NSTX-U

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NSTX-U FY2013 Year-end Report Presentation

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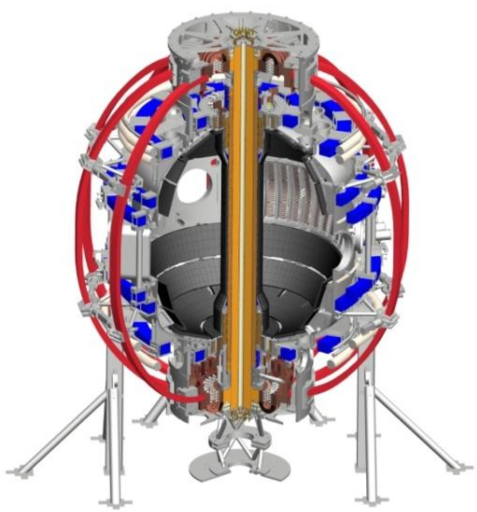
X Science LLC

Ron Strykowsky
Masa Ono
Jon Menard

FES Room G258
PPPL Room B205
October 22, 2013



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Agenda

- NSTX Upgrade progress report – R. Strykowsky
  - 30 minutes
- NSTX-U facility and diagnostic status – M. Ono
  - 30 minutes
- Notable outcomes, research milestones – J. Menard
  - 30 minutes

NSTX-U

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NSTXU Upgrade Quarterly Report
October 22, 2013

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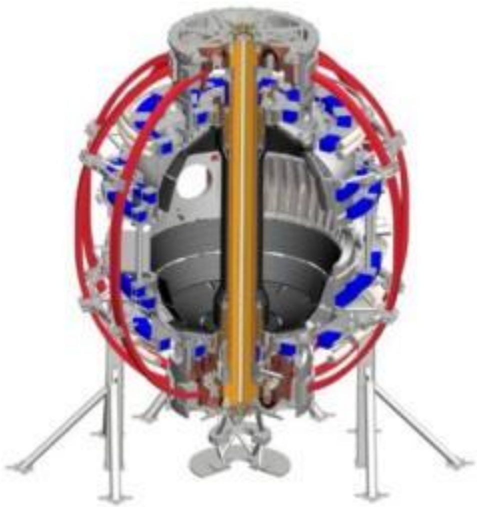
X Science LLC

Ron Strykowsky, Jim Chrzanowski, Larry Dudek, Tom Egebo, Steve Langish, Erik Perry, Tim Stevenson, Mike Williams
and the NSTXU Project Team



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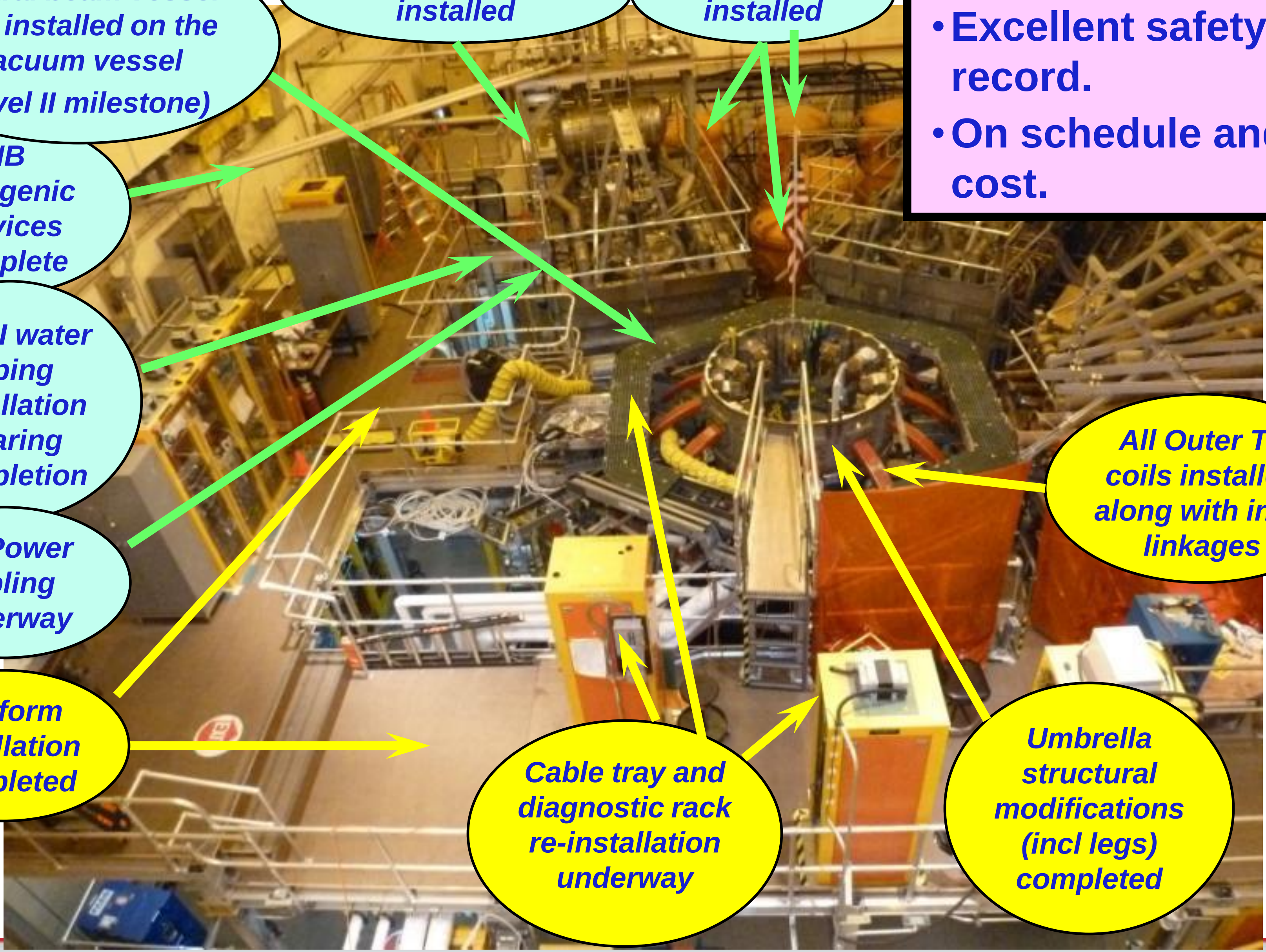
FY2013 - *A Good Year with Significant progress*



- **Excellent safety record.**
- **On schedule and cost.**

Neutral Beams

High Voltage Enclosure relocation completed – 3 HVEs








High Voltage Enclosure relocations completed

NBI Port Extension trial fit completed

TF outer leg clearances maintained

Maintained ¾ inch clearance to Port Extension for OL deflection per spec

Awaiting NBI Duct installation…

Deionized Water Piping subcontract completed (source, dump, HVE)








NBI Armor assembly and installation in progress…

Painstaking trail fit made and supports aligned. Final structural welding completed.

NBI Duct & TVPS duct fabrication completed

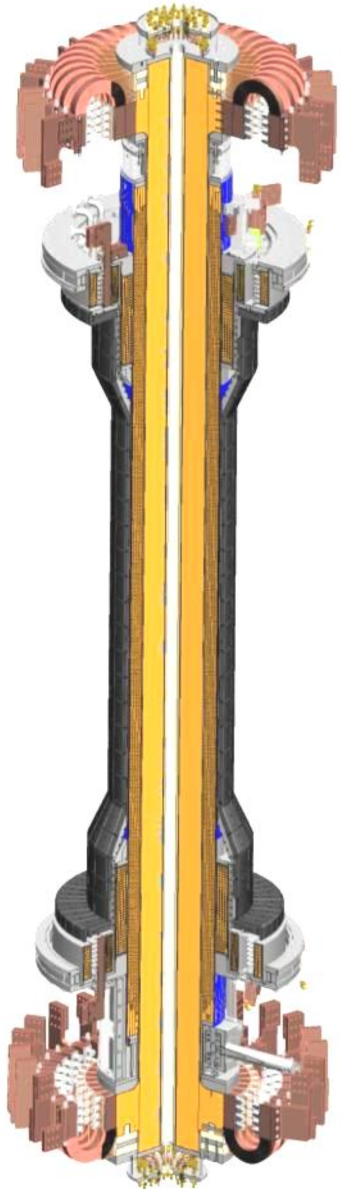
… and leakchecked.

Stainless circular shields complete

Moly shields for rectangular bellows in progress

Centerstack

Center Stack Fabrication is the critical path! Assembly Proceeding Well



- Inner TF Bundle
  - (4) TF Quadrants have been VPI'd and tested
  - Full TF Bundle has been VPI'd and tested
- Assembly tilt fixture fabricated, tested and in-use
- Aqua pour process underway
- OH winding assembly fabricated & installed
- OH Solenoid
  - Begin winding OH solenoid - November 2013
  - VPI OH Solenoid - March 2014
- PF 1 Coils
  - Coils fabricated. PF1B delivery planned November
- Centerstack Casing
  - Delivered and studs have been installed
- Centerstack Assembly-
  - Delivery to NSTX Test Cell - May 2014

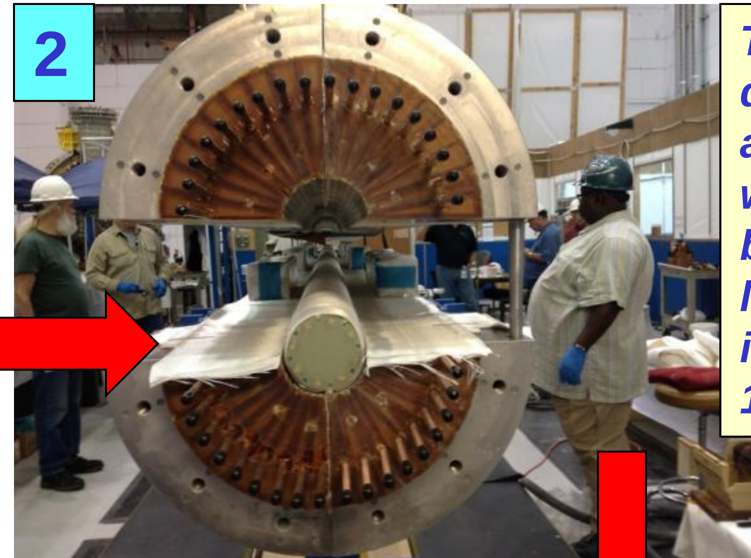
Work was supported by Steve Raftopoulos, Mike Mardenfeld, Irv Zatz & Technician crews led by Mike Anderson and Eugene Kearns

Inner TF Bundle Assembly Was Successful

- **The four VPI's quadrants were then assembled together to complete the full bundle.**

1

2



The quadrants assembled w/ S-2 between layers & pre-insulated G-10 core

3

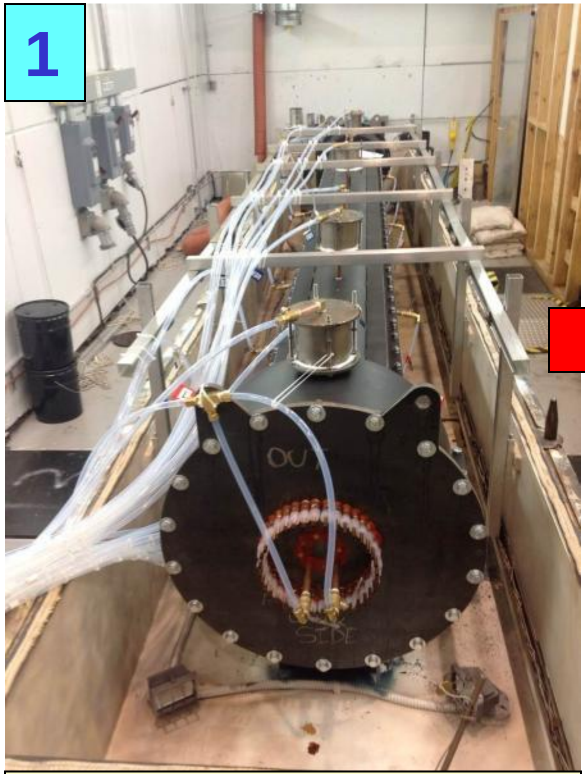
The full TF bundle is Ground wrapped with S-2 glass tape

4

The full TF bundle is placed into a mold and VPI'd

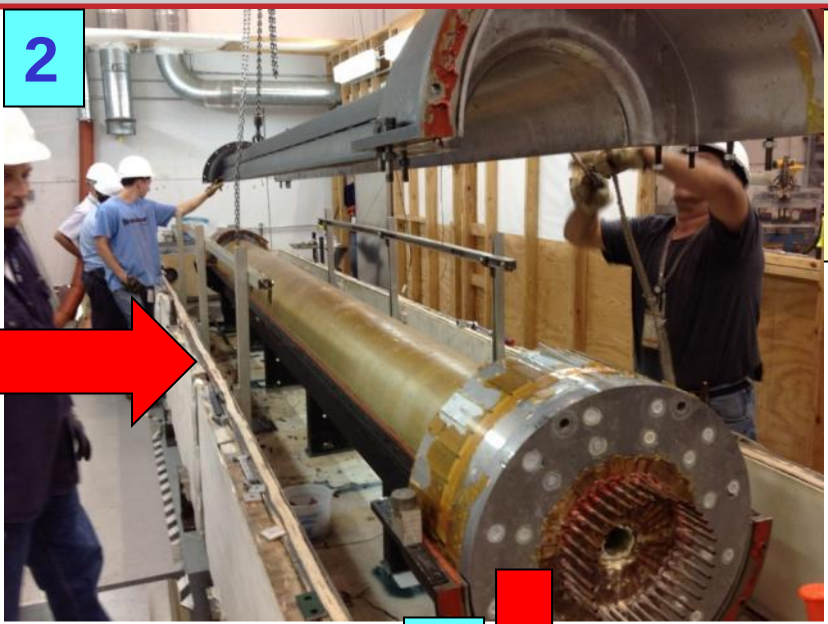
Inner TF Bundle VPI and Test Successful!

1



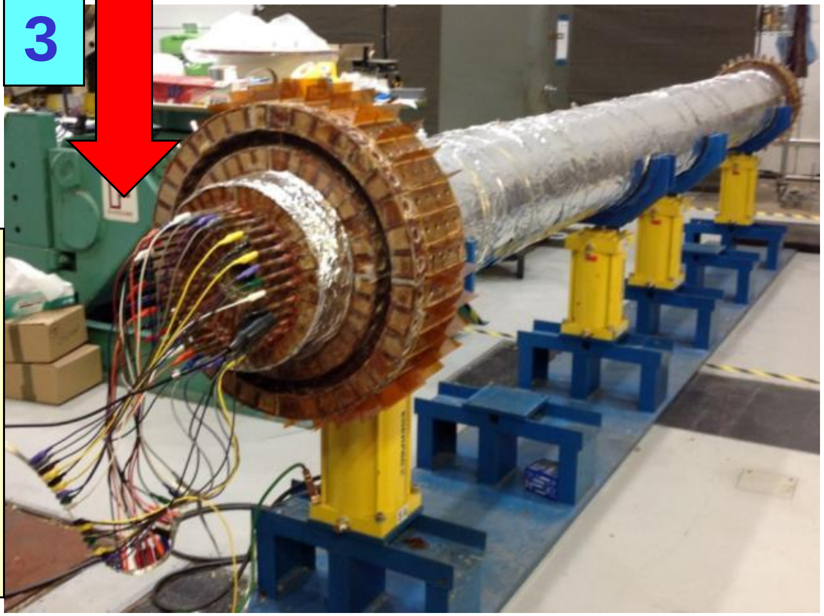
Full TF Bundle in oven and ready for VPI

2



Full TF Bundle after VPI

3

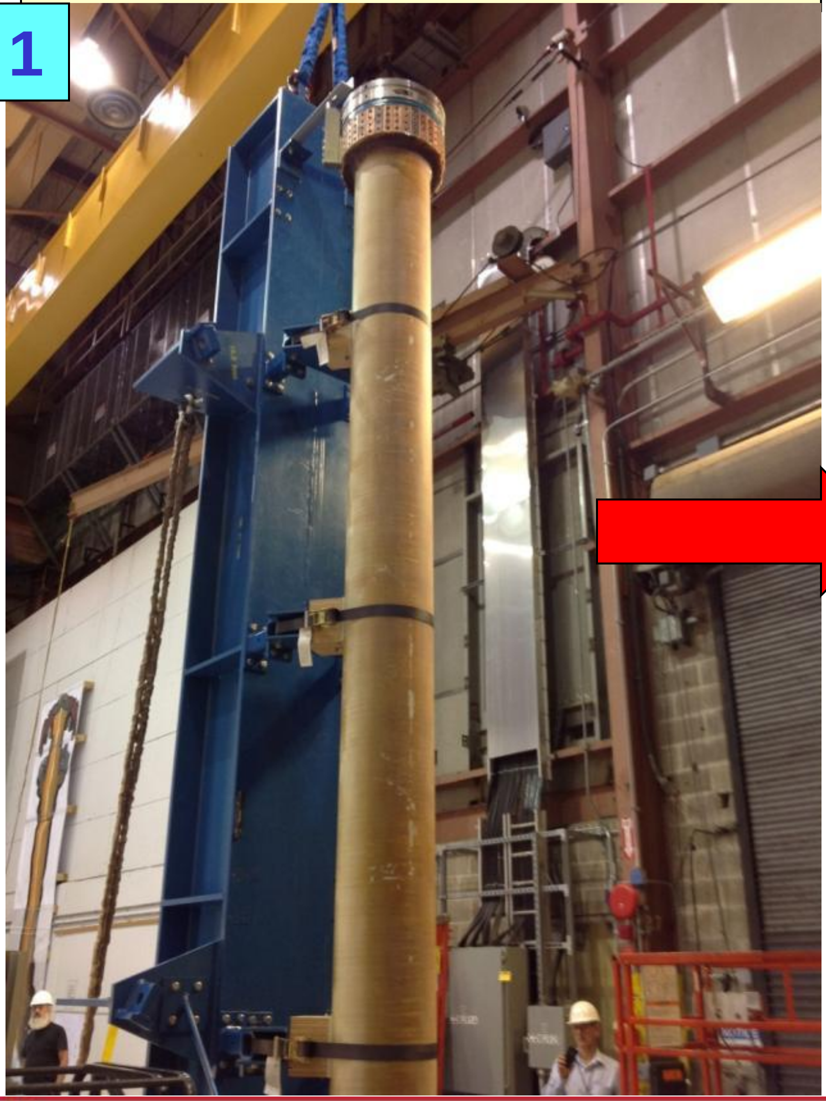


Full TF Bundle during the electrical test

Aquapour process underway

The CS up-right ready for the AquapourTM process

1



"Aquapour" is used as a temporary spacer that will be used to maintain 0.100 inch gap between the TF OD and OH ID surfaces. It is removed post VPI of OH coil

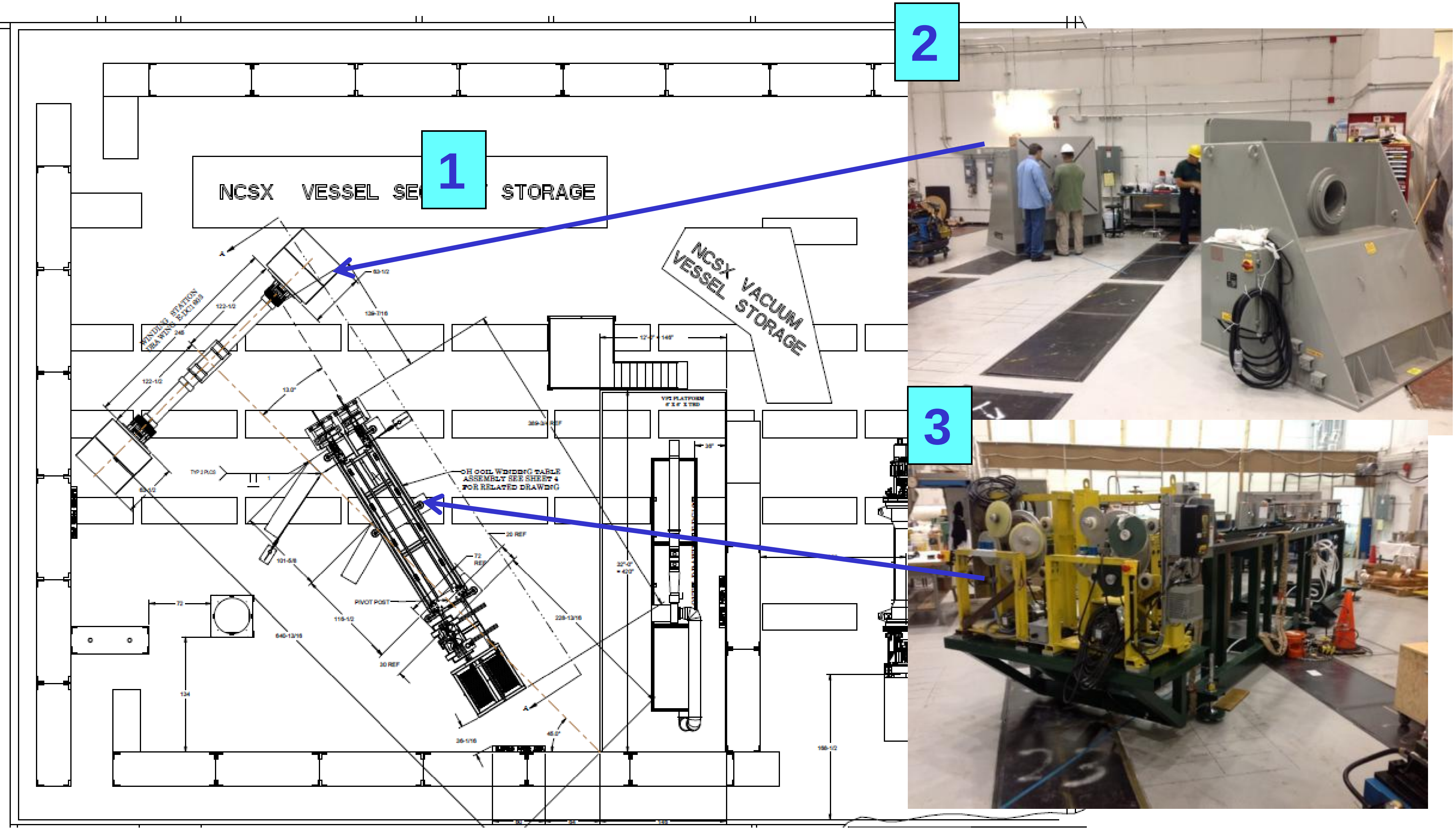
Prototype trials of Aquapour

2

3

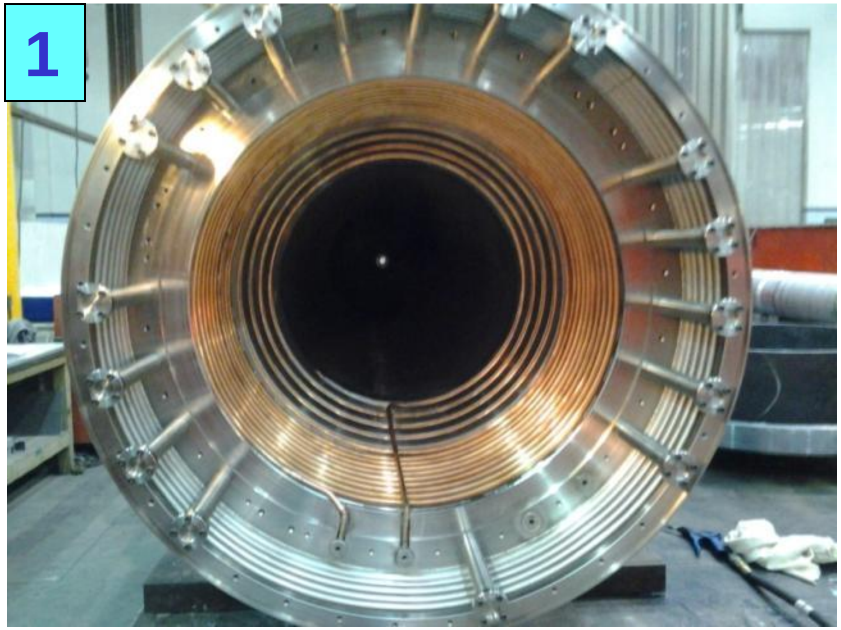
Fabrication of OH Solenoid

- **The OH Solenoid will be wound onto the Inner TF Bundle**
- **The CS High Bay area is being reconfigured to wind the OH coil**



Centerstack Casing

- The Centerstack Inconel casing has been manufactured by **Martinez & Turek located in California.**
- Inconel studs for supporting the PFC's have been installed



Construction and Machine Assembly

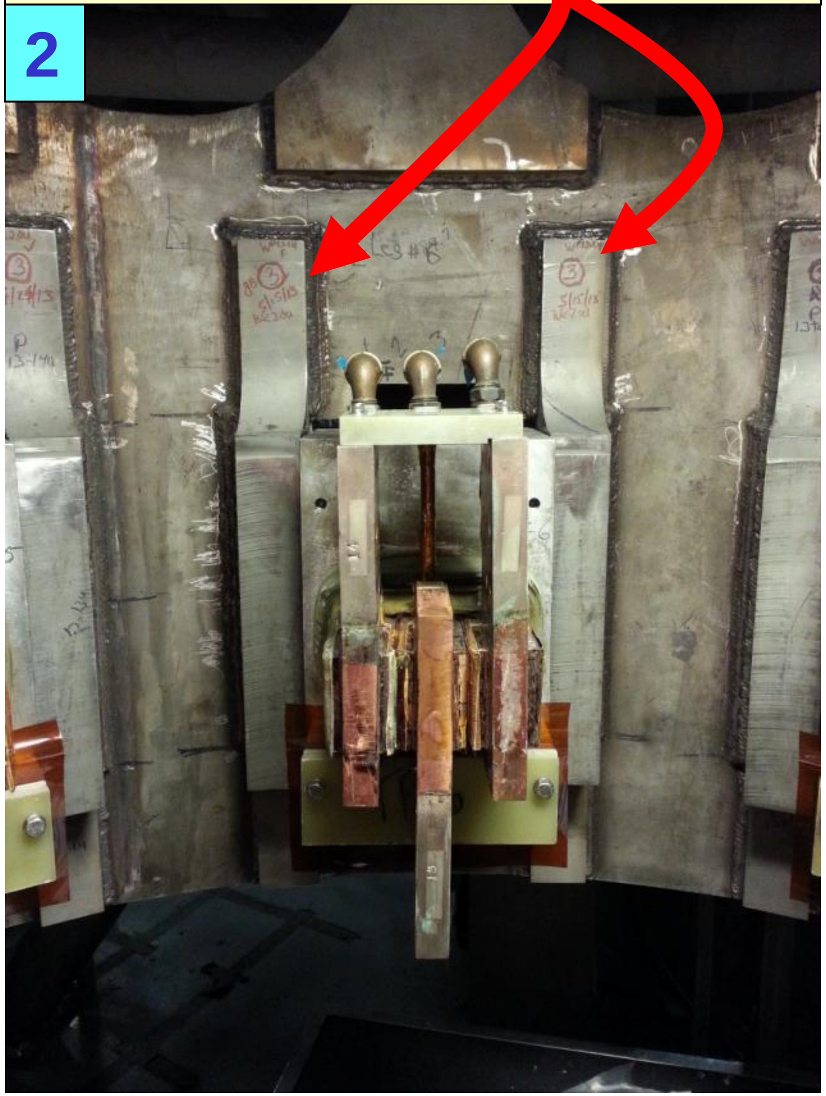
Construction Progress in 2013

- Install new umbrella legs / feet / slides
- Install umbrella arch reinforcements

1

- Install reinforcements for TF to umbrella interface

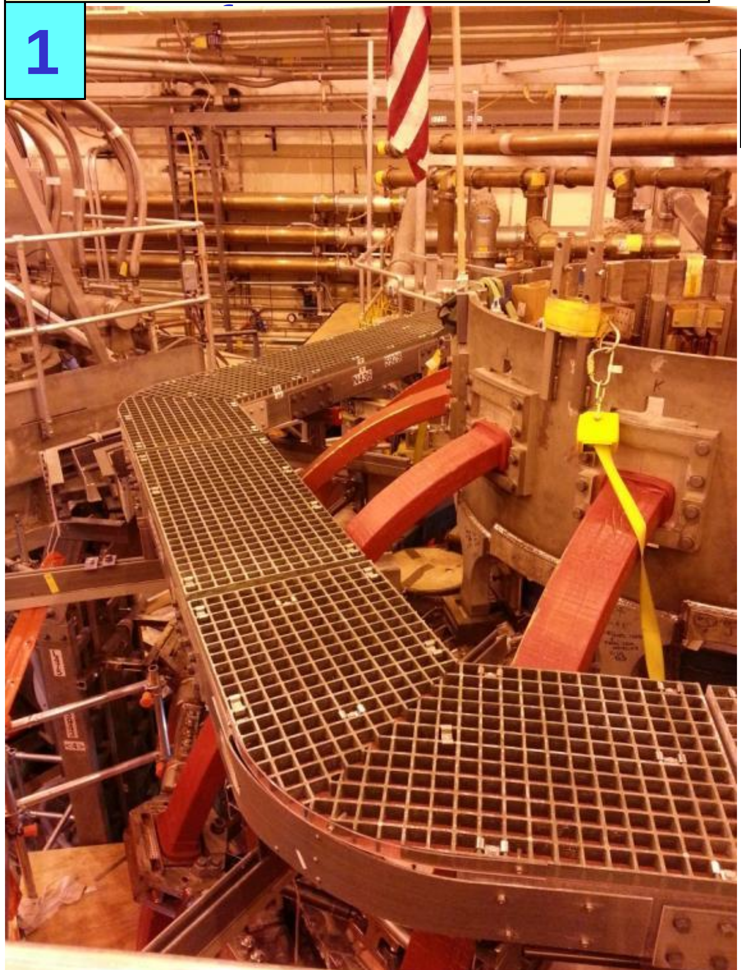
2



Construction Progress in 2013

Installed new cable tray around top of machine (Walking surface included)

1

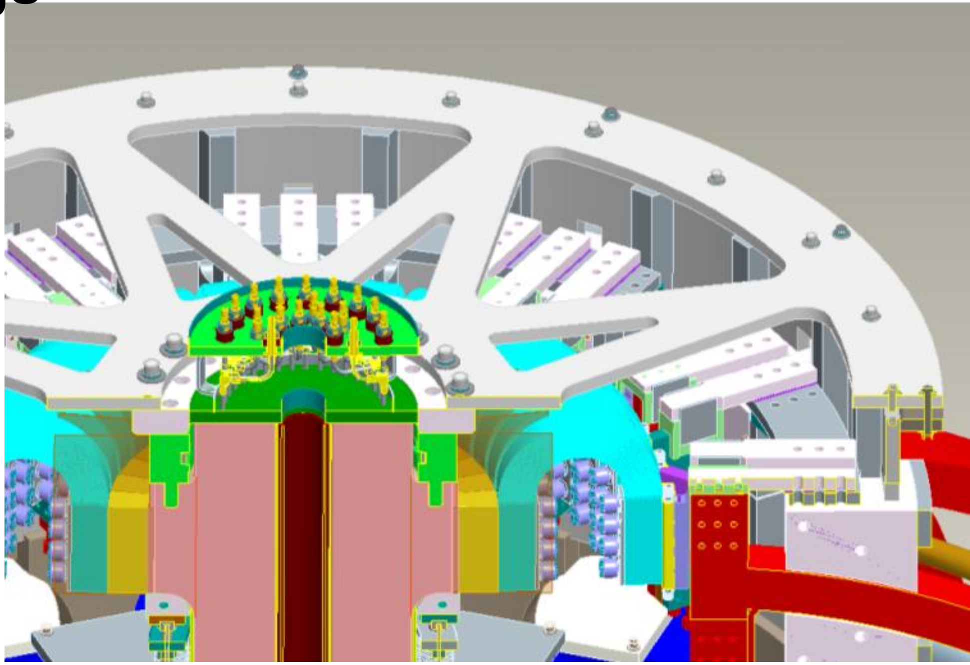


Installed most of the TF outer leg upper support structure

2

Remaining Construction Work in NSTX Test Cell

- Complete Structural work
- Install Centerstack
- 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

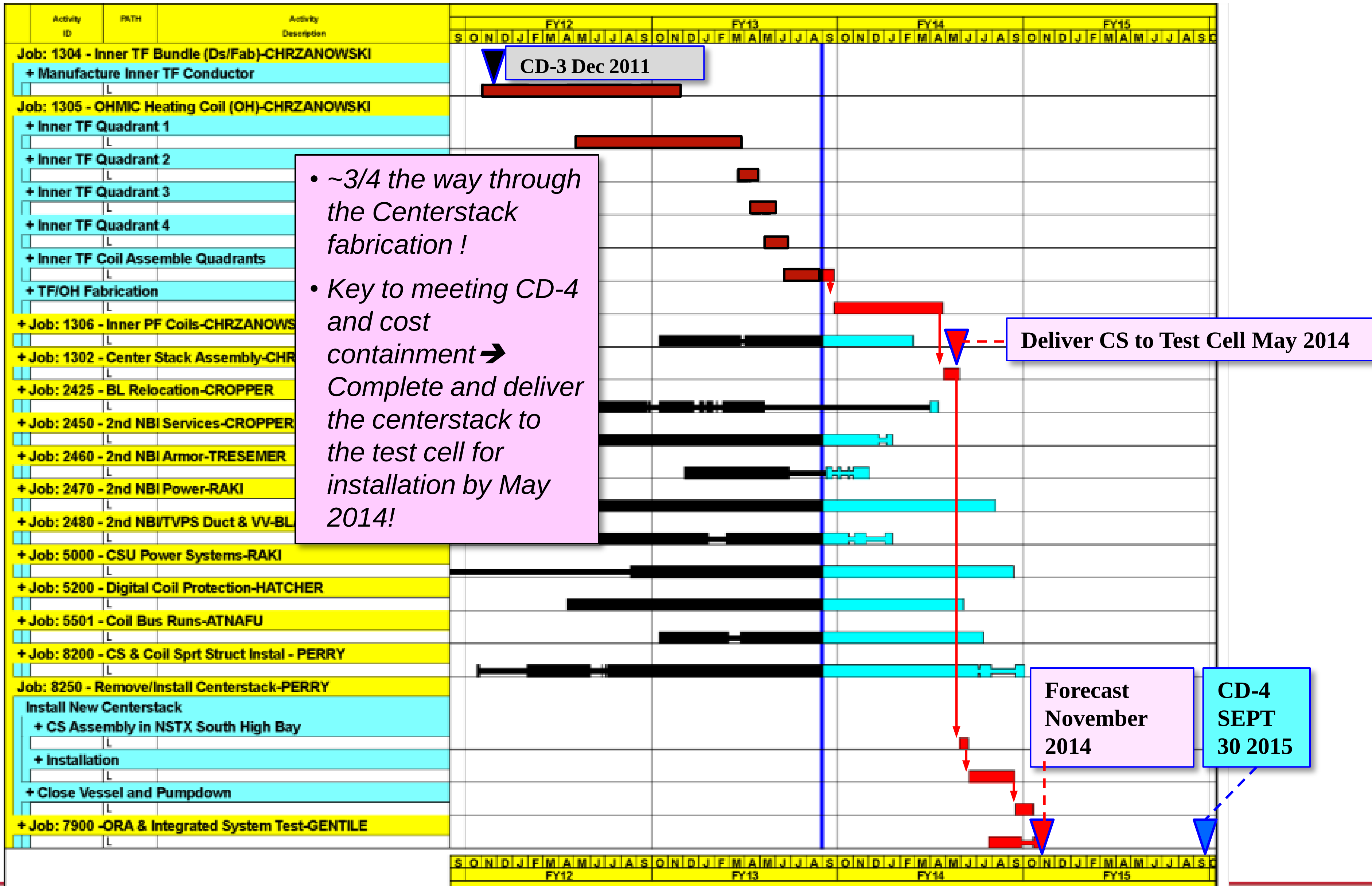


Cost and Schedule

Performance metrics and Costing Good

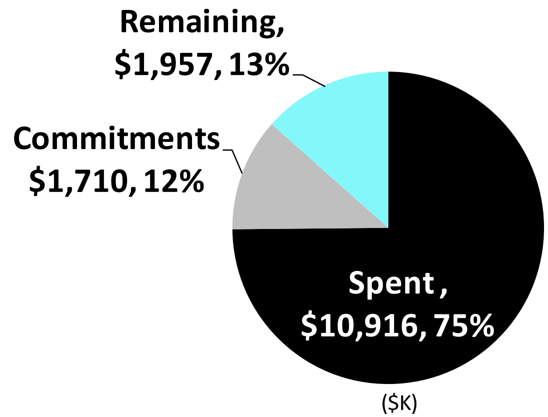
- **Cost**
  - CPI = 0.97
- **Schedule**
  - SPI = 0.98
  - Total float = 10 1/2 months to late finish CD-4
  - CD-4 Completion
    - Forecast = November 2014
    - DOE Milestone (Late Finish) = September 2015
- BAC =$86.1 EAC= $88.7 TPC =94.3M
- Cost to date = $66.2 M 75% complete *(through Sept)*

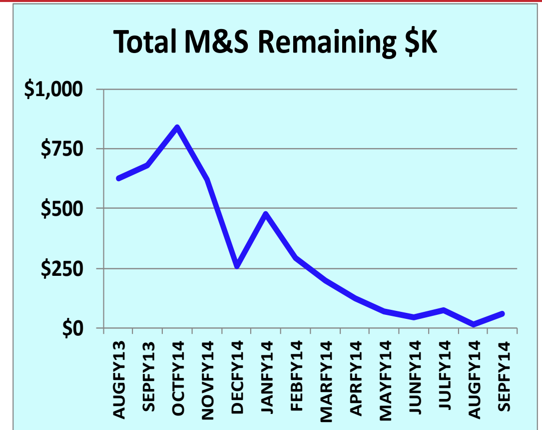
Schedule on track for early finish



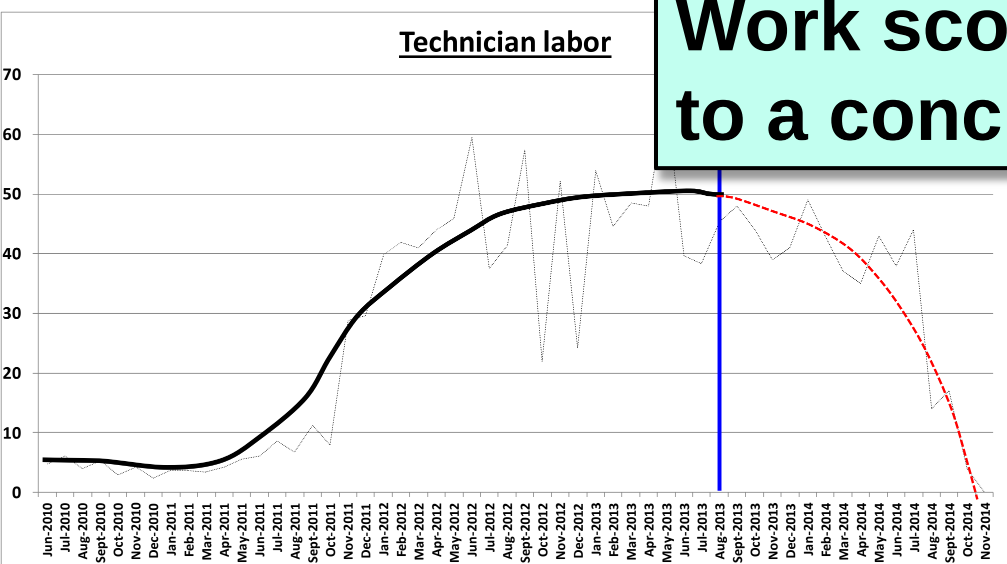
FY2014 - *year ahead in perspective*

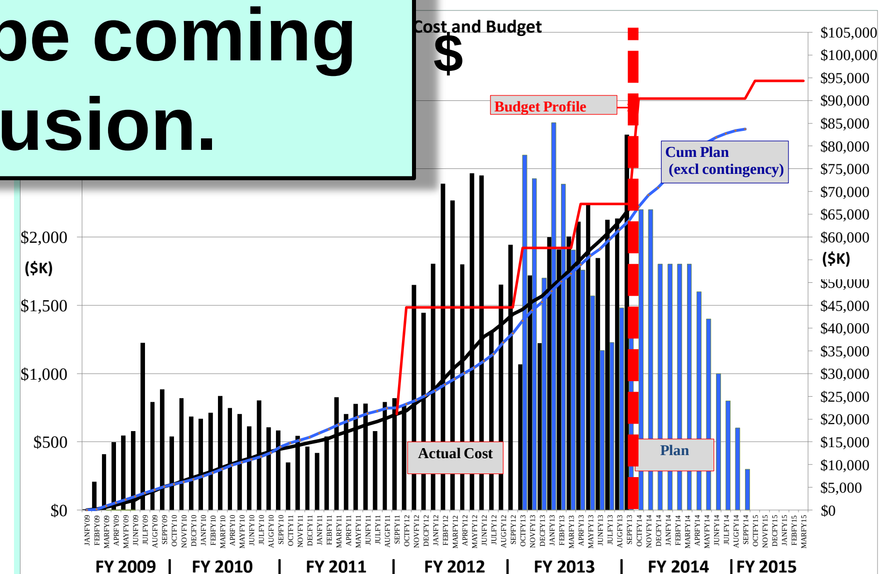
Procurements winding down





Work scope coming to a conclusion.





Startup activities underway

- QA Audit of NSTX-U Startup Documentation April 2014
- ACC – Summer 2014
- DOE – Summer 2014

FY2014 - *Financial position good*

DOE Funding and anticipated CR consistent with and supportive of early finish

	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	Total
BA	$5.2	$9.0	$9.9	$20.4	$22.8	$23.7	$3.3	$94.3
BO	$5.1	$8.3	$7.6	$21.9	$23.2	*$20.7*	$0.7	$87.6

Contingency position good

	@ CD-2 *(Dec 2010)*	@ Current (Sept 2013)
% Complete	18%	75%
Contingency remaining	$17M	$6.3M
	26.6%	29%

FY2014 - *Keys for Success*

- **Worker and investment safety while Maintaining the highest degree of technical quality**

- **Milestones:**
  - **Transport Centerstack to the NSTXU Test Cell**
    Forecast: MAY 2014
  - **CD-4**
    DOE commitment: SEPTEMBER 2015
    Forecast: NOVEMBER 2014

- **Risk:**
  - **TF/OH VPI and electrical test**

- **Cost:**
  - **Transition into Startup and Operations**

Lehman Review Conducted Oct 2nd-3rd

Charge Questions

1. *Construction Efforts: Are construction efforts being executed safely? Does the project have adequate resources and the appropriate skills mix to execute the project per the plan?* ***YES***

2. *Baseline Cost and Schedule: Are the current project cost and schedule projections consistent with the approved baseline cost and schedule? Is the contingency remaining adequate for the risks that remain?* ***YES***

3. *Management: Evaluate the management structure as to its adequacy to deliver the scope within budget and schedule. Are risks being actively managed? Has the project responded satisfactorily to the recommendations from the previous project reviews?* ***YES***

4. *Transition to Operations: Is the Project appropriately aligned for completion of construction efforts and transitioning to NSTX-U for CD-4 approval?* ***YES***

Lehman Review Conducted Oct 2^{nd}-3^{rd}

Recommendations

Technical

1) Identify lower risk CS tasks that can be performed by additional personnel or off-shift to gain schedule contingency. ***Plan being Updated***

2) Generate an interim milestone for DCPS for earlier commissioning of a reduced scope system able to support all system testing and initial machine operation. ***Plan being Updated***

Cost & Schedule

3) Include schedule contingency impacts in the ECP forms for the future ECPs. ***OK***

4) The EAC calculation should include items and activities that are likely to occur. **Done**

5) Ensure risk register is updated and maintained ***Updated***

Management

6) Evaluate a broader range of likely project outcomes to better understand and communicate with DOE the limits of cost and schedule contingencies to ensure project success by **November 1, 2013**. ***Done. To be reviewed with DOE-PSO***

7) Work with the Site Office and program develop a focused "end game plan" to monitor and communicate critical project activities to better ensure project success by **November 1, 2013**. **Done**

8) Action Item; Site Office to schedule a status review **in mid-January 2014**. ***Will be scheduled***

Summary

- **The project has maintained a safe working environment.**
- **The project continues to make good technical progress.**
- **The project is on schedule and cost with adequate contingency to finish.**
- **The project is on track for meeting CD-4 baseline within OFES budgetary guidance.**
- **The project is preparing for transitioning into operations.**

NSTX-U Project Status

Masa Ono

for the NSTX-U Team

NSTX-U FY 2013 Q4 Review Meeting
October 22, 2013

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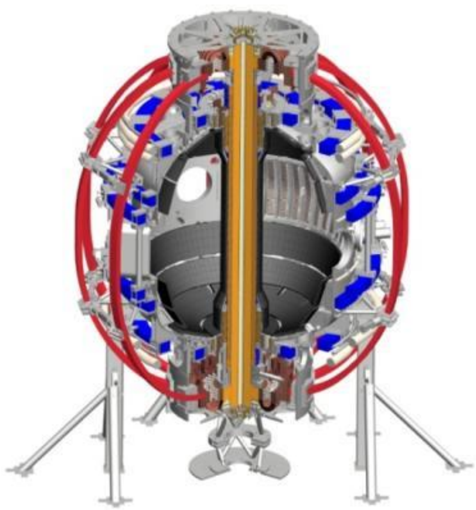

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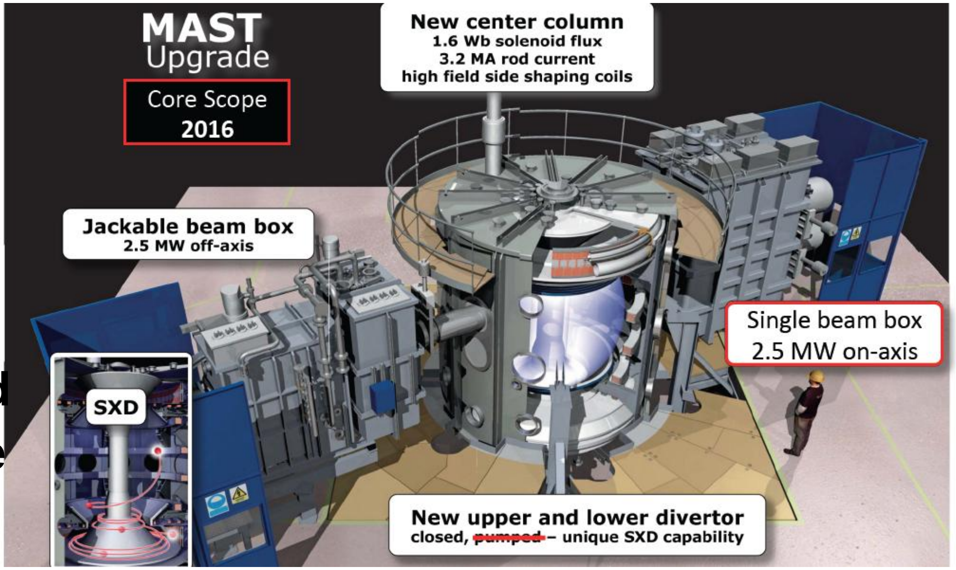
International ST Workshop in York UK

Sept 16 – 19, 2013, http://www.york.ac.uk/physics/ypi/istw2013/

- **NSTX-U related presentations were NSTX Upgrade Project (M. Ono), NSTX Upgrade Program (J. Menard), FNSF Design (J. Menard), CHI (B. Nelson, UW), HHFW Theory/Modeling (M. Peng, ORNL)**
- **Many nice science talks particularly from the MAST team.**
- **MAST-U generated 70 kA with 70 kW of ECH at 28 GHz. QUEST also generated ~ 65 kA with ECH at 28 GHz.**
- **A. Sykes of Tokamak Solutions talked about very compact ST reactor concept with R_0 ~ 1 m using high temperature SC with minimal neutron shields.**
- **GLOBUS-M is now upgrading the machine for GLOBUS-M2. It aims to increase the toroidal field B_T and plasma current I_p by a factor of 2.5 to 1 T and 0.5 MA.**
- **MAST has concluded its operation and started its upgrade outage. Plan to be operational by 2016.**



Third International Li Symposium in Rome, Italy

Oct. 7 - 11, 2013, http://www.isla2013.enea.it

- **Over 50 presentations from US, China, Russia, Japan, Italy, and Spain, Israel, Latvia, Ukraine, Kazakhstan, Greece, and Netherlands. Fusion Devices: FT-U NSTX, HT-6, EAST, T-10, T-11M, RFX, TJ-2, Lithium Facilities: IFMIF, KTM, UI, MAGNUM-PSI, TJ-2.**
- **NSTX Invited: "RLLD/ARLLD" by M. Ono, "High-temperature, LL plasma-facing component research for NSTX-U" by M. A. Jaworski, and "Li sputtering from lithium-coated graphite plasma facing components in NSTX divertor" by F. Scotti (PU).**
- **NSTX Orals: "Divertor deuterium recycling and oxygen influxes in Li experiments on NSTX" by V. A. Soukhanovskii (LLNL), "Measurements and Interpretive 2D Edge Modeling of Lithiated NSTX Discharges" by T.K Gray (ORNL), "Erosion and re-deposition of Li coatings on TZM molybdenum and graphite during high-flux plasma bombardment" by T. Abrams (PU), "An apparatus for the repetitive injection of Li granules into fusion research devices" by D. K. Mansfield, "A LL dripper for fueling and ELM pacing in NSTX-U" by D. Andruczyk (UI), and "E-beam flash evaporator for NSTX-U" by A.L. Roquemore.**
- **NSTX Poster: "Effect of Charge Exchange on Lithium Cooling in the Tokamak Scrape-Off Layer near the Divertor Surface" by M. Constantin (PU).**
- **R. Nygren (SNL) led a special session on Lithium-Safety and Lithium Handling,**
- **R. Goldston (PPPL) led a Panel Discussion on lithium feasibility for fusion reactors.**

Successful Implementation of FY13 Milestones

Mainly Through Data Analyses, Theory/Modeling, and Collaborations

FY 2013 NSTX-U Facility Joint Research Milestone

Conduct experiments on major fusion facilities, to evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs), and to improve understanding of the underlying physical mechanisms that allow increased edge particle transport while maintaining a strong thermal transport barrier. … Candidate regimes and techniques have been pioneered by each of the three major US facilities (C-Mod, D3D and NSTX). … Exploiting the complementary parameters and tools of the devices, joint teams will aim to more closely approach key dimensionless parameters of ITER, and to identify correlations between edge fluctuations and transport. The role of rotation will be investigated. The research will strengthen the basis for extrapolation of stationary high confinement regimes to ITER and other future fusion facilities, for which avoidance of large ELMs is a critical issue. Stefan Gerhardt of NSTX-U coordinated the FY 2013 JRT and the final report has been submitted to DOE.

FY 2013 NSTX-U Milestones

Research	Milestone Description	Baseline	Achieved
R(13-1)	Perform integrated physics and optical design of new high-k_θ FIR system	Sep 13	Sep 13
R(13-2)	Investigate the relationship between lithium-conditioned surface composition and plasma behavior	Sep 13	Sep 13
R(13-3)	Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios	Sep 13	Sep 13
R(13-4)	Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER	Sep 13	Sep 13

Facility	Milestone Description	Baseline	Achieved
F(13-1)	Complete procurement of components and begin installation of refurbished D-Site Rectifier Firing Generators	Sep 13	Sep 13

Diagnostics	Milestone Description	Baseline	Achieved
D(13-1)	Complete final design of the Multi-Pulse Thomson Scattering (MPTS) diagnostic modifications and begin installation of the modifications	Sep 13	Sep 13

F(13-1) *Complete procurement of components and begin installation of refurbished D-Site Rectifier Firing Generators*

- **The D-site rectifiers (74 identical Transrex AC/DC Convertors of the NSTX Field Coil Power conversion System (FCPC)) provide a pulsed power capability of 1800 MVA for 6 seconds every 300 seconds.**
- **The new 34 Firing Generator (FG) delivers firing pulses to 68 convertors with far greater resolution, precision, and repeatability for NSTX-U. Becomes particularly critical for the new 8-parallel, 130kA TF system configuration.**

Status:

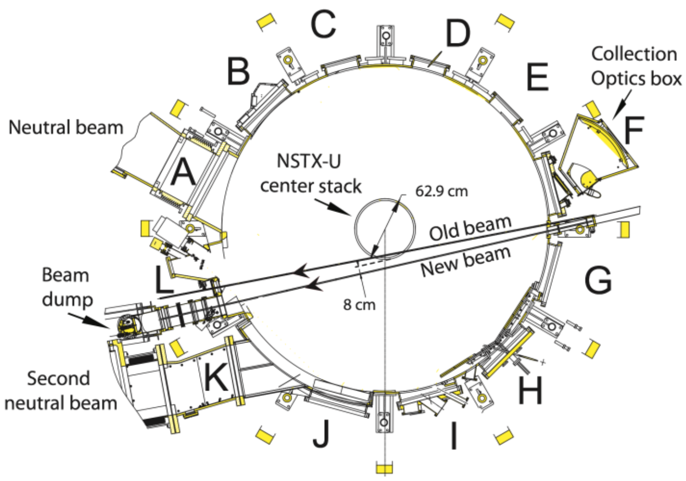
- **All 34 Firing Generators have been completed and delivered to FCPC. More than half have been installed in rectifiers.**
- **Fiber-optic control/communication links to be installed by end of November. Controls testing is expected to be complete by the end of the CY.**
- **Open circuit rectifier testing will be in progress by the early spring. Multiple rectifier power testing is expected by June, 2014.**

Transrex AC/DC Convertors

D(13-2) Complete final design of the Multi-Pulse Thomson Scattering (MPTS) diagnostic modifications and begin installation

- **Modification of the MPTS system is needed to accommodate the larger diameter NSTX-U Center Stack - Re-aim the laser beam, the light collection optics, redesign the beam dump, and calibration probe to be ready for the first plasma.**

MPTS Midplane Cross Section



FY 13 Accomplishments:

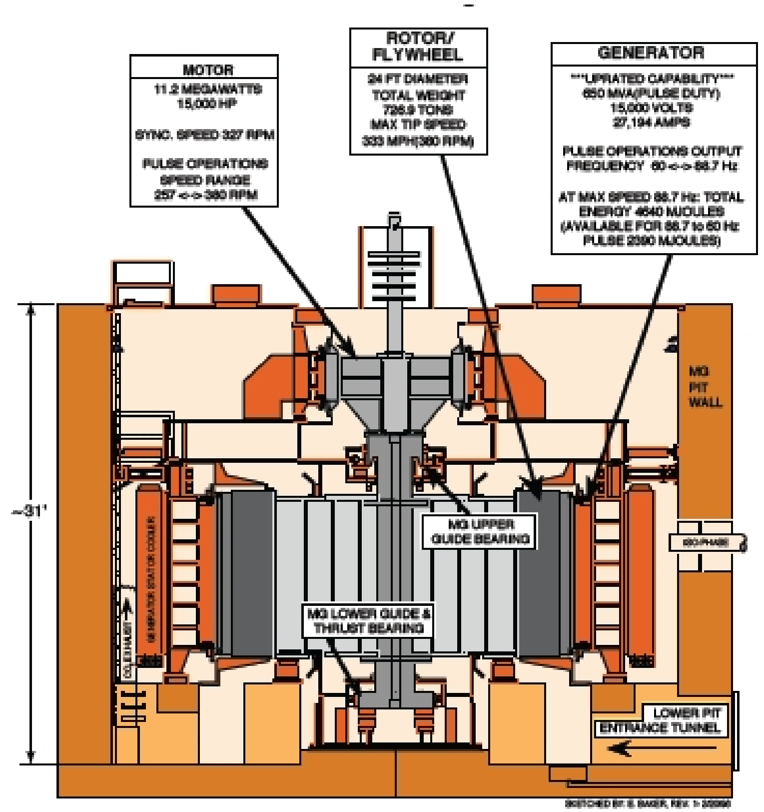
- **Design of the reconfigured MPTS system to meet these requirements was completed in FY2013 and three final design reviews were held to validate the design of the ex-vessel components.**
- **The new laser exit port and the new laser input port were installed on the vacuum vessel in FY2013.**
- **Fabrication and procurement of many of the needed ex-vessel components is underway and fabrication drawings for the remaining ex-vessel components are being prepared.**
- **The reconfigured MPTS diagnostic will be installed in FY2014 prior to NSTX-U first plasma and commissioned in early experimental operation following first plasma.**

- **Ahmed Diallo recently received an Early Career Research Program award - will install a fast rep rate (10-15 kHz) burst mode (5 ms) third laser for studies of ELMs and other fast phenomena in FY15.**

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).**

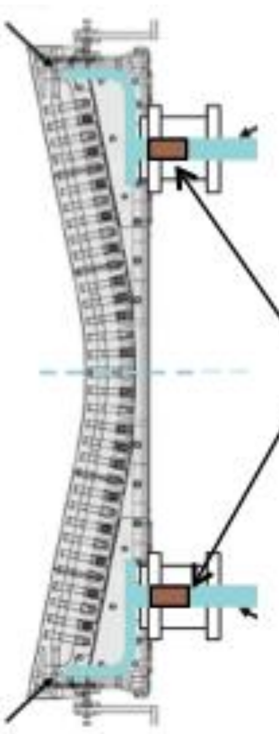


Status: Target completion date in Feb. 2014

- **A Statement of Work to perform the scope described in the repair procedure has been reviewed and approved.**
- **Fixed-price proposals for the weld repairs have been received. A WAF capturing all project costs (PPPL and Sub-contractor) is being generated.**
- **A draft Project Management Plan has been developed.**

New Compliant HHFW Antenna Feeds

Will allow antenna feedthroughs to tolerate 2 MA disruptions



Prototype electroformed compliant section

Installation on feed-thru

HHFW antenna tests planned in RFTF

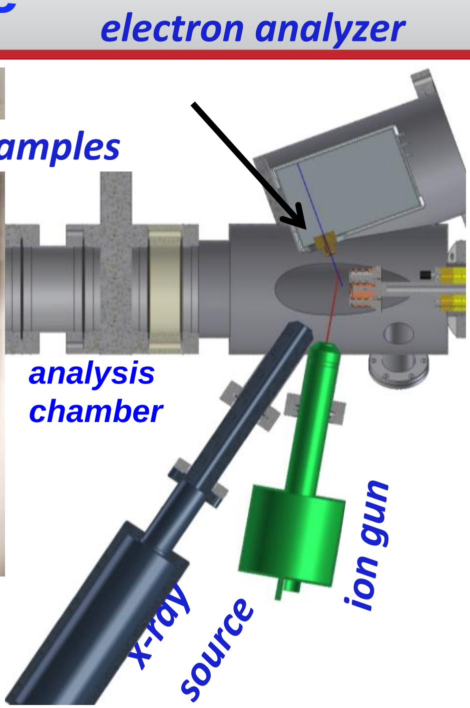
Inside of RF Test Stand with one antenna assembly.

- Prototype feeds procured.
- Feeds to be tested in the RF test-stand before FDR, installation in spring 2014.

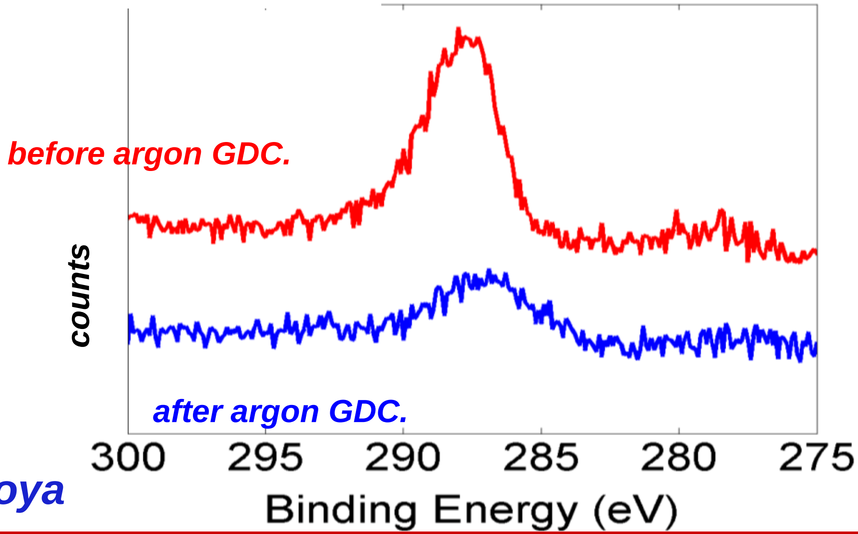
MAPP measurements of LTX surface after wall conditioning

Contributed to R13-2 Milestone

- **The Materials Analysis Particle Probe (MAPP) enables the prompt analysis of components exposed to tokamak plasmas.**
- **Lithium Tokamak Experiment is dedicated to the study of liquid lithium as a plasma-facing component (PFC).**
- **Argon Glow Discharge Cleaning (GDC) on LTX:**
  - **doubled the tokamak plasma current to > 20 kA**
  - **extended the duration to 25 – 30 ms.**
- **MAPP X-ray photo-electron spectroscopy showed reduction of surface carbon with GDC.**
- **Direct measurements of effect of GDC on surface of tokamak plasma-facing components.**



Carbon XPS spectra



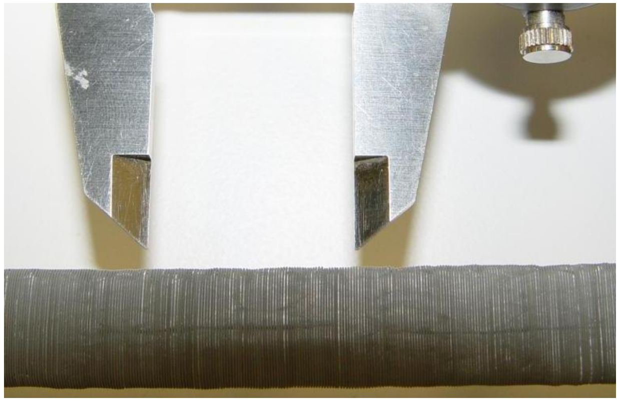
R. Kaita, M. Lucia J.P. Allain, F. Bedoya

Most Center Stack Diagnostics Fabricated

- **Manufacture of Mirnov coils and Rogowski coils complete**
  - Includes extra Mirnov coils and “segmented” Rogowski coils for halo current measurements
- **All copper and thermocouple wires procured**
  - Satisfy specialized material and insulation requirements for installation under plasma-facing components
- **Graphite Langmuir probe tips complete**
  - Fabrication of all center stack diagnostic components will be finished when insulators for probes in tiles are machined
- **Procedures nearly complete for installation of diagnostics when center stack is ready**

Plasma Current Rogowski Coil

Halo Current Rogowski Coil



NSTX-U diagnostics to be installed during first 2 years

Half of NSTX-U Diagnostics Are Led by Collaborators

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

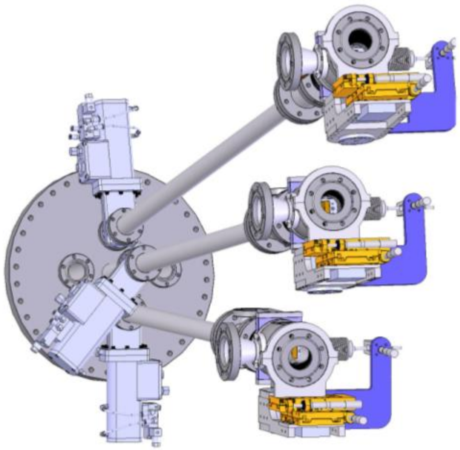
New capability, Enhanced capability

New Port Covers Have Been Designed For Bays E, I, J, and L

Detailed Design to Accommodate Enhanced NSTX-U Diagnostic Access Needs

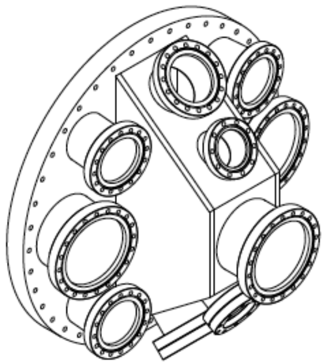
Bay E Supports 3

UV Spectrometers (LoWEUS, XEUS, MonaLisa) and MIG1



Bay J Supports

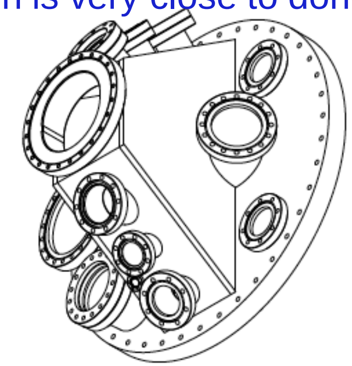
IR and Visible Cameras, UT-K and Divertor Spectrometers, Upward LITER, UCLA Reflectometer and Polarimeter, LBO, RF Probe.



Bay I Supports

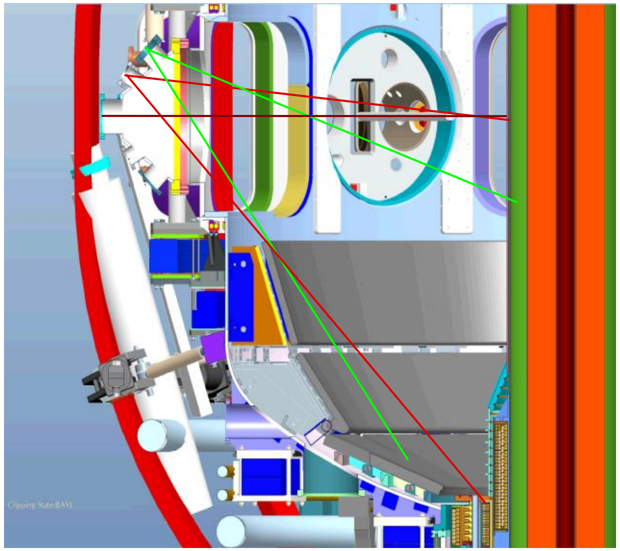
XCS, TGS, IR & Visible Cameras, SSNPA, SGI, 1D CCD & EIES, Microwave Imaging, QMB, Bolometers

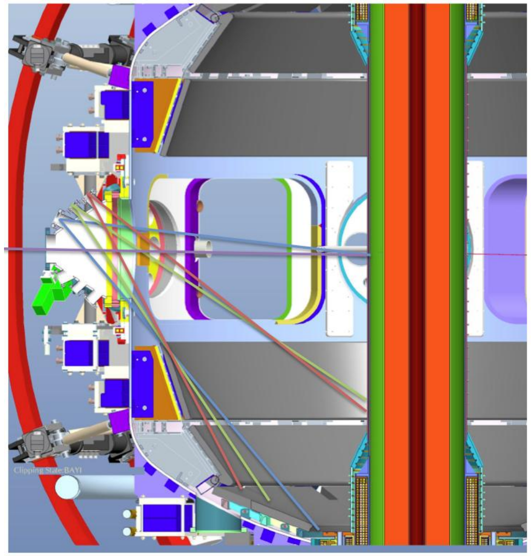
Design is very close to done.



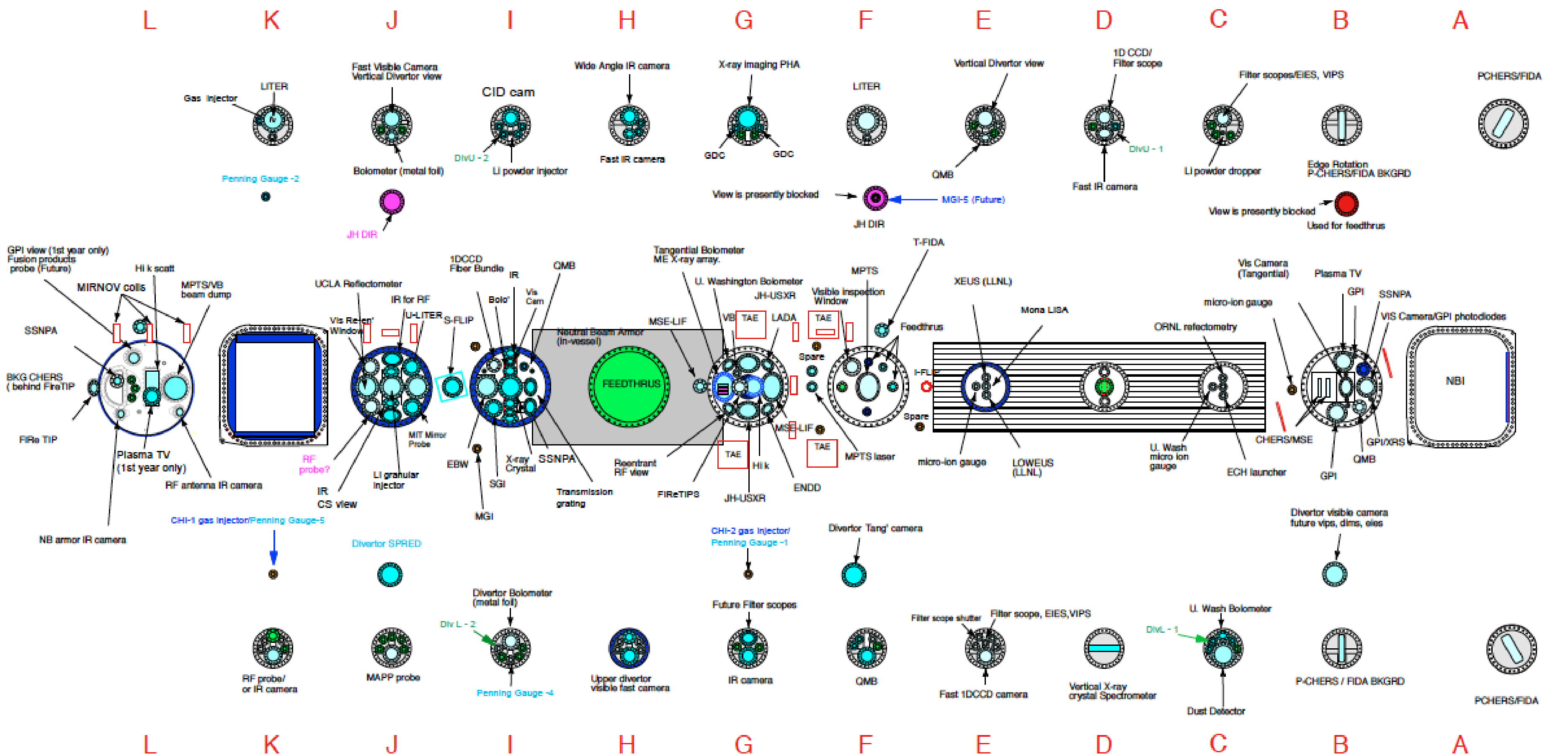
Bay-L Cap (not shown) Supports

MPTS exit window, High-k exit, plasma TV+GPI view, SSNPA, spectroscopy & CHERS view, GDC feedthroughs, magnetics feedthroughs.





NSTX-U facility/diagnostics port assignment
Port flanges designed and being procured



Engineering and Diagnostic Development/Operations Supporting Numerous Diagnostic Upgrades

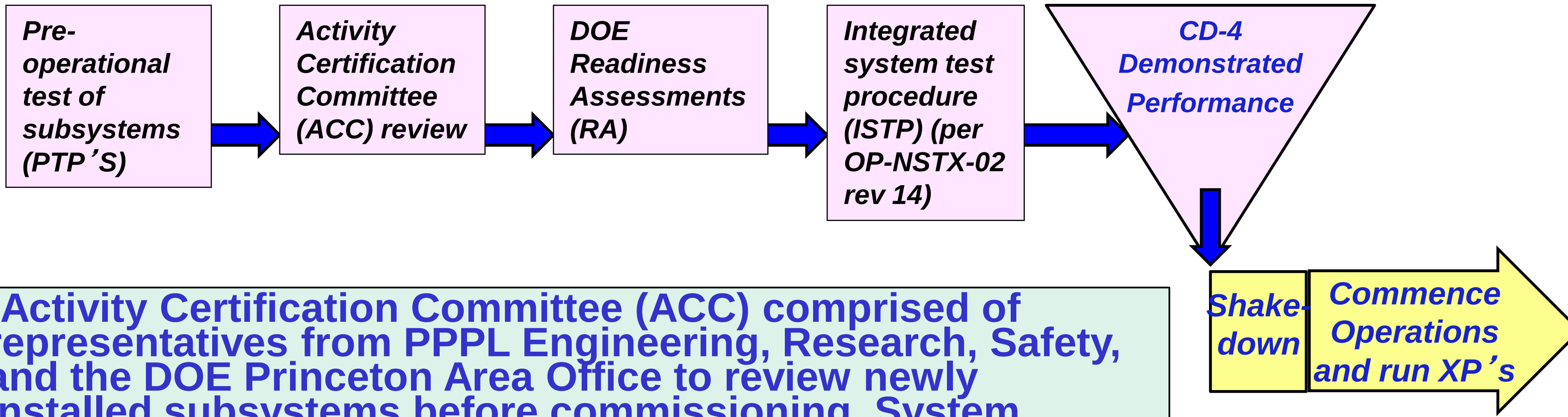
•Oct. 1 - Dec. 13: Basic diagnostic interface installation, first calibrations.
•Dec. 16 - Feb. 28: Test pump-down, leak checking and repair.
•March 1 - April 15: Finish diagnostic installations and calibration.

- Mid-plane Port Covers:
  - Bay E port cover is finished and ready for installation.
    - Supports suite of LLNL EUV instruments.
  - Bay J port cover is nearly finished…needs some modifications at vendor.
    - Supports LITER, Reflectometer & Polarimeter, RF Probe, various spectroscopy
  - Bay I port cover design is at the vendor…working out final details of their fabrication plan.
    - Supports SSNPA, TGIS, Bolometry,XICS, IR Cameras, QMB,…
- Diagnostic systems that are unchanged will be installed as part of a generic procedure.
- Diagnostic systems that are new or heavily modified will need dedicated installation procedures.
- Key near term task: get as many diagnostic vacuum interfaces as possible on machine by December.

Transition into operations- planning underway

NSTX-U Start-up Process Similar to NSTX

NSTX-U ISTP, Commissioning, and Startup will follow the same process as NSTX initial commissioning and startup from February 1999.



- **Activity Certification Committee (ACC) comprised of representatives from PPPL Engineering, Research, Safety, and the DOE Princeton Area Office to review newly installed subsystems before commissioning. System reviews are performed at completion of construction activities.**

- **Led by the DOE Princeton Site Office (PSO), a Operational Readiness Assessment (ORA) will be made based on ACC and QA Audit reports before the project moves to start-up.**

- **Safety Certificates allowing Power and then Plasma Operation will be issued upon the recommendations of the ORA.**

NSTX-U Coil Energization

- A programmable Digital Coil Protection System (DCPS) with control algorithms appropriate for NSTX-U parameters is being developed to protect both coils and structures.
- Includes data acquisition, user interfaces, auto-testing, and standalone codes for algorithm verification and scenario development.
- Systems are currently being installed with plans to begin pre-operational testing in Feb. 2014, and full system commissioning in June 2014.
- 1st year operating space parameters will be established and control algorithms verified.
- Same algorithms will be applied to the Power Supply real Time Control System (PSRTC).
- DCPS/PSRTC systems will be configured to support limited FCPC rectifier dummy load testing in Mar. 2014.

Plans to Rapidly Recover Physics Operations Capabilities

ISTP:
(Integrated Systems Test Procedure)
Establishes facility in state of readiness for operations.

Plasma Operations with:
$I_p \leq 1.0$ MA, $B_T \leq 0.5$
Develop:
Breakdown and current ramp scenarios
Shape & position control
Reliable H-mode
Diagnostic operations

Continue to add diagnostic & control capabilities while initiating physics experiments.

$I_p \leq 1.5$-1.6 MA
$B_T \leq 0.75$-0.8

Aug-Nov. 2014

ISTP-1 & CD-4 Prep	MPTS Calibrations, Bake Out, CD-4	Operations Commissioning	Phys. Ops	ISTP-2	Phys. Ops

~ 2-3 Months

Attempt 50 kA CD-4 plasma before bake-out. If water in PFCs prevents success, then repeat after bake-out.

ISTP-2
Required to increase the field and current for later research phase

Formulating Strategy Toward Full NSTX-U Parameters

After CD-4, the plasma operation could enter quickly into new regimes

	NSTX (Max.)	Year 1 NSTX-U Operations (2015)	Year 2 NSTX-U Operations (2016)	Year 3 NSTX-U Operations (2017)	Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160
I_P Flat-Top at max. allowed I^2t, I_P, and B_T [s]	~0.4	~3.5	~3	5	5

- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year 1 data has been accumulated
- 3rd year goal: Full capability

NSTX-U Operation Preparation Well Underway
Exciting Opportunities and Challenges Ahead

- **NSTX-U Team has been quite productive in all areas.**
- **NSTX-U researchers participated strongly in ISTW-2013 (STs) and ISLA-2013 (Lithium) workshops.**
- **All of the NSTX-U FY 2013 milestones accomplished on schedule.**
- **NSTX upgrade outage activities are progressing well**
  - **Diagnostics were stored and secured for the upgrade activities. Collaborator diagnostics are being refurbished and enhanced.**
  - **Researchers are working productively on data analysis, collaboration, preparation for the NSTX-U operation.**
  - **NSTX operations technical staff were shifted to the Upgrade Project tasks in FY 2012 – 13. They will be shifted back to the NSTX-U operational preparation in FY 2014 as the Upgrade Project scopes are completed.**
  - **NSTX Upgrade Project is thus far progressing on budget and on schedule.**
  - **NSTX-U operational preparation is well underway.**
  - **Diagnostic reinstallation are starting.**
  - **Various engineering operations tools are being refurbished / upgraded including CHI gap, rectifier control, motor generator, plasma control system, and PF control.**

NSTX-U

Supported by

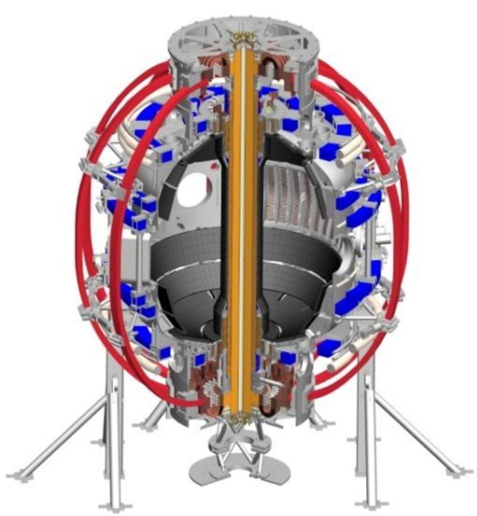
U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U FY2013 Year-end Report:
Notable outcomes, research milestones

J. Menard (PPPL)

FES Room G258
PPPL Room B205
October 22, 2013

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

FES FY2013 Notable Outcomes for NSTX-U

- Outcome 1.1a "Support the FES joint research target to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER."

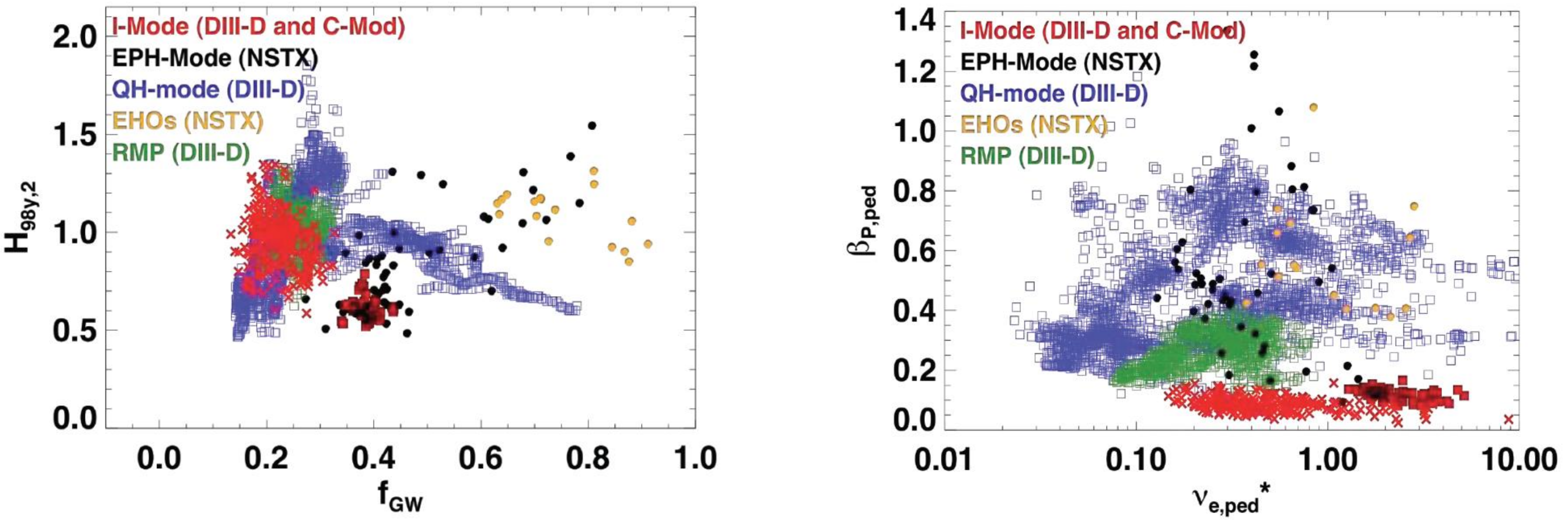
- Outcome 1.2a "Carry out high impact research relevant to NSTX-U through domestic and international collaborations"

- Outcome 3.1b – "Develop a prioritized research plan for NSTX-U to provide an assessment, within five years, of the viability of the ST concept as an attractive Fusion Nuclear Science Facility"

Outcome 1.1a "Support the FES joint research target (1)

to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER."

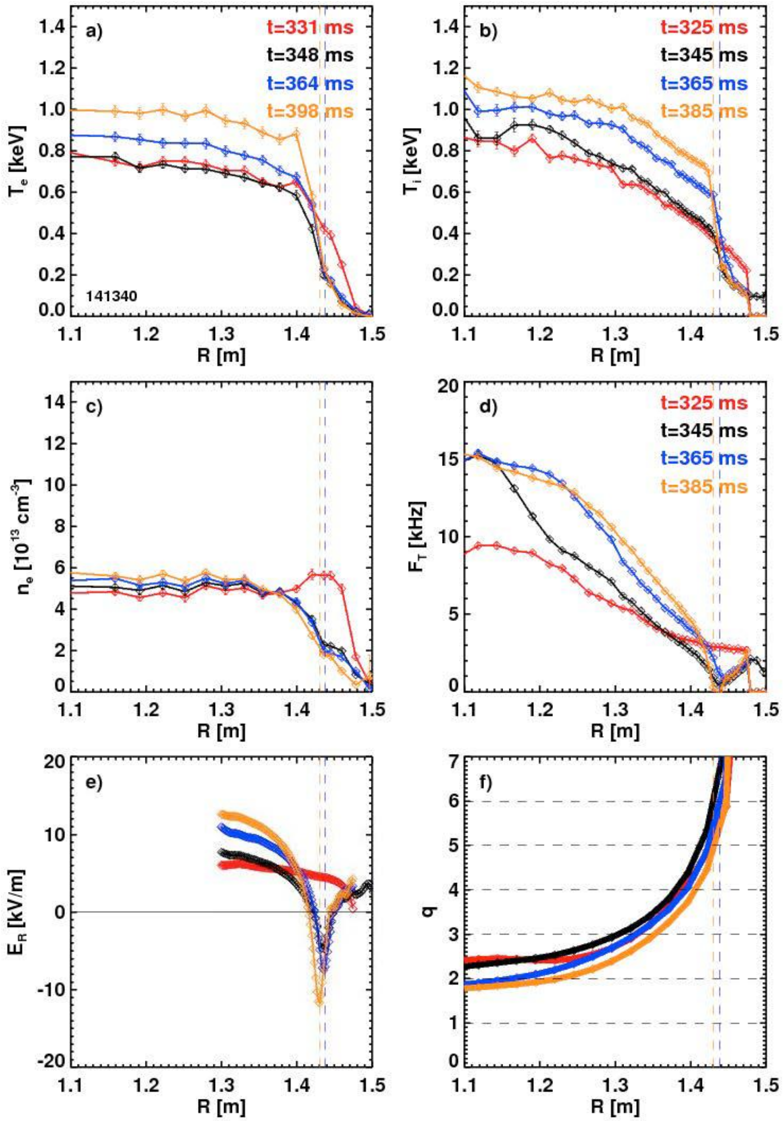
- Stefan Gerhardt (PPPL) was JRT leader and coordinated group telecons and discussions/meetings between the participating researchers
- NSTX team contributed data from Enhanced Pedestal H-mode (EP H-mode) – an attractive regime of nearly stationary high confinement + high β



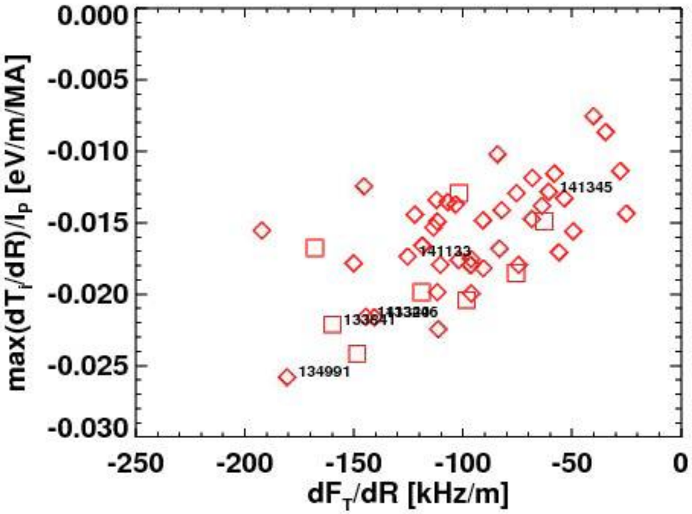
- NSTX research into EP H-mode developed:
  - Better understanding of the range of ion temperature profile shapes in EPH
  - Improved correlations between T_i pedestal parameters and the edge rotation shear
  - An assessment of turbulence as inferred from the edge reflectometer (UCLA), and examined those results with XGC0 and GS2 modeling

Outcome 1.1a "Support the FES joint research target (2)

to explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier and to extrapolate these regimes to ITER."



- Maximum normalized Ti gradient proportional to rotation shear



- BES, FIR: no reduction in fluctuation amplitudes evident during EPH
- XGC0: ion thermal profiles most consistent w/ kinetic neoclassical
- GS2: plasma is 2nd stable (KBM not observed), increasing ∇T_i stabilizing, most dominant mode TEM/KBM hybrid

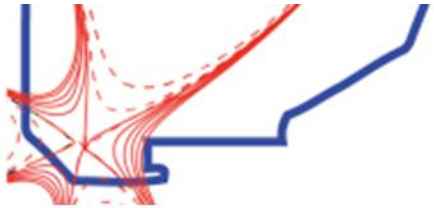
Outcome 1.2a "Carry out high impact research relevant to NSTX-U through domestic and international collaborations"

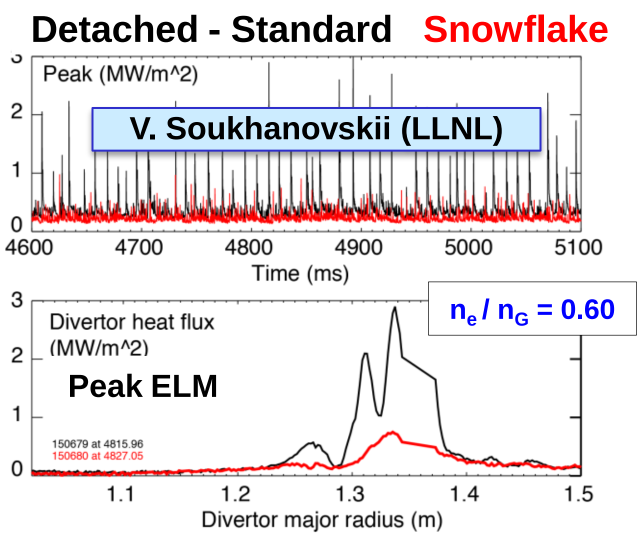
A few examples:

- Heat-flux mitigation development on DIII-D
- CHI start-up system design for QUEST at Kyushu, Japan
- EBW start-up, fast-ion, and transport research on MAST
- MHD stability and NTV research on KSTAR

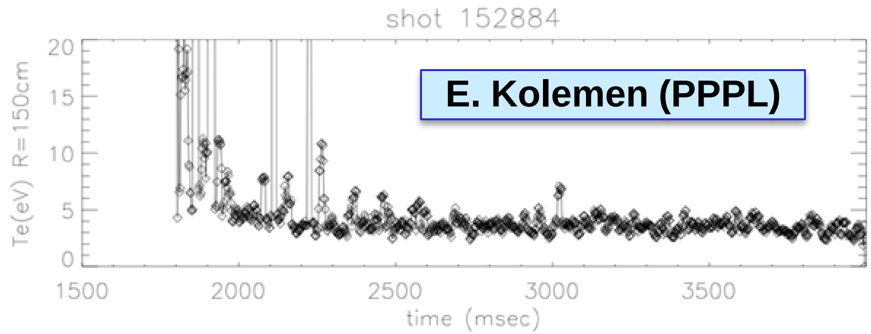
Developed snowflake and radiative detachment control on DIII-D in preparation for usage on NSTX-U

- Significant heat flux reduction between and during ELMs in DIII-D snowflake
- Developed SF magnetic control





- Real-time divertor radiation / detachment control developed, sustained detachment achieved



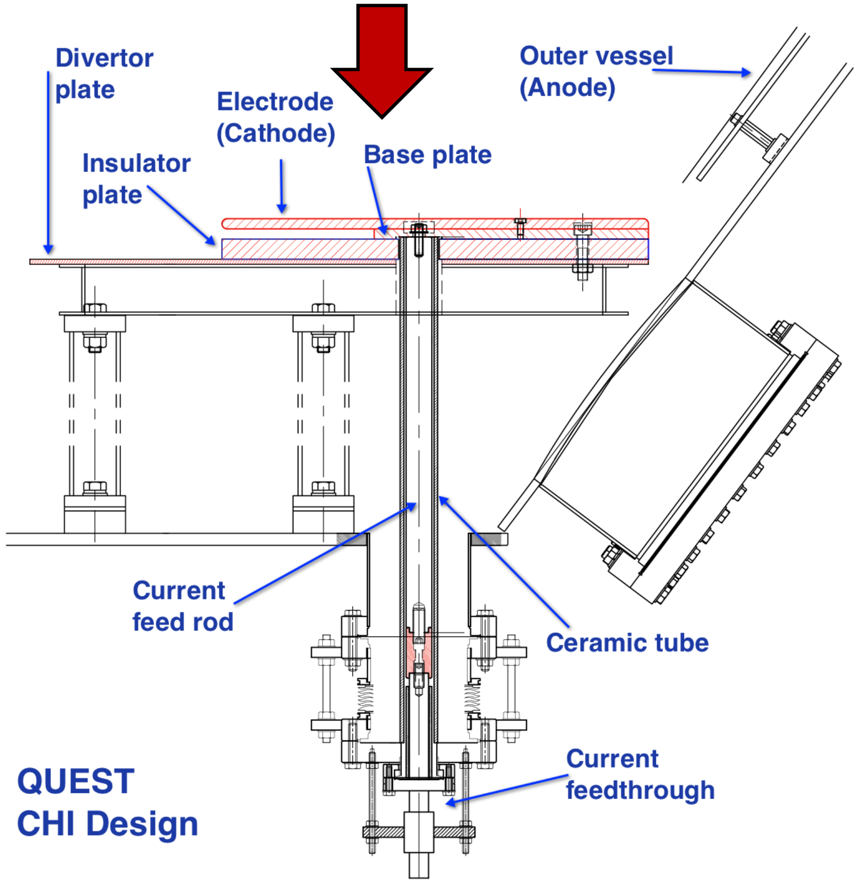
- Real-time diagnostics: bolometry, D_β, interferometry, Thomson (divertor, core, tangential)
- Actuators: D_2 and Ne gas puffing to obtain desired level of detachment and/or radiation.

V. Soukhanovskii was co-leader of snowflake-divertor portion of heat-flux mitigation experiments in recently completed DIII-D "National Campaign"

CHI Design for QUEST Supports NSTX-U and FNSF Research

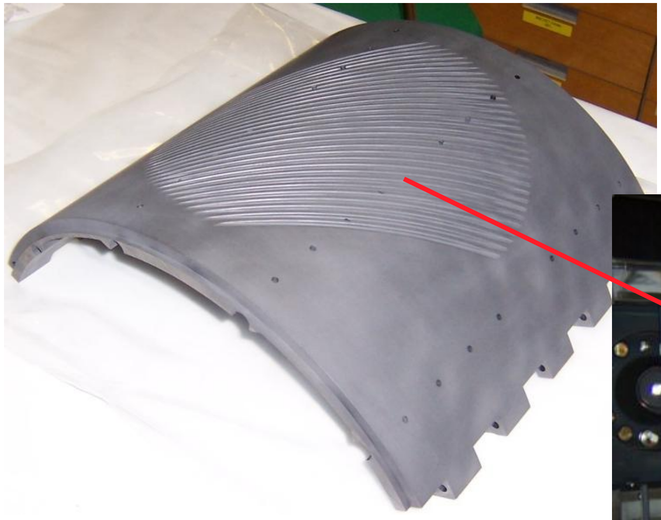
R. Raman (Univ. Washington) collaboration with Kyushu University (Japan)

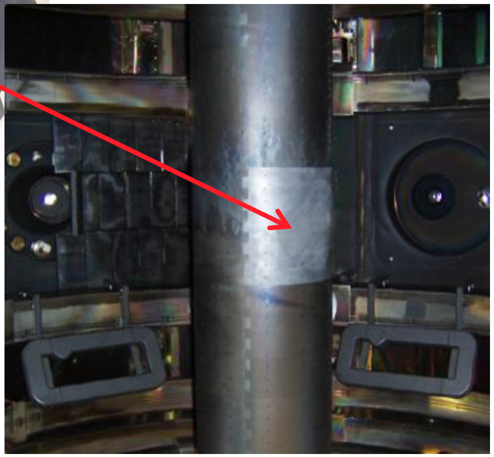
Electrodes mounted on top of existing divertor plate



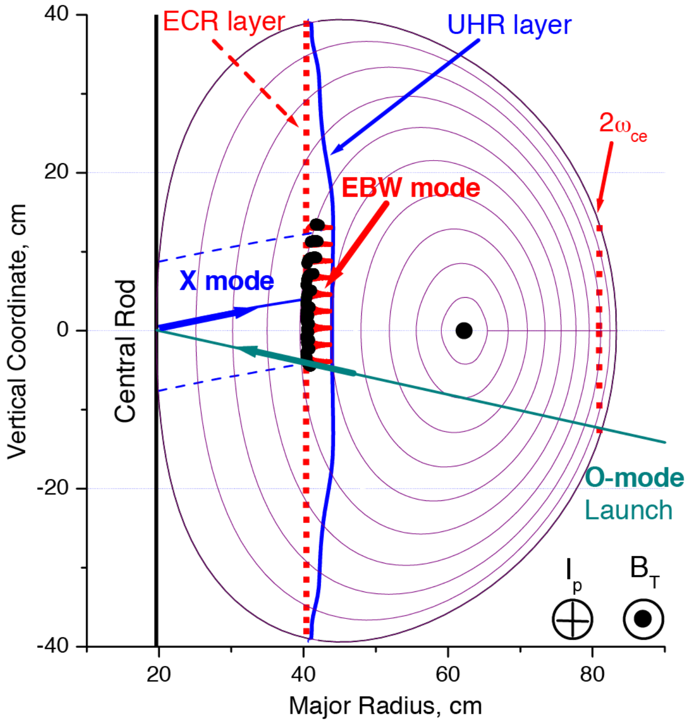
- QUEST ST aims to develop technologies for SS operation
  - Use CHI in biasing mode to vary edge density gradient for EBW experiments
  - High CHI current provides new target for SS CD studies on QUEST
  - Interested in potential of steady-state CHI for edge current drive (aided by all metal nature of QUEST + ECH)
- Benefits to NSTX-U & QUEST
  - Test metal electrodes to reduce low-Z impurities
  - Test ECH heating of CHI target at 0.5MW level
  - Test new electrode configuration to enhance compatibility with FNSF

MAST: 28 GHz EBW start-up campaign in 2013 used new low-loss transmission line to achieve record plasma current





Grooved reflecting polarizer machined into center column in MAST

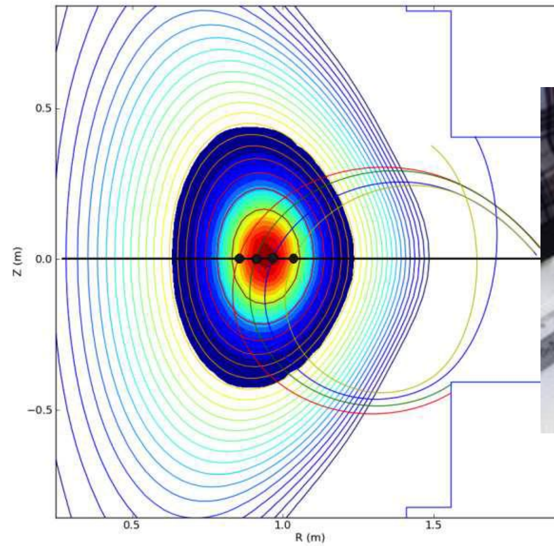


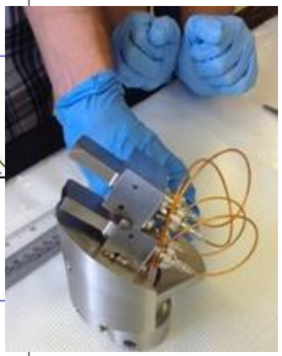
- 28 GHz O-mode weakly absorbed (< 2%) below $n_e \sim 1 \times 10^{19}$ m^{-3} cut off
- Polarizer on center column converts to X-Mode that then 100% converts to EBWs
- Previously achieved I_p~33 kA but arcs in waveguide limited RF power [Sept 2009]
- **During two one-week EBW start-up campaigns in 2013 coupled 70-100 kW for 300-400 ms achieving I_p = 50-75 kA**

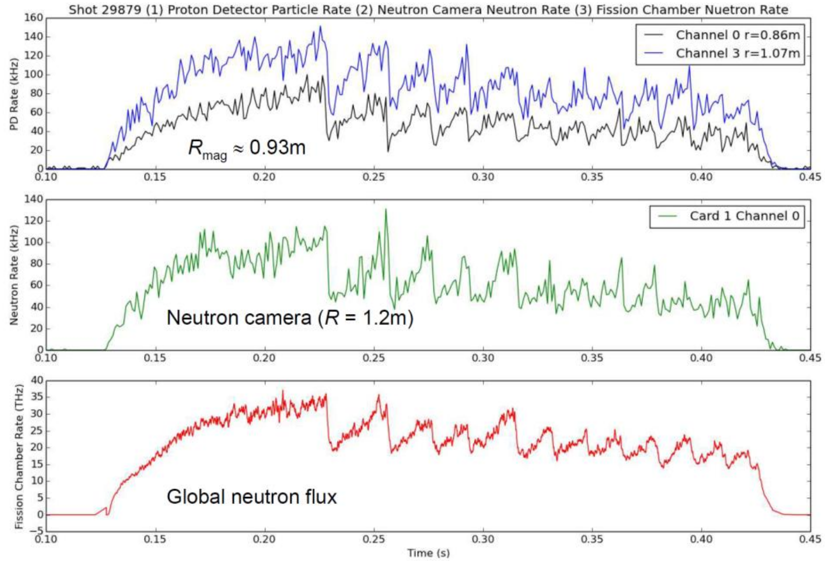
G. Taylor (PPPL), with ORNL

Fast ion diagnostic collaboration with MAST

- D. Darrow (NSTX-U/PPPL) visited MAST August 2013 to contribute to tests of Florida International University (FIU) MeV proton detector on MAST
- Detector measures radial profile of DD fusion reactivity through detection of the 3 MeV protons and 1 MeV tritons produced in DD reactions
  - Testing conducted in conjunction with Prof. W. Boeglin and R. Perez (FIU), and the MAST team.
- Data on the radial profiles obtained under range of conditions:
  - Quiescent plasmas, sawtoothing discharges, and during fishbone modes
- Comparisons with profiles obtained from MAST neutron camera are underway
- Results encouraging for development of a higher channel count system for NSTX-U







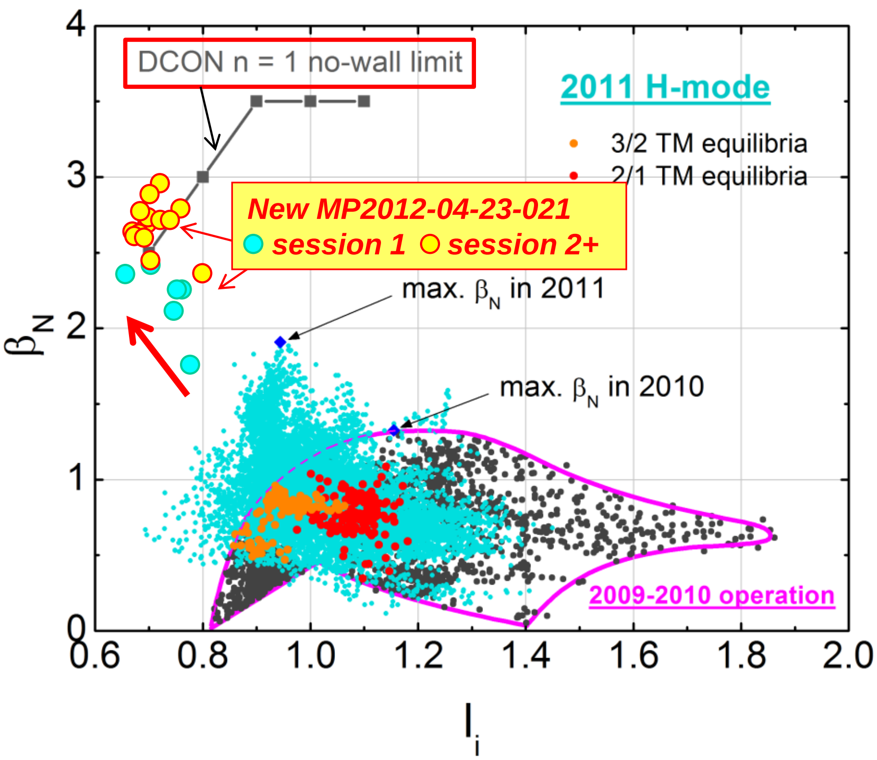
Additional fast-ion and transport collaborations with MAST during M9

- Studied fast ion redistribution caused by TAE avalanches, extending previous studies on NSTX (Podesta, Fredrickson)
  - D-alpha emission found to be sensitive to fast-ion losses
- Measured momentum transport in MAST L-modes using 3D field perturbations for rotation braking (W. Guttenfelder)
  - Also initiated particle transport exts (gas puffs, high time-res Thomson)
- DBS diagnostic implemented on MAST – collaboration with UCLA and NSTX-U (A. Diallo, M. Podesta)
  - Observed transitions from a negative- to a positive-frequency-peaked spectrum related to change in core intrinsic rotation
  - Fluctuations with f~100–150 kHz from TAEs, possibly due to a fluctuating ExB flow associated with the TAE electric field perturbation
  - Diagnostic will be installed on NSTX-U after MAST M9 is complete

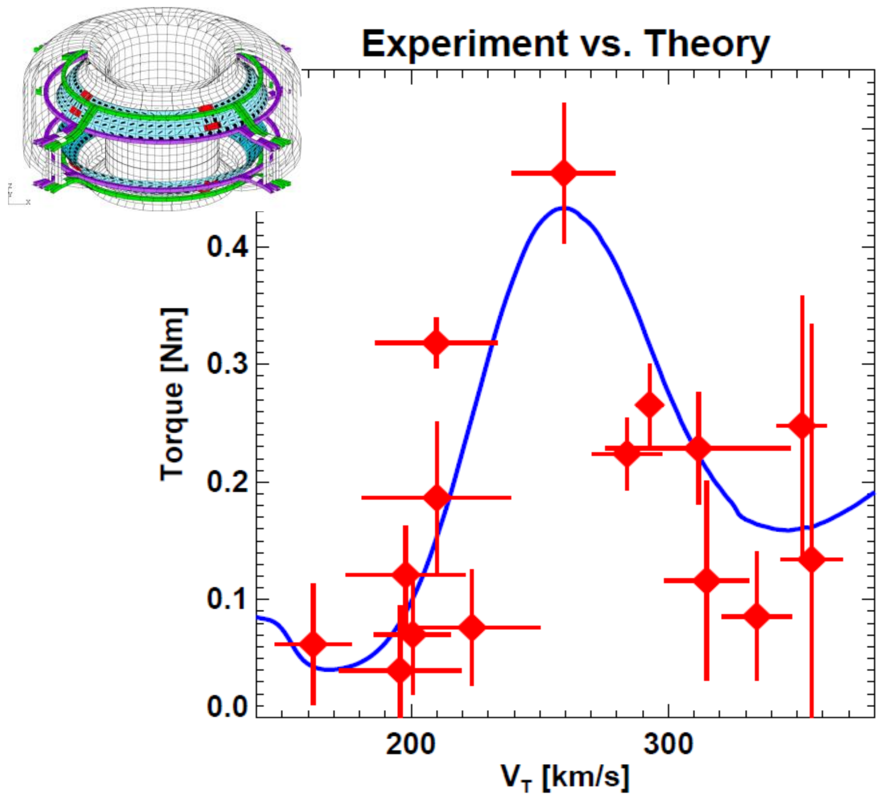
NSTX experience in scenario development, high-beta, and 3D physics is having significant impact on KSTAR research

- Improved shape control, improved access to low l_i + high κ: D. Mueller, D. Battaglia, E. Kolemen (PPPL)

- Studying MHD stability near no-wall beta limit: S. Sabbagh (CU)



- Bounce-harmonic resonance in NTV observed in KSTAR for the first time in tokamak, and compared to theory/IPEC: J-K Park (PPPL – 2010 ECRP)
  → Published in PRL



Outcome 3.1b – "Develop a prioritized research plan
for NSTX-U to provide an assessment, within five years, of the viability of the ST concept as an attractive Fusion Nuclear Science Facility"

Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
2. Access reduced ν* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

Longer-term (5-10 year) goal:

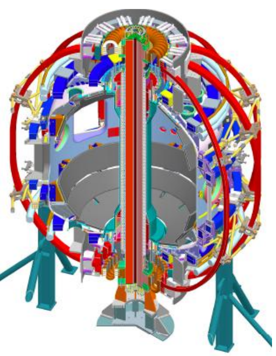
Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

NSTX-U goal staging: first establish ST physics + scenarios, transition to long-pulse + PMI integration (5YP incremental)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage | **Establish ST physics, scenarios** | **Integrate long-pulse + PMI solutions**

New center-stack



Start-up and Ramp-up
- Increase CHI closed-flux current
- Achieve NI start-up/ramp-up
- Assess plasma gun start-up at increased device size
- Develop/understand ECH/EBW H&CD for ST
- Increase/extend ramp-up heating and off-axis current-drive for advanced scenarios

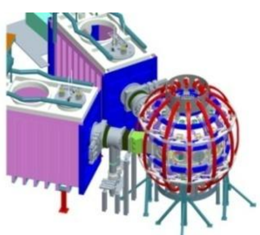
Boundary Physics
- Establish main-ion density and ν* control
- Understand snowflake divertor performance
- Understand high-Z first-wall erosion, migration, particle sources & sinks

Materials and PFCs
- Assess baseline graphite PFC performance
- Assess high-Z tile/divertor impact and performance
- Assess high-Z divertor and/or first-wall
- Assess impact of high-temperature first-wall

Liquid metals / lithium
- Establish low impurities / Z_{eff}, assess increased Li coverage, replenishment
- Test flowing liquid metal for heat-flux mitigation, surface replenishment
- Assess flowing LM PFC with full toroidal coverage

MHD
- Understand kinetic MHD, extend mode and disruption detection, develop mitigation
- Enhance non-axisymmetric field spectrum and capabilities with off-midplane coils for control of: RWM, EF, RMP, rotation, NTM, EP

Transport & Turbulence
- Understand ES and EM turbulence at high β, low ν*, emphasizing e-transport
- Extend wave-number coverage of turbulence measurements



2nd NBI

Waves and Energetic Particles
- Characterize AE stability, fast-ion transport, NBI-CD, support plasma start-up, assess effectiveness of fast-wave in NBI H-modes
- Prototype driving edge-harmonic oscillations (EHOs) and/or *AE

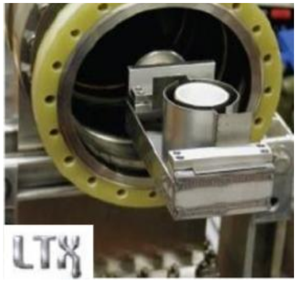
Scenarios and Control
- Demonstrate full non-inductive, high I_P & P_{AUX} operation
  Control: boundary, β, divertor heat flux, Ω & q profiles
- Assess integrated control of long-pulse / high-performance

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

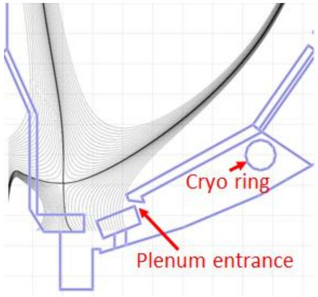
5 year plan includes longer-term facility enhancements to fully utilize Upgrade capabilities, support ITER and FNSF

- **Improved particle control tools**
  - Control deuterium inventory and trigger rapid ELMs to expel impurities
  - Access low ν^*, understand role of Li

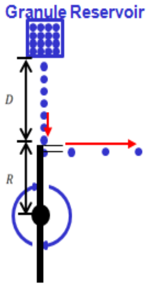
Upward Li evaporator



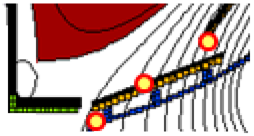
Divertor cryo-pump



Li granule injector (LGI)

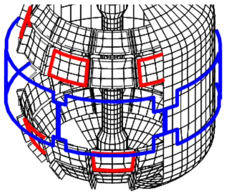


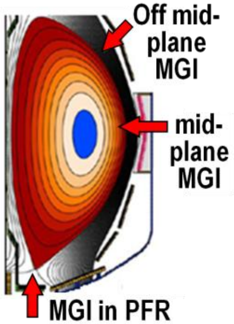
- **Disruption avoidance, mitigation**
  - 3D sensors & coils, massive gas injection



Extended low-f MHD sensor set

Midplane + off-midplane
non-axisymmetric control coils (NCC)





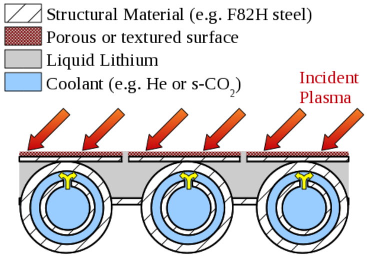
- **ECH to raise start-up plasma T_e to enable FW+NBI+BS I_P ramp-up**
  - Also EBW-CD start-up, sustainment

1-2MW 28 GHz gyrotron

- **Begin transition to high-Z PFCs, assess flowing liquid metals**
  - Plus divertor Thomson, spectroscopy

High-Z tiles

Actively-supplied, capillary-restrained, gas-cooled LM-PFC



The NSTX-U 5 Year Plan review comments were largely favorable

- **Programmatic comments (from debrief report):**
  - "The quality of the proposed research is excellent, employing state-of-the-art diagnostics to obtain data that will be compared to theory using a wide variety of numerical models."
  - "The proposed research addresses fundamental problems in magnetic fusion and will advance the state of knowledge in a number of areas."
  - "The proposed research is essential for advancing the ST to a nuclear science mission."
- **Facility enhancement comments (from written report):**
  - "The addition of a divertor cryo-pump will be an excellent addition to their program."
  - "NCC will greatly enhance physics studies and control"
  - "Given the essential need for non-inductive startup for FNSF-ST, acquisition of a 28 GHz gyrotron to provide capability for heating CHI plasmas to allow better absorption of HHFW, is important to the long-term program"
  - "The proposed additions of the flowing liquid Lithium divertor and divertor Thomson scattering diagnostic are desirable.
    - Reassessment of the importance of the flowing Lithium divertor relative to other items covered under base funding is recommended."

NSTX-U FY2013 Research Milestones

- R(13-1): Perform integrated physics and optical design of new high-k_θ FIR system

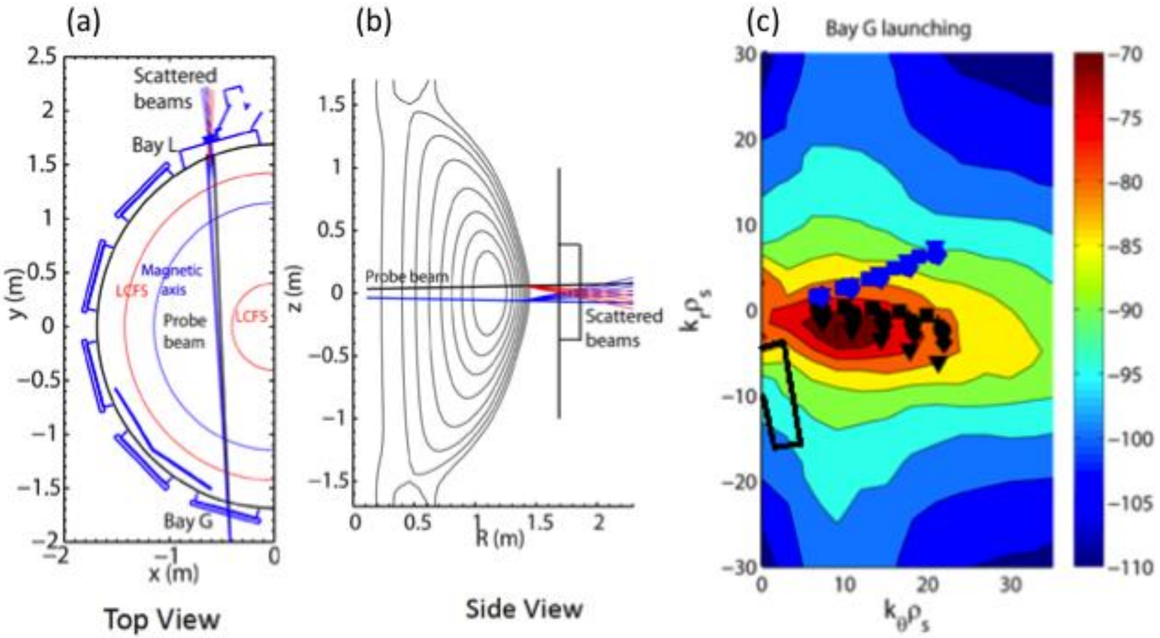
- R(13-2): Investigate the relationship between lithium-conditioned surface composition and plasma behavior
  - See results slide in Masa's presentation

- R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios

- R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER

R(13-1): Perform integrated physics and optical design of new high-k_θ FIR system

- **System will provide measurement of k_θ-spectrum of both ETG and ITG modes**
  - NSTX 280 GHz high-k tangential system of NSTX will be replaced by a 604 GHz (CO_2-pumped FIR laser) poloidal scattering system being developed by UC Davis
  - The reduced wavelength in the poloidal system will result in less refraction and extend the poloidal wavenumber coverage from the current 7 cm^{-1} up to > 40 cm^{-1}
- **Anisotropy in 2D k-spectrum of ETG turbulence (i.e. ETG streamers), can be determined by comparing k-spectrum measured by different schemes:**
  - Total of 4 scattering schemes possible w/ different combinations of toroidal, poloidal tilt angles



a) Schematic of the toroidal cross section of the high-k scattering beam geometry

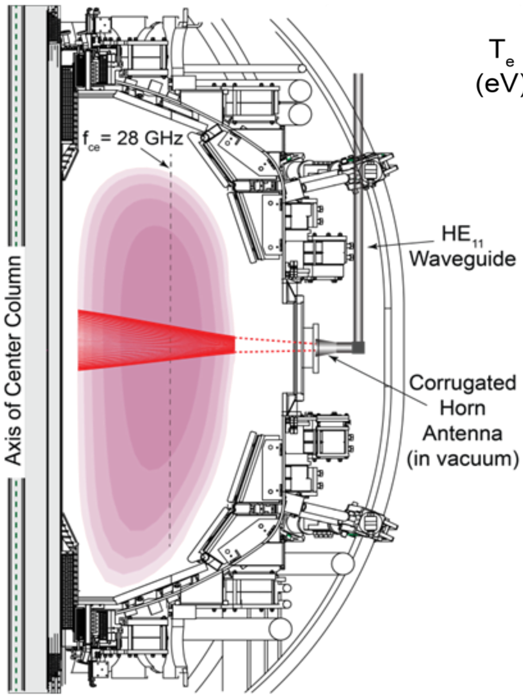
b) Poloidal cross sectional view of the beam geometry

c) Regions in 2D k_r and k_θ space covered by two scattering schemes

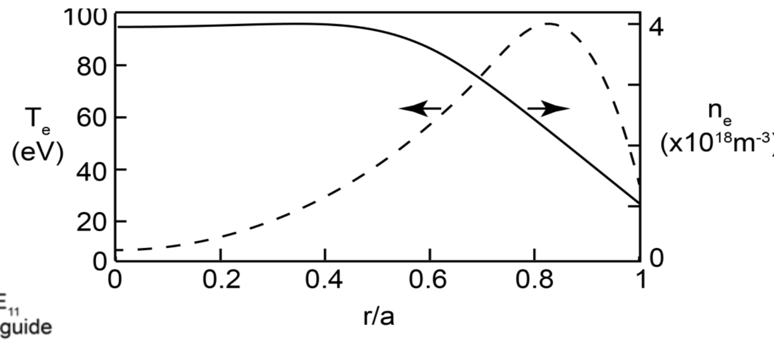
Y. Ren (PPPL), with UC Davis

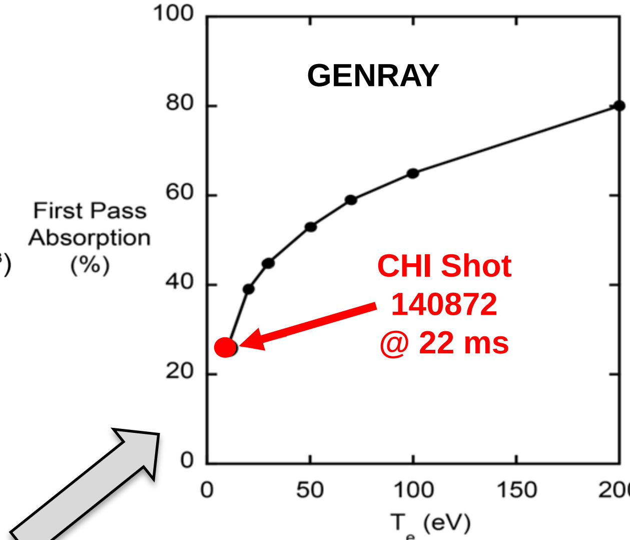
R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios (1)

- **Low n_e = 3-4 x 10^{18} m^{-3} CHI discharges amenable to 28GHz EC heating:**



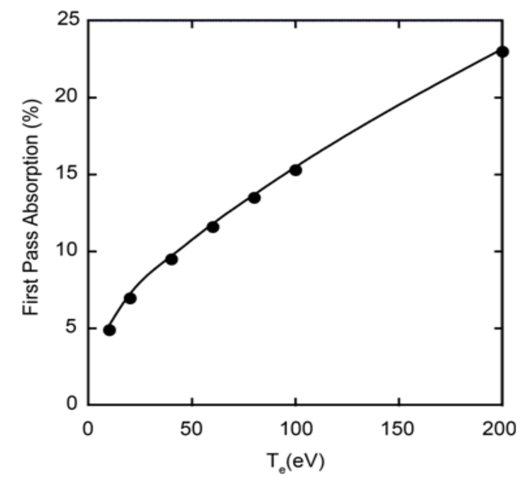
NSTX CHI Shot 140872 @ 22 ms





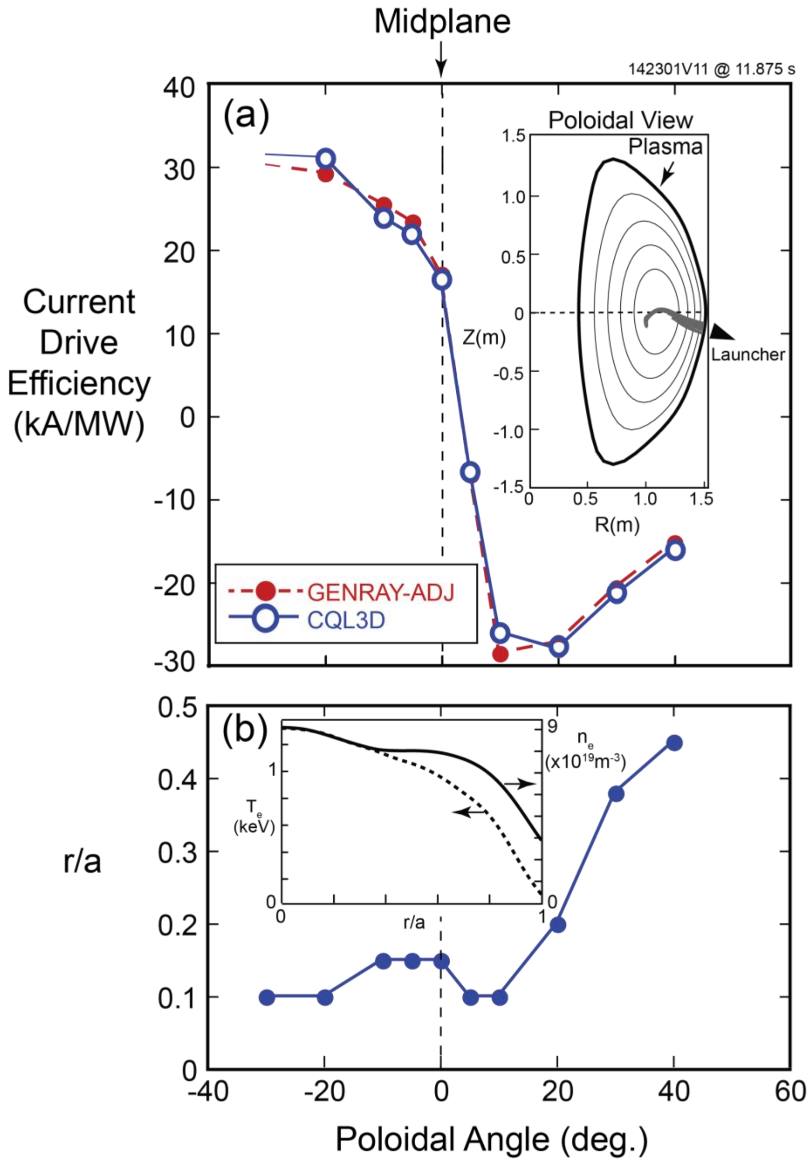
- At $B_T(0)$ = 0.55T, first pass EC absorption ~25% → expect rapid heating to ~200 eV

- At $B_T(0)$ = 1T, first pass EC absorption (at fundamental) is reduced by factor of ~4



G. Taylor (PPPL), with CompX

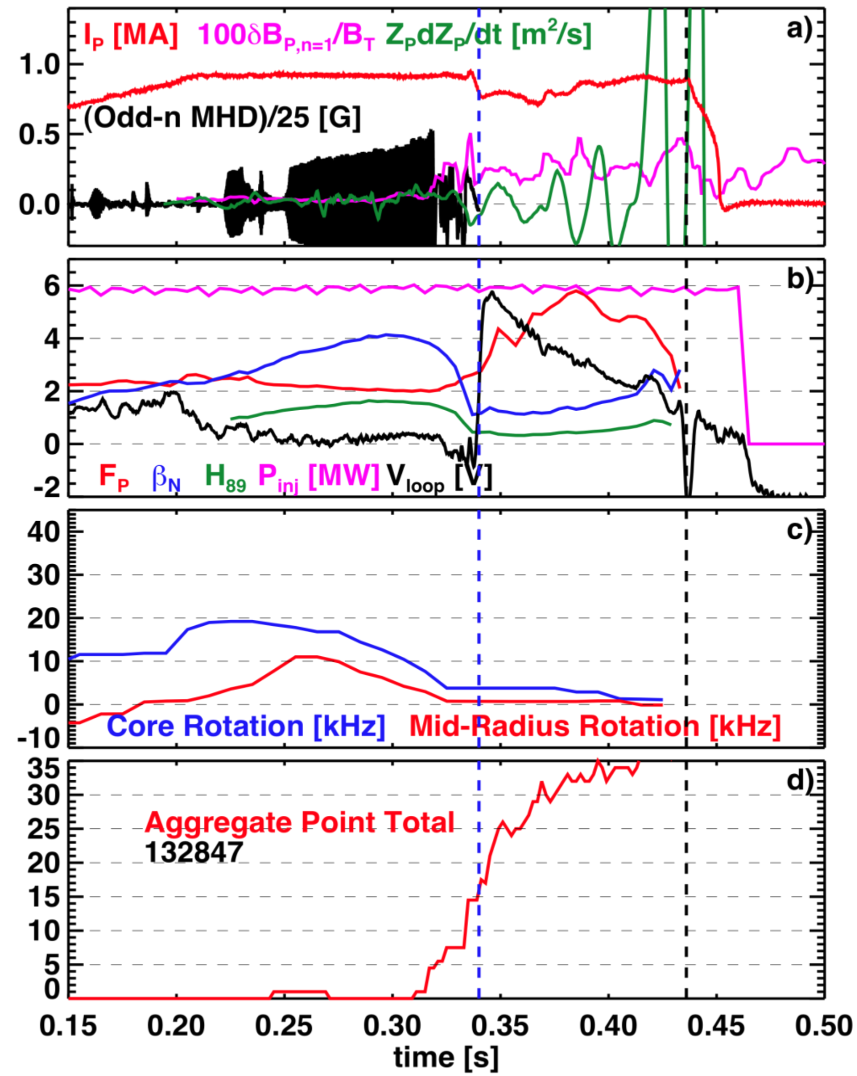
R(13-3): Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios (2)



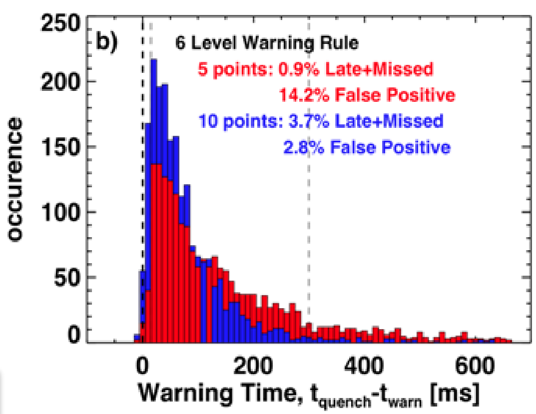
- I_P =1.1 MA, $B_T(0)$ = 1T, H-mode
- EBWH, CD modeling tools:
  - GENRAY ray tracing + ADJ quasi-linear package
  - CQL3D Fokker-Planck
- Max. O-X-B mode conversion efficiency: $n_{||} = \pm 0.7$ at launch
- Poloidal launch angle scanned from -30˚ to 40˚
  - Max CD efficiency: ~±30kA/MW
  - **Normalized efficiency comparable to NBICD**
- Deposition minor radius variable between 0.1 to 0.5
- Adjusting B_T or f_{RF} → can position peak J_{EBWCD} at r/a ≥ 0.8

R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (1)

- Most critical measurements, analysis:
  - I_P vs request, δB, Z^*dZ/dt, F_P, β_N, H_{89}, V_{LOOP}, rotation frequency, neutron rate…
- Disruption warning methodology:
  - Each threshold test is executed, # of points for each test is evaluated
  - Points from individual tests are totaled to form "aggregate" total
  - Disruption warning declared if total exceeds a pre-defined threshold

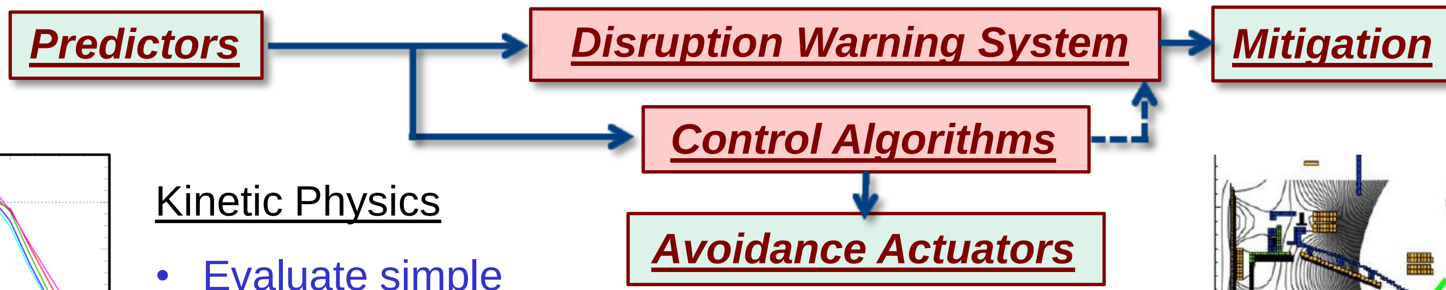


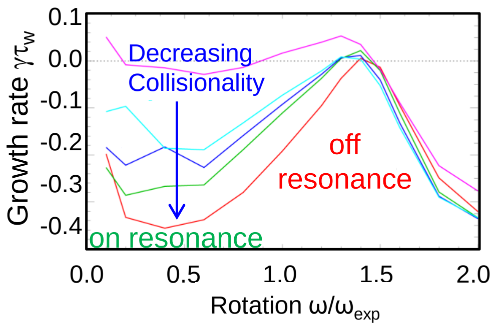
- Late or missed disruptions can be traded against false-positives

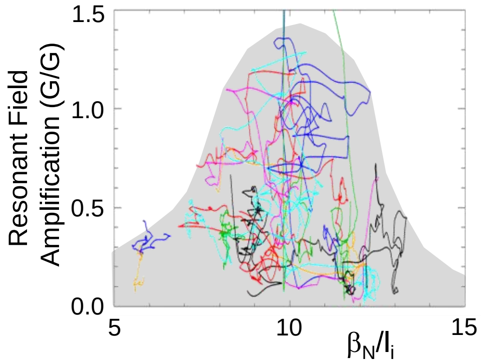


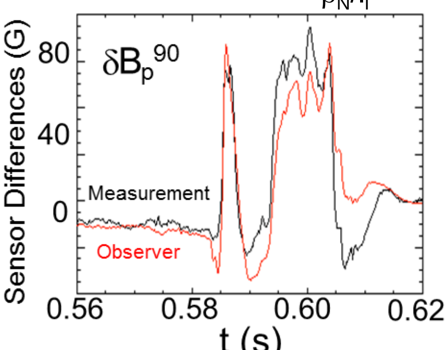
S. Gerhardt (PPPL)

R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (2)









Kinetic Physics

- Evaluate simple physics criteria for global mode marginal stability in real-time

MHD Spectroscopy

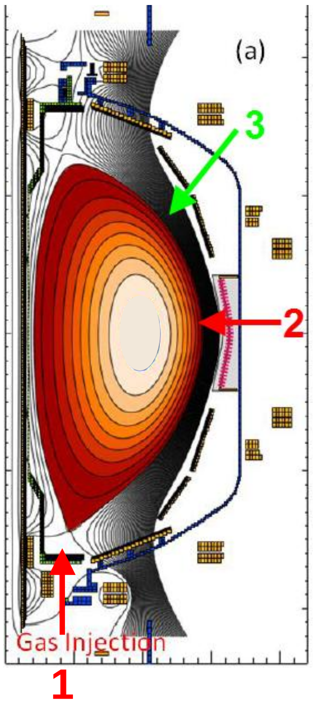
- Use real-time MHD spectroscopy while varying rotation, q_{min}, and β_N to predict disruptions

q, v_ϕ, β_N control

RWMSC observer

- Compare mismatch between the RWMSC observer and sensor measurements, and disruption occurence

3D fields, feedback

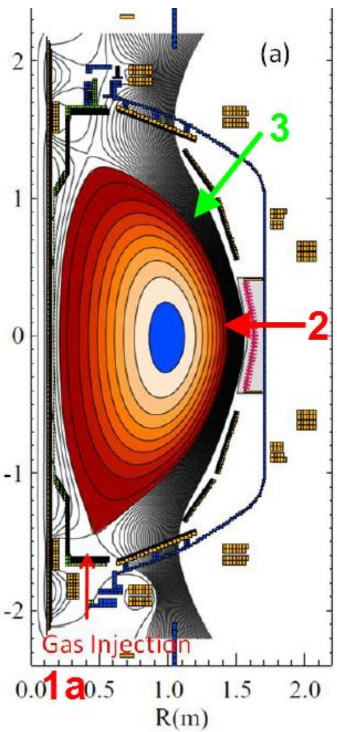


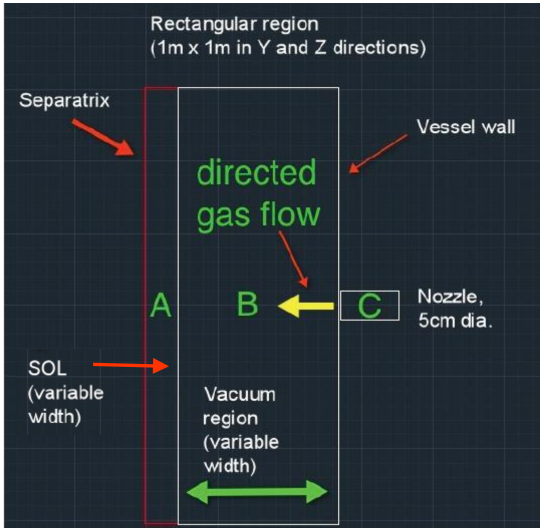
ITER gas-loading :

Injection into private flux region with higher assimilation efficiency?

R(13-4): Identify disruption precursors and disruption mitigation and avoidance techniques for NSTX-U and ITER (3)

MGI research will assess gas penetration efficiency by injection at different poloidal locations

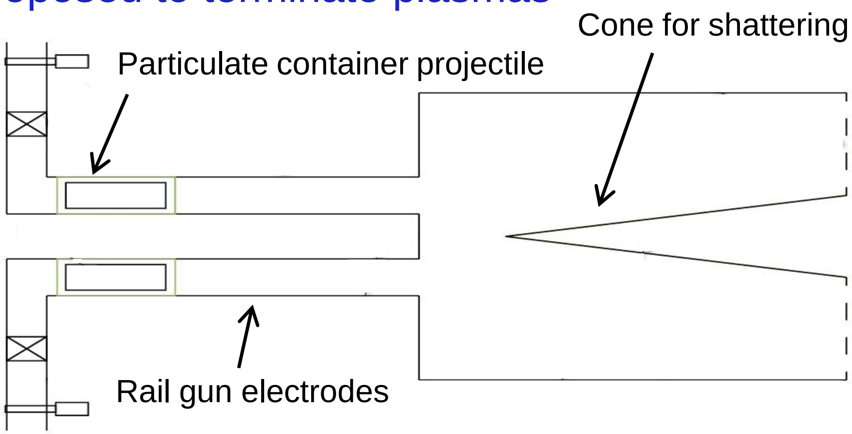




Predictive capability: Modeling using DEGAS-2 is quantifying the gas penetration past the SOL for NSTX-U

- NSTX-U can offer new insight by
  - Reducing the amount of gas
  - Injecting gas into the private flux and lower x-point regions of divertor to determine if these are more desirable locations for MGI.

Development of a novel mitigation technology – an electromagnetic particle injector (EPI) – is proposed to terminate plasmas



- The EPI is capable of delivering:
  - A large particle inventory
  - All particles at nearly the same time
  - Particles tailored to contain multiple elements in different fractions and sizes
  - Tailored particles fully ionized only in higher current discharges (to control current quench rates)
- Well suited for long stand-by periods

R. Raman (U. Washington)

Maintained strong team and publication and conference participation, development of early career researchers

	PPPL/PU	National Team (non-PPPL/PU)	International	Total
Total Researchers	79	166	61	306
Post-Docs	5	9	0	14
Students	3	26	4	33

Number of institutions	
Total	61
Domestic	32
International	29

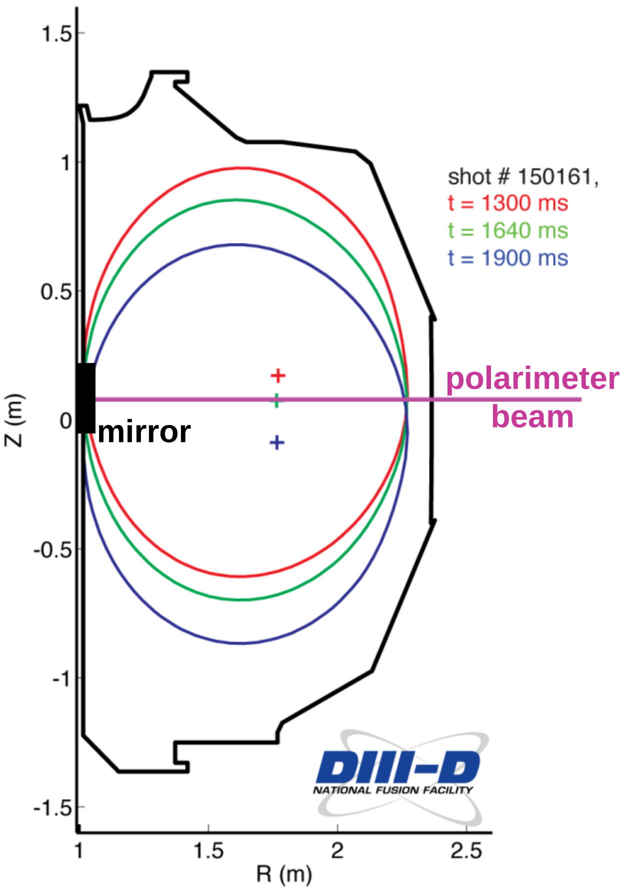
Calendar Year	Refereed Publications	PRLs	APS Invited	IAEA Papers
2009	45	6	5	
2010	63	5	10	25
2011	58	5	8	
2012	56	1	4	30
2013	52 so far	4 (so far)	6	

- Ahmed Diallo (PPPL) received 2013 DOE Early Career Research Program (ECRP) award for: “Edge Pedestal Structure Control for Maximum Core Fusion Performance”
- NSTX snowflake divertor team featured in October 2012 FES Science Highlights, led by V. Soukhanovskii (LLNL - 2010 ECRP) – also leading DIII-D snowflake expts.

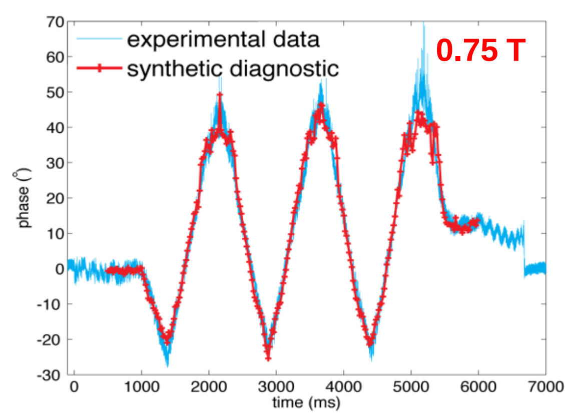
Thank you!

UCLA successfully tested 288 GHz polarimeter for NSTX-U on DIII-D

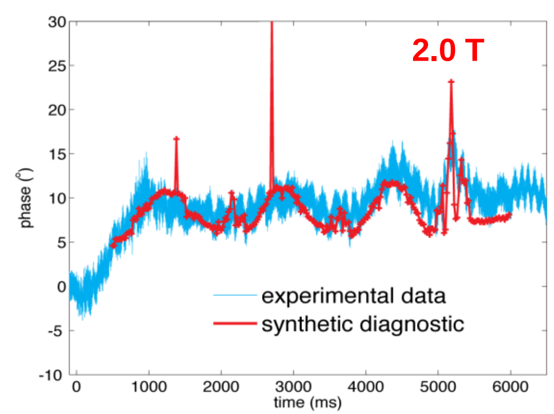
UCLA Graduate Student: J. Zhang – Thesis Project



- Dedicated DIII-D run time to test polarimeter over wide range of conditions: phase response predicted to vary strongly with vertical position and B_T.
  - Moving plasma vertically → Faraday rotation due to horizontal B ranges from weak to strong
  - Wide range of B_T → elliptization (Cotton-Mouton effect) ranges from weak to strong
- Synthetic diagnostic calculations agree with measured phase over wide range of B_T (0.75-2.0 T), plasma height



Faraday rotation dominated

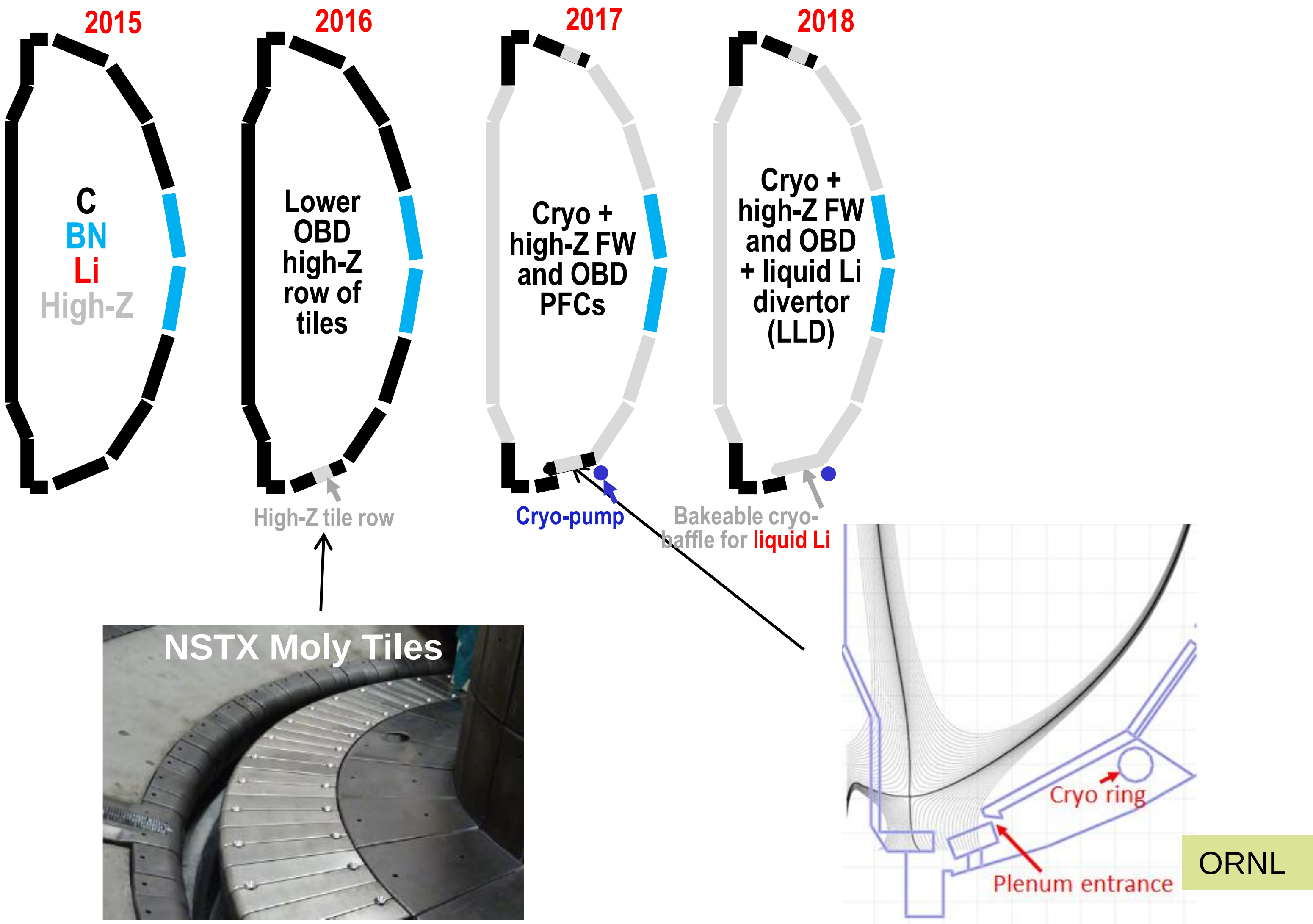


Cotton-Mouton effect dominated

- **Polarimetry planned to be used to measure μ-tearing δB in NSTX-U**

Boundary Facility Capability Evolution

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

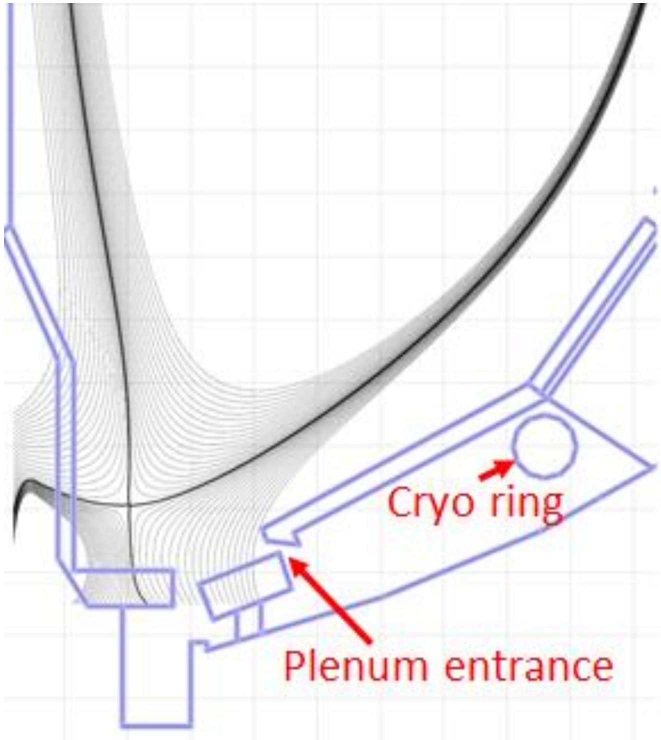


Divertor Cryo-pump for particle control

Particle pumping for broad range of divertor parameters

Basis for Divertor Cryo-Pump Budget:

- Divertor cryo-pump is well developed. DIII-D has a long history of cryo-pump implementation.
- NSTX-U will adopt DIII-D cryo-pump design.
- Utilize DIII-D cryo-pump actual cost and adapt it to NSTX-U.



Cost Estimate Assumptions:

- No credit taken for smaller radius of NSTX-U
- SWIP cryo-pump system design achieved 14,000 hours design effort reduction. NSTX-U will take 50% of the credit.

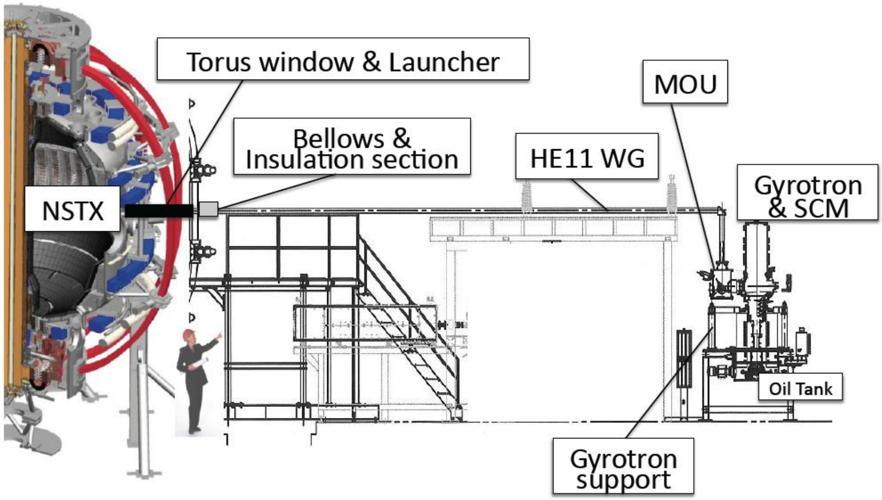
Scaling from DIII-D to NSTX-U System	$k
Inflation adjusted DIII-D actuals	$7,283
Liquid helium and nitrogen system tie in	$1,000
Credit of the design effort reduction by 7,000 hours	-$1,050
Cryo-pump tile work is covered elsewhere	-$1,000
The total estimate cost =	$6,233

1 MW 28 GHz Gyrotron System

For bridging the start-up temperature gap and EBW research

Basis for 1 MW 28 GHz Gyrotron Budget:

- System is well defined. Similar system working in Japan (Tsukuba and QUEST).
- PPPL has a collaboration with DIII-D on ECH. Some internal ECH expertise.
- ~ 50% of budget is procurement
- Antenna and waveguide is costed elsewhere.
- But with some implementation uncertainties:
  - Actual location is not finalized.
  - Power supply configuration not finalized. Utilize NBI power supply? Need for a polarity switch. Procure a new power supply?



Sub tasks	Cost Estimate (k$)	Basis for cost estimate
gyrotron system procurement	$1,760	(estimate from Tsukuba University)
water system	$560	(PPPL estimate)
power supply	$3,000	(pursuing various options)
control & instrumentation	$1,500	(previous experience on similar system)
Total Cost Estimate	$6,820	

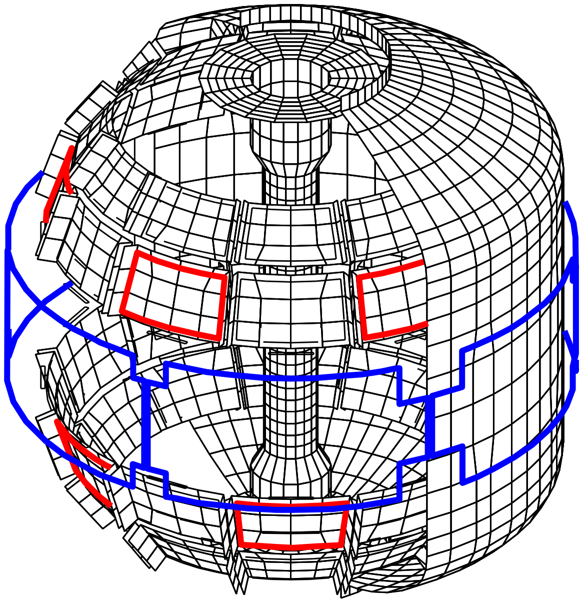
Partial NCC Coils - New MHD and Plasma Control Tools

Sustain high β_N, control rotation, modify edge transport

Basis for Partial NCC Budget:

- NCC utilized the cost actuals from the DIII-D I-Coil work.
- Actual hours spent on the I-coil tasks are the same for the NCC coils by the PPPL personnel with similar skills ($).
- M&S cost is inflation adjusted.
- DIII-D spent significant R&D and Testing of I-Coils. Assume the same level of effort for the NCC coil R&D and Testing. This may generate savings.

Partial NCC option (2 x 6 odd parity)



Cost Estimate Assumptions:

- The # of coils are the same for NCC and I-Coil systems.
- No credit taken for the NCC coil size to be half that of the I-Coil.
- NCC (RWM) diagnostics are separately funded.

Tasks	actual hours	Cost ($k)
Design	2886	$495
Fabrication	5270	$793
Installation	4102	$617
R&D Testing	8565	$1,352
M&S	inflation adj	$569
Total		$3,825

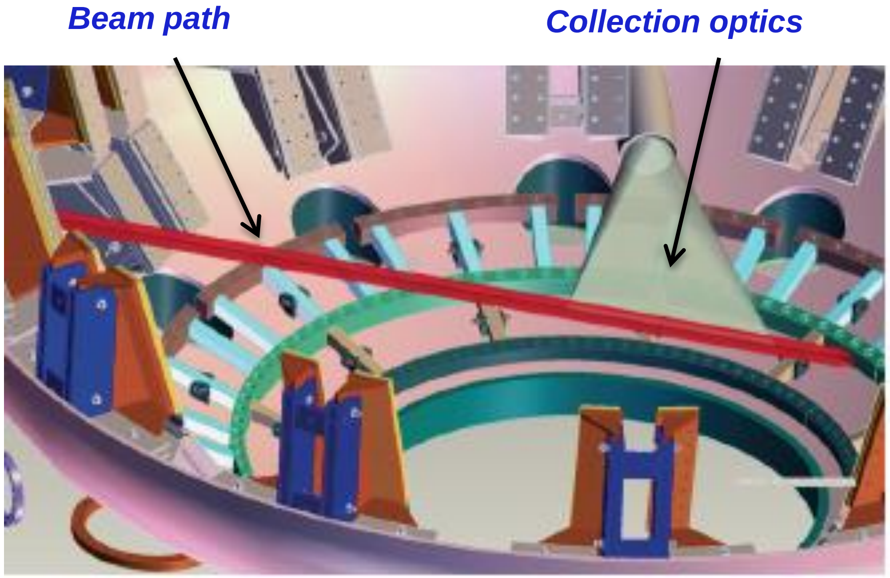
Divertor Thomson Scattering System

For divertor and SOL heat and particle transport studies

Basis for Divertor Thomson Budget:

- Relatively detailed engineering study was performed in 2008.
- A base-up cost estimate developed.
- There are two main components: Thomson scattering laser system related items and related vacuum vessel modifications and utilities.

Divertor Thomson Scattering Geometry



Cost Estimate Assumptions:

- Laser components and related items are estimated to cost ~ \$950k. This includes computer, laser optics, laser safety, cooling, and 10% contingency.
- Device modification estimate is ~ \$3,550k. This includes system design, laser room, AC power, interlocks, E-stop, diagnostic racks, light collection optics, laser focusing optics, vacuum vessel modification, cable tray, flight tube. We assume ~ 35% contingency due to relative complexity of the in-vessel work.
- The total cost estimate is \$5.6M with overall 30% contingency.