NSTX-U

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

Overview of Research Plans for NSTX Upgrade*

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
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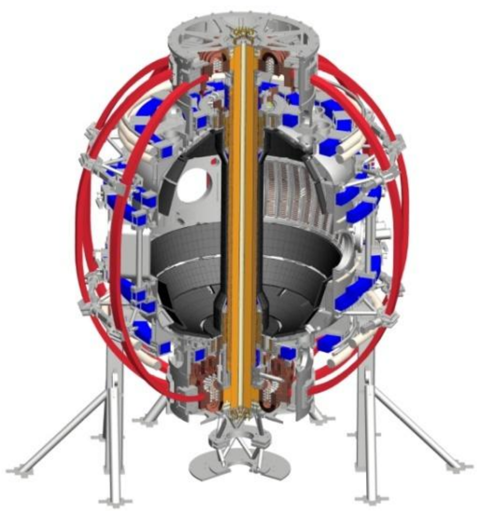
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

Jon Menard (PPPL)

NSTX-U Program Director

17th International Spherical Torus Workshop
University of York
16-19 September 2013



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
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Niigata U
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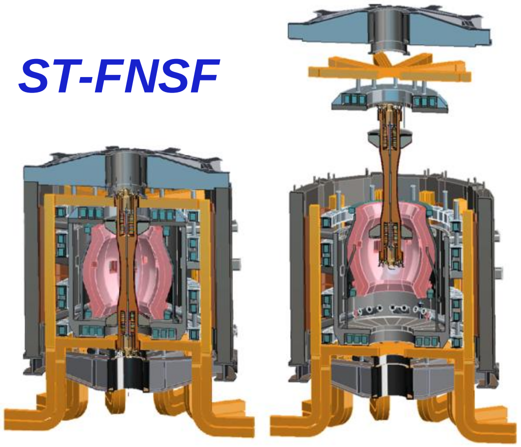
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

*This work supported by the US DOE Contract No. DE-AC02-09CH11466

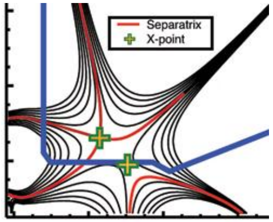
NSTX Upgrade mission elements

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

ST-FNSF



- **Develop solutions for the plasma-material interface challenge**

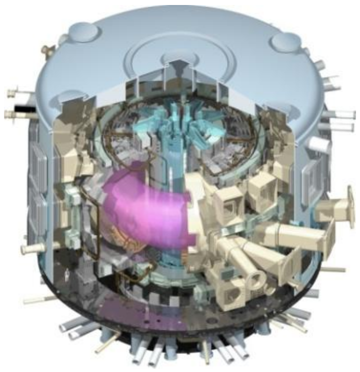


"Snowflake"

Lithium

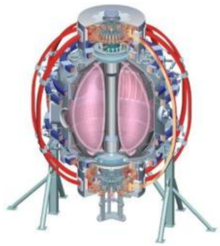
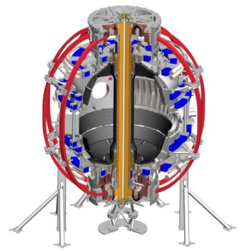
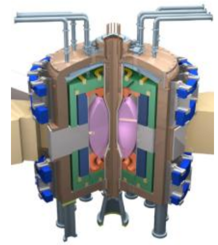
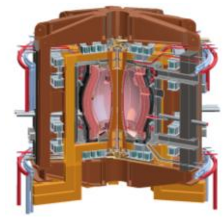
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**

ITER



- **Develop ST as fusion energy system**

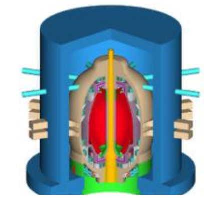
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs

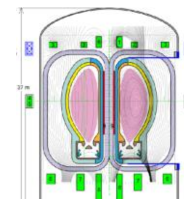
Parameter	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	22 – 45	50 – 85
P/R [MW/m]	10	**20**	30 – 60	70 – 90
P/S [MW/m^2]	0.2	**0.4-0.6**	0.6 – 1.2	0.7 – 0.9
Fusion Gain Q			1 – 2	2 – 10

** Includes 4MW of high-harmonic fast-wave (HHFW) heating power*

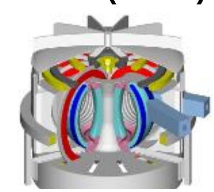
Low-A Power Plants



ARIES-ST (A=1.6)



JUST (A=1.8)



VECTOR (A=2.3)

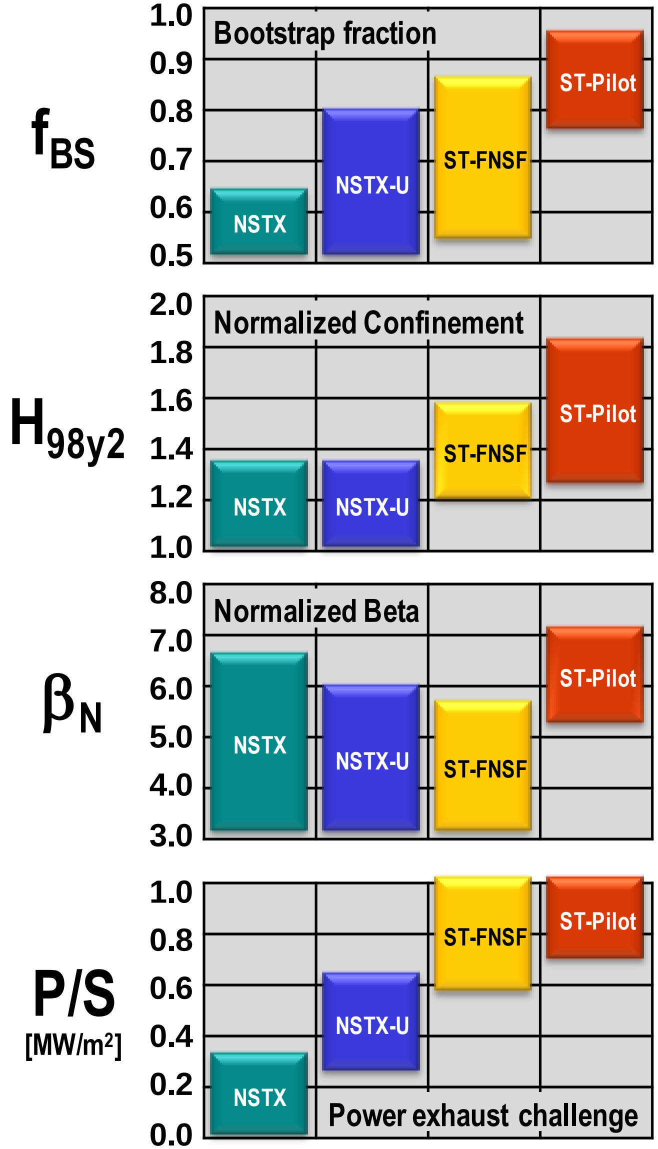
Key issues to resolve for next-step STs

- **Non-inductive start-up, ramp-up, sustainment**
- **Confinement scaling (esp. electron transport)**
- **Stability and steady-state control**
- **Divertor solutions for mitigating high heat flux**

NSTX-U aims to access performance levels of next-steps, approach Pilot-Plant regimes

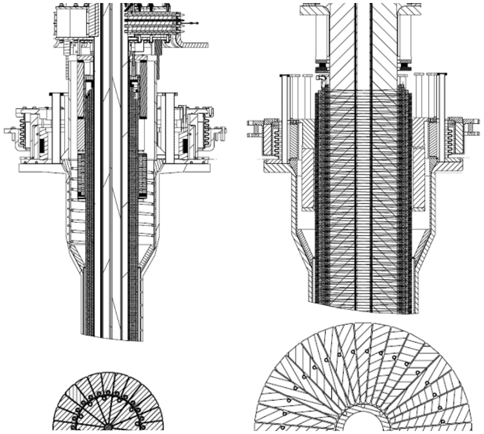
Requirements for ST / tokamak next-steps:

- **Full non-inductive (NI) current drive for steady-state operation**
  - ST requires NI start-up/ramp-up
- **High confinement to minimize auxiliary heating, device size**
- **Sustained high β to minimize magnet size, forces, power**
- **Divertor/first-wall survival with intense power/particle fluxes**



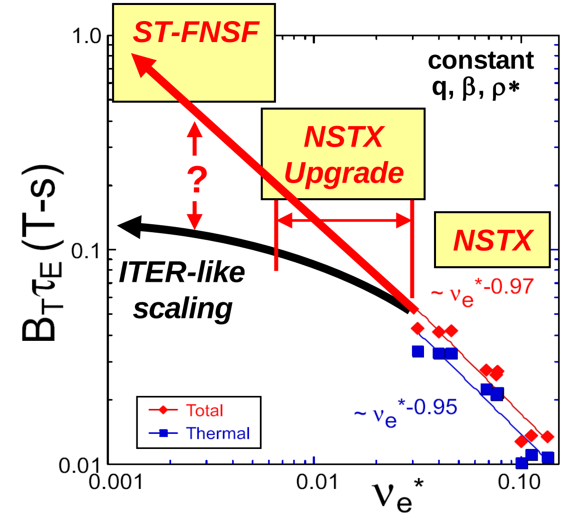
NSTX Upgrade incorporates 2 new capabilities:

Previous center-stack | New center-stack

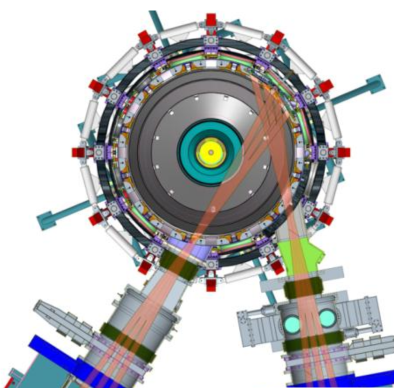


TF OD = 20cm | TF OD = 40cm

- Reduces ν^* → ST-FNSF values to understand ST confinement
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- 5x longer pulse-length
  - q(r,t) profile equilibration
  - Test non-inductive ramp-up

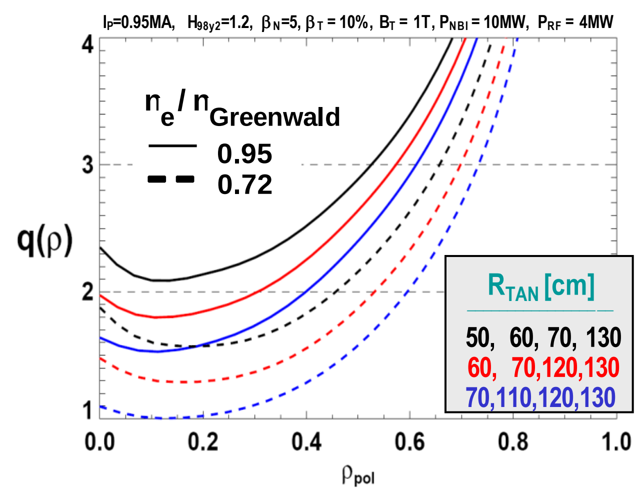


Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI | New 2nd NBI

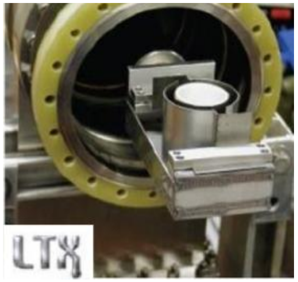
- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position (not shown)



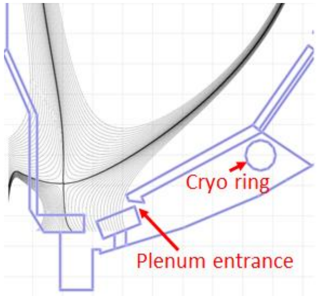
Proposed longer-term facility enhancements:
(2014-2018)

- **Improved particle control tools**
  - Control deuterium inventory and trigger rapid ELMs to expel impurities
  - Access low ν^*, understand role of Li

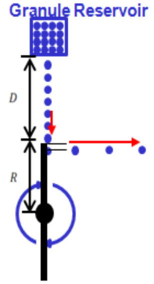
Upward Li evaporator



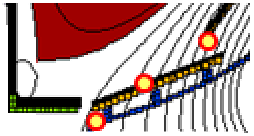
Divertor cryo-pump



Li granule injector (LGI)

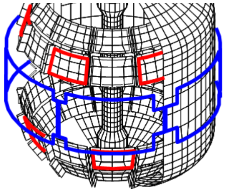


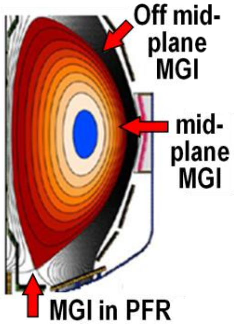
- **Disruption avoidance, mitigation**
  - 3D sensors & coils, massive gas injection



Extended low-f MHD sensor set

Midplane + off-midplane non-axisymmetric control coils (NCC)





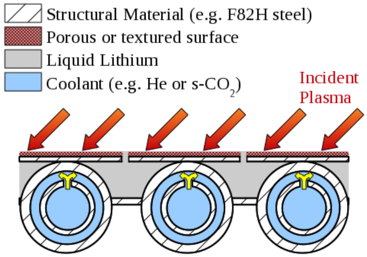
- **ECH to raise start-up plasma T_e to enable FW+NBI+BS I_P ramp-up**
  - Also EBW-CD start-up, sustainment

1-2MW 28 GHz gyrotron

- **Begin transition to high-Z PFCs, assess flowing liquid metals**
  - Plus divertor Thomson, spectroscopy

High-Z tiles

Actively-supplied, capillary-restrained, gas-cooled LM-PFC



NSTX-U team developed 5 year plan for FY2014-18
Highest priority goals:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

5 year plan successfully peer-reviewed in May 2013

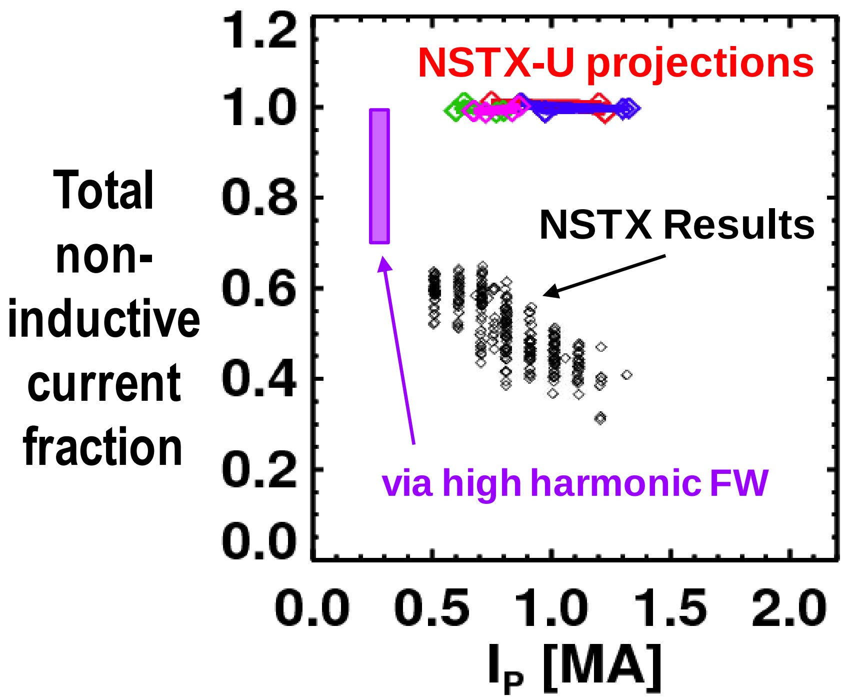
Highest priority research goals for NSTX-U:

1. Demonstrate 100% non-inductive sustainment
2. Access reduced ν^* and high-β combined with ability to vary q and rotation
3. Develop/understand non-inductive start-up, ramp-up (overdrive) for ST-FNSF with small/no solenoid
4. Develop high-flux-expansion “snowflake” divertor + radiative detachment to mitigate high heat fluxes
5. Assess high-Z + liquid Li plasma facing components

TRANSP simulations support goal of accessing and controlling 100% non-inductive plasma operation

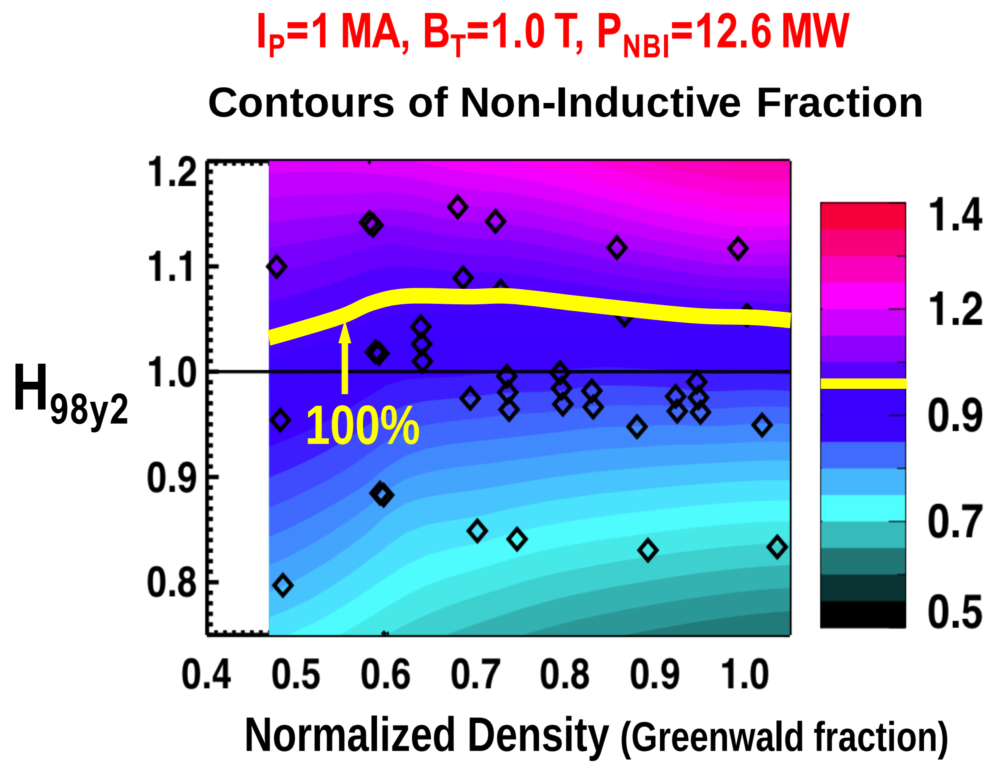
NSTX achieved:

- Maximum sustained non-inductive fractions of 65% w/NBI at I_P = 0.7 MA
- 70-100% non-inductive transiently with HHFW current-drive + bootstrap



NSTX-U projections (TRANSP):

- 100% non-inductive at I_P = 0.6-1.3MA for range of power, density, confinement

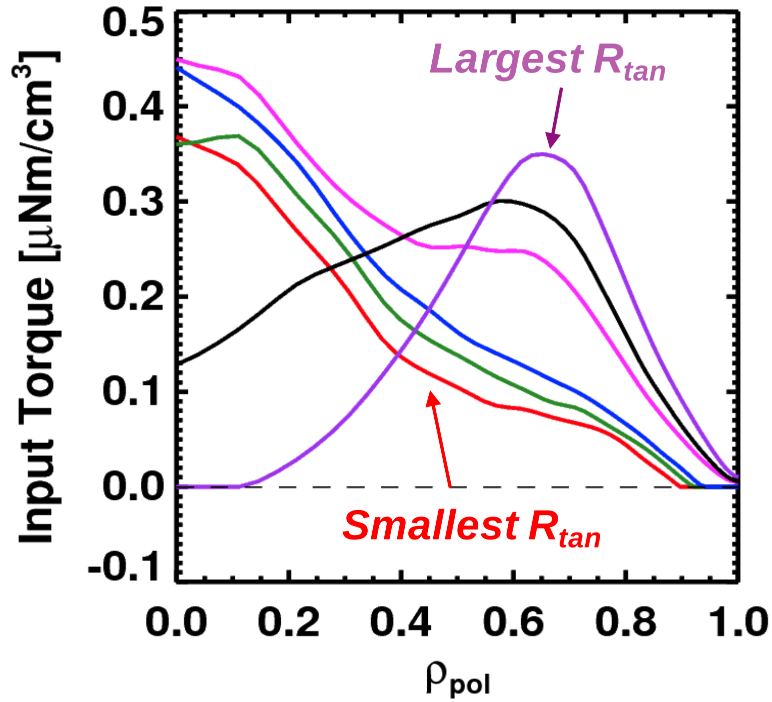


Advanced Scenarios and Control 5 Year Goals:

- 100% non-inductive operation
- Lower ν^*: high-current, partial-inductive scenarios, extend to long-pulse
- Implement axisymmetric control algorithms and tools
  - Current and rotation profile control
  - Improved shape and vertical position control
  - Heat flux control for high-power scenarios
- Develop disruption avoidance by controlled plasma shutdown

Rotation Profile Actuators

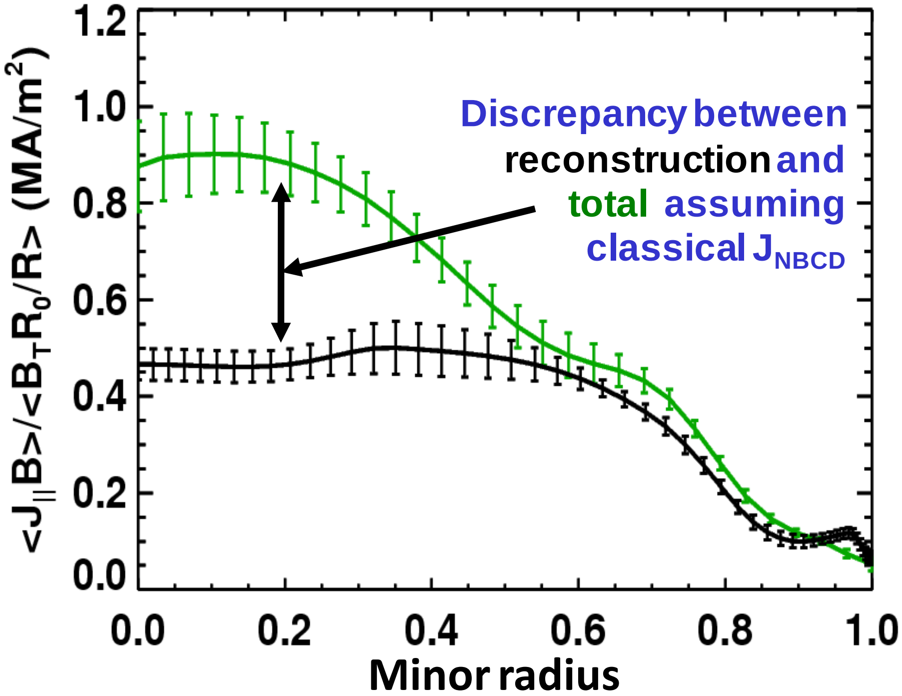
Torque Profiles From 6 Different NB Sources



- **Also torques from 3D fields**

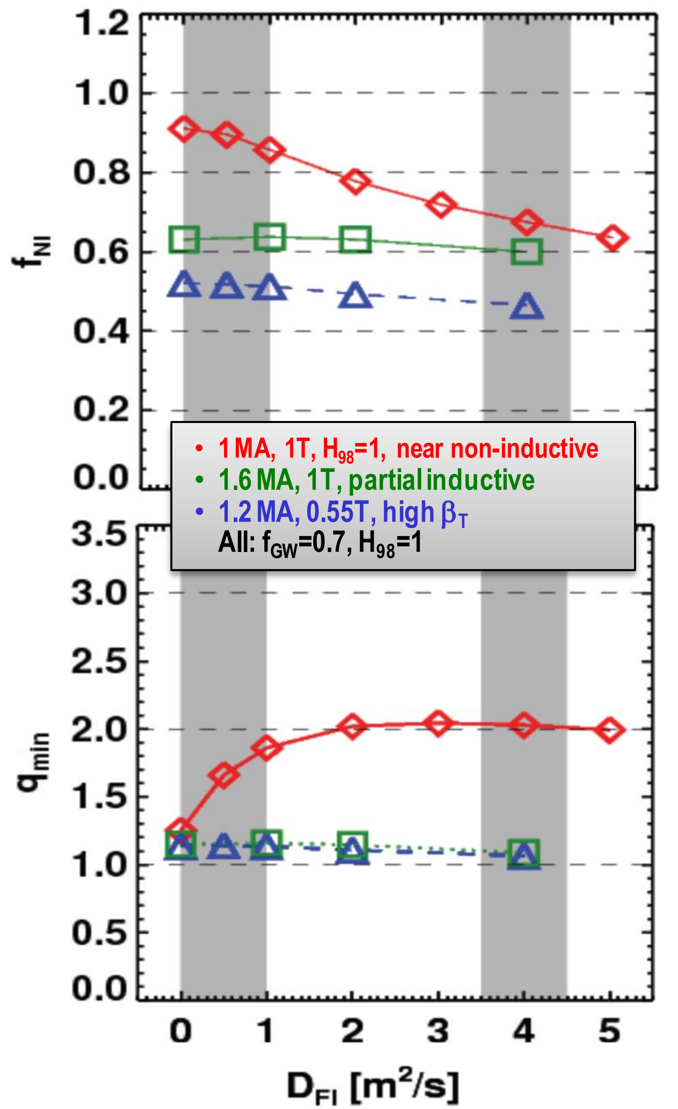
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

NSTX: rapid avalanches can lead to redistribution/loss of NBI current drive



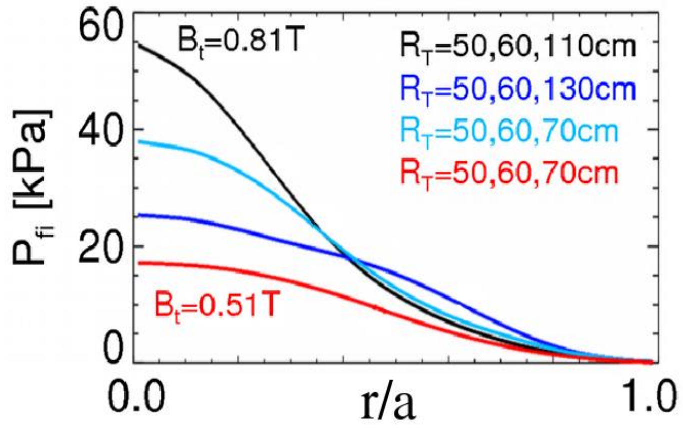
700kA high-β_P plasma with rapid TAE avalanches has time-average D_{FI} = 2-4m^2/s

NSTX-U TRANSP simulations



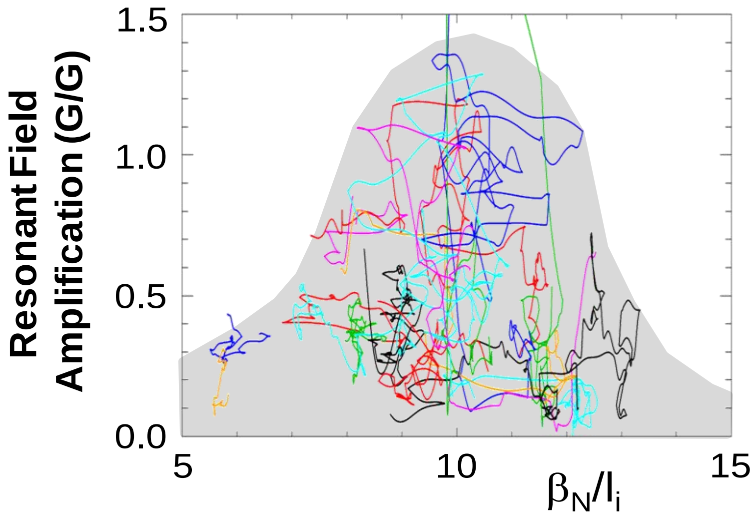
Energetic Particle 5 Year Goals:

- Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER
  - Vary fast-ion instability drive using NBI, q, rotation, 3D fields
  - Measure *AE mode structure
    - Magnetics, BES, reflectometry
  - Characterize fast ion transport vs. *AE type
  - Compare data to simulation, develop reduced models
    - ORBIT, NOVA-K, M3D-K, HYM to understand mode-induced transport

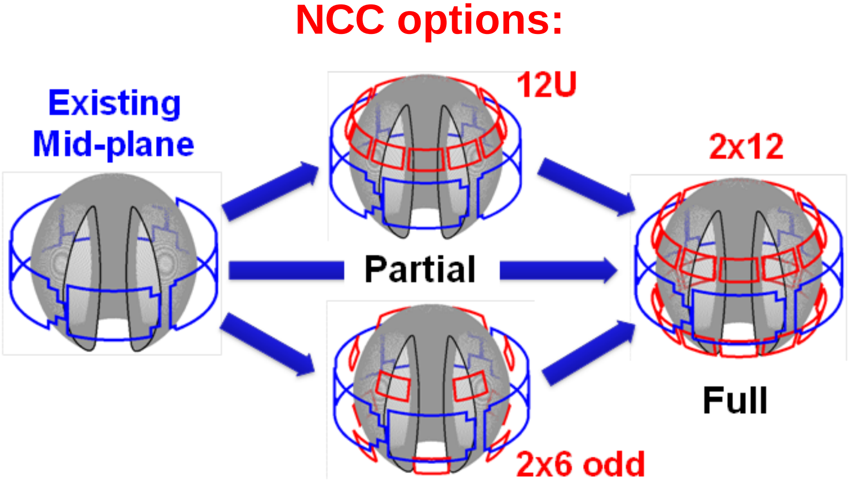


- Assess requirements for fast-ion phase-space engineering
  - AE spectroscopy, also stability control using NBI, q, rotation, 3D fields

NSTX/NSTX-U is making leading contributions to high-β_N stability physics, and assessing possible 3D coil upgrades



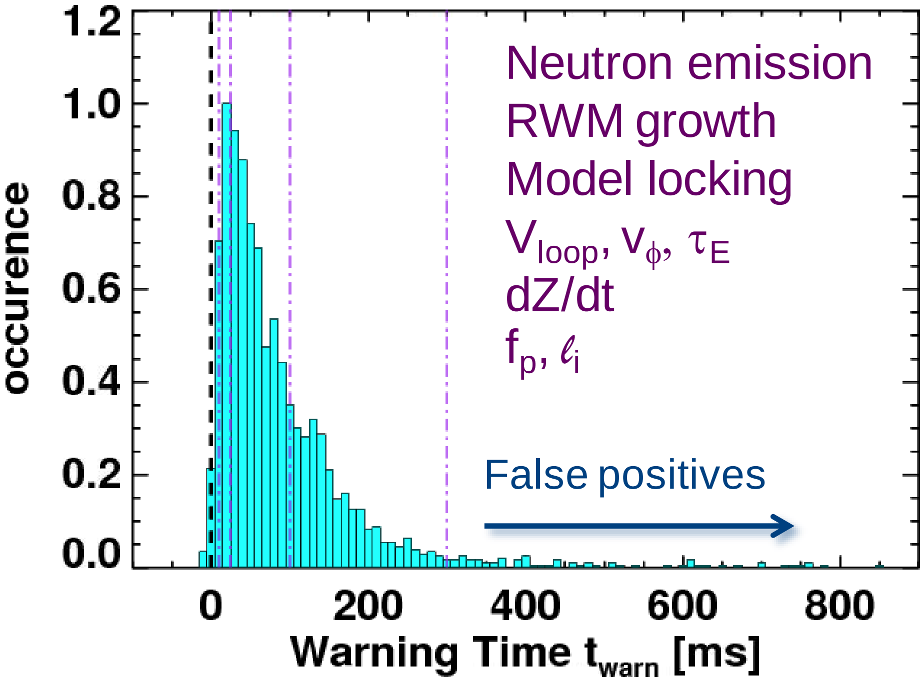
- n=1 MHD spectroscopy: high β_N can be more stable
  - Combination of rotation and current profile effects at high beta
  - Important for advanced scenarios



- Identified several off-midplane 3D coil sets favorable for profile and mode control
  - ~40% increase in n=1 RWM β_{active} / $\beta_{no\text{-}wall}$
  - ~5x reduction in n=1 EF resonant torque
  - ~10-100x variation in ratio of non-resonant to resonant n=3 torque in edge
    - Important for control, understanding of RMP ELM control, NTV rotation profile control

NSTX has also made leading contributions to disruption warning research

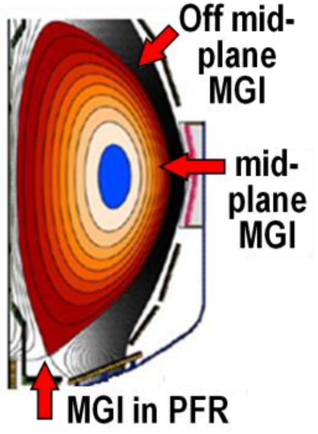
- **Disruption warning algorithms:**
  - **Based on sensors + physics-based variables (not neural net)**
  - < 4% missed, 3% false positives
  - ITER requires 95-98% prediction success for VDE, thermal quench
  - Will assess applicability to ITER through ITPA Joint Activity
  - Will also assess for ST-FNSF



- **Will use to trigger ramp-down and/or mitigation in NSTX-U**

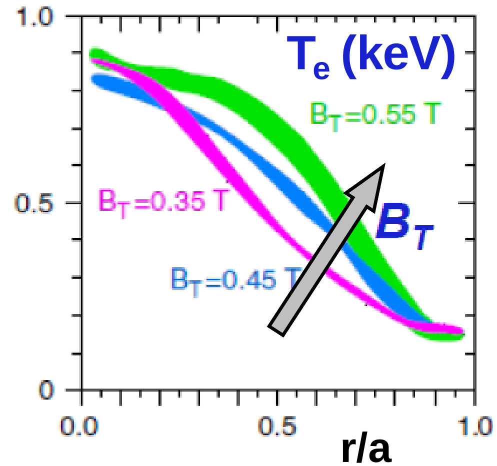
Macroscopic Stability 5 Year Goals:

- Study effects of reduced ν^*, q and rotation on LM, RWM, NTM
- Test state-space control for EF, RWM for ITER, next-steps
- Assess 3D field effects to provide basis for optimizing stability through rotation profile control by 3D fields
  - EF penetration, rotation damping, ELM triggering and suppression
- Understand disruption dynamics, develop prediction and detection, avoidance, mitigation
  - Enhance measurements of disruption heat loads, halos
  - Develop novel particle delivery techniques for mitigation:
    - MGI in private-flux-region (PFR), electromagnetic particle injector

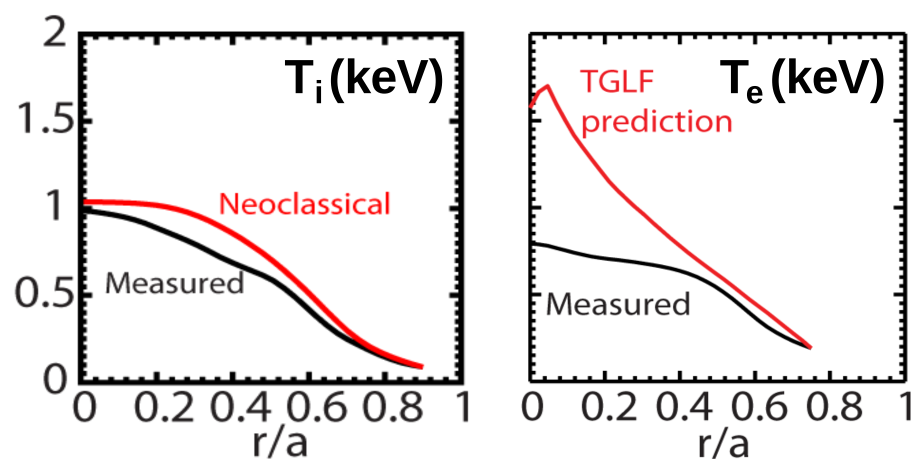


Beginning to test/utilize transport models to predict NSTX temperature profiles, identify possible missing physics

- NSTX H-modes showed broadening of T_e profile as B_T was increased
  - Similar broadening trend observed with increased lithium deposition
  - $B_T\tau_E$ scales as ~$1/\nu^*$ in both datasets



- Utilizing neoclassical + drift wave models to simulate NSTX T_i and T_e profiles (collaboration with GA)
  - Need model for χ in edge region
  - Discrepancy in core T_e prediction for beam-heated H-modes



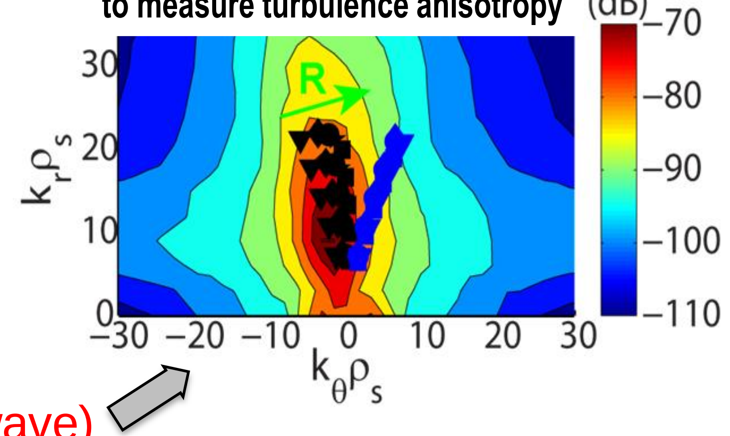
- Over-prediction of core T_e in NSTX may be due to transport from GAE/CAE modes not included in gyro-Landau-fluid model

Transport and Turbulence 5 Year Goals:

- Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U
- Identify modes causing anomalous electron thermal, momentum, particle/impurity transport
  - Exploit scaling dependencies of modes
    - Example: μ-tearing $\chi_e \sim \nu^1$, ETG $\chi_e \sim \nu^0$
  - Relate predicted turbulence to data:
    - Low-k (BES), δB (polarimetry), high k_r & k_θ (μ-wave)
  - **Builds on identification of ETG w/ novel high-k_r scattering in NSTX**

New high-k scattering

to measure turbulence anisotropy



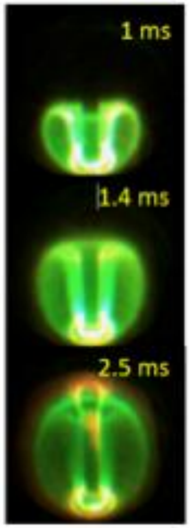
- Establish and validate reduced transport models

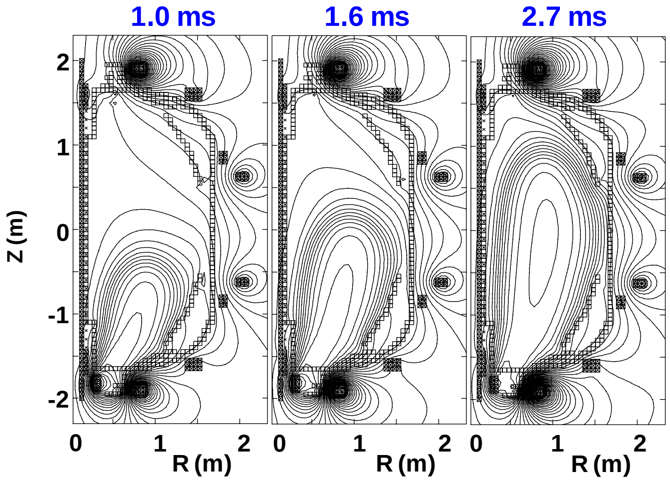
Highest priority research goals for NSTX-U:

1. Demonstrate 100% non-inductive sustainment
2. Access reduced ν^* and high-β combined with ability to vary q and rotation
3. Develop/understand non-inductive start-up, ramp-up (overdrive) for ST-FNSF with small/no solenoid
4. Develop high-flux-expansion "snowflake" divertor + radiative detachment to mitigate high heat fluxes
5. Assess high-Z + liquid Li plasma facing components

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

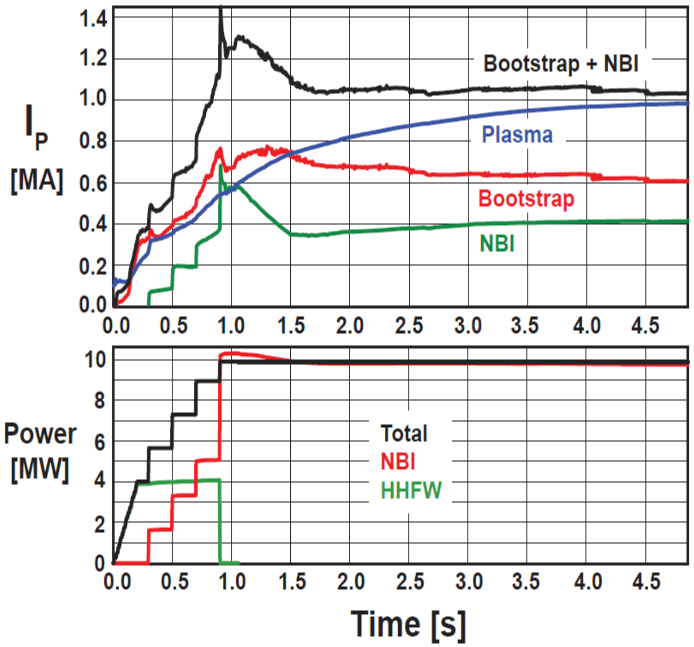
- TSC code (2D) successfully simulates CHI I_P ~200kA achieved in NSTX





- TSC + tools included in 5 year plan support CHI I_P → 400kA in NSTX-U
  - Higher injector flux, toroidal field, CHI voltage
  - 1MW 28GHz ECH (increases T_e)

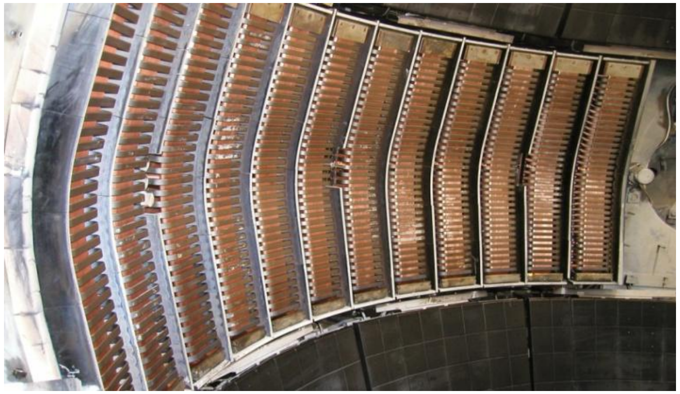
- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
- TSC: non-inductive ramp-up from 0.4MA to 1MA possible w/ BS + NBI



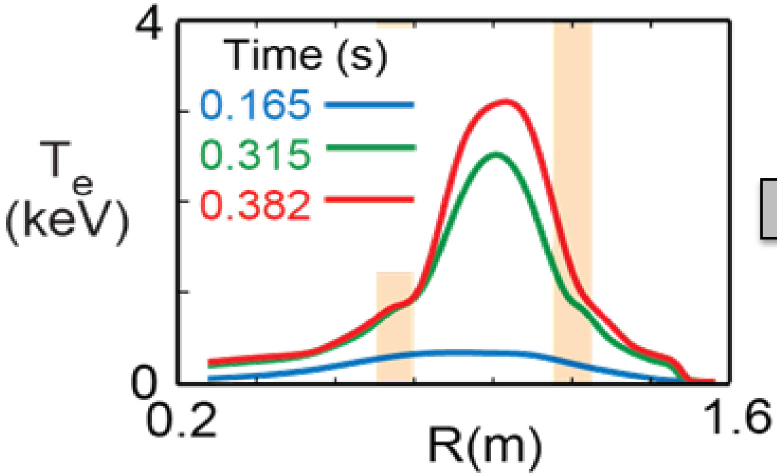
- But, RF heating (ECH and/or HHFW) of CHI likely required to couple to NBI

HHFW can efficiently heat low I_P targets for plasma start-up

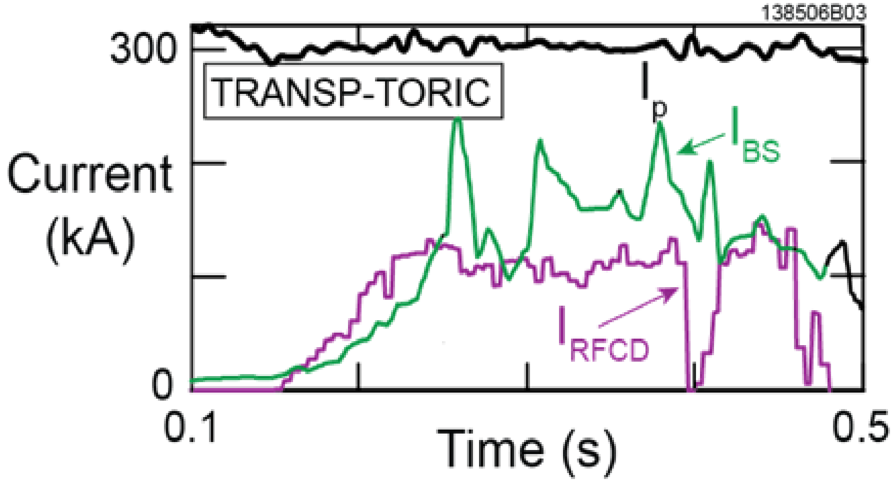
- NSTX high-harmonic fast-wave (HHFW) antenna will also be utilized on NSTX-U
  - 12 strap, 30MHz, $P_{RF} \leq$ 6MW
  - HHFW: highest ST $T_e(0)$ ~ 6keV



- $T_e(0)$=3keV RF-heated H-mode at I_P = 300kA with only P_{RF} = 1.4MW

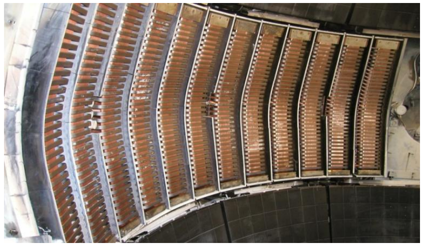


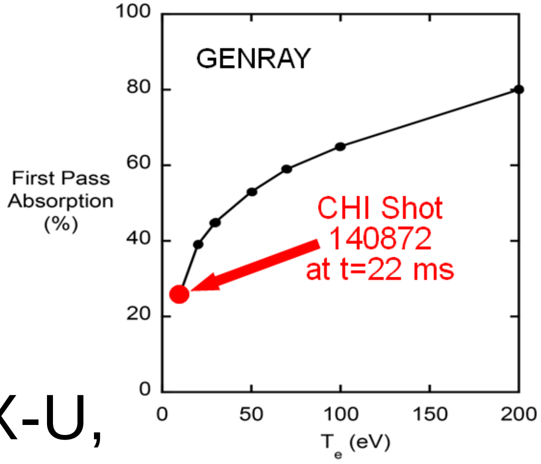
- Non-inductive fraction ≥ 70%
  - f_{BS} ~50%, f_{RFCD} ~ 20-35%



Start-up/Ramp-up + RF Heating/Current Drive Goals:

- Test higher-current CHI start-up (~400kA)
- Test NBI + bootstrap current overdrive/ramp-up
- Develop HHFW and EC heating for fully non-inductive plasma current start-up and ramp-up
  - Extend HHFW to higher power (3-4MW), demonstrate HHFW-driven 100% non-inductive at 300-400kA
    - Goal: maintain I_P to confine 2nd NBI fast-ions
  - Use ECH (~1MW, 28GHz), then HHFW to increase T_e of CHI plasmas for NBI
  - Test high-power EBW to generate start-up current - builds on MAST results
- Validate advanced RF codes for NSTX-U, predict RF performance in ITER and FNSF



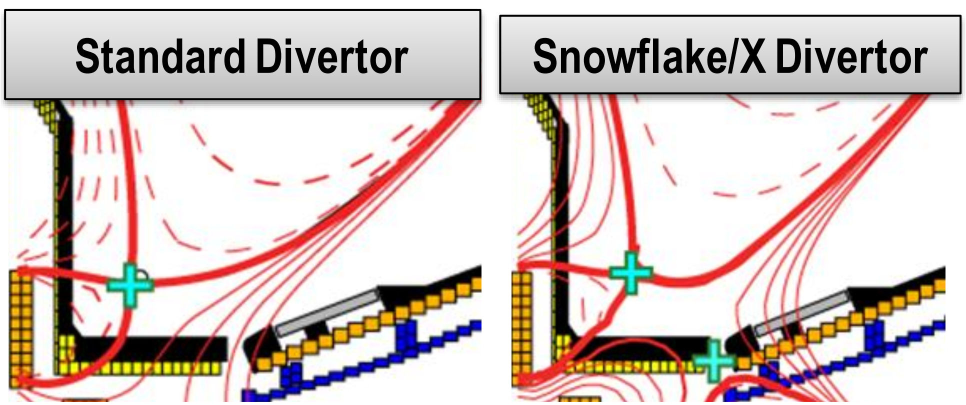


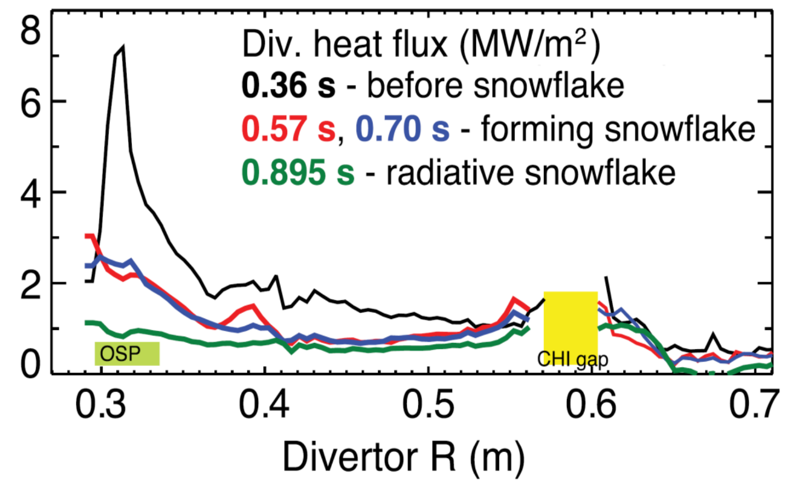
Highest priority research goals for NSTX-U:

1. Demonstrate 100% non-inductive sustainment
2. Access reduced ν^* and high-β combined with ability to vary q and rotation
3. Develop/understand non-inductive start-up, ramp-up (overdrive) for ST-FNSF with small/no solenoid
4. Develop high-flux-expansion “snowflake” divertor + radiative detachment to mitigate high heat fluxes
5. Assess high-Z + liquid Li plasma facing components

Snowflake divertor effective for heat flux mitigation

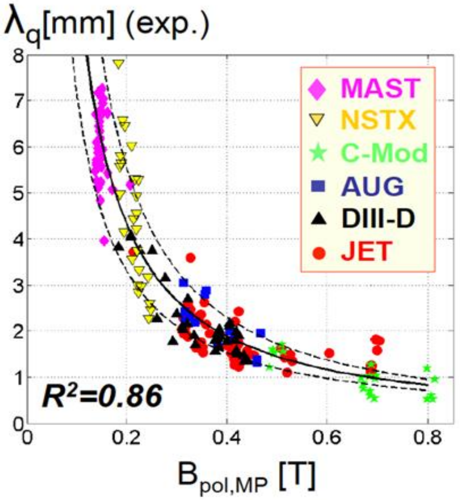
- NSTX: can reduce heat flux by 2-4 × via partial detachment
- Snowflake → additional x-point near primary x-point
  - NSTX: High flux expansion = 40-60 lowers incident $q_{\perp}$
  - Longer field-line-length promotes temperature drop, detachment



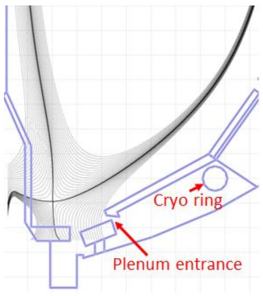


Boundary Physics, SOL/Divertor, PMI 5 Year Goals:

- Assess, optimize, control pedestal structure, transport, stability
- Assess and control divertor heat fluxes
  – Measure SOL widths at lower ν, higher B_T, I_P, P_{SOL}
    - Compare data to fluid and gyro-kinetic models
  – Assess, control, optimize snowflake/X-divertor
  – Develop highly-radiating divertor w/ feedback control
  – Assess impact of high-Z tile row(s) on core impurities

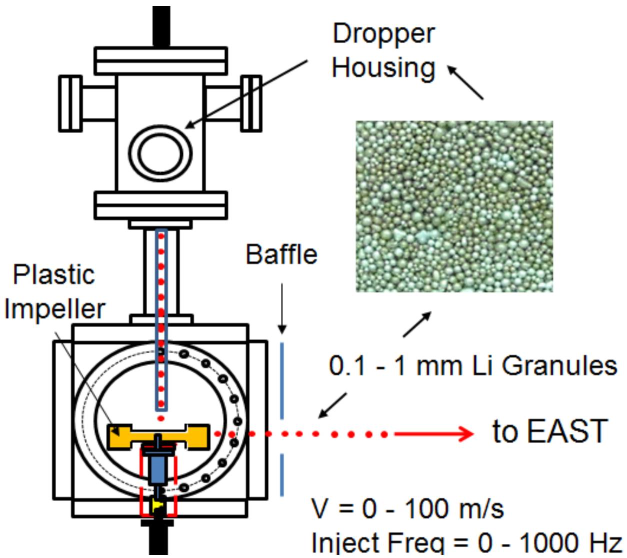


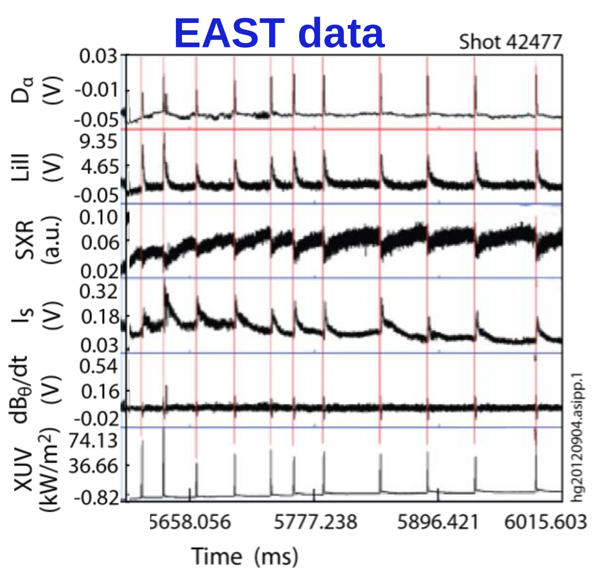
- Establish, compare particle control methods
  – Validate cryo-pump physics design, assess density control
  – Compare cryo to lithium coatings for n_e, impurity, ν^* control



- Explore Li/liquid-metal plasma material interactions
  – Li surface-science, continuous vapor-shielding, material migration and evolution, lab R&D: flowing Li loops, capillary-restrained Li surfaces

Lithium Granule Injector (LGI) developed for NSTX is promising tool for pedestal control and scenario optimization





- Successful EAST collaboration
  - Demonstrated LGI ELM-pacing at 25 Hz with nearly 100% triggering reliability
  - Capable of up to 1 kHz injection
- LGI will be tested on NSTX-U for high-frequency ELM pacing
  - Possible density control technique:
    - Combine Li coatings for D pumping with LGI for ELM-expulsion of carbon
  - Goal: reduce Z_{eff} to ~2-2.5
  - Injection of Li granules could also potentially replenish PFC Li coatings
- JET/ITER: potentially interested in testing Be granules for ELM pacing

Summary: NSTX-U aims to carry out leading research in support of FNSF/next-steps and ITER

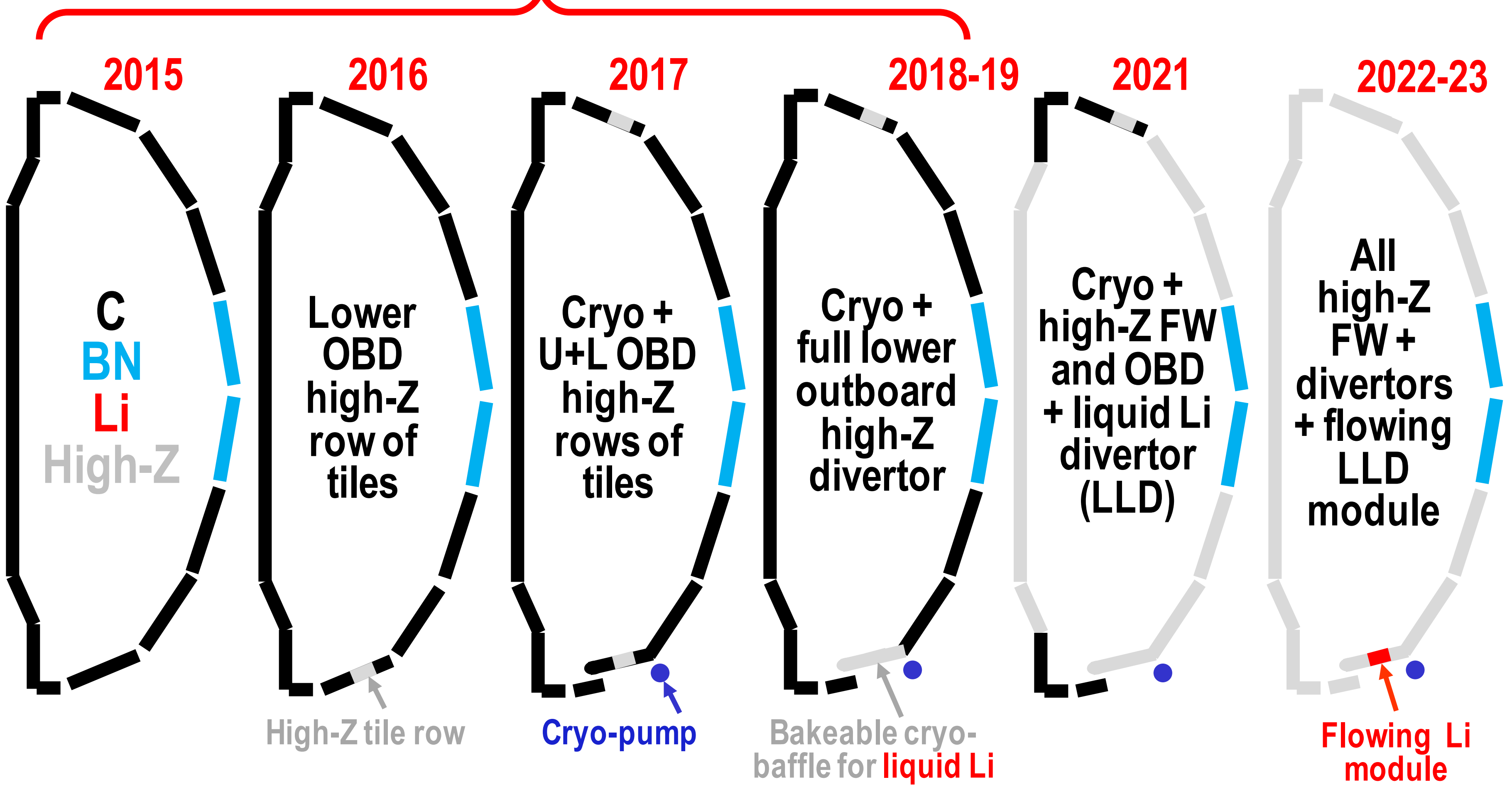
- Non-inductive sustainment: NSTX-U aims to be the ST leader, will complement AT approach (DIII-D, KSTAR, EAST)
- Aim to make major advancements in transport understanding: Low ν^* + high β + turbulence diagnostics unique in world
- NSTX-U will advance non-inductive start-up/ramp-up using unique combination of helicity injection + RF + NBI techniques
- With MAST-U, STs will lead development of novel divertors:
  - Snowflake / X-divertor, Super-X
  - NSTX-U aiming to lead development of replenishable / liquid metal PFCs

Backup

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

Base budget case

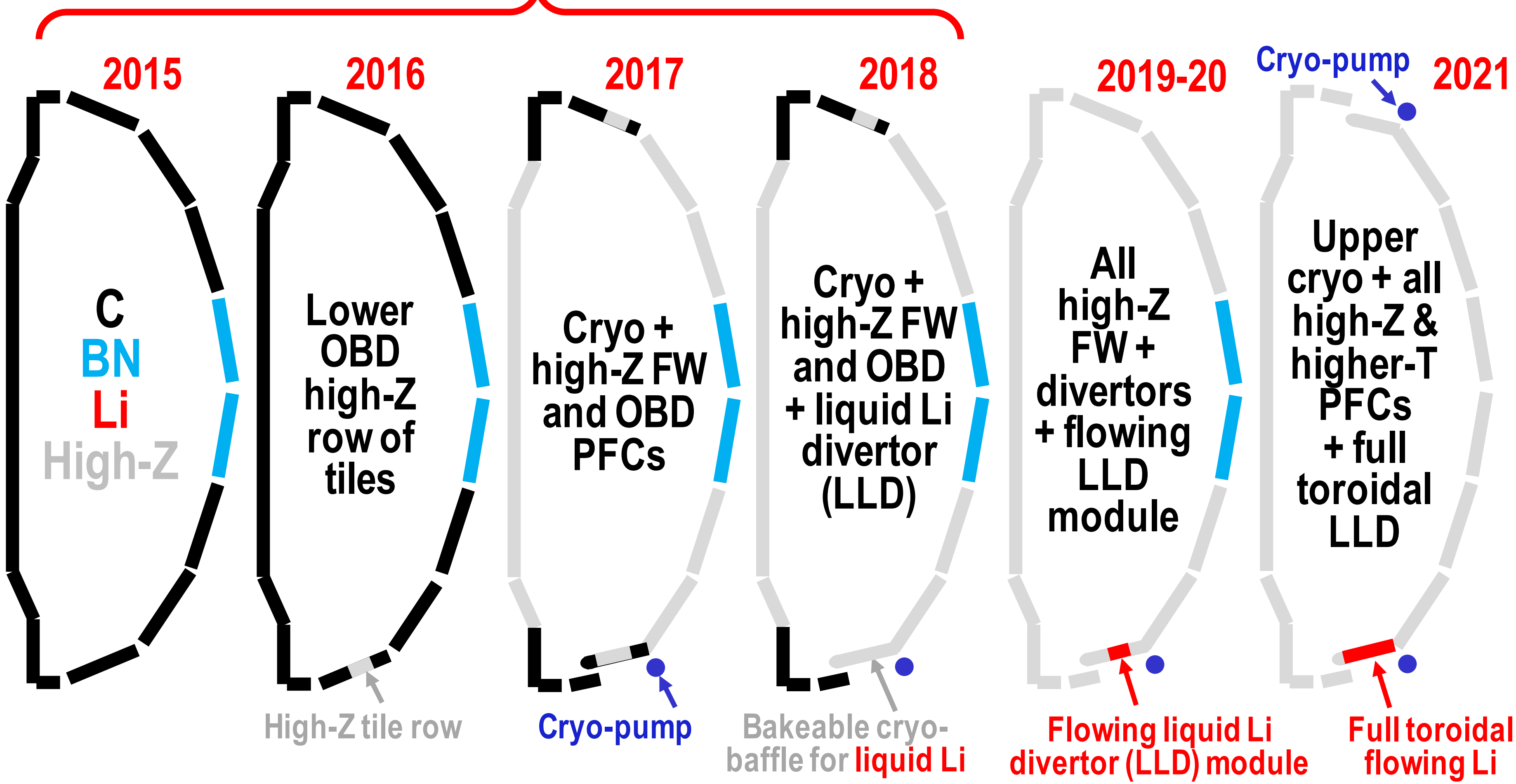
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



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

Incremental budget case

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



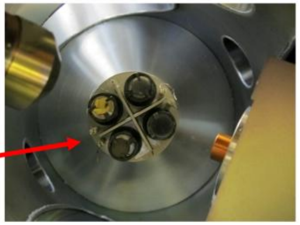
Initiate comparative assessment of high-Z and liquid metal PFCs for long-pulse high-power-density next-step devices

MP Thrusts:

1. Understand Li surface-science at extended PFC operation
   - "Atoms to tokamaks" collaboration with PU
   - Materials Analysis Particle Probe (MAPP) (Purdue - J.P. Allain, 2010 ECRP) to identify in-situ between-shot surface composition (LTX→NSTX-U)

MAPP capabilities:
TDS LEISS
XPS DRS

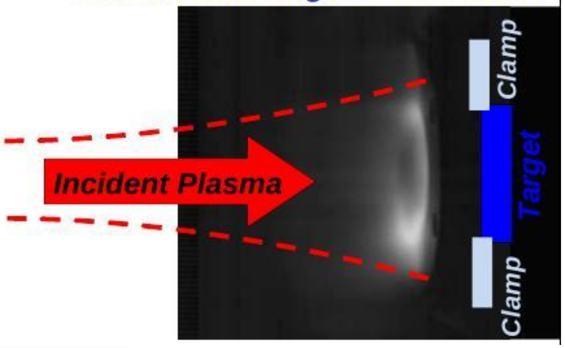
Up to 4 samples exposed



2. Assess tokamak-induced material migration and evolution
   - QCMs, marker-tiles, MAPP + QCM for shot-to-shot analysis of migration

3. Establish the science of continuous vapor-shielding
   - Continue studies of Li vapor-shielding in linear plasma device Magnum-PSI
   - Extend Magnum results to NSTX-U

Fast-camera Image Li-I Emission

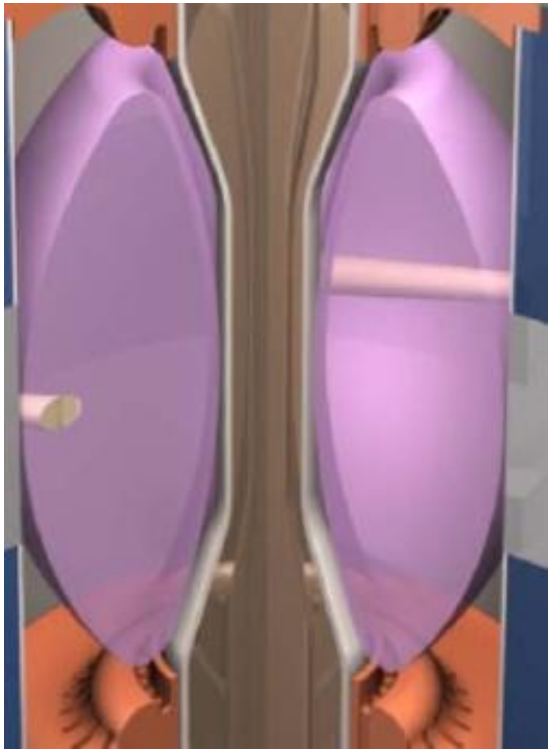


Magnum-PSI collaboration: M. Jaworski, T. Abrams (grad student) (PPPL)

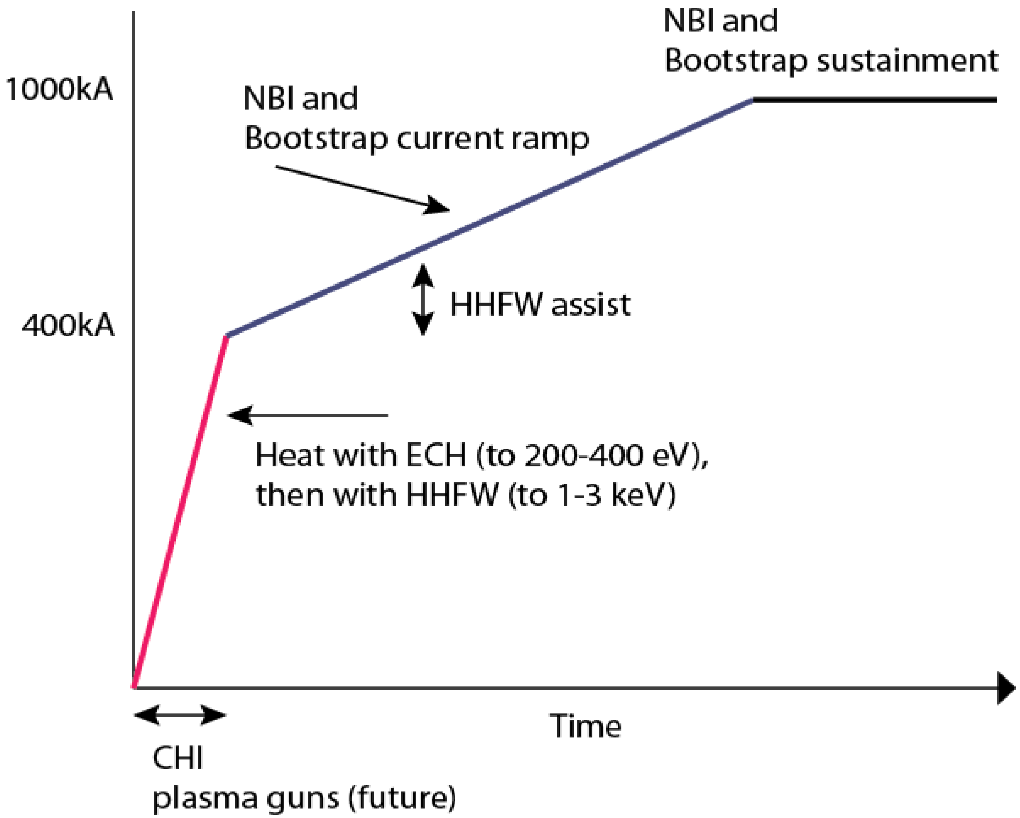
- Lab-based R&D: flowing Li loops, capillary-restrained Li surfaces

Plasma initiation with small or no transformer is unique challenge for ST-based Fusion Nuclear Science Facility

ST-FNSF has no/small central solenoid



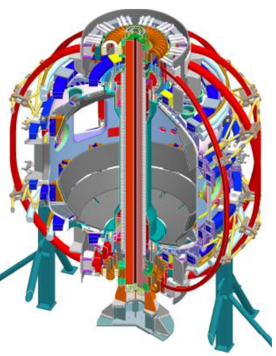
NSTX-U Non-Inductive Strategy:



NSTX-U goal staging: first establish ST physics + scenarios, transition to long-pulse + PMI integration (5YP incremental)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Upgrade Outage	Establish ST physics, scenarios				Integrate long-pulse + PMI solutions				

New center-stack



2nd NBI

Topic	Establish ST physics, scenarios	Integrate long-pulse + PMI solutions
Start-up and Ramp-up	Increase CHI closed-flux current; Assess plasma gun start-up at increased device size; Develop/understand ECH/EBW H&CD for ST; Achieve NI start-up/ramp-up	Increase/extend ramp-up heating and off-axis current-drive for advanced scenarios
Boundary Physics	Establish main-ion density and ν^* control; Understand snowflake divertor performance	Understand high-Z first-wall erosion, migration, particle sources & sinks
Materials and PFCs	Assess baseline graphite PFC performance; Assess high-Z tile/divertor impact and performance	Assess high-Z divertor and/or first-wall; Assess impact of high-temperature first-wall
Liquid metals / lithium	Establish low impurities / Z_{eff}, assess increased Li coverage, replenishment	Test flowing liquid metal for heat-flux mitigation, surface replenishment; Assess flowing LM PFC with full toroidal coverage
MHD	Understand kinetic MHD, extend mode and disruption detection, develop mitigation	Enhance non-axisymmetric field spectrum and capabilities with off-midplane coils for control of: RWM, EF, RMP, rotation, NTM, EP
Transport & Turbulence	Understand ES and EM turbulence at high β, low ν^*, emphasizing e-transport	Extend wave-number coverage of turbulence measurements
Waves and Energetic Particles	Characterize AE stability, fast-ion transport, NBI-CD, support plasma start-up, assess effectiveness of fast-wave in NBI H-modes	Prototype driving edge-harmonic oscillations (EHOs) and/or *AE
Scenarios and Control	Demonstrate full non-inductive, high I_P & P_{AUX} operation; Control: boundary, β, divertor heat flux, Ω & q profiles	Assess integrated control of long-pulse / high-performance

Inform choice of FNSF: **aspect ratio, divertor, and PFCs**

10 year plan tools with 5YP incremental funding

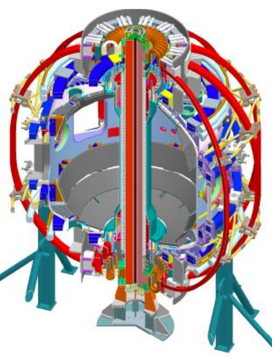
1.1 × (FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage | 1.5 → 2 MA, 1s → 5s | Metallic PFCs, 5s → 10-20s

Run Weeks: 20 16 16 20 22 6 18 22 22

New center-stack



Start-up and Ramp-up: Upgraded CHI for ~0.5MA; 0.5-1 MA CHI; up to 1 MA plasma gun; Extend NBI duration to 10-20s and/or implement 2-4 MW off-axis EBW H&CD; 1 MW ECH/EBW → 2 MW

Boundary Physics: Lower divertor cryo-pump; Divertor Thomson; Upper divertor cryo-pump

Materials and PFCs: High-Z tile row on lower OBD; High-Z first-wall + lower OBD tiles; High-Z PFC diagnostics; All high-Z PFCs; Hot high-Z FW PFCs using bake-out system

Liquid metals / lithium: Li granule injector; Upward LiTER; LLD using bakeable cryo-baffle; Flowing Li divertor or limiter module; Full toroidal flowing Li lower OBD

MHD: MGI disruption mitigation; Partial NCC; Enhanced MHD sensors; NCC SPA upgrade; Full NCC

Transport & Turbulence: δB polarimetry; High k_θ; DBS, PCI, or other intermediate-k

Waves and Energetic Particles: 1 coil AE antenna; 4 coil AE antenna; HHFW limiter upgrade; Charged fusion product, neutron-collimator; HHFW straps to excite EHO; High-power AE antenna

Scenarios and Control: Establish control of: Snowflake, $\bar{n}_e$, Rotation, q_{min}, Divertor P_{rad}; Control integration, optimization; Control integration, optimization with long-pulse and full metal wall

Inform choice of FNSF: **aspect ratio, divertor, and PFCs**

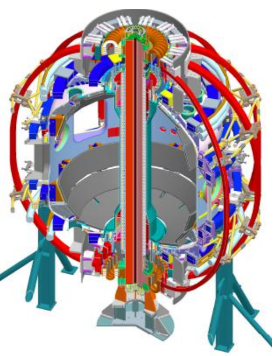
2nd NBI

5 year plan tools with 5YP base funding

(FY2012 + 2.5% inflation)

	2014	2015	2016	2017	2018
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		16	14	14	16

New center-stack



Start-up and Ramp-up: Upgraded CHI for ~0.5MA; 1 MW ECH/EBW; up to 0.5 MA plasma gun

Boundary Physics: Lower divertor cryo-pump; High-Z PFC diagnostics

Materials and PFCs: High-Z tile row on lower OBD; High-Z tile row on cryo-baffle; Full high-Z lower OBD

Liquid metals / lithium: Li granule injector; Upward LiTER; LLD using bakeable cryo-baffle

MHD: MGI disruption mitigation; Partial NCC; Enhanced MHD sensors

Transport & Turbulence: δB polarimetry; High k_θ

Waves and Energetic Particles: Charged fusion product; 1 coil AE antenna; 4 coil AE antenna

Scenarios and Control: Establish control of: Snowflake; $\bar{n}_e$; Rotation; q_{min}; Divertor P_{rad}

2nd NBI

- Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017
  - NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

NSTX-U 5 year plan aims to develop ST physics and scenario understanding necessary for assessing ST viability as FNSF