NSTX

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Research Operations and Upgrade Plan

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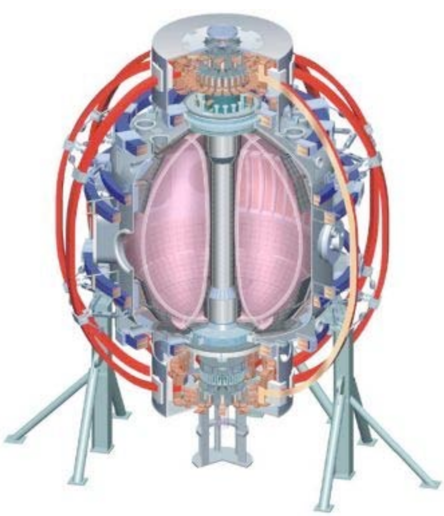
M.G. Bell, PPPL

for the NSTX Research Team

NSTX Facility Operations Review
Princeton Plasma Physics Laboratory
July 30-31, 2008



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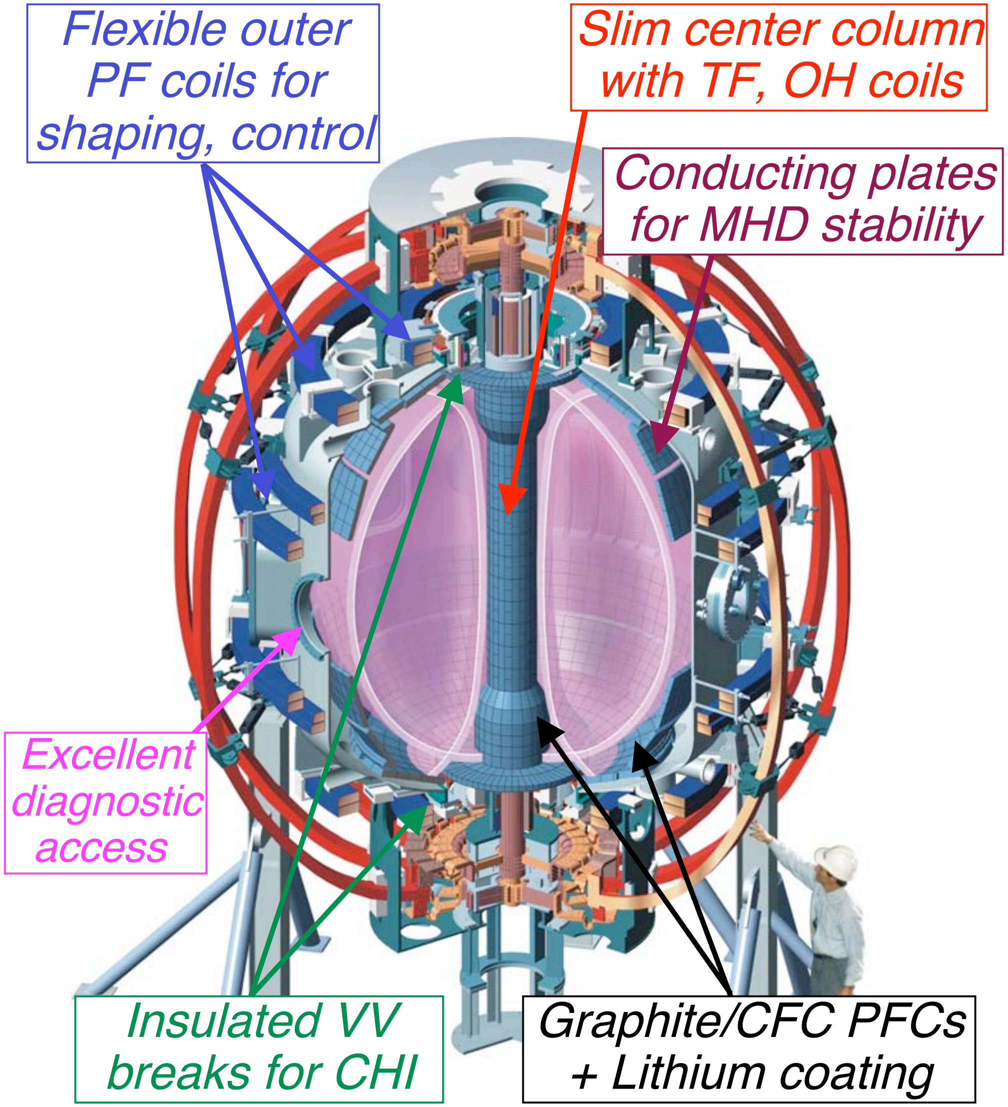
Topics in Relationship to Review Charge

- Capabilities of NSTX
  - Ranges in operational and plasma parameters
  - Plasma control
  - Lithium coating of plasma-facing components
- Support from PPPL as host organization
- NSTX diagnostics
- Process used to allocate research time
  - Role of Topical Science Groups
  - Research Forum
  - Development and execution of NSTX Experimental Proposals
  - Followup activities: Results Review and Run Assessment
- Summary of recent experimental operation
- Upgrade plans

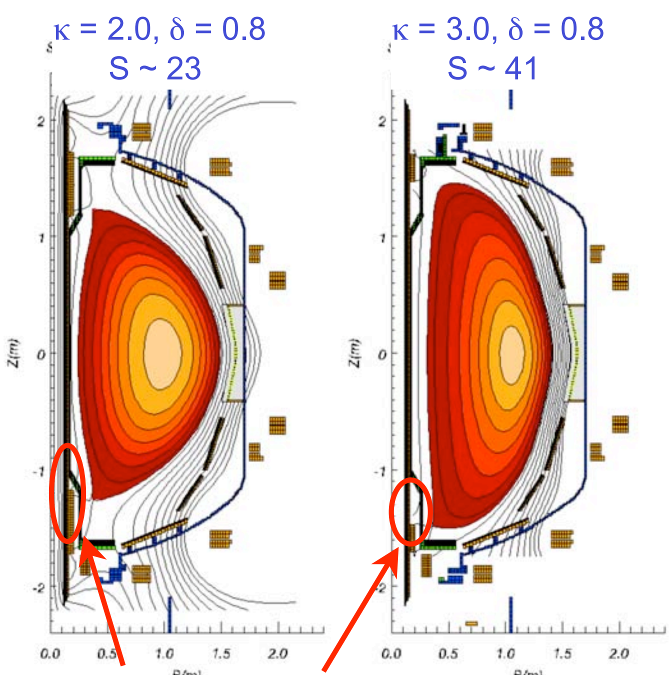
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.4 – 0.55 T
(Pulse Length	~2 – ~1 s)
Auxiliary heating:	
NBI (100kV)	5 – 7 MW
(Pulse Length	5 – 2 s)
RF (30MHz)	6 MW (5 s)
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20} m^{-3}$

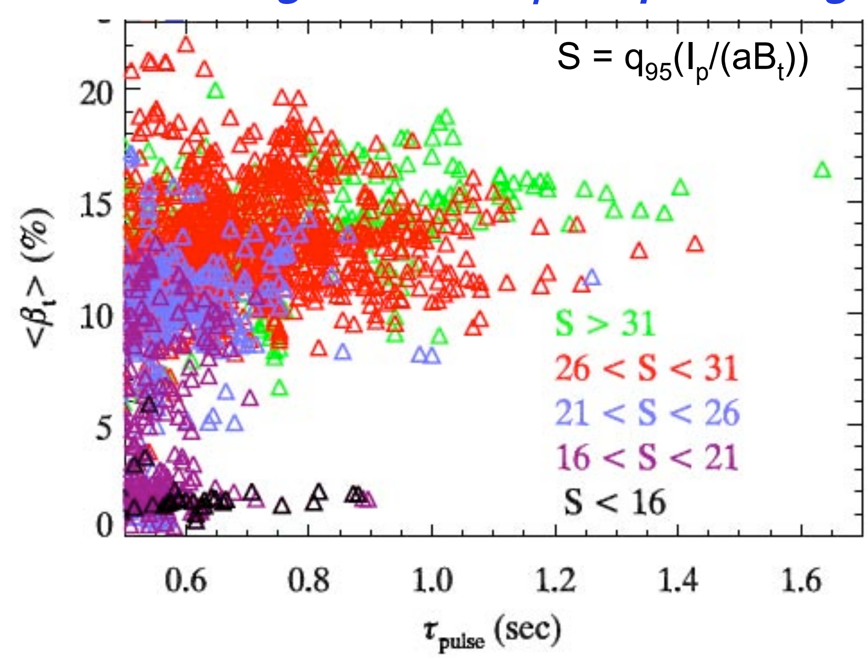
Advanced Plasma Control Key to Achieving NSTX Research Goals

- rtEFIT (collaboration with GA) has enabled reliable plasma shape control
- Control system hardware improvements have produced higher elongation κ
- PF coil modification enabled allowed high triangularity δ at high κ
- Achieved record shaping parameter $S = q_{95}I_p/(aB_t)$ - doubled in last 5 years
- Combining highest S and highest β_N produced record pulse length in 2008
  - Non-axisymmetric error-field control important for sustaining high β_N



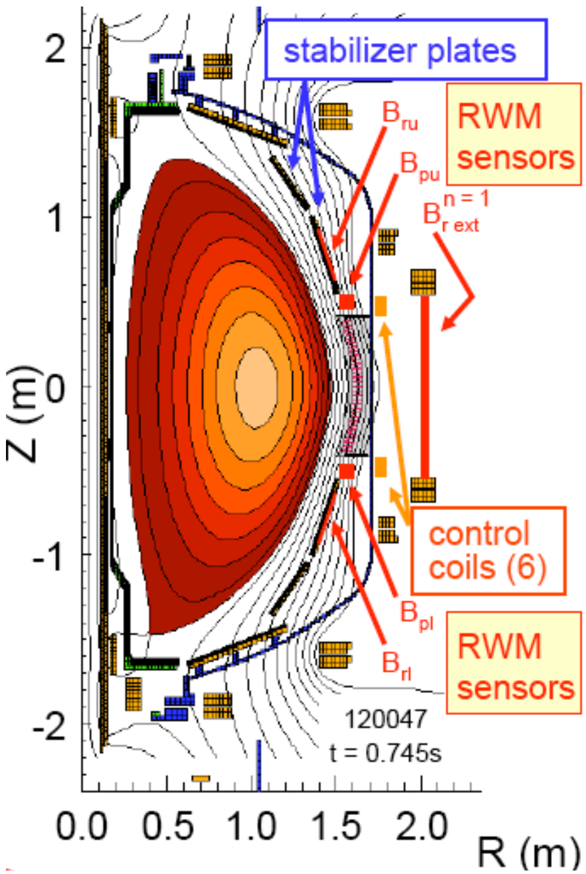
PF1A coils changed prior to 2005 run

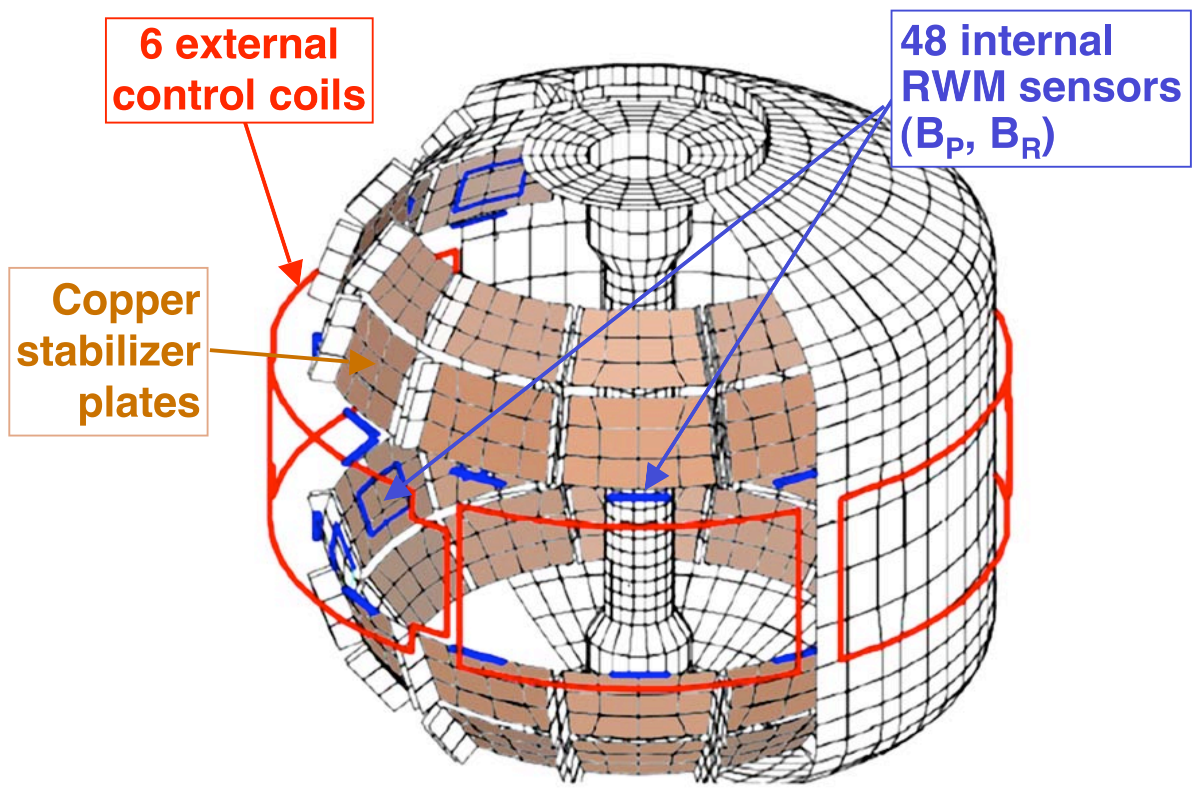
Pulse averaged toroidal β vs. pulse length



Non-Axisymmetric Coil System with Fast Power Amplifiers Contributed to MHD Control

- 6 external midplane coils powered by 3 Switching Power Amplifiers
- Provide dominant n = 1, 3 or 2 (4) radial field components
  - Intrinsic error-field correction, RWM control, RMP for ELM control
- Real-time signal processing & feedback algorithm in Plasma Control System





NSTX is Exploring and Developing Lithium-Coated Plasma Facing Components

2005: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

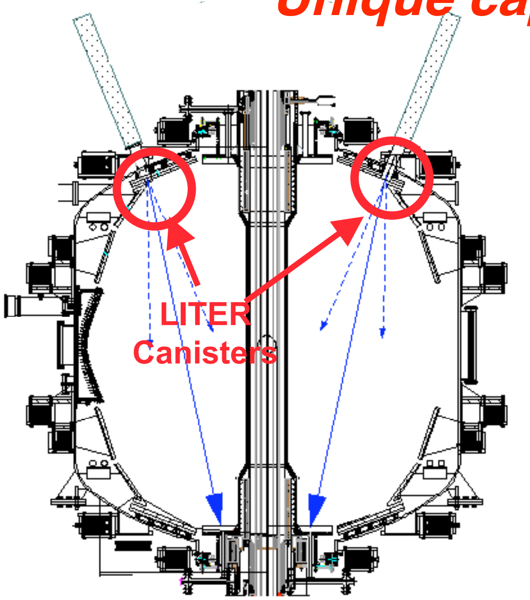
2006: LIThium EvaporatoR (LITER) deposited lithium on divertor between shots

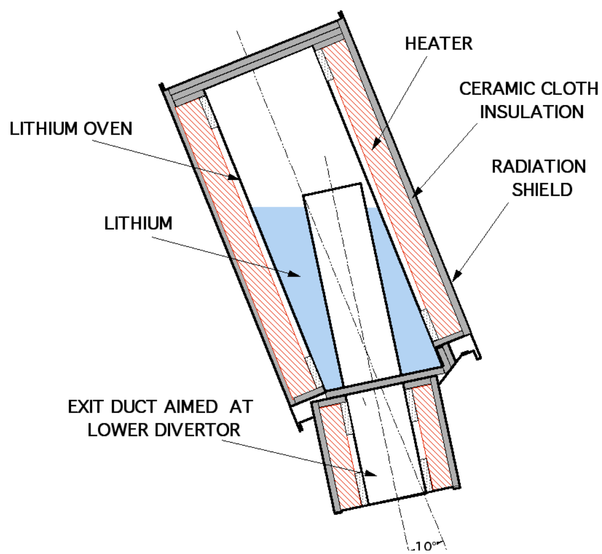
2007: Enlarged nozzle, re-aimed at lower divertor to increase deposition rate

2008: Dual LITERs covered entire lower divertor; shutters interrupted lithium stream during plasmas; evaporated ~200g lithium (reloaded 3 times)

- **Reduced D recycling, improved confinement, suppressed ELMs**
- Also used "lithium powder dropper" successfully

Unique capability amongst divertor tokamaks





NSTX Draws on and Benefits from the Resources, Infrastructure and Staff at PPPL

Research environment and resources

- NSTX Test Cell and associated diagnostic laboratories
- Pulse power systems: *flywheel MG sets, rectifiers*
- Auxiliary plasma heating equipment and expertise: *NBI, ICRF*
- Machine shops: *diagnostics, lithium technology*
- Coil winding facilities: *new PF1A coils*
- Computing facilities and networks: *data management and access*

Experienced, well-qualified staff

- Research staff (including 41 APS Fellows of DPP, 3 PU faculty)
- Graduate students & post-doc (from PU)
- Engineering expertise: *design, electrical, I&C, mechanical, software*
- Procurement and quality assurance organizations
- ES&H organization

see accompanying presentation by A. vonHalle for more details

NSTX is Equipped with Comprehensive Diagnostics Including Strong Contributions from Collaborators

• *Collaboration contributions*

MHD/Magnetics/Reconstruction

Magnetics for *equilibrium reconstruction*
Diamagnetic flux measurement
Halo current measurement
High-n and high-frequency Mirnov arrays
Locked-mode detectors
RWM sensors (n = 1, 2, and 3)

Profile Diagnostics

Multi-pulse Thomson scattering (30 ch, 60 Hz)
T-CHERS: $T_i(R)$, $V_\phi(R)$, $n_C(R)$ (51 ch)
P-CHERS: $V_\theta(R)$ (51 ch)
MSE-CIF (15 ch)
FIReTIP interferometer (119mm, 6 ch)
Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics

Tangential microwave high-k scattering
Microwave reflectometers
Ultra-soft x-ray arrays – tomography (4 arrays)
Fast X-ray tangential camera (2μs)

Energetic Particle Diagnostics

Neutral particle analyzer (2D scanning)
Solid-state neutral particle analyzer
Fast lost-ion probe (energy/pitch angle resolving)
Fusion neutron measurements
Fast Ion D_α profile measurement

Edge Divertor Physics

Reciprocating Edge Probe
Gas-puff Imaging (2μs)
Fixed Langmuir probes (24)
Edge Rotation Diagnostics (T_i, V_f, V_{pol})
1-D CCD H_a cameras (divertor, midplane)
2-D divertor fast visible camera
Divertor bolometer (12 ch)
IR cameras (30Hz) (3)
Tile temperature thermocouple array
Edge deposition monitors
Dust detector
Scrape-off layer reflectometer
Edge neutral pressure gauges

Plasma Monitoring

Fast visible cameras
Wall coupon analysis
EBW emission radiometer
Visible bremsstrahlung radiometer
Visible survey spectrometer
Visible filterscopes
UV survey spectrometer
SXR transmission grating spectrometer
XUV crystal spectrometer

NSTX Scientific Leadership for 2008 Run

	Coordinator	Deputy
Run coordination	Michael Bell	Roger Raman (U. Washington)

Topical Science Group	Leader	Deputy Leader
Macroscopic Stability	Steve Sabbagh (Columbia U.)	Stefan Gerhardt
Transport and Turbulence	Stan Kaye	Kevin Tritz (Johns Hopkins U.)
Boundary Physics	Vlad Soukhanovskii (LLNL)	Rajesh Maingi (ORNL)
Wave-Particle Interactions	Gary Taylor	Eric Fredrickson
Advanced Scenarios and Control	David Gates	Jon Menard
Solenoid-free Start-up and Ramp-up	Roger Raman (U. Washington)	Dennis Mueller

- Forms an integrated research team to take advantage of unique facilities

Annual NSTX Research Forum Provides Team Members the Opportunity to Propose Experiments

- Held at PPPL over $2^{1}/_{2}$ days ~2 months before start of experiments
  - Involves wide participation, both on-site and by teleconference
- ***Follows an open invitation to submit ideas for experiments***
  - TSG leaders defined 2 highest priority themes for each topical area
- NSTX Program Head provides initial guidance on runtime allocation
  - Reserve 20% for “cross-cutting” activities and 20% for later allocation
  - Distribute balance *per stirpes* to TSGs, adjusted for contributions to expected milestones, facility development, and ITPA, BPO interests
- Include presentations from other facilities (e.g. DIII-D, C-Mod, MAST)
- Proposals for experiments discussed and prioritized by TSGs in breakout sessions (3 serial, 2 parallel, accessible by teleconference)
  - TSGs asked to identify gaps, overlaps and combine if appropriate
- Final plenary session reviews recommended prioritized experiments from TSGs and plans for developing Experimental Proposals (XPs)

NSTX Experimental Proposals Guide Operation

- Experimental Proposals (XPs) are documents describing
  - justification for the experiment and that it is well suited to NSTX
  - the plan for executing the required shots and scans efficiently
  - the required machine and diagnostic capabilities
  - plans for analysis, reporting and publication of the results
- XPs are discussed in TSG meetings and recommended for review by the research team led by the Run Coordinator
  - All meetings are open and accessible by teleconference from off-site
  - Review "chits" may be submitted, pointing out deficiencies and/or recommending changes to improve the experiment
- Final version is approved, posted on the Web and a formal "run copy" is prepared when the experiment is scheduled
- NSTX also provides Experimental Machine Proposals (XMPs) which are used to commission new systems or capabilities
  - Reviewed and approved by Experimental Research Operations

In 2008, the NSTX Team Performed 43 Experimental Proposals

- 12 Experimental Machine Proposals were also performed
- Run lasted from Feb 18 through July 14 (21 calendar weeks)
- Included 4 scheduled maintenance weeks, 4 days unscheduled maintenance time and 2 holidays
  - Scheduled maintenance to avoid running during major meetings
- Achieved 16.6 run weeks, exceeding milestone target of 15
- Schedule for experiments in the next 1 - 2 weeks is developed at a weekly Program/Operations meeting chaired by Run Coordinator
  - Adapt schedule to evolving status and availability of facility, heating systems, diagnostics, collaborator travel *etc.*
  - Meeting is accessible by teleconference, schedule is posted on Web and updated as conditions change
  - Schedule up to 4 experiments (XPs and/or XMPs) on each run day
- Daily plan is discussed at "8:30am Meeting" and summarized in an email distributed widely

Final Allocation of Run Time Matched Target Reasonably Well in 2008

- For the 2008 run, 3 days were initially provided for specific ITER support
- The XMPs were counted as "cross-cutting and enabling"

Topic	Experiments performed	Run time guidance (%)	Run time used (%)
Advanced scenarios	5	9	8
Boundary physics*	11	12	18
Macro-stability*	8	12	16
Solenoid-free startup*	1	10	11
Transport & Turbulence*	10	12	16
Wave-Particle Interactions	7	9	10
Cross-cutting & enabling	12	13	12
ITER support	2	4	9
Reserve		19	

** 2008 Milestone experiments*

Number of Experiments Performed in Recent Years Limited by Run Time Available

TSG	2008#				2007*				2006			
	Proposals		Rundays		Proposals		Rundays		Proposals		Rundays	
	Submitted	Executed	Requested	Used	Submitted	Executed	Requested	Used	Submitted	Executed	Requested	Used
ASC (ISD)	14	5	12	6	14	4	24.5	7	16	2	14	4.5
BP	22	11	25.5	14.5	36	12	34	10.5	34	9	32.5	15
MS (MHD)	16	8	17.5	12.5	32	15	20.5	17	7	4	8	8.5
SFS	6	1	11	8.5	7	2	18	4.5	6	3	16	6.5
TT	19	10	20	12.5	25	9	11.5	13	24	7	27	9
WPI	26	6	24	7	9	3	14.5	5.5	13	4	15.5	5.5
Cross-cutting		14		16		3		6		8		8.5
Total	**103**	**55**	**110**	**77**	**123**	**48**	**123**	**63.5**	**100**	**37**	**113**	**57.5**

In 2008, "Cross-cutting" included 2 ITER ELM XPs for 7 rundays

* in 2007 only, MHD TSG included fast-ion MHD otherwise in WPI

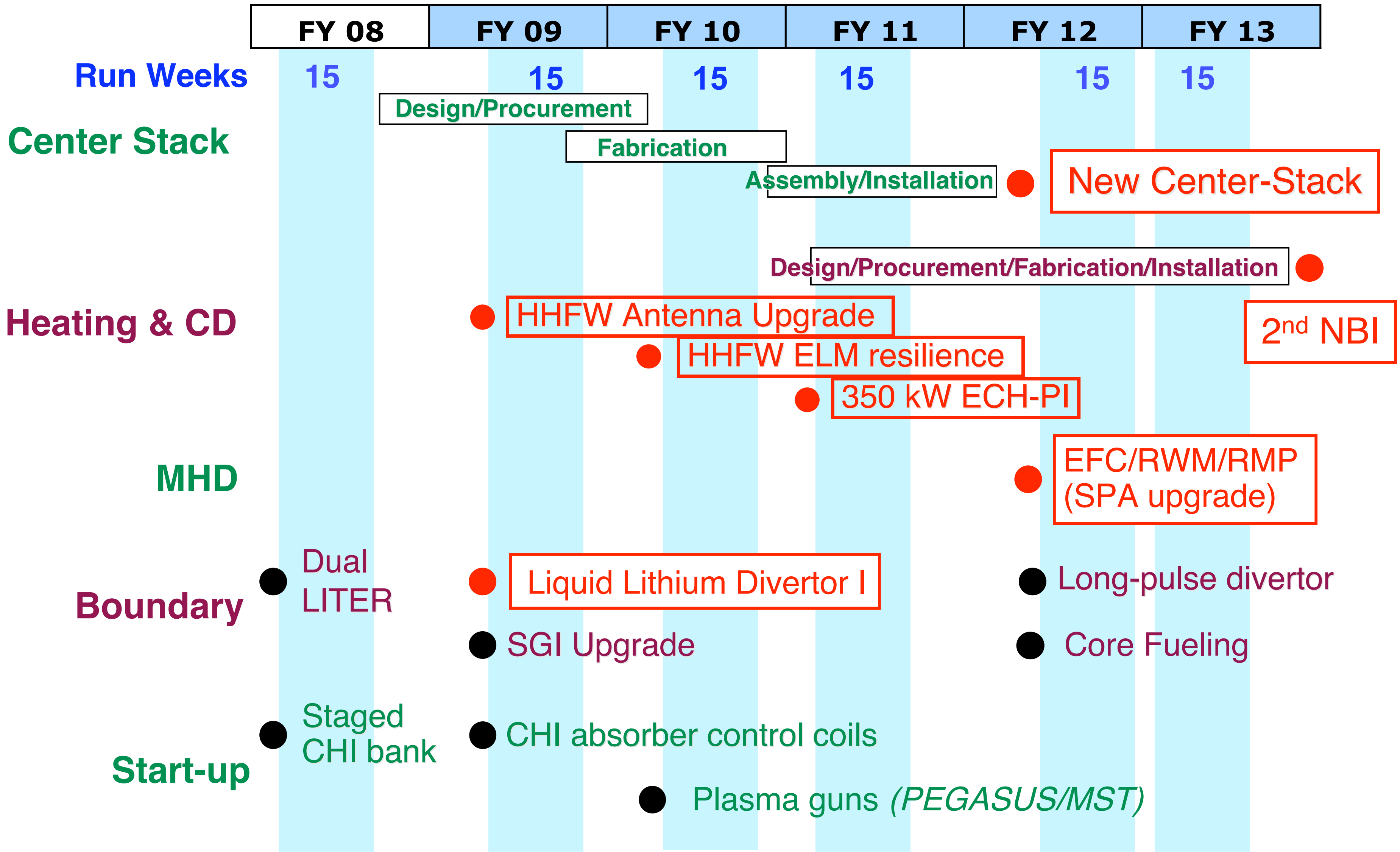
"Cross-cutting" includes XMPs for startup plasmas, HHFW conditioning, hardware & diagnostic commissioning & calibration

Results and Analysis of Experiments Presented to and Discussed by the Whole Team

- 5:00pm "end of runday" meeting
  - Progress on performing the plan and highlights of data
- Weekly Physics Meeting
  - Preliminary analysis
- Mid-run Assessment
  - Progress towards meeting milestones
  - Needs for additional runtime to complete experiments
  - Need for experiments not foreseen at Research Forum
- Annual Results Review
  - Progress towards comprehensive analysis and conclusions
  - Plan for publication
- Annual Run Assessment
  - Discussion of successes and difficulties encountered
  - Improving planning and execution of experiments and communication

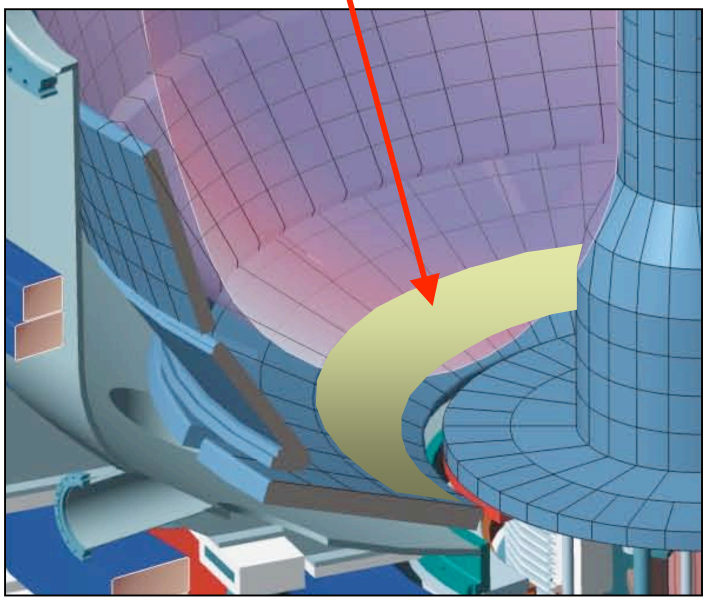
All meetings are accessible by teleconference

An Exciting Program of Facility Upgrades is Proposed in the FY09-13 Plan



In 2009, NSTX Will Begin Investigating Liquid Lithium on Plasma Facing Components

Liquid Lithium Divertor (LLD)

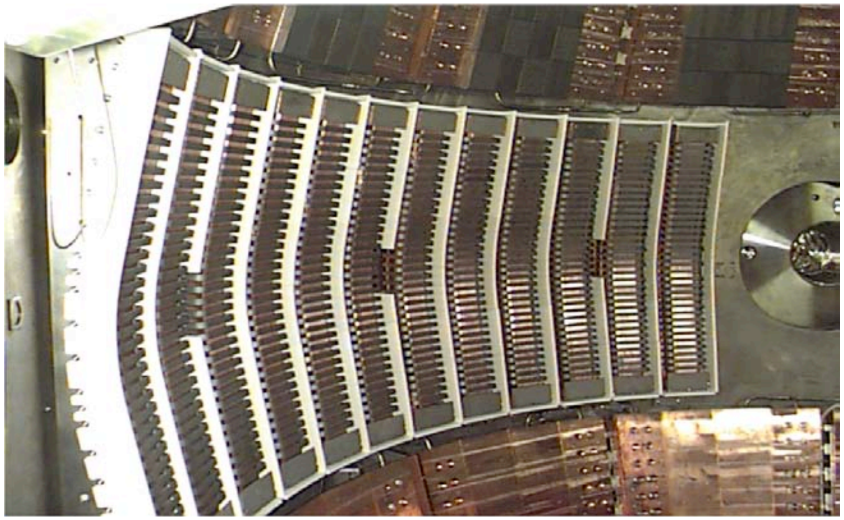


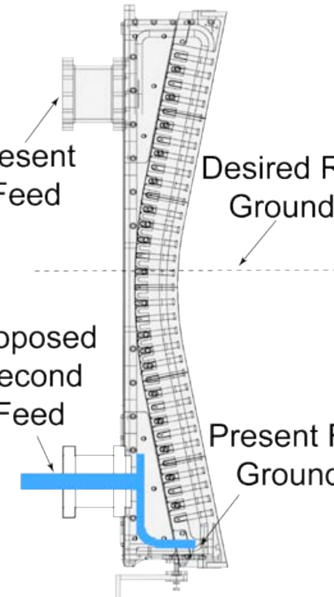
- Collaborating with SNL on design, fabrication and instrumentation
- Segmented sections of conical surface
- Molybdenum surface on copper substrate with temperature control
  - Heated above Li melting point 180°C and cooled to counteract plasma heating
- Initially supply lithium with LITER and lithium powder dropper

- Install LLD during 2008 outage (just beginning)
- Start LLD operation in 2009
- Upgrade to long-pulse divertor in 2012
  - Will require method for core fueling, *e.g.* CT injection, pellets
- Very high power flux divertor with 2nd NBI in 2013 (incremental)

Upgrades Proposed for HHFW Antenna to Improve Coupling in H-mode and for ECH Startup Assist

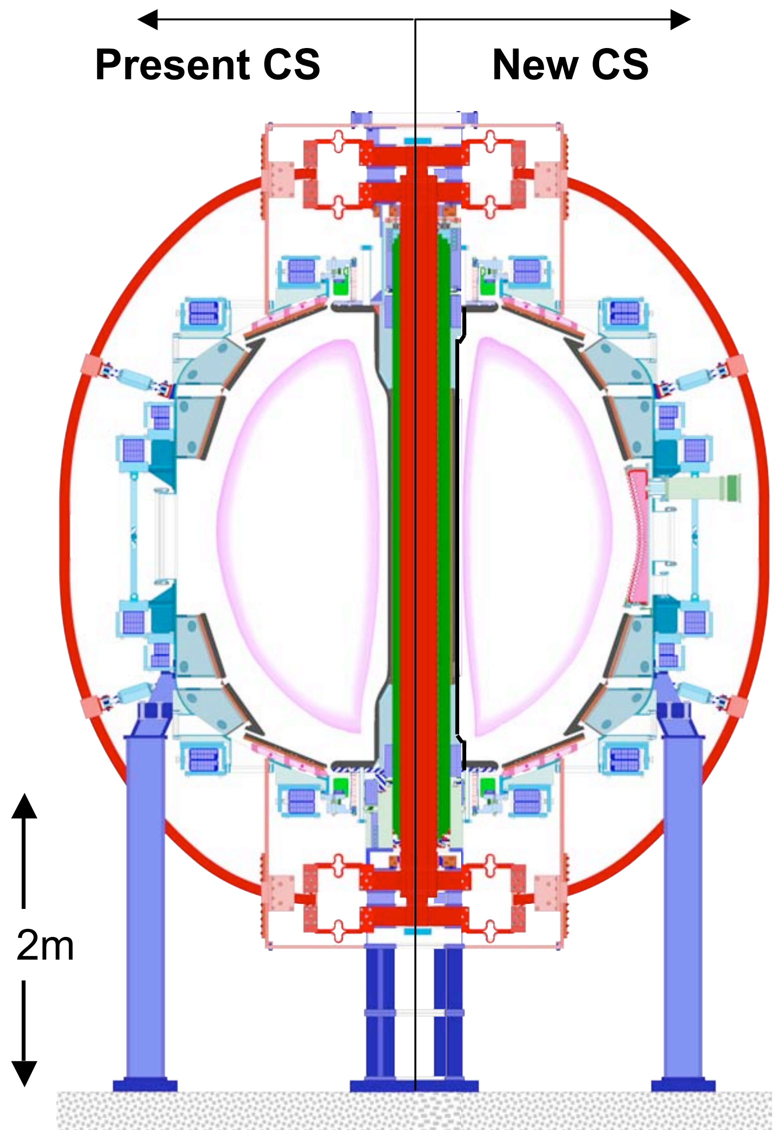
NSTX 12-Strap HHFW Antenna





- HHFW: heating advanced scenarios, q(0) control & bootstrap overdrive
  - **2009**: double symmetric feed upgrade will permit larger plasma-antenna gap, with better loading stability and power per strap in H-mode
  - **2010**: add power dump for ELM resilience
- ECH: pre-ionization & non-inductive startup assistance
  - **2011**: 28 GHz, 350 kW gyrotron and midplane launcher
  - **2012** (incremental): add second gyrotron

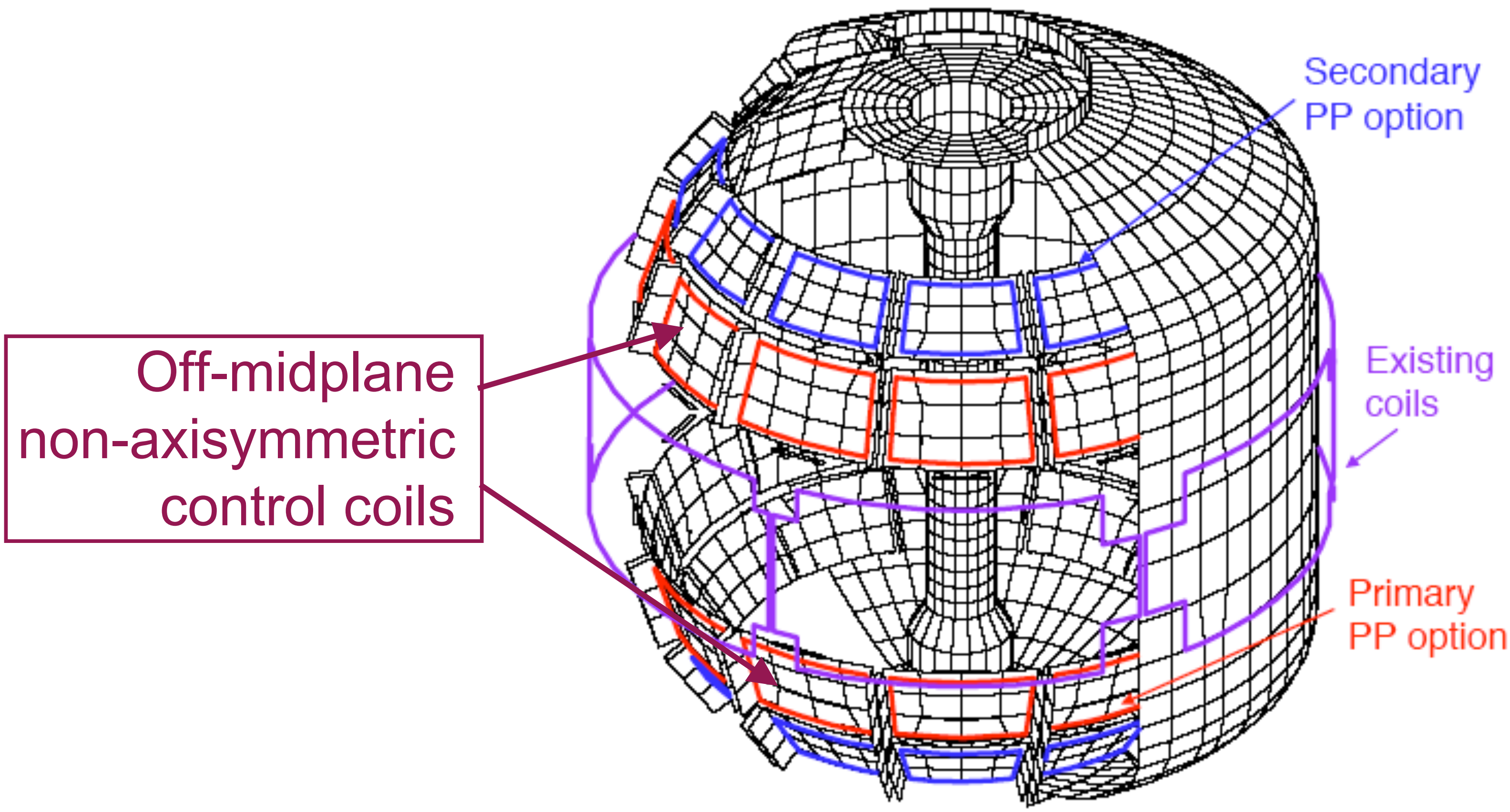
New NSTX Center Stack Builds Upon 10 Years of Design, Manufacturing, Operational Experience



Parameters	Units	Present CS	2nd CS
Minimum A		1.28	1.5
R_0	cm	85	91
A	cm	67	61
R_0-a	cm	18.5	30.5
I-TF	kA	71	119
BT_0	T	0.55	1
τ-TF-flat top	sec	0.8	5.6
OH-flux	V-S	0.75	2.59
Ip	MA	1	2
Flat-top VS	VS	0.29	1.59

- Every TF joint monitored on every shot
- TF joints operated stably at 0.55T (~ design value) since their last maintenance in 2004

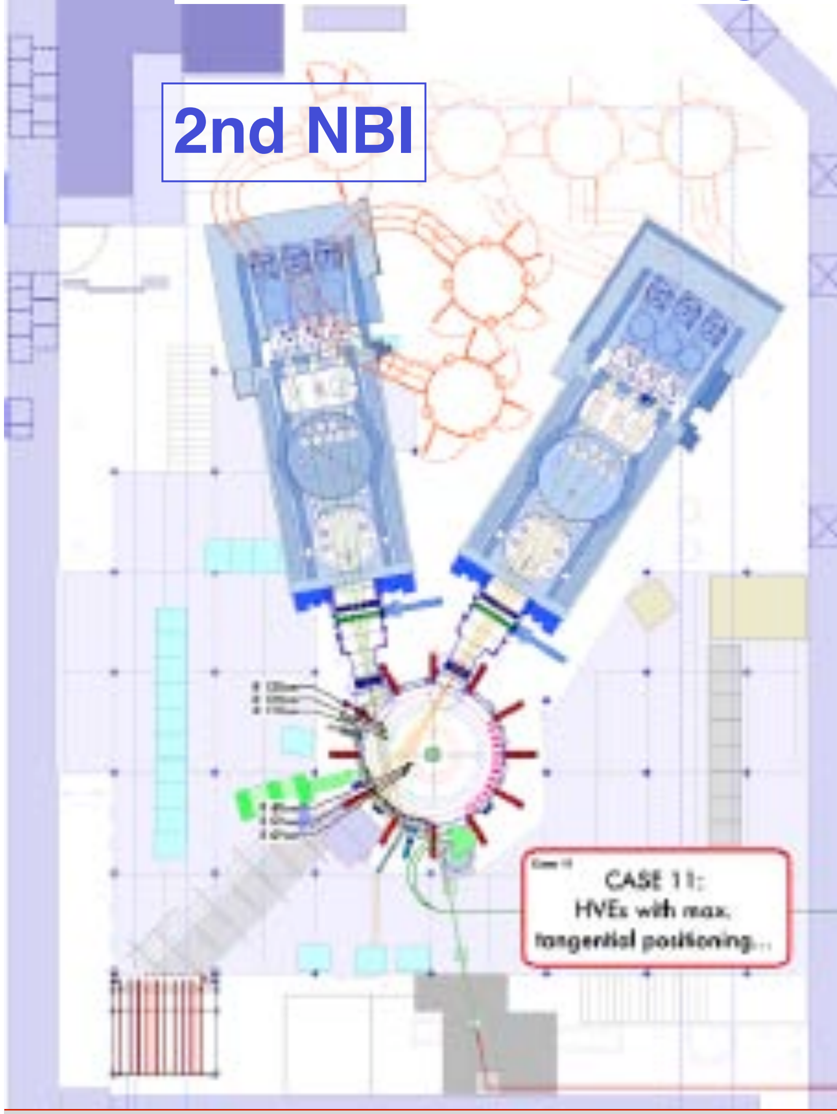
Non-Axisymmetric Control Coils Upgrades Planned for More Adaptable Control of MHD Modes



- Increase Switching Power Amplifiers (SPAs) from 3 to 6 to provide arbitrary mix of even and odd n components (2012 - base)
- Install upper/lower Non-Axisymmetric Control Coils (NCC) for improved EF/RWM/RMP control (2013 - Incremental)

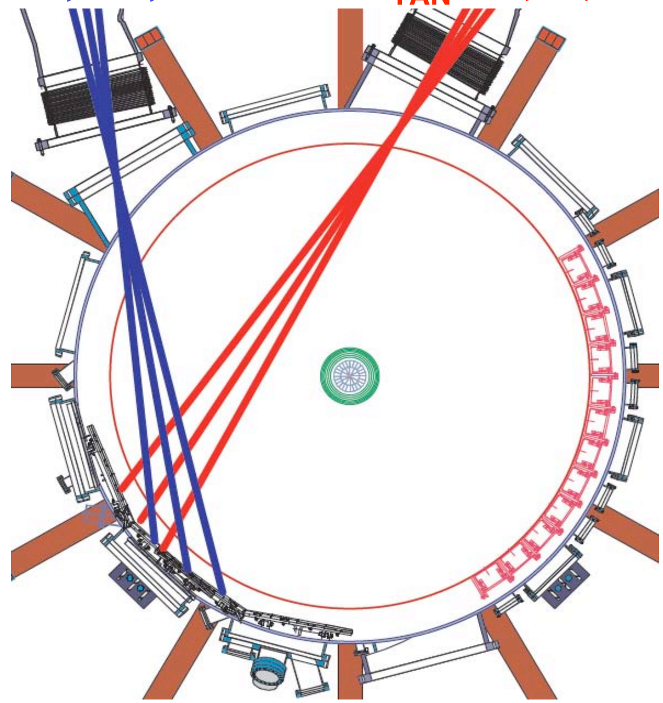
Second NBI Upgrade Enables Profile Control and Fully Non-Inductive Current-Drive Scenarios

2nd NBI was in the original NSTX design for installation at Bay K



2^{nd} NBI — R_{TAN}=110,120,130cm

Present NBI — R_{TAN}=50,60,70cm



Greatly enhanced capabilities

– **P_{NBI} doubles: 7 – 14 MW (at 95 keV for 2 s),
5 – 10 MW (at 80 keV for 5 s)**

– **Higher CD efficiency and j(r) control**

5 Year Plan for Control and Diagnostic Upgrades

	FY 08	FY 09	FY 10	FY 11	FY 12	FY 13
Run Weeks	15	15	15	15	15	15
Control	• Improved EFC, RWM control • NBI control	• HHFW loading control • β control	• Real-time V_ϕ	• V_ϕ control • Real-time MSE	• MSE rt-EFIT	• q(0) control (HHFW-CD then 2nd NBI)
Profile	• P-CHERS(70 ch) • MSE/CIF (16 ch) • Multi-Color-T_e(r)	• MSE/LIF	• MSE/CIF (19 ch) • MPTS higher spatial resolution		• MPTS 90Hz	
MHD	• Divertor Halo Current			• Non-magnetic RWM-ID		
Turbulence	• Corr. Reflect. • High-k Scattering remote control	• BES		• Magnetic turbulence diagnostic • High-k Scattering k-θ		
Energetic Particles	• Fast-ion D_α camera	• FIReTIP (2 MHz)		• Neutron Collimator		
Waves	• Improved EBW Radiometer	• High-k HHFW (30 MHz)				
Boundary	• Dust Detector	• Divertor Bolometer • Surface analysis probe • Fast IR • Ion Flow	• Edge USXR • Divertor spectrometer			

Diagnostic relocation for 2nd NBI

NSTX Provides an Open and Productive Research Environment for All Team Members

- Drawing on highly qualified staff from PPPL and a broad group of domestic and international collaborators, NSTX has created a well integrated research team to exploit its unique facilities
  - Access to unique plasma regimes, powerful heating systems, flexible control
  - Comprehensive, state-of-the-art diagnostics
- Topical Science Groups provide scientific leadership for NSTX research
  - About half of the TSG leaders are collaborators
  - About half of invited talks and publications are led by collaborators
- Allocation of experimental runtime is through an open process
  - Research forum generates a wealth of ideas
  - Experimental proposal development and review
  - Scheduling runtime
  - Off-site access to meetings, data, presentations and documents
- Processes are established to promote continuous improvement
- An exciting program of upgrades is planned for the next five years to develop and exploit NSTX potential