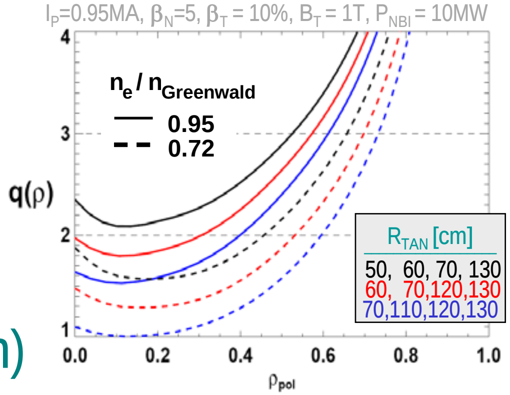
Non-inductive current fraction



Gerhardt, NF (2012)

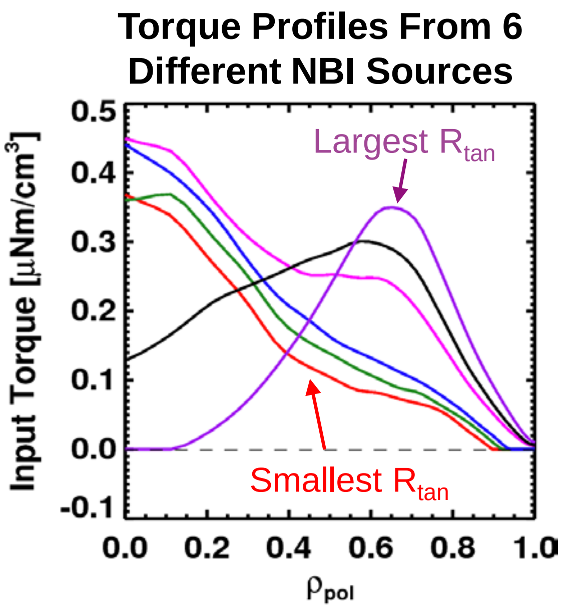
Boyer, NF (2015)

Vary & control q_{min} via:
- beam source
- plasma density
- outer gap (not shown)



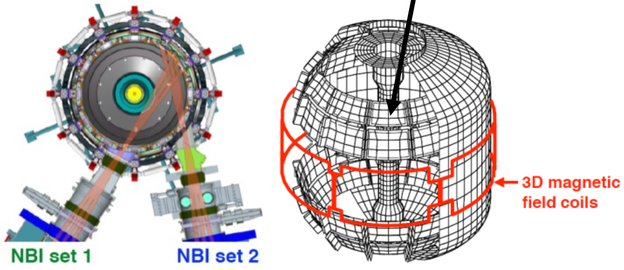
NSTX-U will be leading (only) ST able to access and study kinetic RWM physics in-depth

- NSTX showed that resonant damping can stabilize resistive wall mode (RWM)



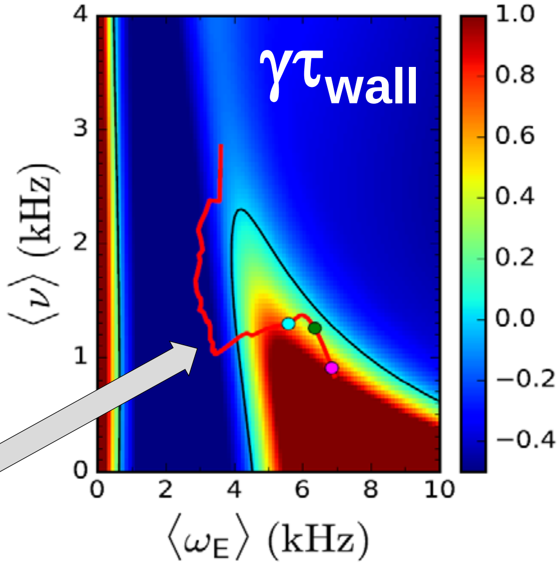
Passive stabilizing plates:

$\beta_N \approx 4$ (no-wall) → 6 (with-wall)



Use neutral beams, rotation damping from 3D fields, other actuators to control rotation for RWM stability

Reduced drift-kinetic MHD RWM stability map



J. Berkery, Phys. Plasmas (2017)

NSTX-U at high plasma current will play important role in understanding power exhaust width scaling

Significant uncertainty (factor of 2) in projected scrape-off layer heat flux width λ_q at full performance NSTX-U (2MA, 1T, 10MW)

- **Heuristic Drift Scaling [Eich, PRL 2011]: 1.9 [mm]**

$\boldsymbol{\lambda_q \sim B_T^{-7/8} q_{cyl}^{9/8}}$ **(used for Recovery PFC re-design** – *see Gerhardt presentation***)**

- Multi-machine Eich Scaling (Eich, NF 2013): 2.0 [mm]
- NSTX scaling (Gray, JNM 2011): 3.0 [mm]
- MAST scaling (Thornton, PPCF 2014): 4.1 [mm]
- XGC-1 simulation (unpublished – see backup): 3.0 [mm]

See M. Reinke presentation for more detail

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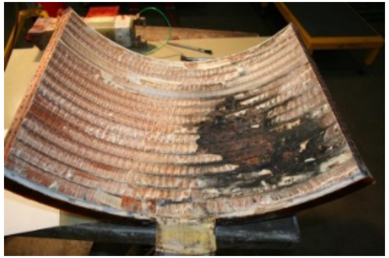
REMINDER: In FY2016 NSTX-U had scientifically productive 1st year, but had to cease operations due to failed divertor PF coil

- Achieved H-mode on 8th day of 10 weeks of operation
- Surpassed magnetic field and pulse-duration of NSTX
- Matched best NSTX H-mode performance at ~1MA
- Identified, corrected dominant error fields (more to do…)
- Commissioned all magnetic and kinetic profile diagnostics
- New 2nd NBI suppresses Global Alfven Eigenmodes (GAE)
  – Fredrickson – APS invited, PRL 2017
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation

Several papers on NSTX-U results published, in-press, or submitted

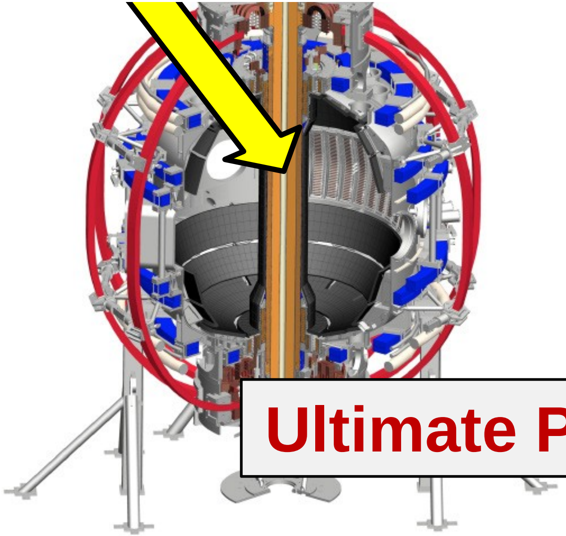
- PF1A upper coil failed very slowly over ~1000 pulses

Section of failed PF1AU

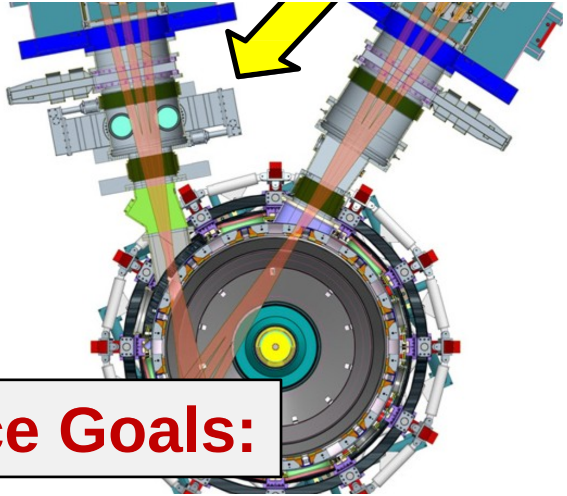


NSTX-U targeting major increase in performance

1. New Central Magnet



2. Tangential 2nd Neutral Beam

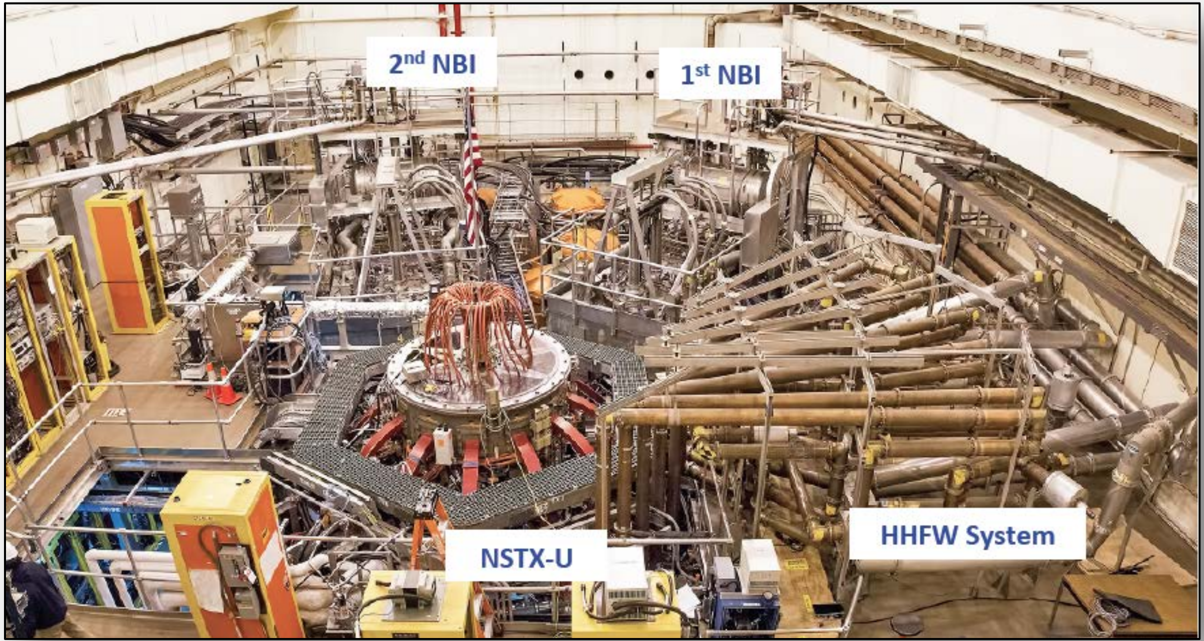


Ultimate Performance Goals:

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

Achieving NSTX-U Ultimate Performance Goals requires Recovery Project (see S. Gerhardt presentation)

- **FY2017: DOE requested PPPL to review "Extent of Condition" of entire NSTX-U facility including reliability, submit Corrective Action Plan (CAP)**



- Recovery = Implement CAP using operations funding: $48M base + $15M contingency
- Normal / planned maintenance and run preparation: $34M base + $4M contingency
- Recovery following DOE 413.3b guidelines

Major program impacts due to Recovery (1)

- Research operations delayed until sometime in FY20
  - Several FY17 and FY18-19 research Milestones redirected toward Recovery / future operations
  - In April, FES redirected NSTX-U funded “science” collaborators to new FES “ST” solicitation (international) and DIII-D solicitation
  - NSTX-U University and Industry diagnostic collaborations remain funded in FY18, but smaller diagnostics can be relocated to other facilities
    - Modest Recovery scope/funding for collaborating national labs – PFCs, diagnostics
  - Within PPPL, NSTX-U researchers redirected to find collaboration opportunities – preferably aligned with NSTX-U research goals
  - S. Kaye helped coordinate DIII-D National Campaign (FY17 only)
    - S. Kaye also coordinating PPPL MAST-U collaborations, M. Ono for QUEST

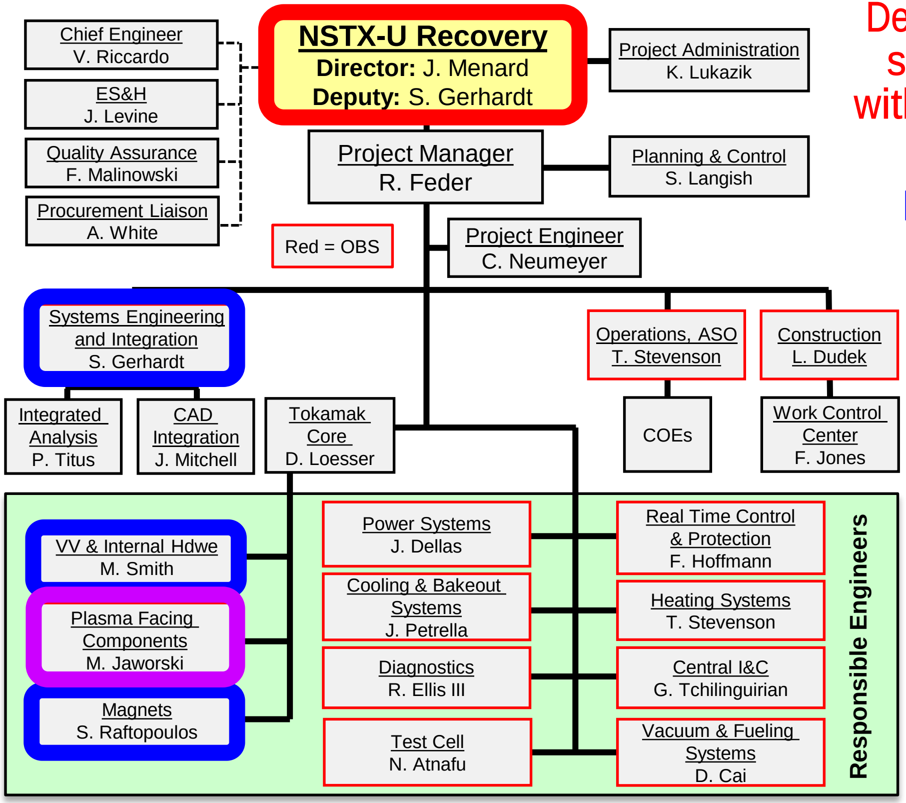
Major program impacts due to Recovery (2)

- Improved / more in-depth understanding of divertor heat and halo loads requires re-design of some plasma facing components (Gerhardt presentation)
- Changes to “polar regions” to minimize vacuum and magnet risk eliminate lower insulator, reduce inboard-outboard gap → no Coaxial Helicity Injection (Gerhardt presentation)
  - Non-inductive start-up research carried out through collaborations → NSTX-U implementation deferred (Raman presentation)
- No high-harmonic fast-wave (HHFW) enhancement scope in Recovery + budget uncertainty
  - HHFW program on hiatus, retaining staff for re-start (budget-dependent)
  - Recovery: modeling / projections of antenna limiter heat loading
  - Possible future activities: Design of dedicated non-HHFW outboard limiter, RF test-stand activities to improve voltage stand-off / RF power coupling

NSTX-U researchers actively engaged in Recovery

- Aided Extent of Condition reviews:
  - Aided in System Design Description (SDD) formulation, edits
  - Design Validation and Verification Reviews (DVVRs)
    - Aided in preparation of presentations, chit submission, chit response
- New PFC requirements working group (click here for more info)
  - Extent of Condition review process identified PFC power handling issues
    - Narrower SOL width not incorporated in General Requirements Document (2009-2012)
    - Increased halo peaking on IBDH → T-bar design insufficient
  - Extensive equilibrium & heat-flux scans performed, more to come
- Topical Science Group contributions:
  - Re-assessed scenario needs: first 2yrs of ops + 5/7 year plan
    - Magnetic balance and δ variations influence PFC design considerations
  - Assessed impact of polar region mods on research plans

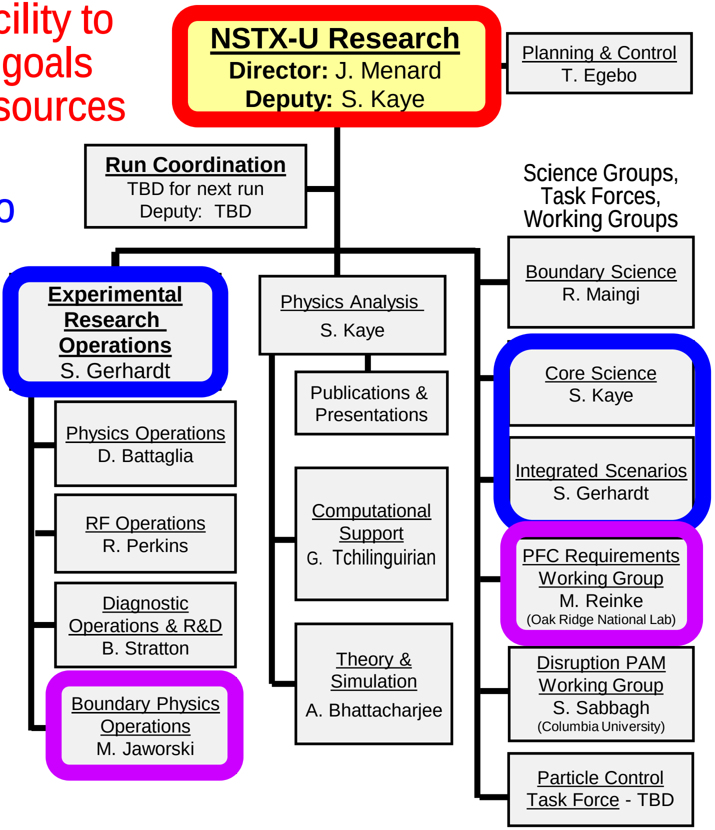
Overall NSTX-U goals balanced and coordinated across Recovery and Research departments



Deliver reliable facility to support science goals within available resources

Requirements to achieve operational scenarios (example: magnet alignment vs error-fields)

PFC RE is physicist ensuring requirements and research goals are met



FY18 Recovery Notable Outcomes

(Notable Outcome = annual DOE management contract goal)

- Complete final design reviews for the 6 PF1 coils 3/31/2018
- Prepare Recovery project to be ready for baselining (4/30/2018)
- Build at least one prototype PF1A coil (7/15/2018)
  - Qualify coil by operating at both max required current, max heating
  - Verify the quality of the coil's insulation system through electrical testing followed by destructive sectioning and inspection
- Build and test at least one of each type (PF1A, B, C) of production inner poloidal field coil (9/30/2018)
  - Qualify a PF1A coil by operating at both max required current, max heating

FY18 Research Milestones

- **Notable Outcome:** Provide leadership, coordination, support to FES joint research target (JRT) with goal of testing predictive models of fast-ion transport by multiple Alfven eigenmodes.
- **Research:**
  1. Develop/benchmark reduced heat flux & thermo-mech. models for PFC monitoring
  2. Develop simulation framework for ST breakdown and current ramp-up
  3. Validate & further develop reduced transport models for electron thermal transport
  4. Optimize energetic particle distribution function for improved plasma performance
- **Facility:** Evaluate PFC operational limits and develop integrated diagnostic plans for operations

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Science Group presentations address key questions

Science Group and presenter

Scenarios
D. Battaglia

Core
W. Guttenfelder
M. Podesta
S. Sabbagh

Boundary
A. Diallo
M. Reinke
M. Jaworski

Scenarios
R. Perkins
R. Raman

Key research questions: First 1-3 years, 3-5 years, 5-10 years

- Can a high-performance ST have 100% non-inductive current, equilibrated?
- Does "ST" confinement scaling persist to (3× to 6×) lower collisionality ν^*?
- Can Alfvénic instabilities be modelled/understood, manipulated to control core?
- Can passive & active RWM stabilization be achieved at low ν^* and sustained?
- How will pedestal transport & turbulence vary vs lower ν^*, higher I_P, Li coatings
- How does heat-flux width scale? Can n_e control be sustained? (see backup)
- Can heat fluxes be mitigated consistent with high core performance?
- Can liquid metals provide a solution for higher confinement, power exhaust?
- Can high-harmonic fast-waves provide reliable heating and CD in H-mode?
- Can NSTX-U demonstrate solenoidal-free initiation, ramp-up, and flat-top?

NSTX-U will be world-leading ST in several research areas when operations resume

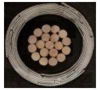
- Access up to 3× higher ST pressure, temperature
- Study transport physics in unique regime: high β, low ν^*
  - Advanced diagnostics for electron and ion-scale turbulence
  - Li-coatings (on C) for confinement vs. recycling in large ST
- Only ST to access to wall-stabilized regime, highest β values through kinetic stabilization, advanced control
- High-power NBI heating and current drive tools ready to:
  - Pursue 100% non-inductive scenarios at high-performance
  - Study high divertor heat flux mitigation (sweep, flare, detach, …)
  - Explore fast-ion instabilities and control for burning plasmas
- Complement DIII-D higher-A, MAST-U boundary emphasis

Summary: NSTX-U will address key scientific issues to accelerate fusion science understanding, performance

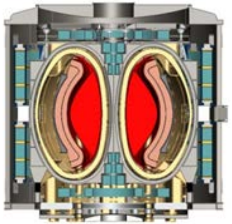
Fusion Technology and Performance

ST = Spherical Torus:
A magnetic confinement configuration that could lead to a smaller and more cost-competitive fusion energy source

High-temperature superconductors for compact and efficient ST fusion core



ST Pilot Plant for net electricity



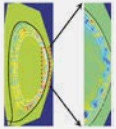
ST-based fusion neutron source

Provide steady-state fusion neutron environment for nuclear material and component R&D

Liquid metal blankets for high thermal efficiency

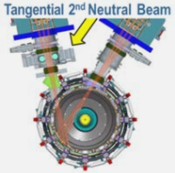
NSTX Upgrade Facility and Research Program

Extend ST confinement understanding to fusion-relevant temperatures

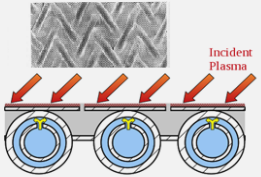


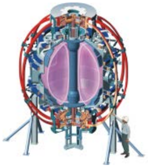
Advanced diagnostics + computation provide fundamental understanding and basis for next-step ST devices

Demonstrate sustainment for future steady-state operation



Longer-term: High-power tests of liquid metals as transformative wall solution





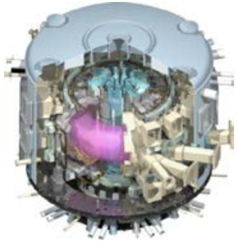
NSTX Explored ST stability & confinement

Fundamental Plasma and Materials Science

NSTX-U Backup

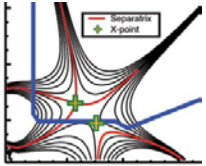
NSTX-U Mission Elements

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



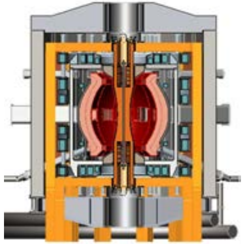
- Develop solutions for plasma-material interface challenge

Liquid metals / Lithium

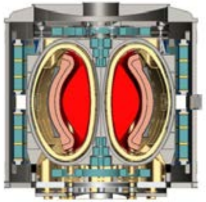


Snowflake / X

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant



ST-FNSF / Pilot-Plant



NSTX-U and DIII-D are powerful and complementary tools enabling U.S. leadership in core fusion science

DIII-D

A = 3

GENERAL ATOMICS

San Diego, CA

NSTX-U

A = 1.6

PPPL

Princeton, NJ

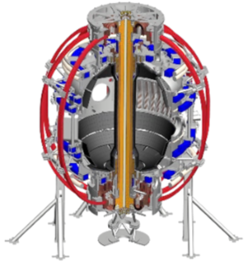
- Variation of aspect ratio A provides robust physics validation
  - Understand tokamak MHD stability, thermal and fast ion transport, pedestal structure
- Together, NSTX-U and DIII-D provide the U.S. world-leading and complementary capabilities to address core physics issues
  - Both have excellent diagnostics, strong and flexible beam and wave heating systems
  - Complementary boundary approaches: cryo-pumping vs. lithium, solid vs. liquid
  - Together, can identify optimal aspect ratio for possible fusion next-steps

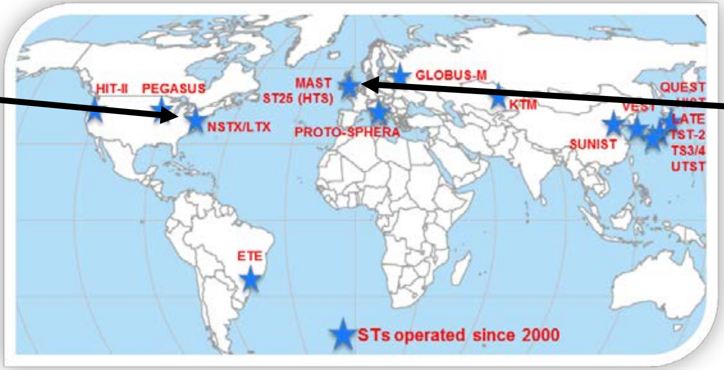
NSTX-U and MAST-U are the most capable ST devices in a world-wide ST research program

NSTX-U

PPPL

Princeton, NJ



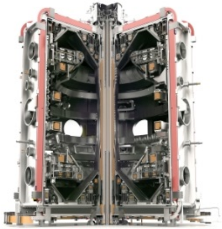


MAST-U

CCFE

CULHAM CENTRE FOR FUSION ENERGY

Culham, UK

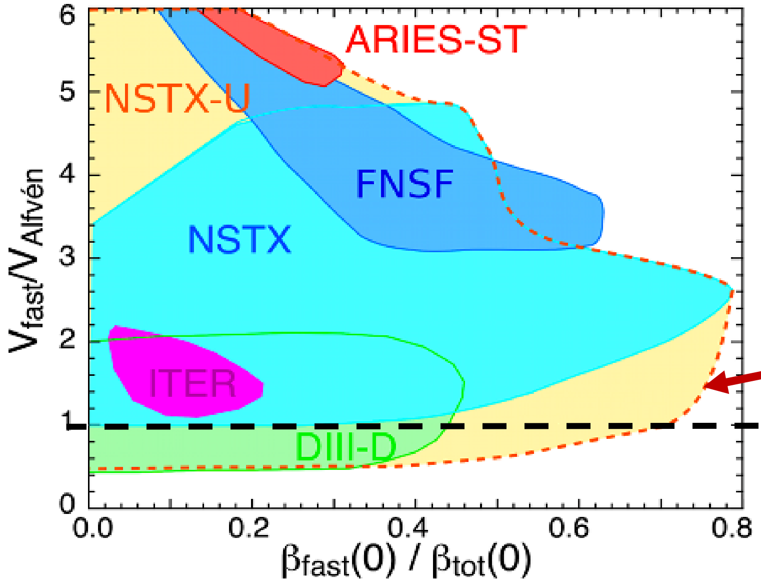


Complementary Research:

- **NSTX-U – emphasis on core**
  - Designed to access highest ST plasma pressure, temperature by 3×, β_T & β_N by 1.5×
  - Diagnose, understand core transport and turbulence, stability, sustainment
- **MAST-U – emphasis on boundary**
  - Designed with world's most flexible, well-diagnosed power exhaust system (super-X divertor) for heat-flux mitigation studies

Together, NSTX-U and MAST-U will provide majority of ST physics basis

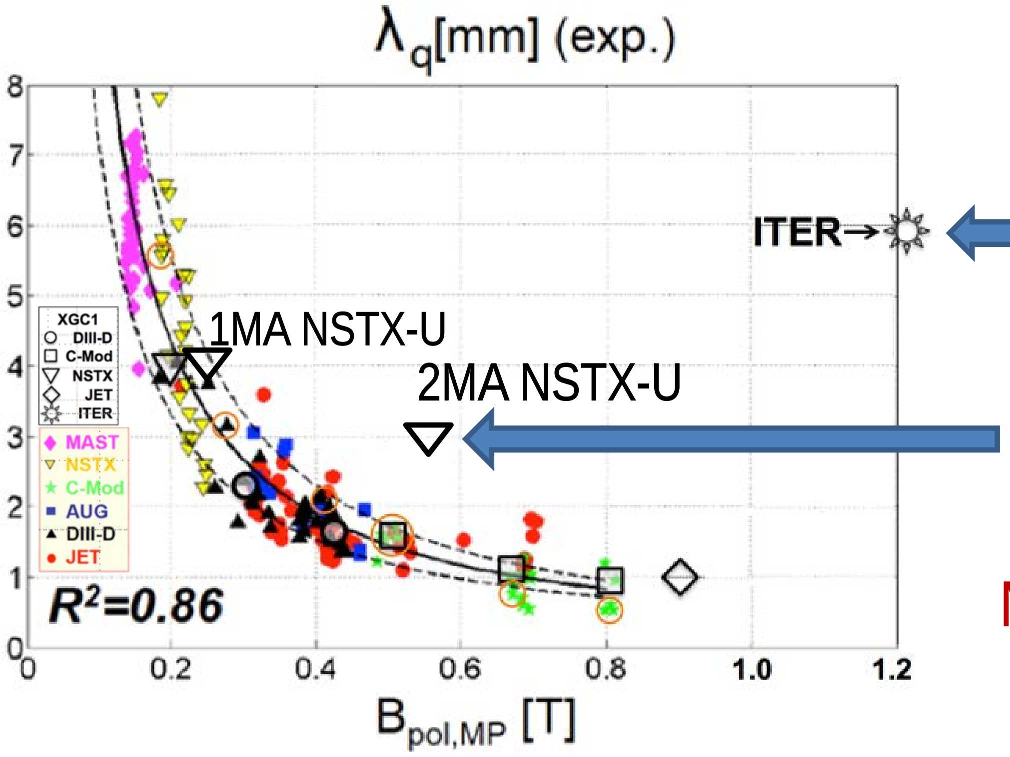
NSTX-U excellent testbed for α-particle physics



- NSTX-U: larger fast-ion dynamic range spanning ST and conventional A
  - **Toroidal field 2× NSTX →** can stabilize modes ($V_f < V_A$)
  - **Tangential 2nd NBI →** highly flexible fast-ion distribution
    - Vary pitch angle, pressure profile

- **Are fast-ions well confined in high-performance ST regimes?**
- **Can we predict fast-ion confinement for burning plasmas / ITER?**

NSTX-U experiments at higher plasma current will play important role in understanding power exhaust width



XGC1 simulations predict turbulence will widen edge heat flux in ITER

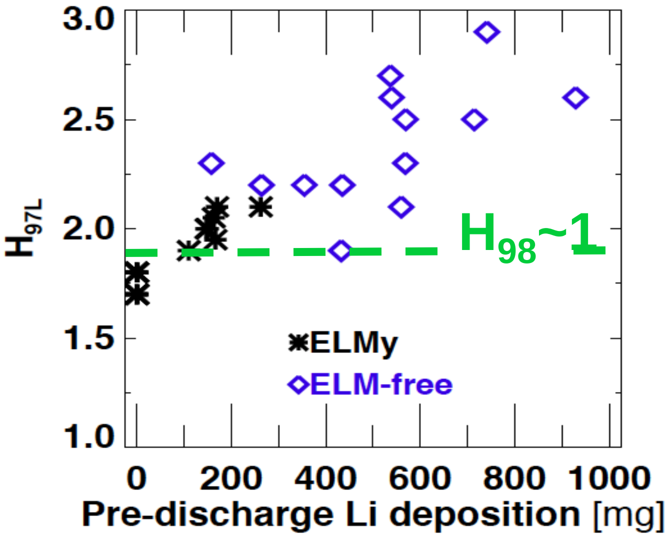
C.S. Chang et al 2017 Nucl. Fusion 57 116023

Preliminary XGC1 shows deviation from $\lambda_q \sim I_P^{-1}$ for full current (2MA) NSTX-U

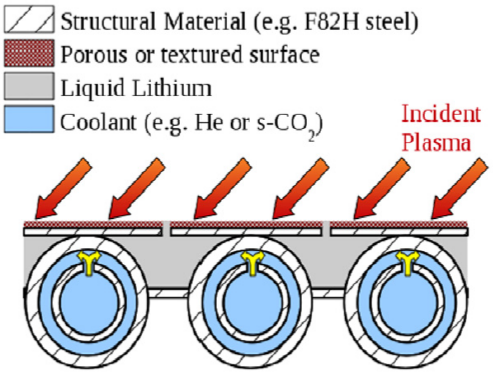
Need additional simulations and analysis to better understand underlying physics, implications for STs

NSTX-U will study confinement improvement from Li wall coatings, and power exhaust on liquid metal divertors

NSTX: Higher lithium deposition
→ higher confinement



D.P. Boyle, et al., J. Nucl. Mater. 438 (2013) S979



Example: Capillary Porous System

M. Jaworski, PPCF (2013)

NSTX-U: Will double Li deposition, increase confinement

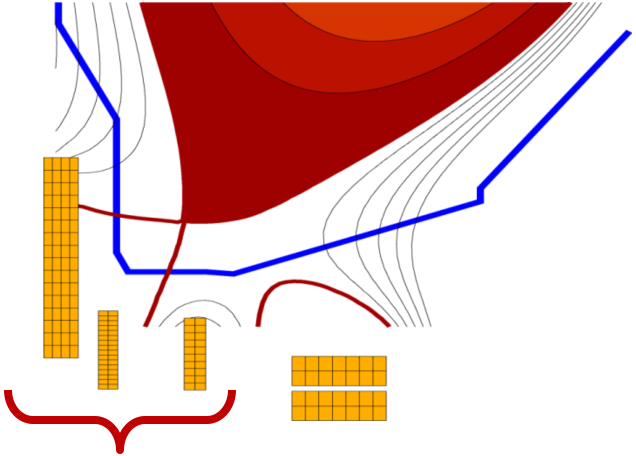
Test liquid metals for power handling

STs leading advanced divertor development

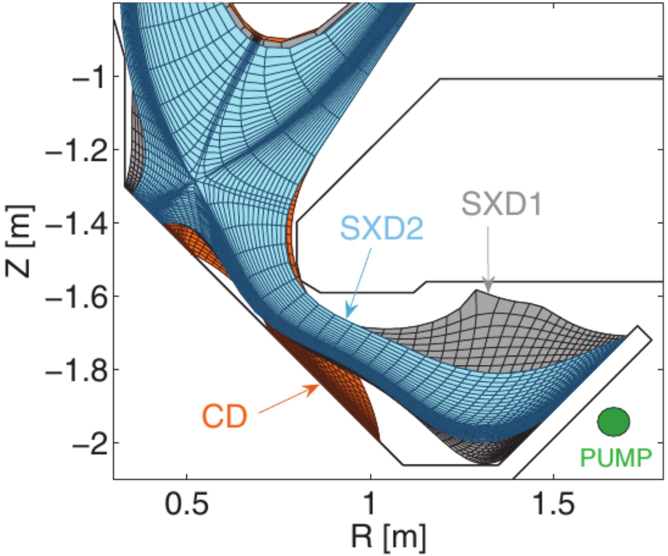
NSTX-U / MAST-U collaborating on 1st plasma, scenarios, divertors

NSTX-U: Flared divertor using "snowflake / X" + radiation

MAST-U: world-leading tests of long-leg/super-X w/ variable flaring

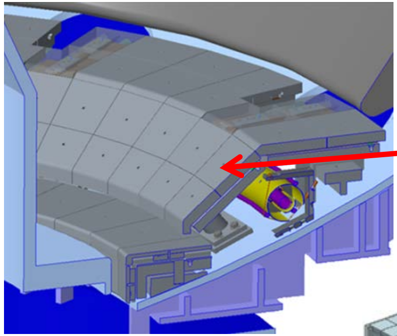


New PF1 coils in NSTX-U central magnet



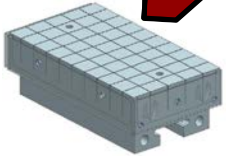
E. Havlickova, et al., Plasma Phys. Control. Fusion 56 (2014) 075008

Motivations for future facility enhancements



Divertor cryo-pump (graphite → high-Z PFCs)

– Control density and ν* without Li, compare to Li wall-coatings
– Use bakeable baffle + high-Z PFCs for initial liquid metal tests

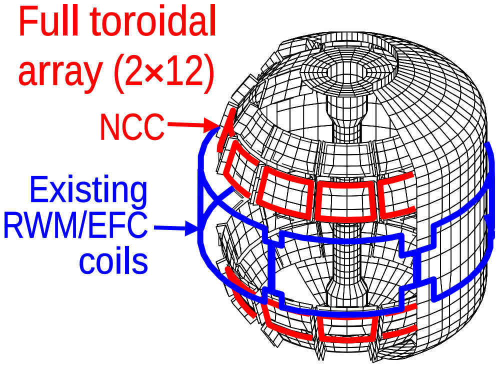


Transition from all graphite to W/TZM PFCs

– Assess integration of high-performance ST with reactor-relevant wall
– Implement wall compatible with bulk / flowing liquid metals
– Extend LTX-β liquid-Li confinement experiments to higher performance

28GHz / 1-2MW gyrotron (Tsukuba)

– EC/EBW-only current-drive for start-up
– Heat helicity injection target with ECH for HHFW/NBI
– Longer-term: EBW CD for sustainment



Non-axisymmetric control coils (NCC)

– Resonant/non-resonant NTV rotation control, enhanced RWM/EF control
– Assess RMP ELM suppression (not yet achieved in ST)

FNSF / Pilot Plant Backup

Design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) or Pilot Plant

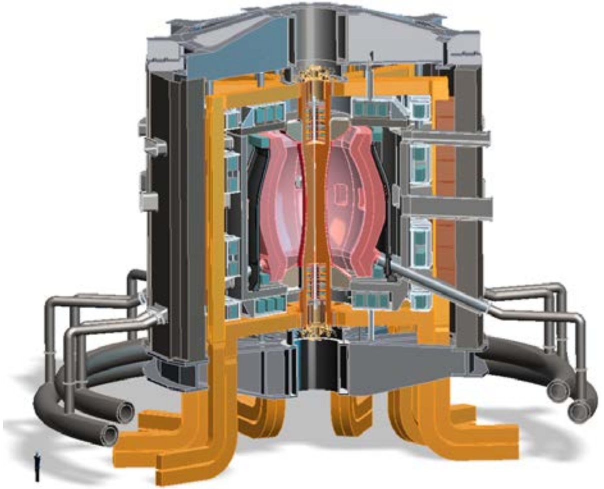
FNSF: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

Pilot Plant: Electrical self-sufficiency: $Q_{eng} = P_{elec} / P_{consumed} \geq 1$ (+ FNSF mission?)

FNSF with copper TF coils

$A=1.7$, $R_0 = 1.7m$, $\kappa_x = 2.7$

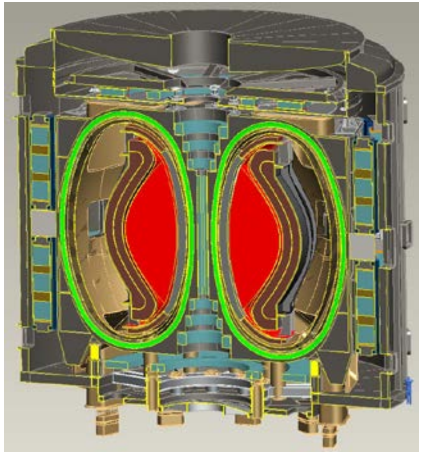
Fluence = $6MWy/m^2$, TBR ~ 1



FNSF / Pilot Plant with HTS TF coils

$A=2$, $R_0 = 3m$, $\kappa_x = 2.5$

$6MWy/m^2$, TBR ~ 1, Q_{eng} ~ 1

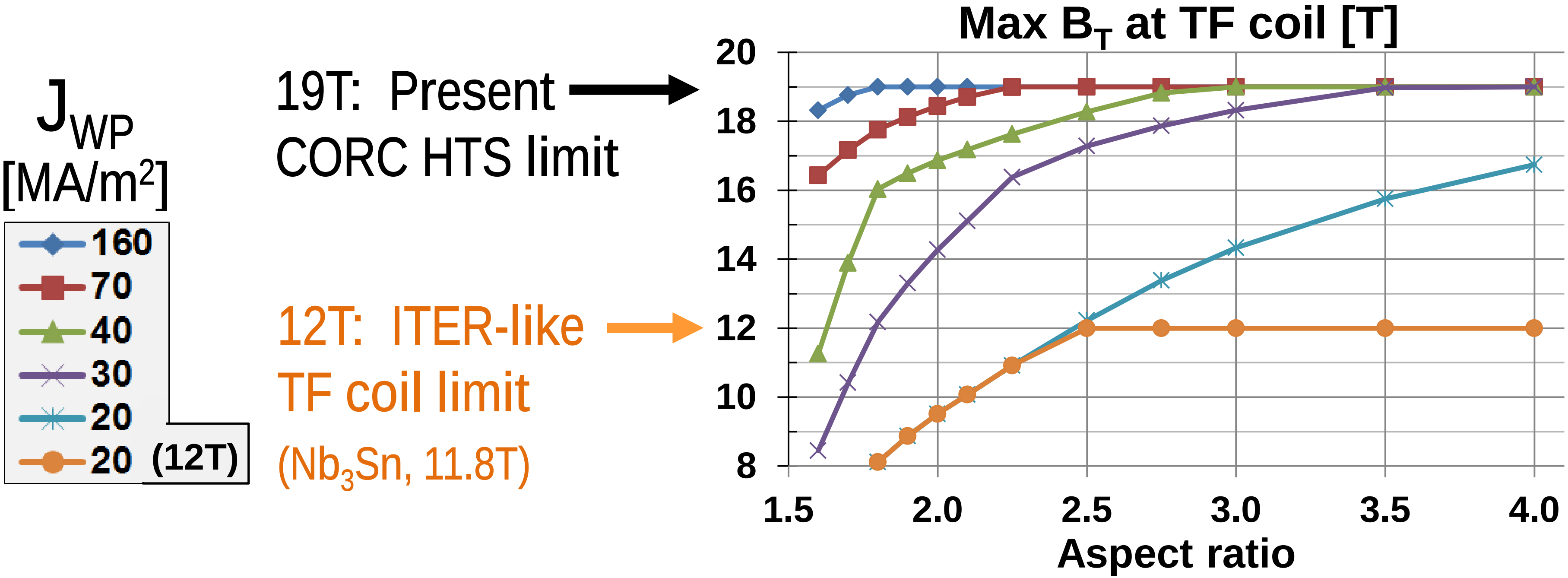


At lower A, high TF winding-pack current density enables access to maximum allowed B_T at coil

J_{WP} [MA/m²]

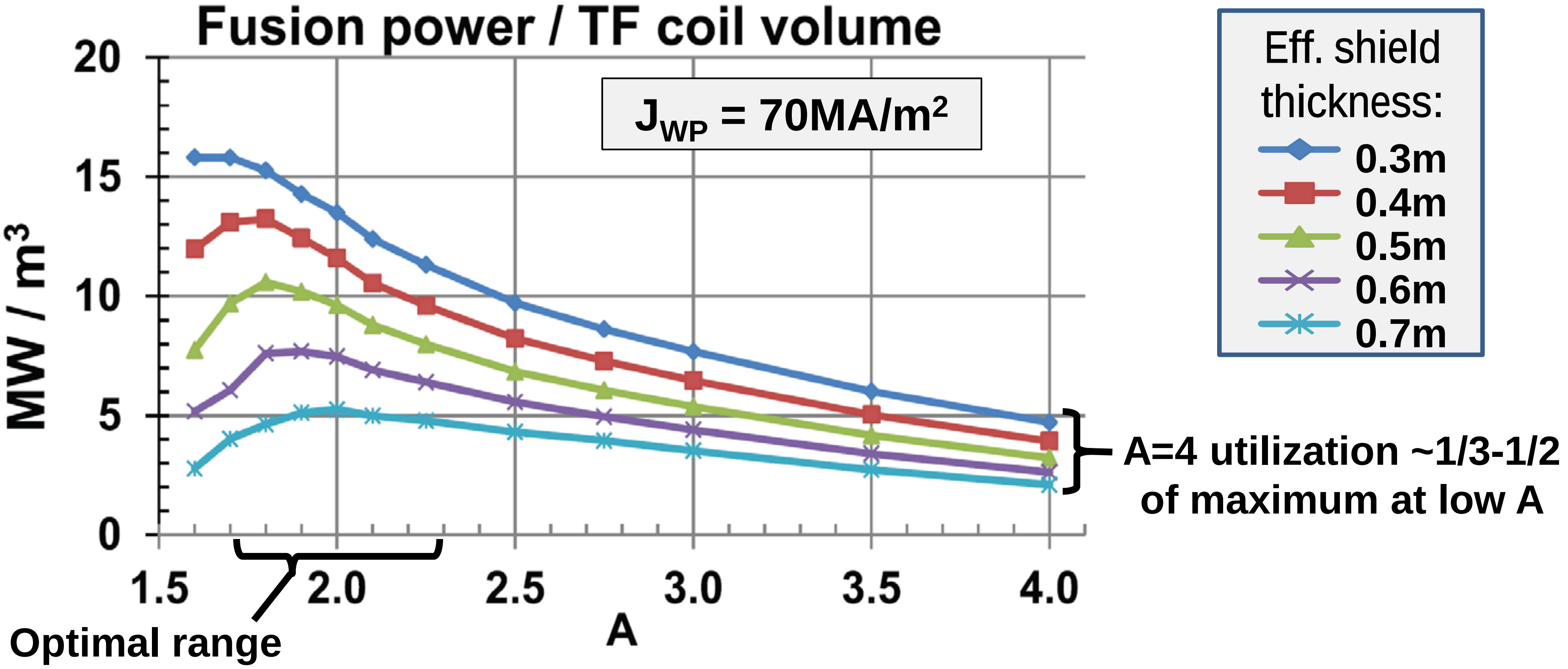
19T: Present CORC HTS limit

12T: ITER-like TF coil limit (Nb_3Sn, 11.8T)

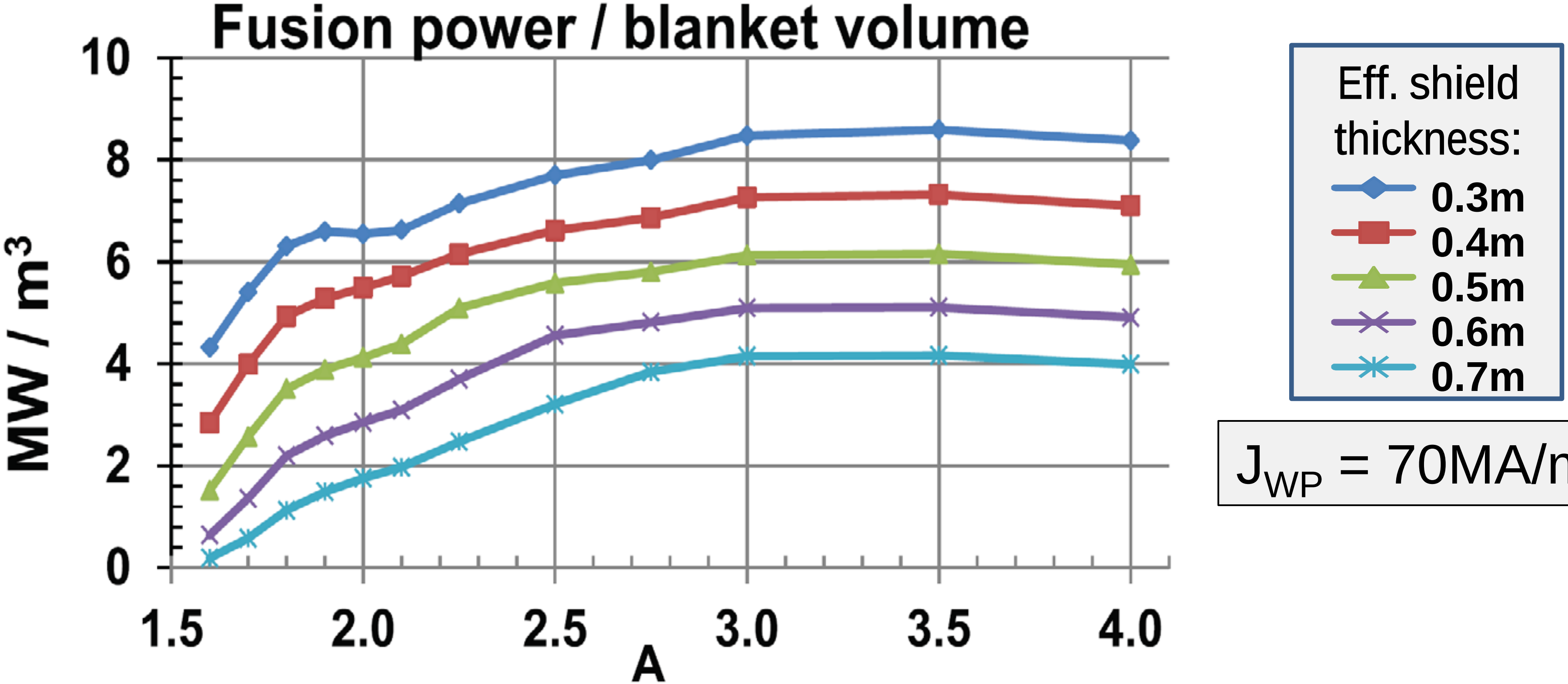


- Coil structure sized to maintain ≤ 0.3% strain on winding pack
- Effective inboard tungsten carbide (WC) neutron shield thickness = 60cm

A = 1.8-2.3 maximizes TF magnet utilization, and TF will be significant fraction of core cost



A ≥ 3 maximizes blanket volume utilization



$J_{WP} = 70MA/m^2$