NSTX-U

Supported by

U.S. DEPARTMENT OF ENERGY | Office of Science

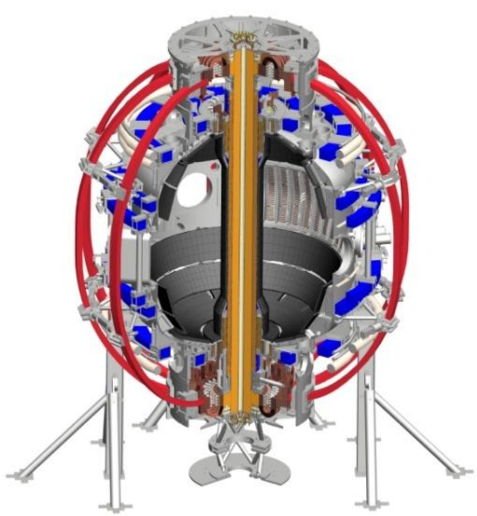
NSTX-U Research Program Overview

FY2012-14 research, collaboration, and 5 year planning

Jonathan Menard, PPPL

For the NSTX Research Team

NSTX PAC-31 Meeting
PPPL – B318
April 17-19, 2012



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

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

- NSTX program/project events since PAC-29
- Schedule for 5 year plan preparation
- PAC-31 charge questions
- FY2012-14 plans and milestones
- Overview of 5 year plan elements
- ST-FNSF development study
- Summary

NSTX Program/Project events since PAC-29 (I)

- Research Forum for FY11-12 run – March 15-18
  - See previous description by S. Sabbagh
- Five year plan (2009-13) mid-term review – June 6-7
- NSTX Upgrade Final Design Review (FDR) – June 22-24
- **NSTX systems tested, ready for plasma ops – July 19, 2011**
- **NSTX central TF bundle electrical short/failure – July 20, 2011**
- PAC-30 review of program letter for diag. collab. – Aug 2011
- Successful independent forensic review of TF fault – Sept 2011
- **Extensive FES + team discussions → decided to begin Upgrade**
- DOE-OFES approval to commence outage – Sept 2011
- **DOE CD-3 approval to begin construction – Dec 2011**
- FY2012-14 milestones revised to reflect non-operation – Dec 2011-Jan 2012
  - Increased emphasis on data analysis, simulations & projections to NSTX-U, collaboration

NSTX Program/Project events since PAC-29 (II)

- Preparation for 5 year plan (to cover 2014-18):
  - Outline for 8 year plan (2011-18) circulated to NSTX team – April 2011
  - Brainstorming sessions:
    - 3 meetings: Diagnostics, facility enhancement, theory/simulation needs
    - Very positive team/lab-wide response ~ 150 ideas total

    For more info: http://nstx-u.pppl.gov/five-year-plan/five-year-plan-2014-18

- Impact of presidential fusion budget guidance for FY2013-14:
  - NSTX Upgrade delayed ~1 year → 1st plasma mid-late 2015
  - Lab-wide/NSTX-U reductions in direct research staff: 50-100/15-17 FTEs
  - Collaboration on C-Mod eliminated, substantially reduced on DIII-D
  - No funding for engineering design of longer-term (5 yr plan) upgrades

    Masa's presentation (next talk) will cover facility and budget issues

- 5 retirements from NSTX-U experimental staff in early FY2012
  - Impacts capabilities in lithium/PFCs, operations, turbulence
  - Need experience/continuity from NSTX for successful NSTX-U ops
    - Several early career/post-doctoral researchers relocated to DIII-D to maintain skills, enhance PPPL off-site collaboration, prepare for NSTX-U operation

Schedule for 5 year planning preparation

- Now: Presenting initial ideas to PAC-31, get feedback
- May-June 2012 – formulate/finalize plan elements and outline, identify/finalize authors, begin writing chapters
- October 2012 – First drafts of plan chapters due
- Nov-Dec 2012 – internal review/revision/editing of plan
- Jan/Feb 2013 – 5 yr plan presentation ‘dry-run’ to PAC-33
- Plan presented to review committee and FES Mar/Apr 2013

Response to NSTX PAC-29 recommendations

- Excel table of responses to PAC-29 recommendations in backup of this presentation, and on PAC-31 website
- Detailed responses to PAC-29 provided (and enumerated) in presentations over next 2 days
- Presentation by J. Canik responsive to recommendations to:
  - Perform more device-realistic design study for divertor cryo-pumping
  - More quantitatively project D particle control w/ Li-coatings for NSTX-U

NSTX-U PAC-31 charge questions:

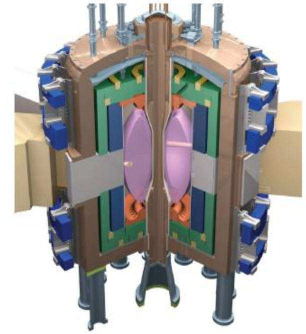
1. Are the planned NSTX-U team science activities appropriate during the Upgrade outage?
   a. Comment on progress toward research milestones
   b. Comment on the NSTX-U team plans and preparations for collaboration with other facilities to prepare for NSTX-U operation and contribute to fusion science generally.

2. Are the plans, preparation, and progress for the next 5 yr plan strongly supportive of NSTX-U and FES missions? Consider two time periods:
   a. Initial operation of NSTX-U, i.e. the first 1-2 run years
   b. Longer term, i.e. years 3-5 of NSTX-U operation

- Research milestones addressed in highlights and topical presentations
- Collaboration plans in topical presentations, and summarized in backup
- 5 year plan ideas contained in this and subsequent presentations

NSTX Upgrade Mission Elements

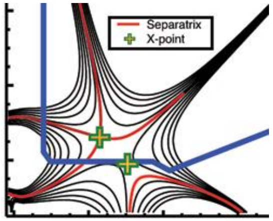
- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**



ST-FNSF

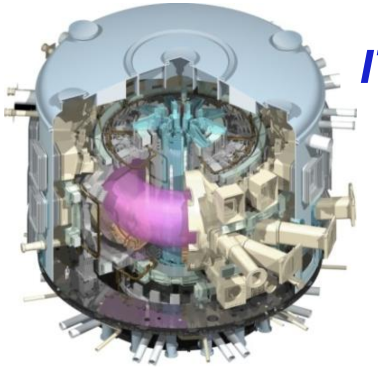
- **Develop solutions for plasma-material interface**

Lithium



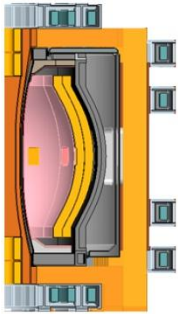
"Snowflake"

- **Advance toroidal confinement physics predictive capability for ITER and beyond**



ITER

- **Develop ST as fusion energy system**



ST Pilot Plant

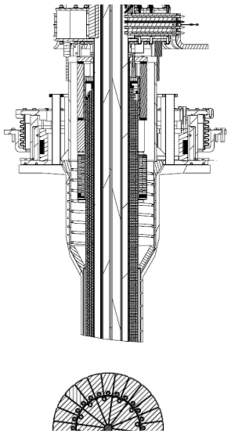
NSTX-U contributes strongly to FES vision for where U.S. fusion program should be in 2021

(From E.J. Synakowski - Associate Director, Office of Science for FES – APS-DPP November 14-18, 2011)

- ITER Research
  - The U.S. has strong research team hitting the ground on completed ITER project
  - This 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 has assessed technical risks associated with moderate vs small aspect ratio and scope of mission, and 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 new international research opportunities, including program leadership, in long pulse plasma control science and 3-D physics.
  - Opportunities also include the plasma-wall interaction science made possible with long pulses.
- Validated predictive capability
  - The U.S. is a world leader in integrated computation, validated by experiments at universities & labs. Such computation should be transformational, as it must reduce risks associated with fusion development steps.
- Plasma science for discovery
  - The U.S. is the world leader in plasma science for discovery. Leverage has been successfully applied across agencies in Discovery Science with NNSA and NSF, and overseas

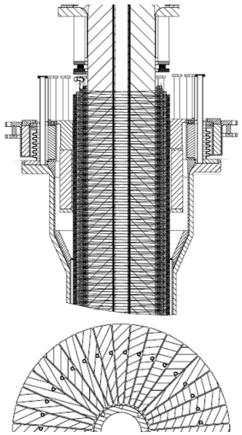
NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities

Previous center-stack



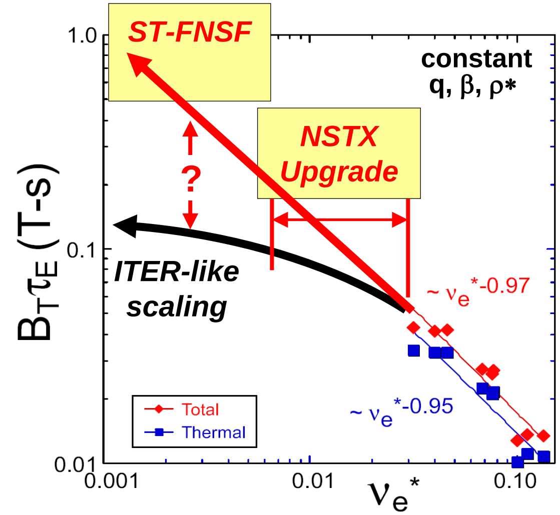
TF OD = 20cm

New center-stack

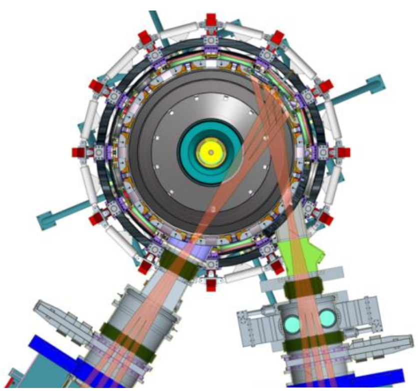


TF OD = 40cm

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



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



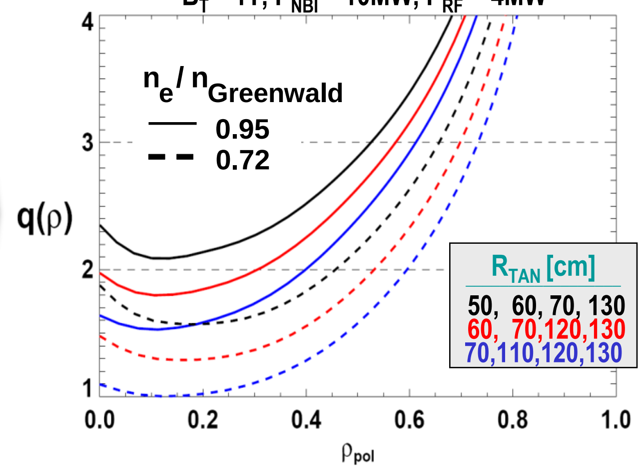
Present NBI

New 2nd NBI

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

I_P=0.95MA, H_{98y2}=1.2, β_N=5, β_T = 10%

B_T = 1T, P_{NBI} = 10MW, P_{RF} = 4MW



8 Topical Science Groups organize research and five year planning, preparation for NSTX-U operation

NSTX-U Topical Science Groups	Summary of research activities during Upgrade outage
Advanced Scenarios and Control S. Gerhardt, E. Kolemen	• Advanced scenario modeling for NSTX-U, q(r) + rotation profile control development with Lehigh on DIII-D
Boundary Physics V. Soukhanovskii##, A. Diallo Theory: D. Stotler	• Understand snowflake + detachment + control, assess and project pedestal structure, turbulence, transport
Lithium Research C. Skinner, M. Jaworski Theory: D. Stotler	• Perform lab-based R&D to understand Li surface chemistry, develop flowing liquid Li prototypes/modules
Macroscopic Stability J.-K. Park, J. Berkery** Theory: A. Boozer**	• Assess kinetic effects for RWM, NTM, NTV, analysis of proposed 3D coils (NCC), characterize disruptions
Solenoid-free start-up & ramp-up R. Raman#, D. Mueller Theory: S. Jardin	• Simulate CHI start-up + ramp-up with TSC + NIMROD, extend to include ECH for current ramp-up w/ NBI-CD
Transport and Turbulence Y. Ren, W. Guttenfelder Theory: G. Hammett	• Simulate low-k to high-k micro-instabilities, compare to measured χ, prepare for high-k_θ scattering, polarimetry
Waves and Energetic Particles G. Taylor, M. Podestá Theory: N. Gorelenkov	• Optimize HHFW and design ECH system for start-up, develop predictive capability for fast-ion transport, design active system to excite/study AE modes
Cross-Cutting / ITER needs J. Menard, R. Maingi* Theory/Modeling: J. Canik*	• Physics design of cryo-pump, assess Li D pumping and extrapolation to NSTX-U, ***next***: lead off-midplane 3D coil physics design (w/ MS TSG), assess flowing LLD needs

* ORNL
** Columbia Univ.
# Univ. of Wash.
LLNL

Baseline: FY12-14 research milestones emphasize analysis, simulation, projection to/preparation for NSTX-U, FNSF, ITER

Expt. Run Weeks:	FY2012	FY2013	FY2014
Transport and Turbulence		R(13-1) Perform integrated physics+optical design of new high-k_θ FIR system	*NSTX-U ops in mid FY2015* →
Macroscopic Stability	R(12-1) Investigate magnetic braking physics and toroidal rotation control at low ν* (with ASC TSG)		R(14-1) Assess access to reduced density and ν* in high-performance scenarios (with ASC, BP TSGs)
Boundary and Lithium	R(12-2) Project deuterium pumping using lithium coatings and cryo-pumping	R(13-2) Assess relationship between lithium-conditioned surface composition and plasma behavior	
Waves+Energetic Particles		R(13-3) Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios	R(14-2) Assess reduced models for *AE mode-induced fast-ion transport
Solenoid-free Start-up/ramp-up	R(12-3) Simulate confinement, heating, and ramp-up of CHI start-up plasmas (with HHFW TSG)		
Adv. Scenarios and Control			R(14-3) Assess advanced control techniques for sustained high performance (with MS, BP TSGs)
ITER Needs + Cross-cutting		R(13-4) Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER	
Joint Research Target (3 facility)	Understand core transport and enhance predictive capability	Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport	TBD

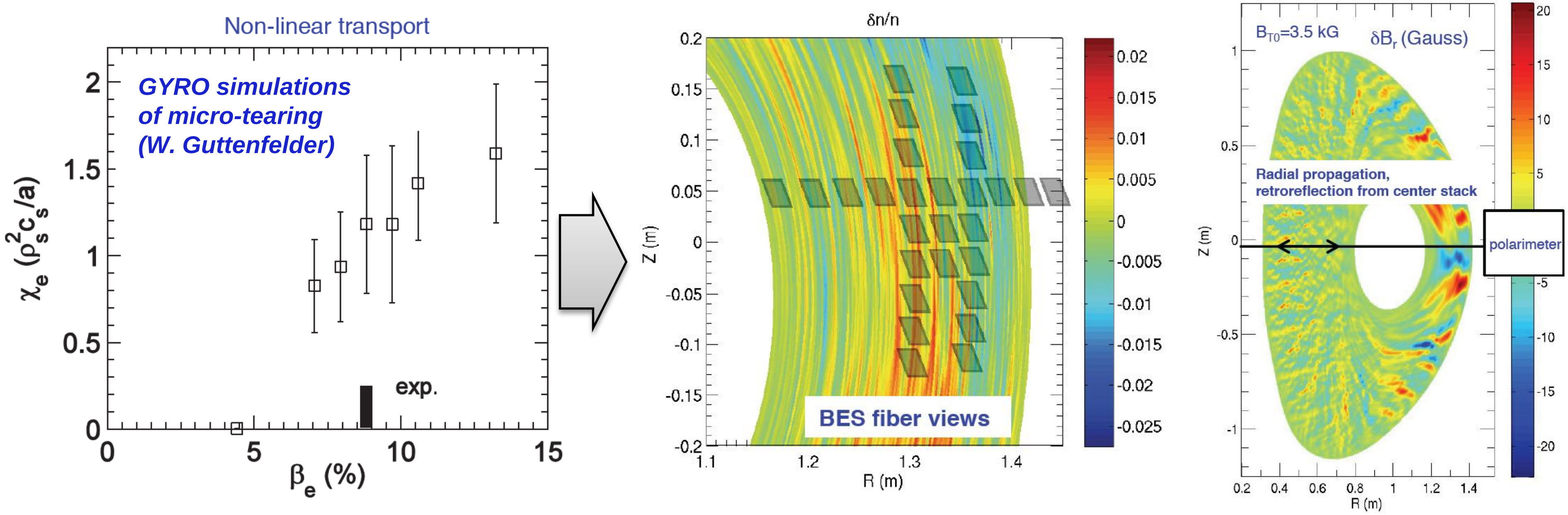
Incremental funding would accelerate first-plasma to FY2014, enabling access to new physics + assessment of ST for FNSF

	FY2012	FY2013	FY2014
Expt. Run Weeks:			~10
Transport and Turbulence		**R(13-1)** **Perform integrated physics+optical design of new high-k_θ FIR system**	**Assess τ_E vs. higher I_P, B_T**
Macroscopic Stability	**R(12-1)** **Investigate magnetic braking physics and toroidal rotation control at low ν*** (with ASC TSG)		**R(14-1)** **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)
Boundary and Lithium	**Project deuterium pumping using lithium coatings and cryo-pumping** **R(12-2)**	**R(13-2)** **Assess relationship between lithium-conditioned surface composition and plasma behavior**	
Waves+Energetic Particles		**R(13-3)** **Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios**	**R(14-2)** **Assess reduced models for *AE mode-induced fast-ion transport**
Solenoid-free Start-up/ramp-up	**R(12-3)** **Simulate confinement, heating, and ramp-up of CHI start-up plasmas** (with HHFW TSG)		
Adv. Scenarios and Control			**Assess NBICD w/ larger R_{TAN}** **R(14-3)** **Assess advanced control techniques for sustained high performance** (with MS, BP TSGs)
ITER Needs + Cross-cutting		**R(13-4)** **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**	
Joint Research Target (3 facility)	**Understand core transport and enhance predictive capability**	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**TBD**

Outline

- FY12-14 research plans
  - Transport and Turbulence
  - Macroscopic Stability
  - Energetic Particles
  - Solenoid-Free Plasma Start-up (Coaxial Helicity Injection)
  - Wave Heating and Current Drive
  - Advanced Scenarios and Control
  - Boundary Physics and Lithium Research

NSTX-Upgrade will extend diagnosis and understanding of micro-instabilities potentially responsible for anomalous transport in STs



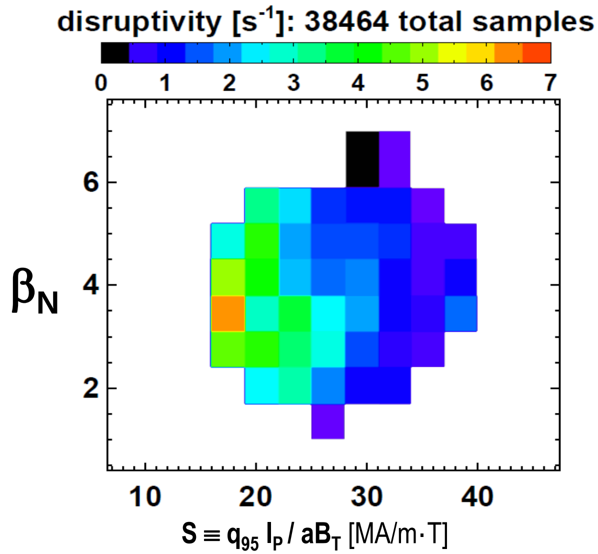
- Electrons dominant loss channel for ST thermal confinement
  - Micro-tearing strong candidate for anomalous thermal e-transport at higher β
  - ETG can also contribute to e-transport at lower β
  - Alfvénic instabilities (GAE/CAE) can also cause core electron transport
- NSTX-U goal is to study full turbulence wave-number spectrum:
  - low-k – ITG/TEM/AE/μ-tearing (BES, polarimetry) + high-k – ETG (μ-wave scattering)
- NSTX-U enables access to unique turbulence regime with high β + lower ν*

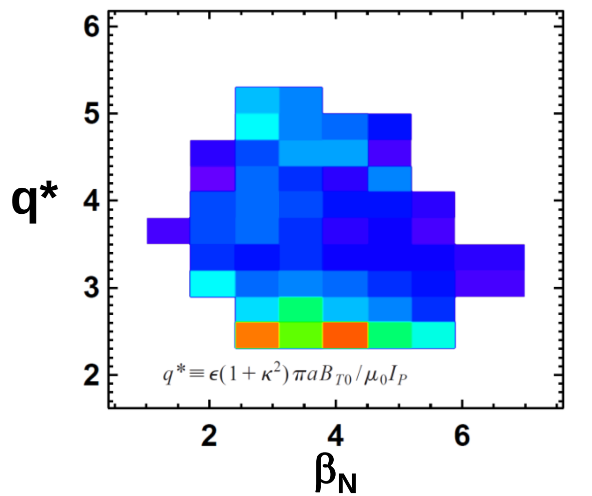
Transport and Turbulence Research Plans for FY2012-14:

Develop advanced turbulence diagnostics, reduced transport models

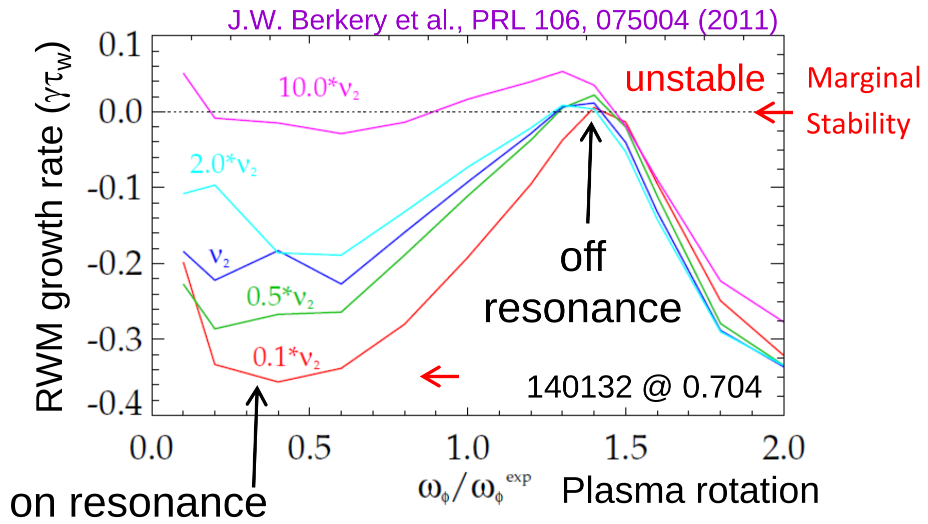
- FY12/JRT: Simultaneous comparison of electron thermal and particle/impurities transport channels in NSTX, coupled with turbulence measurements and gyro-kinetic simulations
  - Test TGLF profile predictions for NSTX discharges (with GA)
- FY12-13: Identify diagnostics for micro-tearing, intermediate $k_\theta \rho_s$ ~ 1-4 turbulence as possible drive for e-transport
  - Work/collaborate with DIII-D (polarimetry), C-Mod (PCI, polarimetry)
- FY13: Develop integrated physics and optical design of the new high-k_θ FIR scattering system
  - Investigate micro-tearing mode by varying relevant parameters (β, ν, Z_{eff}) and using BES diagnostics on MAST
- FY14: Work toward development of reduced transport models and validation of existing models using ST data and linear and non-linear gyro-kinetic simulations

Resistive wall mode studies and systematic disruption analysis inform control requirements for FNSF, ITER





- NSTX disruptivity is minimized for S > 30, q* > 2.5
  - Weaker dependence on β_N (confinement limited)
- NSTX-tested kinetic RWM stability theory shows dependence on rotation and collisionality
  - Reduced ν strongly stabilizing "on-resonance"
  - Expect NSTX-U, tokamaks at lower ν (e.g. ITER) could have stronger RWM stability dependence on rotation



Results motivate high κ, δ + control of ω_ϕ, q profiles (2nd NBI, NTV) for ST-FNSF

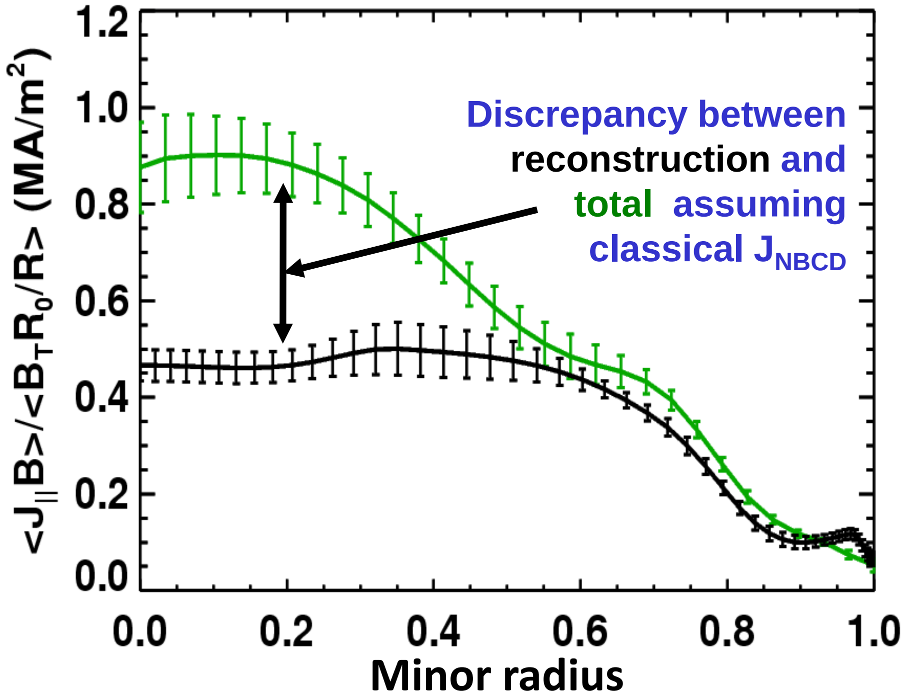
Macroscopic Stability Research Plans for FY2012-14:

Investigate kinetic RWM and disruption physics, assess new 3D coils

- FY12-13: Investigate RWM kinetic stability w/ MISK for NSTX & NSTX-U + experimental (DIII-D and KSTAR) and computational (MARS-K, HAGIS) RWM collaborations
- FY12-13: Compile NSTX disruption database, study NSTX disruptions, combine various precursors/signals for disruption characterization and prediction
  - Develop disruption mitigation + avoidance strategies for NSTX-U, ITER
- FY13-14: Assess access to reduced density and collisionality by investigating RWM, tearing mode physics, and 3D physics including error field + magnetic braking in NSTX-U scenarios
  - Collaborate with DIII-D, KSTAR, and MAST
- FY13-14: Assess utility of new Non-axisymmetric Control Coils (NCC) for RWM, TM, RMP, EFC, NTV/v_ϕ control for NSTX-U
  - Collaborate with DIII-D, KSTAR, MAST to identify optimal coil set

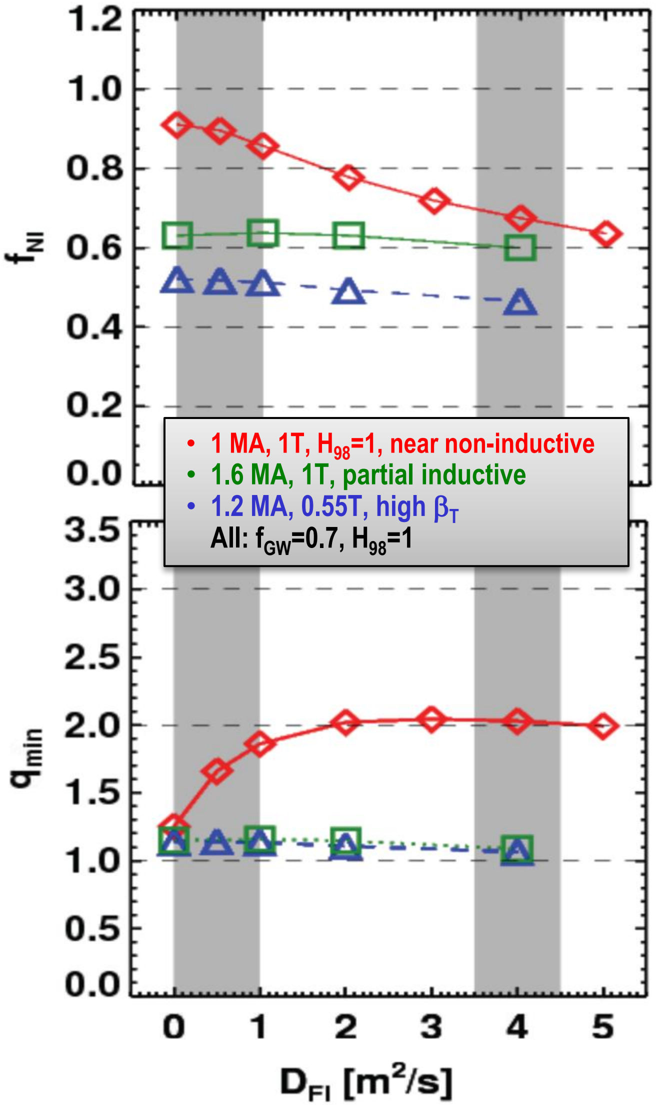
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

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



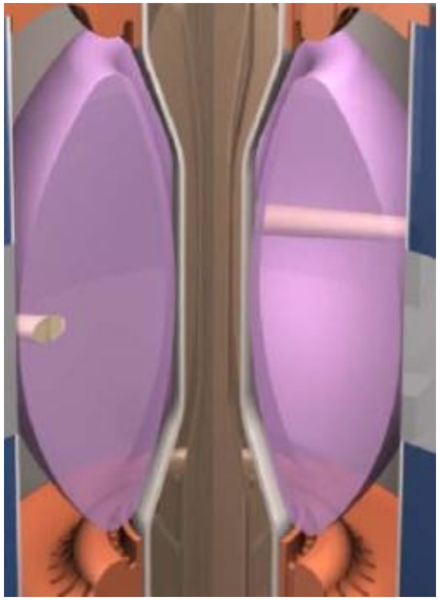
Energetic Particle Physics Research Plans for FY2012-14:

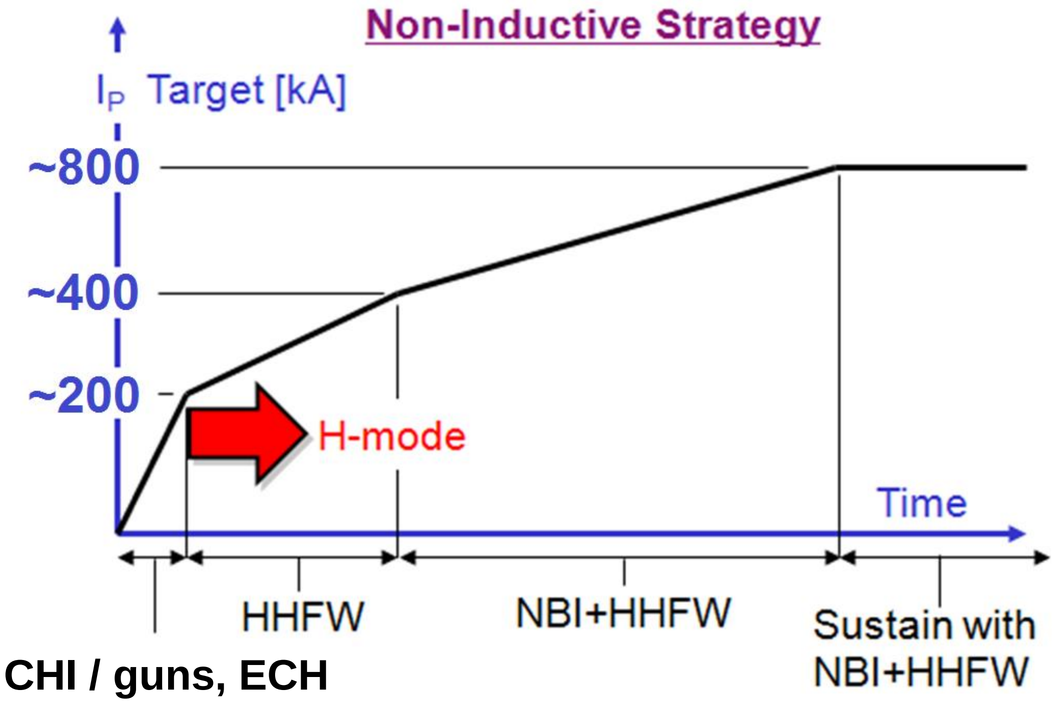
Develop full and reduced models of fast-ion transport, f(v) diagnostics

- FY12: Model TAE stability for NSTX, project to NSTX-U H-mode plasmas w/ NOVA & M3D-K codes
- FY12-13: Improve model of fast ion response to high-frequency GAE/CAE (Develop interface between SPIRAL and HYM codes)
- FY12-13: Collaborate with MAST and DIII-D on AE experiments, ID optimal FI diagnostics for NSTX-U
- FY13-14: Develop reduced model for AE-induced fast ion losses – needed for NBICD in STs/ATs/ITER
  - Collaboration with MAST, DIII-D, Irvine
- FY13-14: Finalize design of prototype AE antenna and of upgraded solid-state NPA diagnostic

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

ST-FNSF has no/small central solenoid

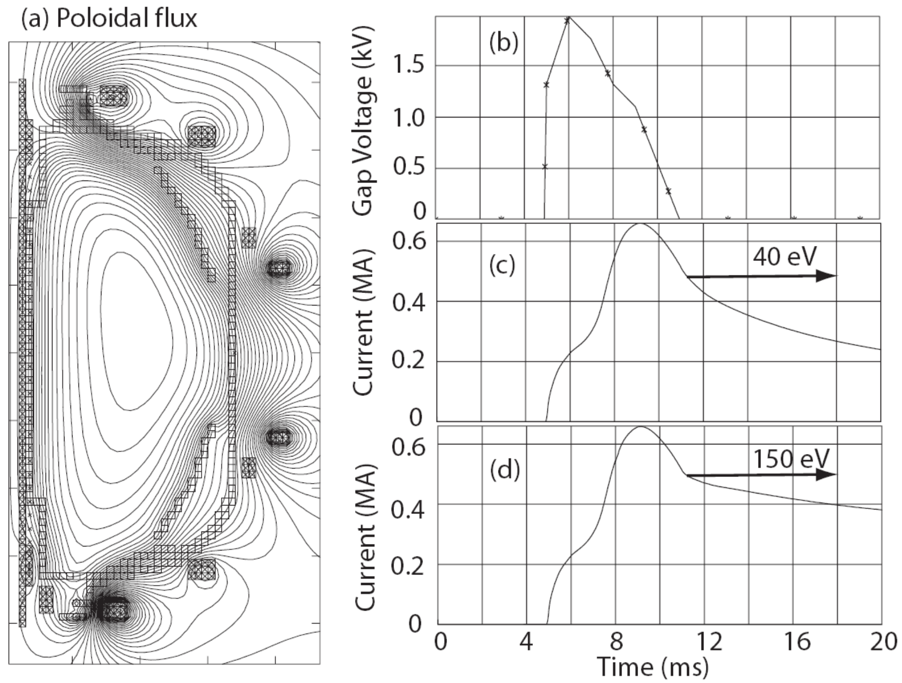




- **NSTX-U goals:**
  - Generate ~0.3-0.4MA full non-inductive start-up with helicity injection + ECH and/or fast wave heating, then ramp to ~0.8-1MA with NBI
  - Develop predictive capability for non-inductive ramp-up to high performance 100% non-inductive ST plasma → prototype FNSF

Simulations of CHI project to increased start-up current in NSTX Upgrade, highlight need for additional electron heating

- TSC simulations of transient CHI consistent with NSTX trends
- Favorable projections for NSTX-U:
  - TF increased to 1T and injector flux increased to about 80% of max allowed → **can generate up to ~400kA closed-flux current**
  - **Figs (a-c): T_e = 40 eV, Z_{eff} = 2.5**
  - **Fig (d): T_e = 150 eV for t > 12 ms**



- T_e ~150-200eV needed to extend current decay time to several 10's of ms
- Low density and β of CHI plasma + transient position (i.e. outer gap) evolution → HHFW coupling and heating very challenging
- NSTX CHI plasmas not over-dense → 28GHz ECH heating of 1T CHI plasma likely best option for generating non-inductive ramp-up target

See presentations by R. Raman and G. Taylor for more details

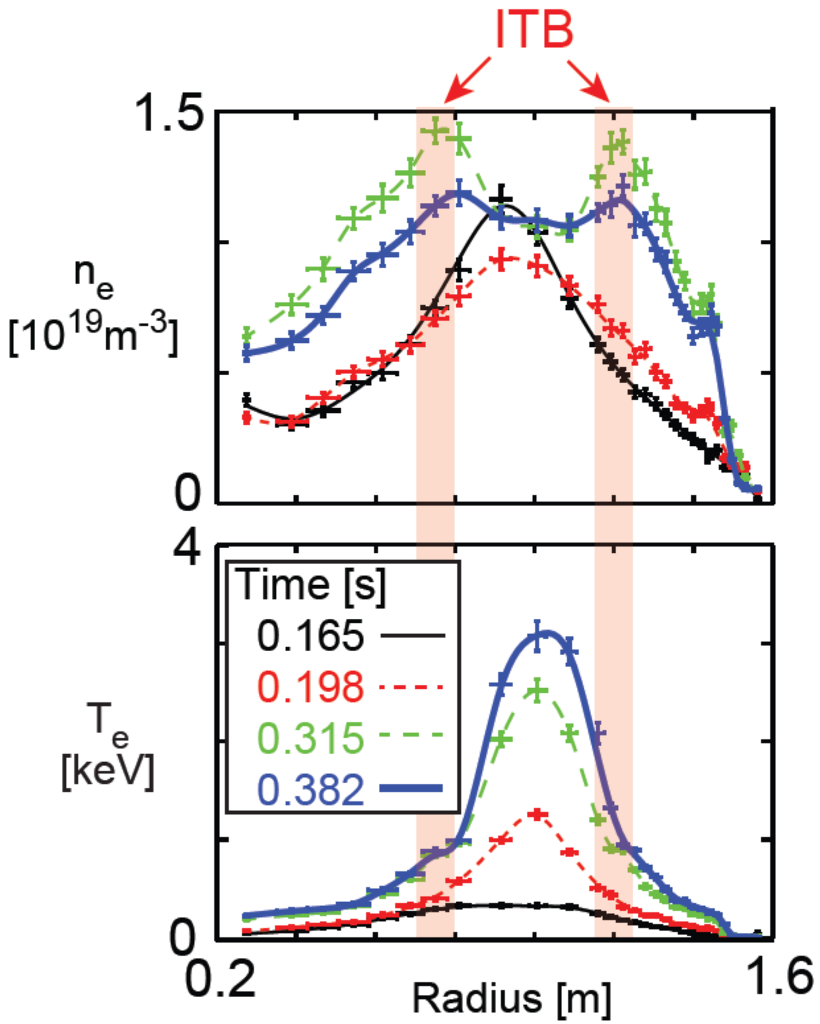
Solenoid-Free Start-up and Ramp-up Research Plans for FY2012-14:

Simulate CHI start-up/ramp-up, prepare CHI/guns for NSTX-U

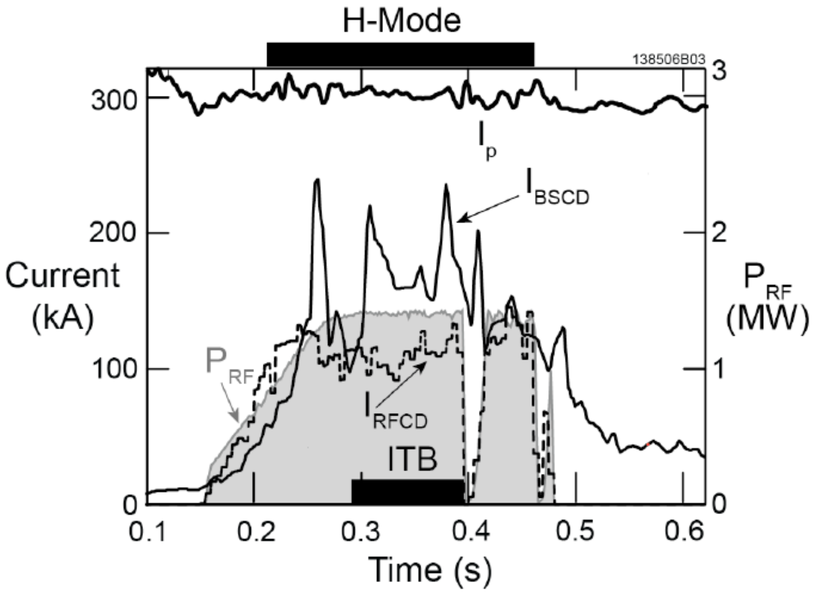
- FY12-13: Model CHI start-up → HHFW+NBI ramp-up scenarios using the NSTX-U vessel + coil geometry
  - Use TSC simulations w/ free-boundary capabilities, identify and develop CHI experiments using FY14 reduced coil set
  - Use TRANSP to vary I_P, T_e, n_e and study how NBI couples to these plasmas with low and zero loop voltage
- Design (FY12) and implement (FY13) upgrades to CHI capacitor bank and diagnostics for NSTX-U
- FY12-13: Participate in PEGASUS plasma gun start-up experiments to identify hardware requirements for implementation on NSTX-U
- FY13-14: Finish CHI design study for QUEST, work with QUEST group for possible CHI usage on QUEST

HHFW promising for heating low current target plasma for NBI non-inductive ramp-up

Can heat I_P ~ 300kA, 200eV plasma to T_e = 3keV w/ low P_{RF} ~1.4MW



- Form core + edge transport barriers
- Non-inductive fraction of 65-85%
  - 40-50% bootstrap, 25-35% RF-CD
- Projects to 100% non-inductive at P_{RF} = 3-4MW in NSTX-U
  → Target for NBI I_P ramp-up

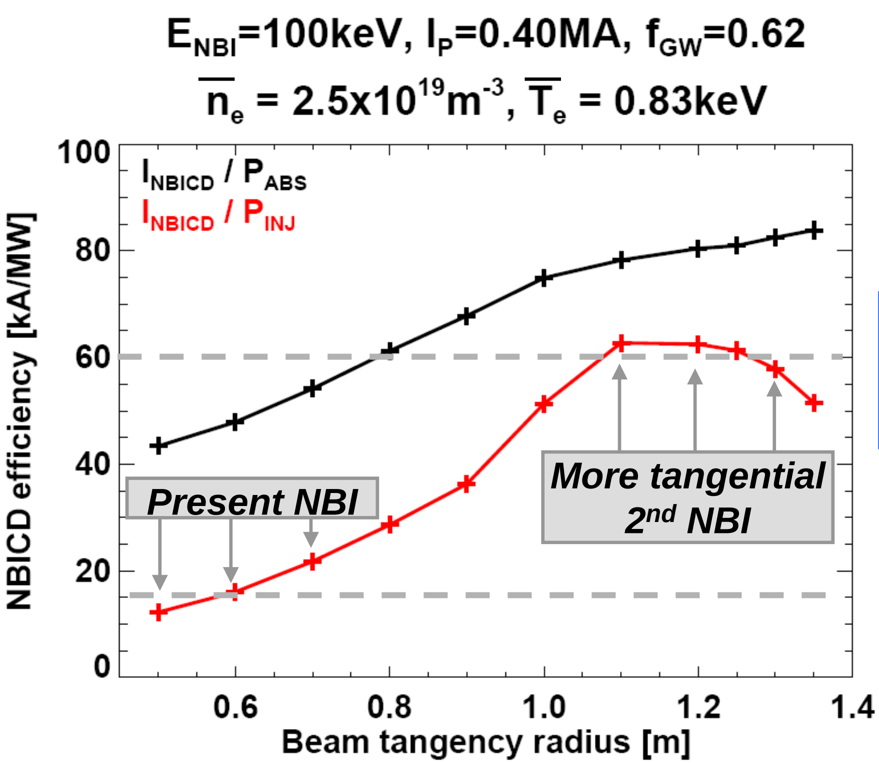


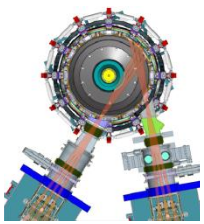
Wave Physics Research Plans for FY2012-14:
Simulate & develop reliable ICRF H-mode, prepare ECH/EBW/EHO design

- FY12-13: Extend HHFW coupling/heating calculations to higher I_P, B_T NSTX-U equilibria, including fast-ion interactions
- FY12: Collaborate w/ MAST on EBW start-up
- FY12-13: Collaborate on development of reliable ICRF-heated H-mode scenarios for NSTX-U and ITER
  - ICRF H-mode on EAST - extend work on NSTX RF-only H-modes
  - ICRF + NBI H-mode experiments on DIII-D to further study NSTX SOL power loss mechanisms with application to ITER
- FY13-14: Physics design for ECH/EBW system (28GHz, 1→2MW) for start-up heating and sustainment CD
- FY13-14: Physics design of EHO excitation system, assist in antenna design for AE spectroscopy

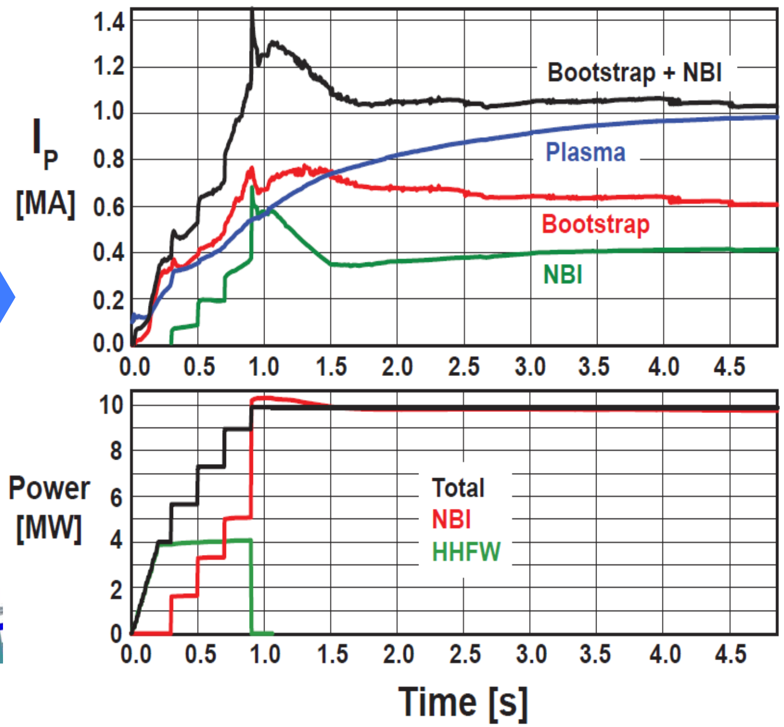
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new CS + more tangential 2nd NBI

- **New CS provides higher TF (improves stability), 3-5s needed for J(r) equilibration**
- **More tangential injection provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
  - 1.5-2x higher current drive efficiency

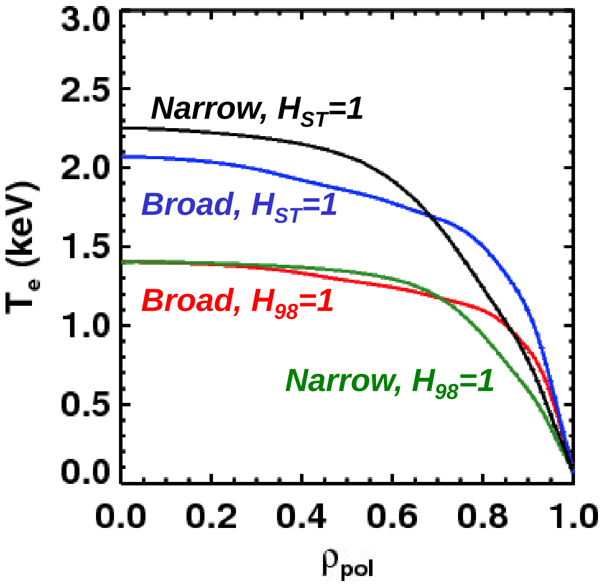


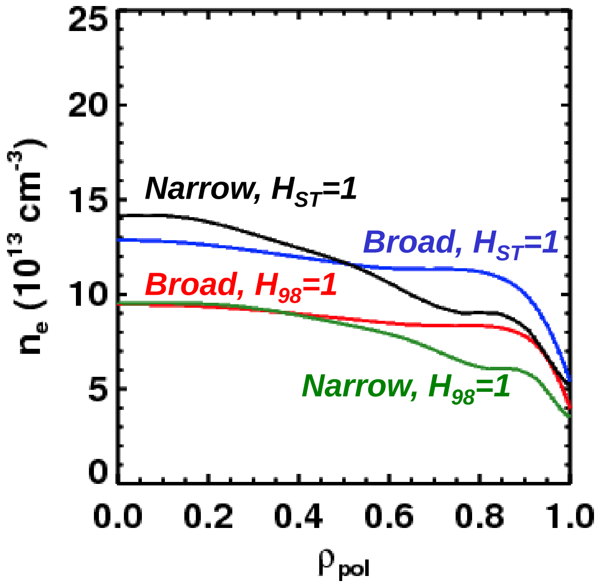


TSC simulation of non-inductive ramp-up from initial I_P = 0.1MA, T_e=0.5keV target



Scenario modeling using TRANSP projects to 100% non-inductive current at I_P = 0.9-1.3MA at B_T=1.0 T



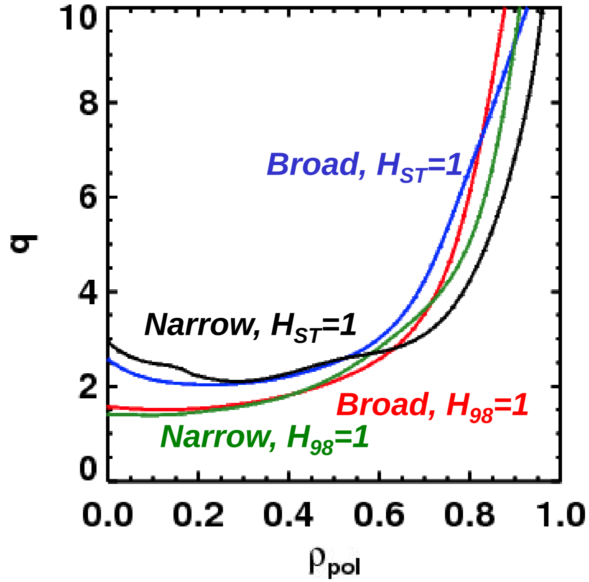


Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

Solid: ST confinement scaling

$$\tau_{ST} \propto I_P^{0.57} B_T^{1.08} \overline{n}_e^{0.44} P_{Loss}^{-0.73}$$



- **Fix: 1.0T, P_{inj}=12.6 MW, f_{GW}=0.72**
- **Fix: A=1.75, κ=2.8**
- Find the non-inductive current level for 2 confinement and 2 profile assumptions…*yields 4 different projections.*

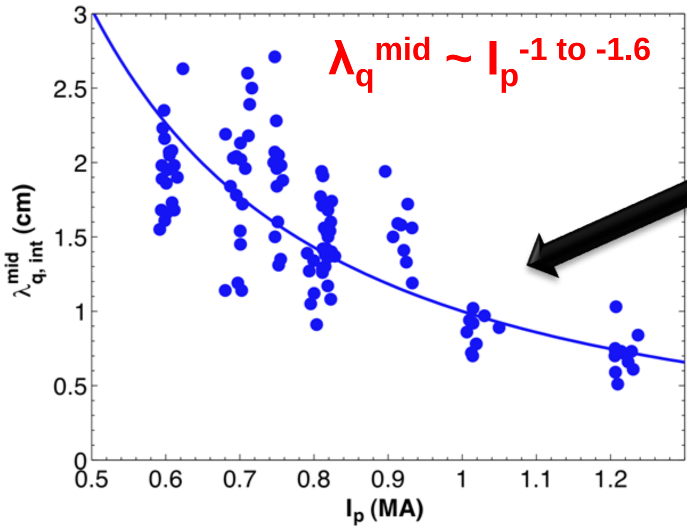
Confinement	Profiles	I_P [kA]	β_N
H_{98}=1	Broad	975	4.34
H_{ST}=1	Broad	1325	5.32
H_{98}=1	Narrow	875	4.87
H_{ST}=1	Narrow	1300	5.97

Advanced Scenarios and Control Research Plans for FY2012-14:

Simulate scenarios for NSTX-U, develop advanced control algorithms

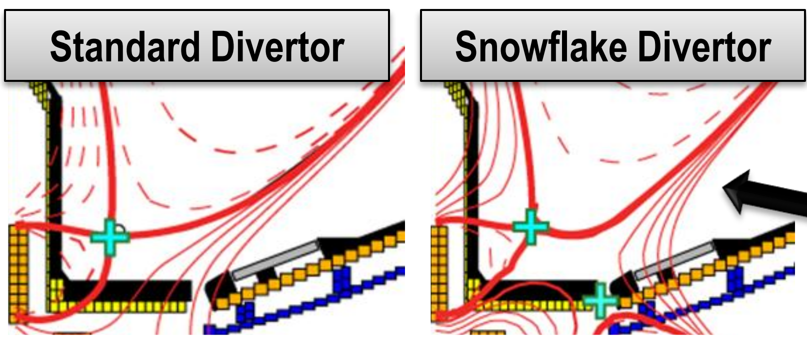
- FY12-13: TRANSP scenario/equilibrium simulations
  - RF-assisted start-up/ramp-up/sustainment simulations – w/ SFSU+WEP
  - Scenario guidance for cryo-pump design (shapes, particle inventories)
  - Provide relevant scenario targets for physics studies + diagnostic design
- JRT-2013: "Evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs), and to improve understanding of the underlying physical mechanisms that allow increased edge particle transport while maintaining a strong thermal transport barrier"
- FY13-14: Assess and/or implement advanced control algorithms in preparation for NSTX-U operation
  - Proposing to develop NSTX-U snowflake control on DIII-D (PPPL+LLNL)
  - J profile control using off-axis NBI on DIII-D for NSTX-U 2nd NBI
    - Implement rt-MSE (if funded) in rt-EFIT for q-profile reconstruction
  - Assess simultaneous J profile, rotation, and beta control
  - Project improvement in NSTX-U rotation control using 2nd NBI deposition flexibility + improved NTV control w/ proposed NCC coils

NSTX-U will investigate high flux expansion snowflake divertor + detachment for large heat-flux reduction



- Divertor heat flux width decreases with increased plasma current I_P
  - Major implications for ITER, FNSF

→ NSTX Upgrade with conventional divertor projects to very high peak heat flux up to 30-45MW/m²



- Divertor heat flux inversely proportional to flux expansion over a factor of five

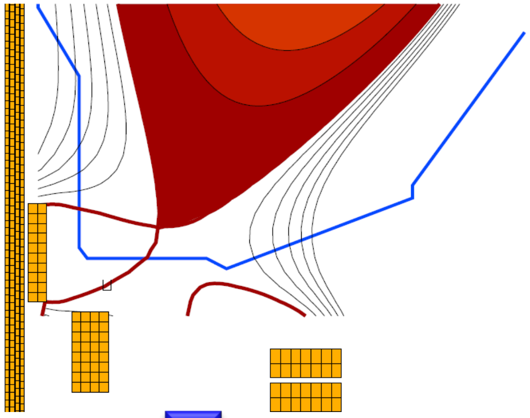
Snowflake→ high flux expansion 40-60, larger divertor volume and radiation

→U/D balanced snowflake divertor projects to acceptable heat flux < 10MW/m² in Upgrade at highest expected I_P = 2MA, P_{AUX}=10-15MW

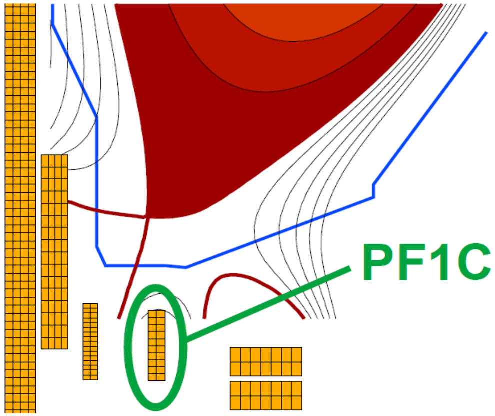
→Partial detachment → ~2x reduction in NSTX (modeling underway)

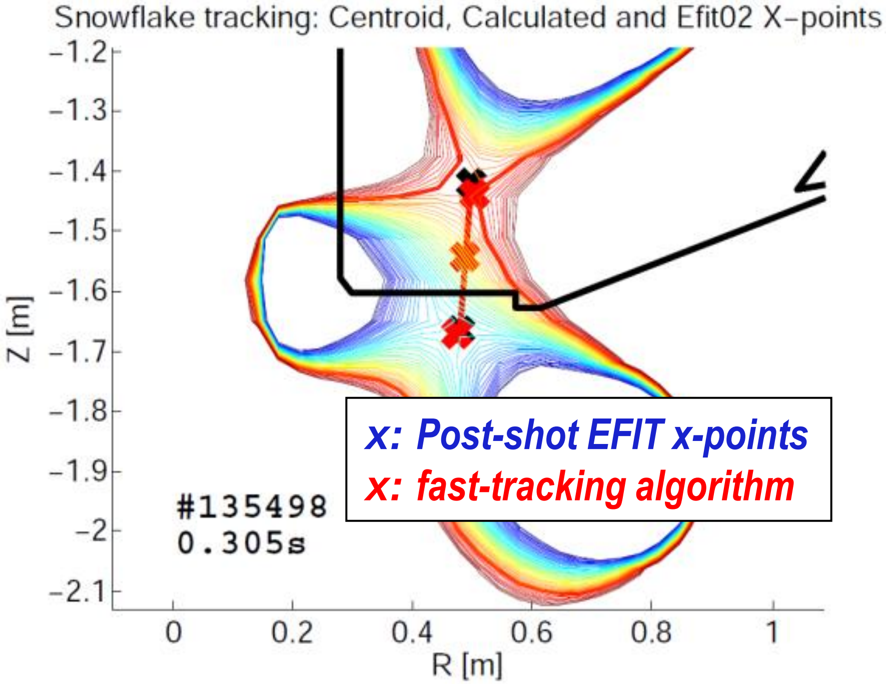
Upgrade CS design provides additional coils for flexible and controllable divertor including snowflake

NSTX Snowflake



NSTX-U Snowflake





- Substantial progress made in developing fast algorithms for ID of multiple X-points suitable for real-time snowflake control
- Next-step is to implement into PCS through PPPL/LLNL collaboration with GA

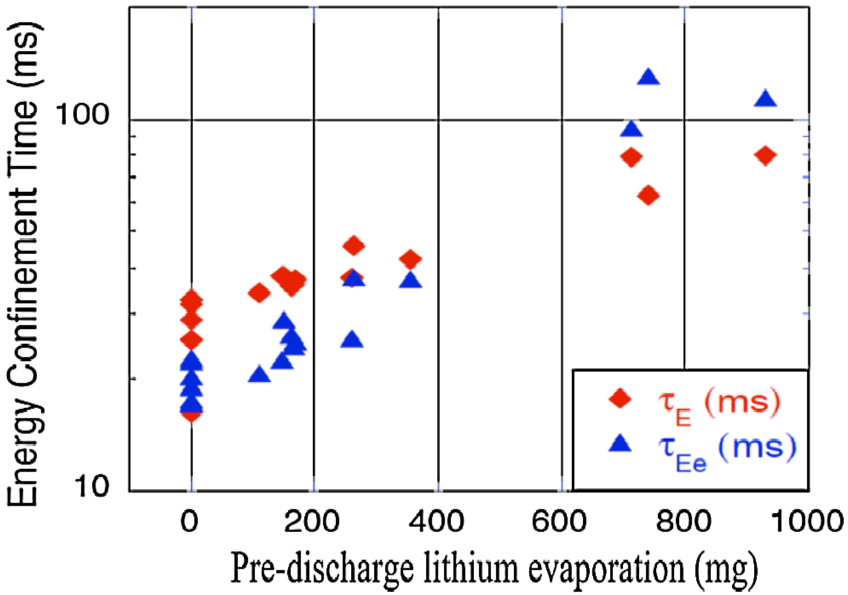
Boundary Physics Research Plans for FY2012-14:

Advance snowflake & edge turbulence understanding, plan cryo & PFCs

- FY12-13: Perform modeling of synergy of snowflake with radiative divertor in NSTX, project to NSTX-U and beyond
- FY12-13: Perform cryo-pumping physics design for NSTX-U compatible with vessel geometry and snowflake shapes
  - Use SOLPS to interpret/reproduce heat and particle flux profiles from high I_P and P_{NBI} discharges from NSTX, project to NSTX Upgrade *(Initial results indicate snowflake compatible with cryo-pumping)*
- FY12-14: Study divertor power exhaust with high-Z Mo PFCs on C-Mod & EAST, assess for NSTX-U
  - Assess Mo with low-Z (B & Li) coatings, study cryo-pumping for density control with moly PFC (particle balance, supersonic gas jet fueling), possibly radiative divertor control development (C-Mod)
- FY12-14: Investigate pedestal transport & turbulence:
  - Utilize correlation reflectometer on C-Mod, EPH/VH expts + XGC0 simulations on DIII-D, SOL turbulence with GPI on EAST and C-Mod

Lithium coatings will continue to be an important research tool for NSTX-U

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

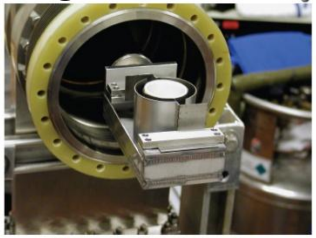


- Energy confinement increases continuously with increased Li evaporation in NSTX
- High confinement very important for FNSF and other next-steps

what is τ_E upper bound?

- Work with LTX to understand Li chemistry, impact of wall temperature, Li coating thickness
- Assess D pumping vs. surface conditions (MAPP), lab-based surface studies, PFC spectroscopy
- Design/develop methods to increase Li coating coverage:
  - upward evaporation
  - evap into neutral gas
  - Li paint sprayer

LTX



Y_2O_3 crucible, Ta heater
➤Tested to 700 °C

- Assess impact of full wall coverage on pumping, confinement
- Test Li coatings for pumping longer τ_{pulse} NSTX-U plasmas

Lithium Research Plans for FY2012-14:

Advance-Li PFC understanding and technology, R&D for flowing Li

- FY12: Model D pumping from Li coatings in NSTX, project to NSTX-U conditions, compare to cryo-pumping projections
- FY12-13: Collaborate with EAST/HT-7 on lithium research
  - Assess interplay between cryo-pumping and lithiumization, and high-Z PFC interactions/synergies with lithium
  - Study effects of Li on thermal and particle transport, further develop sustained/long-pulse lithium delivery systems (Li slapper, dropper)
- FY12-14: Measure Li coating lifetime on ATJ, TZM, W for NSTX-U like divertor conditions: Magnum-PSI collaboration
- FY13: Study lithium-conditioned surface composition using MAPP (Purdue) between-shot surface analysis on LTX
- FY13-14: Develop Li-coating tool for upper PFCs of NSTX-U, +
  - Perform lab-based R&D to develop circulation of Li in/out of divertor
  - Physics/pre-conceptual design of next-generation LLD with flowing Li and/or capillary porous system (CPS)

NSTX-U team continuing to strongly support ITER through participation in ITPA joint experiments and activities

NSTX typically actively participates in ~25 Joint Experiments/Activities

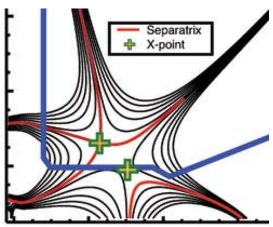
- **Advanced Scenarios and Control (4)**
  - IOS-1.2 Study seeding effects on ITER baseline discharges
  - IOS-4.1 Access conditions for advanced inductive scenario with ITER-relevant conditions
  - IOS-4.3 Collisionality scaling of confinement in advanced inductive plasmas
  - IOS-5.2 Maintaining ICRH coupling in expected ITER regime
- **Boundary Physics (10)** (R. Maingi PEP co-chair)
  - PEP-6 Pedestal structure and ELM stability in DN
  - PEP-19 Edge transport under the influence of resonant magnetic perturbations
  - PEP-23 Quantification of the requirements of ELM suppression by magnetic perturbations from internal off mid-plane coils
  - PEP-25 Inter-machine comparison of ELM control by magnetic field perturbations from mid-plane RMP coils
  - PEP-26 Critical edge parameters for achieving L-H transitions
  - PEP-27 Pedestal profile evolution following L-H/H-L transition
  - PEP-28 Physics of H-mode access with different X-point height
  - PEP-31 Pedestal structure and edge relaxation mechanisms in I-mode
  - PEP-32 Access to and exit from H-mode with ELM mitigation at low input power above P_{LH}
  - DSOL-24 Disruption heat loads
- **Macroscopic Stability (5)**
  - MDC-2 Joint experiments on resistive wall mode physics (Led by S. Sabbagh)
  - MDC-4 Neoclassical tearing mode physics – aspect ratio comparison
  - MDC-14 Rotation effects on neoclassical tearing modes
  - MDC-15 Disruption database development
  - MDC-17 Physics-based disruption avoidance
- **Transport and Turbulence (7)** (S. Kaye recently chaired T&C)
  - TC-9 Scaling of intrinsic plasma rotation with no external momentum input
  - TC-10 Experimental identification of ITG, TEM and ETG turbulence and comparison with codes
  - TC-12 H-mode transport at low aspect ratio
  - TC-14 RF rotation drive
  - TC-15 Dependence of momentum and particle pinch on collisionality
  - TC-17 ρ^* scaling of the intrinsic torque
  - TC-19 Characteristics of I-mode plasmas
- **Wave-Particle Interactions (4)**
  - EP-2 Fast ion losses and redistribution from localized AEs
  - EP-3 Fast ion transport by small scale turbulence
  - EP-4 Effect of dynamical friction (drag) at resonance on non-linear AE evolution
  - EP-6 Fast ion losses and associated heat loads from edge perturbations (ELMS and RMPs)

Formulating FY2014-18 5 year plan to access new ST regimes with Upgrade + additional staged & prioritized upgrades

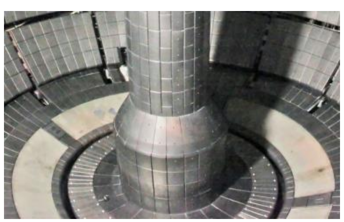
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

1 MA Plasma	Upgrade Outage	1.5 → 2 MA Plasma

- CHI Control Coils
- LLD
- Moly-tile
- HHFW Upgrade

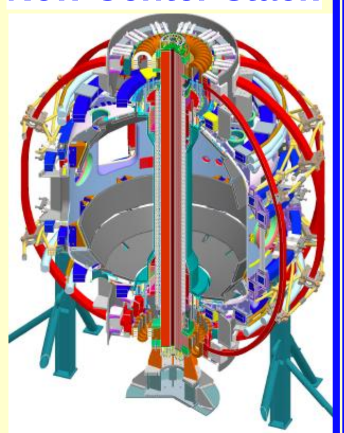


"Snowflake"

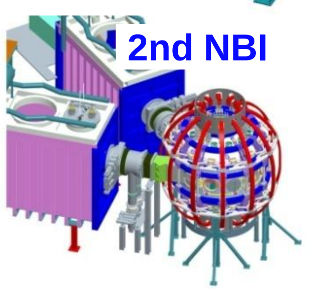

Lithium

- New Center-Stack
- 2[nd] NBI

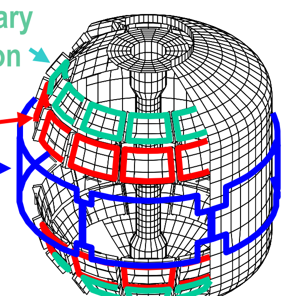
New Center-stack



2nd NBI



- 0.5 MA CHI
- 1 MA CHI / Plasma Gun
- ECH/EBW 1MW → 2 MW
- 0.5 MA Plasma Gun
- Long–pulse Divertor
- NCC Upgrade



Non-axisymmetric Control Coils (NCC)

NSTX Upgrade research goals in support of FNSF and ITER

- Low collisionality plasma regimes
- 100% non-inductive operation
- Long-pulse, high power divertor
- Advanced high-β scenarios

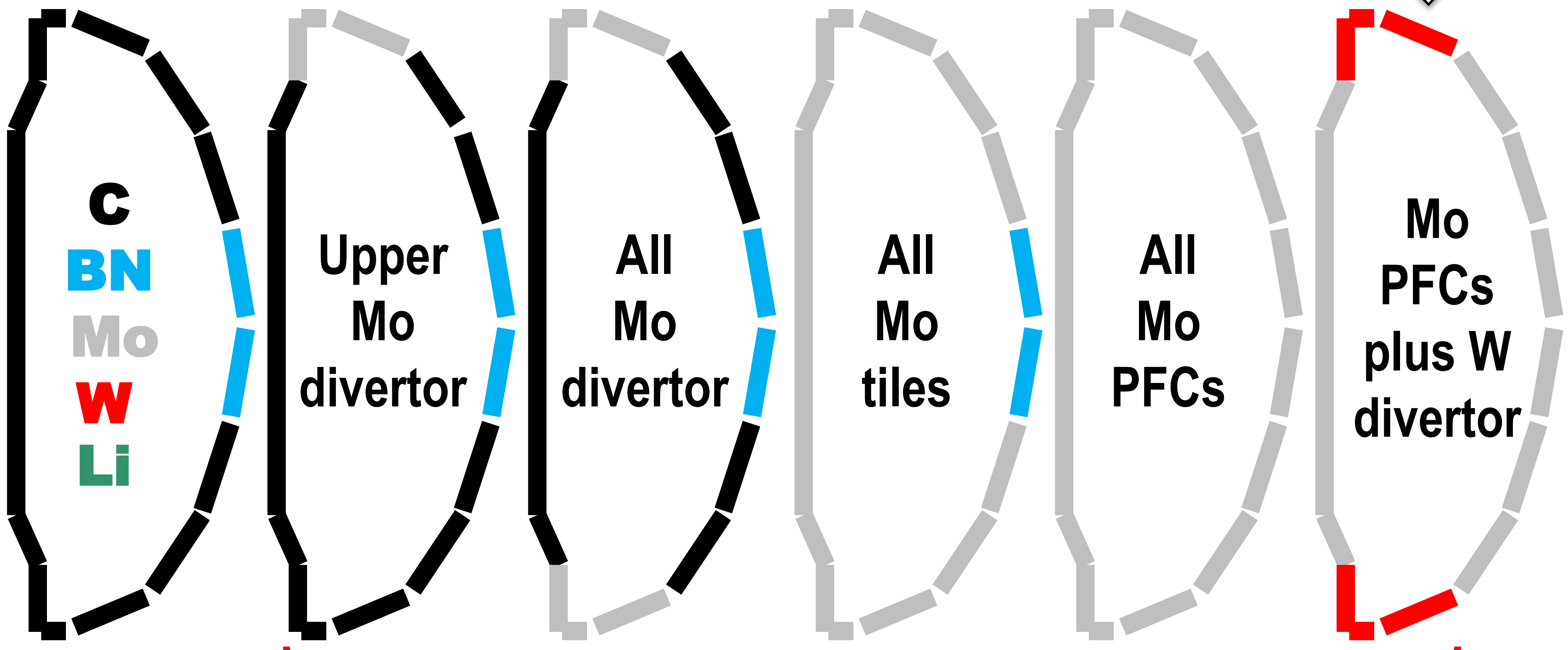
NOTE: Upgrade operation would be delayed ~1 year to mid-2015 w/o incremental, other follow-on upgrades are further delayed

NSTX-U 5 year plan goal: transition to (nearly) complete wall coverage w/ metallic PFCs to support FNSF PMI studies

- Assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Baseline

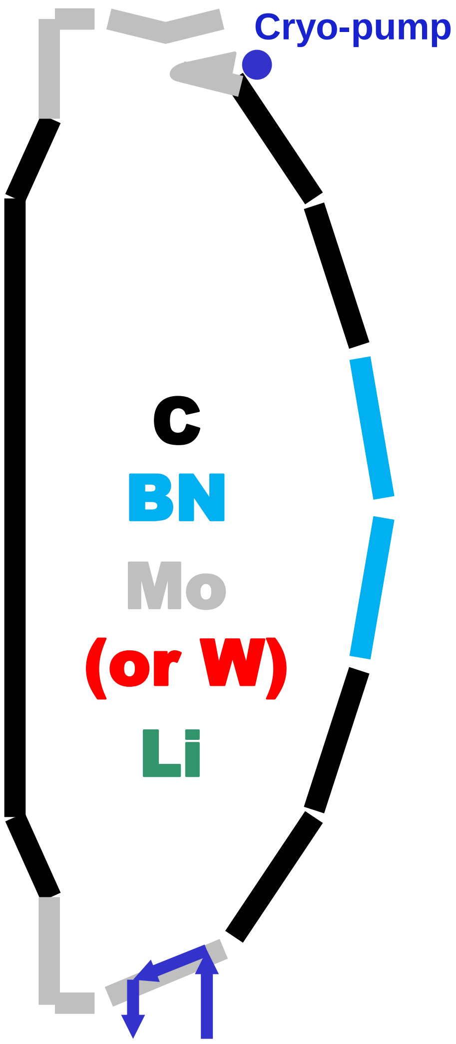
W is leading candidate material for FNSF/Demo divertor



Possible implementation paths for high-Z PFCs

Beginning of 5 yr plan → **End of 5 yr plan**

Direct comparison of cryo-pumping and flowing LLD by end of next 5 yr plan would inform FNSF divertor decisions

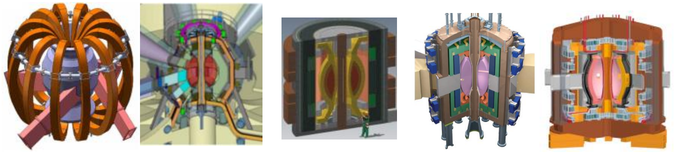


Flowing LLD, MAPP probe, possible replaceable divertor module (RDM)

- Partially-detached snowflake + cryo-pump may provide sufficient heat-flux mitigation and particle control for NSTX-U, FNSF
  - *Presentation by J. Canik will discuss cryo-design*
- However, erosion of solid PFCs could pollute plasma, damage FNSF divertor/FW
  - FNSF at 30% duty factor → ~10^2 - 10^3 kg net erosion / year for typical FNSF size & power
  - Further motivates research in flowing liquid metals
- 5 year plan for divertors (present thinking):
  - Dedicate upper divertor to cryo-pump
  - Dedicate lower divertor to flowing liquid Li tests, materials analysis particle probe (MAPP)

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

- Overarching goal of study:
  - Determine optimal mission, performance, size



- Goals of study:
  - Review existing designs, identify advantageous features, utilize these features in an updated and potentially improved configuration
  - Assess potential of designs to achieve T self-sufficiency
  - Assess maintainability and upgradeability of internal components
    - Consider divertors, shields, blankets, and identify maintenance strategies
  - Perform at least one self-consistent and detailed physics and engineering assessment for use by community

- Strong ST community participation in the study so far
  - Input from 13+ NSTX physicists + other US & UK researchers, LDRD supporting modest engineering and neutronics analysis

Summary: NSTX-U plan strongly supports OFES vision for fusion for next decade emphasizing ITER, PMI, FNSF

- **Plasma dynamics and control**
  - NSTX performed detailed measurements of turbulence, transport, core/edge stability, and integrating this knowledge to develop advanced high-β ST scenarios
  - NSTX Upgrade will extend these scenarios to full non-inductive operation with current profile control + advanced stability control w/ application to FNSF, ITER-AT
- **Plasma material science and technology, support FNSF**
  - NSTX has provided critical data on SOL-width scaling and SOL turbulence, novel high-flux-expansion divertors for heat-flux mitigation, and lithium-based PFCs
  - NSTX Upgrade will extend these studies to substantially higher heat flux, τ_{pulse}
  - NSTX + Upgrade providing critical data for assessing the ST as potential FNSF
- **Validated predictive capability, discovery science**
  - Performing leading validation efforts for turbulent transport, RWM stability and 3D MHD effects, edge turbulence, fast-ion transport from AE - **important to ITER, ST**
  - Upgrade will substantially extend range of collisionality, rotation, fast-ion drive, enabling access to a unique parameter regime of order-unity β and low ν^*

Backup material – PAC-29 recommendations

Table of responses to PAC-29 recommendations (1)

PAC Recommendation Number	PAC Report Section		PAC Recommendations	NSTX-U Response	Action for Speaker	Responsible person(s)
PAC29-1	1	Introduction	The NSTX Team should install the full complement of inner-divertor molybdenum tiles before the next run period and devote sufficient run time and research effort to evaluate the impact of the tiles, both with and without Li deposition.	Agree: Mo tiles will be installed in either the upper or lower divertor of NSTX-U as soon as economically feasible	Discuss programmatic and project objectives for Mo tiles and metal PFCs generally	Menard: include discussion in program talk, Ono: discuss how/when to implement in facility talk
PAC29-2	1	Introduction	Before deposition of Li, the PAC recommends re-establishment of an ELMing H-mode baseline with boronized carbon (and Mo) plasma facing surfaces. The purposes of these experiments are (i) to observe density and impurity control with more conventional ELM regimes and plasma material interactions, (ii) to contrast and better understand the impact of Li in NSTX, and (iii) to provide discharge performance characteristics that will inform your divertor planning for the NSTX Upgrade	Agree: Boronization will be used to re-establish baseline operating conditions and ELMing H-mode, and controlled Li evaporation will also be assessed following a boron-only phase of initial operation.	Describe this plan	Ono: facility presentation
PAC29-3	1	Introduction	During these pre-lithium runs, take the opportunity to demonstrate two-feed antenna, full- power HHFW heating and demonstrate the compatibility of HHFW with NBI and your NSTX Upgrade discharge targets	Agree: however, HHFW may need some small lithiumization to control edge density and reduce surface wave excitaion and edge power losses	Describe this plan	Taylor: HHFW talk
PAC29-4	1	Introduction	Since a primary focus of the NSTX Upgrade five-year plan must be the demonstration of stationary, high-performance, non-inductive spherical torus (ST) discharges that will inform next-step fusion development choices, the PAC suggests the NSTX Team launch a serious cyropump and divertor geometry design study and develop an alternative to insure against uncertainties associated with the use of any next generation LLD in the NSTX Upgrade.	Agree	Present cryo-analysis performed to-date	Canik: particle control talk
	1	Introduction	Finally, in time for the PAC-31 meeting, the PAC asks that the NSTX Team describe their planning for the post April 2012 outage activities including:			
	1	Introduction	Design and scoping studies for the upgrade project:	Several areas for scoping studies were identified by NSTX at the last PAC, including:		
PAC29-5a				Start-up: CHI upgrades, point helicity injection (plasma guns)	Describe CHI TSC modeling, NIMROD results, CHI hardware needs, etc	Raman: SFSU talk
PAC29-5b				Boundary: Divertor cryo-pumps, divertor diagnostics	Describe cryo-pump analysis	Canik: particle control talk
PAC29-5c				Lithium: Additional Mo tiles, upward Li evaporators, next-gen LLD	Describe planning for and status of Mo tiles, new evaporators, next-gen LLD	Skinner: Lithium research talk
PAC29-5d				Transport, EP: New high-k scattering, polarimetry, assess solid-state NPA	Describe design progress for new high-k system, progress and plans for polarimetry/delta Bz	Ren for high-k/polarimetry, Podesta for fast-ion diagnostics
PAC29-5e				MHD: 3D-coil physics design for RWM/RMP/TM/EFC/NTV/TAE + disruption force diagnostics, disruption precursor ID	Describe previous work by Todd Evans/S. Sabbagh for 3D coils, disruption ID work by Gerhardt, mitigation system status (from Raman)	Park: macrostability talk
PAC29-5f				Control: Real-time-MSE for NBI J-profile control, rt-control of heat flux	Describe progress and plans for these activities (Kolemen and Soukanovskii work at DIII-D)	Gerhardt: ASC talk
PAC29-6	1	Introduction	Planning for start-up and initial discharges	Agree	Describe operational scenarios that will be targeted during first run year and expected field, current, power, pulse-length capabilities	Gerhardt: ASC talk
PAC29-7	1	Introduction	Longer-term discharge scenarios needed to achieve the project goal	Agree	Describe scenario modeling performed for full non-inductive, long-pulse, and high Ip scenarios	Gerhardt: ASC talk
PAC29-8	1	Introduction	The PAC sees an opportunity to optimize how personnel will be assigned, how collaborators will contribute, and how best to use the many experts on the NSTX Team to continue ST research and maximize preparations for the Upgrade.	Agree	Describe collaboration plans for Upgrade outage	Menard: program talk

Table of responses to PAC-29 recommendations (2)

PAC29-9	2	Specific Comments Pertaining to the Two Charge Questions	Regarding preparation for the Upgrade, the PAC endorses plans to emphasize divertor physics, the study of upper-null Snowflake, and the installation and study of Li-coated molybdenum tiles. Additionally, because of uncertainties associated with impurity accumulation, the PAC recommends the next run period include studies that inform your divertor planning for the Upgrade. These could include: (i) exploration and development of ELMing H-mode discharges with and without Li deposition, (ii) studies of impurity transport and confinement, and (iii) further investigations of impurity control techniques, like central electron heating and divertor gas puffing.	Agree, but these studies will need to be deferred to initial ops of NSTX-U		
PAC29-10	3.1	Boundary Physics	Develop effective strategy for particle control, *e.g.* , perform a serious cryo-pump design study	Agree	Present cryo-analysis performed to-date	Canik: particle control talk
PAC29-11	3.1	Boundary Physics	Identify/characterize impurity sources (spatial/temporal) and determine SOL/edge screening efficiency, including clarification of the divertor plasma characteristics and impurity generation mechanism; consider ELMing vs. ELM-free for impurity control	Agree		
PAC29-12	3.1	Boundary Physics	Consider performance of "conventional" divertors as backup to advanced Snowflake or Super-X configurations. For all divertor options, examine impact of divertor geometry for pumping and heat-flux control, e.g., open vs closed divertor and tilted divertor plates.	Agree	Present comparison of conventional vs. snowflake for cryo-pumping analysis (Canik) and discuss divertor modelling generally (Soukhanovskii)	Canik: particle control talk, Soukhanovskii: boundary physics talk
PAC29-13	3.1	Boundary Physics	Obtain measurements of ne, Te, and Ti in the divertor and the midplane, though Ti is most challenging; include mean and fluctuation levels for assessment of importance of turbulent or "blobby" SOL transport (repeated from last year). These investigations will help to understand divertor heat-flux-width scaling and if there is any transport mechanism specific in the ST plasma.	Agree - but this can only be addressed in NSTX-U, and over the longer term	Discuss plans for divertor/SOL diagnostics planned for initial NSTX-U ops and longer-term 5 year plan	Soukhanovskii: boundary physics talk
PAC29-14	3.1	Boundary Physics	Clarify the nature and implications of Li reduction of heat-flux width, λq; is this reduction due to a sheath-limited SOL? What are the implications for divertor power handling with a Li divertor for the Upgrade with higher power and longer pulse length? In addition, determination of the power balance in the divertor (exhaust power from main plasma, radiation loss power and target heat load) is desirable.	Agree	address these questions	Soukhanovskii: boundary physics talk
PAC29-15	3.1	Boundary Physics	Establish pre-lithium baseline discharges with boron (Snowflake, Mo tiles, HHFW)	Agree	Describe discharge scenarios to be tested pre-lithium	Soukhanovskii: boundary physics talk
PAC29-16	3.1	Boundary Physics	Provide data and participate in comparison with theory/simulations including neoclassical and turbulent transport in the edge/SOL.	Agree	Discuss any recent analysis results, and plans for this	Soukhanovskii: boundary physics talk
PAC29-17	3.1	Boundary Physics	With the new installation of Mo tiles on the inner divertor, and reuse of the Mo trays on the outer divertor, it is desirable to initially obtain baseline discharges without lithium evaporation (but with boron conditioning) and then move to lithium coatings. In all cases, measurements should be made of Mo influx in the divertor and edge/core, as well as plasma parameters in the divertor and edge.	Agree	Discuss divertor impurity diagnostics that will be available during initial ops and longer term	Soukhanovskii: boundary physics talk
PAC29-18	3.2	Lithium and Divertor Physics	Given the present evidence, we agree with the NSTX strategy to install Mo tiles but this must be properly integrated into the entire run plan to provide several go/no-go decisions on Upgrade. These include (i) assure proper mechanical installation/alignment, (ii) cleaned Mo surfaces, even if it takes dedicated runs, (iii) optimized lithium deposition rates (e.g. ~ 0.1–1 micron), (iv) thermography, recycling, MAPP, and material mixing. Make diagnostics and quantitative assessment of Li/Mo/C PMI critical to this campaign.	Agree	Soukhanovskii: discuss tile alignment requirements , Skinner: Discuss ongoing lithium research program for surface cleaning, optimum Li deposition rate, recycling analysis, and MAPP plans on LTX for NSTX-U	Soukhanovskii: boundary physics talk, Skinner: lithium research talk
PAC29-19	3.2	Lithium and Divertor Physics	Given the central role of PMI to the NSTX/ST program, continue the investments and upgrades to PMI science capabilities in Upgrade regardless of the divertor path selected. These include divertor Thomson scattering, material probes, investigations of the Snowflake at small angles between the magnetic field and divertor surface, and similar research tasks.	Agree	Soukhanovskii: discuss proposal for divertor MPTS and any snowflake-specific diagnostic requirement	Soukhanovskii: boundary physics talk
PAC29-20	3.3	Macro-stability Research	We encourage the group to explore further the commonalities between RWM and RMP physics, in particular as regards kinetic effects on the plasma response.	Agree	Describe progress and plans for inclusion of kinetic effects for RWM and other MHD modes	Park: macrostability talk

Table of responses to PAC-29 recommendations (3)

PAC29-21	3.3	Macro-stability Research	We approve of the plans for NSTX to address ITER-relevant questions relating to the forces during disruptions, and encourage the group to give these experiments suitable priority before the shutdown.	Agree	Describe disruption precursor identification/prediction from Stefan	Park: macrostability talk
PAC29-22	3.4	Turbulence and Transport	Therefore the PAC encourages the NSTX team to pursue its investigations to clarify the relative role of microtearing, GAE and ETG modes. The combination of low and high k fluctuation measurements will certainly be useful in that matter. Regarding this point, the PAC was very pleased to see that the NSTX team is making progress in designing a new high-k diagnostic, which will replace the present one in FY 13 or 14.	Agree	Describe design progress for new high-k system, progress and plans for polarimetry/delta Bz	Ren for high-k/polarimetry, Podesta for reflectometry for GAE/CAE
PAC29-23	3.4	Turbulence and Transport	Also it appears that the L-H power threshold is sensitive to the major radius at the X-point, in accordance with predictions of the XGC0 code. Among the various unresolved issues, one may quote the large difference in the level of fluctuations that is observed with and without Li, the dynamics of the L-H transition and its propagation to the core, and the conditions for the onset of the EP H mode. These issues certainly deserve some attention, given the central importance of this topic for MFE.	Agree	Discuss results and plans for edge turbulence with and without Li, and related to the L-H transition	Ren: transport and turbulence talk
PAC29-24	3.4	Turbulence and Transport	Progress on impurity transport is also noticeable. This is an important issue in view of long pulse operation on NSTX. Preliminary measurements using the new SXR diagnostic are encouraging. This activity should be amplified in order to assess impurity transport in the core. Molybdenum should be given special attention, as it is a possible choice for divertor tiles.	Agree, but these studies will need to be deferred to initial ops of NSTX-U	Discuss core lithium concentration analysis and paper by Podesta, any recent work from JHU group on this, JK Park projections of 2D vs. 3D neoclassical particle transport, possibly Scotti's work on neoclassical particle transport of Li and C	Ren: transport and turbulence talk
PAC29-25	3.4	Turbulence and Transport	Also the PAC recognizes the effort that has been done to develop techniques for controlling the impurity content, in particular ELM triggering, unfavourable ion ∇B direction controlling impurities in the core should be further investigated.	Agree, but these studies will need to be deferred to initial ops of NSTX-U	Discuss any recent work from D. Battaglia or others on this topic	Ren: transport and turbulence talk
PAC29-26	3.5	Energetic Particles	The PAC agrees with plans of the Wave-Particle Group to continue to validate simulation capability in this area, as this will aid assessment of fast ion losses for NSTX-U. In particular we think it is important to pursue eigenfunction modeling with the HYM code using GAE experiments, comparison of non-linear M3D-K against experiment (mode structure, bursting and chirping behavior), and extend the NOVA-K + ORBIT simulations to include the use of the SPIRAL code. The PAC recommends this validated simulation capability be applied to H-mode plasmas in both NSTX and NSTX-U, especially considering the effect of redistribution of NBI ions due to MHD activity on current profiles in the Upgrade. Because of the increased toroidal field range in NSTX-U, we note that it may be possible to explore the transition regime between V > VAlfven and V < VAlfven.	Agree	Discuss progress and/or plans for all of these recommended research areas	Podesta: energetic particle talk
PAC29-27	3.5	HHFW	In the upcoming experimental run period it is highly recommended that baseline antenna operation with boronization be carried out before the start of the lithium campaign, thus providing information on performance of the upgraded antenna system in the absence of lithium. This will allow a more direct comparison to pre-reconfiguration performance.	Agree	Discuss plans for wall conditioning for optimal HHFW antenna performance in NSTX-U (perhaps describe what combinations of B and/or Li previously optimized HHFW performance)	Taylor: HHFW talk
PAC29-28	3.5	HHFW	Production of RF plus NBI H-modes at higher plasma current should be done to establish their feasibility and assess the level of parasitic losses in combined HHFW-NBI experiments.	Agree	Discuss plans and any recent modelling of HHFW for NSTX-U at higher field and current	Taylor: HHFW talk
PAC29-29	3.5	HHFW	Also, observations of density pump-out in H-mode plasmas should be pursued to determine if this is a carbon pump-out effect or not.	Agree	Discuss any analysis of core C impurity concentration changes in response to HHFW	Taylor: HHFW talk
PAC29-30	3.5	HHFW	In light of the fact that the magnetic field for the Upgrade will be 1 T and the harmonic resonances will be correspondingly lower, it is again recommended that the NSTX Team revisit the absorption and propagation physics of HHFW in NSTX-U. We encourage them to use the AORSA+ORBIT RF simulation capability to assess HHFW-NBI interaction at lower harmonic number in these plasmas and to use 3-D AORSA simulations to assess surface wave excitation, accounting for any differences that are expected in the scrape off layer plasma of NSTX-U	Agree	Discuss any modelling that has been performed or is planned to be performed to address this physics	Taylor: HHFW talk
PAC29-31	3.6	Solenoid-Free Start-up	The PAC is also pleased to see that TSC modeling has been performed not only to better understand ongoing experiments but also to project the current with higher toroidal field as will be provided in the upgrade. The projected larger plasma current could be helpful to simplify the start-up and ramp-up scenario. Further TSC modeling in support of ongoing experiments is encouraged.	Agree	Describe recent TSC modelling activities related to CHI and plasma current ramp-up	Raman: SFSU talk
PAC29-32	3.6	Solenoid-Free Start-up	We urge that more complete diagnosis of CHI plasmas be high priority in these experiments. It is clear that data such as Thomson scattering profiles have been essential to understand how CHI works.	Agree	Describe diagnostics needed for CHI start-up research in NSTX-U	Raman: SFSU talk

Table of responses to PAC-29 recommendations (4)

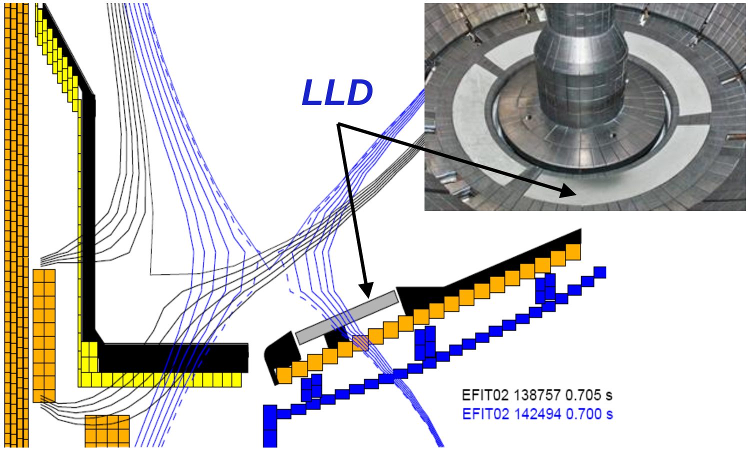
PAC29-33	3.6	Solenoid-Free Start-up	The PAC also notes that the milestone calling for an assessment of confinement in CHI plasmas means that complete diagnosis needs to be implemented as soon as possible. This will also better expose the unique qualities of CHI plasmas, such as the ability to attain low density.	Agree	Describe diagnostics needed for CHI start-up research in NSTX-U	Raman: SFSU talk
PAC29-34	3.6	Solenoid-Free Start-up	The PAC agrees that the NSTX plan for adding molybdenum tiles on the inboard divertor will be interesting for CHI experiments, as this will provide a metal cathode surface that seemed to be preferred in HIT experiments. The PAC urges measurements of impurity content in the core to assess quantitatively the effect of the plasma-electrode interaction, which may lead to high-Z impurity production.	Agree	Describe impurity diagnostics needed for CHI start-up research in NSTX-U, and role/importance of high-Z PFCs in NSTX-U divertor	Raman: SFSU talk
PAC29-35	3.6	Solenoid-Free Start-up	The PAC recommends maintaining a focus on non-inductive sustainment in steady current conditions to optimize HHFW, which has a number of issues discussed above in section 3.5. Here we emphasize the importance of HHFW experiments early in the campaign before large amounts of lithium are used to facilitate high power antenna operation with the modified antenna-grounding scheme.	Agree	Describe analysis, modeling results, and plans for 100% non-inductive current drive of low-Ip HHFW-sustained plasmas in NSTX-U	Taylor: HHFW talk
PAC29-36	3.7	Advanced Scenarios and Control	the PAC suggests a balanced approach between the searches for a low-fueling/low core impurity ELM-free H-mode solution with the development of non- ELM-free scenarios for impurity/ density control.	Agree, but these studies will need to be deferred to initial ops of NSTX-U	N/A	N/A
PAC29-37	3.7	Advanced Scenarios and Control	During the upcoming operating period prior to the outage, the PAC recommends that experiments emphasize experiments that will form the basis for rapid exploitation of the new tools to be available in NSTX-U. The emphasis in scenario development research should continue to focus on techniques for long-pulse density and impurity control including exploration of non- ELM-free H-mode scenarios	Agree, but these studies will need to be deferred to initial ops of NSTX-U	N/A	N/A
PAC29-38	3.7	Advanced Scenarios and Control	Additionally, increased emphasis should be placed on determining the compatibility of HHFW (in particular plasma-antenna gap) and long-pulse, high power NBI.	Agree, but these studies will need to be deferred to initial ops of NSTX-U	Describe any analysis/modelling of effect of outer gap on NBI-heated scenarios (Gerhardt) and any related modelling done for effect of gap on HHFW (Taylor)	Taylor: HHFW talk, Gerhardt ASC talk
PAC29-39	3.7	Advanced Scenarios and Control	Near-term EP-H mode experiments should focus on operation space and control methods for achieving this regime more reliably	Agree, but these studies will need to be deferred to initial ops of NSTX-U	N/A	N/A
PAC29-40	3.7	Advanced Scenarios and Control	The PAC recommends the NSTX team take steps to reduce the uncertainties with regard to long- pulse, high performance operation on NSTX-U. In particular, the NSTX Team needs to develop a path forward for density/impurity control in high-performance plasmas. While the proposed increased coverage of Li/Mo may be successful in suppressing the density/impurity buildup, the PAC notes that the results obtained to date in NSTX are very reminiscent of ELM-free H-mode operation in conventional aspect-ratio tokamaks, which have essentially abandoned this operation regime because of the uncontrolled density/impurity buildup. In this regard, the PAC recommends that the NSTX team begin to evaluate other options for density control in NSTX-U including divertor cryopumps and non- ELM-free H-mode scenarios	Agree	Describe cryo-pump analysis	Canik: particle control talk
PAC29-41	3.7	Advanced Scenarios and Control	Additionally, the PAC recommends detailed modeling of non-inductive capability in NSTX-U. Results presented at this PAC indicate that the most favorable experimental case (i.e., with high βp, high q95) achieved ~ 50% bootstrap current. Separate calculations indicate that off-axis NBI will provide ~ 350 kA @ 6 MW. Simple current drive balance suggests that the maximum plasma current in which fully non-inductive current drive could be obtained is ~ 700 kA. Scenario modeling with realistic transport models should be done to determine the expected limitations	Agree we should improve modelling of this	Describe extensive TRANSP analysis performed for NSTX-U scenarios	Gerhardt: ASC talk
PAC29-42	3.8	ITER urgent needs, cross-cutting and enabling	As the use of neither liquid (LLD) nor solid lithium (LiTER) so far did provide the much needed solution to the particle/impurity accumulation problem in the ELM free high performance discharges the PAC encourages the team to research more conventional fallback solutions such as stationary type-I ELMy H-mode or small ELM regimes together with a cryo-pump alongside the more experimental solution (liquid Li, Li dropper, Li pellets etc.).	Agree, but the experimental studies will need to be deferred to initial ops of NSTX-U	Describe cryo-pump analysis, projected pumping persistence of lithium coatings, and ELM pacing effects on impurities	Canik: particle control talk

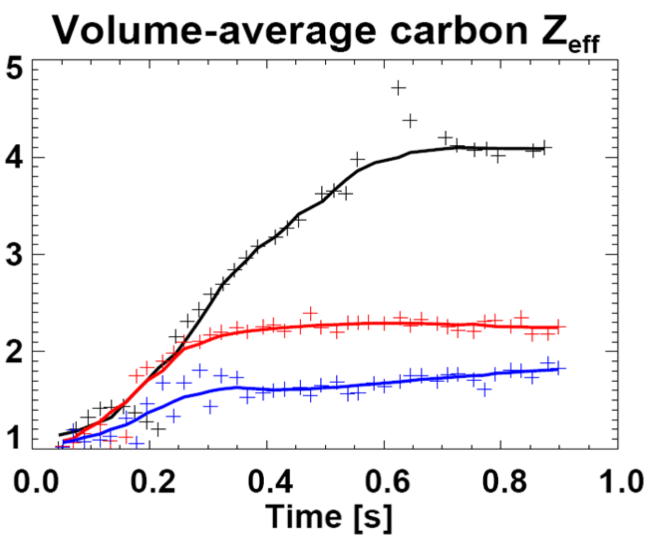
Table of responses to PAC-29 recommendations (5)

PAC29-43	3.8	ITER urgent needs, cross-cutting and enabling	In this context, the PAC agrees that the installation of Mo tiles at the inner divertor to serve as a possible substrate for a liquid Li PFC remains a high priority in order to allow for an informed decision about the PFC material in the upgrade. However, it is important that if technically possible full toroidal Mo coverage is provided, and enough time is devoted to characterizing the PFC choice. Here, it is important to allow for comparison discharges on clean as well as boronized C and Mo surfaces before the first Li evaporation.	Agree, and full toroidal coverage of Mo tiles was implemented prior to the TF fault, and future experimental studies will need to be deferred to initial ops of NSTX-U	Discuss Mo tile and metal PFC plan for NSTX-U	**Ono:** discuss how/when to implement in facility talk
PAC29-44	3.8	ITER urgent needs, cross-cutting and enabling	The PAC also recommends quantifying the wall pumping with and without Li (solid or liquid). This should be compared to studies of possible cryo-pump performance in different divertor geometries as conventional fallback solution.	Agree	Describe projected pumping persistence of lithium coatings	**Canik:** particle control talk
	3.8	ITER urgent needs, cross-cutting and enabling	Nevertheless, the PAC feels that the NSTX team should also consider strongly contributing the following other urgent ITER needs. These areas provide a large overlap with the NSTX-U needs. In the case of disruptions (items 1, 2) a characterization of halo currents, toroidal peaking factors and first wall heat loads is important since disruption forces in the upgrade will be much higher than in the current device. Also the NSTX team should work on viable ramp down scenarios to avoid disruptions in the first place. With respect to (items 2, 3) emphasis should be given to the characterization of impurity and particle sources.			
PAC29-45	3.8	ITER urgent needs, cross-cutting and	1. Contribution to a new disruption DB including conventional and advanced scenarios and heat loads on wall/targets.	Agree, but the experimental studies will need to be deferred to initial ops of NSTX-U	Describe halo current analysis by Gerhardt, other disruption studies by Gerhardt	**Park:** macrostability talk
PAC29-46	3.8	ITER urgent needs, cross-cutting and	2. Understand the effect of ELMs/disruptions on divertor and first wall structures.	Agree, but the experimental studies will need to be deferred to initial ops of NSTX-U	Describe any (new) divertor heat flux analysis or simulations during disruptions	**Park:** macrostability talk
PAC29-47	3.8	ITER urgent needs, cross-cutting and	3. Improve understanding of SOL plasma interaction with the main chamber.	Agree, but the experimental studies will need to be deferred to initial ops of NSTX-U	Describe any analysis or modelling of this that has been done	**Soukhanovskii:** boundary physics talk
PAC29-48	3.8	ITER urgent needs, cross-cutting and	4. Predict ELM characteristics and develop small ELM and quiescent H-mode regimes and ELM control techniques.	Agree, but the experimental studies will need to be deferred to initial ops of NSTX-U	Describe pedestal stability analysis studies carried out during last year by Diallo, Maingi	**Soukhanovskii:** boundary physics talk

Backup: LLD results and needs for flowing LLD

Operation with outer strike-point on liquid lithium divertor (LLD) (porous Mo coated w/ Li) compatible w/ high plasma performance





LLD FY2010 results:

- **LLD did not increase D pumping beyond that achieved with LiTER**
- **No evidence of Mo from LLD in plasma during normal operation**
- **Operation with strike-point on LLD can yield reduced core impurities**
- **Row of inboard Mo tiles installed for FY11-12 run, can re-use in NSTX-U**

◄Strike-point on inner C divertor (no ELMs)

◄Strike-point on LLD, $T_{LLD} < T_{Li\text{-}melt}$

◄Strike-point on LLD, $T_{LLD} > T_{Li\text{-}melt}$ (+ fueling differences)

- **No ELMs, no → small, small → larger**

Li + plasma-facing component research will be continued, extended in NSTX-U

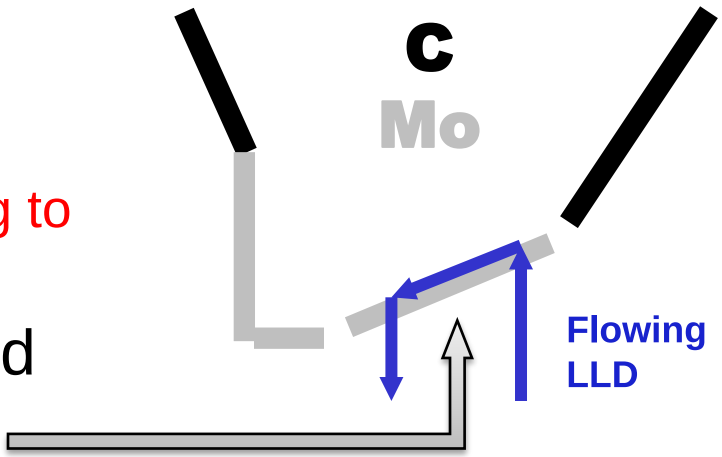
Flowing LLD will be studied as alternative means of particle and power exhaust, access to low recycling

- LLD, LTX → liquid Li required to achieve pumping persistence
  - Flowing Li required to remove by-products of reactions with background gases
- Substantial R&D needed for flowing Li
- Need to identify optimal choice of concept for pumping, power handling:
  - Slow-flowing thin film (FLiLi)
  - Capillary porous system (CPS)
  - Lithium infused trenches (LiMIT)

  All systems above require active cooling to mitigate highest heat fluxes of NSTX-U
- Elimination of C from divertor needed for "clean" test of LLD D pumping
  - May need to remove all C PFCs?

Possible approach:

- Dedicate 1-2 toroidal sectors (30-60˚ each) to LLD testing (and/or integrate with RDM?)
- Test several concepts simultaneously
- Full toroidal coverage after best concept is identified



Backup: summary of collaboration activities

Collaborations: Held team-wide discussion on FY12-13 opportunities and expectations in Sep-Dec 2011

- Collaboration should aim to support NSTX-Upgrade mission
  - Also support toroidal physics generally, ICCs, and non-fusion applications
- For all researchers, use Upgrade outage as opportunity to:
  - Extend and improve your ongoing and future research on NSTX
  - Learn about other facilities – bring back knowledge, best practices
  - Try or learn something new – new physics, diagnostics, analysis, …
- Aim to form small teams from NSTX (PPPL + non-PPPL)
  - Coordinate research plans, analysis, travel, and participation
- Expectations for researchers:
  - Select 1 primary and 1 secondary/backup collaboration project
  - Aim for 1st author papers, invited talks – PRL/NF/PoP, APS/IAEA
  - Present your results periodically to NSTX, PPPL research seminars
- Facilities: MAST, DIII-D, C-Mod, LHD, EAST, KSTAR, JET, more to come
- Funding: PPPL covers salaries of PPPL NSTX researchers by default
- Challenge: no additional NSTX funding dedicated to collaboration
- Working closely with PPPL off-site research department

Collaborations in materials/PMI, boundary physics

- EAST is only other divertor H-mode facility using lithium
  - Li/transport expts on EAST – D. Mansfield, J. Menard, M. Jaworski, K. Tritz
- Li surface chemistry issues on LTX, working with PU, Purdue
  - Use Purdue MAPP on LTX + surface/PMI studies – C. Skinner, M. Jaworski
  - Improve equilibrium reconstruction/control on LTX – Gerhardt, Menard
- Assess high-Z PFCs for NSTX-U through collaboration on C-Mod
  - LLNL group to assess: Mo with low-Z coatings, study cryo-pump for density control with moly PFC (particle balance, supersonic gas jet fueling), possibly radiative divertor control development
- Develop NSTX-U snowflake control on DIII-D
  - V. Soukhanovskii + E. Kolemen
- Test LLNL SPRED, NIR for NSTX-U divertor diagnosis
  - LLNL to work with Y. Raitses' LTP source
- Pedestal/SOL transport, turbulence, stability research for ITER and NSTX-U
  - Pedestal turbulence using correlation reflectometer on C-Mod - A. Diallo
    - A. Diallo also planning XPs on DIII-D (R. Groebner), possibly MAST
  - XGC0 simulations of DIII-D edge transport w/ 2D & 3D fields - D. Battaglia
  - SOL turbulence measurements with GPI on EAST, C-Mod - S. Zweben

Collaborations on core transport and turbulence

- Pursue TGLF/TGRYO studies for scenario prediction for NSTX-U and DIII-D, also DIII-D transport studies
  - W. Guttenfelder, Y. Ren, and S. Kaye
- Comparison of NSTX and MAST transport physics, BES data
  - S. Kaye, W. Guttenfelder, D. Smith/Univ. Wisconsin
- Exploration of new/needed turbulence diagnostics for NSTX-U
  - PCI for intermediate $k_\theta \rho_s$ (C-Mod) – Y. Ren
  - Polarimetry for δB from μ-tearing (DIII-D & C-Mod) – Ren, Guttenfelder
- Impurity transport studies, perturbative transport
  - Exploring use of ME-SXR on EAST for profile meas. – K. Tritz (JHU)
- 3D field effects on transport and turbulence
  - Transport simulations on LHD - D. Mikkelsen & (maybe) W. Guttenfelder

Collaborations in start-up, scenarios/control, MHD

- Plasma start-up
  - Work with Pegasus on plasma guns, possibly DIII-D to improve PF-only + EC start-up and inform proposed NSTX-U ECH/EBW – D. Mueller
  - Investigate application of CHI on QUEST – R. Raman (U. Wash)
  - EBW startup experiments on MAST - G. Taylor
- Advanced Scenarios and Control - E. Kolemen (relocated to GA)
  - Prepare for current and rotation profile control in NSTX-U through collaboration on DIII-D using off-axis NBI (and counter-NBI), NTV
  - Contribute to development of ITER plasma control specification
  - MAST vertical control analysis/experiments – prep for NSTX-U/MAST-U
  - Long-pulse tokamak ops/control experience (EAST/KSTAR) – D. Mueller
- MHD Physics
  - Assist DIII-D in new 3D δB sensors - N. Logan, J-K Park, J. Menard
  - 3D field physics in long-pulse H-mode in KSTAR – J.-K. Park, S. Sabbagh
  - RWM physics at reduced ν^* on DIII-D, NTV on MAST – S. Sabbagh/CU

Collaborations in waves and energetic particles, and diagnostic development

- RF coupling and edge-loss studies in DIII-D for NSTX-U, ITER
  - J. Hosea, R. Perkins, G. Taylor
- RF-only H-mode in EAST – R. Wilson, G. Taylor
  - Supports RF-only plasma heating/start-up studies for NSTX-U
- Energetic particles and Alfvén eigenmode physics
  - Study fast-ion physics on JET (2 year relocation), prep for possible DT campaign, beam ion loss measurements on LHD - D. Darrow
  - Several fast-ion/AE physics opportunities on MAST
    - Assess operation of MAST *AE antenna, participate in expts – E. Fredrickson
    - Assess performance of neutron collimator, NBI fast-ion redistribution models – M. Podesta
    - Fusion product loss detector – D. Darrow, W. Boeglin
- Diagnostic development
  - Assist with ITER diagnostics – B. Stratton
  - Assist with MPTS on JET, LTX, maybe KSTAR & Pegasus – B. LeBlanc
  - Develop/prepare new Accurate Wavelength Lens Spectrometer (AWLS) on LTX for installation/usage on NSTX-U – R. Bell

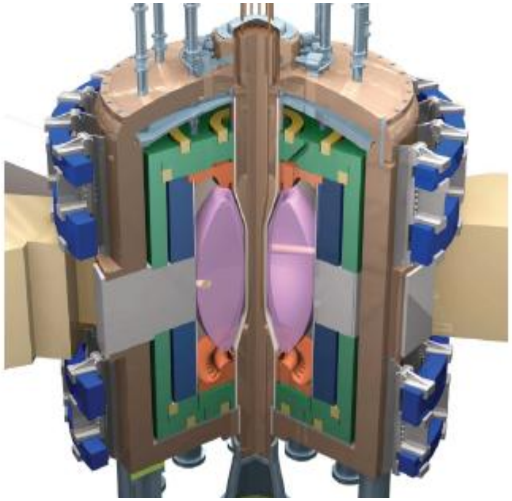
Some statistics, and issues going forward

- Tracking 30-35 researchers, including on-site collaborators
  - ~90% of researchers have definitive plans well-aligned with NSTX-U and/or PPPL research goals
- Approximate order of collaboration emphasis by facility:
  - DIII-D, C-Mod, EAST, MAST, KSTAR, LHD, LTX, …
  - U.S. facilities most mature in diagnostics, tools, analysis, and are therefore often most attractive to researchers
- EAST and KSTAR have expressed strong interest in collaboration from PPPL/NSTX researchers
  - EAST, KSTAR still developing diagnostics, heating systems, organization for integrating collaborators – improving
- Prep for NSTX-U operation highest priority by late 2013
  - Also tracking who/what is needed for operations and diagnostics

Additional backup

Mission of ST-FNSF

- **Provide a continuous fusion nuclear environment of copious neutrons to develop an experimental database on:**
  - Nuclear-nonnuclear coupling phenomena in materials in components for plasma-material interactions
  - Tritium fuel cycle
  - Power extraction



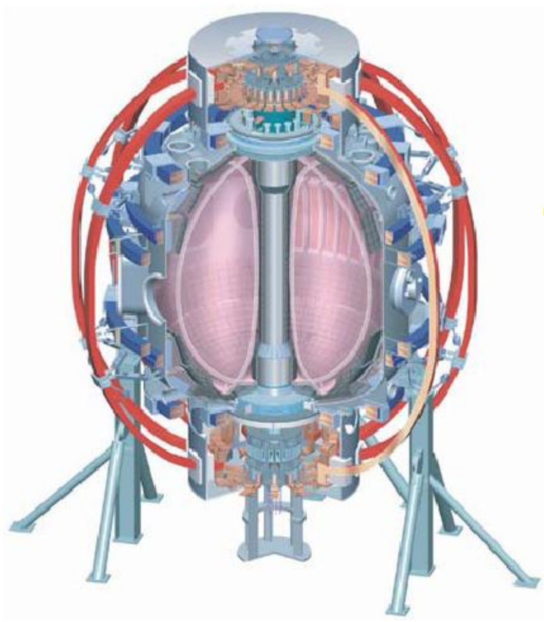
ST-FNSF

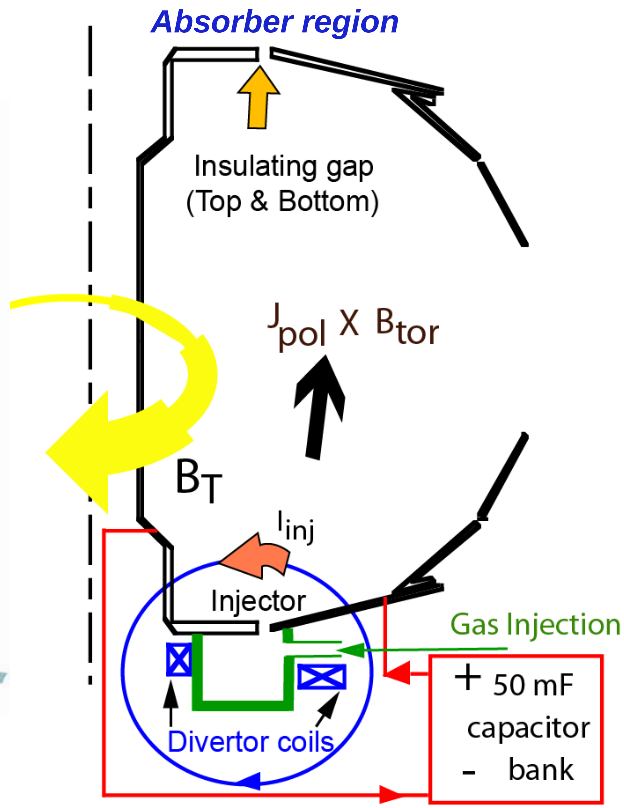
(M. Peng, ORNL)

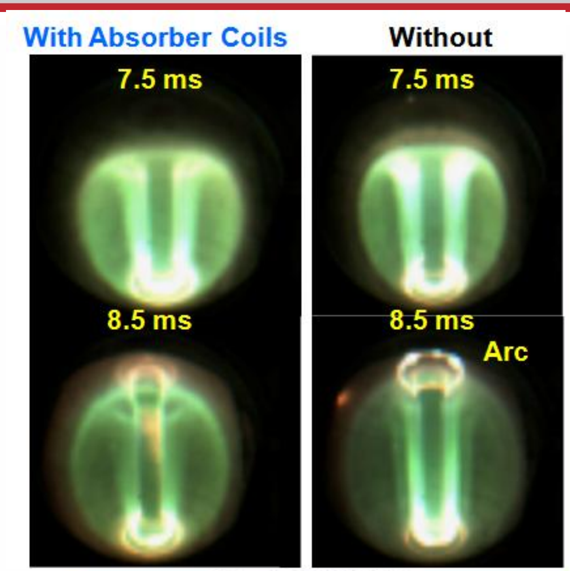
- **Complement ITER, prepare for component test facility (CTF):**
  - Low Q (≤ 3): 0.3 x ITER
  - Neutron flux ≤ 2 MW/m^2: 3 x
  - Fluence = 1 $MW\text{-}yr/m^2$: 5 x
  - t_{pulse} ≤ 2 wks: 1000 x
  - Duty factor = 10%: 3 x

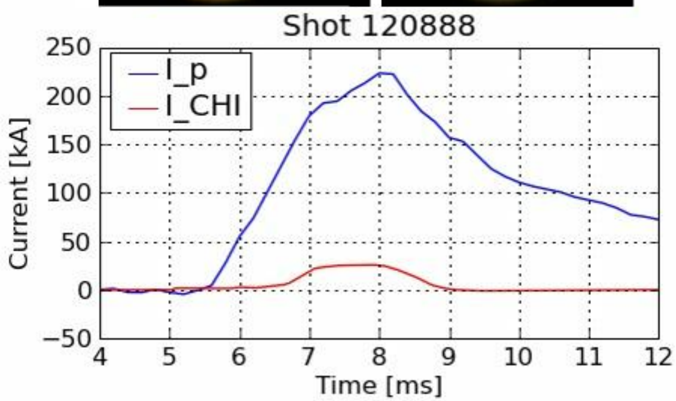
Low-aspect-ratio "spherical" tokamak (ST) is most compact embodiment of FNSF

Transient CHI: Axisymmetric Reconnection Leads to Formation of Closed Flux Surfaces









$$I_P = I_{inj}(\psi_T / \psi_{inj}) \qquad I_{inj} = 2\psi_{inj}^2 / (\mu_o^2 d^2 I_{TF})$$

- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - High efficiency (10 Amps/Joule in NSTX)