NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX Upgrade: ST research to accelerate fusion development

Jon Menard (PPPL)

For the NSTX-U Research Team

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MIT
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Nova Photonics
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ORNL
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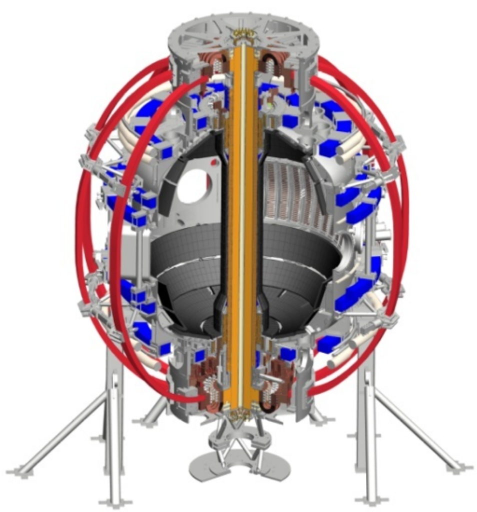
X Science LLC

FESAC Strategic Planning Panel Meeting

Gaithersburg Marriott - Washingtonian Center

July 8-10, 2014



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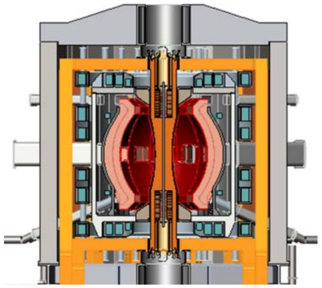
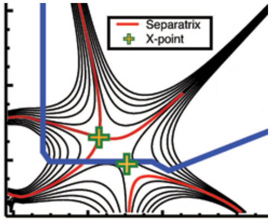
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

NSTX Upgrade mission elements

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
- Develop solutions for the plasma-material interface challenge
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
- Develop ST as fusion energy system



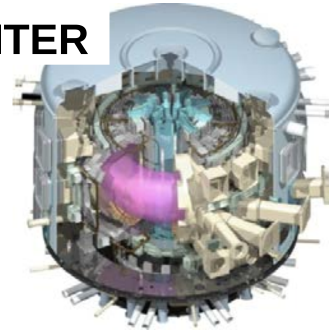
ST-FNSF

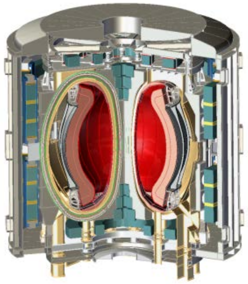


Snowflake/X

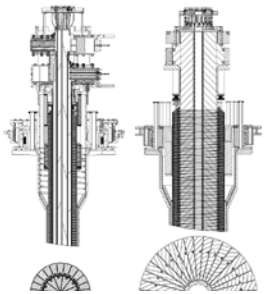
Liquid metals/Li

ITER



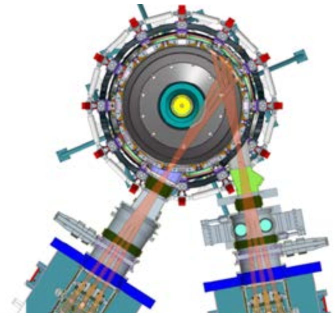


NSTX-U provides world-leading research capabilities across all 5 ReNeW Themes

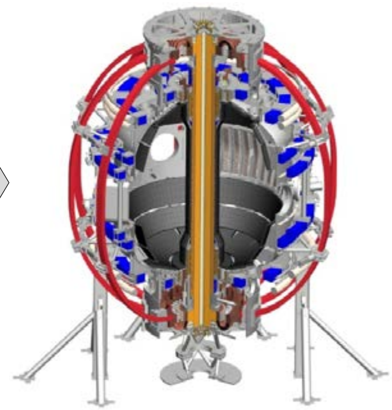


Previous New
Center-stack

+



Present New 2nd
Neutral Beam Injector (NBI)



- B_T = 0.5 → 1T
- I_P = 1 → 2MA
- Full non-inductive ~1MA
- 5× longer pulse
- 5-10× higher $nT\tau$
- 1st plasma Jan/Feb 2015

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/program in world for assessing ST for FNSF**

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

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

Establish ST physics / scenarios	High-performance + metal walls
2015-2019	**2015-2019**

2× field, power, current, 5× pulse-length

10-20s pulses for PFC/LM equilibration

100% non-inductive:
- Start-up to 0.4MA
- Ramp-up 0.4 → ~1MA
- Sustain at ~1MA
- (Density control needed for all phases)

Inform choice of FNSF aspect ratio and divertor configuration (with divertor data from MAST-U Super-X + other experiments)

Inform choice of FNSF/DEMO plasma-facing materials for divertor and first-wall

Reduce collisionality: ~10× lower vs. NSTX

Sustain high β_N ~ 6 with profile/mode control

Mitigate high q_{div}: up/down snowflake/X+radiation

Divertor C → high-Z, Li vapor shielding

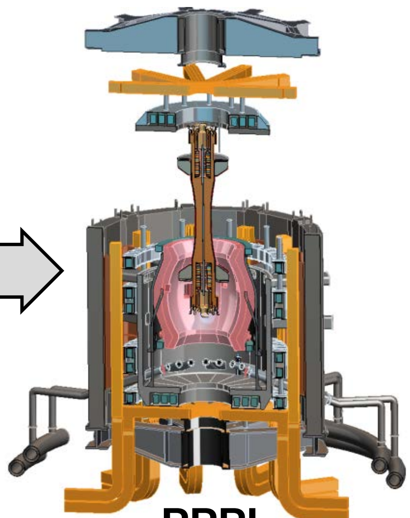
All high-Z PFCs, hot walls, static Li-wall

Liquid Li modules → flowing Li/LM modules → flowing Li divertor

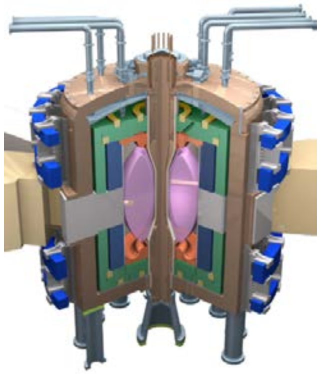
ST is potentially attractive as Fusion Nuclear Science Facility (FNSF)

- 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

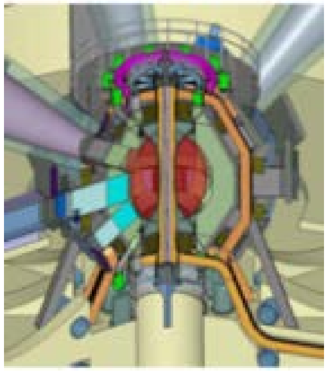
Example ST-FNSF concepts



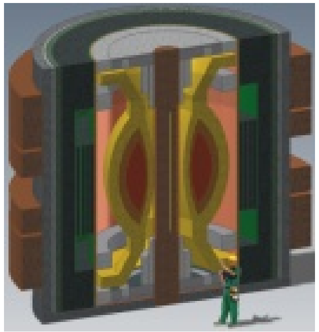
PPPL



ORNL



Culham (UK)



UT Austin

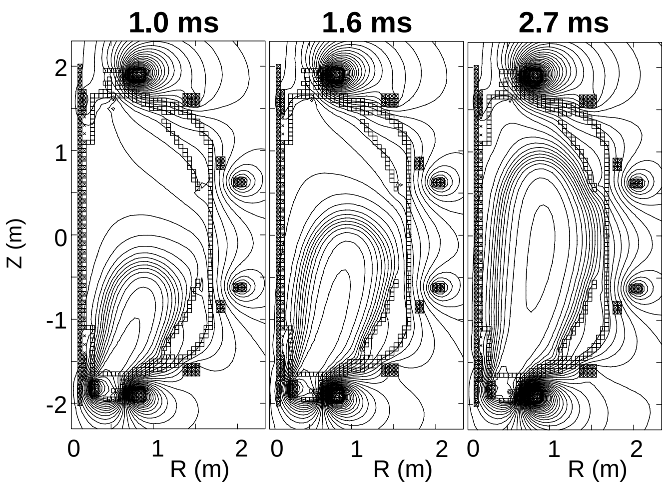
Gap 1: Start-up/ramp-up with small/no transformer

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

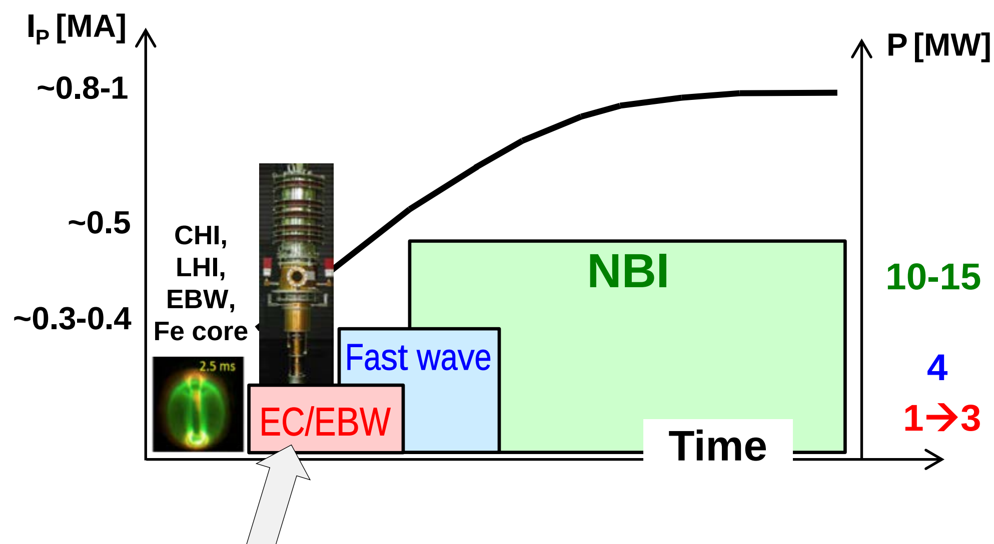
- Helicity injection (HI) start-up: 150-200kA → projects to ~0.4MA on NSTX-U
- New 2nd NBI projected to enable non-inductive ramp-up from ~0.4 → 1MA
- HI start-up T_e too low for fast-wave or NBI coupling → **use ECH to raise T_e**

CHI startup

TSC Simulations of CHI



NSTX-U start-up/ramp-up strategy



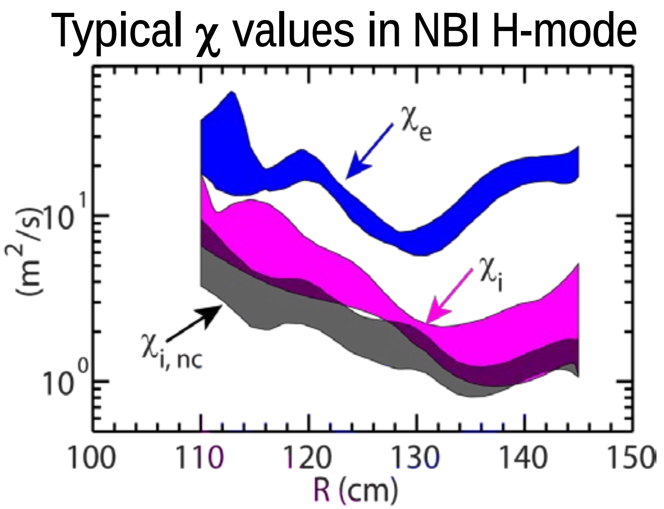
- 1 → 3MW 28GHz (with 2nd NBI) → world-leading start-up/ramp-up for ST/AT
- EBW: efficient off-axis current drive for over-dense ST/RFP/AT plasmas

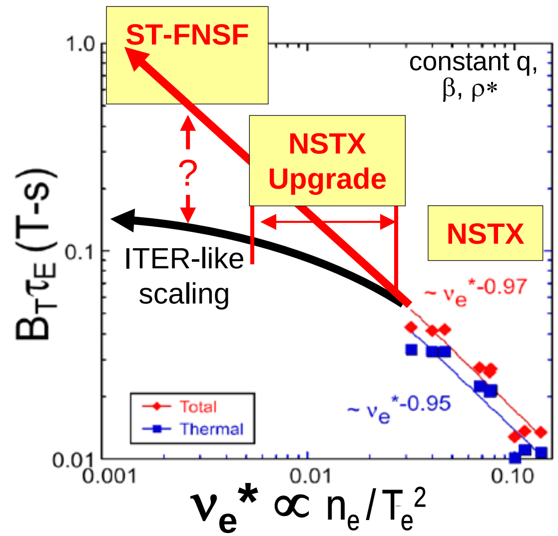
➢ See Raman Whitepaper: "Simplifying ST and AT Concepts"

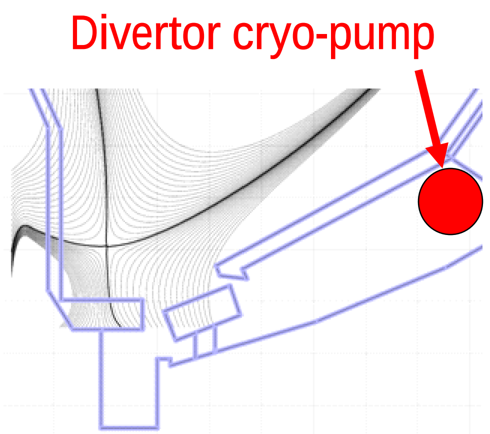
Gap 2: Understand/optimize ST energy confinement

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

- Ion thermal transport ~neoclassical, electron transport anomalous
- Confinement scaling: $B\tau_E \sim \nu^{-0.9}\,\beta^{-0.2}$ differs from ITER-98y,2 $\sim \nu^{0}\,\beta^{-0.9}$
- High-β → electromagnetic turbulence (μ-tearing, Alfvénic, kinetic ballooning)
- Doubling I_P, B_T → 2× $T_{e,i}$, but need improved pumping to sustain lowest n_e, ν^*







- To reliably project to FNSF-ST/AT → need to understand transport vs. β, ν
  - ➢ Diagnostics: Beam emission spectroscopy, high-$k_{r,\theta}$, polarimetry, Doppler back-/cross-polarization scattering
- Leading opportunity to measure, model, understand electron transport

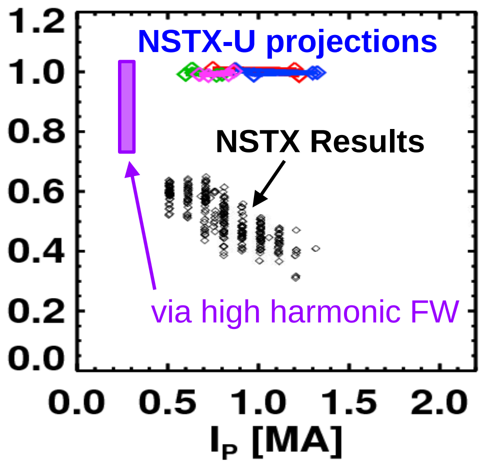
➢ See Guttenfelder/Crocker whitepaper “Validating EM turbulence/transport effects for burning plasmas”, also A. White whitepaper

Gap 3: Plasma sustainment, stability, and control

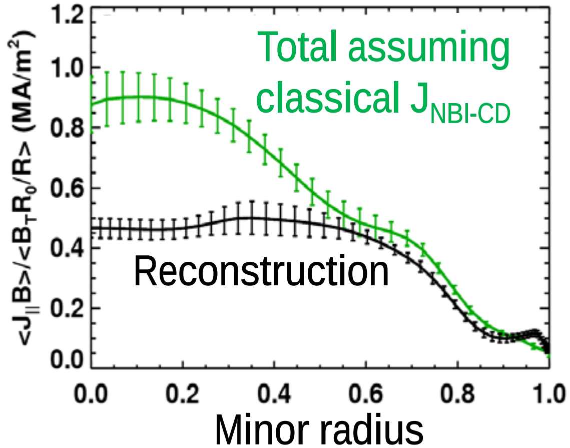
Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- NSTX achieved ~65% non-inductive current drive at FNSF-level β_T ~ 15-20%
- NSTX-U designed for 100% non-inductive using more tangential 2nd NBI
- TAE avalanches can cause redistribution/loss of NBI current drive
- High β_N ~ 6 sustained w/ active feedback, optimized/broad p, rotation profiles

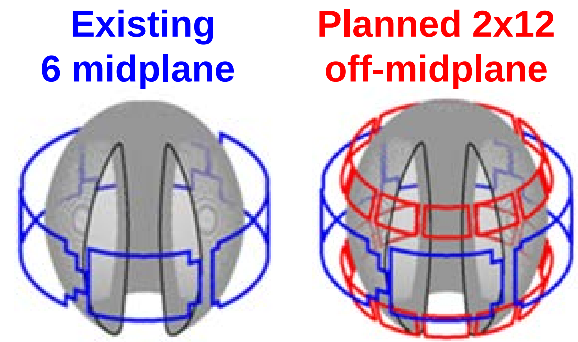
Non-inductive fraction



Plasma w/ rapid TAE avalanches



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

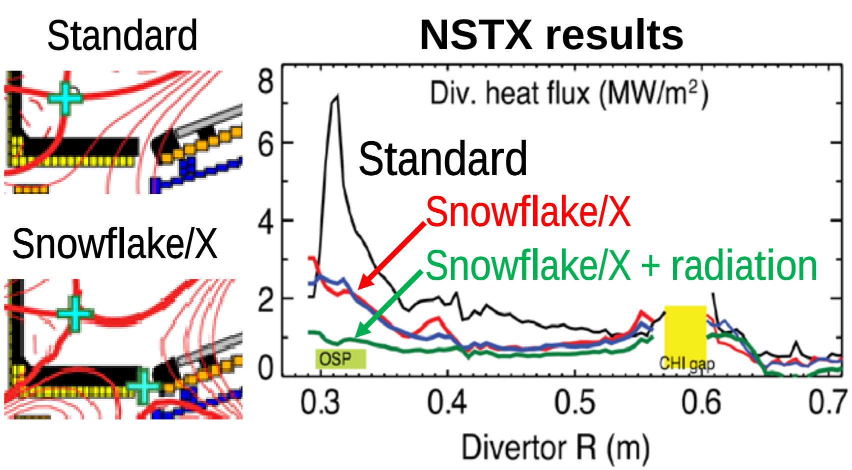
Gap 4: Mitigating high heat (and particle) flux (+ core/edge integration with high-Z / liquid metal PFCs)

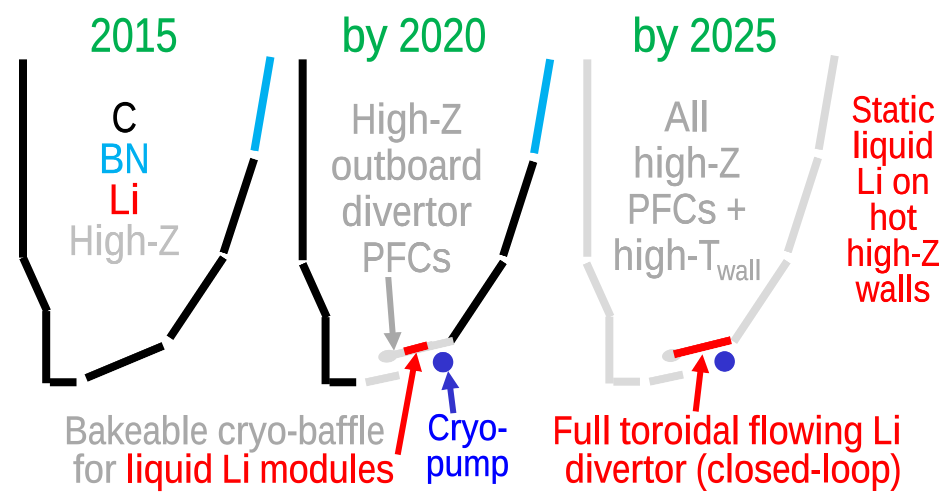
Achievements since Greenwald Report, NSTX-U base-program research, remaining gaps/enhancements needed

- High-flux-expansion snowflake/X-divertor + radiation reduce $q_{pk\text{-}div}$ (up to 5×)
- NSTX-U: 2× P_{NBI}, I_P, 0.5× λ_q → $q_{pk\text{-}div}$ ~4× higher → 30-40MW/m^2 unmitigated
- Will test mitigation of high $q_{pk\text{-}div}$ w/ double snowflake/X + partial detachment

- Steady-state FNSF scenario not demonstrated in any device w/ high-Z walls

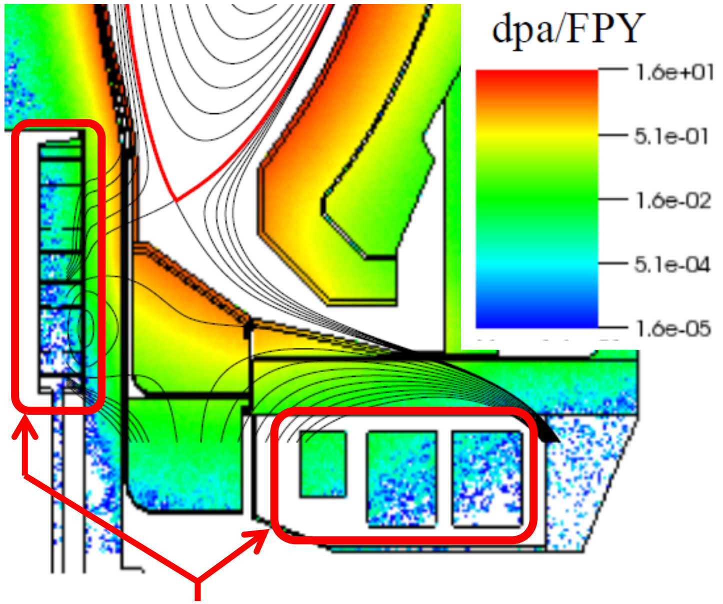
→ NSTX-U aims to integrate full non-inductive with high-Z + liquid metal PFCs

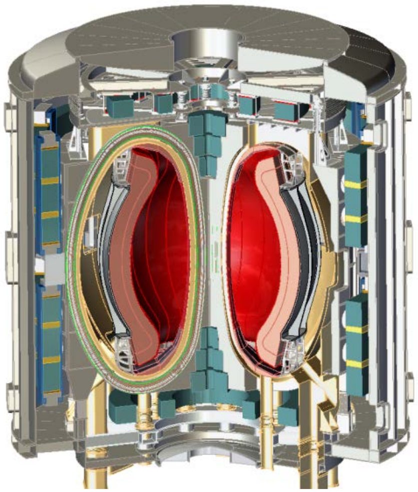




➢ See Maingi / Jaworski / Allain whitepapers on liquid metals, Hill whitepaper on FNSF PMI, ADX whitepapers

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





- Ex-vessel equilibrium PF coils
  - Shielding + MgO insulation → 6 FPY
- Long-leg divertor: $q_{pk\text{-}div} < 5MW/m^2$
- 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

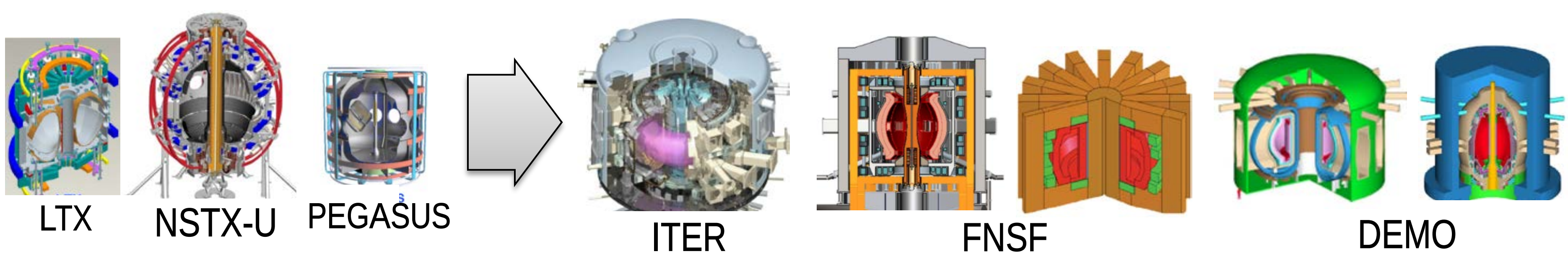
**Work supported by Tokamak Energy (UK)*

- 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

US STs aim to accelerate fusion development
(see LTX and Pegasus presentations later this afternoon)

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



Backup slides

Cost estimates for facility enhancements to address Gaps

NSTX-U 5YP base / +10% sustained for 10 years → $65M / $95M for enhancements

10 year total:	Gap	Tool / initiative	2015-19	2020-24	10 yr total ($M)
~$19M	Gap 1: Start-up / ramp-up with small / no transformer	1MW, 28GHz ECH/EBW	7		7
		Additional 1-2MW (2-3MW total) ECH/EBW		10	10
		Steerable mirror		2	2
		Gap sub-total:	7	12	19
~$8M	Gap 2: Understand / optimize ST energy confinement	Full polarimetry	1.5		1.5
		Full 2D high-k	1.5		1.5
		Doppler back-scattering	1		1
		Cross-polarization scattering	1	3	4
		Gap sub-total:	5	3	8
~$23M	Gap 3: Plasma sustainment, stability, and control	Lower divertor cryo-pump	7		7
		Partial non-axisymmetric control coils (NCC)	5		5
		Electromagnetic particle injector	1		1
		Full non-axisymmetric control coils (NCC)		3	3
		Enhance MHD sensors: RWM + halo current	2		2
		Additional NCC power supplies (6 → 12 chan)		5	5
		Gap sub-total:	15	8	23
~$45M	Gap 4: Mitigating high heat (and particle) flux + core / edge integration w/ high-Z + LM PFCs	High-Z lower outboard divertor	3		3
		Divertor Thomson scattering		5	5
		Flowing liquid Li test module	3		3
		Partial → all high-Z PFCs		4	4
		Hot high-Z PFCs (bakeout system for 350C)		5	5
		Full toroidal coverage flowing Li divertor		10	10
		10-20s NBI (PFC thermal/LM flow equilibration)		15	15
		Gap sub-total:	6	39	45

$65M (Gaps 1–3 + first items of Gap 4, through Partial → all high-Z PFCs)

$95M (all Gaps)

NSTX-U plan: ST physics/scenarios → integrate high-perf core + metal walls (high-Z + Li) → flowing / large area liquid metals

Establish ST physics/scenarios	High-performance + metal walls	Flowing LM divertor/wall
2015-2019	**2020-2024**	**2025-2029**

- $2\times$ B_T, I_P, P_{NBI}, 5× pulse-length
- 10-20s pulses for PFC/LM equilibration
- **LTX-U results**

100% non-inductive:
- Start-up to 0.4MA
- Ramp-up 0.4 → ~1MA
- Sustain at ~1MA
- (Density control needed for all phases)

- Reduce collisionality ν^* ~ factor of 10
- Sustain high β_N ~ 6 w/ advanced control
- Mitigate high divertor heat flux

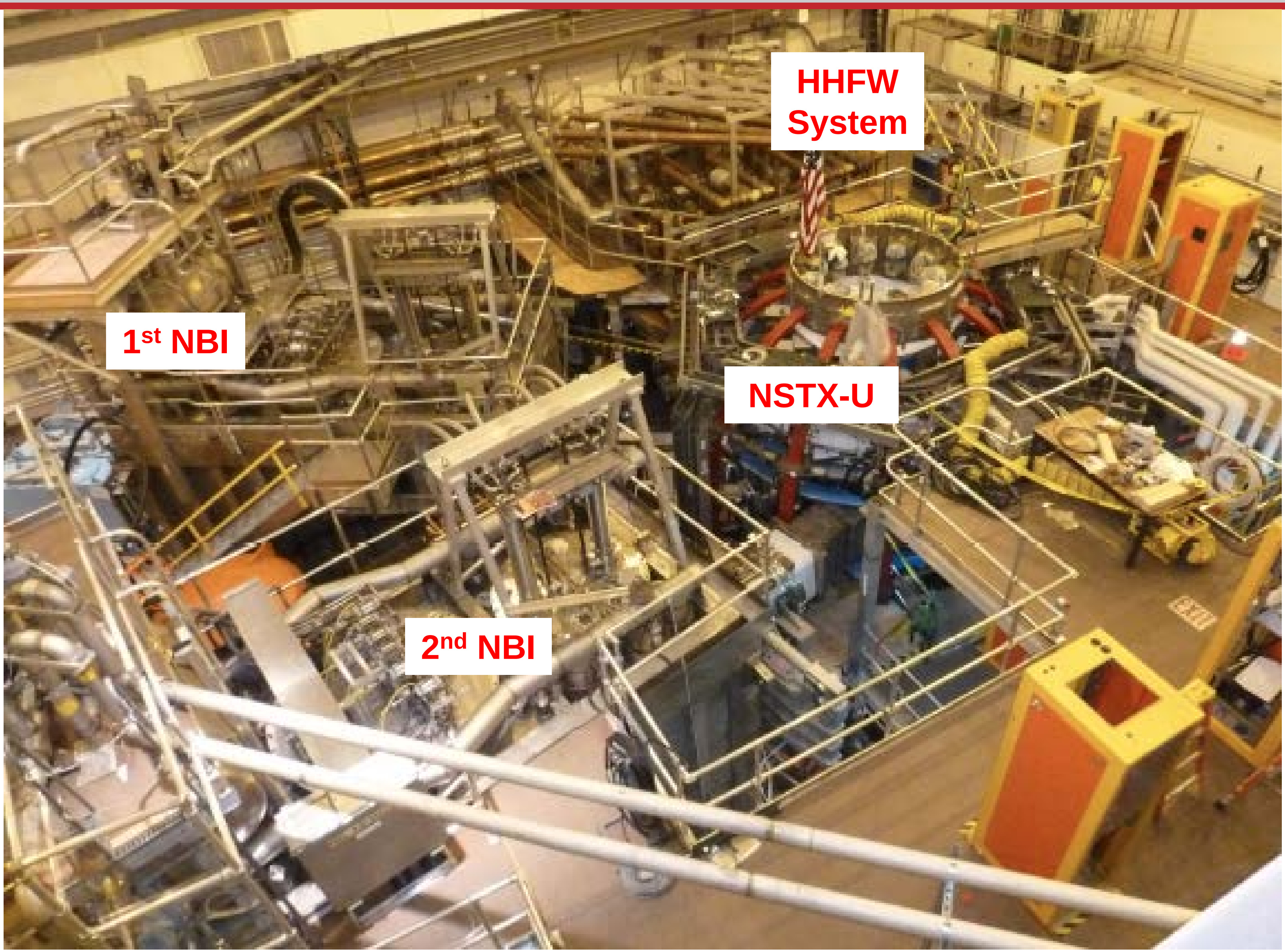
Inform choice of FNSF aspect ratio and divertor configuration

Inform choice of FNSF/DEMO plasma-facing materials for divertor and first-wall

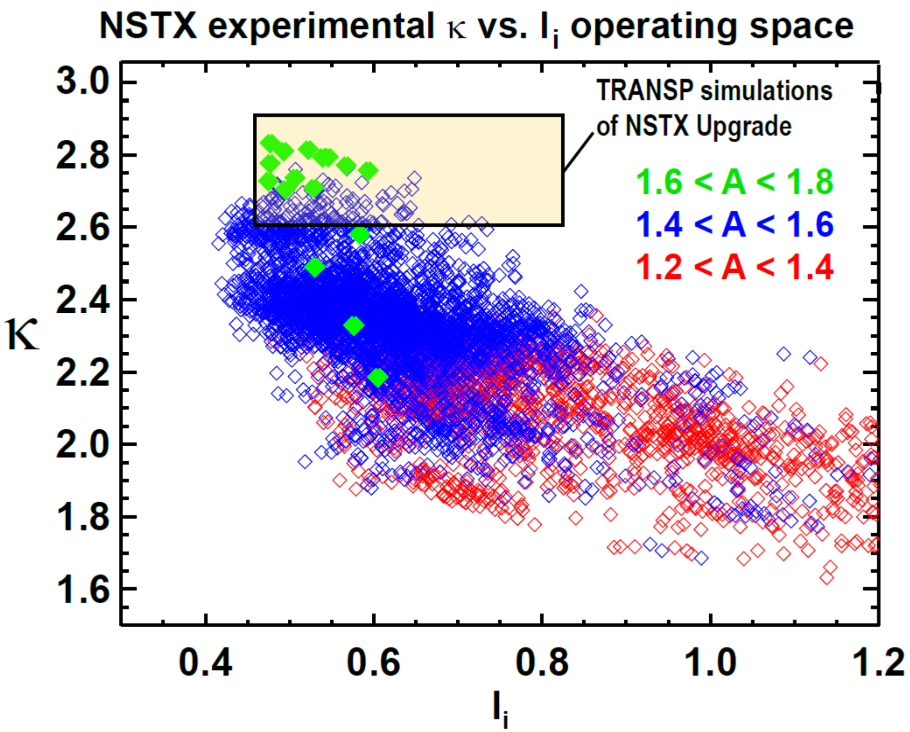
Test large area liquid Li for very high energy confinement, flowing LM divertors for PFC resilience to off-normal events: ELMs, disruptions

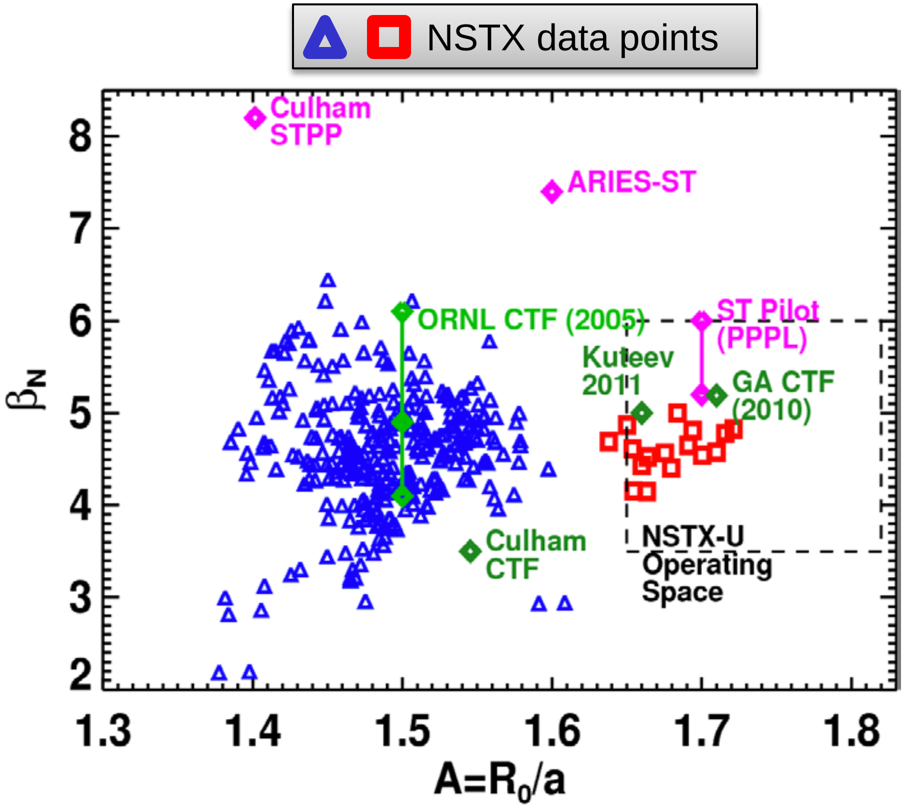
- Div. C → high-Z, Li vapor shielding
- All high-Z PFCs, hot walls, static Li-wall
- Slow-flow Li wall segment
- Static liquid Li modules → flowing Li modules → flowing Li divertor
- Flowing Li / Sn divertor

NSTX-U Test Cell Aerial View (May, 2014)
Upgrade project now ~90% complete



NSTX has already accessed shaping and stability performance needed for an ST-FNSF

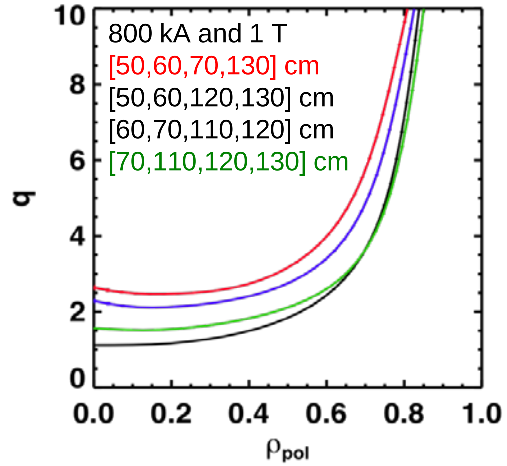




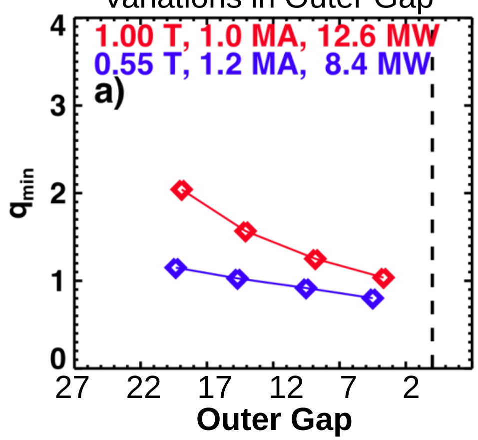
NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

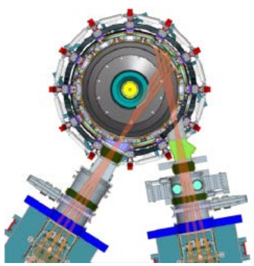
q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive, 87% < f_{NI} < 100%



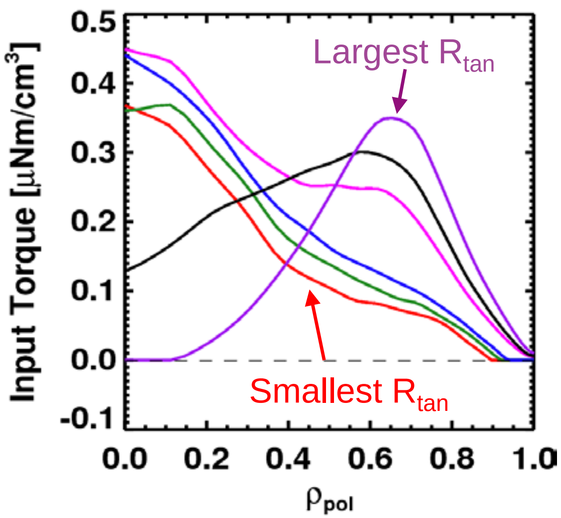
Variations in Outer Gap

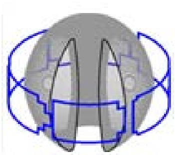




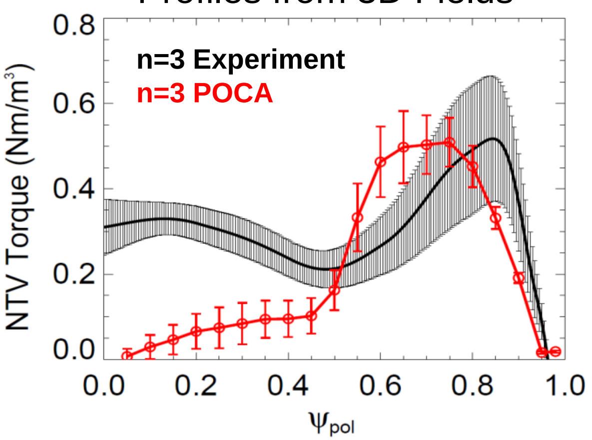
Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources

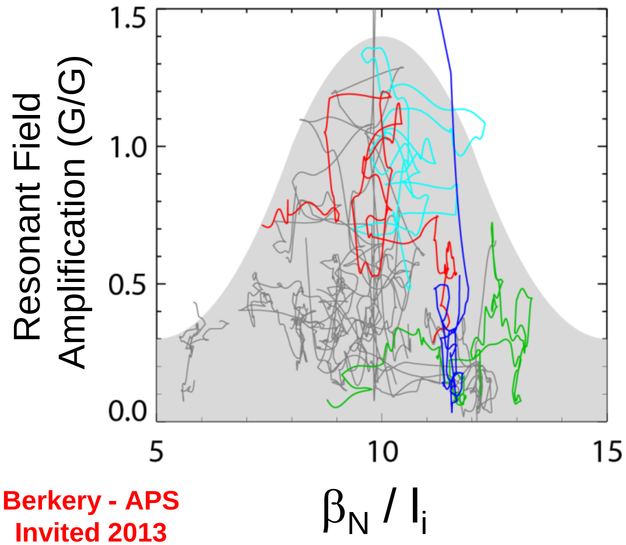




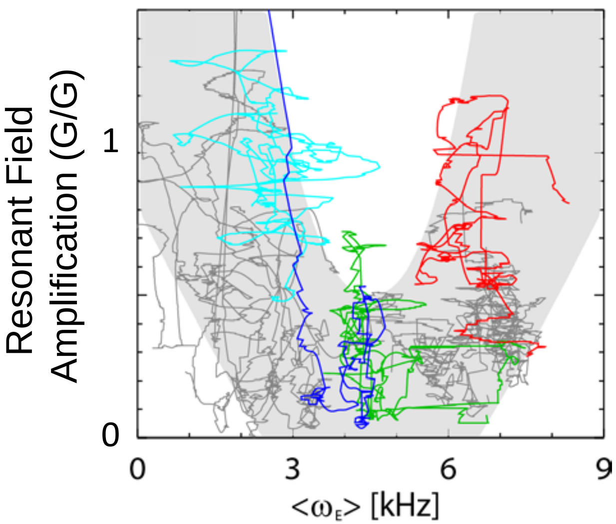
Measured and Calculated Torque Profiles from 3D Fields



Rotation profile control will be an important tool for accessing and sustaining high β

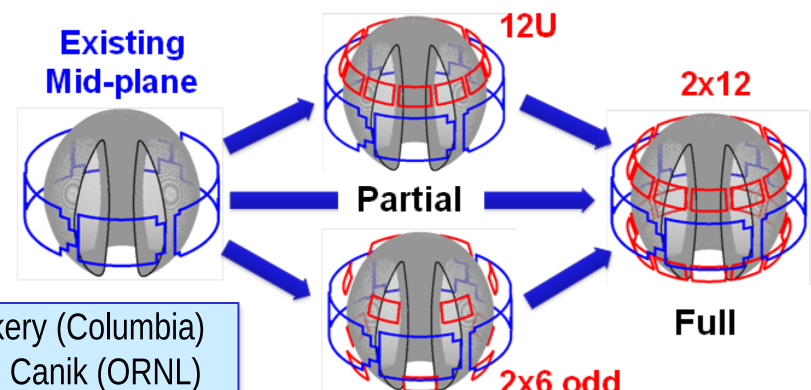


Berkery - APS Invited 2013



E×B rotation frequency

- n=1 MHD spectroscopy: high β_N can be more stable → important for advanced scenarios
- For these plasmas, high β_N was correlated with rotation that maximizes RWM damping
  - Stabilization from ion precession drift resonance
  - Strong motivation for rotation profile control
- 5YP: Off-midplane 3D coils enable control of resonant vs. non-resonant torques, v_ϕ profile

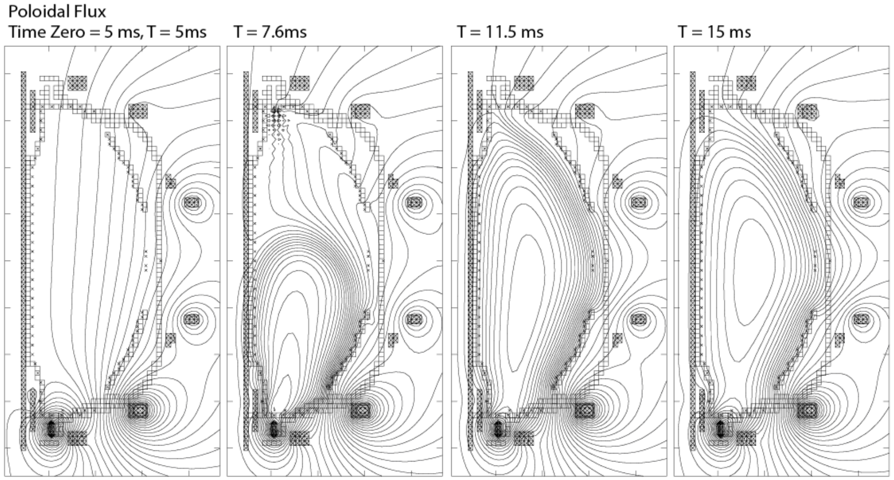


S. Sabbagh, J. Berkery (Columbia)
J-K Park (PPPL), J. Canik (ORNL)

Simulations support non-inductive start-up/ramp-up strategy

- TSC code successfully simulates CHI I_P ~200kA achieved in NSTX

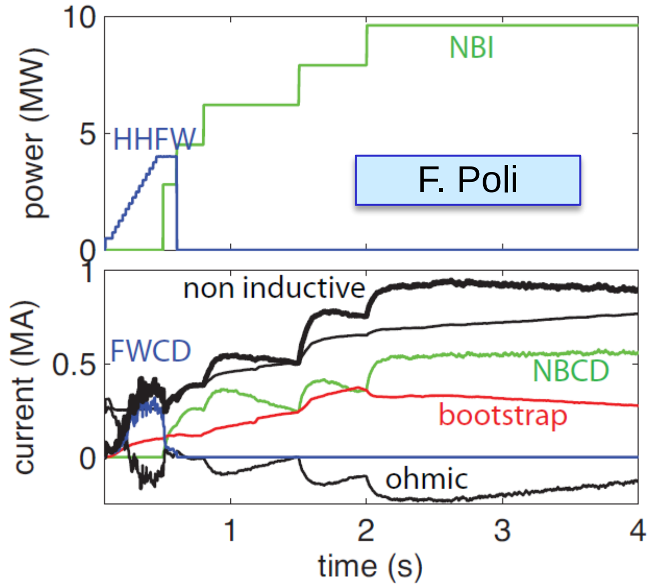
FY14: Implemented NSTX-U geometry in TSC



- TSC + tools included in 5 year plan support CHI I_P → 400kA in NSTX-U
  - 2.5 x higher injector flux (scales with I_P)
  - Higher B_T = 1T (increases current multiplication)
  - > 2kV CHI voltage (increases flux injection)
  - 1MW 28GHz ECH (increases T_e)

R. Raman (U-Wash)

- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
  - 1.5-2x higher CD efficiency, 3x lower prompt loss
- New TRANSP simulations of ramp-up: 0.3MA→0.9MA with FW+BS→NBI+BS
  - 1st self-consistent NBI-CD calcs during NI ramp-up

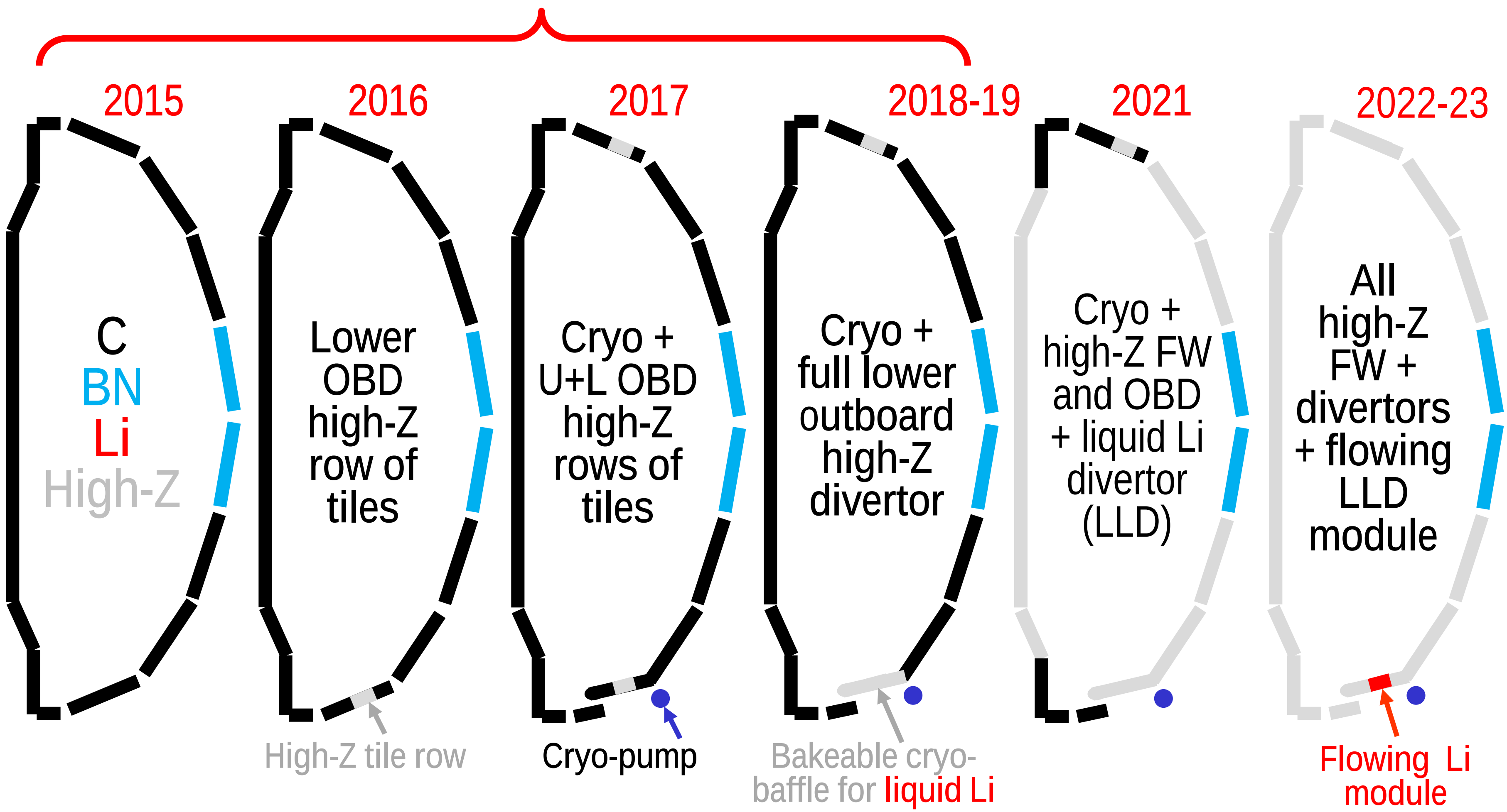


- $V_{surface}$ = 0 constraint → need to add induction from PF coil swing (future)

NSTX-U internal component staging supports goal to assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Base budget case (from 5 Year Plan for FY2014-18)

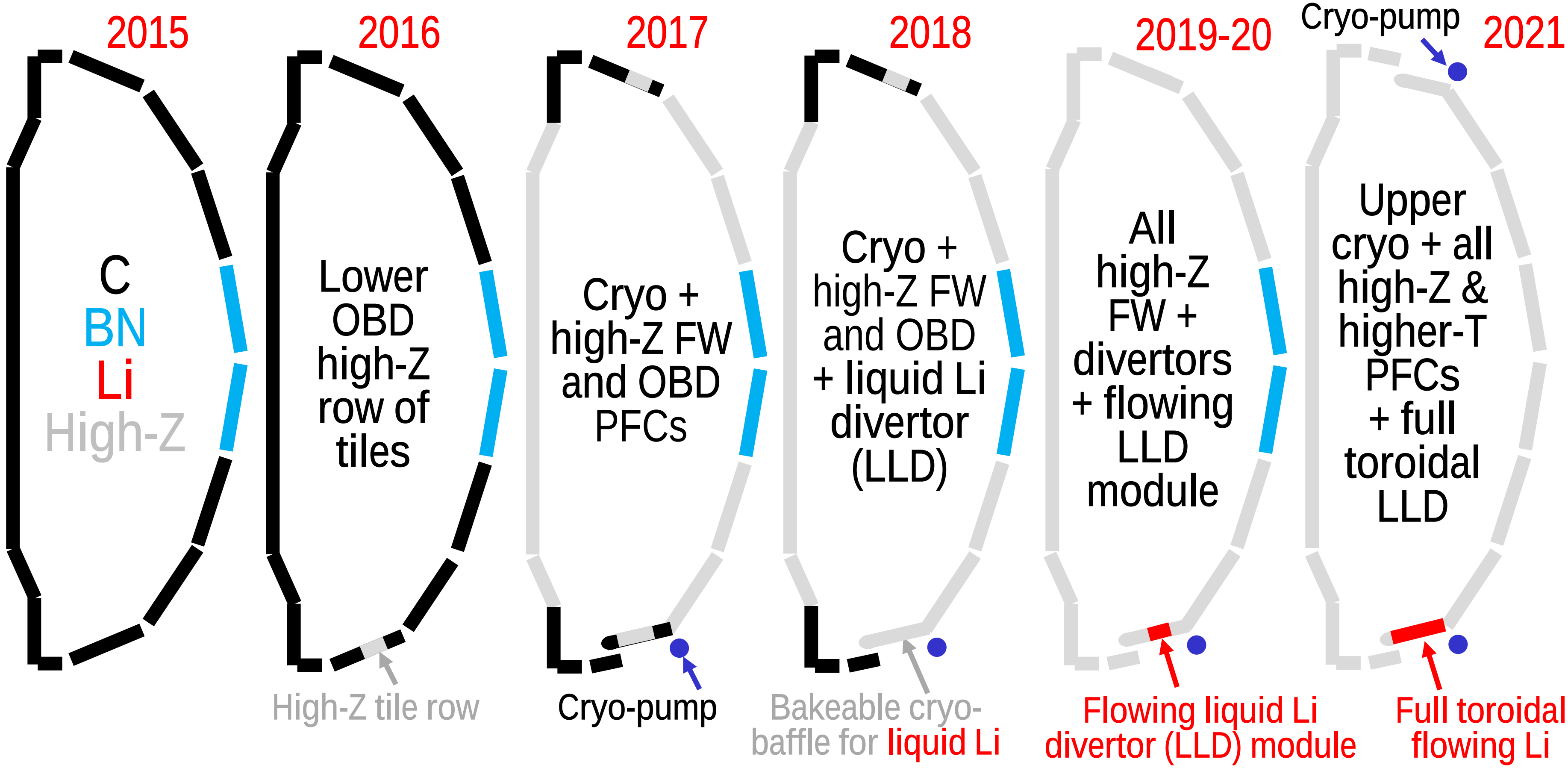
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



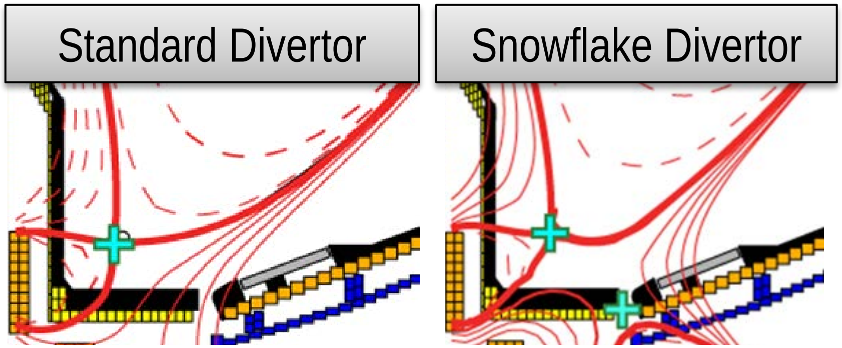
NSTX-U internal component staging supports goal to assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Incremental budget case (from 5 Year Plan for FY2014-18)

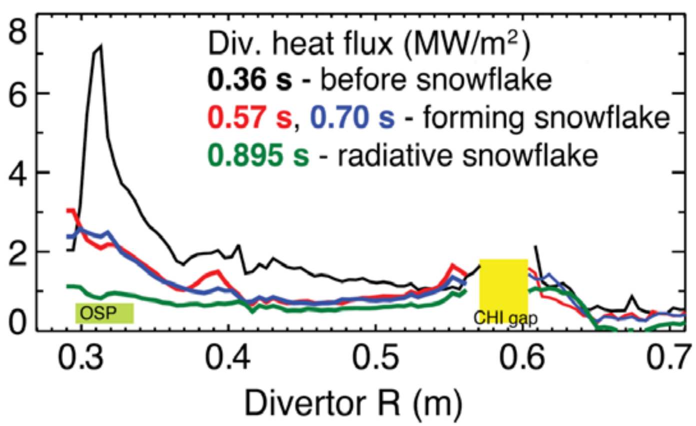
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD

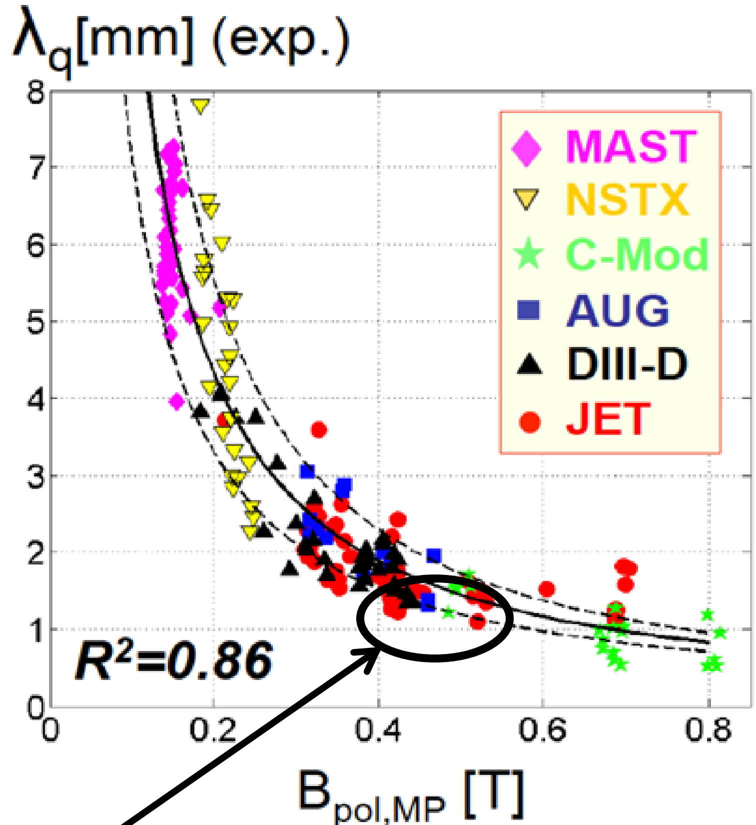


NSTX-U will explore advanced divertor operation, and extend scaling and understanding of power exhaust



- Snowflake→ high flux expansion = 40-60 lowers incident $q_{\perp}$, promotes detachment

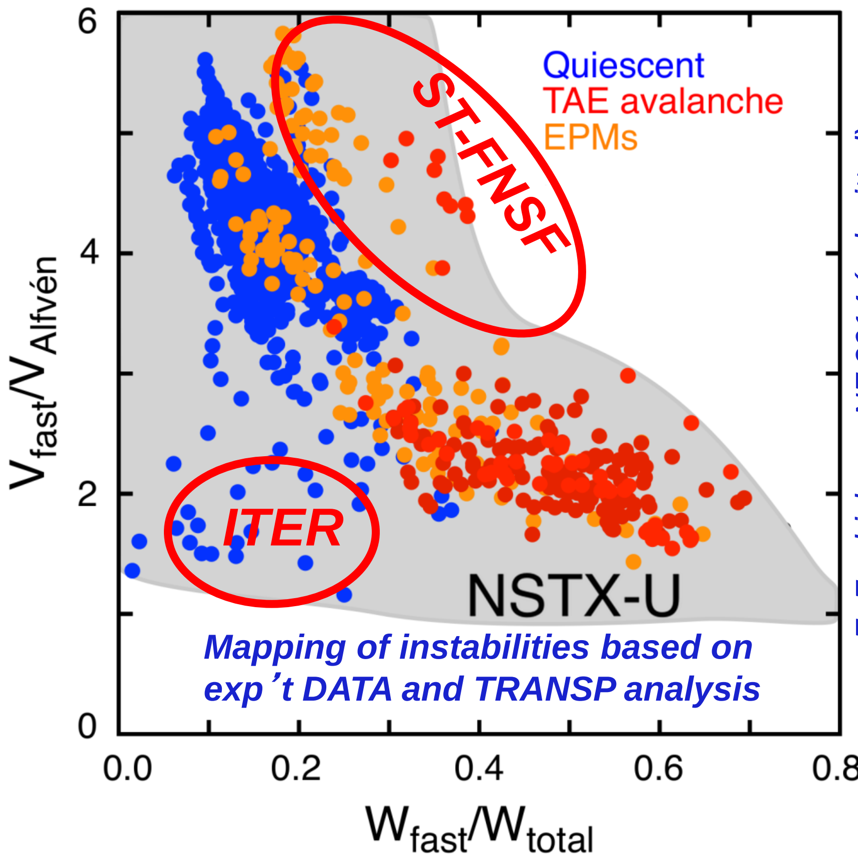




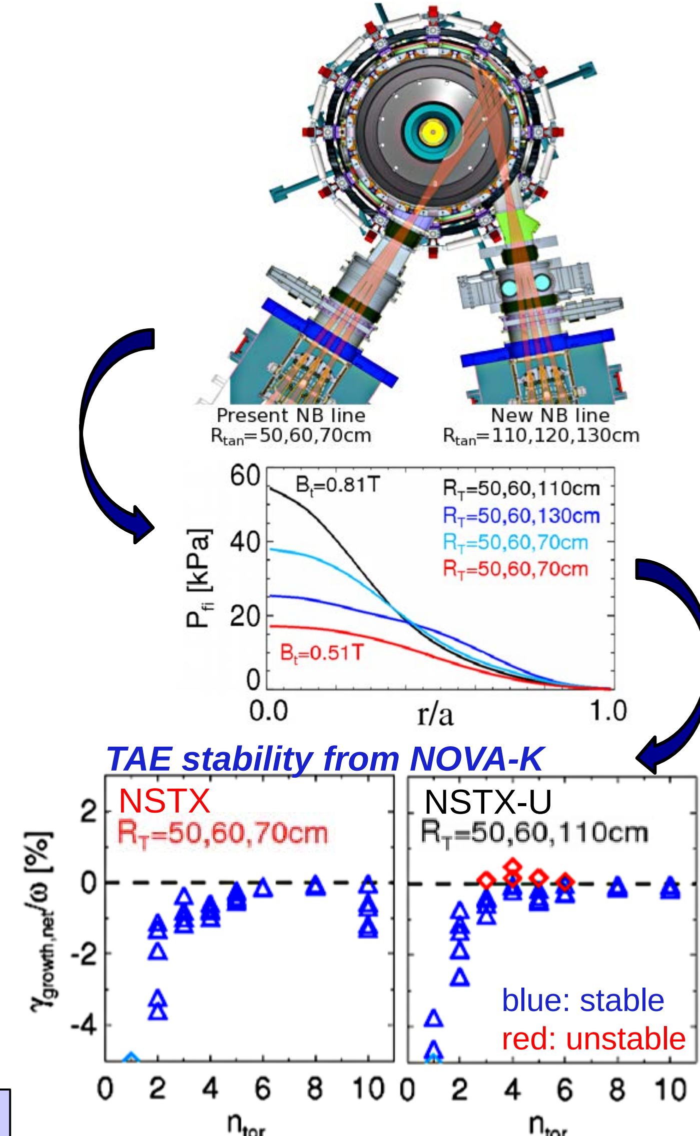
- NSTX-U: 2× higher I_P and P_{NBI} → access $q_{||}$ 4-5× higher than NSTX
- Will ~$1/B_P$ scaling still hold?

➢ See R. Maingi and D. Hill whitepapers

NSTX-U will explore broad range of fast-ion instability physics and control for ITER and FNSF



E. Fredrickson, NF 2014 (submitted)



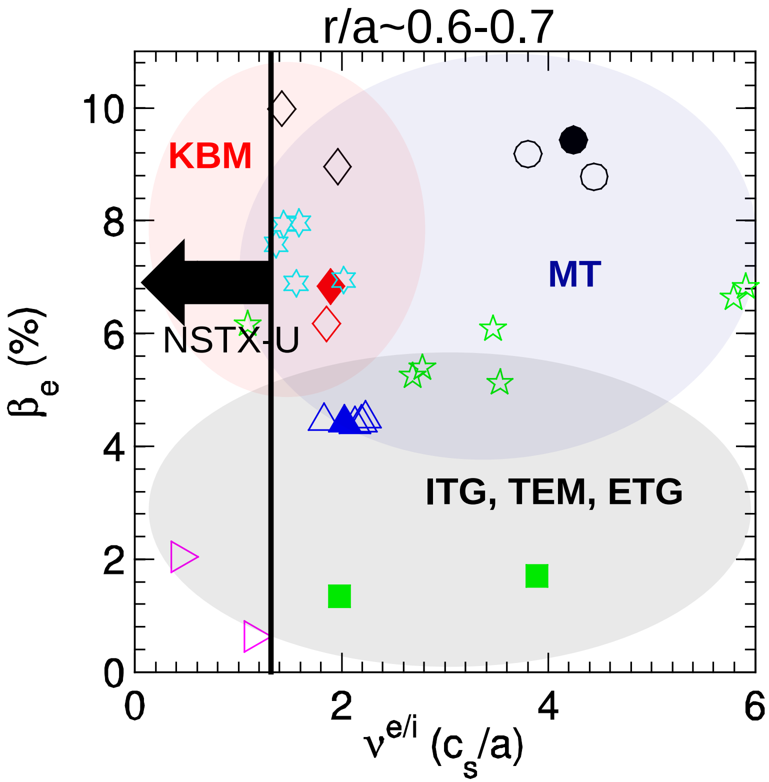
M. Podestà, PoP 2013

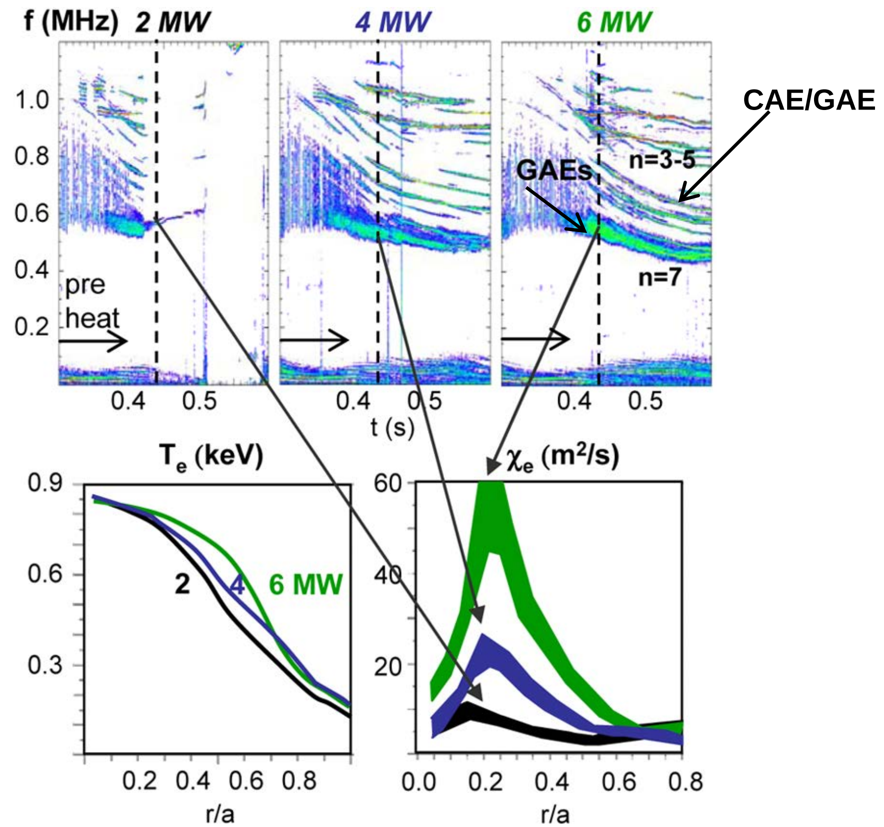
- Fast-wave heating, 3D fields (NSTX), ECH (DIII-D) also influence AE stability

➢ See Podestá whitepaper on fast-ion instability control

NSTX-U will explore a new high β + low ν* transport and turbulence regime

Will access a variety of drift wave and AE transport mechanisms:



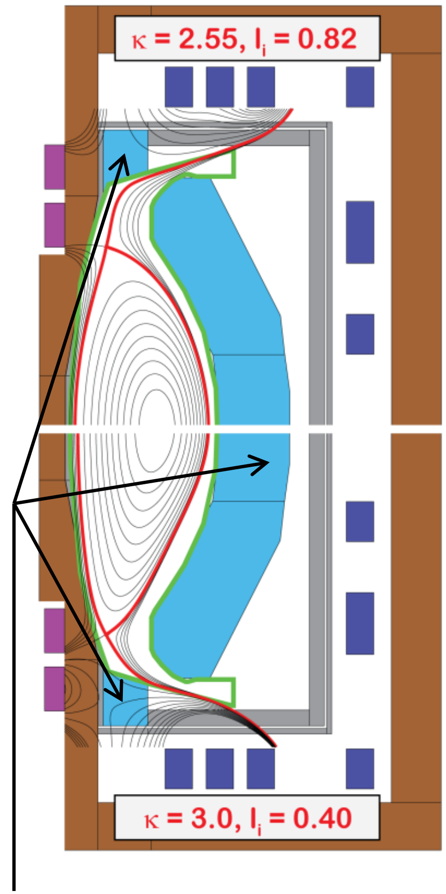


- Will τ_E~$1/\nu_*$ remain valid?
- Will microtearing be suppressed?
- Will $\chi_i \approx \chi_{i,NC}$ & $D_{imp} \approx D_{imp,NC}$ hold?
- Is core χ_e from stochastic fields, or mid-radius KAW excitation → e-heating?

➤ See Guttenfelder/Crocker whitepaper on electromagnetic effects in transport

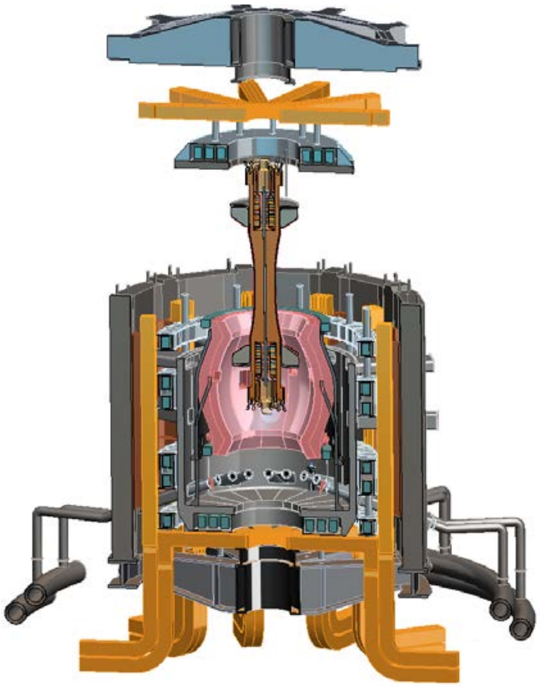
Self-consistent ST configurations identified for Fusion Nuclear Science Facility (FNSF)

- Current drive: bootstrap + NNBI
- Neutron wall loading ~1 MW/m^2
- Tritium breeding ratio (TBR) ~ 1
  - Requires breeding blanket near top + bottom of centerstack (CS)
- PF coil configuration:
  - Strong shaping (κ ~ 2.8-3, δ ~ 0.5-0.6)
  - Flexibility in equilibrium β_N and l_i
  - All equilibrium PF coils are ex-vessel
  - Long-legged Super-X/snowflake divertor
    - q_{peak} ~ 3-5MW/m^2, partially detached
  - Breeding in CS end region + vertical maintenance scheme
- Exploring plasma start-up options
  - Identified locations for electrodes for coaxial helicity injection (CHI) start-up
  - Retractable plasma "guns" may be more compatible with FNSF environment



Blanket regions

Vertical maintenance

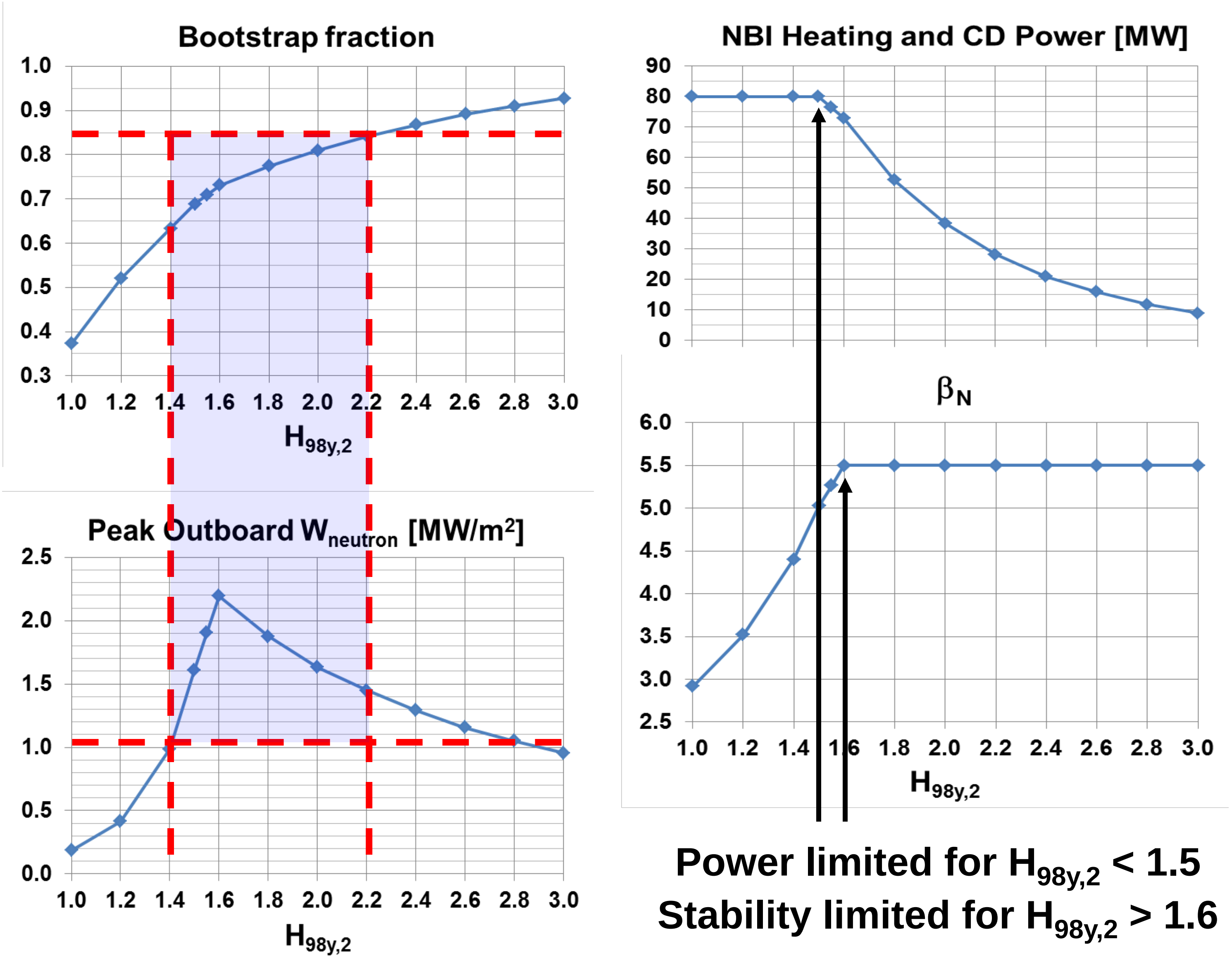


$R_0 = 1.6$m, $B_T = 3$T, $I_P = 10$MA, $P_{fus} = 160$MW

$H_{98y,2}$ range of 1.4-2.2 favorable for achieving FNSF-relevant neutron wall loading ≥ 1MW/m^2 , f_{BS} < 85% for external control

ST-FNSF

- $A = 1.75$
- $R_0 = 1.7$m
- $B_T = 2.9$T
- $\kappa, \delta = 2.8, 0.55$
- $f_{Greenwald} = 0.8$
- $f_{NICD} = 100\%$
- $E_{NNBI} = 0.5$MeV
- $P_{NNBI} \leq 80$MW

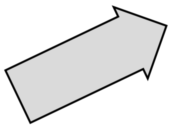


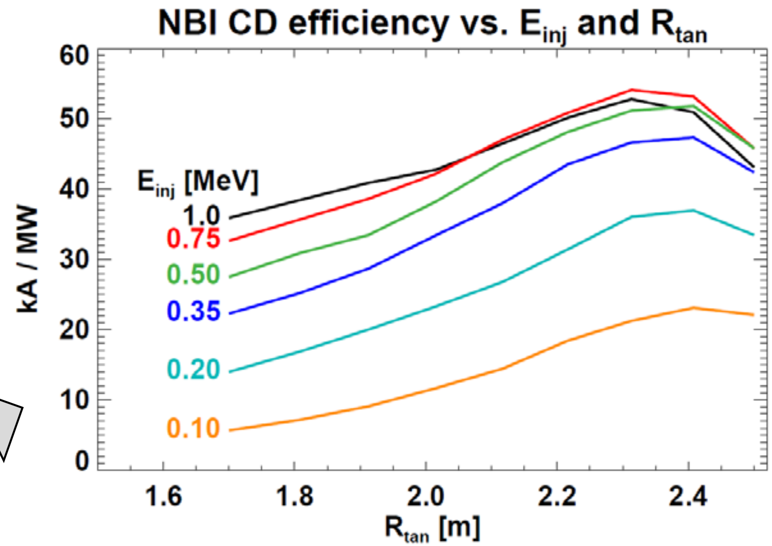
Power limited for $H_{98y,2}$ < 1.5

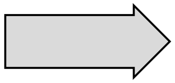
Stability limited for $H_{98y,2}$ > 1.6

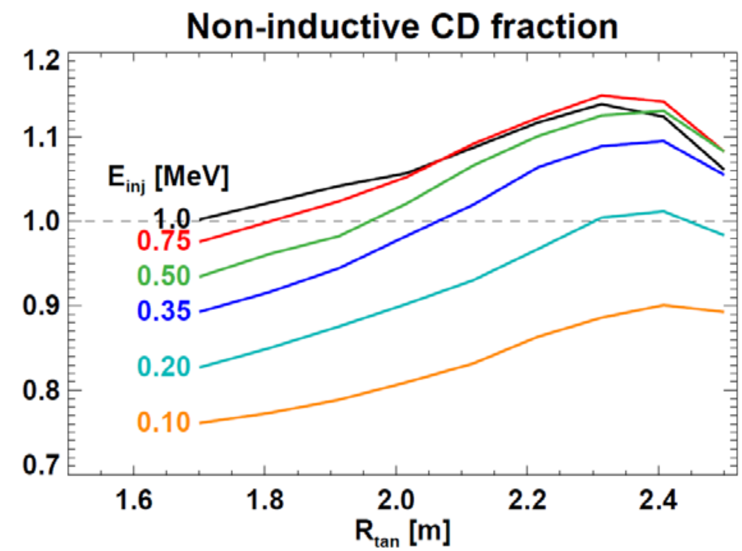
NNBI CD efficiency vs. injection tangency radius and energy for R=1.6m using TRANSP

- Fixed target parameters in DD
  - I_P = 7.5MA, β_N = 4.5, l_i = 0.5
  - $n_e / n_{Greenwald}$ = 0.75, $H_{98y,2}$ = 1.5
  - A=1.75, R=1.7m, B_T = 3T, κ = 2.8
  - $\langle T_e \rangle$=5.8keV, $\langle T_i \rangle$=7.4keV
- Little current drive benefit from injecting above 0.5MeV
- Shine-thru onset for R_{tan} > 2.4m
- Achieve full non-inductive for R_{tan} > 2m with P_{NBI} = 60MW
  - (Note: P_{fusion} in DT is ~160MW)







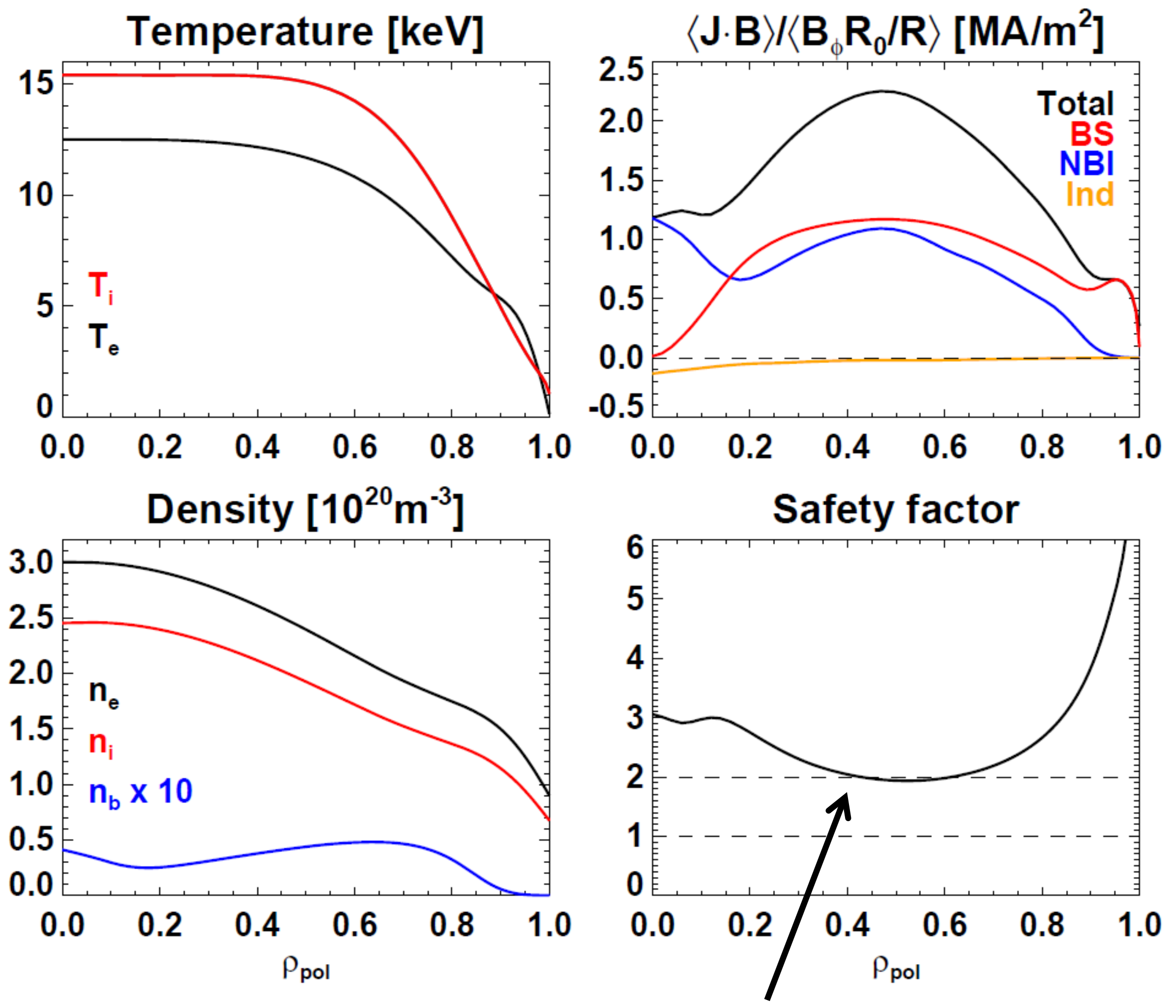


→ 0.5MeV NNBI is good choice

(as has been assumed for this configuration)

Free-boundary TRANSP used to compute 100% non-inductive Q_{DT} ~ 2 plasma equilibrium consistent with 0D scalings

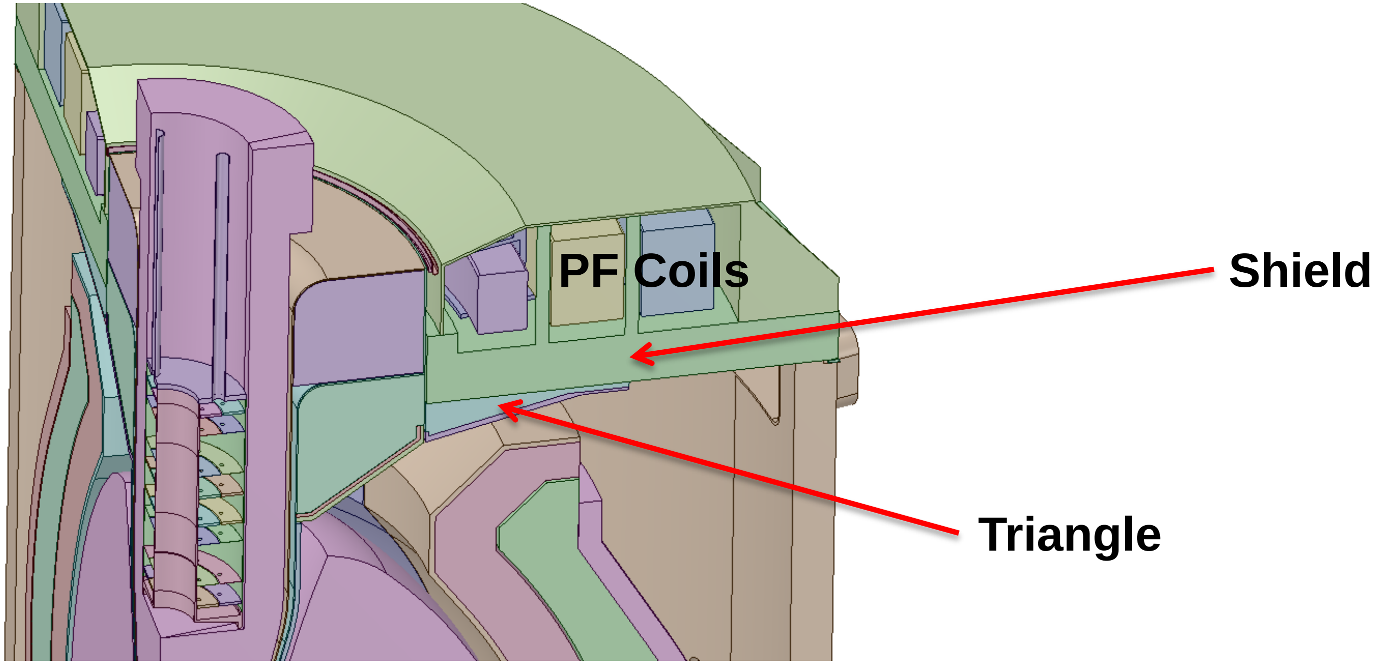
- TRANSP-ISOLVER (boundary-fit)
- Neoclassical χ_i
- Scaled NSTX T_e, n_e
  - Z_{eff} ~ 2-2.5
- n_e / $n_{Greenwald}$ = 0.65
- I_P = 9.8MA, B_T = 2.9T
- $H_{98,y2}$ = 1.55
- β_N = 5.9, W_{tot} = 67MJ
  - W_{fast} / W_{tot} = 14%
- f_{NICD} = 100%, f_{BS} = 65%
- E_{NNBI} = 0.5MeV
- P_{NNBI} = 80MW
- P_{fusion} = 160MW (50-50 DT)
  - ~3% alpha bad orbit loss



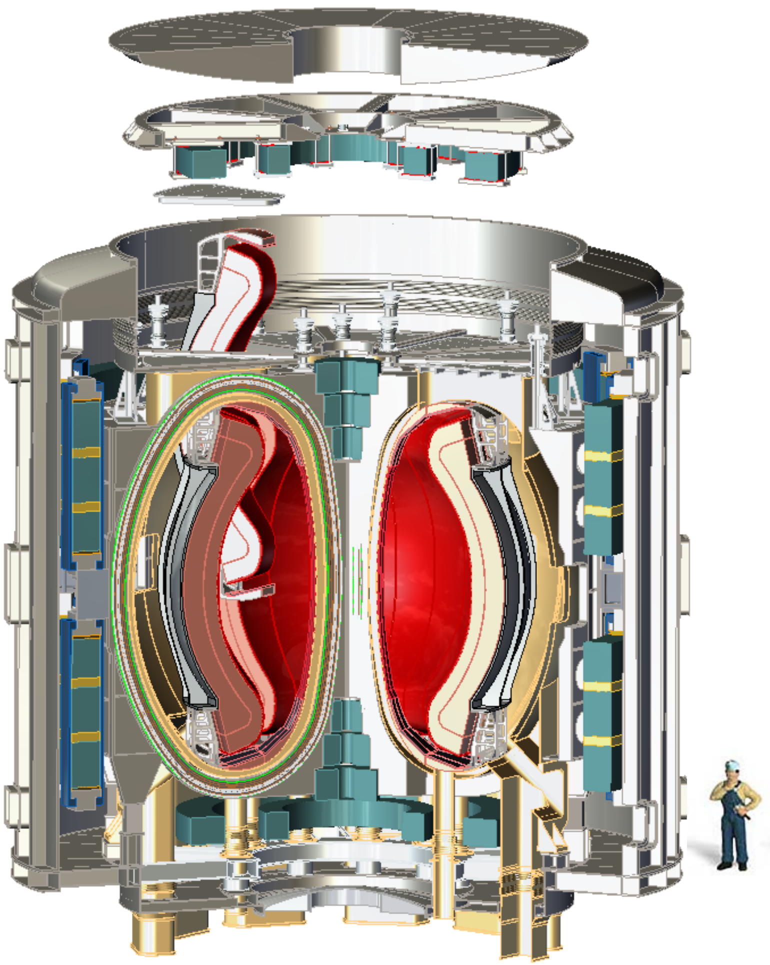
Need to further tweak NBI-CD to reduce reversed-shear and maintain q_{min} > 2

Ideas to enhance TBR for latest ST-FNSF design

- Uniform OB blanket (1 m thick everywhere; no thinning)
- Less cooling channels and FCIs within blanket
  - Need thermal analysis to confirm
- Replace PF coil shield and triangle by blanket (TBD)
- Thicker IB VV with internal breeding
- Smaller opening to divertor to reduce n leakage



HTS potentially attractive for making electrically efficient ST* (~10× lower magnet cooling power vs. copper)



R_0 = 1.4m, B_T = 3.2T, I_P = 7-8MA, $P_{fusion\text{-}DT}$ = 100MW

*This work supported by Tokamak Energy (UK)

- Possible missions:
  - Steady-state toroidal PMI facility
  - ST Pilot Plant (Q_{eng}~1 for weeks/months)
- Initial configurations favorable:
  - A=1.8 w/ strong shaping: κ~2.7, δ~0.5
  - All equilibrium PF coils outside TF
    - No joints needed for HTS TF coils
  - Long-legged divertor for $q_{div\text{-}pk}$ < 5MW/m^2
  - Vertical port-based maintenance
  - WC inboard thermal shield for TF
- Many remaining issues:
  - HTS lifetime in radiation environment
  - Blanket/shield thickness, location, TBR

➢ Endorse Minervini / Whyte whitepapers for HTS R&D