National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

MAGNET SYSTEMS

NSTX-U-RQMT-SRD-002-02

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Stefan Gerhardt Digitally signed by Stefan Gerhardt
DN: cn=Stefan Gerhardt, o=Physics, ou=PPPL, email=sgerhard@pppl.gov, c=US
Date: 2018.03.08 08:49:28 -05'00'

Prepared By: S. Gerhardt, Systems Engineering and Integration

Steve Raftopoulos Digitally signed by Steve Raftopoulos
Date: 2018.03.08 12:04:16 -05'00'

Reviewed: S. Raftopoulos, Magnets RE

Lawrence E. Dudek Digitally signed by Lawrence E. Dudek
Date: 2018.03.08 12:19:39 -05'00'

Reviewed By: Larry Dudek, Mechanical Technical Authority

John C. Lacenere Digitally signed by John C. Lacenere
Reason: I am approving this document
Date: 2018.03.12 16:14:23-04'00'

Reviewed By: John Lacenere, Electrical Technical Authority

Charles L. Neumeyer Digitally signed by Charles L. Neumeyer
DN: cn=Charles L. Neumeyer, o=PPPL, ou, email=neumeyer@pppl.gov, c=US
Date: 2018.03.12 17:15:17 -04'00'

Reviewed: Charles Neumeyer, NSTX-U Project Engineer

Russell Feder Digitally signed by Russell Feder
Date: 2018.03.12 18:08:39 -04'00'

Reviewed By: Russ Feder, NSTX-U Project Manager

Valeria Riccardo Digitally signed by Valeria Riccardo
Date: 2018.03.12 22:25:05 -04'00'

Approved By: Valeria Riccardo, PPPL Chief Engineer

3/13/2018

Jonathan E. Menard Jonathan Menard

Accepted By: Jon Menard, NSTX-U Project Director

Change Record

Revision	Date	Description of Change
0	12/11/2017	Initial Release
1	1/29/2018	Reduced PF-1a ESW time from 2.1 seconds to 1.9 seconds
2	3/8/2018	Modified signature block as per new QAPD and ENG-050
		Replaced all interface tables w/ new tables as per the interface spreadsheet
		Updated table 2-1 for a two-wire configuration on the PF-1a coil
		Changed 7.5a to indicated that only PF-1a may require the bipolar upgrade
		Removed statement 1b, which was not actionable.
		Added a footnote on Section 3.4 clarifying the meaning of ESW
		Removed mention of PF-1a and PF-1b in Section 3.5
		Corrected erroneous statement on TF outer legs in 5.3a
		Moved repetition rate statement on inner-PF coils from 7.2 to 7.4.
		Fixed section numbering of Bus Work section; is now Section 9
		Added a footnote with the implied meaning of '2E+1' in Section 2.
		Removed 7.2b, which had put a 100 C limit on the inner-PF end-of-pulse temperature.
		Added Ref. 7
		Added requirement 2.0i that cooling features must be compatible with DI water service.

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References

[1] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*
[2] NSTX-U-RQMT-RD-010, *NSTX-U Magnetic Permeability Requirements*
[3] NSTX-CRIT-0001, *NSTX Structural Design Criteria*
[4] NSTX-U Design Point Spreadsheet, Design Point Spreadsheet Page
[5] NSTXU-CALC-10-03, *Design Point Calculations for NSTX Center Stack Upgrade*
[6] NSTX-U-RQMT-RD-003, *NSTX-U Disruption Requirements*
[7] Procedure ENG-037, *General Welding and Brazing Requirements*
[8] NSTX-U-RQMT-SRD-004, *Vacuum Vessel and Internal Hardware*

1. Scope and Format

a. The format of this document, including interfaces specifications, is provided in the General Requirements Document [1].

b. Any and all constraints on the simultaneous current distribution in the TF, PF, and OH coils, and the plasma, besides the individual peak coil current ratings, shall be explicitly identified as an outcome of the design process.

2. Common Requirements

a. Permeability requirements are as per Ref. [2], while mechanical design shall be governed by the NSTX-U Structural Design Criteria [3].

b. Static EM loads are defined in the Design Point Spreadsheet [4,5], while disruption loads are derived from the specification in Ref. [6].

c. Up-down symmetry of the vessel and magnets shall be a feature of the design to the greatest extent possible. Symmetry deviations greater than 0.5 cm shall be approved by Project Physics.

d. Toroidally continuous passive structures shall be minimized to the extent that other design constraints permit, and shall be made of high resistivity materials where possible.

e. Pressurized elements must comply with PPPL Standard ES-MECH-15 as appropriate.

f. Final values for turn counts, turn layouts, maximum currents, maximum voltages, required action integrals, and other numerical parameters for the coils shall be recorded in the revision controlled Design Point Spreadsheet [4].

g. All coil designs shall allow for operation of the toroidal field in either direction, and of the plasma current in either direction.

h. All coils shall be fabricated from copper conductor with internal cooling channel sized to support a 1200 second repetition period.

i. Water fitting materials shall be compatible with deionized water service.

j. Operational scenarios for coils shall accommodate any combination of PF, OH, and TF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with $I_P=0$ or $\neq 0$ except where this is judged impractical and special exception is taken as per Section 6.1.3.1.1e of the General Requirements Document [1].

k. 20000 full power pulses shall be used as the fundamental design basis. The shot spectrum from the GRD may be used only if that proves impractical.

l. Terminal voltage, three-wire stack-up factors, and hipot requirements are provided in Table 2-1. These follow the '2E+1' rule.[1]

m. Brazes on coils shall meet requirements of PPPL procedure Eng-037 [7].

***Table 2-1**: Terminal voltages and high pot voltages*

	# Series Supplies	Terminal Voltage	Three-Wire Factor[2]	Hipot Requirement (To Ground)
	---	V	1 or 2	kV
TF	1	1013	1	3.0
OH	6	6078	1	13.2
PF-1a	2	2026	1	5.1
PF-1b	2	2026	2	9.1
PF-1c	2	2026	2	9.1
PF-2	2	2026	2	9.1
PF-3	2	2026	2	9.1
PF-4	2	2026	1	5.1
PF-5	3	3039	1	7.1
RWM	1	1000	1	3.0

[1] The 2E+1 rule states that the ground insulation shall satisfy a high pot voltage of that value in kV, where E is the maximum voltage to ground (in kV) that the coil may be exposed to during any operations scenario. The '1' is an implied 1 kV.

[2] Three wire factor indicates if the coil will have a three-wire ($f_{three\text{-}wire}$=2) or four-wire ($f_{three\text{-}wire}$=1) configuration. Three wire configuration have the potential for twice the maximum terminal voltage to appears across the ground insulation on certain fault conditions. The required high-pot voltage is given by $2V_{terminal}f_{three\text{-}wire}+1$, where $V_{terminal}$ is the maximum terminal voltage.

3. Outer PF Coils (WBS 1.1.3.1)

3.1: Functions

The function of the poloidal field (PF) coil system is to:

a. Support the plasma against radially expanding current and pressure forces.

b. Provide plasma shaping and divertor/scrape-off control.

c. Provide vertical/radial position control using active feedback.

d. Help compensate for poloidal fields (leakage flux) from the ohmic heating solenoid.

e. Provide additional poloidal flux to the plasma.

3.2: Materials and Design Requirements

a. See Section 1.

3.3: Configuration Requirements & Essential Features

a. The outer PF magnets shall consist of four pairs of water-cooled copper coils designated as PF 2a/2b, 3a/3b, 4b/4c, and 5a/5b. The pairs shall be symmetric about the horizontal mid-plane of the NSTX-U device. All coils PF 1a/1b/1c are part of the Inner PF subsystem, WBS 1.1.3.3.3.

b. Coils identified on the S-1 spheromak as EF coils #1, #2 and #3 shall be used for the outer PF coils PF2, PF3, and PF4 on NSTX-U.

c. PF5 shall be the new coil fabricated for NSTX.

d. The outer PF coils shall be mechanically supported by the vacuum vessel structure. The support mechanism shall be compatible with the vacuum vessel thermal expansion during bakeout and operations, as well as coil thermal expansion and electromagnetic loads. Outer PF coil support systems are described in Ref. [8].

e. The outer PF coils shall be connected in series groups as indicated in Table 3.3-1.

Table 3.3-1: *Series PF Coils*

Coil Grouping
PF2a, PF2b, upper
PF2a, PF2b, lower
PF3a, PF3b, upper
PF3a, PF3b, lower
PF4b, PF4c, upper & lower
PF5a, PF5b, upper & lower

f. All series coil connections shall result in current flow which is equal in magnitude, and in the same ϕ direction, in the upper and lower coils.

3.4: Baseline Performance & Operational Requirements

a. The outer PF coils shall be capable of supplying 100% of their rated ampere-turns in the form of a linear ramp-up, flat top, and linear ramp-down waveform synchronized with the I_p waveform. See Ref. [1] for the plasma current waveform.

b. The outer PF coils shall be able to conduct the pulse currents once every 1200 seconds.

c. Each series group of outer PF coils shall be able to operate with the terminal voltages indicated in table 2-1.

d. Outer PF coils must satisfy a hipot voltage of 2E+1. Any coils connected in a three-wire configuration shall have E as the sum of the maximum terminal voltages of the coils which share the central connection to FCPC. If connected with a two-wire connection, then E shall be the maximum terminal-to-terminal voltage. Numerical values are provided in Table 2-1.

e. All upper and lower PF coil pairs, with the exception of the PF4's and PF5's, shall have separate control of the current in the upper and lower coils.

f. PF-3U and PF-3L shall be capable of bipolar operation with ampacity and voltage to null the leakage flux from the OH coil for a full 24 kA precharge while also transitioning to the confining polarity sufficiently quickly following breakdown.

g. Action integrals, ESW duration[3], final turn counts, and ampacities are found in the Design Point Spreadsheet [4].

3.5: Upgrade Performance & Operational Requirements

a. The configuration of the PF-5 coils should be compatible, with modest modifications, with a potential upgrade to 34 kA current level.

b. Bipolar operations of the PF-2 and PF-4 coils may be required in the future.

[3] The Equivalent Square Wave (ESW) duration is the duration of a square wave of the stated amplitude which brings the coil to the design integral(I^2dt) limit.

3.6: Interfaces

***Table 3.6.1**: Interfaces for the Outer PF Coils (WBS 1.1.3.1)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.3.2	Outer PF Supports	Structural	The outside of the coil ground insulation and/or ground plane.	Mechanical support interface with allowance for thermal and EM distortions	Calculations, Mechanical Design Drawings
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid or flexible bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid or flexible bus bars connect to the coil terminal are supported to some extent by the terminals	Calculation, Mechanical Design Drawing
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At water fittings on the end of each coil loop	Provides cooling water to the outer-PF	P&ID

4. TF Outer Legs (WBS 1.1.3.2)

4.1: Functions

The function of the toroidal field (TF) coil system is to provide the toroidal magnetic field which is necessary to magnetically confine the NSTX-U plasma.

4.2: Materials and Design Requirements

a. See Section 1.

4.3: Configuration Requirements & Essential Features

a. NSTX-U shall use the TF outer legs fabricated for NSTX, with remanufacture of coils of similar design as necessary to replace any deemed not reliable.

b. The outer TF coils consist of an outer array of twelve coil bundles, each with three conductors. The inner legs of the TF coils are part of the Center Stack subsystem.

c. The outer TF coils shall be supported from the NSTX-U vacuum vessel.

d. Demountable joints shall be provided between the TF outer legs and TF inner legs to allow removal/replacement of the Center Stack assembly.

4.4: Baseline Performance & Operational Requirements

a. The baseline design of the outer legs of the TF coils shall be capable of producing the toroidal fields as given in Figure 4.4-1. Here, LPPI refers to a “Long Pulse Partial Inductive” scenario, while “SPFI” refers to a short pulse full inductive scenario. These are specified numerically in Tables 4.4-1 and 4.4-2.

***Figure 4.4-1**: Reference Waveforms for the toroidal field. Here, S&B refers to the case with a rectifier suppress and bypass immediately preceding the final TF ramp-down (i.e. the time which results in the greatest heating).*

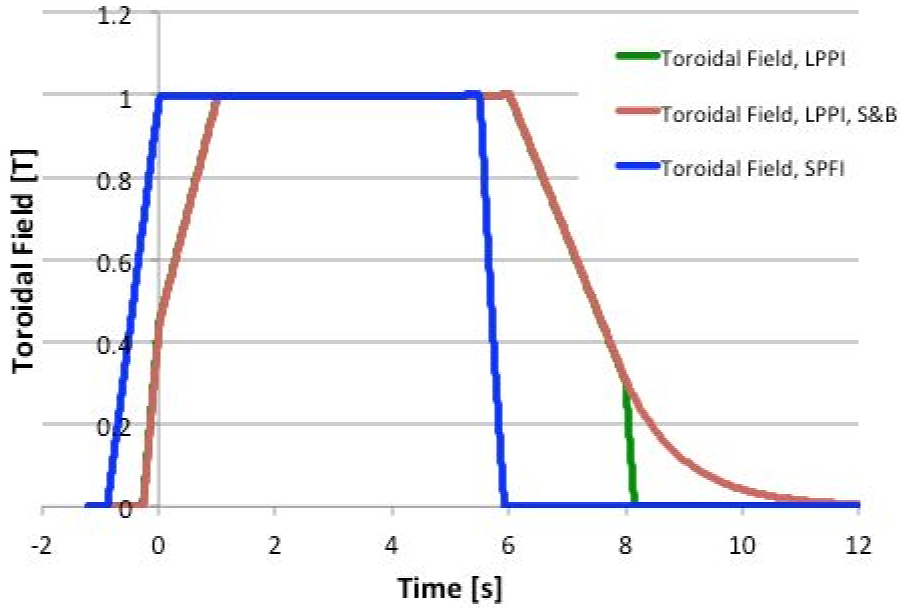

***Table 4.4-1:** TF Performance for the LPPI Scenario*

Time [s]	Bt [T]
-0.28	0
0.00	0.45
1.00	1.00
6.00	1.00
8.00	0.30
8.18	0

***Table 4.4-2:** TF Performance for the SPFI Scenario*

Time [s]	Bt [T]
-0.89	**0**
0.00	1.00
5.50	1.00
5.96	0

c. The TF coils shall be able to supply the pulse currents required to produce the fields given in Tables 3.4-1 and 3.4-2 once every 1200 seconds.

d. Outer TF coils must satisfy a hipot voltage of 2E+1. Here, E shall be the maximum terminal-to-terminal voltage of 1012 V. Numerical values are provided in Table 2-1.

g. Action integrals, ESW duration, and ampacities are found in the Design Point Spreadsheet [4].

4.5: Upgrade Performance & Operational Requirements

a. There are no upgrade requirements on the TF coil outer legs.

4.6: Interfaces

Table 4.6.1*: Interfaces for the TF coil outer legs (WBS 1.1.3.2)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.3.3.1	TF Inner Legs	Electrical Power	at electrical faces of the coils	a set of bus work, some of which is water cooled, connects the inner to the outer legs	Calculation, Mechanical Design Drawing
1.1.3.3.1	TF Inner Legs	Fluid	at the fittings on the coils	water from the low-pressure distribution is run through the outer legs, then the inner legs. This reduces thermal shock to the inner legs.	P&ID
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.4.1.2.4	Diamagnetic Loop System	Structural	Outside of coil ground insulation	A rogowski is mounted to the outer TF leg, for use in the diamagnetic flux measurement	Mechanical Design Drawing
1.1.2.3.1	Outer TF Truss System	Structural	The outside of the coil ground insulation and/or ground plane.	Mechanical support interface with allowance for thermal and EM distortions	Calculations, Mechanical Design Drawings
1.1.2.1.2	Umbrella structure & Spoked Lids	Structural	At surface of blocks that are glued to the TF outer legs	TF torques are reacted through the umbrella structure	Mechanical Drawing, Calculation
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At water fittings on both sides of the outer legs.	Provides cooling water for outer legs, before water is passed to inner legs	P&ID
1.7.3.4.1	Fiber optic strain, temp., disp. meas.	Diagnostic	Surface of coil	Sensors measures strain in the TF outer leg	Mechanical Drawing

5. TF Inner Legs (WBS 1.1.3.3.1)

5.1: Functions

a. The function of the TF coils is described in WBS 1.1.3.2

5.2: Materials and Design Requirements

a. See Section 1.

5.3: Configuration Requirements & Essential Features

a. The TF magnet shall consist of a 36 turn inner leg bundle connected in series with the existing 12 outer legs, each of which has three turns.

b. The inner legs of the TF coils shall consist of tightly-nested fully-bonded copper conductors. The utilization of cross sectional area shall be optimized to maximize the conductor cross sectional area and minimize the radial build of the center stack assembly.

c. Structural support of the TF coil shall allow for axial thermal expansion while ensuring that the coil remains centered when subject to electromagnetic loads.

d. The water cooling for each inner leg shall be in series with the associated outer leg, with the outer leg receiving the cooling water first.

5.4: Baseline Performance & Operational Requirements

a. The TF inner legs shall be designed to, in concert with the outer legs, produce the toroidal field evolution described in Fig. 4.4-1 and Tables 4.4-1 and 4.4-2.

b. Cooling shall be provided consistent with a 1200 sec repetition period, or a 2400 sec repetition period upgradeable to a 1200 sec repetition period without modification to the coil.

c. Electrical insulation design for the TF inner legs, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1, for both coil-to-ground and inter-turn tests. E shall correspond to the maximum power supply line-to-line DC voltage. Numerical values are provided in Table 3.4.1.

d. The TF turn-to-turn transitions shall include features to minimize stray field due to net toroidal turn. Alternatively it may be demonstrated that the field error due to turn-to-turn transitions can be nullified to a magnitude less than 1 gauss anywhere between $R_0-a \le r \le R_0+a$, z=0.

g. Action integrals, ESW duration, turn counts, and ampacities are found in the Design Point Spreadsheet [4].

5.5: Upgrade Performance & Operational Requirements

There are no upgrade requirements on the TF coil inner legs.

5.6: Interfaces

Table 5.6.1: *Interfaces for the TF coil inner legs (WBS 1.1.3.3.1)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.2	Umbrella structure & Spoked Lids	Structural	At the interface between the torque plate and the spoked lid.	Torque is transferred to the upper umbrella structure through the spoked lid	Calculations, Mechanical Design Drawings
1.1.3.3.7	Pedestal	Structural	At the interface between the lower torque plate and the upper surface of the pedestal.	The CS pedestal supports the Inner TF legs, as well as the rest of the CS assembly, against gravity, as well as supporting the TF out-of-plane loads.	Calculations, Mechanical Design Drawings
1.1.3.3.2	Ohmic Heating Solenoid	Structural	Vertically, on the horizontal planes on either end of the TF inner legs; the OH preload spring stack is a component of this interface. Radially, the teflon slip-plane and aquapour/CTD-425 material sets the interface.	Mechanical support interface with allowance for thermal and EM distortions	Calculations, Mechanical Design Drawings
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bar connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.6	Center Stack Casing	Structural	At surface of G10 plate bonded to the lower inner legs.	The casing is supported by the inner-TF legs, via a series of components including the OH skirt and casing support weldment	Mechanical Drawing
1.1.3.2	TF outer legs	Electrical Power	at electrical faces of the coils	a set of bus work, some of which is water cooled, connects the inner to the outer legs	Calculation, Mechanical Design Drawing
1.1.3.2	TF outer legs	Fluid	at the fittings on the coils	water from the low-pressure distribution is run through the outer legs, then the inner legs. This reduces thermal shock to the inner legs.	P&ID
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At water fittings on both sides of the inner legs.	Provides cooling water for inner legs, after water has passed through outer legs	P&ID
1.7.3.4.1	Fiber optic strain, temp., disp. meas.	Diagnostic	Surface of coil insulation	Sensors measure strain in multiple directions on the surface of the TF bundle	Mechanical Drawing

6. OH Solenoid (WBS 1.1.3.3.2)

6.1: Functions

a. The Ohmic Heating (OH) solenoid's primary function is to provide sufficient loop voltage for plasma initiation, and sufficient flux swing for inductive plasma current drive.

6.2: Materials and Design Requirements

a. See Section 1.

6.3: Configuration Requirements & Essential Features

a. The OH coil shall consist of a solenoid surrounding the inner legs of the TF coil. The utilization of cross sectional area shall be optimized to maximize the conductor cross sectional area and minimize the radial build of the center stack assembly.

b. The height of the OH coil shall be maximized within the available envelope to maximize the flux linkages with the plasma and minimize the stray fields during plasma initiation.

c. Structural support of the OH coil shall allow for axial thermal expansion while ensuring that the stresses remain within allowables when subject to electromagnetic loads.

d. An array of thermocouples shall be mounted to the OH coil, to assess temperature excursions during normal operations and bakeout [4].

e. The surface of the new OH coil shall be provided with a ground plane of sufficient conductivity to serve as an electrostatic shield while limiting induced currents. Suitable ground plane leads shall be provided for a ground connection on both the upper and lower ends of the coil.

f. A vertical array of flux loops shall be mounted on the OH coil outside the ground plane [4].

g. The OH lead shall utilize a coaxial design to minimize net force and field error.

6.4: Baseline Performance & Operational Requirements

a. The OH coil shall be designed to operate with a maximum terminal to terminal voltage of 6077 volts, and a current limit of +/- 24 kA.[4]

b. For engineering purposes, the required parameters of the OH coil can be found in Table 6.4-1.

[4] The 24 kA limit is derived from the capacity of a single TRANSREX power supply, while the 6077 V value is the sum of 6 series connected TRANSREX supplies.

***Table 6.4-1**: Engineering requirements on the OH coil*

Parameter	Units	Value
Initiation Loop Voltage	V	4.665
Initiation Duration	s	0.020
Ramp Up Flux Swing	Wb	0.700
Ramp Up Duration	s	1.000
Flat Top Flux Swing, LPPI	Wb	0.812
Flat Top Duration, LPPI	s	5.000
Flat Top Loop Voltage, LPPI	V	0.162
Flat Top Flux Swing, SPFI	Wb	1.285
Flat Top Duration, SPFI	s	2.500
Flat Top Loop Voltage, SPFI	V	0.514

c. Electrical insulation design for the OH coil, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. For the OH coil, E shall correspond to the maximum power supply line-to-line DC voltage. Numerical values are provided in Table 2-1.

e. The current evolution of the OH coil shall be such that the condition $T_{OH}>T_{TF}$ is maintained.

g. Action integrals, ESW durations, final turn counts, ampacities, vertical forces, and hoop forces are found in the Design Point Spreadsheet [4].

6.5: Upgrade Performance & Operational Requirements

a. Operation of the coil to 105 C may be utilized in the future to allow $T_{OH}>T_{TF.}$.

6.6: Interfaces

***Table 6.6-1**: Interfaces for OH Solenoid (WBS 1.1.3.3.2)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.2	Umbrella structure & Spoked Lids	Structural	At the interface between the torque plate and the spoked lid.	Torque is transferred to the upper umbrella structure through the spoked lid	Calculations, Mechanical Design Drawings
1.1.3.3.7	Pedestal	Structural	At the interface between the lower torque plate and the upper surface of the pedestal.	The CS pedestal supports the Inner TF legs, as well as the rest of the CS assembly, against gravity, as well as supporting the TF out-of-plane loads.	Calculations, Mechanical Design Drawings
1.1.3.3.2	Ohmic Heating Solenoid	Structural	Vertically, on the horizontal planes on either end of the TF inner legs; the OH preload spring stack is a component of this interface. Radially, the teflon slip-plane and aquapour/CTD-425 material sets the interface.	Mechanical support interface with allowance for thermal and EM distortions	Calculations, Mechanical Design Drawings
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bar connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.6	Center Stack Casing	Structural	At surface of G10 plate bonded to the lower inner legs.	The casing is supported by the inner-TF legs, via a series of components including the OH skirt and casing support weldment	Mechanical Drawing
1.1.3.2	TF outer legs	Electrical Power	at electrical faces of the coils	a set of bus work, some of which is water cooled, connects the inner to the outer legs	Calculation, Mechanical Design Drawing
1.1.3.2	TF outer legs	Fluid	at the fittings on the coils	water from the low-pressure distribution is run through the outer legs, then the inner legs. This reduces thermal shock to the inner legs.	P&ID
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At water fittings on both sides of the inner legs.	Provides cooling water for inner legs, after water has passed through outer legs	P&ID
1.7.3.4.1	Fiber optic strain, temp., disp. meas.	Diagnostic	Surface of coil insulation	Sensors measure strain in multiple directions on the surface of the TF bundle	Mechanical Drawing

7. Inner PF Coils (1.1.3.3.3 - 1.1.3.3.5)

7.1: Functions

The functions of the inner-PF coils are to:

a. provide poloidal field enabling a diverted (or X-point) plasma configuration

b. control the divertor poloidal flux expansion

b. assist in controlling the inner plasma-wall gap

c. sweep the divertor strike-points in order to distribute the PFC heat fluxes

7.2: Materials and Design Requirements

a. See Section 1

7.3: Configuration Requirements & Essential Features

a. The inner-PF coils shall consist of three upper and lower coil pairs, denoted PF-1a, PF-1b, and PF-1c.

<u>All Coils</u>

b. Coils shall be fabricated from conductors with embedded cooling channels.

c. Cooling holes shall be sized to permit a 1200 second repetition rate at the stated current levels and ESW.

d. Coils shall be designed with turn-to-turn and turn-to-ground insulation with significant (>x10) margin on expected operating voltages, including fault cases.

e. Coils shall be designed and manufactured in a fashion that facilitates turn-to-turn insulation testing before final installation

<u>PF-1a</u>

f. The centroid of the coil shall be at R=0.325, Z=+/- 1.591. Deviation on order of 1.0 cm in radial or vertical position shall be allowed in consultation with Project Physics.

g. Each PF-1a coil shall have the following diagnostics mounted outside the ground insulation, but underneath any support slings or structures [4]:

- Four flux loops
- Two thermocouples

<u>PF-1b</u>

h. The centroid of the coil shall be at R=0.400, Z=+/- 1.804. Deviation on order of 1.0 cm in radial or vertical position shall be allowed in consultation with Project Physics.

i. Each PF-1b coil shall have the following diagnostics mounted outside the ground insulation, but underneath any support slings or structures [4]:
- Two flux loops
- Two thermocouples

<u>PF-1c</u>

j. The centroid of the coil shall be at R=0.550 m, Z=+/- 1.814 m. Deviation on order of 1.0 cm in radial or vertical position shall be allowed in consultation with Project Physics.

k. Each PF-1c coil shall have the following diagnostics mounted outside the ground insulation, but underneath any support slings or structures [4]:
- Two flux loops
- At least two thermocouples

7.4: Baseline Performance & Operational Requirements

a. The minimum required amp-turns and ESW durations for the three inner-PF coils are as per the following table:

Table 6.4-1: *Minimum ampacity and ESW requirements for the inner-PF coils*

		PF-1a	PF-1b	PF-1c
Ampacity	kA-turns	1200	400	320
ESW at Stated Ampacity	s	1.9	1.0	1.4

b. This ampacity must be achieved within the 24 kA rating of the Transrex power supplies.

c. Electrical insulation design for the inner PF coils, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. For the inner-PF coils, E shall correspond to twice the maximum power supply line-to-line DC voltage, as appropriate for three wire power configurations. Numerical values are provided in Table 2-1.

g. The repetition period of the inner-PF coils shall be 1200 seconds.

h. Final values of action integrals, ESW durations, turn counts, and ampacities are found in the Design Point Spreadsheet [4].

7.5: Upgrade Performance & Operational Requirements

a. Bipolar operations of the PF-1a may be required in the future.

7.6: Interfaces

Table 7.6-1: *Interfaces for the PF-1a coils (WBS 1.1.3.3.3)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.3.2.1.2	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first	P&ID, Mechanical Design Drawing
1.7.3.4.2	Center stack coil thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil	Mechanical Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing
1.1.3.3.6	Center Stack Casing	thermal	At surface of coil	microtherm blanket provides thermal isolation between coils and casing	Mechanical drawing, Calculation
1.1.3.3.11	PF-1a Support Structure	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack	Mechanical drawing, Calculation
1.1.3.3.11	PF-1a Support Structure	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly. Pre-load is applied to the coils by the coil supports.	Calculation, Mechanical Design Drawing
1.4.1.2.2	Mirnov and Flux Loop System	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing
1.1.3.3.10	Vertical Target Cooling System	spatial	at the surface of the heat transfer tubes	heat transfer tubes need to allow the PF-1a coil to fit through with sufficient clearance for alignment.	Mechanical Drawing

Table 7.6-2: *Interfaces for the PF-1b coils (WBS 1.1.3.3.4)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.3.2.1.2	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first	P&ID, Mechanical Design Drawing
1.7.3.4.2	Center stack coil thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil	Mechanical Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing

1.1.3.3.6	Center Stack Casing	thermal	At surface of coil	microtherm blanket provides thermal isolation between coils and casing	Mechanical drawing, Calculation
1.1.3.3.12	PF-1b Support Structure	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack	Mechanical drawing, Calculation
1.1.3.3.12	PF-1b Support Structure	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly. Pre-load is applied to the coils by the coil supports.	Calculation, Mechanical Design Drawing
1.4.1.2.2	Mirnov and Flux Loop System	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing

***Table 7.6-1**: Interfaces for the PF-1c coils (WBS 1.1.3.3.5)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.3.2.1.2	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first	P&ID, Mechanical Design Drawing
1.7.3.4.2	Center stack coil thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil	Mechanical Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.4	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing
1.1.3.3.8	Ceramic Break Assembly & PF-1c Support	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack	Mechanical drawing, Calculation
1.1.3.3.8	Ceramic Break Assembly & PF-1c Support	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly	Calculation, Mechanical Design Drawing
1.4.1.2.2	Mirnov and Flux Loop System	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils	Mechanical Drawing

8. Resistive Wall Mode Coils (WBS 1.1.3.5)

8.1: Functions

a. The resistive wall mode coils are designed to apply midplane radial field in order to correct error fields and provide feedback on slowly growing external kink modes (resistive wall modes)

8.2: Materials and Design Requirements

a. See Section 1

8.3: Configuration Requirements & Essential Features

a. The RWM coils shall be formed from six approximately rectangular window-pane coils, located at the vessel midplane, and conformal to the vessel outer wall.

b. RWM coils shall be mounted outside the vessel, and may be mechanically restrained against the vessel. Provision for relative expansion due to both coil operational Ohmic heating and vessel bakeout shall be made if the coils are mounted to the vessel.

c. The area of the RWM coils shall be approximately 2.4 m^2, and the areas of opposing coils shall be matched to within 5%.

d. The RWM coils shall be capable of individual power feeds, or opposing coils should be capable of series or anti-series connections.

e. Current transducers should be placed on the coil leads or bus works after any patch panel or connection box, allowing the polarities of coil currents to be determined.

c. Electrical insulation design for the RWM coils, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. For the RWM coil, E shall correspond to the maximum power supply line-to-line DC voltage. Numerical values are provided in Table 2-1.

8.4: Baseline Performance & Operational Requirements

a. The coils shall be capable of 6 kA-turn operations, for 5 seconds, every 1200 seconds.

8.5: Upgrade Performance & Operational Requirements

a. There are no upgrade requirements for the RWM coils.

8.6: Interfaces

***Table 8.6-1**: Interfaces for the RWM coils (WBS 1.1.3.5)*

Interfacing System	Interfacing WBS	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.1	Vacuum vessel	Structural	At the vessel outer radius	The RWM coils are mounted directly to the vessel	Mechanical Drawings, Calculation
1.1.3.4	Bus Bar Systems and Bus Tower	Electrical Power	At coil terminals	Connection of bus work to RWM Coils	Schematic

9. Bus Bar Systems (WBS 1.1.3.4)

9.1: Functions

a. Bus bar systems shall provide electrical connections from coil terminals to the cabling from FCPC.

9.2: Materials and Design Requirements

a. See Section 1.

9.3: Configuration Requirements & Essential Features

a. The OH current feed shall be coaxial in design.

b. RWM current feeds shall allow individual feeds, or opposing coils should be capable of series or anti-series connections, with less than three hours to reconfigure the connections.

c. Current feeds to at the top of the machine shall accommodate the thermal growth of the casing during bakeout and of the TF inner bundle during bakeout and plasma operations.

d. Grounding switches shall be installed in the test cell to enable grounding of all coil systems.

e. Structures shall be built to support bus runs to the midplane and upper level of the machine.

9.4: Baseline Performance & Operational Requirements

a. Structural support of bus runs should accommodate the full range of allowed PF, OH, and TF currents, except where this is judged impractical and special exception is taken. See 6.1.3.1.1e of Ref. [1].

b. Thermal capacity of coil bus runs shall be consistent with the action integrals of the coils to which they are attached.

c. Current and ampacity requirements for the bus work are tabulated in the Design Point Spreadsheet.

d. Electrical insulation design for bus runs shall be conservatively designed based on a hipot test voltage equal to the hipot voltage of the coil to which they are attached. Numerical values are provided in Table 2-1.

9.5: Upgrade Performance & Operational Requirements

a. There are no Upgrade requirements on the bus work.

9.6: Interfaces

***Table 9.6-1**: Interfaces for the bus work (WBS 1.1.3.4).*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.6.1.1	Control I/O systems	Electrical Signal	At digitizer input	Signals from the coil current transducers on RWM coil cables are digitized	CWD
1.1.2.1.2	Umbrella structure & Spoked Lids	structural	Where supports are welded/bolted to umbrella	Supports for the -1a, -1b, & -1c leads are supported from the umbrella structure.	Mechanical Drawing, Calculation
1.1.2.1.2	Umbrella structure & Spoked Lids	Spatial	N/A	Bus bars for the PF-1a, -1b, -1c, and -2 coils enter/leave the umbrella structure through the arches	Mechanical Drawing
1.1.2.1.2	Umbrella structure & Spoked Lids	Spatial	N/A	Bus bars for the TF and OH coils enter the umbrella through the opening in the spoked lid.	Mechanical Drawing
1.3.3.3.2	MTWS Manifolds and Vessel-Mounted Piping	Structural	Where supports attach to the bus tower	Pipes for the medium temperature water system are supported from the bus tower	Mechanical Drawing
1.1.2.3.2	Outer PF Supports	Structural	At surface of support structure	Some inner-PF and PF-2 lead supports are mounted to the PF-3 coil support	Mechanical Drawing, Calculation
1.1.3.1	Outer PF coils	Electrical Power	Flat surface of the coil flags.	Solid or flexible bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.1	Outer PF coils	Structural	Flat surface of the coil flags.	Solid or flexible bus bars connect to the coil terminal are supported to some extent by the terminals	Calculation, Mechanical Design Drawing
1.1.3.2	TF outer legs	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.1	TF Inner Legs	Electrical Power	Flat surface of the coil flags.	Solid bus bar connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.2	Ohmic Heating Solenoid	Electrical Power, Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.3	PF-1a Coils	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.3	PF-1a Coils	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing
1.1.3.3.4	PF-1b Coils	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing

1.1.3.3.4	PF-1b Coils	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing
1.1.3.3.5	PF-1c Coils	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal	Calculation, Mechanical Design Drawing
1.1.3.3.5	PF-1c Coils	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run	Calculation, Mechanical Design Drawing
1.1.3.5	Resistive Wall Mode Coils	Electrical Power	At coil terminals	Connection of bus work to RWM Coils	Schematic
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At water fittings on the end of each cooling loop	Provides cooling water to various bus bars	P&ID
1.8.1.1.8	NTC Floor	Structural	NTC Floor, Platforms	Bus tower is supported by NTC floor.	General Arrangement
1.8.1.1.1	NTC Platforms	Structural	NTC Platform	RWM cabling supported from platform.	General Arrangement
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	NTC Penetration	Cables from SPAs through NTC Penetrations	General Arrangement
1.8.1.1.4	NTC Walls	Structural	NTC Walls	Junction Box and cables supported from NTC Wall	General Arrangement
1.5.3.1	TF Convertor DC Systems	Electrical Power	At the Power Cable Termination Structure	Current is delivered to the bus work, and therefore coils.	Electrical Schematic, Mechanical Drawing
1.5.3.2	OH Convertor DC Systems	Electrical Power	At the Power Cable Termination Structure	Current is delivered to the bus work, and therefor coils.	Electrical Schematic, Mechanical Drawing
1.5.3.3	PF Convertor DC Systems	Electrical Power	At the Power Cable Termination Structure	Current is delivered to the bus work, and therefor coils.	Electrical Schematic, Mechanical Drawing
1.5.3.4	Switching Power Amplifier DC Systems	Electrical Power	At SPA interconnection box, in the test cell	Current is delivered to the bus work, and therefor coils.	Electrical Schematic, Mechanical Drawing
1.3.2.4	Water System PLC	Electrical Signal	At the PLC I/O points	Sense-switches on the coil bus run ground switches are fed to the water systems PLC, where they can be used to determine the FCPC permissive status.	CWD