National Spherical Torus eXperiment Upgrade

NB Duct Shield and Vessel Blackening

(Alternative to Aerodag)

WBS 1.04.01.03

NSTX-U Recovery Project FDR – March 17-19, 2020

A. Cao - Cognizant Engineer

Last edit: 03/09/2020

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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Outline

1. Overview
2. Scope
3. Requirements and Interfaces
4. Analysis/Prototyping
5. Chit Closure
6. Procurement, Fabrication, Installation, and Test
7. Risk - Project Risks and Design FMECA
8. Quality, Environmental, Safety, and Health
9. Summary

Overview - WBS 1.04.01.03

WBS Title	Alternative to Aerodag	WBS #	1.04.01.03
Project Cog.	Austin Cao	Assoc. Proj. Man.	W. Gattoni
Technical Impact of Scope	A. Assists proper function of diagnostic by minimizing reflected light B. Protects wall of Bay K beam duct from reionization effect		
Design Scope	A. Design and implement a method to blacken the inside of the NSTX-U vessel along the lines of sight of key plasma diagnostics B. Design thermal shielding for the interior of the NB duct at Bay K		
Design Status	Vessel Blackening FDR completed on 1/30/2020 NBI Duct Guard FDR completed on 12/16/20 Drawings signed (link); chits resolved (link); calculations done (link)		
Fabrication Status	Permission to fabricate this scope is included in the CDE-3B request.		
Installation Status			

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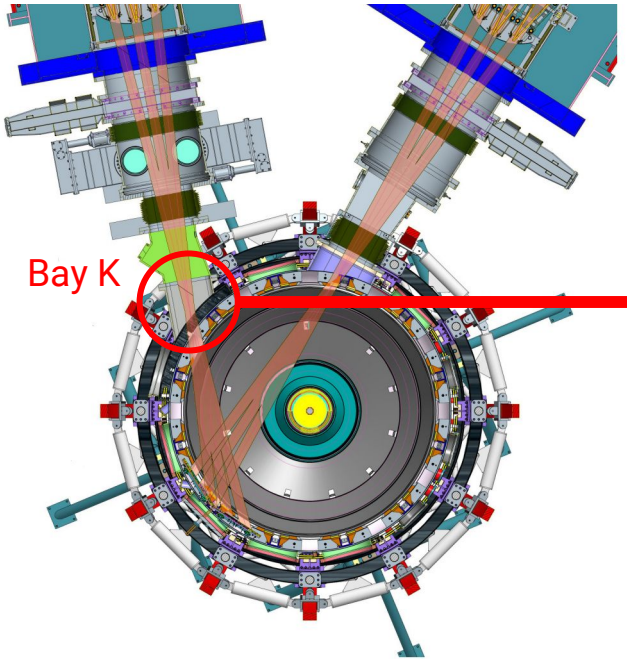
Duct Shields Will Protect Against Neutral Beam

- Neutral beams pass through powerful magnetic fields.
- Beam interactions with residual gasses (scaling with vacuum pressure) will cause reionization.
- Poloidal and toroidal fields will deflect up to 50 kW of reionized beam onto the duct surface.
- TZM molybdenum guard in Bay K prevents vessel damage and sputtering of SS into the plasma.

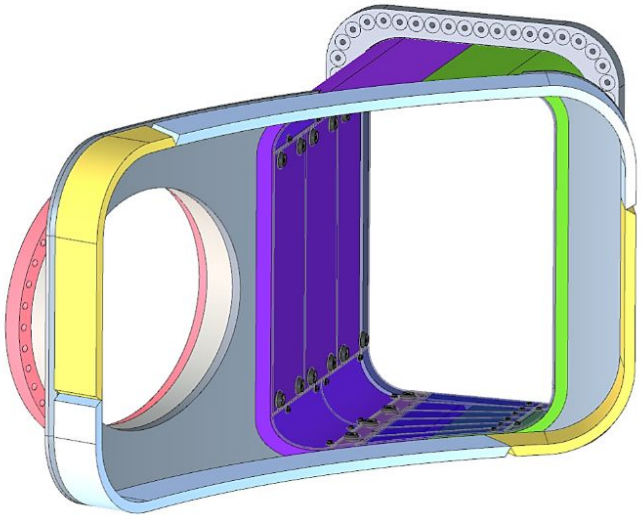


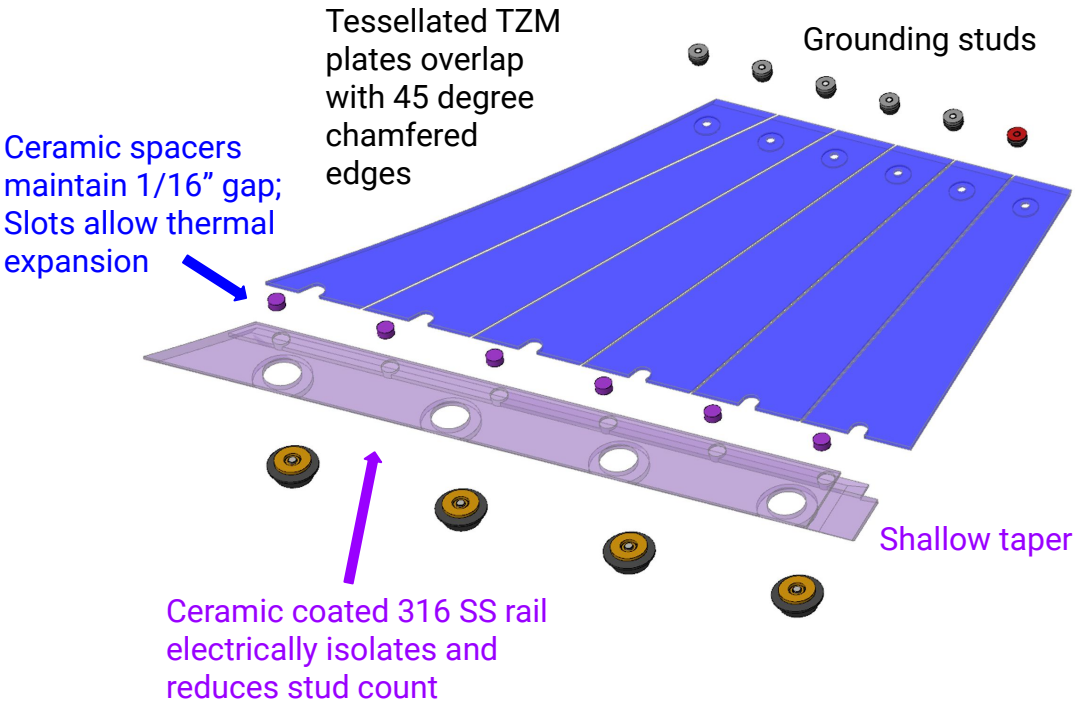
Section view of vacuum vessel

Neutral beam duct at Bay K

Individual Plates Minimize Disruption Loads

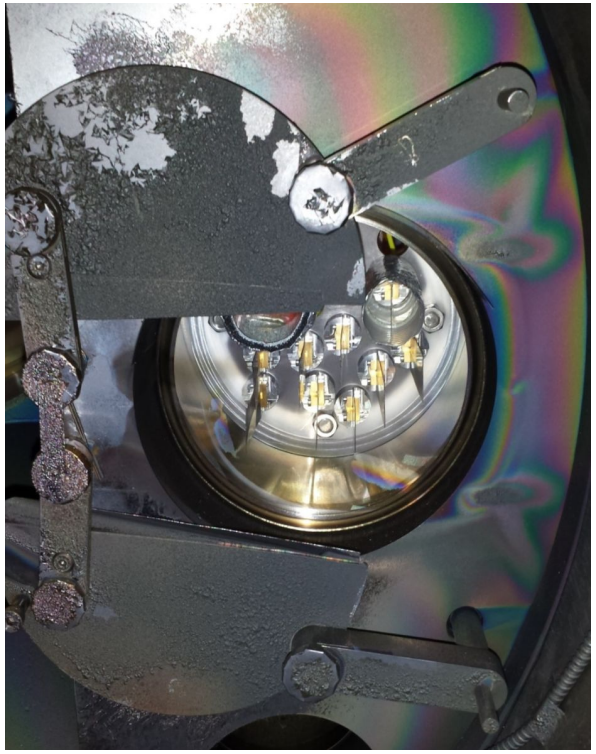
- Full 360 degree coverage of neutral beam duct at Bay K.
- 24x plates, each electrically isolated.





Robust Blackening Solution Will Be Implemented

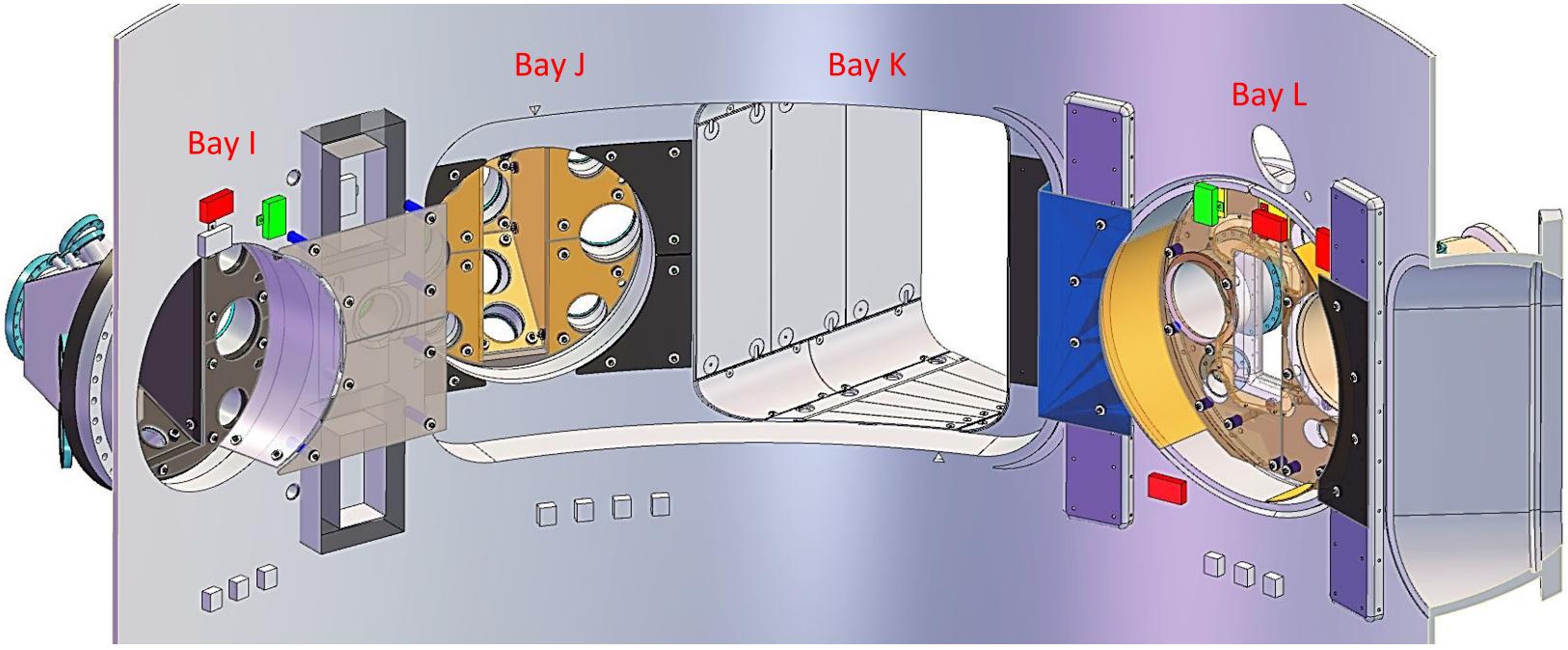
- Aerodag (graphite spray) has been used in the NSTX vessel to darken areas in diagnostics fields-of-view.
  - Multipoint Thomson Scattering (MPTS)
  - Charge Exchange Recombination Spectroscopy (CHERS)
  - Real Time Velocity (RTV)
  - Motional Stark Effect (MSE)
- Final design proposes to install black-oxide coated plates at various regions near vessel mid plane.
  - Alternative in-situ options explored and rejected due to durability concerns.



Aerodag sprayed on Synthetic Aperture Microwave Imaging (SAMI) shutter

Small Plates Will Be Used to Provide Vessel Blackening

- Coverage driven by diagnostics fields-of-view (FOV).
- Entered vacuum vessel on 12/06/19; back-illuminated diagnostic fibers to confirm FOV.



Section view of internal vacuum vessel

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Requirements Defined and Met

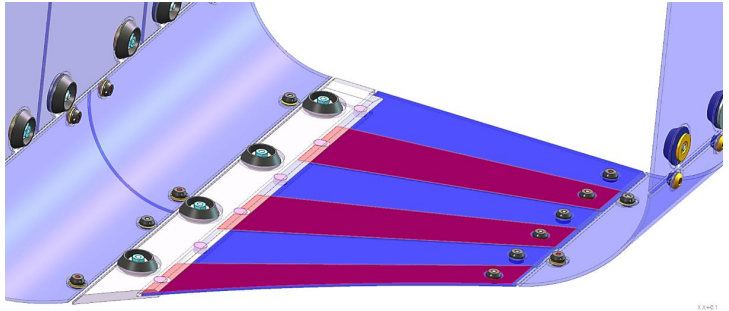
Source	Requirements	Comment	Met
NSTX-U-RQMT-GRD-001	Waveform Specifications, Duty Cycle	Provides highest level requirements for 2 MA, 1 T, 10 MW, 5 second operation	✓
NSTX-CRIT-0001	Design Criteria	Provides the project definition of margin for loads vs. allowables	✓
NSTX-U-RQMT-RD-015	Bakeout Upgrades	Describes thermal requirements for the NSTX-U Vessel	✓
NSTX-U-RQMT-RD-003	Disruptions	Provides requirements for disruption analysis	✓
NSTX-U-RQMT-SRD-007	Heating Systems	States requirements to provide appropriate shielding in the NB duct	✓
NSTXU_1-2-4-3-1_RD_100	Neutral Beam Duct	Provides specific requirements for the heat loads on the neutral beam duct shielding plates	✓

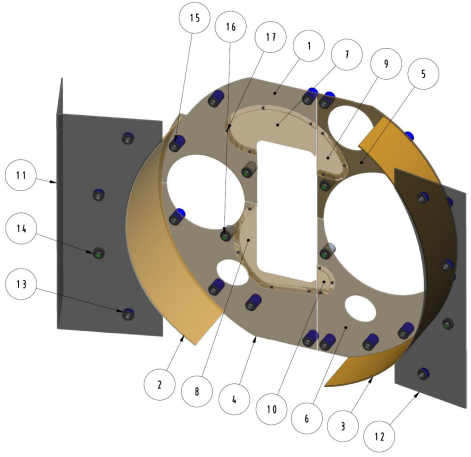
- Complete RVTM maintained by Project Systems Engineering

The Design Accommodates Required Interfaces

- Duct shield downstream plates are shadowed by upstream shielding plates.
  - Does not impinge neutral beam; protects against reionization.
- Blackened plates do not block diagnostic equipment in port openings.
  - Installation templates provide stud locating to specified tolerances.
  - Oversized holes allow for variation in stud welding.

Bay K Shielding





Bay I Blackening

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Diagnostics	Vacuum Vessel	link	Defines interface between the Vessel Blackening and the Vacuum Vessel

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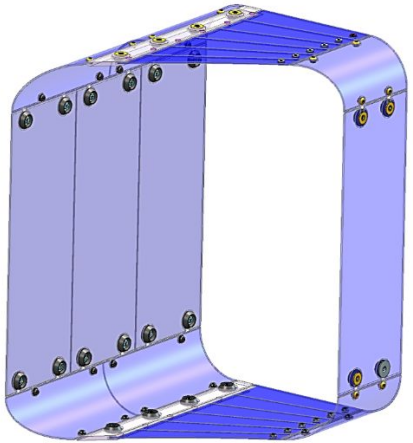
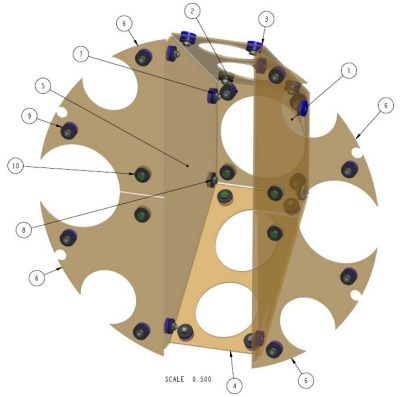
Comprehensive Calculations Verify Design will Meet Requirements

Physical Quantity or Title	Calculation #	Content
Thermal and EM disruption for NB Duct Guard	NSTXU_1-2-4-3-1_CALC_100	Shows that the NB duct guard can handle disruption and thermal loads from plasma and neutral beam operations
Thermal and EM disruption for Blackened Plates	NSTXU_1-4-1-23_CALC_100	Shows that the blackened plates can handle disruption and thermal loads from plasma operations

- Resistivity of TZM Molybdenum is 10% that of 316 SS.
  -> high EM loads scaling with area
  -> small plates resolve high stresses
- All analyses using worst case disruption and thermal loads from models near mid-plane duct region.
- All plates and fasteners to be installed meet SDC requirements after summing stresses due to thermal and EM effects at points of interest.



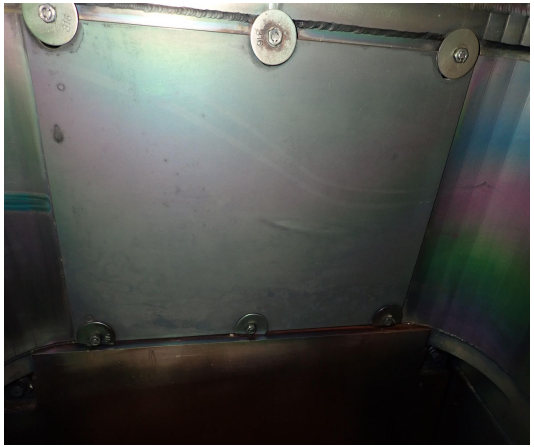
Segmented TZM Mo Plates
Peak temp: 544 deg C
Recrystallization @ 1400 deg C
Melting temp @ 2620 deg C



Blackened 316 SS plates
Peak temp: 282 deg C
Recrystallization @ 800 deg C
Melting temp @ 1370 deg C

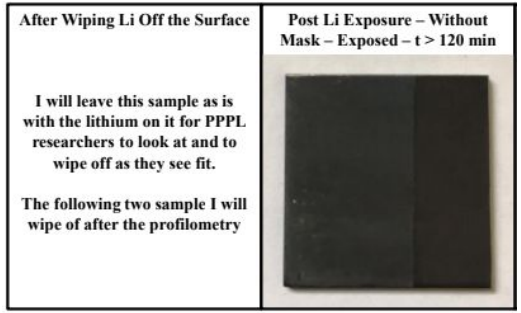
Design Assurances: Testing and Previous Use at PPPL

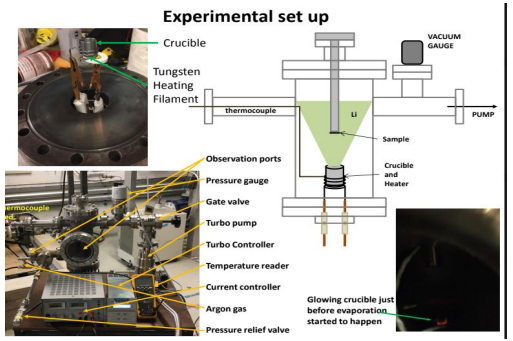
Neutral Beam Duct Shielding



- TZM Mo has been used for neutral beam shielding in Bay A.
  - No visible surface degradation
  - Similar fastening scheme
- Qualified for NSTX-U EM loads in NSTXU_1-4-1-23_CALC_100

Vacuum Vessel Blackening





- Tested at Univ. of Illinois for lithium durability.
- Tested at General Atomics DIII-D for outgassing.
- Black oxide coating has been previously used to reduce reflections.
  - Alcator C-Mod
  - PPPL CDX-U lithium tray limiter
    -> High temperature & exposed to lithium
    -> No visible surface degradation

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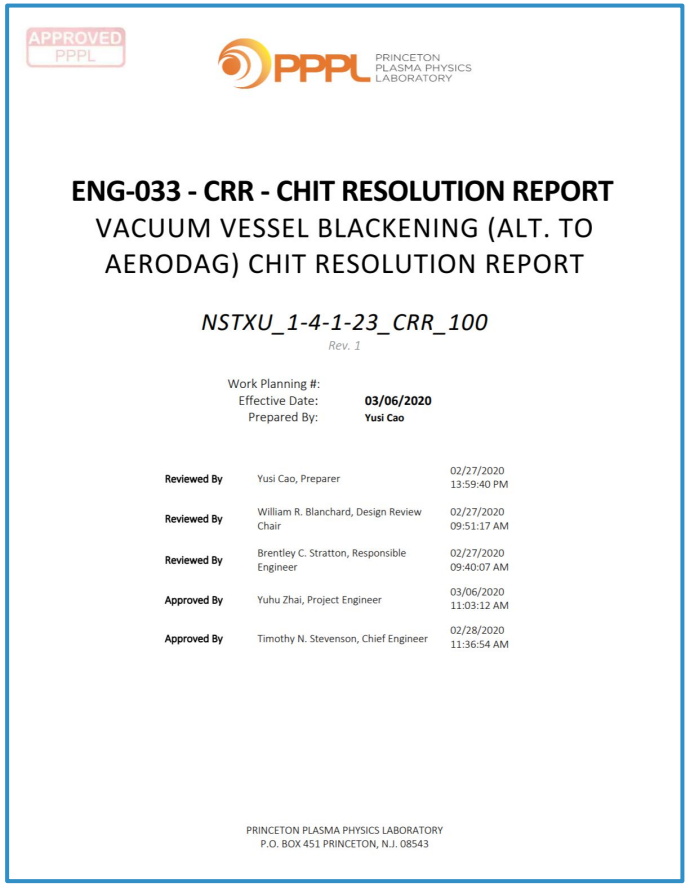
All Chits Have Been Closed



APPROVED PPPL

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ENG-033 - CRR - CHIT RESOLUTION REPORT

VACUUM VESSEL BLACKENING (ALT. TO AERODAG) CHIT RESOLUTION REPORT

NSTXU_1-4-1-23_CRR_100

Rev. 1

Work Planning #:
Effective Date: **03/06/2020**
Prepared By: **Yusi Cao**

Reviewed By	Yusi Cao, Preparer	02/27/2020 13:59:40 PM
Reviewed By	William R. Blanchard, Design Review Chair	02/27/2020 09:51:17 AM
Reviewed By	Brentley C. Stratton, Responsible Engineer	02/27/2020 09:40:07 AM
Approved By	Yuhu Zhai, Project Engineer	03/06/2020 11:03:12 AM
Approved By	Timothy N. Stevenson, Chief Engineer	02/28/2020 11:36:54 AM

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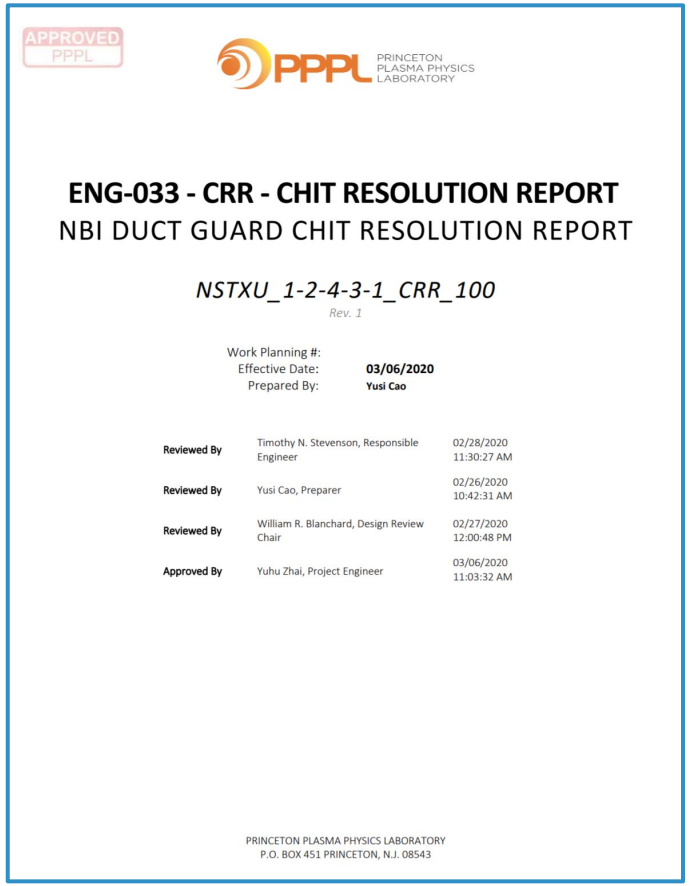
Chit Resolution Report: link



APPROVED PPPL

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ENG-033 - CRR - CHIT RESOLUTION REPORT

NBI DUCT GUARD CHIT RESOLUTION REPORT

NSTXU_1-2-4-3-1_CRR_100

Rev. 1

Work Planning #:
Effective Date: **03/06/2020**
Prepared By: **Yusi Cao**

Reviewed By	Timothy N. Stevenson, Responsible Engineer	02/28/2020 11:30:27 AM
Reviewed By	Yusi Cao, Preparer	02/26/2020 10:42:31 AM
Reviewed By	William R. Blanchard, Design Review Chair	02/27/2020 12:00:48 PM
Approved By	Yuhu Zhai, Project Engineer	03/06/2020 11:03:32 AM

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Fabrication, Procurement, Installation

- All metal plates will be waterjet.
  - 24 plates for duct shield. 6 bent in-house.
  - 39 plates for vessel blackening.
  - 20 plates for stud installation templates.
  - TZM Mo has been purchased at PPPL before.
- Black oxide coating is well understood.
  - Multiple qualified vendors identified; spec written.
  - Capable of coating plates up to 24” x 24”.
  - Selection of blank CF flanges will be coated.
  - All SS hardware will be coated.
  - Shutters to be installed in the future will be black-oxide treated.
- Ceramic coating is well understood.
  - All insulating washers and bushings are alumina coated 316 SS.
  - Qualified vendor identified; spec written.

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Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
No WBS-specific risks			

Note: many risks associated with later delivery, improper fitup, are carried at the Project level.

Design Failure Modes and Effects

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Diagnostic Vessel Wall Blackening	Fastener failure	Excessive disruption loads	Plate becomes loose; reduced diagnostic performance	9	DCPS Software	None	None	3
Diagnostic Vessel Wall Blackening	Material failure	Excessive disruption loads	Plate deforms; reduced diagnostic performance	9	DCPS Software	None	None	3
Neutral Beam Duct Guard	Shield material failure (EM)	Excessive disruption loads	Plates restraint compromised, may become mobile under disruption load or protrude into the path of the beam causing melting	9	DCPS Software	None	None	3
Neutral Beam Duct Guard	Failure of fasteners holding shield to the duct	Excessive disruption loads	Impingement of neutral beam aperture; plasma contamination; must vent vessel to extract failed components	9	DCPS Software	None	None	3
Diagnostic Vessel Wall Blackening	Black oxide coating failure	Degradation due to excessive heat, exposure to lithium, or mechanical surface wear	Plasma contamination; reduced diagnostic performance	6	Multi-pulse Thompson Scattering (MPTS)	CHERS	None	6

Digital Coil Protection System (DCPS) limits disruption loads by ensuring NSTX-U operation stays within the design basis envelope

Design Failure Modes and Effects

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Neutral Beam Duct Guard	Shield melts	Poor vacuum pressure --> high reionization losses and excessive prolonged heating of shield	Plasma contamination and surface damage to vessel duct	6	None	None	None	6
Neutral Beam Duct Guard	Shield material failure (bakeout)	Thermal growth of the plates (ops or bakeout)	Plates restraint compromised, may become mobile under disruption load or protrude into the path of the beam causing melting	3	None	None	None	3
Neutral Beam Duct Guard	Shield material failure	Embrittlement of molybdenum due to manufacturing process or repeated thermal cycling	Plasma contamination; must vent vessel to extract failed components	3	None	None	None	3
Neutral Beam Duct Guard	Shield surface material sputters into plasma	Poor vacuum pressure --> high reionization losses and excessive heat flux on shield surface	Plasma contamination	0	None	None	None	0

9 failure modes identified, all mitigated to acceptable risk

DCPS limits disruption loads to those in the design basis by ensuring NSTX-U operations remain in the design basis space.

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Quality, Environmental Safety, & Health

- Hazards are mitigated by standard PPPL safety programs, per ES&H 5008, including:
  - Confined Space Entry
  - Pre-job briefs
  - Job Hazard Analysis (JHA)
- Follow PPPL QAPD as appropriate for A-1 systems.
- PQA for supplier qualifications, review of procurement, and oversight of supplier activities.
- PPPL representatives have Stop Work Authority to resolve quality issues, NCRs, and safety issues.
- QA will check that black oxide coated plates meet NSTX-U requirement of 1.2 µ. Calibrated Severn gauges available down to 1.01 µ.

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Summary

- NB Duct Shield and Vessel Blackening scope is well defined.
  - All chits have been closed.
  - Interfaces are considered and documented in the ICDs.
- Comprehensive calculations verify design will meet requirements defined in GRD and SRDs.
  - Standalone calculation documents written and filed for each design.
- Material selection and coatings are well understood.
  - Previously used at other labs and at PPPL.
  - Testing improved understanding of black oxide coating.
- Design maturity is high and clear path forward to installation.
  - Project plans and PPPL safety programs adequately mitigate risk.
  - Accelerator and industrial safety has been considered in all stages of design review and will continue to be monitored.