NSTX-U

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NSTX Upgrade Project Status, Facility/Diagnostic Progress and Plans

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for the NSTX-U Team

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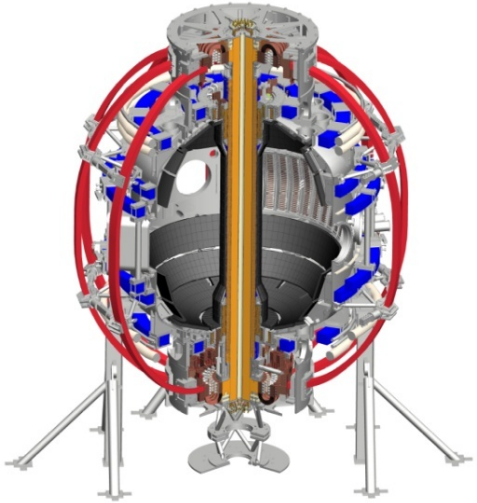
NSTX-U PAC 35
June 11-13, 2014



Talk Outline

- **NSTX Upgrade Project Update**
- **NSTX-U Facility-Diagnostic Status and Plan**
- **FY2014-16 Facility-Diagnostic Plan**
- **Summary**

NSTX Upgrade Project Progress Overview

R. Strykowsky, E. Perry, T. Stevenson, L. Dudek, S. Langish, T. Egebo, M. Williams and the NSTX-U Team

New Center Stack Project Scope

- ✓ Inner TF bundle
- ✓ TF Flex bus
- • OH coil
- • Inner PF coils

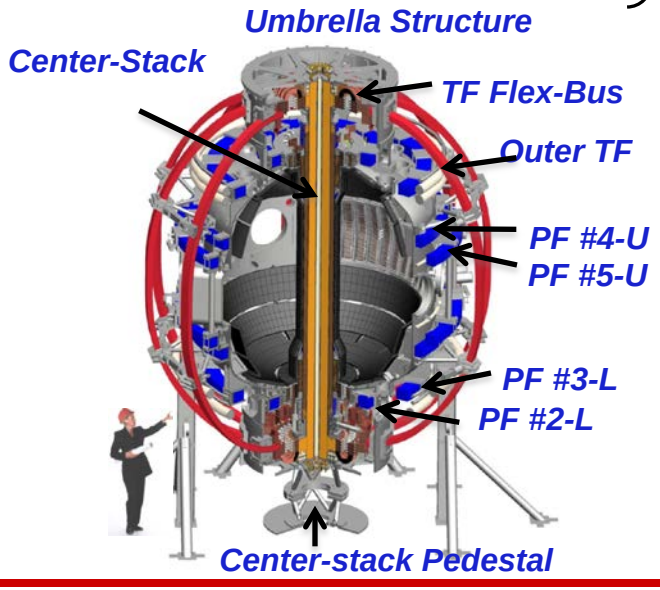
Center stack

- ✓ Enhance outer TF supports
- ✓ Enhance PF supports
- ✓ Reinforce umbrella structure
- • New umbrella lids

Structure

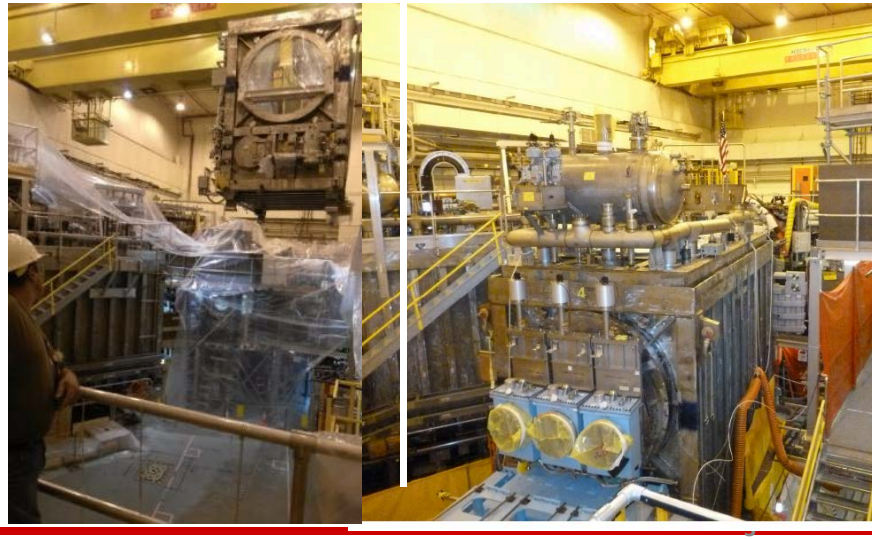
- • Power systems
- • I&C, Services, Coil protection

Ancillary Sys



2nd NBI Project Scope

- ✓ Decontaminate TFTR beamline
- ✓ Refurbish for reuse
- ✓ Relocate pump duct, 22 racks and numerous diagnostics to make room in the NSTX Test Cell
- ✓ Install new port on vacuum vessel to accommodate NB2
- ✓ Move NB2 to the NSTX Test Cell
- • Install power, water, cryo and controls

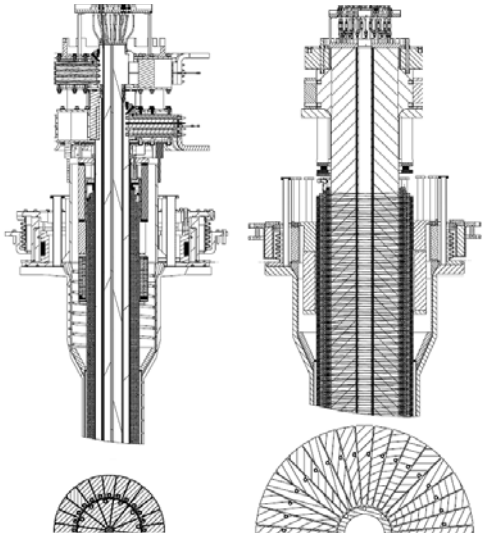


Substantial Increase in NSTX-U Device / Plasma Performance

To provide data base to support ST-FNSF designs and ITER operations

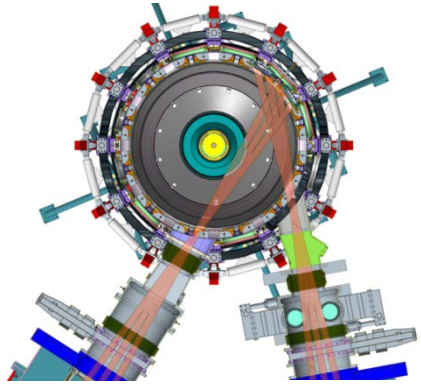
Previous center-stack

New center-stack



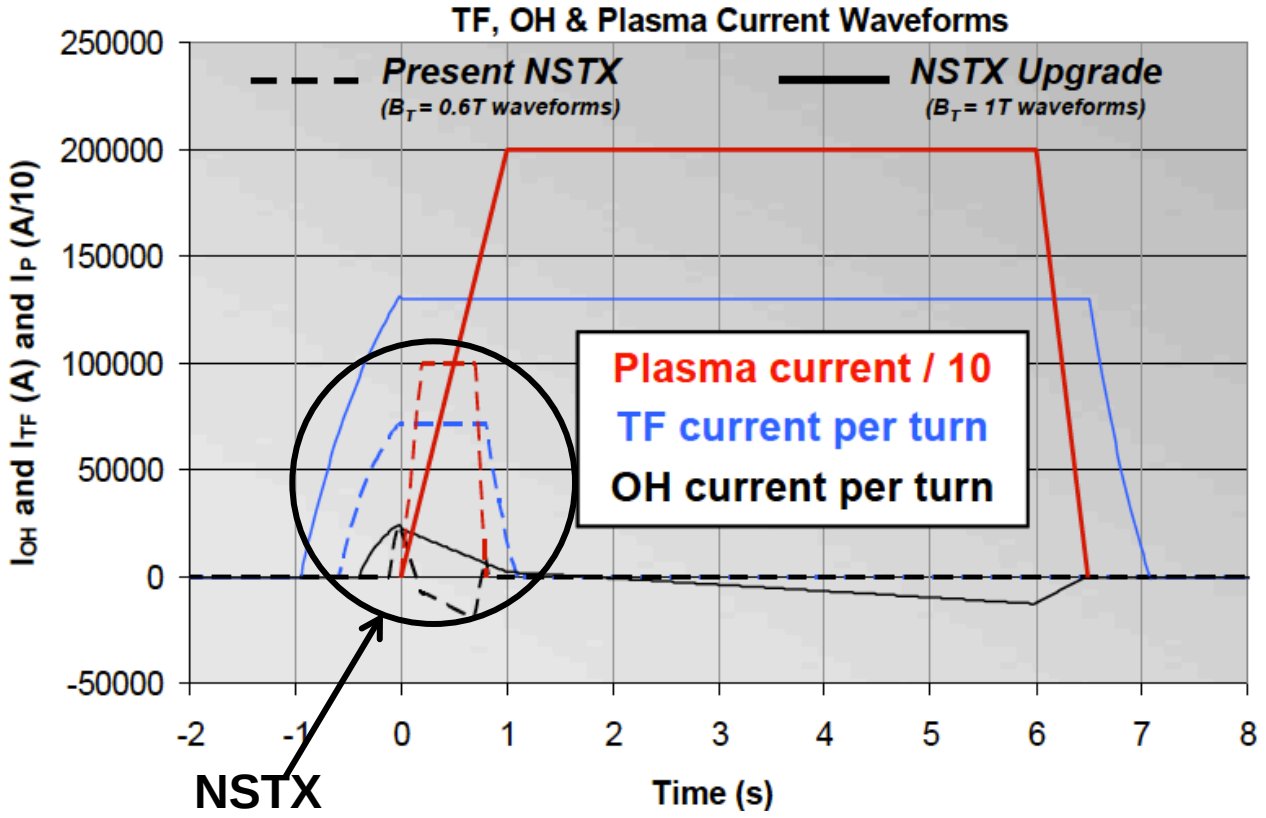
TF OD = 20cm

TF OD = 40cm



Present NBI

New 2nd NBI



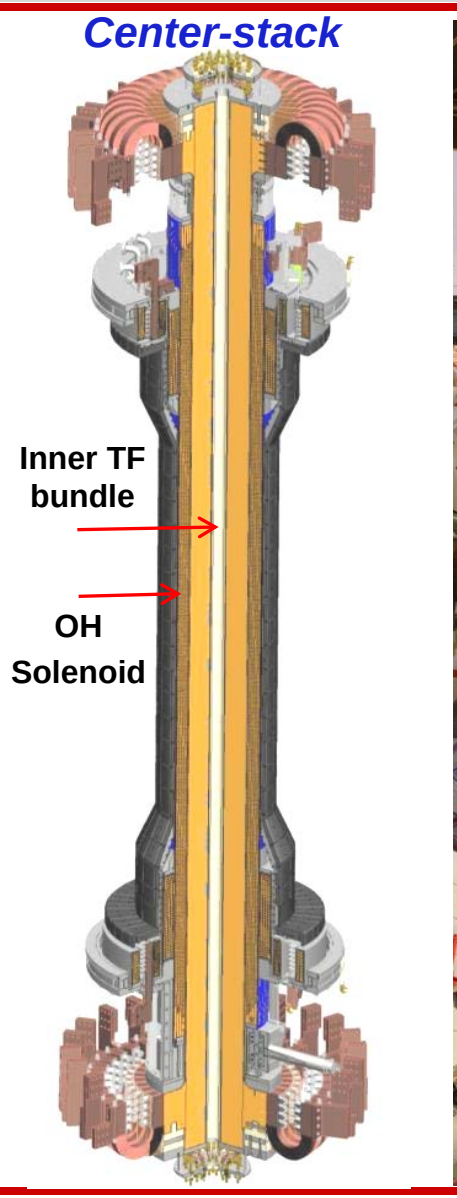
	R_0 (m)	A_{min}	I_p(MA)	B_T (T)	T_{TF}(s)	R_{CS} (m)	R_{OB} (m)	OH flux (Wb)
NSTX	0.854	1.28	1	0.55	1	0.185	1.574	0.75
NSTX-U	0.934	1.5	2	1	6.5	0.315	1.574	2.1

~ X 5-10 increase in $n\tau T$ from NSTX

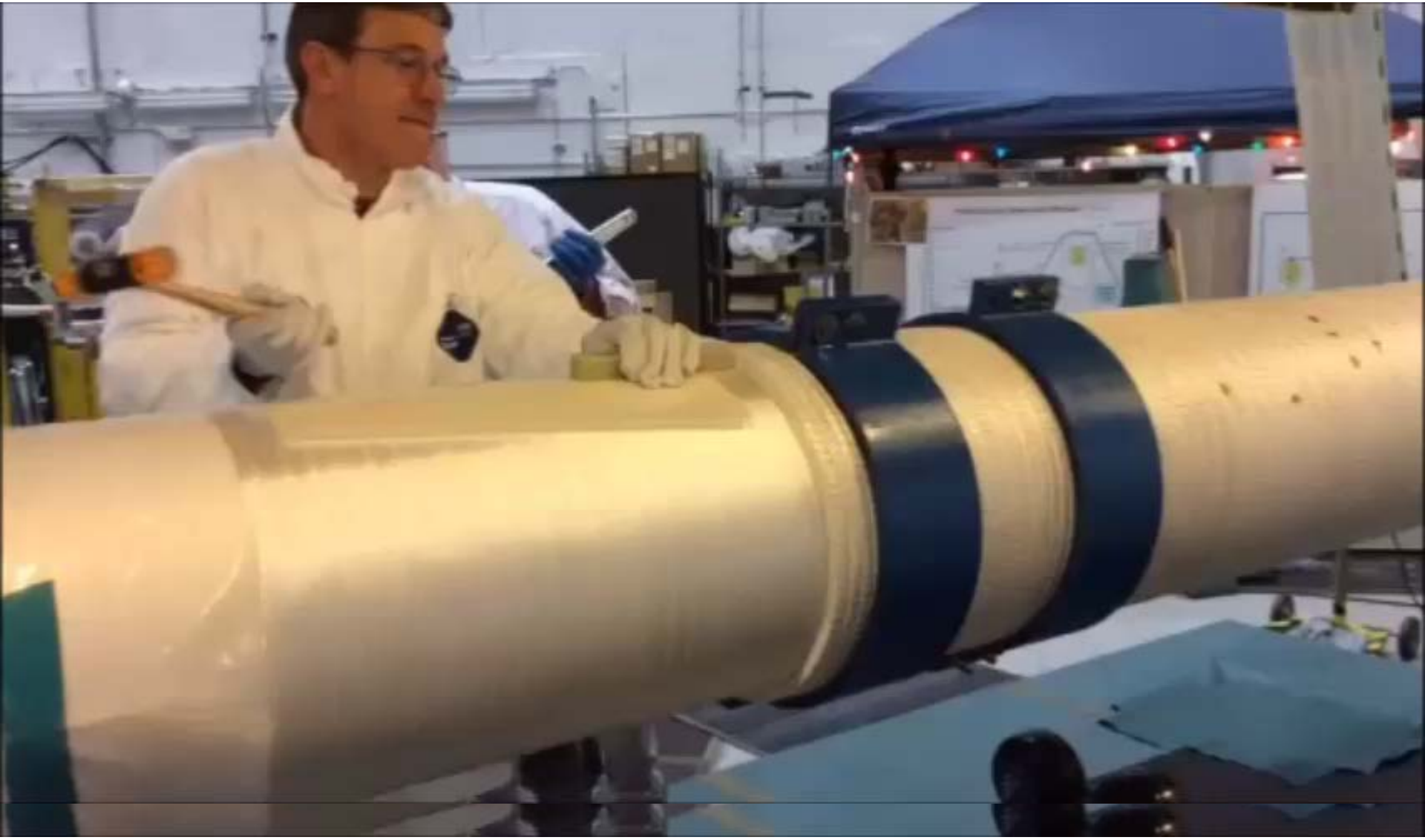
NSTX-U average plasma pressure $\propto B_{T0}^2 \beta_T (T^2\%)$ ~ tokamaks

OH Coil Winding Complete

OH Coil VPI being readied



A movie of OH coil winding..

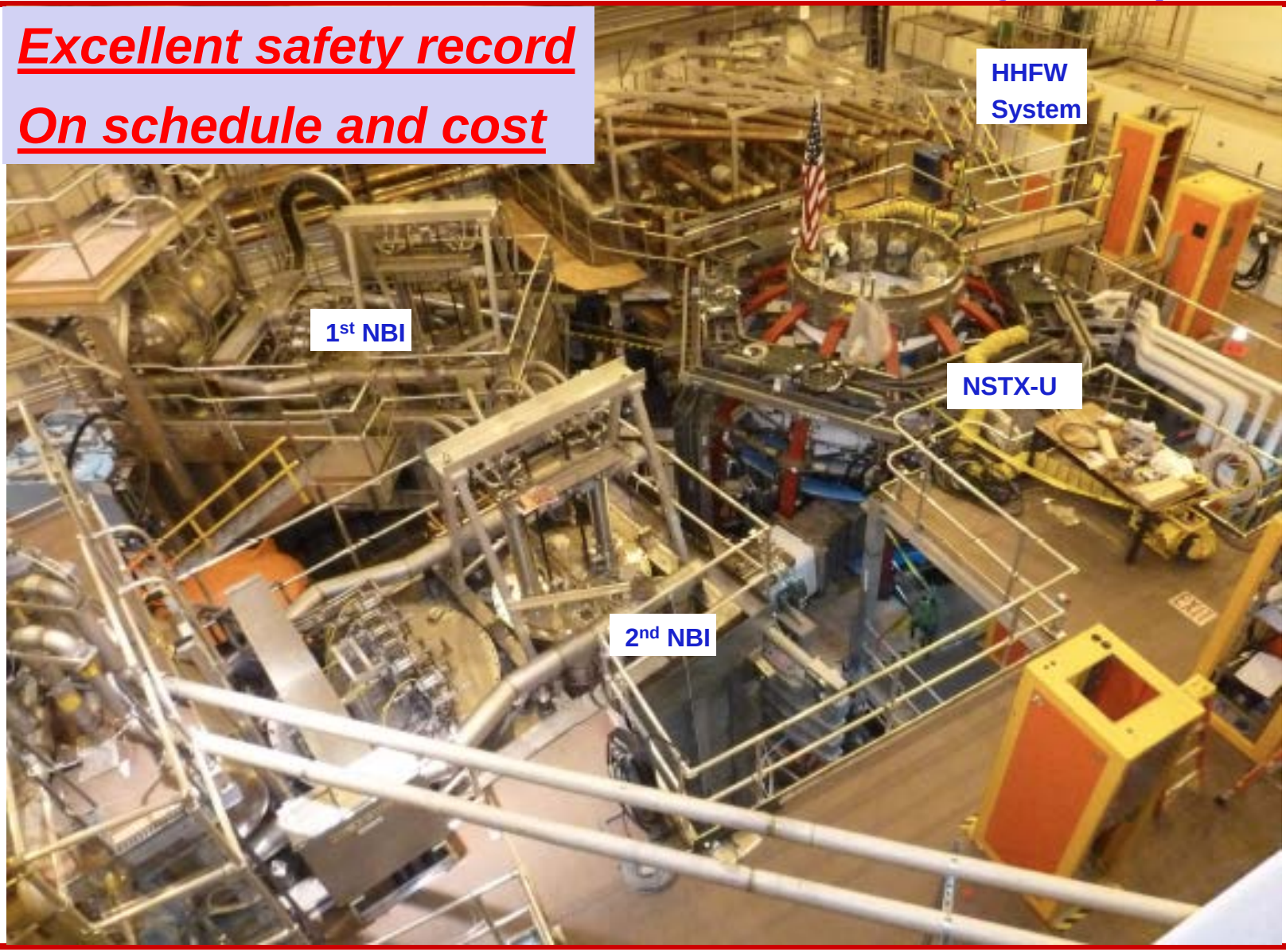


NSTX-U Test Cell Aerial View (May, 2014)

2nd NBI and Structural Enhancement Nearly Complete

Excellent safety record

On schedule and cost

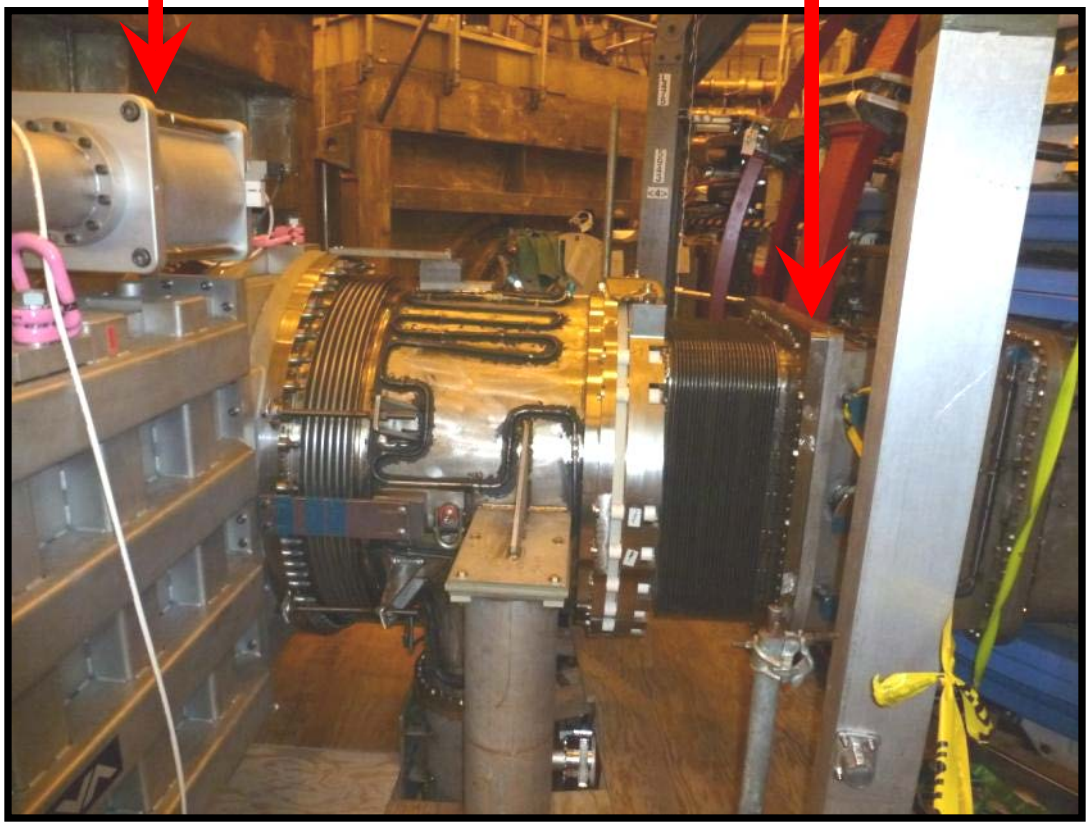


Final 2nd NBI Components being Installed

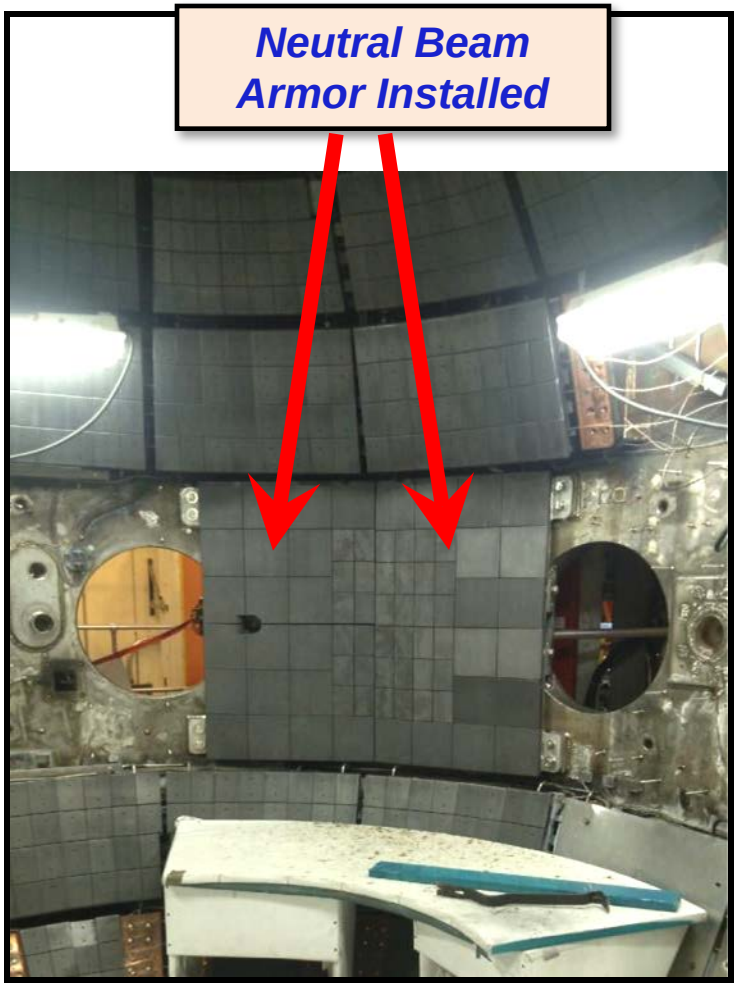
2nd NBI duct with pumping section and NBI armor installed

Neutral Beam & TIV valve

Vacuum Vessel Bay J/K port



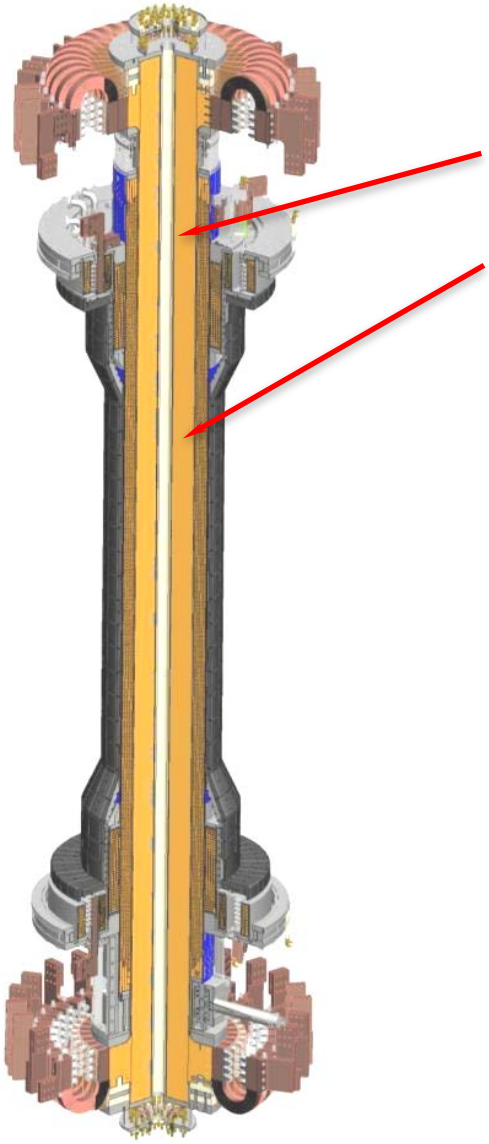
Neutral Beam Armor Installed



Source installation planned for June

Upgrade Project Scope ~ 86% complete

with 27% contingency on work remaining



Centerstack Is on the Critical Path

- **Components & Hardware**
- **Inner TF Bundle**
- **OH Solenoid**
  - OH solenoid winding
  - VPI OH – ***June 2014***
- **Centerstack Assembly-**
  - Delivery to NSTX TC - ***August 2014***
- **Install Centerstack -** ***September 2014***
- **Readiness review -** ***September 2014***
- **Pumpdown -** ***November 2014***
- **ISTP -** ***December 2014***
- **CD-4 -** ***January 2015***

NSTX-U diagnostics to be installed during first 2 years

Diagnostics presently being installed prior to the center-stack installation

MHD/Magnetics/Reconstruction

- Magnetics for equilibrium reconstruction
- *Halo current detectors*
- *High-n and high-frequency Mirnov arrays*
- Locked-mode detectors
- RWM sensors

Profile Diagnostics

- MPTS (42 ch, 60 Hz)
- T-CHERS: $T_i(R)$, $V_\phi(r)$, $n_C(R)$, $n_{Li}(R)$, (51 ch)
- P-CHERS: $V_\theta(r)$ (71 ch)
- *MSE-CIF (18 ch)*
- *MSE-LIF (20 ch)*
- *ME-SXR (40 ch)*
- Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics

- *Poloidal Microwave high-k scattering*
- *Beam Emission Spectroscopy (48 ch)*
- Microwave Reflectometer,
- *Microwave Polarimeter*
- Ultra-soft x-ray arrays – multi-color

Energetic Particle Diagnostics

- *Fast Ion D_α profile measurement (perp + tang)*
- Solid-State neutral particle analyzer
- Fast lost-ion probe (energy/pitch angle resolving)
- Neutron measurements

Edge Divertor Physics

- Gas-puff Imaging (500kHz)
- Langmuir probe array
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- *1-D CCD H_α cameras (divertor, midplane)*
- *2-D divertor fast visible camera*
- Metal foil divertor bolometer
- AXUV-based Divertor Bolometer
- IR cameras (30Hz) (3)
- *Fast IR camera (two color)*
- Tile temperature thermocouple array
- *Divertor fast eroding thermocouple*
- Dust detector
- Edge Deposition Monitors
- Scrape-off layer reflectometer
- Edge neutral pressure gauges
- *Material Analysis and Particle Probe*
- *Divertor VUV Spectrometer*

Plasma Monitoring

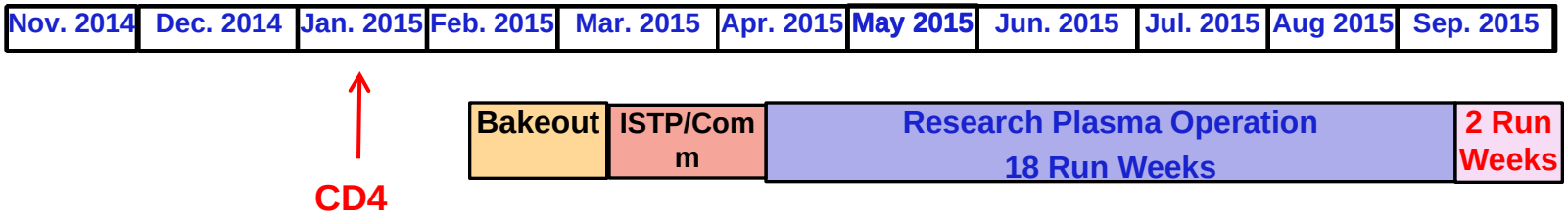
- FIReTIP interferometer
- Fast visible cameras
- Visible bremsstrahlung radiometer
- *Visible and UV survey spectrometers*
- *VUV transmission grating spectrometer*
- *Visible filterscopes (hydrogen & impurity lines)*
- Wall coupon analysis

New capability, Enhanced capability

Aiming for Extended Research Operation in FY15

Research operation preparation on going in parallel with Upgrade Project

Run Plan for FY 2015



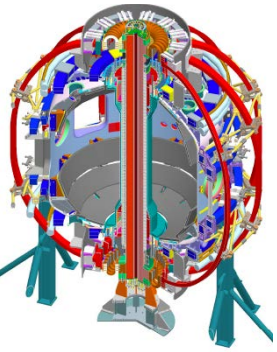
- **CD-4 in January should allow scheduling of the research campaign up to 20 run weeks (Base – 18 run weeks and Incremental – 2 run weeks).**
- **The run assumes three weeks operation and one maintenance weeks. Some extended run weeks for the latter part of operation.**
- **~ 3 month period is allocated between CD-4 and the research plasma operation. More details in S. Gerhardt's talk.**
- **The Upgrade team is exploring ways to bring the CD-4 schedule earlier by increasing the resources available.**

10 Year Facility Plan Targets Research Goals

1.1 × (FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Upgrade Outage	1.5 → 2 MA, 1s → 5s				Metallic PFCs, 5s → 10-20s				
Run Weeks:	20	16	16	20	22	6	18	22	22

New center-stack



2nd NBI

Start-up and Ramp-up
- Upgraded CHI for ~0.4MA
- 0.4-1 MA CHI
- up to 1 MA plasma gun
- Extend NBI duration to 10-20s and/or implement 2-4 MW off-axis EBW H&CD
- 1 MW ECH/EBW → 2 MW

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson
- Upper divertor cryo-pump

Materials and PFCs
- High-Z tile row on lower OBD
- High-Z first-wall + lower OBD tiles
- High-Z PFC diagnostics
- All high-Z PFCs
- Hot high-Z FW PFCs using bake-out system

Liquid metals / lithium
- Li granule injector
- Upward LiTER
- LLD using bakeable cryo-baffle
- Flowing Li divertor or limiter module
- Full toroidal flowing Li lower OBD

MHD
- MGI disruption mitigation
- Partial NCC
- Enhanced MHD sensors
- NCC SPA upgrade
- Full NCC

Transport & Turbulence
- δB polarimetry
- High k_θ
- DBS, PCI, or other intermediate-k

Waves and Energetic Particles
- HHFW limiter upgrade
- HHFW straps to excite EHO
- High-power AE antenna
- 1 coil AE antenna
- 4 coil AE antenna
- Charged fusion product, neutron-collimator

Scenarios and Control
- Establish control of: Snowflake, $\bar{n}_e$, Rotation
- q_{min}
- Divertor P_{rad}
- Control integration, optimization
- Control integration, optimization with long-pulse and full metal wall

Inform choice of FNSF: aspect ratio, divertor, and PFCs

Significant Near Term Upgrade Scopes Are Highlighted

ECH, Cryo-Pump and NCC system require resources starting in 2015

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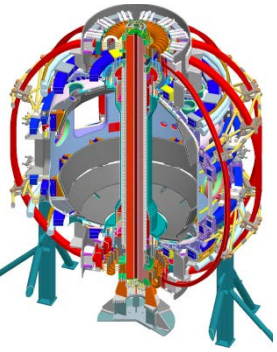

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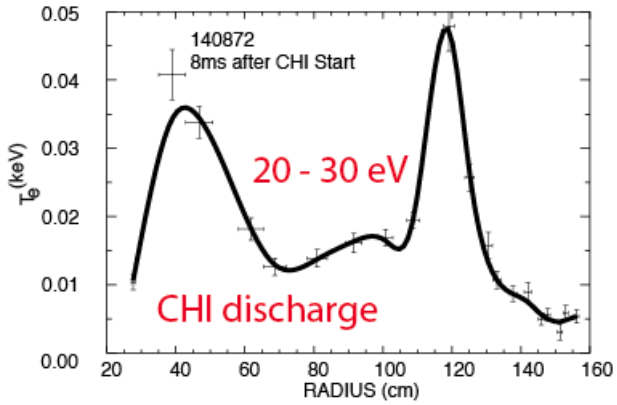
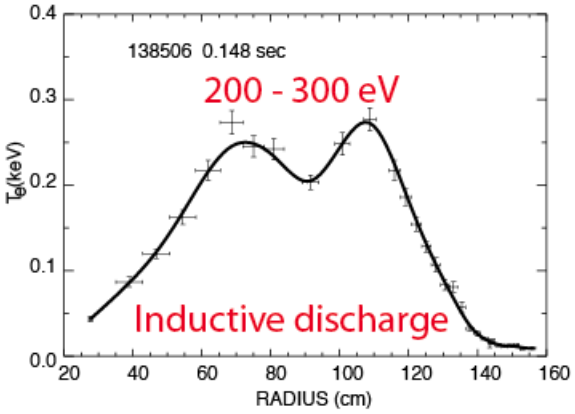
Inform choice of FNSF: aspect ratio, divertor, and PFCs

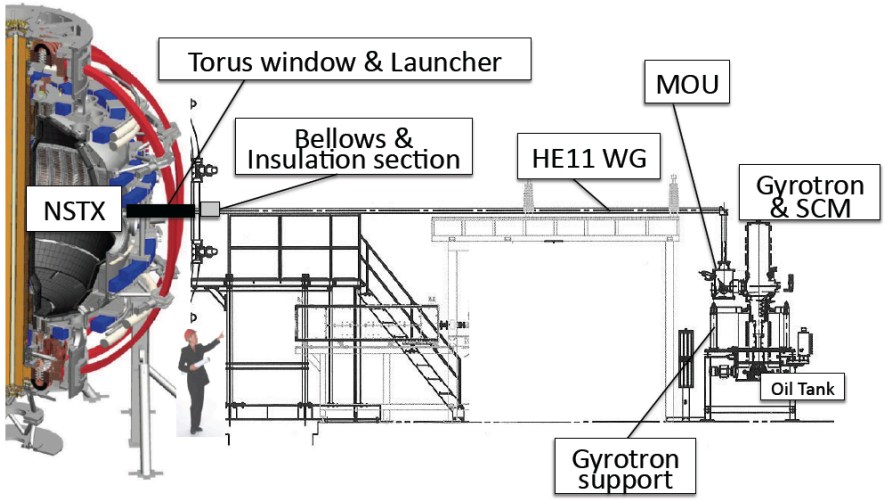
1 MW ECH system: Required to bridge T_e Gap Between CHI Start-up and HHFW + NBI Current Ramp

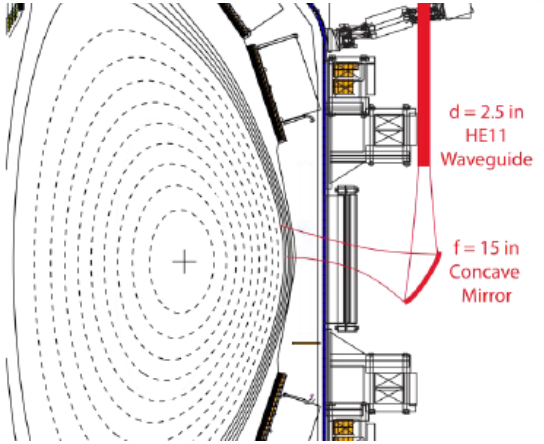


1MW ECH



28 GHz, 1.5 MW Tsukuba Gyrotron





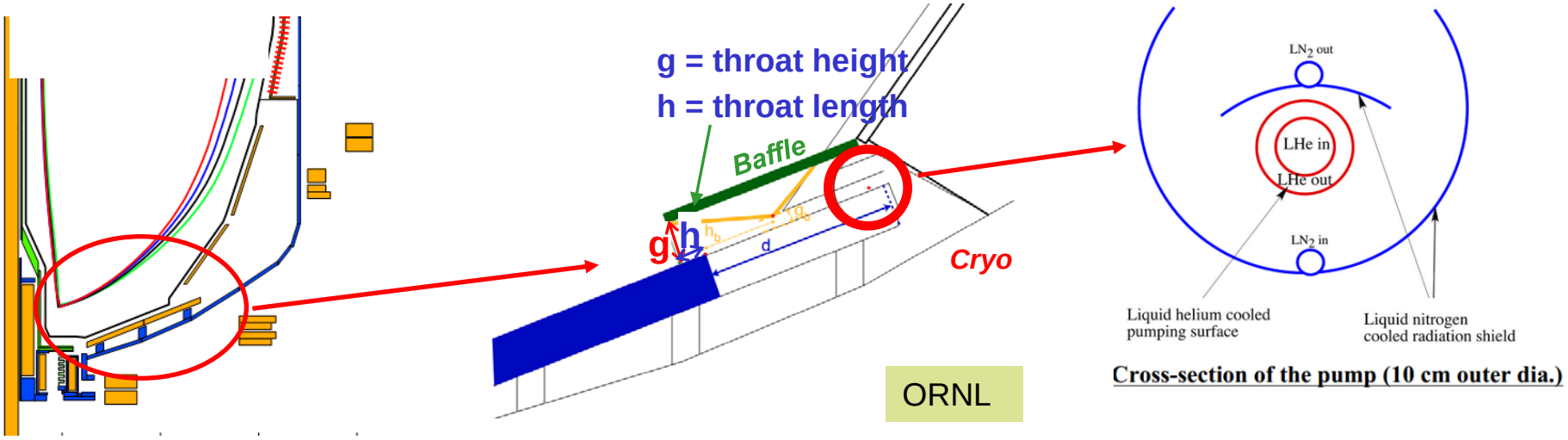
28 GHz ECH/EBWH waveguide and mirror concept

Tsukuba U
MIT
ORNL

FY 2016 Perform MW-class ECH/EBW system engineering design for non-inductive operations. Incremental funding will enable start of engineering design and procurement in FY 2015.

Divertor Cryo-pumping will be used for Particle Control in Long-pulse ELMy H-mode

- **Cryo-pump is proven technology for plasma density control**
  - More conventional pumped stationary ELMy H-mode scenario
  - Enables comparison with lithium based pumping
- **NSTX-U design will leverage DIII-D experience**
  - Plenum located under new baffling structure near secondary passive plates
  - Pumping capacity of a toroidal liquid He cooled loop
    - S=24,000 l/s @ R=1.2m
  - Need plenum pressure of 0.6 mTorr to pump beam input

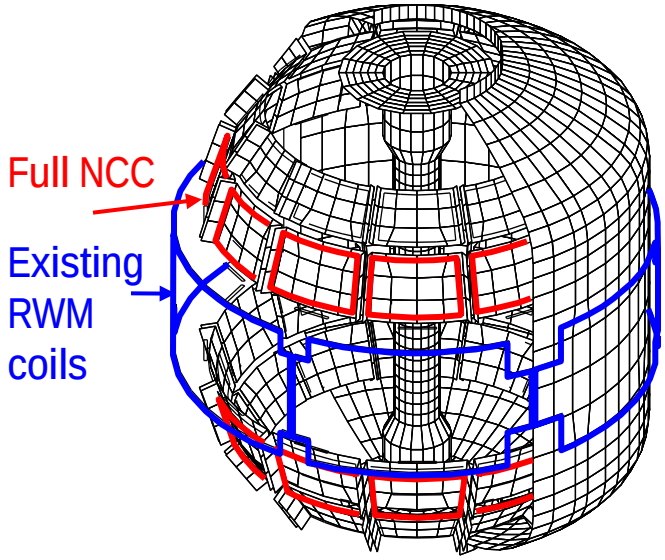


Base - Perform cryo-system engineering design for particle control in FY 2016. Incremental funding will enable start of engineering design in FY 2015 and procurement in FY 2016.

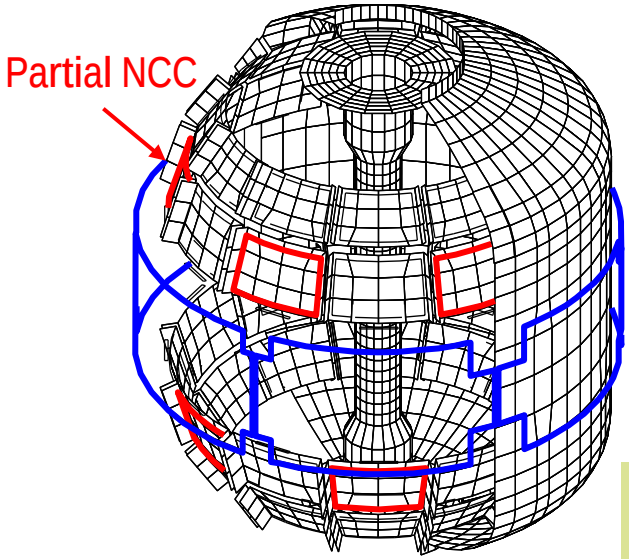
NCC will greatly enhance MHD physics studies and control

Range of off-midplane NCC coil configurations is assessed

Full toroidal NCC array (2 x 12)



Partial toroidal NCC array (2 x 6)



Columbia U
General Atomics

- **NCC (non-symmetric control coils) can provide various NTV, RMP, and EF selectivity with flexibility of field spectrum (n ≤ 6 for full and n≤ 3 for partial).**
- **6-channel Switching Power Amplifier (SPA) powers independent currents in existing EFC/RWM and NCC coils.**

Base – No work on NCC until 2017. Incremental funding will enable start of engineering design in FY 2015 and procurement in FY 2016.

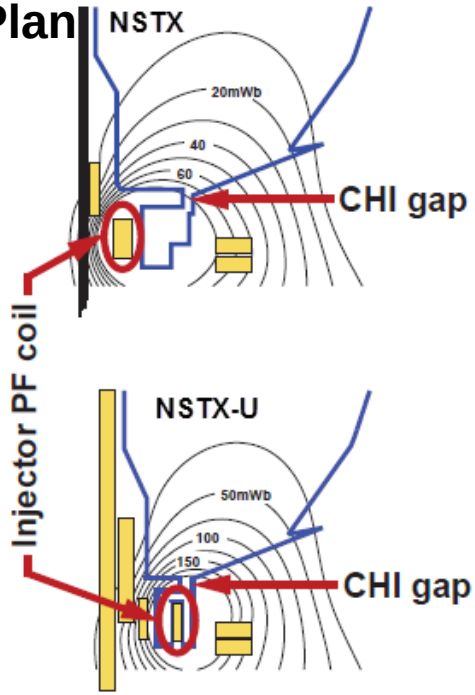
Solenoid-free Start-up

High priority goal for NSTX-U in support of FNSF

CHI Start-Up Base Plan

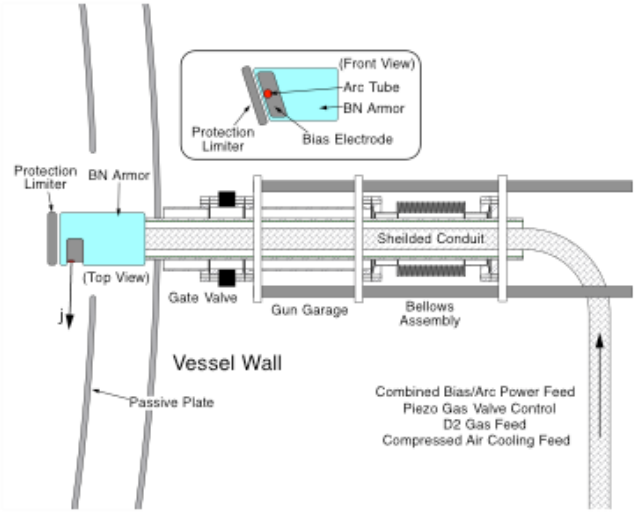
- Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX
- NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation

U. Washington



Point source under developed in PEGASUS

PEGASUS Plasma Gun



U. Wisconsin

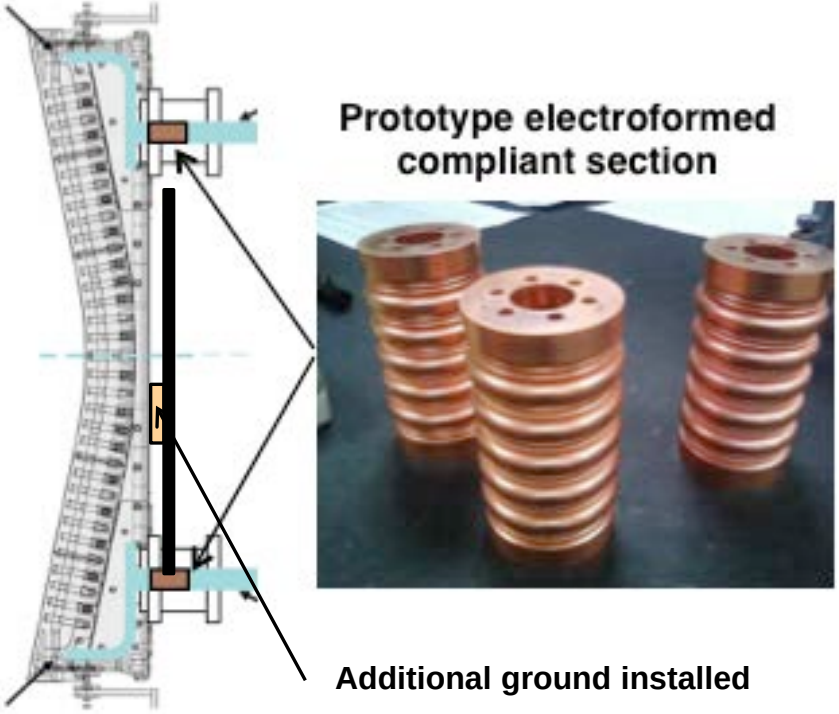
FY 2014-15 Non-Inductive Start-up Systems Design for Post-Upgrade Operations

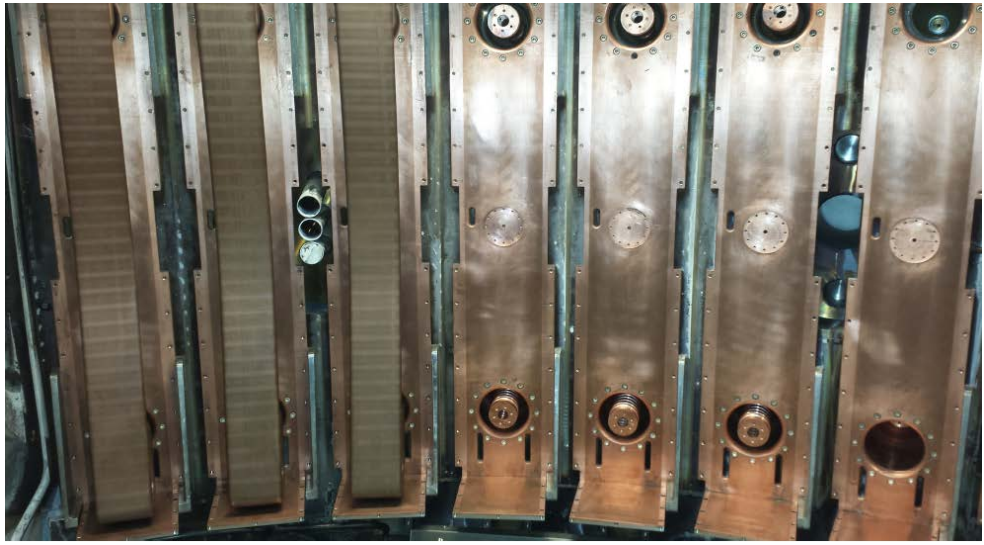
- CHI will start with the present 2 kV capability then enhanced to ~ 3 kV higher voltage as needed.
- PEGASUS gun start-up producing exciting results Ip ~ 160 kA. The PEGASUS gun concept is technically flexible to implement on NSTX once fully developed. High voltage gun for the NSTX-U will be developed utilizing the PEGASUS facility in collaboration with University of Wisconsin.

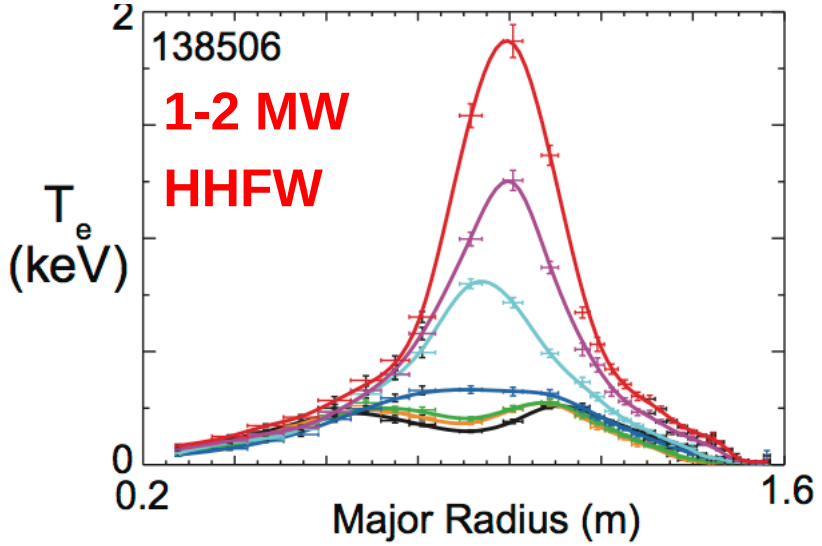
HHFW System for Electron Heating and Current Ramp-up Antennas were improved for NSTX-U

New Compliant Antenna Feeds

Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions







G. Taylor , et al.,

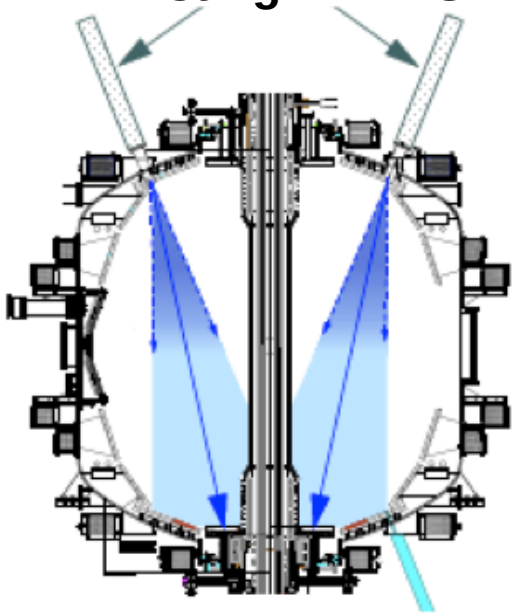
- **Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.**
- **Antennas were re-installed with the new feeds and back-plate grounding**

NSTX-U Li Capability During Initial Two Years

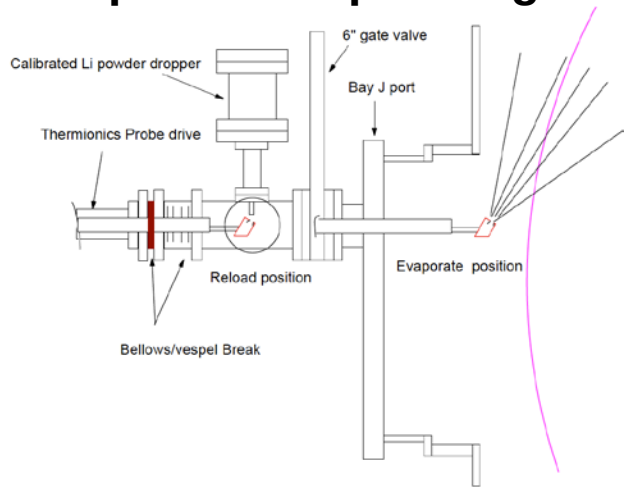
Boronization, Li Evaporators and Granular Injector

NSTX-U Day 1: Boronization planned for the initial operation to establish a base plasma performance prior to turning on lithium.

Existing LITERS



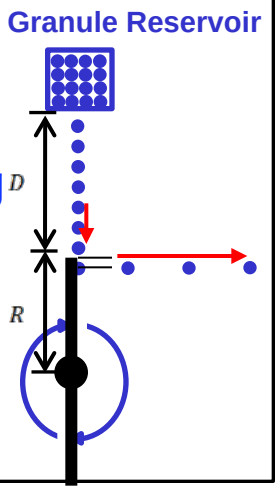
New Upward Evaporating LITER



- Upward Evaporating LITER to increase Li coverage for increased plasma performance

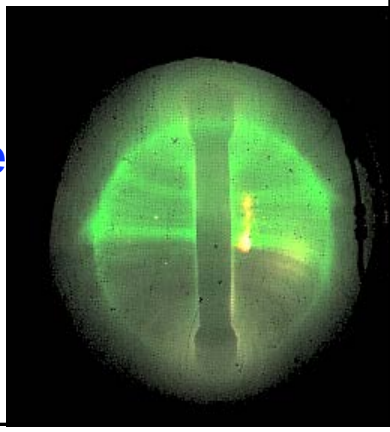
NSTX-U li granular injector for ELM pacing

- High frequency ELM pacing with a relatively simple tool.
- ELM pacing successfully demonstrated on EAST (D. Mansfield, IAEA 2012)



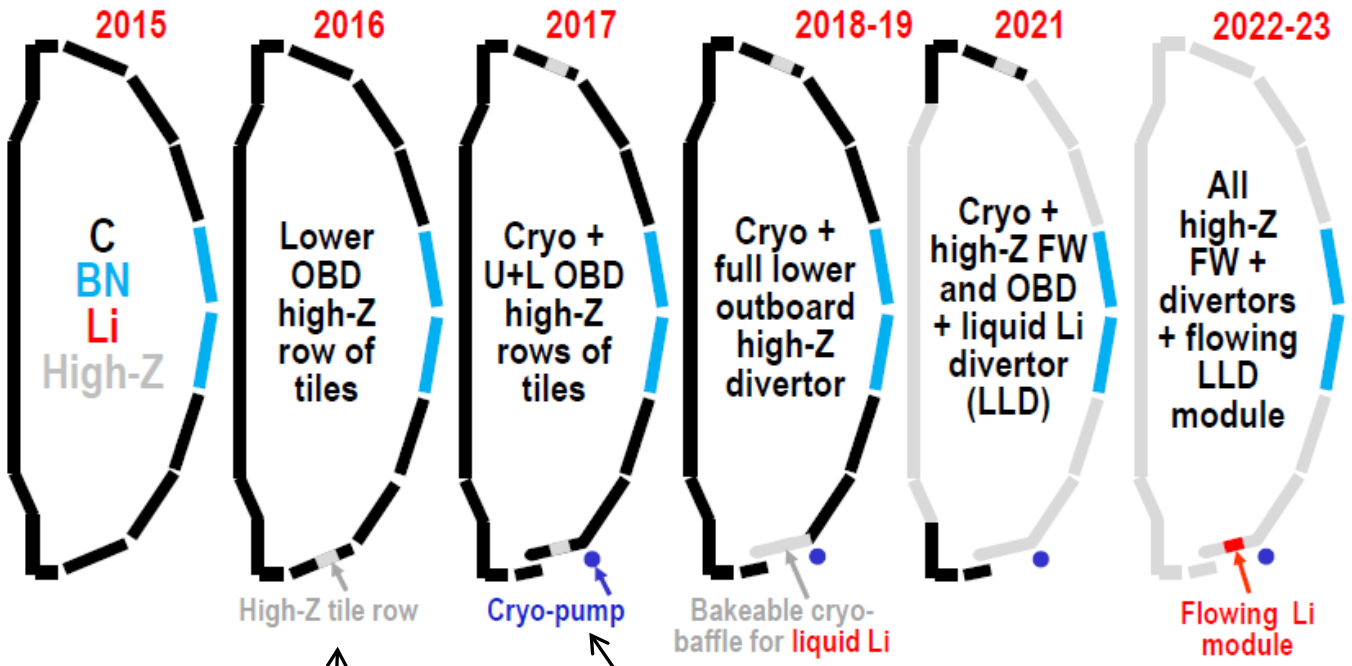
NSTX-U li dropper used for collaborations

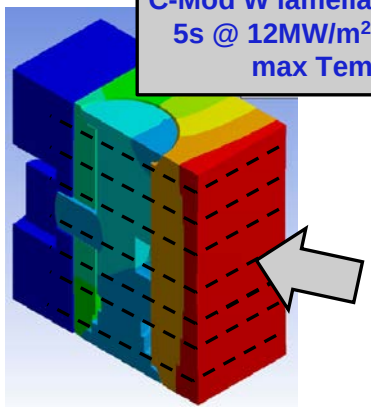
- Helped EAST achieve long H-mode
- In DIII-D, H-mode pedestal modified with improved confinement.



Boundary Facility Capability Evolution

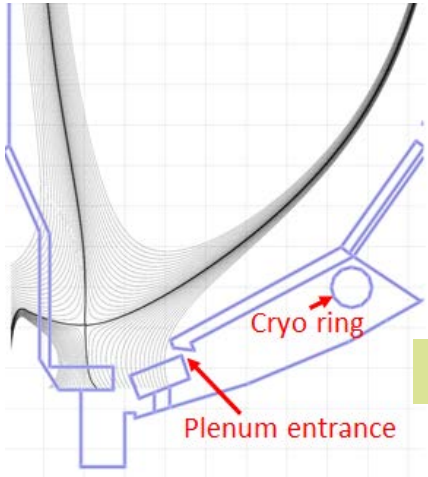
NSTX-U will have very high divertor heat flux capability of ~ 40 MW/m^2





C-Mod W lamellae design, 5s @ 12MW/m^2, 2000C max Temp

Incident heat flux

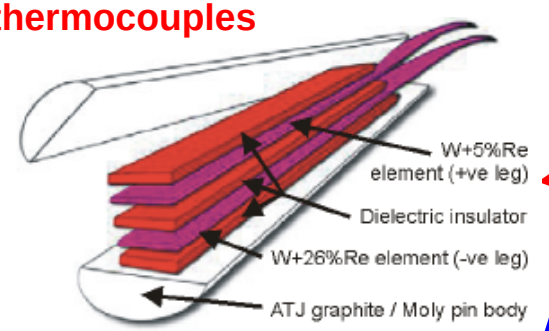


ORNL

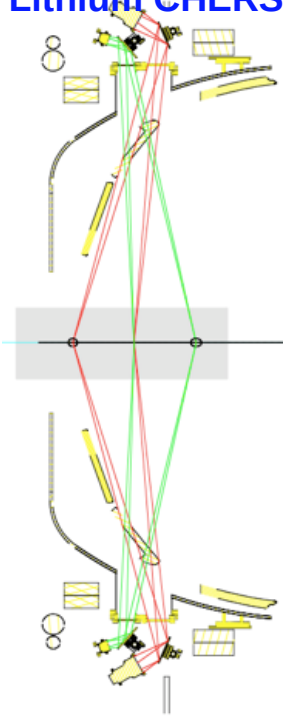
- High heat flux regions (strike-point regions)
  - TZM or W lamellae
- Intermediate heat flux regions (cryo-baffles, CS midplane)
  - TZM tiles or TZM/W lamellae
- Low heat flux regions (passive plates, CS off-midplane)
  - W-coated graphite (e.g. ASDEX-U)

Enhanced Capability for PMI Research
Multi-Institutional Contributions

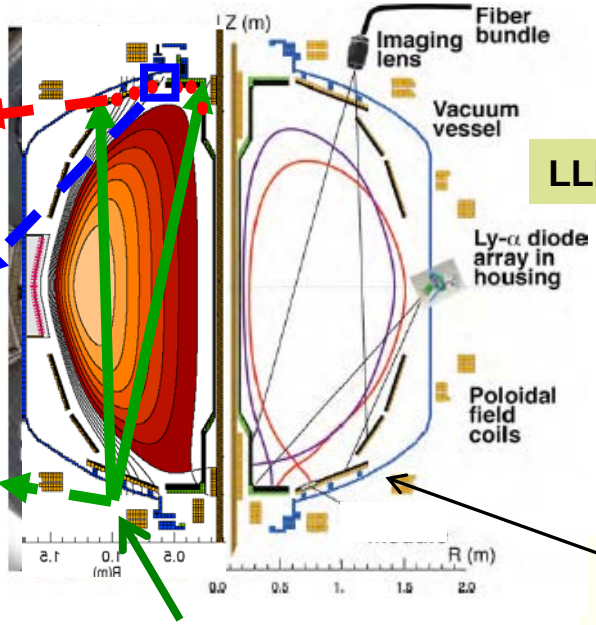
Divertor fast eroding thermocouples



Lithium CHERS



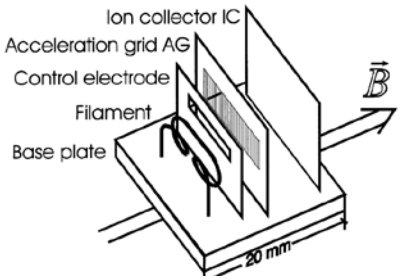
Divertor Imaging Spectrometer



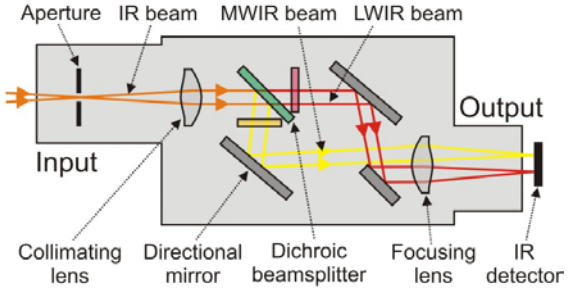
LLNL

ORNL

Divertor fast pressure gauges

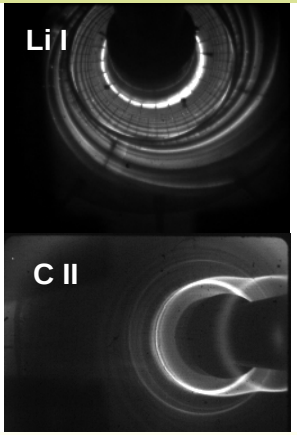


Dual-band fast IR Camera

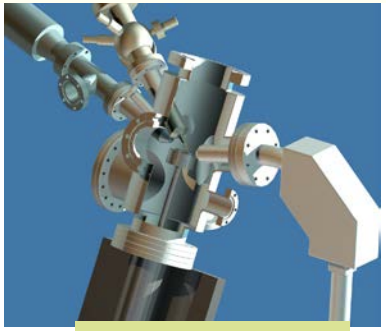


Two fast 2D visible and IR cameras with full divertor coverage

LLNL, ORNL, UT-K

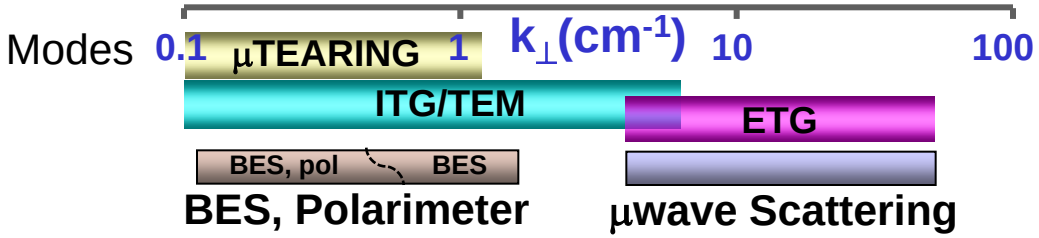


MAPP probe for between-shots surface analysis – Tested in LTX

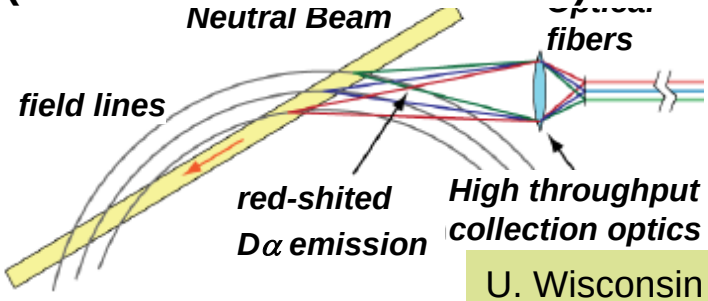


U. of Illinois

Transport and Turbulence: BES and high-k scattering provide comprehensive k-spectrum coverage of microturbulence



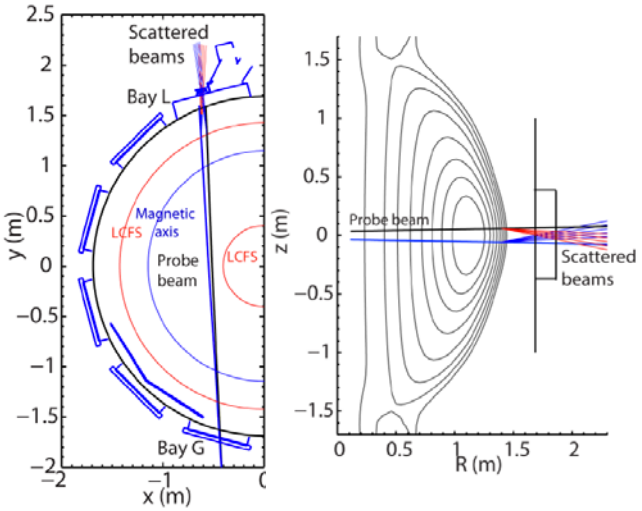
48 ch BES available for NSTX-U (24 ch BES available in 2011)



U. Wisconsin

New high-k scattering system for allowing 2-D k spectrum

UCD



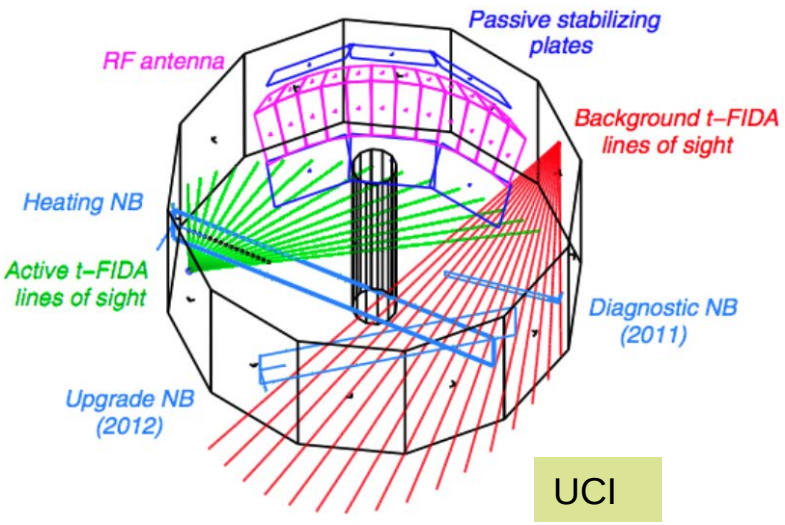
A 288 GHz polarimetry system for magnetic fluctuation measurements is being tested on DIII-D.

UCLA

Energetic Particle Research Capabilities: Will have the capability to assess NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics

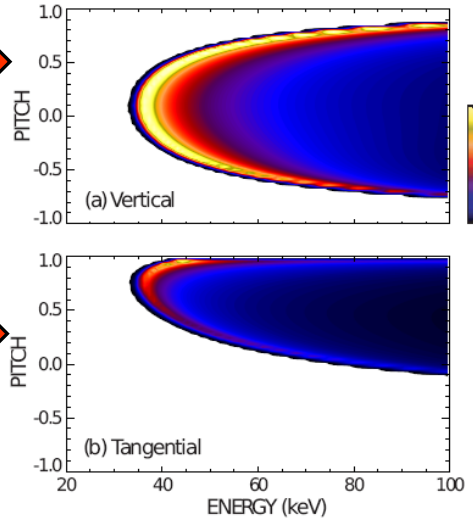
FIDA Views



UCI

A vertical FIDA system measures trapped or barely passing (co-going) fast ions.

A new tangential FIDA system measures co-passing fast ions.

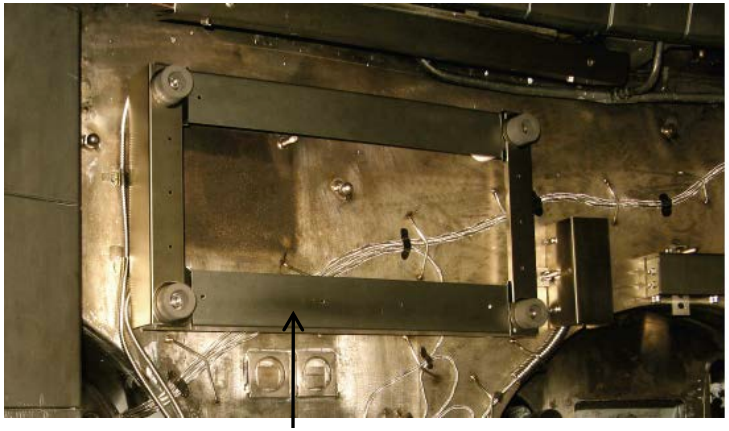


FY 2014 - 15 Energetic Particle Conceptual Design and Diagnostic Upgrade

- SS-NPA enhancement due to removal of scanning NPA

UCI

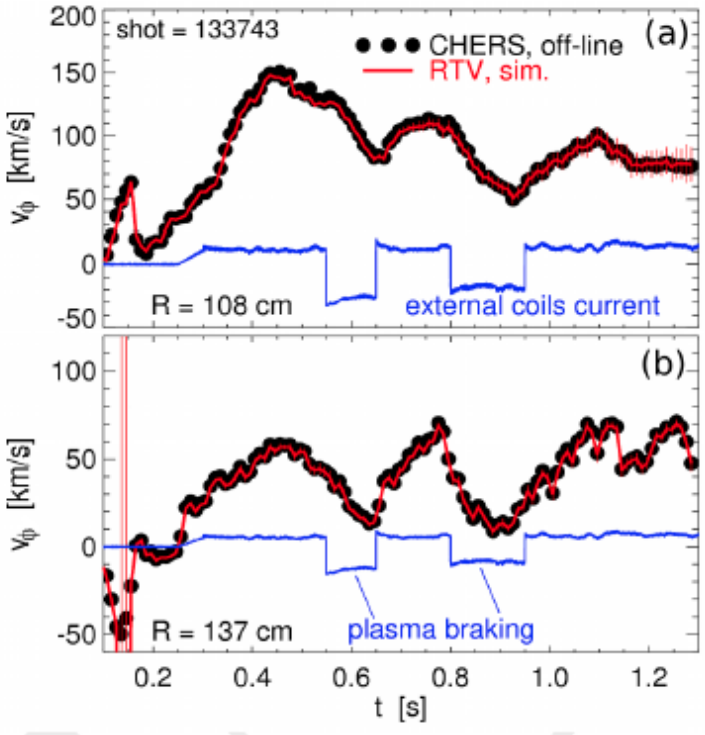
- Active TAE antennas and sFLIP

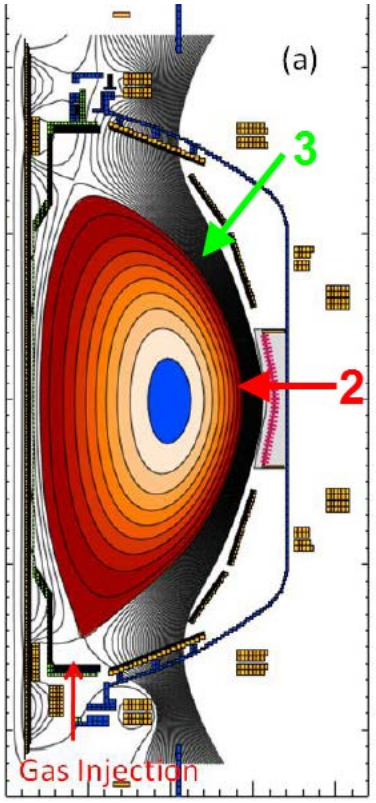


2 x 2 5-turn radial active TAE antennas installed

Advanced Scenario and Plasma Control Tools for NSTX-U
Real time rotation control and disruption mitigation

RTV fitting vs off-line CHERS data





Massive gas injector system at multi-poloidal location

U. Washington

FY 2014-15:

- **A Real-Time Velocity (RTV) diagnostic will be incorporated into the plasma control system for feedback control of the plasma rotation profile.**
- **Multi-poloidal location massive gas injector system for disruption mitigation will be implemented to test the efficiency vs location.**

Base NSTX-U Facility/Diagnostic Milestones

Crucial to complete ECH/EBW and Cryo-pump Engineering Designs in FY 2015

Facility	Milestone Description	Baseline
F(14-1)	Complete installation and testing of refurbished D-Site Rectifier Firing Generators.	Sep 14
F(15-1)	Complete 18 run week research operation	Sep 15
F(15-2)	Complete high-Z tile design and begin procurement	May 15
F(15-3)	Begin electron cyclotron heating / electron Bernstein wave (ECH/EBW) system engineering design and gyrotron procurement.	Sep 15
F(15-4)	Develop cryo-pump engineering design concept	Sep 15
F(16-1)	Complete 16 run week research operation	Sep 16
F(16-2)	Complete ECH/EBW system engineering design and begin installation	Sep 16
F(16-3)	Complete cryo-pump engineering design and begin procurement of components	Sep 16

Diagnostics	Milestone Description	Baseline
D(14-1)	Complete the Multi-Pulse Thomson Scattering (MPTS) diagnostic in-vessel modifications	Apr 14
D(15-1)	Install and commission Material Analysis Particle Probe (MAPP)	Sep 15
D(16-1)	Install and commission high k-theta diagnostic system	Mar 16

NSTX-U Optimized Facility Plan Has Been Developed

Exciting Opportunities and Challenges Ahead

- **NSTX upgrade outage activities are going well**
  - The Upgrade Project progressing on cost and on schedule. CD-4 completion in January 2015 and the research operation starting in April 2015 for 18 run weeks.
  - Researchers are preparing for NSTX-U operation while working productively on data analysis, collaboration, and carrying out five year plan.
  - NSTX-U operations plan has been developed (see next talk)
- **Facility / diagnostic plans developed and being implemented to support exciting 5 Year NSTX-U research plan**
  - ECH/EBW, Divertor Cryo-pump, and NCC coils are the high priority major enhancements requiring engineering design in 2015 to be ready in 2017
- **FY 2014-15 budget guidance will enable the timely NSTX-U research operations start while completing the Upgrade Project.**
  - The base budget restores the budget to the FY 2012 level (inflation adjusted) and enables timely start of the NSTX-U research operations.
  - Incremental budget will enable full facility utilization and a timely implementation of the Five Year Plan enhancements including ECH, Cryo-pump and partial NCC.

Backup Slides

NSTX Upgrade Project Key Milestones On-Track

Level	Milestone	DOE Commitment Date	Forecast	Actual
Level I	**Receive CD-2 Approval**	**Jan-11**		**Dec-10**
Level II	Project FDR	Jun-11		Jun-11
Level I	**Receive CD-3 Approval**	**Jan-12**		**Dec-11**
Level II	Receive First Delivery Machined Inner Tf Conductor	Jun-12		Apr-12
Level II	Nstx Complete Operations	Jul-12		Sep-11
Level II	Begin Upgrade Outage	Aug-12		Sep-11
Level II	Award Neutral Beam (NB) Vessel Cap	Jun-13		Feb-11
Level II	Begin Inner Tf Quadrant Fab (Apply Turn Insul #1	Apr-13		Jun-12
Level II	Complete Assy and Pot Of 4th Inner TF Quadrant	Oct-13		**Jun-13**
	VPI CS OH/TF Bundle		*May-14*	
	Install NB Sources		*Jun-14*	
Level II	Complete Fabricate & Test Inner TF/OH Coil Assy	Jun-14	*Jun-14*	
	PTP NB VPS		*Jul-14*	
Level II	NB Cap Installed	Oct-14		Jan-13
	Deliver Center Stack to the NSTX TC		*Aug-14*	
Level II	Lift In New Centerstack	Jan-15	*Aug-14*	
	Pumpdown		*Nov-14*	
Level II	Complete ISTP	Aug-15	*Dec-14*	
Level II	Resume Operations	Sep-15	*Dec-14*	
Level I	**CD-4**	**Sep-15**	***Dec-14***	

Remaining Assembly Steps for the Centerstack

- ❑ Ground wrap insulation around the OH/TF bundle
- ❑ Assemble VPI mold around bundle
- ❑ **Vacuum Pressure Impregnation (VPI) - end MAY**
- ❑ Remove Aqua pour
- ❑ **Pressure and Electrical Test - June 23rd** ⟵ *Highest remaining risk and Level II milestone*
- ❑ Install upper and Lower crown assemblies -
- ❑ Assemble PF 1A with ceramic break
- ❑ Install PF 1A onto the centerstack bundle
- ❑ Apply Microtherm insulation around bundle
- ❑ Lower casing over the bundle
- ❑ Install flash shields
- ❑ **READY FOR INSERTION INTO NSTX - Mid August**

Remaining Construction Work in NSTX-U Test Cell

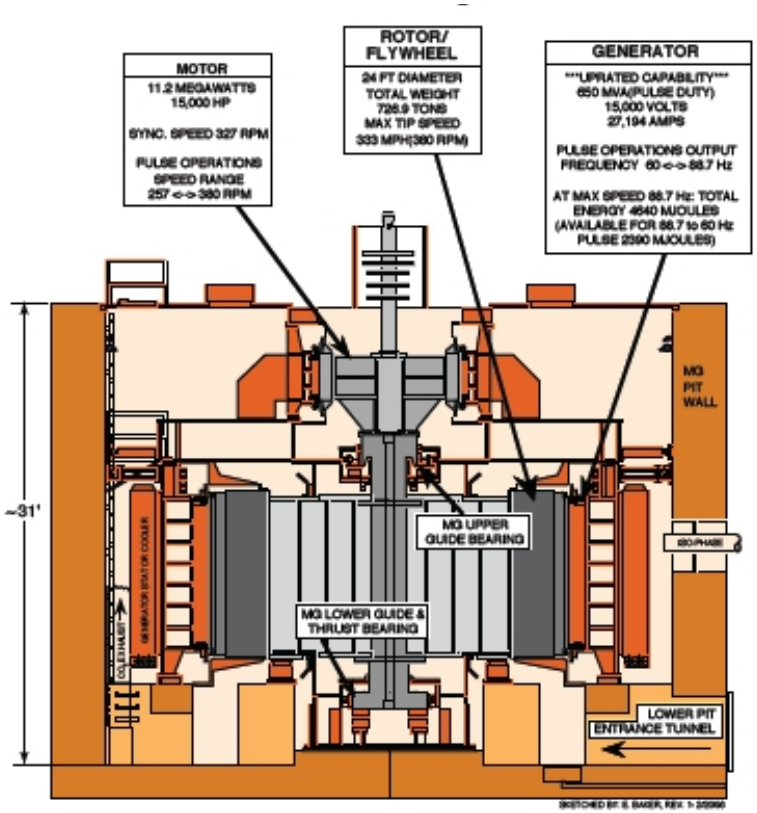
- **Install Centerstack – mid August**
- Install bus inside umbrella and back to racks
- Install new TF flex bus
- Field measure space between centerstack and all TF flags
- Fabricate 72 unique centerstack to TF flag links
- Install umbrella lid support rings
- Install new umbrella lids
- Clean, photo and close the vacuum vessel
- Pumpdown
- Leak check
- Bakeout

Engineering / Research Operations Preparation
Ramping up for the NSTX-U Operations in Dec. 2014

- **Upgrading the Plasma Control System (PCS) for NSTX-U.**
- **Upgrading HHFW antenna feedthroughs for higher disruption forces.**
- **Boundary Physics Operations**
  - **Improving the PFC geometry at the CHI gap to protect the vessel and coils.**
  - **Upgrading gas injection system including the massive gas injection disruption mitigation system.**
  - **Boronization system will be readied to support initial research operations.**
  - **Preparing lithium systems (LITERs, granule injector for ELM trigger, upward LITER).**
- **Diagnostic Enhancements**
  - **MPTS re-alignment and laser dump relocation.**
  - **Fabricated new port covers to support high-priority diagnostics. The last large port being installed.**
  - **Installing additional, redundant magnetic sensors.**
  - **Upgrading diagnostics: Bolometry (PPPL), ssNPAs, spectroscopy (collaborators)**
- **Physics & Engineering Operations**
  - **Firing generators for 68 Transrex rectifiers replaced. Testing starting.**
  - **Repair of the Motor Generator radial arm weld cracks to complete in July.**
  - **Upgrading the poloidal field coil supplies to support up-down symmetric snowflake divertors on-going.**

Repair of the Motor Generator (MG#1)

- **In 2004, Magnetic Particle Inspections identified cracking in the weld fillet of multiple joints between the radial arms of MG#1. Cracks were in primary load paths, taking that set out of service. MG#2 is in limited operations (run and monitor at reduced parameters) with cracks in "stiffener" welds intended to limit elastic deformation (not in primary load paths).**
  - **Over 250" of welds in 19 rotor spider joints will be ground out and replaced to restore MG#1 to its original design configuration.**
  - **A jacking system has been engineered to relieve all loads on the rotor assembly during the repair.**
  - **PPPL and GE engineering collaborated on the detailed repair procedure (D/NSTX-RP-MG-07).**



Status: Target completion date is July 2014

• A Statement of Work to perform the scope described in the repair procedure and a draft Project Management Plan has been developed.

•The repair work has started in early June.

Incremental NSTX-U Facility/Diagnostic Milestones

Accelerates ECH/EBW, Cryo-pump, NCC enhancements by one year

Facility	Milestone Description	Baseline
F(14-1)	Complete installation and testing of refurbished D-Site Rectifier Firing Generators.	Sep 14
IF(15-1)	Complete 20 run week research operation	Sep 15
F(15-2)	Complete high-Z tile design and begin procurement	May 15
IF(15-3)	Complete electron cyclotron heating / electron Bernstein wave (ECH/EBW) system engineering design and begin gyrotron procurement.	Sep 15
IF(15-4)	Complete cryo-pump engineering design and begin procurement	Sep 15
IF(16-1)	Complete 20 run week research operation	Sep 16
IF(16-2)	Begin ECH/EBW system installation	Sep 16
IF(16-3)	Complete procurement of cryo-pump major components	Sep 16
IF(16-4)	Develop non-axisymmetric control coil (NCC) engineering design	Sept 16

Diagnostics	Milestone Description	Baseline
D(14-1)	Complete the Multi-Pulse Thomson Scattering (MPTS) diagnostic in-vessel modifications	Apr 14
D(15-1)	Install and commission Material Analysis Particle Probe (MAPP)	Sep 15
D(16-1)	Install and commission high k_q diagnostic system	Mar 16