NSTX-U

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NSTX-U Five Year Plan Research Program Overview

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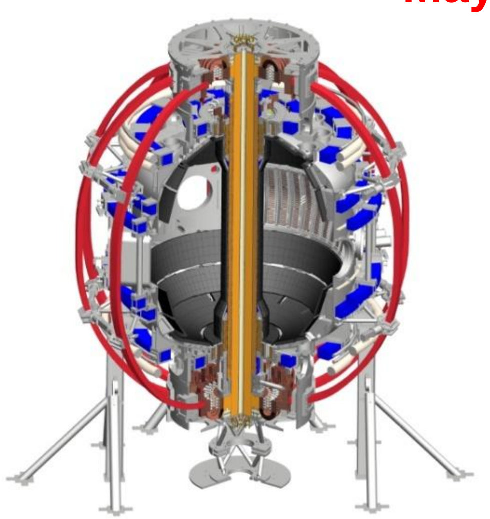
Jon Menard (PPPL)
NSTX-U Program Director

NSTX-U 5 Year Plan Review
LSB B318, PPPL
May 21-23, 2013



Culham Sci Ctr
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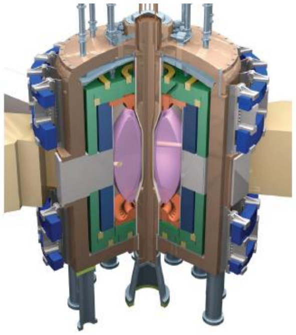
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

- NSTX-U mission and capabilities
- Five year plan goals
- Proposed facility enhancements
- Role of collaborations
- Plan organization
- Overview of research plans by science area
- Plan summary
- Mapping of presentations to charge questions

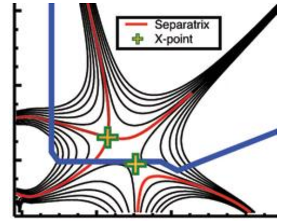
NSTX Upgrade mission elements

- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**
  - Motivation for ST as FNSF: high neutron wall loading, potentially smaller size, cost, and tritium consumption, accessible / maintainable
- **Develop solutions for the plasma-material interface challenge**
  - Exploit strong heating + smaller R → high P/R and P/S approaching FNSF/Demo levels
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - Non-linear Alfvénic modes, fast-ion dynamics
  - Study electron gyro-scale turbulence at low ν^*
  - High β, rotation, shaping, for transport, MHD
- **Develop ST as fusion energy system**

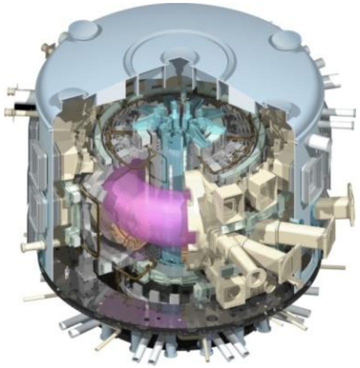


ST-FNSF

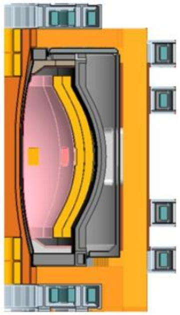
Lithium



"Snowflake"

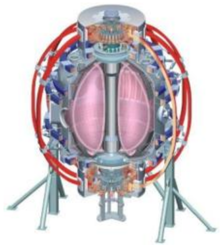
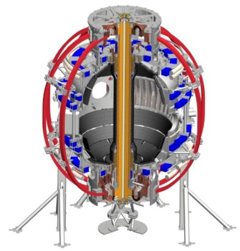
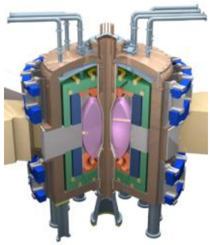
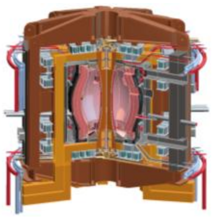


ITER



ST Pilot Plant

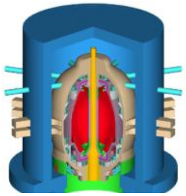
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs

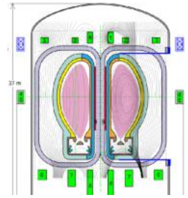
Parameter	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	22 – 45	50 – 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

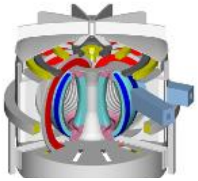
Low-A Power Plants



ARIES-ST (A=1.6)



JUST (A=1.8)



VECTOR (A=2.3)

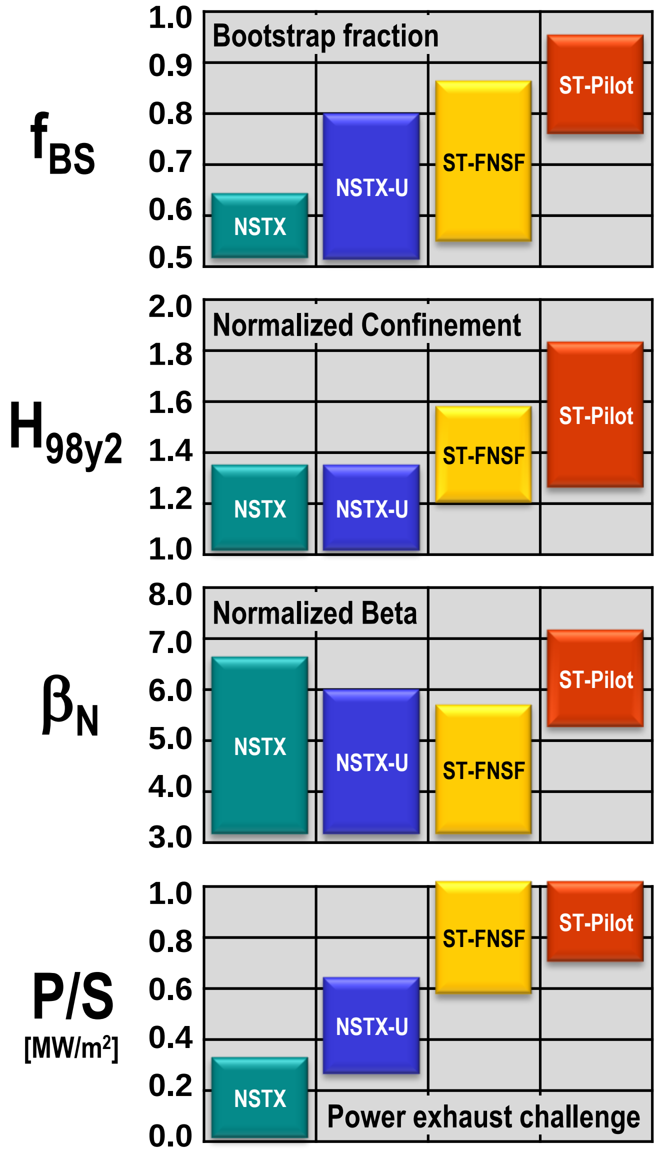
Key issues to resolve for next-step STs

- **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

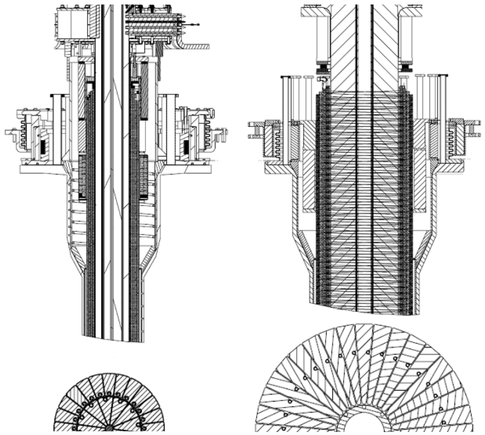
Requirements for ST / tokamak next-steps:

- **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**



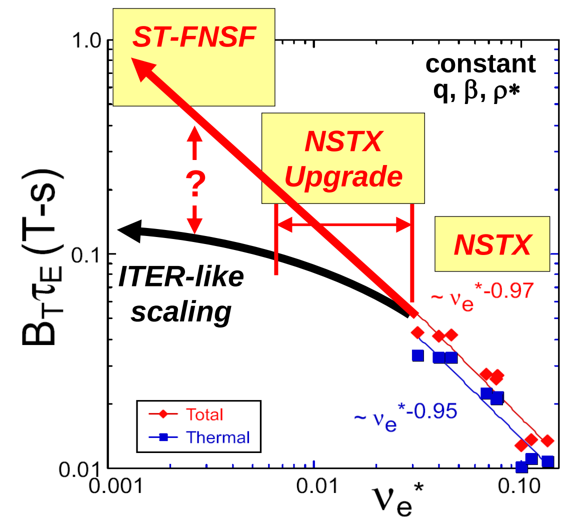
NSTX Upgrade incorporates 2 new capabilities:

Previous center-stack | New center-stack

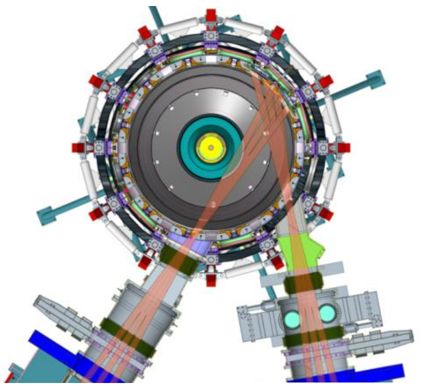


TF OD = 20cm | TF OD = 40cm

- 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

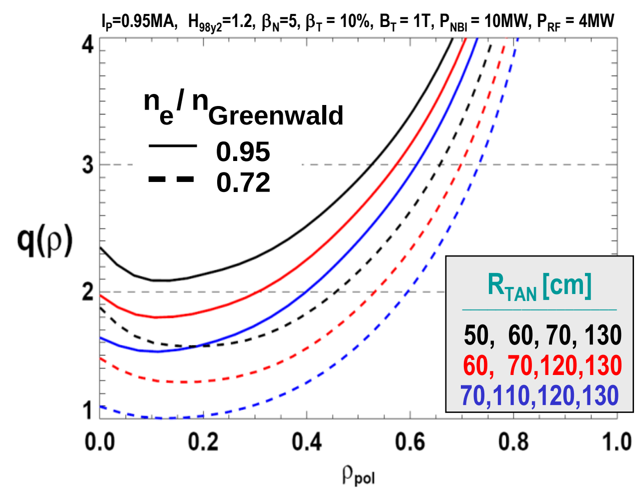


Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



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)



Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/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

Longer-term (5-10 year) goal:

Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

Additional facility enhancements will greatly aid achievement of high-priority goals

- Extensive diagnostic/facility idea input gathered 2011-2012
- Options ranked according to program impact, cross-links, cost
- Programmatic impact includes:
  - Importance to next-step ST viability
  - Physics or operational contributions to ITER
  - Uniqueness for ST or in world program
- Highest priority facility enhancements (5YP base funding):
  1. **Cryo-pump**: n_e , collisionality control important to all science areas and scenarios, also enables comparison between cryo and Li-coatings
  2. **ECH/EBW (1MW, 28GHz)**: ECH critical for heating helicity-injection start-up plasma for HHFW/NBI ramp-up, longer-term: off-axis EBW H&CD
  3. Off-midplane non-axisymmetric control coils (**NCC**): far greater variation of poloidal & toroidal spectrum for EF, RWM, rotation, ELM physics & control
- Boundary/PMI research highest priority for incremental funding:
  - High-Z walls, flowing liquid Li divertor, Divertor Thomson Scattering

5 year plan goals embody world-leading research

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF

➢ **NSTX-U will be ST leader, complement AT approach (DIII-D)**

2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

➢ **Low ν^* + high β + turbulence diagnostics unique in world**

3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid

➢ **Unique helicity injection + RF + NBI start-up/ramp-up techniques**

4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes

➢ **With MAST Super-X, STs leading development of novel divertors**

5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

➢ **Aiming to lead development of replenishable / liquid metal PFCs**

Achievement of NSTX-U goals will continue to rely on extensive collaborator involvement

- Collaborations involve broad group of domestic and international users
  - Collaborators were involved in originally proposing, designing NSTX
  - Many diagnostic systems are built and operated by collaborators

	PPPL/PU	National Team (non-PPPL/PU)	International	Total
Total Researchers	79	166	61	306
Post-Docs	5	9	0	14
Students	3	26	4	33

Number of institutions	
Total	61
Domestic	32
International	29

- DOE annually solicits proposals for collaboration by U.S. researchers
  - Collaborations are competitively peer-reviewed on a 3-4 year cycle
- Collaborators participate fully in the research program
  - Leadership positions in research team to plan upgrades and research
    - Authorship of 3 of 8 topical science chapters were led by collaborators
  - Propose, develop, and execute experiments
  - Data analysis, review, publications, presentations

See Chapter 11 for FES-funded NSTX-U collaborator plans

Plan organization and research thrusts

- NSTX-U topical science groups (TSGs) are responsible for program plan definition and 5 year plan presentations + chapters
  - TSG structure: experimental leader/deputy + theory co-leader for strong theory-experiment linkages

- Each chapter contains 2-4 research "thrusts" defining actions to achieve the 5 high-level goals (see previous page) for the 5 year plan

- **The remainder of this presentation will review research highlights, provide an overview of the TSG research thrusts**
  - TSG presentations also note respective FY2013-15 research milestones for FES field work proposal (FWP)

NSTX-U Topical Science Groups

Macroscopic Stability
J.-K. Park, J. Berkery**
Theory: A. Boozer**

Transport and Turbulence
Y. Ren, W. Guttenfelder
Theory: G. Hammett

Boundary Physics
V. Soukhanovskii##, A. Diallo
Theory: C.S. Chang

Materials and PFC Research
C. Skinner, M. Jaworski
Theory: D. Stotler

Waves and Energetic Particles
G. Taylor, M. Podestá
Theory: N. Gorelenkov

Solenoid-free start-up & ramp-up
R. Raman#, D. Mueller
Theory: S. Jardin

Advanced Scenarios and Control
S. Gerhardt, E. Kolemen

Cross-Cutting / ITER needs
J. Menard, R. Maingi
Theory/Modeling: J. Canik*

*** Columbia University, ## LLNL*
*# University of Washington, *ORNL*

Highest priority research goals for 5 year plan:

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
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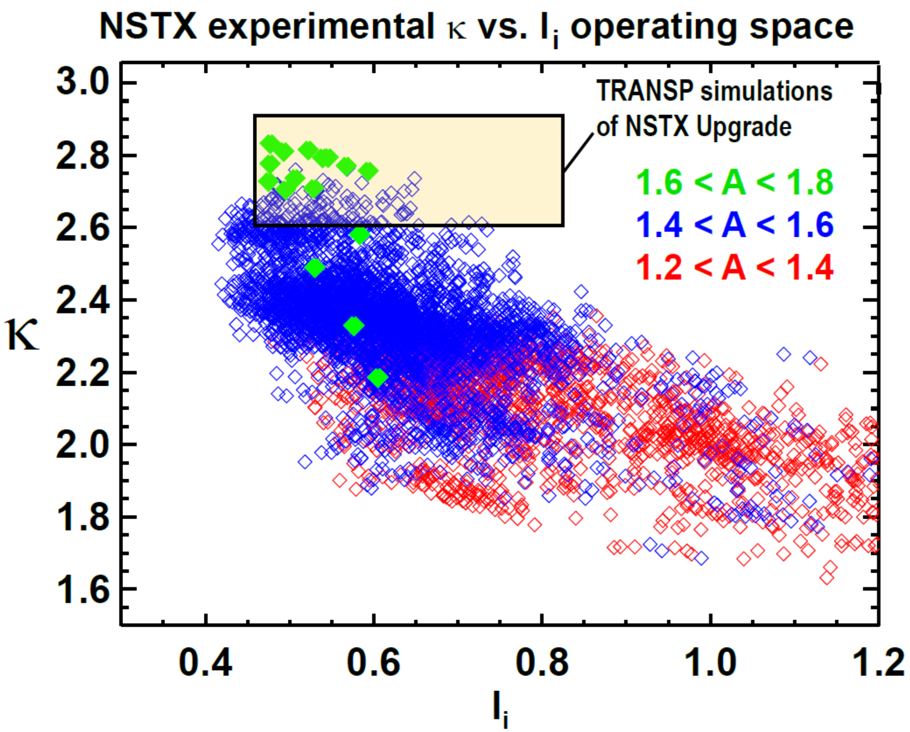
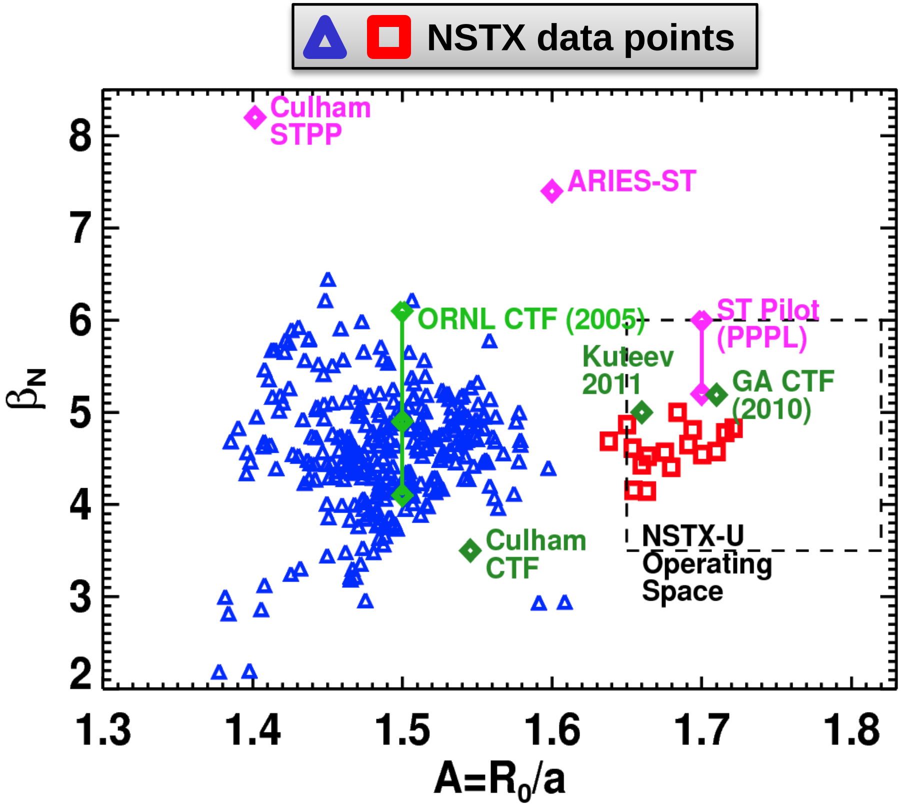
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

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





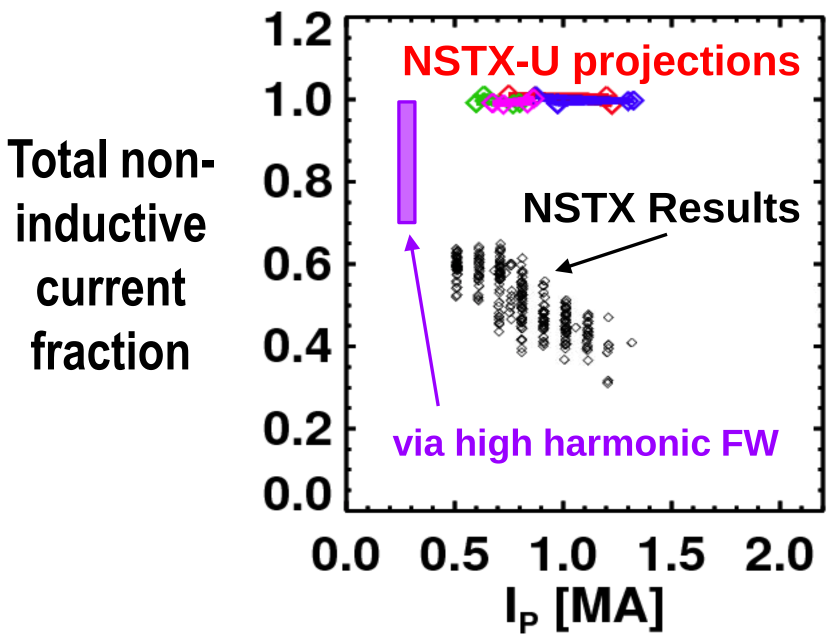
Next step is to access & control 100% non-inductive plasmas

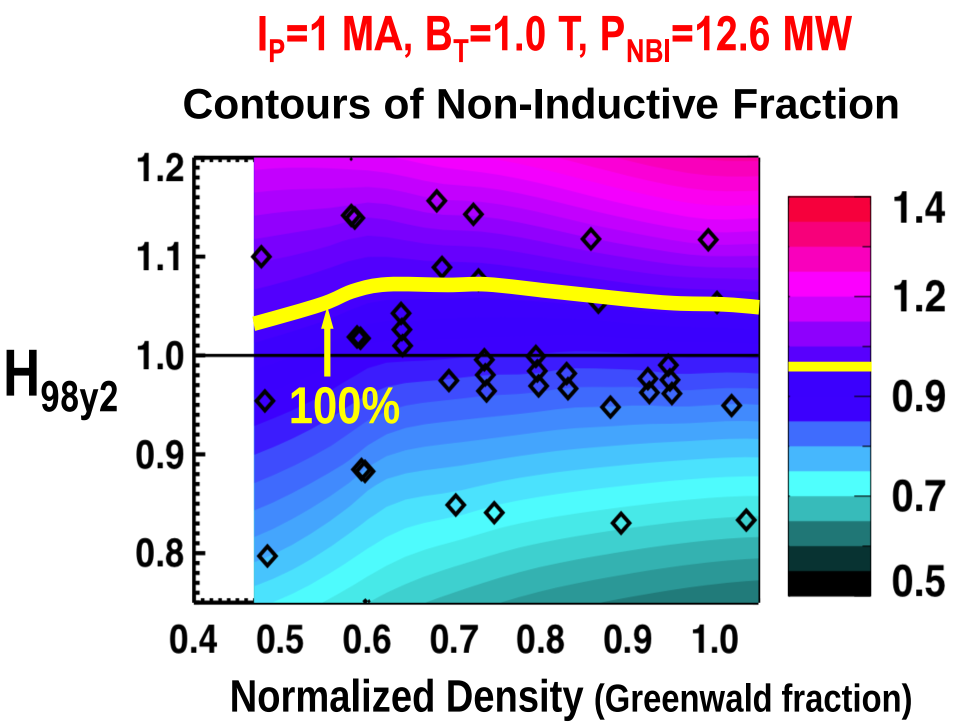
NSTX achieved:

- 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):

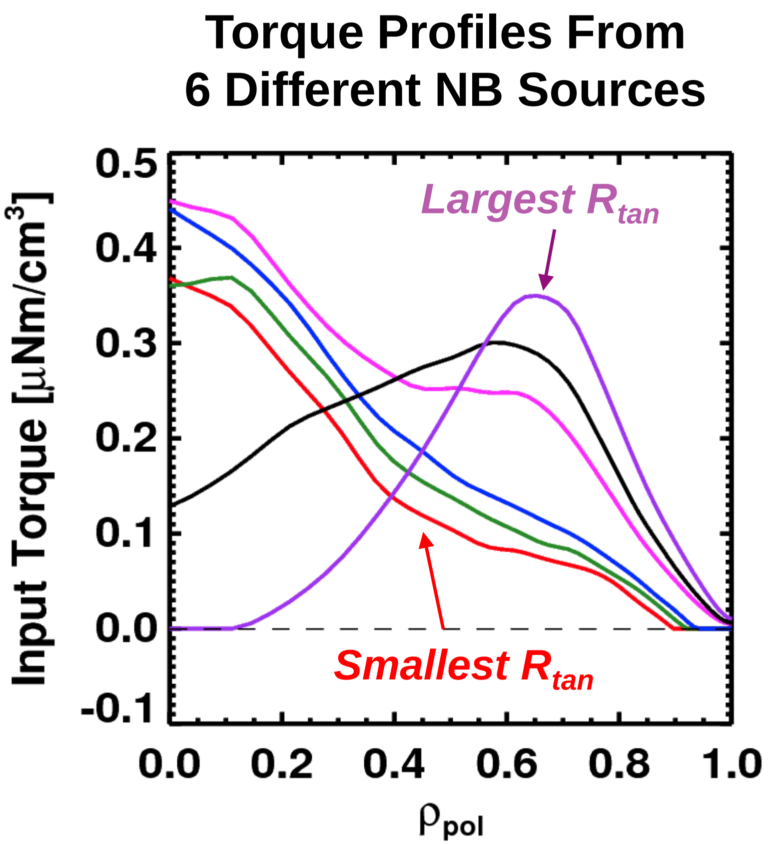
- 100% non-inductive at I_P = 0.6-1.3MA for range of power, density, confinement





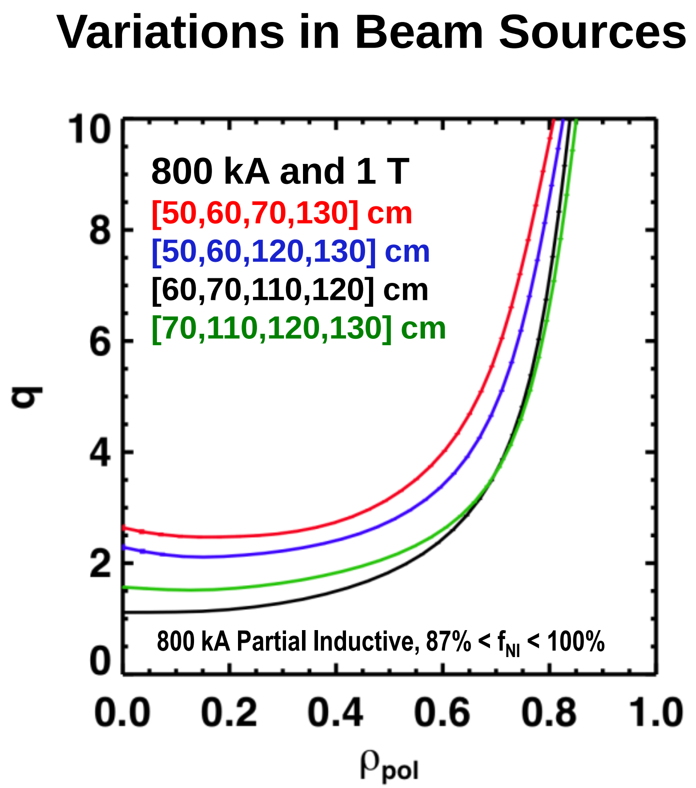
NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

Rotation Profile Actuators



- Also torques from 3D fields

q-Profile Actuators



- Also density and outboard gap

Advanced Scenarios and Control (ASC) 5 Year Goal:

Develop basis for steady-state operation/control for next-step STs, help resolve key scenario and control issues for ITER

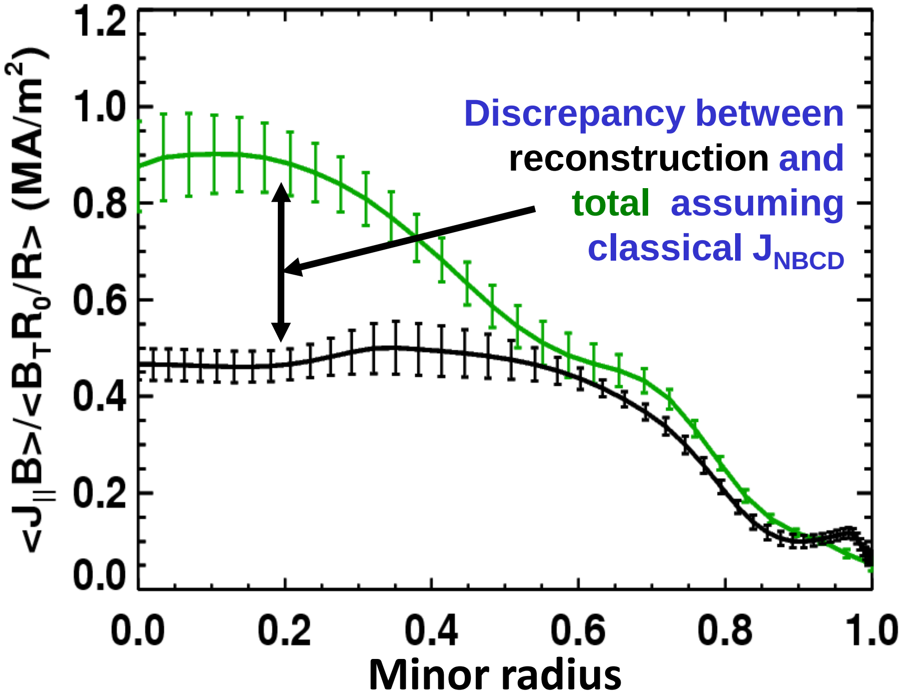
ASC Thrusts:

1. Develop and assess new physics scenarios
   - 100% non-inductive operation
   - Lower ν^*: high-current, partial-inductive scenarios, extend to long-pulse
2. Implement axisymmetric control algorithms and tools
   - Rotation and current profile control
   - Improved shape and vertical position control
   - Heat flux control for high-power scenarios
3. Develop disruption avoidance by controlled plasma shutdown
4. Assess scenario physics for next-step devices

See presentation by Stefan Gerhardt

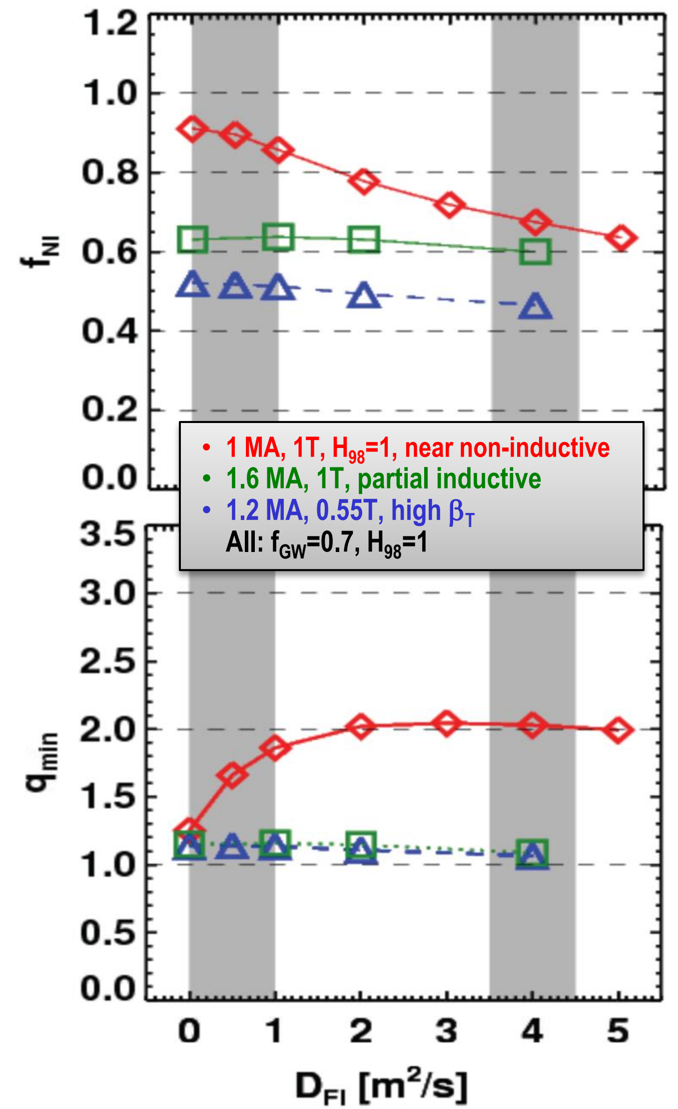
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

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

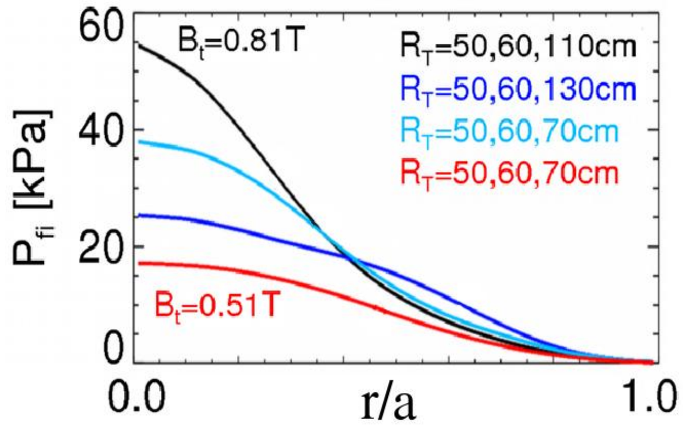


Energetic Particle (EP) 5 Year Goal:

Develop predictive capability for fast-ion transport caused by Alfven Eigenmodes (AEs), explore control of AE modes

EP Thrusts:

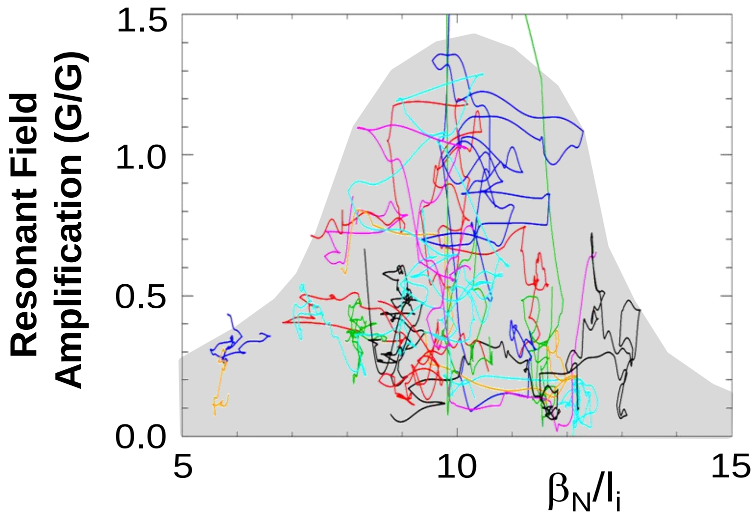
1. Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER
   - Vary fast-ion instability drive using NBI, q, rotation, 3D fields
   - Measure *AE mode structure
     - Magnetics, BES, reflectometry
   - Characterize fast ion transport vs. *AE type
   - Compare data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



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

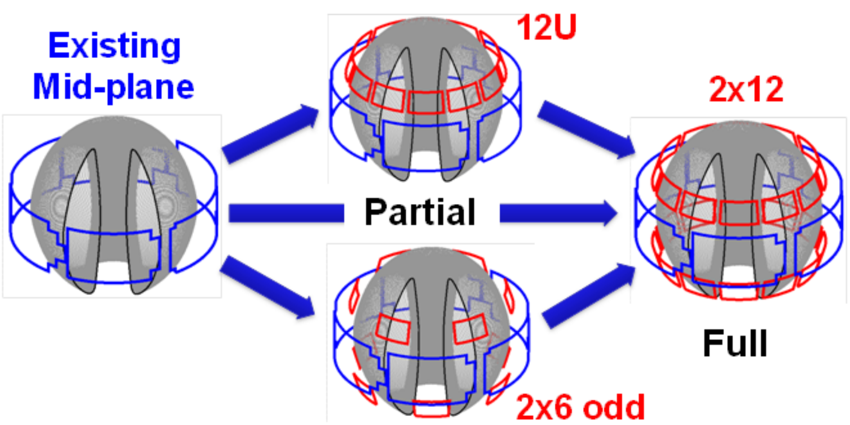
See presentation by Mario Podestá

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

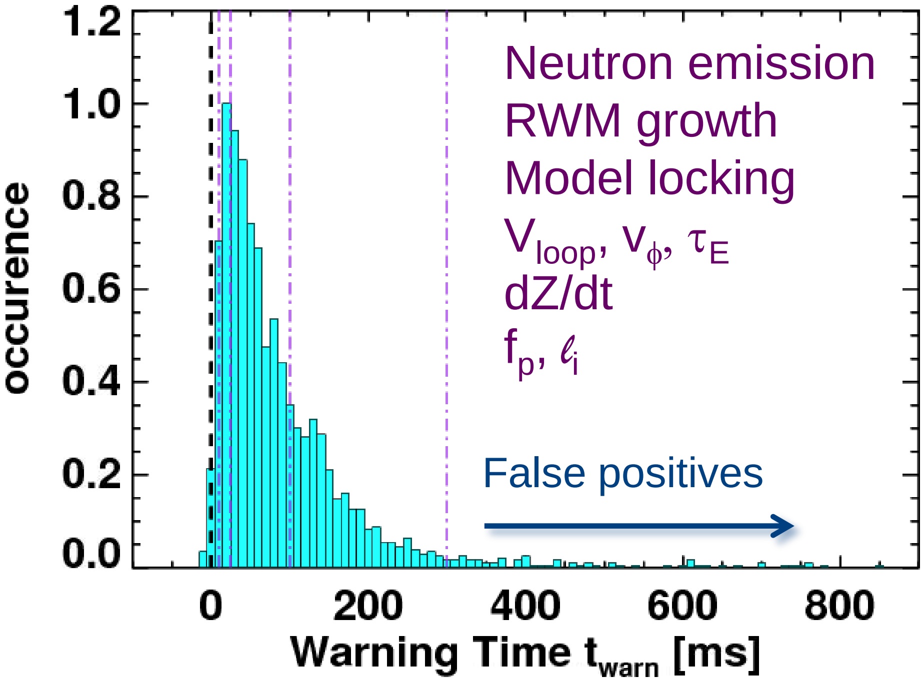
NCC options:



- Identified several off-midplane 3D coil sets favorable for profile, mode 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 (MS) 5 Year Goal:

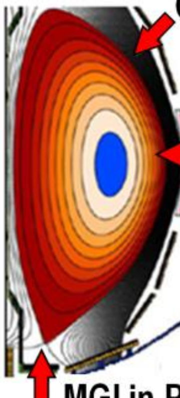
Establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

MS Thrusts:

1. Understand and advance passive and active feedback control to sustain macroscopic stability
   - Study effects of reduced ν^*, also q and rotation on LM, RWM, NTM
   - Advance RWM state-space control for EF, RWM for ITER, next-steps

2. 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

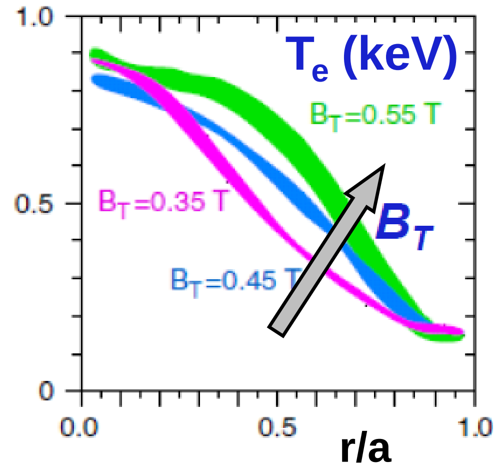
3. Understand disruption dynamics, develop prediction and detection, avoidance, mitigation
   - Enhance measurements of disruption heat loads, halos
   - Develop novel particle delivery techniques for mitigation:
     - MGI in private-flux-region (PFR), electromagnetic particle injector



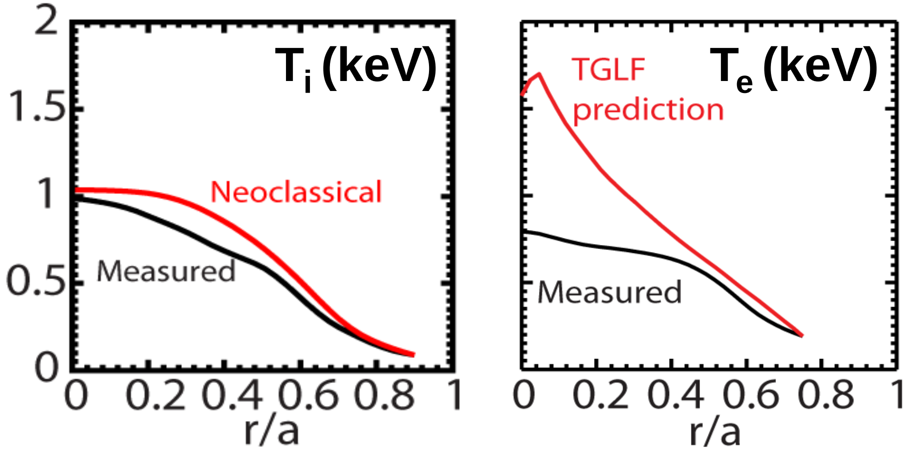
See presentations by Jack Berkery, Jong-Kyu Park

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/ν* 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



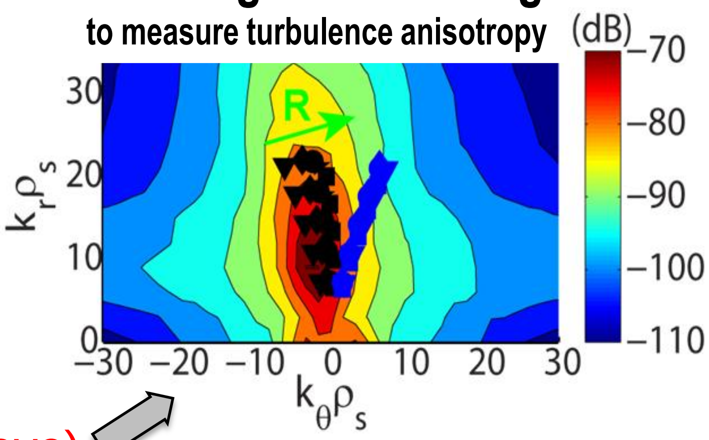
- Over-prediction of core T_e in NSTX may be due to transport from GAE/CAE modes not included in gyro-Landau-fluid model

Establish predictive capability for transport in next-step devices focusing on the ST high-β + low-collisionality regime

TT Thrusts:

1. Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U

2. 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**



3. Establish and validate reduced transport models

See presentation by Yang Ren

Highest priority research goals for 5 year plan:

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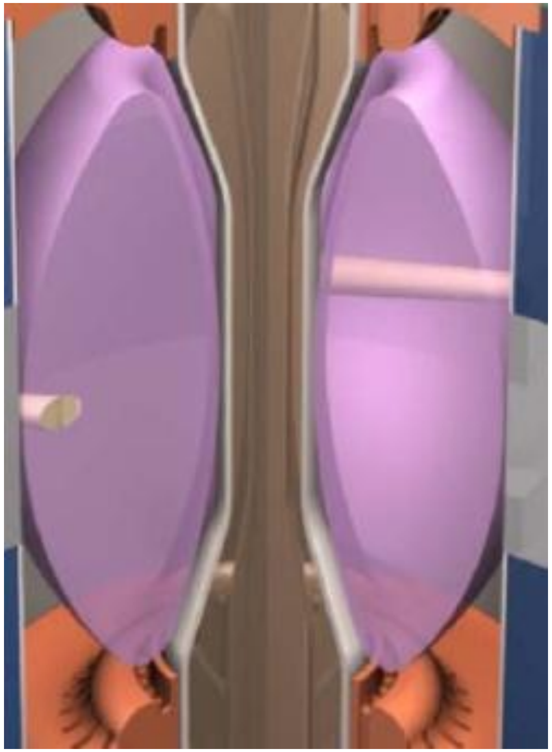
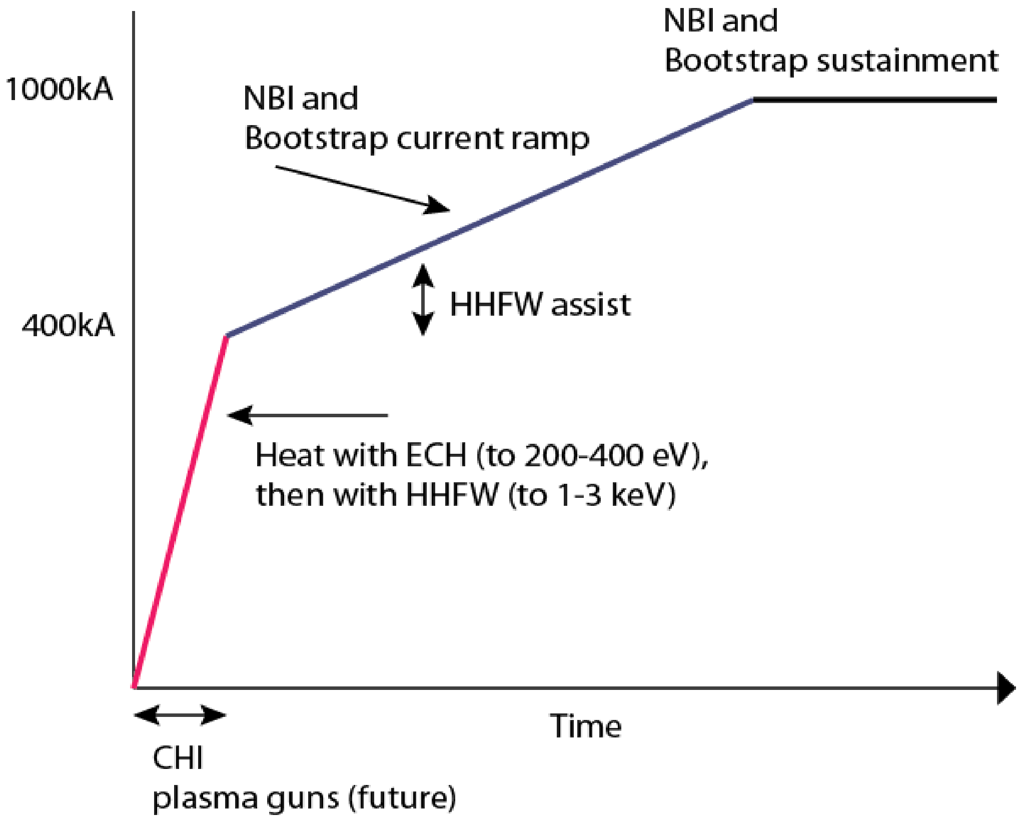
4. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

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

ST-FNSF has no/small central solenoid

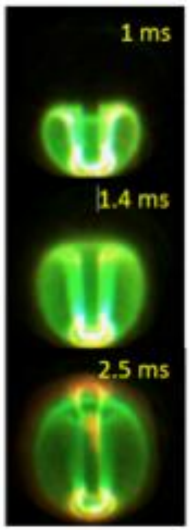


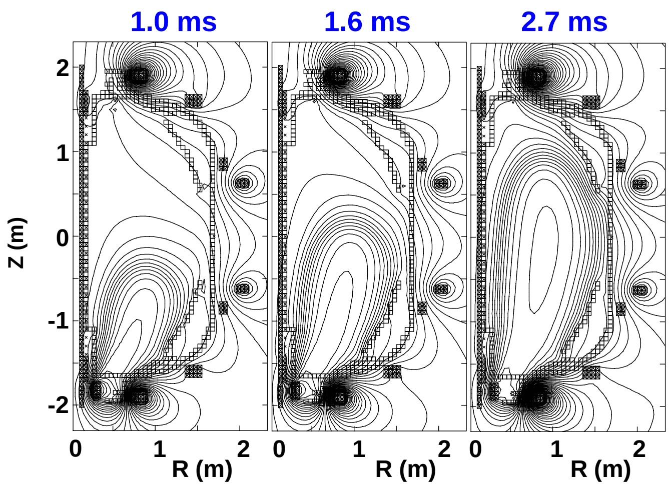
NSTX-U Non-Inductive Strategy:



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

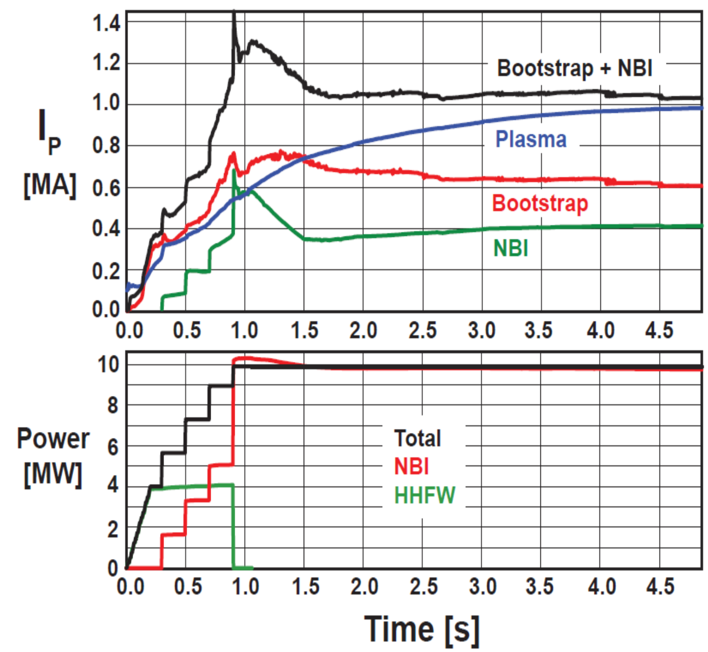
- TSC code (2D) successfully simulates CHI I_P ~200kA achieved in NSTX





- 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

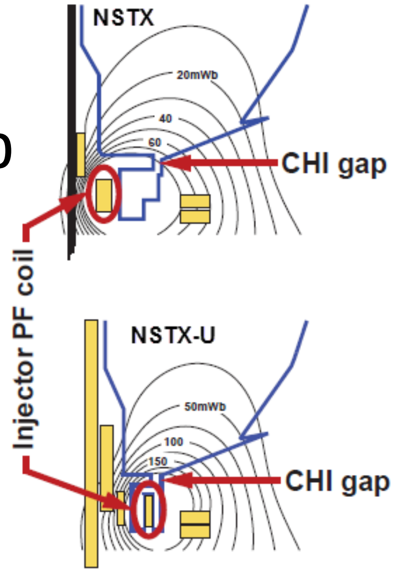


- But, RF heating (ECH and/or HHFW) of CHI likely required to couple to NBI

Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid

PSR Thrusts:

1. Initial years: Establish, extend solenoid-free plasma start-up, test NBI+BS over-drive ramp-up
   - Assess impact of new gap geometry, PF coil positions
   - Increase CHI closed-flux I_P from 200kA → 300-400kA
   - Assess NBI H&CD in 300-400kA ohmic target
   - Attempt NBI + bootstrap ramp-up: ΔI_P ~ 100-400kA

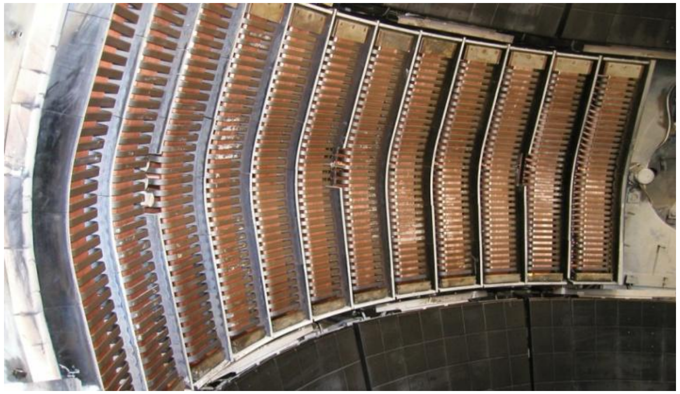


2. Later years: Ramp-up CHI plasma using ECH + HHFW + NBI, test "plasma gun" (point-helicity source) start-up
   - Maximize levels of CHI-produced I_P, extend with ECH and HHFW
   - Test NBI coupling to heated CHI, attempt full non-solenoidal start-up
   - Commission, test plasma guns (being developing on Pegasus) on NSTX-U

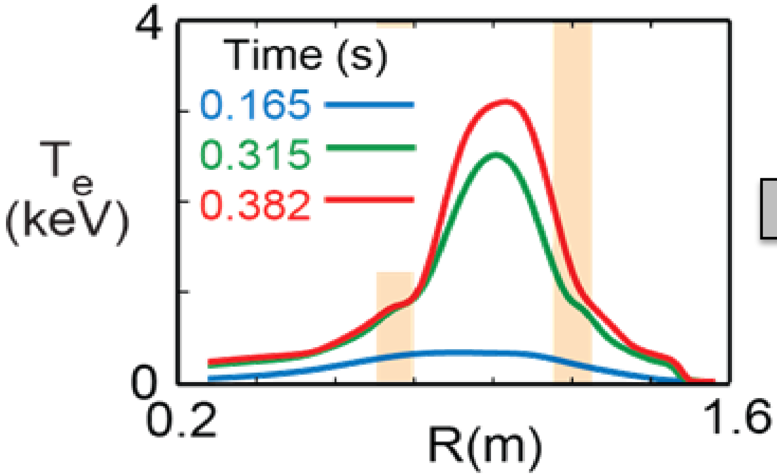
See presentation by Roger Raman

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

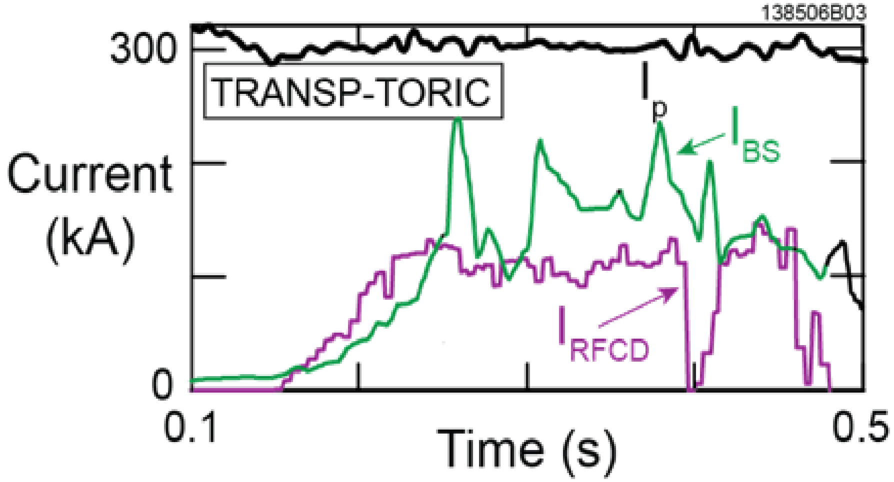
- NSTX high-harmonic fast-wave (HHFW) antenna will also be utilized on NSTX-U
  - 12 strap, 30MHz, $P_{RF} \leq$ 6MW
  - HHFW: highest ST $T_e(0)$ ~ 6keV



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



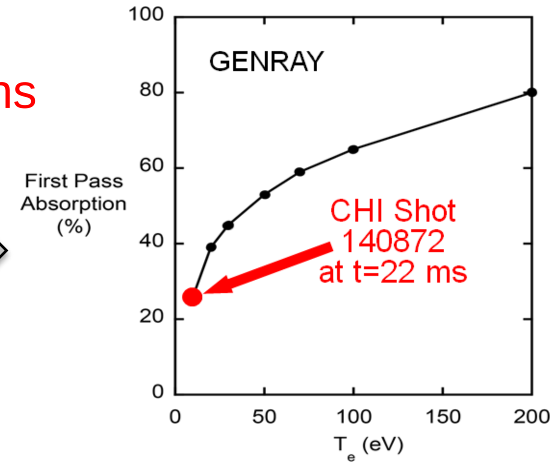
- Non-inductive fraction ≥ 70%
  - f_{BS} ~50%, f_{RFCD} ~ 20-35%



Provide and understand heating and current-drive for full non-inductive (NI) start-up and ramp-up in support of FNSF

RF Thrusts:

1. 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



2. Validate advanced RF codes for NSTX-U, predict RF performance in ITER and FNSF

See presentation by Gary Taylor

Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF

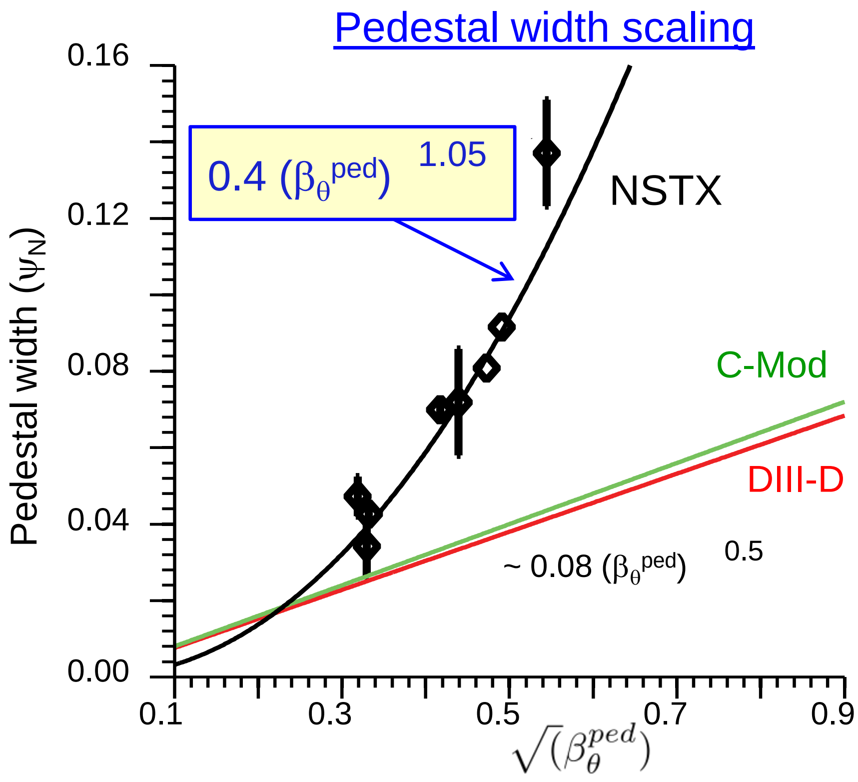
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

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

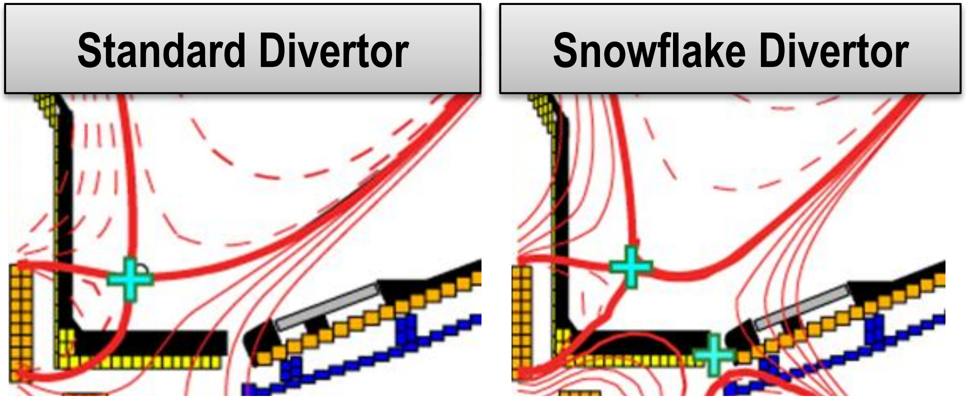
Pedestal width scaling differs from conventional aspect ratio

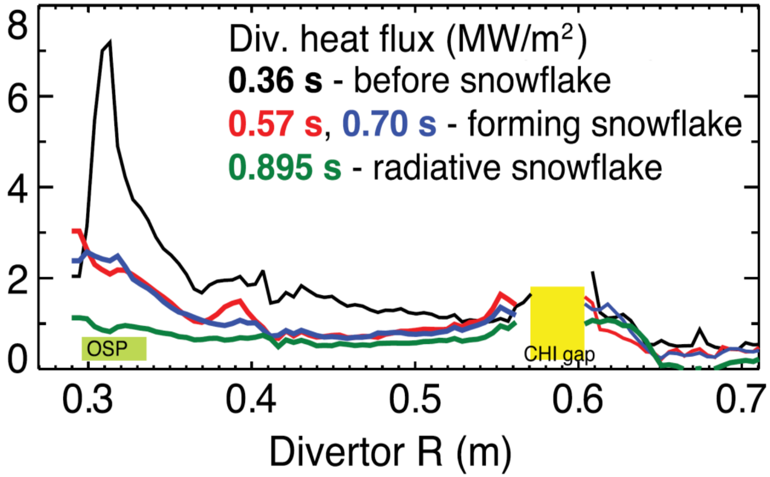


- Pedestal width scaling β_θ^α applies to multiple machines
- NSTX pedestal width is larger
  - Data → stronger scaling: ~β_θ vs. $\beta_\theta^{0.5}$
  - Preliminary EPED calculations: ~$\beta_\theta^{0.8}$
  - Measured low-k turbulence correlation lengths consistent with XGC1 predictions

Snowflake divertor effective for heat flux mitigation

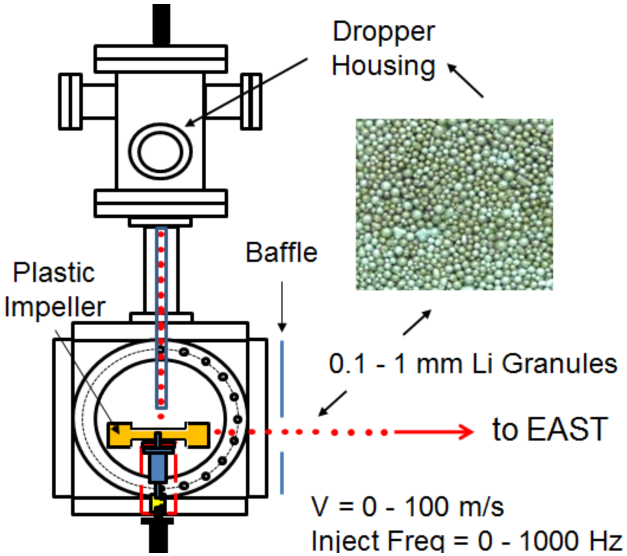
- NSTX: can reduce heat flux by 2-4 × via partial detachment
- Snowflake → additional x-point near primary x-point
  - NSTX: High flux expansion = 40-60 lowers incident $q_{\perp}$
  - Longer field-line-length promotes temperature drop, detachment



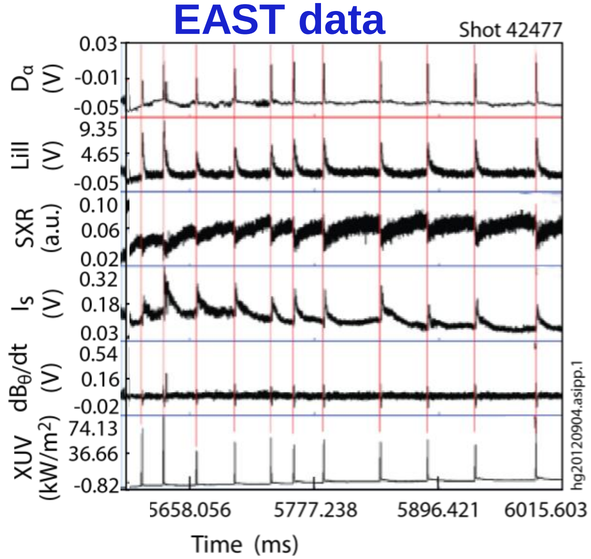


Note: X-divertor (UT-Austin) also places secondary x-point near limiter, but flares flux much farther from primary x-point and requires larger number of coils

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



EAST data



- 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

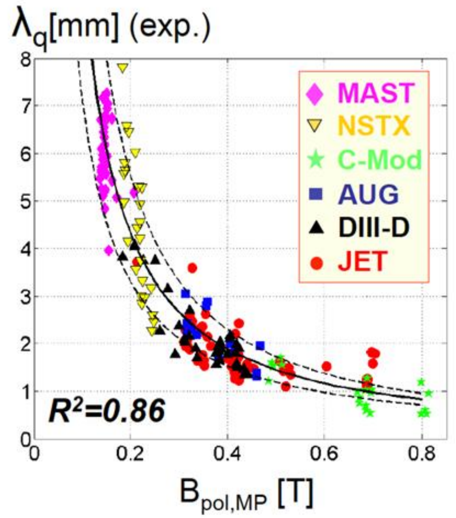
Boundary Physics (BP) 5 Year Goal:

Develop and understand integrated plasma exhaust solutions compatible with high core performance for FNSF and ITER

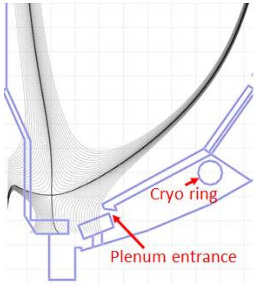
BP Thrusts:

1. Assess, optimize, control pedestal structure, transport, stability

2. 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 divertor
   - Develop highly-radiating divertor w/ feedback control
   - Assess impact of high-Z tile row(s) on core impurities

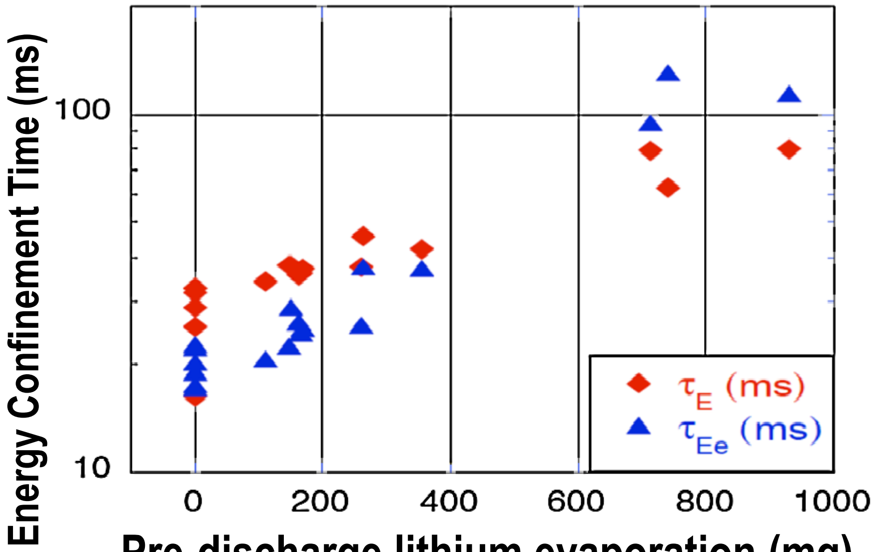


3. Establish and compare long-pulse particle control methods
   - Validate cryo-pump physics design, assess density control
   - Compare cryo to lithium coatings for n_e, impurity, ν^* control

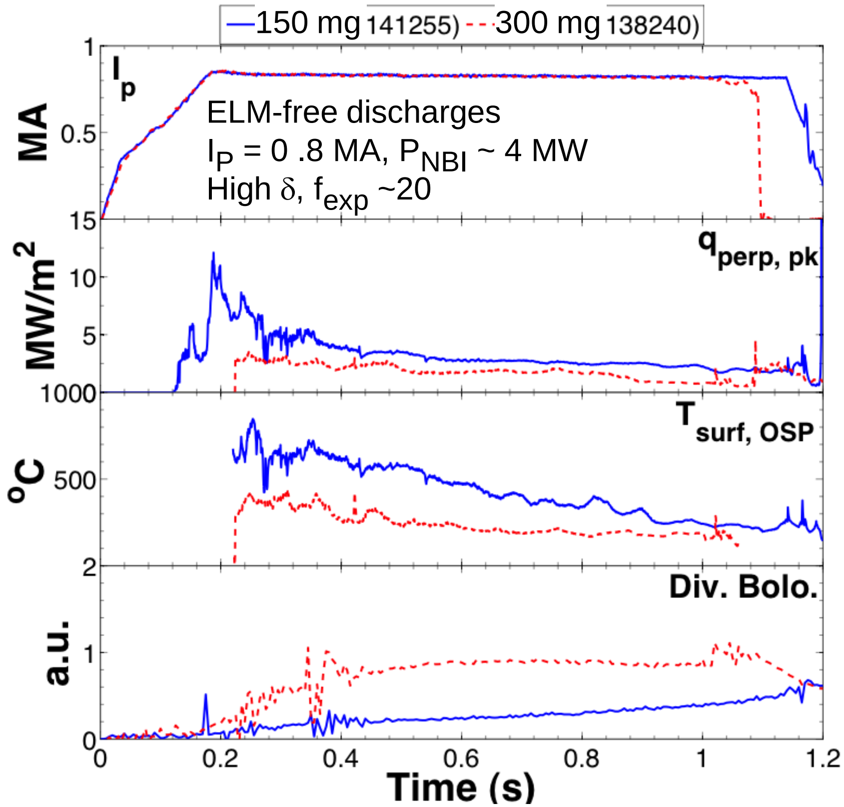


See presentations by Rajesh Maingi, Vlad Soukhanovskii

Plasma confinement increases continuously with increasing lithium coatings; Li may also be means of heat flux mitigation



R. Maingi, et al., PRL 107 (2011) 145004



- Global parameters improve
  - H98(y,2) increases from ~0.9 → 1.3-1.4
  - No core Li accumulation
- ELM frequency declines to zero
- Edge transport declines
- High τ_E critical for FNSF, next-steps

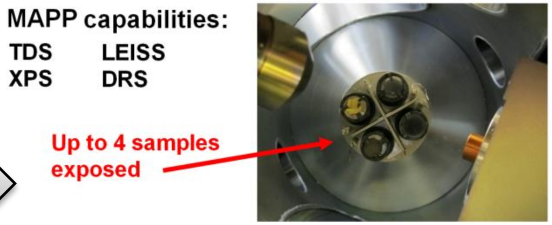
What is τ_E upper bound?

- Increased Li deposition may be advantageous for power handling
  - Lower peak divertor heat flux and $T_{surface}$
  - Increased divertor radiation
- May require threshold Li level
- Motivates “vapor-shielding” research

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

MP Thrusts:

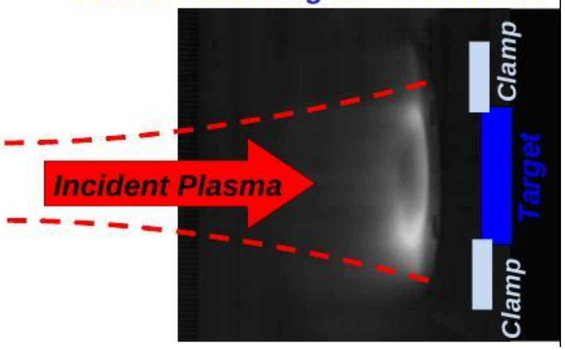
1. Understand Li surface-science at extended PFC operation
   - "Atoms to tokamaks" collaboration with PU
   - Utilize Materials Analysis Particle Probe (MAPP) to ID in-situ between-shot coating composition



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
   - Study Li vapor-shielding in linear plasma device Magnum-PSI
   - Extend Magnum results to NSTX-U

Fast-camera Image Li-I Emission



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

See presentation by Mike Jaworski

Thrusts strongly support all 5 high-level goals, but MS, TT, BP, ASC thrusts contribute most broadly

1. **Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF**

MS1	**MS2**	**MS3**	**TT1**	**TT2**	TT3	**BP1**	**BP2**	**BP3**	**MP1**	MP2	MP3	**EP1**	EP2	**RF1**	RF2	PSR1	PSR2	**ASC1**	**ASC2**	**ASC3**	**ASC4**

2. **Access reduced ν* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding**

MS1	**MS2**	**MS3**	**TT1**	**TT2**	**TT3**	**BP1**	**BP2**	**BP3**	MP1	MP2	MP3	**EP1**	**EP2**	RF1	RF2	PSR1	PSR2	**ASC1**	**ASC2**	**ASC3**	**ASC4**

3. **Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid**

MS1	MS2	MS3	**TT1**	TT2	TT3	**BP1**	**BP2**	**BP3**	**MP1**	MP2	MP3	**EP1**	EP2	**RF1**	**RF2**	**PSR1**	**PSR2**	**ASC1**	**ASC2**	ASC3	ASC4

4. **Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes**

MS1	MS2	MS3	**TT1**	**TT2**	TT3	**BP1**	**BP2**	**BP3**	**MP1**	**MP2**	MP3	EP1	EP2	RF1	RF2	PSR1	PSR2	**ASC1**	**ASC2**	ASC3	ASC4

5. **Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps**

MS1	MS2	MS3	**TT1**	TT2	TT3	**BP1**	**BP2**	**BP3**	**MP1**	**MP2**	**MP3**	EP1	EP2	RF1	RF2	PSR1	PSR2	**ASC1**	**ASC2**	ASC3	ASC4

Summary: NSTX-U 5 year plan will make leading contributions to fusion science, next-step applications

- **Provides ST basis (and assists AT) for FNSF and for ITER**
  - Actuators + controls for 100% non-inductive at high confinement, β
  - Non-inductive formation and ramp-up - needed for ST, benefits AT
  - Disruption warning/detection, novel disruption mitigation

- **Novel plasma-material-interface solutions for next-steps**
  - Lead "snowflake" development, combine with radiation/detachment
  - Lead in liquid metals for recycling/erosion control, vapor-shielding

- **Unique contributions to toroidal predictive capability**
  - Non-linear AE instabilities relevant to ITER burning plasmas/DEMO
  - High β + low ν EM-effects on transport
    - Example: micro-tearing relevant to ST, potentially relevant to ITER pedestal

Mapping of presentations to charge questions

Summary of presentation content to aid addressing review charge question 1

1. **Assess the scientific and technical merit of the ongoing and planned research**
   a) Does the proposed research effectively address important issues in plasma and fusion energy science and technology at the forefront of the field e.g., those issues described in the FESAC reports:
      i. Research Needs for Magnetic Fusion Energy (2010)
      ii. Priorities of the Magnetic Fusion Energy Science Program (2013)?
   b) How well does the proposed research compare with that carried out at other U.S. and foreign tokamak facilities, both in terms of merit and originality?
   c) How well does it maintain a U. S. leadership position in key areas of fusion research?
   d) What is the likelihood that the research will lead to new or fundamental advances in fusion science and technology?

Menard backup

Kaye, Maingi, Soukhanovskii

Menard, All

Summary of presentation content to aid addressing review charge question 2

2. Comment on the appropriateness of the proposed research plan.

a) Is the proposed plan adequately developed and likely to lead to scientifically valid conclusions?

b) Does the proposed research employ innovative concepts or methods, and are potential problems identified along with appropriate mitigation strategies?

c) Assess the strengths of the program w.r.t. manpower development through graduate student training.

All

Ono

Summary of presentation content to aid addressing review charge question 3

3. **Evaluate the competency of the proposed senior research personnel, adequacy of the proposed research environment & resources.**
   a) How well qualified are the applicant's personnel to carry out the proposed research? — Ono
   b) Does the proposed work provide for an:
      i. adequate set of diagnostics, necessary facility upgrades — Ono
      ii. interactions with theory and modeling — All, Bhattacharjee
      iii. collaborations involving a broad group of domestic and international users? — Menard & backup, Plan Chapter 11
   c) Assess the program's governance practices and the performance of the program management team, as well as the support to collaborators provided by PPPL. — Menard backup – governance section
   d) How well do the collaborative arrangements achieve the goal of an integrated research team? — All, Menard backup, Plan Chapter 11

Summary of presentation content to aid addressing review charge question 4

4. **Assess the reasonableness of the proposed costs for fusion research and facility operations.**
   a) The cost review should be done at a summary type level, examining major items and using projections from ongoing operational experience.
   b) Does the technical proposal call for the equipment and components, labor skill mix, and hours set forth in the summary cost information, and are these reasonable to carry out the proposed research?
   c) Are the overall proposed costs reasonable? (Please note that the cost details of the proposal will also be reviewed separately by DOE. However, we are interested in hearing your views on this topic.)

Ono, Ono backup

Summary of presentations and documents to aid addressing review charge question 5

5. **Assess the performance of the NSTX research team during the previous five-year period.**
   a) Were research and diagnostic milestones met? — Ono backup
   b) Were NSTX research results appropriately disseminated, and are they having an impact on the international fusion effort? — Ono, Publication Listings
   c) How well did the NSTX team compare theory and experiment to further the FES goal of improving predictive modeling? — All, Bhattacharjee

Also, assess the plans for NSTX Upgrade facility operations (at a top level)

   d) Are planned operating, maintenance, repair and upgrade schedules appropriate to support the planned research program?
   e) Are environment, safety, health and quality assurance matters being given appropriate priority?

   (d, e) — Ono, Ono backup

Supplementary Material

Governance

NSTX-U

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

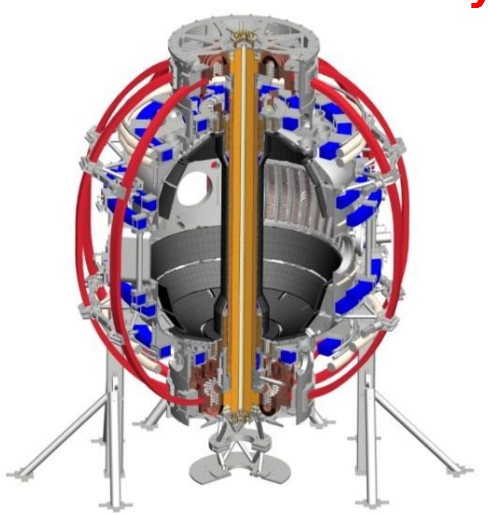
NSTX-U Program Governance, Collaborator Support, Research Planning Process

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

Jon Menard and Masa Ono (PPPL)

NSTX-U Program and Project Directors

NSTX-U 5 Year Plan Review
LSB B318, PPPL
May 21-23, 2013



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
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

Outline and relationship to review charge

- NSTX-U Organization
- Support from PPPL

Evaluate the competency of the proposed senior research personnel and the adequacy of the proposed research environment and resources

- Role of collaborators

How well do the collaborative arrangements achieve the goal of an integrated research team?

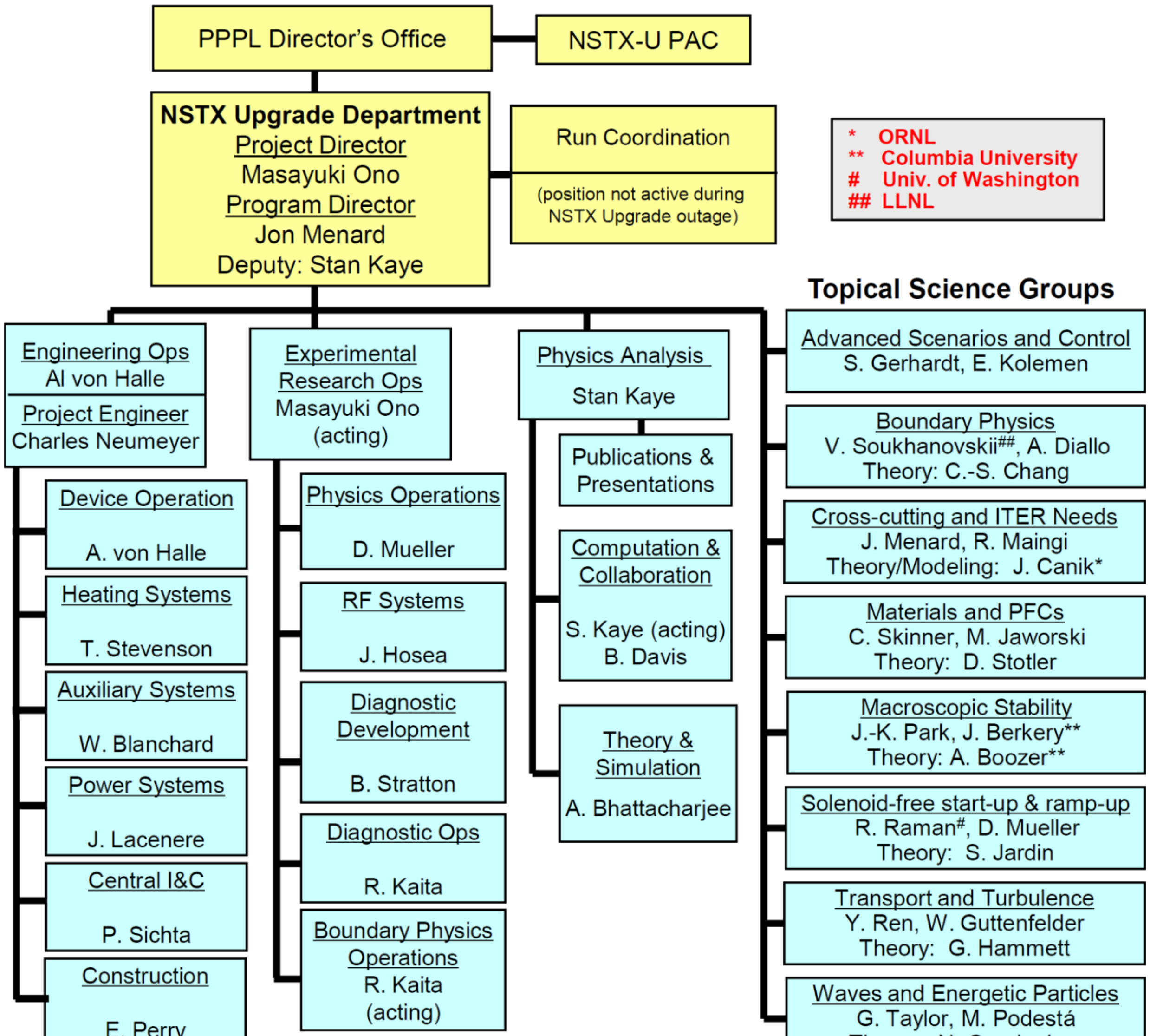
- Developing the research program
  - Research priorities and major directions
  - Formulating annual research plan
  - Developing and executing experiments

Assess the program's governance practices and performance of program management team, and support to collaborators provided by PPPL

- Milestone performance history
- Scheduling operation, maintenance & upgrades
- Managing environment, safety & health concerns

Assess the current **performance** of **facility operations at a top level**

NSTX-U Organization within PPPL



NSTX-U Organization – 2013

NSTX-U continues extensive collaborator involvement

- Collaborations involve a broad group of domestic and international users
  - Collaborators were involved in originally proposing, designing NSTX
  - Many diagnostic systems are built and operated by collaborators
- DOE annually solicits proposals for collaboration with NSTX
  - Both new proposals and renewal of existing collaborations
  - Collaborations are competitively peer-reviewed on a 3-4 year cycle
- Collaborators participate fully in the research program
  - Meetings of research team to plan upgrades and research
  - Proposing, developing and executing experiments
  - Reviewing, analyzing and discussing results
  - Publishing and presenting the results of their work

All NSTX-U collaborations are governed by documented agreements reviewed by Program and Project directors

- Record of Discussion
  - Results of discussions between prospective collaborators and an NSTX-U Research Contact in support of proposals submitted to DOE
  - Includes goals of research, describes on- and off- site components of work involved and estimates of support required from NSTX
- Record of Agreement
  - Describes agreed commitments of resources, equipment and facilities by a collaborating institution and NSTX-U
- Data Usage Agreement
  - Governs access to and publication of data
  - Provides for project and peer review of external publications
  - Policies for access to, use, and publication of NSTX-U data are the same for PPPL staff and collaborators

Development of the NSTX-U Research Program

- Guided by NSTX-U 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

  and evolving device and diagnostic capabilities

- Research Milestones and plans for facility enhancements are:
  - Developed by NSTX-U program and project leadership in discussion with Topical Science Group leaders
  - Reviewed by the NSTX-U Program Advisory Committee (PAC)
  - Agreed with DOE as part of the Field Work Proposal (FWP) process
  - Complemented by Facility and Diagnostic Milestones

Topical Science Groups (TSGs) play major role in governing the research program

- Lead brainstorming, organization, writing of 5 year plan
- Determine and address highest priority scientific issues through discussion and consensus at open meetings
- Organize the NSTX-U Research Forum sessions for the TSG
- Draft scientific milestones utilizing expertise of the TSG
- Propose and execute experiments to achieve milestones and address priorities
- Define facility and theory resources to achieve research goals
- Aid dissemination of results with Physics Analysis Division
  - Journal publications, invited talks, seminars, colloquia, conferences, ITPA, BPO
- Provide summaries of scientific progress at NSTX-U team meetings and other venues to promote discussion
- Assist and report to the NSTX-U Program and Project directors

Annual NSTX-U Research Forum provides all team members opportunity to propose experiments

- Held at PPPL over 2 ½ days ~3-6 months before start of experiments
  - Involves wide participation, both on-site and by web + teleconference
- **Follows an open invitation to submit ideas for experiments**
  - Provided guidance from TSG Leaders on 1-2 highest priority themes for each topical area
- In opening plenary session, NSTX-U Program Director provides initial guidance on runtime allocation
  - Based on: milestones, facility development, ITER needs, contingency
- Includes presentations from other facilities (e.g. DIII-D, MAST, EAST)
- Proposals for experiments discussed and prioritized by TSGs:
  - Opening and summary plenary sessions, 3-4 parallel break-out sessions
  - TSGs asked to identify gaps, overlaps and combine if appropriate
- Final plenary session reviews recommended prioritized experiments from TSGs and plans for developing Experimental Proposals (XPs)

NSTX-U experimental proposals guide usage of facility during experimental operation

- Experimental Proposals (XPs) are documents describing:
  - Justification for the experiment and that it is well suited to NSTX
  - The plan for executing the required shots and scans efficiently
  - The required machine and diagnostic capabilities
  - Plans for analysis, reporting, and publication of the results
- XPs are discussed in TSG meetings and recommended for review by the research team led by the Run Coordinator
  - All meetings are open and accessible by web + telecon from off-site
  - Review "chits" may be submitted, pointing out deficiencies and/or recommending changes to improve the experiment
- Final version is approved, posted on the Web and a formal "run copy" is prepared when the experiment is scheduled
- NSTX-U also provides Experimental Machine Proposals (XMPs) which are used to commission new systems or capabilities
  - Reviewed and approved by Experimental Research Operations

Results and analysis of experiments are presented to and discussed by the whole team

- 5:00pm “end of run-day” meeting
  - Progress on performing the plan, very preliminary highlights of data
- Weekly Physics Meeting (Monday afternoons at 1:30PM)
  - Preliminary analysis
- Mid-run Assessment
  - Progress towards meeting milestones
  - Needs for additional runtime to complete experiments
  - Need for experiments not foreseen at Research Forum
- Annual Results Review
  - Progress towards comprehensive analysis and conclusions
  - Plans for publication
- Annual Run Assessment
  - Discussion of successes and difficulties encountered
  - Generate, log, and track suggestions to improve planning and execution of experiments, communication

All meetings are accessible by web + teleconference

In 2008, the NSTX team performed 43 experimental proposals

- 12 Experimental Machine Proposals were also performed
- Run lasted from Feb 18 through July 14 (21 calendar weeks)
- Included 4 scheduled maintenance weeks, 4 days unscheduled maintenance time and 2 holidays
  - Scheduled maintenance to avoid running during major meetings
- Achieved 16.6 run weeks, exceeding milestone target of 15
- Schedule for experiments in the next 1 - 2 weeks is developed at a weekly Program/Operations meeting chaired by Run Coordinator
  - Adapt schedule to evolving status and availability of facility, heating systems, diagnostics, collaborator travel *etc.*
  - Meeting is accessible by web + teleconference, schedule is posted on web and updated as conditions change
  - Schedule up to 4 experiments (XPs and/or XMPs) on each run day
- Daily plan discussed at “8:30am Meeting” and summarized in an email distributed widely

Maintenance, repair and upgrade activities are carefully planned and managed

- PPPL Work Planning system used to approve and track progress on major activities and upgrades
- Work Permits used to maintain configuration control and proper work practices in NSTX Test Cell
  - Requirements for procedures and permits (*e.g.* RWP)
  - Provides record for checks of area before resuming operation
- Specific training required for both PPPL and collaborator staff to work in the NSTX Test Cell
  - General Employee Training
  - Radiation Safety Training
  - Lockout/Tagout (Control of Energy Sources)
  - Basic Electric Safety
  - Knowledge of applicable Administrative Procedures
- Periodic Preventive Maintenance is performed on critical systems
  - On-Line Management System is being implemented

Attention to Environment, Safety and Health central to NSTX planning, maintenance, and operation

- DOE Integrated Safety Management is used throughout PPPL to integrate safety into all work planning and execution
- ES&H is a line management responsibility
  - e.g. performing regular safety walkthroughs & work observations
- A Safety Assessment Document is maintained for NSTX
  - Identifies hazards of systems and components
  - Addresses design features & administrative controls to mitigate hazards
  - Provides detailed FMEA of NSTX systems
- Work on NSTX performed using Job Hazard Analyses (JHAs).
- Targeted safety inspections conducted by NSTX Activity Certification Committee for new/modified installations with safety implications
- Safety issues are presented and discussed all Team Meetings
- NSTX received a special NJ State award in March 2008 for working 7 consecutive years (1/1/01-12/31/07) without an away-from-work case

Summary: NSTX-U provides an open, productive, and safe research environment for all team members

- Drawing on highly qualified staff from PPPL and a broad group of domestic and international collaborators, NSTX/NSTX-U has created a well integrated research team to exploit its unique facilities
- Governance practices are designed to promote collaborative research
  - Open access to meetings, data, presentations and documents
  - Allocation of experimental runtime is through an open process
- Topical Science Groups provide scientific leadership for NSTX research
  - Approximately 1/3-1/2 of the TSG leaders are collaborators
  - Approximately half of invited talks and publications led by collaborators
- PPPL provides resources and support to promote NSTX-U research
- Detailed planning and control are applied to ensure that operation is efficient and that commitments are met
- NSTX/NSTX-U has consistently achieved its operational goals and its milestones for science, facility upgrades, and diagnostic development
- Processes have been established to promote continuous improvement
- There is a strong focus on safety, well supported by PPPL management

Supplementary Material

Support of ReNeW Thrusts

NSTX-U research strongly supports ReNeW Thrusts

ITER burning plasma (1-4), creating & predicting high-performance/steady-state (5-8)

1. Develop measurement techniques to understand and control burning plasmas
   – Developing MSE-LIF diagnostic to measure |B| to constrain q(r) + total pressure profile w/o heating NBI
2. Control transient events in burning plasmas
   – Extend development of advanced high-β MHD mode-ID and state-space feedback control techniques
   – Achieve ELM suppression and/or triggering with lithium coatings and granules, 3D fields
3. Understand the role of alpha particles in burning plasmas
   – Vary $f_{NB}(v)$, multi-mode *AE fast-ion transport + full profile/fast-ion diagnostic set + theory/modeling
4. Qualify operational scenarios and the supporting physics basis for ITER
   – Assess transport processes during current ramp-up – both inductive and non-inductive
   – Extend extensive studies of H-mode threshold scalings and physics to higher B_T, I_P, P_{aux}, lower ν^*
   – Use high-power HHFW to study H-mode confinement with dominant e-heating, low torque input
   – Improve understanding of unique low-A, high-β H-mode pedestal structure, turbulence, transport

5. Expand the limits for controlling and sustaining fusion plasmas
   – NSTX-U targeting fully-non-inductive high-β_T (10-20%) plasmas with q and rotation profile control
6. Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement
   – Provide unique low-A, low ν^*, high-β, high v_{fast} / $v_{Alfvén}$ data to challenge wide range of theory, simulations
7. Exploit high-temperature superconductors, magnet innovations to advance fusion research
8. Understand highly integrated dynamics of dominantly self-heated/sustained burning plasmas

NSTX-U research strongly supports ReNeW Thrusts

Taming the PMI (9-12), harnessing fusion power (13-15), configuration optimization (16-18)

9. Unfold the physics of boundary layer plasmas
   - Provide unique low-A, high-β data on SOL/divertor widths/transport and turbulence (GPI, BES)
   - Exploring/understanding fast-wave antenna coupling to edge, power loss to divertor
10. Decode and advance the science and technology of plasma-surface interactions
    - Leaders in exploration of lithium PFCs, will extend to high-power, long-pulse, vapor-shielded regimes
11. Improve power handling through engineering innovation
    - Advanced radiative + high-flux-expansion divertors + static/flowing liquid Li at high power density
12. Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma
    - Will test integration of liquid metal and high-Z PFCs, radiation, snowflake with high performance core
13. Establish the science and technology for fusion power extraction and tritium sustainability
14. Develop the material science and technology needed to harness fusion power
15. Create integrated designs and models for attractive fusion power systems
    - A world-leader in informing physics basis and design of low-A fusion power systems
16. Develop the spherical torus to advance fusion nuclear science
    - NSTX-U is lead U.S. ST program and facility covering extensive range of ST research topics
17. Optimize steady-state, disruption-free confinement w/ 3D shaping, emphasizing QS
    - Providing unique ST data and understanding of how 3D fields influence core/edge transport/stability
18. Achieve high-performance toroidal confinement w/ minimal externally applied magnetic field

Supplementary Material

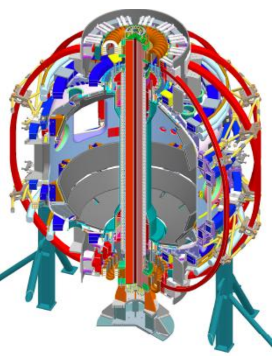
5-10 year plan goals and tools

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



Start-up and Ramp-up
- Increase CHI closed-flux current
- Achieve NI start-up/ramp-up
- Assess plasma gun start-up at increased device size
- Develop/understand ECH/EBW H&CD for ST
- 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

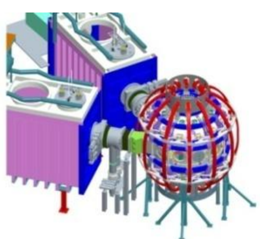
Liquid metals / lithium
- Establish low impurities / Z_{eff}, assess increased Li coverage, replenishment
- Test flowing liquid metal for heat-flux mitigation, surface replenishment
- Assess flowing LM PFC with full toroidal coverage

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



2nd NBI

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

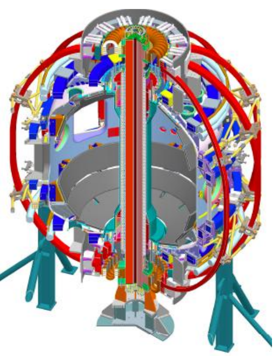
10 year plan tools with 5YP incremental funding

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

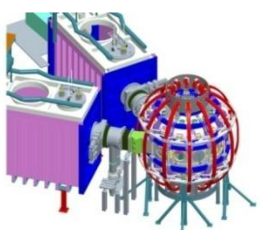
MHD
- MGI disruption mitigation
- Partial NCC
- Enhanced MHD sensors
- NCC SPA upgrade
- Full NCC

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
- HHFW straps to excite EHO
- High-power AE antenna
- Charged fusion product, neutron-collimator

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**

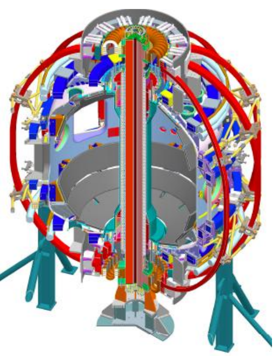


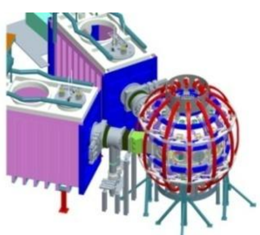
2nd NBI

5 year plan tools with 5YP base funding

(FY2012 + 2.5% inflation)

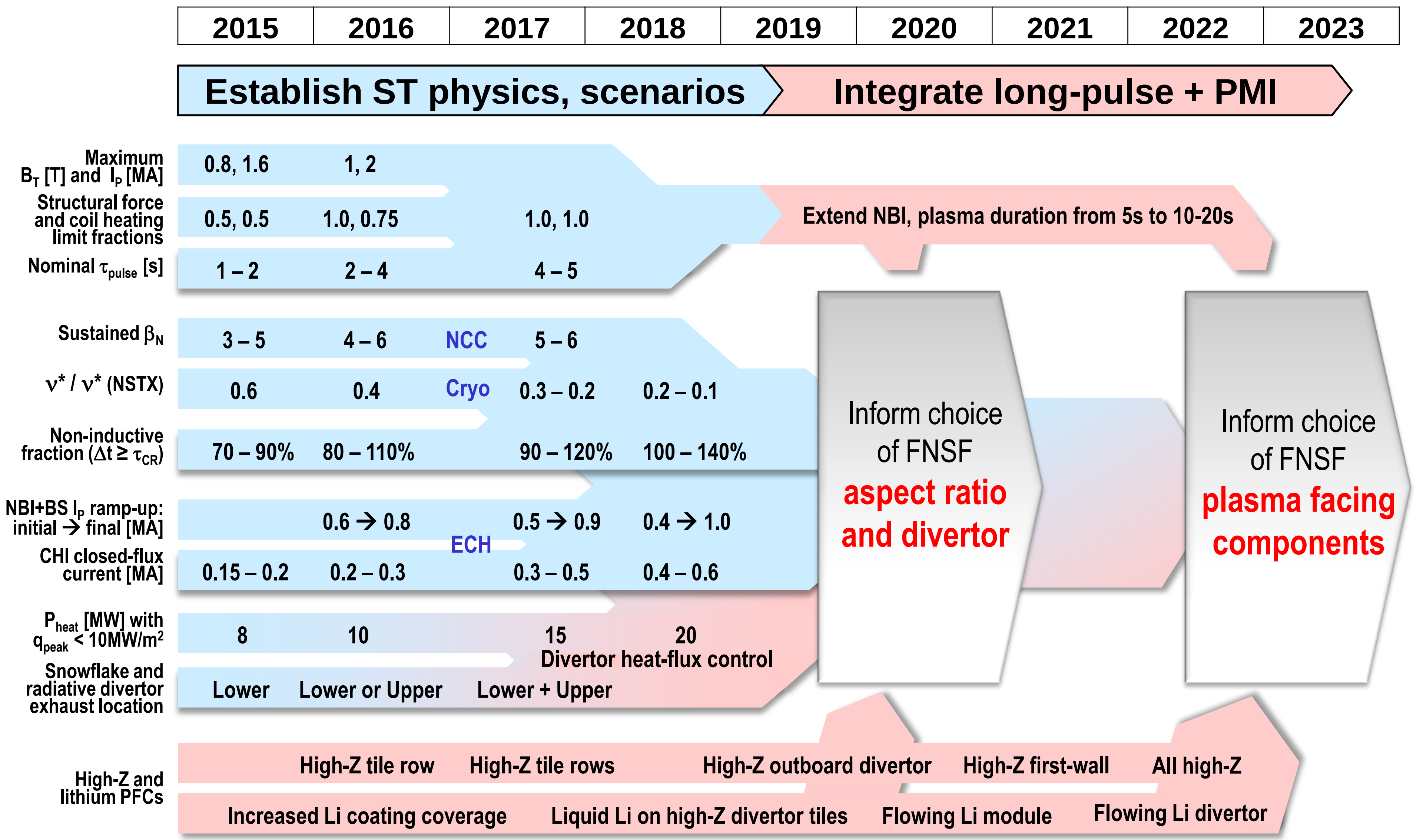
	2014	2015	2016	2017	2018
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		16	14	14	16
Start-up and Ramp-up		Upgraded CHI for ~0.5MA	1 MW ECH/EBW	up to 0.5 MA plasma gun	
Boundary Physics			Lower divertor cryo-pump		High-Z PFC diagnostics
Materials and PFCs		High-Z tile row on lower OBD	High-Z tile 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		1 coil AE antenna; 4 coil AE antenna	Charged fusion product		
Scenarios and Control		Establish control of: Snowflake, $\bar{n}_e$, Rotation		q_{min}	Divertor P_{rad}





- 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

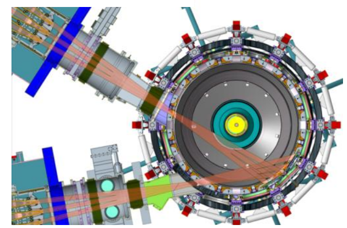


NSTX-U five year plan utilizes cross-cutting set of existing/early tools + additional facility enhancements

Requirements for next-step STs:

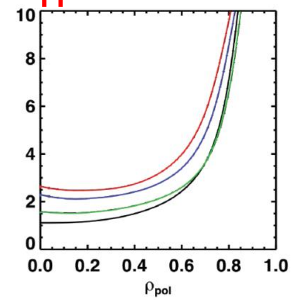
- **Full non-inductive (NI) current drive for steady-state operation**
  - Including NI start-up/ramp-up
- **High confinement to minimize auxiliary heating, device size**
- **Sustained high β to minimize magnet size, forces, power**
- **Divertor/first-wall survival with intense power/particle fluxes**

Present NBI



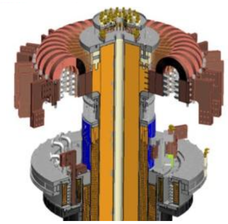
New 2nd NBI → 2 × P_{NBI}

q profile control



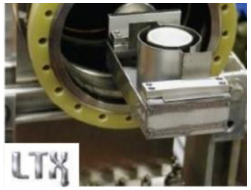
28 GHz, 1-2MW Gyrotron

ECH / EBW for start-up (Longer-term: EBW H&CD)

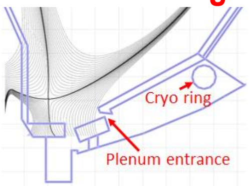


New CS: 2 × B_T, I_P
5 × longer pulse

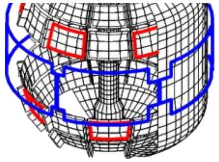
Vary PFC Li coverage to vary recycling, p(ρ), τ_E

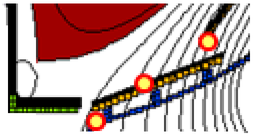


Cryo-pump for D, n_e, ν* control w/o Li coatings

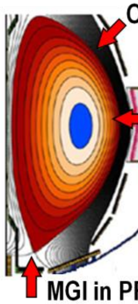


Midplane + off-midplane non-axis. control coils (NCC) for EFC, RWM, ELM-RMP, NTV



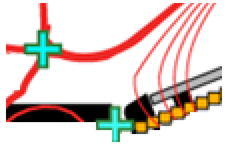


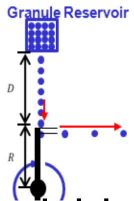
Extended low-f MHD sensor set



Off mid-plane MGI
mid-plane MGI
MGI in PFR

Snowflake divertors + partial detachment





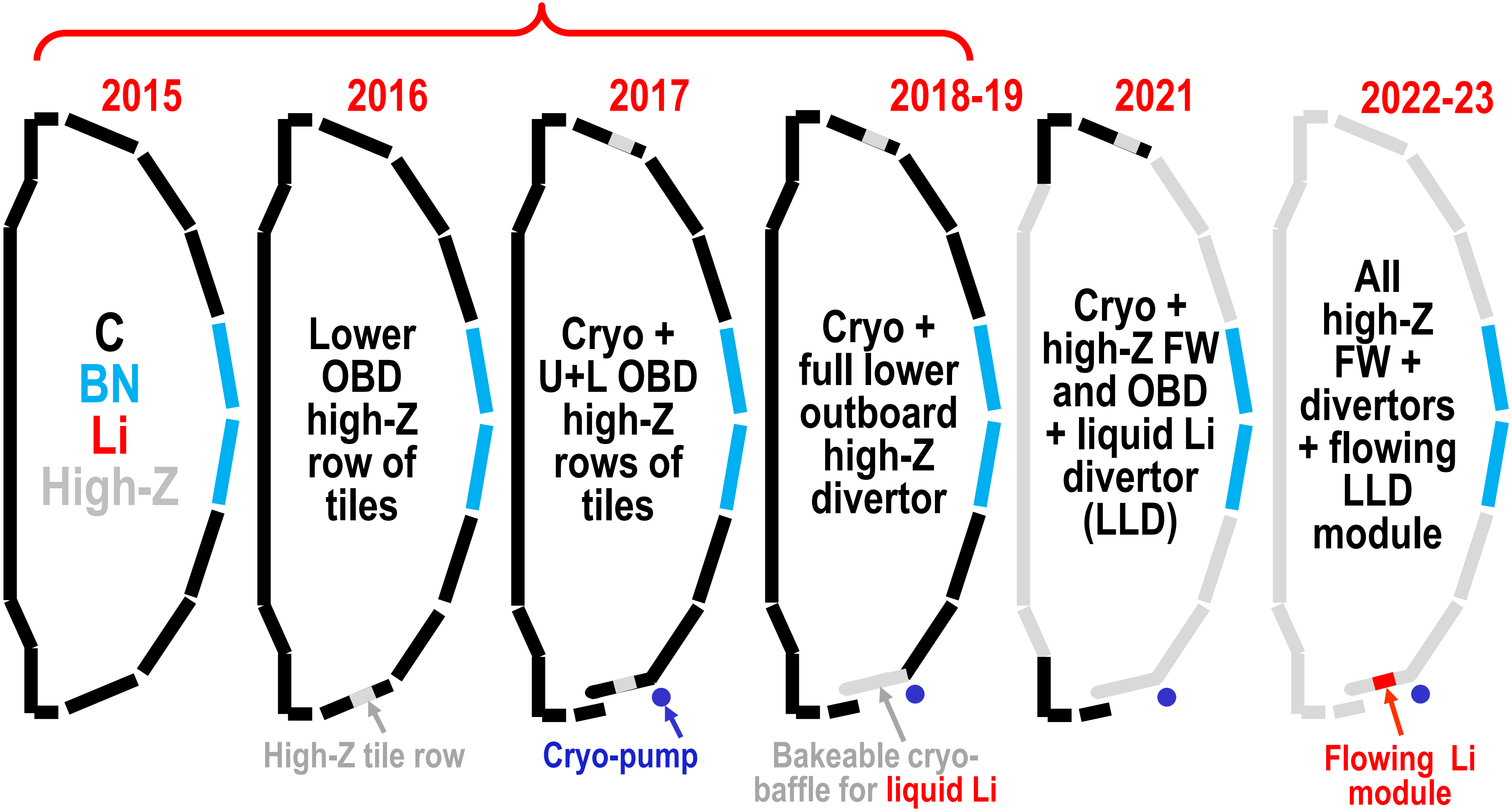
Li granule injector (LGI) for ELM pacing

Erosion & shielding of high-Z tiles + Li

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

Base budget case

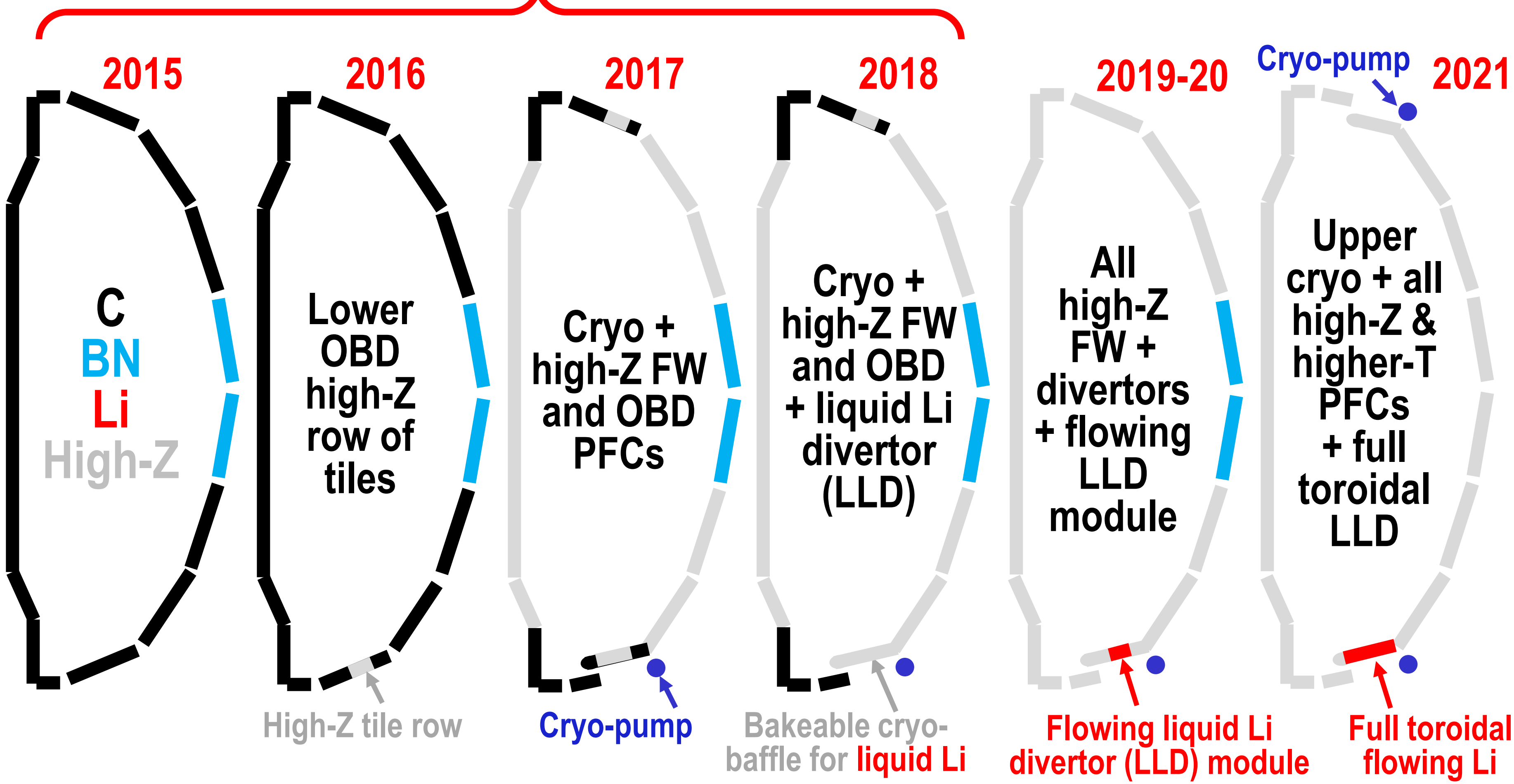
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



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



Base 5 year plan funding provides run-time and field + current to exploit new Upgrade capabilities

	FY2013	FY2014	FY2015
Expt. Run Weeks:	0	0	16
Macroscopic Stability		R14-1 **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	R13-1 **Perform integrated physics+optical design of new high-k_θ FIR system**		R15-1 **Assess H-mode τ_E, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}** (with BP, M&P, ASC, WEP TSGs)
Boundary Physics			
Materials & PFCs	R13-2 **Assess relationship between lithium-conditioned surface composition and plasma behavior**		
Waves+Energetic Particles	**Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios** R13-3	R14-2 **Assess reduced models for *AE mode-induced fast-ion transport**	R15-2 **Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile** (with SFSU, MS, ASC TSGs)
Solenoid-free Start-up/ramp-up			
Adv. Scenarios and Control		R14-3 **Assess advanced control techniques for sustained high performance** (with MS, BP TSGs)	R15-3 **Develop physics+operational tools for high-performance discharges** (with CC, ASC, MS, BP, M&P TSGs)
ITER Needs + Cross-cutting	R13-4 **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks**	**TBD**

Incremental funding accelerates snowflake + start-up/ramp-up research for FNSF, fully utilizes facility during 1st year of ops

	FY2013	FY2014	FY2015
Expt. Run Weeks:	0	0	20
Macroscopic Stability		R14-1 **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	R13-1 **Perform integrated physics+optical design of new high-k_θ FIR system**		R15-1 **Assess H-mode τ_E, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}** (with BP, M&P, ASC, WEP TSGs)
Boundary Physics			**Develop snowflake configuration, study edge and divertor properties** (with ASC, TT, MP) IR15-1
Materials & PFCs	R13-2 **Assess relationship between lithium-conditioned surface composition and plasma behavior**		
Waves+Energetic Particles	**Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios** R13-3	R14-2 **Assess reduced models for *AE mode-induced fast-ion transport**	R15-2 **Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile** (with SFSU, MS, ASC TSGs)
Solenoid-free Start-up/ramp-up			**Assess CHI & low-I_P FW heating at higher B_T, test NBI+BS I_P ramp-up** (with WEP, ASC TSGs) IR15-2
Adv. Scenarios and Control		R14-3 **Assess advanced control techniques for sustained high performance** (with MS, BP TSGs)	R15-3 **Develop physics+operational tools for high-performance discharges** (with CC, ASC, MS, BP, M&P TSGs)
ITER Needs + Cross-cutting	R13-4 **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks**	**TBD**

Supplementary Material

Support of ITER, predictive capability, and FNSF

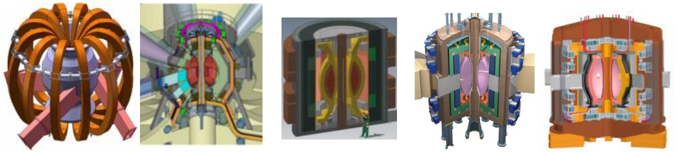
NSTX has made, and NSTX-U will continue to make substantial contributions to ITER

- **MS:** Plasma response effects in error field correction, kinetic effects on RWM, mode control and NTV, physics-based disruption warning system, novel disruption mitigation tests
- **TT/BP**: ELM pacing with 3D fields (future: possible suppression or triggering w/ 3D fields or granules), impurity transport, SOL heat-flux-width scaling, divertor detachment physics
- **EP**: Non-linear *AE avalanche dynamics and fast-ion transport + transport by 3D fields – highly relevant to burning plasmas
- **RF**: Power coupling, edge power loss, interactions w/ fast-ions
- **ASC**: Advanced integrated plasma control, contributions to disruption prediction-avoidance-mitigation framework

Unique physics regimes + advanced diagnostics strongly support predictive capability development

- **MS**: Kinetic MHD for RWM stability, plasma response and momentum transport from 3D fields (MISK, IPEC, POCA, VALEN, …)
- **TT**: High-β/electromagnetic effects on electron transport from micro-tearing and Alfvenic instabilities (GYRO, GTS, …, HYM, ORBIT)
- **BP/MP**: Edge kinetic neoclassical & turbulent transport (GENE, GS2, XGC0-1), SOL turbulence (SOLT), snowflake/detachment: neutrals, impurities (UEDGE, SOLPS, BOUT++, EIRENE, DEGAS2, DIVIMP)
- **EP**: Gyro-center and full orbit following (ORBIT, SPIRAL), linear and non-linear Alfven instability,fast-ion transport (NOVA-K, M3D-K, HYM)
- **RF**: heating, edge power loss (AORSA, TORIC, SPIRAL), RF/fast-ion interactions (hybrid FOW CQL3D), ECH/EBW heating & CD (GENRAY)
- **PSR/ASC**: 2D/3D helicity injection physics (TSC, NIMROD), time-dependent ramp-up/sustainment modeling (TSC/TRANSP/NUBEAM)

NSTX/ST researchers contributing to LDRD-funded study of Mission and Configuration of an ST-FNSF



- Overarching goal of study:
  - Determine optimal mission, performance, size
- Goals of study:
  - Review existing designs, ID advantageous features, improve configuration
  - Key considerations for configuration:
    - T self-sufficiency
    - Maintainability, upgradeability, overall flexibility
    - Key components: coils, divertors, shields, blankets, ports
  - Develop self-consistent assessment + configuration for use by community
- FY2013 progress:
  - Developing/comparing configurations with range of sizes: R=2.2, 1.6, 1.0m
  - Assessing impact of different divertors: conventional, snowflake, super-X
  - May be minimum device size (R~1.5-1.6m) for TBR > 1 with DCLL
    - Preliminary: breeding in divertor and/or centerstack first-wall/shield may be required