National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

Diagnostics

NSTX-U-RQMT-SRD-011-00

Revision 0

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Change Record

Revision	Date	Description of Change
0	12/27/17	Initial Release

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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 WBS 1.4.1. These diagnostics are listed in Table 6.4.1-1 of the GRD [1]. They are:

- Plasma Current Rogowski Coils (WBS 1.4.1.2.1)
- Poloidal Flux Loops (WBS 1.4.1.2.2)
- Mirnov Sensors (WBS 1.4.1.2.2)
- Plasma TV System (WBS 1.4.1.4)
- Filterscope Diagnostic (WBS 1.4.1.13)
- Fission Chamber Neutron Detectors (WBS 1.4.1.1)
- Multi-Pulse Thomson Scattering Diagnostic (WBS 1.4.1.3)
- Plasma Facing Component Thermocouples (WBS 1.1.1.1)
- Plasma Facing Component Langmuir Probes (WBS 1.4.1.17)
- Extreme Ultraviolet Spectrometers (WBS 1.4.1.15)
- Machine Instrumentation (WBS 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 WBS 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.

2: Magnetics Diagnostics (WBS 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 (WBS 1.4.1.2.1); 2) Mirnov Sensors to measure the poloidal magnetic field at specific locations (WBS 1.4.1.2.2); and 3) Poloidal Flux Loops to measure the poloidal flux at specific locations (WBS 1.4.1.2.2). 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].

2.3: Configuration Requirements and Essential Features

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.

h. 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]

i. 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.

j. 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.

k. 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.

l. 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.

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

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

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

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

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, Rogowski, and flux loop sensor signals shall be digitized at a minimum rate of 2 kHz.

Table 2.4-1: Required signal levels for magnetic diagnostics

B, CSC	T	0.9
B, Plate, OBD, Vessel	T	0.5
flux, CSC	Wb	1.5
flux, Plate, OBD, Vessel	Wb	2.55

2.5 Upgrade Performance and Operational Requirements

a. None.

2.6 Interfaces

Table 2.6-1: Interfaces for the magnetics diagnostics.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Center Stack Casing	1.1.3.3.2	Diagnostic	Ohmic heating Solenoid	Rogowski Coils mounted on the OH Solenoid	Mechanical drawing, Calculation
Vacuum Vessel	1.1.2.1	Diagnostic	Vacuum vessel outer surface	Rogowski Coils mounted on outer surface of vacuum vessel via insulated supports	Mechanical drawing
Vacuum Vessel	1.1.2.1	Diagnostic	Vacuum vessel inner and outer surfaces	Poloidal Flux Loops mounted on inner and outer surfaces of vacuum vessel	Mechanical drawing
Passive Plates	1.1.1.2	Diagnostic	Passive Plates	Poloidal Flux Loops mounted behind the primary and secondary passive plates	Mechanical drawing
Ohmic Heating Solenoid	1.1.3.3.2	Diagnostic	Ohmic Heating Solenoid Ground Plane Surface	Poloidal Flux Loops mounted on the Ohmic Heating Solenoid	Schematics or mechanical drawings
Inner Poloidal Field Coils	1.1.3.3.3	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical drawing
Passive Plates	1.1.1.2	Diagnostic	Passive Plates	Mirnov Sensors mounted behind and between the passive plates	Mechanical drawing
Center Stack and Inboard Divertor PFCs	1.1.1.1	Diagnostic	Center Stack and Inboard Divertor PFCs	Mirnov Sensors mounted inside tiles on the Center Stack and Inboard Divertor (horizontal and vertical targets)	Mechanical drawing
Outboard Divertor PFCs	1.1.1.1	Diagnostic	Outer Divertor PFCs	Mirnov Sensors mounted inside tiles on the Outboard Divertor	Mechanical drawing
Vacuum Vessel	1.1.2.1	Diagnostic	Vacuum vessel inner surface	Leads for Poloidal Flux Loops and Mirnov Sensors secured to the vacuum vessel	Mechanical drawing, CWD
Vacuum Vessel	1.1.2.1	Diagnostic	Electrical feedthroughs mounted on vacuum vessel ports	Electrical Feedthroughs for leads to Poloidal Flux Loops and Mirnov Sensors mounted inside vacuum vessel	Mechanical drawing, CWD
Test Cell	1.8.1	Electrical signal	Cable trays	Cables between Rogowski Coils, Poloidal Flux Loops, and	CWD

				Mirnov Sensors and signal processing electronics and digitizers located in racks	
Test Cell	1.8.1	Space allocation	Racks located in Test Cell	Rack space in Test Cell required for signal processing electronics and digitizers for Rogowski Coils, Poloidal Flux Loops, and Mirnov Sensors	Mechanical drawing
Data Acquisition	1.6.1.1	Electrical Signal	Connectors on CAMAC digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD

3: Plasma Facing Component Thermocouples (WBS 1.1.1.1)

3.1 Functions

a. The Plasma Facing Component (PFC) Thermocouples (WBS 1.1.1.1) measure the transient and time-averaged temperature of the PFCs during plasma operation and during bakeout.[1]

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.

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 passive plate 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]

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]

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

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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Center Stack and Inboard Divertor PFCs	1.1.1.1	Diagnostic	Center Stack and Inboard Divertor PFCs	Thermocouples mounted inside tiles on the Center Stack and Inboard Divertor	Mechanical drawing
Outboard Divertor PFCs	1.1.1.1	Diagnostic	Outboard Divertor PFCs	Thermocouples mounted inside tiles on the Outboard Divertor	Mechanical drawing
Vacuum Vessel	1.1.2.1	Diagnostic	Vacuum vessel inner surface	Thermocouple leads mounted inside vacuum vessel	Mechanical drawing, CWD
Vacuum Vessel	1.1.2.1	Electrical Signal	Electrical feedthroughs mounted on vacuum vessel ports	Electrical Feedthroughs for thermocouple leads	Mechanical drawing, CWD
Test Cell	1.8.1	Electrical Signal	Cable trays	Cables between electrical feedthroughs and signal processing electronics and digitizers located in racks	CWD
Test Cell	1.8.1	Space allocation	Racks located in Test Cell	Rack space in Test Cell required for signal processing electronics and digitizers for thermocouples	Mechanical drawing
Data Acquisition	1.6.1.1	Electrical Signal	Connectors on digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connector on digitizers	Facility clock signal to trigger digitizers	CWD

4: Plasma Facing Component Langmuir Probes (WBS 1.4.1.17)

4.1 Functions

a. The Plasma Facing Component (PFC) Langmuir Probes (WBS 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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Center Stack and Inboard Divertor PFCs	1.1.1.1	Diagnostic	Center Stack and Inboard Divertor PFCs	Langmuir Probes mounted inside tiles on the Center Stack and Inboard Divertor	Mechanical drawing
Outboard Divertor PFCs	1.1.1.1	Diagnostic	Outboard Divertor PFCs	Langmuir Probes mounted inside tiles on the Outboard Divertor	Mechanical drawing
Vacuum Vessel	1.1.2.1	Diagnostic	Vacuum vessel inner surface	Langmuir Probe leads secured to the vacuum vessel	Mechanical drawing, CWD
Vacuum Vessel	1.1.2.1	Electrical signal	Electrical feedthroughs mounted on vacuum vessel ports	Electrical Feedthroughs for Langmuir Probe leads	Mechanical drawing, CWD
Test Cell	1.8.1	Electrical signal	Cable trays	Cables between electrical feedthroughs and signal processing electronics and digitizers located in racks	CWD
Test Cell	1.8.1	Space allocation	Racks located in Test Cell	Rack space in Test Cell required for signal processing electronics and digitizers for Langmuir Probes	Mechanical drawing
Data Acquisition	1.6.1.1	Electrical Signal	Connectors on digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD

5: Fission Chamber Neutron Detectors (WBS 1.4.1.1)

5.1 Functions

a. The Fission Chamber Neutron Detectors (WBS 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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Test Cell	1.8.1	Diagnostic	Test Cell Platform	Fission chambers installed at various locations on the platform	Mechanical drawing
Test Cell	1.8.1	Space allocation	Rack located in Test Cell	Rack space in Test Cell required for signal processing electronics and CAMAC digitizers.	Mechanical drawing
Test Cell	1.8.1	Electrical signal	Cable trays	Cables between detectors and signal processing electronics	CWD
Data Acquisition	1.6.1.1	Electrical Signal	Connector on CAMAC digitizers	Signals from digitizers interfaced to NSTX-U data acquisition system	CWD
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connector on CAMAC digitizers	Facility clock signal to trigger digitizers	CWD
Central Instrumentation and Control	1.6	Electrical Signal	Connectors on signal processing electronics and CAMAC digitizers	Cables between signal processing electronics and digitizers	CWD

6: Plasma TV System (WBS 1.4.1.4)

6.1 Functions

a. The Plasma TV system (WBS 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 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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Test Cell	1.8.1	Space Allocation	Test Cell Platform	TV cameras installed at various locations on the platform	Mechanical drawing
Vacuum Vessel	1.1.2.1	Diagnostic	Ports on vacuum vessel	Reentrant viewports, shutters, and lenses installed on vacuum vessel	Mechanical drawing
Vacuum PLC	1.6.1.2	Electrical Signal	Shutter on port	Shutter control and status signals	CWD
Test Cell	1.8.1	Fiber Optic	Cable trays	Fiber optics bundles between lenses and TV cameras	Mechanical drawing
Data Acquisition	1.6.1.1	Electrical Signal	Ethernet connectors on cameras	Ethernet connection to cameras used for camera control and data acquisition	CWD
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connectors on cameras	Facility clock signals to trigger cameras	CWD

7: Filterscope Diagnostic (WBS 1.4.1.13)

7.1 Functions

a. The Filterscope diagnostic (part of WBS 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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Vacuum Vessel	1.1.2.1	Diagnostic	Ports on vacuum vessel	Windows, shutters, and lenses installed on vacuum vessel	Mechanical drawing
EPICS	1.6.1.2	Electrical Signal	Shutter on port	Shutter control and status signals	CWD
Test Cell	1.8.1	Fiber Optic	Cable trays	Fiber optics bundles between various windows on the vacuum vessel and detection system	Mechanical drawing
DARM	1.8.1.4	Space	DARM	Rack space and/or shelf space	Mechanical

		allocation		in DARM required for detector units and digitizers	drawing
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connectors on digitizers	Facility clock signals to trigger detectors	CWD
Data Acquisition	1.6.1.1	Electrical Signal	Digitizers located in DARM	Acquisition of data from digitizers	CWD

8: Extreme Ultraviolet Spectrometer System (WBS 1.4.1.15)

8.1 Functions

a. The Extreme Ultraviolet (EUV) spectrometer system (WBS 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.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Test Cell	1.8.1	Space Allocation, Structural	Test Cell platform	EUV spectrometers mounted on stand that is supported from the Test Cell platform	Mechanical drawing
DARM	1.8.1.4	Space allocation	DARM	Rack space in DARM required for detector control/data acquisition PCs	Mechanical drawing
Vacuum Vessel	1.1.2.1	Vacuum	Ports on	Beamlines between EUV	Mechanical

			vacuum vessel	spectrometers and vacuum vessel	drawing
EPICS	1.6.1.2	Electrical Signal	Shutters beamlines	Shutter control and status signals	CWD
Central Instrumentation and Control	1.6.1.3	Fiber Optic	Ethernet connector on web power switch	Fiber optic Ethernet line to web power switch for detectors, vacuum pumps, and gauges	CWD
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connectors on detectors	Facility clock signals to trigger detectors	CWD
Central Instrumentation and Control	1.6.1.3	Fiber Optic	Connectors on Fiber to USB convertor	Fiber optic USB link to connect detectors to PC located in DARM	CWD
Data Acquisition	1.6.1.1	Electrical Signal	PCs located in DARM	Data from detectors	CWD

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

9.1 Functions

a. The Multi-Point Thomson Scattering (MPTS) diagnostic (WBS 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.

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 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.

9.6 Interfaces

Table 9.6-1: Interfaces for the MPTS Diagnostic.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Test Cell	1.8.1	Space Allocation, Structural	Test Cell floor	Collection optics box supported from Test Cell floor	Mechanical drawing
Test Cell	1.8.1	Space Allocation, Structural	Test Cell platform	Flight tubes for laser input and exit to the vacuum vessel supported by platform.	Mechanical drawing
Test Cell	1.8.1	Space Allocation, Structural	Test Cell wall	Laser beam optics box supported by south wall of test cell	Mechanical drawing
Test Cell	1.8.1	Space Allocation	Test Cell wall	Penetrations through Test Cell wall for laser flight tube and light collection fiber bundles	Mechanical drawing
Data acquisition	1.6.1.1	Electrical Signal	Ethernet connectors on cameras	Ethernet connection to alignment cameras located on beam dump flight tube	CWD

Vacuum Vessel	1.1.2.1	Vacuum	Ports on vacuum vessel	Light collection window on vacuum vessel port	Mechanical drawing
Vacuum Vessel	1.1.2.1	Vacuum	Ports on vacuum vessel	Laser beam entrance and exit flight tubes (with windows) on vacuum vessel ports	Mechanical drawing
EPICS	1.6.1.2	Electrical Signal	Shutters on port	Shutter control and status signals	CWD
Test Cell	1.8.1	Fiber Optic	Cable trays	Fiber optics bundles between light collection optics and detection system	Mechanical drawing
Laser/Detector Room	1.8.1.5	Space Allocation, Structural	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
Laser Cooling Water	NA	Fluid	Laser cooling water system	Laser cooling water heat exchanges with facility HVAC water.	P&ID
AC Power Systems	1.5.1	Electrical Power	AC power outlets	AC Power for lasers, racks, and other equipment located in the laser/detector room	CWD
Central Instrumentation and Control	1.6.1.3	Electrical Signal	Connectors on digitizers and lasers	Facility clock signals to trigger digitizers and laser	CWD
Data Acquisition	1.6.1.1	Electrical Signal	Connectors on digitizers	Digitized data from detectors and lasers	CWD
Hard-wired Interlock System	1.7.3.1	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

10.0 Machine Instrumentation (WBS 1.7.3.4)

10.1 Functions

The functions of the machine instrumentation (WBS 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]

10.2 Materials and Design Requirements

a. For design, components will be defined as per Table 9.2-1

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
Convenience	Related solely to benchmarking and not required for trending or operations

10.3: 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

10.4 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 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 assess the twist 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".

10.5 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.

10.6 Interfaces

Table 9.6-1: Interfaces for the machine instrumentation.

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
Data I/O Systems	1.6.2.1	Electrical Signal	At digitizer input	Some signals from the instrumentation system will have their signals digitized	CWD
MDS+	1.6.2.2	Software	Software within data processing unit	Some element of the instrumentation system will directly input data to MDS+	none
TF OL Coils	1.1.3.2	Diagnostics	Surface of coil	Sensors measures strain in the TF outer leg	Mechanical Drawing
TF Trusses (Coil Supports)	1.1.2.3	Diagnostic	Surface of truss	Sensors measure strain in the TF trusses	Mechanical Drawing
Spoked Lids (Coil Supports)	1.1.2.3	Diagnostic	Surface of spoked lid	Sensors measure strain in the spoked lides	Mechanical Drawing
CS Lateral Support Members	1.1.3.3.4	Diagnostic	Surface of support member	Sensors measure strain or pressure in the load bearing members of the CS lateral supports	Mechanical Drawing
OH Coil	1.1.3.3.2	Diagnostic	Surface of pre-load mechanism	Sensors measure displacements of the belleville stack that provides preload	Mechanical Drawing
TF Inner Legs	1.1.3.3.1	Diagnostic	Surface of coil insulation	Sensors measure strain in multiple directions on the surface of the TF bundle	Mechanical Drawing
Outer PF Coil Radial Slides	1.1.2.3	Diagnostic	Surface of slide mechanism	Sensors measure displacements of the radial slides.	Mechanical Drawing