National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

Diagnostics

NSTX-U-RQMT-SRD-011-02

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Brentley C. Stratton
Digitally signed by Brentley C. Stratton
Date: 2019.05.24 09:17:33 -04'00'

Prepared By: Brent Stratton, Diagnostic TA

Stefan Gerhardt
Digitally signed by Stefan Gerhardt
DN: cn=Stefan Gerhardt, o=Physics, ou=PPPL, email=sgerhard@pppl.gov, c=US
Date: 2019.05.24 04:37:03 -04'00'

Reviewed By: Stefan Gerhardt, Systems Engineering and Integration

Robert Ellis
Digitally signed by Robert Ellis
Date: 2019.05.24 08:01:59 -04'00'

Reviewed: Robert Ellis, Diagnostics RE, Mechanical Technical Authority

Yuhu Zhai
Digitally signed by Yuhu Zhai
Date: 2019.05.25 08:00:44 -04'00'

Reviewed: Yuhu Zhai, NSTX-U Project Engineer

Leslie M. Hill
Digitally signed by Leslie M. Hill
Date: 2019.06.04 09:31:13 -04'00'

Reviewed By: Les Hill, NSTX-U Project Manager

W. Blanchard
Digitally signed by W. Blanchard
Date: 2019.05.31 13:28:26 -04'00'

Reviewed By: William Blanchard, Vacuum Technical Authority

PAUL SICHTA Digitally signed by PAUL SICHTA
Date: 2019.06.05 09:34:21 -04'00'

Reviewed By: Paul Sichta, Control and Data Technical Authority

Charles L. Neumeyer Digitally signed by Charles L. Neumeyer
DN: cn=Charles L. Neumeyer, o=PPPL, ou, email=neumeyer@pppl.gov, c=US
Date: 2019.06.12 08:54:42 -04'00'

Approved By: C. Neumeyer, PPPL Chief Engineer, Electrical Technical Authority

Richard J. Hawryluk Digitally signed by Richard J. Hawryluk
Date: 2019.06.12 10:24:57 -04'00'

Accepted by: R. Hawryluk, NSTX-U Project Director

Change Record

Revision	Date	Description of Change
0	12/27/17	Initial Release
1	3/15/2018	Modified signature block as per new QAPD and ENG-050
		Adjusted interface tables as per new interface spreadsheet
		Added labels in Table 2.4-1
		Added requirements for the diamagnetic loop in the magnetics section of the SRD
		Split the configuration requirements section for the magnetics into 4 sections
		Added requirement in Section 11 for measurement of PF-1a and -1b coil preload
		Added Section 10 describing the Toroidal CHERS diagnostics
		Added requirements for RWM coils in 2.3.5 and 2.4
		Added 2.2d on vacuum compatibility of in-vessel magnetic diagnostics
		Added 3.3d requiring that PFC TCs be isolated
2	5/24/19	Updated all signatures
		Added 11.4i, slight modification of the language in 11.4f
		Replace WBS by SBS everywhere in keeping with updated requirements from ENG-063

Table of Contents

References

[1] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*

[2] NSTX-U-RQMT-RD-008, *Machine Instrumentation Requirements*

[3] NSTX-U-RQMT-RD-004, *PFC Diagnostics and Fueling Requirements*

[4] NSTX-U-RQMT-RD-005, *Center Stack Air-Side Diagnostics*

[5] NSTX-U Design Point Spreadsheet, https://sites.google.com/pppl.gov/systemengineering/home

[6] NSTX-U-RQMT-SRD-003, *Plasma Facing Components System Requirements Document*

[7] NSTX-U-RQMT-SRD-004, *Vacuum Vessel and Internal Hardware System Requirements Document*

[8] NSTX-U-RQMT-SRD-005, *Auxiliary Systems System Requirements Document*

[9] NSTX-PLAN-12-207, *NSTX-U Structural Benchmark Instrumentation*

1.0 Scope

a. This document gives the requirements for the set of basic plasma and machine diagnostics required for basic NSTX-U operation or integrated into plasma facing components that are included in SBS 1.4.1 and 1.1.1.1.8. These diagnostics are listed in Table 6.4.1-1 of the GRD [1]. They are:

- Plasma Current Rogowski Coils (SBS 1.4.1.2.1)
- Poloidal Flux Loops (SBS 1.4.1.2.2)
- Mirnov Sensors (SBS 1.4.1.2.2)
- Plasma TV System (SBS 1.4.1.4)
- Filterscope Diagnostic (SBS 1.4.1.13.1)
- Fission Chamber Neutron Detectors (SBS 1.4.1.1)
- Multi-Pulse Thomson Scattering Diagnostic (SBS 1.4.1.3)
- Plasma Facing Component Thermocouples (SBS 1.1.1.1.8)
- Plasma Facing Component Langmuir Probes (SBS 1.4.1.17)
- Extreme Ultraviolet Spectrometers (SBS 1.4.1.15)
- Machine Instrumentation (SBS 1.7.3.4)

b. Diagnostics listed in 1.0-a are a subset of the larger NSTX-U diagnostics set. All diagnostics installed in, on, or near NSTX-U shall meet the engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

c. This document gives the requirements for the machine instrumentation included in SBS 1.7.3.4. The machine instrumentation shall meet the requirements given in Section 6.7.3.3 of the GRD [1] and in the NSTX-U Machine Instrumentation Requirements Document [2].

d. The format of this document, including interface specifications, is provided in the GRD [1].

e. For the purposes of this document, 'basic operation' of NSTX-U is defined to be a 1 second duration I_P= 600 kA L-mode plasma. Plasmas with parameters beyond these may require additional diagnostics, as may any specific physics experiment.

f. Additional essential diagnostics required for the first experimental campaign are also included in this document, including:

- Toroidal Charge Exchange Recombination Spectroscopy Diagnostic (SBS 1.4.1.5.1)

2: Magnetics Diagnostics (SBS 1.4.1.2)

2.1 Functions

a. The magnetics diagnostics required for basic routine operation of NSTX-U are: 1) the Plasma Current Rogowski coils (SBS 1.4.1.2.1); 2) Mirnov Sensors to measure the poloidal magnetic field at specific locations (SBS 1.4.1.2.2); 3) Poloidal Flux Loops to measure the poloidal flux at specific locations (SBS 1.4.1.2.2), 4) Resistive Wall Mode (RWM) sensors to measure slowly growing non-axisymmetric perturbations (SBS 1.4.1.2.3), and 5) the Diamagnetic Loop used to measure the toroidal flux in the plasma (SBS 1.4.1.2.4). These diagnostics are required for off-line equilibrium reconstructions, for real-time equilibrium reconstructions, for plasma position control, and, in the case of the Plasma Current Rogowski, for interlocks. Note that these diagnostics are a subset of the complete NSTX-U magnetics diagnostics set.

2.2 Materials and Design Requirements

a. The magnetics diagnostics shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

b. The tile-mounted Mirnov sensors shall meet the requirements given in Section 1.1 of the PFC Diagnostics and Fueling Requirements Document [3].

c. The Poloidal Flux Loops that are mounted on the center stack shall meet the requirements given in the Center Stack Air-Side Requirements Document [4].

d. All material used in-vacuum as part of the magnetic diagnostics design shall satisfy GRD vacuum materials requirements [1].

2.3: Configuration Requirements and Essential Features

2.3.1: Plasma Current Measurement Systems

a. The Plasma Current Rogowski coils shall link the plasma current. They may also link currents in poloidal field coils and the vacuum vessel as well as the plasma current.

b. Plasma Current Rogowski coils shall be located outside the NSTX-U vacuum vessel.

c. The Plasma Current Rogowski coils shall be wound on flexible mandrels (e.g., Teflon) to allow them to be installed on the air-side surface of the center stack casing and the vacuum vessel.

d. The radial build of the Plasma Current Rogowski coils shall be consistent with the space available within the center stack casing plus sufficient clearance to avoid damage to them during installation. This allocation is provided in the Design Point Spreadsheet. [5]

e. The Plasma Current Rogowski coils shall be covered by a copper electrostatic shield.

f. The electrostatic shield for the Plasma Current Rogowski coils shall be covered in flexible insulation (e.g., Kapton) with a high voltage standoff rating consistent with the NSTX-U hi-pot requirements.

g. Three Plasma Current Rogowski coils shall be installed. At least two of them shall be instrumented during NSTX-U operations. The third coil shall serve as a spare that can be instrumented in the event of failure of one of the other two coils.

2.3.2: Poloidal Flux Loop Systems

a. The Poloidal Flux Loops shall be installed at the following locations: 1) on the outer surface of the outer vacuum vessel; 2) on the inner surface of the outer vacuum vessel; 3) behind the primary and secondary passive plates; 4) on the OH coil; 5) on the inner-PF coils and potentially their supports, and 6) on the casing, a. [3]

b. The voltage signals from the Poloidal Flux Loops installed on the center stack and inner-PF coils shall be integrated as the difference with the voltage measured by a flux loop on the midplane to minimize common mode effects. The signals from all other flux loops shall be directly integrated.

c. The voltages on selected Poloidal Flux Loops shall also be directly measured (without integration) to allow the currents flowing in the vacuum vessel to be measured. The number and locations of these sensors shall be determined by the required accuracy of the vacuum vessel current measurement.

2.3.3: Mirnov Sensor Systems

a. The Mirnov sensors shall be of two types: 1-D sensors capable of measuring the poloidal magnetic field along one axis and 2-D sensors capable of measuring the poloidal field along two orthogonal axes.[1]

b. The Mirnov sensors shall be installed at the following locations: 1) between and behind the passive plates; 2) inside tiles mounted on the center stack casing; and 3) inside tiles in the outboard, horizontal, and vertical inner divertor regions.

c. The Mirnov sensors shall be wound of bare copper wire on a ceramic mandrel.

d. The Mirnov sensor windings shall be covered in a high-temperature insulating cement.

[1] Two axes in this case refers to two axes in the [R,Z] plane, orthogonal to the toroidal direction.

e. The Mirnov sensors shall be provided with electrostatic shields.

f. The Mirnov sensor windings shall be connected to the lead wires by TIG welding.

2.3.4: Diamagnetic Loop System

a. The diamagnetic loop system shall utilize a rogowski coil return lead to measure the total toroidal flux.

b. The diamagnetic loop system shall utilize a rogowski sensor mounted on the TF outer leg.

c. Electronic differencing of the diamagnetic loop signal and the TF outer leg sensor shall be done before integrations.

d. A primary and spare loop systems shall be deployed, for redundancy. They may utilize the same rogowski sensor mounted on TF outer leg.

2.3.5: Resistive Wall Mode Sensors

a. Sensors shall be installed inside the vessel in order to measure slowly growing 3D field perturbations.

b. These sensors shall be located above and below the midplane.

c. At each of these two locations, there shall be measurements of both the normal and poloidal field perturbations.

2.4 Baseline Performance and Operational Requirements

a. All materials used in the fabrication of the Plasma Current Rogowski coils shall be capable of tolerating a temperature of at least 150 C without damage.

b. All materials used in the fabrication of the Flux Loops and their leads shall be capable of tolerating the maximum bakeout temperature at their installed locations without damage.

c. All materials used in the fabrication of the Mirnov sensors and their leads shall be capable of tolerating the maximum bakeout temperature at their installed locations without damage.

d. The Plasma Current Rogowski coils shall be instrumented with both high- (10^5 A/V) and low-gain (10^6 A/V) channels to allow up to 4 MA of linked current flowing in the plasma, PF coils, and vacuum vessel to be measured (2 MA plasma current and 2 MA currents in vacuum vessel and divertor coils).

e. The Plasma Current Rogowski coil signals shall be digitized at a minimum rate of 2 kHz.

f. The number of installed and instrumented Poloidal Flux Loops shall be sufficient to reliably support the magnetic reconstruction and plasma position control functions given in Section 1.1. Spare flux loops shall be installed to provide redundancy.

g. The number of Mirnov sensors, their locations and the type of Mirnov sensor (1-D or 2-D) at each location shall be determined by requirements for equilibrium reconstruction and plasma position control.

h. Mirnov sensors shall be designed to measure fields up to the levels indicated on Table 1.4-1 with appropriate setting on integrators.

i. Poloidal flux loops on the shall be configured to measure poloidal flux up to levels indicated in Table 2.4-1.

j. Poloidal flux loops on the CS shall be differenced with respect to the CSC midplane loop, and configured to assess levels up those indicted in Table 2.4-1.

k. The Mirnov, flux loop, and diamagnetic loop sensor signals shall be digitized at a minimum rate of 2 kHz.

Table 2.4-1: Required signal levels for magnetic diagnostics

Quantity and Location	Units	Value
B, CSC	T	0.9
B, Passive Plates, Outboard Divertor, Vacuum Vessel	T	0.5
flux, CSC	Wb	1.5
flux, Passive Plates, Outboard Divertor, Vacuum Vessel	Wb	2.55

l. The RWM sensors shall be designed for the diagnosis of perturbations growing with a 1 millisecond growth rate.

m. The RWM sensors shall be designed to measure perturbations with toroidal mode number 1 through 3.

n. The sensors shall be capable of resolving perturbations of order 2 G when fully calibrated and processed.

2.5 Upgrade Performance and Operational Requirements

a. None.

2.6 Interfaces

Table 2.6-1*: Interfaces for the magnetics diagnostics, Plasma Current Rogowski System (SBS 1.4.1.2.1).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.2	Ohmic Heating Solenoid	Structural	Ohmic heating solenoid ground insulation surface	Rogowski coils mounted on the OH solenoid, under the microtherm insulation	Mechanical Drawing
1.1.2.1.1	Vacuum vessel	Structural	Vacuum vessel outer surface	Rogowski Coils mounted on outer surface of vacuum vessel via insulated supports	Mechanical Drawing
1.1.3.3.11	PF-1a Support Structure	Spatial	At surface of rogowski	Rogowski coils must pass through holes in the PF-1a support structure to exit the CS assembly	Mechanical Drawing
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At inputs to digitizers	Rogowski signals are integrated before being digitized	CWD
1.8.1.1.7	NTC Racks	Location	At cross-connects on rack	Field cables terminate in cross-connects located in the racks, interface to electronics located in racks	N/A
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At input to integrator	Rogowski signals are integrated to determine the plasma current, after which the signal is i) digitized, and ii) sent to Ip calculator hardware	Spreadsheet
1.7.3.6.8	Ip Calculator System	Electrical Signal	Through integrators	Integrated signal from plasma current Rogowski coil provided to Ip Calculator system	Schematic
1.8.1.1.2	NTC Cable Trays	Structural	Surface of tray	Plasma current measurement resides in the NTC trays	N/A
1.4.1.2.4	Diamagnetic Loop System	Spatial	At the rogowski return lead	The diamagnetic loop is based on a spare return lead of the Ip Rogowski. In that sense, it has all the same interfaces as the Rogowski itself	Mechanical Drawing

***Table 2.6-2**: Interfaces for the magnetics diagnostics, Mirnov and Flux Loop System (SBS 1.4.1.2.2).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.1	Vacuum vessel	Diagnostic	Vacuum vessel inner and outer surfaces	Poloidal Flux Loops mounted on inner and outer surfaces of vacuum vessel; leads mounted to vessel surface.	Mechanical Drawing
1.1.1.2.1	Passive plates	Diagnostic	Passive Plates	Poloidal Flux Loops mounted in grooves behind the primary and secondary passive plates, used to estimate current flowing in plates	Mechanical Drawing
1.1.3.3.2	Ohmic Heating Solenoid	Diagnostic	Ohmic Heating Solenoid Ground Plane Surface	Poloidal Flux Loops mounted on the Ohmic Heating Solenoid	Schematics or mechanical drawings
1.1.3.3.3	PF-1a Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing
1.1.3.3.4	PF-1b Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing
1.1.3.3.5	PF-1c Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing
1.1.1.2.1	Passive plates	Structural	Passive Plates	Mirnov Sensors mounted behind and between the passive plates	Mechanical Drawing
1.4.1.22	Diagnostic Port Covers	Vacuum	Electrical feedthroughs mounted on vacuum vessel ports covers	Electrical Feedthroughs for leads to Poloidal Flux Loops and Mirnov Sensors mounted to various diagnostic port covers.	CWD
1.1.3.3.6	Center Stack Casing	Vacuum	At flange on end of organ pipe	Sensors leads leave vacuum via the organ pipes on the casing flanges	Wiring Diagram
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At digitizer or integrator input	Signals from mirnov and flux loops are in some cases integrated, and in all cases digitized	Spreadsheet
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At realtime digitizer input	Some signals from flux loops are directly digitized by the realtime stream w/o any intermediate integrator (there is likely a passive voltage divider in these cases).	Spreadsheet
1.4.1.22	Diagnostic Port Covers	Vacuum	At flange on port cover	Vacuum feedthroughs for sensors mounted to diagnostic port cover	CWD
1.8.1.1.2	NTC Cable Trays	Structural	At surface of tray	Field cables and similar for sensors use trays to move from the vessel feedthrough to the appropriate racks	N/A
1.8.1.1.7	NTC Racks	Location	At cross-connects on rack	Field cables terminate in cross-connects located in the racks, interface to electronics located in racks	N/A
1.1.1.1.5	Outboard	Spatial	Graphite boundary of the	Mirnov coils are installed in or	Mechanical

	Divertor PFCs		tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	between the tiles.	Drawings, Calculations for stresses at tile features, CWDs
1.1.1.1.4	Horizontal Target PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Mirnov coils installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features
1.1.1.1.3	Vertical Target PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Mirnov coils embedded in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.1	Center Stack First Wall PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Mirnov coils are embedded in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.7.3.6.8	Ip Calculator System	Electrical Signal	At input to the electronics chassis in the NTC	Poloidal flux loops are used to generate estimates of the current flowing in the vessel under loop voltage.	CWD

Table 2.6-3: Interfaces for the magnetics diagnostics, RWM Sensors (SBS 1.4.1.2.3).

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At digitizer or integrator input	Signals from RWM BP and BR sensors are integrated and	Spreadsheet

				digitized. They are then send to both transient and realtime digitizers	
1.4.1.22	Diagnostic Port Covers	Vacuum	At flange on port cover	Vacuum feedthroughs for sensors mounted to diagnostic port cover	CWD
1.8.1.1.2	NTC Cable Trays	Structural	At surface of tray	Field cables and similar for sensors use trays to move from the vessel feedthrough to the appropriate racks	N/A
1.8.1.1.7	NTC Racks	Location	At cross-connects on rack	Field cables terminate in cross-connects located in the racks, interface to electronics located in racks	N/A
1.1.1.1.6	Passive Plate PFCs	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	RWM BR sensors on primary passive plate front surface, supported by machined features in tiles; RWM Bp sensors supported tab inserted under T-bars that support the tiles	Mechanical Drawings, CWDs
1.1.1.2.1	Passive plates	Structural	At the tabs that hold the sensor boxes	The RWM poloidal field sensors (BP) sensors are supported from the primary passive plates	Calculation

***Table 2.6-4**: Interfaces for the magnetics diagnostics, Diamagnetic Loop System (SBS 1.4.1.2.4).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation

1.8.1.1.2	NTC Cable Trays	Structural	At surface of tray	Field cables and similar for sensors use trays to move from the vessel feedthrough to the appropriate racks	N/A
1.8.1.1.7	NTC Racks	Location	At cross-connects on rack	Field cables terminate in cross-connects located in the racks, interface to electronics located in racks	N/A
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At inputs to digitizers and integrators	Diamagnetic loop system utilizes various integrators and digitizers	Spreadsheet
1.5.1.2	D-Site Auxiliary Power	Electrical Power	Wall plug	Power for the electronics in the diamagnetic loop system	N/A
1.4.1.2.1	Plasma Current Rogowski System	Spatial	At the rogowski return lead	The diamagnetic loop is based on a spare return lead of the Ip Rogowski. In that sense, it has all the same interfaces as the Rogowski itself	Mechanical Drawing
1.1.3.2	TF outer legs	Structural	Outside of coil ground insulation	A rogowski is mounted to the outer TF leg, for use in the diamagnetic flux measurement	Mechanical Design Drawing

***Table 2.6-5**: Interfaces for the magnetics diagnostics, Digitizers and Integrators (SBS 1.4.1.2.5).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.6.2.1	Data I/O systems	Electrical Signal	Connectors on CAMAC digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for magnetics digitizers and integrators	N/A
1.8.1.1.7	NTC Racks	Location	Front or back of racks	Various electronics modules located in racks	N/A
1.4.1.2.1	Plasma Current Rogowski System	Electrical Signal	At inputs to digitizers	Rogowski signals are integrated before being digitized	CWD
1.7.3.6.1	FPDP Data Stream	Electrical Signal	Output of Integrators (Cat4,3 Crates)	Magnetics measurements for realtime control	CWD
1.7.3.6.8	Ip Calculator System	Electrical Signal	At input to fiber optic transmitter in NTC	Plasma current signal brought from integrator output to the FO transmitter	CWD
1.4.1.2.2	Mirnov and Flux Loop System	Electrical Signal	At digitizer or integrator input	Signals from mirnov and flux loops are in some cases integrated, and in all cases digitized	Spreadsheet
1.4.1.2.3	RWM Sensors	Electrical Signal	At digitizer or integrator input	Signals from RWM BP and BR sensors are integrated and digitized. They are then send to both transient and realtime digitizers	Spreadsheet
1.4.1.2.4	Diamagnetic Loop System	Electrical Signal	At inputs to digitizers and integrators	Diamagnetic loop system utilizes various integrators and digitizers	Spreadsheet
1.4.1.2.1	Plasma Current Rogowski System	Electrical Signal	At input to integrator	Rogowski signals are integrated to determine the plasma current, after which the signal is i) digitized, and ii) sent to Ip calculator hardware	Spreadsheet
1.4.1.2.8	Tile and Rogowski Halo Current Measurements	Electrical Signal	At input to integrator	Halo current rogowski coils are integrated before being digitized	Spreadsheet

***Table 2.6-7**: Interfaces for the Tile and Rogowski Halo Current Measurements (SBS 1.4.1.2.8).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.6	Center Stack Casing	Vacuum	At flange on end of organ pipe	Sensors leads leave vacuum via the organ pipes on the casing flanges	Wiring Diagram
1.4.1.22	Diagnostic Port Covers	Vacuum	At flange on port cover	Vacuum feedthroughs for sensors mounted to diagnostic port cover	CWD
1.8.1.1.2	NTC Cable Trays	Structural	At surface of tray	Field cables and similar for sensors use trays to move from the vessel feedthrough to the appropriate racks	N/A
1.8.1.1.7	NTC Racks	Location	At cross-connects on rack	Field cables terminate in cross-connects located in the racks, interface to electronics located in racks	N/A
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At input to integrator	Halo current rogowski coils are integrated before being digitized	Spreadsheet
1.1.3.3.6	Center Stack Casing	Structural	At surface of casing	Halo current rogowski coils are wrapped around the casing, under the tiles	Mechanical Drawing
1.1.1.1.5	Outboard Divertor PFCs	Eddy/Halo Current	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Shunt tiles are installed in or under select tiles	Mechanical Drawing
1.1.1.1.1	Center Stack First Wall PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Current measurements under tiles	Mechanical Drawings
1.1.1.2.2	Outboard Divertors	Eddy/Halo Current	At surface of divertor	Shunt tiles measure current flowing through tiles to the divertor slats	Mechanical Drawing
1.1.1.1.2	CSAS PFCs	Spatial	At surface of tile	Space behind tiles for the halo rogowskis to reside	Mechanical Drawing
1.1.1.1.3	Vertical Target PFCs	Spatial	At surface of tile	Space behind tiles for the halo rogowskis to reside	Mechanical Drawing

3: Plasma Facing Component Thermocouples (SBS 1.1.1.1.8)

3.1 Functions

a. The Plasma Facing Component (PFC) Thermocouples (SBS 1.1.1.1) measure the transient and time-averaged temperature of the PFCs during plasma operation and during bakeout.[2]

3.2 Materials and Design Requirements

a. The PFC Thermocouples shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

b. The PFC Thermocouples shall meet the requirements given in Section 1.3 of the PFC Diagnostics and Fueling Requirements Document [3].

3.3: Configuration Requirements and Essential Features

a. The thermocouples shall be embedded into the PFC tiles with the leads routed through channels in the tiles or mounting hardware and through the vacuum vessel to electrical feedthroughs located at suitable ports.

b. If possible, at least one of the divertor PFCs that is instrumented with thermocouples should be in the field of view of each of the infrared thermography diagnostics to allow the thermocouple measurements to be used to cross-calibrate the thermography diagnostics.[3]

c. Thermocouples shall be installed in locations that allow spatial non-uniformities in the PFC temperatures to be assessed during bakeout.

d. Thermocouples shall be electrically isolated from the tiles.

3.4 Baseline Performance and Operational Requirements

a. The thermocouples shall be located in the CSFW PFCs, angled, vertical, inboard, and outboard divertors PFCs, as well as on the primary and secondary passive plate and neutral beam armor PFCs.

b. Thermocouple implementations in the high heat flux regions shall allow 100 kJ deposited heat to be resolved from noise taking into account interpretation uncertainties. [3]

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[2] Thermocouples on the vessel, passive plates, and diverters are described in Ref. [7]

c. The thermocouples located in high heat flux regions of the divertor shall be chosen to remain functional in the event that the PFC surface temperature exceeds the allowable value by 50% [5].

d. The locations of the thermocouples on the PFCs not in the high heat flux regions of the divertor shall be chosen to allow the bulk tile temperature during bakeout to be measured with 10 minute time response to temperature changes. [3]

3.5 Upgrade Performance and Operational Requirements

The PFC thermocouple system shall be designed to allow implementation of additional thermocouples.

3.6 Interfaces

Table 3.6-1: *Interfaces for the Plasma Facing Component Thermocouples (SBS 1.1.1.1.8).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.1.1.7	Neutral Bean Armor PFCs	Diagnostic	At features machined in the PFC back-sides	Thermocouples in neutral beam armor used to assess bakeout, assess aiming of beams, assess shine-through power	Mechanical Drawing
1.8.1.1.2	NTC Cable Trays	Structural	Cable trays	Cables between electrical feedthroughs and signal processing electronics and digitizers located in racks	N/A
1.8.1.1.7	NTC Racks	Spatial	Racks located in Test Cell	Rack space in Test Cell required for signal processing electronics and digitizers for thermocouples	N/A
1.6.1.1	Control I/O systems	Structural	Connectors on digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
1.1.3.3.6	Center Stack Casing	Vacuum	At flange on end of organ pipe	Sensors leads leave vacuum via the organ pipes on the casing flanges	Wiring Diagram
1.1.1.1.6	Passive Plate PFCs	Diagnostic	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Thermocouples mounted in tiles	Mechanical Drawings, CWDs
1.1.1.1.5	Outboard Divertor PFCs	Diagnostic	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	thermocouples are installed in tiles.	Mechanical Drawings, Calculations for stresses at tile features, CWDs
1.1.1.1.4	Horizontal Target PFCs	Diagnostic	Graphite surface of the tile, in some cases	thermocouples are installed in or between the tiles.	Mechanical Drawings,

			machined by PFC engineering to provide a space or volume for the diagnostic		Calculations for stresses at tile features
1.1.1.1.3	Vertical Target PFCs	Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Thermocouples embedded in or in between tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.2	CSAS PFCs	Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	i) Thermocouples in the tiles ii) Wireways allowing wires from CSFW diagnostics	Mechanical Drawings, Calculations for stresses at tile features
1.1.1.1.1	Center Stack First Wall PFCs	Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Thermocouples in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.2.4.8	Armor Protection Systems	Electrical Signal	At vacuum connector on the port cover	TCs read by electronics in NTC rack for archiving and protection functions	CWD

4: Plasma Facing Component Langmuir Probes (SBS 1.4.1.17)

4.1 Functions

a. The Plasma Facing Component (PFC) Langmuir Probes (SBS 1.4.1.17) measure the electron density and temperature and the floating potential in the plasma near the PFC surfaces. The measurements are used for physics studies and as a machine operator aid.

4.2 Materials and Design Requirements

a. The PFC Langmuir Probes shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

b. The PFC Langmuir Probes shall meet the requirements given in Section 1.2 of the PFC Diagnostics and Fueling Requirements Document [3].

4.3: Configuration Requirements and Essential Features

a. The PFC Langmuir Probes shall be installed at locations on the Center Stack and inboard and outboard divertor regions where the strikepoint or limiter contact could occur.

b. The PFC Langmuir Probes may be embedded into the PFC tiles or tile features (e.g., the castellations) or they may be located in the gaps between the tiles.

c. The plasma facing components of the Langmuir Probes shall be made of carbon materials.

d. The Langmuir Probe tips may be mounted flush or proud relative to the tile surface, consistent with other design constraints as described in Ref. [3].

e. The Langmuir Probe tips must conform to the PFC requirements for the edge temperature limit. [5]

f. See Ref. [3] for specific requirements on spatial locations.

g. A subset of LPs in the outboard target may be designed for high-bandwidth applications; these will be referred to as “HHFW Langmuir Probes”. See Ref. [3] for additional details.

4.4 Baseline Performance and Operational Requirements

a. The PFC Langmuir Probes shall be capable of measuring the electron density (n_e) over the range 10^{17}-10^{21} m^{-3} and the electron temperature (T_e) over the range 1-40 eV. Note that these are not simultaneous parameters, i.e., $n_e=10^{21}$ m^{-3} and $T_e=40$ eV are not likely to be achieved simultaneously.

b. The PFC Langmuir Probe data shall be digitized at a rate of 100 kHz or better; bandwidth requirements for HHFW Langmuir Probes may be substantially higher.

c. A Langmuir Probe should be electrically isolated from the bulk of the PFC in which it is mounted with a stand-off voltage of 300 V.

d. The Langmuir Probes should be capable of tolerating the increased power flux due to the swept probe bias voltage.

4.5 Upgrade Performance and Operational Requirements

a. None.

4.6 Interfaces

***Table 4.6-1**: Interfaces for the Plasma Facing Component Langmuir Probes (SBS 1.4.1.17).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.4.1.22	Diagnostic Port Covers	Vacuum	Electrical feedthroughs mounted on vacuum vessel ports	Electrical Feedthroughs for Langmuir Probe leads	N/A
1.8.1.1.2	NTC Cable Trays	Structural	Cable trays	Cables between electrical feedthroughs and signal processing electronics and digitizers located in racks	N/A
1.8.1.1.7	NTC Racks	Spatial	Racks located in Test Cell	Rack space in Test Cell required for signal processing electronics and digitizers for Langmuir Probes	Mechanical drawing
1.6.2.1	Data I/O systems	Electrical Signal	Connectors on digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
1.8.1.1.2	NTC Cable Trays	Structural	At tray	Cables reside in cable trays	N/A
1.1.3.3.6	Center Stack Casing	Vacuum	At flange on end of organ pipe	Sensors leads leave vacuum via the organ pipes on the casing flanges	Wiring Diagram
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for Langmuir probe electronics	N/A
1.1.1.1.5	Outboard Divertor PFCs	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the	langmuir probes are installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features, CWDs

			diagnostic		
1.1.1.1.4	Horizontal Target PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Langmuir probes are installed in or between the tiles	Mechanical Drawings, Calculations for stresses at tile features
1.1.1.1.3	Vertical Target PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Langmuir probes embedded in or in between tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.1	Center Stack First Wall PFCs	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Langmuir probes are located in or between tiles	Mechanical Drawing, Calculations for stresses at tile features

5: Fission Chamber Neutron Detectors (SBS 1.4.1.1)

5.1 Functions

a. The Fission Chamber Neutron Detectors (SBS 1.4.1.1) measure the total neutron rate as a function of time during a NSTX-U discharge. The fission chambers are a basic physics diagnostic and are also used to ensure regulatory compliance by providing data for the calculation of the total number of neutrons per year produced by NSTX-U.

5.2 Materials and Design Requirements

a. The fission chamber neutron detector system shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

5.3: Configuration Requirements and Essential Features

a. The fission chamber neutron detector system shall consist of a set of fission chambers located in the NSTX-U Test Cell and associated signal processing and data acquisition electronics.

b. The number of fission chambers, their locations in the Test Cell, and the amount of fissionable material in each one shall be determined by the requirement to operate at low neutron rates for calibration and at highest expected neutron rates for measurements during plasma operation.

c. The fission chambers shall be enclosed in neutron energy moderators to reduce the energy of the detected neutrons to enhance sensitivity of the system.

d. The signal processing electronics shall be capable of operating in count mode and in current mode.

e. High voltage bias shall be provided to the fission chambers.

f. At least one of the fission chambers shall have sufficient sensitivity to allow calibration of the system during NSTX-U shutdown using a low-activity Cf-252 source (e.g. 100 mCi) temporarily placed in the NSTX-U vacuum vessel.

g. The system shall be designed to allow transfer of the Cf-252 source calibration of the most sensitive detector to the less sensitive detectors during a low neutron rate NSTX-U discharge.

5.4 Baseline Performance and Operational Requirements

a. The fission chamber neutron detector system shall be capable of measuring the neutron rate over a range of 0 to 1 x 10^{16} neutrons/s to allow measurements during NSTX-U discharges and during calibration.

b. The system shall be capable of measuring both D-D (3.5 MeV) and D-T fusion (14 MeV) neutrons.

c. The data acquisition electronics shall support data acquisition for a time duration of not less than 8 seconds to support NSTX-U long pulse operation.

d. The current mode signals from the signal processing electronics shall be digitized at a rate not less than 1 kHz.

e. The data shall be automatically archived by the NSTX-U data acquisition system after each discharge.

5.5 Upgrade Performance and Operational Requirements

a. The fission chamber neutron detector system shall be designed to allow straightford expansion of the system to include additional fission chambers.

5.6 Interfaces

Table 5.6-1*: Interfaces for the Fission Chamber Neutron Detectors (SBS 1.4.1.1).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.7	NTC Racks	Spatial	Rack located in Test Cell	Rack space in Test Cell required for signal processing electronics and CAMAC digitizers.	Mechanical drawing
1.8.1.1.2	NTC Cable Trays	Electrical signal	Cable trays	Cables between detectors and signal processing electronics	N/A
1.6.2.1	Data I/O systems	Electrical Signal	Connector on CAMAC digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
1.6.1.3	Timing and Synchronization System	Electrical Signal	At trigger input to digitizers and other hardware	Facility clock signals to trigger detectors	N/A
1.8.1.1.1	NTC Platforms	Structural	At platform surface	Fission chambers installed at various locations on the platform	General Arrangement Drawing
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Electrical power for neutron detectors	N/A

6: Plasma TV System (SBS 1.4.1.4)

6.1 Functions

a. The Plasma TV system (SBS 1.4.1.4) provides wide-angle TV views of the interior of the NSTX-U vacuum vessel during NSTX-U discharges. The purposes of the system are to aid the machine operator in identifying problems in a discharge by visual observation and to identify macroscopic events to aid interpretation of other diagnostic data.

6.2 Materials and Design Requirements

a. The Plasma TV system shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

b. The viewing windows should have broadband transmission over the visible and near-infrared regions of the spectrum.

6.3: Configuration Requirements and Essential Features

a. The Plasma TV system shall consist of reentrant viewports and optics to provide two or more wide-angle visible light views of the interior of the NSTX-U vacuum vessel and associated optics, optical fiber bundles, support structures and cameras.

b. The viewing locations shall be on or near the midplane of the NSTX-U vacuum vessel.

c. The number of views, locations of the views and field of view of each one shall be chosen to maximize coverage of the interior of the NSTX-U vacuum vessel. A minimum of two wide-angle views located on near-opposite sides of the vacuum vessel are required.

d. The viewing windows shall be provided with remotely-controlled shutters.

e. A capability shall be provided to remotely reset the cameras when required due to a fault condition.

f. The system shall be designed for automated operation and data archival with high reliability during NSTX-U operation.

g. Software shall exist to automatically display camera image sequences following the discharge for analysis by operations staff.

6.4 Baseline Performance and Operational Requirements

a. The optical angular resolution of the system shall be 30" or better.

b. The TV cameras shall provide color images in the visible region of the spectrum (400-700 nm).

c. The TV cameras shall have sensors with dimensions of 800 X 600 pixels or larger.

d. The TV cameras shall be capable of operating at a frame rate of 1 kHz or higher for readout of all sensor pixels.

e. The TV camera data shall be automatically archived by the NSTX-U data acquisition system following each discharge.

f. The data acquisition electronics shall support data acquisition for a time duration of not less than 10 seconds to support NSTX-U long pulse operation.

g. Lenses shall be mounted in the reentrant viewports in a way that allows them to be easily removed for NSTX-U bakeout and then reinstalled in their original position following bakeout or the lenses shall be compatible with the bakeout temperature.

6.5 Upgrade Performance and Operational Requirements

a. Future upgrades to the Plasma TV System may be required to accommodate the higher neutron flux during high-power NSTX-U operation, e.g., additional shielding may have to be added to reduce noise on the images and to limit radiation damage to the cameras.

b. The Plasma TV system shall be designed to allow straightford expansion of the system to include additional cameras.

6.6 Interfaces

Table 6.6-1*: Interfaces for the Plasma TV System (SBS 1.4.1.4).*

Interfacing System	Interfacing SBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.1	NTC Platforms	Structural	Test Cell Platform	TV cameras installed at various locations on the platform	General Arrangement Drawing
1.4.1.22	Diagnostic Port Covers	Diagnostic	Ports on vacuum vessel	Reentrant viewports, shutters, and lenses installed on vacuum vessel	Mechanical drawing
1.8.1.1.2	NTC Cable Trays	Fiber Optic	Cable trays	Fiber optics bundles between	N/A

				lenses and TV cameras	
1.6.2.2	Data Archiving Systems	Software	At ethernet port	Archival of plasma TV files	MDS+ API
0.1.1.3	PPPL Network Infrastructure	Ethernet	Ethernet connectors on cameras	Ethernet connection to cameras used for camera control and data acquisition	N/A
1.3.1.3	TIV and Shutter Actuation System	Gas	Where air line connects to valve or shutter mechanism	Control of shutters for the plasma TV	P&ID
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to plasma TC diagnostics	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Electrical power for the plasma TV systems	N/A

7: Filterscope Diagnostic (SBS 1.4.1.13)

7.1 Functions

a. The Filterscope diagnostic (part of SBS 1.4.1.13) measures the time evolution of the intensities of deuterium and impurity atom and ion line emissions during NSTX-U discharges. The data provide the machine operator with signals used to assess the state of PFC conditioning and recycling and are entered into a database to allow long-term trends to be assessed.

7.2 Materials and Design Requirements

a. The Filterscope diagnostic shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

7.3: Configuration Requirements and Essential Features

a. The Filterscope diagnostic shall consist of optical fibers to relay the light from windows on the vacuum vessel to remotely located detection systems, and detection systems each consisting of an interference filter to isolate the spectral line of interest, a photomultiplier tube (PMT), transimpedance amplifier, and digitizer. Light-collecting optics may be used to couple the plasma light to the fibers but are not required for intense spectral lines.

b. The detection system shall be capable of being configured to view the lower and upper divertor regions, the center stack (radial midplane view), the outer wall (tangential midplane view) and other in-vessel regions of NSTX-U for which suitable windows and fibers exist.

c. The diagnostic shall be capable of being reconfigured in a simple way during non-operating periods (e.g., via fiber optic connectors) to provide the flexibility to allow a given view to be coupled to a detector unit that is setup to measure a specific line.

d. The detector units shall be remotely located in an area outside the Test Cell, e.g., the diagnostic room located off the gallery known as the Data Acquisition Room, or DARM.

7.4 Baseline Performance and Operational Requirements

a. The Filterscope diagnostic shall have sufficient channels to allow the spectral lines and locations listed in Table 7.4-1 to be observed.

b. There shall be detector units equipped with filters to measure the Deuterium H-alpha and H-gamma lines and lines of He^+, C^+, O^+, B^+, Li, and Li^+. The detector units shall allow straightforward exchange of filters to allow other lines to be measured as needed.

c. The spectral lines and locations in Table 7.4-1 shall be permanently configured to facilitate trending analysis, while other channels may be adjusted based on research priorities.

Table 7.4-1*: Permanently configured spectral lines for the filterscope system*

Location	Species	Wavelength (nm)
Upper divertor, lower divertor, radial midplane	Hydrogen/Deuterium Balmer-alpha	656.1
Upper divertor, lower divertor, radial midplane	C II	515.0
Upper divertor, lower divertor, radial midplane	O II	441.5
Upper divertor, lower divertor, radial midplane	B II	494.0
Upper divertor, lower divertor, radial midplane	Li I	670.8
Lower divertor	He II	468.6

d. The high voltage bias to the PMTs shall be independently adjustable for each PMT.

e. The transimpedance amplifiers shall have adjustable gain and a minimum bandwidth of 2 kHz.

f. The data shall be digitized at minimum rate of twice the amplifier bandwidth for 10 seconds starting 0.5 seconds prior to discharge initiation.

7.5 Upgrade Performance and Operational Requirements

a. The Filterscope diagnostic shall be designed to allow straightford expansion of the system to include additional channels.

7.6 Interfaces

Table 7.6-1: Interfaces for the Filterscope diagnostic (SBS 1.4.1.13.1).

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.4.1.22	Diagnostic Port Covers	Diagnostic	Ports on vacuum vessel	Windows, shutters, and lenses installed on vacuum vessel	Mechanical drawing
1.8.1.1.2	NTC Cable Trays	Fiber Optic	Cable trays	Fiber optics bundles between various windows on the vacuum vessel and detection system	N/A
1.8.1.4	Diagnostic DARM	Location	DARM	Rack space and/or shelf space in DARM required for detector units and digitizers	N/A
1.6.1.3	Timing and Synchronization System	Electrical Signal	Connectors on digitizers	Facility clock signals to trigger detectors	CWD
1.6.2.1	Data I/O systems	Electrical Signal	Digitizers located in DARM	Acquisition of data from digitizers	CWD
1.3.1.3	TIV and Shutter Actuation System	Gas	Where air line connects to valve or shutter mechanism	Control of shutters on various filterscope diagnostics	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Electrical power for the filterscope diagnostics	N/A
1.1.1.2.2	Outboard Divertors	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A
1.1.1.1.5	Outboard Divertor PFCs	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A

8: Extreme Ultraviolet Spectrometer System (SBS 1.4.1.15)

8.1 Functions

a. The Extreme Ultraviolet (EUV) spectrometer system (SBS 1.4.1.15) provides time-resolved measurements of impurity spectra in the EUV region of the spectrum (approximately 1-40 nm) for identification of the impurity species present in NSTX-U discharges and to allow monitoring of the relative impurity content of the discharges.

8.2 Materials and Design Requirements

b. The EUV spectrometer system shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

8.3: Configuration Requirements and Essential Features

a. The EUV spectrometer system shall consist of one or more grazing incidence spectrometers with the spectral coverage of each spectrometer chosen to meet the requirement for overall wavelength coverage and resolution (8.4-b) of the system.

b. If more than one spectrometer is required to simultaneously meet the overall spectral coverage of the system while meeting the spectral resolution requirement, the wavelength coverage of each spectrometer shall overlap the coverage of the spectrometers covering the adjacent wavelength regions to avoid gaps in spectral coverage.

c. The spectrometers shall have the capability to change the width of the entrance slits to allow the spectral resolution and etendue to be varied.

d. The detectors shall be low-noise pixelated detectors (e.g., CCDs) with high sensitivity in the EUV spectral region and variable pixel binning and readout and integration times.

e. The ancillary electronics and controls shall be located outside the Test Cell to the extent possible to protect them from the effects of radiation produced by NSTX-U.

f. Each detector shall have remotely controlled AC power to allow the power to be cycled to clear detector fault modes.

g. The EUV spectrometer system shall be directly coupled to the NSTX-U vacuum vessel with no windows via one or more beamlines which define the spectrometer sightlines.

h. The spectrometer beamlines shall include bellows that allow minor adjustment of the spectrometer sightlines by vertical motion of the spectrometers on mechanical stages.

i. The spectrometer beamlines shall be aimed to provide views of plasma core region near the magnetic axis for typical NSTX-U discharges.

j. The beamlines shall have remotely-operated TIVs that can be used to isolate the spectrometers and beamlines from the NSTX-U vacuum vessel.

k. The EUV spectrometer system shall have a dedicated vacuum pumping system that will allow it to be pumped independently of the NSTX-U vacuum system when the TIVs are closed.

l. The EUV spectrometer system shall have pressure gauges with interlocks that can be set to close the TIVs when the spectrometer pressure exceeds a set value.

m. The beamlines shall incorporate electrical isolation breaks that meet the voltage stand-off requirements for NSTX-U hi-pot [1].

8.4 Baseline Performance and Operational Requirements

a. The overall wavelength coverage of the system shall be chosen to allow strong lines of the higher ionization states of all intrinsic or extrinsic impurity species that could be found in NSTX-U to be observed. At a minimum, these impurity species are He, Li, B, C, N, O, Ne, Ar, Ti, Cr, Fe, Ni, Cu, Kr, Mo, Ag, and W. This defines a requirement for overall wavelength coverage of 1-40 nm or greater.

b. Spectral resolution of 0.01 nm (line FWHM) or better is required to provide adequate resolution of nearby spectral lines.

c. The detectors shall be capable of full pixel (unbinned mode) readout in 5 ms or less which determines the maximum time resolution of the system.

8.5 Upgrade Performance and Operational Requirements

a. The EUV spectrometer system shall be designed to allow radiation shielding of the detectors to be added if it is found to be necessary to reduce noise on the data and to minimize radiation damage to the detectors.

8.6 Interfaces

Table 8.6-1*: Interfaces for the EUV spectrometers (SBS 1.4.1.15).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.1	NTC Platforms	Structural	Test Cell	EUV spectrometers mounted on	General

			platform	stand that is supported from the Test Cell platform	Arrangement Drawing
1.8.1.4	Diagnostic DARM	Location	DARM	Rack space in DARM required for detector control/data acquisition PCs	Mechanical drawing
1.4.1.22	Diagnostic Port Covers	Vacuum	Ports on vacuum vessel	Beamlines between EUV spectrometers and vacuum vessel	Mechanical drawing
0.1.1.3	PPPL Network Infrastructure	Ethernet	Ethernet connector on web power switch	Fiber optic Ethernet line to web power switch for detectors, vacuum pumps, and gauges	CWD
1.8.1.1.2	NTC Cable Trays	Fiber Optic	Tray surface	Fibers located in trays	N/A
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	Connectors on Fiber to USB converter	Fiber optic USB link to connect detectors to PC located in DARM	N/A
1.3.1.3	TIV and Shutter Actuation System	Gas	Where air line connects to valve or shutter mechanism	Control of TIVs on vacuum spectrometer diagnostics	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for vacuum spectroscopy systems	N/A
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to vacuum spectroscopy diagnostics	CWD
1.6.2.2	Data Archiving Systems	Software	At ethernet port	Software associated with the cameras writes data to the data archival system	MDS+ API

9: Multi-Point Thomson Scattering Diagnostic (SBS 1.4.1.3)

9.1 Functions

a. The Multi-Point Thomson Scattering (MPTS) diagnostic (SBS 1.4.1.3) provides time-resolved measurements of the electron temperature (T_e) and electronic density (n_e) profiles versus major radius (R) during NSTX-U discharges. The time resolved electron pressure profile and the line-integrated n_e are derived from the n_e(R) and T_e(R) measurements.

9.2 Materials and Design Requirements

a. The MPTS diagnostic shall be designed to meet the NSTX-U engineering requirements given in Section 6.4.2 of the NSTX-U General requirements Document (GRD) and in Section 4.2 of the GRD [1].

9.3: Configuration Requirements and Essential Features

a. The MPTS diagnostic shall consist of one or more laser beams injected into the NSTX-U vacuum vessel, optics to collect the scattered laser light, optic fiber bundles to relay the light to the remotely-located detection systems, and detection systems (consisting of polychromators and avalanche photodiodes) to measure the spectra of the scattered laser light.

b. The lasers and detection systems shall be located in an area that is outside the Test Cell to allow access to these systems during operation (with appropriate interlocks and safety precautions) without requiring access to the Test Cell.

c. The MPTS diagnostic laser beams shall have a tangential trajectory in the midplane of the NSTX-U vacuum vessel, with a tangency radius of 39 cm or smaller (consistent with minimizing stray light due to laser scattering from the CS), where tangency is relative to a circle in the horizontal plane centered on the axis of the CS casing).

d. The laser beam delivery optics and light collection optics shall be supported in a way that is mechanically independent of the NSTX-U device to avoid the effects of vibration during NSTX-U operation.

e. The laser aiming accuracy shall be 0.5 mm or better at a distance of 20 m and it shall be stable over time.

f. The light collection optics shall view the laser beam through a window that is equipped with a remotely-controlled shutter system to prevent the window from being coated during bakeout and plasma operation and to reduce background plasma light when necessary.

g. The viewing window shall be demountable to allow it to be easily replaced when the vacuum vessel is at atmospheric pressure.

h. The collection optics shall be fitted with a kinematic mount arrangement such that alignment is retained following its removal and re-installation.

i. The window through which the laser beam passes into the vacuum vessel shall be at a location where the laser power density incident on the window during a laser pulse is sufficiently low to minimize risk of laser damage to the window.

j. A beam dump shall be provided to capture the laser beam after it has passed through the vacuum vessel to prevent stray laser light from contributing to the Thomson Scattering signal.

k. The laser beam dump shall have an optical path that is long enough to provide a time delay to prevent residual scattered laser light emanating from the beam dump from contributing to the Thomson Scattering signal during the laser pulse.

l. The portions of the laser beam flight tubes that are connected to the NSTX-U vacuum shall have TIVs to allow them to be isolated from the NSTX-U vacuum vessel, and ports to allow them to be independently pumped when the TIVs are closed.

m. The entrance and exit laser beam flight tubes shall incorporate electrical isolation breaks capable of voltage stand-off consistent with NSTX-U hi-pot requirements [1].

n. The MPTS diagnostic shall have a system of alignment fibers viewing above and below the axis of the laser beam path. These fibers shall be grouped in a minimum of three sets permitting measurement of the relative alignment between the laser beams and the collection optics in different sections along the laser-beam axis. These sections shall include the inner and outer portions of the field of view.

o. Cameras located a each of the laser-beam optics turning mirrors shall be used to measure the position of the beams in real space. The measurements shall be made by viewing the small fraction of transmitted light through a mirror, or by viewing the mirror surface away from the reflected-beam angle.

p. The MPTS diagnostic shall incorporate the features necessary to ensure personnel safety for operation of Class IV lasers at PPPL. These shall include a fully-enclosed beam path, interlocks, and appropriate administrative controls.

q. The MPTS diagnostic shall have a shutter that blocks the laser path when Test Cell access is permitted. This shutter shall be interfaced to the hard-wired interlock system.

r. The MPTS diagnostic shall be designed to allow absolute calibration of the system using Rayleigh and Raman scattering signals from low-pressure gases introduced into the NSTX-U vacuum vessel during shutdown periods.

s. A high vacuum compatible light-absorbing coating shall be applied to the portion of the vacuum vessel interior that is within the field of view of the MPTS sightlines to reduce the effect of straylight during calibration.

t. The MPTS diagnostic shall incorporate a probe with a stable light source that can be inserted into the vacuum vessel during non-operational periods to measure changes in the transmission of the light collection window.

9.4 Baseline Performance and Operational Requirements

a. The laser system shall have a pulse repetition rate of 60 Hz or higher.

b. The light collection optics shall be capable of measuring the scattered laser light over a range of points on the laser beam trajectory that correspond to values of the major radius from 7.5 cm larger than the center stack radius to the radius of the RF limiter with spatial resolution of 4 cm or better in the plasma core and 1 cm or better at the plasma edge.

c. The light collection optics, optical fibers, and detection systems shall support measurements at a minimum of 42 spatial locations located across the entire plasma diameter and scrape-off layer.

d. The MPTS diagnostic shall be designed to measure T_e over a range of 0.003-10 keV.

e. The MPTS diagnostic shall be designed to measure n_e over a range of 5×10^{12}-5×10^{14} cm^{-3}.

9.5 Upgrade Performance and Operational Requirements

a. The light collection optics and optical fibers shall be designed to support expansion to provide measurements at up to 48 spatial locations by implementation of additional detection systems.

b. An upgrade for realtime data acquisition and processing may be required in the future.

9.6 Interfaces

***Table 9.6-1**: Interfaces for the MPTS Diagnostic (SBS 1.4.1.3).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.8	NTC Floor	Structural	At NTC floor surface	Collection optics box supported from Test Cell floor	Mechanical drawing
1.8.1.1.1	NTC Platforms	Structural	Test Cell platform	Flight tubes for laser input and exit to the vacuum vessel supported by platform.	General Arrangement Drawing
1.8.1.1.4	NTC Walls	Structural	At NTC wall	Laser beam optics box supported	Mechanical

				by south wall of test cell	drawing
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	Test Cell wall	Penetrations through Test Cell wall for laser flight tube and light collection fiber bundles	General Arrangement
0.1.1.3	PPPL Network Infrastructure	Ethernet	Ethernet connectors on cameras	Ethernet connection to alignment cameras located on beam dump flight tube	CWD
1.4.1.22	Diagnostic Port Covers	Vacuum	Ports on vacuum vessel	Light collection window on vacuum vessel port	Mechanical drawing
1.1.2.1.1	Vacuum vessel	Vacuum	Ports on vacuum vessel	Laser beam entrance and exit flight tubes (with windows) on vacuum vessel ports; blackening of inner vessel wall required within field of view of the collection optics, in order to reduce stray light	Mechanical drawing
1.3.1.3	TIV and Shutter Actuation System	Electrical Signal	Shutters on port	Shutter control and status signals	CWD
1.8.1.1.4	NTC Walls	Fiber Optic	At NTC wall	Flight tube supported from the vessel walls	Mechanical drawing
1.8.1.5	MSE & MPTS Mezzanine	Location	Dedicated room near Test Cell	A dedicated climate-controlled room adjacent to the Test Cell is required to house the lasers and associated optics, detection systems, racks, digitizers and other electronics	Mechanical drawing
0.1.1.1	D-Site Facility Chilled Water	Fluid	Laser cooling water system	Laser cooling water heat exchanges with facility chilled water.	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	AC power outlets	AC Power for lasers, racks, and other equipment located in the laser/detector room	Electrical Schematic for Directly Wired Components
1.6.2.1	Data I/O systems	Electrical Signal	Connectors on digitizers	Digitized data from detectors and lasers	CWD
1.7.3.1	Hardwired Interlock System	Electrical Signal	Limit switch on laser blocking shutter	Shutter that blocks laser beam to prevent inadvertent personnel exposure during Test Cell access requires a hard-wired interlock to the access system	CWD
1.3.1.3	TIV and Shutter Actuation System	Gas	Where air line connects to valve or shutter mechanism	Control of shutters and TIVs for MPTS	P&ID
1.8.1.1.7	NTC Racks	Location	N/A	Electronics located in NTC racks	N/A
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to instruments in the MPTS diagnostic	CWD
1.8.1.3	North and East Galleries	Location	N/A	MPTS cooling water system and power supplies reside in a cage in the gallery	General Arrangement

10: Charge Exchange Recombination Spectroscopy Diagnostic (SBS 1.4.1.5)

10.1 Functions

a. The toroidal-viewing Charge Exchange Recombination Spectroscopy (CHERS) diagnostic (SBS 1.4.1.5.1) provides time-resolved profile measurements of carbon impurity ion temperature (T_i), toroidal plasma velocity (V_t), and carbon impurity density (N_c) versus major radius (R) during NSTX-U discharges.

10.2 Materials and Design Requirements

a. The CHERS diagnostic shall be designed to meet the NSTX_U engineering requirements given in Section 6.4.2 of the General requirements Document (GRD) and in Section 4.2 of the GRD

10.3 Configuration Requirements & Essential Features

a. The toroidal-viewing CHERS diagnostic shall consist of one or more spectrometer/detector systems, collection optics, and optical fibers, which will couple spectrometers to the collection optics.

b. The spectrometers and detectors shall be located outside of the NSTX-U test cell to allow access to these systems during operation. Fiber optics shall be routed through penetrations in the test cell wall from the collection optics to the spectrometers.

c. The toroidal CHERS collection optics shall be on the midplane and located to optimize the spatial resolution of the CHERS measurements. The original NSTX neutral beam (NB1) shall be viewed so as to cross the NB1 trajectory at or near the tangency radius of the sightlines.

d. The toroidal-viewing CHERS system shall be designed to allow isolation of the intrinsic background emission of the carbon impurity ions from the active emission that occurs in the NB1 path, such as second set of collection optics that do not view any neutral beam and/or a capability to modulate the NB1 beam source(s) in a manner such that they can be synced to the CHERS detector timing.

e. The collection optics shall be mounted behind a vacuum window that is protected by a shutter system to prevent coating of the window during bakeout, boronization, lithium evaporation, and plasma operation.

f. The number of fiber optics shall allow measurements across the outer half of the plasma from the magnetic axis to the plasma edge in order to provide profile measurements.[3]

[3] For purposes of this document, the radius of the magnetic axis can be taken as 105 cm.

g. The spectral coverage of the CHERS spectrometers shall be adequate to allow wavelength calibration and measurement of the instrumental function using neon glow discharges.

10.4 Baseline Performance and Operational Requirements

a. The detector shall be capable of operating at 100 Hz frame rate or higher.

b. The spatial resolution of the system shall be 4 cm or less in the plasma core and 1 cm or less near the plasma edge.

c. The CHERS system shall support ion temperature measurements up to 5 keV.

d. The CHERS system shall support toroidal velocity measurements up to 400 km/s.

e. The operation of one or more of the NB1 sources is required for CHERS measurements.

f. Modulation of one or more NB1 sources is required for CHERS measurements when any NB2 sources are operated.

10.5 Upgrade Performance and Operational Requirements

a. The light collection optics and fiber optics shall be designed to allow expansion for charge exchange spectroscopy measurements for impurities other than carbon.

10.6 Interfaces

Table 10.6-1*: Interfaces for the CHERS diagnostic (SBS 1.4.1.5.1)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.3.1.3	TIV and Shutter Actuation System	Gas	Where air line connects to valve or shutter mechanism	Control of shutters on Toroidal CHERS diagnostics	P&ID
1.8.1.4	Diagnostic DARM	Location	N/A	Spectrometers and computers reside in the DARM	N/A
1.8.1.1.2	NTC Cable Trays	structural	At tray	Fibers reside in cable trays	N/A
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	At penetration	Fiber optics leave NTC via penetrations	N/A
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for Toroidal CHERS diagnostics	N/A
1.1.2.1.1	Vacuum vessel	Other	Vessel inner surface	View dumps or blackening required where optics views intersect the vessel	N/A
1.2.4.9	Generated Neutral Beam	Spatial	N/A	Toroidal CHERS systems designed to image the beam with specific geometry	N/A
1.1.2.1.1	Vacuum vessel	Vacuum	At flange on vessel	CHERS background view is via window mounted directly to	N/A

				vessel	
0.1.1.3	PPPL Network Infrastructure	Ethernet	At connectors on computer	Computers have network access for various HMI, data acquisition, and data transfer functions	N/A
1.6.2.2	Data Archiving Systems	Software	At ethernet port	Computers archive data in MDS+	MDS+ API
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to Toroidal CHERS diagnostic suite	CWD
1.4.1.22	Diagnostic Port Covers	Vacuum	At flange on diagnostic port cover	instruments view with vacuum windows w/ shutters; optics may be supported from port cover	N/A

11.0 Machine Instrumentation (SBS 1.7.3.4)

Note: further elaboration on these topics is provided in Ref. [2]

11.1 Functions

The functions of the machine instrumentation (SBS 1.7.3.4) are to provide:

a. Provide benchmarking for structural models of NSTX-U.
b. Provide post-shot warning that some component limit may have been reached, or that the mechanical behavior of a component has begun to diverge from either similar components ("out of family") or historical trends. This will be referred to as "protection" in this Section, with the understanding that this does not imply a realtime or interlock role. [9]

11.2 Materials and Design Requirements

a. For design, components will be defined as per Table 11.2-1

Table 11.1-1*: Categorization of sensor types.*

Classification	**Implication**
Critical	If not functional, cannot operate NSTX-U or operation will be severely constrained. Redundancy is critical.
Necessary	Used for trending or out of family assessments. Operations can proceed on any given day, through the system should be repaired at the earliest reasonable time. Redundancy may not be required.
Convenience	Related solely to benchmarking and not required for trending or operations

11.3: Configuration Requirements and Essential Features

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

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

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

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

g. Calibrated data shall be archived or available in the MDS+ tree.

h. 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

i. 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

11.4 Baseline Performance and Operational Requirements

a. Sensors shall be placed at 9 locations along the length of each of the TF outer legs for the purposes of trending and benchmarking the outer leg deflections. These sensors shall be used for both benchmarking and protection and will be considered "Necessary"

b. Sensors shall be placed on all TF trusses in order to determine truss loading uniformity. These sensors will be used for benchmarking and will be considered "Necessary"

c. Sensors shall be placed on the upper and lower spoked lids in order to measure the torsional and axial loading of the lid. These sensors will be used for both benchmarking and protection and will be considered "Necessary".

d. Sensors shall be placed on the features that transfer lateral CS loads across the upper CS bellows. These sensors will be used for both benchmarking and protection and will be considered "for convenience".

e. Sensors shall be placed on the OH pre-load assembly, to monitor expansion and displacement of the OH coil, as well as loss of preload. These sensors will be used for both benchmarking and protection and will be considered "Necessary".

f. Sensors shall be placed on the TF bundle, immediately behind the Belleville washer stack, in order to measure and trend the torsional strain of the TF bundle. These sensors will be used for both benchmarking and protection and will be considered "Necessary".

g. Sensors shall be placed on the PF-4 and PF-5 slides to assess the behavior of these slides during operations and bakeout. These sensors will be used for both benchmarking and protection and will be considered “Necessary”.

h. Sensors shall be placed on the PF-1a and -1b support structures to assess loss of preload. These sensors will be considered “Necessary”.

i. A system shall be deployed to measure and trend the total twist of the inner-TF bundle, with sensitivity sufficient to detect progressive delamination of the bundle ends . These sensors will be used for both benchmarking and protection and will be considered “Necessary”.

11.5 Upgrade Performance and Operational Requirements

a. The system is likely to expand in the future as additional requests are made; easy expansion of both the hardware and software capability shall be design features.

11.6 Interfaces

Table 11.6-1: *Interfaces for the machine instrumentation (SBS 1.7.3.4.1).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.6.2.1	Data I/O systems	Electrical Signal	At digitizer input	Some signals from the instrumentation system will have their signals digitized	CWD
1.6.2.2	Data Archiving Systems	Software	Software within data processing unit	Some element of the instrumentation system will directly input data to MDS+	none
1.1.3.2	TF outer legs	Diagnostic	Surface of coil	Sensors measures strain in the TF outer leg	Mechanical Drawing
1.1.2.3.1	Outer TF Truss System	Diagnostic	Surface of truss	Sensors measure strain in the TF trusses	Mechanical Drawing
1.1.2.1.2	Umbrella structure & Spoked Lids	Diagnostic	Surface of spoked lid	Sensors measure strain in the spoked lides	Mechanical Drawing
1.1.3.3.13	Lateral Support Structures	Diagnostic	Surface of support member	Sensors measure strain or pressure in the load bearing members of the CS lateral supports	Mechanical Drawing
1.1.3.3.2	Ohmic Heating Solenoid	Diagnostic	Surface of pre-load mechanism	Sensors measure displacements of the belleville stack that provides preload	Mechanical Drawing
1.1.3.3.1	TF Inner Legs	Diagnostic	Surface of coil insulation	Sensors measure strain in multiple directions on the surface of the TF bundle	Mechanical Drawing
1.1.2.3.2	Outer PF Supports	Diagnostic	Surface of slide mechanism	Sensors measure displacements of the radial slides.	Mechanical Drawing
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	At penetration	Fiber optics leave NTC via penetrations	N/A

1.8.1.1.2	NTC Cable Trays	Structural	At tray	Fibers for sensors reside in cable trays	N/A
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for the instrumentation	N/A
1.1.3.3.11	PF-1a Support Structure	Diagnostic	Where sensor mounts to assembly	Sensor(s) used to detect pre-load on the PF-1a coils.	Mechanical Drawing
1.1.3.3.12	PF-1b Support Structure	Diagnostic	Where sensor mounts to assembly	Sensors used to detect pre-load on the PF-1b coils.	Mechanical Drawing
1.8.1.1.7	NTC Racks	Location	N/A	Some electronics located in NTC racks	N/A
1.8.1.4	Diagnostic DARM	Location	N/A	Some electronics located in the Diagnostic DARM	N/A
1.6.1.3	Timing and Synchronization System	Electrical Signal	At inputs to electronics	Timing markers and triggers delivered to instrumentation systems	CWD

***Table 11.6-1**: Interfaces for the TF Twist measurements (SBS 1.7.3.4.5).*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.1	TF Inner Legs	Structural	TBD	The TF twist instrumentation is physically mounted to bundle, allowing the twist of the bundle to be transferred to the measurement	Mechanical Drawing
1.6.2.2.1	MDSplus Server	Ethernet	TBD	The TF twist instrumentation sends data to the MDS+ servers via the internet	N/A
1.8.1.1.4	NTC Walls	Structural	At wall surface	System is mounted to NTC walls	Drawings
1.5.1.2	D-Site Auxiliary Power	Structural	TBD	System uses AC power distribution in the NTC	N/A
1.6.1.3	Timing and Synchronization System	Structural	TBD	Camera triggers come from timing system	CWD
1.7.3.8	Central Control System (CCS)	Structural	TBD	CCS MAY control the turning on of the laser	CWD