National Spherical Torus eXperiment Upgrade

NSTX-U Machine Instrumentation

NSTX-U-RQMT-RD-008-04

1/15/20

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References

[1] NSTX-PLAN-12-207, NSTX-U Structural Benchmark Instrumentation
[2] NSTX-U-RQMT-GRD-001, NSTX-U General Requirements Document
[3] NSTX-U-RQMT-SRD-011, NSTX-U SRD - Diagnostics
[4] Design Point Spreadsheet, https://sites.google.com/pppl.gov/systemengineering/home
[5] NSTX-U-RQMT-RD-012, NSTX-U RD - Inner-PF Coil Interfaces

Change Record

Revision	Date	Description of Change
0	12/14/17	Initial Release
1	3/12/18	Updated to account for additional measurements of preload on the -1a and -1b coils. This involved creating a new Section 4.8 and promoting the old Section 4.8 to 4.9. Also modified the (now) table 4.9-1, for the additional sensors.
2	5/24/19	Updated signatures
		Added table of contents
		Clarification text in Sections 2-4 to make clear that these requirements apply to the fiber-optic based systems
		Added Section 5 on the new inner-TF twist system
3	10/11/19	Modifications to 4.6: ● Requirements for upper strain sensors placed in a new Section 4.6.1 ● Increased # of upper sensors for torsional shear on the bundle ● Added Section 4.6.2, describing requirements for measurements of torsional shear lower at the bottom of the bundle ● Update requirements for the range of strain at both locations.
		Updated titles on signature block
4	1/15/2020	Added requirements for differential measurement between the CS casing on the top of the outer vessel. Renumbered various sections accordingly.
		Updated the requirements for the PF slides to measure the displacements at all 12 of the PF-5 slides (6 upper and 6 lower). This resolves a chit from the instrumentation FDR.

1: Introduction and Goals

The goals of the NSTX-U strain and displacement 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.

The legacy TF outer legs (TFOL) in particular are considered to be at risk for delamination and cyclic failure, and therefore should be carefully monitored as part of this system. Other components of interest include the TF truss structure, the spoked lids, and halo shims.

These goals are described in greater detail in the document *NSTX-U Instrumentation and Benchmarking Test Plan* (NSTX-Plan-12-207, Rev. 1), including references to relevant mechanical calculations.

Note that additional general requirements can be found in References [2] and [3].

In addition to the strain and displacement measurements, a system shall be installed to measure the twist of the TF bundle. This is described in Section 5.

2: Sensor Requirements for Strain and Displacement Measurements

a. Sensors shall provide appropriate galvanic isolation from NSTX-U coil and vessel grounds; fiber-optic based sensors shall be used.

b. The sensors and any related structures shall not impede or modify the underlying mechanical, electrical, or thermal design features of the component to which they are applied.

c. Sensors and their interconnections shall protected from physical damage.

d. Sensors, associated interconnects and mechanical protection devices mounted shall be mechanically rated for temperatures between (and including) 12C and the maximum operating temperature of the coil or system to which they are applied. Maximum operating temperatures on coil can be found in the design point spreadsheet [4].

e. The system shall function reliably and accurately with confidence in the magnetic and radiation environment of NSTX-U.

f. The strain sensitivity of shall be 1% of the maximum strain indicated in Section 5.

3: Data Acquisition and Archiving Requirements for Strain and Displacement Measurements

The data acquisition for this system shall satisfy the following high-level requirements:

a. The system shall synchronize sampling with the NSTX-U clock system to an accuracy of 0.01 seconds compared to the sample clock.

b. The archiving window for shot data shall be from from SoP to a user configurable stop time. This stop time will be between 10 and 1200 seconds after SoP.

c. The archived shot data sampling rate shall be at least 100 Hz, and should not exceed 1 kHz.

d. Raw data, in whatever format is native to the instrumentation system, shall be archived in the MDS+ tree.

e. Calibrated data, with units of microstrain, shall be archived or available in the MDS+ tree. When temperature data is simultaneously collected, it shall be calibrated to units of degC for storage.

f. The archived shot data shall be in a format that can be plotted with common tools such as dwscope, jscope, or webtools, and accessed in table form via webtools

g. The raw and calibrated data shall have MDS+ tag names that clearly identify the sensor location as per the established naming convention.

Associated metadata shall also be stored in the MDS+ shot tree. These may include sensor type, sensor location, calibration coefficients associated with the conversion from raw to calibrated data, etc.

Archiving at a slower rate on a wall-clock basis may be supported as a secondary requirement.

Post-processing, multi-sensor plotting, DCPS comparisons, and CoE alarms, based on the archived MDS+ data, shall be specified in a future revision to this document or follow-on requirement document.

4: Location and Channel Count Specification for Strain and Displacement Measurements

a. A clear sensor naming convention shall be established. This convention shall unambiguously identify the sensor location and sensor type. This same convention shall be used in CWDs, fiber labels, and MDS+ tree naming

b. Temperature compensations shall be applied as necessary to achieve the required accuracy.

c. All sensors shall be within 0.5” of the location specified in governing drawings; deviations from this require approval of the Integrated Design and Analysis Responsible Engineer at the FDR.

d. For each elevation on the TFOL, there shall be at least 4 sensors on any given side of the coil.

4.1: TFOL Trending and Benchmarking

At a minimum, the three mid-span locations [2, 5, and 8] shall be instrumented for strain, as indicated in Fig. 4.1-1 and Table 4.1-1. These sum to 36 measurements. A remaining set of 6 high stress locations per TFOL are also strongly recommended for trending and for eliminating uncertainties in coil fabrication and analysis.

The expected range of strain at these locations is +/-2000 microstrain. The strain is measured in the direction along the coil.

The FISO-based sensors installed on the TFOLs during the summer 2016 shall be retained as a benchmark for the new system. These were installed under D-NSTX-IP-3831, and their as-installed locations are indicated in the run-copy.

Table 4.1-1: Locations for strain sensors on the TF outer legs

Location	Location
1	6 Inches from Upper Block
2	Mid-Span
3	6 Inches Above Upper Clamp
4	6 Inches Below Upper Clamp
5	Mid-Span

6	6 Inches Above Lower Clamp
7	6 Inches Below Lower Clamp
8	Mid-Span
9	6 Inches from Lower Block

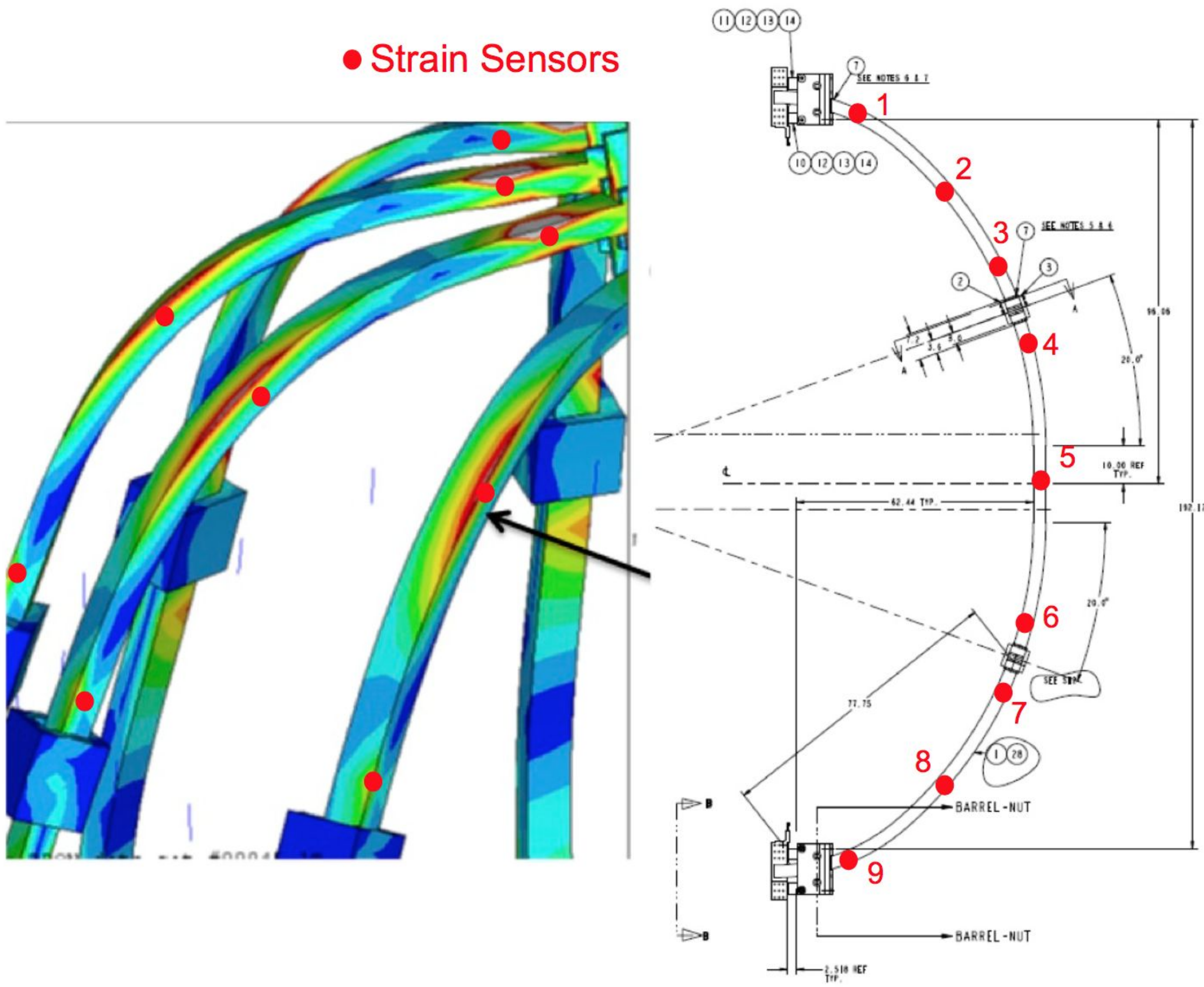

Fig. 4.1-1: *Locations of strain measurements along the arc of the outer leg*

4.2: Trusses

There are 12*2*2 = 48 total trusses on the machine. For purely benchmarking purposes, two pairs at 90 degree intervals, for each of top and bottom, should be instrumented. This is a total of 2 (upper/lower)*4 (toroidal angles) * 2 trusses = 16 measurements. It is strongly recommended to measure the remaining trusses in a similar way, to ensure uniform loading of the clevis blocks. This is shown in FIg. 4.2-1.

The radial location shall be specified in the installation drawings. _They shall be centered on the trusses and away from the threaded features that may result in local strains._

The expected range of strain at these locations is 2000 microstrain. The direction of strain to measure is along the truss.

The truss sensors shall accommodate rotation of the trusses.

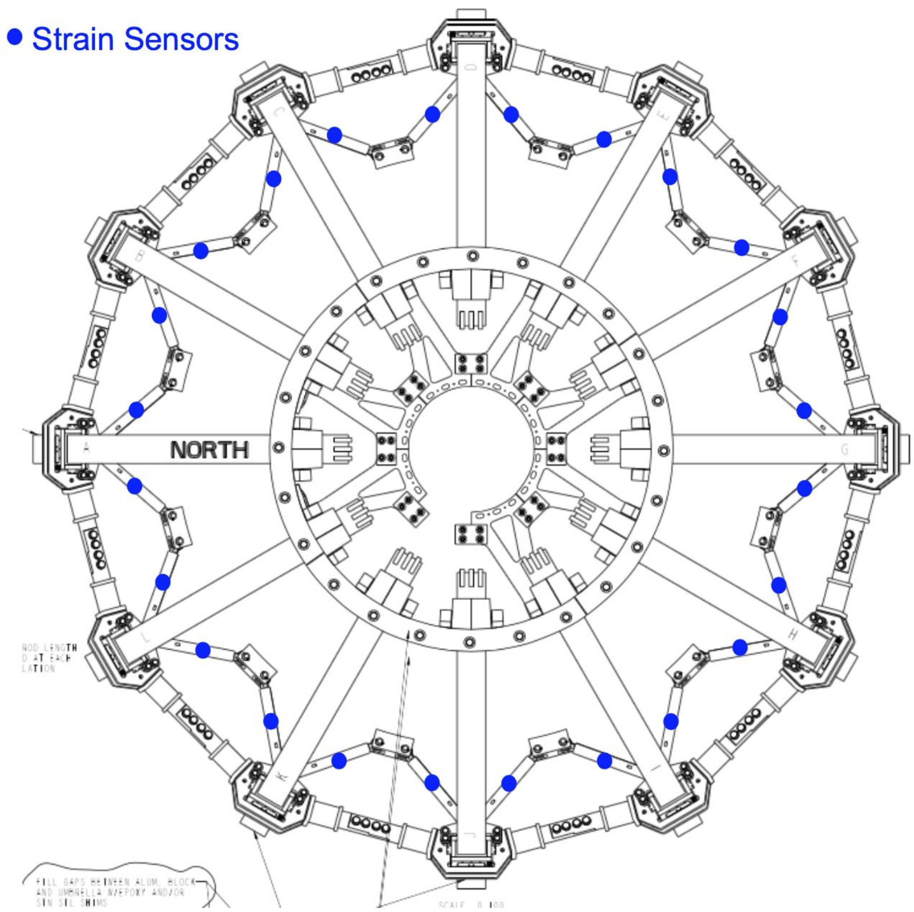

***Fig. 4.2-1**: Locations of strain measurements on the TF trusses*

4.3: Spoked Lids

It is desired to measure the strain at multiple locations on the spoked lids. At each location, there shall be a measurement on the top and bottom of the lid, at the same radius and toroidal angle; see Fig. 4.3-1.

It is required to measure the strain at 2 locations each top and bottom, for a total of 8 measurements. If cost effective, the additional locations should be measured as per Fig. 4.3-2.

The expected range of strain at these locations is 2000 microstrain.

The direction of strain to measure is that in the large major radius direction. The upper and lower measurements need to be aligned within 0.25” to allow proper differencing.

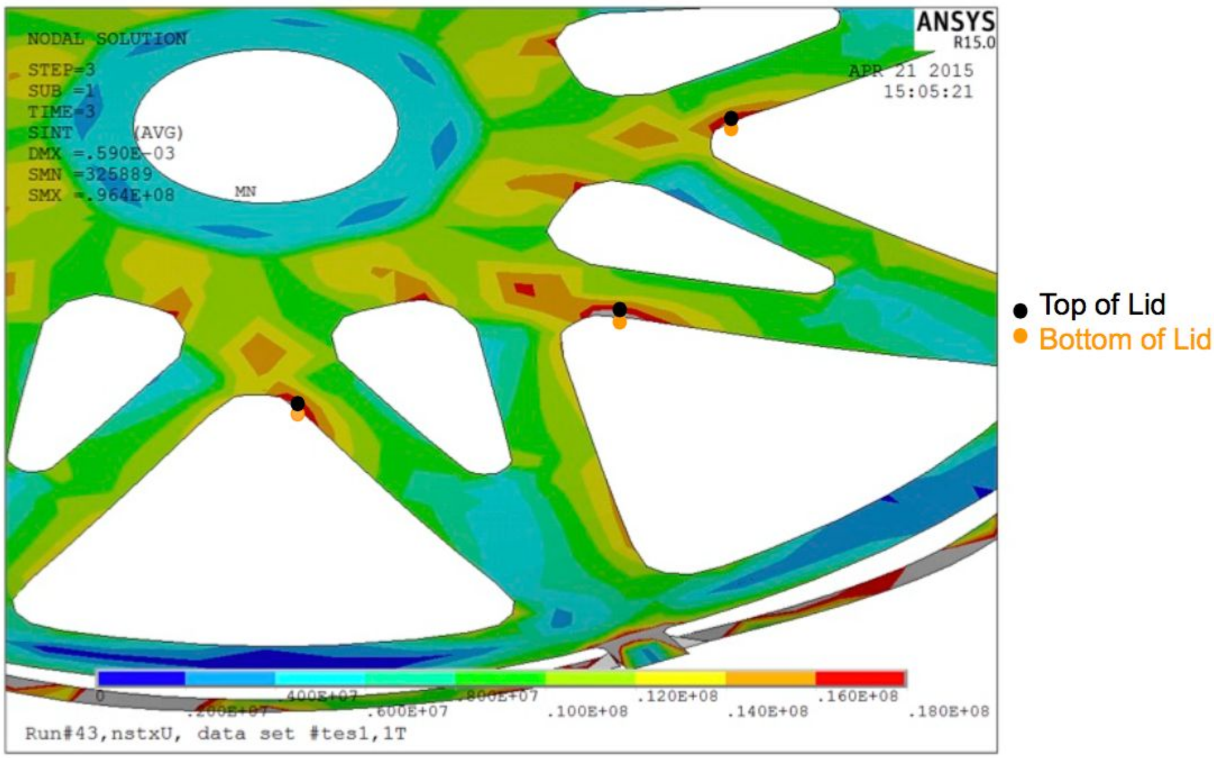

Fig. 4.3-1*: Locations of strain measurements on top and bottom of lid.*

These locations shall accommodate removal of the spoked lids, i.e. have some accommodation to disconnect the sensors. Note that the lower spoked lid is segmented and comes off in individual parts.

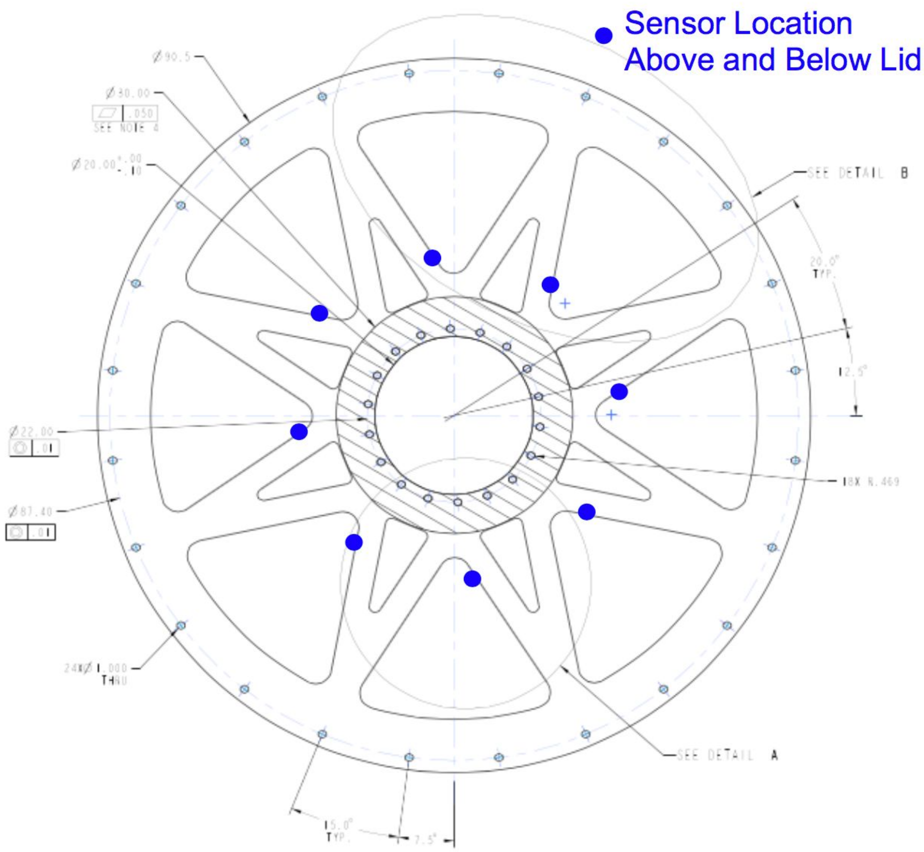

Fig. 4.3-2*: Locations of strain measurements on top and bottom of lid. This configuration should be applied to both the top and bottom lids.*

4.4: Halo current side loads

Toroidally peaked halo currents flowing on the CS can lead to a sideways force; this load will be supported by a system of “radius rods” or similar feature that transfer this load across the bellows, and ultimately to the outer vessel through the ceramic break assembly.

The magnitude of this load can be detected and assessed if the radius rods or equivalent feature are measurement for force or strain. It is desirable that they be permanently monitored, but this is not a requirement.

The expected range of strain at these locations will be determined once the design of the radius rods or equivalent feature is determined.

4.5: OH Preload

There are presently two FISO LVDTs on the Belleville washer spring stack, monitored by the FISO chassis. These shall continue to be instrumented.

4.6: TF Torsional Strain

4.6.1 Bundle Top

The torsional strain of the TF shall be measured at at least 8 toroidal angles. This to be accomplished by installing strain gauges in a rosette configuration. Fig. 4.6-1 shows a potential Rosette configuration; other Rosette configurations are possible and may be used if they are more easily implemented.

They shall be placed at a location beneath the bottom of the conductor faces. The exact height shall be determined by that which leads to appropriate measurement sensitivity, within the constraints of potential interferences (for instance, with the preload mechanism).

They shall be designed in such a manner that the belleville washer stack does not interfere with the sensors mounting, and the sensor cables can be extracted from behind the washer stack. The system shall also be consistent with any high voltage insulation put in that region.

Fig. 4.6-1: *Locations of the TF twist measurements on the upper part of the bundle.*

Four toroidal angles of the sensor pairs should correspond to the angles of the quadrant joints, i.e, at the angles between the following conductor pairs:

- TFB1 and TFB2

- TFE1 and TFE2
- TFH1 and TFH2
- TFK1 and TFK2

The other four sensors shall be placed at intermediate angles.

The expected range of strain is +/- 2000 microstrain..

4.6.2 Bundle Bottom

Strain rosette sensors shall be placed on the lower portion of the TF bundle, as accessible through the arches of the OH inner skirt (E-DC1535). A minimum count corresponding 2 rosette sensors, and ideally up to one rosette sensor per arch shall be utilized (there are 8 arches in the inner OH skirt).[1]

The vertical location of the sensors shall be determined as that which provides the maximum sensitivity to loss of shear capacity of the TF bunde.

The expected range of strain matches that for the upper sensors described in Section 4.6.1.

4.7: PF Slides

The sliding joints on some of the outer PF coils should be measured, in order to assess proper behavior during thermal growth.

· The PF-5 upper and lower slides on the fixed supports are Bays A/B, C/D, E/F, G/H, I/J, and K/L should be instrumented for radial motion (12 total).

· The PF-4 upper and lower slides on the fixed supports at A/B, C/D, E/F, G/H, I/J, and K/L should be instrumented for radial motion (12 total).

· If possible, the sliding joints on the floating supports should also be instrumented. The priority would be on those farthest from the fixed points, i.e., Bays D/E and K/L, top and bottom (up to 12).

[1] Mean of bringing the fibers out of the OH outer skirt (E-DC11143) will be of primary concern in completing this design.

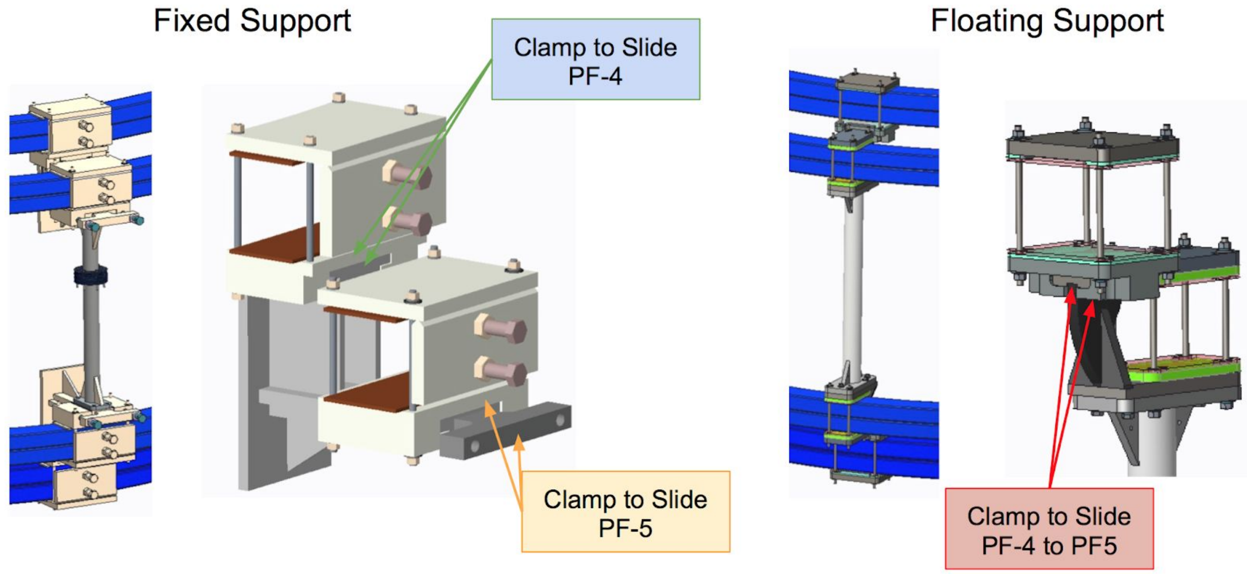

Figure 4.7-1: *Locations of LVDTs*

The range of movement is + 6 mm in the radial direction when the coils thermally grow, and -1 cm in the radial direction when the vessel expands during bakeout.

4.8 Preload on Inner-PF Coils

The inner-PF coils PF-1aU, PF-1aL, PF-1bU, and PF-1bL require pre-load to mitigate insulation thermal strain during cooldown. The required level of preload is given in Ref. [5].

Sensors shall be installed to measure the preload on these four coils. Redundant sensors shall be installed to guard against failure of the primary sensor; these redundant sensors need not be instrumented if that can result in some system simplification.

4.9 Vessel Vertical Growth

The CS casing and outer vessel grow differing amounts in various operations scenarios; while it is not anticipated, collision between various components on the casing and the outer vessel may occur in extreme cases of thermal differences. Examples of these differences are provided in Table 4.9-1.

Table 4.9-1: Thermal differential expansion scenarios between the inner and outer vessel

	Operations Mode	Casing Growth [mm]	Vessel Growth [mm]	Delta [mm]
Cold Casing, Cold Vessel	Baseline	0	0	0
Hot Casing, Cold Vessel	Bakeout	19	0	19

Cold Casing, Hot Vessel	Bakeout	0	6	-6
Hot Casing, Hot Vessel	Bakeout	19	6	13

Instrumentation shall be provided to measure these ranges of displacements.

The instrumentation shall provide this measurement with three sensors, at least two of which are separated by 90° toroidal.

4.10: Summary Table on Channel Count

The electronics and data acquisition will be required to accommodate the following sensor counts. Note that the distinction of “trending” and “benchmarking” is somewhat arbitrary, as sensors whose installation is motivated by one intention can be used for the other.

Location	**Type**	**Required for Permanent Trending**	**Required for Benchmarking**
TF OL Mid-Span Upper and Lower	Strain	12	12
TF OL Near Aluminum Block, Umbrella Side	Strain	12	12
TF OL Near Umbrella	Strain	12	12
TF OL, midplane	Strain	12	
TF OL, Near Aluminum Block, Midplane Side	Strain	24	
Trusses	Strain	32	16
Spoked Lids	Strain	24	8
Side loads in shims	Strain	8	
PF-⅘ Slides	LVDT	24	
OH Preload	LVDT	2	
TF Torsional Shear - Upper	Strain		24
TF Torsional Shear - Lower	Strain		24[2]

[2] This count assumed that all 8 lower arches are instrumented.

Inner-PF Pre-Load (minimum count)	Strain or LVDT	8	
Vessel Displacement	LVDT	3	
Spare	Strain	5	5

Table 4.10-1: Summary list and rough channel counts

5. TF Twist Measurements

A system shall be installed to measure the twist of the top of the TF bundle under imposed EM load during operations. If it is practical to install a twist measurement for the bottom of the bundle, this shall be done as well.

Where installed, the system shall have redundant measurement capabilities at each measurement location.

If a laser-based system is used, the system shall comply with all requirements in ES&H 5008, Section 3, *Laser Safety*.

The system shall have the capability to reject other motions of the machine (i.e. sideways shifts from vacuum loads, vertical thermal growth of the bundle, various vibrations, etc.) either intrinsically as a design feature or as a matter of post-processing.

The system shall be capable of measuring twist with a sensitivity of at least 0.04 mrad, with capability to measure up to 3 mrad[3].

The twist measurement shall be bi-directional, i.e. capable of measuring clockwise or counter-clockwise twists of equal magnitude.

The system shall have a time resolution of greater than or equal to 100 Hz.[4]

The system shall have appropriate galvanic isolation from NSTX-U coil and vessel grounds

Raw data shall be archived in the NSTX-U MDS+ database. Appropriate metadata shall also be archived as deemed appropriate by the cognizant engineer. Algorithms shall be provided to convert the raw data to interpretable engineering data.

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[3] Per Pete Titus, a laser based system would see ~0.01 m of deflection based on a 10 m moment arm for the full 1T, 2MA case, without any delamination. This implies a twist of 1 mrad for full performance. Given that this twist is dominated by the OHxTF interaction, a minimum useful toroidal field of 0.4 T, and the typical operation of the OH at full pre-charge, a minimum twist is 0.4 mrad. Dividing this into 10 units provides an approximate resolution of 0.04 mradians.

[4] The twists measured are driven by the OH and TF currents, which vary on a time-scale of ~100 msec (or 10 Hz).

System components shall be protected from physical damage.

The system shall function reliably and accurately in the magnetic, radiation and thermal environment of NSTX-U.