NSTX Program Overview and

NSTX Upgrade Physics Design Progress

J.E. Menard, PPPL

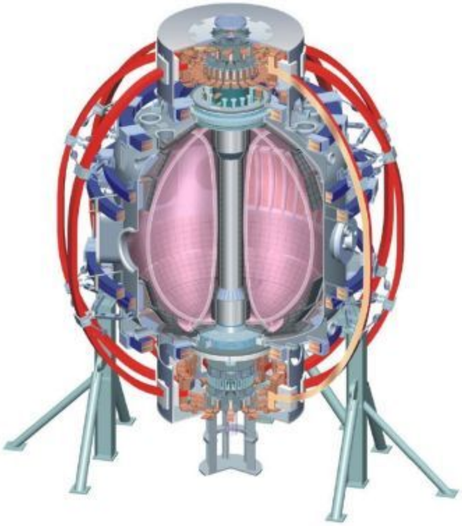
For the NSTX Research Team

NSTX PAC-27

February 3-5, 2010

LSB-B318, PPPL

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin



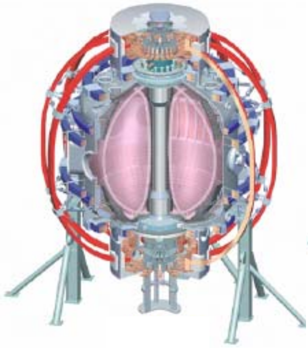
Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

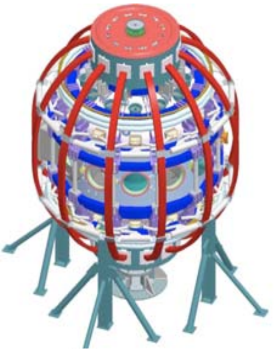
Outline

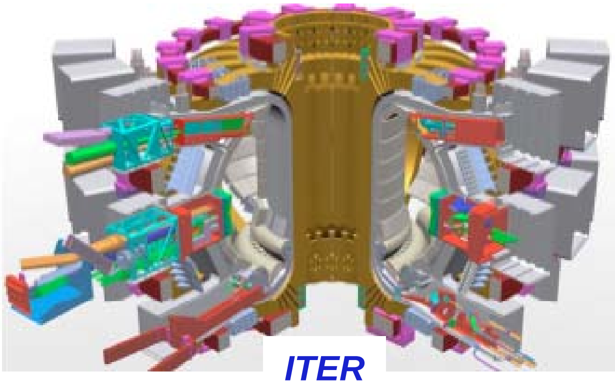
- NSTX Mission
- Linkages to ReNeW Themes and Thrusts
- FY2010-12 Research Milestones and ITER support
- FY2010-12 Milestone Timeline
- NSTX Upgrade Motivation, Progress, Needs
- Summary
- PAC-25 Responses

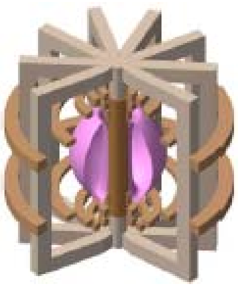
NSTX Mission Elements

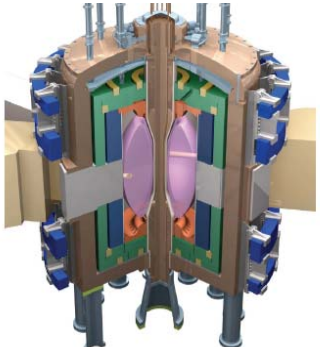
- **Understand unique physics properties of ST**
  - Assess impact of low A, high β, high v_{fast} / v_A on toroidal plasma science + impact of high power density on PMI
  - Longer term NSTX → NSTX Upgrade goals:
    - Study high beta plasmas at reduced collisionality
    - Access full non-inductive start-up, ramp-up, sustainment
    - Prototype solutions for mitigating high heat & particle flux
- **Extend tokamak physics understanding, support ITER**
  - Exploit unique and complementary ST features
  - Benefit from tokamak research and development
- **Establish attractive ST operating conditions**
  - Understand and utilize ST for addressing key gaps between ITER and FNSF / DEMO
    - ReNeW Thrusts 14-15 (FNS), 9-12 (PMI), 8 (self-driven high-Q_{DT})
  - Advance ST as fusion power source


NSTX


NSTX-U

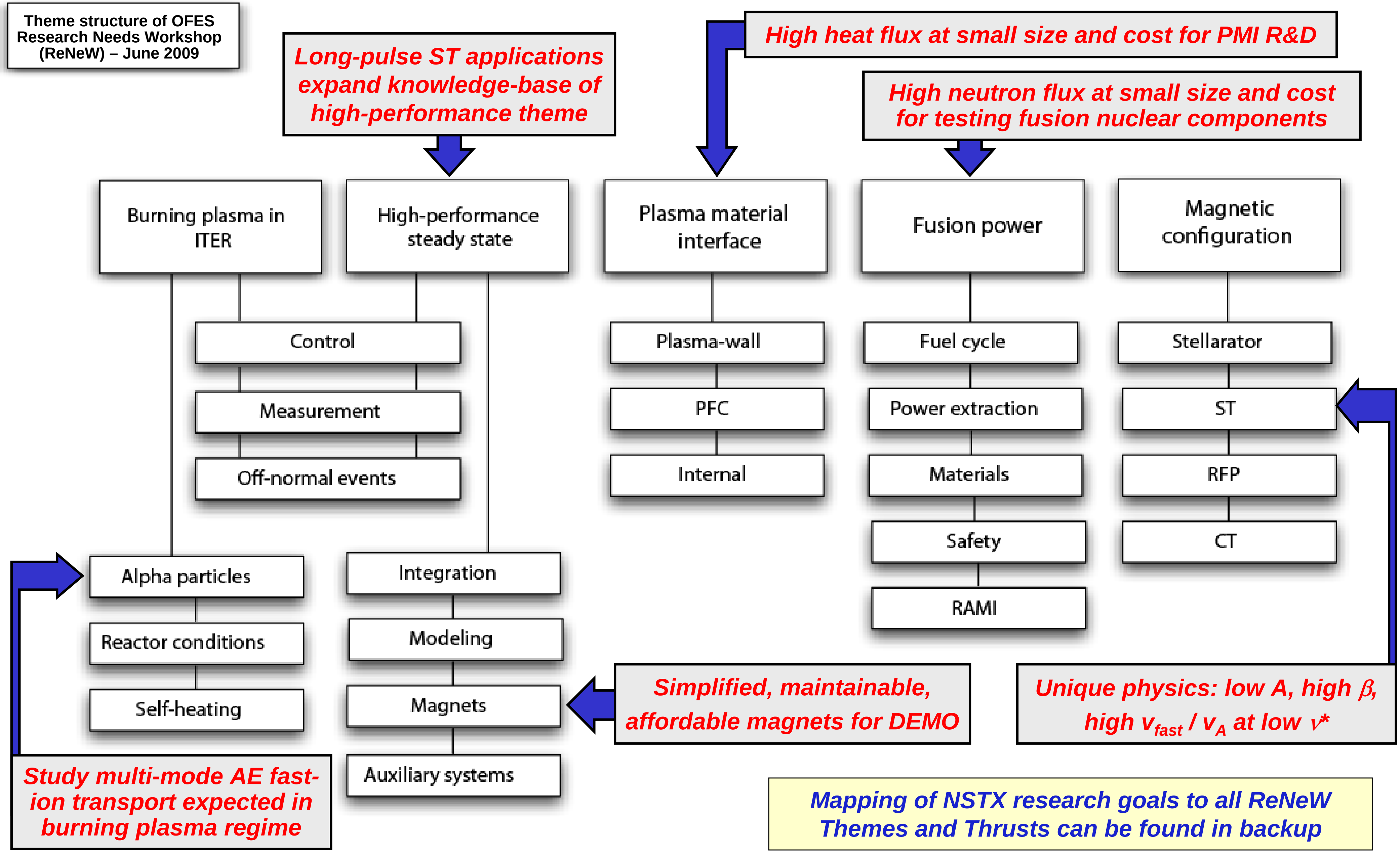

ITER


ST-based Plasma Material Interface (PMI) Science Facility


ST-based Fusion Nuclear Science (FNS) Facility

The ST provides unique contributions to all magnetic fusion research needs as expressed in the 5 ReNeW Themes

Theme structure of OFES Research Needs Workshop (ReNeW) – June 2009



Long-pulse ST applications expand knowledge-base of high-performance theme

High heat flux at small size and cost for PMI R&D

High neutron flux at small size and cost for testing fusion nuclear components

Burning plasma in ITER
- Control
- Measurement
- Off-normal events
- Alpha particles
- Reactor conditions
- Self-heating

High-performance steady state
- Control
- Measurement
- Off-normal events
- Integration
- Modeling
- Magnets
- Auxiliary systems

Plasma material interface
- Plasma-wall
- PFC
- Internal

Fusion power
- Fuel cycle
- Power extraction
- Materials
- Safety
- RAMI

Magnetic configuration
- Stellarator
- ST
- RFP
- CT

Study multi-mode AE fast-ion transport expected in burning plasma regime

Simplified, maintainable, affordable magnets for DEMO

Unique physics: low A, high β, high v_{fast} / v_A at low ν^*

Mapping of NSTX research goals to all ReNeW Themes and Thrusts can be found in backup

NSTX and Upgrade research goals and milestones strongly support research actions identified in ReNeW ST Thrust 16:

1. Develop MA-level plasma current formation and ramp-up
    - **CHI start-up and fast-wave ramp-up in NSTX, NBI ramp-up to ~1MA in Upgrade**

2. Advance innovative magnetic geometries, first wall solutions (liquid metals)
    - **"Snowflake" divertor, detachment, solid/liquid PFCs in NSTX and Upgrade**

3. Understand ST confinement and stability at fusion-relevant parameters
    - **Understand μ-turbulence and AEs in NSTX, extend to lower ρ^* and ν^* in Upgrade**

4. Develop stability control techniques for long-pulse disruption-free operation
    - **Advanced mode-ID and rotation control in NSTX, q(r) optimization in Upgrade**

5. Employ energetic particle beams, plasma waves, particle control, and core fueling techniques to maintain the current, control plasma profiles
    - **High $f_{\text{non-inductive}} \leq 70\%$ in NSTX (FW+NBI+BS), 100% NI + J(r) control in Upgrade**

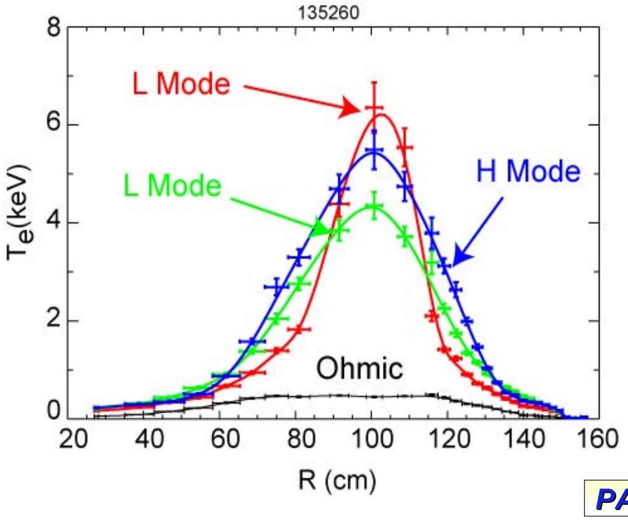
6. Develop normally-conducting radiation-tolerant magnets for ST applications
    - **Design and utilize higher-field TF magnet (0.5T → 1T) in Upgrade**

7. Extend ST performance to near-burning-plasma conditions
    - **NSTX and Upgrade + tokamak program provide physics basis for next-step STs**

The above list is also the outline for the FY2010-12 NSTX Research Milestones that follow:

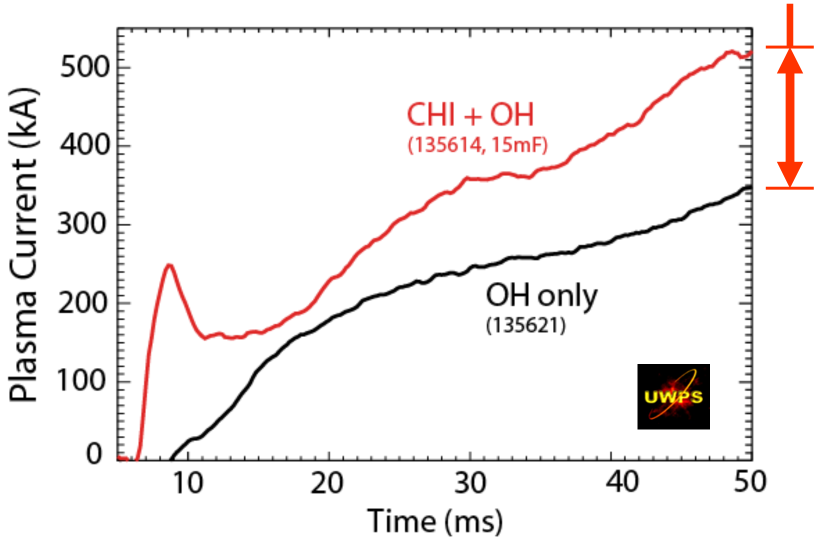
Non-inductive start-up and ramp-up using fast-wave heating and CHI will be developed and integrated for the ST

Upgraded HHFW has heated 100-200eV plasma to > 5keV in H-mode, maintained power during LH transition, ELMs



PAC25-4

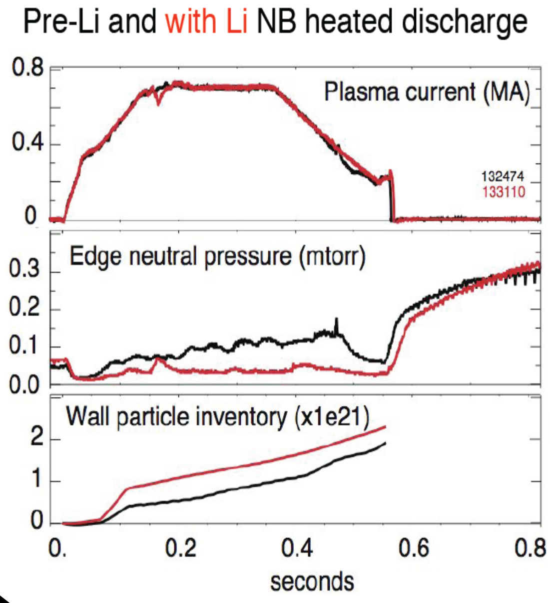
ΔI_P = 180kA OH flux savings achieved with CHI via low-Z impurity reduction

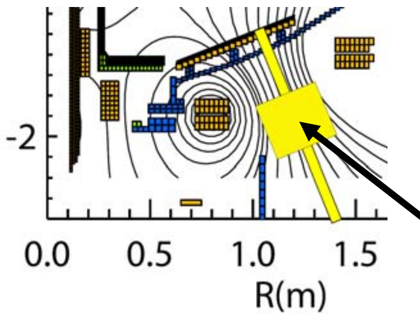


- Characterize HHFW heating, current drive, ramp-up in D H-mode [R10-2]
  - Attempt to sustain 100% non-inductive plasma (I_P = 250-400kA bootstrap CD)
  - Building on above sustained plasma, develop bootstrap current over-drive ramp-up
  - Heat electrons in reduced-density NBI-sustained H-mode to enhance NBI-CD
- Assess confinement, heating, and ramp-up of CHI start-up plasmas [R12-3]
  - Understand confinement of CHI plasmas - important for projecting start-up, ramp-up
    - Use HHFW to compare confinement, heating of CHI → OH plasmas vs. OH-only
  - Apply HHFW heating progressively earlier in shot → reduce OH swing toward zero

Lithium research will develop and assess novel Li-based PMI concepts for NSTX, NSTX Upgrade, and next-step ST/ATs

- Measured global retention ~90%
- Up to 2× increase in D pumping w/ Li
- Qualitatively correlates with surface conditions





FY10 emphasis: LLD wetting, loading, replenishment, D pumping, power handling

PAC25-4

- Assess the relationship between lithiated surface conditions and edge and core plasma conditions [R11-2]
  - Assess pumping, retention vs. Li coverage, LLD temperature, R_{strike}, flux expansion
  - Measure retention, surface composition near LLD in-vacuo with Materials Analysis and Particle Probe (MAPP), compare to dynamic retention measurements/models
  - Measure recycling on carbon and LLD surfaces with Lyman-α AXUV diode array
  - Measure C, Li density, transport from edge to core with toroidal, poloidal CHERS

NSTX collaborator Jean Paul Allain (Purdue University) awarded DOE-SC Early Career Award for research proposal for:
“Harnessing Nanotechnology for Fusion Plasma-Material Interface Research in an in-situ Particle-Surface Interaction Facility”

Boundary research will support two OFES joint research milestones: divertor heat flux, H-mode pedestal structure

FY2010: "Conduct experiments on major fusion facilities to improve understanding of the heat transport in the SOL plasma, strengthening the basis for projecting divertor conditions in ITER"

- Measure divertor heat flux profiles and plasma characteristics in the SOL
- Exploit range of SOL ν^*, β, $q_{||}$, divertor geometry spanned by 3 facilities

FY2011 Theory-Expt Milestone: "Understand mechanisms responsible pedestal structure, develop a predictive capability"

Experiment:

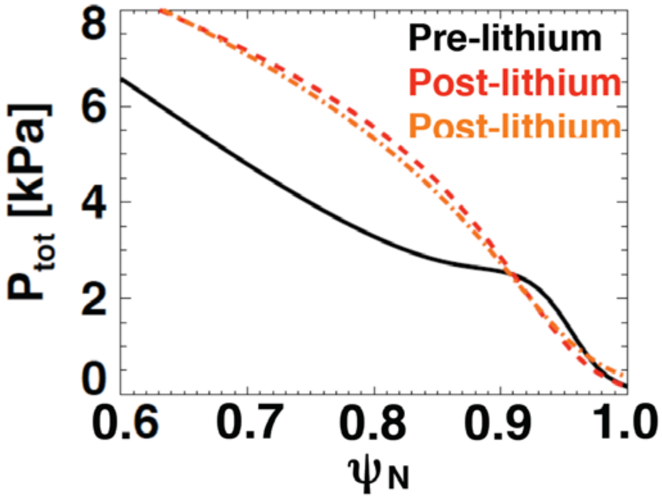
- Perform experiments to test physics models in pedestal on multiple devices
- Higher resolution pedestal structure data (MPTS upgrade - ARRA), E_r
- Perform initial measurements of turbulence in pedestal region (BES, GPI)

Theory:

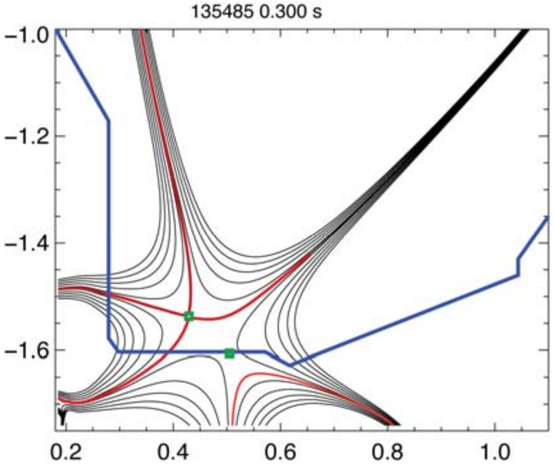
- Focused analytic theory/computation effort, include large-scale simulations
- Model key physics mechanisms in experiments, compare to observations

Boundary research will improve understanding of H-mode pedestal structure/control, improve divertor power handling

Li suppresses ELMs via profile modification



Testing high flux expansion “snowflake” divertor



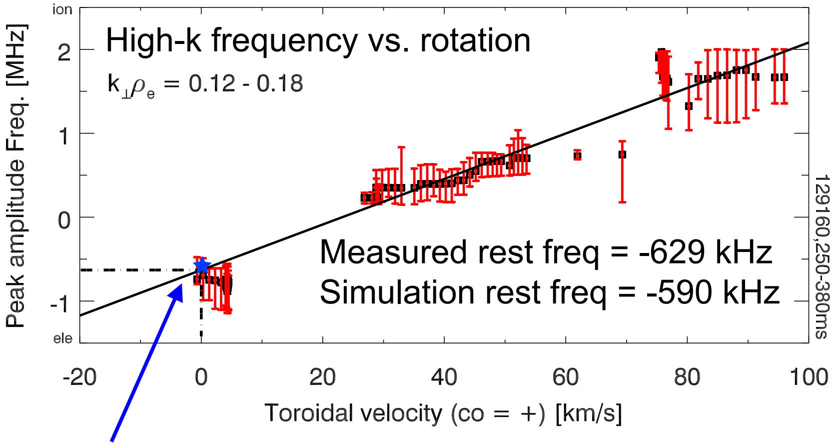
2009: NSTX measured reduced C influx and reduced peak heat flux with snowflake

PAC25-4

- Assess H-mode pedestal, ELM stability vs. ν^*, Li conditioning [R10-3]
  - Determine the relative roles of n_e, ν^* vs. direct effects of Li from LiTER and LLD
  - Assess L-to-H threshold, pedestal height/width/stability, down-stream conditions
- Assess pedestal/SOL response to applied 3D fields [IR11-2 (incremental)]
  - Improve understanding of physics of pedestal/SOL stability/transport vs. 3D fields
- Characterize very high flux expansion divertor operation [R12-2]
  - Investigate controllability, plasma response to “snowflake” and “x-divertor” divertor
    - Divertor power handling, LLD pumping, impurity production, SOL turbulence, ELMs
  - Considering high-Z metallic inboard divertor – if available, compare high-Z vs. Li

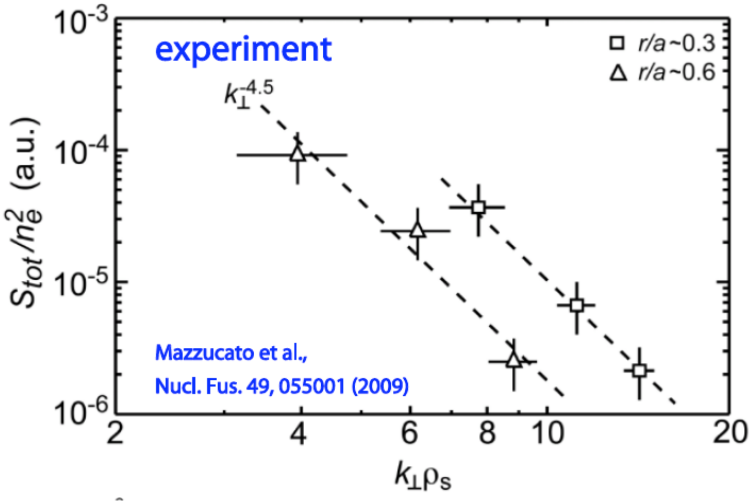
Transport research will exploit new diagnostics and modeling to better understand turbulent transport for the ST, tokamak

Linear GS2 / GYRO simulations of ETG mode frequency (and growth rate) consistent with high-k measurements



Rest frequency of peak amplitude mode measured by subtraction of Doppler shift due to plasma rotation

High-k turbulent $k_\perp$-spectrum exponent = -4.5 intermediate between k_r (-2.6) and k_θ (-5.3) exponents from non-linear GTS simulations

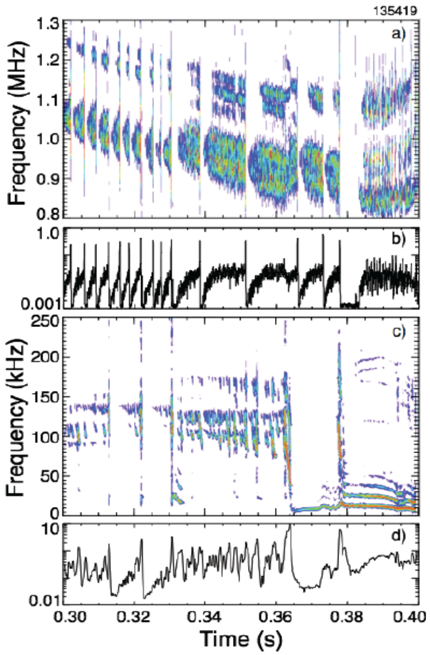


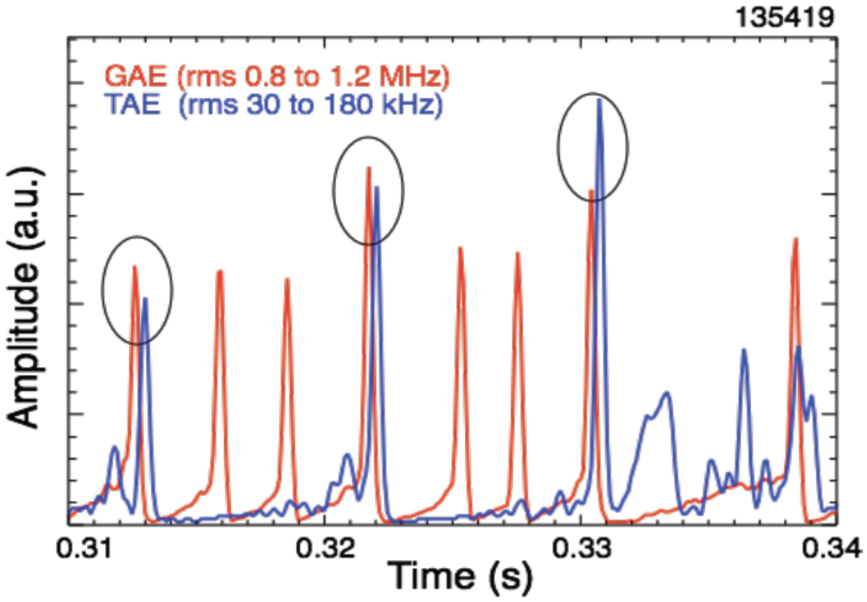
Mazzucato et al., Nucl. Fus. 49, 055001 (2009)

- Measure fluctuations responsible for turbulent energy transport [R11-1]
  - New: measure low-k turbulent δn/n with Beam Emission Spectroscopy (BES)
    - High-k portion will be measured with existing high-k μ-wave scattering diagnostic
  - Vary μ-instability drive parameters: ν*, Li, q-shear, E×B shear, I_P, B_T, …
  - Correlate turbulent k-spectrum with energy diffusivities inferred from power balance
- Enhance turbulent transport understanding by comparing measured fluctuations to theory and simulation [R12-1]
  - Compare measurements to micro-instability codes: GYRO, GTS, GS2, GTC-NEO

Energetic particle research will emphasize prediction of fast-ion transport from AE avalanches in H-mode for ST and ITER

GAE avalanches can spatially redistribute fast-ions, triggering TAE avalanches



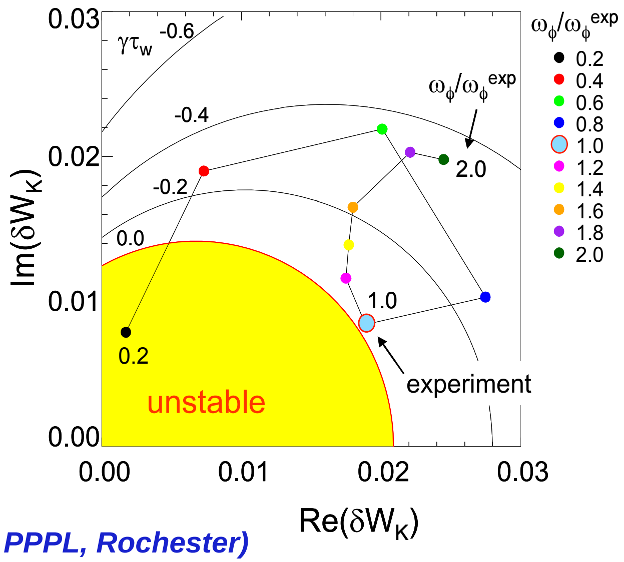


(incremental milestone)

- Assess predictive capability of mode-induced fast-ion transport [IR12-1]
  - Measure $\xi_r(R,t)$ **in H-mode** with BES + enhanced-resolution reflectometry
  - Improved measurements of the fast-ion distribution function utilizing a tangentially viewing Fast-Ion D_α (FIDA) diagnostic (extends existing perpendicular view)
  - Extend validation of NOVA-K/ORBIT TAE avalanche transport simulations, develop multi-AE + multi-mode + fast-ion transport predictions with M3D-K

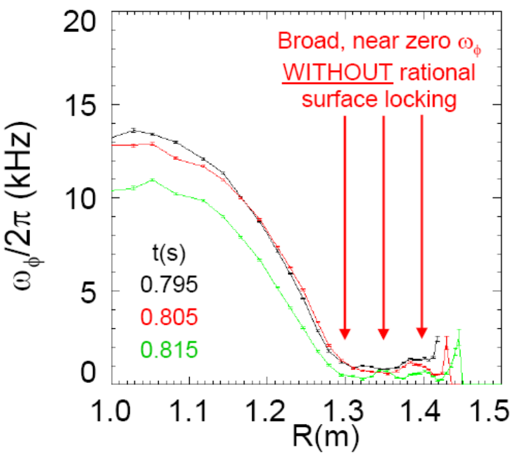
MHD research will assess and optimize mode and rotation control for sustained high-β scenarios for the ST and ITER

Due to influence of multiple kinetic resonances, RWM marginal stability depends on rotation non-monotonically



MISK modeling (CU, PPPL, Rochester)

NTV rotation damping also sensitive function of kinetic resonances: **observe stronger damping in super-banana plateau regime**

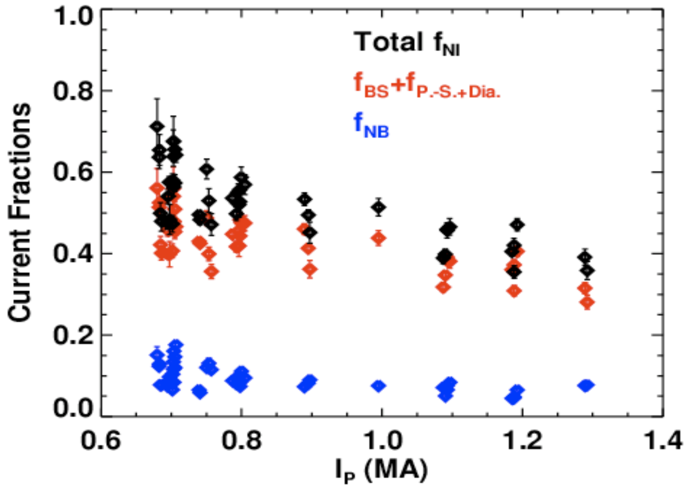


- Assess sustainable β and disruptivity near/above ideal no-wall limit [R10-1]
  - Assess impact of improved control: β_N control, improved RFA/RWM mode detection (sensor compensation), RWM state-space controller, effects of multi-mode RWM
  - Characterize degree to which other instabilities (2/1 NTM) impact disruptivity
- Assess RWM, rotation damping at reduced collisionality [IR11-1] (incremental)
- Investigate physics and control of toroidal rotation at low collisionality [R12-4]
  - Rotation control utilizing NTV braking (possibly NBI) will be assessed w/ ASC TSG
  - Develop NTV physics understanding vs. n=1-3, ν^*, β (RFA), rotation
  - MISK calculations of rotation profiles for optimized global & edge stability

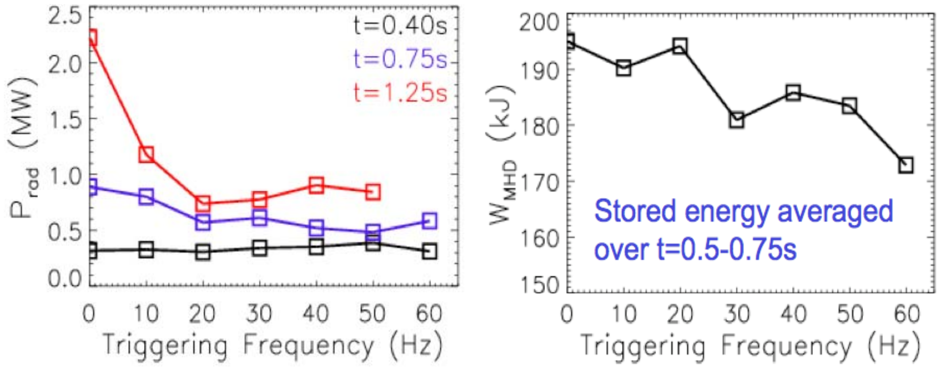
Advanced Scenarios/Control group developing tools needed for ST performance and understanding, prepare for NSTX-U

Goal: increase non-inductive CD from 70→100%:

Higher bootstrap → higher p_e thru higher T_e
Higher NBI-CD → lower ν^* → higher T_e, lower n_e



Pulsed 3D fields used to trigger ELMs to control impurity content, density in Li ELM-free plasmas



New for FY11: Independent control of n=1,2,3 fields to optimize ELM pacing, rotation braking and control

- Assess dependence of integrated plasma performance on ν^* [R11-2]
  - Use LLD to reduce the density and increase τ_E, HHFW to heat the electrons
  - Assess non-inductive current fraction, confinement, core and pedestal stability, pulse-duration, impurity content – evaluate with time-dependent TRANSP, TSC
- Investigate physics & control of toroidal rotation at low collisionality [R12-4]
  - Explore role of rotation profile on transport, bootstrap current, ELMs, impurities
    - Utilize new 2nd SPA (ARRA) to control profile with independent control of n=1,2,3 NTV
  - Real-time rotation to implemented in PCS in FY2011 to support control in FY2012
  - Rotation control algorithms already being modeled w/ momentum transport models

In FY2010-12, NSTX will support confinement, pedestal, ELM research identified as high priority by the ITER Organization

NSTX will dedicate 5 run-days in FY2010 specifically to ITER high-priority:

From ITER Physics Work Programme 2009-2011 - Sections 2.1 - ITER Short term activities (2008-2010) and 2.2 - ITER Medium term activities (2011 and beyond)

2.1.1 Transport and Confinement during transient phases

Assess NSTX confinement, H-mode threshold, etc. during ramp-up/down

2.1.2 Access to high confinement regimes in ITER during steady/state and ramp-up/down H, D and DT phases

Complete/extend NSTX L-H, H-L threshold experiments from FY2009 in FY2010-11

2.1.3 Characterization of proposed schemes for active ELM control, compatibility with scenario requirements

Contribute NSTX understanding of RMP ELM pacing results

2.2.1 Pedestal width, pedestal energy and uncontrolled ELM energy loss in ITER

Utilize OFES 3 facility joint research milestone on pedestal structure in FY2011

2.2.2 Development of alternative regimes providing high fusion performance in ITER without or with small ELMs compatible with overall scenario requirements

Attempt to extrapolate NSTX Type V ELMs to low ν*, explore access to QH mode

2.2.3 Develop alternative methods for ELM control/suppression in ITER & integration w/ scenario requirements

Extend NSTX vertical jogs and RMP fields for ELM pacing to smaller ELM size

Develop NSTX Li ELM-free H-mode with reduced/halted impurity accumulation

2.2.6 Momentum transport in ITER reference scenarios & expected plasma rotation in ITER

Use NSTX HHFW to reduce input torque, use NB pulses + CHERS for T_i and rotation

NSTX researcher Jong-Kyu Park (PPPL) awarded DOE-SC Early Career Award for proposal for:
“Self-consistent Calculations of Pedestal Structure Modification by 3D Fields in Tokamaks”

NSTX is presently participating in 26 ITPA joint experiments, and is actively engaged in 21

- **Advanced Scenarios and Control**
  - IOS-5.1 Ability to obtain and predict off-axis NBCD
  - IOS-5.2 Maintaining ICRH Coupling in expected ITER Regime
- **Boundary Physics and Lithium Research**
  - PEP-6 Pedestal structure and ELM stability in double null
  - PEP-16 C-MOD/NSTX/MAST small ELM regime comparison
  - PEP-19 Edge transport under the influence of resonant magnetic perturbations
  - PEP-23 Quantification of the requirements for ELM suppression by magnetic perturbations from internal off mid-plane coils
  - PEP-25 Inter-machine comparison of ELM control using mid-plane RMP coils
  - PEP-26 Critical edge parameters for achieving L-H transition
  - PEP-27 Pedestal profile evolution following L-H transition
  - DSOL-21 Introduction of pre-characterized dust for dust transport studies in divertor and SOL
- **Macroscopic Stability**
  - MDC-2 Joint experiments on resistive wall mode physics
  - MDC-4 Neoclassical tearing mode physics - aspect ratio comparison
  - MDC-12 Non-resonant magnetic braking
  - MDC-14 Rotation effects on neoclassical tearing modes
  - MDC-15 Disruption database development
  - MDC-17 Physics-based disruption avoidance
- **Transport and Turbulence**
  - TC-2 Power ratio - hysteresis and access to H-mode with H~1
  - TC-4 H-mode transition and confinement dependence on ionic species
  - 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 and confinement at low aspect ratio
  - TC-14 RF Rotation Drive
  - TC-15 Dependence of momentum and particle pinch on collisionality
- **Waves-Particle Interactions**
  - EP-1 Measurement of damping rate of intermediate toroidal mode number Alfvén Eigenmodes
  - EP-2 Fast ion losses and redistribution from localized Alfvén Eigenmodes
  - EP-4 Effect of dynamical friction (drag) at resonance on nonlinear AE evolution

Proposed NSTX FY2010-12 Research Milestones

(base and *incremental*)

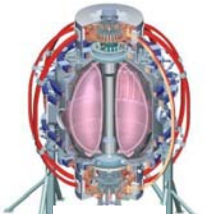
	FY2010	FY2011	FY2012
Expt. Run Weeks:	15 w/ ARRA	14 (20)	14 (20)
1) Transport & Turbulence		**Measure fluctuations responsible for turbulent ion and electron energy transport**	**Compare measured turbulence fluctuations to theory & simulation**
2) Macroscopic Stability	**Assess sustainable beta and disruptivity near and above the ideal no-wall limit**	*Assess RWM and rotation damping physics at reduced collisionality*	
3) Boundary/Lithium Physics	**Assess H-mode characteristics as a function of collisionality and lithium conditioning** PAC25-2	**Assess relationship between lithiated surface conditions and edge and core plasma conditions** PAC25-2 *Assess pedestal and SOL response to externally applied 3D fields*	**Assess very high flux expansion divertor operation** PAC25-2
4) Wave-Particle Interaction	**Characterize HHFW heating, CD, and ramp-up in deuterium H-mode** (joint with solenoid-free start-up TSG) PAC25-2		*Assess predictive capability of mode-induced fast-ion transport*
5) Solenoid-free start-up, ramp-up			**Assess confinement, heating, and ramp-up of CHI start-up plasmas** (joint with WPI-HHFW TSG) PAC25-2
6) Advanced Scenarios & Control		**Assess integrated plasma performance versus collisionality** PAC25-2	**Investigate physics and control of toroidal rotation at low collisionality** (joint with MS TSG) PAC25-2
Joint Research Targets (3 US facilities):	**Understanding of divertor heat flux, transport in scrape-off layer** PAC25-2	**Characterize H-mode pedestal structure** PAC25-2	Not yet decided

NSTX Upgrade will contribute strongly to toroidal plasma science and preparation for a fusion nuclear science (FNS) program

- NSTX:
  - Providing foundation for understanding ST physics, performance

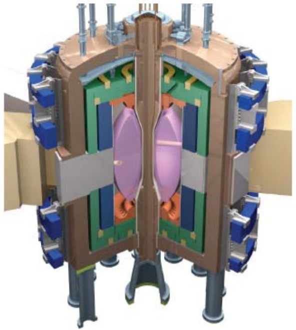
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality
    - Vital for understanding confinement, stability, start-up, sustainment
  - Assess full non-inductive current drive operation
    - Needed for steady-state operating scenarios in ITER and FNS facility
  - Prototype solutions for mitigating high heat, particle exhaust
    - Can access world-leading combination of P/R and P/S
    - Needed for testing integration of high-performance fusion core and edge

- NSTX Upgrade contributes strongly to possible next-step STs:
  - ST Fusion Nuclear Science Facility
    - Develop fusion nuclear science, test nuclear components for Demo
    - Sustain $W_{neutron} \sim 0.2\text{-}0.4 \rightarrow 1\text{-}2\,\mathrm{MW/m^2}$, $\tau_{pulse} = 10^3 \rightarrow 10^6\,\mathrm{s}$
  - ST Plasma Material Interface Facility
    - Develop long-pulse PMI solutions for FNSF / Demo (low-A and high-A)
    - Further advance start-up, confinement, sustainment for ST
    - High $P_{heat}/S \sim 1\,\mathrm{MW/m^2}$, high T_{wall}, $\tau_{pulse} \sim 10^3\,\mathrm{s}$

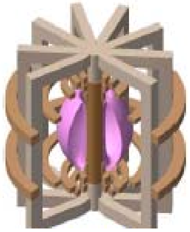


NSTX

NSTX-U



FNSF (ST-CTF)



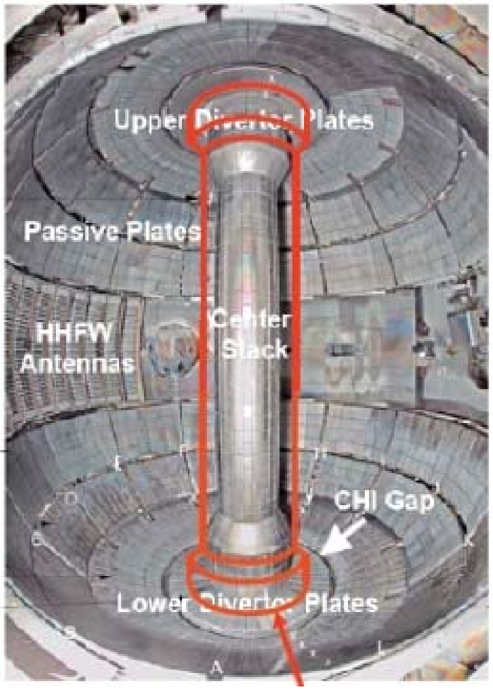
PMIF (NHTX)

Upgrades provide major step along ST development path

(next factor of 2 increase in current, field, and power density)

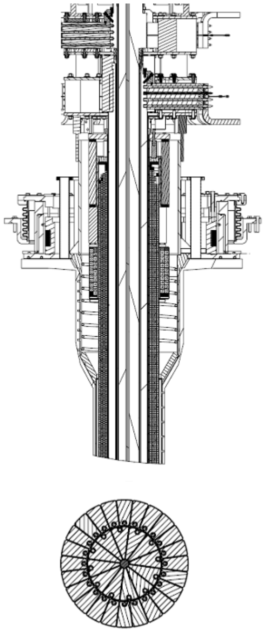
	NSTX	NSTX Upgrade	Plasma-Material Interface Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.7	≥ 1.5
Plasma Current (MA)	1	2	3.5	10
Toroidal Field (T)	0.5	1	2	2.5
P/R, P/S (MW/m,m^2)	10, 0.2*	20, 0.4*	40, 0.7	40-60, 0.8-1.2

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



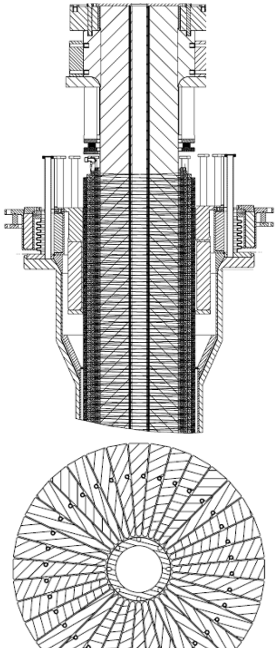
Outline of new center-stack (CS)

Present CS



TF OD = 20cm

New CS



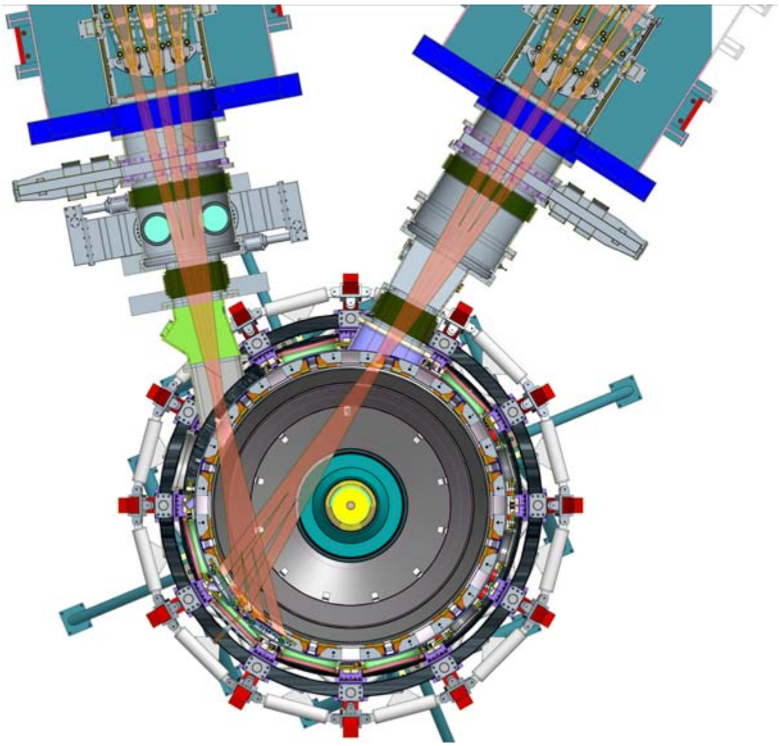
TF OD = 40cm

New 2^{nd} NBI

(R_{TAN}=110, 120, 130cm)

Present NBI

(R_{TAN}= 50, 60, 70cm)



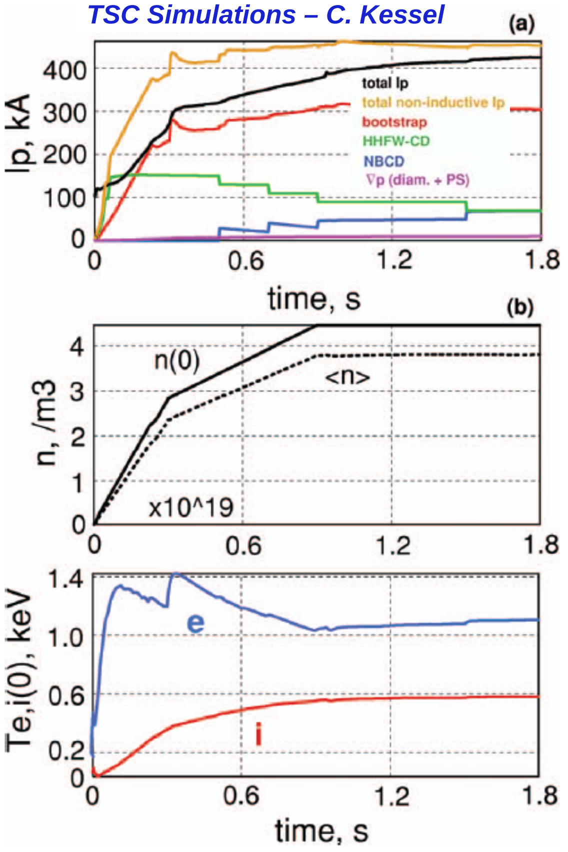
Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

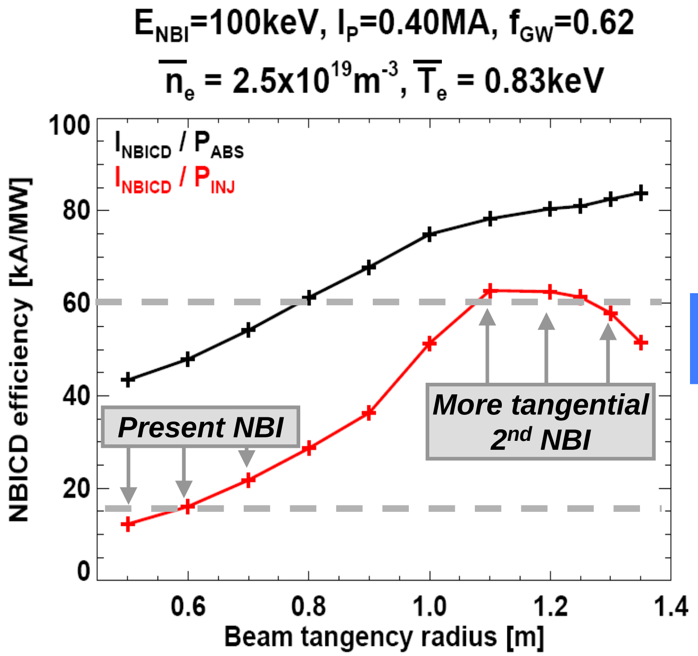
Ramp to ~0.4MA with fast wave heating:

- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

Extend ramp to 0.8-1MA with 2nd NBI:

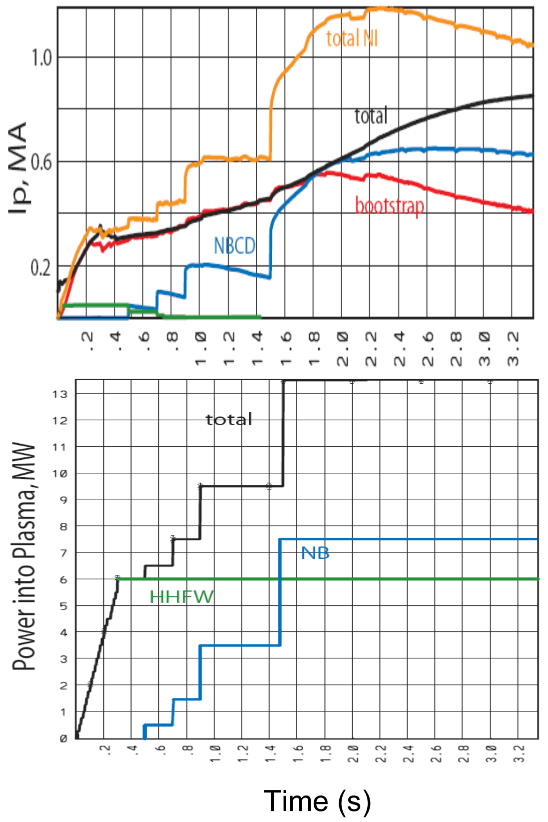
- Benefits of more tangential injection:
  - Increased NBI absorption = 40→80% at low I_P
  - Current drive efficiency increases: ×1.5-2
- New CS needed for ~3-5s for ramp-up equilibration
  - Higher field 0.5→1T also projected to increase electron temperature and NBI-CD efficiency


TSC Simulations – C. Kessel



E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5\times10^{19}m^{-3}$, $\overline{T}_e$ = 0.83keV

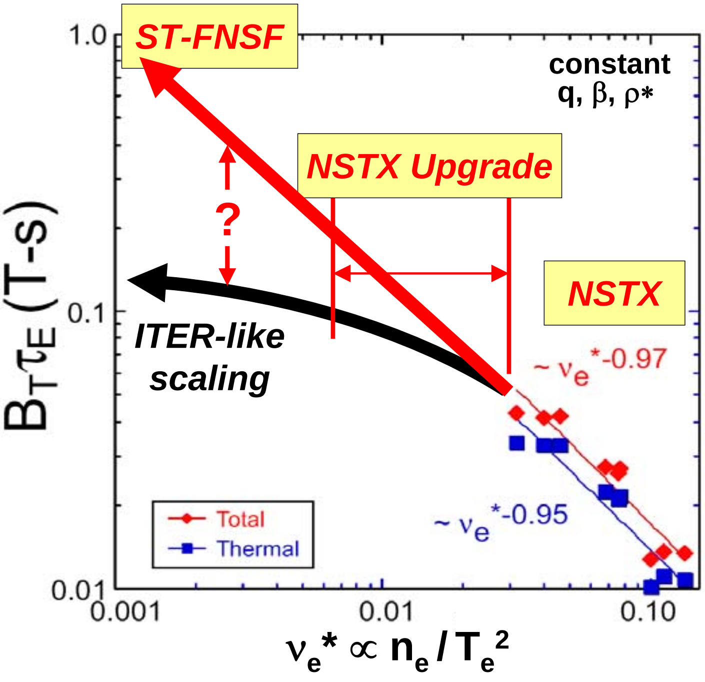


NSTX Upgrade will address many important questions for fusion

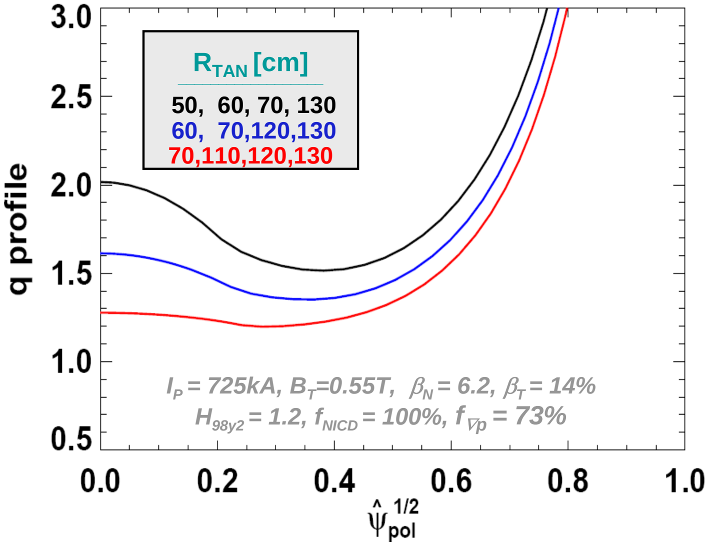
How does confinement vary with normalized temperature, pressure?

Can we create, sustain, and control high β, low l_i ST plasmas without induction?

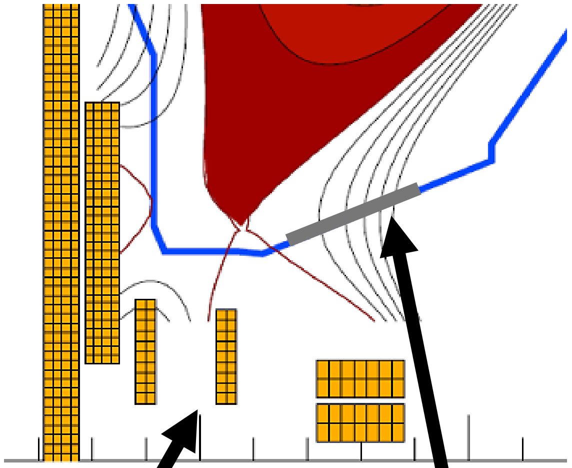
Can we manage the power & particle exhaust of high-performance plasmas?



Normalized electron collisionality reduction from higher temperature from higher field, current, heating



q profile control in 100% non-inductive plasma using mix of existing and additional NBI sources



Improved LLD, capillary porous system, other…

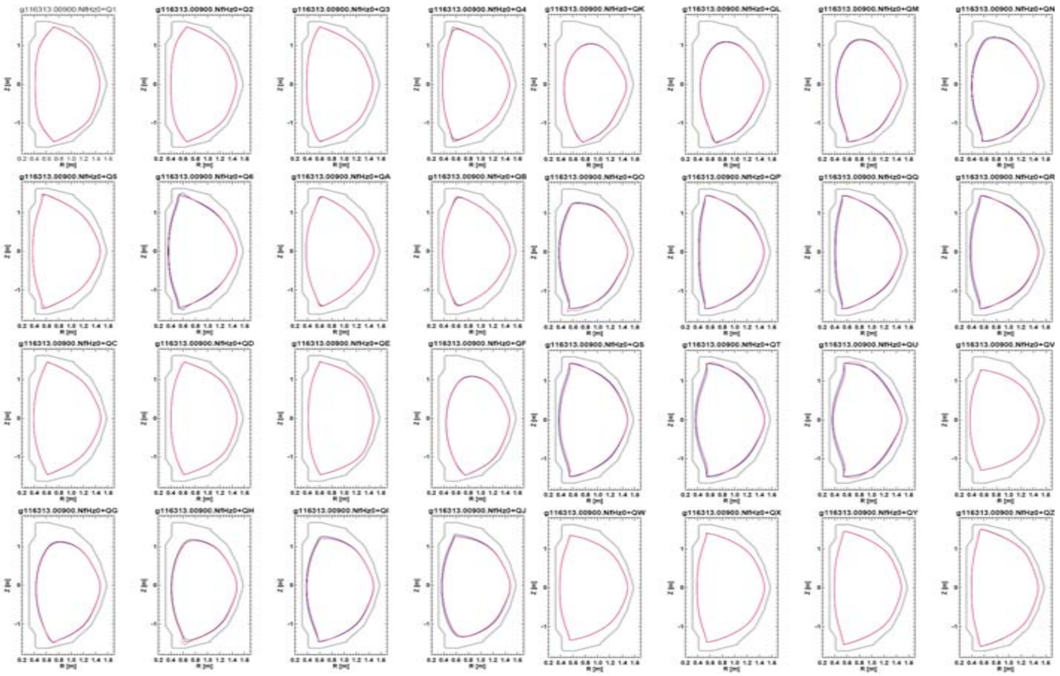
New divertor poloidal field coils

Range of I_P = 2MA free-boundary equilibria generated to support design of TF and PF coil support structures

Free boundary equilibrium parameters:

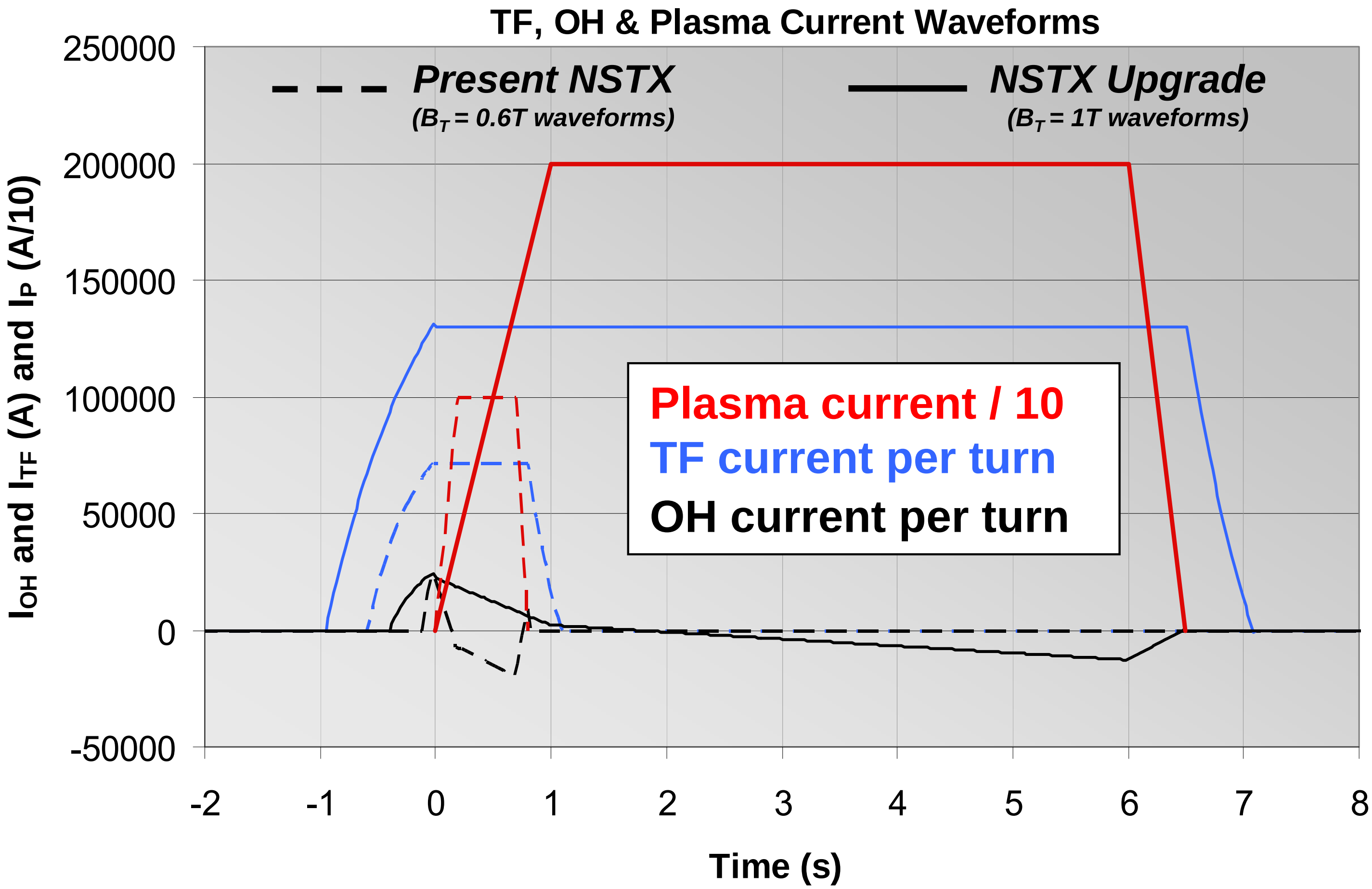
- Aspect ratio A: 1.6 – 1.9
- Internal inductance l_i: 0.4 – 1.1
- Elongation κ: 2.1 – 2.9
- Triangularity δ: 0.2 – 0.7
- Squareness ζ: -0.15 – 0.12
- Magnetic balance: -1.5 – 0cm
- I_{OH}: zero and +/- supply limit
  - For computing PF needed for cancellation of OH leakage flux
- Pressure variation: β_N = 1, 5, 8

32 free boundary equilibria × 3 OH conditions = 96 cases



- NOTE: Negative “squareness” boundary shape cases are included:
  - More shaping flexibility/capability than in present NSTX (requires PF4 usage)
  - Expect could be important for controlling edge stability (NSTX will test in FY2010)
- With coil/machine protection system + nominal operating currents, analysis indicates enhanced vertical field coil structure can support above scenarios

Upgrade provides substantial increase in device performance

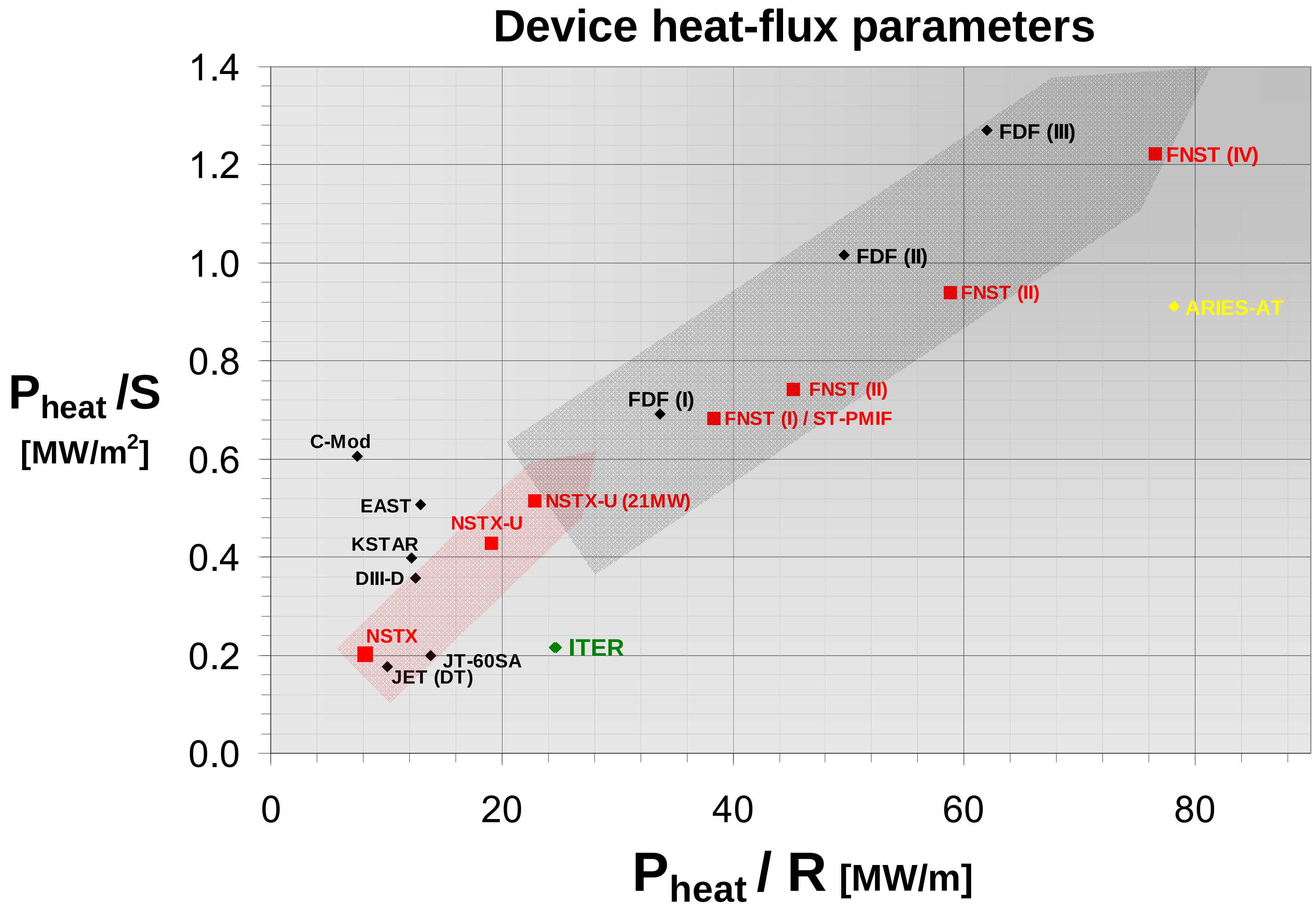


	Base NSTX	NSTX Upgrade
R_0 [m]	0.854	0.934
Min. aspect ratio	1.28	1.5
I_p [MA]	1	2
B_T [T]	0.55	1
T_{pulse} [s]	1	5
$T_{repetition}$ [s]	600	1000
$R_{center\_stack}=R_0-a$ [m]	0.185	0.315
$R_{antenna}=R_0+a$ [m]	1.574	1.574
Total OH flux [Wb]	0.75	2.1

Relative performance of Upgraded NSTX vs. Base:

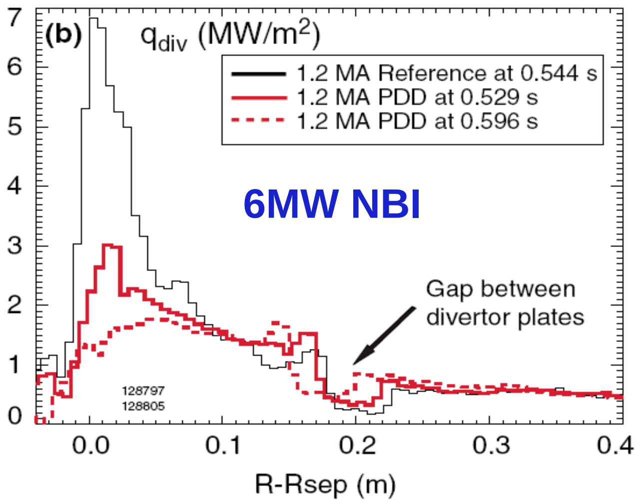
- Center-stack radius increased 13cm → A=1.3 → 1.5
- Available OH flux increased 3×, 3-5× longer flat-top
- I_P increased 2×, B_T increased 2× at same major radius
- Plasma stored energy increased up to 4× (0.25→ 1MJ)

NSTX Upgrade will extend normalized divertor and first-wall heat-loads much closer to FNS and Demo regimes

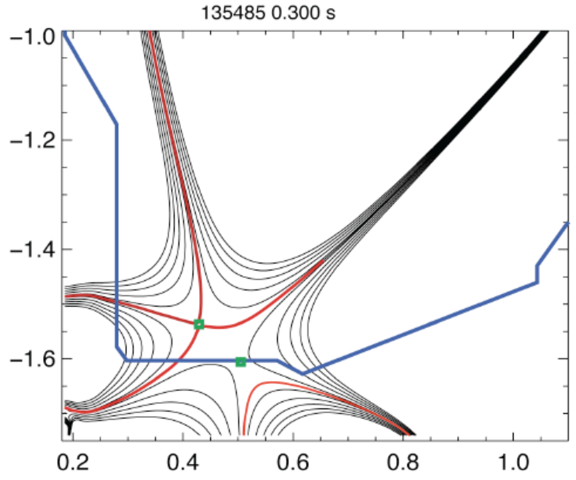


A combination of advanced PMI solutions will likely be required to manage the power exhaust of NSTX Upgrade

- **High divertor heat flux can be reduced in NSTX with partially detached divertor (PDD)**



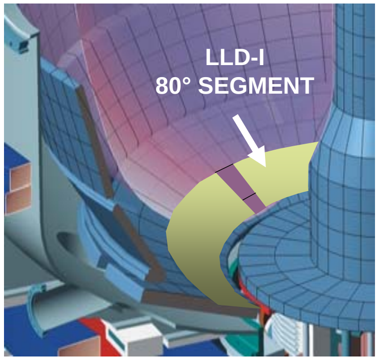
- **NSTX has demonstrated the formation of high flux-expansion "snowflake" divertor**



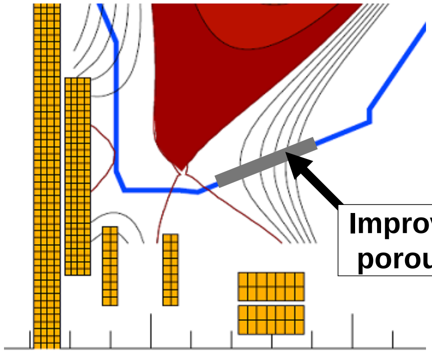
- **The PDD operating regime and other PMI solutions will be challenged in NSTX-U due to:**
  - 2-3× higher input power
  - 30-50% reduction in Greenwald fraction
  - 3-5× longer pulse duration, leading to substantial increase in $T_{divertor}$

- **NSTX and NSTX-U will test the compatibility of high flux expansion, PDD, and a liquid lithium divertor (LLD) at higher power/energy**

- NSTX LLD



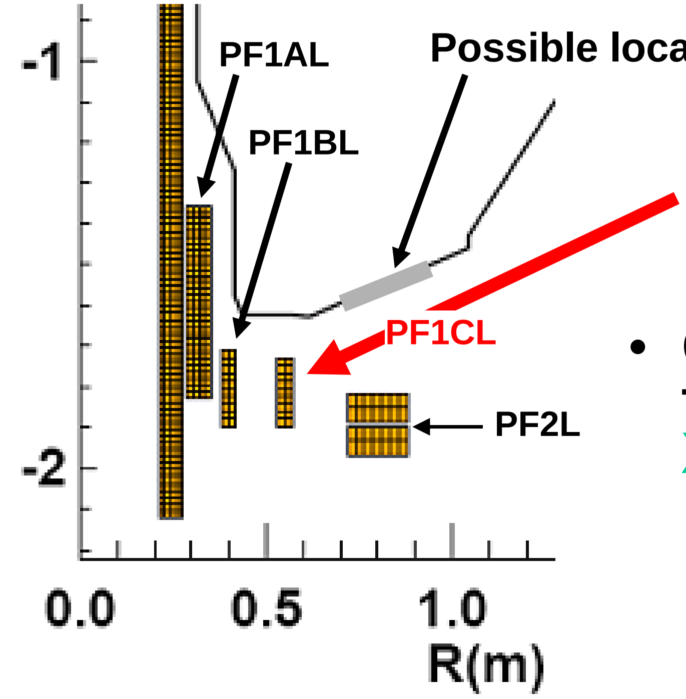
- NSTX-U high flux expansion:



f_{exp} = 32

Improved LLD, capillary porous system, other?

The divertor PF coil system for NSTX Upgrade includes an additional coil to enhance control of power exhaust

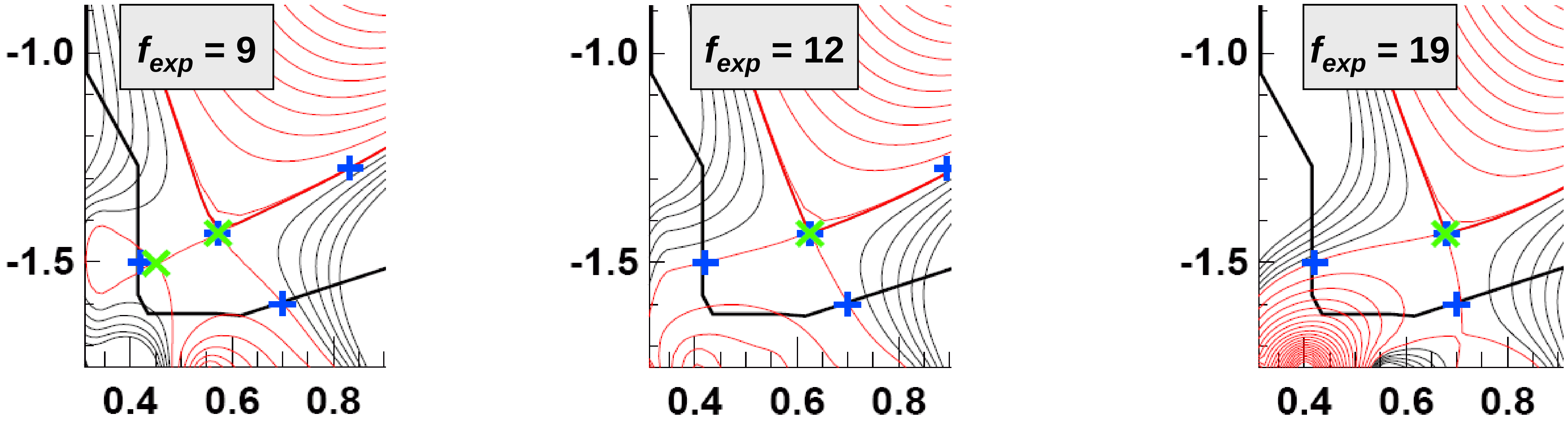


Possible location of liquid lithium divertor in Upgrade

Additional coil added = PF1C

- Combination of PF1A,B,C + PF2 enables **flux expansion variation** with fixed **X-point** height and strike-point location:

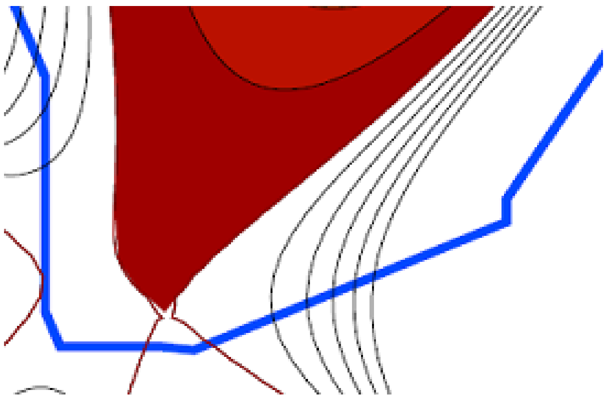
Outboard poloidal flux expansion factor $f_{exp} \equiv |\nabla\psi|_{\text{mid-plane}} / |\nabla\psi|_{\text{strike-point}}$



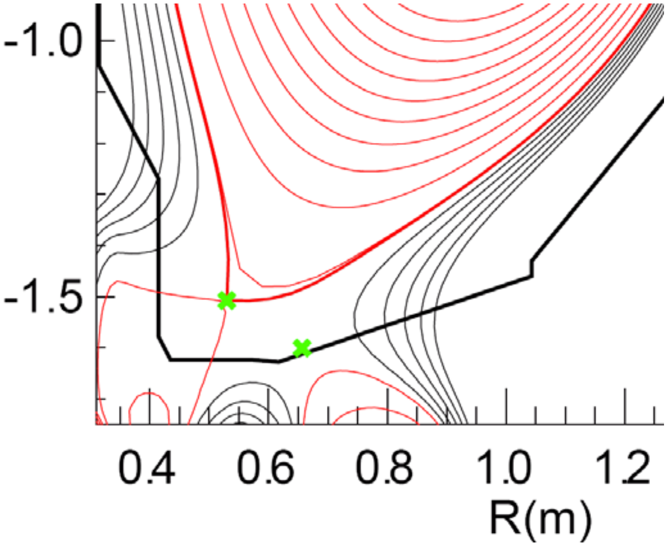
Center-stack Upgrade divertor coil set supports conventional, snowflake, and X/Super-X divertor options

- **Implication:** CS divertor coil location and configuration now finalized

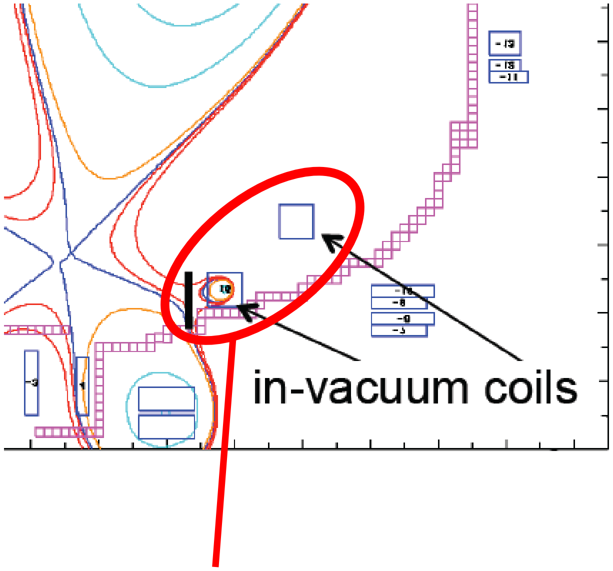
Conventional



Snowflake



X/Super-X



Possible location for cryo-pumps?

- X/Super-X requires in-vessel PF coils which are **<u>NOT</u>** part of Upgrade project
- Design/analysis of Upgrade divertor is collaborative effort (ORNL, LLNL, UT, PPPL)

Vlad Soukhanovskii (LLNL) recently received DOE-SC Early Career Award for proposal to study "Advanced High Heat Flux Divertor Program on the NSTX"

- NSTX-U divertor design will be strongly influenced by NSTX LLD results
  - To be prepared for possible favorable results from LLD, NSTX is initiating a conceptual design study of heated inboard Mo divertor tiles to support test of high-δ LLD-pumped plasma

Summary

- **The NSTX and NSTX Upgrade programs will contribute strongly to ST and ITER, and to all ReNeW themes and many thrusts**

- **These plans and upgrades enable exciting new understanding and ST performance across in all topical science areas:**
  - Push to integrate **CHI start-up w/ HHFW BS-overdrive non-inductive ramp-up**
  - Understand role of ν^* and **Li on transport, stability, and divertor** physics
  - Develop **advanced power and particle exhaust solutions** for ST, FNSF, Demo
  - Measure and understand instabilities causing **anomalous energy transport**
  - Develop understanding of **fast-ion transport from multi-mode AE** for ST, ITER
  - Understand **RWM critical rotation, viscous torques**, dependence on lower ν_i
  - Push to **100% non-inductive sustainment** by increasing bootstrap and NBI-CD

NSTX Response to PAC-25 Recommendations

Quick response to PAC-25 programmatic recommendations

- PAC25-2 “…consider ways to insure highest priority research emphasized, especially LLD and boundary physics, HHFW, integrated scenarios…”
  - Response: agree - see FY2010-12 milestone overview page 17

- PAC25-4 “…higher priority should be given to support upcoming NSTX upgrades and ST development. For the FY2009 run, consider allocating "cross-cutting" and "reserve" run days to experiments that enhance understanding Li, effectiveness of HHFW, plans for post-upgrade divertor”
  - Response: agree - run days were allocated to assess impurity accumulation in Li ELM-free plasmas, initial upgraded HHFW ops, “snowflake” divertor

- PAC25-7 “…would benefit from more cross-talk between BP group and other groups (RF group) …continue to pursue novel concepts to spread heat load… focus on candidate solution for 5s pulse after upgrades…”
  - Response: agree – HHFW group working more closely with boundary group on RF divertor heat loads, ELM effects on coupling. Strike-point control implemented for LLD enhanced/enabled snowflake divertor experiments

NSTX response to PAC-25 recommendations - 1

	PAC Recommendation/ Response Number	PAC Report Section	Issue	PAC Recommendations	NSTX Response	Action for Speaker	Responsible person(s)
	PAC25-1	2.1	NSTX organization, high-priority research plans and upgrades, LLD, HHFW	The PAC believes that there is a shortage of people to run, analyze, plan, maintain, and carry out the NSTX research mission. To address this shortage, the PAC recommends that PPPL should use the opportunity provided by the start of an exciting 5-Year Plan to expand the staff and strengthen collaborations at NSTX.	Agree	Describe increased number of post-docs from PPPL, collaborators, and ARRA. Also describe present and anticipated funding situation	Ono
	PAC25-2	2.1	NSTX organization, high-priority research plans and upgrades	The PAC believes more can be done to achieve top-level research priorities when allocating resources for the NSTX run plan. Considering the programmatic importance of resolving technical and scientific issues prior to the installation of the center-stack and NBI upgrades, the NSTX Team should consider ways to insure that highest priority research efforts are emphasized, especially research involving lithium divertor and boundary physics, the use of HHFW heating, and integrated scenario development. Indeed, during the next three years, experiments should be planned to resolve technical questions and reduce scientific uncertainty associated with the longer-pulse, higher-power discharges planned for the post-upgrade period.	Agree	Describe how high priority research areas are being addressed with research milestones - both NSTX and DOE joint research	Menard
	PAC25-3	2.1	NSTX organization, high-priority research plans and upgrades, LLD, HHFW	The PAC recommends that the NSTX Team consider ways to devote additional resources to the investigation and development of a high heat flux divertor for NSTX. A high heat flux divertor with sufficient particle control is critical to the NSTX Program. Therefore, the PAC recommends even greater emphasis be placed in the research program, run plan, and diagnostic implementation plan for addressing Li divertor issues. For next year's PAC meeting, we request that the NSTX National Team make an explicit presentation detailing what will be the heat flux targets required in post-upgrade discharges and identification of high-heat flux divertor options compatible with reasonable density control targets.	Agree	Need to give a presentation incorporating heat flux width projections to upgrade, expected techniques for heat-flux mitigation (PDD, snowflake), possible divertor configurations for upgrade, and expected requirements for active cooling and pumping	Maingi and Soukhanovskii
	PAC25-4	3.1	NSTX organization, high-priority research plans and upgrades	While NSTX should continue to make unique and strong contributions to resolving issues identified by ITER/ITPA and to understanding fundamental toroidal physics, with scarce run-time resources, higher priority should be given to support upcoming NSTX upgrades and ST development. For the FY2009 run, the NSTX Team should consider allocating "cross-cutting" and "reserve" run days to experiments that enhance understanding of the effects of Li, maximize the effectiveness of HHFW, and further develop the plans for post-upgrade divertor options. In subsequent years, the run plans should reflect the critical importance of research supporting ST development paths and the NSTX upgrades in the 5-Year Plan.	Agree	Describe usage of cross-cutting and reserve days in FY09 and especially FY10 for achieving high priority goals	Menard
	PAC25-5	3.2	NSTX organization, high-priority research plans and upgrades	As explained in the NSTX presentations, experiments in the upcoming runs have the potential to produce significant performance breakthroughs by demonstrating large non-inductive current fractions which are sustained at high-normalized beta and which appear transiently during periods of noninductive current drive. Additionally, the PAC anticipates significant progress resulting from the two major new NSTX capabilities: experiments using the liquid lithium divertor (LLD) and the use of HHFW as a research tool for comparative discharge studies. Because of the importance of boundary and pedestal physics, the PAC suggests that the installation of additional multipoint Thomson scattering channels should be accelerated.	Agree	Describe how this is now funded for FY11 through ARRA funding (Ono), and how this will benefit pedestal research and FY11 joint research milestone (Soukhanovskii)	Ono and Soukhanovskii
	PAC25-6	3.3	NSTX organization, high-priority research plans and upgrades	The PAC believes the NSTX Research Plan is appropriately responsive to the FESACTAP report. In the high priority area of Ip start-up and ramp-up, the PAC recommends that increased emphasis should be placed on current ramp-up because the increased effectiveness of the HHFW provides an exciting opportunity to explore the potential of bootstrap "over-drive". NSTX should continue to explore non-inductive plasma current start-up in collaboration with related efforts using MAST, Pegasus, and DIII-D. In the longer term, after the installation of the center-stack and NBI upgrades, the NSTX research program will become even more "aligned" with the FESAC-TAP research goals.	Agree	Describe FY10 milestone on HHFW research emphasizing BS overdrive and non-inductive sustainment in HHFW talk	Taylor (and Menard)
	PAC25-7	4.1	Boundary physics	We believe NSTX would benefit from more cross-talk between the BP group and other topical groups, especially RF (but also transport/turbulence, MHD, and integrated scenarios). Additionally, the central stack (CS) and 2nd NBI upgrade will challenge existing PFCs on NSTX with high heat loads of 20-30 MW/m2 and may present a major challenge. We note that shape control efforts have been proceeding nicely, and it will be wise to continue to pursue novel concepts to spread the heat load, such as the X-divertor, snowflake, and asymmetric bias. Investigations should focus on the goal of candidate solution for 5 sec pulse after the major upgrades, and we believe NSTX will benefit from the modeling of NSTX performance of divertor heat loads for standard and novel configurations.	Agree	Describe cross-TSG LLD Physics Survey XP, BP and LLD research on divertor	Menard
	PAC25-8	4.1	Boundary physics	The NSTX presentations made a compelling case for more edge Thomson channels. These channels should not be part of the incremental funding request. The additional channels are required for the FY 2011 Joule Milestone, and we recommend installation to advance at least 6 - 8 months, if possible.	Agree	Describe MPTS upgrade status, ARRA funding, readiness for FY11 in "Project" talk	Ono

NSTX response to PAC-25 recommendations - 2

	PAC25-9	4.1	Boundary physics	Issues related to long-pulse operation are most important, such as impurity transport/buildup, long-pulse pumping capability of solid Li, density control, and ELMs. The PAC also suggests that more systematic characterization of differences/similarities of effects on edge plasma with different Li approaches (LITER, dropper, LLD) would be a good goal and a unique contribution. We endorse further studies to understand Li elimination of ELMs (a unique capability) and to expand research to control particle rise. With the CS and NBI upgrades, new power levels will require more emphasis on experiments and modeling in the boundary physics area. Since much of the boundary area research is performed by collaborators, the NSTX program would benefit from additional collaborator support after the upgrades.	Agree	Describe LITER vs. Dropper results from FY2009, plans for FY2010, and SGI deuterium density control results in BP talk	Soukhanovskii
	PAC25-10	4.2	Lithium Research	We remain concerned about the pace of Plasma-Material Interaction (PMI) diagnostic and modeling efforts, both in-house and with collaborators, and the over-commitment of PPPL personnel. This point must be emphasized due to the exceptional importance of the LLD to the NSTX program. We repeat the PAC-2008 recommendation to understand the physics behind plasma effects correlating with Li usage, sooner rather than later, and give priority to studies of Li effects in the allocation of reserve experimental run time.	Agree	Describe additional post-docs working on Li/boundary area (PPPL and ORNL) (Ono), Describe Li modelling results (Skinner) in Li TSG talk	Ono and Skinner
	PAC25-11	4.2	Lithium Research	An assessment of the effect of lithium coatings, in combination with carbon, on recycling should be performed this fiscal year, if at all possible. This will help address questions such as: Is the variation of performance with lithium deposition due to thicker coatings or more extensive coverage, as a function of evaporation rate and total evaporated inventory? What is the role of mobilized carbon? Carbon dust deposited on lithium coatings will be relevant to LLD performance. What role does water play? NSTX is beginning to address PMI specific issues, but more work is needed.	Agree to discuss	Summarize analysis results of J.P. Allain in Lithium TSG talk	Skinner
	PAC25-12	4.2	Lithium Research	A focus on transient gas injection (via the SGI or other fast acting gas puffers) may shed light on tau-p* and global recycling coefficients. Even if a determination of global recycling is not possible, pulsed fueling experiments with lithium coatings will certainly provide qualitative information on the coating performance and should be pursued. For example, the results of transient fueling experiments with evaporative coatings and with powder injection could be compared.	Agree	Summarize retention results from FY2009 and plans for FY2010 and beyond	Skinner
	PAC25-13	4.2	Lithium Research	NSTX should investigate whether the increase in electron stored energy is due to a confinement increase or whether there is another mechanism	Agree	Summarize transport analysis results in T&T talk	Yuh or Kaye
	PAC25-14	4.2	Lithium Research	The design, and two alternative constructions, of the LLD is advancing well. Two concerns have been identified. First, the possibility of liquid lithium attacking the brazed material and exposed copper at the lower edge of the LLD needs to be investigated. It is important that formation of a silver-lithium eutectic, with subsequent debonding of the SS-copper braze, be avoided, as well as possible transport of copper back onto the divertor target surface of the LLD. This can be addressed in offline tests. Secondly, fill techniques that result in a thicker layer of lithium on the LLD are desirable. Confining the lithium fill to the LLD surface, rather than involving the surrounding carbon, would also be desirable in order to quantify the effect of the LLD. The PAC is aware that the use of a liquid fill technique places greater stress on the need to avoid degradation of the underlying copper by liquid lithium.	Agree	Describe side coatings on LLD plates, and status of LLD fill techniques being developed in L245 in Li TSG talk	Skinner
	PAC25-15	4.2	Lithium Research	The problems in extension of the LLD design to longer pulse and higher power density should be investigated. What would an LLD design for the upgrade look like? Characterization of the surface temperature of the LLD as a function of power deposition profile would provide helpful information, and should be available in FY 2010, from IR cameras and the diagnostic tiles.	Agree	Discuss long-pulse LLD design options..	Maingi and Soukhanovskii - see PAC25-3
	PAC25-16	4.2	Lithium Research	We note a modeling cross-cut issue: Should/can blob-transport code results be integrated with Li boundary response modeling?	Consider	Discuss in boundary physics overview talk	Soukhanovskii
	PAC25-17	4.3	Macrostability Research	The FY 2009 research plan in macro-stability calls for a milestone on understanding RWM stabilization and control versus plasma rotation. This is an important and timely area of research. The PAC makes several recommendations in connection with this milestone: (1) use n=3 magnetic breaking to further reduce the plasma rotation and test n=1 RWM feedback control in low rotation plasmas, (2) maintain a close collaboration with the DIII-D team to explore the differences in RWM stability of low rotation plasmas attained by magnetic breaking (DIII-D) versus magnetic breaking (NSTX), (3) explore the implications of the newly measured poloidal flow on RWM stability (and also neo-classical tearing modes), and (4) increase the effort on theory and modeling, either through collaboration or on-site staff, to help resolve and understand the influence of plasma flow and identify important mechanisms, e.g. collisionality, kinetic damping, and Alfven wave damping. We note that theoretical tools like MISK and MARS-K are ready to be fully exploited in such studies.	Agree	Discuss recommendations in MHD overview talk	Sabbagh

NSTX response to PAC-25 recommendations - 3

	PAC25-18	4.3	Macrostability Research	With respect to longer term NSTX macro-stability research, the PAC recommends that scenario development be initiated for the use of HHFW heating to provide access to high beta. Used in conjunction with neutral beam heating, HHFW could provide a large range of plasma rotation without resorting to magnetic breaking techniques. In particular, it will be important to understand the intrinsic rotation of NSTX plasmas at high beta. We note that the addition of a second neutral beam will be helpful for investigating macro-stability at very high, possibly supersonic, rotation speeds. The stability properties of the plasma might be surprisingly different in this regime. Lastly, the PAC also supports the continuing design of the NCC coil system.	Agree	Discuss in ASC overview talk, and MHD overview talk	Gerhardt and Sabbagh
	PAC25-19	4.4	Transport and Turbulence	In addition, the PAC recommends an assessment of the interplay between edge plasmas with Li PFCs and electron transport. On a longer term, the PAC suggests exploring ways to measure magnetic field fluctuations. Also, the impact of doubling the magnetic field and current should be evaluated. In particular, since the ion gyroradius will likely be smaller at higher magnetic field, it appears mandatory to verify that the microwave scattering diagnostic will still be able to measure high k?s fluctuations.	Agree	Describe edge electron thermal diffusivity analysis performed by ASIPP collaborators	Yuh or Kaye
	PAC25-20	4.4	Transport and Turbulence	Regarding the other items proposed for FY09-11, the programme for studying ion heat transport as a possible cause of confinement degradation when NBI will be upgraded makes sense, in particular once the new BES diagnostic is operational. However it is also recommended to investigate impurity transport. Impurity peaking appears clearly as a potential limitation in discharges with Li coated PFCs. Hence it might have detrimental effects in future experiments with LLD. One solution to solve this problem, already tested on NSTX, is to mimic ELMs with external coils. Another solution would be to look for conditions where ITG/TEM turbulence is weakly excited - this might actually be a natural consequence of increasing core heating power with HHFW.	Agree	Describe results and plans for analysis and control of impurity transport in transport overview talk, and in ASC talk	Yuh/Kaye and Gerhardt
	PAC25-21	4.4	Transport and Turbulence	The program to study the LH transition is attractive. The future upgrades will allow an extension of the domain of explored parameters. It is recommended, however, to investigate in somewhat more detail the physics of turbulent transport suppression at the LH transition and the residual transport after the transition. Regarding this question, correlation length measurements by reflectometry appear very promising. Also, CHERS measurements of the poloidal velocity should be very helpful.	Agree	Describe GPI turbulence measurement at LH transition, and other relevant data in transport overview talk	Yuh or Kaye
	PAC25-22	4.4	Transport and Turbulence	As a final recommendation, the NSTX staff is encouraged to pursue its efforts to strengthen the interaction between theoreticians and experimentalists and also to continue its fruitful collaborations with US and foreign laboratories.	Agree	Describe any strengthening of these interactions in transport overview talk	Yuh or Kaye
	PAC25-23	4.5	Energetic Particles	The PAC encourages NSTX to push forward important cross-cutting research in the topics of (i) fast ion effects on RWM stability (with MHD TSG), (ii) simulation of multi-mode avalanches, also with rotation shear, and (iii) consideration of simulating alpha heating with on-axis 2nd harmonic HHFW on protons (with HHFW TSG).	Agree	Describe fast-ion effects on RWM stability in MHD overview talk,	Sabbagh

Backup Slides

NSTX research strongly supports ReNeW Thrusts

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

1. Develop measurement techniques to understand and control burning plasmas
   - Developing MSE-LIF diagnostic to measure |B| to constrain q(r) + total pressure profile w/o heating NBI
2. Control transient events in burning plasmas
   - Continue development of advanced high-β MHD mode-ID and feedback control techniques
   - Achieved ELM suppression with lithium, developing 3D fields to controllably trigger ELMs
3. Understand the role of alpha particles in burning plasmas
   - Multi-mode *AE fast-ion transport + full profile/fast-ion diagnostic set + theory/modeling
4. Qualify operational scenarios and the supporting physics basis for ITER
   - NSTX and Upgrade will assess transport processes during current ramp-up (inductive, non-inductive)
   - Continue extensive studies of H-mode threshold scalings and physics
   - Can use high-power HHFW to study H-mode confinement with dominant e-heating, low torque input
   - Improving understanding of unique low-A, high-β H-mode pedestal structure, turbulence, transport
5. Expand the limits for controlling and sustaining fusion plasmas
   - NSTX Upgrade targeting fully-non-inductive high-β_T (10-20%) plasmas with NBI J-profile control
6. Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement
   - Providing unique low-A, high-β, high V_{fast} / $V_{Alfvén}$ data to challenge wide range of theory and simulations
7. Exploit high-temperature superconductors, magnet innovations to advance fusion research
8. Understand highly integrated dynamics of dominantly self-heated/sustained burning plasmas

NSTX research strongly supports ReNeW Thrusts

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

9. Unfold the physics of boundary layer plasmas
    - Providing unique low-A, high-β measurements of SOL/divertor turbulence (GPI, BES) and transport
    - Exploring/understanding fast-wave antenna coupling to edge, power loss to divertor
10. Decode and advance the science and technology of plasma-surface interactions
    - A leader in exploration of lithium PFCs – will assess liquid lithium divertor (LLD) in near-term
11. Improve power handling through engineering innovation
    - Continue advancement of radiative divertors at high power density + high flux expansion divertors
12. Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma
    - NSTX and Upgrade will test/prototype integration of Li-based PFCs with high performance core

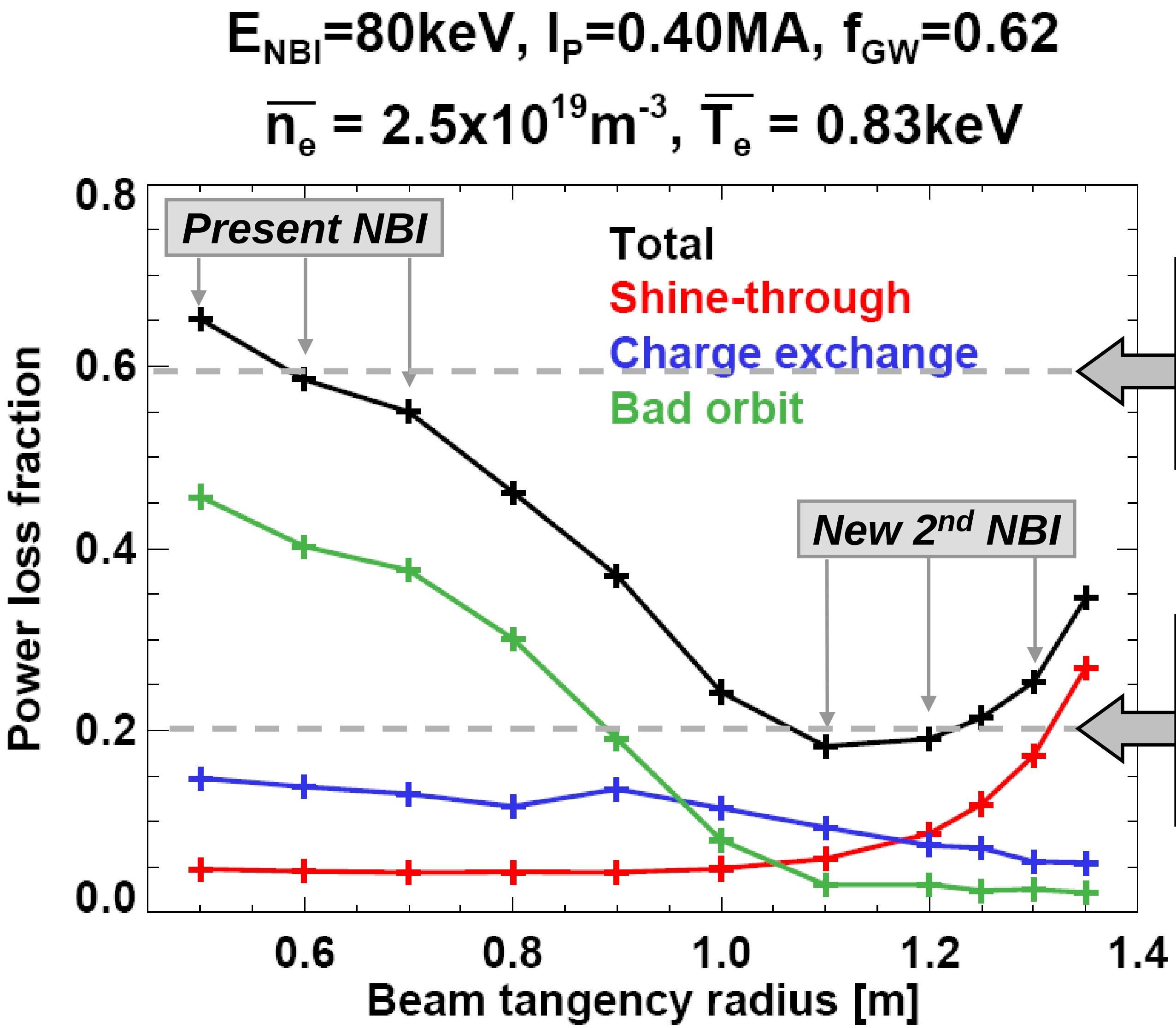
---

13. Establish the science and technology for fusion power extraction and tritium sustainability
14. Develop the material science and technology needed to harness fusion power
15. Create integrated designs and models for attractive fusion power systems
    - Strongly informing physics basis and design of low-A fusion power systems

---

16. Develop the spherical torus to advance fusion nuclear science
    - NSTX is lead US ST program and facility covering extensive range of ST research topics
17. Optimize steady-state, disruption-free confinement w/ 3D shaping, emphasizing QS
    - Providing unique ST data and understanding of how 3D fields influence core/edge transport/stability
18. Achieve high-performance toroidal confinement w/ minimal externally applied magnetic field

For NBI I_P ramp-up, more tangential 2nd NBI has 3× lower power loss than present NBI at low I_P = 400kA



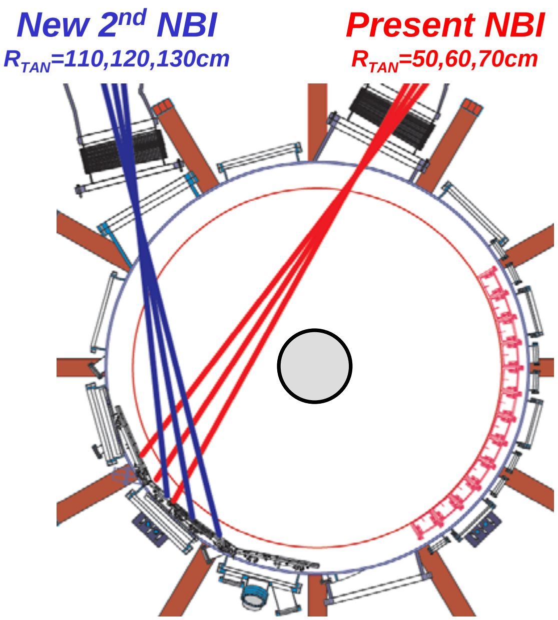
- 60% of power of present NBI lost
  - Absorb 2 of 5 MW (80kV)

- 20% of power of new 2nd NBI lost
  - Absorb 4 of 5 MW (80kV)

→ *2nd NBI can efficiently heat 400kA HHFW-driven ramp-up plasma*

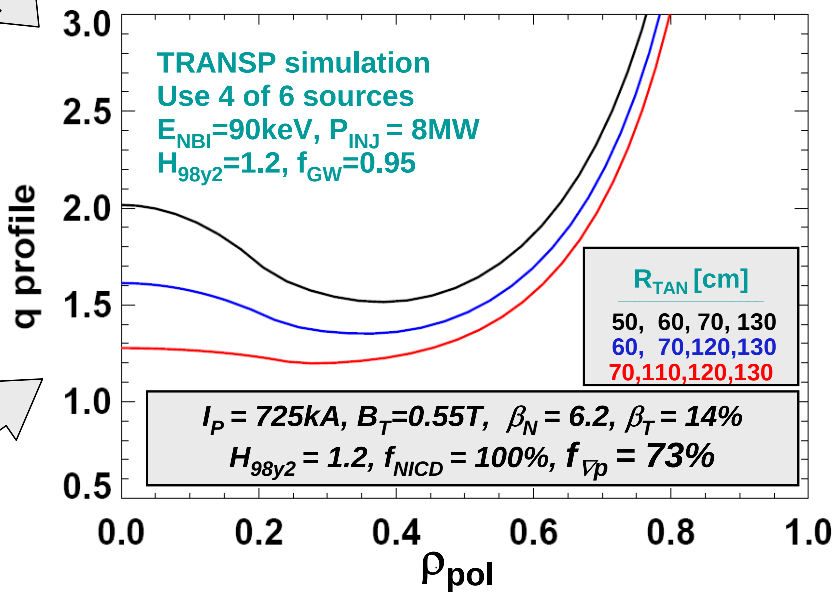
Upgrade 2nd NBI injecting at larger $R_{tangency}$ will greatly expand performance and understanding of ST plasmas

- Improved NBI-CD and plasma performance
  - Higher CD efficiency from large R_{TAN}
  - Higher NBI current drive from higher P_{NBI}
  - Higher β_P, f_{BS} at present $H_{98y2} \leq 1.2$ from higher P_{HEAT}
  - Large R_{TAN} → off-axis CD for maintaining $q_{min} > 1$
  - Achieve 100% non-inductive fraction (presently < 70%)
  - Optimized $q(\rho)$ for integrated high τ_E, β, and f_{NI}



- Expanded research flexibility by varying:
  - *q*-shear for transport, MHD, fast-ion physics
  - Heating, torque, and rotation profiles
  - β, including higher β at higher I_P and B_T
  - Fast-ion $f(v_{||},v_{\perp})$ and *AE instabilities
    - 2nd NBI more tangential – like next-step STs
  - Peak divertor heat flux, SOL width

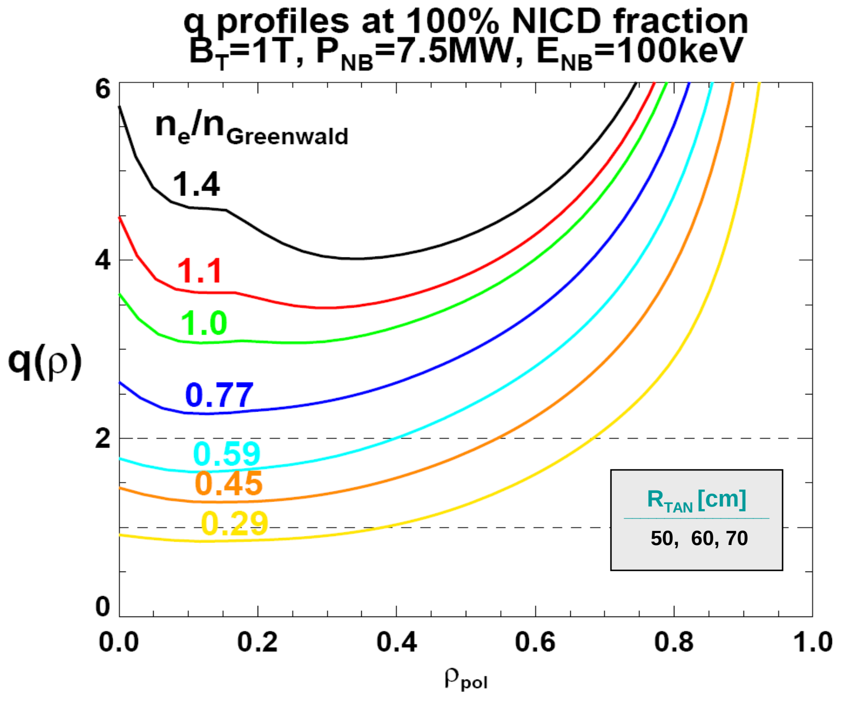
- q(r) profile variation and control very important for global stability, electron transport, Alfvénic instability behavior



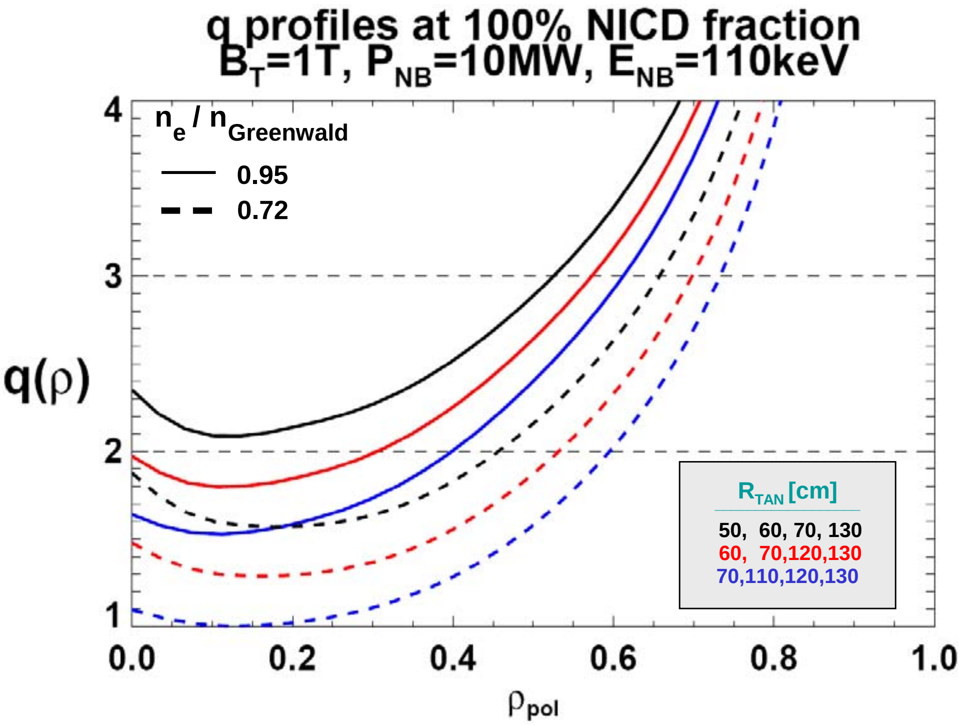
Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- **New CS + present NBI-CD + fast wave:**
  - Study confinement scaling vs. I_P and B_T
    - Limited range of auxiliary power levels
  - 100% non-inductive for 1-1.5s (~1 τ_{CR})
    - NBI duration limited to 2s at 7.5MW
    - Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)

- **Addition of 2nd NBI would enable:**
  - Study confinement scaling vs. I_P and B_T with:
    - Full range of auxiliary power available
    - Assured access to high-β at reduced ν^*
  - 100% non-inductive for 3-4 τ_{CR} → relaxed J(r)
    - 10MW NBI available for 5s
    - Control q_{min} & q-shear w/ NBI source, n_e, & B_T
    - Study long-pulse NTM stability with q > 2
  - Study compatibility of high-β w/ PMI solutions

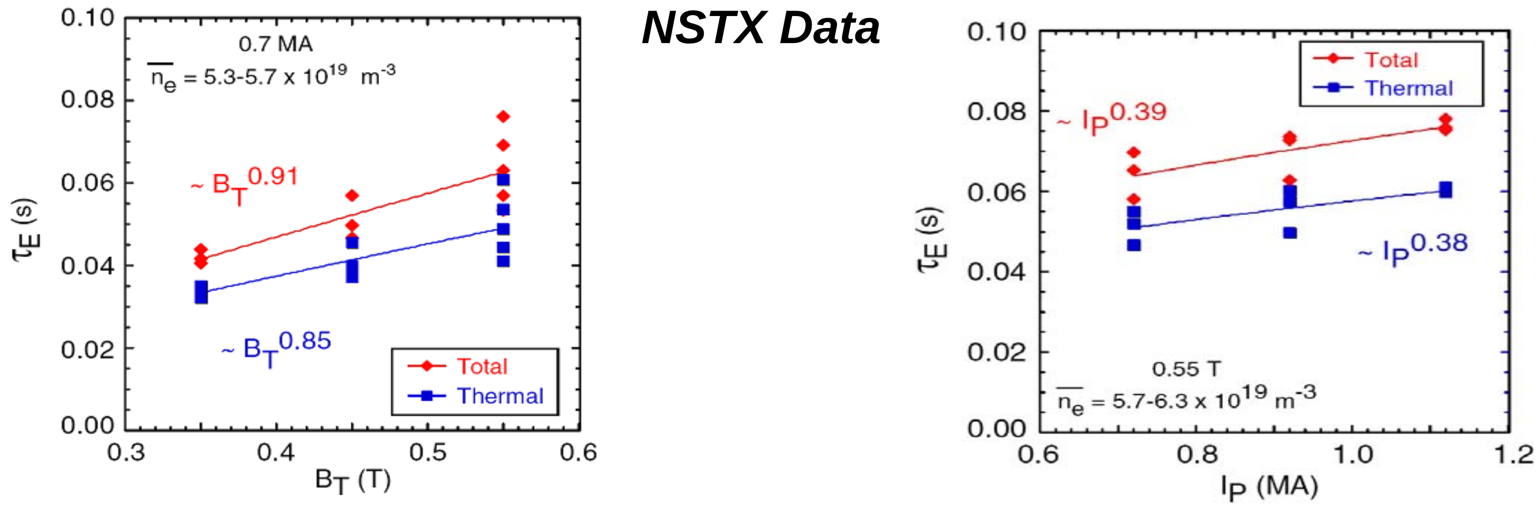


I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4, β_N = 4.5-5, β_T = 10-12%, 4MW RF



I_P = 0.95MA, H_{98y2} = 1.2, β_N = 5, β_T = 10%, 4MW RF

Access to higher field and current is needed to understand scaling of ST confinement, implications for next-steps


NSTX Data

- NSTX (and MAST) energy confinement time τ_E scales much more strongly with magnetic field and more weakly with current than ITER scaling

ST H-mode: $\tau_E \propto B_T^{1.2} I_P^{0.6} n^{0.2} P^{-0.6}$ **ITER H-mode: $\tau_E \propto B_T^{0.15} I_P^{0.9} n^{0.4} P^{-0.7}$**

- For scaling from NSTX to NSTX-U assume:
  - n / $n_{Greenwald}$ decreases 30% (~1 → ~0.7) via planned density control
  - Toroidal, normalized beta held ~constant: increase -20% (ITER) to +10% (ST)

- **To achieve: 3-6× reduction in collisionality →**
  - Field and current must double, heating power P = 6MW increases to 10-16MW
  - Also require 3-5× increase in pulse duration for profile equilibration