National Spherical Torus eXperiment Upgrade

Beam Emission Spectroscopy (BES) Shutter Repair

WBS 1.04.01.07

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

Austin Cao - Cognizant Engineer

Last edit: 03/10/2020

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

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 1.04.01.07

WBS Title	BES Shutter Repair	WBS #	1.04.01.07
Project Cog.	Austin Cao	Assoc. Proj. Man.	William Gattoni
Design Scope	- Implement design improvements to BES diagnostic shutter assembly - Remanufacture select shutter blades using Inconel 625.		
Technical Impact of Scope	- Mitigates risk of shutter failure due to mechanical and disruption loads.		
Design Status	- BES Shutter Repair FDR on November 14, 2019. - Peer Review for shutter material modification on February, 19, 2020. - Drawings signed (link); Chits resolved (link); Calculations done (link)		
Fabrication / Procurement Status	- Drawings signed and ready for procurement/fabrication pending CDE-3B.		

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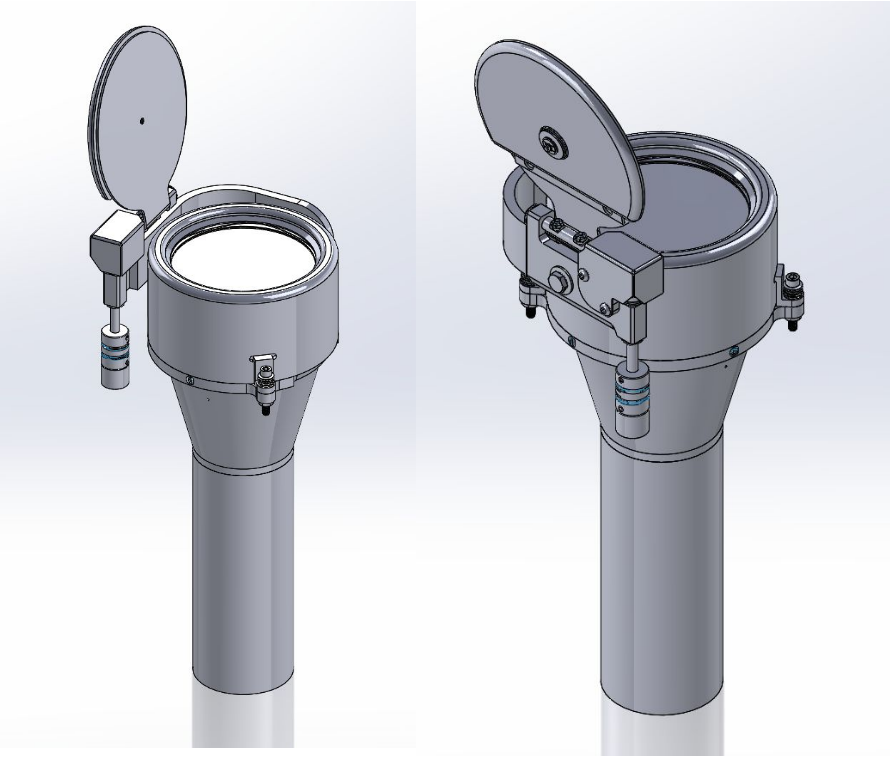
WBS Task Addresses BES Shutter Failure

- Diagnostic installed in 2010 and operated successfully until shutter failure during 2016 run
- Fragments of boron nitride (BN) found on the lower inboard diverter in 2016
- Connections for shutter actuation reversed during installation and caused the shutters to slam closed

Study of Legacy Design Reveals Opportunities for Improvement

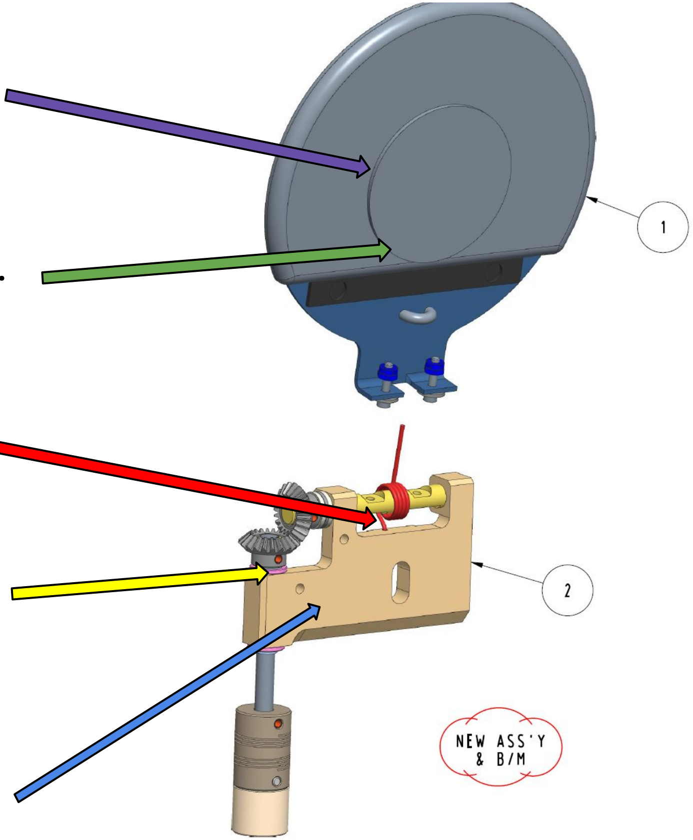
- Shutter OPEN requires significantly more air pressure to oppose gravity
- Excessive forces during shutter actuation if lines reversed
- Stress on BN is dependent on radius of central washer

Legacy BES Shutter Design



Comprehensive Design Improvements Mitigate Risk of Failure

1. Implement a strongback to reduce stress in the boron nitride shutter covers.
2. Replace the existing Belleville washer design with wave springs for more accurate preload.
3. Implement a torsion spring to balance gravitational forces during actuation.
4. Replace zirconia shaft with ceramic coated 316 SS shaft for reliability.
5. Use shaft spacers (0.002” minimum thk) instead of snap rings for better gear mating (fewer friction losses).



Diagnostic Shutters Must be Qualified for NSTX-U Loads

Geometry Name	Diagnostic System	Thickness (inch)	Material
Type 1 Shutter	Lyman Alpha Detector	1/16	304 SS
Type 2 Shutter	Synthetic Aperture Microwave Imaging (SAMI)	1/16	304 SS
Type 3 Shutter	Generic for 6" CF Flange	1/32	304 SS
Type 4 Shutter	CHERS/MSE	1/8	304 SS
Type 5 Shutter	MSE Bay G	1/32	Inconel 625
Type 6 Shutter	Small IR Camera	1/32	304 SS
Type 7 Shutter	HIGH-K	1/16	304 SS
Type 8 Shutter	Thomson Scattering	1/32	304 SS
USXR	Ultra-Soft X-Ray (JHU Diagnostic)	3/16	304 SS
LITER	Lithium Evaporator Probes	3/16	6061 T6 Al

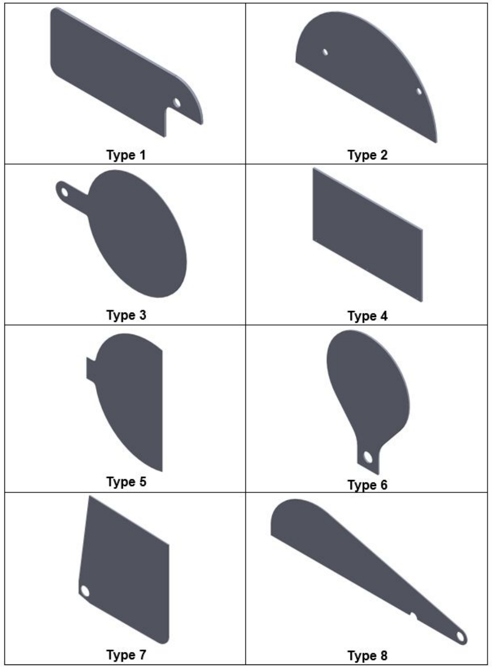


Figure 1. Eight variants of in-vessel shutter geometries.

- Comprehensive EM analysis indicates that type 3 and type 7 shutters must be remanufactured using Inconel 625 to reduce high stresses.

Perform disruption force calculations for shutters, with NSTX-U fields and quench rate.

Resolves Diagnostics DVVR Chit

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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-003-02	Disruption Analysis	Provides requirements for disruption analysis loading	✓
NSTX-U-RQMT-SRD-011-02	Diagnostic Systems	Provides requirement to have shutters for various diagnostics	✓

Complete RVTM maintained by Project Systems Engineering

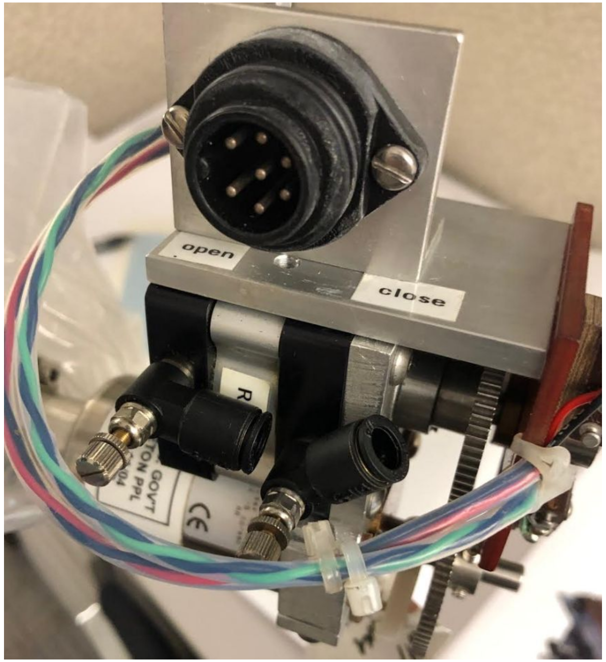
The Design Accommodates Required Interfaces

- Shutter material modifications are part-for-part replacements within previous design envelopes

- Open/close changes depending on shutter orientation. Inlet and outlet are labeled at time of assembly and testing
    - Implement adapters w/ different size threads -> open ¼” NPT, close ⅛” NPT

- Drawings revised after testing step to include shutter actuators & orientation

- Included in ECN for BES Shutter assem



Generic Labelled Shutter Actuator

Outline

Comprehensive Calculations
Verify Design will Meet Requirements

Physical Quantity or Title	Calculation #	Content
Mechanical actuation and EM disruption for BES Shutter	NSTXU_1-4-1-7-1_CALC_100	Shows that the BES shutter can handle disruption loads from plasma operations and mechanical loads from actuation
EM disruption for other diagnostic shutters	NSTXU_1-4-1_CALC_100	Shows that all in-vessel diagnostic shutter assemblies can handle disruption loads from plasma operations
Thermal for all diagnostic shutters	NSTXU-CALC-40-01-00	Shows that all in-vessel diagnostic shutter plates can handle thermal loads from plasma operations

- EM analyses use worst case disruption loads from models near mid-plane duct region, 500 T/s.

- 6/8 in-vessel shutter geometries meet SDC requirements
  - Type 3 and Type 7 require material change to Inconel 625

- Minimum shutter thickness:
  - 1/32”

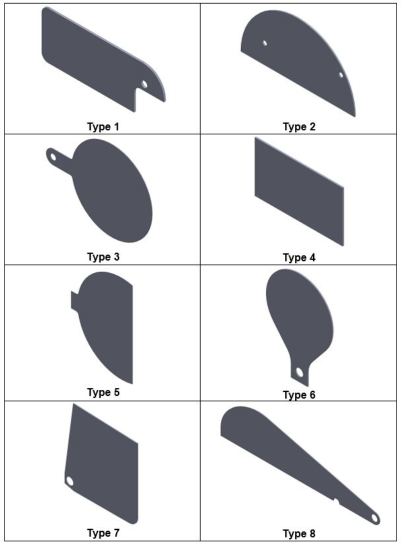


Figure 1. Eight variants of in-vessel shutter geometries.

Shutter Geometry	Peak EM Stress (MPa)	Peak Deflection (mm)	Comment
Type 1 (304 SS)	7 (1 ksi)	0.01 (0.0004 in)	PASS
Type 2 (304 SS)	4 (0.6 ksi)	0.005 (0.0002 in)	PASS
Type 3 (304 SS)	400 (58 ksi)	4.0 (0.16 in)	FAIL
Type 4 (304 SS)	85 (12 ksi)	0.2 (0.008 in)	PASS
Type 5 (Inconel 625)	300 (43 ksi)	6.0 (0.24 in)	PASS
Type 6 (304 SS)	75 (11 ksi)	0.3 (0.01 in)	PASS
Type 7 (304 SS)	300 (43 ksi)	7.0 (0.28 in)	FAIL
Type 8 (304 SS)	50 (7.2 ksi)	0.2 (0.008 in)	PASS

Table 2. Summary of results for each shutter geometry.

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All Closeable Chits Have Been Closed

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ENG-033 - CRR - CHIT RESOLUTION REPORT

BES SHUTTER UPGRADE CHIT RESOLUTION REPORT

NSTXU_1-4-1-7-1_CRR_100

Rev. 1

Work Planning #:
Effective Date: **02/28/2020**
Prepared By: **Yusi Cao**

Reviewed By	Brentley C. Stratton, Responsible Engineer	02/24/2020 16:40:31 PM
Approved By	Yuhu Zhai, Project Engineer	02/26/2020 09:50:49 AM
Approved By	Timothy N. Stevenson, Chief Engineer	02/28/2020 11:32:24 AM

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Chit Resolution Report: link

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ENG-033 - CRR - CHIT RESOLUTION REPORT

Shutter Mat Mod Peer Review Chit Resolution

NSTXU_1-4-1_CRR_101

Work Planning #:
Effective Date: **03/10/2020**
Prepared By: **Yusi Cao**

Reviewed By	Yusi Cao, Preparer	03/10/2020 14:37:30 PM
Reviewed By	Yuhu Zhai, Project Engineer	03/10/2020 14:35:42 PM
Reviewed By	Brentley C. Stratton, Responsible Engineer	03/10/2020 14:49:50 PM
Approved By	Timothy N. Stevenson, Design Review Chair	03/10/2020 15:37:55 PM

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Chit Resolution Report: link

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Procurement is ready pending CDE-3B approval

- Boron nitride grade AX05 and Inconel 625 are widely available
- Redesigned shutter components will be manufactured in-house prior to installation
- No in-vessel components will be removed for modification.
  - All newly manufactured parts
- Ceramic coating technical specification has been written and vendor has been qualified

Boron Nitride Grade AX05

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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 fit up, are carried at the Project level.

FMECA - BES Shutter Repair

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
BES Vacuum Vessel Interfaces Subsystem	Shutter failure with shutter in open position	Failure of mechanism	Window coated with metallic impurities, diagnostic becomes inoperative	6	TIV and Shutter Actuation System	None	None	6
BES Vacuum Vessel Interfaces Subsystem	Window break	Mechanical impact to window by tool; stress imposed by temperature gradients	Potential injury; catastrophic loss of vacuum	6	Vacuum Gauges and Residual Gas Analyzers	None	None	6
BES Vacuum Vessel Interfaces Subsystem	Rotary drive assembly failure	Bellows leak; rotary drive failure.	Diagnostic becomes useless; vacuum compromised	6	Vacuum Gauges and Residual Gas Analyzers	None	None	6
BES Vacuum Vessel Interfaces Subsystem	Boron nitride shutter cover failure	Excessive stresses during shutter actuation	Must vent vessel and extract failed components	3	Physics Imaging Systems	Plasma TV	None	3
BES Vacuum Vessel Interfaces Subsystem	Shutter failure with shutter in closed position	Failure of mechanism	Diagnostic becomes inoperative	2	TIV and Shutter Actuation System	None	None	2

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ES&H, QA

- Sharps, confined spaces, & hand tools are hazards during installation.
- Hazards are mitigated by standard PPPL safety programs, per ES&H 5008, including:
  - Confined space entry permits
  - Pre-job briefs
  - Job Hazard Analysis (JHA)
  - Personal Protective Equipment (PPE)
- 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.

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- Diagnostic shutter repair and replacement scope is well defined.
  - All closeable chits have been closed.
  - Designs accommodate required interfaces.
- Comprehensive calculations verify design will meet requirements defined in GRD and SRDs.
  - Standalone calculation documents written and filed.
- Material selection and coatings are well understood.
  - Inconel 625 widely used at PPPL.
  - Ceramic coating spec is shared with other WBS tasks.
- 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.