National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

Plasma Facing Components

NSTX-U-RQMT-SRD-003-02

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Change Record

Revision	Date	Description of Change
0	12/15/17	Initial Release
1	07/14/18	In Table 4.2-1, reduced the Case 1 (1 degree, 5 second) heat flux to 6.5 MW/m^2, from 7.0 MW/m^2 , based on NSTX-U-DOC-101-00
		In Table 4.4-1, reduced the Case 1 (1 degree, 5 second) heat flux to 5.4 MW/m^2, from 6.0 MW/m^{2,} based on NSTX-U-DOC-101-00
		In Table 4.4-1, eliminate the previous Case 4; not required for 5 second operations.
		Modified signature block as per new QAPD and ENG-050 and adjusted names to reflect up-to-date roles and responsibilities
		Added an Extent of 11 cm to CASE#1 in table 4.4-2 as per guidance from PFCR-MEMO-011
		Removed CASE#4 in Table 4.4-3 as per guidance from PCFR-MEMO-011
		Added an Extent of 11 cm to CASE#1-#3 in table 4.4-3 for OBD R4 as per guidance from PFCR-MEMO-011. Specified Extent of 4 cm for OBD R5 based on estimated overlap.
		Removed text at end of section 4.0 which described process for requesting relaxation in heat flux requirements. This is now handled a more formal change process to the SRD.
		Clarified how tiles are judged to meet requirements (now 4.0-d), which explicitly excludes enhancement from coil misalignments as per PCFR-MEMO-013
		Added requirement that temperature limited tiles must estimate what heat flux and resulting surface temperature would lead to stress limit (now 4.0-e) as suggested in PFCR-MEMO-013
		Updated all interface tables as per the new interface spreadsheet, to ensure consistency of language with other SRDs.
		Significant changes to Section 4.4. This clarifies pre-existing scope that these cutouts are maintained from FY16 NSTX-U.
		Updated Table 4.5-1 per recommendation of PFCR-MEMO-018, adding ‘Extent’ and ‘Range of Application’.
		Added to 4.0-a clarification that the ‘Range of Application’ is in the poloidal direction along the tile surface and refers to peak location.

		Added requirement 4.0-c which clarifies that the heat fluxes given in the tables are the normal heat flux and how parallel heat flux is computed using angle of incidence
		Updated Fig. 2.3-2 and clarified description
		Updated 3.2a for 350 C bake (was 300).
		Clarified the meaning of the envelope in 3.3a.
		Created 2.3e out of what was otherwise a floating sentence that clarified Fig 2.3-1 and Fig 2.3-2.
		Added reference to dimensional control requirements document in 3.3e and requirement that PFCs and mounting structures allow for alignment flexibility per RD-11.
		Added 3.3f providing requirements for fasteners to be sufficiently well hidden within bolt holes
		Added clarification to 2.1.e regarding Li coatings not being considered to impact PFC impacting
		Removed footnote 3.1.g regarding ignoring erosion which is now included in Section 3.1.m
		Added 3.1.j to avoid surfaces that include multiple shapes to simplify observation and interpretation.
		Clarification to 3.1.d, addition of 3.1.e taken from 3.1.j specifying helicity direction and isolating reversed helicity.
		Clarified 3.1.i requirement for need for eliminating edge following guidance in PFC-180706-MAJ-01
		Removed 3.1.f as disruption thermal impacts are covered by ablation/erosion in 3.1.m
		Added 3.1.m requirement for allowance of shaping features to accommodate erosion/ablation as per PFCR-MEMO-022
		Added clarification of 1 mm gaps being toroidal to 3.3.d
		Increased alignment target in 4.1.a to be 0.035” from 0.030” and added clarifying language based on discussions between COGs and RE.
		Table 4.2.1, duration of CASE #1 to 1.5 seconds, reduced heat flux of CASE #2 to 5.4 MW/m2 and set min angle 5.0, eliminate CASE #3 from Rev 0 based on guidance from Project Director. Using beta_max=1.0 deg, Accommodates for a 300 degC ratcheting. Also adjusted CASE numbering.
		Table 4.3.1, removed CASE #2 from Rev0, adjusted min angle to 5.5 and dropped heat flux to 5.3 MW/m2 in CASE #1 using beta_max=1.2 deg. Accommodates for a 300 degC ratcheting. Based on guidance from Project Director.
		Table 4.4.1, duration of CASE #1 to 1.5 seconds, reduced heat flux of CASE #2 to 5.4 MW/m2 and set min angle 5.0, based on guidance from Project Director. Using

		beta_max=1.0 deg. Accommodates for a 300 degC ratcheting.
		Added 3.1.n which motivates minimizing beta within constraints of shaping requirements in 3.1
2	9/25/18	Modified Table 3.1.1; changed the 5th from top and bottom ΔR value from 0 to 0.0254 m. This does not change the design in any sense, but simply allows the gap between the OBD and IBDH to shift to larger radius.
		Modified table 4.2.1 (IBDH), Case 3 (reversed heat flux) change heat flux from 1 to 0.7 MW/m^2.
		Modified table 4.3-1 (IBDV), Case 3 (reversed heat flux) change heat flux from 1 to 0.7 MW/m^2.
		Modified table 4.4-3 (OBD-R4/5) Case 1 change heat flux from 4.3 to 3.1 MW/m^2. The requirement change is necessary to accommodate the large diagnostic cut-outs in the far reaches of the outboard divertor.
		Modified signature page to reflect current Mechanical Technical Authority

Table of Contents

References

[1] NSTX-SRD-11-031, *System Requirements Document, Plasma Facing Components*
[2] NSTX-U-SRD-111-013, *System Requirements Document, Plasma Facing Components*
[3] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*
[4] PFCR-MEMO-010-00, *Heat Fluxes on the IBDH and Near OBD Regions*
[5] PFCR-MEMO-009-00, *Heat Fluxes on the Vertical Target*
[6] PFCR-MEMO-008-00, *Heat Fluxes on the CSAS and Far OBD Region*
[7] NSTX-CRIT-0001-02, *NSTX Structural Design Criteria*
[8] NSTX-U-RQMT-RD-003, *NSTX-U Disruption Requirements*
[9] NSTX-U-RQMT-RD-014, *Thermal Analysis Requirements*
[10] PFCR-MEMO-003-00, *Carbon Blooms and CFCs*
[11] NSTX-U-RQMT-RD-011, *NSTX-U Dimensional Control*
[12] NSTX-U-RQMT-RD-004, *PFC Diagnostics and Gas Delivery*
[13] NSTXU-CALC-11-05-00, *Thermal Analysis of Neutral Beam Armor Array*
[14] NSTXU-CALC-24-02-00, *Armor Plate Backing Plate (Neutral Beam Armor E/M)*

0.0 Scope

a. This document provides requirements for plasma facing components on NSTX-U. All statements in this document supersede the requirements in [1] and [2] in the event of conflict.

b. The format of this document, including interfaces specifications, is provided in the General Requirements Document [3].

c. Tile regions are named in this document as described in Table 0-1:

Table 0-1: Full name and acronyms used to describe plasma facing component regions.

Name	**Acronym**
Center Stack First Wall	CSFW
Center Stack Angled Section	CSAS
Inboard Divertor Vertical	IBDV
Inboard Divertor Horizontal	IBDH
Outboard Divertor	OBD
Secondary Passive Plates	SPP
Primary Passive Plates	PPP

1.0 Functions

The plasma facing components are designed with two complementary goals:

a. They must protect the metallic structures of the vessel (the vessel wall, passive plates, etc.) from damaging heat fluxes from the plasma.

b. They must protect the plasma from contaminating influx of medium- and high-Z impurities.

Specific tile areas have specific functions such as :

IBDH Tiles

c. The IBDH tiles protect the horizontal casing flange and any cooling features mounted to that flange, while protecting the plasma from impurities generated from those objects. They also protect the PF-1c coil reentrant flanges, in concert with the outboard divertor PFCs.

d. The IBDH tiles are a primary heat flux handling surface for the outer magnetic strikepoint for high performance (H-mode) plasmas.

e. Additional information on the research program uses of these tiles can be found in Ref. [4]

IBDV Tiles

f. The IBDV tiles protect the centerstack casing, while protecting the plasma from impurities generated by that surface.

g. The IBDV tiles are a primary heat flux handling surface for the inner magnetic strikepoint for high performance (H-mode) plasmas.

h. Additional information on the research program uses of these tiles can be found in Ref. [5]

CSFW Tiles

i. The CSFW tiles are used to protect the centerstack casing, while protecting the plasma from impurities generated by that surface.

j. The CSFW tiles are the primary heat flux handling surface during discharge initiation and rampdown, and may serve as a heat flux handling surface for inner wall limited plasmas.

CSAS Tiles

k. The CSAS tiles are used to protect the angled part of the center stack casing, while protecting the plasma from impurities generated by that surface.

l. The CSAS tiles are a primary heat flux handling surface for the inner magnetic strikepoint for lower elongation plasmas.

m. Additional information on the research program uses of these tiles can be found in Ref. [6].

OBD Tiles

n. The OBD tiles are used to protect the outboard divertors, while protecting the plasma from impurities generated by that surface. They also protect the PF-1c coil reentrant flanges, in concert with the inboard horizontal target PFCs.

o. The OBD tiles are a primary heat flux handling surface for the outer magnetic strikepoint for L-mode plasmas, and as well as some H-mode plasmas.

p. Additional information on the research program uses of these tiles can be found in Refs. [4, 6].

Passive Plate Tiles

q. The passive plate tiles are used to protect the surface of the copper primary and secondary passive plates, while protecting the plasma from impurities generated by that surface.

2.0 Materials and Design Requirements

2.1: Materials Requirements

a: All PFCs in NSTX-Upgrade shall be made from either fine grain isotropic graphite, or from other carbon based materials, for instance carbon-carbon composites, here referred to as CFCs.

b. The exception to this is the RF antenna guard which can be made from boron nitride. The RF antenna guard shall not be regarded as a surface on which it is acceptable to intentionally limit the plasma.

c: For isotropic graphite and carbon-carbon composites, the brittle materials qualification shall be used, as per the structural design criterion [7], where PFCs are defined as critical components.

d: The PFCs themselves and any related materials should be compatible with an ultra-high vacuum environment, as approved by the PPPL Vacuum Materials Committee.

e: PFCs should be compatible over their lifetime with the following:

- Application of boron thin films as deposited by the dTMB system.
- Application of lithium thin films as deposited, for instance, by the LITER probes, including the ability to remove lithium deposited on front surfaces and in tile gaps; a scheme should be developed for this cleaning as a product of the design. Lithium coatings of up to 0.02” should be anticipated for regions immediately under the LITER probes.[1]; this Li coating need not be considered when defining tile shaping requirements.
- Glow discharge cleaning with hydrogen, deuterium, helium, neon, and argon.

e: 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].

[1] Email from Mike Jaworski to Stefan Gerhardt, 9/11/2017

Table 2.1-1: Temperature and durations for tile vacuum bakeout following machining (note: only required as per 2.1.f)

Temp (degC)	Time at Temperature (hours)
1300	5
1200	7
1100	9
1000	11
900	13
800	16
750	18
650	22
550	27

f: Following manufacture and before diagnostic installation or final installation on NSTX-U, the PFCs should be compatible with, and subject to, a high temperature bake following one of the protocols in Table 2.1-1[2]. 1000 deg C for 11 hours is the recommended case.

2.2: Mechanical Design Requirements

a: Disruption mechanical and thermal loads shall be computed as per the NSTX-U Disruption Specification [8].

b: Tile designs should have a well defined current path for halo currents entering the tile front surface to flow to backing structures.

c: The design of the IBDH and OBD tiles (top and bottom) should accommodate halo currents bridging that gap during disruptions, with currents levels as per Ref. [8].

2.3 Field Helicity Requirements

a. The field directions are indicated in Figures 2.3.1 and 2.3.2, along with exaggerated ramped tiles. Field lines approach the surfaces at very shallow angles, and those given in tables of Section 4 are referenced such that 90^o would make the field line normal to the PFC surface.

b. In two cases, the sign of the field line helicity may vary:

[2] The values from NSTX-SPEC-11-047 and W7X-SPEC-TDUS-014

- The horizontal target (IBDH) may have heat from either the inner or outer strikepoint deposited on it; these two cases have opposite field helicity at the strikepoint. For the purpose of this document, “standard target helicity” refers to the field line direction when the Outer Strike Point (OSP) is located on the IBDH tiles, for clockwise toroidal field and counter-clockwise plasma current (when viewing the tokamak from above). “Reversed target helicity” refers to cases where this direction is reversed.
- The vertical target (IBDV) typically receives heat from the inner strikepoint, called “standard target helicity” in this document. In rare cases, the IBDV may have heat from the outer strikepoint fall on the portion nearest the horizontal target, or have intermediate legs of advanced divertors. These rare cases will have “reversed target helicity”.

c. For the IBDH and OBD, “standard” helicity is illustrated as per Fig. 2.3-1.

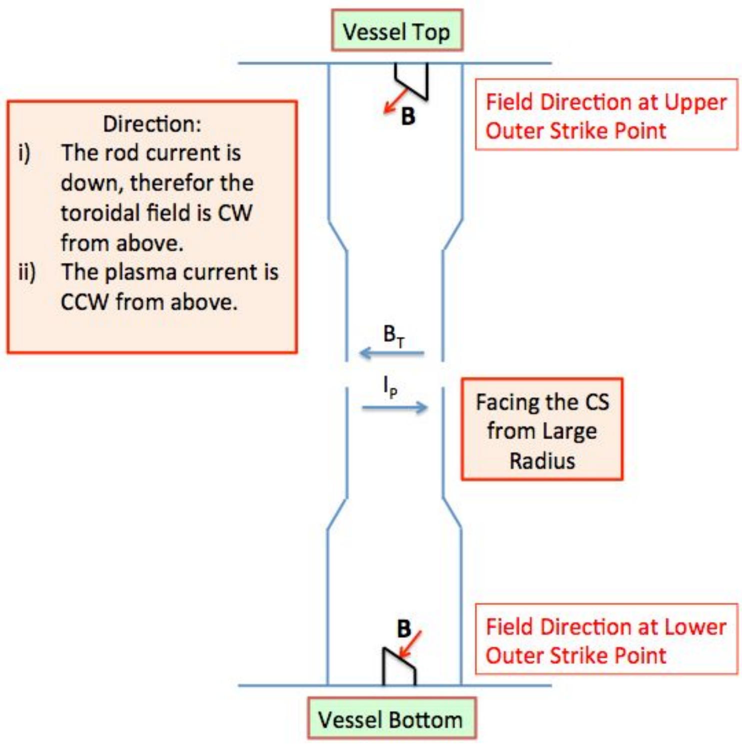

***Fig: 2.3-1**: Field line direction on the horizontal target for “Standard Helicity”*

d. For the IBDV, “standard” helicity is illustrated as per Fig. 2.3-2.

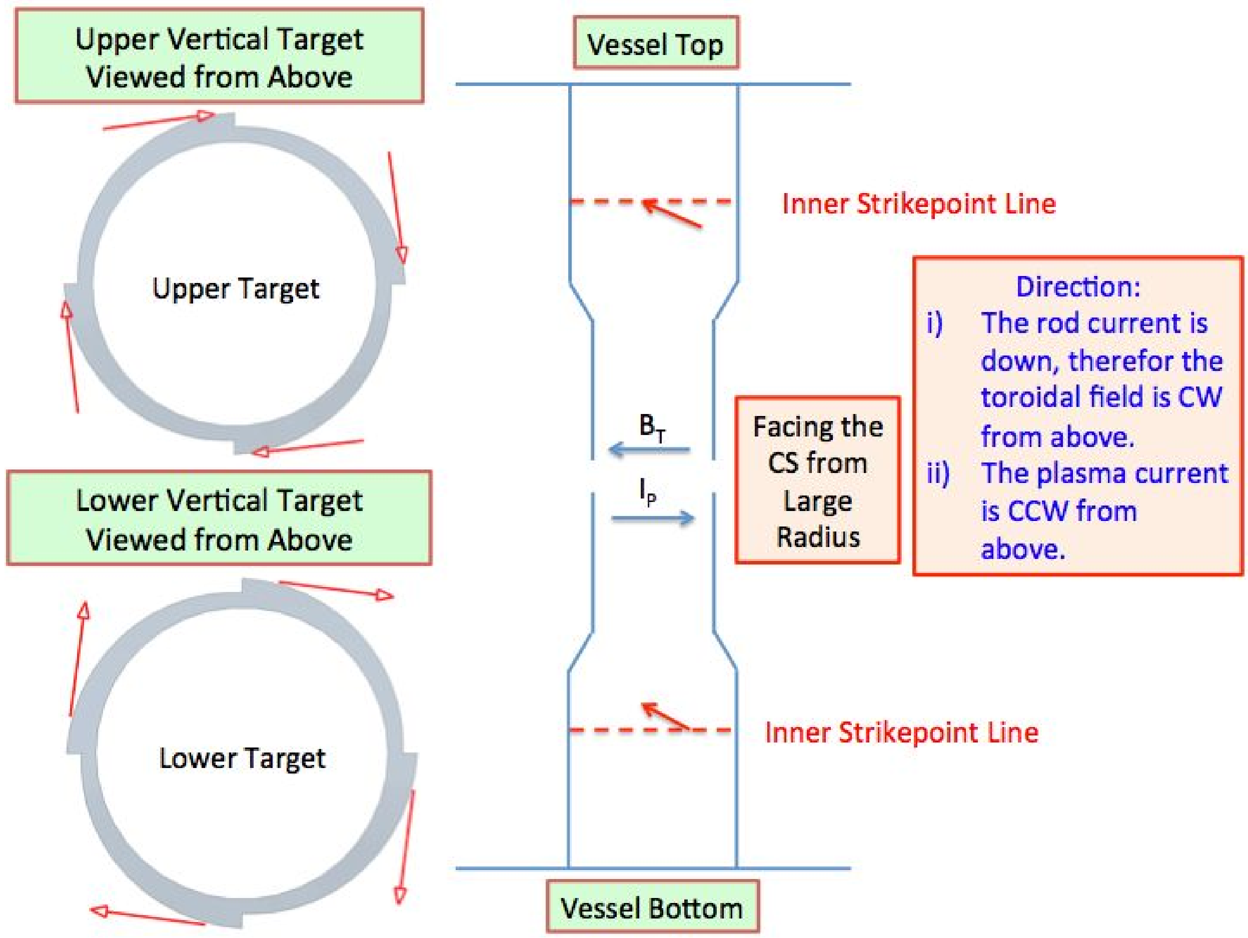

Fig: 2.3-2: *Field line direction on the vertical target for "Standard Helicity"*

2.3e: In the interpretation of Figs. 2.3-1 and 2.3-2, it is assumed that PFC heat load is due solely to parallel heat flux, such that heat flows along the magnetic field line from the plasma towards the PFC surface in both cases, regardless of field line direction.

3: Configuration Requirements and Essential Features

3.1: Thermal and Shaping of Plasma Facing Surface Requirements:

a: The design scenarios described in sections below shall be qualified for repetition rate of ≤ 2400 second repetition rate with the base cooling. Baseline cooling is defined in Reference [9].

b: A 1200 second repetition rate shall be possible with application of additional cooling, but no modifications to the tokamak core. [9]

c: Tiles shall be designed so that the peak surface temperature of the wetted top face, away from local peaks at the edges (as defined in 3.1-d), at the end of the pulse shall not exceed 1600 °C [10]; disruption heating need not be included in this consideration.

d: For forward helicity, tiles shall be designed so that the edge temperatures of local surface features (e.g. access holes) or edge features of non-shaped tiles shall not exceed 2000 ^{o}C and meet 3.1-c at distance of 2 mm from the edge/feature ; disruption heating need not be included in this consideration.

e: Reversed helicity cases shall be held to the same temperature limit as edges (see 3.1-d).

f: Unless otherwise stated, the duration of heat flux is to be taken as 5 seconds.

g: Components for mounting, aligning and securing PFCs should be qualified for the full lifetime of NSTX-U as per the GRD shot spectrum [3]. Disruption loading may be developed based on the disruption requirements in Ref. [8].

h: Tile designs with surfaces shaped to favor one target helicity (referred colloquially as 'ramping' or 'fishscaling') may be used if necessary. Specifics of the helicity direction are identified generally in Section 2.3, and in Section 4.1-4.9 per each individual PFC region.

i: When tile surface shaping (see 3.1-h) is utilized to prevent edge heating in forward helicity, edges across poloidal[3] gaps shall be shadowed to the maximum angle listed in tables in section 4 below.

j: When shaped tiles are used, the design should attempt to make the heat flux on the wetted portions of the tile uniform in the toroidal direction. This does not need to include the heat flux at or near local surface features (3.1-k).

k: Vertical gaps, front-surface holes, etc. are allowed provided that designs can meet stress, temperature and other requirements.

l: Emissivity of 0.7 shall be used for calculations.

m: Designs for tile shaping features shall accommodate a reduction[4] in fishscale angle consistent with a reduction in step height, Δd, of 0.003" over the their lifetime and still maintain shadowing.

n. Consistent with all other requirements in section 3.1, the tile surface ramp angle should be minimized.

3.2: Bakeout Considerations

a: All in-vessel graphite, including that used for PFCs, shall be capable of being baked to at least 350 C with the note that the higher He inlet temperatures may result in some tiles exceeding this temperature by some 10s of degrees.

b: The gap between the upper IBDH and OBD tiles should be designed to satisfy a 1000 Voltage differential without arcing as per a Paschen's curve. The following pressure levels and gas species

[3] A poloidal gap is one which can be drawn in the poloidal plane of the machine, i.e. it is a discontinuity in the PFC material that is encountered as one moves along the surface in the toroidal direction.
[4] Assumed to be due to erosion and/or ablation from plasma/disruptions.

should be evaluated: atmospheric pressure of air, NSTX-U operational vacuum with D_2 ($1x10^{-8}$ Torr), and NSTX-U bake out with water vapor ($5x10^{-4}$ Torr - $5x10^{-6}$ Torr).

3.3: PFC Locations and Spatial Configuration

a: PFCs surfaces should not extend beyond the envelope stated in Figure 3.3.1 and Table 3.3.1. The table indicates the nominal PFC boundary, as well as allowed radial or vertical size increases of the PFCs in order to meet requirements.

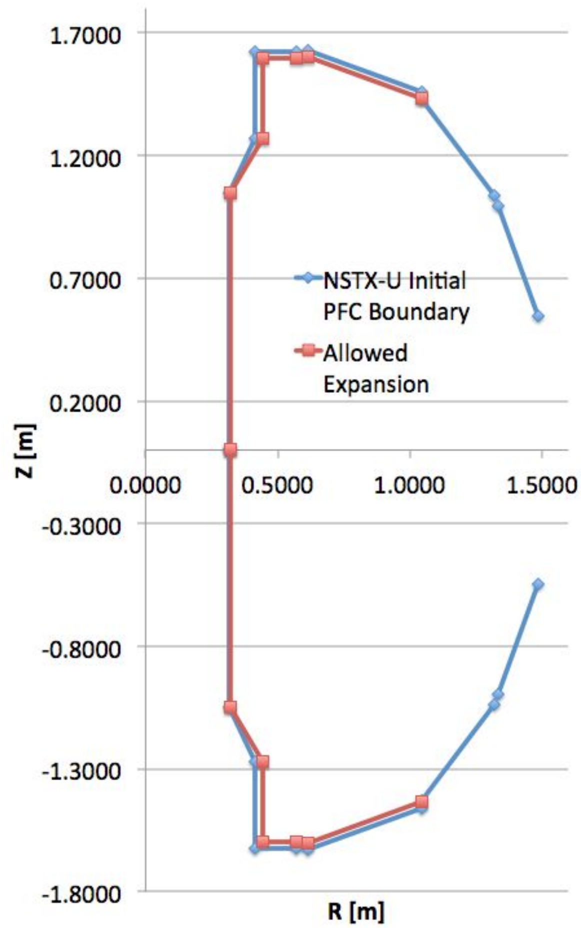

Figure 3.3.1: *NSTX-U PFC boundary and allowed expansion of PFCs to accommodate new requirements*

b: The center radius of the IBDH/OBDR1 interface shall be at R=59.5 +/- 0.5 cm.

c: PFCs design should ensure that there is no large line-of sight from the plasma to the centerstack casing, centerstack bellows, or outer vacuum vessel in the “polar regions” or PF-1c reentrant housing; included in this is the requirement that graphite armor be present in continuous form from the outboard divertor to the secondary passive plates as per Fig. 3.3.1, except at locations of “diagnostic cutouts” as per Section 3.4. Here, “large gaps” do not preclude nominally small tile-to-tile gaps.

d: Regions on the casing and PFC mounting surfaces not protected from direct lines of sight shall be minimized. Any toroidally running gap wider than 1 mm must be evaluated and approved during the design review process.

e. PFC and mounting structure designs shall allow, coordinated with magnet and vessel structure adjustability, for sufficient positional adjustability to meet tolerances for PFCs relative to magnets, as described in Ref. [11] and derived documents.

f. For each region, field lines impinging on PFCs at angles 1.5 times the maximum given in Tables 4.2.1-4.5.1 shall not impact fasteners or other metallic components used for securing tiles.

***Table 3.3.1**: Baseline PFC boundary and allowed expansion of PFCs to accommodate requirements*

	R	Z	Allowed ΔR	Allowed ΔZ
	m	m	m	m
Upper CS	0.3148	0.0000	0.0050	0.0000
	0.3148	1.0500	0.0050	0.0000
	0.4150	1.2700	0.0300	0.0000
	0.4150	1.6234	0.0300	-0.0254
	0.5715	1.6234	0.0254	-0.0254
Upper OBD	0.6171	1.6280	0.0000	-0.0254
	1.0433	1.4603	0.0000	-0.0254
Upper SPP	1.0433	1.4300		
	1.3192	1.0397		
Upper PPP	1.3358	0.9976		
	1.4851	0.5450		
Lower PPP	1.4851	-0.5450		
	1.3358	-0.9976		
Lower SPP	1.3192	-1.0397		
	1.0433	-1.4300		
Lower OBD	1.0433	-1.4603	0.0000	0.0254
	0.6171	-1.6280	0.0000	0.0254
Lower CS	0.5715	-1.6234	0.0254	0.0254
	0.4150	-1.6234	0.0300	0.0254
	0.4150	-1.2700	0.0300	0.0000

	0.3148	-1.0500	0.0050	0.0000
	0.3148	0.0000	0.0050	0.0000

3.4: Diagnostic Requirements

a. PFCs shall accommodate the following types of sensors :

- Langmuir probes
- Mirnov coils
- Rogowski coils
- Shunt tiles
- Thermocouples

b. Detailed requirements for PFC diagnostics for specific locations are provided in Ref. [12]

3.5: Installation and Maintenance Requirements

a: No module or single component installed by a single person shall weigh more than 50 lbs, per OSHA recommendation, unless lifting and handling equipment and procedures are specially developed.

b: Any module and component must fit through the Bay A duct without the use of an overhead crane.

c: Tiles of the base design should be able to bear the weight and typical movement of technicians working in vessel. For design purposes, this can be assumed to be 300 lbf distributed over an area of 4 in^2. Langmuir probe tips or other specific fine features are an exception to this rule, and may require protection.

d: The design shall be such that removal replacement of any tile shall not mandate the removal of the center-stack or outboard divertor copper/stainless structure.

e: An assembly sequence shall be provided with the design that takes account of machine assembly (including CS insertion to the machine), wire management, and any industrial hygiene and health physics concerns.

f: No permanently installed component on the outboard divertor shall extend inside the radius of the main vessel flanges (R_{vessel_flange}=23.625”), and no permanently installed component on the CS shall extend more than ¼” beyond the radius of the CS horizontal flanges (R_{flange}=21.875”, for $R_{max}=R_{flange}+1/4$ = 22.125”).

3.6: In-Vessel Requirements for Gas Delivery:

Specific detailed requirements for gas fueling interfaces are provided in Ref. [11]

a. Two gas fuelling outlets shall be provided near the CS midplane for core fuelling.

b. One gas fuelling outlet shall be provided near the CSAS tiles on the upper portion of the CS for core fuelling.

c. Two gas fuelling outlets shall be provided near the corner of the row 1 tiles in the outboard divertor for divertor fuelling.

d. Two gas fueling lines, with outlets near the upper and lower IBDH/IBDV interfaces, shall be provided for private flux region divertor fuelling.

4.0 Baseline Performance and Operational Requirements

This section defines the heat load requirements by location. The mechanical pre-loads and thermal loads so-derived should be added to those from halo currents and eddy currents.

The heat fluxes in the tables below are based on the Ref [4-6]. All justification for these requirements can be found in those memos.

a. For some cases an Extent is given. This extent should be used to define a triangular heat flux profile, as shown in Figure 4.0.1, the peak of which should be able to be located anywhere over the Range of Application along the length of the tile in the poloidal direction.

b. if there is no 'Extent' given, or is stated as "full", then the heat flux should be applied uniformly over the Range of Application.

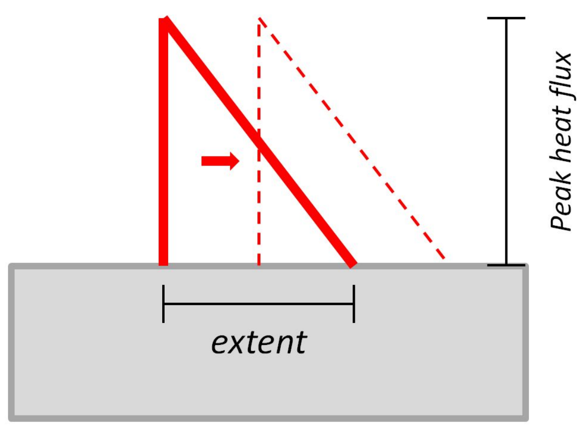

Figure 4.0.1: Example of heat flux profile that should be used for stationary cases in the region-specific requirements tables in Section 4.1-4.5.

c. The heat fluxes given in Tables 4.2-1 through 4.5-1 are the heat fluxes normal to an axisymmetric surface. Parallel heat flux can be computed from dividing the heat flux by sin(α), where α is the angle of incidence also given in those tables.

d. To judge if PFCs satisfy requirements, heat fluxes shall be applied as described in Tables 4.2-1 through 4.5-1 over the given PFC surface, for the given angles of incidence for the listed duration. The effects of tile shaping, surface features (e.g. fish-scaling and bolt-holes), and fabrication and assembly tolerances enhance the nominal, axisymmetric, heat flux and should be included to satisfy requirements. This shall assume axisymmetric mounting surfaces and *exclude* heat flux enhancements due to coil misalignments and other non-axisymmetric magnetic effects (e.g. coil leads, bus work).

e. To judge operational flexibility for PFCs that are shown to reach the temperature limit (defined in Section 3.1) prior to reaching the stress allowable (2.1-c), the magnitude of the heat flux, applied as per Tables 4.2-1 through 4.4-1, and resulting surface temperature that leads to the PFCs reaching their stress allowable shall also be estimated and included in design reports or calculations.

4.1: CS First Wall (CSFW)

a: The radial step between adjacent tiles shall not exceed 0.035”. There is not an expectation that eccentricities in the casing itself will be compensated out by this tile installation.

b: A uniform normal heat flux of 1 MW/m^2 for 5 seconds should be used. This is consistent with the 100% radiation scenario defined in Section 4.1.5 of the GRD [1], but computed for the CSFW geometry.

4.2 Inner Horizontal Target

a: Heat flux requirements on this surface are given in Table 4.2-1.

Note that there is a region for R<0.47 where reduced thermal performance is allowed.

IBDH	**Case # ->**	**1**	**2**	**3**	**4**
Range of Application	m	0.47 < R < 0.6		R < 0.6	R < 0.47
Extent	cm	15	full	full	full
Max Angle	degrees	1.0	5.0	-1	4.0
Min Angle	degrees	1.0	5.0	-5	1.0
Heat Flux	MW/m^2	6.5	5.4	0.7	3.5
Duration	sec	1.5	5	1	5
Reference Scenario	---	Stationary High Ip/Bt w/ large poloidal	High Ip/Bt Long Pulse Swept Case	Reversed Helicity Requirement	Spill Over From HHF Regions

		flux expansion			

***Table 4.2-1**: Required heat flux parameters for the IBDH. Cases 1, 2, and 4 have the "normal" helicity.*

4.3: Vertical Target

a: Heat flux requirements on the vertical target are as per Table 4.3-1.

IBDV	**Case# ->**	**1**	**2**	**3**
Range of Application	m	1.27< |Z| < 1.5	|Z|>1.5	|Z| > 1.27
Extent	cm	11	10	full
Max Angle	degrees	5.5	4.0	-1
Min Angle	degrees	5.5	1.0	-5
Heat Flux	MW/m^2	5.3	3.5	0.7
Duration	sec	5	5	1
Reference		High I_p and B_T DN w/ Sweeping	Spill Over from Scans in HHF region	Reversed Helicity Requirement

***Table 4.3-1**: Heat flux requirements on the vertical target*

4.4: Outboard Divertor

a. The outboard divertor should be designed to handle heat flux from an outer strike point. Unlike the IBDH and IBDV, no reversed target helicity heat flux handling is required. The helicity is as indicated in Fig. 3.2.1

b: The requirements so derived are shown in Tables 4.4-1 through 4.4-3 [4,6]

c. Field line impingement on metal components at diagnostic cut-outs shall be prevented by custom protective tile features.

d. Diagnostic cut-outs (defined in 4.4-f) for R4/R5 shall be included in the lower outboard divertor at Bays: B, C, E, F, G, H, I, J and K

e. Diagnostic cut-outs (defined in 4.4-f) for R4/R5 shall be included in the upper outboard divertor at Bays: B, C, D, E, F, G, H, I, J, K and L

f. Diagnostics cutouts are areas in the outer divertor where tiles and their mounting structures have been removed at locations above the vertical viewing vessel ports, facilitating views by plasma diagnostics.

g. The diagnostic cutouts in general shall not intrude on the outboard diverter row-3 region.

h. To the extent possible, diagnostic cutouts should have a uniform design.

i. Specialized diagnostic cutouts facilitating the poloidal CHERS and related diagnostics shall be included between Bay-A and Bay-L in the lower and upper outboard divertor.

j. Legacy custom outboard divertor cut-outs exist between Bays B/C and F/G in the lower outboard divertor at R4 and R5, aligned with custom cut-outs in the secondary passive plates. These two divertor cut-outs may be either preserved or covered by PFCs, depending on which solution most expediently allows all other requirements in this document to be met.

Near OBD (aka R1,R2)	**Case # ->**	**1**	**2**	**3**
Range of Application	m	R < 0.7	R < 0.7	0.70 < R < 0.81
Extent	cm	13	10	full
Max Angle	degrees	1.0	5.0	4.4
Min Angle	degrees	1.0	5.0	2.6
Heat Flux	MW/m^2	5.4	5.4	3.3
Duration	sec	1.5	5	5
Reference Scenario	---	'Spillover' for stationary large poloidal flux expansion	'Spillover' for High Ip/Bt Long Pulse Swept Case	Swept Case on OBD

***Table 4.4-1**: Heat fluxes on the OBD Row 1 & 2 tiles*

OBD-R3	Case # ->	1	2
Max Angle	degrees	7.9	10
Extent	cm	11	full
Min Angle	degrees	2.2	8.5
Heat Flux	MW/m^2	10.5	3.0
Duration	sec	1.0	5.0
Reference Scenario		short duration high power	MPFC Far-OBD MAPP Scan

***Table 4.4-2**: Heat fluxes on the OBD Row 3 tiles*

OBD-R4/5	Case # ->	1	2	3
Max Angle	degrees	14	8.2	16.5
Extent (R4)	cm	11	11	11
Extent (R5)[5]	cm	4.0	4.0	4.0
Min Angle	degrees	9.2	4.8	13.5
Heat Flux	MW/m^2	3.1	1.8	3.0
Duration	sec	2.0	2.0	2.0
Reference Scenario		High I_P/B_T LSN Swept L-Mode	Low I_P/B_T LSN Swept L-Mode	High I_P/B_T LSN Swept L-Mode

***Table 4.4-3**: Heat fluxes on the OBD Row 4 & 5 tiles*

4.5: CSAS

a: Heat fluxes for the CSAS are as per Ref. [6], and provided in Table 4.5-1.

[5] This 4 cm is the portion of the tile not shadowed by the secondary passive plate.

CSAS	Case # ->	1	2
Max Angle	degrees	9.2	12
Min Angle	degrees	7.3	9.5
Extent	cm	8	8
Range of Application	m	|Z| > 1.1	|Z| > 1.1
Heat Flux	MW/m^2	5.2	3.6
Duration	sec	2.0	2.0
Reference Scenario		High I_P/B_T LSN L-Mode, 3 MW	High I_P/B_T LSN L-Mode, 2 MW

Table 4.5-1: *Heat flux requirement for the CSAS.*

4.6: Passive Plates

a: The passive plate PFCs shall be qualified to a normal heat flux implied by the 100% radiated power scenario from the GRD.

b: This statement applied to both the primary and secondary passive plates.

4.7: Outboard Limiter

NSTX-U does not possess a true outboard limiter. BN antenna guards protect the antenna, but are not designed for direct plasma contact.

This section will be updated in a future revision to this document if such a limiter is deemed necessary.

4.8 Neutral Beam Armor

a: The neutral beam armor shall tolerate radiative normal heat fluxes implied by the 100% radiated power scenario from the GRD.

b: The armor must also tolerate neutral beam fluxes, as described in Ref. [13] & [14]. These need not be applied simultaneously with the radiative heat flux from the plasma.

4.9 Regions not otherwise specified

This section will be updated in a future revision to this document to specify requirements for other regions, e.g., minimum heat fluxes for components not protected by PFCs including expected fluxes during disruptions.

5.0 Interfaces

The baseline interfaces for PFCs are described in Table 5-1 - 5-6.

Table 5-1: Interfaces for the passive plate PFCs (WBS 1.1.1.1.6)

Interfacing WBS	Interfacing System	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.1.2.1	Passive plates	Structural	At plasma facing copper surface of the passive plate	Tiles react disruptions loads to the passive plates. Flexing of the plate transfers load to the tiles	Mechanical Drawings, Calculations
1.1.1.2.1	Passive plates	Thermal	At plasma facing copper surface of the passive plate	Tiles transfer heat during bakeout and operations	Mechanical Drawings, Calculations
1.1.1.1.8	PFC Thermocouples	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Thermocouples mounted in tiles	Mechanical Drawings, CWDs
1.4.1.2.3	RWM Sensors	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	RWM BR sensors on primary passive plate front surface, supported by machined features in tiles; RWM Bp sensors supported tab inserted under T-bars that support the tiles	Mechanical Drawings, CWDs
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile: i) imposes thermal and mechanical loads ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.1.1.2.1	Passive plates	Eddy/Halo Current	At plasma facing copper surface of the passive plate	Tiles react disruptions loads to the passive plates. Flexing of the plate transfers load to the tiles	Calculations

Table 5-2: Interfaces for the outboard divertor[6] PFCs (WBS 1.1.1.1.5)

Interfacing WBS	Interfacing System	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.1.2.2	Outboard divertors	Structural	At surface of the outboard divertor structures	Tiles react disruptions loads to the divertor structures	Mechanical Drawings, Calculations for i) forces, ii) heat balance
1.1.1.2.2	Outboard divertors	Thermal	At surface of the outboard divertor structures	Tiles transfer heat during bakeout and operations.	Mechanical Drawings, Calculations for i) forces, ii) heat balance
1.4.1.2.2	Mirnov and Flux Loop System	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Mirnov coils are installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features, CWDs
1.4.1.17	Langmuir Probes	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	langmuir probes are installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features, CWDs
1.4.1.2.8	Tile Halo Current Measurements	Eddy/Halo Current	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Shunt tiles are installed in or under select tiles	
1.1.1.1.8	PFC Thermocouples	Spatial	Graphite boundary of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	thermocouples are installed in tiles.	Mechanical Drawings, Calculations for stresses at tile features, CWDs
1.4.1.13	Visible Spectroscopy	Spatial	At edge of tiles in the gaps of OBD rows 4 & 5	Many plasma diagnostics view through gaps in the OBD in rows 4 & 5, having their field of view set by the edges of tiles.	N/A
1.4.1.14	Physics Imaging Systems	Spatial	At edge of tiles in the gaps of OBD rows 4 & 5	Many plasma diagnostics view through gaps in the OBD in rows 4 & 5, having their field of view set by the edges of tiles.	N/A
1.1.1.1.4	Horizontal Target PFCs	Spatial	At tile surfaces or edges in the region of the previous CHI gap	i) Minimal radial gap between tiles consistent with installation requirements electrical requirements, and mechanical displacements. These include thermal growth of the casing during operations and bakeout, static EM loads, and lateral halo current loads. ii) At room temperature, there should be no difference in vertical position (Z) between the outermost	Mechanical Drawings

[6] The HHF OBD-R2 and LHF OBD-R3 tiles should be designed with a step such that |Z| increases when moving radially outward across the interface.

				point on the IBDH and innermost point on the OBD-R1	
1.3.4.2.3	Outboard Divertor Injection Systems	Spatial	Surface of gas delivery tube	Provision in tiles to run tubes for lower outboard divertor gas fueling, including provision of an orifice.	Mechanical Drawings
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile: i) imposes thermal and mechanical loads, ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.3.5.3	Li Evaporator (LITER)	Spatial	Surface of PFCs, surface of LITER	LITER probe is driven to a position in the gaps of the outboard divertor when it is evaporating.	N/A
1.1.1.2.2	Outboard divertors	Eddy/Halo Current	At surface of outboard divertor copper structures	Halo currents and potentially eddy currents transferred from the tiles and their mounting structures to the outboard divertor	N/A
1.4.1.5	CHERS	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma for the PCHERS system	N/A
1.4.1.6	FIDA	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A
1.4.1.13	Visible Spectroscopy	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A
1.4.1.13.1	Filterscopes	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A
1.4.1.19	MAPP	Spatial	At cut-out in outboard divertor structures	Cut-out allows probe insertion	N/A
1.4.1.20	Bolometers & Vacuum Radiation Sensors	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A
1.4.1.21	IR Cameras for Thermography	Spatial	At cut-out in outboard divertor structures	Cut-out allows diagnostic views of the plasma	N/A

Table 5-3: Interfaces for the inner horizontal target (IBDH) PFCs (WBS 1.1.1.1.4)

Interfacing WBS	Interfacing System	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation

1.1.3.3.9	Horizontal Target Cooling System	Structural	At the surface of the casing flange or cooling plate.	Tiles and their backing structures react disruptions loads to the casing	Mechanical Drawings, Calculations for forces
1.1.3.3.9	Horizontal Target Cooling System	Thermal	At the surface of the casing flange or cooling plate.	Tiles and their backing structures transfer heat during bakeout and operations.	Mechanical Drawings, Calculations for heat balance
1.4.1.2.2	Mirnov and Flux Loop System	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Mirnov coils installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features
1.4.1.17	Langmuir Probes	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Langmuir probes are installed in or between the tiles	Mechanical Drawings, Calculations for stresses at tile features
1.1.1.1.8	PFC Thermocouples	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	thermocouples are installed in or between the tiles.	Mechanical Drawings, Calculations for stresses at tile features
1.1.1.1.3	Vertical Target PFCs	Spatial	At surface or edges of tiles.	Wireways and tubing routes bridging the IBDV and IBDH must be aligned	Mechanical Drawing
1.3.4.3.1	High field side injectors	Spatial	Surface of gas delivery tube	Provision in tiles or backing structures to run tubes for shoulder, midplane, and divertor gas injection lines	Mechanical Drawing
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile: i) imposes thermal and mechanical loads, ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.1.3.3.9	Horizontal Target Cooling System	Eddy/Halo Current	At surface of the target cooling system	Halo currents and potentially eddy currents transferred from the tiles and their mounting structures to the horizontal target cooling system'	N/A
1.1.3.3.9	Horizontal Target Cooling System	Spatial	At surface of cooling plate	Allowance for wire bundles from CSFW, CSAS, and IBDV diagnostic wires to run to the organ pipes on the casing flange; allowance for gas delivery tubing	Mechanical Drawing
1.1.1.1.5	Outboard divertor PFCs	Spatial	At tile surfaces or edges in the region of the previous CHI gap	i) Minimal radial gap between tiles consistent with installation requirements electrical requirements, and mechanical displacements. These include thermal growth of the casing during operations and bakeout, static EM loads, and lateral halo current loads. ii) At room temperature, there should be no difference in vertical position (Z) between the outermost point on the IBDH and innermost point on the OBD-R1	Mechanical Drawings

1.3.4.2.5	Private Flux Region Fueling	Spatial	Hole in horizontal target PFC	Gas from PFR injectors passes through holes in PFCs	Mechanical Drawing
1.3.4.3.2	Massive gas injectors	Spatial	Hole in horizontal target PFC	Gas from MGI valves passes through holes in PFCs	Mechanical Drawing

Table 5-4: Interfaces for the inner vertical target (IBDV) PFCs (WBS 1.1.1.1.3)

Interfacing WBS	**Interfacing System**	**Type of Interface**	**Interface Boundary**	**Interface Description**	**Required Interface Documentation**
1.1.3.3.6	Center stack casing	Structural	At the surface of the casing.	Vertical target tiles, or structures designed to hold these tiles, are mounted to the casing, reacting loads on the PFCs	Mechanical Drawings, Calculations for forces
1.1.3.3.6	Center stack casing	Thermal	At the surface of the casing.	Vertical target tiles, or structures designed to hold these tiles, are mounted to the casing, transferring heat to PFCs during bakeout and from PFCs during operations.	Mechanical Drawings, Calculations for heat balance
1.4.1.2.2	Mirnov and Flux Loop System	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Mirnov coils embedded in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.4.1.17	Langmuir Probes	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Langmuir probes embedded in or in between tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.8	PFC Thermocouples	Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic.	Thermocouples embedded in or in between tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.2	CSAS PFCs	Spatial	At surface or edges of tiles	i) CSAS tiles shall shadow IBDV tiles when viewed from the midplane ii) Wireways and tubing routes on CSAS and IBDV must be aligned	Mechanical Drawing
1.3.4.3.1	High field side injectors	Spatial	Surface of gas delivery tube	Provision in tiles or backing structures to run tubes for shoulder, midplane, and divertor gas injection lines	Mechanical Drawings
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile: i) imposes thermal and mechanical loads,ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.1.3.3.6	Center stack casing	Spatial	At casing surface	Allowance for wire bundles from CSFW, CSAS, and IBDV diagnostic wires to run to the organ pipes on the casing flange; allowance for gas delivery tubing	Wiring Schematic, Mechanical Drawing
1.1.1.1.4	Horizontal Target PFCs	Spatial	At surface or edges of tiles.	Wireways and tubing routes bridging the IBDV and IBDH must be aligned	Mechanical Drawing
1.1.3.3.6	Center stack casing	Eddy/Halo Current	At casing surface	Halo currents and potentially eddy currents transferred from the tiles and their mounting structures to the casing.	N/A

Table 5-5: Interfaces for the Center Stack Angled Section (CSAS) PFCs (WBS 1.1.1.1.2)

Interfacing WBS	Interfacing System	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.6	Center stack casing	Structural	At surface of casing.	CSAS tiles are mounted to the casing, reacting loads PFCs during operations.	Mechanical Drawings, Calculations for forces
1.1.3.3.6	Center stack casing	Thermal	At surface of casing.	CSAS tiles are mounted to the casing, transferring heat to PFCs during bakeout and from PFCs during operations.	Mechanical Drawings, Calculations for heat balance
1.1.1.1.8	PFC Thermocouples	Spatial, Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	i) Thermocouples in the tiles ii) Wireways allowing wires from CSFW diagnostics	Mechanical Drawings, Calculations for stresses at tile features
1.3.4.3.1	High field side injectors	Spatial	Surface of gas delivery tube	Provision for i) shoulder injector gas lines and outlets ii) midplane injector gas lines	Mechanical Drawing
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile i) imposes thermal and mechanical loads ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.1.3.3.6	Center stack casing	Spatial	At surface of casing	Allowance for wire bundles from the CSFW and CSAS diagnostics; allowance for gas delivery tubing	Mechanical Drawing
1.1.1.1.3	Vertical Target PFCs	Spatial	At surface or edges of tiles	i) CSAS tiles shall shadow IBDV tiles when viewed from the midplane ii) Wireways and tubing routes on CSAS and IBDV must be aligned	Mechanical Drawing
1.1.1.1.1	Center Stack First Wall PFCs	Spatial	At tile surfaces/edges	Wireways and tubing routes on CSAS and CSFW must be aligned	Mechanical Drawing
1.1.3.3.6	Center stack casing	Eddy/Halo Current	At casing surface	Halo currents and potentially eddy currents transferred from the tiles and their mounting structures to the casing.	N/A

Table 5-6: Interfaces for the Center Stack First Wall (CSFW) PFCs (WBS 1.1.1.1.1)

Interfacing WBS	Interfacing System	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.6	Center stack casing	Structural	At surface of casing.	CSFW tiles are mounted to the casing, reacting loads on the PFCs	Mechanical Drawings, Calculations for forces
1.1.3.3.6	Center stack casing	Thermal	At surface of casing.	CSFW tiles are mounted to the casing, transferring heat to PFCs during bakeout and from PFCs during operations.	Mechanical Drawings, Calculations for heat balance
1.4.1.2.2	Mirnov and Flux Loop System	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Mirnov coils are embedded in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.4.1.17	Langmuir Probes	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Langmuir probes are located in or between tiles	Mechanical Drawing, Calculations for stresses at tile features
1.1.1.1.8	PFC Thermocouples	Diagnostic	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Thermocouples in tiles	Mechanical Drawing, Calculations for stresses at tile features
1.4.1.2.8	Tile Halo Current Measurements	Spatial	Graphite surface of the tile, in some cases machined by PFC engineering to provide a space or volume for the diagnostic	Current measurements under tiles	Mechanical Drawings
1.1.1.1.2	CSAS PFCs	Spatial	At tile surfaces/edges	Wireways and tubing routes on CSAS and CSFW must be aligned	Mechanical Drawing
1.3.4.3.1	High field side injectors	Spatial	Surface of gas delivery tube	Tiles shall have provision for tube routing and gas deliver orifices	Mechanical Drawings
0.1.1.2	Plasma	Plasma	Front surface of tiles	Plasma interacting with tile: i) imposes thermal and mechanical loads ii) Causes sputtering and tile erosion.	Calculation for forces and heat balance
1.1.3.3.6	Center stack casing	Spatial	At surface of casing	Allowance for wire bundles from the CSFW diagnostics; allowance for gas delivery tubing	Mechanical Drawing
1.1.3.3.6	Center stack casing	Eddy/Halo Current	At casing surface	Halo currents and potentially eddy currents transferred from the tiles and their mounting structures to the casing.	Calculation