National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

Heating Systems

NSTX-U-RQMT-SRD-007-01

March 30, 2018

Stefan Gerhardt Digitally signed by Stefan Gerhardt
DN: cn=Stefan Gerhardt, o=Physics, ou=PPPL, email=sgerhard@pppl.gov, c=US
Date: 2018.03.30 10:18:04 -04'00'

Prepared By: Stefan Gerhardt, Systems Engineering and Integration

Timothy N. Stevenson Digitally signed by Timothy N. Stevenson
DN: cn=Timothy N. Stevenson, o=PPPL, ou=ENGR, email=tstevens@pppl.gov, c=US
Date: 2018.03.30 09:31:50 -05'00'

Reviewed by: Tim Stevenson, Heating Systems RE, Heating Systems 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: 2018.03.30 11:01:46 -04'00'

Reviewed: Charles Neumeyer, NSTX-U Project Engineer

Russell Feder Digitally signed by Russell Feder
Date: 2018.03.31 15:26:35 -04'00'

Reviewed By: Russ Feder, NSTX-U Project Manager

Reviewed By: Larry Dudek, Mechanical Technical Authority

Digitally signed by John Lacenere
DN: cn=John Lacenere, o=PPPL, ou=PPPL Engineering/AC Power, email=lacenere@pppl.gov, c=US
Date: 2018.04.03 08:04:08 -04'00'

Reviewed By: John Lacenere, Electrical Technical Authority

W. Blanchard Digitally signed by W. Blanchard
Date: 2018.04.03 08:15:02
-04'00'

Reviewed By: Bill Blanchard, Vacuum Technical Authority

PAUL SICHTA Digitally signed by PAUL SICHTA
Date: 2018.04.03
09:34:02 -04'00'

Reviewed By: Paul Sichta, Control and Data Technical Authority

Nevell Greenough Digitally signed by Nevell Greenough
Date: 2018.04.03 11:21:17 -04'00'

Reviewed By: Nevell Greenough, RF Technical Authority

Mark B. Cropper Digitally signed by Mark B. Cropper
Date: 2018.04.04 09:32:10
-04'00'

Reviewed By: Mark Cropper, Cryogenics Technical Authority

Valeria Riccardo Digitally signed by Valeria Riccardo
Date: 2018.04.04 09:58:13 -04'00'

Approved By: Valeria Riccardo, PPPL Chief Engineer

4/4/2018

Jonathan E. Menard Jonathan Menard

Accepted By: Jon Menard, NSTX-U Project Director

Change Record

Revision	Date	Description of Change
0	1/10/18	Initial Release
1	3/30/2018	Added explanatory text in Sections 3.6 and 4.6.
		Updated signature page for full QAPD and ENG-050 compliance
		Updated interface tables as per interface spreadsheet
		Corrected 3.3.2c to note that the beam TIVs may be open or closed in this operations mode.
		Clarified language in 3.5a

Table of Contents

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-0001-02, *NSTX Structural Design Criteria*
[4] NSTX-U-RQMT-RD-003, *NSTX-U Disruption Requirements*
[5] ES-MECH-015, *Pressure Systems Program*
[6] NSTX-U-RQMT-SRD-004, *System Requirements Document - Vacuum Vessel and Internal Hardware*
[7] NSTX-U-RQMT-SRD-010, *Systems Requirements Document - Test Cell*
[8] NSTX-U-RQMT-SRD-006, *System Requirements Document - Power Systems*

1.0 Scope

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

b. In general, this document does not delve into specific sub-system requirements and interfaces within the neutral beam, EC pre-ionization, or HHFW (High Harmonic Fast Wave) systems. Rather, it seeks to establish functional requirements for those systems as they interact and interface with other NSTX-U WBS elements.

2.0 General Requirements

a. All materials exposed to the high vacuum within the plasma chamber must be approved by the PPPL Vacuum Materials Committee for high vacuum compatibility.

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

c. Disruption loads are derived from the specification in Ref. [4].

d. Up-down symmetry of the vessel shall be maintained to the greatest extent possible.

e. All viton O-rings shall be maintained under 180^{o}C under all thermal scenarios (bakeout, plasma operations,...)

f. All materials utilized within the primary vacuum boundary shall be designed to withstand the anticipated temperatures during plasma and bakeout operation.

g. All pressure systems shall comply with PPPL standard ES-MECH-015 [5].

h. All materials at risk of exposure to lithium films shall be approved for use under that condition.

i. Electrical isolation from the vessel shall be as specified in the GRD [1].

j. Electrical isolation for signals leaving the test cell shall be as specified in the GRD [1].

3.0 Neutral Beams

3.1 Functions

a. The primary function of the neutral beams is to heat the plasma through the injection of energetic neutral particles.

Secondary functions include:

b. Injection of toroidal momentum into the plasma

c. Providing for current drive by the circulating fast ions

d. Providing fuelling of the plasma

e. Providing light that is collected by specific diagnostics in order to make measurements internal to the plasma.

3.2 Materials and Design Requirements

a. See Section 2.

3.3: Configuration Requirements and Essential Features

3.3.1 Spatial Configuration

a. There shall be two TFTR era neutral beamlines installed on NSTX-U, each of which has the full complement of beamline hardware including but not limited to:
   - Source platform
   - Ion sources
   - Source isolation valves
   - Neutralizers and gas injection
   - Bending magnets
   - Ion dumps
   - A calorimeter
   - Cryo-panels and LN_2 and LHe distribution manifolds
   - A turbo-molecular pump

b. Each beamline shall have three ion sources. The sources shall be denoted A,B, and C, with the A source on the left and C source on the right when facing the beamline from behind.

c. The neutral beam system shall be configured to inject in the co- direction, i.e. parallel to the plasma current. As per the GRD, the base plasma current direction will be counterclockwise when viewed from above.

d. Beamline #1 shall be configured such that the tangency radius of the sources [A,B,C] are R_{tan}=[70, 60, 50] cm.

e. Beamline #1 shall be configured to inject at Bay A.

f. Beamline #2 shall be configured such that the tangency radius of the sources [A,B,C] are R_{tan}=[130,120,110] cm.

g. Beamline #2 shall be configured to inject at Bay K.

h. Beamline components, with the exception of the drift ducts, shall be isolated from the NSTX-U primary vacuum by torus isolation valves (TIVs)

i. Drift ducts shall be provided to interface the beamline TIV to the main torus.

j. Armor shall be placed in the drift ducts as appropriate to protect against heating from the neutral beam itself or any reionization in the duct.

k. The beamlines shall be electrically isolated from the vacuum vessel as per the GRD.

l. The vessel shall be protected with a beam armor acting as a back stop such that no beam may impinge on the vessel proper but rather will impinge on carbon tiles. (Specific requirements for the beam armor are provided in Ref. [6]).

3.3.2 Modes of operations

Provision shall be made for the following modes of operations:

a. During *Plasma Operations*, the neutral beams are injected into the torus at powers and durations up to the limits given in Table 3.4-1.

- The beam is interlocked to the plasma current.
- The calorimeter is in the raised position
- The torus isolation valves are open

b. During *Source Conditioning Operations*, the neutral beams are injected into the lowered calorimeter for shorter pulses.

- The beam is not interlocked to the plasma current.
- The calorimeter is in the lowered position
- The torus isolation valves can be open or closed

c. During *Armor Conditioning Operations*, the neutral beams are injected into the armor for 50ms as allowed by the plasma current interlock system.

- The beam is interlocked to the plasma current.
- The calorimeter is in the raised position
- The torus isolation valves are open

d. During *Beam Aiming/ MSE Calibration Operations*, the neutral beams are injected into the armor for longer durations (~0.5 s), under strict administrative control, as well as interlocks in Section 3.3.4.

- The beam is not interlocked to the plasma current.
- The calorimeter is in the raised position
- The torus isolation valves are open

3.3.3 Control and Data Acquisition

a. Provision shall be made for control of the beam on/off status from the output stream of the plasma control system.

b. Measurements of the ion source voltage and current shall be provided to the realtime data stream on a per-source basis, and the formula for conversion to source power provided.

c. Indicators of the two calorimeter positions shall be provided to the realtime data stream.

d. Measurements of the ion source voltage and current shall be archived in the MDS+ database at a sampling rate >5 kHz, and the formula for conversion to source power provided.

e. Indicators of the two calorimeter positions shall be provided to the MDS+ database.

f. A PLC or similar shall be provided for control of the NB systems and interface to other control systems

3.3.4 Interlocks

a. The neutral beams shall be interlocked to the plasma current signal, such that low plasma current ends the beam pulse after a pre-determined short delay of up to 50 msec, to avoid overheating of the neutral beam armor.

b. The neutral beam accel high voltage shall be interlocked to the NSTX-U Hardwired Interlock System, preventing application of high voltage when the test cell is in a safe state (i.e. free access or controlled access [7]).

c. The neutral beam torus isolation valve position shall be interlocked to torus pressure.

d. An over-temperature condition on the neutral beam armor TCs shall prevent the next NB shot into the plasma or armor until reset by neutral beam operators.

3.3.5 Power

a. 13.8 kV power shall be delivered from the MG with capacity for full power operation of two beamlines. [8]

b. Operation of any combination of three ion sources from the power grid shall be possible.

3.4 Baseline Performance and Operational Requirements

a. Each beamline shall be capable of delivering power in the Plasma Operations mode as per Table 3.4-1. Additionally, the design shall not preclude voltage levels corresponding to powers exceeding 7.5 MW per beamline.

b. The two beamlines shall be capable of delivering these powers simultaneously

Table 3.4-1: *NBI Power To Plasma per Beam Line*

Pulse length (sec)	Power to Plasma (MW)
5	5.0
4	5.4
3	6.0
2	6.8
1.5	7.5

3.5 Upgrade Performance and Operational Requirements

a. The single O-ring vacuum seals in the ducts may be upgraded to i) double O-ring seals, ii) metal seals, or iii) a configuration with guard vacuum at the single O-ring seals.

b. A spectroscopic system for assessing the beam species mix may be instituted in the future.

3.6 Interfaces

Interfaces for the neutral beam systems are given in the tables below. Note that these tables do not articulate interfaces between the various level-4 WBS elements within the beam system, only interfaces to systems outside of WBS 1.2.4.

Table 3.6-1*: Interfaces for the Beamlines (WBS 1.2.4.2)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.8	NTC Floor	Structural	At NTC floor surface	Beamlines sit on floor	Drawings
1.8.1.1.2	NTC Cable Trays	Structural	Where any clamps or support structures are fixed to the beamlines	Beamlines support various cable trays	Mechanical Schematic
1.3.5.2	Trimethylboron (TMB) System	Structural	Where clamp parts are attached to beamline	Gas delivery line for the dTMB system supported by the beamline	Mechanical Drawing
1.8.1.1.8	NTC Floor	Structural	At NTC floor surface	source platform is supported from the floor	General Arrangement
1.3.1.1	Valves, Vacuum Pumps and Roughing Pumps	Structural	At location where clamps and supports touch beamline	Piping for the system is attached to the side of the beamline	Mechanical Drawing
0.1.1.9	Instrument Air	Structural	At beamline surface	Lines for instrument air supported by the beamline	N/A
0.1.1.10	House Air	Structural	At beamline surface	Lines for house air supported by the beamline	N/A
	House Air	Gas	At the fitting on the TIV	Air is used for operation of pneumatic valves	P&ID
0.1.1.9	Instrument Air	Gas	At the fittings on the various valves	Air is used for operation of pneumatic valves	P&ID

Table 3.6-2*: Interfaces for the Beamline Ducts (WBS 1.2.4.3)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.1	Vacuum vessel	Vacuum	Front face of flanges at Bays A and K	Drift ducts are mounted to the flanges at Bays A and K w/ single O-ring vacuum seals.	Mechanical Drawings
1.1.2.1.1	Vacuum vessel	Structural	Front face of flanges at Bays A and K	Vacuum side-load applied to vessel when NB TIVs are open.	Mechanical Drawings
1.3.1.1	Valves, Vacuum Pumps and Roughing Pumps	Vacuum	Flanges on the bottom of the drift duct	TVPS turbo pumps pump NSTX-U through, ducts mounted to the flanges at the bottom of the drift duct.	Mechanical Drawing
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 neutral beam #1 duct	P&ID

Table 3.6-3*: Interfaces for the Neutral Beam Services (WBS 1.2.4.4)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	NTC walls	Beamline services come through NTC wall penetrations	General Arrangement Drawing
1.3.1.6	Vacuum Pump Cooling Water System	Fluid	At port on turbo	Cooling water for NB pump provided by TVPS cooling system.	P&ID
1.3.2.3	Deionized Make-Up System	Fluid	Valves on expansion tanks in the D-site pump room	Provide make-up DI water to neutral beam systems	P&ID
0.1.1.4	D-Site Tower Water	Thermal	Heat Exchange	Ion source and ion dump water may heat exchange with tower water	P&ID
0.1.1.1	D-Site Facility Chilled Water	Thermal	Heat Exchange	Ion source water may heat exchange with facility chilled water	P&ID
1.8.1.2	South High Bay	Spatial	Surface of wall where the filling station is mounted	LHe filling station in the south high bay	N/A
0.1.1.8	D-Site Vent Stack	Gas	Valve on NSTX vacuum exhaust line	neutral beam pumps exhaust to the vent stack	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	various	Electrical power for various beamline services	Electrical Schematic for Directly Wired Components
0.1.1.6	Other D-Site Physical Infrastructure	Location	various	Neutral beam services located in pump room, transition through other areas at D-site	N/A
1.8.1.1.4	NTC Walls	Structural	At NTC wall	Various neutral beam services are supported by the test cell wall	General Arrangement Drawing
1.8.1.1.8	NTC Floor	Structural	At NTC floor surface	Various neutral beam services reside on the test cell floor	General Arrangement Drawing

0.1.1.9	Instrument Air	Gas	At the fittings on the various valves	Air is used for operation of pneumatic valves	P&ID

***Table 3.6-4**: Interfaces for the Liquid Helium Refrigerator(WBS 1.2.4.5)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
0.1.1.4	D-Site Tower Water	fluid	Valves on Tower water manifolds	Heat exchanger water for compressors	P&ID
0.1.1.4	D-Site Tower Water	fluid	Valves on Tower water manifolds	Turbine expander package can heat exchange w/ tower water	P&ID
0.1.1.1	D-Site Facility Chilled Water	fluid	Valves on Chilled water manifolds	Turbine expander package can heat exchange w/ facility chilled water	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	various	Electrical power for the cryogenic systems	Electrical Schematic for Directly Wired Components
0.1.1.6	Other D-Site Physical Infrastructure	Location	various	Neutral beam cryogenic systems are distributed throughout D-site.	N/A
0.1.1.9	Instrument Air	Gas	At fittings on various system configuration valves	Air is used for operation of pneumatic valves	P&ID

***Table 3.6-5**: Interfaces for the Neutral Beam Power System (WBS 1.2.4.6)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.5.1.1	Fixed and Variable Frequency 13.8 kV Experimental Power	Electrical Power	Selector switches within the neutral beam switchgear.	13.8 kV power provided by the MG or directly from the grid for Accel power	Electrical Drawings
0.1.1.4	D-Site Tower Water	fluid		Cooling water for power supplies heat exchange with tower water	P&ID
0.1.1.6	Other D-Site Physical Infrastructure	Location	various	Neutral beam power systems are distributed to multiple locations in D-site	N/A
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	various	Neutral beam power system cables come through various penetrations in the test cell walls	N/A
1.8.1.1.8	NTC Floor	---	At NTC floor surface	Components such as the high voltage enclosures (HVEs) are supported from the floor	General Arrangement
1.5.1.2	D-Site Auxiliary Power	Electrical Power	Various Places	Power for beam auxiliaries (decel, arc, filament, magnet, pumps, cryo, control)	Electrical Schematic for Directly Wired Components

***Table 3.6-6**: Interfaces for the Neutral Beam Control System (WBS 1.2.4.7)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At outputs/inputs of	Source voltages and currents	CWD

			realtime hardware	are digitized by the realtime data stream	
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At outputs/inputs of realtime hardware	Source on/off signals provided by FPDP digital output module to the neutral beam control systems	CWD
1.6.1.1	Control I/O systems	Electrical Signal	At digitizer panel	Various signals (voltage, current) archived with the shot.	CWD
1.3.1.2	Vacuum Gauges and Residual Gas Analyzers	Software	PLC Permissive	Vacuum pressure interlock provided through the vacuum PLC.	CWD
1.7.3.1	Hardwired Interlock System	Electrical Signal	Relay contact	Relay in LCC	CWD
1.7.3.6.8	Ip Calculator System	Fiber Optic	At output of IP Calculator Permissive	Permissive is removed, with delay, when plasma current drops beneath threshold	CWD
1.8.1.3	North and East Galleries	Location	N/A	Numerous neutral beam control systems located in the East Gallery	N/A
1.5.1.2	D-Site Auxiliary Power	Electrical Power	various	Electrical power for neutral beam control systems	Electrical Schematic for Directly Wired Components
0.1.1.6	Other D-Site Physical Infrastructure	Location	various	Control components are distributed to various locations at D-Site.	N/A
1.3.1.4	Vacuum System PLC	Electrical Signal	At connector on vacuum PLC.	Control/interlock signals	CWD
1.3.3.4	Bakeout PLC and Controls	Electrical Signal	At data highway connector	Interlock and status signal transfer between the Bakeout and TVPS PLC's via the NB PLC	CWD
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to neutral beam control systems	CWD
1.3.1.6	Vacuum Pump Cooling Water System	Electrical Signal	NB PLC	provides cooling water interlock	CWD
1.6.1.2	Plant Control and Monitoring	Electrical Signal	Connection to NB PXI equipment	An Industrial PC Connects to Neutral Beam PCI eXtensions I/O	CWD
1.8.1.1.2	NTC Cable Trays	Structural	At tray	Trays support cables for neutral beam controls	N/A

***Table 3.6-7**: Interfaces for the Armor Protection Systems (WBS 1.2.4.8)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.5.1.2	D-Site Auxiliary Power	Electrical Power	various	Electrical power for armor protection systems	Electrical Schematic for Directly Wired Components
1.1.1.1.8	Armor PFC Thermocouples	Electrical Signal	Isolated Thermocouple System	TCs read by electronics in NTC rack for this purpose	CWD

Table 3.6-8: *Interfaces for the Generated Neutral Beam(WBS 1.2.4.9)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.1.2.3	Neutral Bean Armor Mechanical	Thermal	At the surface of the PFC Tiles	Power from the neutral beam impinges on the armor PFC tiles, a fraction of which is ultimately transferred to the armor mechanical structures	Mechanical Calculation
1.4.1.5.1	Toroidal CHERS	Spatial	N/A	Toroidal CHERS systems designed to view the beam with specific geometry	N/A
1.4.1.5.2	Poloidal CHERS	Spatial	N/A	Poloidal CHERS systems designed to view the beam with specific geometry	N/A
1.4.1.6	FIDA	Spatial	N/A	FIDA systems designed to view the beam with specific geometry	N/A
1.4.1.7	BES	Spatial	N/A	BES systems designed to view the beam with specific geometry	N/A
1.4.1.8	MSE	Spatial	N/A	MSE systems designed to view the beam with specific geometry	N/A
1.4.1.9.1	SSNPAs	Spatial	N/A	SSNPAs designed for specific orientation to the heating beam	N/A

4: High Harmonic Fast Wave Heating

4.1 Functions

The High Harmonic Fast Wave (HHFW) Heating and Current Drive system consists of the RF generators, transmission lines, tuning and matching systems, RF feedthroughs and internal transmission lines, antennas with Faraday shields and protective limiters, and the associated diagnostic and control systems. The functions of the High Harmonic Fast Wave (HHFW) system are to:

• Provide heating power to the plasma via absorption of fast magnetosonic waves excited by the antenna.

• Provide non inductive current drive.

• Provide control over the heating / current drive deposition profile, through the antenna phasing.

4.2 Materials and Design Requirements

a. See Section 2.

b. The design and construction of the antenna, internal transmission line, and feed through shall be consistent with good vacuum practices. All materials utilized within the primary vacuum boundary shall be on the PPPL Vacuum Committee approved list, or shall be approved by the committee.

c. The antenna, feed through, and internal transmission line construction shall be consistent with good electrical practices at radio frequencies and high radio frequency voltages.

4.3: Configuration Requirements and Essential Features

4.3.1 General Configuration

a. The HHFW system shall utilize RF power produced by the six existing Tokamak Fusion Test Reactor (TFTR)-era Ion Cyclotron Range of Frequencies (ICRF) sources located at C-Site.

b. The HHFW system shall utilize twelve antennas mounted on the vacuum vessel wall in the gap between the upper and lower primary passive stabilizing plates. The antennas shall be arranged toroidally between the NSTX-U vacuum vessel mid plane ports. Each antenna shall consist of a current strap, a back plane, a Faraday shield, and a local limiter structure. The antennas shall be compatible with bakeout and glow discharge modes of operation.

c. The set of six sources (and twelve antennas) shall be capable of operation at a frequency of 30 MHz. All RF generators operating shall be phase locked to provide control over the wave number spectrum excited in the plasma at that frequency.

d. Switches shall be provided to isolate HHFW power from the NSTX-U test cell. These switches shall be interlocked with the test cell access control system. Both electrical and mechanical (Kirk Key) interlocks shall be provided.

4.3.2 Electrical Requirements

a. The antenna back-plane with attached Faraday shield shall be electrically connected to the vacuum vessel wall via a low inductance ground.

b. The antenna straps shall be end fed, with a center ground to the antenna shield enclosure. The ends shall be fed out of phase, so that a voltage null exists at the antenna mid-point ground location.

c. Both the inner and outer conductors of the transmission line shall be electrically isolated from the vacuum vessel with a voltage rating of 2 kV AC rms.

4.3.3 Mechanical Requirements

d. The antenna, internal transmission line, and feed through assemblies shall be compatible with glow discharge cleaning of the NSTX-U vessel and limiters.

e. The current straps, back planes, Faraday shields, internal transmission lines and RF feedthroughs shall be bakeable to the same temperature as the outboard vacuum vessel wall, namely 150^{o}C. They shall be designed to tolerate the significantly higher temperature (~350^{o}C) of adjacent components (passive plates, outboard diverters, etc.)

f. The dead load imposed onto the vacuum vessel includes the weight of the antenna assembly and bumper limiters. The dead load imposed on structures external to the vacuum vessel, including those sections of transmission line connected to the feed through and isolated from the remainder of the line by the mechanical isolation bellows, shall be adequately taken by external supports from the NSTX-U structure. The dead load for the remainder of the transmission line run includes the transmission line itself with associated components including tees, decoupling loops, stubs, and line stretchers, shall be taken by the transmission line support system. This support system shall accommodate motion of the vessel without undue stress to vacuum feedthroughs and similar components due to vacuum vessel vertical and radial motion.

g. To provide reliability and provide a margin of safety the RF vacuum feedthrough shall withstand a pressure of 30 psi.

h. The bumper limiter assembly shall accommodate a heat load of 1 MW/m^2. The Faraday shield shall accommodate the heat load associated with line-of-site radiation and neutral particle flux from the plasma, along with RF losses as calculated for the detailed design.

i. Design of the antenna assembly shall consider the electromagnetic loads induced during normal operation of the device as well as the electromagnetic loads induced during abnormal operating events. Events such as disruptions, plasma control failures, power supply failures, bus opens or shorts, or magnetic faults shall be included in the design and associated disruption loads.

4.3.4 Diagnostic and Control Requirements

a. Diagnostics, signal detection, and data recording for antenna strap current, voltage, and relative phase shall be included in the HHFW system.

b. Diagnostics, signal detection and data recording for forward power, reverse power, and phase shall be included in the HHFW system.

c. Features shall be provided for real time control (preprogrammed with feedback modification) of the relative antenna current strap phasing.

d. Features shall be provided for real time control (preprogrammed with feedback modification) of the RF power.

e. The HHFW system shall be equipped with a plasma current interlock.

4.3.5 Interlocks

a. The HHFW system shall not be allowed to direct power into the test cell when the NSTX-U Hardwired Interlock System (HIS) is in a safe state (i.e. free access or controlled access [7]).

b. Systems shall detect and respond to excessive reflected power by blanking RF power for a duration of order msec.

4.4 Baseline Performance and Operational Requirements

4.4.1 RF Conditioning

a. The HHFW system shall permit vacuum conditioning of the antenna at pulse lengths of up to 5 sec.

b. Cooling shall be sufficient to maintain strap, Faraday shield, and limiter temperature at or below 350^{o}C during conditioning.

c. RF power supplied during vacuum conditioning shall be sufficient to bring the 6 port cube voltages to a peak voltages of 35 kV if vacuum conditioning permits.

4.4.2 Plasma Operations

a. The HHFW system shall be capable of delivering at least 4 MW of power to the NSTX-U plasma for 5 seconds, once every 1200 seconds.

b. Strap cooling shall be sufficient to maintain strap temperature at or below 350^{o}C during operation.

c. Strap-to-strap phase accuracy shall be equal or better than 5 degrees.

4.4.3 Transmission Line Testing Mode

a. A mode shall exist for testing leakage from transmission lines.

4.5 Upgrade Performance and Operational Requirements

a. An upgrade to a field-aligned configuration may be taken in the future

4.6 Interfaces

Interfaces for the HHWF systems are given in the tables below. Note that these tables do not articulate interfaces between the various level-4 WBS elements within the HHFW system, only interfaces to systems outside of WBS 1.2.1.

Table 4.6-1: *Interfaces for the HHFW System (WBS 1.2.1)*

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	Various signals are digitized as part of the primary NSTX-U data I/O system	CWD
1.6.1.2	Plant Control and Monitoring	Electrical Signal	PPPL ethernet	Plant Control and Monitoring (EPICS) system used for various HHFW controls	CWD
1.7.3.1	Hardwired Interlock System	Electrical Signal	Relay contact in the RFE	Used to ensure that HHFW systems are in a safe state when people are accessing the NSTX-U test call and other potentially unsafe areas.	CWD
1.7.3.6.8	Ip Calculator System	Electrical Signal	At output of IP Calculator Permissive	Permissive is removed, with delay, when plasma current drops beneath threshold	CWD
0.1.1.7	C-Site Deionized Water	Fluid	---	Deionized water is used to cool the HHFW sources	P&ID
1.6.1.3	Timing and Synchronization System	Electrical or Fiber Optic Signal	At diagnostic or electronics input	Shot synchronization and timing information provided to HHFW control systems	CWD
0.1.1.11	C-Site Power	Electrical Power	C-Site Rectifier-Transformer output (27kV DC – 16 kV DC	Provide power to HHFW systems	Electrical Schematic
1.8.1.1.1	NTC Platforms	Structural	At platform surface	Transmission lines supported from platforms	Mechanical Drawings
1.8.1.1.4	NTC Walls	Structural	At NTC wall	Transmissions lines supported from walls	Mechanical Drawings
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	At the penetration	Transmission lines penetrate the NTC wall	General Arrangement Drawing
1.7.3.1	Hardwired Interlock System	Electrical Signal	Rack, RF-A1	Indicates HHFW systems are shutdown; No E-stops; Permissives to unsafe	CWD
0.1.1.6	Other D-Site Physical Infrastructure	Location	Waveguide surface	Waveguides, switches, and other RF components located the RF enclosure, attached to walls, penetrate walls	Transmission line route drawings

5: EC Preionization System

5.1 Functions

The electron cyclotron heating (ECH) system consists of a microwave source and power supply, a transmission system, a vacuum interface and a launching structure along with suitable diagnostics and controls.

The functions of the ECH system is to provide pre-ionization for plasma breakdown.

5.2 Materials and Design Requirements

a. See section 2

b. The launcher construction shall be consistent with good electrical practices at radio frequencies and high radio frequency voltages.

a. The design and construction of the window shall be consistent with good vacuum practices. All materials utilized within the primary vacuum boundary shall be on the PPPL Vacuum Committee approved list, or shall be approved by the committee.

5.3: Configuration Requirements and Essential Features

5.3.1 General Configuration Requirements

a. One ECH launcher shall be installed at an outboard location in the Vacuum Vessel to direct the microwave radiation toward the desired absorption location. The launcher must be compatible with bakeout and glow discharge modes. The launcher shall have a vacuum window connecting it to the external transmission system. This window must have low electrical loss at microwave frequencies and satisfy the thermal and mechanical requirements for vacuum interfaces.

b. The transmission system shall efficiently transport the microwave power from the RF sources to the vacuum window. It shall consist of a waveguide and special components for power measurement.

c. The RF source shall be located inside the test cell and will provide the microwave power. It shall include local controls and interlocks.

5.3.2 Electrical Requirements

a. The launcher shall be electrically connected to the vacuum vessel wall via a low inductance ground.

b. The transmission line shall be electrically isolated from the vacuum vessel with a voltage rating of 2 kV AC rms.

5.3.3 Mechanical Requirements

a. The window shall be compatible with glow discharge cleaning of the NSTX-U vessel and limiters.

b. The window and launcher assembly shall be bakeable to the same temperature as the outboard vacuum vessel wall, namely 150^{o}C.

c. This support system for waveguides shall accommodate motion of the vessel without undue stress to vacuum feedthroughs, windows, and similar components due to vacuum vessel vertical and radial motion.

d. To provide reliability and provide a margin of safety the vacuum window shall withstand a pressure of 30 psi.

5.3.4 Diagnostic and Control Requirements

a. RF start/stop triggering shall be externally controlled.

b. A launched power signal shall be digitized.

5.3.5 Interlocks

a. The ECH-PI system shall be interlocked to the NSTX-U Hardwired Interlock System (HIS), preventing operation when the test cell is in a safe state (i.e. free access or controlled access [7]).

b. The ECH-Pi system shall have additional interlocks necessary for self-protection (reflected power, cooling water, etc.)

5.4 Baseline Performance and Operational Requirements

a. The ECH system shall be designed to deliver >5 kW for 10 ms.

5.5 Upgrade Performance and Operational Requirements

a. Future ECH upgrades to NSTX-U may substantially increase the power, at a higher frequency.

5.6 Interfaces

Table 5.6-1: *Interfaces for the EC-PI system (WBS 1.2.3)*

Interfacing WBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.1.2.1.1	Vacuum vessel	Structural	At vessel flanges	RF launchers mount to vessel flanges	Mechanical Drawing
1.1.2.1.1	Vacuum vessel	Vacuum	At vessel flanges	Window as part of laucher forms vacuum boundary	Mechanical Drawing
1.8.1.1.1	NTC Platforms	Structural	Platform floor	ECH system resides in the NSTX-U test cell, on the platform	General Arrangement Drawing
1.6.1.1	Control I/O systems	Electrical Signal	At Digitizer	Various signals are digitized as part of the primary NSTX-U data I/O system	CWD
1.6.1.2	Plant Control and Monitoring	Electrical Signal	PPPL Ethernet and CAMAC Serial Highway	Plant Control and Monitoring (EPICS) system used for various EC-PI controls	CWD
1.7.3.1	Hardwired Interlock System	Electrical Signal	Relay contact in the RFE	Used to ensure that EC-PI systems are in a safe state when people are accessing the NSTX-U test call and other potentially unsafe areas.	CWD
1.3.2.1.1	Low-Pressure NTC Cooling Water Distribution	Fluid	At hose connection on source	De-Ionized cooling water provided to ECH source	P&ID
1.5.1.2	D-Site Auxiliary Power	Electrical Power	various	Electrical power for ECH pre-ionization system	Electrical Schematic for Directly Wired Components