NSTX

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

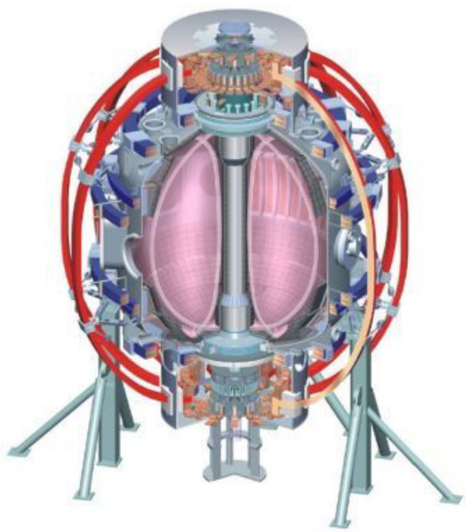
NSTX Research Program Overview for 2009-11 and Beyond

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
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

Jon Menard, PPPL

For the NSTX Research Team

NSTX PAC-25 Meeting
LSB B318, PPPL
February 18-20, 2009



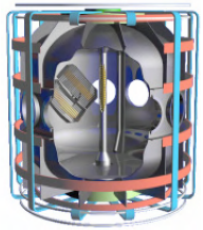
Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline:

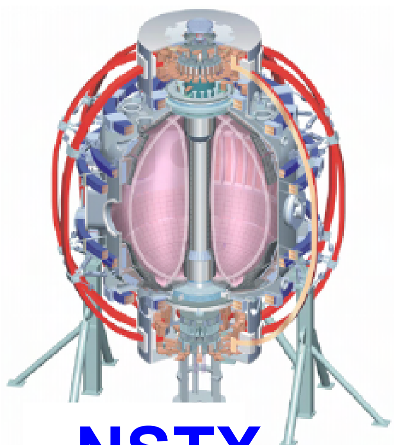
- Role of the ST in fusion research
- Missions of NSTX and Next-step STs
- Prioritization of Near-term Research
- Motivation for NSTX Major Upgrades
- Contributions to ITER and Tokamak Research
- Summary
- Appendix: Response to PAC-23 Recommendations

Present and future spherical tori complement ITER and accelerate the development paths of all DEMO concepts

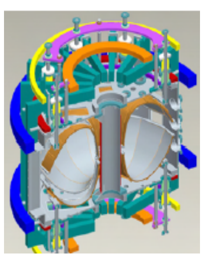
STs



PEGASUS
Plasma gun start-up, edge filaments

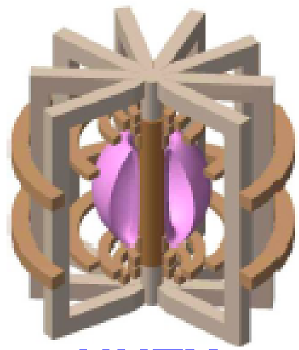


NSTX
U.S. flagship ST



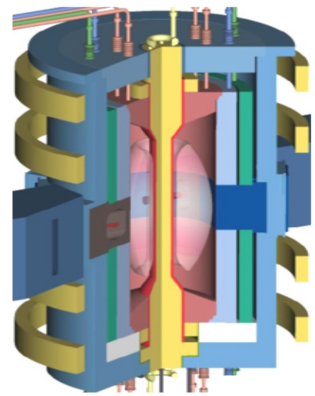
LTX
Li PFCs - very low recycling wall

Plasma-Material Interface R&D + Advanced Physics



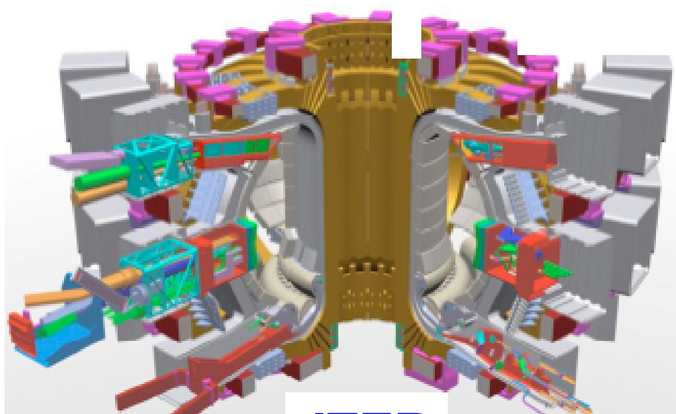
NHTX

Nuclear Component Testing



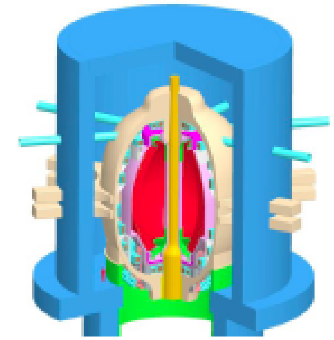
ST-CTF

Burning Plasma Physics

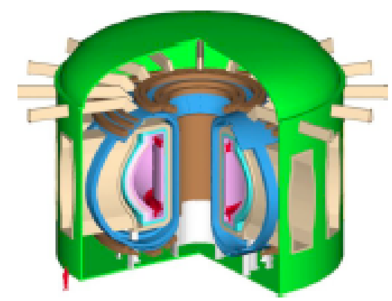


ITER

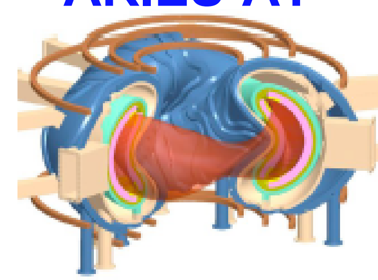
DEMO



ARIES-ST

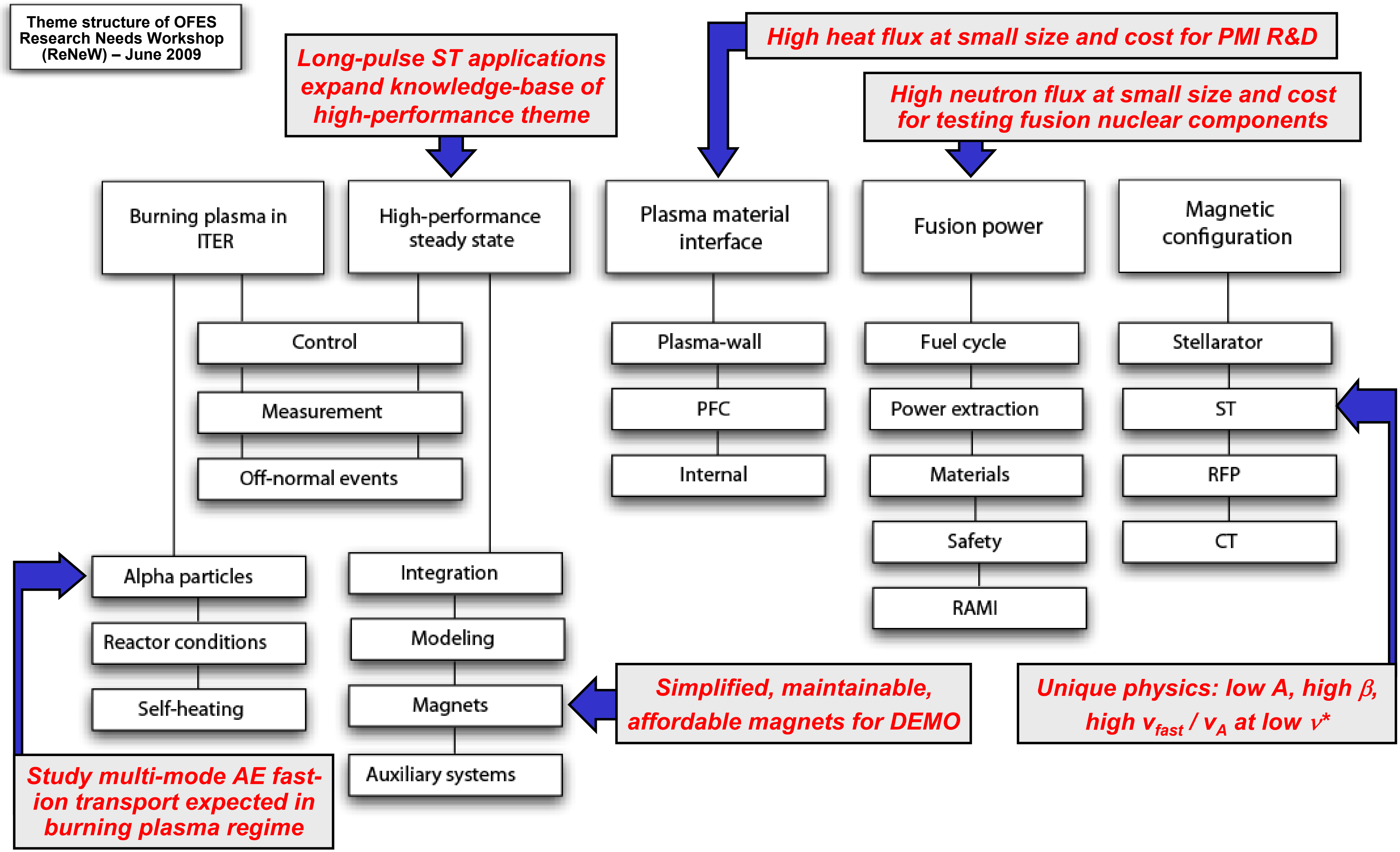


ARIES-AT



ARIES-CS

The ST provides unique contributions to all magnetic fusion research needs – for the ITER era and beyond



FESAC Toroidal Alternates Panel (TAP) recently prioritized issues and gaps for the Spherical Torus (ST) for the ITER era

ST ITER-era goal: ***"Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility …. to inform the design of a demonstration fusion power plant"***

"Tier 1" issues and key questions from TAP, and NSTX goals:

1. **Startup and Ramp-Up**: Is it possible to start-up and ramp-up the plasma current to multi-MA levels using non-inductive current drive w/ minimal or no central solenoid?
   – NSTX goal: demonstrate non-inductive ramp-up and sustainment

2. **First-Wall Heat Flux**: What strategies can be employed for handling normal and off normal heat flux consistent with core and scrape-off-layer operating conditions?
   – NSTX goal: assess high flux expansion, detached divertors, liquid metals

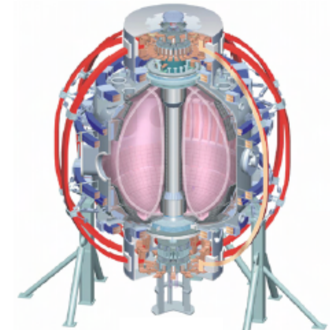
3. **Electron Transport**: What governs electron transport at low-A & low collisionality?
   – NSTX goal: determine modes responsible for electron turbulent transport and assess the importance of electromagnetic (high β) and collisional effects

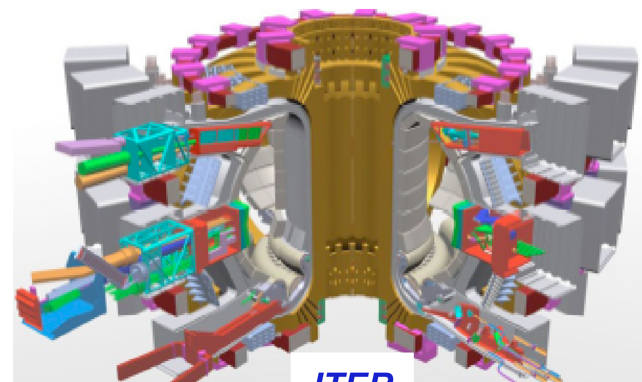
4. **Magnets**: Can we develop reliable center-post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?
   – NSTX goal: develop and utilize higher performance toroidal field magnet

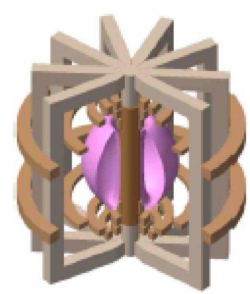
NSTX advances toroidal plasma science and burning plasma physics, and provides attractive near-term fusion options

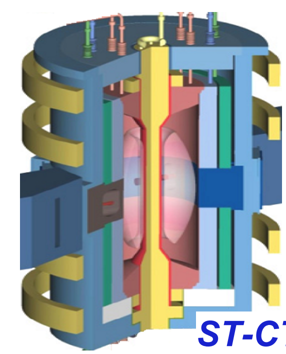
NSTX Mission Elements:

- Understand unique physics properties of ST
  - Assess impact of low A, high β, high v_{fast} / v_A, etc. on all aspects of toroidal plasma science
- Complement tokamak physics, support ITER
  - Exploit unique ST features to improve tokamak understanding, while also benefiting from tokamak R&D
- Establish attractive ST operating conditions for future fusion applications
  - **Long-term goal:** Understand and utilize advantages of the ST configuration for addressing key gaps between ITER performance and that needed for DEMO


NSTX


ITER

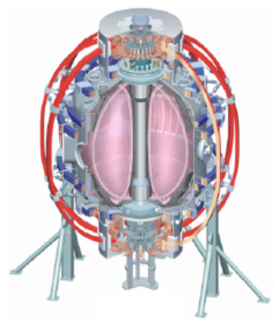

NHTX


ST-CTF

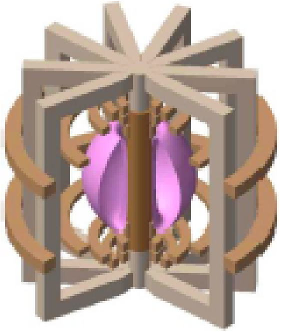
Pre-conceptual designs

NSTX research and major upgrades will prepare the U.S. to address FESAC Priorities, Gaps, and Opportunities

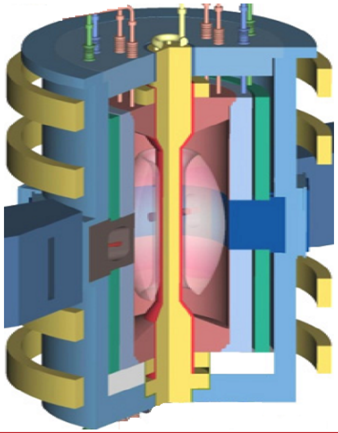
- NSTX:
  - Providing foundation for understanding ST physics and performance
- Upgraded NSTX:
  - Study high beta plasmas at reduced collisionality – important for further understanding confinement, stability, start-up, current drive
  - Assess full non-inductive current drive operation – needed for steady-state ST applications and ITER advanced operating scenarios
  - Prototype heat and particle exhaust solutions for next-step facilities



- Tame the plasma-material interface
  - Exploit intrinsic high heat flux of ST to understand boundary physics at fusion-relevant edge plasma conditions and heat/particle fluxes



- Advance fusion engineering science
  - Exploit high β, compactness of ST to achieve high neutron flux and fluence at reduced size and cost, reduced T consumption



NSTX is making world-leading contributions to ST development and contributing strongly to ITER & fundamental toroidal science

Outline:

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- Missions of NSTX and Next-step STs
- Prioritization of Near-term Research
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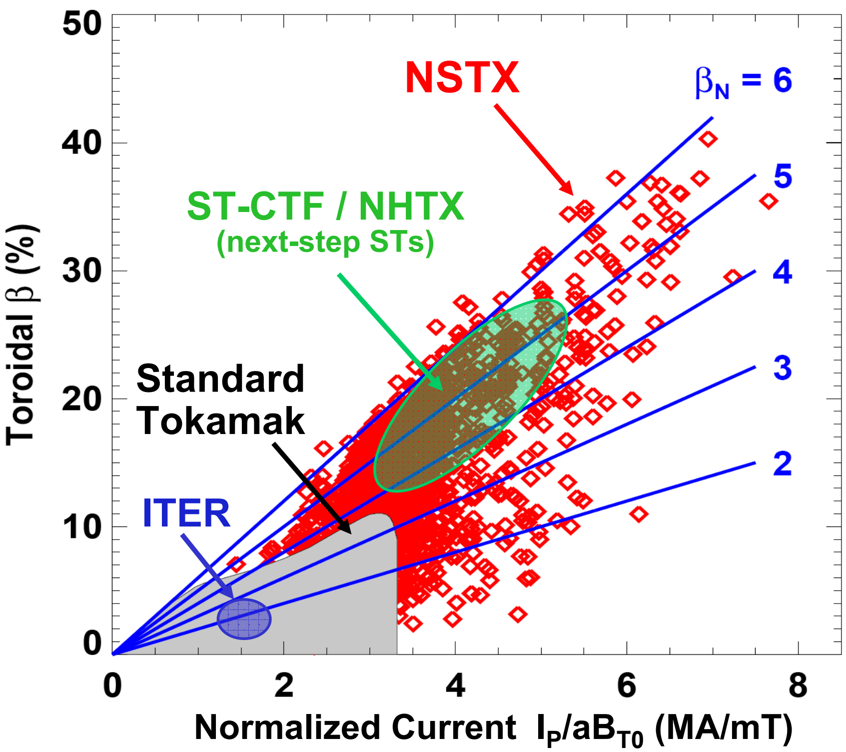
NSTX creates stable, well diagnosed plasmas at high β enabling a wide range of toroidal physics studies

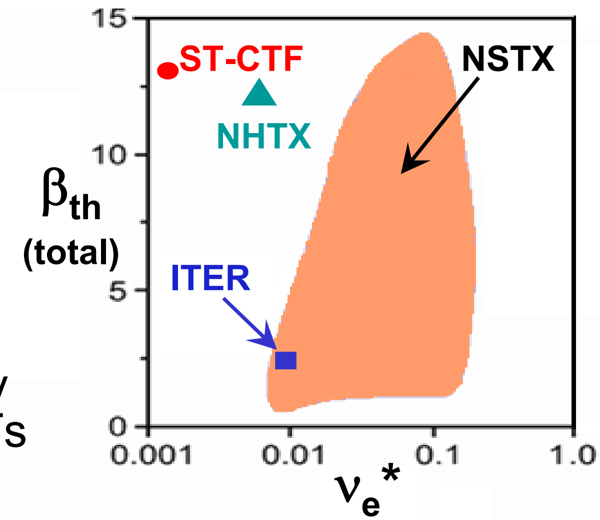


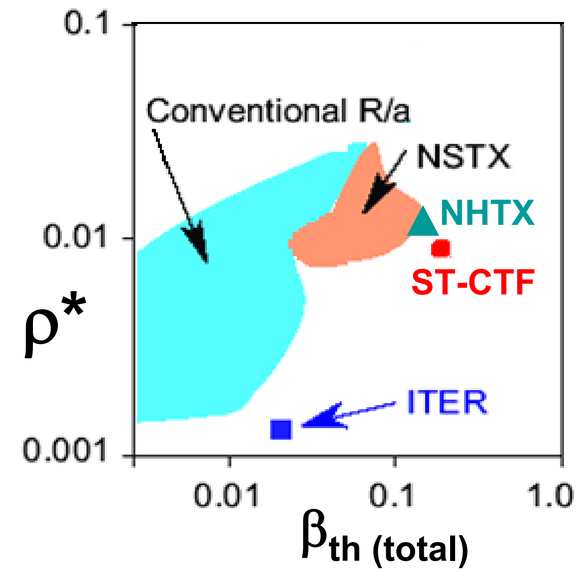
- ST accesses higher normalized current & higher normalized β

➡ higher $\beta_{Toroidal}$

(High β_N results in part from rotational stabilization of resistive wall mode)

- Access ITER-level ν^*, extending confinement understanding to high β
- Next-step STs expected to operate at significantly lower ν^* than present STs
- ST operates at higher ρ^* than tokamaks / ITER - impacts thermal and fast-ion transport, MHD
- Extrapolation in ρ^* from present STs to next-step STs is small





Performance gaps between present and next-step STs motivate near-term research prioritization and upgrades

Gaps to next-step STs:

For NHTX, ST-CTF: reduce: n_e & ν^*_e, increase: NBI-CD, confinement, start-up/ramp-up
For ARIES-ST: increase: elongation, β_N, f_{BS}, confinement, start-up/ramp-up

Near-term highest priority is to assess NHTX → ST-CTF scenarios

Present high β_N and f_{NICD}	NSTX	Upgraded NSTX	NHTX	ST-CTF	ARIES-ST
A	1.53	1.65	1.8	1.5	1.6
κ	2.6-2.7	2.6-2.8	2.8	3.1	3.7
β_T [%]	14	10-16	12-16	18-28	50
β_N [%-mT/MA]	5.7	5.1-6.2	4.5-5	4-6	7.5
$l_i(1)$	0.5-0.65	0.55-0.75	0.5-0.7	0.25-0.5	0.24
f_{NICD}	0.65	1.0	1.0	1.0	1.0
$f_{BS+PS+Diam}$	0.54	0.6-0.8	0.65-0.75	0.45-0.5	0.99
f_{NBI-CD}	0.11	0.2-0.4	0.25-0.35	0.5-0.55	0.01
$f_{Greenwald}$	0.8-1.0	0.6-0.8	0.4-0.5	0.25-0.3	0.8
ν^*_e	0.15	0.04	0.01	0.002	0.007
H_{98y2}	1.1	1.15-1.25	1.3	1.5	1.3
Dimensional/Device Parameters:					
Solenoid Capability	Ramp+flat-top	Ramp+flat-top	Ramp to full I_p	No/partial	No
I_P [MA]	0.72	1.0	3-3.5	8-10	28
B_T [T]	0.52	0.75-1.0	2.0	2.5	2.1
R_0 [m]	0.86	0.92	1.0	1.2	3.2
a [m]	0.56	0.56	0.55	0.8	2.0
I_P / aB_{T0} [MA/mT]	2.5	1.8-2.4	2.7-3.2	4-5	6.7

Performance gaps between present and next-step STs motivate near-term NSTX research prioritization

1. Increase and understand beam-driven current at reduced collisionality
   – Next-step STs ***require*** full non-inductive CD to achieve missions, and NBI-CD is largest gap
   → *Assess NBI-CD vs. reduced n_e, higher T_e, higher P_{Heat}*

2. Increase and understand H-mode confinement at reduced collisionality
   – Need to understand (electron) confinement to extrapolate to next-steps with high confidence
   → *Determine ST transport mechanisms + B_T, I_P, P_{Heat} scaling*

3. Demonstrate and understand non-inductive start-up and ramp-up
   – Non-inductive start-up/ramp-up essential to ST-CTF and ST-DEMO *(NHTX has OH for ramp-up)*
   → *Increase ramp-up heating & current drive – especially NBI*

4. Demonstrate and understand means to "tame the plasma-material interface"
   – PMI solution for very high particle/heat/neutron flux needed for ST-CTF and ST-DEMO
   → *Near-term: Short-pulse pumping → long-pulse + heat-flux mitigation*

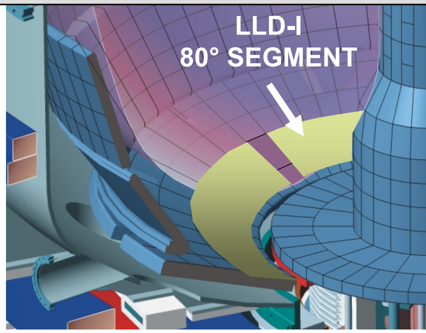
5. Sustain β_N and understand MHD/disruptivity near/above no-wall stability limit
   – NHTX/ST-CTF to operate near no-wall limit, higher β_T improves CTF, essential for ST-DEMO
   → *Improve RWM/EF/ELM, rotation, q(r) control*

NSTX near-term prioritization is compatible with FESAC-TAP ITER-era physics prioritization:
Start-up/ramp-up/sustainment, PMI, electron energy transport, integration, disruptions,
RF heating and current drive, 3D fields (ELM/EF/RWM), ion scale transport, fast particle instabilities, NTMs

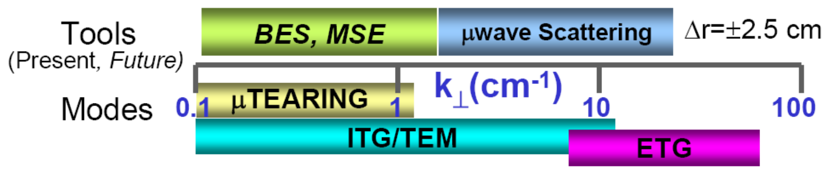
NSTX 2009-2013 5 year plan proposed major upgrades to extend understanding and performance toward next-steps

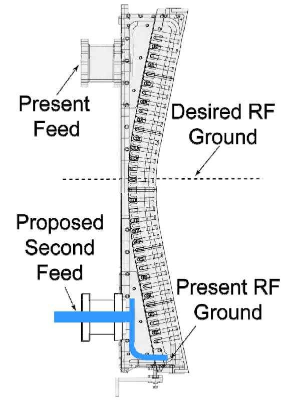
FY2009-11

Liquid lithium divertor (LLD) for density control for higher NBI current-drive fraction



BES to complement high-k scattering turbulence measurements to develop predictive capability for ST transport



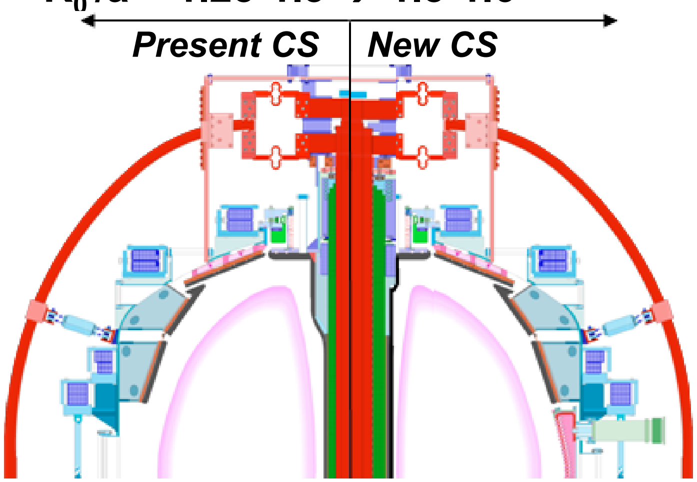


Higher-power fast-wave e-heating + ELM resilience for ramp-up and sustainment of H-mode plasmas

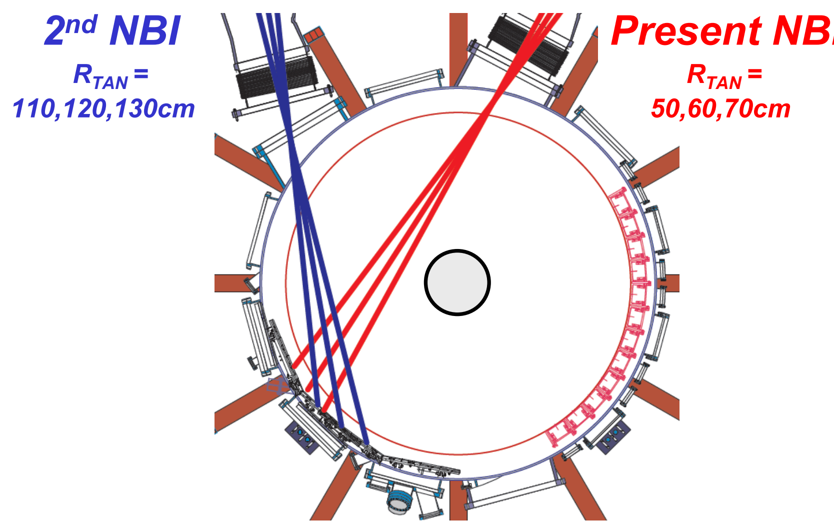
FY2012-13

New center stack for 1T, 2MA, 5s to access reduced ν*, 100% non-inductive ST plasmas

R_0/a = 1.25-1.3 → 1.5-1.6



2nd NBI with larger $R_{tangency}$ for sustained and controllable 100% NICD + high β at low ν*



Performance gaps between present and next-step STs motivate near-term NSTX research prioritization and upgrades

1. Increase and understand beam-driven current at reduced collisionality
   → *Assess NBI-CD vs. reduced n_e, higher T_e, higher P_{Heat}* → ***LLD, HHFW, new CS, 2nd NBI***

2. Increase and understand H-mode confinement at reduced collisionality
   → *Determine ST transport mechanisms + B_T, I_P, P_{Heat} scaling* → ***BES, HHFW, new CS, 2nd NBI***

3. Demonstrate and understand non-inductive start-up and ramp-up
   → *Increase ramp-up heating & current drive – especially NBI* → ***HHFW, new CS, 2nd NBI***

4. Demonstrate and understand means to "tame the plasma-material interface"
   → *Near-term: Short-pulse pumping → long-pulse + heat-flux mitigation* → ***LLD, new CS, 2nd NBI***

5. Sustain β_N and understand MHD/disruptivity near/above no-wall stability limit
   → *Improve RWM/EF/ELM, $\Omega_\phi(r)$, q(r) control* → ***2nd SPA+ off-midplane coils (increm.), 2nd NBI***

NSTX FY2009-11 Research Milestones
(base and incremental)

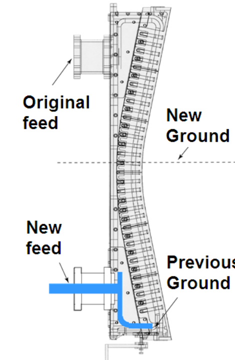
	FY2009	FY2010	FY2011
Expt. Run Weeks:	14 (20)	14 (20)	14 (20)
1) Transport & Turbulence			Study turbulence regimes responsible for ion and electron energy transport (formerly FY2010)
2) Macroscopic Stability	Understand physics of RWM stabilization & control vs. rotation	Assess sustainable beta and disruptivity near and above the ideal no-wall limit.	Assess sustained operation above the no-wall limit at reduced collisionality
3) Boundary Physics		Assess H-mode characteristics as a function of collisionality and lithium conditioning PAC23-1	Relationship between lithiated surface conditions and edge and core plasma conditions PAC23-1
4) Wave-Particle Interaction	Study how j(r) is modified by super-Alfvénic ion-driven modes	Characterize HHFW heating, CD, and ramp-up in deuterium H-mode *Joint milestone w/ solenoid-free TSG* PAC23-1	Assess predictive capability of mode-induced fast-ion transport
5) Solenoid-free start-up, ramp-up			
6) Advanced Scenarios & Control	Perform high-elongation wall-stabilized operation at lower n_e Integrate MHD mode modification of j(r) into optimized operation	←	Dependence of integrated plasma performance on collisionality *(FY2010 incremental accelerates this by 1yr if LLD and/or HHFW achieve FY2010 goals)*

Joint Research Targets (3 US facilities):

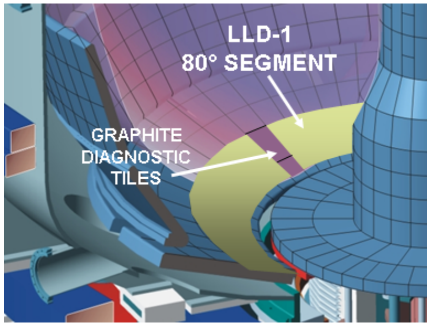
FY2009	FY2010	FY2011
Particle control and hydrogenic fuel retention PAC23-1	Understanding of divertor heat flux, transport in scrape-off layer	TBD *(…Characterize H-mode pedestal structure…)*

FY2009-11 upgrades support highest priorities and enable key research thrusts:

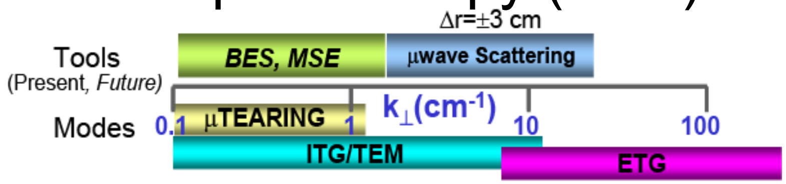
- FY2009-11: Upgraded fast wave heating for ramp-up, sustainment
  - Antenna modified to double RF power, ELM resilience for heating in H-mode
  - Utilize strong electron heating for self-generated “bootstrap” current ramp-up
  - Ramp-up is critical issue for future ST devices
  - Wave coupling/heating physics in advanced ST H-mode scenarios, ITER



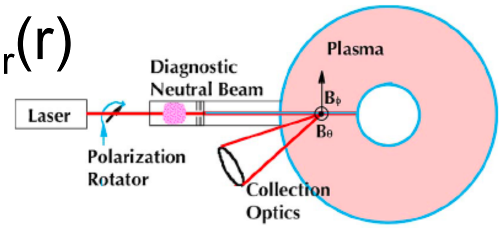
- FY10 - Access new physics regimes by utilizing a novel particle pumping technique: Liquid Lithium Divertor (LLD)
  - Will study impact of reduced collisionality and liquid lithium on NBI-CD, edge energy and particle transport, and edge stability
  - Solid Li coatings previously led to transient pumping, improved energy confinement, ELM reduction/elimination



- FY10 – First low-k turbulence data w/ Beam Emission Spectroscopy (BES)
  - Expand turbulence measurements to cover full k-range
  - **Goal:** determine and understand modes responsible for anomalous transport in the ST (also aids higher-A)



- FY11 – MSE-LIF for pitch angle & |B| w/o heating beam, $E_r(r)$
  - Greatly expanded flexibility for all topical science areas
  - Especially beneficial for HHFW, energetic particle research
    - q(r) during RF-only heating, reconstruct NBI fast-ion p from total – thermal



Run time/schedule priority will be given to milestones

List below is prioritized based on relative importance of gaps to next-steps

- Key tools (existing + upgrades) utilized for milestones are shown in **red**
- Note that all milestones below are "high priority", since milestones are allocated as much run-time as is needed (within reason) to achieve their goal

	FY2009 Milestones	Tools
Joint	Particle control and hydrogenic fuel retention in tokamaks	Li evap. (LiTER), sample probe
1.	Perform high-elongation wall-stabilized operation at reduced n_e	LiTER, NBI control
2.	Study how j(r) is modified by super-Alfvénic ion-driven modes	Fast-ion D-alpha
3.	Understand physics of RWM stabilization and control vs. rotation	NBI control, NTV braking

	FY2010 Milestones	Tools
Joint	Understanding of divertor heat flux, transport in scrape-off layer	Div. bolom & fast IR, LLD
1.	Characterize HHFW heating, CD, and I_P ramp-up in H-mode plasmas	Upgraded HHFW
2.	Assess pedestal characteristics and ELM stability as a function of ν^* & Li	LLD, Li CHERs, sample probe
3.	Assess sustainable β and disruptivity near and above ideal no-wall limit	Improved β & mode control

	FY2011 Milestones	Tools
Joint	(TBD) Improve understanding of H-mode pedestal structure	Higher-res MPTS *(incremental)*
1.	Dependence of integrated plasma performance on collisionality	LLD, HHFW, MSE-LIF
2.	Study turbulence regimes responsible for ion, electron energy transport	BES, HHFW, LLD
3.	Relationship between lithiated surface & edge/core plasma conditions	LLD, MAPP, div. spectrosc.

Li research highlights impact of collisionality on plasma physics and performance across all topical science areas

- Macroscopic Stability
  - RWM critical rotation and neoclassical viscous torques may increase at lower ν_i
- Transport & Turbulence
  - Underlying instabilities (micro-tearing, CTEM, and ETG) scale differently versus ν^*
  - If $T_e(r)$ is set by a critical ∇T_e, H-mode confinement may be reduced at reduced n_e
- Boundary Physics
  - ELM ΔW increases at lower ν_e * - could impact confinement, plasma purity, divertor
  - ELM stability may improve at lower ν_e* - through transport, second-stability access?
  - Detachment for heat flux reduction more challenging at reduced SOL density
- Wave-Particle Interactions
  - AE avalanches may be more easily triggered at reduced collisionality due to increased fast-ion pressure fraction → possible fast-ion redistribution and/or loss
- Plasma Start-up, Ramp-up, Sustainment
  - NBI-CD and RF-CD efficiency for ramp-up are increased at reduced n_e, increased T_e
  - ST-CTF scenarios rely on reduced n_e and increased T_e to increase NBI current drive efficiency to achieve 100% non-inductive current fraction.

NSTX has recently formed a "Lithium Research Thrust"
to coordinate Li research on NSTX and with the broader Li program

PAC23-2

- Motivation:
  - Need to better understand underlying physics of how Li impacts plasma
    - And how plasma and non-Li PFCs impact Li PFCs
  - Impact of Li is cross-cutting
    - Impacts all NSTX topical science areas, and several programs at PPPL
- Goals:
  - Develop integrated NSTX Li research plan – 3 yr time horizon (FY09-11)
    - Increase emphasis on Li diagnostics, theory, simulation support
  - Coordinate Li research plans between NSTX, LTX, theory, and growing group of collaborators: Sandia, Purdue, University of Illinois, UCSD, ORNL, LLNL, …
- Leadership:
  - C. Skinner (leader): NSTX representative – coordinates NSTX Li experiments
  - R. Kaita (deputy): LTX representative, coordinates NSTX Li diagnostics
  - D. Stotler (deputy): Li theory and modeling coordinator for NSTX and LTX
  - Meet with all TSG leaders as needed to capture cross-cutting issues
- Time-line:
  - Initiated this year with 3-4 run days – will focus on Li D retention, Li dropper
  - Will also coordinate FY09 LLD research prep and FY2010 LLD experiments

NSTX is making world-leading contributions to ST development and contributing strongly to ITER & fundamental toroidal science

Outline:

- Role of the ST in fusion research
- Missions of NSTX and Next-step STs
- Prioritization of Near-term Research
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NSTX 5 year plan review panel endorsed the NSTX mission, research priorities, and proposed major facility upgrades

- "Proposed research clearly aims to position the ST as a candidate for future high priority US research missions, as articulated in recent FESAC reports
  - High heat flux facility for PMI research, as embodied in NHTX
  - Nuclear component testing, as embodied in ST-CTF"

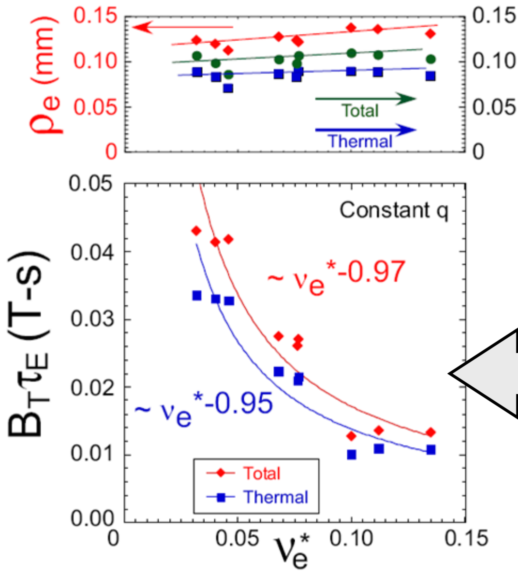
- "The panel agrees that the proposed research priorities address these missions
  - 100% non inductive current drive
  - Particle and heat flux control
  - Non inductive start up and ramp up
  - Sustained high beta operation"

Further motivation for formation of NSTX "Lithium Research Thrust"

- "The major facility upgrades are appropriately sequenced:
  1. The liquid lithium divertor (LLD) is an innovative approach to density control
     - Potential for high reward, but no guarantee LLD will provide necessary control
     - Measuring and modeling effects associated with lithium will be critical to understanding the science and projecting future applications.
     - It is not clear that there is sufficient attention paid to this in the proposal.
     - A backup strategy for density control should be better developed
  2. The center stack upgrade is very well motivated and should be installed as soon as possible
  3. The second neutral beam source is essential to take advantage of higher B_T and current capability from center stack upgrade"

Increased temperature and duration needed to address key issues for toroidal plasma science, ITER, and next-step STs

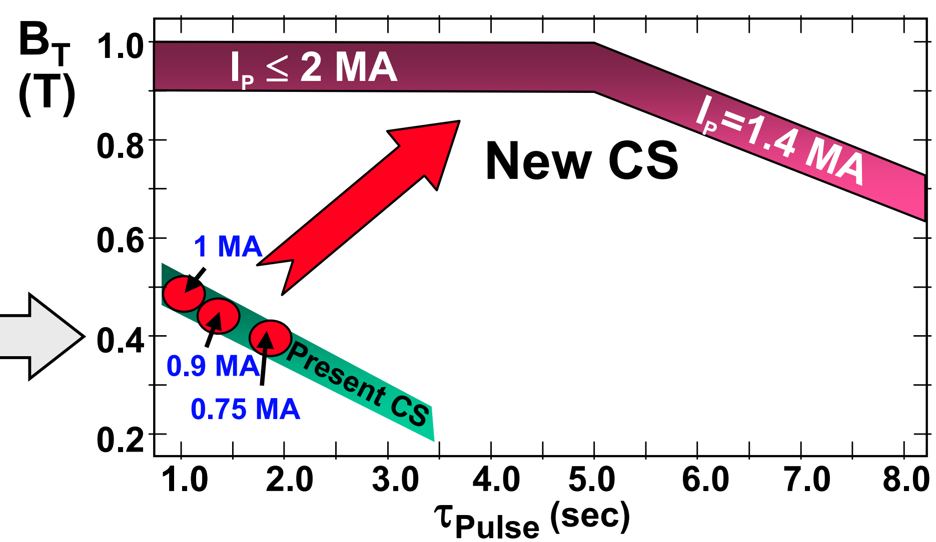
- Higher field and current enable access to higher temperature
- Higher temperature reduces collisionality and increases efficiency of non-inductive current-drive sources, and increases equilibration time
- New CS with B_T = 1T, I_P = 2MA (with induction), $t_{flat\text{-}top}$ = 5s would provide:
  - Longer pulse to assess RF ramp-up, 100% non-inductive sustainment at ~1MA
  - Higher field to stably accept high power for edge heat/particle transport studies
  - Extended range of field, current, β, collisionality to obtain unique data to aid development of first-principles understanding of turbulent transport
  - Magnet operation at ~1T (vs. 0.55T), within factor of 2 of next-step STs



ITER $B\tau_E$ (e-static g-Bohm)
$\propto \rho_*^{-3}\ \beta^0\ \nu_*^{-0.14}\ q^{-1.7}$
Petty et al., PoP, Vol. 11 (2004)

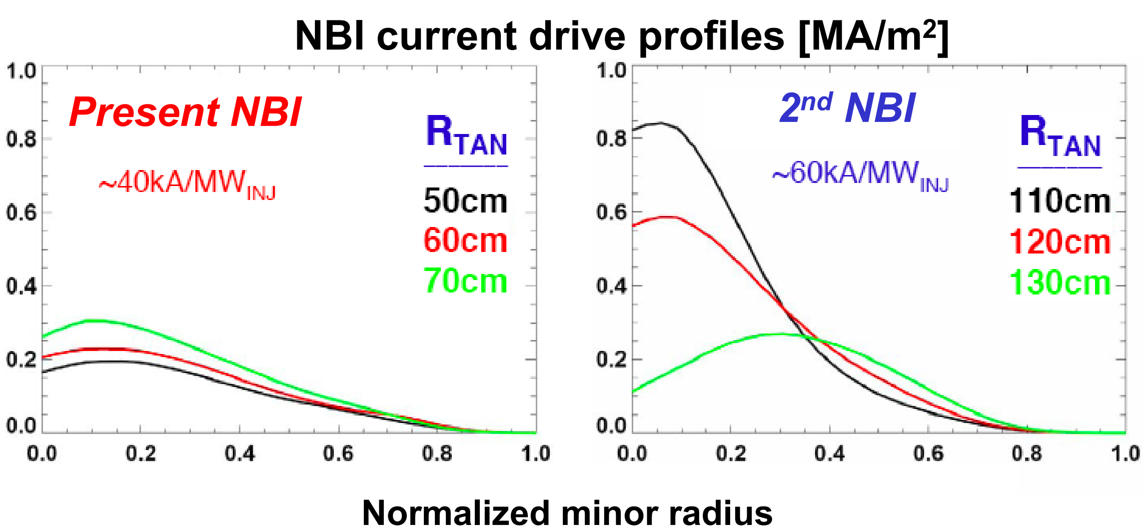
Does NSTX strong and favorable increase in confinement at reduced ν* persist at lower ν*, higher B_T

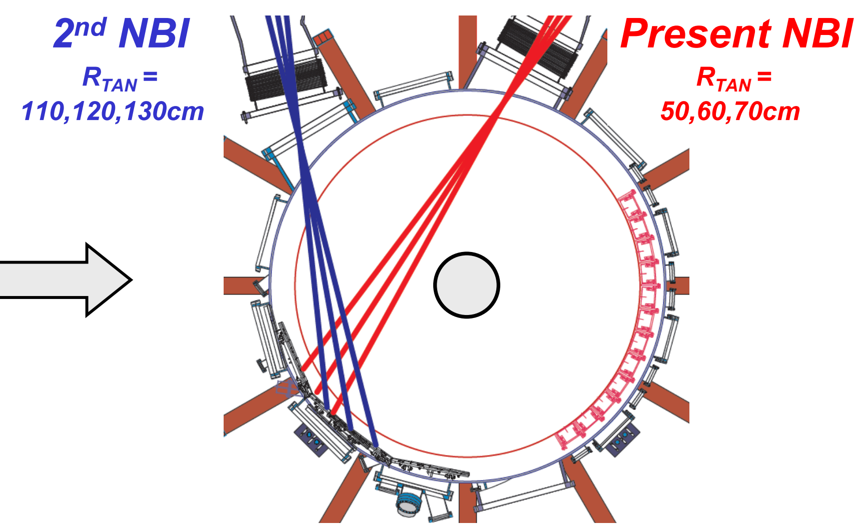
Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$



More tangential 2nd NBI would enhance heating & current-drive for start-up, sustainment, heat-flux, transport studies

- More tangential 2nd NBI would provide:
  - Up to 2 times higher current-drive efficiency, and current profile control
  - Tests of NBI ramp-up to ~1MA
  - World-leading capabilities for plasma boundary physics at high heat flux
    - Double NBI power: P/R = 12 → 20 MW/m (includes 4MW RF)
    - ITER / CTF / DEMO = 19 / 40-50 / 40-130 MW/m
  - Increased heating power to access very high β at low collisionality – important for fundamental studies of transport and global stability
  - Overall, a highly flexible tool for toroidal physics research by varying current, heating, and torque profiles, and fast-ion distribution function $f(v_{||},v_{\perp})$



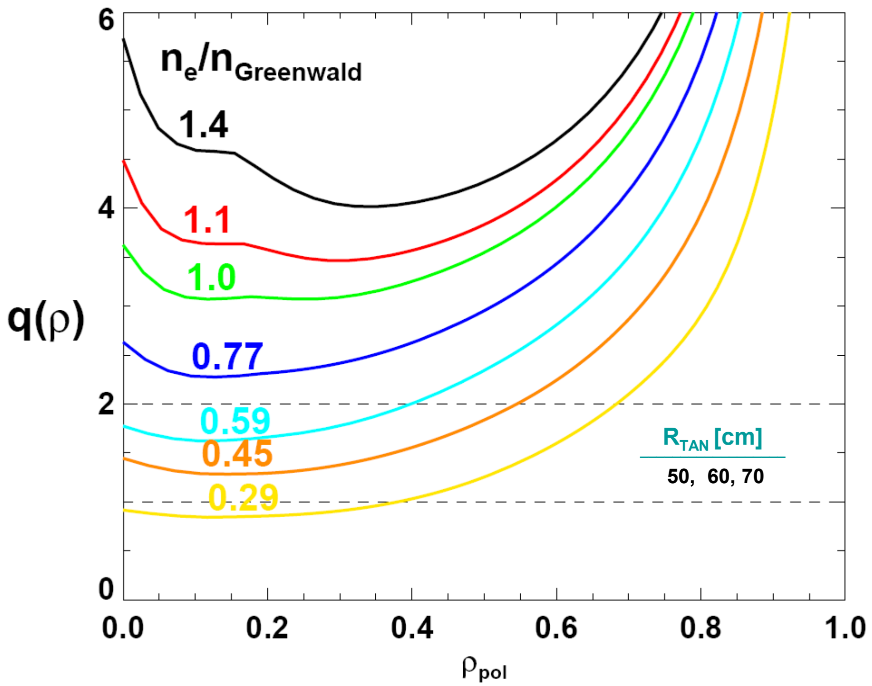


Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- Use present NBI-CD + fast wave heating
- Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)
- State sustained for 1-1.5s (~1 τ_{CR})
  - NBI duration limited to 2s at 7.5MW

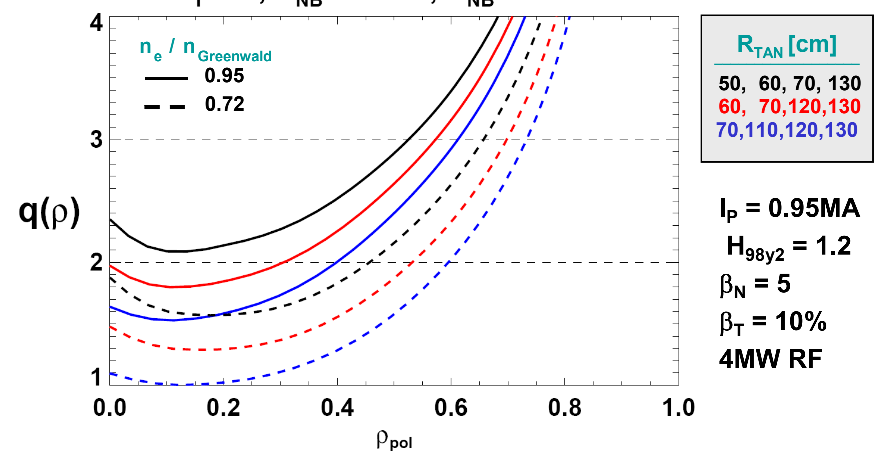
- Addition of 2nd NBI would enable:
  - Longer NBI duration → profile relaxation
    - 10MW NBI available for 5s → 3-4 τ_{CR}
  - Control q_{min} & q-shear with NBI source and B_T
  - Study long-pulse MHD stability, PMI performance

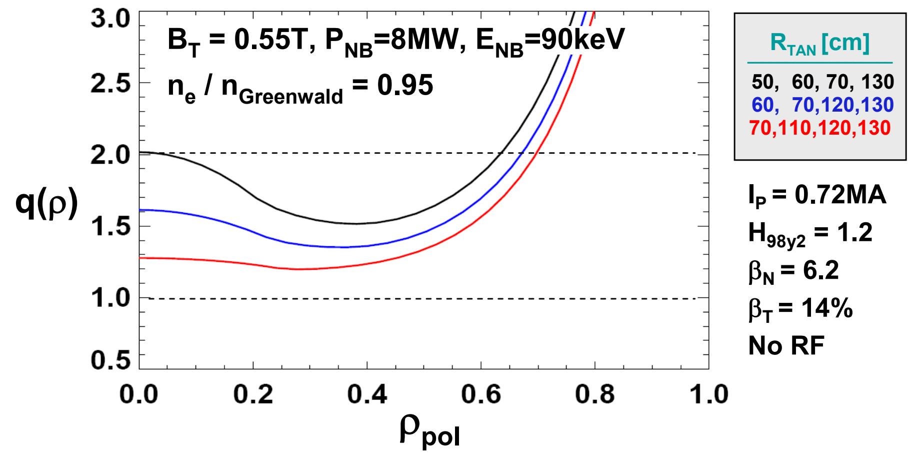
q profiles at 100% NICD fraction
B_T=1T, P_{NB}=7.5MW, E_{NB}=100keV



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

q profiles at 100% NICD fraction
B_T=1T, P_{NB}=10MW, E_{NB}=110keV





Higher plasma current enables confinement and stability studies over wide parameter range to aid understanding and projection to next-steps

- Higher plasma current expected to expand range of accessible T and ν^*
  - Accessible ν^* will depend on how confinement scales at higher field and current
  - Present ST confinement scaling → 3-4× higher W_{TOT} with 2× higher B_T, I_P, P_{HEAT}
- Access to higher current important for variety of physics issues – examples:
  - High-β_T physics at lower ν^* (RWM, NTV) – requires access to high I_P/aB_T
  - Core transport and turbulence at reduced ν^*, reduced $\chi_{i\text{-neoclassical}}$
  - Pedestal transport/stability, SOL width, heat flux scaling vs. current, …
- High I_P =1.6MA and B_T = 1T partially-inductively driven scenarios identified:
  - f_{NICD} = 65% with $\mathbf{q_{min} > 1}$, β_N = 5, β_T =14%, NBI profile computed with TRANSP
    - Similar to present high NI-fraction discharges, but with 2× field and current
  - These scenarios also require ≥ 8MW of NBI heating power for $H_{98} \leq 1.2$
- Solenoid in new CS and PFs being designed to support 2MA plasmas for 5s
  - I_P = 2MA requires increased vertical field capability to support l_i > 0.5 plasmas

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NSTX participation in International Tokamak Physics Activity (ITPA) benefits both ST and tokamak/ITER research

Actively involved in 21 joint experiments – contribute/participate in 33 total

MHD, Disruption Control

• 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 Confinement

• TC-1 (was CDB-2)	Confinement scaling in ELMy H-modes: beta degradation
• TC-2 (was CDB-10)	Power ratio – Hysteresis and access to H-mode with H~1
• TC-4 (was CDB-12)	H-mode transition and confinement dependence on ionic species
• TC-6	Effect of Rotation on Plasma Performance
• TC-10 (was TP-7)	Experimental ID of ITG, TEM and ETG turbulence + comparison w/ codes
• TC-15	Dependence of momentum and particle pinch on collisionality

Energetic Particles

• EP-2	Fast ion losses and redistribution from localized *AE

Pedestal and Edge Physics, Divertor, Scrape-off Layer

• PEP-6	Pedestal structure and ELM stability in DN
• PEP-19	Edge transport under the influence of resonant magnetic perturbations
• PEP-25	Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils
• DSOL-17	Cross machine comparisons of pulse-by-pulse deposition
• DSOL-21	Introduction of pre-characterized dust for dust transport studies in divertor and SOL

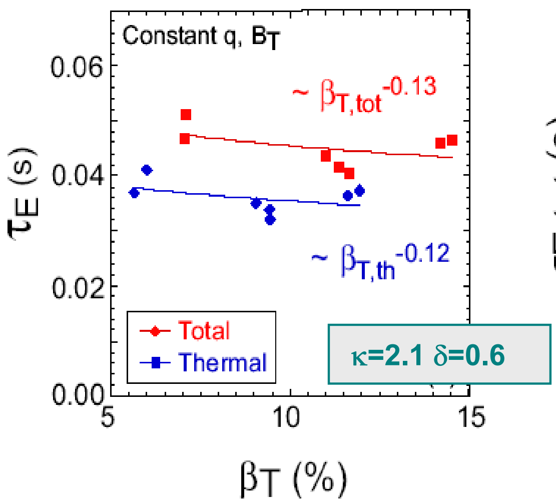
Integrated Operation Scenarios

• IOS-4.1	Access conditions for hybrid with ITER-relevant restrictions
• IOS-5.1	Ability to obtain and predict off-axis NBCD
• IOS-5.2	Maintaining ICRH coupling in expected ITER Regime

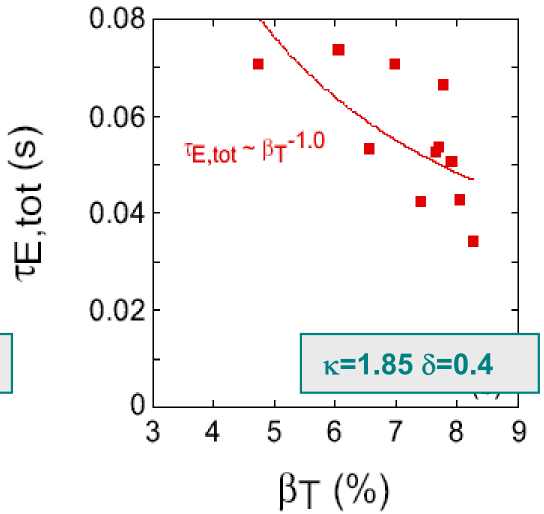
Previous examples of NSTX contributions to ITPA for ITER:

- **Transport:** β-dependence of H-mode confinement important to ITER advanced scenarios ($B\tau_{98y2} \sim \beta^{-0.9}$)
  - NSTX performed β-scan (factor of 2-2.5) at fixed q, B_T
  - Degradation of τ_E with β weak on NSTX for strongly shaped plasmas, stronger for more weakly shaped plasmas
  - Implies shape and/or ELM-type influences β dependence of H-mode confinement scaling

Small Type V ELMs

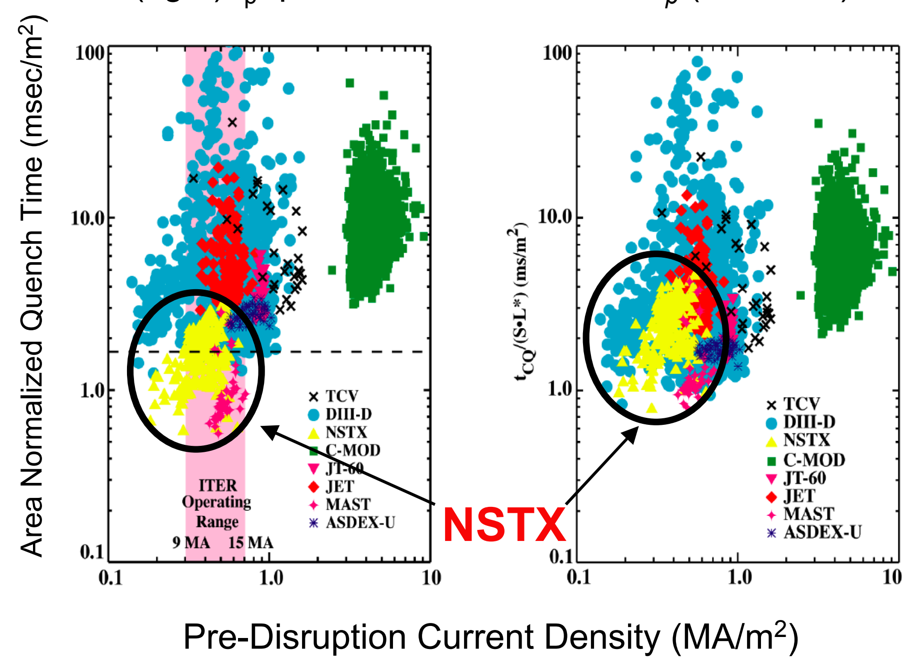


Type III/No → Type I ELMs



- **MHD:** Reduced normalized external inductance of low-A explains difference in I_P quench-rate
  - Implies tokamaks & STs have similar T_e during I_P quench phase (impurity radiation dominates dissipation of plasma inductive energy)

Area-normalized (left), Area and L_{ext}-normalized (right) I_p quench time vs. toroidal J_p (ITER DB)



In FY2009-10, NSTX will support several high priority research tasks identified by ITER Organization

- Impact of He (and possibly H) operation on H-mode
  - Important for commissioning phase of ITER operation
  - **NSTX**: Examine L→H threshold, global confinement, ELM stability
- ELM modification, suppression, control
  - Important for ITER divertor survivability at high fusion gain
  - **NSTX**: Understand ELM modification results:
    - ELM stabilization with Lithium
    - ELM destabilization of with resonant magnetic perturbations (RMP)
  - **NSTX**: RMP ELM control at lower q_{95}, reduced ν^* (HHFW, LLD), vertical jogs(?)
- Validate neoclassical toroidal viscosity (NTV) flow damping theory
  - Important for minimizing mode locking during ITER RMP ELM control
  - **NSTX**: Additional expt/theory comparisons at varied ν^*, rotation, RMP spectrum
- Simulation of ITER test blanket module impact on plasma
  - Important for understanding impact of large predicted error fields
  - **NSTX**: Use EF/RWM coils to approximate TBM spectrum

Summary: NSTX will make world-leading contributions to ST development, and contribute strongly to ITER and fundamental toroidal science

- The FY09-11 plan:
  - Focuses research to address key gaps in extrapolating to next-step STs
    - Increased beam-driven current and higher non-inductive fraction at reduced ν^*
    - Electron and ion H-mode confinement
    - Non-inductive start-up and ramp-up
    - Density control and novel means to "tame the plasma-material interface"
    - Sustaining high normalized beta plasmas to maximize future fusion performance
  - Plan is well aligned with FESAC-TAP, and is responsive to ITER high priorities

- These plans and upgrades enable exciting new science in all topical science areas:
  - Measure & understand underlying instabilities that cause **anomalous energy transport**
  - Understand **RWM critical rotation and viscous torques** and dependence on lower ν_i
  - Understand role of ν^* and **Lithium on pedestal transport/stability** and divertor physics
  - Develop predictive capability for **fast-ion redistribution from multi-mode AE** for ST, ITER
  - Integrate CHI into normal ops, develop/understand I_P **ramp-up w/ HHFW BS overdrive**
  - **Push toward 100% non-inductive operation** by increasing NBI-CD w/ reduced collisionality

Appendix

NSTX response to PAC-23 recommendations - 1

PAC Recommendation/ Response Number	PAC Report Section	Issue	PAC Recommendations	NSTX Response	Action for Speaker	Responsible person(s)
1	2.2	NSTX organization, high-priority research plans and upgrades, LLD, HHFW	The NSTX Team should consider organizational and planning decisions that strengthen the research associated with these priorities and that measure and highlight progress. For example, the NSTX Team should consider allocating "cross-cutting" and "reserve" run days in FY 2008 to experiments that enhance understanding of the effects of Li and that maximize the effectiveness of HHFW. The NSTX Team should formulate additional and explicit milestones that will measure your progress in the key research associated with the LLD and the HHFW. Program management should consider adding a FY 2008 milestone for demonstrating and understanding the effects of the second LITER, and consider adding FY 2009 milestones to measure progress with the LLD and the dual-feed HHFW antenna.	FY09 Joule milestone on retention will address pumping characteristics of Li surfaces using LITER. This work will continue in subsequent years. LLD will not be operational until FY10. FY10 research milestone will assess impact of LLD on edge plasma performance. Will use sample probe to assess surface chemistry of LITER and LLD and impact on edge/core plasma performance. FY11 BP milestone will utilized new surface analysis diagnostic (MAPP) to analyze surface chemistry in 'real-time'	Fold this response into boundary physics and/or Li program presentations.	Maingi, Skinner
2	2.2	NSTX organization, high-priority research plans and upgrades	The NSTX Team would benefit from identifying an organizational structure, with clearly defined leadership and responsibilities, for the 4 "cross-cutting" efforts associated with your key upgrade priorities (the LLD, the HHFW, and the BES), and key research priorities (NBICD, H-mode confinement, sustained high-?N operation and non-inductive current start-up and ramp-up.) Although the NSTX Team should not abandon those efforts that advance scientific investigations broadly and are well suited to the TSGs, the need to focus on priorities is urgent. As a consequence, the PAC urges the NSTX Team to identify one or more additional organizational structures to aid the implementation of priority upgrades and the coordination of high-priority research. The PAC acknowledges that this might be accomplished in several ways; the important point is that the chosen way should empower certain individuals with leadership and responsibility for each of your high-priority activities.	The NSTX research team agrees there is a need for a 'Lithium thrust', both to oversee the Li program on NSTX, and to aid the BP TSG in managing the broader range of BP issues. Particular attention must be paid to diagnostics and modelling for Li and LLD.	Form a 'Lithium research thrust' in parallel with the TSGs. This will be led by Charles Skinner (research plan and diagnostics) and Darren Stotler (modelling). Menard will discuss in program talk. Skinner+Stotler will give Li program/diagnostics/modelling presentation.	Menard, Skinner
3	3.1	NSTX organization, high-priority research plans and upgrades, LLD, HHFW	The PAC encourages the NSTX Team to further strengthen high priority activities in the FY 2008 run plan. The critical importance of the LLD for the achievement of FY 2010 goals suggests strengthening efforts to understand the underlying behavior of lithium in NSTX, in support of the role of lithium in the achievement of density reduction and other discharge performance goals. The PAC recommends that a FY 2008 milestone be defined to highlight new results from the dual LITER. Additionally, research that would directly benefit the utilization of future key upgrades and key research goals should have priority in the allocation of "cross-cutting" and "reserve" run days. Examples include experiments using the dual-LITER and experiments that yield new HHFW understanding.	Agree, and see responses #1 and #2 above, and corresponding actions.	Taylor to refer to success of LITER in improving HHFW performance in D H-mode. This shows we are already addressing some cross-cutting implications of Li.	Taylor
4	4.1	Transport	The observation that global confinement studies have given way to local transport studies is correct. Therefore, to have impact, NSTX global confinement studies must be clearly linked to local transport studies and conceptual understanding, for example, through coordinated modeling and theory efforts. The combination of low-k BES with high-k diagnostics to study phenomena across electron/ion scales should be matched with the development of modeling efforts that seek to address disparate scales and the significant physics likely occurring across those scales. Predictive capability and validation need to be backed up with specific plans like the joint design of experiments by experimenters, modelers, and theorists, and the development and implementation of validation metrics.	Agree	In transport presentation, discuss progress and plans to compare simulations of low-k and high-k turbulence to measurements, and the experiments to be performed and diagnostics that will be used to support this.	Tritz
5	4.1	Transport	Planned work with lithium provides unique opportunities for particle transport studies that should not be missed. Where possible these should be combined with other resources known to affect particle transport, like RMPs. NSTX's combination of neoclassical ions and anomalous electrons also offers unique opportunities for transport studies. Comparisons with MAST, where chi-phi appears to be more closely correlated with chi-i, would be instructive for characterizing transport across STs, as well as helping to advance understanding of momentum transport. Related questions should be pursued like understanding the role of pinch anomalies in momentum transport when chi-phi remains smaller than a neoclassical chi-i.	Agree	In transport presentation, discuss impact of RMP field on ELM triggering and impurity accumulation (i.e. particle transport). Also discuss momentum pinch results, and if available, compare NSTX results to MAST results	Tritz
6	4.2	Boundary Physics	As discussed last year and also during this year's meeting, it is very important to determine the physics behind the changes in plasma performance correlated with the use of Li. Are the positive effects on plasma performance and plasma profiles the result of changes in recycling (pumping)? If the Li pumping is the dominant effect, is the important pumping occurring at the divertor or around the first-wall generally? Is it possible that lithium coatings primarily bind deuterium loaded into the carbon wall, making it unavailable for recycling? Could it be that the positive effects correlating with Li usage are due to suppression of some impurities (e.g. C, O) and/or their replacement with Li in the plasma? Closer collaborations with FTU, which is the largest metal-walled tokamak performing extensive lithium PFC work, may also provide information on the role of carbon-lithium interactions.	Agree these are critical issues and questions for the Lithium program. See response #1 above. The FY09 milestone on retention will give us significant insight into retention and pumping. This research will continue in subsequent year.	Incorporate responses to these questions, or the plan the respond to these questions, in a presentation from the "Lithium Research Thrust".	Skinner
7	4.2	Boundary Physics	Returning to the issue of pumping, such experiments should include particle accounting (i.e., how much gas is injected versus how much is left in the vessel after a shot, as well as postmortem analysis of the tiles). Experiments should be done with bare walls after a vacuum break (no Li on surfaces) and then, after lithium is introduced, for each shot (which was a direct recommendation from PAC-21).	Agree. These experiments were performed in 08, more to come in 09 and beyond.	Incorporate response in a presentation from the "Lithium Research Thrust".	Skinner

NSTX response to PAC-23 recommendations - 2

8	4.2	Boundary Physics	Based on the importance of this issue for NSTX, STs in general, and all fusion devices, we urge the NSTX staff to devote more resources to understanding the physics that lead to changes in plasma behavior with Li along the lines of the questions above. By more resources is meant more personnel, more diagnostics, an increased integrated modeling effort, and more experiments. The latter should come from allocation of the 'cross-cutting' and 'reserve' days, as well as from allocation of the additional 6 run weeks if those become available.	See responses 1, 2, 3 6, 7 above	Incorporate response in a presentation from the "Lithium Research Thrust".	Skinner
9	4.2	Boundary Physics	We also recommend studies, if possible, of the efficacy of impurity puffing (e.g., N2, Ne) for achieving detachment. Comparison of the effectiveness of impurity puffing to enhance divertor radiation with and without a fresh Li surface may lead to some useful information about the effect of Li on core impurities as well.	Will consider. But are there risks to trapping impurity ions in Lithium coatings?	Discuss issues associated with impurity puffing for detachment in boundary physics talk	Maingi
10	4.3	HHFW and EBW	An upgrade to the HHFW system is planned, to increase the voltage handling capability of the antenna. This upgrade should result in higher power coupling during both startup and full current operation. The NSTX team should accordingly ensure that sufficient resources are allocated to prepare for and take advantage of this upgrade. In FY08, it is planned to extend the L-mode helium plasma studies to L- and H-mode NBI-heated D plasmas, with a phase scan and MSE measurements to determine the non-inductive current profile. Sufficient run time should be allocated for a thorough study, and the work should be extended to higher neutral beam power	Agreed.	In HHFW talk, describe FY09-11 plans to utilize higher power and ELM resilience capabilities. Also describe FY08 results of HHFW heating of D H-mode heated with NBI, and role of lithium coatings.	Taylor
11	4.3	HHFW and EBW	Results with - 90 degree (co-) phasing are clearly relevant to startup and provide benchmarking of 3D RF codes. However, the peaking of the current profile produced by on-axis current drive at 90 degree phasing and the resultant drop in q(0) is undesirable. Consideration should be given to additional work with symmetric or counter (+ 90 degree) phasing to heat without additional current peaking, or even broaden the current profile. If absorption at - 150 degree is very strong and significantly off-axis, it may also be useful for broadening the current profile.	Agreed.	In HHFW talk, decribe FY08 HHFW-CD results, and describe FY09-11 plans to utilize higher power and ELM resilience capabilities + alternative phasing options to optimize HHFW-CD.	Taylor
12	4.3	HHFW and EBW	Since fast wave heating or current drive in either NHTX or CTF would very possibly operate at lower normalized harmonic, we once again recommend that consideration be given to operation at 5.5 kG in hydrogen, perhaps at the end of the FY08 run to minimize impact on machine operations. Note also that the onset density for surface wave excitation should decrease as the normalized frequency decreases, for fixed wavenumber, which should further illuminate the role of surface waves in NSTX.	We did not do this in FY08. We are considering H and He experiments for L-H threshold physics studies. If we use H for those experiments, we can also test HHFW coupling and heating.	Discuss this in HHFW talk	Taylor
13	4.3	Fast particle physics	The synthetic diagnostic in the NOVA code was used to reproduce the radial mode structure seen with reflectometers. However, it was not clear whether these modes were the energetic particle multi modes or the TAE avalanche-or something else. It was stated that the computed mode structure, as verified against the experimental measurements, could then be put into the ORBIT code to simulate fast ion redistribution. However, no results were presented to allow comparison with DIII-D experiments (in which PPPL scientists are heavily involved) where a large discrepancy between the ORBIT prediction for redistribution and the measured result was found.	Agree this is an important issue.	In EP physics talk, describe which modes we are talking about, describe NOVA-K/ORBIT modeling effort and initial results (i.e. discrepancies), and linkage to DIII-D results and experiments.	Fredrickson
14	4.3	Fast particle physics	Another important result in FY07 was the finding that HHFW suppresses CAE/GAE modes that exhibit hole-clump frequency chirping. It would be interesting to check if this result is consistent with the Berk-Breizman nonlinear theory, which predicts that high "collisionality" (which can be supplied by an RF wave) tends to eliminate the instability.	Agree it would be interesting.	In EP physics talk, describe status and/or plans to assess impact of HHFW on CAE/GAE stability - is this a good project for HYM?	Fredrickson
15	4.4	Macro-stability	Given that the ITER design is expected to be finalized in FY 2008, there are several near-term, high-priority experiments in macro-stability that have been identified by the NSTX Team and the broader community that are included in the FY 2008 program. These are tests of resonant magnetic perturbations for ELM control, experiments to increase the understanding of the neoclassical toroidal viscosity, and tests of an ITER-like RWM coil configuration. Completing these experiments as early as possible in FY 2008 will represent a significant and timely contribution from NSTX to the ITER design decisions.	Agree.	In MHD talk, describe Joule milestone results on NTV, ITER-like RWM coil configuration, and RMP ELM mitigation experiments (pacing will be covered in BP talk)	Sabbagh
16	4.4	Macro-stability	The PAC notes that the NSTX team has clearly identified important and high-priority research in macro-stability, both in support of next-step ST options as well as in contribution to the science of toroidal confinement more generally. This area of research enjoyed a large amount of run time in FY 2007. Since the PAC is recommending more emphasis in other topical areas for FY 2008, we feel that the clear identification of high priorities in macro-stability research will be beneficial to ensure a productive year in this area of research in FY 2008.	Agree	In MHD talk, state what the highest priority experiments were for FY2008, and that they were completed.	Sabbagh
17	4.4	Macro-stability	The experiments in FY 2007 on the aspect-ratio comparison of neoclassical tearing mode stability were very efficient and effective, producing interesting comparisons of the marginal island width for stabilization and tearing onset conditions as a function of plasma rotation at different aspect ratios (in particular, comparing NSTX and DIII-D). The PAC recommends that a similar level of run time be devoted to tearing studies in FY 2008, and that the research focus might best be aimed at plasma rotation effects, since rotation is more generally a Joule milestone. Experiments probing dependencies on normalized gyroradius and collisionality might need to be deferred.	Agree	In MHD talk, describe successful correlation of NTM onset threshold with flow-shear. Describe plans to extend NTM research in FY09 and beyond	Sabbagh/Gerhardt

NSTX response to PAC-23 recommendations - 3

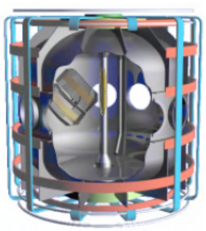
18	4.4	Macro-stability	The new set of 12 internal coils (the non-axisymmetric control coils NCC) proposed in the five year plan appears to be well motivated and will add significant new capability for a wide range of research. The PAC agrees that this upgrade will not be possible if NSTX does not operate past FY 2010. However, if it becomes clear that post-FY 2010 operation is possible, then we recommend pursuing a more detailed design so that the option to install NCC would be available.	Agree - but need to point out that NCC coils are now incremental in 5yr plan, and new CS and 2nd NBI are higher priority.	In MHD talk, describe NCC coil analysis done by CU group, and status/plans of GA collaboration on coil design for NSTX.	Sabbagh
19	4.5	Start-up and ramp-up	Currently, PF start-up is scheduled to begin in FY 2009. The PAC believes that outer-PF start-up could possibly begin in FY 2008, since pre-ionization is probably already good enough from CHI to initiate the outer-PF ramp-up. The PAC suggests investigating an earlier start for outer-PF start-up, as it appears to be a promising technique. The Plasma Gun also looks promising, and the PAC endorses the continuation of this work. With the Plasma Gun coming online in FY2010, it is uncomfortably close to the end of the three-year time period.	CHI work will focus on using absorber field-nulling coils and CHI-startup with non-zero OH. There are no proposals for PF-only startup. We do not have scenarios modelled which indicate coupling CHI to PF-only induction is possible/probable. The HHFW power will likely not be available in FY09 to re-visit PF-only startup. Pegasus group is developing capability and understanding of plasma guns and will bring to NSTX when technically ready - perhaps in FY11 or later. SFSU TSG will work jointly with HHFW TSG to assess BS-current overdrive.	In SFSU presentation, provide these responses.	Mueller/Taylor
20	4.5	Start-up and ramp-up	In a three-year program horizon, the current focus on CHI is appropriate. The PF Startup and Plasma Gun will be more difficult to master in a 3-year time frame, and it may be difficult to make progress on all three approaches with the limited run time available. We recommend that the NSTX team weigh carefully the benefits of CHI, PF, and plasma gun startup techniques, taking into account the availability of run time and resources. All of the techniques would benefit from an extended operational period lasting until FY 2013.	Agree, and this is true even in context of 5 year plan. The NSTX team has effectively down-selected to 1) CHI for start up and 2) HHFW for BS-overdrive ramp-up. We may not be able to couple these (CHI and HHFW) without ECH heating of CHI for HHFW absoprtion. NBI ramp-up from 0.4 to 0.8 MA is predicted to be possible with 2nd NBI and higher TF.	In SFSU presentation, provide these responses.	Mueller
21	4.6	Integrated Scenarios	An important by-product of the very-high-kappa capability is the ability to provide key information on vertical stability issues for ITER. This is a key issue for ITER, in which NSTX can play an important role in the scaling of the maximum controllable displacement from present-day devices to ITER. While there appears to be experimental time provided for this research in the FY 2008 plan, a description of the exact research to be done was not provided to the PAC, giving the impression that this is lower-priority research. The PAC encourages the NSTX team to place relatively high priority on providing this critical information to ITER.	Agree this is important, and experiments were performed in FY2008	In ASC presentation, describe vertical displacement experimental results for ITER.	Gates
22	4.6	Integrated Scenarios	The NSTX approach to push further towards the required operating space (for 100% non-inductive current drive) involves the use of liquid lithium for enhanced density control and improved confinement and HHFW for electron heating. The PAC is concerned that each of these enabling elements are presently at a limited level of maturity. In this regard, the PAC recommends that the NSTX team develop a multi-year plan that both develops these individual elements to the necessary level and combines these elements systematically into a self-consistent integrated scenario. The PAC realizes that each of these activities is a first-of-a-kind activity, so the development of such systems may require increased resources (manpower and experimental time) and an extended research program to develop the necessary knowledge base. While the PAC believes some level of integration may be possible in FY 2010, NSTX operation beyond FY 2010 will likely be required (rather than simply desired) in order to demonstrate this important capability.	Agree this is a good idea.	In ASC presentation, describe (transient) density reduction achieved in FY08, and elimination of He glow, and operational benefits. Describe confinement improvement (M. Bell scatter plot) with LITER/Li. Describe e-heating from HHFW in D H-mode with NBI, and plans for increased HHFW power and ELM resilience. Describe 3 year research program to integrate these. Also describe plans for beta-control.	Gates
23	4.6	Integrated Scenarios	The PAC is concerned that there appears to have been limited progress on refining the modeling of scenarios that were presented at PAC-21 since the scenarios presented this year are the same as those presented at PAC-21. The development of self-consistent scenarios will require several iterations between experiments and scenario simulation/modeling in order to identify the most favorable development path. In particular, it is important to establish the credibility of the models through comparison with experimental data. NSTX is now equipped with sufficient profile diagnostics that modeling of the obtained data can and should be an integral part of scenario development.	Agree this is an important issue.	In ASC presentation, describe how most recent scenario modelling focused on assessing higher TF (new CS) and 2nd NBI. Also mention ramp-up to 0.8MA modelling by Kessel using HHFW --> 2nd NBI. Mention that Kessel is now unavailable to NSTX (C-MOD, ITPA, ITER work). Emphasize new work on strikepoint control and rotation control.	Gates

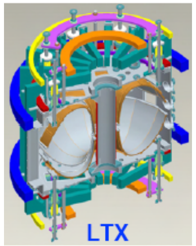
Backup Slides

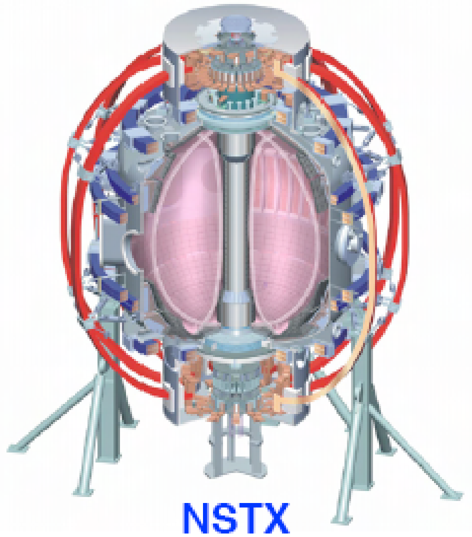
The ST offers attractive near-term applications for fusion development complementary to ITER

ST characteristics:

- High normalized pressure
- Compact geometry
- Simplified magnets





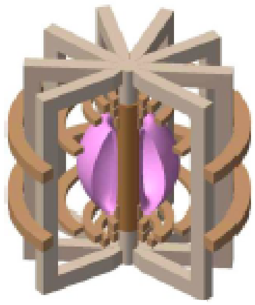


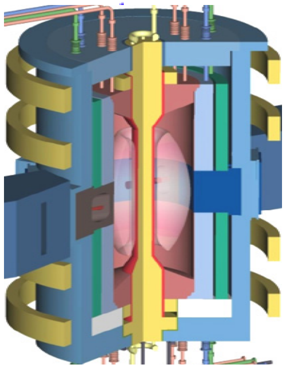
Implications:

- High heat flux at small size and reduced cost
- Simplified construction, access, and maintenance
- High neutron flux at small size and reduced cost, reduced tritium consumption

Near-term ST Applications:

Plasma-Material Interface R&D + Advanced Physics





Fusion Nuclear Component Testing

Longer term: ST Power Plant offers simplest magnets, easiest maintenance

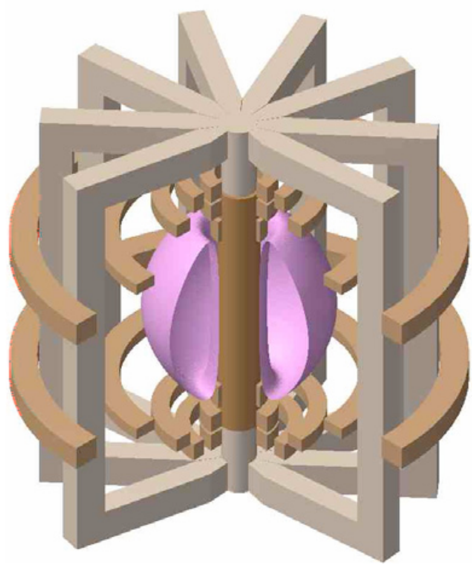
ST is attractive configuration for "Taming the plasma-material interface"

- FESAC-PP identified PMI issue as highest priority: "…solutions needed for DEMO not in hand, …require major extrapolation and substantial development"

Scientific mission of National High-power advanced Torus eXperiment (NHTX):

"Integration of a fusion-relevant plasma-material interface with stable sustained high-performance plasma operation"

- **PMI research and integration goals:**
  - Create/study DEMO-relevant heat-fluxes
  - Perform rapid testing of new PMI concepts
    - Liquid metals, X-divertor, Super-X divertor
  - PMI research at DEMO-relevant $T_{wall} \sim 600°C$
  - Plasma-wall equilibration: $\tau_{pulse} = 200\text{-}1000s$
  - Develop methods to avoid T retention
  - Demonstrate compatibility of PMI solutions with high plasma performance:
    - High confinement without ELMs
    - High beta without disruptions
    - Steady-state, fully non-inductive
  - Study high β_N, f_{BS} for ST-DEMO and ST-CTF
  - Test start-up/ramp-up for ST-CTF and ST-DEMO



National High-power advanced Torus eXperiment (**NHTX**)

Baseline operating scenario:

P_{heat}	50MW
R_0	1m
A	1.8-2
κ	≤ 3
B_T	2T
I_P	3-3.5MA
β_N	4.5
β_T	14%
n_e/n_{GW}	0.4-0.5
f_{BS}	$\approx$ 70%
f_{NICD}	100%
$H_{98Y,2}$	≤ 1.3
E_{NB}	110keV
P/R	50MW/m
Solenoid	½ swing to full I_P

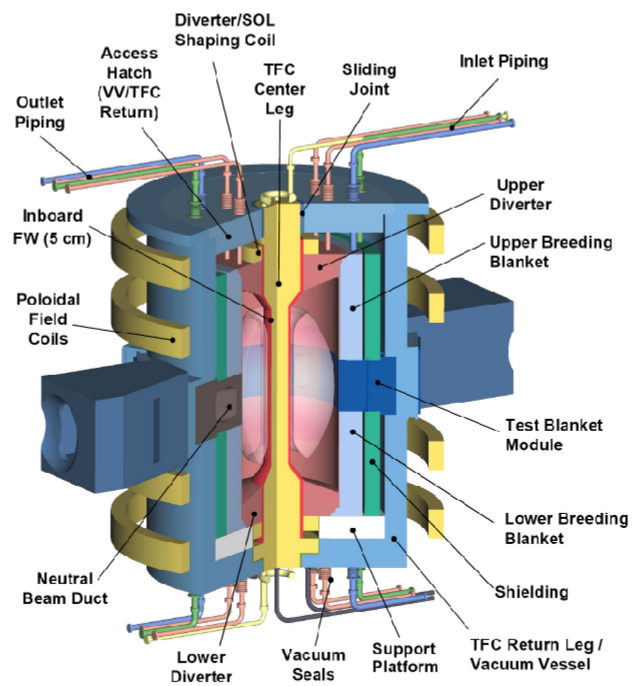
ST-based Component Test Facility (ST-CTF) is attractive concept for "Harnessing Fusion Power"

- **ST-CTF Required Conditions:**

From M. Peng APS-2007, based on NCT presentation to FESAC 8/7/2007

Performance metrics	ITER	Required Conditions	Demo Goals
Continuous operation	~hour	weeks	~months
14-MeV neutron flux on module (MW/m^2)	~0.8	1.0-2.0	~3
Total neutron fluence goal (MW-yr/m^2)	~0.3	6	~6-15
Duty factor goal	~1%	30%	~80%
Tritium self-sufficiency goal (%)	~0	~100	≥100

- **ST advantages for CTF:**
  - Compact device, high β
    - Reduced device cost
    - Reduced operating cost ($P_{electric}$)
    - Reduced T consumption
  - Simplified vessel and magnets
    - Fully modularized core components
    - Fully remote assembly/disassembly

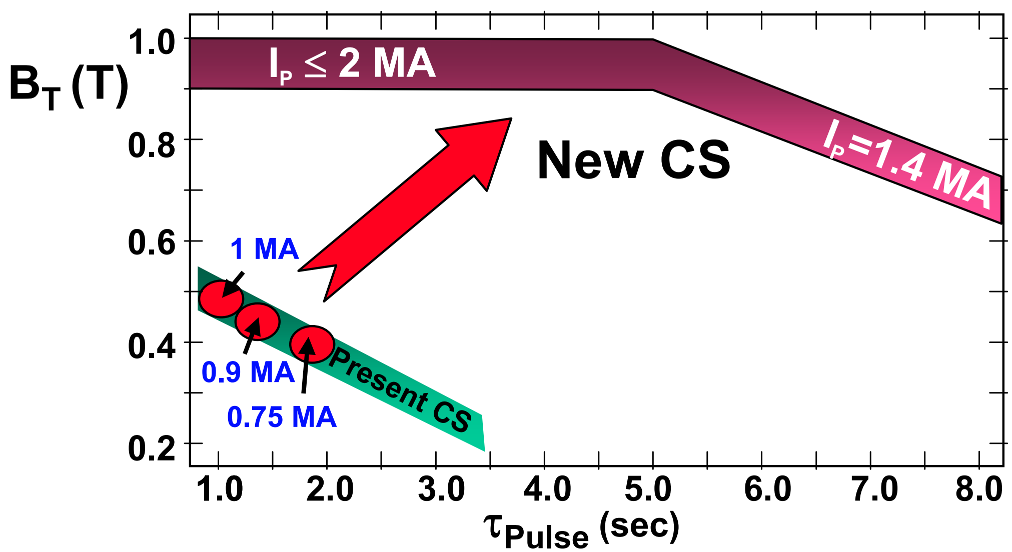


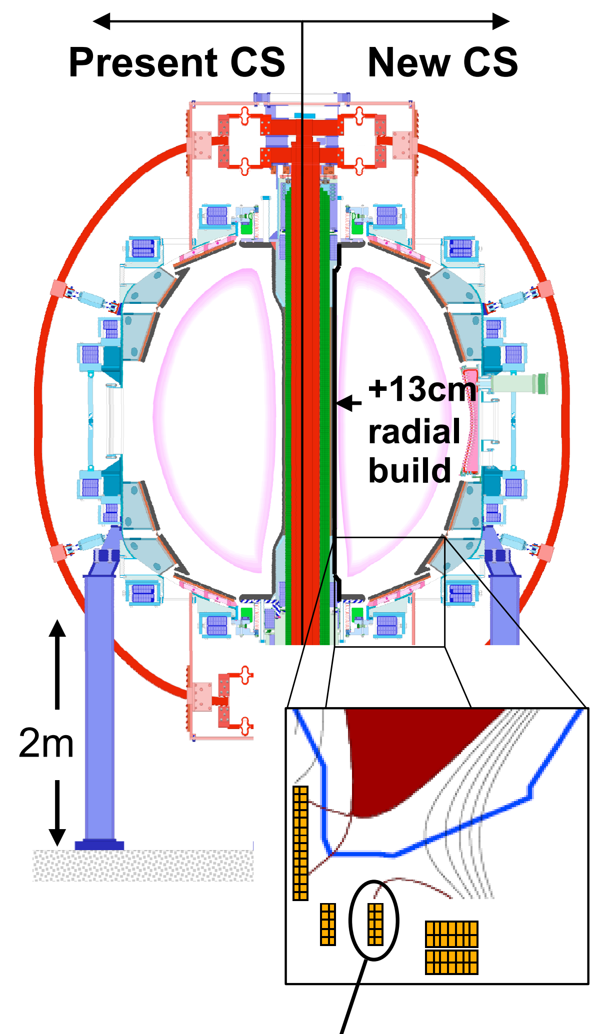
ST-based **C**omponent **T**est **F**acility (**ST-CTF**)

W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]	1.20		
A	1.50		
kappa	3.07		
qcyl	4.6	3.7	3.0
Bt [T]	1.13	2.18	
Ip [MA]	3.4	8.2	10.1
Beta_N	3.8		5.9
Beta_T	0.14	0.18	0.28
n_e [10^{20}/m^3]	0.43	1.05	1.28
f_{BS}	0.58	0.49	0.50
T_{avgi} [keV]	5.4	10.3	13.3
T_{avge} [keV]	3.1	6.8	8.1
HH98	1.5		
Q	0.50	2.5	3.5
P_{aux-CD} [MW]	15	31	43
E_{NB} [keV]	100	239	294
P_{Fusion} [MW]	7.5	75	150
T M height [m]	1.64		
T M area [m^2]	14		
Blanket A [m^2]	66		
$F_{n-capture}$	0.76		
P/R [MW/m]	**14**	**38**	**61**
Solenoid	**Iron core or MIC solenoid for startup**		

New high-performance interchangeable center-stack (CS) is needed to address key issues for next-step STs

- New CS with B_T=1T, I_P=2MA, $t_{flat\text{-}top}$=5s is needed to:
  - Assess RF ramp-up to ~0.4MA, 70→100% non-inductive ~1MA
    - Higher B_T,T_e for RF,BS,NBI + 5× longer pulse for ramp/equilibration
  - Stably accept high power for long-pulse heat flux mitigation tests with more flexible divertor poloidal field coil set
    - Max. P/R = 8→12 MW/m with present NBI + RF, 5× longer pulses
    - Test increased poloidal flux expansion: 20 → 40-60
  - Understand confinement vs. field, current, β, collisionality
    - Assess electrostatic ITG/TEM/ETG vs. electromagnetic μ-tearing/*AE
    - With present NBI+4MW RF, access 0.8-0.9× present β, 3-4× lower ν*
  - Assess magnet operation closer to field of next-steps
    - Present / upgrade / next-step = 0.55 / 1 / 2 Tesla

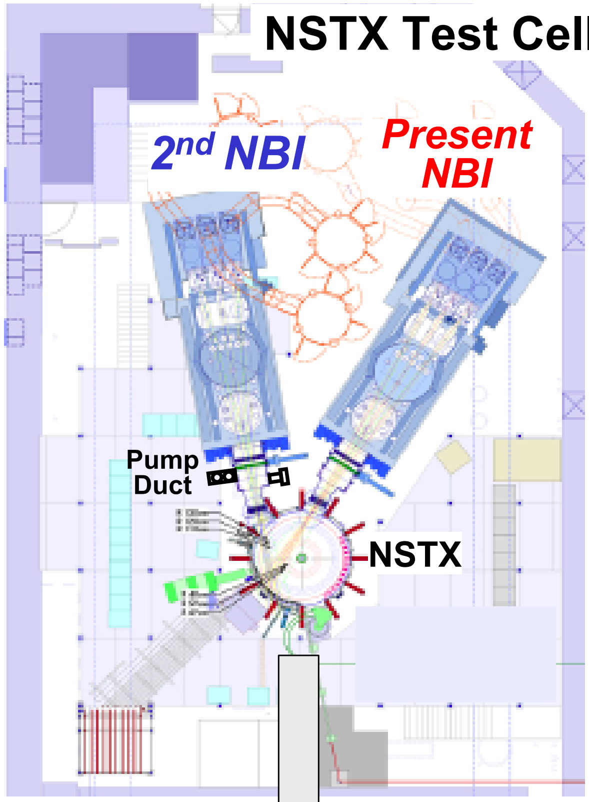




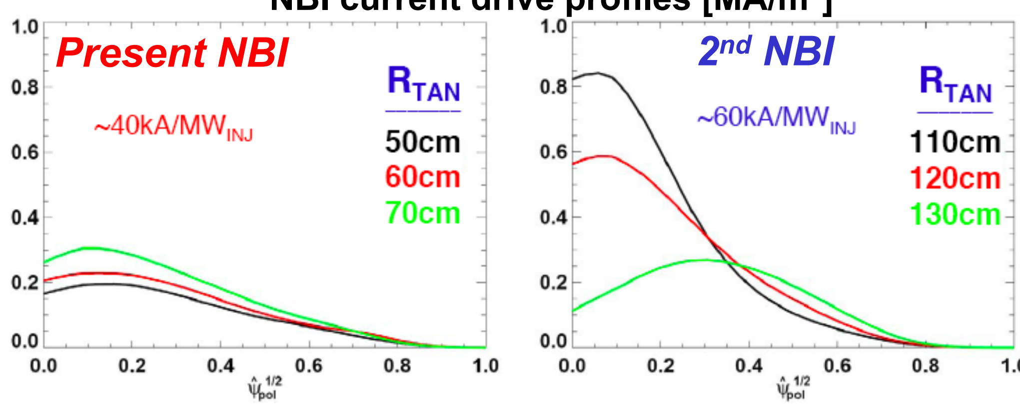
Additional divertor poloidal field coil for very high flux expansion and improved exhaust control

More tangential 2^{nd} NBI would enhance heating & current-drive for start-up, sustainment, heat-flux, transport studies

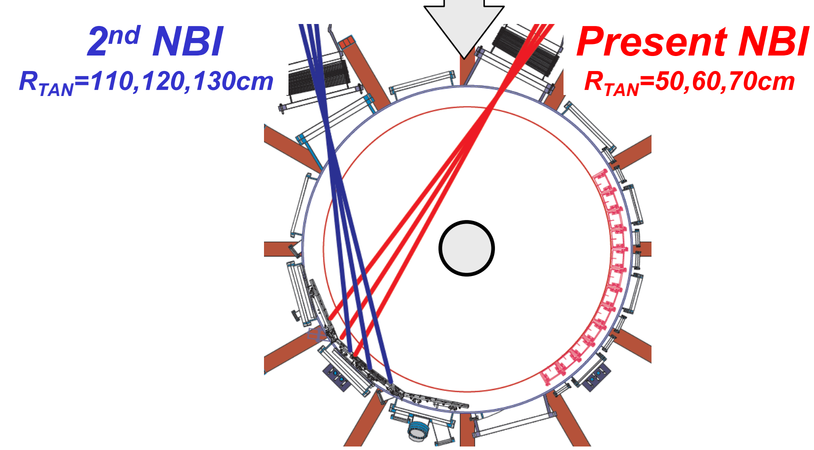
- More tangential 2^{nd} NBI would provide:
  - Tests of NBI ramp-up to ~1MA, relaxed 100% non-inductive
    - Higher absorbed fraction (40%→80%) at low I_P=0.4MA
    - 1.5-2× higher NBI current-drive efficiency
    - Present + 2^{nd} NBI can be stacked/interleaved for 2× pulse-length
    - J profile control by varying mix of present and 2^{nd} NBI sources
  - World-leading high heat flux studies
    - Double NBI power: P/R = 12 → 20 MW/m (includes 4MW RF)
    - ITER / CTF / DEMO = 19 / 40-50 / 40-130 MW/m
  - Flexible tool for transport studies
    - With both NBI + 4MW RF, access 0.9-1.2× present β, 4-6× lower ν^*
    - Vary q, heating, torque, fast-ion $f(v_{||},v_{\perp})$ and Alfvénic instabilities to identify/decouple modes causing anomalous transport



NBI current drive profiles [MA/m²]



P_{NBI}=2MW E_{NBI}=90keV, I_p=0.82MA, f_{GW}=0.58 $\overline{n}_e = 4.4\times10^{19} m^{-3}$, $\overline{T}_e$ = 1.2keV

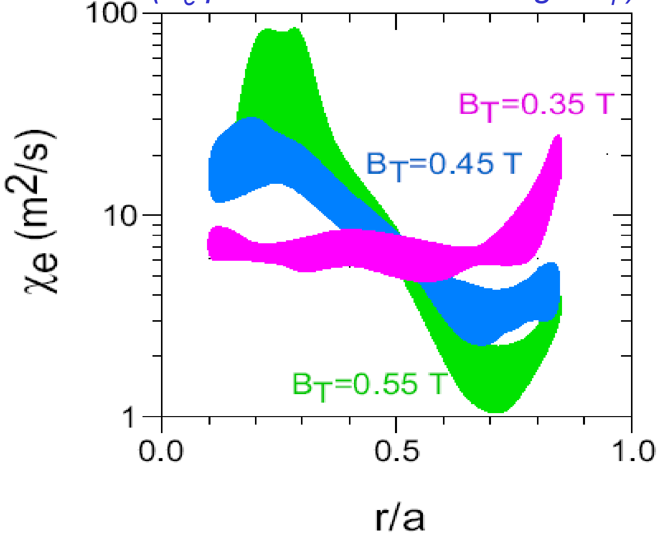


New center-stack is needed to extend ST confinement scaling studies to higher field and current and lower collisionality

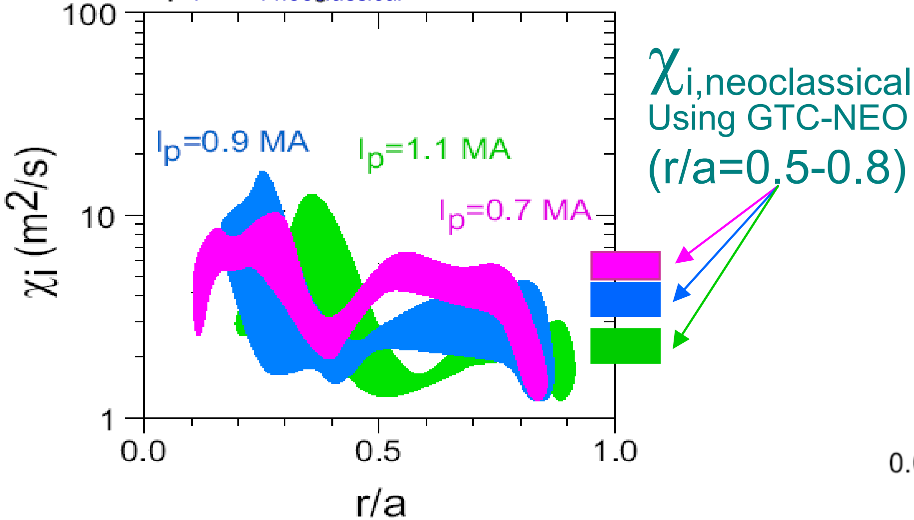
- **NSTX H-mode thermal confinement scaling differs from higher aspect ratio scaling:**

$\tau_{E,NSTX} \propto B_T^{0.9}\ I_p^{0.4}$ → strong B_T scaling $\tau_{E,98y,2} \propto B_T^{0.15}\ I_p^{0.93}$ → weak B_T scaling

Electrons largely responsible for B_T scaling of confinement
(T_e profile broadens at high B_T)

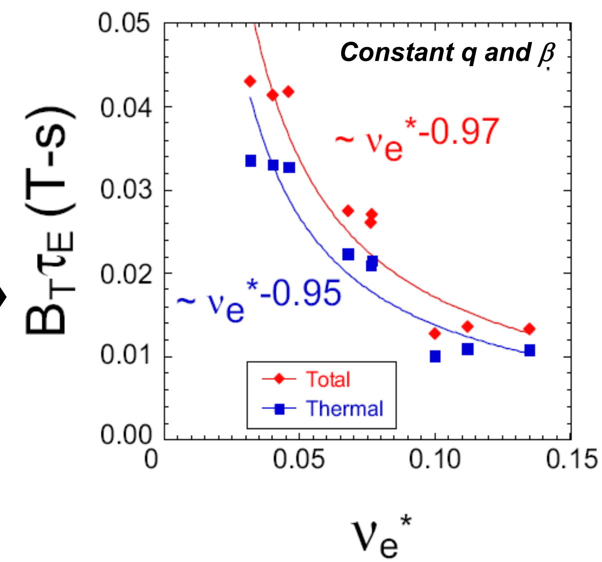


Ions largely responsible for I_P scaling of confinement
($\chi_i \approx \chi_{i\text{-neoclassical}}$ at large r/a)



New CS with 1T, 2MA operation:

- Increased range of B_T, I_P variation from 1.6 to nearly a factor of 3
- Does strong confinement dependence on ν^* extend to lower ν^*?
- Assume $\tau_E \propto B_T^{1.3}$ at fixed q, $\tau_E \propto P_{heat}^{-0.5\text{ to }-0.7}$, and $n_e/n_{gw} \propto I_P^{-0.5}$
  - –Present NBI + 4MW RF, access ~ 0.75-0.9× present β, 3-4× lower ν^*
  - –Present + 2nd NBI + 4MW RF: access ~0.9-1.1× present β, 4-6× lower ν^*



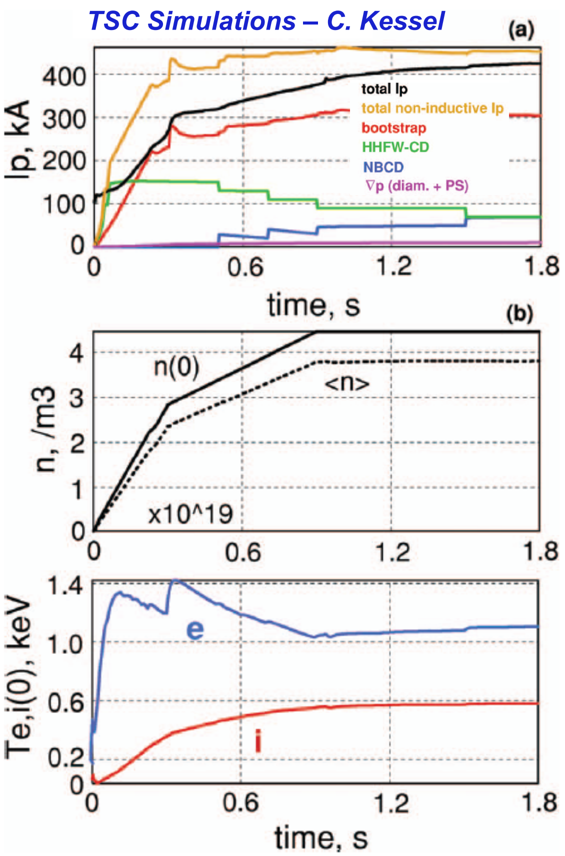
Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

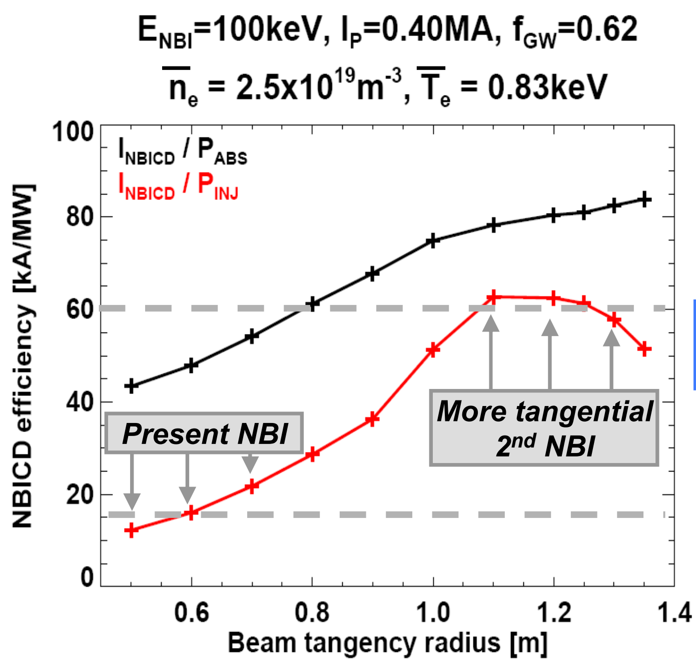
Ramp to ~0.4MA with fast wave heating:

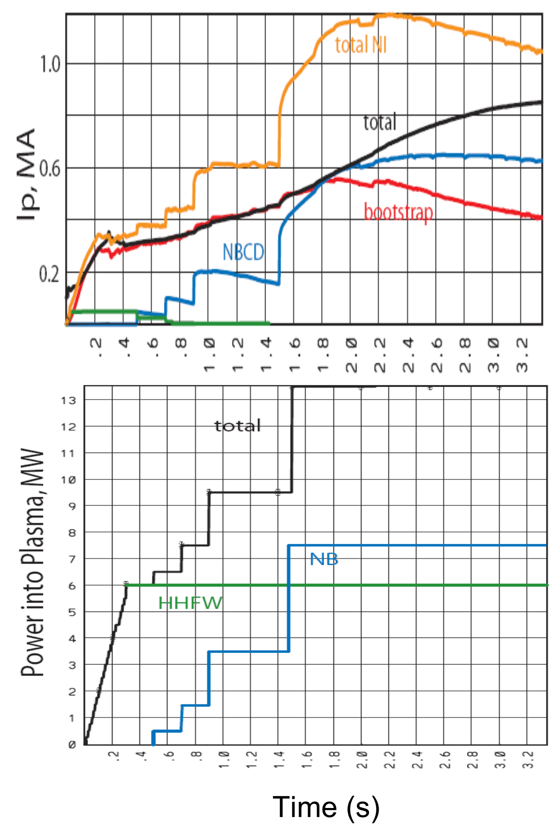
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

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



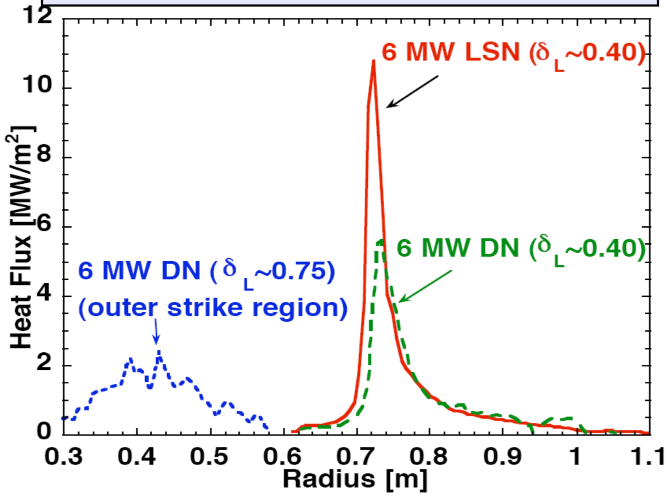




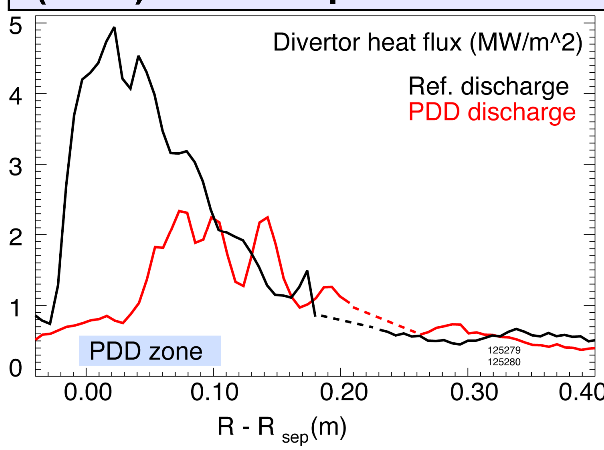
Additional PF coils of new CS would provide flexibility to control flux-expansion for heat flux control

Present NSTX:

Magnetic geometry strongly influences peak heat flux

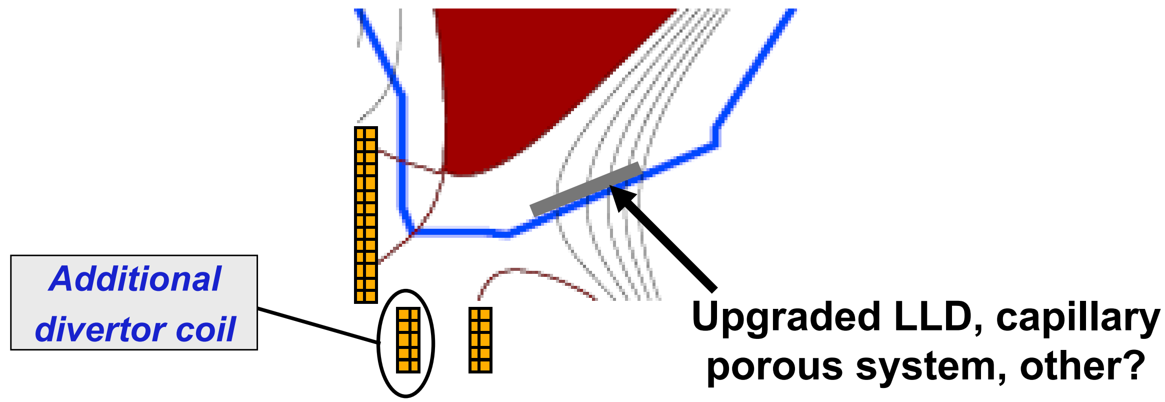


Partial divertor detachment (PDD) reduces peak heat flux

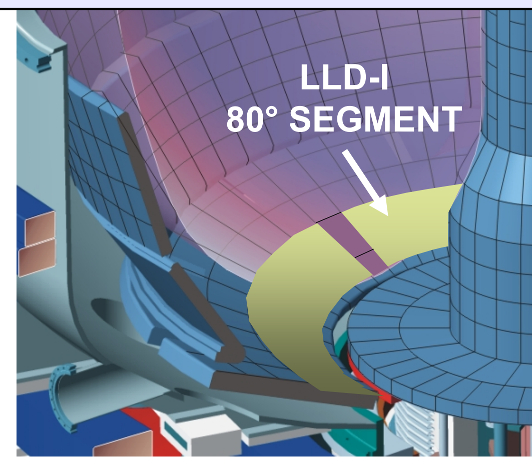


NSTX with new CS:

New divertor poloidal field coils on new CS would extend present high flux expansion ~20 to 40-60



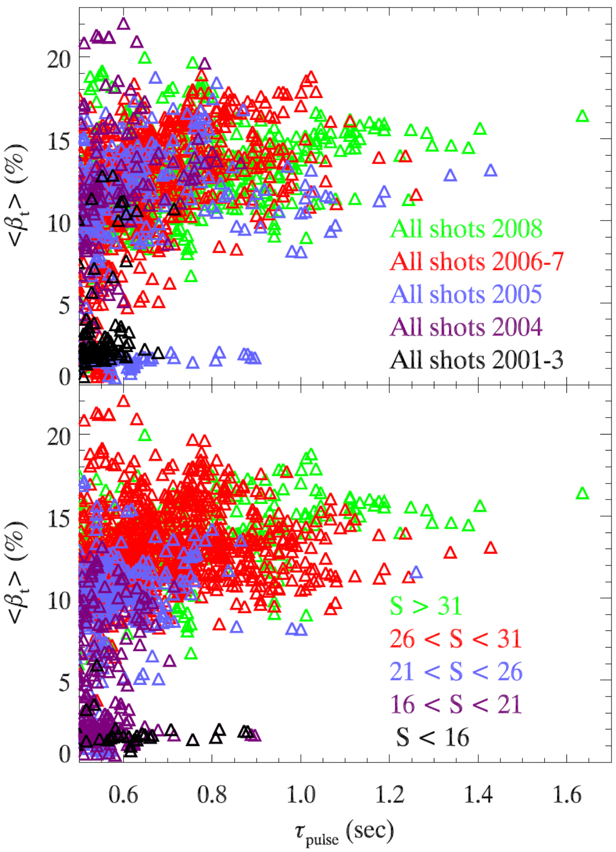
Upgraded NSTX would test compatibility of high flux expansion, PDD, a liquid lithium divertor (LLD), and up to 5× longer pulse-length and 2-3× higher divertor heat flux



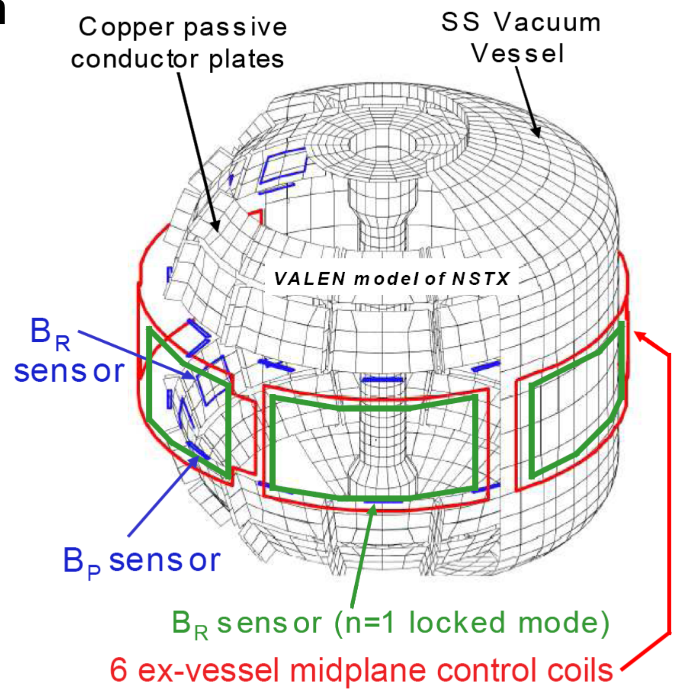
Improved control of plasma instabilities has significantly increased the duration of sustained high β in NSTX

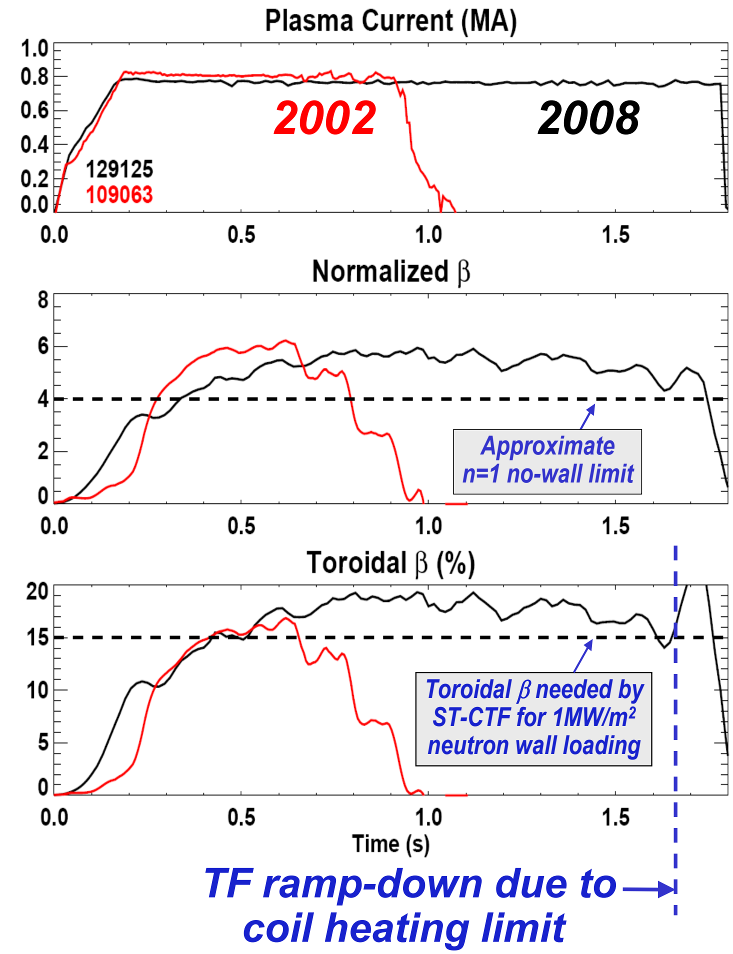
Increased plasma shaping from improved n=0 control for high κ and δ operation **+ n ≥ 1 EF/RWM control =** **Duration of β_T > 15% increased factor of 4 from 2002 to 2008**

NSTX has sustained β_T needed for ST-CTF for 4 current redistribution times



$S \equiv q_{95} I_P/aB_T$ [MA/mT]



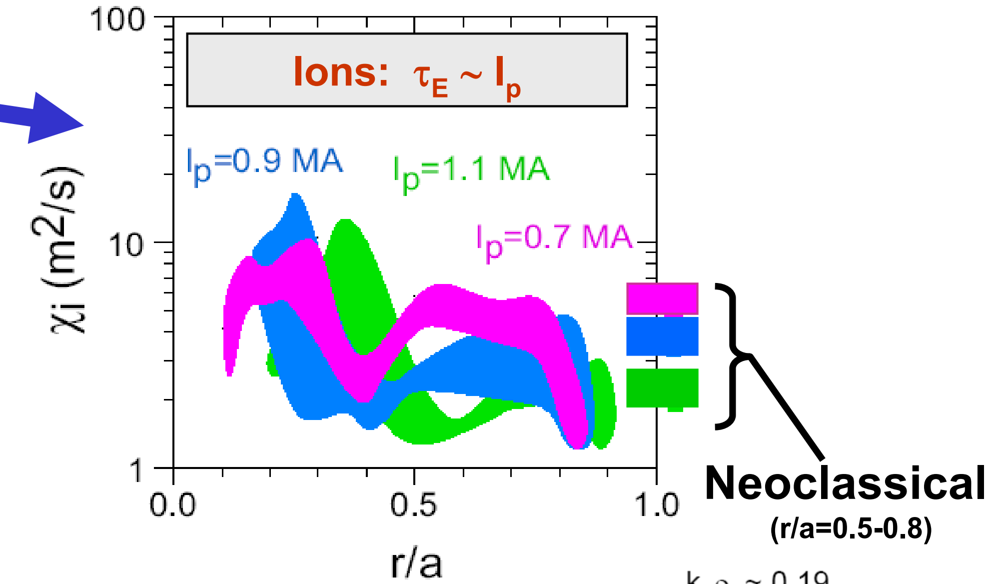


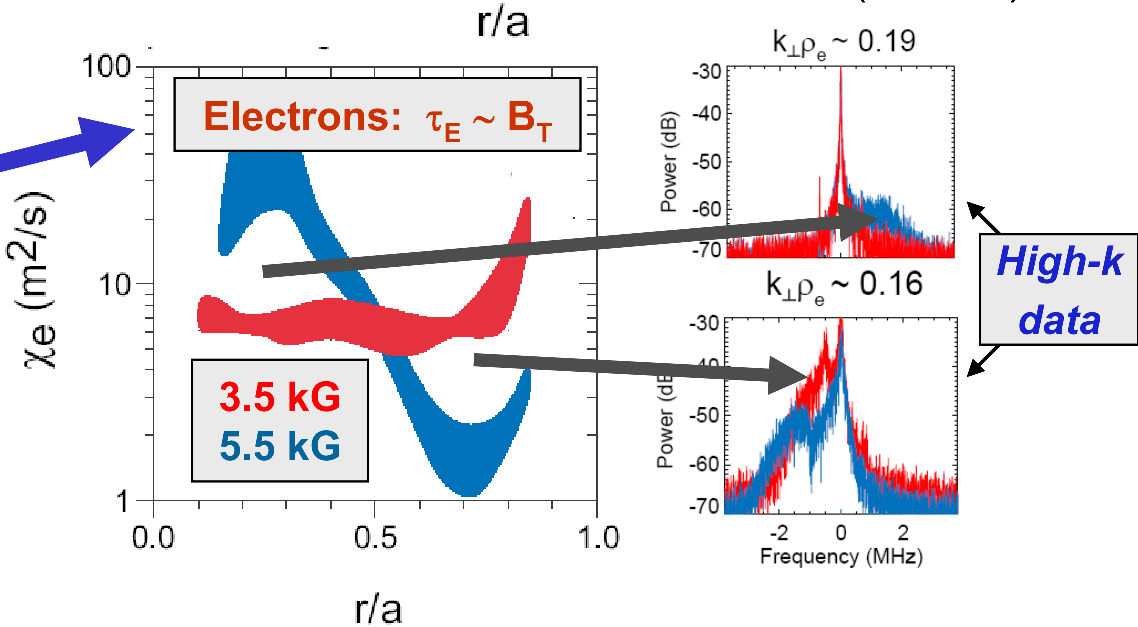
Control coils also used to study:
- Locked mode thresholds
- Resonant field amplification
- Rotation damping from NTV
- Anomalous momentum transport
- Pedestal transport and stability

Near-term goal: Improve/characterize sustainment of high-β, understand RWM/NTV physics at lower ν*

NSTX is developing a deeper understanding of ion and electron energy transport for STs and tokamaks

- Ion $\tau_E \sim I_P$, consistent with neoclassical ion transport
  - Implies ion turb. suppressed by high E×B shear → possibility of isolating causes of e-transport
- Electron & ion τ_E scale differently, and different than at higher A:
  - Ion $\tau_E \sim I_P$, electron $\tau_E \sim B_T$
- High-k scattering data indicates χ_e correlated w/ high-k density fluctuations
  - Correlation holds both spatially and versus B_T
  - Consistent with ETG at large r/a (i.e. in T_e gradient region)





Near-term goal: Measure low-k turbulence, understand modes responsible for anomalous e/i transport

NSTX accesses broad range of fast ion parameters, and a broad range of fast particle modes

- Figure at right illustrates NSTX operational space, as well as projected operational regimes for: ITER (α's only), ST-CTF (α+NBI), ARIES-ST (α's)
- Also shown are parameters where typical fast particle modes (FPMs) have been studied.
- Conventional beam heated tokamaks typically operate with $V_{fast}/V_{Alfven} < 1$.
- CTF in avalanche regime motivates studies of fast ion redistribution
  - ITER with NBI also unstable to AE
- Higher ρ^* of NSTX compensated by higher beam beta

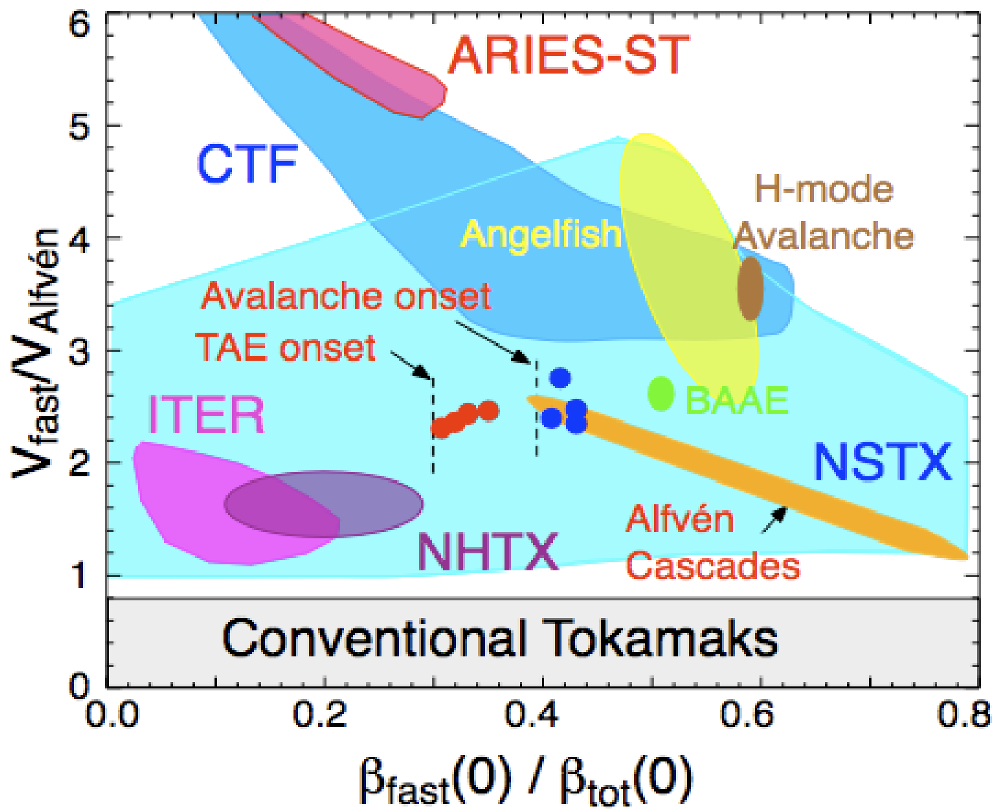
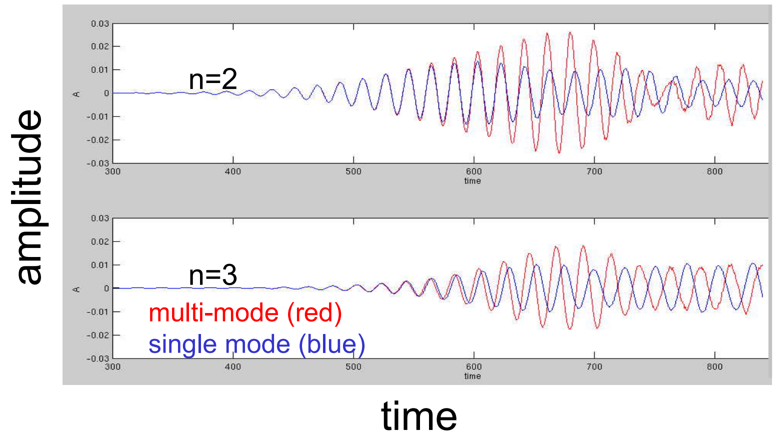


Figure above is simplified picture - there are other dependences, such as *q* profile, ρ^*

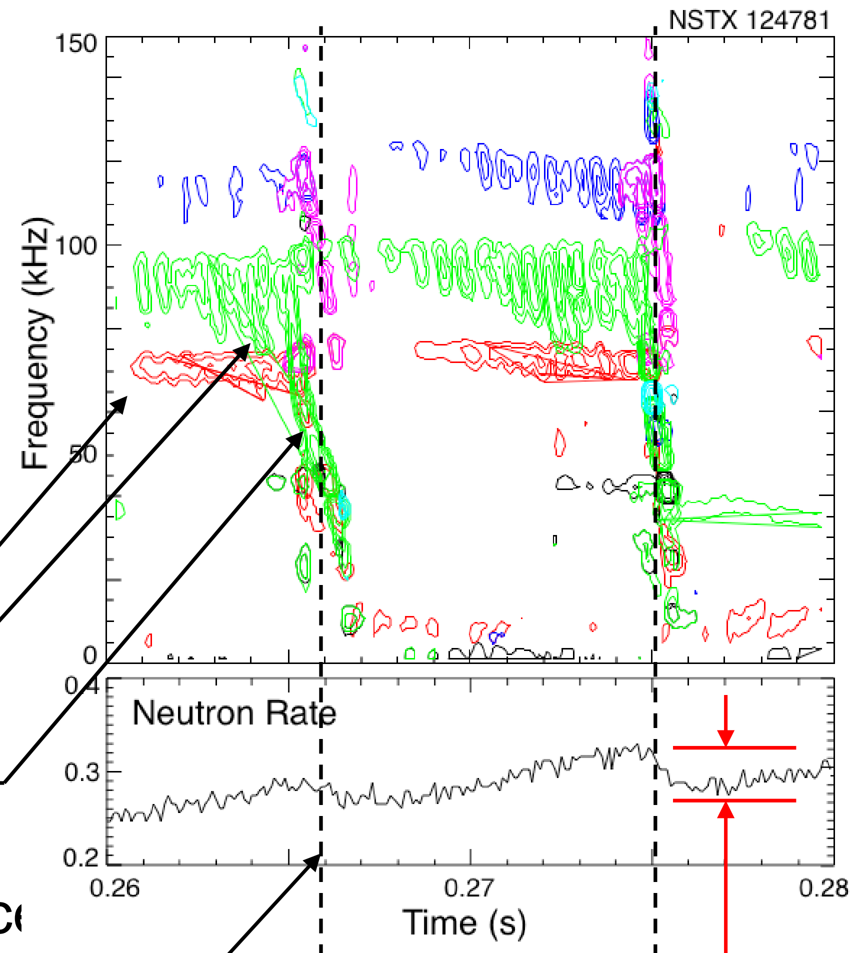
NSTX finds AE avalanches can induce fast-ion redistribution and/or loss - potentially important for ITER and ST-CTF

M3D-K simulations: overlapping resonances + multiple modes cause larger mode amplitude → larger fast-ion f(v) perturbation



Experiment:

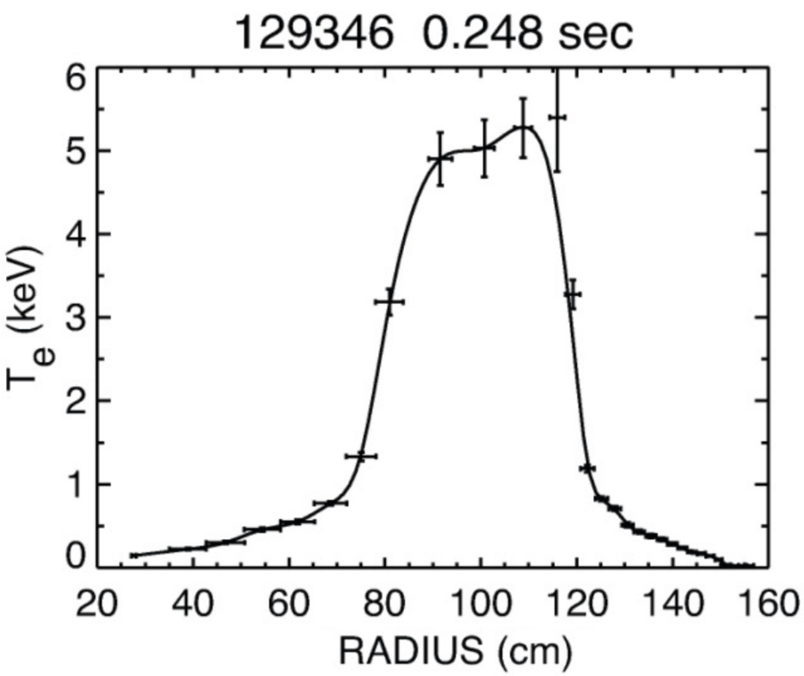
- As power is raised, first see AE
  - then chirping AE
  - then avalanches, multi-mode transport
- Avalanches are strong bursts of multiple AE modes (2 ≤ n ≤ 6) overlapping in space and frequency
- Avalanches correlate with neutron drops indicating fast ion redistribution and/or loss



Near-term goal: Improve ξ(r) data and predictive capability for fast-ion transport, extend to H-mode

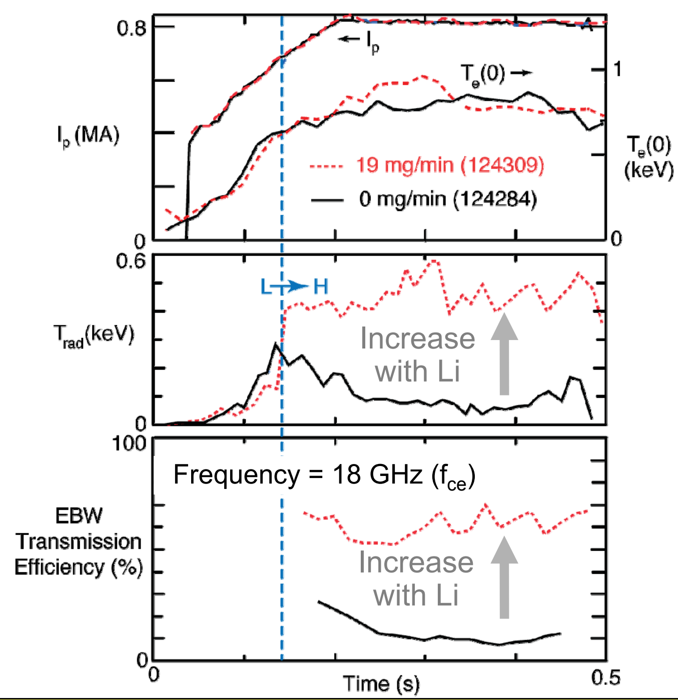
NSTX has improved the understanding and performance of wave heating & CD techniques in over-dense plasmas

- High-harmonic fast-wave (HHFW)
  - Discovered that surface waves reduce heating efficiency if density near antenna is too high
  - Control of edge density improves heating → record T_e = 5keV in NSTX achieved with HHFW



$n_e(0) = 1.5 \times 10^{19}\ m^{-3}$

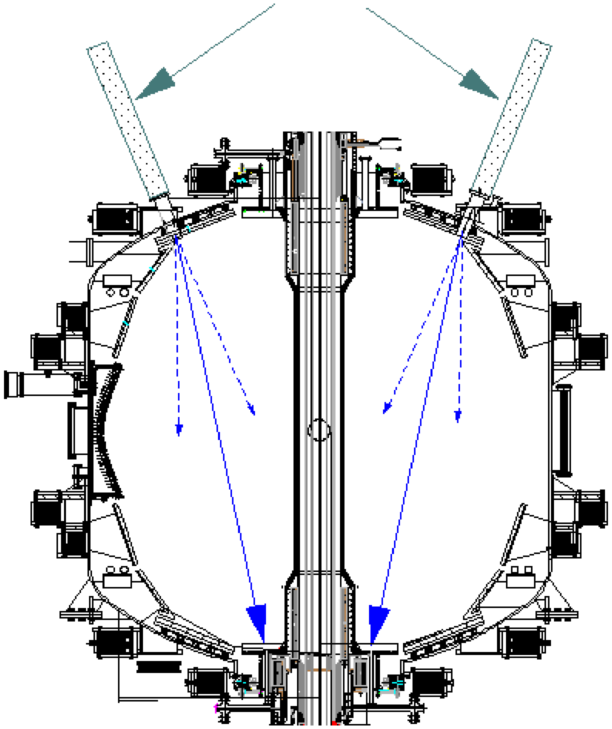
- Electron Bernstein Wave (EBW)
  - Discovered that collisional damping at mode conversion layer reduces coupling
  - Higher T_e at MC layer via Li-conditioning increases EBW transmission efficiency from 10% to 50-60% in H-mode→ Improved prospects for EBW as H&CD tool
- **EBW de-emphasized due to resource limitations**



Near-term goal: Improve HHFW heating in D H-mode for ramp-up & sustainment, MAST EBW collaboration

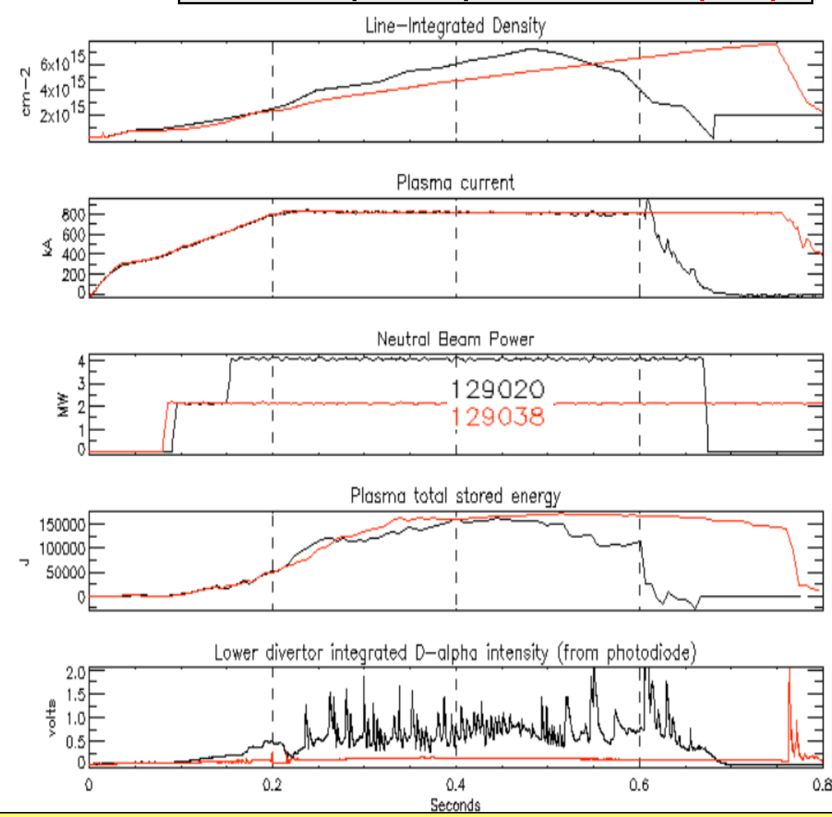
NSTX is unique in the world program in exploring lithium in a diverted H-mode plasma

- Dual Lithium evaporators (LITERs) provide complete toroidal coverage of lower divertor
  - Improved performance vs. 1 LITER
  - 2008: High-performance operation with **NO** between-shot He glow → increased shot-rate



- Reproducible ELM elimination from Li
  - Plasma density reduced
  - Pulse-length extended
  - At 800kA, power must be reduced to avoid β limit
  - Confinement time doubled (up to 80ms)
  - Large reduction in divertor D_α → reduced recycling

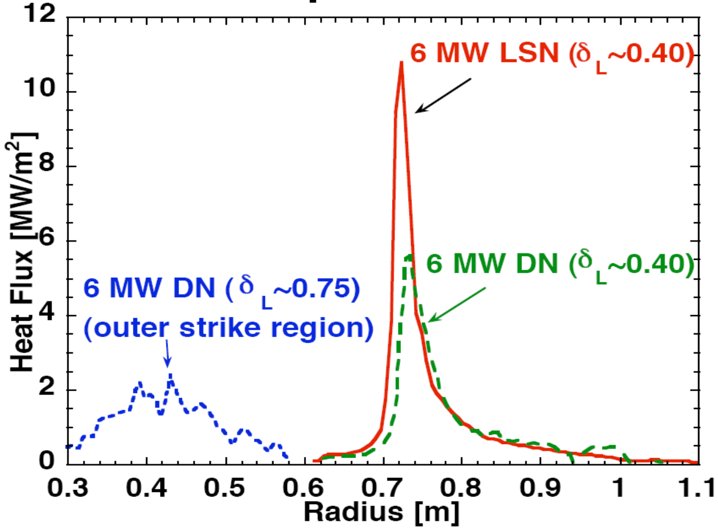
No Li (black) **With Li (red)**



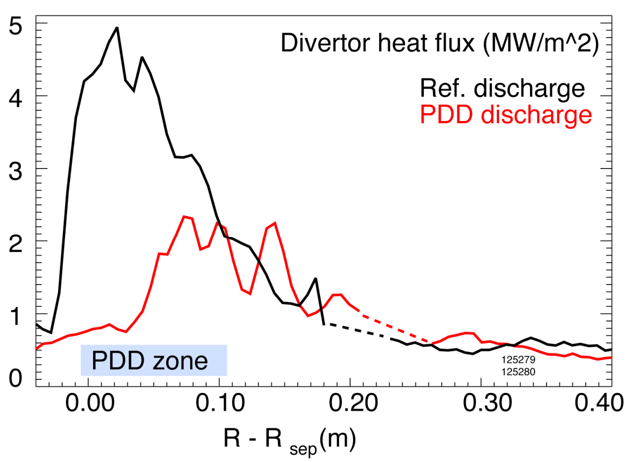
Near-term goal: Understand Li-plasma interaction, achieve density control with Liquid Lithium Divertor

NSTX accesses ITER-level divertor heat fluxes and is exploring mitigation of steady-state and transient heat fluxes

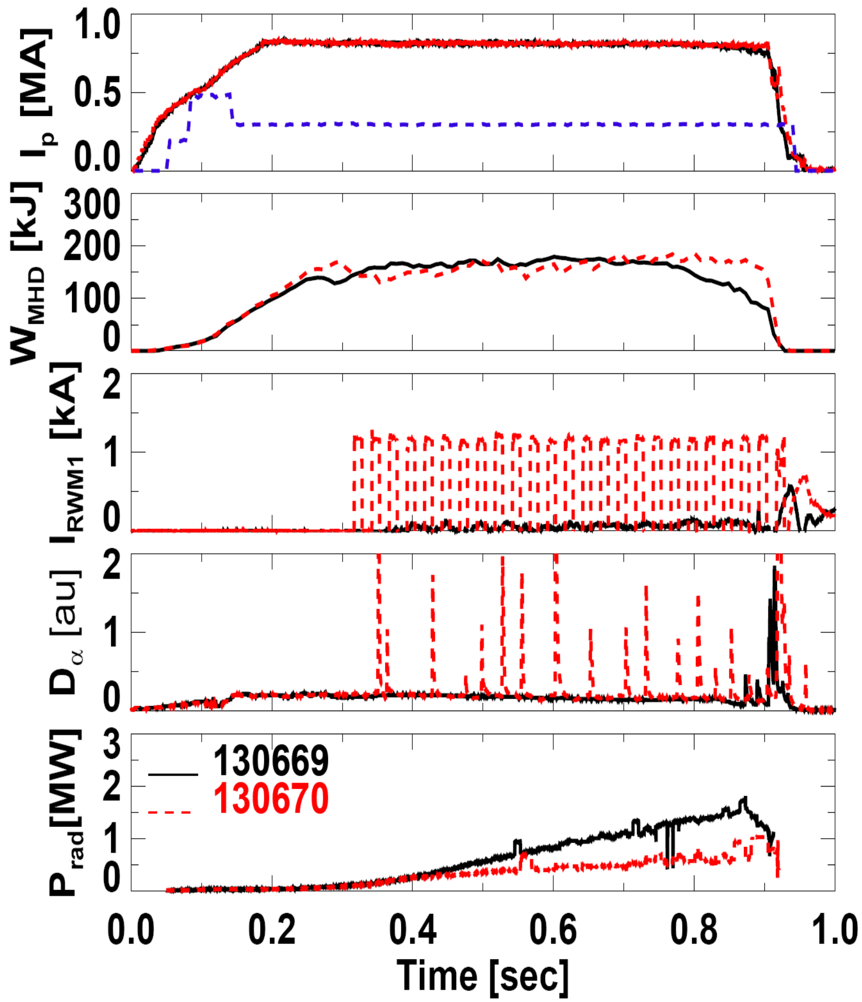
- **Magnetic geometry strongly influences peak heat flux**



- **Partial detachment reduces peak heat flux**



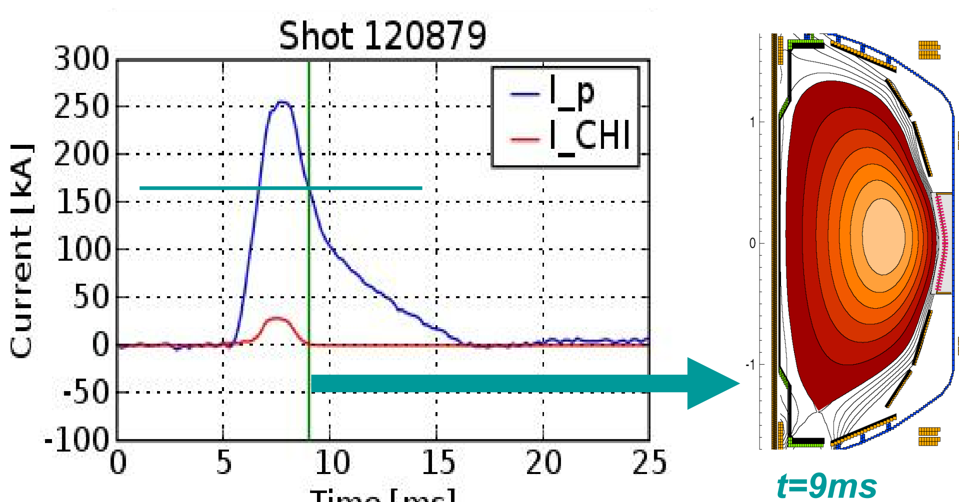
- **Lithium conditioning can eliminate ELMs**
- **RMPs can controllablly trigger ELMs and expel impurities from Li-ELM-free plasmas**



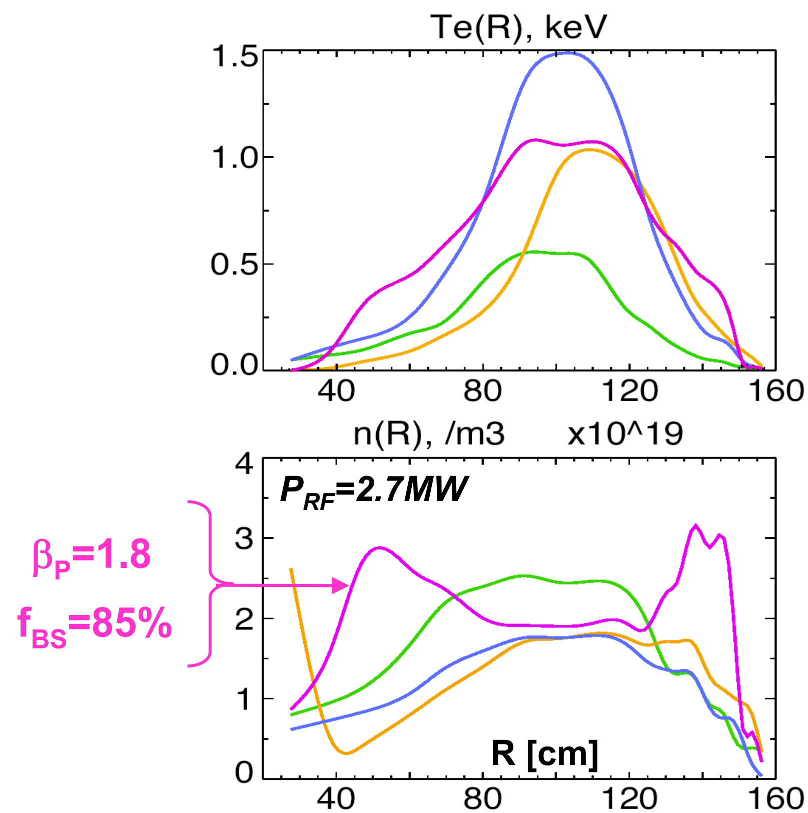
Near-term goal: Understand & develop steady-state heat-flux mitigation, ELM control for STs and ITER

NSTX is testing unique methods of non-solenoidal plasma current start-up and ramp-up for STs

- Start-up: Coaxial Helicity Injection
  - Generated record closed-flux I_P=160kA
  - Demonstrated coupling to induction and compatibility with high performance H-mode
  - Higher I_P limited by lack of auxiliary heating, possibly impurities/divertor conditions



- Ramp-up: High Harmonic Fast Wave
  - HHFW heats 250kA plasma to T_e=1keV
  - Produces f_{BS}=85% H-mode plasma
  - Limited by antenna voltage stand-off, ELMs

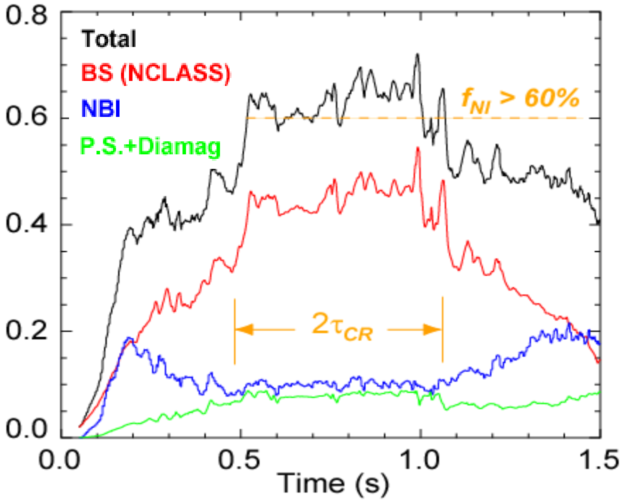


Near-term goal: Improve CHI start-up (LLD target plates, Li, absorber coils), high-P_{HHFW} for ramp-up

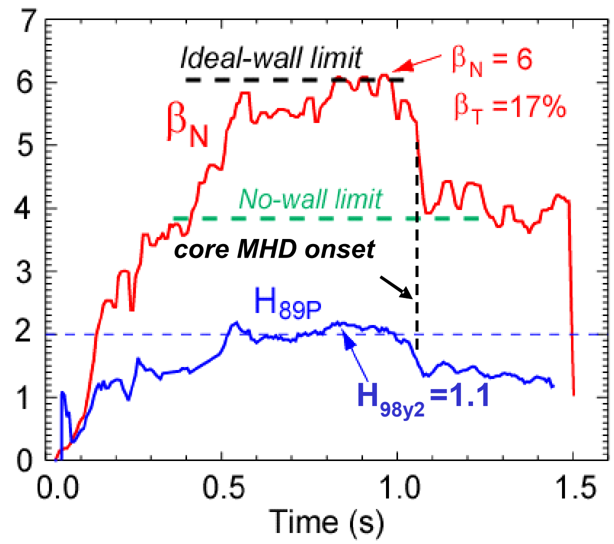
NSTX has developed and sustained scenarios with high non-inductive fraction and high normalized β

- f_{NICD} = 65%
- $f_{\nabla p}$ = 55%

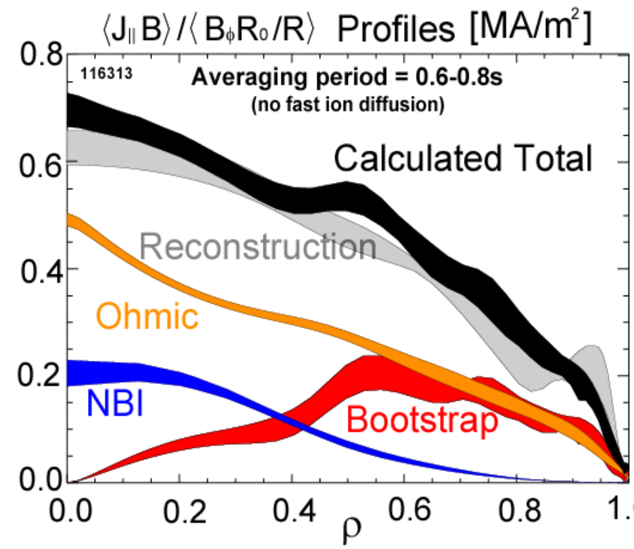
TRANSP non-inductive current fractions for NSTX shot 116313G12



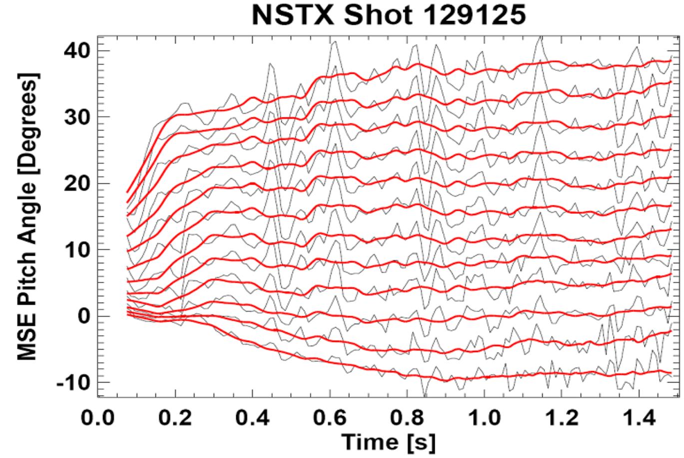
- β_N = 5.5-6
- H_{98} = 1-1.1
- $f_{Greenwald}$ → 1



Predicted and reconstructed J profiles are in agreement when MHD activity is weak



NSTX Shot 129125



- Recent long-pulse discharges which avoid core rotating MHD activity exhibit J-profile equilibration
  - Spikes in MSE pitch angle are low-f MHD (early) and large ELMs (late)

Near-term goal: Density, β, RFA/RWM, ELM, impurity control for sustained & higher non-inductive fraction