National Spherical Torus eXperiment Upgrade

Machine Instrumentation

WBS 1.04.01.01

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

Chris Freeman - Cognizant Engineer
Austin Cao - TF Laser Twist Measurement

Last edit: 03/10/20

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 1.01.02.04

WBS Title	Machine Instrumentation	WBS #	1.04.01.01
Project Cog.	Chris Freeman	Assoc. Proj. Man.	Bill Gattoni
Design Scope	Fiber optic (FO) instrumentation to measure coil & coil support stresses, coil preloads, thermal motions; laser-based system to measure twist of the TF		
Technical Impact of Scope	Allows trending of machine performance over time, out-of-family determination, and model benchmarking		
Design Status	Primary FDR for Machine Instrumentation completed on 10/25/19, with supplementary FDR on 1/30/20. FDR for TF Twist Laser on 1/13/20. Chit Resolution: link Calculations: link Drawings: link		
Fabrication Status	Fabrication can not begin until CDE-3B approval is obtained.		
Installation Status	Installation can not begin until CDE-3B approval is obtained.		

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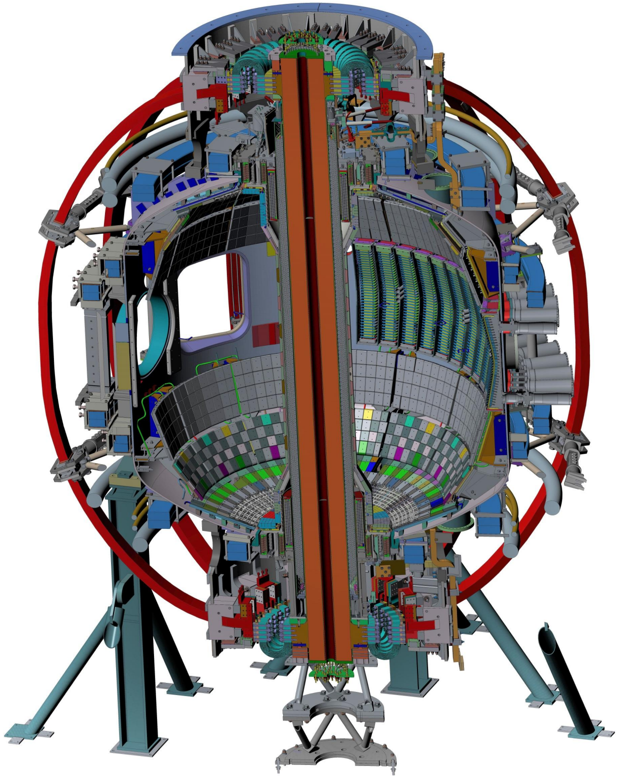
System Design Goals

- The goals of the NSTX-U Fiber Optic Measurement System [1] are two-fold:
  - To benchmark the mechanical models that underlie the signed, posted calculations and the DCPS protection envelope.
  - To provide measurements that can be used to i) evaluate any unexpected mechanical behavior of components and ii) trend possible slow degradation or deformation of critical components.

Machine Instrumentation Scope

- Fiber Routing and Infrastructure Design
- CI&C Interface Design
- Sensor Locations
  - PF1A/B Preload Strain
  - V/V Centerstack Vertical Displacement
  - OH PreLoad Displacement
  - PF4 and PF5 Slides Displacement
  - TFOL and Truss Strain and Temperature
  - Spoked Lid Strain and Temperature
  - Halo Current Side Load Strain and Temperature
  - TF Bundle Twist Rosette Strain and Temperature

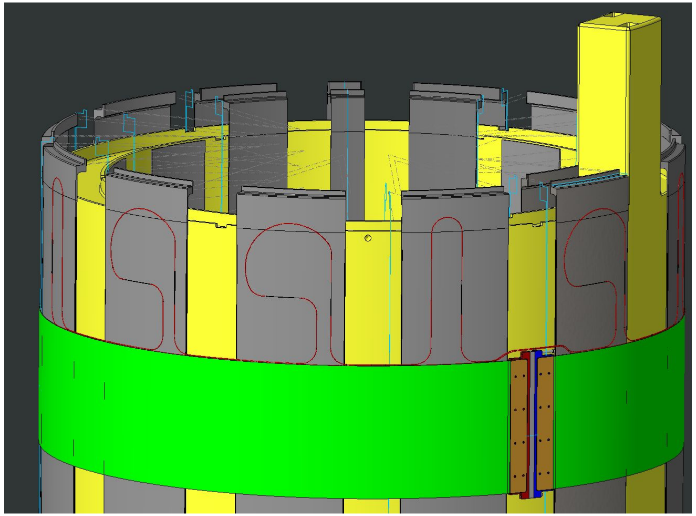
SBS: 1.7.3.4 Categorization: A2



PF1A/B Preload Measurement

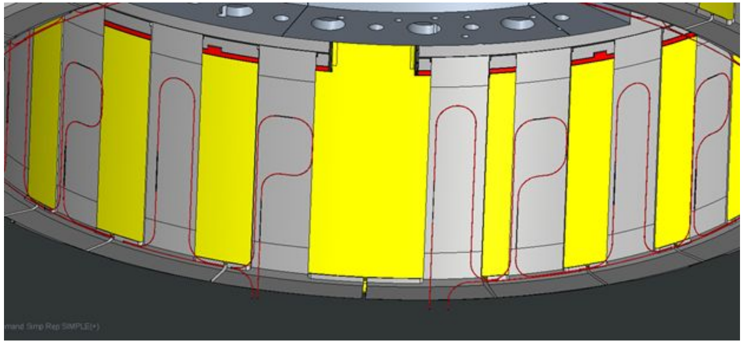
- Sensors will be applied to the sling assemblies of the PF1AU/L, and PF1BU/L to verify that the necessary preload is still being applied to the PF1A and PF1B coils.

- Each sling of the four coils will be instrumented allowing for preload determination at each location
  - 13 - PF1A Slings - Instrumented on the O/D of PF1A
  - 24 - PF1B Slings - Instrumented on the I/D of PF1B



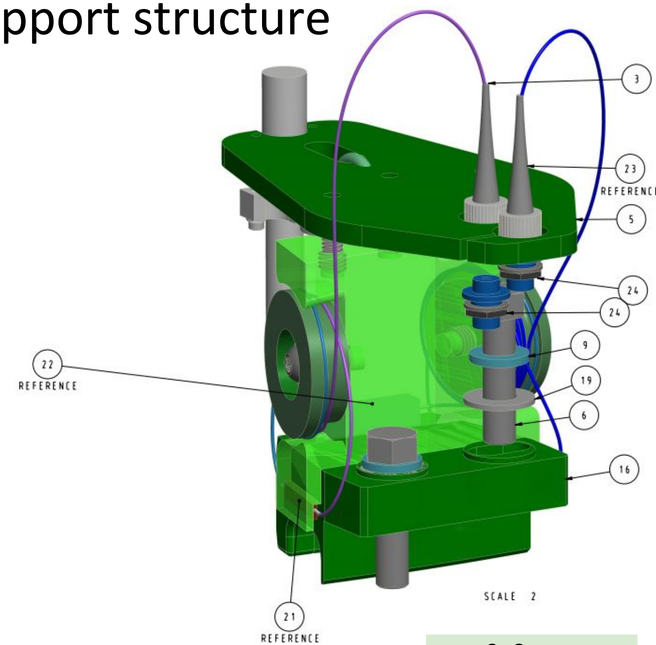
- Bare fiber FBG sensors will be used to minimize sensor thickness and to handle bakeout temps.

- For protection, a 900um teflon jacketing will be applied to the fiber strands between sensor locations.



Centerstack V/V Vertical Displacement

- Measure the displacement of the Centerstack wrt to the Vacuum Vessel.
- Particularly important during bakeout.
- Use Opsens Fabry-Perot displacement transducers.
- Displacement transducer is integrated into the support structure of the centerstack lateral load assembly.
  - A total of 4 locations will be instrumented



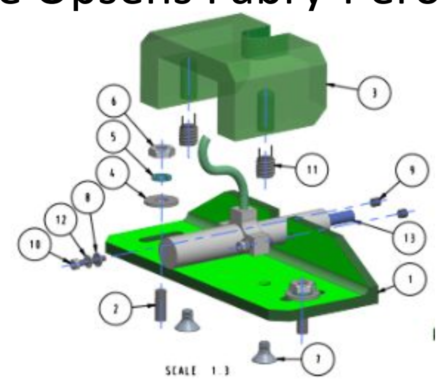
OH Preload Displacement

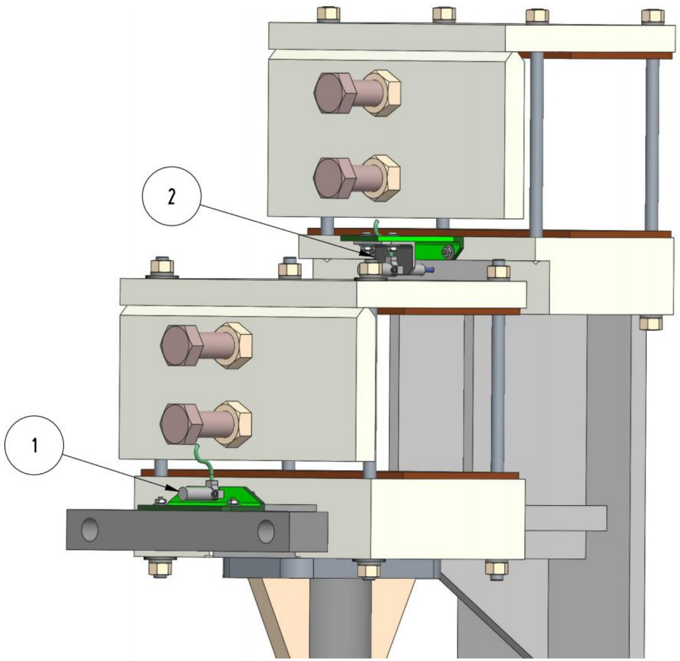
- Existing FISO Fabry-Perot Displacement Transducers will be replaced with OpSens Displacement Transducers for compatibility with new signal conditioning hardware.
  - OpSens PN: ODP-A-X-62-FCA-10-PM4-XN-XN-D25
  - 25mm Linear Stroke

- Form factor of new sensor is very similar to old FISO sensor.

PF4 and PF5 Displacement

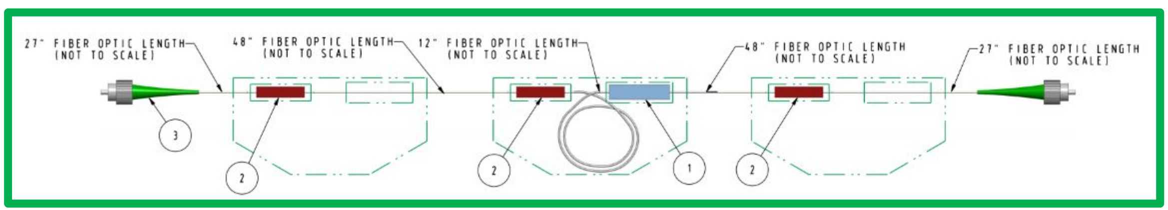
- Measure displacements on the sliding supports of the outer PF coils.
- PF-5 upper and lower slides on fixed supports.
  - 4 upper, 4 lower supports for 8 total, measuring radial m
  - C/D, E/F, I/J, K/L
- PF-4 upper and lower slides on fixed supports.
  - 6 upper, 6 lower for 12 total, measuring radial motion.
  - A/B, C/D, E/F, G/H, I/J, K/L
- Radial motion at floating supports.
  - 12 total
- Use Opsens Fabry-Perot displacement transducer

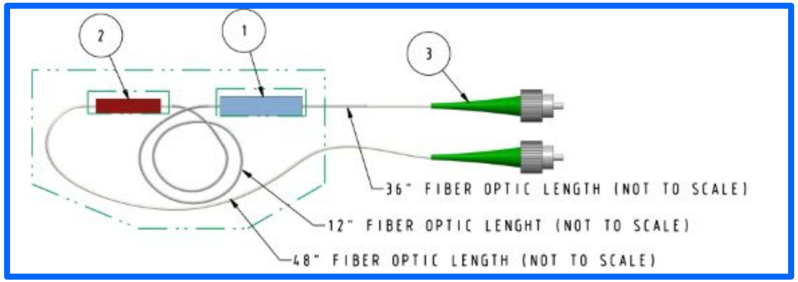


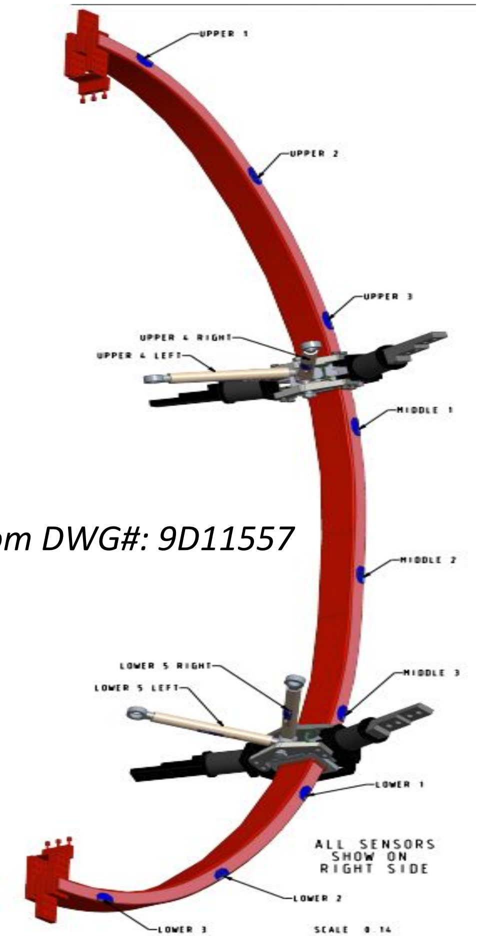


TFOL and Truss Strain and Temp

- Twelve Coils – Bay A through L
  - Total of 13 locations per bay
  - Micron Optics os3200 Strain Sensor
    - Maximum Strain Range: ±2000 microstrain.
  - Seven compensation temperature sensors at the midpoint of each unsupported span and on each truss.



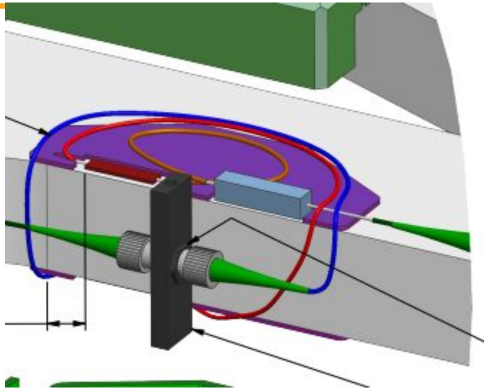


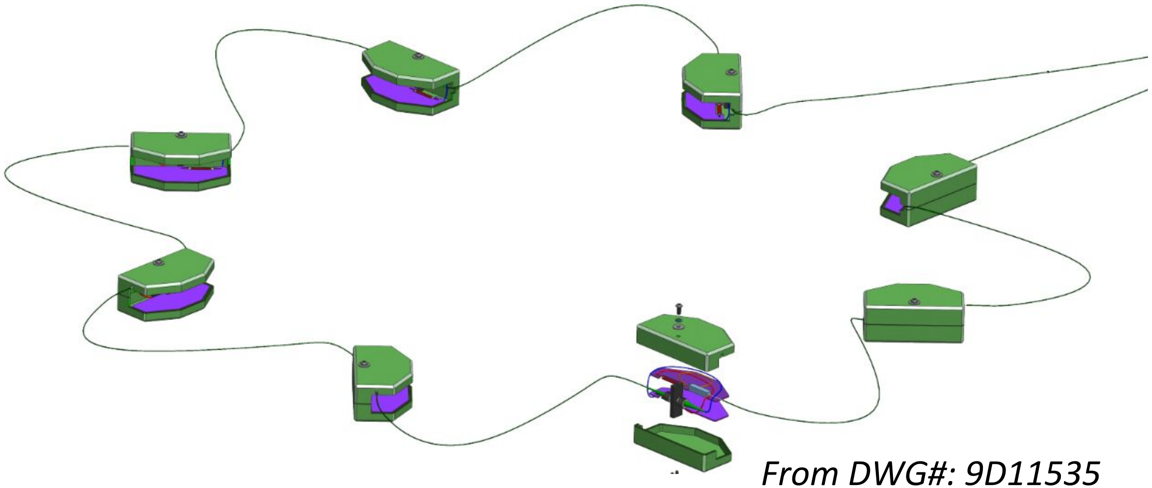


From DWG#: 9D11557

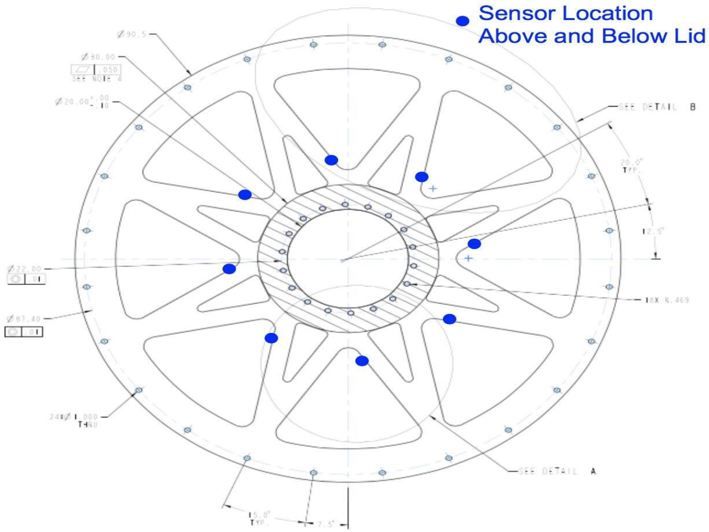
Spoked Lid Strain and Temp

- Eight Spokes Top and Bottom – Total of 16 Locations
  - Two differentially mounted strain sensors per location.
    - Micron Optics os3200
    - Top and bottom of spoked lid at same location.
  - One Temperature Sensor per location.





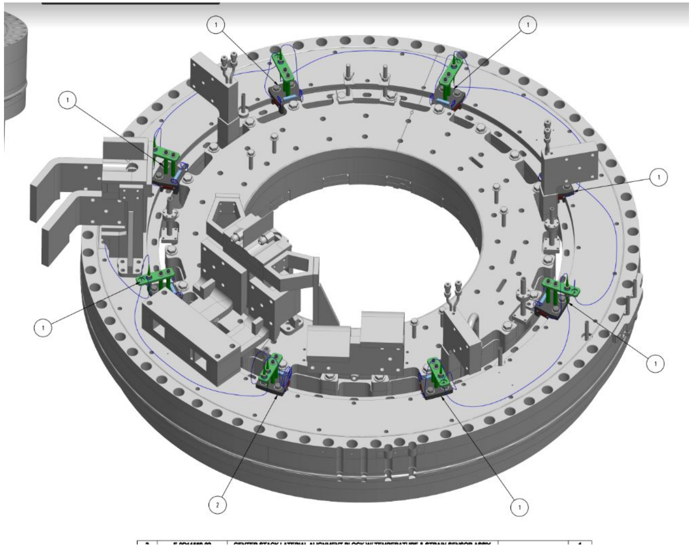
From DWG#: 9D11535

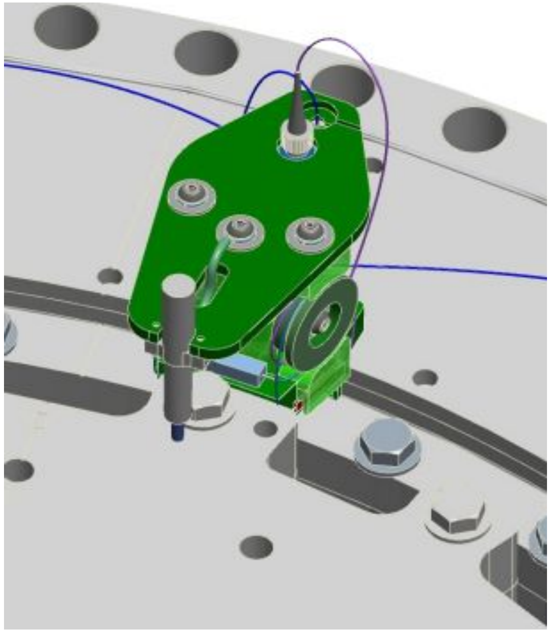


Halo Current Side Load Restraints

- Eight G10 Shims each instrumented with 2 strain sensors and a temperature sensors.

- Strain sensors mounted on each side of the shim to observe the compressive effects on the shim during loading.

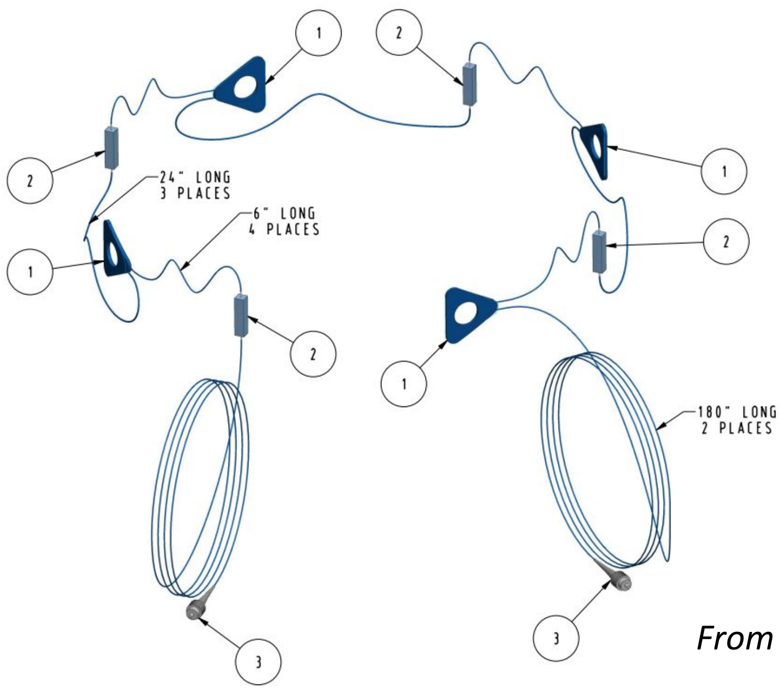


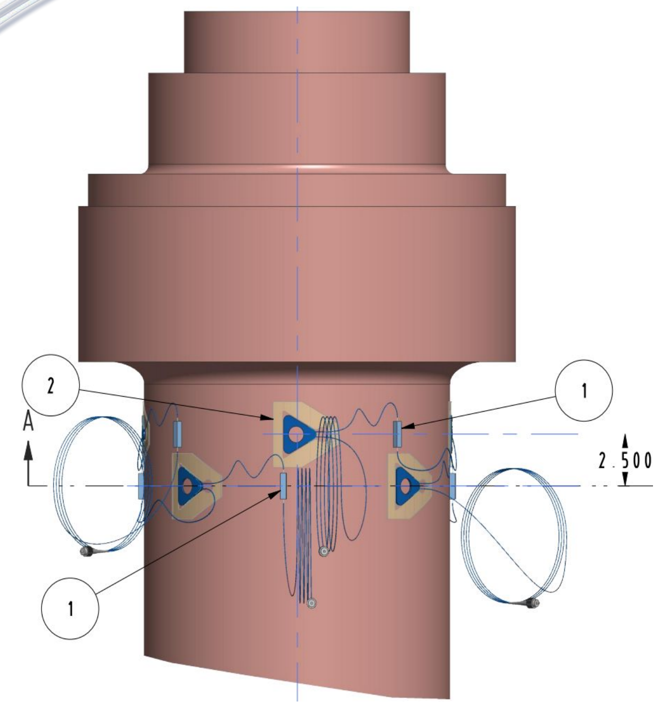


From DWG#: 9D11559

Toroidal Field Torsional Twist

- Eight Strain Rosettes Top and Bottom – Total of 16 Locations
  - HBM K-OP Optical Rosette
  - One HBM temperature sensor per location



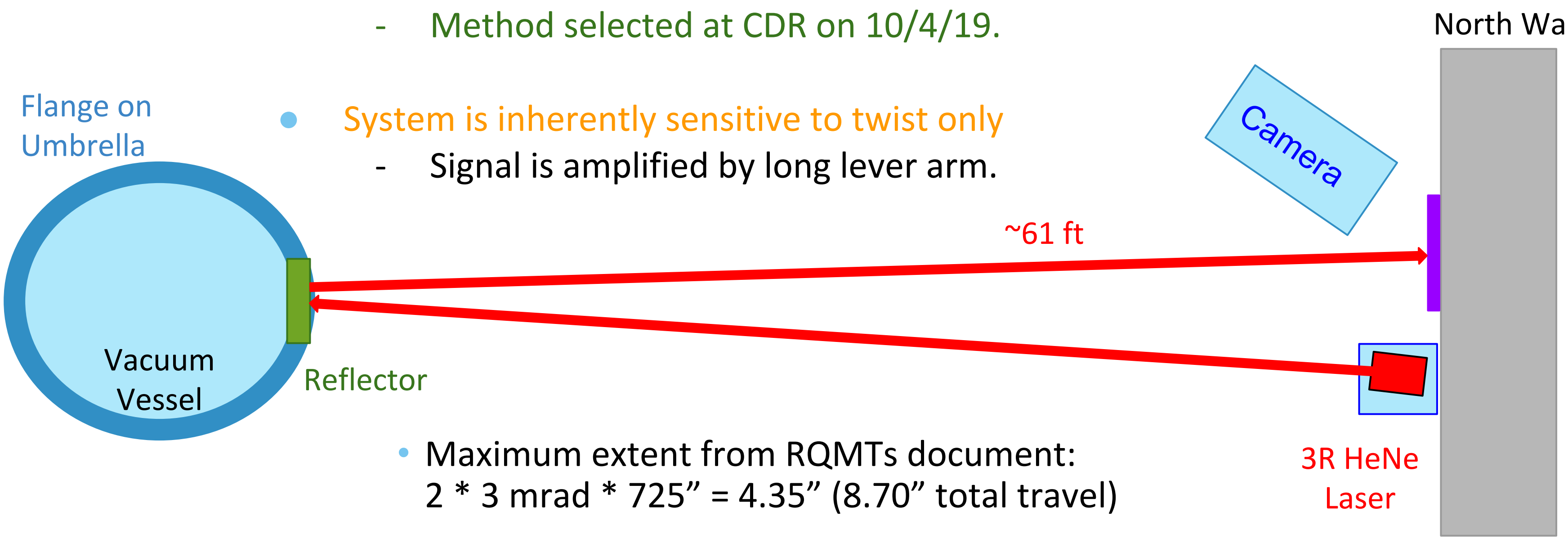


From DWG#: 9D11574

TF Twist Laser Measurement Provides Global Model Benchmarking Capability

- Optically measure twist with laser, mirror, and camera.
  - Similar to laser system used at DIII-D
  - Method selected at CDR on 10/4/19.

- System is inherently sensitive to twist only
  - Signal is amplified by long lever arm.



- Maximum extent from RQMTs document:
  2 * 3 mrad * 725” = 4.35” (8.70” total travel)

- Minimum extent from RQMTs document:
  2 * 0.04 mrad * 725” = 0.06” (0.12”, 3mm total travel)

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Requirements Document

- The requirements for the Machine Instrumentation Fiber Optic Measurement System and TF Laser Measurement System are captured in the following documents:

  - NSTX-U-RQMT-GRD-001
  - NSTXU_1-4-1_SRD_100
  - NSTX-U-RQMT-RD-008-03

Requirements Defined and Met

Source	Requirements	Comment	Met
NSTX-U-RQMT-GRD-001	Provide Instrumentation to validate structural models, and trend long term behavior.	System is designed to be fast enough to resolve mechanical stresses during operation, and allows for lower speed trending of data.	✓
NSTX-U-RQMT-SRD-011	Provide post-shot alarm of out of limit sensor value.	Software is designed to check for out of bounds sensor value and report an error to EPICs.	✓
NSTX-U-RQMT-SRD-011	Sensor shall provide galvanic isolation from coil or vessel grounds.	All sensors are fiber optic.	✓
NSTX-U-RQMT-SRD-011	Sensor shall not modify design of components being instrumented.	All sensors are adhered to the surface of structures, and only minor surface abrasion is permitted for epoxy adhesion.	✓
NSTX-U-RQMT-SRD-011	Reliable in magnetic fields.	All sensors are fiber optic and thus immune to EMI.	✓
NSTX-U-RQMT-SRD-011	Synchronize to Shot Clock.	Synchronized through RTU. System has been tested.	✓
NSTX-U-RQMT-SRD-011	Sampling rate of at least 100Hz.	System samples at 1KHz.	✓
NSTX-U-RQMT-SRD-011	Archive calibration data.	MDS+ Tree uses calibration data to calculate strain, and temperature so all calibration data is archived.	✓

Requirements Defined and Met

Source	Requirements	Comment	Met
NSTX-U-RQMT-SRD-011	Data shall be easily plottable.	All data is easily plotted using traditional MDS+ plotting tools.	✓
NSTX-U-RQMT-SRD-011	Shall instrument 9 locations on TFOL.	Design instruments 9 TFOL locations.	✓
NSTX-U-RQMT-SRD-011	Shall instrument TF Trusses	Design instruments all TF trusses.	✓
NSTX-U-RQMT-SRD-011	Shall instrument upper and lower spoked lid.	Design instruments upper and lower spoked lid.	✓
NSTX-U-RQMT-SRD-011	Shall instrument CS shim.	Design instruments CS shim.	✓
NSTX-U-RQMT-SRD-011	Shall instrument OH preload.	Design instruments OH preload assembly.	✓
NSTX-U-RQMT-SRD-011	Shall instrument top inner TF bundle.	Design instruments inner TF bundle top and bottom.	✓
NSTX-U-RQMT-SRD-011	Shall instrument PF4/5 slides.	Design instruments PF4/5 slides.	✓
NSTX-U-RQMT-SRD-011	Shall instrument PF1A/B preload.	Design instruments PF1A/B slings.	✓
NSTX-U-RQMT-SRD-011	Shall instrument and trend TF bundle data with sufficient resolution to detect progressive delamination.	Analysis shows that rosette sensor design will be sensitive enough to detect bundle delamination.	✓
NSTX-U-RQMT-SRD-011	Shall be expandable.	Design provides spare sensor channels to the vessel for expansion. Additionally, fiber run from DARM to TC is sufficient for significant future expansion.	✓

Requirements Defined and Met

Source	Requirements	Comment	Met
NSTX-U-RQMT-RD-008	Sensors shall be protected from damage.	All sensing locations are either protected from damage, or are inherently not susceptible to damage.	✓
NSTX-U-RQMT-RD-008	Sensors shall be rated for operational temperatures.	All sensors and epoxies are rated for greater than the worst case expected temperature for a particular location.	✓
NSTX-U-RQMT-RD-008	Strain sensitivity of at least 1% of maximum strain.	System can reliable measure strains as low as 1μE.	✓
NSTX-U-RQMT-RD-008	Shall provide for user configurable shot time from 10 to 1200 seconds.	System continuously streams peak information at 1KHz. Shot time is passed as a parameter upon starting the FBG Daemon.	✓
NSTX-U-RQMT-RD-008	Shall store raw peak data.	Design stores raw peak data.	✓
NSTX-U-RQMT-RD-008	Temperature compensation shall be performed.	Design compensates for temperature affects.	✓
NSTX-U-RQMT-RD-008	Sensors shall be placed within 0.5" of nominal.	Sensor design allows for high placement accuracy.	✓
NSTX-U-RQMT-RD-008	Each TFOL elevation shall have at least 4 sensor on either side of the coil.	Design ensures that this is maintained.	✓
NSTX-U-RQMT-RD-008	Measurement shall be centered on truss.	Design centers the strain measurement on the TF truss.	✓

Requirements Defined and Met

Source	Requirements	Comment	Met
NSTX-U-RQMT-RD-008	Strain measurement direction shall be along the truss.	Strains sensors are measuring axially along the TF truss.	✓
NSTX-U-RQMT-RD-008	Shall accommodate rotation of truss.	Sensors are connectorized to allow for truss rotation.	✓
NSTX-U-RQMT-RD-008	Spoked lid measurement shall be taken on top and bottom of lid.	Each sensing location has two strain measurements on the top and bottom of the lid.	✓
NSTX-U-RQMT-RD-008	At least two sensing locations per lid.	Design instruments every spoke of the upper and lower spoked lid.	✓
NSTX-U-RQMT-RD-008	Strain measured in a direction along spoke and placed within 0.25” of nominal.	Protection fixture allows for alignment along the edge of the spoke and for accurate location of sensors.	✓
NSTX-U-RQMT-RD-008	Must allow for segmented removal of lower spokes.	Design is connectorized between sensing locations.	✓
NSTX-U-RQMT-RD-008	TF Twist shall be measured at 8 radial locations.	Design uses 8 rosettes for the upper and lower inner TF bundle twist measurement.	✓
NSTX-U-RQMT-RD-008	Shall have 25mm measurement range on V/V Vertical growth measurement.	Design accommodates this displacement range.	✓
NSTX-U-RQMT-RD-008	Shall instrument 3 locations with at least two 90° apart.	Design instruments four locations each 90° apart.	✓

Requirements Defined and Met

Source	Requirements	Comment	Met
NSTX-U-RQMT-RD-008	Laser shall comply with ES&H 5008 safety rules.		✓
NSTX-U-RQMT-RD-008	Shall be insensitive to non-twist motion of the vessel.		✓
NSTX-U-RQMT-RD-008	Shall measure twist in a range from 0.04 - 3 mrad.		✓
NSTX-U-RQMT-RD-008	Shall be sensitive to bidirectional twist.		✓
NSTX-U-RQMT-RD-008	Shall have time resolution of at least 100Hz.		✓

Interfaces

- Test Cell
  - Test cell equipment racks will be used to house patch panels.
  - TF Twist Laser and Camera are mounted to the north wall of the NTC.
- Magnets
  - Sensors will be directly applied to TF Inner and Outer Legs.
  - Displacement sensors will be attached to PF4 and PF5 slide mechanisms.
- Vessel
  - Sensors will be mounted to the spoked lid, center stack shims, and TF struts.
  - TF Twist mirror welded to the spoked lid of the vessel.
- MCS
  - Sensors will be mounted directly to the slings of the PF1A and PF1B coils.
- CI&C
  - Data from Fiber Bragg and Fabry Perot instrumentation systems will be acquired and archived by the CI&C system.
  - TF twist camera data will be archive by the CI&C system.

Details of Interfaces Defined in Interface Control Documents

System 1	System 2	ICD Link	Exposition
Integrated Machine Operations	Test Cell	link	Defines interface between the Machine Instrumenation and the Test Cell
Integrated Machine Operations	CI&C	link	Defines interface between the Machine Instrumentation and CI&C
Integrated Machine Operations	Vacuum Vessel Structures	link	Defines interface between the Machine Instrumention and the Vacuum Vessel including the umbrella
Integrated Machine Operations	Magnets	link	Defines interface between the Machine Instrumention and the Magnets
Integrated Machine Operations	Center Stack Structures	link	Defines interface between the Machine Instrumention and Center Stack Structures
Integrated Machine Operations	Power	link	Defines interface between the Machine Instrumention and Power System

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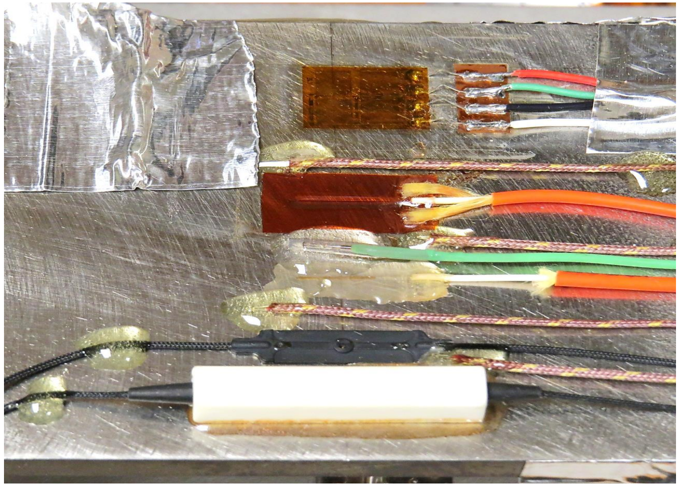
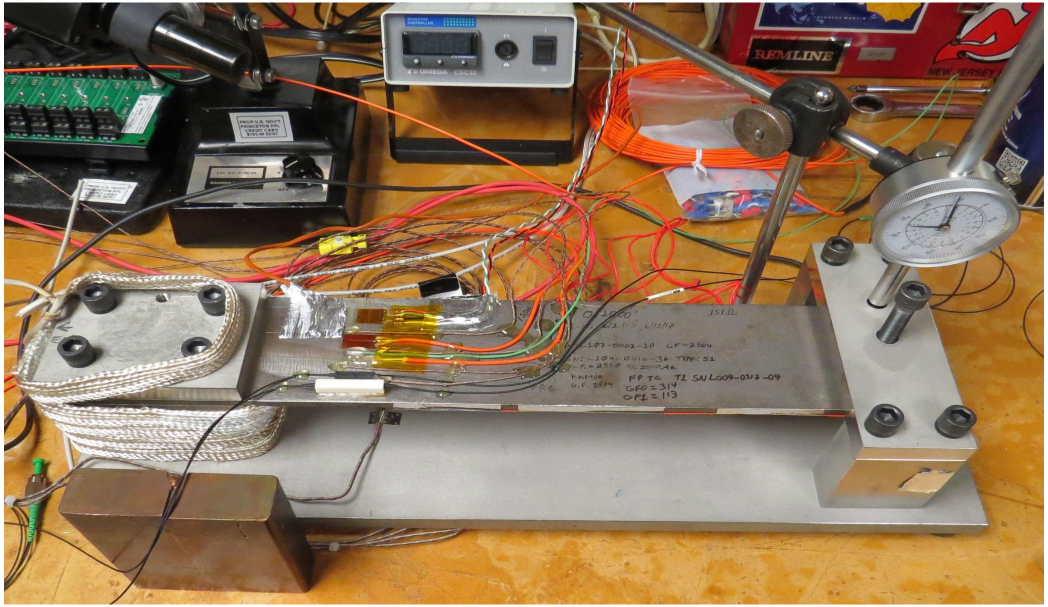
Prototype Testing – Cantilever Beam Testing

- Cantilever beam test fixture was used to verify the performance of FBG strain and temperature sensors against resistive strain gauges and thermocouples.

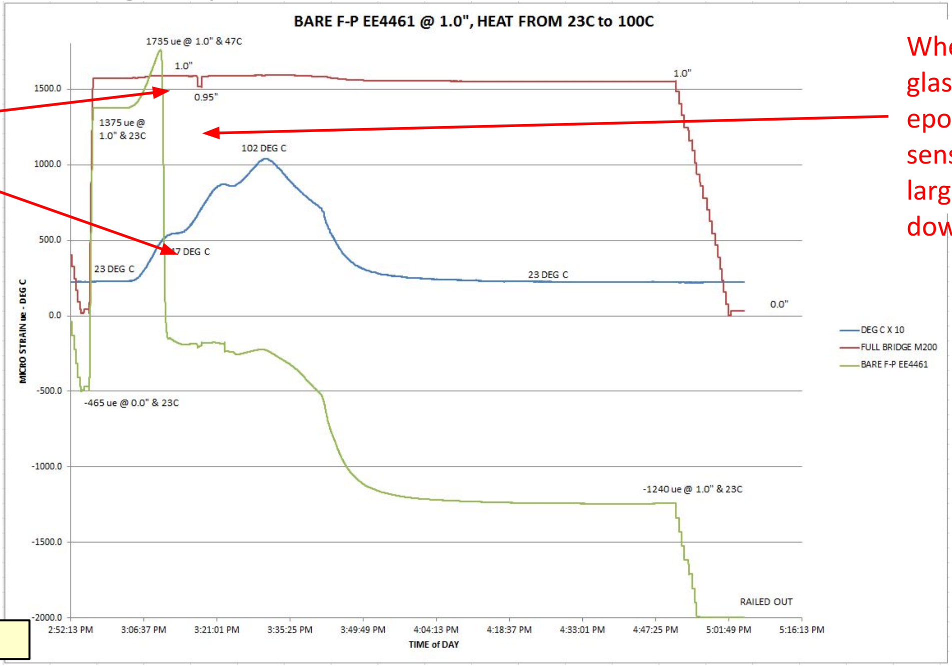




Prototype Testing – Epoxy Testing

- Several room temperature cure strain gauge epoxies were tested using the cantilever beam fixture.
- As the temperature was increased all of the epoxies experienced slipping as the epoxy temperature passed the glass transition temperature. (40°C to 50°C)
- It was determined that any testing location that will potentially exceed 40°C will require an elevated temperature curing step.

As temperature begins to increase the strain on the beam increases



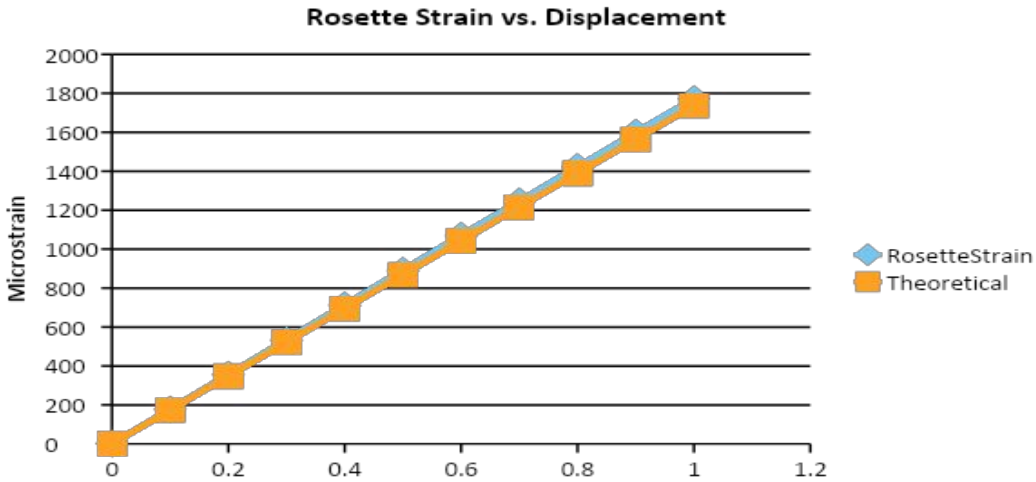
When the temperature hits the glass transition temperature of the epoxy (~47 °C), the tension in the sensor is lost. Resulting in a very large negative offset upon cool down.

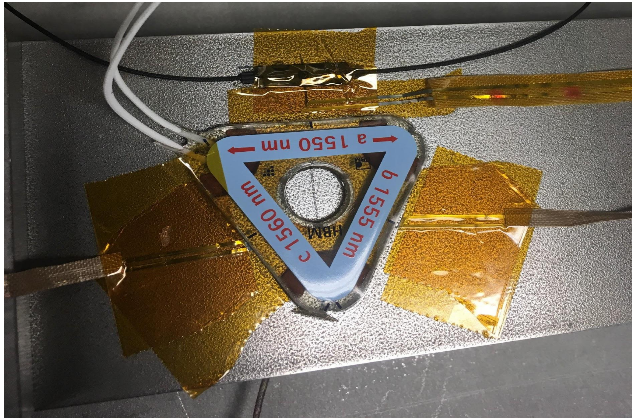
Prototype Testing – Epoxy Testing

- The Machine Instrumentation System will utilize two different epoxies:
  - Cotronics EE4461
    - High temperature rating; Used for adhering sling sensors.
  - AE10/AE15
    - General purpose strain gauge epoxy that has been used to adhere sensors to our composite coils in the past.
    - AE15 has longer pot life potentially reducing waste while installing sensors on the TFOL's.

Prototype Testing – Cantilever Beam Testing

- Strain rosette functionality was verified using the Cantilever Beam Test fixture.
  - One of the rosette strain gauges was aligned with the primary strain axis of the beam and strain readings were verified vs theoretical values.
  - Strain readings matched theoretical values with a maximum error of ~2%.
    - 2% is the stated accuracy of the vendor provided gauge factor.





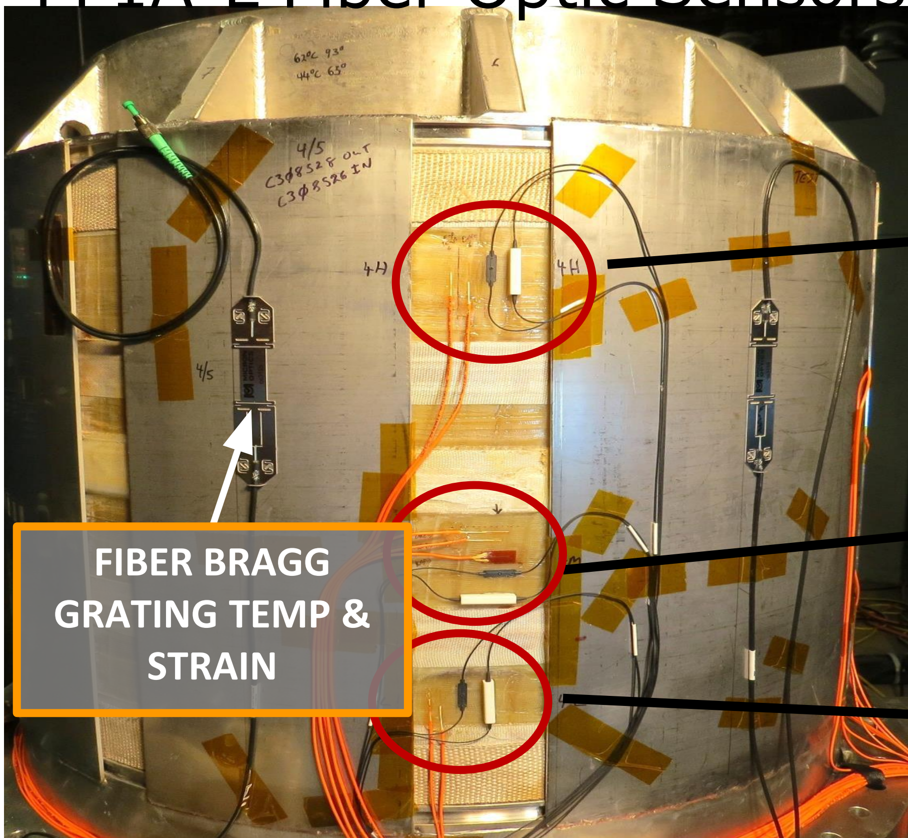
Prototype Testing – PF1AL Coil Testing

- A total of 22 Fiber Bragg Grating Sensors and 24 Fabry-Perot sensors were installed on PF1AL during Energized Coil Testing in early 2018.

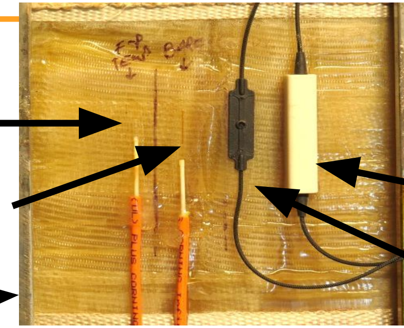
- This testing provided the opportunity to prototype the following aspects of the Machine Instrumentation System:
  - Coil surface preparation and sensor adhesion
  - Epoxy curing technique
  - Sensor functionality
  - FBG sensor configuration and MDSPlus tree setup
  - FBG Daemon triggering, acquisition, and archiving**
  - FBG Temperature Compensation
  - Fabry-Perot sensor configuration
  - Fabry-Perot analog acquisition, and archiving

Prototype Testing – PF1AL Coil Testing

PF1A-L Fiber Optic Sensors

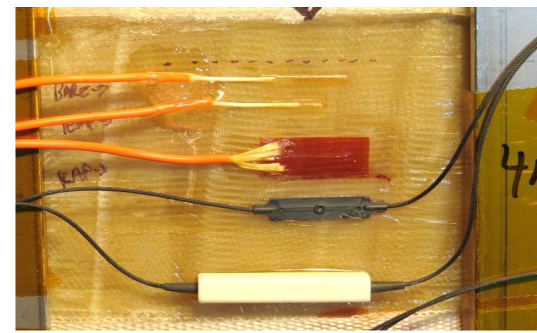


FABRY PEROT TEMP & STRAIN



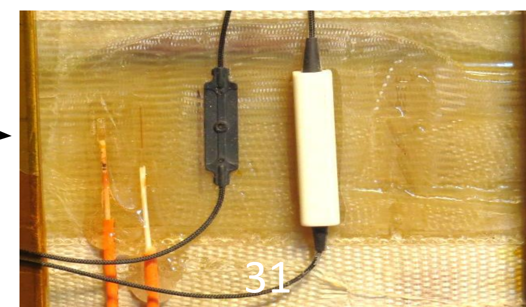
FBG TEMP & STRAIN

SLOT #4 “HI”



SLOT #4 “MID”

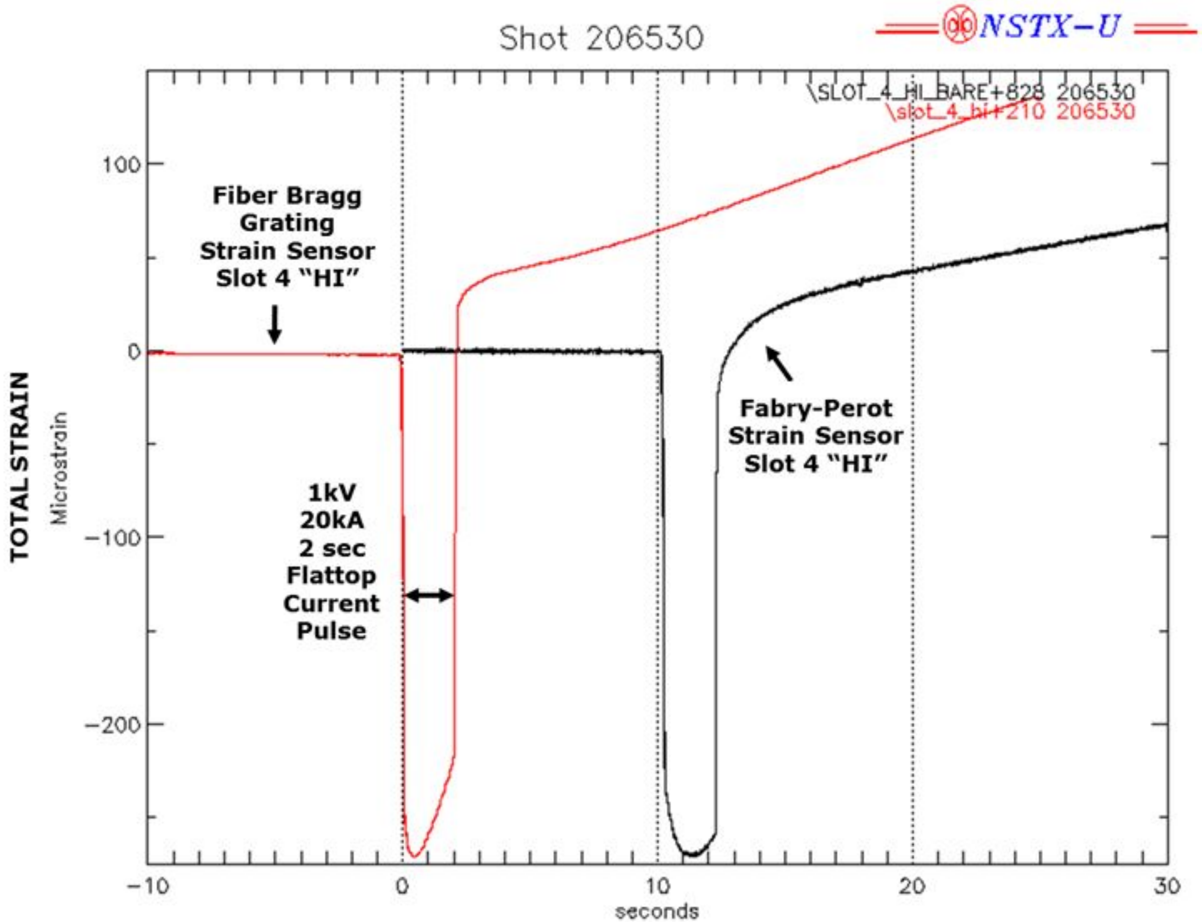
SLOT #4 “LO”



Prototype Testing – Coil Surface Prep.

- An Installation Procedure was developed and successfully executed for surface preparation and bonding of Fiber Bragg Grating sensors to a composite surface on PF1AL.
    - D-NSTX-IP-3964
- The surface preparation procedure details step to gently abrade and clean the coil surface to remove any surface fluctuations and provide a flat and consistent mounting surface.
- The final sensor installation procedure will be a modified version of this procedure.

Prototype Testing – PF1AL Coil Testing

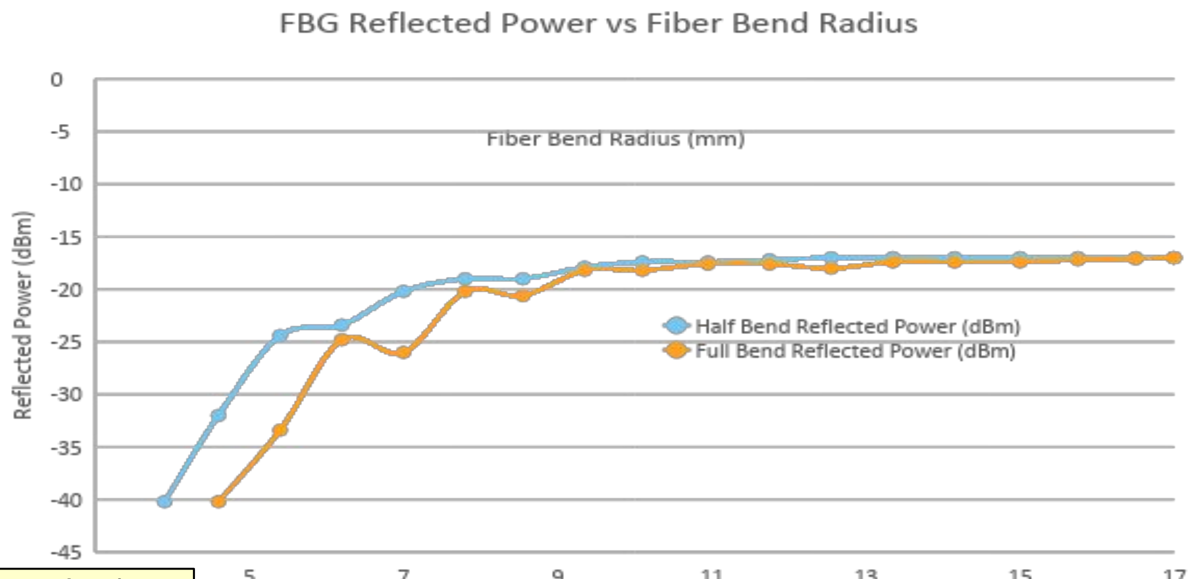


- Tail divergence due to lack of temperature compensation on FBG
- Pulse shape irregularities potentially due to varying epoxy bondlines.

Prototype Testing – Fiber Bend Radius

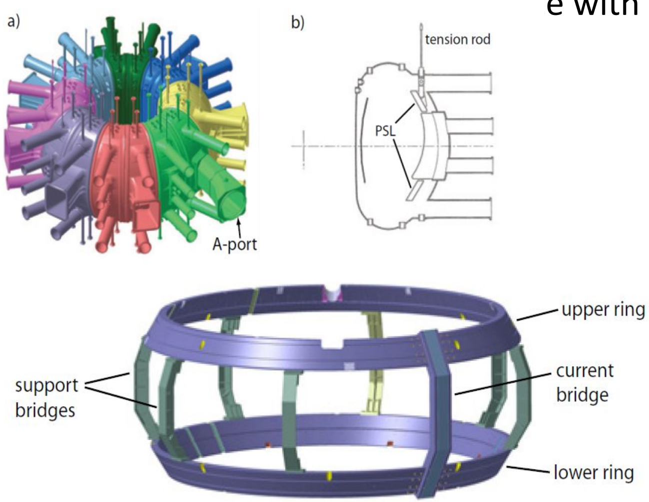
- Testing was conducted to determine the minimum fiber bend radius for fiber routing along the machine.
  - Dramatic attenuation was observed at radii less than 9mm.
  - All fiber routing will maintain a bend radius of greater than 17mm.

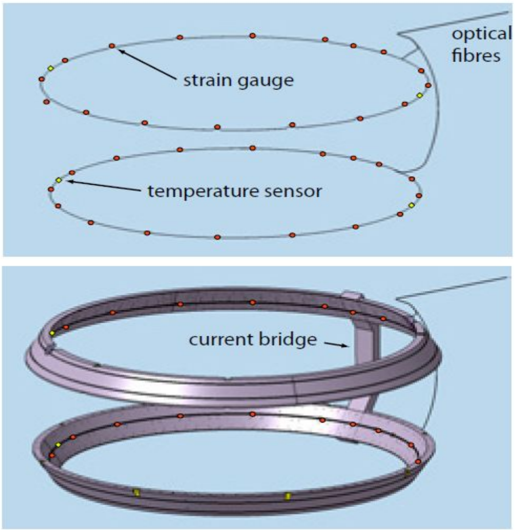
- During Installation, sensors should be connected to the interrogator and connection/signal strength should be verified in real-time using vendor provided software.



FBG Radiation Induced Attenuation

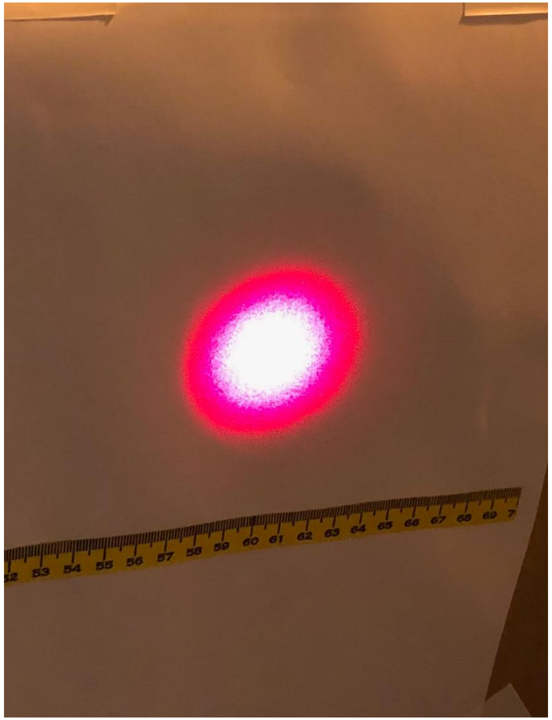
- In 2010 ASDEX Upgrade implemented a Micron Optics FBG system to monitor deformation of in-vessel structures.
- System uses Micron Optics sm130 Interrogator
  - 2 Sensor arrays with 19 FBG elements each.
    - 17 Strain sensors and 2 temperature compensation sensors per array.
    - Polyimide coated fibers with stainless steel sensor carriers.
- Neutron dose of ASDEX Upgrade; ~5e18 n/year.
- Neutron dose of NSTX-U; ~2e18 n/year.





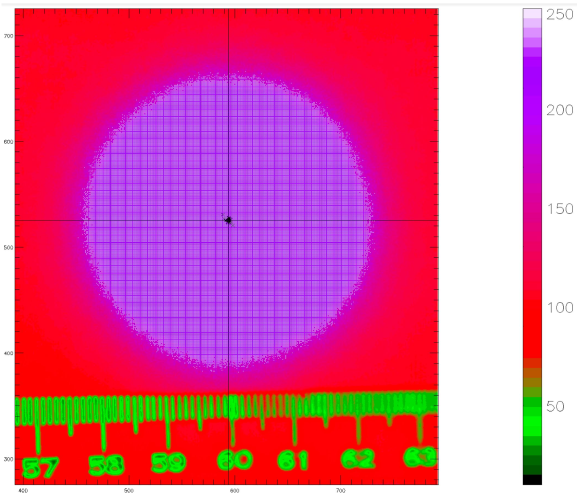
Comprehensive Testing Demonstrates Laser Measurement Capability

- First surface mirror on optical post with ¼-80 adjustment screws.
- 3R Laser, detector, and a camera (not shown) about ~61 ft away.
- Spot size ~ 2.4 inches, expected ~ 2.6 inches.

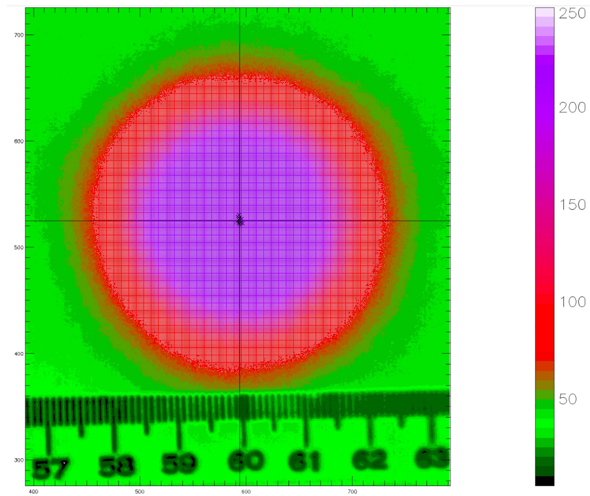


PDR Test #1 Image Processing

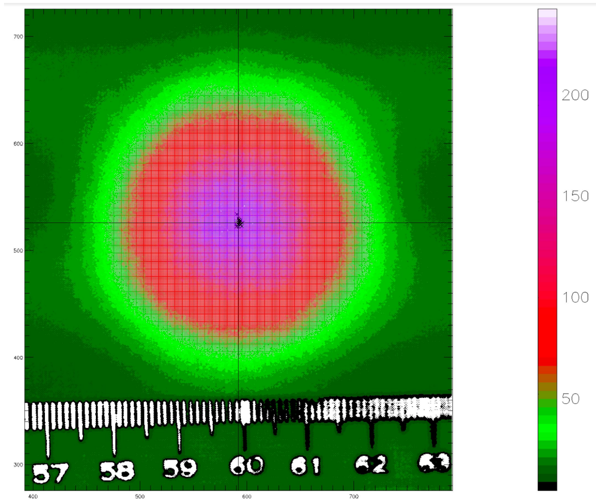
High Exposure, 61 ft



Medium Exposure, 61 ft



Low Exposure, 61 ft

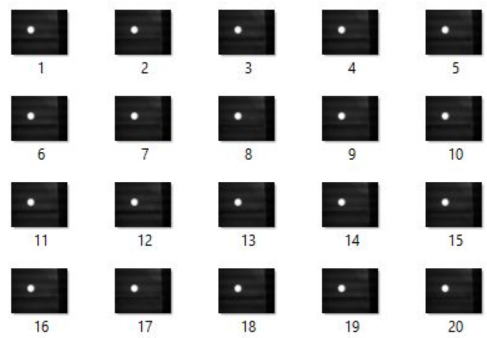


- Script inputs image files and finds horizontal center of mass of the laser spot.
- Scale allow conversion of pixels to mm.
  - 6.281 pixels per mm

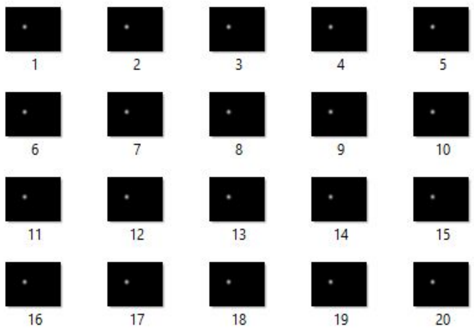
PDR Test #1 Image Processing (cont.)

High Exposure, 61 ft

Medium Exposure, 61 ft



Low Exposure, 61 ft



- Medium exposure dataset performed the best.
- Demonstrates sensitivity of ~6 microradian (~0.25 mm motion on the detector)
  - Exposure w/ least variance in horizontal position of the center of mass.
  - NSTX-U-RD-008 requires 40 microradian measurement sensitivity.
  - Hi-Fidelity Model presented at TF Bundle Stage 2 Review shows: 1.04 mrad baseline vs. 1.07 mrad delaminated (30 microrad, ~1.25 mm motion)

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All Chits have been Closed

APPROVED
PPPL

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ENG-033 - CRR - CHIT RESOLUTION REPORT

TF Inner Bundle Twist Laser Measurement Chit Resolution Report

NSTXU_1-7-3-4-5_CRR_100

Work Planning #:	
Effective Date:	**02/25/2020**
Prepared By:	**Yusi Cao**

Reviewed By	Yusi Cao, Preparer	02/24/2020 14:03:04 PM
Reviewed By	Brentley C. Stratton, Responsible Engineer	02/24/2020 11:15:24 AM
Reviewed By	Yuhu Zhai, Project Engineer	02/24/2020 16:04:26 PM
Reviewed By	Christopher Freeman, Cognizant Individual	02/24/2020 11:58:20 AM
Approved By	George D. Loesser, Design Review Chair	02/25/2020 09:18:34 AM

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Chit Resolution Report: link

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ENG-033 - CRR - CHIT RESOLUTION REPORT

TF Inner Bundle Twist Laser Measurement Chit Resolution Report

NSTXU_1-7-3-4-5_CRR_100

Work Planning #:	
Effective Date:	**02/25/2020**
Prepared By:	**Yusi Cao**

Reviewed By	Yusi Cao, Preparer	02/24/2020 14:03:04 PM
Reviewed By	Brentley C. Stratton, Responsible Engineer	02/24/2020 11:15:24 AM
Reviewed By	Yuhu Zhai, Project Engineer	02/24/2020 16:04:26 PM
Reviewed By	Christopher Freeman, Cognizant Individual	02/24/2020 11:58:20 AM
Approved By	George D. Loesser, Design Review Chair	02/25/2020 09:18:34 AM

PRINCETON PLASMA PHYSICS LABORATORY
P.O. BOX 451 PRINCETON, N.J. 08543

Chit Resolution Report: link

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Procurement Plan

- The process for procuring custom sensor strands has been sorted during the procurement of the TFOL strands for prototyping.
  - Sensors can be purchased from approved vendors with a fiber strand drawing and a PQA attachment listing deliverables.
  - In total 26 unique custom fiber assemblies will be procured from three different vendors.
  - The three sensor vendors are currently in the process of being approved by QA.

- The remainder of the items procured for this system will be purchased as catalog off-the-shelf items.

Major Procurements

- All procurements are dependent upon CD3B Approval.
- Infrastructure
  - Fiber Runs from DARM to TC
  - Conduit, Unistrut, and Cable Trays
  - Patch Panels
  - Signal Conditioning Hardware
- Sensors
  - Micron Optics Custom Sensor Strands
    - TFOL's **Purchased prior to CD3B for prototyping effort
    - Spoked Lid
    - Halo Side Load
  - HBM Custom Sensor Strands for TF Twist Rosettes
  - FBGS Custom Sensor Strands for PF1A/B Sling Preload
  - Opsens Displacement Transducers
    - PF4/5 Slides
    - OH Preload
    - Cenetersack V/V Displacement

Installation Procedures

- An installation procedure is being developed for installing fiber and cable tray in the test cell.

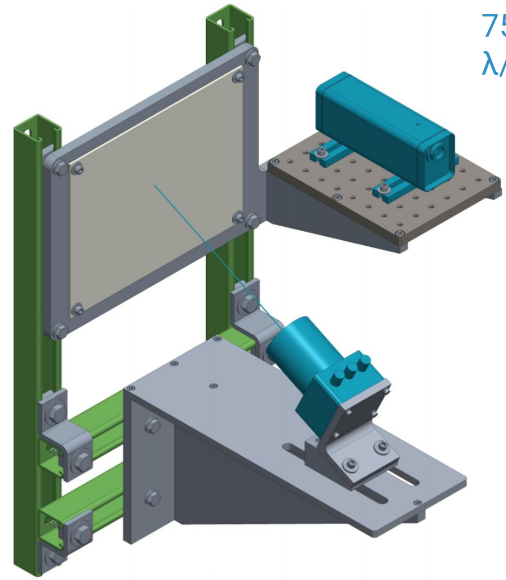
- A separate procedure will cover sensor installation, and adhesion.

System Test Plan

- The overall System Test Plan consists of three main items:
  - Pre-Adhesion Sensor Validation – Captured in PTP
    - Sensor strands will be inspected visually, and connected to the appropriate signal conditioning equipment to verify signal quality.
  - Installation Signal Monitoring – Captured in PTP
    - During installation sensors will be continuously connected to signal conditioning equipment to verify signal quality.
  - Post Installation Sensor Response Testing – Captured in ISTP
    - Prior to installation of sensors, each sensor will be actuated to verify an appropriate response, and to ensure that the sensor mapping and archiving process is functional.

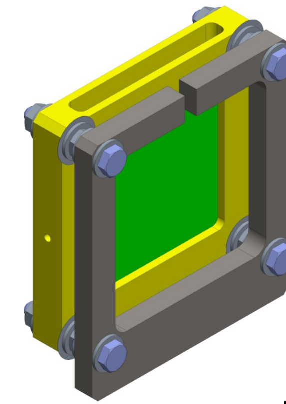
TF Twist Laser Measurement Procurement is Ready Pending CDE-3B Approval

- Off-the-shelf components have been identified and vendors qualified.
- Selected equipment is swappable and maintains the option to install focusing optic (beam expander) as system understanding improves



Unistrut mounted camera/laser

75mm x 75mm x 10 mm
λ/20 silica mirror



HHCS
Jam nuts
Shims
Washers

316 SS, welded to
flange on umbrella

Thorlabs 3R HeNe Laser HNLS008L

National Instruments ISC-1780 Camera, 292 fps

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Project Risks are Actively Being Managed

Risk	Score (1-81)	Open/Retired	Risk Retirement Event
Difficulty in attaching sensors	20	Retired	

More generic risks are held at the Project level in the risk register

FMECA - All Risks are "Acceptable" (I)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	Acquisition Hardware Failure	Electrical defect or anomaly.	Data from all sensors serviced by acquisition hardware is lost.	6	Fiber Optic Strain, Temp., Disp. Meas.	None	None	6
Fiber Optic Strain, Temp., Disp. Meas.	Fiber Optic Trunk From NTC to DARM severed	Damage from construction activity	Data from all sensors is lost.	4	Fiber Optic Strain, Temp., Disp. Meas.	None	None	4
TF Twist Measurement	Laser diode failure	Failure of mechanism	Diagnostic becomes inoperative	3	TF Twist Measurement	None	None	3
TF Twist Measurement	Camera failure	Failure of software; failure of mechanism	Diagnostic becomes inoperative	3	TF Twist Measurement	None	None	3
TF Twist Measurement	Misalignment of laser, camera, or detector	Degradation of components; building movement.	Reduced diagnostic performance; recalibration required	3	TF Twist Measurement	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Upper Inner-TF Strain Rosette; Strain Sensor Fails	Detachment from coil; sensor internal failure	rosette can no longer collect data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Upper Inner-TF Strain Rosette; Temp Sensor Fails	Detachment from coil; sensor internal failure	data from rosette is compromised	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Lower Inner-TF Strain Rosette; Strain Sensor Fails	Detachment from coil; sensor internal failure	rosette can no longer collect data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3

Charge question: 4

FMECA - All Risks are "Acceptable" (II)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	Lower Inner-TF Strain Rosette; Temp Sensor Fails	Detachment from coil; sensor internal failure	data from rosette is compromised	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	OH Prelaod; Sensor Fails	Sensor internal failure; failure of bracket	preload sensor no longer collects data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	OH Prelaod; Fiber Fails Outside of Umbrella	Mechanical impact results in damage, Fiber is severed	preload sensor no longer collects data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	TF Truss; Strain Sensor Fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	TF Truss; Temp Sensor Fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used. Associated Strain Sensor cannot be used.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	TFOL; Fiber Fail	Mechanical impact results in damage, detachment from surface	Sensors after the break are unusable without reconfiguring.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3

FMECA - All Risks are "Acceptable" (III)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	TFOL; Strain Sensor Fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	TFOL; Temp Sensor Fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used. Associated strain sensor cannot be used.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Spoked lid; Strain sensor fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Spoked lid; Temp sensor fail	Mechanical impact results in damage, detachment from surface	Sensor cannot be used. Associated strain sensor cannot be used.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Spoked lid; Fiber fail	Mechanical impact results in damage, Fiber is severed	Sensors after the break are unusable without reconfiguring.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Inner-PF preload; Strain sensor failure	Detachment from sling; sensor internal failure	Sensor cannot be used	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3

FMECA - All Risks are "Acceptable" (IV)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	Inner-PF Preload; Temp Sensor Failure	Detachment from sling; sensor internal failure	Sensor cannot be used. Associated strain sensor cannot be used.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Lateral Support; Strain Sensor Failure	Detachment from shim; sensor internal failure	Sensor cannot be used	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Lateral Support; Temp Sensor Failure	Detachment from shim; sensor internal failure	Sensor cannot be used. Associated Strain Sensor cannot be used.	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	PF4/5 Slides; Sensor Failure	Sensor internal failure; failure of bracket	displacement sensor no longer collects data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	PF4/5 Slides; Fiber Failure	Mechanical impact results in damage, Fiber is severed	displacement sensor no longer collects data	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Vessel growth measurement; sensor failure (bakeout)	Sensor internal failure, failure of bracket	cannot measure relative vessel growth; resort to redundant sensor	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Vessel growth measurement; sensor failure (plasma ops)	Sensor internal failure, failure of bracket	cannot measure relative vessel growth; resort to redundant sensor	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3

Charge question: 4

FMECA - All Risks are “Acceptable” (V)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	Vessel growth measurement; fiber failure (bakeout)	Some mechanical damage that severs or breaks fiber	cannot measure relative vessel growth; resort to redundant sensor	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
Fiber Optic Strain, Temp., Disp. Meas.	Vessel growth measurement; fiber failure (plasma ops)	Some mechanical damage that severs or breaks fiber	cannot measure relative vessel growth; resort to redundant sensor	3	Fiber Optic Strain, Temp., Disp. Meas.	None	None	3
TF Twist Measurement	Reflector failure	Mechanical impact	Diagnostic becomes inoperative. Must extract shards from locations where they fall	2	TF Twist Measurement	None	None	2
TF Twist Measurement	Excessive system vibration	Building vibration; pump vibration; background noise	Diagnostic loses sensitivity	2	TF Twist Measurement	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Upper Inner-TF Strain Rosette; Fiber Fails	Mechanical impact results in damage, Fiber is severed	Sensors after the break are unusable without reconfiguring.	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Lower Inner-TF Strain Rosette; Fiber Fails	Mechanical impact results in damage, Fiber is severed	Sensors after the break are unusable without reconfiguring.	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	OH Preload; Fiber Fails Inside of Umbrella	Mechanical impact results in damage, Fiber is severed	preload sensor no longer collects data	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2

FMECA - All Risks are "Acceptable" (VI)

System	Failure Mode	Failure Cause	Failure Effect	R	Detection/ Mitigation System (1)	Detection/ Mitigation System (2)	Detection/ Mitigation System (3)	R_R
Fiber Optic Strain, Temp., Disp. Meas.	Inner-PF Preload; Fiber Fails	Mechanical impact results in damage, Fiber is severed	Sensors after the break are unusable without reconfiguring.	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Lateral Support; Fiber Fails	Mechanical impact results in damage, Fiber is severed	Sensors after the break are unusable without reconfiguring.	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Sling preload measurement; fiber breaks inside CS assembly	thermal growth leads to fiber being pinched	cannot measure sling stretch/preload	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Sling preload measurement; fiber breaks inside CS assembly	excess temperature on fiber	cannot measure sling stretch/preload	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Sling preload measurement; strain sensor becomes debonded from sling	excess temperature at glued interface	cannot measure sling stretch/preload	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2
Fiber Optic Strain, Temp., Disp. Meas.	Sling preload measurement; temperature sensor becomes debonded	excess temperature at glued interface	cannot measure sling temperature	2	Fiber Optic Strain, Temp., Disp. Meas.	None	None	2

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Custom Fiber Strand Quality Assurance Plan

- Per the PQA attached to Req# 421734, vendors providing custom sensor strands are required to provide the following information:
  - Sensor information sheets containing each sensor's characterization data
  - Sensor characterization data in electronic format.
  - Signed and dated reports for all required inspections and tests. The following apply to this procurement:
    - Dimensional inspections (distance between elements, splice thickness)
    - Verification of per splice optical attenuation (screenshots from sensor characterization analysis is acceptable)
  - Copies of Nonconformance Reports (as applicable).

- All fiber strands are verified for general functionality and signal intensity upon arrival.

TF Twist Laser Safety Interlock

- The TF twist laser is interlocked with the CCS system to disable the laser until the test cell is secure.
  - CCS signal indicates that there is:
    - NO NSTX-U emergency stop condition
    - NTC is in the NO ACCESS state (search & secure completed)

- The software has the capability to override interlock for alignment and maintenance.
  - Class 3R laser (<5 mW)

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Summary

- The Machine Instrumentation system design has satisfied all system level and specific requirements.
- System interfaces are thoroughly understood and documented in the linked ICDs.
- All chits for the Machine Instrumentation System have been closed and documented in the linked CRR.
- Risks are mitigated through:
  - Prototyping of FBG Daemon software with TFOL fiber strands.
- There are no safety related concerns with this design. A USI screening was performed to verify that no safety issues were introduced by the proposed design.

Summary - TF Twist Laser Measurement

- Laser/reflector/detector measures twist externally.
    - Predicted twist angle difference from delamination is measurable.

- Prototype test results provide high confidence in repeatability and measurement capability for global benchmarking.

- Design maturity is high and clear path forward to installation.
    - Procurement and fabrication is well understood.
    - Vendors have been qualified.
    - Good cost and schedule performance to date.
    - Selected equipment is swappable and maintains flexibility as system understanding improves.