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NSTX

NSTX Program Overview for 2009-10 and Beyond

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For the NSTX Research Team

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NSTX PAC-23 Meeting

LSB B318, PPPL

January 22-24, 2008

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
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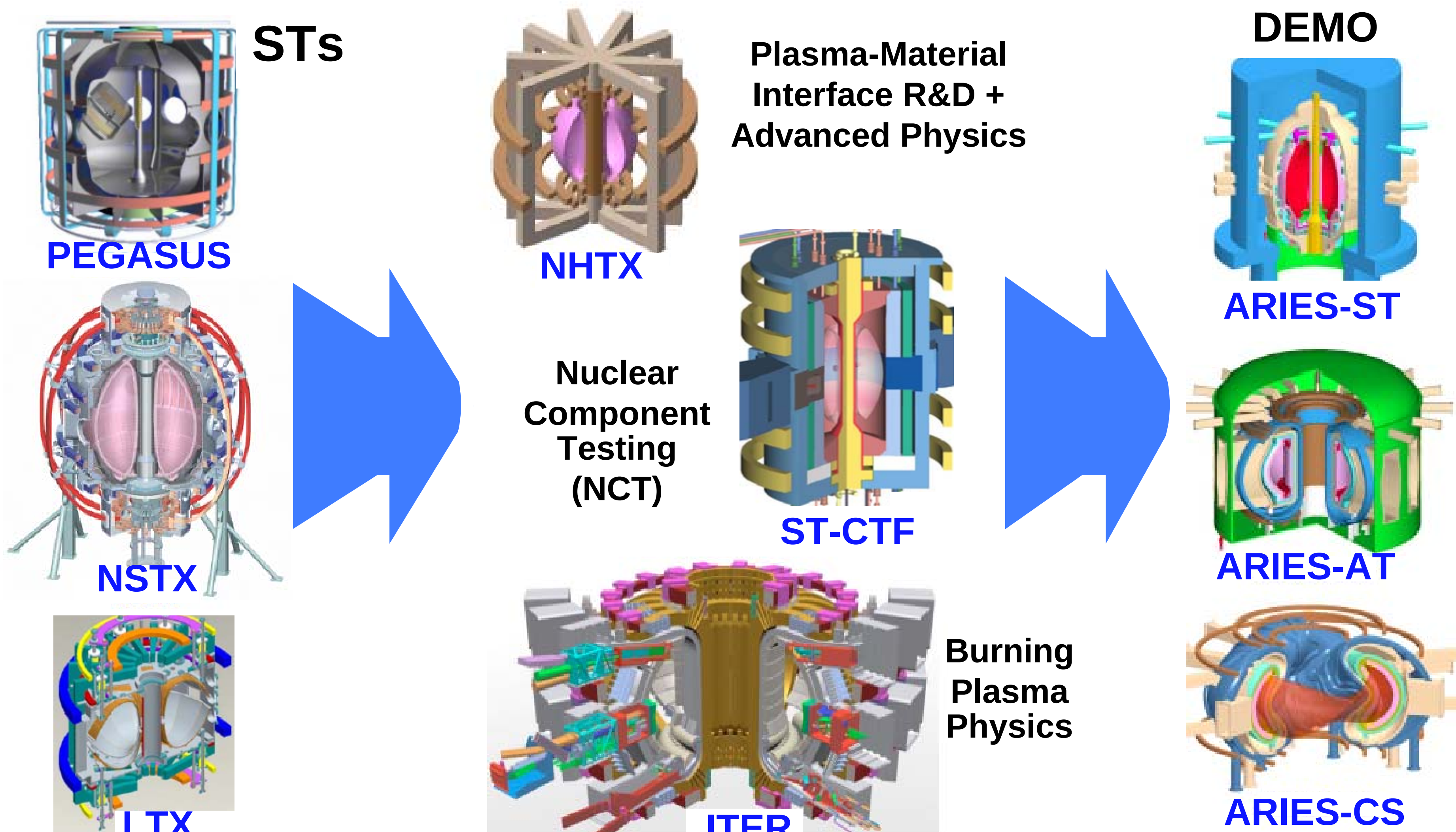
The NSTX, Pegasus, and LTX ST Research Programs Contribute Strongly to US and World Fusion Development

ST offers compact geometry + high β for attractive fusion applications



NSTX Mission Elements
(in priority order)

- Provide the physics basis for future ST-based devices, such as NHTX, ST-CTF, and ST-Demo
- Broaden the physics basis for ITER, actively participating in ITPA and US BPO
- Advance the fundamental understanding of toroidal magnetic confinement generally

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

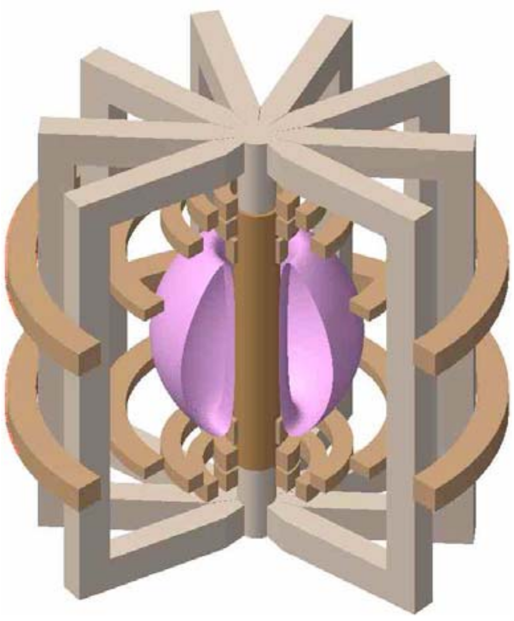
NSTX

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

National **H**igh-power advanced **T**orus e**X**periment (**NHTX**) Mission:

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

- **NHTX goals and design features:**
  - Create next-step-relevant heat-fluxes
    - → High P/R = 50MW/m = 2 × ITER (Demo-level (100MW/m) heat-fluxes possible)
  - Minimize device size and cost
    - → Low-A, compact, high P_{AUX} → high P/R
  - Test fusion-relevant particle/power exhaust
    - → Flexible/solid/liquid divertor, 2D/3D edge
  - Develop methods to avoid T retention
    - → Long-pulse trace-Tritium capability (also short-duration 50/50 D/T α-physics studies)
  - Test retention at reactor-relevant T_{wall}
    - → High temperature first wall - up to 600°C
  - Allow for plasma/wall equilibration
    - →Long pulses (200-1000s) → 100% NICD (100% NICD w/ NBI + BS → high performance)
  - Rapid testing of new PMI concepts
    - → High duty factor, designed for maintainability



P_{heat}	50MW
R_0	1m
A	1.8-2
κ	$\leq$ 3
B_T	2T
I_P	3-4MA
β_N	4.5
β_T	14%
n_e/n_{GW}	0.4-0.5
f_{BS}	$\approx$ 70%
f_{NICD}	100%
$H_{98Y,2}$	$\leq$ 1.3
E_{NB}	110keV
P/R	50MW/m
Solenoid	½ swing to full I_P

ST is attractive configuration for fulfilling NCT mission

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

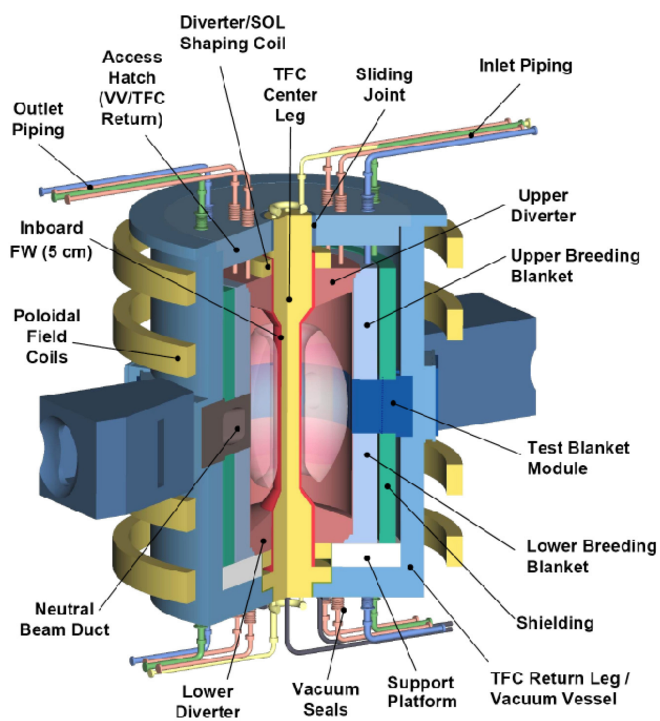
NSTX

- **Nuclear Component Testing (NCT) Mission:**
  - *Use lowered-risk, reduced-cost approach to test and develop components in a fusion nuclear environment beyond the ITER level*
  - *Help establish critically needed physical and engineering science knowledge base for Demo*

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

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	**Small iron core for startup**		

- **ST advantages for NCT:**
  - 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



Gaps in understanding and performance between present NSTX results and next-step STs motivate research goals (I)

- Transport & Turbulence
  - NHTX/ST-CTF assume sustained $H_{98y,2}$ = 1.3/1.5, NSTX can sustain ≤ 1.1
  - Electron & ion transport scale w/ B_T, I_P differently in ST, and differ from high-A
  - χ_e usually dominates, $\chi_i \rightarrow \chi_{i\text{-}NC}$ common… does this extrapolate to high B_T, I_P?

  → *Develop predictive capability for ion and electron thermal transport in ST*

- Macroscopic Stability
  - NHTX does not require, but will study, sustained operation above no-wall limit
    - ST-CTF designed to operate at/below no-wall limit, but would benefit from higher β_N
  - Depending on J_{BS} profile (transport) & J_{NBI}, NHTX/ST-CTF could have $q_{min} < 2$
  - RWM and NTM stabilization physics depends on q, rotation, density, feedback

  → *Optimize RWM & NTM passive & active control, develop predictive capability*

- Boundary Physics
  - NHTX/ST-CTF have P/R twice that of ITER and operate at low n_e/n_{GW} = 0.2-0.5
    - ST-CTF also requires very low T-retention, NHTX goal is to develop this
  - Novel power exhaust and pumping concepts + ELM control needed
  - Unclear how SOL/divertor heat-flux and pedestal transport/stability scale in ST

  → *Test Liquid Lithium Divertor (LLD), understand & control pedestal/SOL/divertor*

Gaps in understanding and performance between present NSTX results and next-step STs motivate research goals (II)

- Wave-Particle Interactions
  - ST-CTF operates in AE avalanche regime, NHTX marginally in this regime
  - Significant redistribution/loss of fast-ions from AE (and other MHD) possible
  - → *Develop predictive capability for fast-ion redistribution and loss*
  - NHTX/ST-CTF plasmas are over-dense, require auxiliary H&CD beyond NBI
  - HHFW/ICRF favorable for heating (maybe core CD), EBW off-axis CD promising
  - Coupling to these waves efficiently has been most significant challenge
  - → *Understand and improve EBW coupling, test heating*
  - → *Understand & improve HHFW coupling, H&CD in H-mode, advanced scenarios*
- Plasma Start-up and Ramp-up
  - NHTX designed with ½-swing OH, ST-CTF will require solenoid-free ramp-up
  - ST-CTF may start-up w/ iron-core, but would benefit from CHI, guns, PF-only
  - → *Demonstrate successful solenoid-free start-up & ramp-up to benefit ST and AT*
- Advanced Scenarios and Control
  - NHTX/ST-CTF assume full NICD operation, primarily from BS and NBICD
  - Need control of J(r), density, β, shape, EF/ELM/RWM etc. for minutes → weeks
  - → *Demonstrate full NICD and J(r) control at high β for first time in ST (with 2^{nd} NBI)*

NSTX has been asked to create plans for 2 operating scenarios
(and will present detailed plans in tomorrow's topical presentations)

- 3 yr plan (FY08-10) – no operation after FY10
  1. Flat budget (i.e. inflation adjusted), with major upgrades converted into run-time
  2. Also consider impact of operating only 2 years (FY08-09)
     → Assess what is lost by not running in FY10

- 6 yr plan (FY08-13) – operation/upgrades thru FY13
  1. Flat budget (i.e. inflation adjusted)
  2. 10% budget increment

NOTE: M. Ono will cover upgrade & run-time details in much more depth in subsequent presentation.

NSTX near-term (FY08-10) key **upgrades** will enable compelling science compatible with both 3yr and 6yr operating scenarios

- Near-term research and corresponding upgrades are prioritized by:
  - Gap/uncertainty in extrapolation to next-steps
  - Uniqueness of contribution to ST and toroidal science
  - Likelihood that research can be “completed” by end of FY10
  - Whether upgrade is affordable with nearly flat-budget

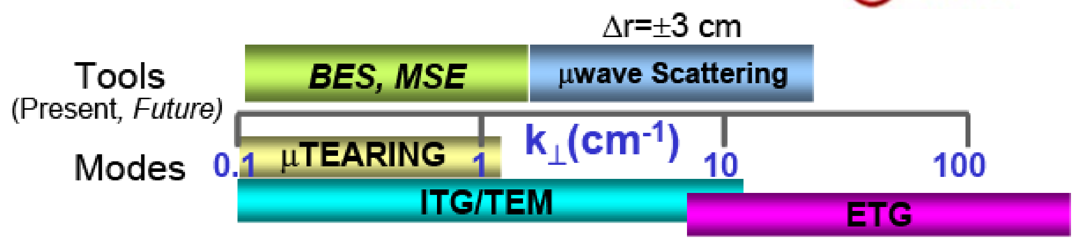
- Key upgrade #1:
  - NSTX providing unique & critical data for electron transport for next-steps
  - Only ST with high-k scattering, have neoclassical ions, but no low-k diagnostics
  - → Accelerate implementation of BES for full k-spectrum turbulence data

- Key upgrade #2:
  - Need particle pump to control density for high NBICD and low-ν physics
  - → Implement Liquid Lithium Divertor (LLD) – unique, only near-term n_e control tool

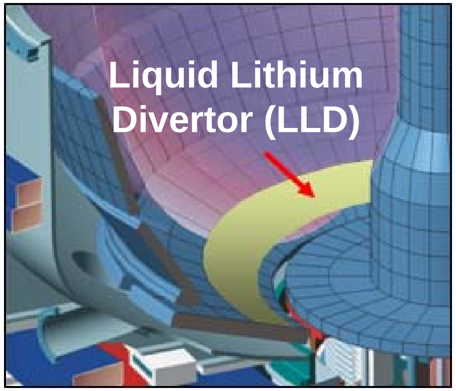
- Key upgrade #3:
  - NHTX considering ICRF/HHFW to supplement NBI, NSTX only ST with HHFW
  - Significant recent improvements in HHFW coupling & heating efficiency
  - ECH/EBW system expensive and has long implementation time
  - → Accelerate HHFW system upgrades, defer ECH/EBW (can be done on MAST)

FY08-10 upgrades enable 3 new scientific thrusts on NSTX

- Determine modes responsible for anomalous transport using full complement of turbulence measurements
  - Full k-range of turbulence

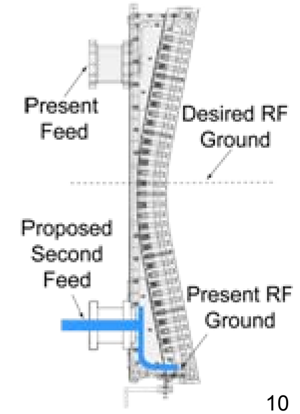


- Investigate if liquid lithium can integrate four important potential benefits for fusion:
  - Divertor pumping over large surface area
    - LLD may be more compatible with high flux expansion solutions to divertor heat flux than cryo-pumps
  - Improved confinement
  - Reduction/elimination of ELMs
  - Longer term: steady-state high-heat-flux handling



- Determine if high-harmonic fast-waves (HHFW) can be utilized for heating & CD in advanced scenarios
  - HHFW/ICRF important for NSTX/NHTX/CTF/ITER
  - Must be compatible with large plasma-antenna gap
  - Must be compatible with H-mode profiles, ELMs

Upgrade for higher P_{RF} & ELM resilience



NSTX FY09-10 milestones exploit proposed upgrades while addressing key uncertainties in extrapolating to next-step STs

- 2009 Milestones:
  - Joule Milestone (proposed):
    - Particle control and hydrogenic fuel retention in tokamaks
  - Research Milestones:
    - Understand physics of RWM stabilization and control as a function of rotation
    - Characterize fast-ion redistribution from super-Alfvénic fast-ion-driven modes
    - Assess non-inductive current drive sources as a function of density at high β
- 2010 Milestones
  - Research Milestones (proposed):
    - Study turbulence regimes responsible for ion and electron energy transport
    - Assess stability & control of sustained operation near the ideal-wall limit
    - Assess pedestal characteristics and ELM stability as a function of collisionality
    - Characterize HHFW heating and current drive in H-mode plasmas

Key collaboration opportunities in FY08-10 program letter for universities & industry are well-aligned with research goals & upgrades

- Macroscopic Plasma Physics
  - Optimize EFC & RWM control far above no-wall limit
  - Identify & understand NTM near ideal stability limits
  - Understand disruptions – current & thermal quench
  - Mode detection/dynamics w/ non-magnetic sensors
- Multi-Scale Plasma Physics
  - Electron transport and relation to high-k turbulence
  - Rotation & momentum transport simulation/expts.
  - Particle fueling and transport w/ application to LLD
- Plasma Boundary Interfaces
  - Novel PFCs for particle and power handling
  - H-mode pedestal stability, including RMP physics
  - Transport & turb. in SOL & impact on div. heat flux

- Waves and Energetic Particles
  - Fast ion transport from fast-ion driven MHD
  - HHFW H&CD for ramp-up and sustainment
  - EBW coupling for heating & CD
- Plasma Start-up & Ramp-up w/o a Solenoid
  - Couple CHI to inductive & non-inductive ramp-up
  - Explore new start-up techniques such as plasma-guns
  - Develop solenoid-free ramp-up via HHFW and NBI
- Physics Integration
  - Model evolution/access for high NICD, high-β plasmas
  - Simulate/develop advanced shape control for LLD & CTF

- 1/3 of potential collaborators submitted proposals for “Plasma Boundary Interfaces”
  - Many submissions related to Li and LLD
- 1/4 of potential collaborators submitted proposals for “Waves & Energetic Particles”
- DOE proposal review process nearly complete

Remainder of presentation provides overview of NSTX research plan for various operating scenarios:

1. FY08-10 operation
2. What is lost w/o FY10 operation
3. FY11-13 upgrades & operation

Plans are organized by topical science area:

1. Transport & Turbulence
2. Macroscopic Stability
3. Boundary Physics
4. Wave-Particle Interactions
5. Plasma Start-up and Ramp-up
6. Advanced Scenarios and Control

Transport & Turbulence high-priority research (FY08-10)

- Understand coupling between ion energy & angular momentum transport
  - Evaluate generation of plasma rotation & momentum transport, and assess the impact of plasma rotation on stability and confinement (FY08 Joule milestone)
  - Assess the role of flow shear in controlling plasma turbulence and transport using poloidal CHERS (FY08 milestone)

- Study turbulence regimes responsible for transport (FY10 milestone)
  - Take advantage of suppressed anomalous ion transport + existing high-k + MSE diagnostics to determine if ETG is the cause of the measured χ_e
    - Test ν^* dependence of e-transport w/ LLD (TEM & ETG scale differently vs. ν^*)
    - Accelerate BES to measure low-k, implement high-k_θ for polarization
    - Add additional Thomson channels to improve resolution of ITBs (incremental)
  - Test leading transport models (ITG,TEM,ETG) vs. measured fluctuation spectra, critical gradients, heat flux, response to perturbations
  - Novel MSE-LIF for E_r, B, p, q profiles w/o heating beam (HHFW heated)
  - Validate transport models for extrapolation to next-step STs

- Understand energy & momentum transport scaling for next-step design
  - Understand differences relative to high-A
- Understand H-mode threshold scaling/physics for next-step STs

Macroscopic Stability high priority research (FY08-10)

- Improve understanding of rotation effects, RWM & NTM stability physics
  - Evaluate MHD sources of plasma viscosity and assess the impact of plasma rotation on plasma stability, including NTM (FY08 Joule milestone)
  - Further understand the physics of RWM stabilization and control as a function of plasma rotation (FY09 Milestone)
  - Determine dependence of NTMs on toroidicity, plasma rotation, error fields
  - Assess impact of LLD operation (low n_e, low Z, no ELMs) on profiles & stability
  - Understand non-resonant and resonant (island) NTV, compare to computation
- Understand & sustain high-β near ideal-wall limit (FY10 Milestone)
  - Implement & utilize real-time β-control using rtEFIT and NBI modulation
  - Implement & utilize rotation control using real-time-v_ϕ + NTV *(incremental)*
  - Decrease RWM poloidal deformation & associated loss of control
  - Characterize disruptions: Extend I_P quench data contributed to ITPA/ITER to include halo currents, thermal quench for design of next-step STs
- Validate stability and/or control models for reliable extrapolation of sustained high-β operation to next-step STs and ITER
  - Model-based controllers for plasma shape and vertical position
  - Test fully 3D RWM control models w/ multi-mode physics and plasma rotation

Boundary Physics high-priority research (FY08-10)

- Understand scaling & mitigation of high divertor heat flux
  - Characterize divertor heat flux and access to detachment (FY08 milestone)
  - Compare divertor heat flux widths to mid-plane density and temperature widths and edge turbulence characteristics

- Access and assess reduced density operation for next-step STs
  - Implement and utilize Liquid Lithium Divertor (LLD) modules
  - Assess particle control & H/D retention w/ LITER/LLD (FY09 Joule milestone)
  - Use LLD + rt-SGI + rt-n_e to sustain & control up to 50% lower n_e

- Predict and control pedestal stability & transport in the ST (FY10 milestone)
  - Study ELM reduction and suppression, with emphasis on studying RMP physics using ITER-relevant mid-plane ex-vessel control coils
    - Note that DIII-D ELM suppression results are most successful at reduced collisionality and with divertor pumping active

    → LLD could be important element of NSTX RMP ELM suppression studies
  - Determine relationship of ELM properties to shape & Li conditioning
    - ELMs eliminated with Li evaporation in some scenarios in 2007
  - Compare stability of pedestal/ELMs with model calculations

- Design non-axisymmetric control coils (NCC) for ELM control

Wave-Particle Interaction high-priority research (FY08-10)

- Develop predictive capability for AE-induced fast-ion transport
  - Focus energetic particle research on fast-ion transport in high NBICD fraction H-mode discharges at reduced density relevant to next-step ST's
  - Study fast-ion redistribution from super-Alfvénic fast-ion modes (FY09 milestone)
  - Fast-ion p(r) from reconstructed total (MSE-LIF) – thermal (MPTS+CHERS)
  - Validate non-linear AE simulations for predicting next-step ST performance

- Develop efficient wave heating and current drive tools needed for heating and control of advanced ST scenarios
  - For high-harmonic fast wave (HHFW), understand and improve coupling to, and heating of, H-mode deuterium NBI-heated plasmas (FY10 milestone)
  - Antenna upgrades + ELM resilience → high-power HHFW H&CD to increase electron stored energy to increase NICD fraction → 1, needed for next-step ST's
  - For Electron Bernstein Wave (EBW), determine and understand plasma conditions that maximize efficiency of coupling to EBW
    - Collaborate on ECH/EBW startup and EBW coupling/heating on MAST & Pegasus

Solenoid-Free Start-up & Ramp-up high-priority research (FY08-10)

- Integrate Coaxial Helicity Injection (CHI) into normal operations
  - Couple inductive ramp-up to CHI plasmas (FY08 Milestone)
  - Develop operating conditions aimed at improving the control and increasing the current and closed poloidal flux of CHI → staged capacitor banks
  - Use CHI-startup to increase pulse lengths of high-performance discharges

- Test non-CHI start-up methods
  - Use CHI as pre-ionization source for vertical field startup
  - Test plasma gun startup (from Pegasus) when technically ready
  - Assist CHI, vertical field startup, and gun startup with high-power ECH pre-ionization *(incremental)*
  - Simulate iron-core plasma formation of ST-CTF using OH solenoid

- Plasma current ramp-up:
  - Use HHFW heating and CD in current ramp to reduce flux consumption
  - With sufficient power (antenna upgrade + ELM resilience), use HHFW for BS current overdrive and RFCD to ramp-up plasma current

Advanced Scenarios & Control high-priority research (FY08-10)

- Develop high non-inductive CD fraction plasmas with high-beta and high bootstrap fraction under sustained conditions:
  - Increase NBICD using lower n_e, higher T_e from LITER/LLD (BP FY09 milestone)
  - Assess impact of AE avalanches on NBICD (WPI FY09 milestone)
  - Assess/increase energy confinement with LITER/LLD
  - Assess NICD sources as a function of density at high β (ASC FY09 milestone)
    - Conditions: κ up to 2.8, $\tau \geq \tau_{CR}$, low-n_e for high NBICD fraction, high β_N for high f_{BS}
  - Increase f_{BS} using HHFW electron heating (WPI FY10 milestone)
  - Characterize and maximize NICD fraction versus n_e, H_{98}, shaping, and *q*
  - **Performance GOAL: decrease inductive I_P by ½ → f_{NICD} = 65-70%→80-90%**

- Improve control, validate predictive modeling
  - Control of NBI in PCS, feedback control of β (with macro TSG)
  - Aim to achieve long-pulse density control (with boundary TSG)
    - Improved pumping (LITER/LLD), real-time fueling (SGI) and n_e measurement (FIR)
  - Validate integrated models of $J(\rho)$, $p(\rho)$ evolution (pTRANSP/TSC)

The following unique ST research opportunities would be lost without operation in FY10: (For more comprehensive list see topical presentations)

- Transport & Turbulence
  - Diagnose and understand k-dependence of ion & electron turbulence & transport
- Macroscopic Stability
  - Test and understand robustness of operation near the ideal-wall limit
- Boundary Physics
  - Test D pumping of LLD, fully assess pedestal transport & stability at low n_e w/ Li
- Wave-Particle Interactions
  - Assess physics/impact of *AE avalanches in H-mode w/ full diagnostics
  - Unique ST test of HHFW heating in H-mode w/ P_{RF} upgrade + ELM resilience
- Plasma Start-up and Ramp-up
  - Unique test of CHI pre-ionization/current with PF-only ramp-up and/or gun startup
- Advanced Scenarios and Control
  - Fully test NBICD at low n_e, J_{NBI} redistribution, LLD, HHFW in advanced scenarios

With operation & upgrades after FY10, NSTX can significantly reduce the uncertainty in extrapolation to next-step STs

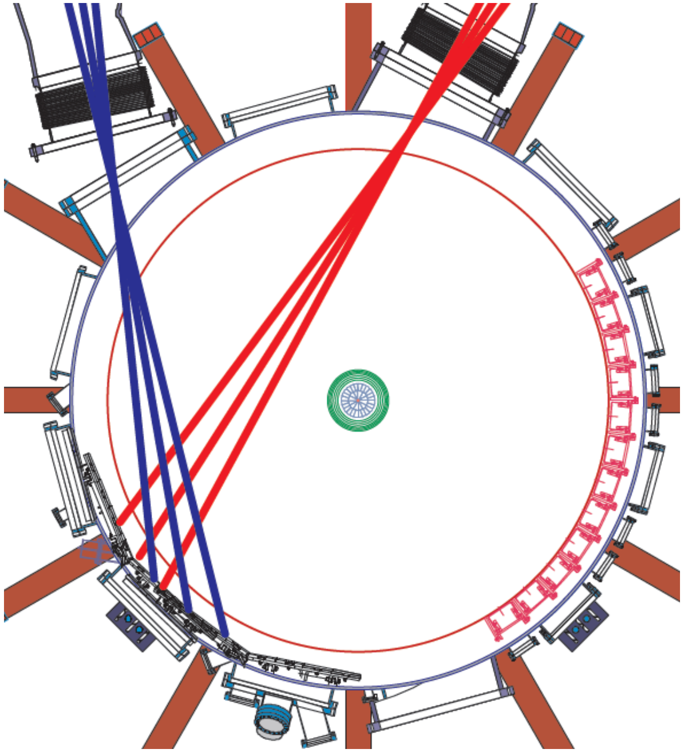
- FY08-10 results → can be extended to next-step demonstration & validation

- Preliminary understanding & optimization ion & electron turbulence vs. k
  - → Complete high-k+low-k studies, momentum, particle transport studies + theory validation
- Passive and active control of vertical, RWM, and NTM instabilities
  - → Demonstrate & validate robust vertical+RWM+EF+ELM+J(r)+rotation control at high-β_N
- Divertor heat-flux mitigation at moderate P/R, understanding SOL transport scaling
  - → Demonstrate heat-flux mitigation at higher P/R, validate SOL transport models
- Initial particle control using Liquid Lithium Divertor (LLD) for low n_e/n_{GW}
  - → Demonstrate long-pulse divertor/LLD for sustained low n_e/n_{GW} at high P/R
- Understand fast-ion transport from AE avalanches in L-mode, low-n_e H-mode
  - → Validate avalanche physics in high-n_e H-mode, ideally w/ NHTX/CTF-like tangential NBI
- Initial optimization of high-power HHFW in H-mode, plus EBW coupling studies
  - → Demonstrate HHFW heating in advanced scenarios, test/collaborate on EBW heating
- Develop CHI, PF-only, & gun start-up, and assess HHFW ramp-up capability
  - → Demonstrate high-I_P startup w/ EC pre-ionization, demonstrate HHFW I_P ramp-up
- Study high NI and NBICD fraction at reduced density for short durations ($1\tau_{CR}$)
  - → Demonstrate full NICD at high β and confinement with J(r) control for $\tau_{flat} >> \tau_{CR}$

2^{nd} NBI is centerpiece of FY11-13 plan (w/ increment), as it would have many cross-cutting research benefits

- **Demonstrate 100% NICD (NBI+BS) w/ n_e, β_N, H_{98} similar to present values**

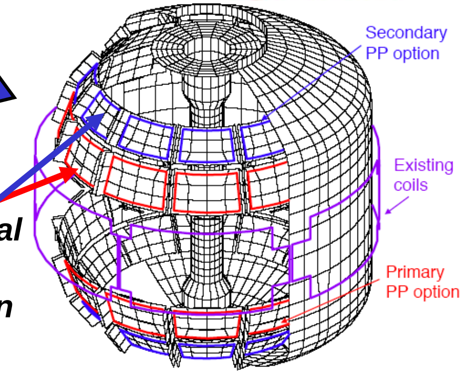
- Higher P_{HEAT} for higher β_P, f_{BS} at presently sustainable $H_{98y2} \leq 1.2$
- Increased NBICD from higher P_{NBI}
  - And higher CD efficiency of large R_{TAN}
- Increased control of *q* profile
  - Optimize $q(\rho)$ for high τ_E, β, f_{NI}
- Increased research flexibility by varying:
  - *q*-shear for transport & MHD physics
  - Heating, torque, rotation profiles
  - β at higher I_P and B_T
  - Fast-ion distribution and instabilities
  - Divertor P/R and pulse-length



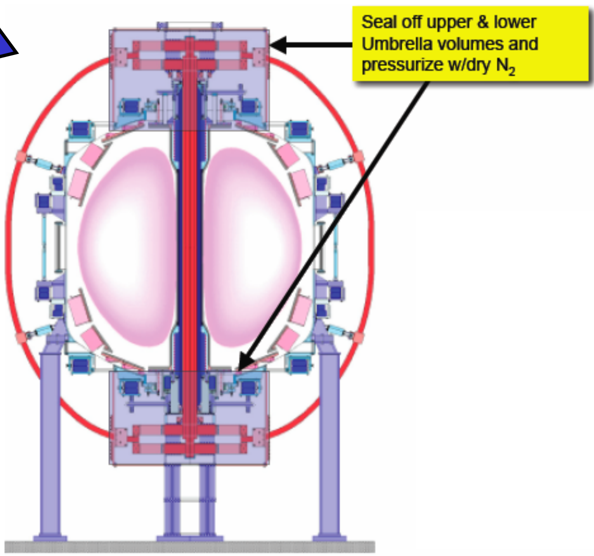
- But, there are challenges…
  - Expensive, and couldn't be installed until after FY10 run at the earliest

Additional upgrades in FY11-13 (beyond 2nd NBI) would significantly enhance NSTX research capabilities

- Improved MHD mode control with off-midplane coils
  - **NSTX is only ST** that can study ELM control at $\beta_N > \beta_{N\text{-no-wall}}$
  - ELM mitigation w/ n up to 6, RWM control w/ $n > 1$ & higher β_N
  - DEFC w/ $n \leq 6$, Ω_ϕ control ($n \leq 6$; $n > 1$ propagation)



- OH/TF sub-cooling for long-pulse operation: $\tau_{\text{flat-top}} \sim 1\tau_{CR} \rightarrow 3\text{-}4\tau_{CR}$ at full-B_T=5.5kG
  - High TF beneficial to high/full NICD scenarios
  - Long-pulse tests of divertor, CD, transport



- Long-pulse divertor development for next-steps
  - If LLD-I & II successful, consider long-pulse LLD
- Core fueling development
  - D-ice pellets, CT Injection
  - CT injection also useful for momentum input/control

- 750kW ECH/EBW + launcher
  - ECH pre-ionization for startup, initial local EBW heating

FY11-13 high-priority research utilizing proposed major upgrades (I)

- Transport and Turbulence
  - Verify scaling trends at high P_{heat} (≤ 12 MW – 2^{nd} NBI) & long-pulse (≤ 2.5 s – sub-cooling)
  - Electron transport w/ internal δB (MSE), full low-k, modulated EBW for varied local $\nabla T_{e\text{-}crit}$
  - v_{pinch}, χ_ϕ assessment with off-midplane control coil braking, torque variation from 2^{nd} NBI
  - Study effects of reduced ν and recycling (from long-pulse LLD) on all transport channels

- Macroscopic Stability
  - Real-time MSE w/ real-time V_ϕ (E_r corr.) for real-time EFIT, β-feedback using stability models
  - Use off-midplane coils to test viscosity theories (n≤6), use 2^{nd} NBI + braking to control V_ϕ
  - RWM control w/ off-midplane coils + non-magnetic sensors (for long-pulse next-steps)
  - Enhanced EF correction from off-midplane control coils to sustain high rotation and β_N

- Boundary Physics
  - LLD performance with higher input power, long pulse from 2^{nd} NBI + sub-cooling
  - SOL turbulence and widths with higher input power
  - High m,n RMP impact on ELMs, heat flux, edge rotation and barrier formation
  - Detachment and heat flux mitigation with higher input power and reduced density (LLD)
  - Develop and utilize core fueling beyond NBI: pellets, compact toroids

FY11-13 high-priority research utilizing proposed major upgrades (II)

- Wave-Particle Interactions
  - Study fast-ion driven modes w/ more tangential NBI, diagnose with neutron collimator
  - Upgrade to remotely-steered O-X-B launcher, 700 kW core & off-axis heating studies

- Plasma start-up and ramp-up
  - Increase pre-ionization and heating power for PF-only/CHI/gun startup
  - Combine upgraded HHFW + ECH/EBW for fully NI plasma startup & ramp-up
  - Extend long-pulse plasmas using flux savings from non-solenoidal startup & ramp-up

- Integrated scenario development
  - Demonstrate full NICD with NBI + BS with J profile control with 2nd NBI
  - Demonstrate profile equilibration w/ extended flat-top to $4\tau_{CR}$ w/ sub-cooled OH/TF
  - Control n_e, increase confinement with long-pulse divertor + core fueling
  - Sustain τ_E, β_N by suppressing ELM, RWM, EF with off-midplane 3D coils

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

Actively involved in 18 joint experiments – contribute/participate in 25 total

Boundary Physics
- PEP-6 Pedestal structure and ELM stability in DN
- PEP-9 NSTX/MAST/DIII-D pedestal similarity
- PEP-16 C-MOD/NSTX/MAST small ELM regime comparison
- DSOL-15 Inter-machine comparison of blob characteristics
- DSOL-17 Cross-machine comparison of pulse-by-pulse deposition

Macroscopic stability
- MDC-2 Joint experiments on resistive wall mode physics
- MDC-3 Joint experiments on neoclassical tearing modes including error field effects
- MDC-12 Non-resonant magnetic braking
- MDC-13: NTM stability at low rotation

Transport and Turbulence
- CDB-2 Confinement scaling in ELMy H-modes: b degradation
- CDB-6 Improving the condition of global ELMy H-mode and pedestal databases: Low A
- CDB-9 Density profiles at low collisionality
- TP-6.3 NBI-driven momentum transport study
- TP-8.1 NSTX/MAST ITB similarity experiments
- TP-9 H-mode aspect ratio comparison

Wave Particle Interactions
- MDC-11 Fast ion losses and redistribution from localized Alfvén Eigenmodes

Advanced Scenarios and Control
- SSO-2.2 MHD in hybrid scenarios and effects on q-profile
- MDC-14: Vertical Stability Physics and Performance Limits in Tokamaks with Highly Elongated Plasmas

NSTX contributes to near-term and long-term issues for ITER

- Near-term (Feb. 08) experiments in support of critical design activities:
  - ELM suppression
    - Any demonstration of ELM suppression using a single row of coils would provide very valuable data for improved RMP understanding
    - n=2, or combination of n=1 and n=3 yet to be tried on NSTX
    - Does braking from RMP vary w/ T_i, ν_i, n, ε as NTV theory predicts?
  - Vertical control
    - Is ITER n=0 control model valid, and/or consistent w/ experiments?
    - Allow plasma to drift vertically, then try to regain control
    - Quantify controllable ΔZ, compare across devices, compare to ITER
    - Could impact ITER PF coils, power supplies, l_i operating range
  - RWM control
    - Simulate proposed ITER port-plug coil design to assess impact of toroidal asymmetry of coil layout (due to NBI interferences) on RWM control capability
- Longer-term ST research benefiting ITER & fundamental toroidal science:
  - Understanding of electron thermal transport, β scaling of confinement
  - RWM feedback at low rotation with mid-plane coils, RWM damping physics
  - RMP physics understanding, heat flux mitigation, pedestal physics
  - Unique multi-AE "avalanche" studies with full diagnostics + non-linear modeling
  - HHFW coupling physics - surface-wave excitation relevant to ITER ICRF

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

- The FY08-10 plan:
  - Focuses research to address key gaps in extrapolating to next-step STs
  - Contains targeted upgrades that enable exciting new science:
    - Understand anomalous electron (and ion) energy transport
    - Assess impact of liquid lithium on pumping, confinement, ELMs
    - Understand and utilize HHFW for advanced scenarios
- With only 2 years of operation (FY08-09), significant research opportunities would be lost in all topical science areas
- The FY08-13 plan goals are to:
  - Develop a strong predictive capability for the ST, also ITER, and beyond
  - Demonstrate the integrated high-performance scenarios of next-step STs
  - Achievement of FY08-13 predictive and performance goals would enable extrapolation to next-step STs with high confidence