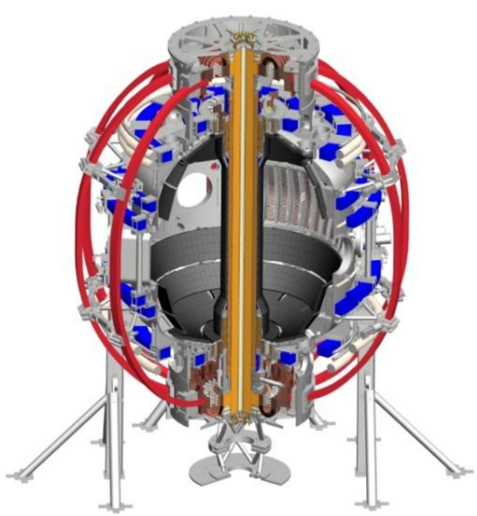
Overview of the NSTX-U 5 Year Plan Research Program for 2014-2018

J. Menard

For the NSTX-U Research Team

NSTX-U PAC-33 Meeting
PPPL – B318
February 19-21, 2013

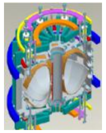
Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin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



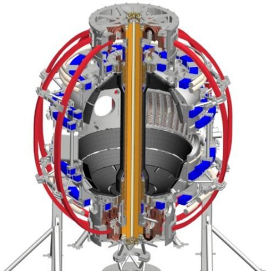
Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech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

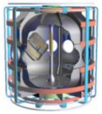
STs and planned NSTX-U program support and accelerate wide range of development paths toward fusion energy

- **Extend Predictive Capability**
  - Non-linear fast-ion dynamics
  - Transport from electron gyro-scale turbulence at low ν^*
  - High beta, rotation, shaping, toroidicity for MHD, transport



LTX





PEGASUS

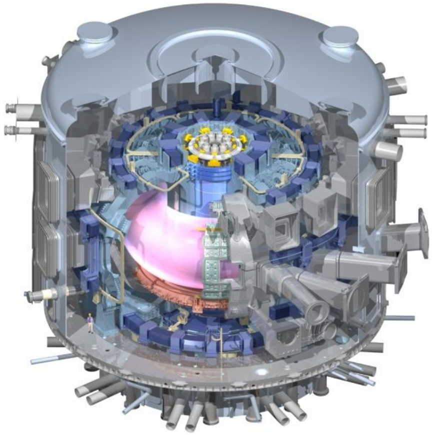
NSTX-U

<u>STs Narrow Gaps to Pilot/DEMO</u>:

- 100% non-inductive + high β
- Plasma-Material Interface
  - Strong heating + smaller R → access high P/R, P/S
  - Novel PMI solutions: snowflake, liquid metals, Super-X (MAST-U)

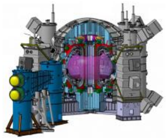
- **Fusion Nuclear Science**
  - High neutron wall loading
  - Potentially smaller size, cost
  - Smaller T consumption
  - Accessible / maintainable

Burning Plasma Physics - ITER



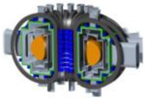
Steady-State, Plasma-Material Interface R&D

EAST



JT-60SA

NHTX



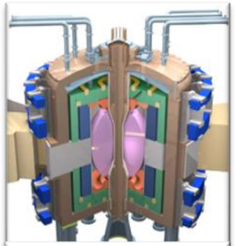
VULCAN

KSTAR

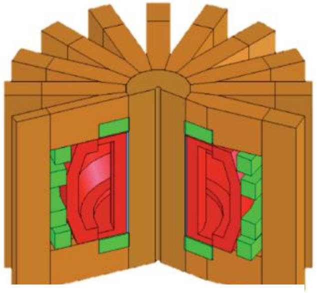
W7-X, LHD

QUASAR

Fusion Nuclear Science Facility

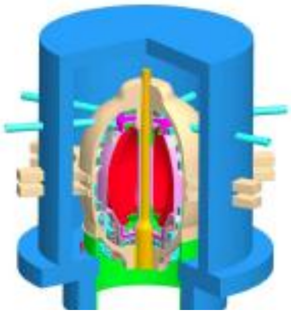


FNSF-ST

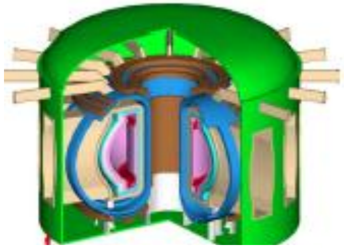


FNSF-AT

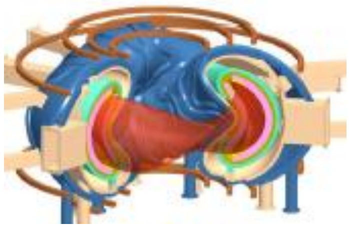
Pilot Plant or DEMO



ARIES-ST



ARIES-AT



ARIES-CS

Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

NSTX-U PAC-33 Charge Background

- The NSTX-U research team is presently engaged in writing a 5 year plan for 2014-18
  - Plan utilizes the new capabilities associated with the NSTX Upgrade project (new centerstack and 2nd neutral beam injector)
  - plus proposed additional high-leverage facility enhancements
- The written plan is due to the Office of Fusion Energy Sciences (FES) in early April 2013,
  - Full plan will be presented to an FES-appointed external review panel in May/June of 2013
- **The NSTX-U research team would very much value a critical assessment of the draft 5 year plan by the PAC to assist the team in preparing for the plan review**
- Charge questions are similar to those expected during 5 year plan review based on FES guidance, previous reviews

NSTX-U PAC-33 Charge Questions

1. Assess the NSTX-U 5 year plan with respect to how well it addresses the key physics issues needed to evaluate the potential of the ST to provide high-performance plasmas for use in a future fusion research facility
   – Example future fusion research facilities include a toroidal plasma-material-interface facility, a fusion nuclear science facility, or a Pilot Plant/DEMO

All presentations

2. Assess the plans to investigate key tokamak physics issues for ITER

Dedicated Kaye presentation

3. Assess plans to contribute to model validation and the development of predictive capability

All presentations

In addressing charges 1-3 above, please comment in particular on the strength of planned NSTX-U contributions to boundary physics and plasma-material-interaction research.

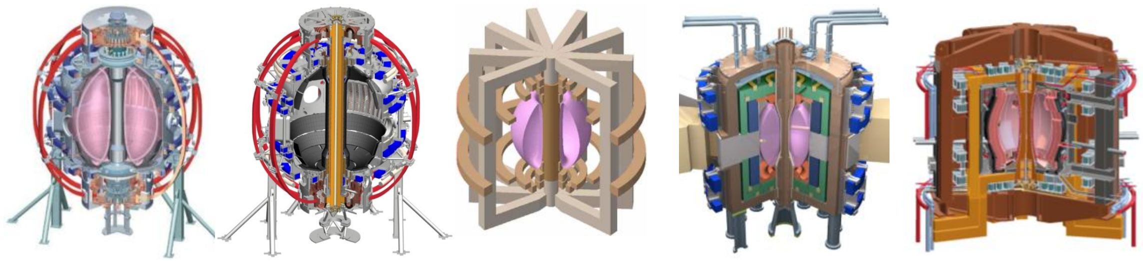
Maingi, Soukhanovskii, Jaworski, Canik presentations

4. Comment on possible improvements to the NSTX-U 5 year plan presentations including logic and format

Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

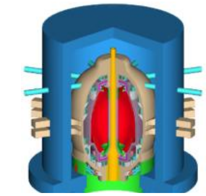
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs



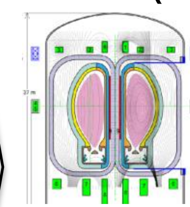
Parameter	NSTX	NSTX Upgrade	Plasma Material Interface Facility	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.0	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.8	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	3 – 4	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	30 – 50	22 – 45	50 – 85
P/R [MW/m]	10	**20**	30 – 50	30 – 60	70 – 90
P/S [MW/m^2]	0.2	**0.4-0.6**	0.7 – 1.2	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

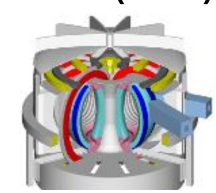
Low-A Power Plants



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**

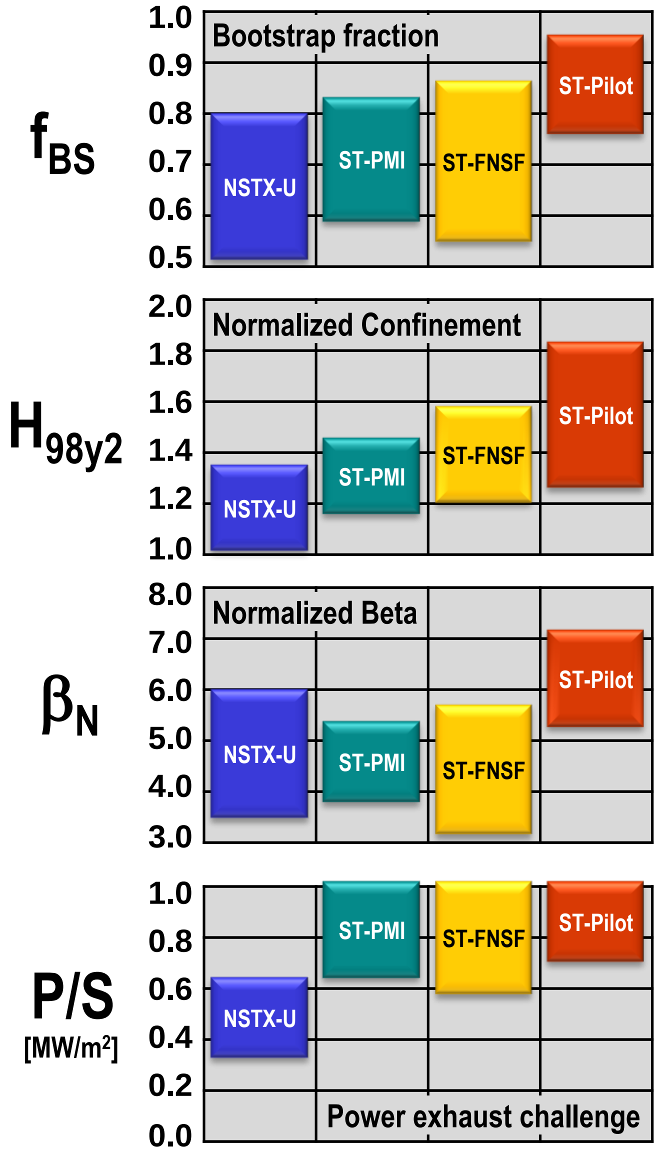
5 year plan addresses key physics + operational questions facing high-performance next-steps, ITER

Requirements for tokamak / ST next-steps:		Key questions to resolve:
• Full non-inductive (NI) current drive for steady-state operation – ST requires NI start-up/ramp-up	⇨	• Are non-inductive plasma J(ρ), p(ρ) profiles consistent with high β, τ_E? • Can J(ρ) profile be controlled, and strong Alfvenic instabilities avoided?
• High confinement to minimize auxiliary heating, device size	⇨	• How does confinement depend on parameters, gradients?: q, ν*, β, Ω_ϕ • How can plasma confinement be controlled and increased?
• Sustained high β to minimize magnet size, forces, power	⇨	• What is maximum sustainable β with passive and active mode control? • Can plasma disruptions be predicted, avoided, mitigated?
• Divertor/first-wall survival with intense power/particle fluxes	⇨	• Can fluxes be reduced below engin. limits at high power & NICD fractions? • Do PFCs/scenarios exist w/ low net erosion, tolerant of off-normal events?

5 year plan goal: access performance levels of next-steps, approach Pilot-Plant regimes

Requirements for tokamak / ST 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**



Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

High-level goals for NSTX-U 5 year plan

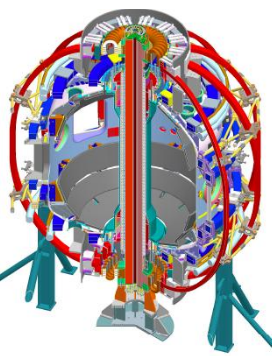
1. Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
   – Note: Non-inductive goal also supports ST-based PMI facility application
2. Access reduced ν* and high-β combined with ability to vary q & rotation to dramatically extend ST plasma understanding
3. Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid
   – Note: ST-based PMI facility could have solenoid for start-up/ramp-up
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 solution for SS-PMI, FNSF, beyond

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



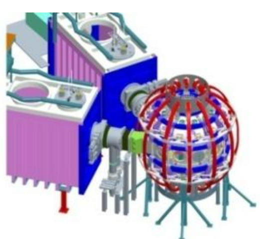
Start-up and Ramp-up
- Increase CHI closed-flux current
- Achieve NI start-up/ramp-up
- Assess plasma gun start-up at increased device size
- Increase/extend ramp-up heating and off-axis current-drive for advanced scenarios
- Develop/understand ECH/EBW H&CD for ST

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



2nd NBI

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 U.S. next-step conceptual design including aspect ratio and divertor optimization

Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

Prioritization of major facility enhancements

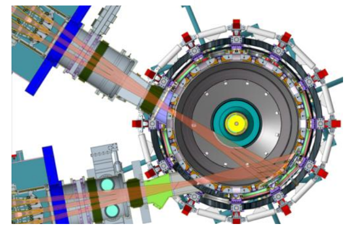
- Extensive diagnostic/facility idea input gathered 2011-2012
- Options ranked according to program impact, cross-links, cost
- Programmatic impact includes:
  - Importance to next-step ST viability
  - Physics or operational contributions to ITER
  - Uniqueness for ST or in world program
- Highest priority **major** facility enhancements: (5YP base funding)
  - **Cryo-pump:** n_e , collisionality control important to all science areas and scenarios, enables comparison between cryo and Li-coatings
  - **ECH/EBW (1MW, 28GHz):** ECH/EBW critical for heating helicity injection/start-up plasma, EBW potentially very efficient for off-axis CD
  - Off-midplane non-axisymmetric control coils (**NCC**): greatly expanded control of poloidal, toroidal spectrum for EF, RWM, ELM, rotation control
- 5YP incremental funding priorities (not in priority order):
  - Divertor Thomson, accelerate high-Z/Li, intermediate-k δn, full NCC, 2MW EC, EHO/EP

NSTX-U plan will address key issues using cross-cutting set of existing/early tools + additional facility enhancements

Key issues to resolve:

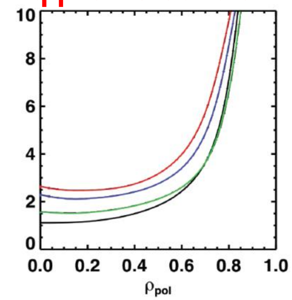
- Non-inductive current profile consistency and control, avoidance of Alfvenic modes
- Confinement dependence on: ν^*, q, β, Ω_ϕ, means to control, increase
- Sustainable β w/ passive and active control, disruption prediction, avoidance, mitigation
- Reduced power/particle fluxes, low net erosion, resilience to off-normal events/disruptions

Present NBI



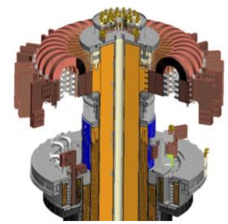
New 2[nd] NBI → 2 × P_{NBI}

q profile control



28 GHz, 1-2MW Gyrotron

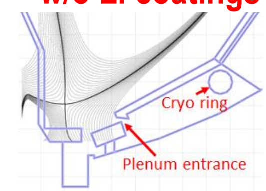
ECH / EBW for start-up (Longer-term: EBW H&CD)



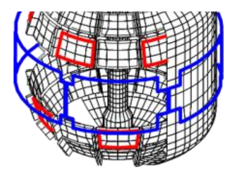
New CS: 2 × B_T, I_P
5 × longer pulse

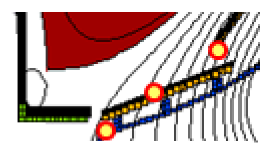
Vary PFC Li coverage to vary recycling, p(ρ), τ_E

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

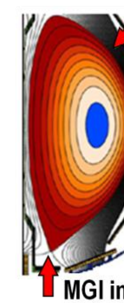


Midplane + off-midplane non-axis. control coils (NCC) for EFC, RWM, ELM-RMP, NTV





Extended low-f MHD sensor set

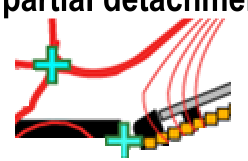


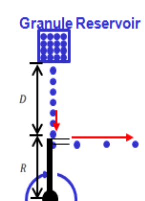
Off mid-plane MGI

mid-plane MGI

MGI in PFR

Snowflake divertors + partial detachment





Li granule injector (LGI) for ELM pacing

Erosion & shielding of high-Z tiles + Li

Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

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" which define actions that will be taken to achieve the high-level goals

- **The remainder of this presentation will summarize the TSG research thrusts of the NSTX-U 5 year plan**

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

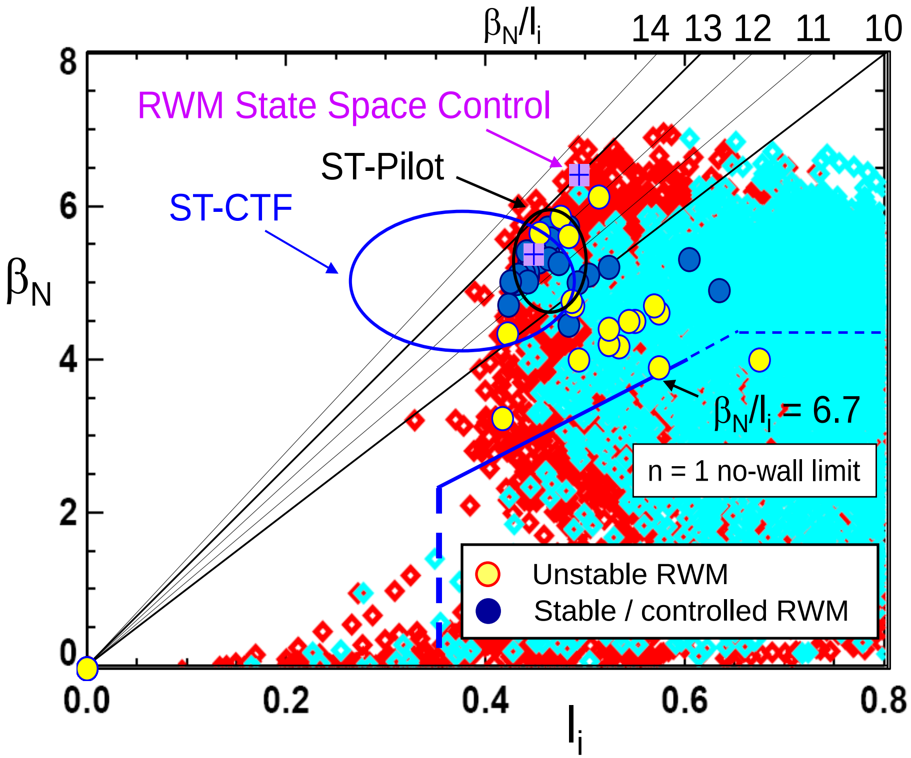
Cross-Cutting / ITER needs
J. Menard, R. Maingi
Theory/Modeling: J. Canik*

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

Overview of NSTX-U 5 year plan research thrusts

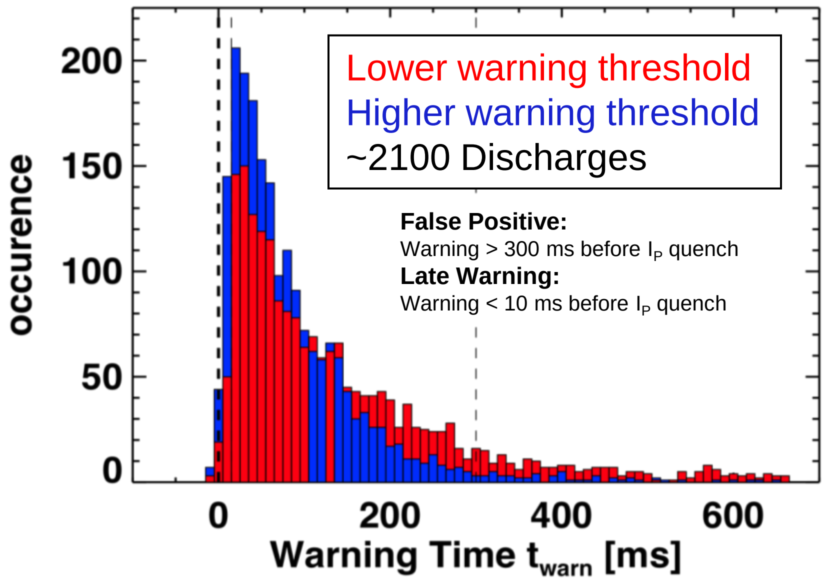
- **Macroscopic Stability (MS)**
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

Stability control improvements significantly reduce unstable RWMs; developed advanced disruption warning



- Disruption probability reduced by a factor of 3 in controlled experiments
  - Reached 2× computed n=1 no-wall limit $\beta_N / l_i = 6.7$
- Lower probability of unstable RWMs at high β_N / l_i

- **Disruption warning algorithm shows high probability of success**
  - Uses combinations of single threshold tests



- Minimize late warnings:
  <1% late warning, ~15% false positive
- Minimize late warn + false positives:
  ~2% late warning, ~4% false positive

Macroscopic Stability (MS) 5 Year Goal:

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

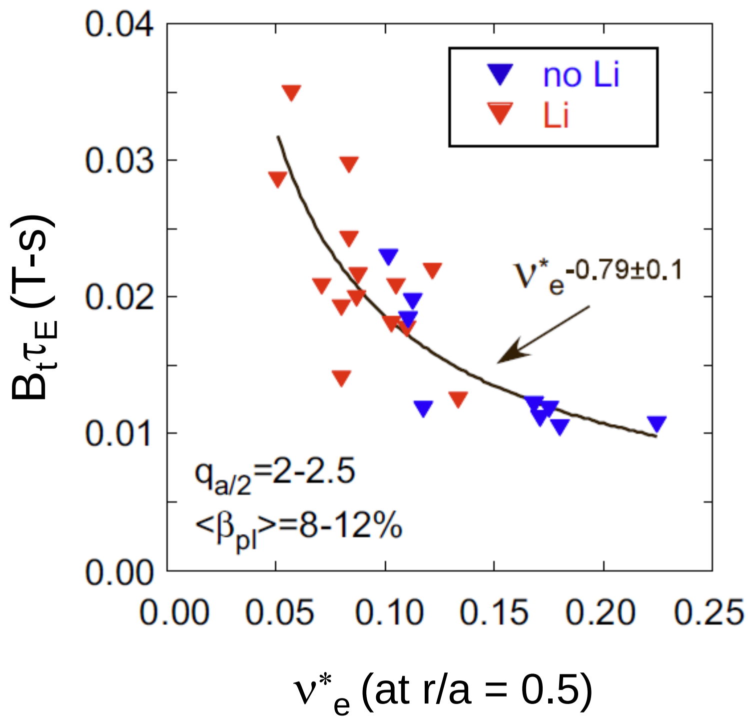
- **Thrust MS-1:** Understand and advance passive and active feedback control to sustain macroscopic stability
  - Study effects of reduced ν^*, also q and rotation on LM, RWM, NTM
  - Advance RWM state-space control for EF, RWM for ITER, next-steps
- **MS-2:** Understand 3D field effects to provide basis for optimizing stability through rotation profile control by 3D fields
  - Study EF penetration, rotation damping, ELM triggering & suppression
    - Utilize varied torque deposition from 2^{nd} NBI, existing/off-midplane NCC
- **MS-3:** Understand disruption dynamics, develop disruption prediction/detection, avoidance, and mitigation
  - rt-ID of global stability limit: low-f, n=1 resonant field amplification (RFA)
  - Enhance measurement, quantification of disruption heat loads, halos
  - Develop/test novel particle delivery techniques for disruption mitigation:
    - MGI in private-flux-region (PFR), electromagnetic particle injector (rail gun)

NSTX results and NSTX-U 5 year plan research thrusts

- Macroscopic Stability (MS)
- **Transport and Turbulence (TT)**
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

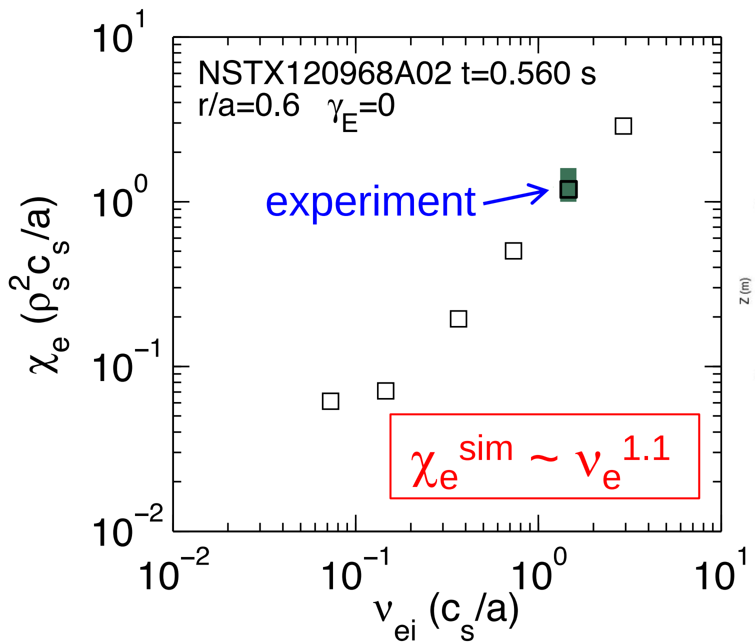
τ_E scalings unified by collisionality; nonlinear microtearing simulations find reduced electron heat transport at lower ν

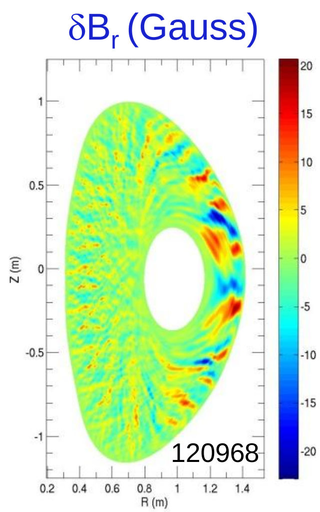
Experiment



- Increase in τ_E as ν^*_e decreases
- Trend continues when lithium used

Theory





W. Guttenfelder, et al., PRL 106 (2011) 155004

- Quantitatively predicted χ_e, scaling ~ $\nu_e^{1.1}$ consistent w/experiment ($\Omega\tau_E \sim B_t\tau_E \sim \nu^*_e{}^{-0.8}$)
- Transport dominated by magnetic "flutter"
  - Significant $\delta B_r/B$ ~ 0.1%

- **NSTX-U computed to extend studies down to < 1/4 of present ν^***

Transport and Turbulence (TT) 5 Year Goal:

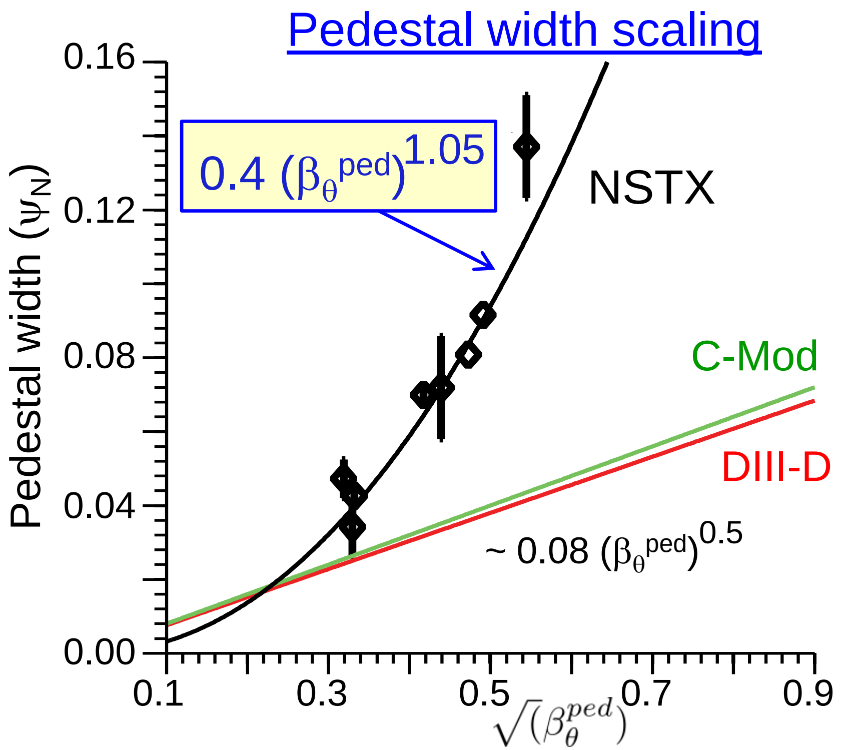
Establish predictive capability for transport in next-step devices focusing on the ST high-β + low-collisionality regime

- **Thrust TT-1:** Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U
  - Extend τ_E scaling to low ν^* by increasing B_T, I_P, P_{NBI}, lowering n_e, Z_{eff}
- **TT-2:** Identify instabilities responsible for anomalous electron thermal, momentum, particle/impurity transport
  - ID isolated regimes for μ-instabilities using theory, 1st principle models
    - Example: microtearing χ_e is linear in ν, while ETG χ_e is independent of ν
  - Relate measured turbulence to prediction:
    - High-k_θ (μ-wave), low-k (BES), EM/δB (polarimetry)
- **TT-3:** Establish and validate reduced transport models
  - Predict/compare $T_{e,i}$ profiles using neoclassical + drift-wave models, develop semi-empirical/analytic models directly from GK simulations
  - Develop model for GAE/CAE-driven electron transport
  - Assess predicted confinement for ST-based next-steps such as FNSF

NSTX results and NSTX-U 5 year plan research thrusts

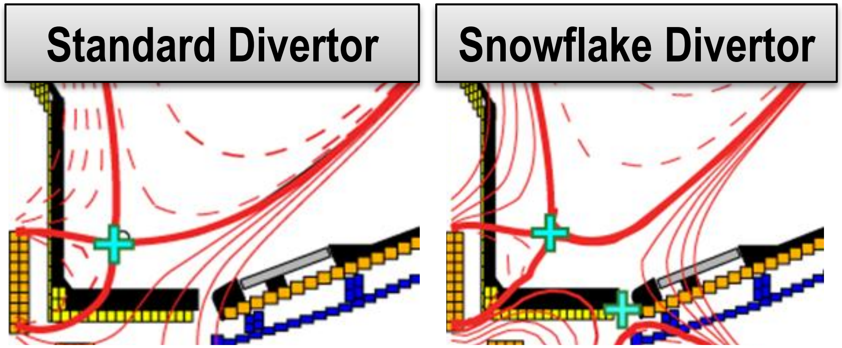
- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- **Boundary Physics (BP)**
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

Pedestal width scaling differs from conventional A; "snowflake" divertor effective for heat flux mitigation

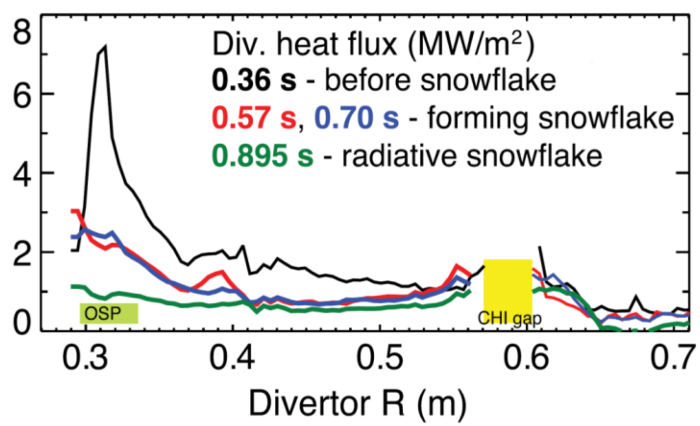


- Pedestal width scaling β_θ^α applies to multiple machines
- In NSTX, observed ped. width is larger
  - Data indicates stronger scaling: β_θ vs. $\beta_\theta^{0.5}$
  - Measured low-k turbulence correlation lengths consistent with XGC1 predictions

- **NSTX: can reduce heat flux by 2-4 × via partial detachment at sufficiently high f_{rad}**



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



Boundary Physics (BP) 5 Year Goal:

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

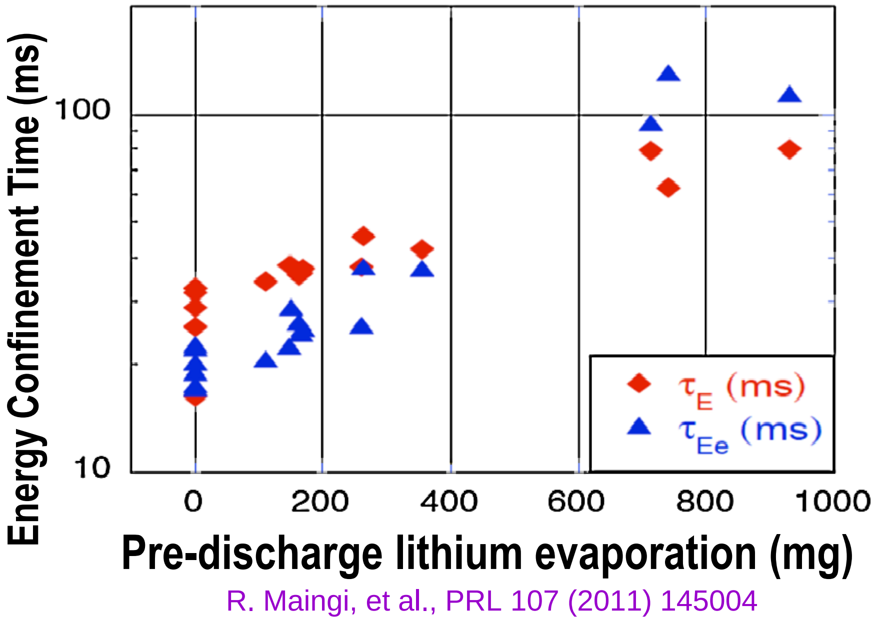
- **Thrust BP-1:** Assess, optimize, and control pedestal structure, edge transport and stability
  - Characterize L-H thresholds, pedestal height/structure vs. B_T, I_P, shape
  - Develop improved control of pedestal transport and stability - tools:
    - Li coverage, fueling, cryo-pumping, ELM triggering/suppression (LGI, NCC)

- **BP-2:** Assess and control divertor heat and particle fluxes
  - Extend/establish heat flux width scalings at lower ν, higher B_T, I_P, P_{SOL}
    - Compare data to multi-fluid turbulence and gyro-kinetic models
  - Assess, control, optimize snowflake divertor
  - Develop highly-radiating boundary solutions with feedback control
  - Validate cryo-pump physics assumptions, characterize n_e control
  - Assess impact of high-Z tile row(s) on power exhaust, core impurities

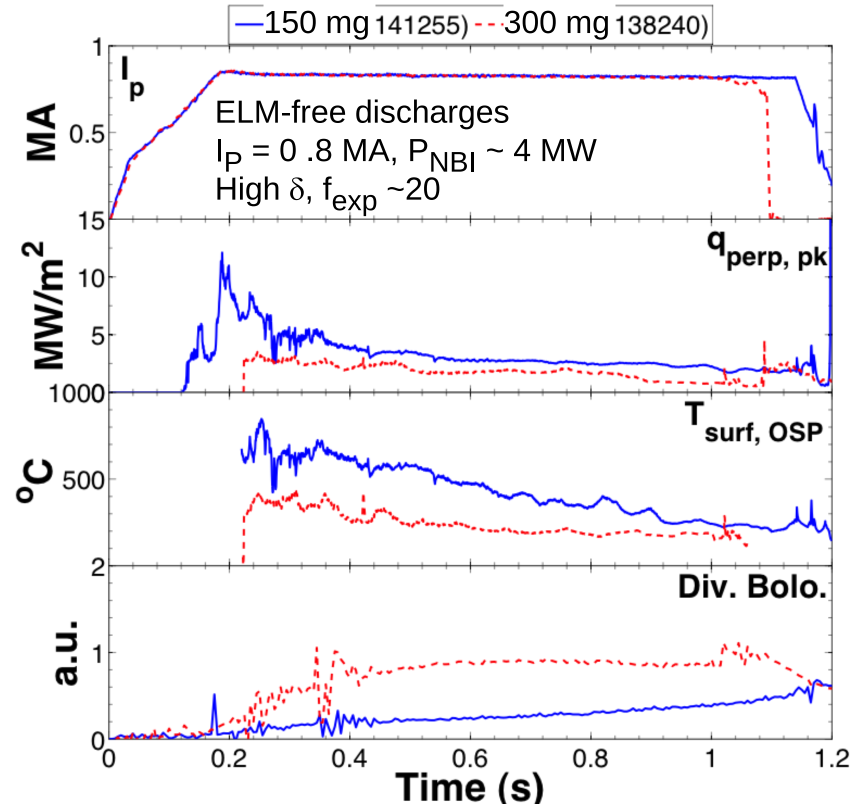
NSTX results and NSTX-U 5 year plan research thrusts

- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- **Materials and Plasma Facing Components (MP)**
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

Plasma confinement increases ~continuously with increasing Li evaporation; 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

Materials and PFCs (MP) 5 Year Goal:

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

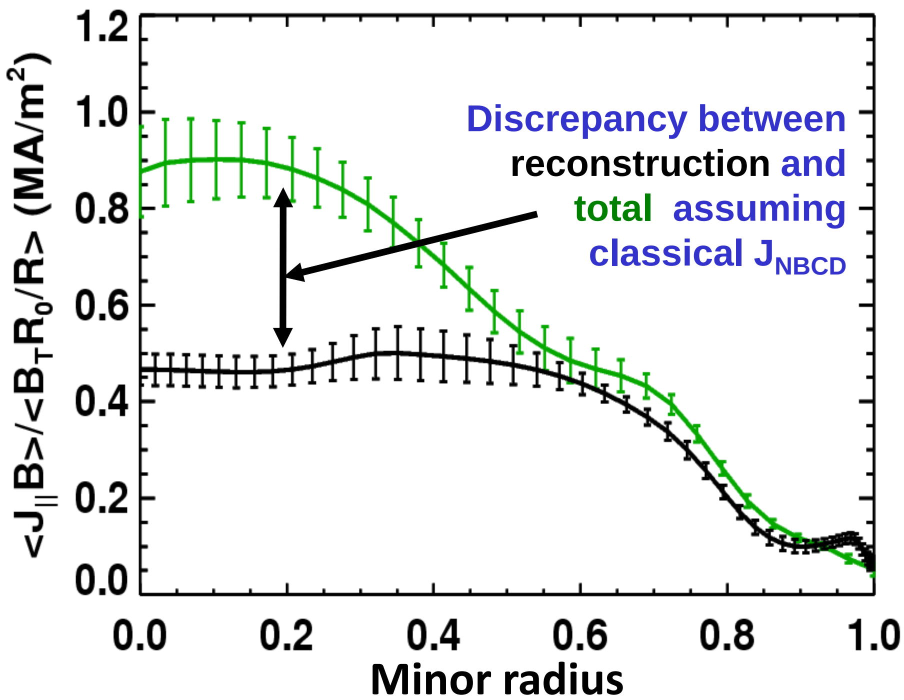
- **Thrust MP-1:** Understand lithium surface-science during extended PFC operation
  - Assess increased coverage of PFCs by Li, compare to B-zation, B+Li
  - Utilize Materials Analysis Particle Probe (MAPP) to identify in-situ between-shot chemical compositions of the coatings
- **MP-2:** Unravel the physics of tokamak-induced material migration and evolution
  - Measure shot-to-shot erosion and redeposition (QCMs, marker-tiles)
  - Utilize MAPP + QCM for shot-to-shot analysis of migration+composition
  - Determine magnitude of wall-erosion for NSTX-U conditions
- **MP-3:** Establish the science of continuous vapor-shielding
  - Study vapor-shielding in long-pulse linear plasma device Magnum-PSI
  - Extend Magnum results to NSTX-U with Li-coated high-Z substrates

NSTX results and NSTX-U 5 year plan research thrusts

- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- **Energetic Particles (EP)**
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

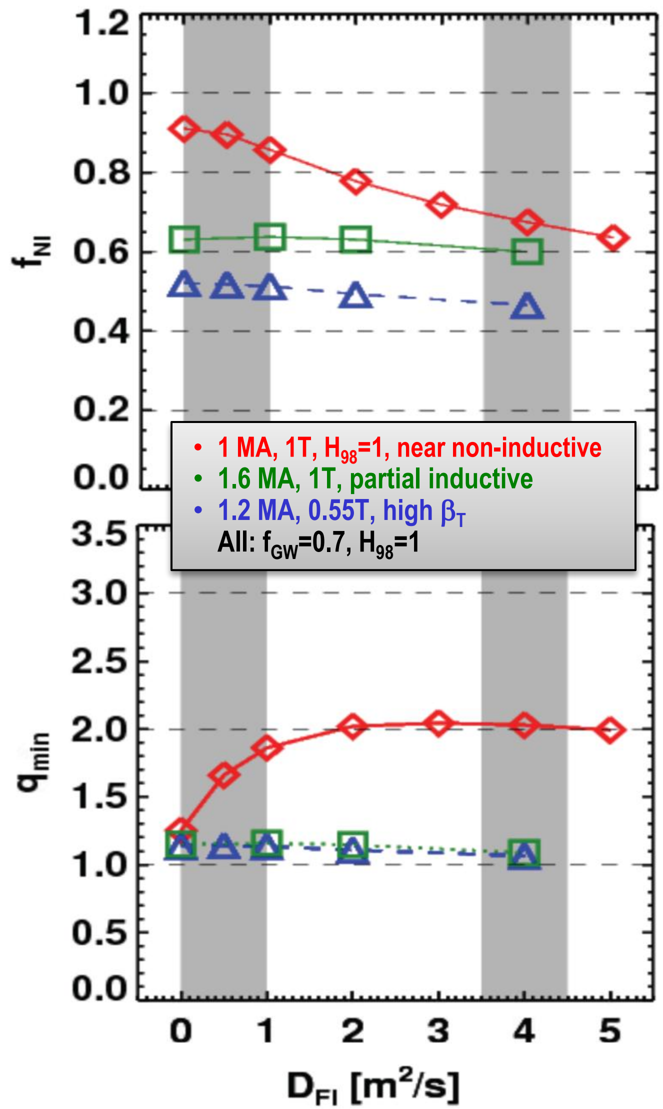
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

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

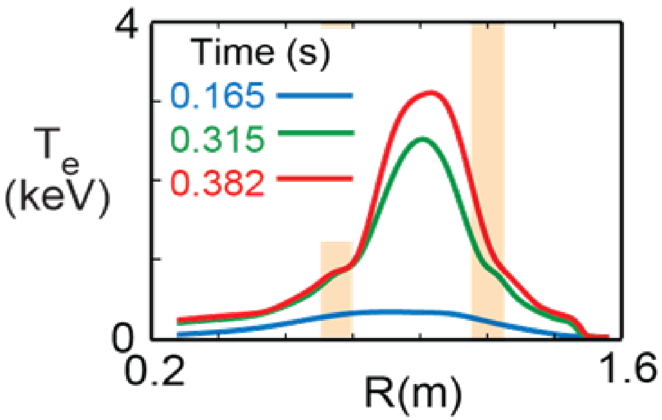
- **Thrust EP-1:** Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER
  - Vary fast-ion instability drive (NBI, q, rotation, 3D fields) and measure *AE mode structure (high-f magnetics, BES, reflectometry)
  - Characterize fast ion transport associated with specific classes of *AEs
  - Compare results to simulation, develop reduced models
    - ORBIT, NOVA-K, M3D-K, HYM to understand mode-induced transport

- **EP-2:** Assess requirements for fast-ion phase-space engineering techniques
  - Perform active spectroscopy to measure linear TAE damping rates
    - Extend/benchmark EP stability codes at low aspect ratio, high β, rotation
  - Extend bandwidth of *AE antennae to study high-f modes (increm.):
    - Higher-f + cyclotron resonances → means to modify distribution function?

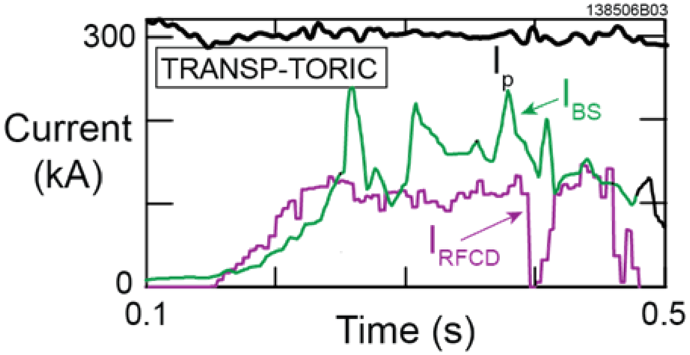
NSTX results and NSTX-U 5 year plan research thrusts

- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- **Wave Heating and Current Drive (RF)**
- Plasma Start-up and Ramp-up (PSR)
- Advanced Scenarios and Control (ASC)

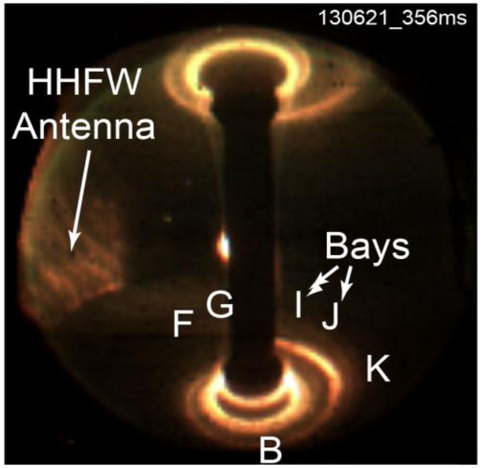
HHFW can efficiently heat low I_P targets for plasma start-up, but can lose power to divertor in SOL in front of antenna



- $T_e(0)$=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%

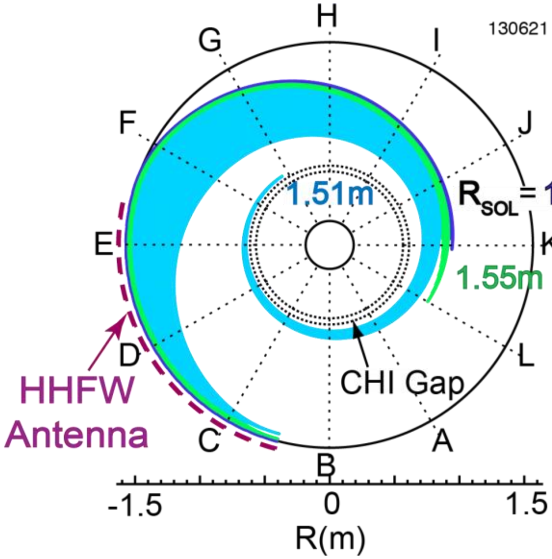


Visible image of RF power flow to Divertor



NSTX
H-Mode
P_{rf} = 1.4 MW
P_{NBI} = 2 MW

SPIRAL modeling of SOL field lines from FW antenna to divertor



Top View

Radio-frequency Heating and Current Drive (RF) 5 Year Goal:

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

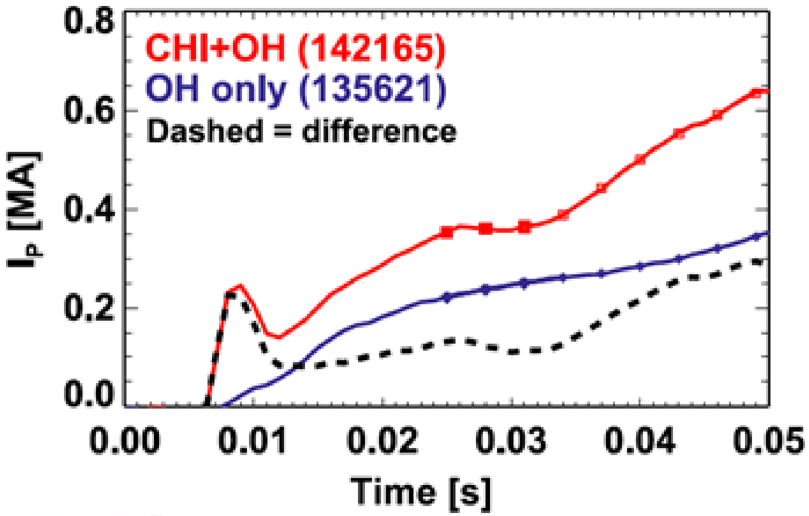
- **Thrust RF-1:** Develop fast wave and EC heating/current-drive for fully non-inductive plasma current start-up and ramp-up
  - Extend HHFW to higher power (3-4MW)
  - Demonstrate HHFW-driven 100% non-inductive ramp-up to ≥ 300kA
    - Goal: generate sufficient target current for confining 2nd NBI fast-ions
  - Use HHFW, ECH (~1MW, 28GHz) to increase T_e of CHI plasmas
  - High-power EBW to generate start-up current - builds on MAST results

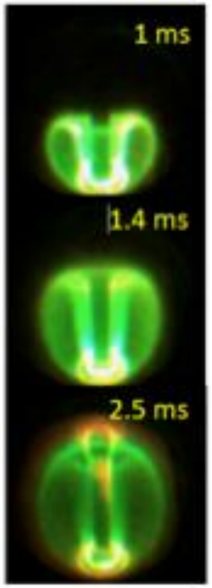
- **RF-2:** Validate advanced RF codes for NSTX-U and predict RF performance in ITER and future burning plasma devices
  - Fast-wave SOL power flows: AORSA, TORIC, SPIRAL
  - RF/fast-ion interactions: "Hybrid" finite orbit width CQL3D FP code
  - ECH absorption, EBW heating and current drive: GENRAY

NSTX results and NSTX-U 5 year plan research thrusts

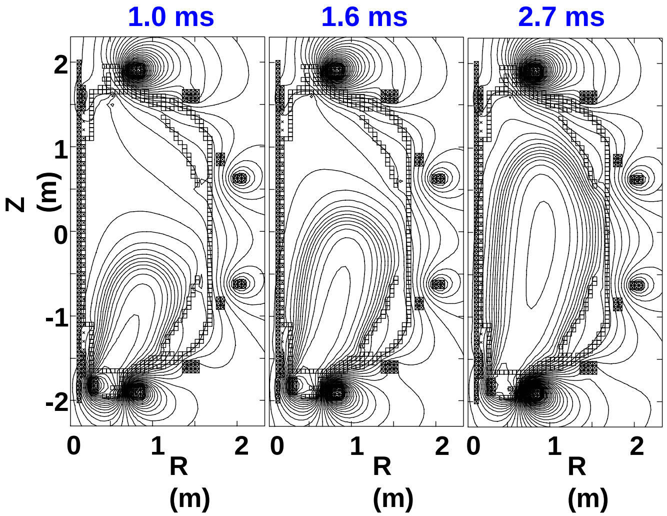
- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- **Plasma Start-up and Ramp-up (PSR)**
- Advanced Scenarios and Control (ASC)

Coaxial Helicity Injection (CHI) has generated ~200kA (closed flux), TSC simulations → start-up/ramp-up to ~1MA possible



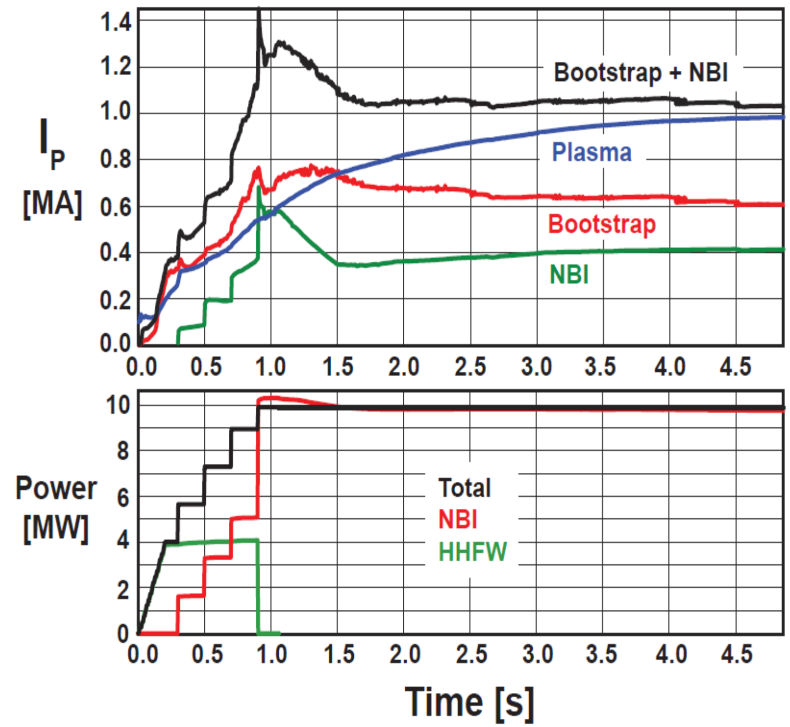


TSC simulation of CHI startup



- **More tangential injection provides 3-4x higher CD at low I_P:**
  - 1.5-2x higher current drive efficiency
  - 2x higher absorption (40→80%) at low I_P = 0.4MA

TSC simulation of non-inductive ramp-up from initial I_P = 0.1MA, T_e=0.5keV target



Plasma Start-up and Ramp-up (PSR) 5 Year Goal:
Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid

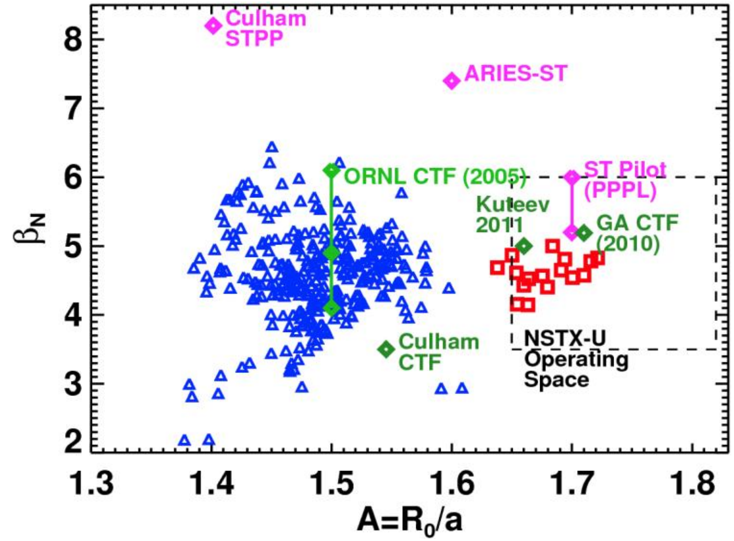
- **Thrust PSR-1:** Establish and extend solenoid-free plasma start-up and test NBI ramp-up
  - Re-establish CHI discharges, increase generated currents → 400kA
  - Assess NBI H&CD in 300-400kA OH targets, compare to TSC/TRANSP
  - Attempt NBI ramp-up of I_P = 0.3-0.6MA (inductive target) to 0.8-1MA

- **PSR-2:** Ramp-up CHI Plasma discharges using NBI and HHFW and Test Plasma Gun Start-up
  - Maximize levels of CHI-produced plasma current (ECH, 2.5-3kV CHI)
  - Use ECH/HHFW to extend duration of high-current CHI target
    - Test effectiveness of NBI coupling to CHI-target
  - Test full non-solenoidal start-up: CHI+ECH/HHFW→HHFW+NBI→1MA
    - Validate ramp-up current drive results with 2D TSC/3D NIMROD simulations
  - If technically ready, commission and test plasma guns on NSTX-U

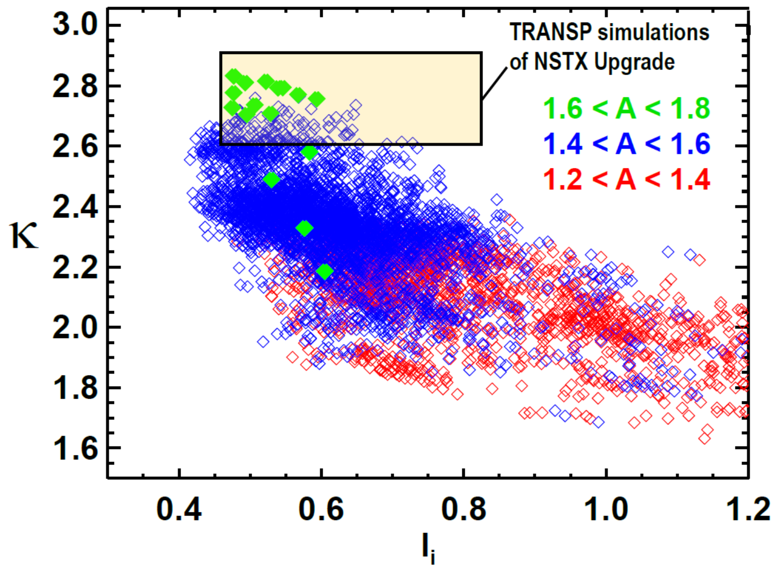
NSTX results and NSTX-U 5 year plan research thrusts

- Macroscopic Stability (MS)
- Transport and Turbulence (TT)
- Boundary Physics (BP)
- Materials and Plasma Facing Components (MP)
- Energetic Particles (EP)
- Wave Heating and Current Drive (RF)
- Plasma Start-up and Ramp-up (PSR)
- **Advanced Scenarios and Control (ASC)**

NSTX has already accessed the A, β_N, κ values needed for an ST-based FNSF – next step is to access 100% non-inductive

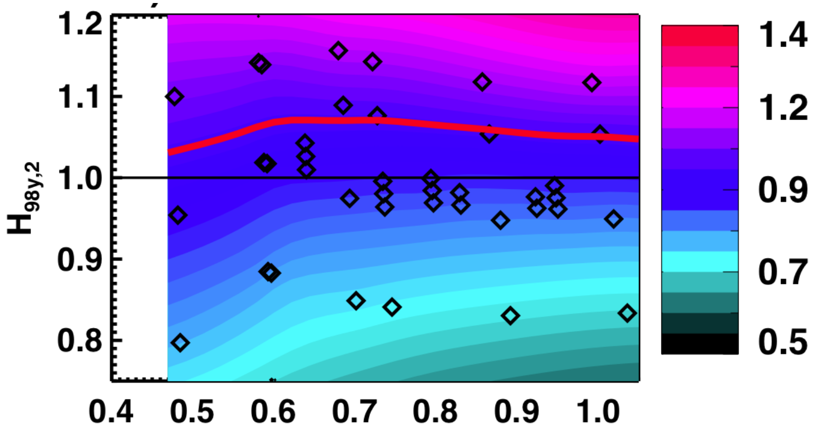


NSTX experimental κ vs. l_i operating space

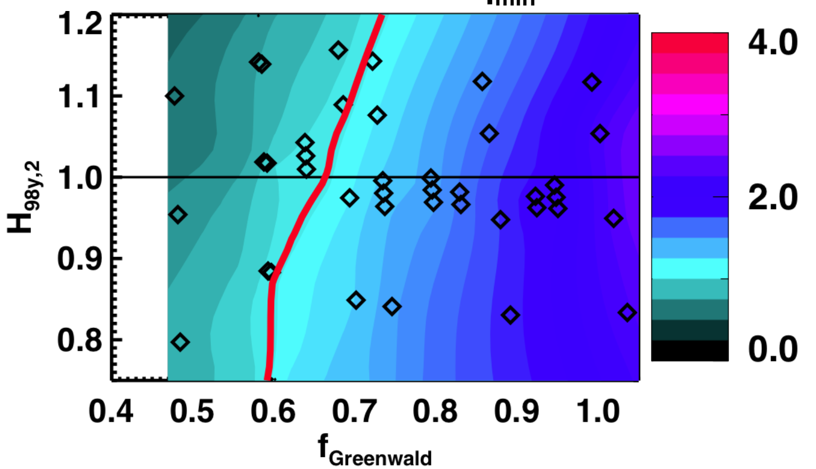


NSTX-U TRANSP predictions:
B_T=1.0 T, I_P=1 MA, P_{inj}=12.6 MW

Contours of Non-Inductive Fraction



Contours of q_{min}



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

- **Thrust ASC-1:** Scenario Physics
  - Develop and assess 100% non-inductive operation
  - Extend the high-current, partial-inductive scenarios to long-pulse
- **ASC-2:** Axisymmetric Control Development
  - Develop methods to control: heat flux for high-power scenarios, rotation and current profile control, improved shape and vertical position control
- **ASC-3:** Disruption Avoidance By Controlled Plasma Shutdown
  - Detect impending disruptions
  - Develop techniques for automated termination
- **ASC-4:** Scenario Physics for Next Step Devices
  - Determine the optimal, simultaneous q- and rotation profiles
  - Study the conditions for classical beam current drive
  - Explore and validate integrated models for projections to FNSF

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

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

MS1	**MS2**	**MS3**	**TT1**	**TT2**	TT3	**BP1**	**BP2**	**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 plasma understanding

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

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

MS1	MS2	MS3	**TT1**	TT2	TT3	**BP1**	**BP2**	**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**	**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 solution for SS-PMI, FNSF, beyond

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

Outline

- Review of PAC-33 charge
- Performance requirements for next-steps
- NSTX-U long-range research goals
- Highest-priority facility enhancements
- Overview of 5 year plan research thrusts
- Contributions to ITER, predictive capability
- Summary

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

See talk by Stan Kaye for more details

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)

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

- Provides ST (and assists AT) basis for next-steps and for ITER
  - Implement actuators/controls for 100% non-inductive at high confinement, β
  - Develop non-inductive formation and ramp-up - needed for ST, benefits AT
  - Advance disruption warning/detection, explore novel disruption mitigation

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

- Uniquely contribute to toroidal confinement predictive capability
  - Access non-linear AE instabilities relevant to ITER burning plasmas/DEMO
  - High β + low ν EM effects on transport, potentially relevant to ITER pedestal

Agenda for remainder of PAC-33

- M. Ono presentation on Upgrade Project and NSTX-U facility and diagnostics will describe tools and budget supporting the planned research program
- S. Kaye presentation will provide overview of NSTX-U five year plan contributions to ITER
- Topical Science Group (TSG) presentations will describe planned research thrusts supporting next-steps, ITER, and the development of predictive capability

Backup

Possible Charge Assessment Criteria

PAC could consider using the following criteria for evaluating the 5 year plan:

A. Assess the **scientific and technical merit of the ongoing and planned research**

   a. How well does it maintain a U.S. leadership position in key areas of fusion research? (consider both merit and originality)
   b. Does the research effectively address important issues in plasma and fusion energy science and technology at the forefront of the field?
   c. Is the research plan adequately developed and likely to lead to new or fundamental advances in fusion science and technology?
   d. Does the proposed research employ innovative concepts or methods, and are potential problems identified along with appropriate mitigation strategies?

B. Assess the **importance and relevance of the proposed 5-year research program**

   a. What is the likelihood of accomplishing the objectives stated in the proposal?
   b. What is the quality of integration of NSTX-U research with other national and international fusion research activities?

NSTX-U 5 Year Plan Well Aligned with FES 10 Year Vision

FES 10 Year Vision

(E.J. Synakowski, APS-DPP 2012)

- **ITER Research**
  - U.S. has a strong research team hitting the ground on a completed ITER project in Cadarache. Team is capable of asserting world leadership in burning plasma science
- **Fusion materials science**
  - The U.S. has made strides in fusion materials science and passed critical metrics in tokamak and ST operations with national research teams. It is prepared to move beyond conceptual design of a fusion nuclear science facility
- **Extend the reach of plasma control science and plasma-wall interactions**
  - U.S. fusion research has successfully levered international research opportunities in long pulse plasma control science, plasma-wall interactions, and 3-D physics
- **Validated predictive capability**
  - The U.S. is a world leader in integrated computation, validated by experiments at universities and labs. Such computation should be transformational, as it must reduce the risks associated with fusion development steps

NSTX-U 5 Year Plan

- Non-linear AE* dynamics, fast-ion transport
- Disruption warning, planned mitigation tests
- Leading models of 3D δB, MHD stability/control
- Developing future leaders for ITER/FNSF era

- 5 year plan goal is to establish physics and operational basis for ST-based FNSF

- Establish J/Ω_ϕ profile + exhaust control, low-f MHD control enabled by advanced 3D coil set
- Snowflake divertors, detachment, Li-based PFCs, SOL widths at very high power density
- Collaboration with KSTAR, EAST, LHD

- Provide data from unique parameter regime of high-β + low ν^* for kinetic/3D MHD, core/edge turbulence, fast-ion transport by non-linear *AE

FES budget guidance for NSTX-U 5 year plan

- Use FY2012 level as the base
  - Regard FY2013 as an anomaly
- For FY2014 and beyond, escalate the FY2012 budget in each successive year using ~2.5% inflation rate ("base funding")
- Include an over-target case that is ~10% higher than the baseline in each year ("incremental")

- **Costs of facility upgrades in subsequent timelines are guesstimates**
- **Substantial engineering analysis is needed to better define costs**
- **However, the guesstimates do fit within the guidance budget profiles**

Base FY13-15 research milestones emphasize analysis and simulation for NSTX-U, FNSF, ITER, + initial NSTX-U ops

	FY2013	FY2014	FY2015
Expt. Run Weeks:	**0**	**0**	**15**
Macroscopic Stability		**Assess access to reduced density and ν^* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	**Perform integrated physics+optical design of new high-k_θ FIR system**		**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	**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**	**Assess reduced models for *AE mode-induced fast-ion transport**	**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		**Assess advanced control techniques for sustained high performance** (with MS, BP TSGs)	**Develop physics+operational tools for high-performance discharges** (with CC, ASC, MS, BP, M&P TSGs)
ITER Needs + Cross-cutting	**Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target (3 facility)	**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 in FY2014-15 would enhance NSTX-U facility utilization, accelerate start-up/ramp-up + snowflake

	FY2013	FY2014	FY2015
Expt. Run Weeks:	0	0	20
Macroscopic Stability		**Assess access to reduced density and ν^* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	**Perform integrated physics+optical design of new high-k_θ FIR system**		**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)
Materials & PFCs	**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**	**Assess reduced models for *AE mode-induced fast-ion transport**	**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 + HHFW start-up at higher field + NBI current ramp-up** (with WEP, ASC TSGs)
Adv. Scenarios and Control		**Assess advanced control techniques for sustained high performance** (with MS, BP TSGs)	**Develop physics+operational tools for high-performance discharges** (with CC, ASC, MS, BP, M&P TSGs)
ITER Needs + Cross-cutting	**Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target (3 facility)	**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**

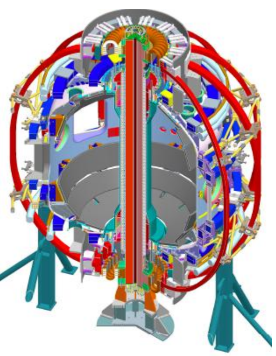
10 year plan tools with 5YP incremental funding

1.1 × (FY2012 + 2.5% inflation)

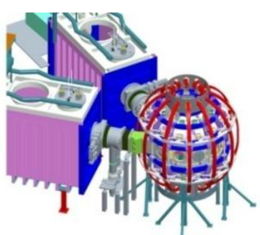
2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

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

New center-stack



2nd NBI



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

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson
- Diagnostics for high-Z wall studies

Materials and PFCs
- High-Z tile row on lower OBD
- Lower high-Z divertor
- U + L high-Z divertors
- 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 divertor

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

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

Waves and Energetic Particles
- HHFW limiter upgrade
- 1 coil AE antenna
- 4 coil AE antenna
- HHFW straps to excite EHO
- High-power AE antenna
- Neutron-collimator, fusion source profile array

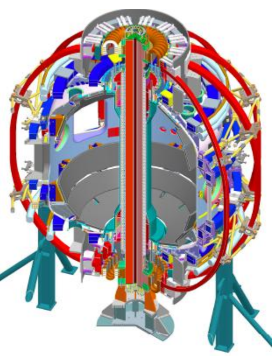
Scenarios and Control
- Establish control of: Snowflake, $\bar{n}_e$, Rotation, q_{min}, Divertor P_{rad}
- Control integration, optimization
- Control integration, optimization with long-pulse and full metal wall

Inform U.S. next-step conceptual design including aspect ratio and divertor optimization

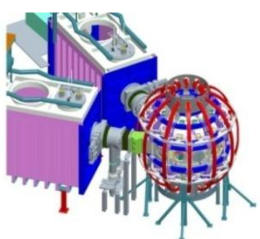
5 year plan tools with 5YP base funding
(FY2012 + 2.5% inflation)

	2014	2015	2016	2017	2018
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			

New center-stack



2nd NBI



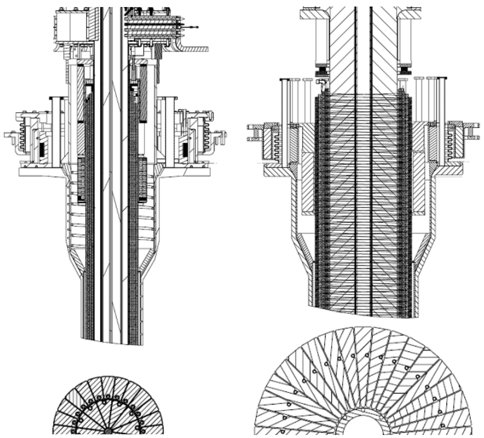
Start-up and Ramp-up	Upgraded CHI for ~0.5MA; Up to 0.5 MA plasma gun; ECH/EBW 1MW
Boundary Physics	Lower divertor cryo-pump
Materials and PFCs	High-Z tile row on lower OBD; High-Z tile row on cryo-baffle; Lower high-Z divertor
Liquid metals / lithium	Li granule injector; Upward LiTER; LLD using bakeable cryo-baffle
MHD	MGI disruption mitigation; Partial NCC; Enhanced MHD sensors
Transport & Turbulence	δB polarimetry; High k_θ
Waves and Energetic Particles	HHFW limiter upgrade; 1 coil AE antenna; 4 coil AE antenna
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

Tool technical detail provided in M. Ono's presentation (next)

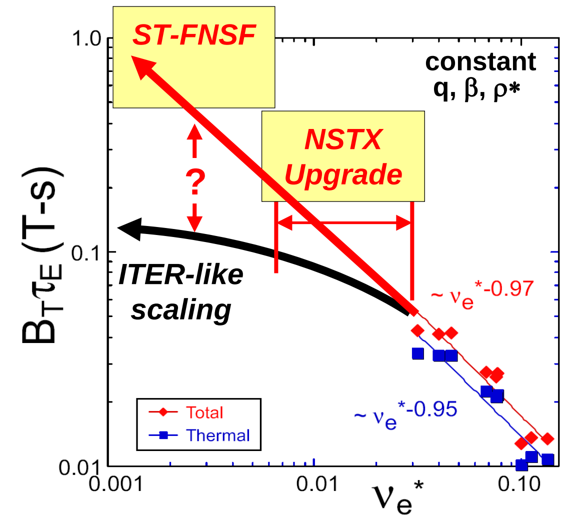
NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities

Previous center-stack | New center-stack

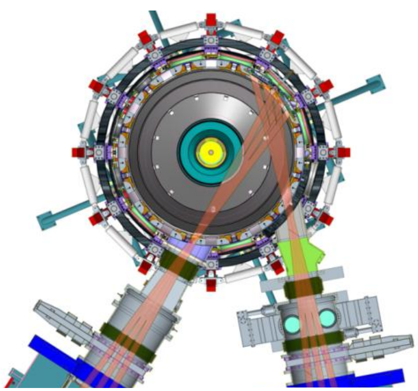


TF OD = 20cm | TF OD = 40cm

- 2x higher B_T and I_P increases T, reduces ν^* toward ST-FNSF to better understand confinement
- Provides 5x longer pulses for profile equilibration, NBI ramp-up



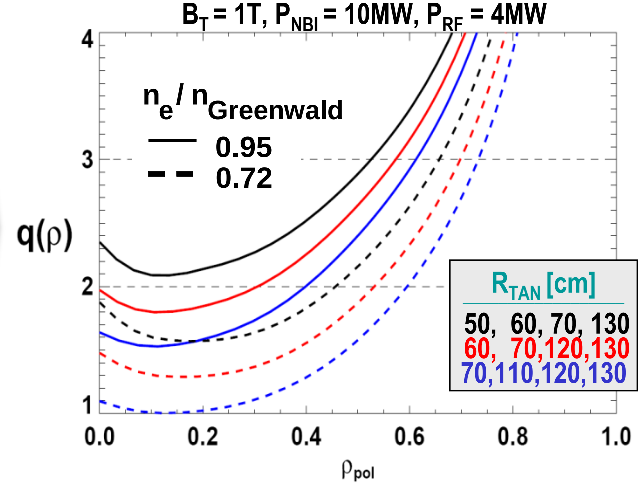
Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI | New 2nd NBI

- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with q(r) profile controllable by: tangency radius, density, position

I_P=0.95MA, H_{98y2}=1.2, β_N=5, β_T = 10%
B_T = 1T, P_{NBI} = 10MW, P_{RF} = 4MW



J. Menard, et al., Nucl. Fusion 52 (2012) 083015