NSTX

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Mission Need for NSTX Center-Stack (CS) and Neutral Beam Injector (NBI) Upgrades

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Princeton Plasma Physics Laboratory (PPPL)

December 3, 2008

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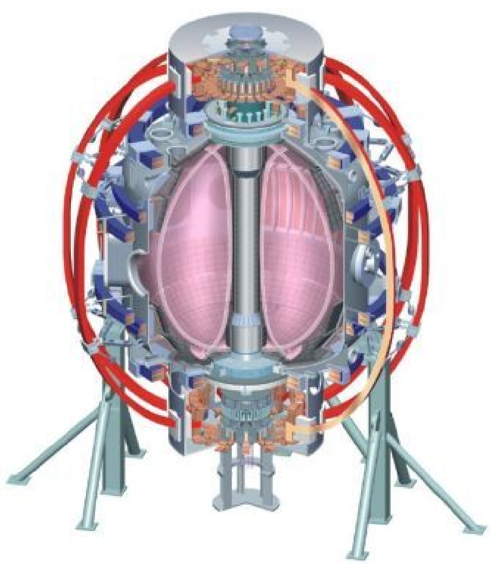

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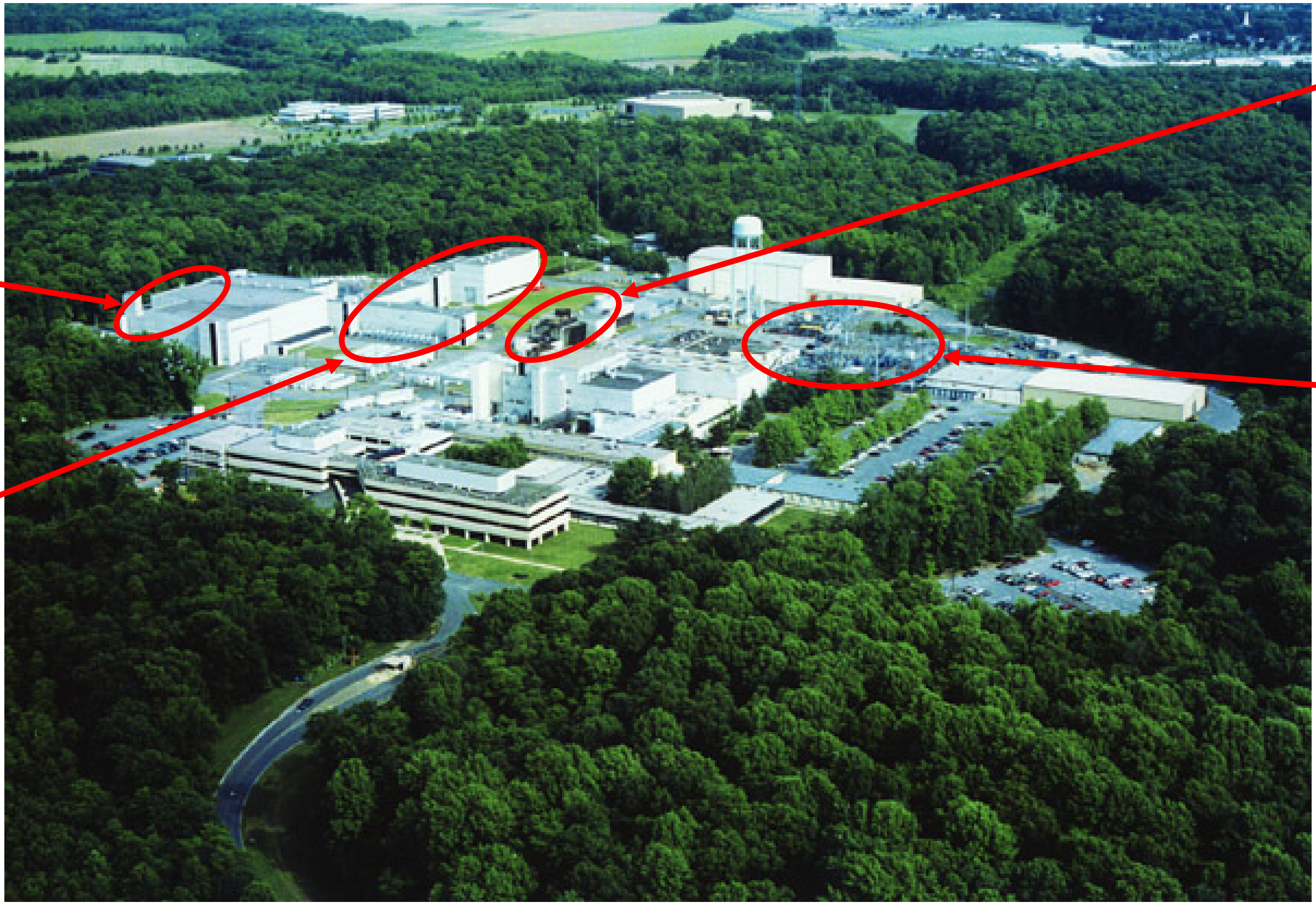
Princeton Plasma Physics Laboratory

Collaborative vision: "Deepening the understanding of plasmas and creating key innovations to make fusion power a practical reality"

- 88 acres, total budget = $80M, 421 employees
- Largest Fusion Energy Sciences research center in U.S.



NSTX Test Cell

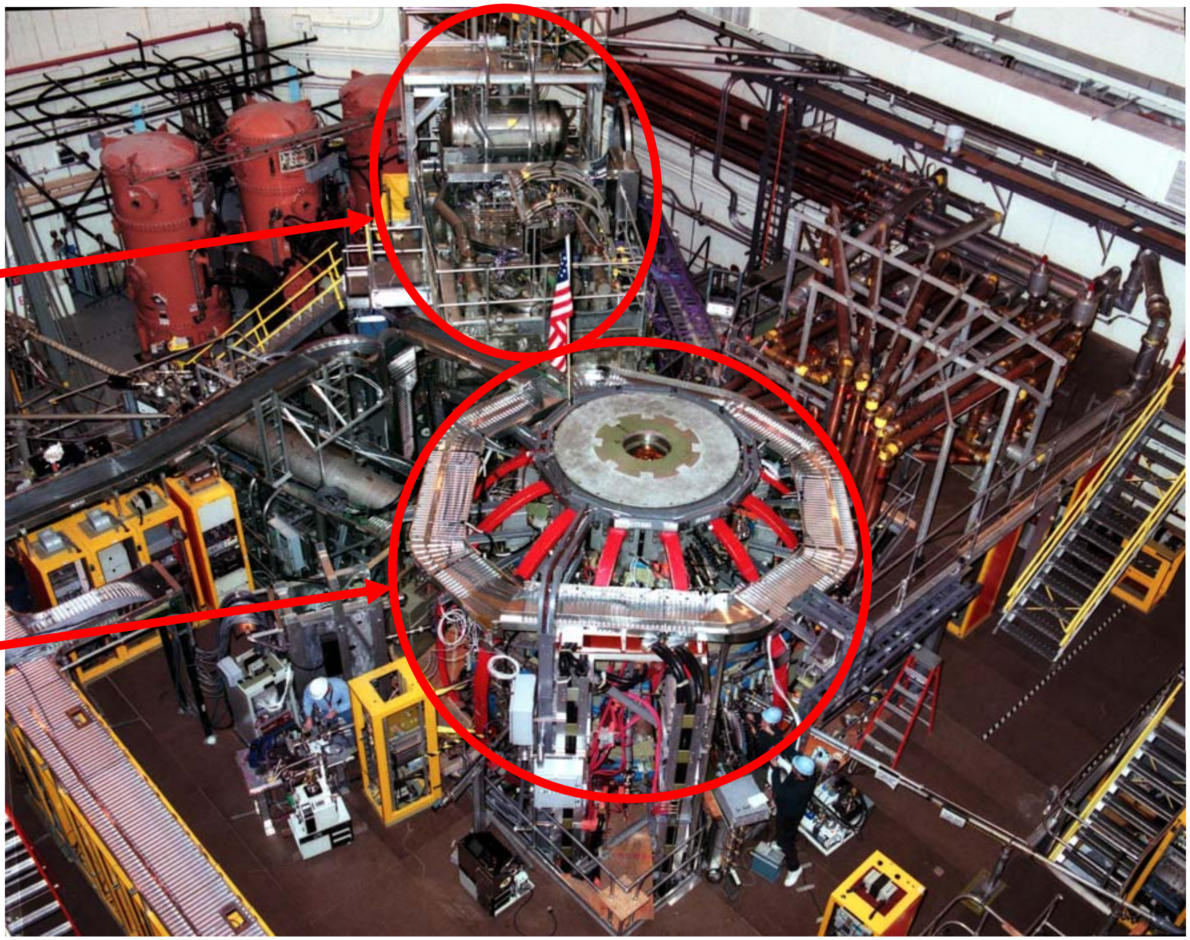
NSTX Power Supplies

NSTX Cooling Towers

PPPL AC Power

NSTX is the most capable Spherical Torus (ST) in the world and is the core of the PPPL experimental research program

- NSTX/PPPL budget = $40M
- 59 PPPL/PU researchers, 91 from 22 other US institutions, 45 international



Neutral Beam Injector

NSTX Device

NSTX first-plasma achieved in 1999

Extensive and novel plasma diagnostics

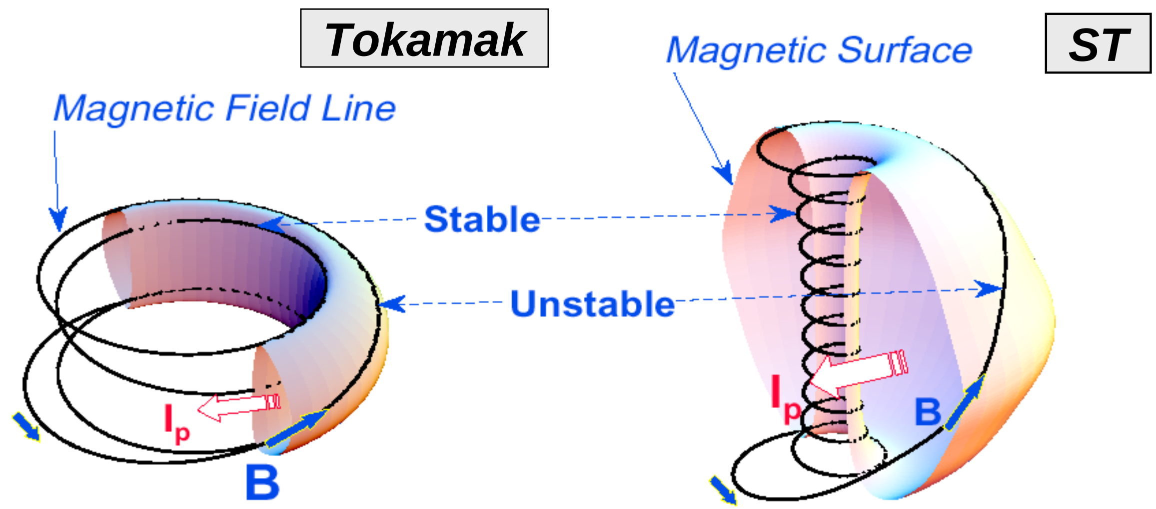
Baseline Parameters:

Major Radius 0.86 m
Minor Radius 0.66 m
Elongation 1.8 – 3.0
Triangularity 0.2 – 0.8
Plasma Current
1 MA ($t > \tau$-skin)
Toroidal Field
0.35 – 0.55 T
Heating and CD
7 MW NBI (2 sec)
5 MW NBI (5 sec)
6 MW HHFW (5 sec)
0.2 MA CHI
Pulse Length
~ 1 sec at 0.55 T
~ 2 sec at 0.38 T

A Spherical Torus (ST) is a low aspect ratio, high-β Tokamak

Aspect Ratio A = R /a
(plasma average major radius / plasma half-width)

$\beta_T = \langle p \rangle / (B_{T0}^2 / 2\mu_0)$
(ratio of kinetic pressure to magnetic pressure)



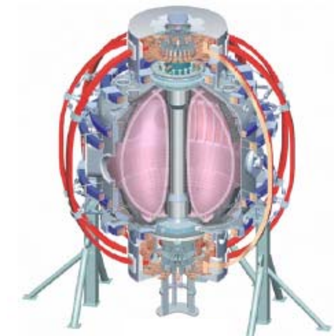
R/a~3-4, κ=1.5-2, q_a=3-4, β_T=3-10%   R/a~1.5, κ=2-3, q_a=8-12, β_T=10-40%

- **New physics regimes are accessed at low aspect ratio, enhancing the understanding of toroidal confinement physics:**
  - Lower A → increased toroidicity → higher β
  - Higher β → electromagnetic effects in turbulence
  - Higher fraction of trapped particles, increased normalized orbit size, plasma flow, and flow shear → broad range of effects on transport and stability
  - Increased normalized fast-ion speed → simulate fast-ion transport/losses of ITER
  - Compact geometry → high power/particle/neutron flux relevant to ITER, reactors

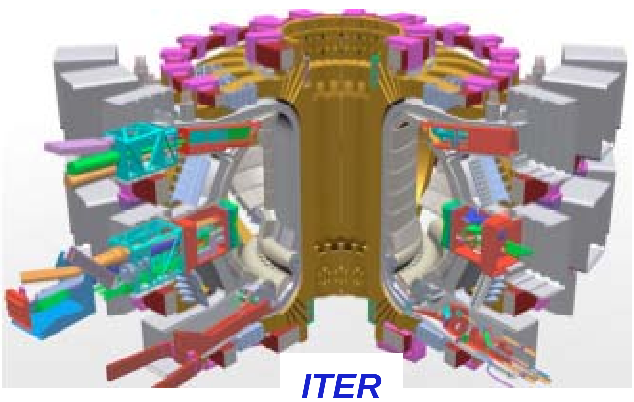
NSTX advances toroidal plasma science and burning plasma physics, and provides attractive near-term fusion options

NSTX Mission Elements:

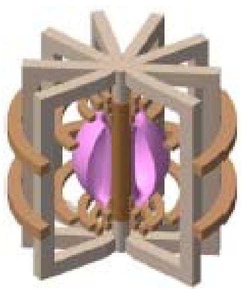
- Understand unique physics properties of ST
  - Assess impact of low A, high β, high v_{fast} / v_A, etc. on all aspects of toroidal plasma science
- Complement tokamak physics, support ITER
  - Exploit unique ST features to improve tokamak understanding, while also benefiting from tokamak R&D
- Establish 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



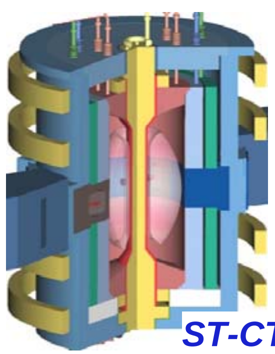
NSTX



ITER



NHTX

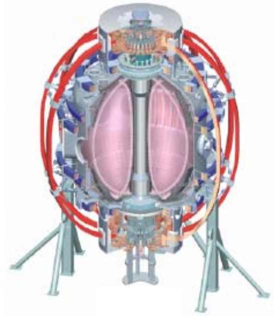


ST-CTF

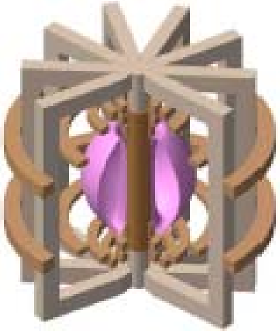
Pre-conceptual designs

NSTX Upgrades will prepare the U.S. to address FESAC Priorities, Gaps, and Opportunities

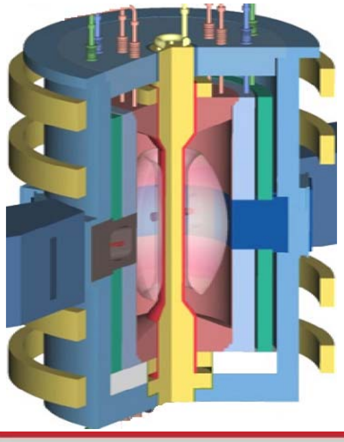
- NSTX:
  - Providing foundation for understanding ST physics and performance
- Upgraded NSTX:
  - Study high beta plasmas at reduced collisionality – important for further understanding confinement, stability, start-up, current drive
  - Assess full non-inductive current drive operation – needed for 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



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

"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

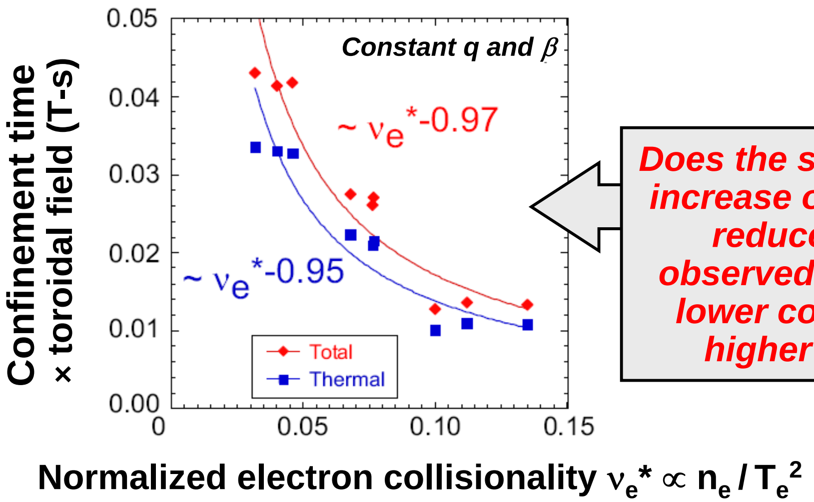
2. **First-Wall Heat Flux:** What strategies can be employed for handling normal and off normal heat flux consistent with core and scrape-off-layer operating conditions?
   – NSTX goal: assess high flux expansion, detached divertors, liquid metals

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

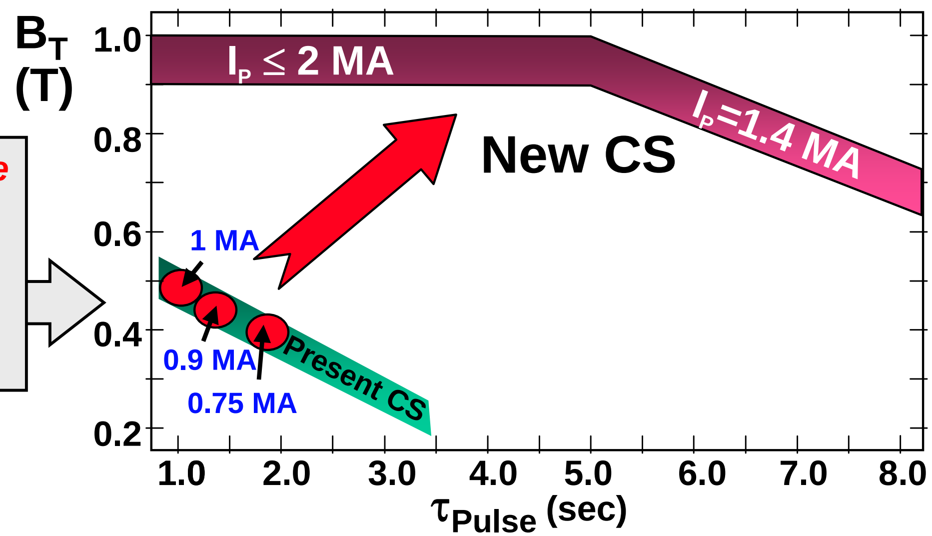
4. **Magnets:** Can we develop reliable center-post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?
   – NSTX goal: develop and utilize higher performance toroidal field magnet

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), $t_{flat-top}$ = 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

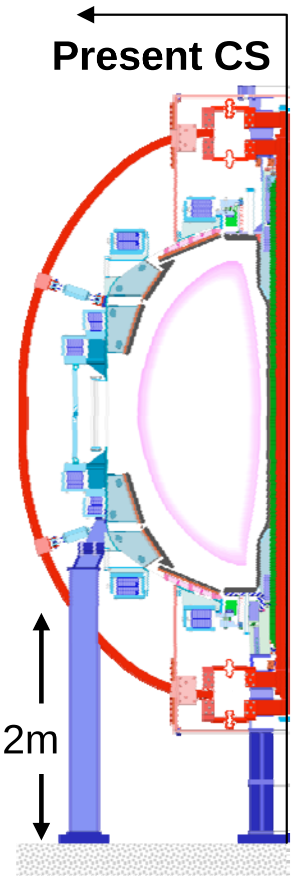


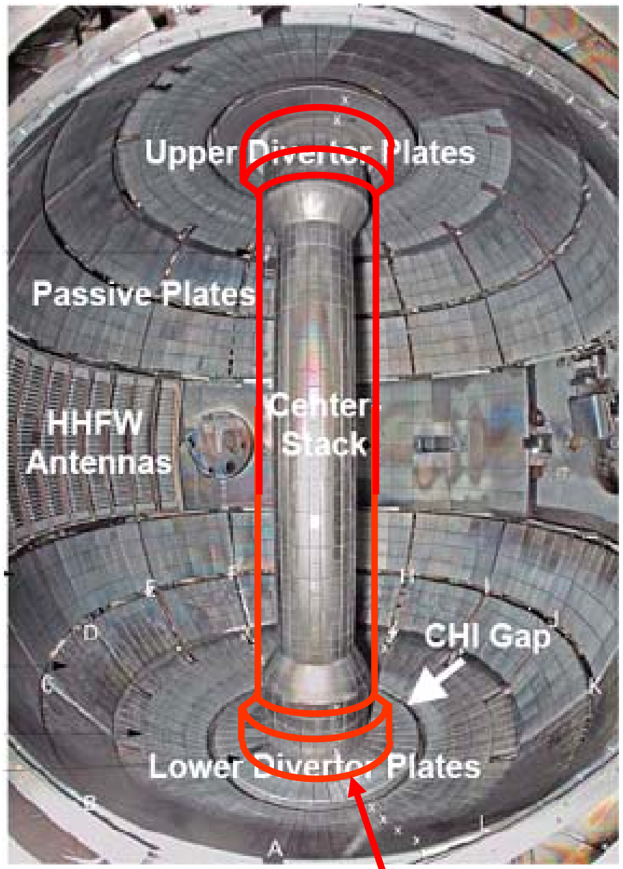
Does the strong and favorable increase of confinement with reduced collisionality observed in NSTX persist at lower collisionality and/or higher magnetic field?

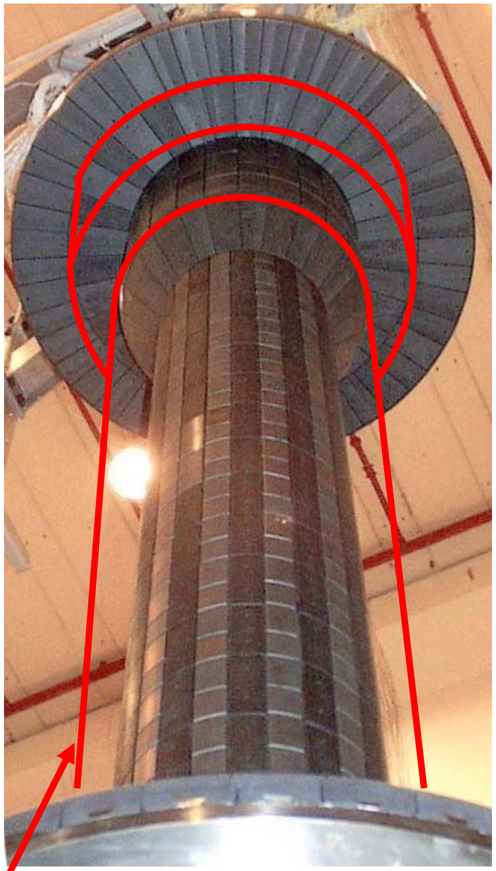


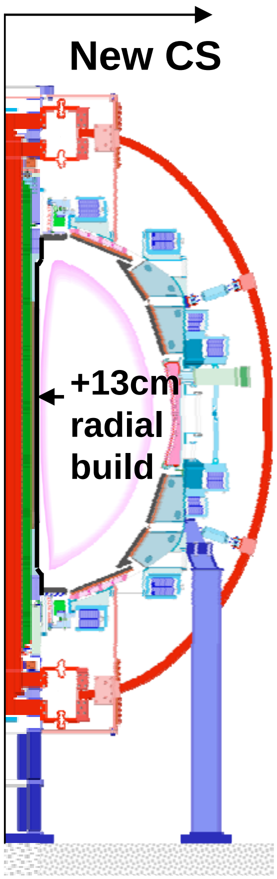
Modular design of NSTX enables removal of present CS and replacement with a new higher-performance CS

- Present CS has been removed and re-installed several times for maintenance and modifications
- New CS would have larger radius for increased conductor area and toroidal field current, while maintaining low aspect ratio A ≥ 1.5
- Construction tolerance requirements are similar to present NSTX CS





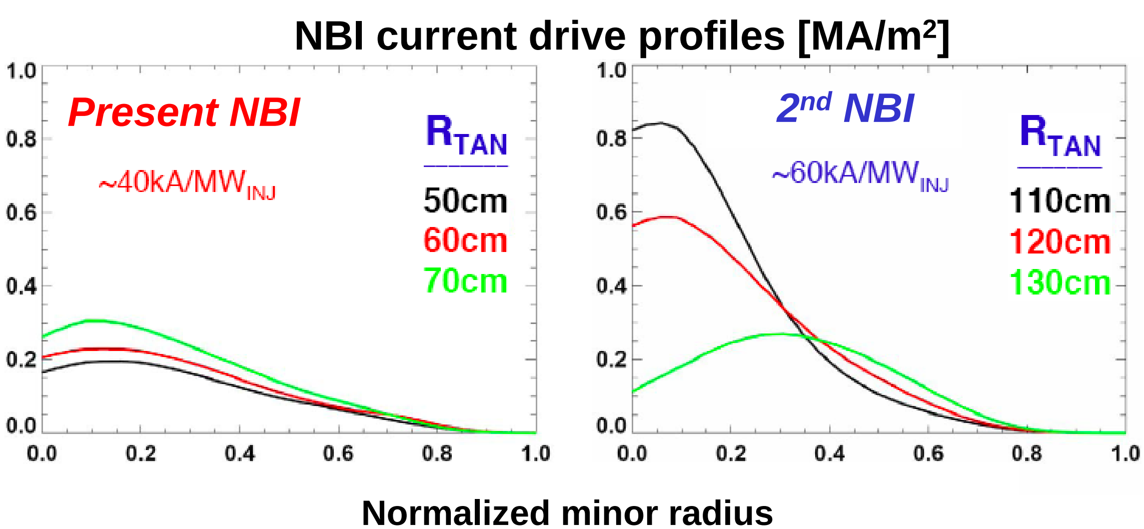


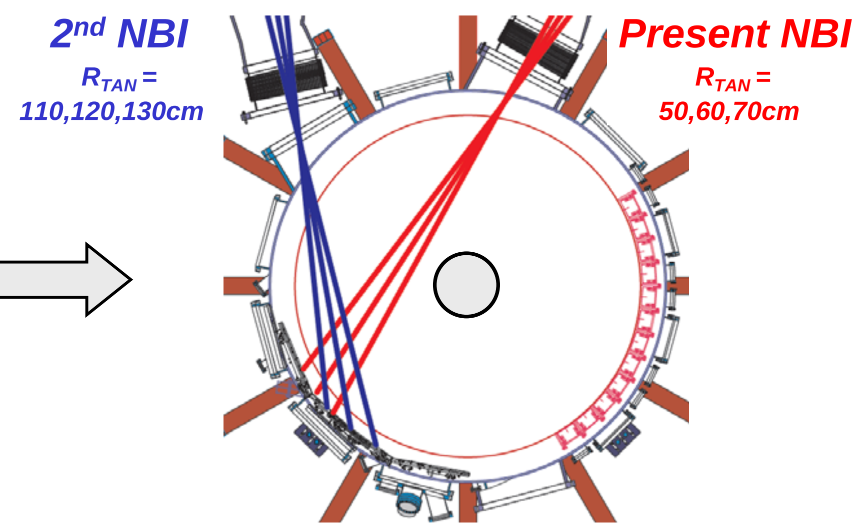


Approximate outline of new Center-Stack

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

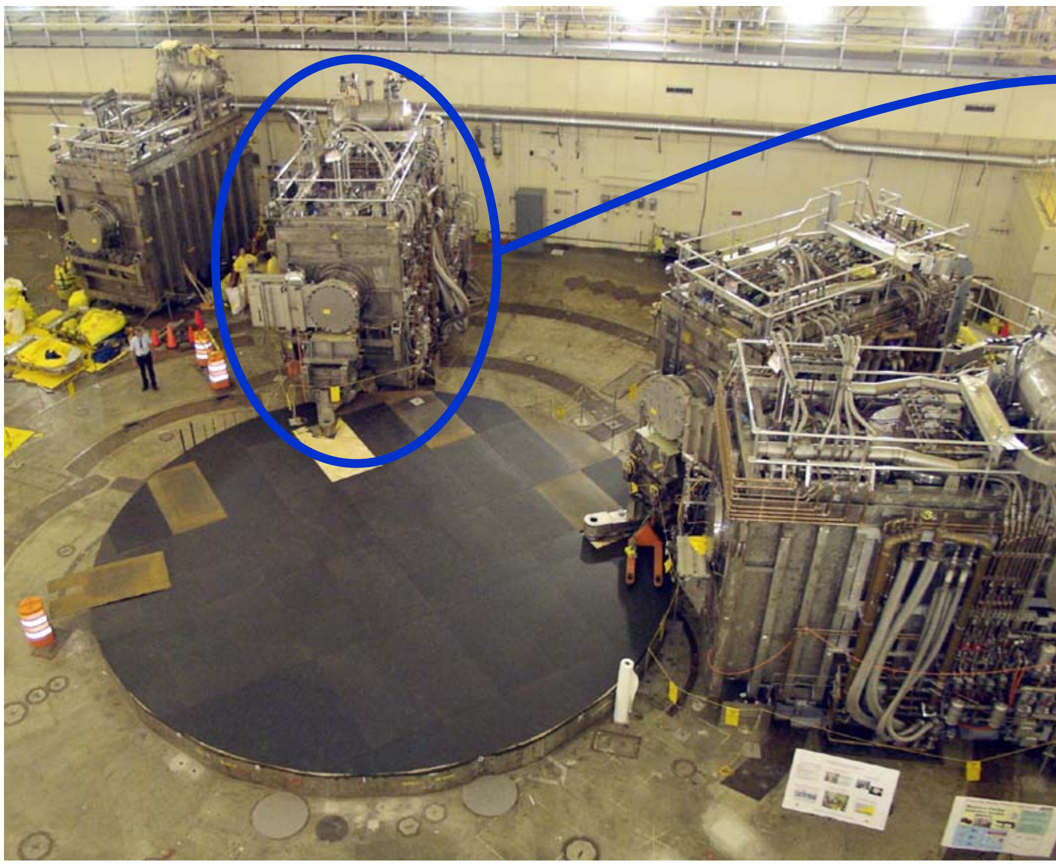
- More tangential 2nd NBI would provide:
  - Up to 2 times higher current-drive efficiency, and current profile control
  - Tests of NBI ramp-up to ~1MA
  - World-leading capabilities for plasma boundary physics at high heat flux
  - Increased heating power to access very high β at low collisionality – 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 $f(v_{||},v_{\perp})$



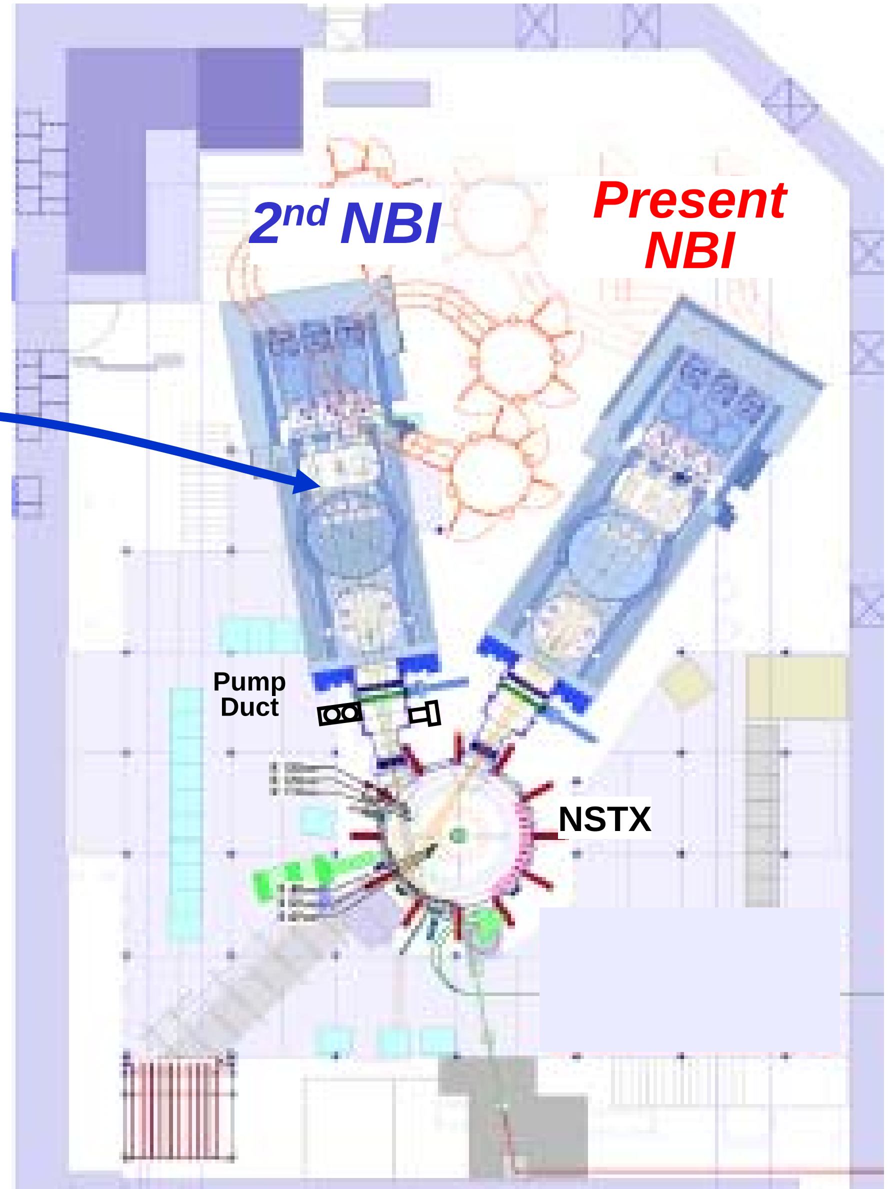


An NBI heating system available from TFTR could be moved to the NSTX test cell and installed next to the present NBI

- PPPL has extensive experience operating, maintaining, refurbishing NBI
- NBI is well understood and has provided reliable heating to high β values in NSTX



TFTR test cell

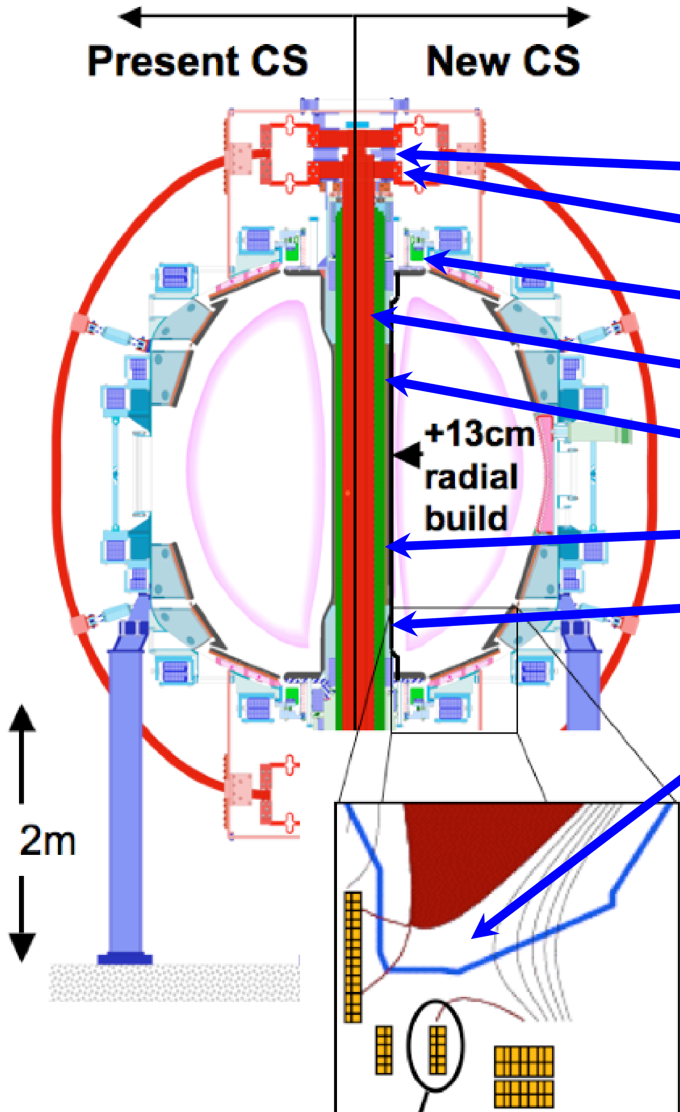


NSTX test cell

Center-stack and NBI upgrades would enable NSTX to maintain world leadership in ST research

- CS and NBI upgrades directly address key scientific gaps identified in recent FESAC toroidal alternates panel report
  - Start-up/ramp-up/sustainment, boundary physics, e-transport, magnets
- Strongly endorsed by NSTX Program Advisory Committee
  - "…the second neutral beam line would be extremely valuable for achievement of the FY2013 long-term performance target, and will likely be required for high-performance discharges created at the high field…"
- Strongly endorsed by NSTX 5 Year Plan Review Panel:
  - "These improvements will significantly expand the operational space for NSTX and provide plasma conditions that are very important to ST development, for example lower collisionality. This upgrade should be installed as soon as possible."
  - "The second neutral beam source will provide increased heating to take advantage of the higher field and current provided by the CS upgrade."

Center Stack Upgrade Scope - 1



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

- Design, Build and Install New CS Assembly including:
  - New TF Hub Assembly
  - New TF Flag Assemblies
  - New Ceramic Break
  - New Inner TF Bundle
  - New Ohmic Heating Coil
  - New Inconel Casing & Insulation
  - New PFC Tiles
  - New Poloidal Field 1a, b & c Coils
- R&D Activities to support above work
  - TF electrical joint testing
  - OH braze joint testing

Center Stack Upgrade Scope - 2

- Design, Build, and Install:
  - Reinforcement to existing coil structures to handle increased magnetic loads
    - Umbrella Structure
    - Outer TF Legs & Possibly Vacuum Vessel
  - PF/TF/OH Lead Bus Connections
- Repair leaks and upgrade the existing cooling water system to cool the outer TF coil legs separately from the inner
- Replace Center Stack Diagnostics
- Power Feed Upgrades
  - Upgrade TF power supply to support full field capability of ~1T. (At ~1T, ~2.5s flattop every 20 min and up to ~5 s every 40 min)
    - Existing cables will be reconnected for TF use. Thus there will be a total of 8 cables per pole for TF.

Estimating Process Description

- The original NSTX construction costs (‘97-’99) were used where possible as a starting point.
  - The original material costs were scaled to account for larger sizes
  - Material costs and current labor rates were escalated for inflation
- For items that did not exist in the original design, comparisons were made to work that had similar characteristics and then scaled up using engineering judgment to account for the size
  - Engineering experience was used to determine material quantities
- The estimates were peer reviewed by non-NSTX PPPL engineers with experience in related disciplines and similar projects and adjusted where needed

Technical Risks

Risk	Plans to Retire
Outer TF Legs have coolant leaks and are currently dry because of defects in the coolant tubes. The tubes need to be repaired or coolant passage redesigned to provide cooling in support of higher TF currents.	Estimate includes budget to implement alternate coil cooling approach if needed Plan to expedite investigation and repair options early in design to preserve range of options.
Reinforcement of the outer TF Legs and Umbrella Structure to handle the higher loads will be challenging to retrofit on an operational device	Early analysis planned to characterize new loads. Design and consultation with outside structural engineer.
The ability to find a cost effective TF Joint that works at the higher fields	Early analysis planned to guide new design. Consultation with MIT engineers (similar design experience) planned for design input.

2nd Beam-Line Upgrade Work Scope

- Decontaminate and prepare a TFTR beam-line (NBL) for installation on NSTX. Evaluate and refurbish internal components as necessary (cryogenic panels, beam dumps, bending magnets, beam scrapers, calorimeter, etc):
  - Assume replacement of all beam impinged copper surfaces
  - Assume replacement of all thermocouples and cabling

- Relocate the NBL and provide a second set of beam-line services (power, water, vacuum, cryogenics). Design will need to consider space constraints in the test cell, mechanical equipment room, penetrations, etc.
  - Procure Turbo-Molecular Pumps
  - Fabricate a new NBL support stand

2nd Beam-Line Upgrade Work Scope - 2

- Design, analysis and fabrication of a NBL to Torus Nozzle Assembly. Modify the Bay K port to accommodate the desired beam tangency radius.
  - Procure new Bellows, Torus Isolation Valves

- Neutral Beam Ion Sources used on TFTR to be refurbished and used on NSTX NBL#2 as is now done in support of the existing NBL#1.

- Design and install tiled, water cooled armor plating in the NSTX torus to protect in-vessel beam impinged surfaces.

2nd Beam-Line Upgrade Work Scope - 3

- High Voltage power supplies and NB controls to be routed to the NSTX Test Cell, and High Voltage Enclosures/ Transmission Lines installed and re-commissioned.
  - Perform pre-operational testing of all sub-systems, and integrated system testing leading to NBL cool-down and ion source power testing per procedures established for NBL#1.

- Relocate the NSTX vacuum vessel pumping duct, vacuum control systems, gas injection systems, and diagnostic systems displaced by the addition of the new NBI system.

Estimating Process Description

- The upgrade for a 2nd NBI system on NSTX is largely similar to the 1st NBI project which was completed on cost/schedule.
  - Original NBI project costs corrected for inflation and current labor rates

- Estimates for NEW scope associated with the use of a tritium contaminated NBL taken from TFTR were developed through a combined effort of engineers from both the neutral beam group and the successful TFTR D&D project (also completed on schedule and under budget).

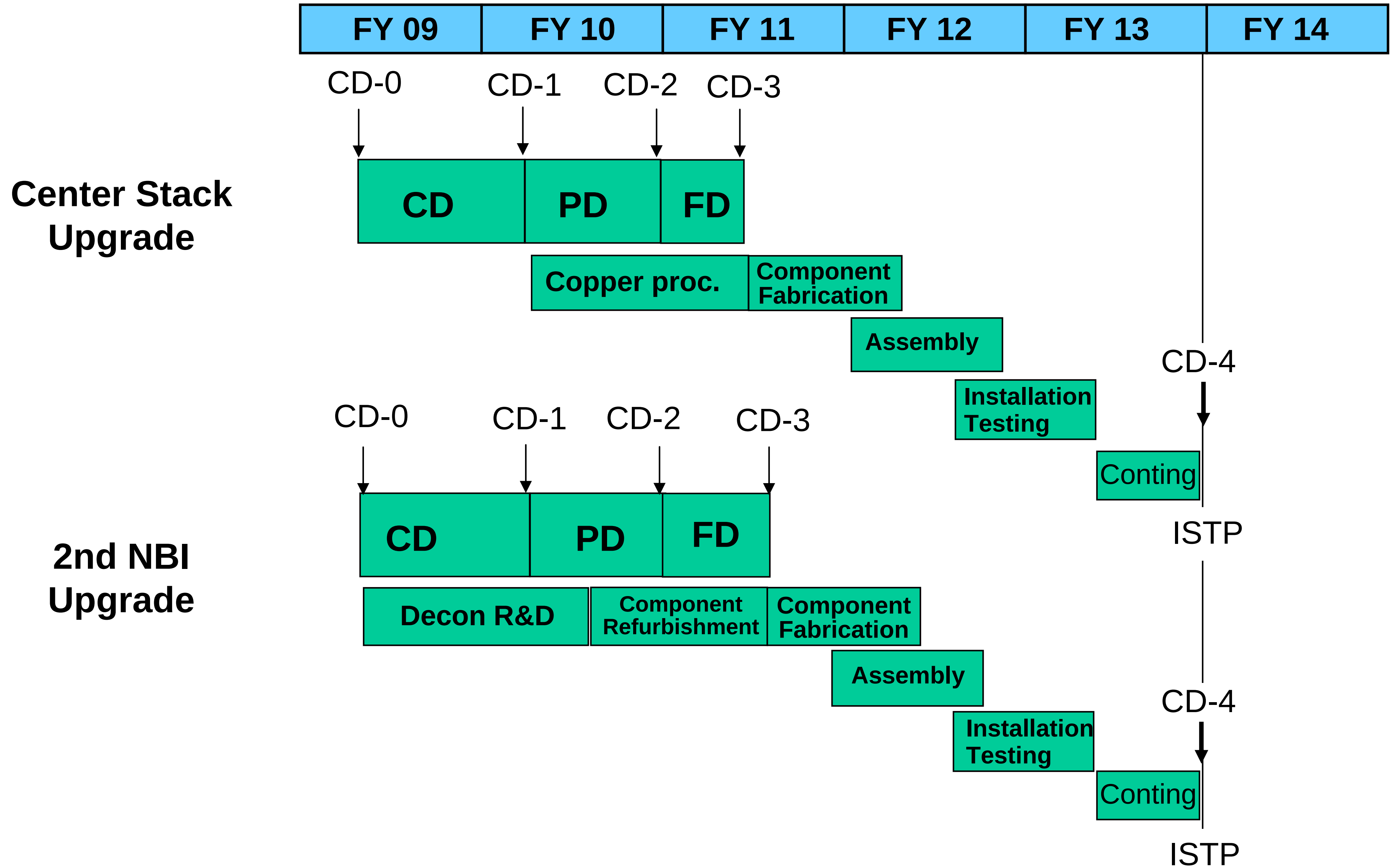
- Estimates for the relocation of non-NB equipment displace by this upgrade (vacuum pumping duct, vacuum & gas systems, diagnostics) are based on repeating the original installations costs

- All estimates were peer reviewed by PPPL engineers with experience in related disciplines and adjusted where needed

Technical Risks

Risk	Plans to Retire
The TFTR NBLs were operating very well in tritium when taken out of service in 1997. Uncertain of present condition of the NBL internals and levels of tritium contamination. Also uncertain of level of effort to decontaminate.	The R&D on decontamination can be initiated in the early stages of the project. Decon techniques well tested during the TFTR D&D project. Considerable experience at PPPL restoring NBL internals.
Uncertainty in the commercial availability of High Voltage Switch-Tubes, cabling and terminations for the 100kV Accelerator System.	Spares currently available on-site Working with vendors and exploring other design options.

CS and NBI Projects can be Completed in FY 13
Without Funding Constraints for FY 10 and beyond



Keeping the NSTX Research Team Productive During Extended Outage Period

- NSTX CS and NBI upgrades represent up to an order of magnitude improvement in NSTX plasma performance (e.g., nτT, collisionality.)
- Extended outages have occurred during major fusion facility change-over:
  - Alcator C → C-Mod (~ 6 years), TFTR → NSTX (~3 years).
- NSTX envisions one to three year outage period depending on the scenarios. For PPPL NSTX researchers:
  - One year outage (CS-only case): Data analysis and preparation for next run.
  - Two - three year outage: Researchers collaborate on domestic (e.g., DIII-D and C-Mod) and overseas facilities (e.g., MAST, KSTAR, EAST, and JET)
- NSTX Research Collaboration (1/3 of research effort on NSTX) will require coordinated planning with OFES and collaborating groups.
  - NSTX collaborators could continue to improve and upgrade their equipment, and DOE could enable them to collaborate elsewhere along with PPPL NSTX staff.

Center-stack and NBI upgrades would enable NSTX to maintain world leadership in ST research

- **NSTX Upgrades would make major contributions to**
  - **Fundamental toroidal physics for fusion, including ITER**
  - **ST science supporting priorities identified by FESAC**

- **Cost ranges have been developed for both new CS and 2nd NBI.**
  - **Experienced managers have been identified**
  - **NCSX Lessons Learned incorporated in plan**

- **Upgrades can be completed in FY 13 with optimized funding, in FY 14 with guidance budget.**

Recommendation: Proceed with CD-0 for both New CS and 2nd NBI, allowing better definition of cost ranges by the time of CD-1.

Backup Slides

Applying NCSX Lessons Learned to NSTX - 1

- Complete requisite R&D and designs prior to establishing a baseline.
  - Conceptual design (including external review) will be completed by CD-1
  - Preliminary design (including external review) and necessary R&D (TF/OH joints and NB decon) will be completed by CD-2
- Implement rigorous, disciplined, and realistic cost estimating techniques early on.
  - Designs and cost estimates will be reviewed at the WBS level by internal and external experts
  - External experts will review the proposals for CD-1 and CD-2
- Conduct regular bottoms-up Estimates To Complete (ETC) to identify and address cost and schedule issues.
  - ETCs will be validated by the job engineers on a monthly basis
  - Bottoms-up ETCs will be developed for the entire project(s) every six months

Applying NCSX Lessons Learned to NSTX - 2

- Develop and execute an effective risk management plan early on.
  - The use of formal risk and opportunity assessment techniques, based on a risk register and analysis of the tasks at the appropriate WBS level will be introduced early in the project cycles
  - Adequate priority will be placed on reducing risks
- Develop, maintain, and execute a staffing plan.
  - The projects will develop and maintain staffing plans early on identifying critical individuals by name
  - NSTX operations personnel are ideally suited for upgrade activities
- Recognize the cost and schedule implications of using high technology tools at or near their capability limits.
  - These projects will utilize well tested conventional technology and tools

Applying NCSX Lessons Learned to NSTX - 3

- Develop strong ties with external resources in key technology areas, including those outside of your area of expertise.
  - The conceptual, preliminary, final design and other review team members will include experts in key technology areas from universities, industry and DOE national laboratories
  - Don Rej, who has completed his assignment on NCSX and has returned to LANL, will provide valuable expertise and mentoring to both project managers and PPPL management on a continuing basis
- Build a strong, effective project management organization early.
  - The NSTX CS Upgrade Project Manager has decades of engineering management experience and has been working on the fabrication/upgrades on NSTX since the construction of NSTX facilities in 1997. The Engineering Integration Manager is also the NSTX Project Engineer and he has been organizing the engineering effort on NSTX since inception of the NSTX Project in 1996.
  - The NSTX 2nd NBI Project Manager has decades of engineering management experience and in particular on the NBI systems on TFTR and NSTX. The NSTX NBI Engineering Manager was in charge of the first NSTX NBI construction and operations since 2000.
- Communicate and act.
  - Issues will be communicated with all stakeholders (particularly PSO and OFES) as soon as they develop
  - The projects will schedule quarterly reviews with the NSTX DOE-PSO Federal Project Director and OFES
  - The Project Managers will prepare formal quarterly project reports to PSO and OFES