National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

REQUIREMENTS DOCUMENT
PFC Diagnostics and Fueling

NSTX-U-RQMT-RD-004-00

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Change Record

Revision	Date	TRB	Description of Change
0	10/17/17		Initial Release

References

[1] NSTX-U-RQMT-SRD-003-00, Plasma Facing Components
[2] NSTX-345 Previous (2013) PFC Diagnostics and Gas Injection Layout for Upper and Lower Outboard Divertor and Passive Plates
[3] ED-1324 Previous (2015) PFC Diagnostics and Gas Injection Layout for Centerstack
[4] NSTX-U-SDD-BAKE-R0, Bakeout System Design Description
[5] NSTX-Plan-12-207, NSTX-U Structural Benchmark Instrumentation
[6] S.P. Gerhardt, et al., Rev. Sci. Instrum **82**, 103502 (2012)
[7] NSTX-U-RQMT-RD-012-00, NSTX-U Gas Delivery and Injection System Parameters

0: Scope

a. This document describes detailed requirements for plasma facing components in the area of gas fueling and diagnostic implementation for the CSFW, CSAS, IBDV, IBDH, OBD and upper/lower passive plates. It therefore supplements the PFC SRD [1] with specific implementation requirements.

b. Diagnostics used to monitor PFCs during/between discharges to ensure NSTX-U operations maintain heat flux to PFCs within SRD limits will be covered in a separate, future document.

c. Diagnostics to monitor neutral beam armor are not included in this document.

d. Diagnostic to monitor the RF limiter tiles are not included in this document.

1: Functions & Requirements

1.1: Function of Magnetics

1.1.1: Functions

a. Magnetics sensors are used in concert with analog integrators to measure the local magnetic field at the location of the sensor.

b. These sensors provide critical information for plasma shape and position control, and NSTX-U cannot operate without a sufficient (as determined by COG Physicist in Section 2.9) number of these sensors. Hence, three critical requirements are:

- Sufficient spatial resolution
- Sufficient spatial coverage
- Sufficient redundancy in case of sensor failure

c. Magnetic sensors mounted in PFCs come in the following varieties.

2D Mirnov Coils: These are small magnetic solenoids mounted within or beneath the tiles. For a 2D Mirnov, there are two solenoids wound on a single mandrel, with solenoid axes orthogonal to each other. [1]

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[1] There are two types of Mirnov sensors in use on NSTX-U. These are:

- The CSFW and IBDH/IBDV sensors are based on the drawing C-9D1010 and C-9D1365. These are referred to as "thick" mandrels below.
- The OBD Mirnov sensors are historically based on the "thin" mandrels as indicated in the drawing B-9D1466.

1D Mirnov Coil: The 1D Mirnov coil is mounted on the same mandrel as the 2D sensor, but with only a single winding.

Tilted Mirnov: The tilted Mirnov coil is standard 1D Mirnov sensor oriented to measure toroidal field, i.e. "tilted" 90 degrees with respect to the traditional Mirnov sensor orientation.

Halo Current Rogowski: The halo current rogowski is a specially constructed rogowski coil designed to function in a high temperature, high vacuum conditions under the CS tiles. They are mounted to the casing and oriented in the horizontal plane, in order to measure the vertical current.

The output voltage of a Rogowski is given by $V_{out} = \mu_0 A\,(N/L)(dI/dt)$, where:
(N/L) : Turn density, the NSTX-U legacy value for the CSC Rogowskis was 3000 turns/m
(dI/dt) : The time rate of change of the current linking the Rogowski
A : The cross-sectional area of the rogowski, the NSTX-U legacy value for the CSC Rogowskis was ~1.15 cm^2.

1.1.2: General Magnetics Requirements

a. All Mirnov coils must be compatible with the full bakeout and operations temperature that will occur at that location in the tile.[2]

b: If the present copper/omega-bond scheme is utilized for Mirnov coils, then the temperature of the Mirnov coils shall not exceed 500 C at any time during the plasma pulse or subsequent between-shot cooling period.

c: Use of the existing Mirnov coil design is encouraged but not required. Any new designs for Mirnov coils should attempt to match the effective loop area * turns of the existing sensors at those locations as best as possible. Mirnov coils may be mounted in tiles themselves as in the present design, or in structure immediately behind/beneath the tiles.

d. The tilt of the measurement axis of the Mirnov coin in the toroidal direction shall be < 2 degrees. [3]

[2] NSTX-U Mirnov coils are historical wound with bare copper on a Macor mandrel. High temperature cement is used to spatially stabilize the windings

[3] There is a ~3 T toroidal field in the vicinity of the CS. The vertical field is on order 0.75 T. The toroidal field pickup should be less than 1 part in 10, so that the the angles becomes atan(0.75/10/3)=1.5 degrees

1.2: Langmuir Probes

1.2.1: Function of Probes

a. Langmuir probes are electrodes, embedded within or between PFCs, but electrically isolated from the tile. A voltage is applied to the electrode, and current drawn from the plasma that is in contact with the electrode.

b. Time dependent measurement and interpretation of the current as a function of voltage, I(V), allows characterization of a range of plasma properties including the local time-evolving electron temperature, density and floating potential.

b. LPs are primarily used to support physics studies but also support operations by providing robust evidence of the plasma contacting PFCs. Ideally, all PFC regions which can be used for non-transient strike point or limiter location should be equipped with Langmuir probes: CSFW, CSAS, IBDV, IBDH and OBD. The shape of the density and temperature profiles in the plasma contact area are non-monotonic, requiring sufficient poloidal spacing (e.g. probes/mm) to meet a variety of physics goals.

c. Some special purpose LP designs are optimized for high-frequency response; these are referred to as “RF Langmuir Probes” below, and serve a purely research function

d. Because Langmuir probes are in direct contact with the plasma, they can fail. To avoid losing access to scientific opportunities, sufficient redundancy is necessary, determined with COG Physicist input.

1.2.2 General Probe Requirements

a: Langmuir probes should be integrated in the CSFW, IBDH, IBDV and OBD regions.

b. Langmuir probes may be embedded into the bulk tiles or between tiles or tile features (e.g. castellations)

c. The plasma facing part of the Langmuir probe must be made from carbon materials

d. Probe tips are not required to be mounted flush with surfaces, but if proud of the surface they must conform to the PFC Requirements for edge temperature limit (see 3.1 in [1]). In order to mimic a proud probe, it is preferable that flush-mounted probes have a shape that is elongated in the toroidal direction (*c.f.* NSTX High-Density Langmuir Probe Array or MIT “Rail Probes”).

e. A target density and temperature defines the allowable probe plasma-facing area assuming a simple current collection model, with a maximum current of 4 A based on existing electronics designs. The probe area should be 1.0e-5 m^2, and width should be < 1.5 mm based on estimates from the PFC requirements[4]. Consult with relevant COG identified in Section 2.9 if necessary .

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[4] The maximum heat flux according to the PFC requirements document is 14 MW/m^2 at 3.6 degrees angle of incidence. Assuming a plasma sheath-edge density of 1e21m^{-3}, the particle flux is

f. Probe body should be electrically isolated from the bulk/neighboring PFC to a voltage of 300 V.

g. Probes should not compromise the structural integrity of the PFC tile they are installed in for the range of temperatures expected during operations.

h. Langmuir probes absorb an increased amount of power flux relative to other plasma facing components due to the swept voltages. Heat fluxes of 1.5 times the nominal heat flux can be expected for a probe swept between -50V and +30V assuming a 9eV plasma with plasma potential at +30V. These are typical values.

i. The Langmuir probe profile should limit or eliminate direct line-of-sight from the probe insulator to the plasma (e.g. zig-zag features of High-Density Langmuir Probe Array probe tips).

1.3: Thermocouples

1.3.1 Function of Thermocouples

a. Thermocouples (TCs) are used for physics, operations and bake to diagnose the transient and time-averaged temperature of the PFCs.

- The TCs function to monitor the PFC temperature during the bake, as discussed in Section 2.2 and 3.2 of the Bakeout SDD [4]. These sensors were used to ensure compliance with the NSTX-U Safety Certificate for the 2015 bakeout, and will likely be used for a similar function in future bakeouts. They are also used to monitor the efficacy of the bakeout heating systems.
- The TCs function to monitor the temperature of the PFCs during plasma operations, when they are heated by interaction with the plasma.
- In high heat flux regions (IBDV, IBDH and OBD R1-2), the TCs function to quantify the energy input into regions of the PFCs for physics research and operations support.

b. Sensors are embedded into the tile with cables routed in channels cut into PFCs, mounted and strain-relieved to vacuum vessel components and attached to vacuum feed-throughs at various locations[5].

c. During coil operations interference due to electromagnetic interference is expected to prevent sensors from reliably reporting temperature.

1.3.2 General Thermocouple Requirements

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approximately 2.98e25 $m^{-2}s^{-1}$. The allowable probe area is 1.33e-5m^2. If the probe is 1.5mm wide, it should be no more than 9mm long to avoid excessive current collection in this scenario. Similar calculations for the plasma current collection for scenarios in tables 3.2.1, 3.3.1, 3.4.1, and 3.4.2 yield a maximum area of 1.03e-5 m^2.

[5] The drawings E-ED1324 and NSTX-345 can be used to ascertain the TC locations as deployed for the 2015 NSTX-U run campaign.

a: Integrated design of thermocouples in the HHF divertor PFCs (IBDH, IBDV and OBD R1-2) should be placed such that, integrated over the discharge, HHF divertor region and assuming axisymmetry, energies deposited of 100 kJ can be resolved from noise and interpretation uncertainty[6]. Consult with relevant COG identified in Section 2.9.

b. Thermocouples in all other PFCs should be located so they can represent the bulk tile temperature for diagnosing the bake on timescales of ~10 minutes.

c: Thermocouples are used as a cross-calibration check for the IR thermography. For this purpose, it is desired that one of the OBD, IBDV and IBDH tiles instrumented with a thermocouple on both the upper and lower divertor be within the FOV of the fast-IR cameras and wide-IR used for inner and outer strike point measurements. Table 1.3.2-1 describes these locations.

Table 1.3.2-1: Location of IR thermography field of views for localization of thermocouples.

Divertor Viewed	Toroidal Field of View	Drawing
Upper IBDV Fast IR	Center of Bay-I (planned)	(planned)
Upper IBDH/OBD R1-R2 Fast IR	Center of Bay-G	ECN not completed
Lower IBDV Fast IR	Center of Bay-I (planned)	(planned)
Lower IBDH/OBD R1-R2Fast IR	Center of Bay-H	E-9D11377
Lower Wide-Angle IR	Bay-I to Bay-G	E-9D11377

d. Integrated design of the HHF TCs should allow chosen type (e.g. Type K if selected) to remain functional in cases where PFC surface temperature exceeds surface allowable by 50%. Consult with relevant COG identified in Section 2.9.

e. Where spatial asymmetries are expected due to the nature of the heating system configuration (e.g. bake), TCs should be installed to assess the asymmetries.

1.4: Shunt Tiles

1.4.1: Functions

a: Shunt tiles are used to measure the current flowing from a tile to the backing structures. They are part of the machine instrumentation program, but are not a formal operations diagnostic.

[6] This is consistent with a noise floor of 0.2-0.3 MW/m^2 for a 5 second pulse with a narrow (e.g 2.5 cm) deposition region, either stationary or moved across the target.

b: Shunt tiles are tiles that are modified so that a low-resistance element resides between the tile bottom and the underlying surface. Steps are taken to ensure that this resistive element is the only electrical path between the PFC surface and the backing structure. [X]

c: signal wires propagate the voltage on the resistive element out of the vessel, where is is processed

1.4.2: Requirements

a: Strict attention must be paid that there are no electrically conducting paths provided by tile fastening hardware. Achieving this can mandate steps such as fabricating parts out of insulating materials, or putting ceramic coatings on metal parts.

b. The voltage on the tile surface, based on the resistance of the tile surface and the maximum halo current that tile can collect, must not exceed 5 V.

1.5: Fueling lines

1.5.1: Functions

a. Gas injection is used to provide fuel or impurities to the plasma to serve a range of operations and physics goals.

b. Neutral gas is ionized in the edge of the plasma near discrete gas injection locations and transported by the plasma throughout the chamber. There are cases in prior work that has demonstrated that the poloidal location of gas injection is important, thus NSTX-U features a range of high field side PFC, low field side main-chamber and divertor PFC gas injectors.

1.5.2: General Requirements

a. In-vessel gas tubing lines shall be made of 316 stainless steel or similar low-permeability , high temperature material.

b. PFCs need to modified to allow for back-surface routing of injection lines and front surface apertures/gaps to allow gas throughput. Metal portions of the injection lines need to be shielded from plasma interaction.

c. there are no additional requirements beyond NSTX-U-RQMT-SRD-003 for heat or particle flux from the gas/plasma interaction.

2: Diagnostics Requirements

2.1: General requirements

a: Tiles should provide for sufficient wire ways to enable all wires to reach their feedthroughs.

b: Any materials used should be compatible with an ultra-high vacuum environment, as approved by the PPPL Vacuum Materials Committee.

c: Non-ferritic materials should be used for all fasteners. SS316, A286, or Inconel are preferred. Magnetic permeability requirements shall be adhered to as per reference [3].

d. Diagnostics should be compatible with NSTX-U bakeout , but do not need to be compatible with the post-fabrication PFC bake (2.1.e in [1]).

e. In HHF regions (IBDV, IBDH and OBDR1-R2), diagnostic wires crossing between tiles at a gap should be suitably covered to avoid direct line of sight to plasma.

2.2: Inboard Vertical Target Diagnostics

2.2.1 General

a. All requirements are elaborated in Section 1 or below in this Section.

b. For the vertical target, the High Heat Flux (HHF) region is defined as |Z|<1.5 m. The Low Heat Flux (LHF) region is defined at |Z|>1.5 m.

2.2.2 Mirnov Sensors on the Vertical Target

a. 2D Mirnov sensors shall be located in approximately the locations indicated in Table 2.2.2-1, which is consistent with E-ED1324. Design deviations in the location of order 5 cm in height are acceptable, as are small variations in radius. Reductions in sensor count may be acceptable following consultation with the magnetics COG.

Table 2.2.2-1: Locations of 1D Mirnov sensors on the vertical target.

Type	Measurement Direction	Sensor Name	R	Z	Angle
2DM, thick	B_Z	2DMIBDVU1T	0.3940	1.3640	228
	B_R	2DMIBDVU1N			
2DM, thick	B_Z	2DMIBDVU2T	0.3940	1.4620	228.00
	B_R	2DMIBDVU2N			
2DM, thick	B_Z	2DMIBDVU3T	0.3940	1.5600	228.00
	B_R	2DMIBDVU3N			
2DM, thick	B_Z	2DMIBDVL1T	0.3940	-1.3640	237.00
	B_R	2DMIBDVL1N			
2DM, thick	B_Z	2DMIBDVL2T	0.3940	-1.4620	237.00
	B_R	2DMIBDVL2N			
2DM, thick	B_Z	2DMIBDVL3T	0.3940	-1.5600	237.00
	B_R	2DMIBDVL3N			
2DM, thick	B_Z	2DMIBDV2U2T	0.3940	1.4620	48.00
	B_R	2DMIBDV2U2N			
2DM, thick	B_Z	2DMIBDV2L2T	0.3940	-1.4620	57.00
	B_R	2DMIBDV2L2N			

2.2.3 Langmuir Probes on the Vertical Target

a. At least 6 probes should be installed in each of the upper and lower IBDV (*i.e.* 6 LPs upper and 6 LPs lower)

b. 5 probes should be installed in the HHF region, and can be at more than one toroidal location, under the following guidance:

- There shall be at least three probes at a fixed toroidal angle, distributed uniformly over the HHF region. This shall be referred to as the "primary" location.

- The probes at the other locations should be placed at intermediate vertical positions, such that they can be combined with the primary array under the assumption of axi-symmetry to make a higher spatial resolution array.

c. 1 probe should be installed in the LHF region

d. The toroidal locations do not need to match in the upper/lower IBDV

e. The distribution in Table 2.2.3-1 is recommended to satisfy this requirement.

Table 2.2.3-1: Recommended Langmuir Probe distribution on the vertical target

Upper Lower	Feedthrough Organ Pipe Angle (Left Handed Coordinates)	Feedthrough Organ Pipe Bay	# Total	# HHF	# LHF
Upper	30	A/B	4	4	0
Upper	360	A/L	3	2	1
Lower	75	C	3	2	1
Lower	360	A/L	4	4	0

2.2.4 Thermocouples on the Vertical Target

a. At least 11 total TCs should be installed in each of the upper and lower IBDV, with at least 2 in the LHF region and 10 in the HHF region.

b. The HHF TCs should be installed under the following guidance:

- At least two toroidal angles should be instrumented
- At one toroidal angle, at least 5 poloidal locations should be instrumented, distributed evenly over the HHF region. This is the “primary” array.
- At the other toroidal angles, the poloidal distribution should attempt to be at intermediate locations relative to the primary array, such that a higher effective spatial resolution profile can be measured on the vertical target under the assumption of axisymmetry.

c. The two LHF TCs should be at the same toroidal angle.

d. The toroidal locations do not need to match in the upper/lower IBDV

e. The distribution in Table 2.2.4-1 is recommended to satisfy this requirement.

Table 2.2.4-1: Recommended TC distribution on the vertical target

Upper/ Lower	Feedthrough Organ Pipe Angle (Left Handed Coordinates)	Feedthrough Organ Pipe Bay	# Total	TC Bay	# HHF	# LHF
Upper	90	C/D	6	C	6	0
Upper	120	D/E	1	E	1	0
Upper	330	K/L	2	K	2	0
Upper	360	L/A	2	A	0	2
Lower	75	C	3	C	3	1
Lower	255	H/I	5	I	5	0
Lower	330	K/L	4	K	2	2

2.2.5 Halo Current Rogowskis on the Vertical Target

a. Halo current Rogowskis shall be installed as per Table 2.2.5-1. Variations in height on order ~10 cm are acceptable, provided the the two Rogowskis on each target are spaced by the majority of the height of the vertical target.

Table 2.2.5-1: Halo current rogowski sensors on the vertical target

Sensor	2015 NSTX-U Vertical Position
ROGCSCL1	Lower Row 4 Tile Row in legacy E-ED1324
ROGCSCL2	Lower Row 2 Tile Row in legacy E-ED1324
ROGCSCU1	Upper Row 4 Tile Row in legacy E-ED1324
ROGCSCU2	Upper Row 2 Tile Row in legacy E-ED1324

b. The previous requirement to implement a segmented rogowski at the L1 location is eliminated.

c. The sensitivity of the Rogowskis should be on order 3000*(0.00015) = 0.45 turns-meters. The cross-sectional area may be adjusted to accommodate the mechanical configuration.

2.3: Diagnostic Requirements for the Horizontal Target

2.3.1: General

a. For the horizontal target, the High Heat Flux (HHF) region is defined as R> 0.47 m. The Low Heat Flux (LHF) region is defined at R<0.47 m.

b: PFC holes centered around the organ pipes as per E-DC1324 shall be included at the bays indicated in Table 2.3.1-1:

Table 2.3.1-1: Locations of PFC through-holes above organ pipes to retain

Upper/Lower	Bay	Angle (Left Handed Coordinates)	Intended Use
Upper	L	345	MGI #3
Lower	F/G	180	MGI #1
Lower	L	345	Spect #1
Lower	I	255	Spect #2

c: The organ pipe access holes should be of dimension matching the PFC holes in the initial NSTX-U design (see E-ED1298), with the critical caveat that they should not extend radially beyond R=47 cm.

d: The holes at the locations in Table 2.3.2-2 shall be eliminated.

Table 2.3.2-2: Locations of PFC through-holes above organ pipes to eliminate compared to the 2015 installation

Upper/Lower	Bay	Angle (Left Handed Coordinates)	Intended Use
Lower	H/I	240	Spect #3
Lower	A	15	MGI #2

2.3.2: Mirnov Sensors on the Horizontal Target

a: Two axis magnetic field sensors (“2D Mirnovs”) should be installed in the horizontal target, with the base design as per Table 2.3.2-1 and drawing E-ED1324. Design deviations in location of order ~5 cm in toroidal and radial locations are acceptable. Reductions in sensor count may be acceptable following consultation with the magnetics COG.

Table 2.3.2-1: Mirnov sensors on the horizontal target

Type	Measurement Direction	Sensor Name	R	Z	Angle
2DM, thick	B_R	B_2DMIBDHL6T	0.4728	-1.6490	236.25
	B_Z	B_2DMIBDHL6N			
2DM, thick	B_R	B_2DMIBDHU5T	0.4728	1.6490	228.75
	B_Z	B_2DMIBDHU5N			
2DM, thick	B_R	B_2DMIBDHU6T	0.4728	1.6490	236.25
	B_Z	B_2DMIBDHU6N			
2DM, thick	B_R	B_2DMIBDHL5T	0.4728	-1.6490	228.75
	B_Z	B_2DMIBDHL5N			
2DM, thick	B_R	2DMIBDH2U6T	0.4728	1.6490	48.75
	B_Z	2DMIBDH2U6N			
2DM, thick	B_R	2DMIBDH2L6T	0.4728	-1.6490	48.75
	B_Z	2DMIBDH2L6N			

2.3.3: Langmuir Probes on the Horizontal Target

a. At least 7 probes should be installed in each of the upper and lower IBDH.

b. 6 probes should be installed in the HHF region, and can be at more than one toroidal location, under the following guidance:

- There shall be at least 4 probes at a fixed toroidal angle, distributed uniformly over the HHF region. This shall be referred to as the “primary” location.
- The probes at the other locations should be placed at intermediate vertical positions, such that they can be combined with the primary array under the assumption of axi-symmetry to make a higher spatial resolution array.

c. 1 probe should be installed in the LHF region

d. The toroidal locations do not need to match in the upper/lower IBDH

e. The distribution in Table 2.3.3-1 is recommended to satisfy this requirement

Table 2.3.3-1: Horizontal target LP allocation

Feedthrough Angle **(Left Handed Coordinates)**	Feedthrough Bay	Total # of Sensors	# HHF Sensors	# LHF Sensors
180, Upper	F/G	5	4	1
360, Upper	L/A	2	2	0
105, Lower	D	5	4	1
360, Lower	L/A	2	2	0

2.3.4: Thermocouples on the Horizontal Target

a. The fast-TC in the upper and lower divertors, as shown in ED1324 are no longer required.

b. At least 12 TCs should be installed in the high heat flux region under the following guidance:

- At least two toroidal angles should be instrumented
- At one toroidal angle, at least 5 radial locations should be instrumented, distributed evenly over the HHF region. This is the “primary” array.
- At the other toroidal angles, the radial distribution should attempt to be at be at intermediate locations relative to the primary array, such that a higher resolution radial profile can be measured under the assumption of axisymmetry.

c. At least 2 TCs should be installed in the LHF region at a single toroidal location, forming a coarse radial array.

d. The toroidal locations do not need to match in the upper/lower IBDH

e. The distribution in Table 2.3.4-1 is recommended is recommended to satisfy this requirement.[7]

[7] This horizontal target TC distribution can be achieved with at most three HHF tile types, corresponding to 5, 4, and 3 TC locations. Alternatively, a single base TC tile design can be implemented with many potential TC locations, with only specific locations populated in any given tile.

Table 2.3.4-1: Horizontal target TC allocation

Upper/Lower	Feedthrough Organ Pipe Angle (Left Handed Coordinates)	Feedthrough Organ Pipe Bay	# Total	TC Bay	# HHF	# LHF
Upper	45	B	5	B	5	0
Upper	315	K	4	I	4	0
Upper	330	K/L	3	K	5	0
Upper	360	L/A	2	A	0	2
Lower	120	E/D	2	E	2	0
Lower	255	H/I	4	H	4	0
Lower	315	K	2	K	0	2
Lower	330	K/L	5	L	5	0

2.4 Outboard Divertor Diagnostic Requirements

2.4.1 General

a: The diagnostic layout should remain similar to that in NSTX-345 to the greatest extent possible.

2.4.2 Mirnov Sensors on the Outboard Divertor

a. Locations of 2D Mirnov coils shall be approximately as in Table 2.4.2-1. Sensors should be reinstalled at these locations, though small (~3-5cm) design shifts poloidally and toroidally are acceptable.

Table 2.4.2-1: Locations of 1D Mirnov sensors on the OBD.

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle
2DM, thin	21.5	B_2DMOBDL1T	0.6816	-1.6153	217.5
2DM, thin	111.5	B_2DMOBDL1N			
2DM, thin	21.5	B_2DMOBDL2T	0.7900	-1.5726	217.5

2DM, thin	111.5	B_2DMOBDL2N			
2DM, thin	21.5	B_2DMOBDL3T	0.9055	-1.5271	217.5
2DM, thin	111.5	B_2DMOBDL3N			
2DM, thin	21.5	B_2DMOBDL4T	1.0211	-1.4816	217.5
2DM, thin	111.5	B_2DMOBDL4N			
2DM, thin	21.5	B_2DMOBDL5T	1.1366	-1.4361	217.5
2DM, thin	111.5	B_2DMOBDL5N			
2DM, thin	-21.5	B_2DMOBDU1T	0.6816	1.6153	217.5
2DM, thin	68.5	B_2DMOBDU1N			
2DM, thin	-21.5	B_2DMOBDU2T	0.7900	1.5726	217.5
2DM, thin	68.5	B_2DMOBDU2N			
2DM, thin	-21.5	B_2DMOBDU3T	0.9055	1.5271	217.5
2DM, thin	68.5	B_2DMOBDU3N			
2DM, thin	-21.5	B_2DMOBDU4T	1.0211	1.4816	217.5
2DM, thin	68.5	B_2DMOBDU4N			
2DM, thin	-21.5	B_2DMOBDU5T	1.1366	1.4361	217.5
2DM, thin	68.5	B_2DMOBDU5N			

2.4.3 Langmuir Probes on the Outboard Divertor

2.4.3.1: Standard Langmuir Probes

Number and approximate distribution of Langmuir probes deployed in the regions occupied by Rows 3-5 and the geometric location formerly occupied by rows 1 and 2 should be replicated from the original NSTX-U distribution [2].

a. In the region formerly occupied by OBD R1 and R2, a total of nine Langmuir probes should be distributed uniformly in the poloidal direction, in at most two toroidal locations.
b. In the region of OBD R3 and R4, eight Langmuir probes should be distributed uniformly in the poloidal direction in at most two toroidal locations.
c. No Langmuir probes are located in OBD R5.
d. Probe distribution should be duplicated on each divertor (upper/lower), but do not need to be deployed at the same toroidal locations.
e. It is desired to locate the probes between Bay-J and Bay-K as per [2]

2.4.3.2: RF Langmuir Probes

RF Langmuir probes shall be installed in a fashion similar to the design used for the FY16 run campaign.

2.4.4 Thermocouples on the Outboard Divertor

a. At least 24 TCs should be installed in the outboard divertor with at least 12 in OBD R1-R2, 8 in OBD R3, 2 in OBD R4 and 2 in OBD R4.

b. At least 12 TCs should be installed in the OBD R1-R2 region under the following guidance:

- At least two toroidal angles should be instrumented
- At one toroidal angle, at least 5 radial locations should be instrumented, distributed evenly. This is the “primary” array.
- At the other toroidal angles, the radial distribution should attempt to be at be at intermediate locations relative to the primary array, such that a higher resolution radial profile can be measured under the assumption of axisymmetry.
- At least one toroidal angle should correspond to TCs installed in R3-R5 under (b) and (c)

c. At least 8 TCs should be installed in the OBD R3, distributed uniformly in the toroidal direction.

d. At least 2 TCs should be installed in each of the OBD R4 and R5 tiles at two toroidal locations where OBD R3 TCs are located, away from any large diagnostic gaps.

e. These distributions should be applied to each of the upper and lower divertors. However, the toroidal locations do not need to match in the upper/lower OBD.

2.4.5: Shunt Tiles on the Outboard Divertor

a. If the revised fixturing design permits the installation of shunt tiles in the outboard divertor, then they should be reinstalled at the locations indicated in NSTX-345.

2.5: CSAS Diagnostic Requirements

2.5.1: General

a: The CS tiles shall have the diagnostics as indicated in drawing E-D1324.

b: Provision shall be made for diagnostic and gas tubing wireways

2.5.2: Magnetics on the CSAS

a. The CSAS is not required to have magnetic sensors.

2.5.3: Langmuir Probes on the CSAS

a. The CSAS is not required to have probes.

2.5.4: Thermocouples on the CSAS

a. 4 TCs should be installed in each of the upper and lower CSAS.

b. 4 TCs should be installed at at least 2 different poloidal locations in at least 2 different toroidal locations.

c. The toroidal locations do not need to match in the upper/lower CSAS.

2.6: Center Stack First Wall (C) Tile Diagnostics and Gas Interface

2.6.1: General

a: Provision shall be made for diagnostic wireways as appropriate.

2.6.2: Mirnov Coils on the CSFW

a. Mirnov coils shall be located at the locations indicated in Tables 2.6.2-1 through 2.6.2-4. Shifts on order of 1-2 cm are acceptable if desired to improve engineering.

b. These Mirnov coils should be designed such that the normal vector to the large face of the coil should point in the pure radial direction.

c. The historical requirement that some in-vacuum cabling on sensors in the vicinity of Bay B use metal-jacketed cabling is now eliminated.[8] However, that cabling may be retained should it prove convenient.

d. The tilted Mirnov sensors labelled 9, 10, 12, and 13 in the 2015 incarnation of NSTX-U are not included. Their pins are repurposed to other diagnostics. The sensors may be abandoned in place should that prove convenient.

[8] This substantial complication was based on the CHI program, and is now removed.

Table 2.6.2-1: Locations of 1D Mirnov sensors on the CSFW.

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle
1D Mirnov, thick	B_z	1DMCSCL1	0.302	-0.033	232.50
1D Mirnov, thick	B_z	1DMCSCL2	0.302	-0.136	232.50
1D Mirnov, thick	B_z	1DMCSCL3	0.302	-0.272	232.50
1D Mirnov, thick	B_z	1DMCSCL4	0.302	-0.408	232.50
1D Mirnov, thick	B_z	1DMCSCL5	0.302	-0.544	232.50
1D Mirnov, thick	B_z	1DMCSCL6	0.302	-0.680	232.50
1D Mirnov, thick	B_z	1DMCSCU2	0.302	0.136	232.50
1D Mirnov, thick	B_z	1DMCSCU3	0.302	0.272	232.50
1D Mirnov, thick	B_z	1DMCSCU4	0.302	0.408	232.50
1D Mirnov, thick	B_z	1DMCSCU5	0.302	0.544	232.50
1D Mirnov, thick	B_z	1DMCSCU6	0.302	0.680	232.50
1D Mirnov, thick	B_z	1DMCSC2L6	0.302	-0.680	52.50
1D Mirnov, thick	B_z	1DMCSC2L4	0.302	-0.408	52.50
1D Mirnov, thick	B_z	1DMCSC2L2	0.302	-0.272	52.50
1D Mirnov, thick	B_z	1DMCSC2L1	0.302	-0.033	52.50
1D Mirnov, thick	B_z	1DMCSC2U2	0.302	0.136	52.50
1D Mirnov, thick	B_z	1DMCSC2U4	0.302	0.408	52.50
1D Mirnov, thick	B_z	1DMCSC2U6	0.302	0.680	52.50

Table 2.6.2-2: Locations of 2D Mirnov sensors on the CSFW.

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle
2DM, thick	B_Z	2DMCSCL1T	0.3020	-0.8170	232.50
	B_R	2DMCSCL1N			
2DM, thick	B_Z	2DMCSCL2T	0.3020	-0.9530	232.500
	B_R	2DMCSCL2N			
2DM, thick	B_Z	2DMCSCU1T	0.3020	0.8170	232.500
	B_R	2DMCSCU1N			
2DM, thick	B_Z	2DMCSCU2T	0.3020	0.9530	232.500
	B_R	2DMCSCU2N			
2DM, thick	B_Z	2DMCSC2L2T	0.3020	-0.9530	52.500
	B_R	2DMCSC2L2N			
2DM, thick	B_Z	2DMCSC2U2T	0.3020	0.9520	52.500
	B_R	2DMCSC2U2N			

Table 2.6.2-3: Locations of Tilted Mirnov sensors on the CSFW.

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle
1D Mirnov, thick	B_T	1DM-ROT-1	0.3017	-0.1360	82.5000
1D Mirnov, thick	B_T	1DM-ROT-2	0.3017	-0.1360	142.5000
1D Mirnov, thick	B_T	1DM-ROT-3	0.3017	-0.1360	202.5000
1D Mirnov, thick	B_T	1DM-ROT-4	0.3017	-0.1360	292.5000
1D Mirnov, thick	B_T	1DM-ROT-5	0.3017	-0.1360	352.5000

Table 2.6.2-4: Locations of Tilted Mirnov sensors on the CSFW.

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle
B_z	B_z	1DMCSCM7	0.3017901	0	292.5
B_z	B_z	1DMCSCM8	0.3017901	0	322.5
B_z	B_z	1DMCSCM11	0.3017901	0.0328676	52.5
B_z	B_z	1DMCSCM14	0.3017901	0	172.5
B_z	B_z	1DMCSCM15	0.3017901	0	202.5
B_z	B_z	1DMCSCM16	0.3017901	0.0328676	232.5

2.6.3: Langmuir Probes on the CSFW

a. The CSFW LPs shall be installed as indicated in Table 2.6.3-1.

Table 2.6.3-1: CSFW LP Locations[9]

PFC Row From E-ED1324	Feedthrough Port
15	75, Lower
18	75, Lower
21	75, Lower
11	90, Upper
9	90, Upper
7	90, Upper

2.6.4: Thermocouples on the CSFW

The CSFW TC layout from E-ED1324 should be duplicated with the following modifications

[9] The previous LP in tile row 13 shown in E-ED1324 is eliminated.

a. Thermocouples on the CSFW shall be at the following locations.

Table 2.6.4-1: CSFW TC Locations

Row from Legacy E-ED1324	**Wire Exit Organ Pipe Bay**
7	E/D Upper
8	E/D Upper
9	E/D Upper
10	E/D Upper
11	E/D Upper
12	E/D Upper
13	E/D Upper
14	E/D Upper
15	E/D Lower
16	E/D Lower
17	E/D Lower
18	E/D Lower
19	E/D Lower
20	E/D Lower
21	E/D Lower

b. The TC CSFW midplane toroidal array from the 2015 Upgrade Installation shall be abandoned if favor of increased TC coverage elsewhere. If convenient, the sensors can be abandoned in the tiles, but disconnected and secured at the feedthroughs.

2.6.4: Shunt Tiles on the CSFW

a. Shunt tiles shall be installed in the floating tiles, at the locations indicated in Table 2.6.4-1.

Table 2.6.4-1: Locations of shunt tiles on the CSFW.

Row (from E-ED1324)	Toroidal Angle (Left Handed Coordinates)
8	322
12	322
16	322
20	322
8	292
12	292
16	262
20	262
8	202
12	202
16	202
20	202
16	82
20	82
8	22
12	22
16	22
20	22

2.7 Primary Passive Plate PFC Diagnostic Requirements

a: The diagnostic layout should remain as in NSTX-345.

2.8 Secondary Passive Plate PFC Diagnostic Requirements

a: The diagnostic layout should remain as in NSTX-345.

2.9 Diagnostic Contacts

The following individuals may be used as contacts for PFC diagnostics

Langmuir Probes: Mike Jaworski and Robert Lunsford
Magnetic Diagnostics: Stefan Gerhardt
Thermocouples: Joe Petrella, Matthew Reinke and Paul Sichta

3: Fueling Requirements:

The PFCs must accommodate and integrate methods of gas delivery, which fall into three categories.

3.1: CS Gas Fuelling

The CS Gas Fuelling in the initial NSTX-U design is indicated by the drawings E-ED1324, E-DC1605 and further drawings indicated therein.

a: Three fueling lines, indicated in Table 3.1-1, with associated puff injectors, should be retained in the revised designs.

Table 3.1-1: Required CS fuelling injectors

Vertical Location of Outlet	**Toroidal Location of Organ Pipe**	**Gas Line**	Drawing
Shoulder	105 degrees	0.25 ”OD x 0.02 wall	E-DC1607
~11” Above Midplane[10]	255 degrees	0.25” OD x 0.02” wall	E-DC1606
Midplane	75 degrees	0.125” OD x 0.016” wall	E-DC1608

Table 3.1-2: Optional CS fuelling injectors

Vertical Location of Outlet	**Toroidal Location of Organ Pipe**	**Gas Line**	Drawing
Shoulder	285 degrees	0.125” OD x 0.016” wall	E-DC1752

[10] Note that the 255 degree midplane injector outlet location is located ~11 inches above the midplane, so that the light cloud produced by the puff does not interfere with the MPTS measurement.

b. The fourth injector, indicated in Table 3.1-2, may be retained if it can be made compatible with the tubing for the upper private flux region injector using the same organ pipe.

c: The diameters of the gas lines listed in Table 2.9.1 should be preserved, and it is likely appropriate to retain the allocation of organ pipes for this usage.

d: The outlet locations should also stay at approximately the previous locations, though small (1”-3”) changes in the location can likely be tolerated with the exception of a movement of the 255 degree injector toward the midplane.

e: The routing behind the PFCs should have the minimum reasonable number of bends, though there is no mandate to retain the previous routing.

f: System pressures and plenum sizes can be found in Ref. [7].

3.2: OBD Fuelling

Divertor gas injectors were installed in the NSTX-U lower outer divertor, at Bays C & I. These systems are described in drawings E-EA3009 & E-EA3010.

a: These fueling lines should be maintained as the PFCs evolve.

b: Provision in the Row-1-equivalent tiles should be made for allowing this gas to enter the plasma volume at approximately the same location as the initial implementation.

If the Row-1-equivalent design has a mechanism to hide/avoid front-surface mounting holes, then this gas inlet need not be accomplished via addition top-surface orifice. For instance, gas could be allowed to flow through one of the existing mounting holes, or potentially via a horizontal orifice directing gas through the remnant of the CHI gap.

c. System pressures and plenum sizes can be found in Ref. [7].

3.3: Private Flux Region Fueling

a: To assist in mitigating large heat fluxes on the IBDV and IBDH, gas fueling lines shall be installed in the private flux region (PFR) (i.e. the region between the inner and outer strike-points). This is generally within the region defined as R<0.48 and |Z|>1.5.

b: These fuelling lines should be implemented at both the top and bottom; these gas orifices need not be at the same toroidal locations.

c: Suggested organ pipes for gas delivery are indicated in Table. 3.3-1. If feasible, the injector at

Table 3.3-1: Suggested organ pipes for private flux region gas feeds

Upper or Lower	Bay	Angle (Left Handed Coordinate)
Upper	J	285
Lower	A	15

d. In-vessel gas delivery tubing should be the largest possible diameter consistent with space constraints.

e: Piezo-electric valve with PCS control shall be used to control the fuelling.

f. System pressures and plenum sizes can be found in Ref. [7].

g: As a minimum requirement, a single gas delivery orifice, at a single toroidal location each of top and bottom, shall be implemented. It is desirable, but not required, to generate designs that lead to a more toroidally uniform distribution of gas. [11]

4: Organ Pipe Usage

a. Organ pipe usage in NSTX-U from 2015 is indicated in Tables 4.1 and 4.2.

b. Angles use the left handed coordinate system from E-ED1324.

c. Bold in the 9D1095 Sheet column indicates that TC wiring is used for the field cable

d. Tables 4.3 and 4.4 indicate the proposed configuration for NSTX-U Recovery. Red cells indicated changes.

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[11] To illustrate potential solutions for this requirement, the following solutions would satisfy the requirement:

Option 1: Gas is puffed into an organ pipe, through which it propagates to the backing structure for the PFCs. The inter-tile/module/block spacing is used to leak gas into the PFR at locations above the organ pipe locations. Mounting plates and PFCs that cover these regions should be perforated resulting in a total area of >=0.5 cm^2.

Option 2: A ~½" OD pipe is run up the organ pipe and to an orifice location at the low heat flux corner of the IBDH/IBDV. A hole is placed in the PFC surface at that location, allowing gas to enter the PFR.

Table 4.1: Upper Organ Pipes (NSTX-U 2015)

		Thermocouples					# Magnetics + Shunt Tiles	# Langmuir Probes		
Angle	9D1095 Sheet	IBDH	IBDV	#CSAS	#CSFW Vertical	CSFW Toroidal		IBDH	IBDV	CSFW
15	106						4			
30	101						5			
45	65	1				3	4			
75	Midplane Injector									
90	70	1								4
105	Shoulder Injector									
120	90				8					
180	52						4			
225	105						8			
240	130						6			
255	Midplane Injector									
270	115						5			
285		Shoulder Injector								
315	95	1		4		2	1			
330	51	3	2				4			
345	MGI #3									
360	55		2					2	3	

Table 4.2: Lower Organ Pipes (NSTX-U 2015)

		Thermocouples					# Magnetics + Shunt Tiles	# Langmuir Probes		
Angle	9D1095 Sheet	IBDH	IBDV	#CSAS	CSFW Vertical	CSFW Toroidal		IBDH	IBDV	CSFW
15	MGI #2									
30	100						5			
45	80						7			
75	60	1					2		3	3
90	132	1					5			
105	82						3	3		
120	75				7	1				
180	MGI #1									
225	85						9			
240	Spect #3									
255	Spect #2									
270	120						9			
285	125						9			
315	81	1		4			3			
330	50	3	4				2			
345	Spect #1									
360	110						2	2	3	

Table 4.3: Upper Organ Pipes (NSTX-U, Recovery)

		Thermocouples					# Magnetics + Shunt Tiles	# Langmuir Probes		
Angle	9D1095 Sheet	IBDH	IBDV	#CSAS	#CSFW Vertical	CSFW Toroidal		IBDH	IBDV	CSFW
15	106						4			
30	101						5		4	
45	65	5				0	4			
75	Midplane Injector									
90	70	0	6							3
105	Shoulder Injector									
120	90		1		8					
180	52						4	5		
225	105						8			
240	130						6			
255	Midplane Injector									
270	115						5			
285	Private Flux Region Fueling Gas Feed+Shoulder Injector if Can be Accommodated									
315	95	4	0	4		0	1			
330	51	3	2				4			
345	MGI #3									
360	55	2	2					2	3	
Tot	-	14	11	4	8	0		7	3	3

Table 4.4: Lower Organ Pipes (NSTX-U, Recovery)

		Thermocouples					# Magnetics + Shunt Tiles	# Langmuir Probes		
Angle	9D1095 Sheet	IBDH	IBDV	#CSAS	CSFW Vertical	CSFW Toroidal		IBDH	IBDV	CSFW
15	Private Flux Region Fueling Gas Feed									
30	100						5			
45	80						7			
75	60	0	3				0		3	3
90	132	0					5			
105	82						3	5		
120	75	2			7	0				
180	MGI #1									
225	85						9			
240	Spect 3									
255	new	4	5							
270	120						9			
285	125						9			
315	81	2		4			3			
330	50	5	4				0			
345	Spect #1									
360	110						2	2	4	
Tot.	-	13	12	4	7	0		7	6	3