NSTX-U Recovery Project

R. J. Hawryluk

FES Quarterly Review

Presentation includes Preliminary Information

June 14, 2017

PPPL

PRINCETON UNIVERSITY

Outline

- ✓**Design Verification and Validation Reviews leading to Extent of Condition Reviews**

- Main Technical Challenges

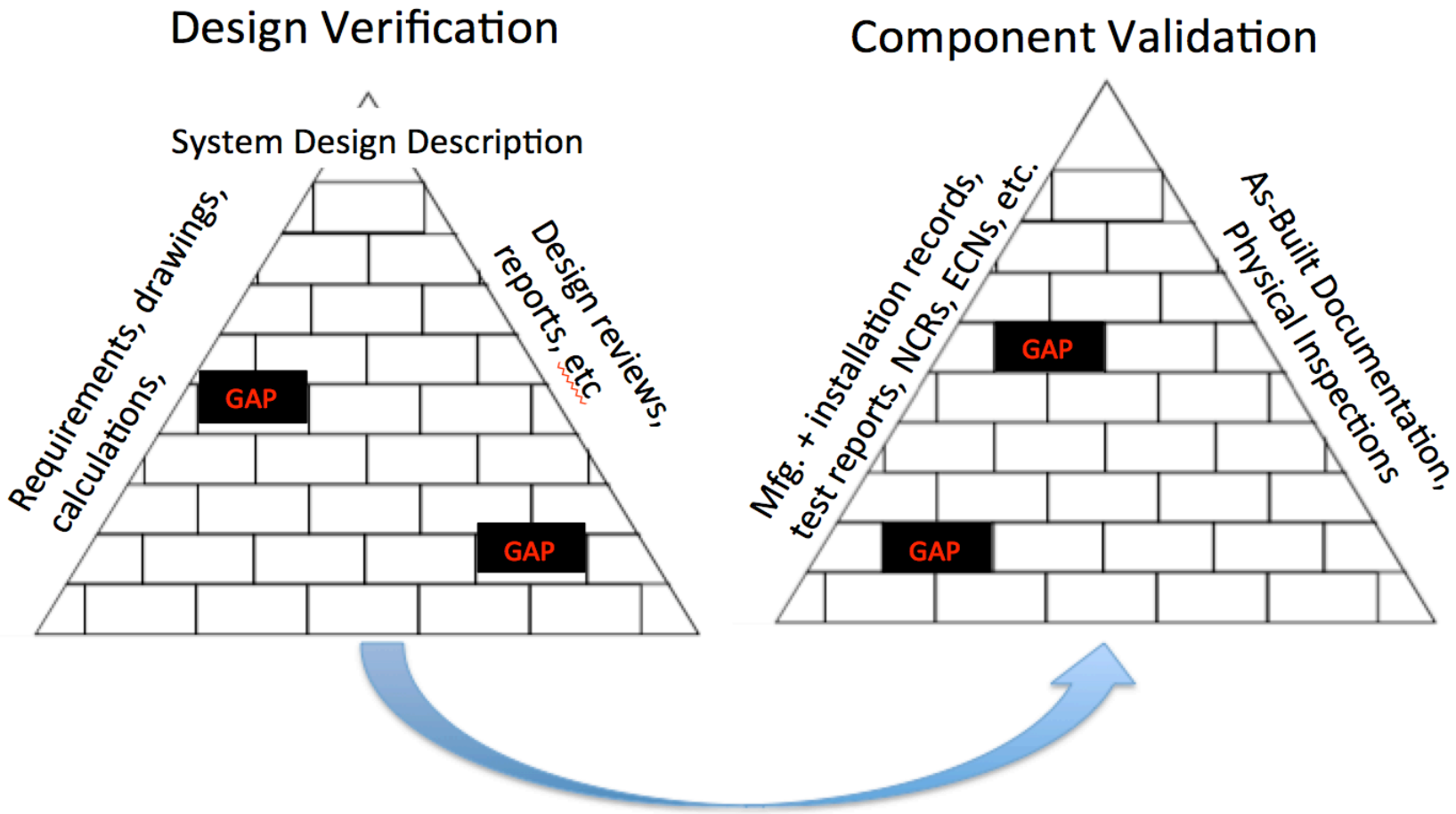
- Next steps toward addressing the Notable Outcome

DOE Notable Outcomes Have Been Near-term Focus

- *EXTENT OF CONDITION*
  - *FES: Complete an extensive extent-of-condition review of NSTX-U* ***to identify all design, construction, and operational issues. Prepare correction action plan (CAP) to include cost, schedule, scope, and technical specifications of actions****. Provide an interim progress report by March 31, 2017 and complete the CAP review and send the final report to DOE by September 30, 2017.*

- *EXTENT OF CAUSE*
  - *SC/PSO: Conduct a review of policies and procedures for design, construction, installation, commissioning and operations of NSTX-U and other construction activities and projects. Develop corrective actions to ensure the highest quality project management across the lab.*

Design Verification & Validation Review
System Design Description (SDD) is Key



- DVVR looks for potential gaps in design basis or as-built configuration
- Corrective Action Plan (CAP), derived from the DVVRs, determines path forward

Design Verification and Validation Reviews Form the Basis for the EOC Review

System	Date	
Central I&C	*18-Jan*	Scope of EOC Review #1
Integrated Project Design	*24-Jan*	
Heating Systems:		
HHFW	*30-Jan*	
NBI	*31-Jan*	
Magnets	*7-Feb*	
VV & Int. Hdwe.	*14-Feb*	
Cooling	*22-Feb*	
Power Systems	*27-Feb*	
EOC Review #1	*6-Mar*	
Test Cell	*16-Mar*	
Vacuum & Fueling	*23-Mar*	
Bakeout	30-Mar	
Submit Notable Interim Report	31-Mar	
Diagnostics	5-Apr	
Realtime Control & Protection	19-Apr	
EOC Review #2	15- May	

- *12 of 12 DVVRs are now complete*
- *47 External reviewers participated in the DVVR and EOC reviews*

Submitted Interim Notable Report

- Background leading to notable outcome
- First five DVVRs by reviewed by EOC
- EOC report
- DVVR's held after EOC but not yet reviewed
- Corrective Action Spreadsheet
  - Including all chits
  - Proposed actions
  - Assessment of risk mitigation due to corrective actions

NSTX-U Extent of Condition (EoC)
Interim Report

Office of Fusion Energy Science
Office of Science
U.S. Department of Energy

PPPL PRINCETON PLASMA PHYSICS LABORATORY Princeton University

Estimated Risk Reduction in Proposed Corrective Action Spreadsheet for Each Issue

System (OBS)	Issues	Applicable Chits	Affected Component	Issue to be Addressed (Event)	Unmitigated Event Duration	Unmitigated Event Impact	Unmitigated Event Likelihood
Magnets	Fabricate new PF1AU coil to replace failed coil	IPF1	PF1A-U	Coil has failed	Duration > 1 year	Dead Stop	Present State

Corrective action	CAP Category	Mitigated Residual Event Duration	Mitigated Residual Event Impact	Mitigated Residual Event Likelihood	Cost	Schedule	Proposed Action
Fabricate new PF1AU coil	Redesign and rebuild	Duration > 1 year	Dead Stop	Unlikely Event	$$	Y	Necessary for Start-Up

- The analysis is detailed in Proposed Corrective Action spreadsheet.

Categorized Each Issue and Proposed Actions

- Categories:
  - Redesign and rebuild
  - Analysis and testing
  - Maintenance and repair
  - Modernize and replace
  - Spares
- Proposed Actions:
  - Necessary for Startup
  - Strongly Recommended for Startup
  - Recommended for Startup
  - Operations
  - Investigate

Extent of Condition Review Committee Reviewed Proposed Corrective Actions

Tom Todd (chair)	CCFE (retired)
Heinrich Boenig	LANL (retired)
Richard Callis	GA (retired)
Frank Casella	US ITER
Martin Cox	CCFE
Ursel Fantz	IPP
Rem Haange	ITER Deputy Director General (retired)
Michel Huguet	Head of Naka site, ITER-EDA (retired)
Dave Humphreys	GA
Brian La Bombard	MIT
Arnie Kellman	GA
Graeme Murdoch	US ITER
Ron Parker	MIT (retired)
John Smith	GA
Dennis Youchinson	ORNL

Two EOC meetings - each four days

Nearly all of the EOC members participated in one or more of the DVVRs

Issues Recorded as Chits for First Extent of Condition Review

- Large number of chits were received:
  - Central I&C 104
  - Integrated Project Design 82
  - Heating Systems 98
  - Magnets 148
  - Vacuum Vessel and Int. Hdw. 216

- Very thoughtful chits enabling a comprehensive review of these systems
  - Thanks to PPPL staff and external reviewers

Extent of Condition Panel Recommendations in March on Major Strategic Choices

- Panel strongly recommended replacing all existing PF1 coils
- Recommended consideration of removable mandrels on PF1 coils to facilitate turn-to-turn acceptance testing
- Retaining 300-350C bakeout strongly recommended
- Strongly recommended "indefinite deferral" of Co-axial Helicity Injection to allow modification and simplification of the end-flanges of the Vacuum Vessel to improve the reliability of the machine
- *Recommendations were supported in May meeting*

Issues Recorded as Chits During Last Seven DVVRs Since First EOC Meeting

- Large number of chits were received to date:
  - Cooling Systems 71
  - Power Systems 84
  - Test Cell 24
  - Vacuum and Fueling 65
  - Bakeout 76
  - Diagnostics 104
  - Realtime Control and Protection 93

- Relative to the first EOC meeting, the impact of issues identified in the second round of DVVRs was less.
- Grand total of 1172 chits (including previous ones)
  - Condensed to 391 system issues and 55 integrated issues

EOC Submitted Their Second Report

- The second meeting reviewed the results from the remaining seven DVVRs
  - Also discussed the main elements associated with the first meeting regarding the polar region and plasma facing components
- Total of 94 recommendations
  - Prior to the second EOC meeting provided a response to the 49 recommendations from the first review.
  - Currently developing a response to their recommendations.
- The review was very productive and in depth.

Extent of Condition Reviewed Issues Arising from DVVRs

- The first Extent of Condition report shows that the primary elements of the Upgrade Project (core magnet assembly and second beamline) are functional
- Identified items to improve the operations reliability
- The second report stated:
  - An informal recommendation is therefore to plan a staged implementation of the agreed scope of the Recovery Project aiming to achieve no impact on the learning curve for the physics and operation of the machine as it moves towards full performance.
  - The Panel affirms that the primary goal of the redesign of NSTX-U should be ultimately to ensure the achievement of full performance operation, i.e. 2MA, 1T, 10MW, 5s, with high robustness and reliability, as a key step in the world programme of Spherical Tokamak fusion research.

Outline

- Design Verification and Validation Reviews leading to Extent of Condition Reviews

✓**Main Technical Challenges**

- Next steps toward addressing the Notable Outcome

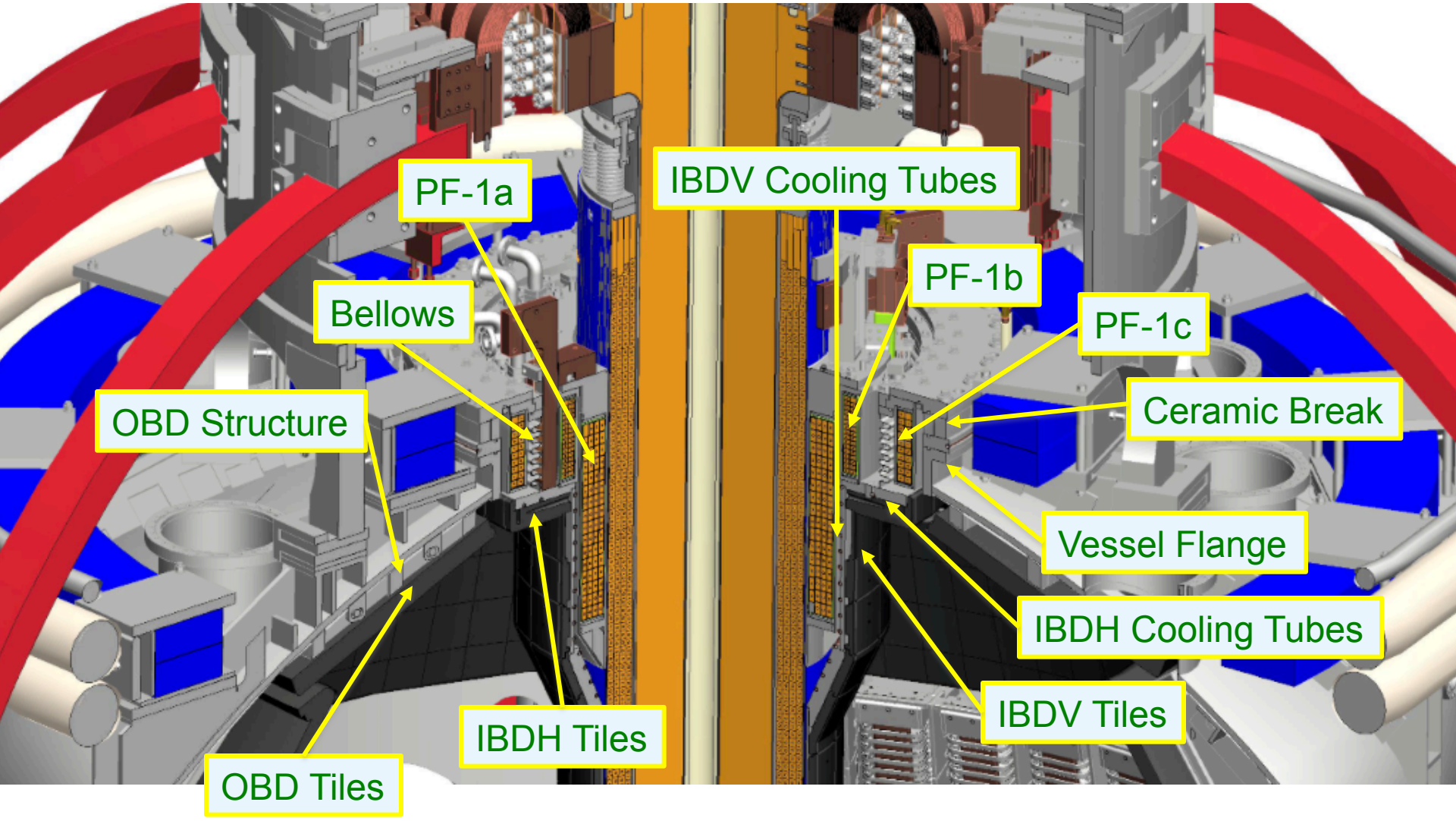
What Are the Major Technical Changes?

- Replacement of all inner poloidal field (PF1) coils in response to possible latent defect(s)
- Reliability improvements to the top and bottom of the vacuum vessel
  - CHI was removed as a design requirement
- Reconfiguration of the PF coils to support bake-out of graphite plasma facing components up to 350 degrees Celsius
- Replacement of plasma facing component tiles to meet upgraded requirements.
- Improved machine instrumentation diagnostics to compare operational data with model analysis.

<u>New from recent DVVRs</u>

- Improved radiation shielding for the NSTX-U test-cell to support plasma operation
- Safety issues with bakeout including pressure vessel documentation

PF-1 Coils Will Be Replaced

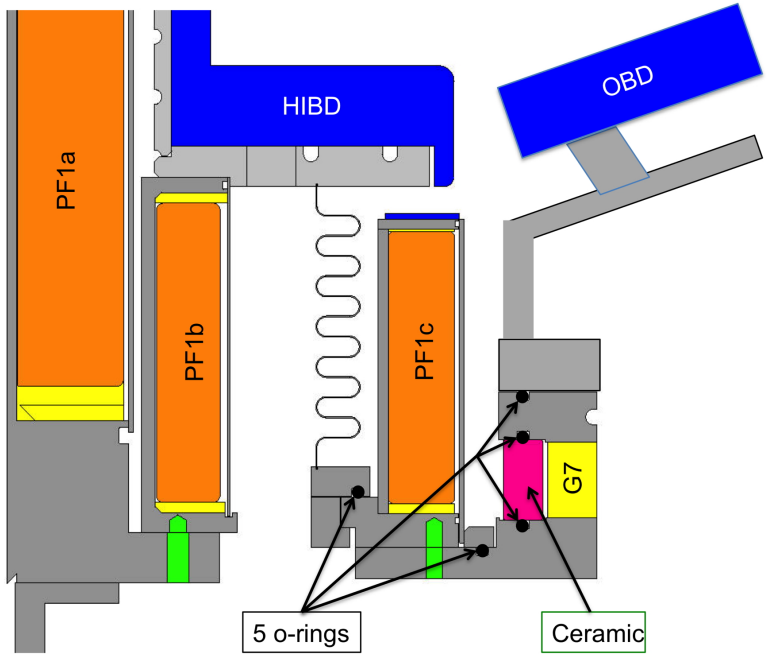


Activities launched to address polar region issues

- Weekly meetings held since March 15
  - One general and another specific to PFCs
- Design Integration Review held April 21
  - Key step to establish interfaces and allow design of components to begin
  - EOC Chair Tom Todd present, other EOC's participated remotely

Friday, April 21

Time	Duration	Topic	Presenter
8:45	0:15	Introduction	V. Riccardo
9:00	0:30	Overview	M. Sibilia
9:30	0:20	Physics Requirements	S. Gerhardt
9:50	0:20	Ohmic Bakeout	C. Neumeyer
10:10	0:10	**Break**	
10:20	0:15	PF1B area - Design	M. Sibilia
10:35	0:30	PF1B area - Analysis	P. Titus
11:05	0:30	PF1C area - Design	M. Sibilia
11:35	0:30	PF1C area - Analysis	P. Titus
12:05	1:00	**Lunch**	
13:05	0:45	PFCs - Technical +Design Considerations	M. Mardenfeld
13:50	0:30	PFCs - Parametric Studies	A. Brooks
14:20	0:20	Center Stack Heating/Cooling Lines	D. Cai
14:40	0:20	Center Stack Casing Centering Scheme	P. Titus
15:00	1:00	Chit discussion	V. Riccardo
16:00	0:30	Conclusions	M. Sibilia



https://sites.google.com/pppl.gov/polar-region-design-integ/home

PF1 Coils Are Being Designed and Will be Replaced

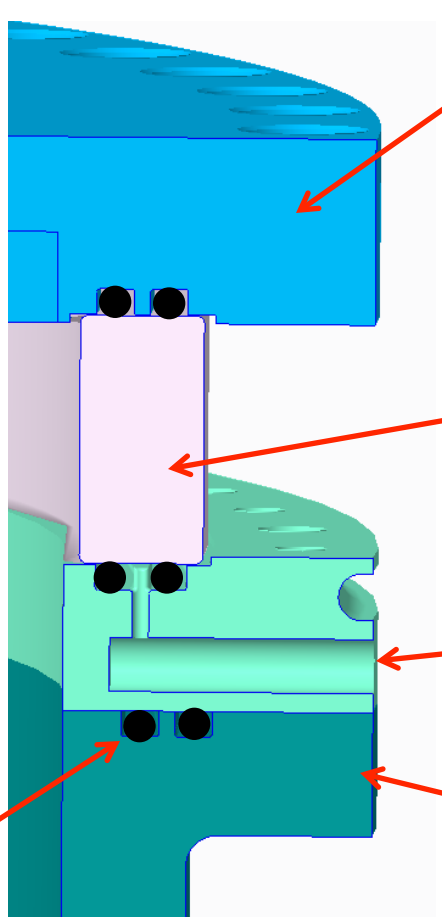
- Redesign will:
  - Increase insulation
  - Eliminate joggles
  - Eliminate braze joints
  - Eliminate mandrels during construction to facilitate testing
  - Accommodate new polar region design to address other reliability issues
    - Bakeout of the vessel
    - Plasma impingement on the vacuum can around PF1C

Coil Fabrication Next Major Step

- Exploring construction at:
  - National and international companies
  - PPPL
  - Other national laboratories
- First step: qualify facilities by construction of a prototype
  - Design review for prototype successfully completed last week
  - Requisition for prototype nearing completion
- Strengthen vendor oversight and QA
- Select vendors based on performance of prototype

Have Reasonable Schemes for Providing Double O-Ring Seals in Polar Region and on Ceramic Break if it is Retained

With Access to Interspace, the Ceramic Break Assembly Can be Fully Leak Checked Before Installation

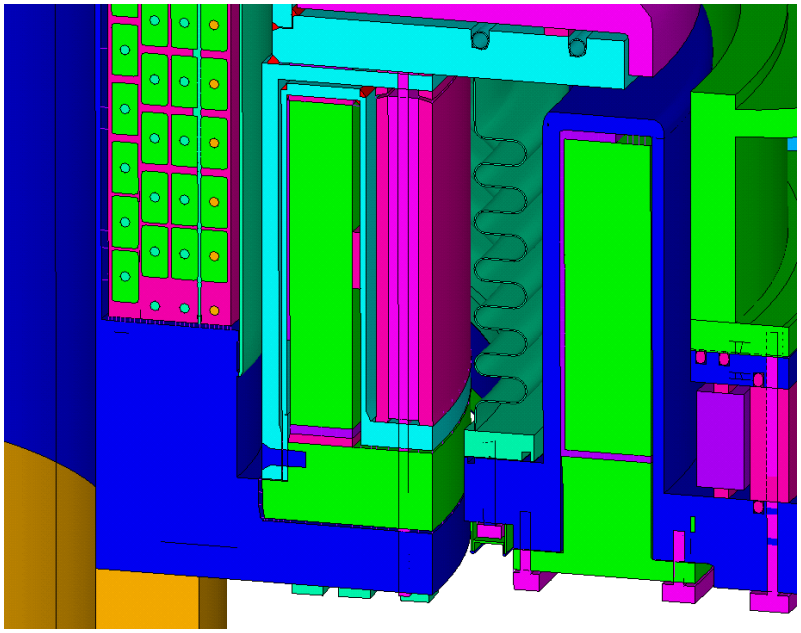


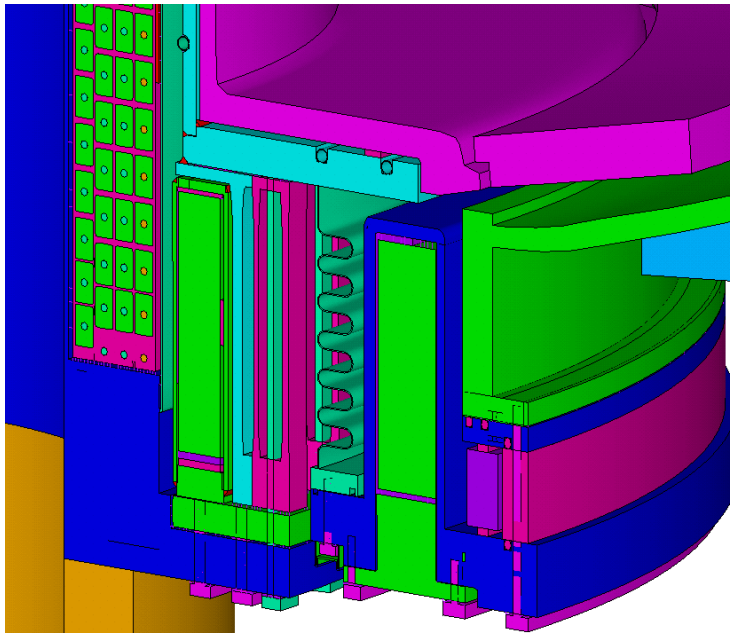
Also looking at options for welded lip seals

Assessed Various Geometries for the Casing Support of PF-1b Coil to Enable Bakeout of the Tiles

Inboard Support for Casing
- Direct Load Path
- During bakeout, hot support piece between the cold PF-1a and PF-1b coils

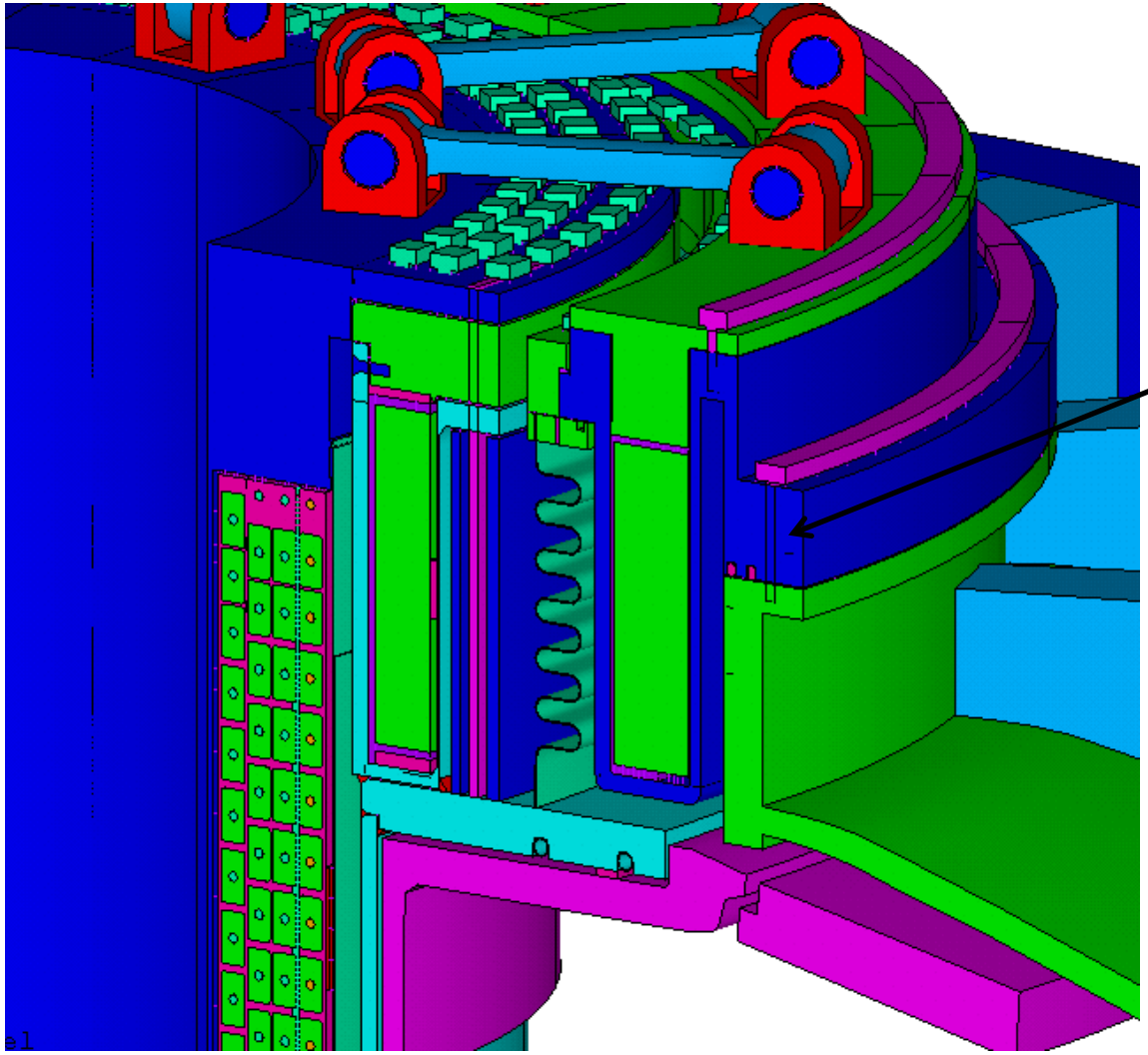
Outboard Support for Casing
- Offset Load Path
- Both cold coils adjacent, and separated from hot components





Preferred

Nearby Designs for PF-1c Region are Consistent With the Elimination of the Insulator



This design mandates one of the revised bakeout schemes.

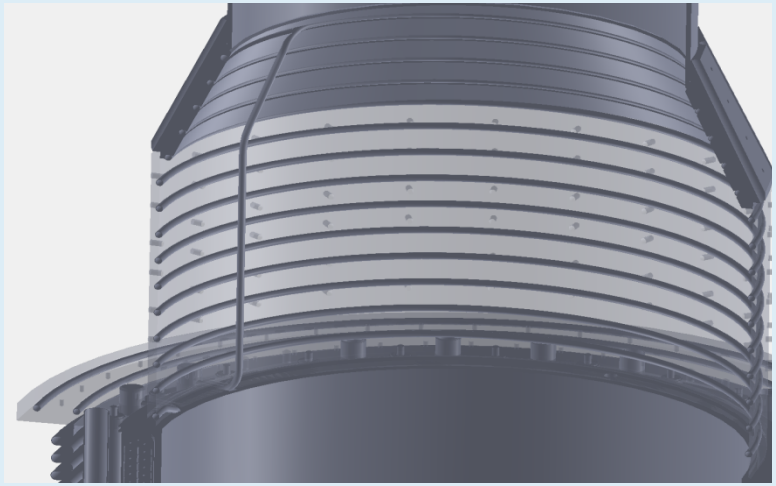
Ceramic Break may be retained in order preserve DC current bakeout

After the EOC Second EOC Meeting Performed a Risk Analysis of Bakeout Options

- To reduce the risk associated with the double O-rings around the ceramic break propose to eliminate the lower break and rely on the upper ceramic break for DC bakeout
  - Perhaps use a ceramic with lower potential for cracking
  - Double O-ring can be tested prior to installation – robust solution
  - Consequence of failure 3-6 months
- AC or TF oscillation to heat the vessel entails prolonged voltage application the OH solenoid or the TF coils
  - Risk to the insulation
  - Risk to the stability of the "aquapour" between the OH and TF
  - Additional cost $2-3M
  - Consequence of failure >2 year outage.
- Project recommends retaining one ceramic break with double O-rings

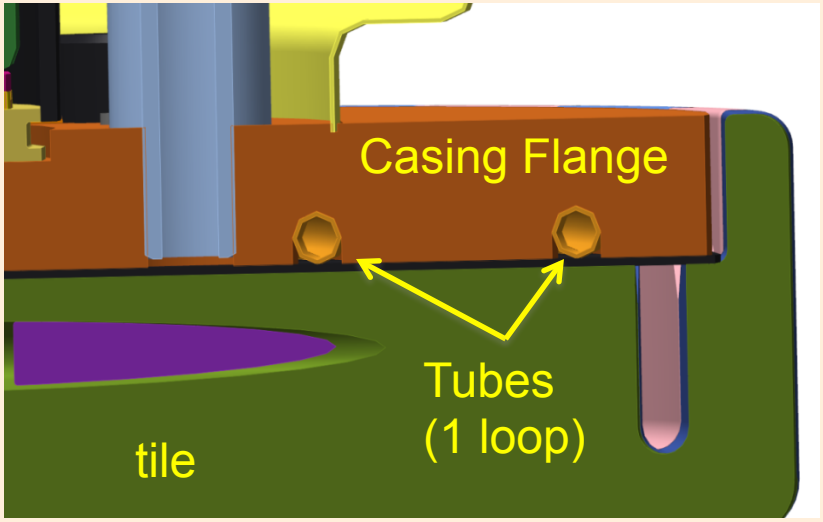
Vertical Cooling Tube is Straightforward, But Horizontal Flange Cooling Design is Still On-going

Vertical Target Cooling



- Water cooling permitted since on air side
- Calculations show little apparent risk in removing the required heat provided appropriate thermal contact provided.

Horizontal Target Heating/Cooling



- Recent requirement banning in-vessel water reduces cooling capability.
- Assessing whether we need to modify the geometry.

Updating PFC Requirements

Table of Contents

0.0 References 5

1.0 Introduction 5

2.0 General requirements 6
- 2.1: Materials and Structural Requirements 6
- 2.2: Disruptions and Halo Currents 6
- 2.3: General Thermal and Cycle Requirements 7
- 2.4: Bakeout Considerations 7
- 2.6: PFC Locations 8
- 2.7: Diagnostic Requirements 8
- 2.8: Installation and Maintenance Requirements 9

3.0 Requirements By Location 9
- 3.1: CS Narrow Section 9
  - 3.1.1 CS Tile Alignment Tolerance: 9
  - 3.1.2 CS Tile Diagnostics: 10
  - 3.1.3 CS Tile Heat Flux: 10
- 3.2 Inner Horizontal Target 10
  - 3.2.1: Stationary Heat Flux with Standard Target Helicity 10
  - 3.2.2: Swept Heat Flux with Standard Target Helicity 11
  - 3.2.3: Stationary Heat Flux with Reversed Target Helicity 13
  - 3.2.4: PFC Dimensions 15
  - 3.2.5: Diagnostic Requirements for the Horizontal Target 15
- 3.3: Vertical Target 15
- 3.4: Outboard Divertor 17
  - 3.4.1 Stationary Heat Fluxes From Cases with the OSP on the IBDH 17
  - 3.4.2 Stationary Heat Fluxes with the OSP on the OBD 17
  - 3.4.3 Standard Divertor Heat Fluxes with the OSP near OBD Center 19
  - 3.4.4 OBD Diagnostic Considerations 21
- 3.5: Passive Plates 21
- 3.6: Outboard Limiter 21

4.0 Interfaces 21
- 4.1: Vessel Heating/Cooling Systems 21
- 4.2: Diagnostics 21

Appendix: 22
- A.1: Heat Flux Computation Methodology 22

1st draft of in review by working group

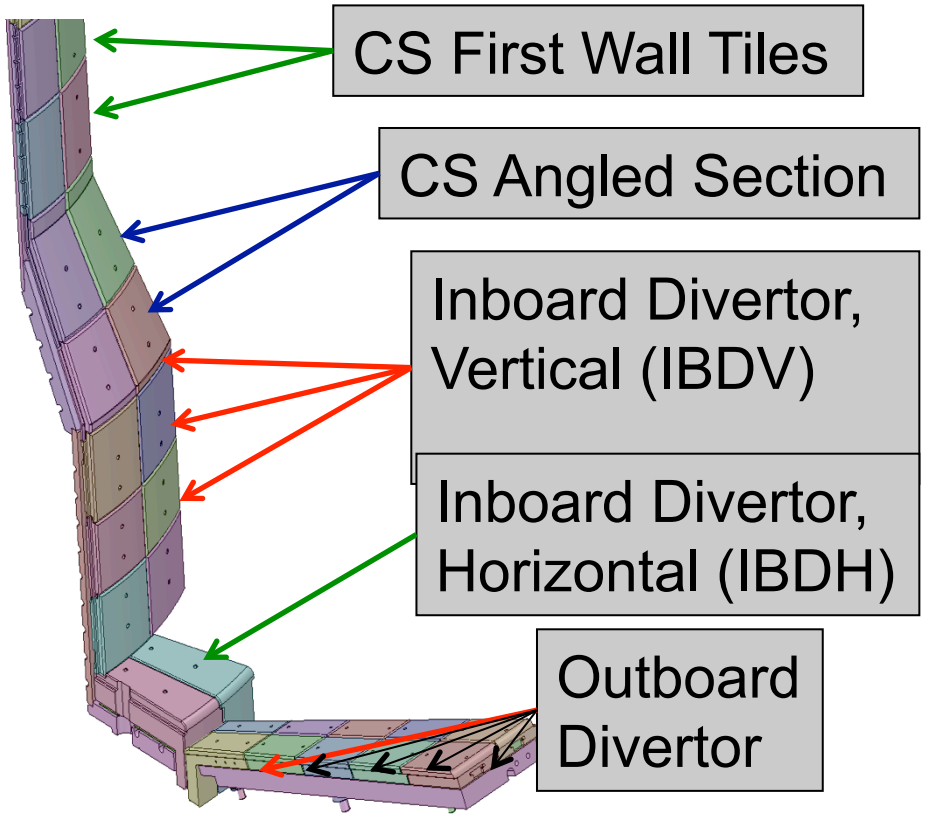
- Substantial effort underway to refine requirements
  - Greater detail than original GRD
  - Incorporation of latest physics
  - Memo issued on halo current requirements (S. Gerhardt)
  - > 100 scan cases of power flux, sweeping, etc. (J. Menard)
- Formed NSTX-U Working Group on PFC Power Handling

https://docs.google.com/document/d/1TOYEJs3tn9T6g-b8RInFitiHtBwkmTH-lh6nn2XJSPA/edit

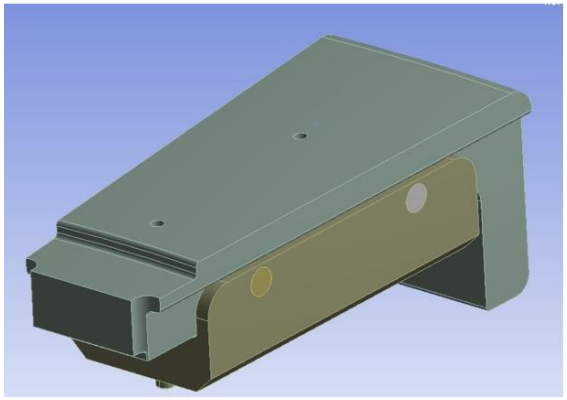
http://nstx-u.pppl.gov/program/working-groups/pfc-requirements-working-group

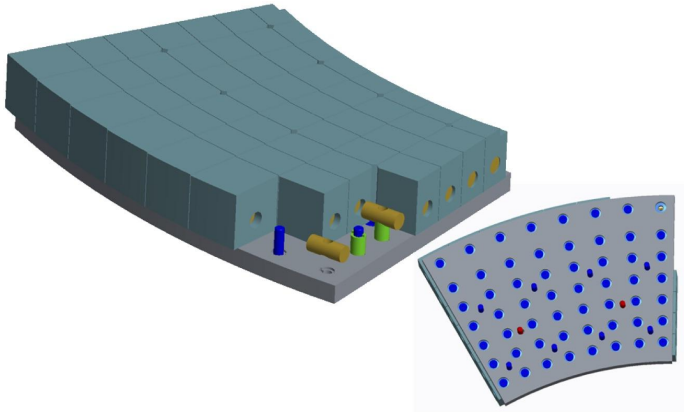
Revised Requirements Affect the PFC Components

- Revised requirements driven:
  - Shorter scrapeoff
  - Refined halo current and disruption loads
- PFC changes to support 2MA, 1T and 10MW of NBI for 5 s now includes:
  - IBD Horizontal
  - IBD Vertical
  - OBD All Rows
  - CS Angled tiles
  - CS First Wall tiles



Addressing New Thermal and Halo Current Requirements For Inner Horizontal Target Tiles





Cassette design:

- Pins react disruption loads
- Thermal stress limited
- Likely lower cost

"Monoblock" design:

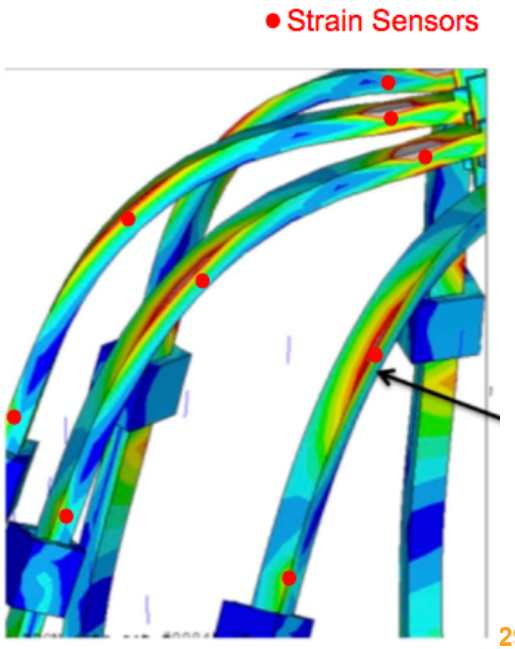
- Small cubes have smaller loads
- Higher thermal performance, likely limited by carbon blooms.
- More complex to implement.

Instrumentation Being Developed For Both Trending and Benchmarking

- Two goals for the instrumentation system:
  - Key mechanical properties to be checked in order to gain confidence in the models used to qualify the machine.
  - Long term trending of key components checked in order to assess system health.
- Will be implemented with modern fiber optic sensors

Example Systems

Displacement transducer on OH Pre-Load Mechanism
Assesses modulus of composite coil structure and trend any loss of preload



Strain Measurements on Outer Legs
Assesses strength of composite beams and trend displacements to identify any delamination.

NSTX-U Radiation Shielding

- On the basis of neutron fluence projection in future operations and with the existing shielding, the site boundary dose could exceed the annual limit.
  - Due to large number of penetrations in the wall.
- Recent testing with source has identified ~13 penetrations that cause most of the dose outside the test cell
  - Shielding is straightforward
- Related issue is that the radiation exposure of electronics may require relocating some equipment in the NSTX-U Test Cell.
  - Under investigation

Bakeout External Vacuum Vessel Heating System Safety Issue

- The vacuum vessel exterior is heated/cooled with water that can reach 150°C (superheated water)
  - Superheated water: water that is heated to a temperature beyond its atmospheric-pressure boiling point
- The system that heats/cools the superheated water was not designed for superheated water and lacks the controls/ interlocks that are needed for such a system
- The present condition can be mitigated through available technologies and standard engineering practices
  - Passively prevent and interlock under-pressurization and over-temperature
  - Add automatic system responses to mitigate under-pressurization and over-temperature events if they were to occur

Technical Challenges are Manageable

- While there is a significant amount of work, it is well defined.
- The DVVR/EOC process has identified **what needs** to be done
- A CDR, August 1-3, will establish **the best technical path** forward to reliable and predictable operation
  - Needed to develop cost and schedule estimate

Outline

- Design Verification and Validation Reviews leading to Extent of Condition Reviews

- Main Technical Challenges

✓**Next steps toward addressing the Notable Outcome**

Status of Developing a Comprehensive Corrective Action Plan

- Defining what scope is needed for restart and what is operations related scope for reliable operations
- CDR (August 1-3) will identify the best path forward considering cost and schedule
- Perform external cost and schedule review after the CDR
- Submit corrective action plan to FES by September 30

Definitions of Recovery Project vs Operating Scope

- Recovery Project – needed for restart
  - Safety related issues not addressed during NSTX-U Upgrade
  - Design, Fabrication, Construction, and Installation of components to meet the objectives of the Upgrade Project
    - e.g. PF1 coils, Polar region, In-vessel tiles
- Operations Scope – needed for restart
  - Repairs of failed components typical of operations
    - Ion source refurbishments, vacuum pumps
  - Previously planned modifications in support of operations
    - Install OH water heater
  - Routine maintenance
  - Minimal support (machine techs, Shift Supervisors) to control work and do routine surveillance
  - Allocations (HP infrastructure, ERWM infrastructure)
  - Energy

Definitions of Recovery Project vs Operating Scope (Cont.)

- Operations Scope – not needed for restart
  - Reliability improvements
    - Including spares and obsolete equipment
  - Desirable enhancements
    - Eliminate noise from SPA amplifiers, filter the noise associated with the PF1 coils
    - Address radiation effects on electronics

Outline of Corrective Action Plan

Introduction

- Background, DVVR/EOC process, Main findings, Details in appendices

Corrective Action Plan Organized by:

- **OBS**
  - Brief description of OBS
- **Job**
  - Description of task – address technical specification
- **Relationship to findings:**
  - Issues (super-chits)
  - Chits
  - Recommendations by EOC
  - Operations Impact

Outline of Corrective Action Plan (Cont.)

- **Cost**
  - Cost uncertainty
- **Schedule duration**
  - Precursors: for example, machine assembly after installation of in-vessel tiles
  - Schedule risk
- **Risk Evaluation**
  - Evaluation of severity and severity reduction using methodology in spreadsheet
- **Designation: Recovery Scope necessary for startup, Operations necessary for startup, Operations**
- **Overall schedule**
- **Overall cost**
- **Contingency estimate**

Project Documentation Deliverables

Documents/Reviews	Expected Date
•Complete Conceptual Design Review	8/3/17
•Complete Conceptual Design Report	8/11/17
•Acquisition Strategy	8/11/17
•Preliminary Hazard Analysis Report	8/11/17
•Complete NEPA determination	8/11/17
•Identify Safeguards/Security Rqmts.	8/11/17
•Develop ISM Plan	Use Existing
•Establish NSTX-U QA Program	8/21/17
•Risk Management Plan	8/28/17
•Cost and Schedule Review – External	9/11/17
•Preliminary Project Execution Plan	9/25/17
•***Notable Outcome Report***	9/30/17

NSTX-U Recovery Issues Are Much Better Understood

- The DVVRs are complete and major progress has been made in identifying the issues that have to be addressed
- The Extent of Condition reviews have enabled us to settle on the scope and identify approaches to resolve the issues.
- The technical challenges are manageable
  - Great deal of work but similar to that done elsewhere and here
- Developing the corrective action plan to satisfy the notable
  - Want to develop a common vision to ensure that it meets expectations