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NSTX

National Spherical Torus Experiment
Introduction, Facility, and Budget

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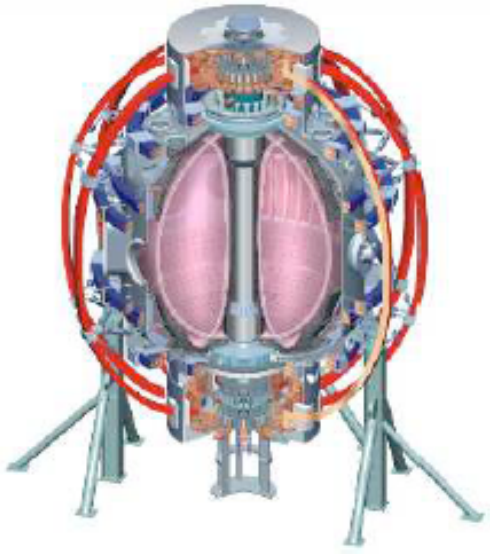
Masayuki Ono

For the NSTX Research Team

DOE Mid-Term Review of Major MFE Facilities

September 21, 2006

Gaithersburg, MD



Culham Sci Ctr
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CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

NSTX Presentation Plan

- **M. Ono - Introduction, Facility Operation, Upgrades, and Budget**

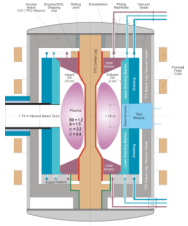
Science Topical Presentations:

- **S. Sabbagh - MHD**
- **S. Kaye - T&T**
- **J. Menard - W&P, Boundary, Integration**

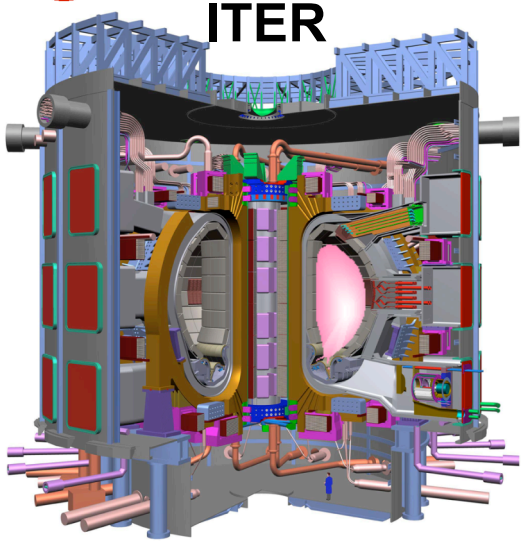
NSTX Strategy to Address Issues Important for ST-CTF and ITER through ITPA and USBPO

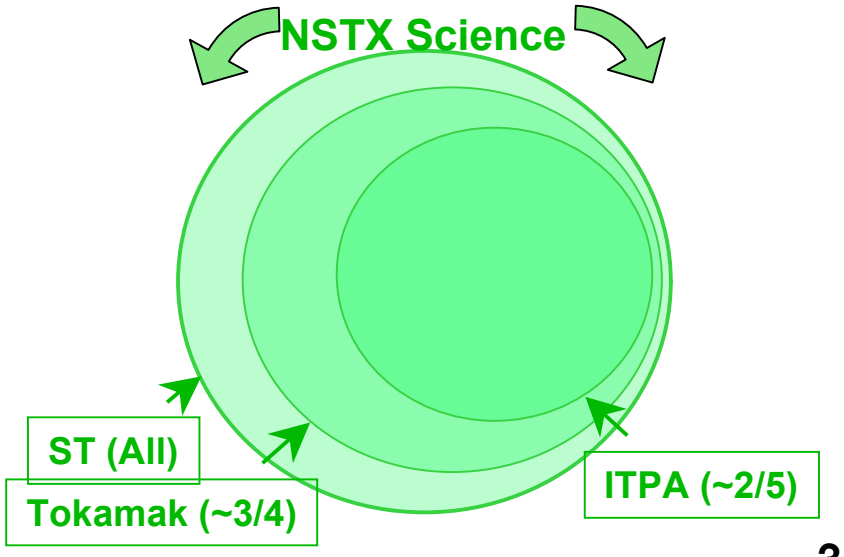
- Explore physics of Spherical Torus / Spherical Tokamak to provide basis for attractive U.S. Component Test Facility (CTF) and Demo.
- Support preparation for burning plasma research in ITER using physics breadth provided by ST; support and benefit from "ITPA Specific" activities.
- Complement and extend tokamak physics experiments, maximizing synergy in investigating key scientific issues of toroidal fusion plasmas

ST CTF



ITER





NSTX Made Significant Progress since 2004

Device Parameters

R = 85 cm

a = 65 cm [design]

κ = 1.7 - 2.9 [< 2.2]

δ = 0.3 - 0.8 [< 0.55]

B_T = 5.5 kG [≤ 6.0kG]

I_p = 1.5 MA [1.0 MA]

V_p = 14 m^3 [12 m]

E_p ~ 430 kJ [200 kJ]

P_{NBI} = 7.4 MW [5MW]

P_{HHFW} = 6 MW [6MW]

350°C bakeout [350°C]

Passive Plates

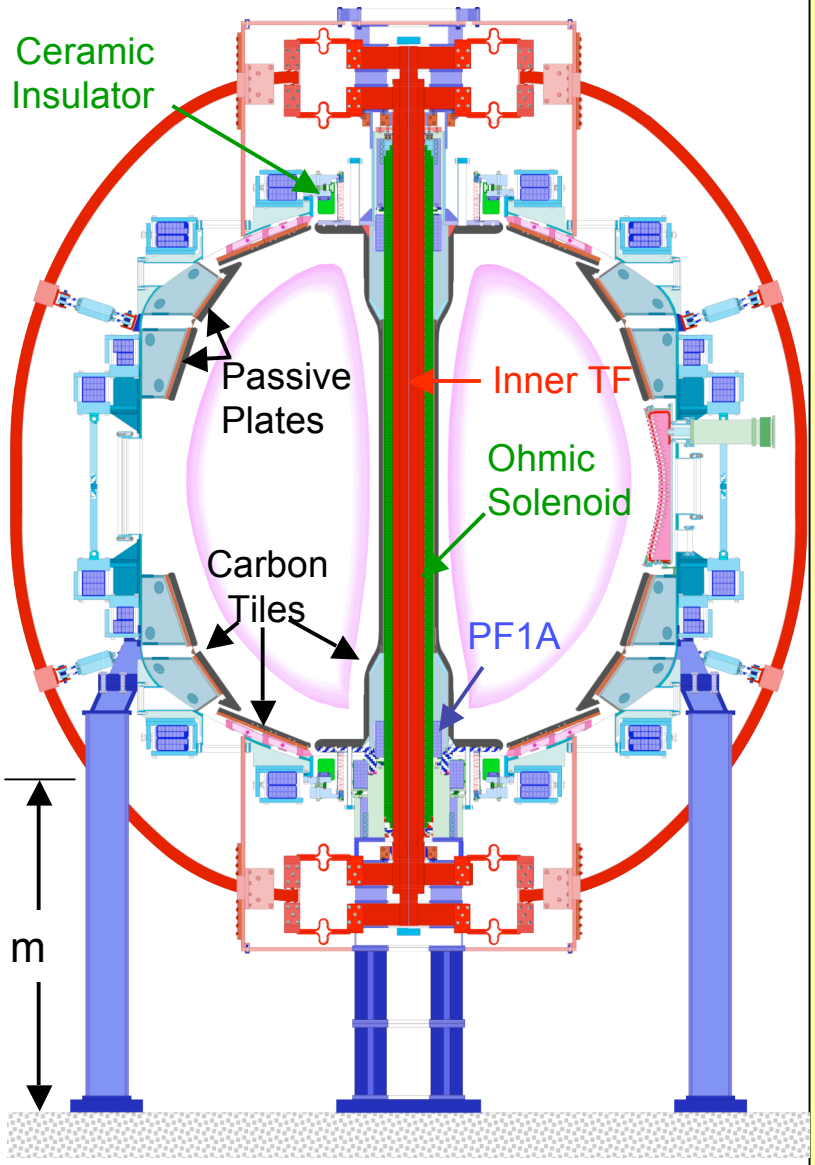
RWM Coils

I_{CHI} ~ 160 kA (I_{inj}=0)

60 cm dia. ports

Wide tang. Access

RED - Since 2004



Major Diagnostic Systems - Confinement Studies-RED - Since 2004

- Magnetic equiplibrium reconstruction
- Diamagnetic flux measurement
- Multi-pulse Thomson scattering (30 ch)
- CHERS: $T_i(R)$ and $V_\phi(r)$ (51 ch)
- Neutal particle analyzer (2D scanning)
- FIReTIP interferometer (6 ch, 600 kHz)
- Density Interferometer (1 mm, 1ch)
- Visible bremsstrahlung radiometer (1 ch)
- Midplane tangential bolometer array
- X-ray crystal spectrometer: $T_i(0)$, $T_e(0)$
- MSE-CIF (12h)

MHD/Fluctuation/Waves

- High-n and high-frequency Mirnov arrays
- Ultra-soft x-ray arrays – tomography (4)
- Fast X-ray tangential camera (2μs)
- RF/TAE Wave reflectometers
- FIReTIP polarimeter (6 ch, 600 kHz)
- Tangential microwave scattering
- Electron B ernstein wave radiometer
- Fast lost-ion probe (energy/pitch)
- Fast neutron measurement
- Locked-mode detectors
- RWM sensors (n = 1, 2, and 3)

Edge/divertor studies

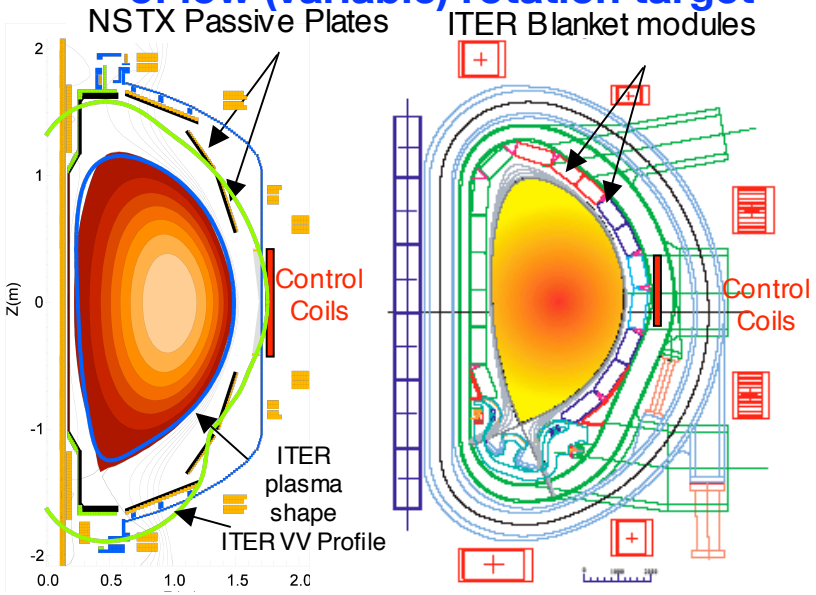
- Reciprocating Langmuir probe
- Gas-puff Imaging (2μsec)
- Fixed Langmuir probes (24)
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- 1-D CCD H_α cameras (divertor, midplane)
- 2-D divertor fast visible camera
- Divertor bolometer (4 ch)
- IR cameras (30Hz) (3)
- Tile temperature thermocouple array
- Scrape-off layer reflectometer
- Edge neutral pressure gauges

Plasma Monitoring

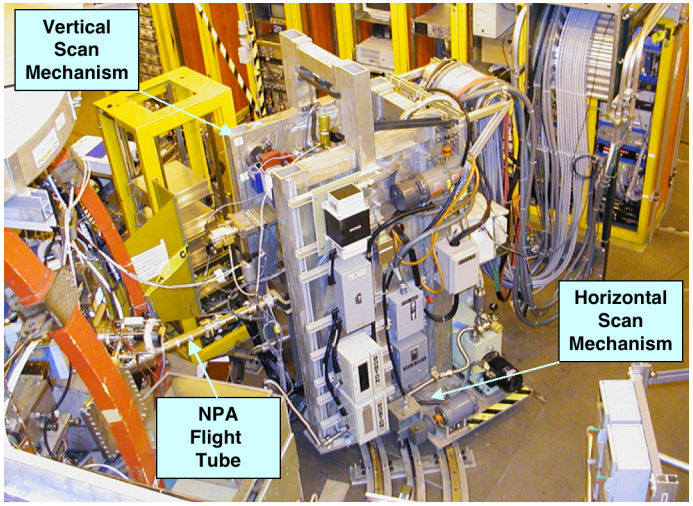
- Fast visible cameras
- Visible survey spectrometer
- VUV survey spectrometer
- X-ray transmission grating spect.
- Fission chamber neutron measurement
- Visible filterscopes
- Wall coupon analysis
- Imaging X-ray crystal spect. (astrophys)

NSTX Facility Addressing Important Issues for ITER

Active EF/RWM Feedback Stabilization of low (variable) rotation target

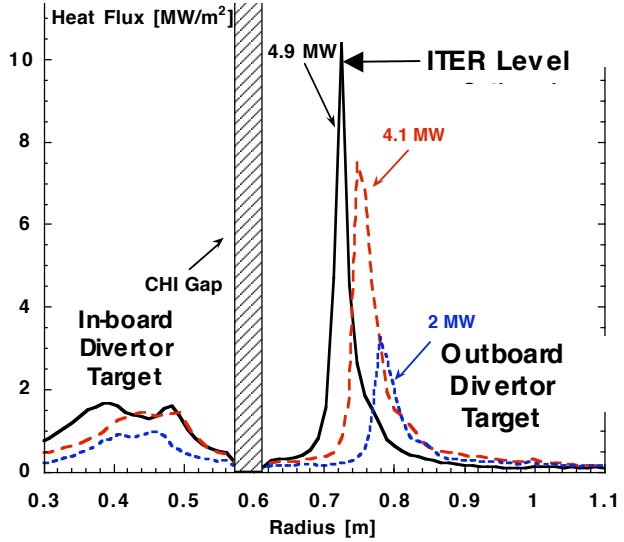


Unique Energetic Particle Physics Capability



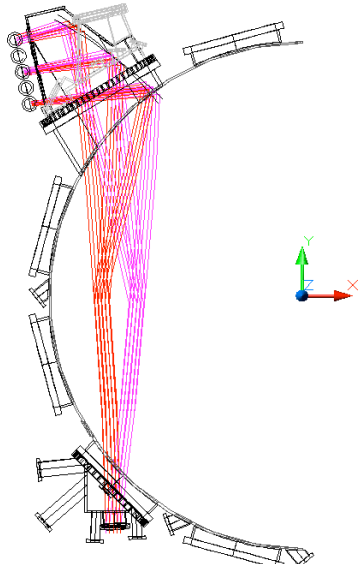
- $V_f >> V_A$ Large β_f
- Full set of diagnostics: MSE for j(r), Scanning NPA for fast particle, SFLIP for escaping particles, TAE diags

Boundary physics with ITER-level heat flux



- Radiative / detached DV / Disruptions
- H-mode pedestal / small ELMs / shaping
- "Blobs" / MARFEs

β Confinement Scaling, Electron Transport



- Confinement scaling with wide range of β_T up to ~ 40 %
- Electron scale high-k turbulence scattering for electron transport physics

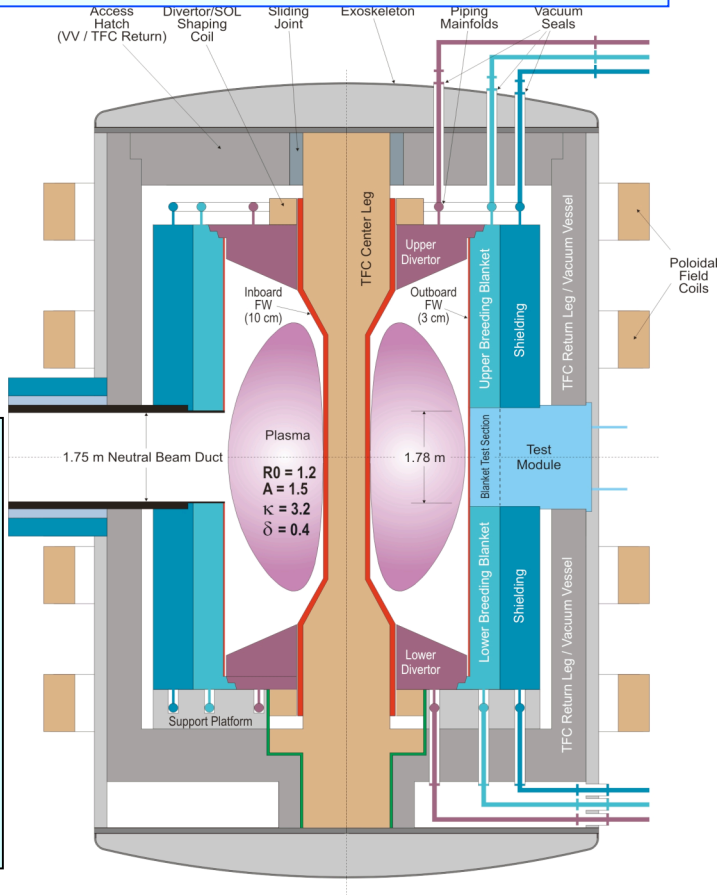
NSTX devoted 1/3 run time to, and completed half of, the planned ITPA 2006-2007 Joint Experiments

ID No	2006 Proposal Title	Devices	Status
CDB-2	Confinement scaling in ELMy H-modes: β degradation	AUG, DIII-D, JET, JT-60U, Tore-Supra(L), MAST, NSTX	complete
MDC-2	Joint experiments on resistive wall mode physics	DIII-D, JET, NSTX, JT-60U, AUG and TEXTOR	complete
MDC-9	Fast ion redistribution by beam driven Alfvén modes and excitation threshold for Alfvén cascades	JT-60U, JET, DIII-D, NSTX, MAST, AUG	complete
TP-8.1	ITB Similarity Experiments	MAST, NSTX	complete
PEP-9	Pedestal similarity study	DIII-D, MAST, NSTX	complete
DSOL-15	Inter-machine comparison of blob characteristics	C-Mod, NSTX, TJ-II,JET, TCV, HT-7, Tore-Supra, AUG, JT-60U	complete
DSOL-18	Impurity migration and deposition study	NSTX, AUG, JET	complete
SSO-2.2	MHD effects on q-profile and confinement for hybrid scenarios	AUG, JET, DIII-D, JT-60U, NSTX	complete
SSO-2.1	Complete mapping of hybrid scenario	JET, JT-60U, DIII-D, AUG, NSTX	complete
CDB-6	Improving the condition of Global ELMy H-mode and Pedestal databases: Low A	MAST, NSTX, DIII-D	partial
CDB-8	rho* scaling along an ITER relevant path at both high and low beta	JET, DIII-D, C-mod, AUG, NSTX	partial
CDB-9	Density profiles at low collisionality	JET, DIII-D, C-mod, AUG, JT-60U, TCV, Tore-Supra, MAST, FTU, NSTX,T-10	partial
MDC-5	Comparison of sawtooth control methods for neoclassical tearing mode suppression	AUG , DIII-D, JET, NSTX, TCV and HL2A, C-mod, FTU	partial
MDC-6	Low beta error field experiments	C-mod, TEXTOR, MAST, DIII-D, NSTX, JET(done)	partial
PEP-16	Small ELM regime comparison	NSTX, MAST, C-mod	partial
DIAG-1	Assessment of the effect of noise on vertical velocity measurement	JET, JT-60U, TCV, NSTX, AUG	partial
DIAG-2	Environmental tests on Diagnostic First Mirrors (FMs)	T-10, TEXTOR, Tore-Supra, JET, DIII-D, TCV, AUG, LHD, FTU, NSTX, C-mod, JT-60U	partial
MDC-4	Neoclassical tearing mode physics - aspect ratio comparison	AUG, MAST, NSTX, DIII-D	2007
TP-6.3	NBI-driven momentum transport study	DIII-D, JT-60U, NSTX, MAST, JET	2007
TP-9	H-mode aspect ratio comparison	NSTX, DIII-D, MAST,T-10	2007
PEP-10	The radial efflux at the mid-plane and the structure of ELMs	AUG, MAST, NSTX, C-mod	2007
PEP-13	Comparison of small ELM regimes in JT-60U and AUG and JET	AUG, JT-60U, JET, NSTX	2007
SSO-2.3	ρ* dependence on confinement, transport and stability in hybrid scenarios	DIII-D, JET, AUG, JT-60U, NSTX	2007

NSTX is Necessary for ST-CTF Option for the U.S.

- CTF is part of the DOE Strategic Plan.
- CTF is required to develop the engineering and technology basis for practical fusion energy.
- ST is very well suited for CTF mission.
  - Achieve 6 MW-yr/m^2 (= 20 x ITER) without exhausting world T supply.

R_0 = 1.2 m, a = 0.8 m, κ = 3.2,
I_p ~ 10 MA, $W_L \leq$ 2 MW/m^2,
Full Remote Maintainability



Each NSTX science area directly addresses CTF design issues:

- MHD - Steady-state β_T = 20-25%, f_{BT} = 50% discharges
- T&T - High confinement HH~ 1.3 for compact size
- Boundary - High heat flux and particle control
- W&EP - J(r) control, NBI, and α-particle (BP) physics
- SFSU- Solenoid-free start up required for compact size
- Integration -Consistent steady-state high performance scenarios

Y-K M. Peng et al., PPCF 2005

NSTX BUDGET OVERVIEW

	FY 04		FY 05		FY 06		FY 07		FY08	
	5YR	BA*	5YR	BA	5YR	BA	5YR	FWP	5YR	FWP
Run Weeks	21	20	21	17	21	11	21	12	21	10
Facility Operations	18.11 $(M)	17.03	18.35	17.94	19.02	17.63	19.73	18.2	20.46	18.4
Research Operations	9.95	10.09	10.09	9.78	10.47	9.37	10.85	9.8	11.25	9.9
Facility Upgrades	2.95	2.16	3.1	0.5	3.1	0.76	1.6	0.5	1.25	0.4
Diagnostic Upgrades	1.63	0.53	1.64	0.66	1.45	0.69	1.11	0.8		0.6
Collaboration interface	0.58	0.75	0.56	0.48	0.53	0.47	0.53	0.6	0.53	0.6
Collaborations	5.73	4.77	6.14	5.13	5.93	5	6.33	5.2	5.73	5.2
Total	38.95	35.33	39.87	34.49	40.5	33.92	40.15	35.1	39.22	35.1

* Budget Authority

- Very tight budget
- Priority given to run time
- Very limited upgrade budget compared to the 5 Year Plan
- Achieved excellent scientific productivity
- Contributed strongly to ITER as well as CTF relevant research areas

NSTX Facility Operated Safely and Productively

- ISM (Integrated Safety Management) culture helped to ensure personnel safety; Received the Continues Safety Excellence Award from NJ for having gone 5 consecutive years without an away from work lost time injury/illness case.
- Met 28 out of 29 FEAs milestones in FY 04, 05 and 06 on or ahead of schedule:
  - All 14 research milestone
  - All 8 facility milestones
  - 7 out of 8 diagnostic milestones*

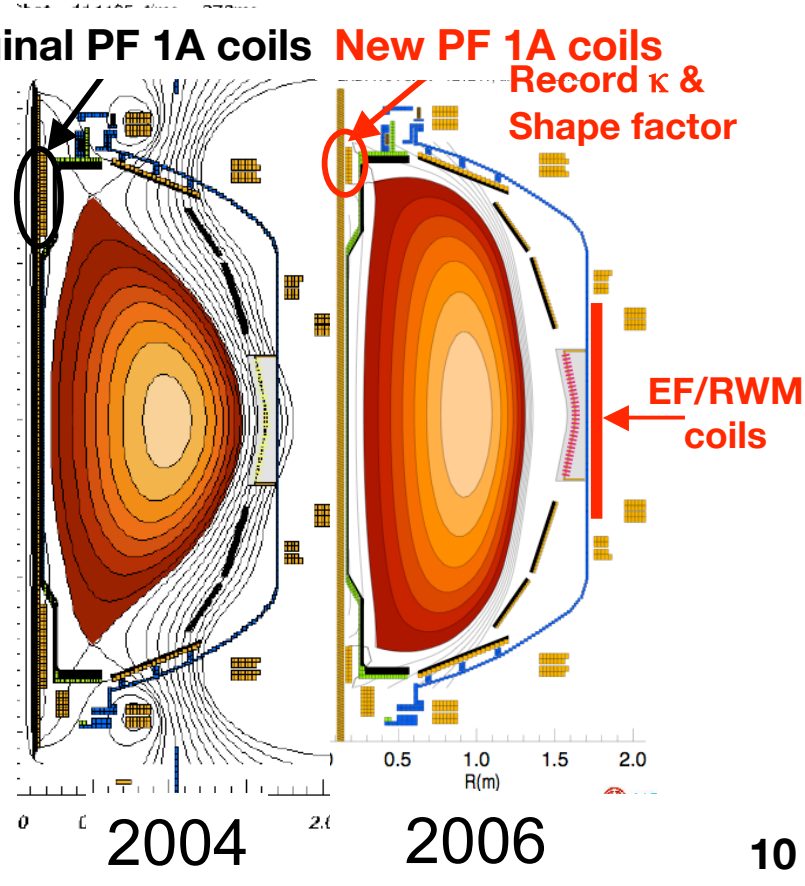
  *P-CHERS milestone was deferred in order to accelerate new PF 1A coil upgrade.
- High operational availability (~90%) maintained while ramping up the facility and diagnostic capability (and sophistication)
- Improved TF joints now performing very well at 5.5 kG in accordance with engineering design

NSTX Implemented Important Facility Upgrades with Small (~ 1/3) Budget Compared to 5 YR Plan

$(M)	FY 04	FY 05	FY 06	Total
5YR	2.95	3.1	3.1	9.15
BA	2.16	0.5	0.76	3.42

Implemented:

- **New PF 1A coils for high shaping and elongation**
- **Active EF/RWM feedback system for long-pulse high performance *(Columbia University)***
- **Real time plasma control with rtEFIT *(GA)***
- **Lithium pellet and evaporator for transient transport & particle control**
- **2 kV CHI capacitor bank for start-up *(Univ. Washington)***
- **Supersonic gas injector for improved fueling and other gas injectors for radiative divertor *(LLNL)***



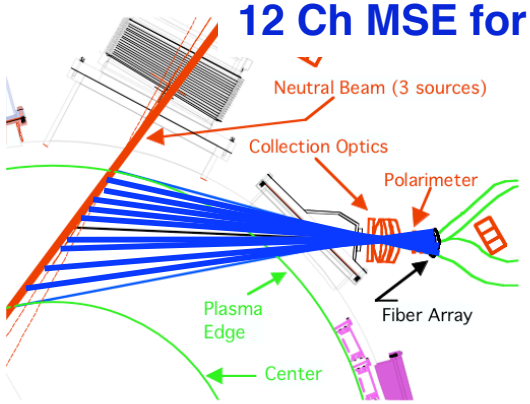
NSTX implemented important diagnostics upgrades with small (~ 1/3) budget compared to 5 YR Plan

$(M)	FY 04	FY 05	FY 06	Total
5YR	1.63	1.64	1.45	4.72
BA	0.53	0.66	0.69	1.88

Diagnostic Upgrades implemented:

- 12 channel MSE-CIF for j(r) *(Nova Photonoics)*
- 51 channel toroidal CHERS system for $T_i(r)$, $V_\phi(r)$
- Tangential high-k (electron-scale) turbulence scattering system for electron transport study *(UCD)*
- 20 -> 30 channels for MPTS for improved pedestal resolution
- Fast Te(r) soft x-ray diagnostics for perturbative transport study *(JHU)*
- Fast lost ion probes and solid state NPA for energetic particle transport *(UCI, JAEA)*
- Dual EBW scannable radiometer to assess EBW coupling *(ORNL)*
- Reflectometry for TAEs and HHFW for W&P study (UCLA, ORNL)
- Boundary diagnostics (Fast probe, IR cameras, divertor tile probs) *(UCSD, ORNL, LLNL)*

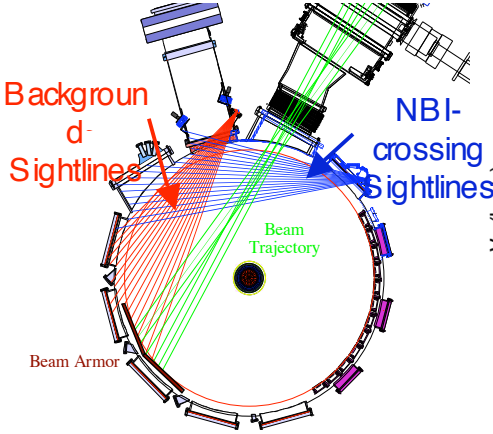
12 Ch MSE for q(r)



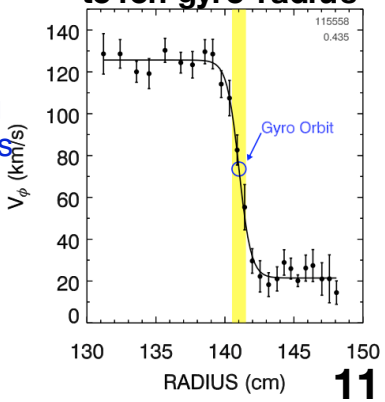
Innovative design enables MSE in kG range for the first time

Nova Photonics

51 Ch CHERS for $T_i(r)$, $V_\phi(r)$



Resolves structure to ion gyro-radius



For FY 07-08, NSTX Team plans to implement Highest Priority Facility Upgrades within Very Limited Resources

Budget $(M)	FY 04	FY 05	FY 06	FY 07	FY08	Total
5YR	2.95	3.1	3.1	1.6	1.25	12
BA/FWP	2.16	0.5	0.76	0.5	0.4	4.32

NSTX Facility Upgrade Plan for FY 07 - 08: Focus few crucial facility upgrades to be available in for the 2008 run in partnership among NSTX collaborating institutions

- **Medium power EBW/ECH system using existing ORNL equipment for EBW heating demonstration, heating CHI plasma to ~ 100 eV, and PF-only start-up.**
- **Liquid lithium divertor module for density control of long-pulse high performance advanced plasma scenarios**
- **Manufacture an OH spare in cost effective manner in collaboration with ASIPP, China. OH is identified as a critical spare in our 5 YR Plan (an agreement in place)**
- **Upgrade processors on real time plasma control system (being prepared for 07 run)**

NSTX Facility Upgrades for FY 09 and beyond
- **High power (1 - 4 MW) EBW heating and current drive system for j(r) control**
- **Advanced fueling / cryo-panel**
- **HHFW antenna upgrade for higher power and improved spectrum**

Medium power EBW/ECH upgrade

- Implement ~100 - 200 kW (15.3 - 28 GHz) EBW/ECH system for 2008 utilizing the existing ORNL equipment and the PPPL NBI power supply which can support 1.2 MW
  - Start EBW heating experiment
  - Heat CHI start-up plasma to ~ 50 - 100 eV enabling HHFW heating and CD
  - Assist PF-only start-up research

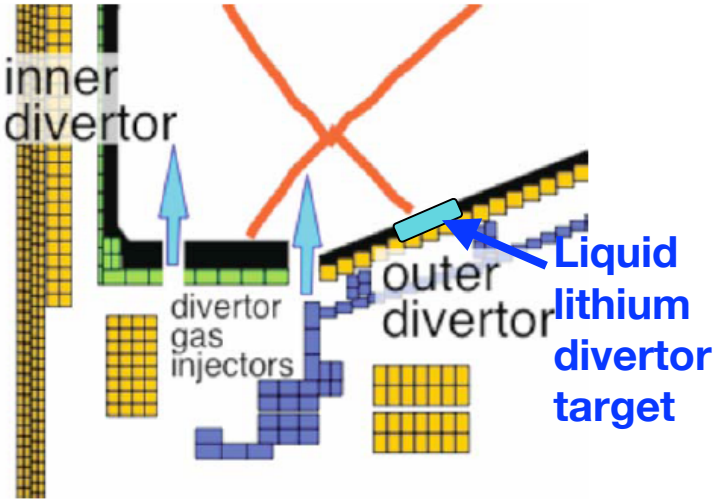
EBW/ECH Gyrotron source specification

- 28 GHz (4 ea.)
  - –200 kW CW (80 kV, 7A)
  - –350 kW pulsed ~ 500 ms (80 kV, 12A)
- TE02 output; high mode purity
- FC-75 cooled window

- EBW/ECH upgrade may be feasible with priority shift within NSTX and through collaborations
- Continue to work with MAST and PEGASUS on EBW Physics

Unique Lithium Particle Control Tool Development

- Lithium pellet injection reduced oxygen and particle recycling 2005
- Lithium evaporation implemented in 2006 reduced oxygen and particle recycling in 2006.
- Liquid lithium divertor target for long-pulse high performance discharge control.



Based on the NSTX LITER results and other lithium experiments (CDX-U, T-11), in order to achieve most effective particle control for long-pulse high performance advanced plasmas, a liquid lithium divertor target is needed.

• The liquid lithium divertor target could replace one row of graphite tile with metal based (mesh or porous) material. R is only ~ 60 cm so the effort may not be extensive.

- **Design and R&D in FY 07**
- **Installation in FY 08 to be ready for the 2008 -2009 run.**
- **Collaboration is crucial for timely implementation.**

For FY 07-08, NSTX Team plans to implement highest priority Diagnostic Upgrades within limited resources

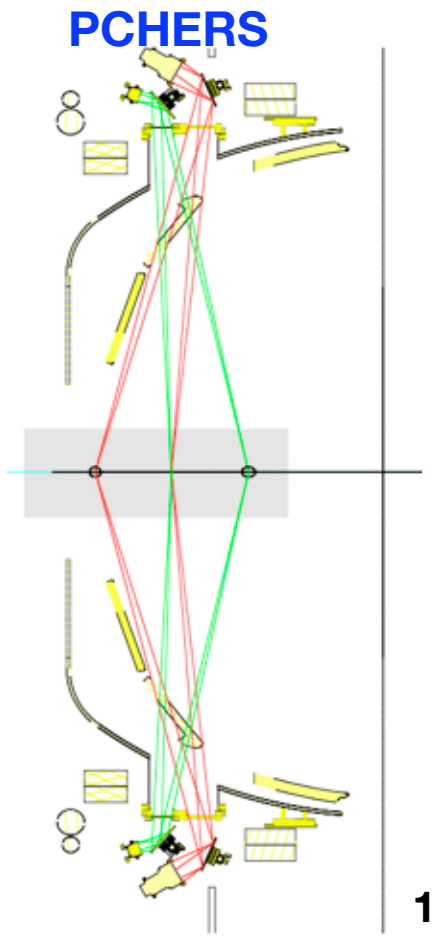
Budget $(M)	FY 04	FY 05	FY 06	FY 07	FY08	Total
5YR	1.63	1.64	1.45	1.11		5.83
BA/FWP	0.53	0.66	0.69	0.8	0.6	3.28

NSTX Diagnostic Plan for 2007-008:

- Install Poloidal CHERS for transport physics (pedestal/ITB-ITPA)
- Work with collaborators to enable upgrade diagnostics to maximize physics output.
  - MSE-CIF from 12 ch to 19 ch *(Nova Photonics)*
  - Fast x-ray Te(r) diagnostic *(Johns Hopkins)*
  - Microwave backscattering, radial polarimeter *(UCLA)*
  - FIReTIP at 2 MHz (UCD)
  - Dynamo edge fast probe (UCSD)
  - Fast-ion D_α (FIDA) diagnostic using PCHERS ports (UCI)

NSTX Diagnostic Upgrades for FY 09 and beyond

- *Advanced turbulence diagnostic*
- *Boundary diagnostics (fast IR cameras, spectroscopy, div.TS, div.bolometers)*
- *Additional laser and 30 -> 40 channels for MPTS*



NSTX Team Achieved High Research Productivity

- Highly experienced research team responsible for exploiting the scientific opportunities by taking advantage of
  - New unique plasma regimes and
  - New tools and sophisticated diagnostics

NSTX Refereed Journal Publication Record for 2004 - 2006

Calendar Years	04	05	06
# published	56	39	47(+12 submitted)

Productive and diversified team:

- 52 invited papers at major [APS, IAEA, EPS] and topical meetings (HTPD, RF, PSI)
- 4 PRLs this year on ITER-relevant key research topics (RWM, Momentum transport, Multi-energetic particle modes, MHD driven fast particle transport)
- 27 post-docs and students
- Presidential Young Investigator Award based on NSTX MHD research
- 38 APS Fellows

With World-Leading Capabilities, NSTX Contributes Strongly to the US and World Fusion Programs

- NSTX carried out the 5 Year Plan through effective operations and facility/diagnostic upgrades within the budget constraints; 4 PRLs this year in ITER-relevant key research areas
- NSTX facility capability addressed important issues for both ITER
- NSTX team contributed strongly to ITPA
- NSTX is developing unique tools

- Made strong progress toward 5 Year Goal within budget constraint
- Adapted very effectively to programmatic changes (e.g. ITER)
- Optimized plan to make strong progress toward 5 Year Goal