National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

REQUIREMENTS DOCUMENT

PFC Diagnostics and Fueling

NSTX-U-RQMT-RD-004-01

February 12 , 2019

Stefan Gerhardt Digitally signed by Stefan Gerhardt DN: cn=Stefan Gerhardt, o=Physics, ou=PPPL, email=sgerhard@pppl.gov, c=US Date: 2019.02.12 08:42:35 -05'00'

Preparer: Stefan Gerhardt, Systems Engineering and Integration

G Douglas Loesser Digitally signed by G Douglas Loesser Date: 2019.02.13 13:03:16 -05'00'

Reviewed: Doug Loesser, VV&IH RE

Dang Cai Digitally signed by Dang Cai DN: cn=Dang Cai, o=PPPL, ou=Engineering, email=dcai@pppl.gov, c=US Date: 2019.02.13 13:30:36 -05'00'

Reviewed: Dang Cai, Vacuum and Fueling RE

Robert Ellis Digitally signed by Robert Ellis Date: 2019.02.13 13:39:47 -05'00'

Reviewed: Robert Ellis, Diagnostics RE

PAUL SICHTA Digitally signed by PAUL SICHTA Date: 2019.02.13 15:12:38 -05'00'

Reviewed: Paul Sichta, Control and Data Technical Authority

Brentley C. Stratton Digitally signed by Brentley C. Stratton Date: 2019.02.13 15:19:48 -05'00'

Reviewed: Brent Stratton, Diagnostics Technical Authority

Yuhu Zhai Digitally signed by Yuhu Zhai Date: 2019.02.14 11:01:32 -05'00'

Approved: Yuhu Zhai, NSTX-U Project Engineer

Change Record

Revision	Date	Description of Change
0	12/20/17	Initial Release
1	2/12/19	Changed 3.4.3.1-a to poloidal locations to be 'different' instead of 'uniformly distributed' as the latter would drive new tile designs due to conflicts with shear-pin and t-bar access. Exact uniformity not required for physics.
		Added the Control and Data and Diagnostics Technical Authorities to the signature list.
		Substantial modifications to 3.7 and 3.8 in order to ensure proper measurements are available for the Recovery Project Bakeout KPP
		Adjusted 3.2.2a to have additional freedom in the toroidal angle of Mirnov sensors.
		Adjustments to the 2D Mirnov Layout on the Vertical Target as specified in Table 3.2.2-1.
		Added Section 2.6
		Updated 2.3.1a to note that thermocouples are also required for the bakeout KPP of the recovery project.
		Converted bulleted lists to tables, resulting in Tables 3.2.3-1, 3.2.4-1, 3.3.3-1, 3.3.4-1, 3.4.3-1, 3.4.4-1.
		Removed excessive digits on the tables that specify the locations of magnetic sensors.
		Added 1f, defining data acquisition and archival to be out of scope.
		Added 1g, noting that poloidal flux loops are critical but not in scope for the present document.
		Added 2.3.2f regarding electrical isolation of thermocouples
		Modified 3.2.1b to define the LHF and HHF tiles on the IBDV in terms of the tile types (castellated or T-bar mounted), rather than by absolute spatial coordinates. This distinction is based on the design presented at the September 2018 FDR.
		Modified 3.3.1a to define the LHF and HHF tiles on the IBDH in terms of castellations, rather than by absolute spatial coordinate. This distinction is based on the design presented at the September 2018 FDR.
		Updated Tables 3.3.1-1 and 3.3.1-2
		Added numerous footnotes explaining the meaning of acronyms
		Voided 3.3.3c

References

[1] NSTX-U-RQMT-SRD-003, *Plasma Facing Components System Requirements Document*
[2] NSTX-U-RQMT-SRD-011, *Diagnostics System Requirements Document*
[3] NSTX-CRIT-0001-02, *NSTX Structural Design Criteria*
[4] NSTX-U-SDD-BAKE, *Bakeout System Design Description*
[5] NSTX-U-RQMT-RD-003, *NSTX-U Disruption Analysis Requirements*
[6] NSTX-U-RQMT-RD-010, *NSTX-U Magnetic Permeability Requirements*
[7] NSTX-345 Previous (2013) PFC Diagnostics and Gas Injection Layout for Upper and Lower Outboard Divertor and Passive Plates
[8] NSTX-U-RQMT-RD-012, *NSTX-U Gas Delivery and Injection System Parameters*

1: Scope

a. This document describes detailed requirements for plasma facing components in the areas of gas fueling and diagnostic implementation for the CSFW[1], CSAS[2], IBDV[3], IBDH[4], OBD[5] and upper/lower passive plates. It therefore supplements the PFC[6] SRD [1] and Diagnostics SRD [2] 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 the neutral beam armor are not included in this document.

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

e. For the purpose of estimating PFC diagnostics sensor counts in this document, castellated tiles are assumed to be used for the high heat flux regions of the IBDV, IBDH, and OBDR1-R2 regions. The assumed number of castellations in the poloidal direction for each region is indicated by Table 1-1.

Table 1-1: Number of castellations in the poloidal direction for each region.

Region	# of Castellations in the Poloidal Direction in High Heat Flux Regions	# of Tiles or Constellations in the Low Heat Flux Regions
IBDV	8	1
IBDH	4	1
OBDR1-R2	7	-

f. Data acquisition and archiving requirements are outside the scope of this document.

g. Poloidal flux loops are also cricitial magnetic sensors for the operation of NSTX-U. However, these sensors are not mounted within tiles, and are therefore excluded from this document.

---

1 CSFW(Center Stack First Wall): The narrow section of the center stack casing on either side of the midplane.

2 CSAS (Center Stack Angles Section): The portions of the casing, top and bottom, connecting the smaller radius CSFW with the larger radius IBDV.

3 IBDV (Inboard Divertor Vertical): The wider portions of the center stack casing, top and bottom, immediately adjacent to the PF-1a coil. The inner magnetic strikepoint often lands on the tiles mounted to the IBDV, and so many of these tiles are designed for high heat fluxes.

4 IBDH (Inboard Divertor Horizontal): The portions of the center stack casing, top and bottom, made up of the large horizontal flange, top and bottom. This region is often exposed to heat flux from the outer magnetic strikepoint, and so the tiles mounted there are designed for high heat fluxes.

5 OBD (Outboard Divertor): The regions on the top and bottom of the vacuum vessel, between the IBDH and the passive plates. This region historically had five tiles rows. In the new PFC design, the former rows 1 and 2 are combined into a single row, often called OBD R1-R2. These first two rows are designed to handle high heat fluxes. The outer three rows, rows 3-5, are designed for more modest heat flux handling.

6 PFC (Plasma Facing Component): Graphite tiles line most of the interior surfaces of the device; these are the primary plasma facing components on NSTX-U. These protect the underlying metallic structures from damage due to exposure to the plasma, while also preventing the medium and high-Z components of the metals from contaminating the plasma.

2: Functions & Requirements

2.1: Magnetics

2.1.1: Functions

a. Magnetics sensors are used in conjunction with analog integrators to measure the local magnetic field at the location of the sensor [2].

b. These sensors provide critical information for plasma shape and position control, and NSTX-U cannot operate without a sufficient number (as determined by COG Physicist in Section 2.9) 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 coil, there are two solenoids wound on a single mandrel, with the solenoid axes orthogonal to each other. [7]

1D Mirnov Coil: The 1D Mirnov coil is mounted on the same mandrel as the 2D sensor, but with only a single winding.[8]

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

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

The output voltage of a Rogowski coil 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 Rogowski coils was 3000 turns/m
(dI/dt) : The time rate of change of the current linking the Rogowski coil

---

[7] There were two types of 2D Mirnov sensors mounted inside tiles on NSTX-U on 2015. These are:

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

[8] A different style of 1D sensor, known as a "Large 1D Mirnov" is mounted between and behind the passive plates, and to the vessel wall.

A : The cross-sectional area of the rogowski, the NSTX-U legacy value for the CSC Rogowskis was ~1.15 cm^2.

2.1.2: General Magnetics Requirements

a. All Mirnov coils and Rogowski sensors must be compatible with the full bakeout and operations temperature that will occur at the location of the sensor in the tile.[9]

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 closely 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 coil in the toroidal direction shall be < 2 degrees. [10]

2.2: Langmuir Probes

2.2.1: Function of Probes

a. Langmuir probes (LPs) are small electrodes, embedded within or between PFC tiles, 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. [2]

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. [2]

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. Sufficient redundancy is necessary to avoid losing data that is useful for physics studies.

---

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

[10] 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

2.2.2 General Probe Requirements

a: Langmuir probes should be integrated into the CSFW, IBDH, IBDV and OBD region PFC tiles.

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 maximum probe area should be at most 1.0e-5 m^2, and the width should be less than 1.5 mm based on estimates from the PFC requirements[11]. Consult with relevant COG identified in Section 2.9 if necessary.

f. The probe body should be designed for electrical isolation from the bulk/neighboring PFC to a voltage of 300 V in air.

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. In order to successfully operate the Langmuir probes, they must be swept through a voltage range of approximately -50V to +30V. This voltage sweep results in an increased power flux to the surface of the probe with a time-average power of approximately 1.5x the nominal PFC heat flux.

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) to avoid compromising the insulator function by material deposited from the plasma.

j. Langmuir probes should be considered 'non-critical components' per Ref [3] for the purposes of determining the allowable stress within the probe itself. PFCs impacted by integrating the probes must still remain as 'critical components'.

[11] The maximum heat flux according to the PFC systems requirements document is 14 MW/m^2 at 3.6 degrees angle of incidence (the note refers to Rev. 0 of the PFC SRD; these heat fluxes have been reduced in subsequent revisions). Assuming a plasma sheath-edge density of 1e21m^{-3}, the particle flux is 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.

2.3: Thermocouples

2.3.1 Function of Thermocouples

a. Thermocouples (TCs) are used for physics, operations and bakeout 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, and to verify achievement of the bakeout requirements for the Recovery Key Performance Parameter demonstration associated with bakeout.
- 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[12].

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

2.3.2 General Thermocouple Requirements

a: Integrated design of thermocouples in the HHF divertor PFCs (IBDH, IBDV and OBD R1-2) should be placed within tiles such that, integrated over the discharge, summed over a single strike point region (e.g. the lower IBDH, independently from the upper IBDH, IBDV, or OBDR1-R2), and assuming axisymmetry, energies deposited of 100 kJ can be resolved from noise and interpretation uncertainty[13]. Consult with the relevant COG identified in Section 3.9.

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. Where possible, TC distributions in any given high heat flux region (IBDV, IBDH, OBDR1-R2) should have some provision to assess n=1 toroidal asymmetries, i.e. three toroidal angles, with a minimum toroidal spacing greater than 60 degrees.

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

[13] 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.

d: 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 2.3.2-1 describes these locations.

Table 2.3.2-1: *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	(planned)	(planned)
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

e. 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 3.9.

f. Thermocouple junctions shall be electrically isolated from the tiles in which they are embedded. Target isolation values are 0.5 kV between the electrical features of the thermocouples and the tiles.

2.4: Shunt Tiles

2.4.1: 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.

b: Shunt tiles are tiles that are modified so that a low-resistance element resides between the tile bottom and the underlying surface. Steps shall be are taken to ensure that this resistive element is the only electrical path between the PFC surface and the backing structure. This can include insulating washers and insulating coatings on the hardware such as bolts and pins

c: Signal wires propagate the voltage on the resistive element out of the vessel, where it is processed using isolation electronics.

2.4.2: 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 10 V. Reference values for current density can be found in Ref [5], and are indicated in Table 2.4.2-1

Table 2.4.2-1: *Halo current density values on a per-region basis.*

		IBDH	IBDV	CSFW	OBD
I_P	A	2.00E+06	2.00E+06	2.00E+06	2.00E+06
R	m	0.36	0.41	0.5	0.8
halo fraction	---	0.1	0.1	0.35	0.35
TPF	---	2	2	2	2
w	m	0.2	0.2	0.2	0.2
whetted area	m^2	0.45	0.52	0.63	1.0
I_halo	A	2.00E+05	2.00E+05	7.00E+05	7.00E+05
J_halo_max	**A/m^2**	**8.84E+05**	**7.76E+05**	**2.23E+06**	**1.39E+06**

2.5: Fueling lines

2.5.1: 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 have 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.

2.5.2: General Requirements

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

b. PFCs need to be 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 [1] for heat or particle flux from the gas/plasma interaction.

2.6: Center Column Wire Routing and Tile Variants

With regard to routing wires beneath the CS tiles and the development of tile variants, the following constraints apply.

a. Wires may not run horizontally between IBDV tile pairs R3-R4 and R4-R5, i.e. between the two high-heat flux tiles, and between the tiles at the IBDV/CSAS interface.

b. For purposes of design, assume that it is possible to fit at most 8 pairs in vertical channels between the IBDV tiles, with understanding that tile vertical gaps are separated by 15 degrees toroidal, and every fourth vertical gap is fully blocked.

c. Where there are 3 cooling tubes passing vertically between IBDV tiles, at most two wire pairs may be run along with those tubes.

d. No wires may traverse toroidally at the CHI gap (gap between IBDH and OBDR1).

e. The directions in Table 2.6-1 shall be followed in order to minimize tile variants.

Table 2.6-1*: Rules to adopt in order to minimize tile variants*

1	Each tile shall have at most a single sensor type
2	Horizontal target tiles with thru-holes for viewing shall not additionally have diagnostics
3	There shall be a single type of horizontal target thru-hole tile.

f. Organ pipes beneath thru-hole tiles in the horizontal target shall not be used for vacuum wire exits.

g. Wire with line of sight to the plasma should have lithium-compatible shield.

3: Diagnostics Requirements

3.1: General requirements

a: Tiles should provide sufficient wireways 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 per reference [6].

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.

3.2: Inboard Vertical Target Diagnostics

3.2.1 General

a. All requirements are elaborated in Section 2 or below in this Section.

b. For the vertical target, the High Heat Flux (HHF) region is defined as that containing the castellated tiles. The Low Heat Flux (LHF) region is defined by containing the T-bar mounted tile.

3.2.2 Mirnov Sensors on the Vertical Target

a. 2D Mirnov sensors shall be located in approximately the locations indicated in Table 3.2.2-1, which is consistent with legacy E-ED1324. Design deviations in the location of order 5 cm in height and in toroidal direction are acceptable, as are small variations in radius. Reductions in sensor count may be acceptable following consultation with the magnetics COG.

Table 3.2.2-1*: Locations of 2D Mirnov sensors on the vertical target.*

Type	Measurement Direction	Sensor Name	Upper or Lower	R [m]	Z [m]	Angle
2DM, thick	B_Z	2DMIBDVU1T	Upper	0.39	1.36	228
	B_R	2DMIBDVU1N				
2DM, thick	B_Z	2DMIBDVU2T	Upper	0.39	1.46	228
	B_R	2DMIBDVU2N				
2DM, thick	B_Z	2DMIBDVU3T	Upper	0.39	1.56	228
	B_R	2DMIBDVU3N				
2DM, thick	B_Z	2DMIBDVL1T	Lower	0.39	-1.36	237
	B_R	2DMIBDVL1N				
2DM, thick	B_Z	2DMIBDVL2T	Lower	0.39	-1.46	237
	B_R	2DMIBDVL2N				
2DM, thick	B_Z	2DMIBDVL3T	Lower	0.39	-1.56	237
	B_R	2DMIBDVL3N				
2DM, thick	B_Z	2DMIBDV2L1T	Upper	0.39	1.36	57.00
	B_R	2DMIBDV2L1N				
2DM, thick	B_Z	2DMIBDV2L3T	Upper	0.39	1.56	57.00
	B_R	2DMIBDV2L3N				
2DM, thick	B_{ZBZ}	2DMIBDV2L1T	Lower	0.39	-1.36	57.00
	B_{RBR}	2DMIBDV2L1N				
2DM, thick	B_Z	2DMIBDV2L3T	Lower	0.39	-1.56	57.00
	B_R	2DMIBDV2L3N				

3.2.3 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. At least 5 probes should be installed in the HHF region, and can be at more than one toroidal location, under the guidance of Table 3.2.3-1.

Table 3.2.3-1*: Guidance for the installation of Langmuir Probes in the HHF region of the vertical target*

1	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.
2	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. At least 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 3.2.3-2 is *recommended* to satisfy this requirement.

Table 3.2.3-2*: 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

3.2.4 Thermocouples on the Vertical Target

a. At least 13 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 guidance of Table 3.2.4-1:

Table 3.2.4-1*: Guidance for TCs in the HHF region of the vertical target*

1	At least three toroidal angles should be instrumented, with > 60 degree separation between the nearest angles.
2	At one toroidal angle, at least the 5 central castellations of the HHF region should be instrumented. This is the "primary" array[14].
3	At the other toroidal angles, the poloidal distribution should match the vertical positions of locations in the primary array.

[14] Based in the data in Table 3.2.4-1, the primary arrays should *likely* be at Bay I for the lower array and Bay C for the upper array.

c. The two LHF TCs should be at different toroidal angles with a space of at least 30 degrees.

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

e. The distribution in Table 3.2.4-2 is *recommended* to satisfy this requirement.

Table 3.2.4-2: *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	4	A	2	2
Lower	75	C	3	C	3	0
Lower	315	K	2	K	2	0
Lower	255	H/I	5	I	5	0
Lower	330	K/L	4	K	2	2

3.2.5 Halo Current Rogowskis on the Vertical Target

a. Halo current Rogowskis shall be installed per Table 3.2.5-1. Variations in height on the order of ~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 3.2.5-1: *Halo current rogowski sensors on the vertical target*

Sensor	2015 NSTX-U Vertical Position	Suggested Organ Pipe
ROGCSCL1	Lower Row 4 Tile Row in legacy E-ED1324	30-L
ROGCSCL2	Lower Row 2 Tile Row in legacy E-ED1324	30-L
ROGCSCU1	Upper Row 4 Tile Row in legacy E-ED1324	15-U
ROGCSCU2	Upper Row 2 Tile Row in legacy E-ED1324	15-U

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.

3.3: Diagnostic Requirements for the Horizontal Target

3.3.1: General

a. For the horizontal target, the High Heat Flux (HHF) region is defined as containing the four castellations at large major radius. The Low Heat Flux (LHF) region is defined as the single radially-wider castellation at the smallest major radius.

b: PFC holes centered around the organ pipes per E-DC1324 shall be included at the bays indicated in Table 3.3.1-1:

Table 3.3.1-1: *Locations of PFC through-holes above organ pipes to retain*

Upper/Lower	Nearby Bay	Angle (Left Handed Coordinates)	Intended Use
Upper	L	345	MGI[15] #3
Lower	F/G	180	MGI #1
Lower	L	345	Spect #1[16]
Lower	I	240	Spect #3
Upper	J	285	Upper PFR
Lower	A	15	Lower PFR

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 3.3.1-2 shall be eliminated.

Table 3.3.1-2: *Locations of PFC through-holes above organ pipes to eliminate compared to the 2015 installation*

Upper/Lower	Bay	Angle (Left Handed Coordinates)	Previously Intended Use
Lower	H/I	255	Spect #3

3.3.2: 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 per Table 3.3.2-1 and drawing E-ED1324. Design deviations in location of order ~15 cm in the toroidal location and ~3 cm in the radial locations are acceptable. Reductions in sensor count may be acceptable following consultation with the magnetics COG.

Table 3.3.2-1: *Mirnov sensors on the horizontal target*

---

[15] MGI (Massive Gas Injection): a system designed to rapidly puff a large volumn of gas into the chamber, with the goal of rapidly terminating the plasma discharge. MGI gas delivery systems are located on both upper and lower organ pipes.

[16] Spect #1 and Spect #3 are organ pipes reserved for visible spectroscopy systems such as filterscopes. There was a Spect #2 view present for the 2015/2016 operation of NSTX-U; this view is being eliminated as per Table 3.3.1-2.

Type	Measurement Direction	Sensor Name	R [m]	Z [m]	Angle
2DM, thick	B_R	B_2DMIBDHL6T	0.47	-1.64	236
	B_Z	B_2DMIBDHL6N			
2DM, thick	B_R	B_2DMIBDHU5T	0.47	1.64	228
	B_Z	B_2DMIBDHU5N			
2DM, thick	B_R	B_2DMIBDHU6T	0.47	1.64	236
	B_Z	B_2DMIBDHU6N			
2DM, thick	B_R	B_2DMIBDHL5T	0.47	-1.64	228.
	B_Z	B_2DMIBDHL5N			
2DM, thick	B_R	2DMIBDH2U6T	0.47	1.64	48
	B_Z	2DMIBDH2U6N			
2DM, thick	B_R	2DMIBDH2L6T	0.47	-1.64	48
	B_Z	2DMIBDH2L6N			

3.3.3: Langmuir Probes on the Horizontal Target

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

b. 6 probes should be installed in the HHF region, and can be at more than one toroidal location, under the guidance of Table 3.3.3-1.

Table 3.3.3-1*: Guidance for locations of Langmuir probes in the HHF region of the horizontal target region*

1	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.
2	The probes at the other toroidal locations may be placed at the same radial positions

c. This requirement is voided in Rev. 1 of the RD.

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

e. The distribution in Table 3.3.3-1 is *recommended* to satisfy this requirement

Table 3.3.3-1*: 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

3.3.4: Thermocouples on the Horizontal Target

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

b. At least 11 TCs should be installed in the high heat flux region under the guidance of Table 3.3.4-1:

***Table 3.3.4-1**: Guidance for the distribution of thermocouples in the high heat flux regions of the horizontal target*

1	At least three toroidal angles should be instrumented, with >60 degree separation between any angles
2	At one toroidal angle, at least 4 radial locations should be instrumented, distributed evenly over the HHF region. This is the “primary” array.
3	At the other toroidal angles, the poloidal distribution should match the horizontal positions of locations in the primary array.

c. At least 1 TC 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 3.3.4-2 is recommended is recommended to satisfy this requirement.

***Table 3.3.4-2**: 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	4	1
Upper	315	K	4	I	4	0
Upper	330	K/L	3	K	3	0
Lower	120	E/D	2	E	2	0
Lower	255	H/I	4	H	4	0
Lower	330	K/L	5	L	4	1

3.4 Outboard Divertor Diagnostic Requirements

23.4.1 General

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

3.4.2 Mirnov Sensors on the Outboard Divertor

a. Locations of 2D Mirnov coils shall be approximately as in Table 3.4.2-1. Sensors should be reinstalled at these locations, though small (~5-10cm) design shifts poloidally and toroidally are acceptable.

Table 3.4.2-1: *Locations of 1D Mirnov sensors on the OBD.*

Type	Measured Field Component[17]	Sensor Name	R (m)	Z (m)	Toroidal Angle	Location
2DM	21.5	B_2DMOBDL1T	0.68	-1.61	217.5	R1 L
2DM	111.5	B_2DMOBDL1N				
2DM	21.5	B_2DMOBDL2T	0.79	-1.57	217.5	R2 L
2DM	111.5	B_2DMOBDL2N				
2DM	21.5	B_2DMOBDL3T	0.90	-1.52	217.5	R3 L
2DM	111.5	B_2DMOBDL3N				
2DM	21.5	B_2DMOBDL4T	1.02	-1.48	217.5	R4 L
2DM	111.5	B_2DMOBDL4N				
2DM	21.5	B_2DMOBDL5T	1.13	-1.43	217.5	R5 L
2DM	111.5	B_2DMOBDL5N				
2DM	-21.5	B_2DMOBDU1T	0.6	1.61	217.5	R1 U
2DM	68.5	B_2DMOBDU1N				
2DM	-21.5	B_2DMOBDU2T	0.79	1.57	217.5	R2 U
2DM	68.5	B_2DMOBDU2N				
2DM	-21.5	B_2DMOBDU3T	0.90	1.52	217.5	R3 U
2DM	68.5	B_2DMOBDU3N				
2DM	-21.5	B_2DMOBDU4T	1.02	1.48	217.5	R4 U
2DM	68.5	B_2DMOBDU4N				
2DM	-21.5	B_2DMOBDU5T	1.13	1.43	217.5	R5 U
2DM	68.5	B_2DMOBDU5N				

3.4.3 Langmuir Probes on the Outboard Divertor

3.4.3.1: 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[18] [7], with the following guidance

[17] The outboard divertor is angled at approximately 21.5 degrees. Therefor, the tangent sensor, measuring the field parallel to the divertor plate, is angled at 21.5 relative to pure radial. Similarly, the normal sensor is oriented at 90+21.5=111.5 degrees.

[18] The original (early 2000s) implementation of Langmuir probes at Bay D is not included in this discussion. Only the circa-2014 implementation near Bay J/K is considered.

a. In the region formerly occupied by OBD R1 and R2, the Langmuir probes should be distributed per the guidance in Table 3.4.3.1-1

Table 3.4.3-1*: Guidance for positions of Langmuir Probes in the outboard divertor rows 1/2*

1	a total of nine Langmuir probes upper and nine lower should be distributed
2	Six should be distributed uniformly in the poloidal direction at one toroidal location
3	The other three should be distributed at two other toroidal locations to allow assessment of n=1 toroidal asymmetries, i.e. three total toroidal angles, with the minimum toroidal spacing > 60 degrees.

b. In the region of OBD R3 and R4, eight Langmuir probes top and eight probes bottom should be placed at different locations the poloidal direction; these may be in a single tile row, or staggered in at most two adjacent 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 per [7].

3.4.3.2: RF Langmuir Probes

RF Langmuir probes in Rows 3 & 4 shall be installed in a fashion similar to the design used for the FY16 run campaign. RF Langmuir probes in the former Row 2 shall be of the rail probe design, consistent with power handling requirements in that region.

3.4.4 Thermocouples on the Outboard Divertor

a. At least 24 TCs should be installed in each of the lower and upper outboard divertors with at least 12 in OBD R1-R2, 8 in OBD R3, 2 in OBD R4 and 2 in OBD R5.

b. At least 12 TCs should be installed in the OBD R1-R2 region under the guidance of Table 3.4.4-1:

Table 3.4.4-1*: Guidance for locations of thermocouples in the outboard divertors.*

1	At least three toroidal angles should be instrumented, with a minimum gap of 60 degrees between angles
2	At one toroidal angle, at least 6 radial locations should be instrumented, distributed evenly. This is the “primary” array.
3	At the other toroidal angles, the poloidal distribution should match the radial positions of locations in the primary array.
4	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.

3.4.5: 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-34 for the 2015 run campaign.

3.5: CSAS Diagnostic Requirements

3.5.1: General

a: The CSAS tiles shall have diagnostics as in the 2015 run as indicated in the revision of drawing E-D1324 active at that time.

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

3.5.2: Magnetics on the CSAS

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

3.5.3: Langmuir Probes on the CSAS

a. The CSAS is not required to have langmuir probes.

3.5.4: Thermocouples on the CSAS

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

b. For each of the upper and lower CSAS, the 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.

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

3.6.1: General

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

3.6.2: Mirnov Coils on the CSFW

a. Mirnov coils shall be located at the locations indicated in Tables 3.6.2-1 through 3.6.2-4. Shifts on order of 1-4 cm toroidally and vertically 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.[19] However, that cabling may be retained should it prove convenient.

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

Table 3.6.2-1*: 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

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

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 3.6.2-2: *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 3.6.2-3: *Locations of Tilted Mirnov sensors on the CSFW.*

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle	Suggested Organ Pipe
1D Mirnov, thick	B_T	1DM-ROT-1	0.3017	-0.1360	82.5000	90-L
1D Mirnov, thick	B_T	1DM-ROT-2	0.3017	-0.1360	142.5000	105-L
1D Mirnov, thick	B_T	1DM-ROT-3	0.3017	-0.1360	202.5000	225-L
1D Mirnov, thick	B_T	1DM-ROT-4	0.3017	-0.1360	292.5000	315-L
1D Mirnov, thick	B_T	1DM-ROT-5	0.3017	-0.1360	352.5000	360-L

Table 3.6.2-4: *Locations of midplane mirnov array sensors on the CSFW.*

Type	Measured Field Component	Sensor Name	R (m)	Z (m)	Toroidal Angle	Suggested Organ Pipe
B_z	B_z	1DMCSCM7	0.3017901	0	292.5	285-L
B_z	B_z	1DMCSCM8	0.3017901	0	322.5	360-L
B_z	B_z	1DMCSCM11	0.3017901	0.0328676	52.5	45-L
B_z	B_z	1DMCSCM14	0.3017901	0	172.5	225-L
B_z	B_z	1DMCSCM15	0.3017901	0	202.5	225-L
B_z	B_z	1DMCSCM16	0.3017901	0.0328676	232.5	315-U

3.6.3: Langmuir Probes on the CSFW

a. The CSFW LPs shall be installed as indicated in Table 3.6.3-1.

Table 3.6.3-1: *CSFW LP Locations*[20]

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

3.6.4: Thermocouples on the CSFW

The CSFW TC layout from the 2015 revision of E-ED1324 should be duplicated with the following modifications

a. Thermocouples on the CSFW shall be at the locations indicated in Table 3.6.4-1.

Table 3.6.4-1: *CSFW TC Locations*

Row from 2015 E-ED1324	Recommended Wire Exit Organ Pipe Bay	Recommended Organ Pipe Angle
7	E/D Upper	120 -U
8	E/D Upper	120 -U
9	E/D Upper	120 -U
10	E/D Upper	120 -U
11	E/D Upper	120 -U
12	E/D Upper	120 -U
13	E/D Upper	120 -U
14	E/D Upper	120 -U
15	E/D Lower	120-L
16	E/D Lower	120-L
17	E/D Lower	120-L
18	E/D Lower	120-L
19	E/D Lower	120-L
20	E/D Lower	120-L

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

21	E/D Lower	120-L

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

3.6.4: Shunt Tiles on the CSFW

a. Shunt tiles shall be installed in the floating tiles, at the locations indicated in Table 3.6.4-1.

Table 3.6.4-1: *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

3.7 Primary Passive Plate PFC Diagnostic Requirements

a: Tiles on four of the upper primary passive plates and four of the lower primary passive plates shall be instrumented with thermocouples for tile bulk temperature measurements.

b. Each plate selected for instrumentation shall have at least two tiles instrumented with TCs. These tiles selected should be approximately centered on the plate surface, consistent with other diagnostic installations such as the RWM sensors.

3.8 Secondary Passive Plate PFC Diagnostic Requirements

a: Tiles on four of the upper secondary passive plates and four of the lower secondary passive plates shall be instrumented with thermocouples for tile bulk temperature measurements.

b. Each plate selected for instrumentation shall have at least two tiles instrumented with TCs. These tiles selected should be approximately centered on the plate surface

c. The secondary passive plates selected for tile temperature instrumentation should, to the extent convenient, be toroidally aligned to the primary passive plates selected for instrumentation.

3.9 Diagnostic Contacts

The following individuals may be used as contacts for PFC diagnostics in addition to the Diagnostics RE.

Diagnostics RE: R. Ellis
Langmuir Probes: Robert Lunsford, Matthew Reinke
Magnetic Diagnostics: Stefan Gerhardt
Thermocouples: Robert Ellis, Matthew Reinke and Paul Sichta

4: Fueling Requirements:

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

4.1: CS Gas Fueling

The CS Gas Fueling 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 4.1-1, with associated puff injectors, should be retained in the revised designs.

Table 4.1-1*: 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[21]	255 degrees	0.25” OD x 0.02” wall	E-DC1606
Midplane	75 degrees	0.125” OD x 0.016” wall	E-DC1608

Table 4.1-2*: Optional CS fueling injectors*

Vertical Location of Outlet	**Toroidal Location of Organ Pipe**	**Gas Line**	Drawing

[21] 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.

Shoulder	285 degrees	0.125” OD x 0.016” wall	E-DC1752

b. The fourth injector, indicated in Table 4.1-2, 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: This requirement voided in Rev. 1 of the RD.

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. [8].

4.2: OBD Fueling

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 an additional 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. [8].

4.3: 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. 4.3-1.

Table 4.3-1*: 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: A piezo-electric valve with PCS control shall be used to control the fuelling.

f. System pressures and plenum sizes can be found in Ref. [8].

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. [22]

[22] 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 or otherwise modified resulting in a total area through which gas may pass 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.