NCSX
SPECIFICATION

General Requirements Document (GRD)

NCSX-ASPEC-GRD-05

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Record of Revisions

Revision	Date	ECP	Description of Change
Rev. 0	5/5/2003	-	Initial issue
Rev. 1	8/17/03		DRAFT A (WTR)
			Updated Appendix A – Technical Data Sheet
			Added requirement for controlled access into the test cell between shots in Section 3.3.5.2.2
			Added Section 3.2.1.5.3.8 to specify coil current measurement.
			Changed the test cell opening width from 18’ to 17’6” in Section 3.2.3.1.2.
			Added Section 3.2.3.1.3.2 to specify a maximum platform floor loading.
			Substituted the Field Line Mapping scenario for the Initial Ohmic scenario throughout.
			DRAFT B (RTS/GHN)
			Cleared numerous TBRs and TBDs
			Replaced “operating temperature” with “cryogenic temperature” to eliminate ambiguity introduced with room temperature operation.
			Added a pre-run temperature requirement for the coils in Section 3.2.1.2.1.3.
			Modified the base pressure requirement in Section 3.2.1.2.2.1.
			Modified the pumping speed requirement in Section 3.2.1.2.2.2 to reflect having only two pumps installed initially.
			Changed “elevated” to “capable of being elevated” in background discussion in Section 3.2.1.2.3.
			GDC was made a future upgrade in Sections 3.2.1.2.3.5 and 3.2.1.4.1.
			DRAFT C (WTR)
			Replaced lettered paragraphs with numbered paragraphs throughout for improved cross-referencing.
			Moved vacuum compatibility requirement from Section 3.2.1.2.2.1 to Section 3.3.1.2.
			Moved requirements in Section 3.3.5.2 under Section 3.3.5.1
			Substituted “first plasma and initial field line mapping” for “initial ohmic operation” throughout.
			Deleted reference to initial limiters in Sections 3.2.1.2.3 and 3.2.1.5.4. Made poloidal limiters an upgrade requirement in Section 3.2.1.5.4.1.
			Deleted requirement for maximum heating power during Initial Ohmic phase of operation in Section 3.2.1.5.4.2.
			Added discussion of room temperature operation in Section 3.2.1.2.1. Changed title of Section 3.2.1.2.1.1to Timeline for Coil Cool-down to Cryogenic Temperature.

Inserted a Field Line Mapping Scenario and removed the Initial Ohmic Scenario in Section 3.2.1.5.3.3.1.2.

Changed the 1.9T High Beta Scenario back to 2T in Section 3.2.1.5.3.3.1.6.

Changed the initial NB requirement from two beamlines to one beamline in Section 3.2.1.5.6.1.1.Changed the requirement for initial operation of the electrical power and cryogenic systems from meeting the requirements of the Initial Ohmic Scenario to meeting the requirements of the First Plasma and Field Line Mapping Scenarios in Section 3.2.1.5.3.3.2.

Explicitly defined the initial diagnostic requirements in Section 3.2.1.5.8.2.

Draft D (WTR)

Updated TDS to reflect more conservative heat leakage and LN2 consumption.

Draft E (WTR)

PDR version – no additional changes

Draft F (WTR)

Updated Figure 3-2 per Nelson comment (cosmetic change only).

Changed base pressure from 2e-8 torr to 5e-8 torr per Blanchard's guidance in Section 3.2.1.2.2.1.

Changed the bakeout timeline from indefinitely to 21 days per Dudek's guidance in Section 3.2.1.2.3.4.

Updated **Table 3-2 Diagnostic Requirements**.

Deleted phrase "by circulating high temperature gas in tubes attached to the vacuum vessel shell and ports" from Background in Section 3.2.1.2.3 per Zarnstorff's request.

Changed ±25ºC to -25ºC +50ºC in the PFC bakeout temperature spec in Section 3.2.1.2.3.2 per Zarnstorff's request.

Draft G (WTR)

Changed the 100 bakeout cycles specified in Section 3.2.1.2.3.6 to 1000.

Modified Section 3.2.1.5.8.2 from:

"All magnetic trapped sensors (e.g., those located between the coils and vacuum vessel or co-wound with the coil), magnetic diagnostics signal processing electronics needed to measure plasma current, a fast visible camera, and field mapping apparatus (e-beam, fluorescent probe, camera) shall be provided.

The facility shall be designed to accommodate the diagnostics identified in **Table 3-2** as future upgrades."

To:

"All magnetic trapped sensors (e.g., those located between the coils and vacuum vessel or co-wound with the coil), magnetic diagnostics, and signal processing electronics needed to measure plasma current, a fast visible camera, and field mapping apparatus (e-beam, fluorescent probe, camera) shall be provided.

The facility shall be designed to accommodate the additional diagnostics identified in **Table 3-2** as future upgrades."

Changed “Electrical power for the TF, PF, and modular coils will be provided through the D-site experimental power systems.” to “Electrical power for the TF, PF, and modular coils will be provided through the C- or D-site experimental power systems.” in Section 3.2.2.3.

Technical data sheet updated to include the equilibria for the reference scenarios. Deleted cryogenic system requirements other than pulsed heat loads.

Revised Section 3.1.2 from:

“The NCSX MIE Project shall include all equipment required for first plasma and initial field line mapping, including the support subsystems required to support that equipment.

In addition, the NCSX MIE Project shall include equipment needed to support coil operation at cryogenic temperatures and the refurbishment and installation of equipment for 1.5 MW of neutral beam heating power.”

to read as follows:

“The NCSX MIE Project shall include all equipment required for first plasma with the coils at cryogenic temperature and for initial field line mapping.

In addition, the NCSX MIE Project shall include the refurbishment and testing of equipment for 1.5 MW of neutral beam heating power.”

Revised the background discussion in Section 3.2.1.2.1 from:

“First plasma and initial field line mapping will be performed with the coils around room temperature to facilitate engineering shakedown and testing with portions of the cryostat removed. The coils will not be cooled to cryogenic temperatures prior to first plasma, but the systems required to support operation at cryogenic temperatures will be provided as part of the MIE Project. (In this context, cryogenic temperatures are around 77K (the saturation temperature of liquid nitrogen at 1 atmosphere).”

to read as follows:

“The Integrated System Test Program (ISTP) will include coil testing and initial field line mapping with the coils around room temperature to facilitate engineering shakedown and testing with portions of the cryostat removed. The coils will be cooled to cryogenic temperatures for first plasma. (In this context, cryogenic temperatures are around 77K (the saturation temperature of liquid nitrogen at 1 atmosphere).”

Added the requirement that the vacuum vessel shell be bakeable at 350C in Sections 3.2.1.2.3, 3.2.1.2.3.1, and 3.2.1.2.3.2.

Deleted :”and cryogenic systems” from Section 3.2.1.5.3.3.2 to be consistent with First Plasma with the coils at cryogenic temperature.

Updated the First Plasma Scenario to be consistent with operation at cryogenic temperature.

Added letters to uniquely identify multi-part requirements.

Updated the QCM to reflect above changes as required.

<u>Draft H (RTS)</u>

Revised Section 3.2.1.2.2.1 a. from:

a. “The device shall be designed and facility shall be upgradeable to produce, through design and the use of baking and wall conditioning, high vacuum conditions with a global leak rate of less than or equal to $2x10^{-5}$ torr-l/s at 293K and, when equipped with a torus pumping speed of 2,600 l/s, a base pressure of less than or equal to $5x10^{-8}$ torr.”

To read:

a. “The device shall be designed and facility shall be upgradeable to produce, through design and the use of baking and wall conditioning, high vacuum conditions with a global leak rate of less than or equal to $2x10^{-5}$ torr-l/s at 293K and a base pressure of less than or equal to $2x10^{-8}$ torr, when equipped with its full pumping compliment.”

Revised Section 3.2.1.2.2.2 a. and b. from:

a. “The device shall be designed and the facility shall be upgradeable to accommodate the four PBX-M 1500 l/s turbomolecular pumps (or equivalent), configured to provide a total net pumping speed at the torus of at least 2600 l/s.”

b. “The device shall be equipped with two of the four PBX-M 1500 l/s turbo-molecular pumps (or equivalent) , configured to provide a total net pumping speed at the torus of at least 1,300 l/s.

To read:

a. “The device shall be designed and the facility shall be upgradeable to accommodate six PBX-M style 1500 l/s turbomolecular pumps (or equivalent), configured to provide a total net pumping speed at the torus of at least 3900 l/s.”

b. “The device shall be equipped with two of the six PBX-M 1500 l/s turbo-molecular pumps (or equivalent) , configured to provide a total net pumping speed at the torus of at least 1,300 l/s.

Rev. 2

Restarted lettered list at a) instead of d) in Section 3.1.2.

Changed requirement from “electropolished” to “polished to a 32 micro-inch finish” in Section 3.3.1.2.

Changed pre-pulse temperature requirement in Section 3.2.1.4.2 from

a. “Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall return to a prescribed pre-pulse temperature in the range of 40ºC.

b. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall, as a future upgrade, be maintained at a temperature of 40ºC in the presence of a hot liner with a temperature of 250 C. This is to facilitate the use of a lithium liner as a possible future upgrade.”

to read as follows:

a. “Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall return to a prescribed pre-pulse temperature in the range of 40-80ºC while maintaining port end flanges in the range of 20-40ºC.

b. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall be capable of being maintained at a pre-pulse temperature of 210ºC (as a future upgrade) to facilitate the use of liquid lithium while maintaining port end flanges at or below 150ºC.”

In order to establish the equivalence between field error correction coils and trim coils, Section 3.2.1.5.1a was changed from:

a. Field error correction coils shall be provided to compensate for fabrication errors.

to read as follows:

a. Field error correction (trim) coils shall be provided to compensate for fabrication errors.

Added proper references for NCSX documents in Section 2.3. Deleted reference to the NCSX Grounding Specification for Personnel and Equipment Safety as it is not referenced in the GRD. Deleted reference to NCSX Vacuum Materials List as that is now the responsibility of the PPPL Vacuum Materials Committee. There is no indication that a formal list of approved vacuum materials will be maintained. Consequently, changed Section 3.3.1.2 c from

“All in-vessel materials shall be approved by the Project for vacuum compatibility. Pre-approved materials are catalogued in the NCSX Vacuum Materials List.”

to read as follows:

“All in-vessel materials shall be approved by the PPPL Vacuum Materials Committee for vacuum compatibility.”

Added requirements to Section 3.6 Personnel and Training. Previously, it was TBD.

Updated Technical Data Sheet to reflect a rectangular cross-section in the TF inner leg.

Rev. 3	10/13/05	Revised Section 3.2.2.3 - second sentence to delete reference to C-Site “experimental” power systems. Revised Section 3.2.2.4 – deleted reference to “gaseous nitrogen”. Revised Section 3.2.3.1.3.1 to read: “The maximum floor loading in the Test Cell shall not exceed 4,500 pounds per square foot on the concrete floor of the building and 150 pounds per square foot on the penetration covers.” Revised Section 3.3.1.1 (Magnetic Permeability) be consistent with the Modular Coil Winding Form Specification (NCSX-CSPEC-141-03-09); i.e., “…relative magnetic permeability shall not exceed 1.02…” Updated Appendix A -Technical Data Sheet based on simulations performed with the following changes: • Updated modular coils to have one additional turn per pancake. • Updated modular coil conductor parameters consistent with the Modular Coil Conductor Specification (NCSX-CSPEC-142-03-01). • Updated PF coil cross-sections consistent with the PF System General Arrangement (SE132-000) and conductor design (Detail Y of SE132-050). Generated and improved OH distribution consistent with the PF coil cross-sections. • Updated TF coil conductor per SC131-014 • Updated total cabling loop resistance per NCSX B-4F1005 SH 1800C in simulations for First Plasma and Field Line Mapping Scenarios. Used current waveforms in “NCSX CD4 with C-site Supplies”, M. Zarnstorff, dated 18 August 2004 directly for those simulations.
Rev. 4	1/13/06	Updated Appendix A – Technical Data Sheet to reflect the use of PF1A for initial operation. *This change was approved as part of ECP-39. No ECP is expected to be required for approval of Rev. 4 because the other changes are editorial in nature.* In Section 3.2.1.2.1 Coil Cool-down (Background), corrected mis-wording by changing “up to less than 150 cool-down and warm-up cycles” to “up to 150 cool-down and warm-up cycles”. In Section 3.3.1.2b Vacuum Compatibility, changed “All in-vessel components shall be made of vacuum compatible materials and degreased and cleaned. They shall be vacuum baked prior to installation, except when authorized by the project.” to “All in-vessel components shall be made of vacuum compatible materials and degreased and cleaned. They shall be vacuum baked *and degassed at a bakeout temperature exceeding the maximum operating temperature* prior to installation, except when authorized by the project.” as suggested by M. Zarnstorff. Section 5 Notes, which was blank, was deleted. Section 2.4 Other Documents, which was blank, was deleted.

Rev. 5	**7/19/07**	**Section 3.2.3.1.2 Maximum Lift – Increased maximum lift from 30 to 45 tons to reflect the crane upgrade in the Test Cell.** **Section 3.2.1.5.3.3.2 Reference Scenarios – Modified requirement to reflect use of PF1A in initial configuration.** **Appendix A – Revised Technical Data Sheet for initial operation consistent with use of PF1A coils, limiting the power supply I^2t to less than 1.5s.** **Section 3.3.1.1 – Added permeability requirement for materials, welds, and attaching hardware outside the cryostat**

TABLE OF CONTENTS

1 SCOPE

1.1 Identification

This document, the National Compact Stellarator Experiment (NCSX) General Requirements Document (GRD), specifies the performance, design, documentation, and quality assurance requirements for the NCSX to be installed and operated at the Princeton Plasma Physics Laboratory (PPPL).

1.2 System Overview

The National Compact Stellarator Experiment (NCSX) will be a proof-of-principle scale facility for studying the physics of compact stellarators, an innovative fusion confinement concept. The facility will include the stellarator device and support systems. It will be constructed at the Princeton Plasma Physics Laboratory.

1.3 Document Overview

The GRD is a system specification. It is to be used as the basis for developing lower level (subsystem and component) technical specifications for the NCSX Project.

1.3.1 Relationship of System to Subsystem Requirements

The specification approach being used on NCSX provides for a clear distinction between system and subsystem requirements as well as between performance requirements and design constraints.

Performance requirements state what functions a system has to perform and how well that function has to be performed. Design constraints, on the other hand, are a set of limiting or boundary requirements that must be adhered to while allocating requirements or designing the system. They are drawn from externally imposed sources (e.g., statutory regulations, DOE Orders, and PPPL ES&H Directives) as well as from internally imposed sources as a result of prior decisions, which limit subsequent design alternatives.

Within this system specification, Section 3.2.1 defines the performance requirements that apply to the system as a whole. Section 3.7 defines the allocation of the system performance requirements to specific subsystems. Those requirements will flow down to subsystem development (or “design-to”) specifications, which are or will be documented as project documents (NCSX-BSPEC-WBS-…). There the subsystem performance requirements contained in Section 3.2.1 are generally drawn from the applicable subsystem allocations within Section 3.7 of this document. Additional performance requirements at the subsystem level may also be included for completeness. Similarly, the subsystem development specification will contain performance requirements allocated to specific major components of the subsystem.

The remainder of Section 3 of this specification is generally considered to consist of design constraints. As a rule, design constraints are not allocated to subsystems within Section 3.7. However, subsystem specific constraints may be interspersed with the system level design constraints if they are considered significant enough for inclusion within the system specification. Within the subsystem development specifications, design constraints for the subsystem, consist of derived system level constraints and other applicable constraints, will be documented.

1.3.2 Incomplete and Tentative Requirements

Within this document, the term “to be determined” **(TBD)** applied to a missing or incomplete requirement means that additional effort (analysis, trade studies, etc.) is required before the requirement can be completed. The term “to be revised” **(TBR)** applied to a requirement means that a tentative requirement has been established but additional effort is needed to fully understand the cost/benefit implications, and thus the requirement is subject to change.

2 APPLICABLE DOCUMENTS

The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of a conflict, the contents of this specification shall be considered a superceding requirement.

2.1 Government Documents

DOE-STD-1020-2002, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities”

29CFR1910

DOE O 420.1

2.2 PPPL Documents

PPPL ESHD-5008, “PPPL Environment, Safety, and Health Directives.”

2.3 NCSX Documents

NCSX Work Breakdown Structure (WBS) Dictionaries (NCSX-WBS-wbs#), where wbs# is the NCSX WBS identifier

NCSX Structural and Cryogenic Design Criteria Document (NCSX-CRIT-CRYO-XX)

NCSX Test and Evaluation Plan (NCSX-PLAN-TEP-XX)

NCSX RAM Plan (NCSX-PLAN-RAM-XX)

3 SYSTEM REQUIREMENTS

3.1 System Definition

3.1.1 General Description

a. The mission of the NCSX is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the physics understanding of three-dimensional plasmas for fusion and basic science.

b. The NCSX device is a medium-scale (R=1.4 m), low aspect ratio (A~4) stellarator-tokamak hybrid. It features modular coils, toroidal field (TF) coils, and poloidal field (PF) coils for plasma shaping and control. It also has a vacuum-tight vessel internal to the coils.

c. The NCSX facility will be sited at C-Site at the Princeton Plasma Physics Laboratory (PPPL). Some subsystems will be located at D-Site at PPPL. The stellarator will be situated in the former PBX-M/PLT Test Cell. This test cell will hereafter be referred to as the NCSX Test Cell.

3.1.2 Major Item of Equipment (MIE) Project Scope

a. The NCSX MIE Project shall include all equipment required for first plasma with the coils at cryogenic temperature and for initial field line mapping.

b. In addition, the NCSX MIE Project shall include the refurbishment and testing of equipment for 1.5 MW of neutral beam heating power.

c. This specification provides requirements for the MIE Project, including requirements to be able to accommodate certain equipment upgrades that may be needed in the future.

d. For equipment not in the MIE Project but required as a future upgrade, the effort required to assure that the equipment can be accommodated shall be included in the MIE Project.

3.1.3 System Elements

All work required to execute the Project has been identified in the NCSX Project Work Breakdown Structure (WBS) Dictionary. A listing of Level 2 (1-digit) WBS elements is provided in **Table 3-1**.

Table 3-1 Level II Work Breakdown Structure

WBS	
1	Stellarator Core Systems
2	Auxiliary Systems
3	Diagnostic Systems
4	Electrical Power Systems
5	Central Instrumentation and Control Systems
6	Facility Systems
7	Test Cell Preparation and Machine Assembly
8	Project Management and Integration
9	Preparations for Operations

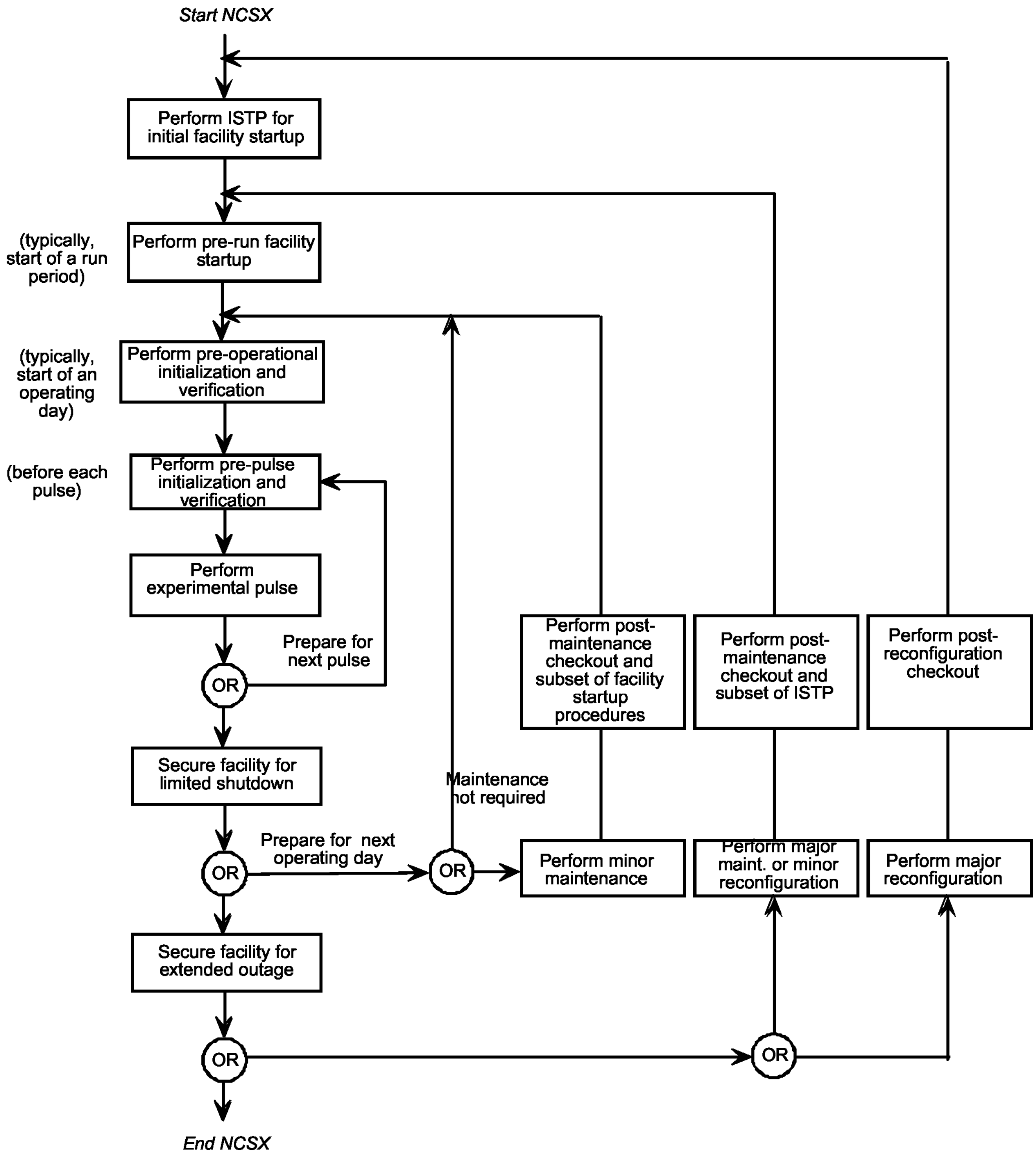

Figure 3-1 NCSX System Functional Flow Diagram

3.1.4 System Functions

The top-level system functions for NCSX are detailed in Figure 3-1. This functional flow diagram provides the foundation for the scope of the requirements within Section 3.2 of this specification.

3.2 Characteristics

3.2.1 Performance Characteristics

3.2.1.1 Initial Facility Startup

Background

Initial facility startup includes all activities required to verify safe operation of NCSX systems after their initial assembly and installation, or after a major facility reconfiguration, and before plasma operations. Initial facility startup activities would be performed prior to First Plasma and will include an Integrated System Test Program (ISTP) to verify that the system operates safely and as expected prior to plasma operation. For example, the ISTP will include verification of proper coil polarities and power supply connections. The ISTP will also include verification that, at First Plasma, the system demonstrates a level of system performance sufficient for the start of research operations, as specified in the Project Execution Plan. A subset of the ISTP will be conducted before the start of a run.

Requirement

The system shall provide the capability to perform a comprehensive integrated system test program, to verify, prior to plasma operation, that the system operates safely and as expected.

3.2.1.2 Pre-Run Facility Startup

Background

Pre-run facility startup includes all activities required to verify safe operation of the NCSX systems after a major maintenance outage or a minor facility reconfiguration (one affecting a small number of subsystems). Pre-run facility startup activities would typically be performed prior to the start of a run period and would include a subset of the full ISTP activities referred to in Section 3.2.1.1.

Requirement

The system shall provide the capability to perform a controlled startup of the facility, and verify that the facility systems are functioning correctly.

3.2.1.2.1 Coil Cool-down

Background

The Integrated System Test Program (ISTP) will include coil testing and initial field line mapping with the coils around room temperature to facilitate engineering shakedown and testing with portions of the cryostat removed. The coils will be cooled to cryogenic temperatures for first plasma. (In this context, cryogenic temperatures are around 77K (the saturation temperature of liquid nitrogen at 1 atmosphere).

Prior to experimental operations, the cryo-resistive coils must be cooled down from room temperature to a pre-pulse operating temperature of approximately 80K. The coils are located in a dry nitrogen environment that is provided by the cryostat, which surrounds the magnets. In order to gain access to the interior of cryostat, the coils must be warmed up from operating temperature to room temperature. The anticipated operational plans are expected to result in up to 150 cool-down and warm-up cycles between room temperature and operating temperature over the lifetime of the machine.

3.2.1.2.1.1 Timeline for Coil Cool-down to Cryogenic Temperature

The cryo-resistive coils (TF, PF, modular, and external trim coils) shall be capable of being cooled down from room temperature (293K) to their operating temperature (80K) within 96 hours.

3.2.1.2.1.2 Cool-down and Warm-up Cycles

The design of the cryo-resistive coils shall allow for at least 150 cool-down and warm-up cycles between room temperature and cryogenic temperature.

3.2.1.2.1.3 Pre-Run Temperatures

a. The device and facility shall be designed to be capable of operating the coils at cryogenic temperature (80K).

b. The device and facility shall be designed to maintain the vacuum vessel and all in-vessel components at a minimum temperature of at least 20ºC when the coils are at cryogenic temperature and the machine is not being pulsed.

3.2.1.2.2 Vacuum Requirements

3.2.1.2.2.1 Base Pressure

a. The device shall be designed and facility shall be upgradeable to produce, through design and the use of baking and wall conditioning, high vacuum conditions with a global leak rate of less than or equal to 2×10^{-5} torr-l/s at 293K and a base pressure of less than or equal to 2×10^{-8} torr, when equipped with its full pumping compliment.

b. The base pressure shall be measured with a standard, magnetically shielded, nude ion gauge. The device shall accommodate additional nude ion gauges and at least one fast neutral pressure gauge as future upgrades. The partial pressure components of the base pressure shall be measured with a Residual Gas Analyzer (RGA) mounted at a location on one of the pump ducts near the turbo-molecular pumps.

3.2.1.2.2.2 Pumping Speed

a. The device shall be designed and the facility shall be upgradeable to accommodate six PBX-M style 1500 l/s turbo-molecular pumps (or equivalent), configured to provide a total net pumping speed at the torus of at least 3900 l/s.

b. The device shall be equipped with two of the six PBX-M 1500 l/s turbo-molecular pumps (or equivalent) , configured to provide a total net pumping speed at the torus of at least 1,300 l/s.

3.2.1.2.3 Bakeout

<u>Background</u>

The temperature of the vacuum vessel shell will be capable of being elevated to a nominal temperature of 150ºC for vacuum vessel bakeout operations and to a nominal temperature of 350ºC to support bakeout of an in-vessel carbon-based liner (to be installed as an upgrade) at that temperature. Initially, there will not be any limiters installed in the vacuum vessel for first plasma or field line mapping. However, later in the program, the liner will be installed inside the vacuum vessel with a surface area that is a substantial part of the vacuum vessel surface area to absorb the high heat loads and to protect the vacuum vessel and internal components. Components that will become hot during bakeout operations must be compatible with their elevated temperatures in terms of strength, compliance for expansion, and vacuum integrity.

3.2.1.2.3.1 Vacuum Vessel Bakeout Temperatures

During vacuum vessel bakeout, the temperature of the vacuum vessel shell and ports shall be maintained at 150ºC +5/-25ºC.

3.2.1.2.3.2 Carbon-based Plasma Facing Components (PFCs) Bakeout Temperatures

During carbon-based PFC bakeout, the temperature of the vacuum vessel shell and carbon-based PFCs (to be installed as a future upgrade) shall be maintained at 350ºC±25ºC, and the temperature of the vacuum vessel ports shall be maintained at 150ºC +5/-25ºC. (The 350ºC bakeout capability is an upgrade.)

3.2.1.2.3.3 Coil Temperatures During Bakeout

During bakeout, the temperature of the cryo-resistive coils shall be capable of being kept below 90 K and returned to their pre-pulse operating temperatures within the 24 hours following completion of bakeout.

3.2.1.2.3.4 Bakeout Timelines

a. The vacuum vessel and all components internal to the vacuum vessel shall be capable of being raised to their bakeout temperatures within 36 hours and maintained at that temperature for a period up to 21 days.

b. Following bakeout, the vacuum vessel and all components internal to the vacuum vessel shall be capable of being returned to 40ºC within 36 hours.

3.2.1.2.3.5 Glow Discharge Cleaning (GDC) During Bakeout

The facility shall provide (as a future upgrade) a glow discharge cleaning (GDC) capability during bakeout operations, meeting the requirements of Section 3.2.1.4.1, except with the vacuum vessel and all components internal to the vacuum vessel at their nominal bakeout temperature.

3.2.1.2.3.6 Bakeout Cycles

The device shall be designed for at least 1000 bakeout cycles over the life of the machine.

3.2.1.3 Pre-operational Initialization and Verification

Background

Pre-operational initialization and verification activities would generally cover those activities required prior to the start of an operating day following an overnight or weekend shutdown.

Requirement

The system shall meet the following requirements in order to make experimental systems ready for the start of operations, and verify that experimental systems are functioning correctly.

3.2.1.3.1 Plasma Chamber Conditioning

3.2.1.3.1.1 Boronization

The facility shall provide (as a future upgrade) the capability for boronization for all surfaces with line-of-sight to the plasma.

3.2.1.3.1.2 Lithiumization

The facility shall provide (as a future upgrade) the ability to apply lithium coatings, either via Li pellets or spray, or other techniques.

3.2.1.4 Pre-pulse Initialization and Verification

Background

Pre-pulse initialization and verification activities cover those activities required prior to the start of each pulse (plasma discharge).

Requirement

The system shall make experimental systems ready for the start of a pulse (plasma discharge) and verify that the experimental systems are functioning correctly prior to the initiation of a pulse.

3.2.1.4.1 Glow Discharge Cleaning (GDC) Between Pulses

a. The facility shall provide (as a future upgrade) the capability to perform GDC between pulses with the vacuum vessel and all components internal to the vacuum vessel at their nominal pre-pulse operating temperatures.

b. The facility shall be capable of using any of the following gases for GDC: hydrogen, deuterium, helium, and other non-corrosive gases.

c. Shutters shall be provided to prevent coating of windows during GDC. Shields shall be provided to prevent coating and high-resistance short circuits across insulators. Provision shall be made to isolate the neutral beams during GDC.

3.2.1.4.2 Pre-Pulse Temperature

a. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall return to a prescribed pre-pulse temperature in the range of 40-80ºC while maintaining port end flanges in the range of 20-40ºC.

b. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall be capable of being maintained at a pre-pulse temperature of 210ºC (as a future upgrade) to facilitate the use of liquid lithium while maintaining port end flanges at or below 150ºC.

c. The Plasma Facing Components shall have a minimum pre-pulse operating temperature of 40ºC.

d. The cryo-resistive coils shall return to a pre-pulse temperature of about 80K, so as to prevent overheating during operation.

3.2.1.5 Experimental Operations

3.2.1.5.1 Field Error Requirements

a. Field error correction (trim) coils shall be provided to compensate for fabrication errors.

b. The toroidal flux in island regions due to fabrication errors, magnetic materials, and eddy currents shall not exceed 10% of the total toroidal flux in the plasma (including compensation).

3.2.1.5.2 Electrical (Eddy Current) Requirements

Background

There are three fundamental reasons for establishing electrical (eddy current) requirements: plasma control, plasma stabilization, and field errors. The plasma will be initiated inductively on closed magnetic surfaces. The PF coils will apply the inductive voltage for plasma initiation and current drive. The toroidal resistance of the surrounding structures must be sufficiently high in order for the voltage to penetrate to the plasma chamber. Limitations on time constants for poloidal currents in the surrounding structures are also required to allow the magnetic fields from the TF and modular coils to penetrate.

The second reason is related to stabilizing external kink modes. The presence of a close-fitting conducting shell can stabilize external kink modes. The longest time constant of close-fitting conducting shells (like the vacuum vessel) should be short enough to preclude kink mode stabilization.

The third reason is related to field errors and their effect on surface quality in the plasma. Eddy currents can give rise to field errors that in turn, can create unacceptably large islands or destroy the outer surfaces of the plasma.

Requirements

a. The time constant of the longest-lived eddy current eigenmode of the vacuum vessel and in-vessel structures must be less than 10 ms.

b. The stellarator core structure out to and including the cryostat (except the vacuum vessel and coils) shall include electrical breaks to avoid having a toroidally continuous current path.

c. The time constant of the longest-lived eddy current eigenmode in the electrically conducting structures outside the vacuum vessel and inside the cryostat (except coils) shall be less than 20 ms.

d. Eddy currents in conducting structures surrounding the plasma shall not give rise to unacceptable field errors, as defined in Section 3.2.1.5.1.

e. Stellarator symmetry shall be preserved in the design of the vacuum vessel, in-vessel structures, and electrically conducting structures outside the vacuum vessel in the stellarator core out to and including the cryostat.

f. The machine shall be positioned high enough above the ground plane such that eddy currents in the ground plane shall not give rise to unacceptable field errors, as defined in Section 3.2.1.5.1.

3.2.1.5.3 Plasma Magnetic Field Requirements

3.2.1.5.3.1 Coordinate System

Figure 3-2 illustrates the right-handed coordinate system used for the stellarator and test cell on NCSX. The Z-axis of the coordinate system is vertical. The major axis of the stellarator is coincident with the Z-axis. The following conventions are followed:

- A positive toroidal (plasma) current or a positive toroidal magnetic field point in the ϕ-direction (counter-clockwise viewed from above).
- A positive vertical magnetic field points in the Z-direction (upward).
- A positive poloidal current (TF or modular coil current in the inner leg) flows in the Z-direction and provides a positive toroidal magnetic field.
- Positive radial magnetic fields and currents are in the R-direction, radially outward from the Z-axis, the major axis of the stellarator.

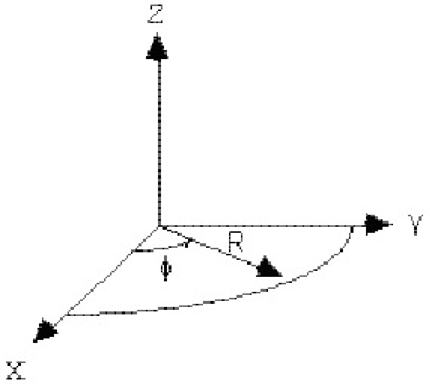

Figure 3-2 NCSX Coordinate System

3.2.1.5.3.2 Magnetic Field Polarity

a. The facility shall be configured for the standard magnetic field polarity to have its toroidal field in the negative direction.

b. The facility shall have the capability to be reconfigured to operate with the magnetic field polarity reversed from its standard direction.

3.2.1.5.3.3 Reference Scenarios

Background

NCSX is designed to be a flexible, experimental test bed. To ensure adequate dynamic flexibility, a series of reference scenarios has been established. TF, PF, and modular coil systems and the vacuum vessel will be designed for a plasma with a nominal major radius of 1.4 m and capability to meet the requirements of all the reference scenarios. Electrical power systems shall be designed and initially configured to meet the requirements of the First Plasma and Field Line Mapping Scenarios and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

The NCSX Project will document coil current center geometries, the first wall surface geometry, and coil current waveforms required for each reference scenario in technical data files.

3.2.1.5.3.3.1 Reference Scenario Specifications

Background

This section provides the specifications for each of the reference scenarios, while the requirements themselves are provided in Section 3.2.1.5.3.3.2. Reference waveforms of engineering parameters such as coil currents, voltages, power dissipation, etc. are derived from the scenario specifications.

3.2.1.5.3.3.1.1 First Plasma Scenario

The First Plasma Scenario is characterized by:

- A magnetic field on axis (R=1.4m) of at least 0.5 T
- A plasma current of at least 25 kA
- At least 50% of the rotational transform provided by stellarator magnetic fields.

3.2.1.5.3.3.1.2 Field Line Mapping Scenario

The Field Line Mapping Scenario is characterized by:

- Ramping the coils to a magnetic field on axis (R=1.4m) of 0.1T. The vacuum iota shall be above 0.5 in the outer half of the plasma.
- Maintain a constant field on axis for 10 seconds.

3.2.1.5.3.3.1.3 1.7T Ohmic Scenario

The 1.7T Ohmic Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 1.7T. The vacuum iota shall be above 0.5 in the outer half of the plasma.
- Holding the coils at pre-initiation values for 100ms
- Inductively initiating the plasma and ramping the plasma current to its maximum value of 120kA at a rate of 3MA/s
- Maintaining the plasma current constant for 300ms

3.2.1.5.3.3.1.4 1.7T High Beta Scenario

The 1.7T High Beta Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 1.7T. The vacuum iota shall be above 0.5 in the outer half of the plasma.
- Holding the coils at pre-initiation values for 100ms.
- Inductively initiating the plasma and ramping the plasma current to 120kA at a rate of 3MA/s.
- Heating the plasma to a beta greater than 4% while ramping the plasma current to 175 kA in 100ms.
- Maintaining the plasma current and beta constant for 200ms

3.2.1.5.3.3.1.5 1.2T High Beta Long-Pulse Scenario

The 1.2T High Beta Long Pulse Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 1.2T. The vacuum iota shall be above 0.5 in the outer half of the plasma.
- Holding the coils at pre-initiation values for 100ms
- Inductively initiating the plasma and ramping the plasma current to 85kA at a rate of 3MA/s.
- Heating the plasma to a beta greater than 4% while ramping the plasma current to 125 kA in 100ms.
- Maintaining the plasma current and beta constant for 1.5 sec

3.2.1.5.3.3.1.6 2T High Beta Scenario

The 2T High Beta Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 2T
- Holding the coils at pre-initiation values for 50ms
- Inductively initiating the plasma and ramping the plasma current to 134kA at a rate of 3MA/s
- Heating the plasma to a beta greater than 4% while ramping the plasma current to 200 kA in 100ms

3.2.1.5.3.3.1.7 320 kA Ohmic Scenario

The 320 kA Ohmic Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 1.7T
- Holding the coils at pre-initiation values for 100ms
- Inductively initiating the plasma and ramping the plasma current to its maximum value of 320kA at a rate of 3MA/s
- Maintaining the plasma current constant for 300ms

3.2.1.5.3.3.2 Reference Scenario Requirements

a. TF and modular coil systems and the vacuum vessel will be designed to meet the requirements of all the reference scenarios.

b. Electrical power shall be designed and initially configured to meet the requirements of the First Plasma and Field Line Mapping Scenarios and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

c. The PF coil system shall be initially configured using two surplus solenoid coils, .i.e. the NSTX PF1A coils. In this initial configuration, the PF coil system shall be capable of meeting the requirements of the First Plasma and Field Line Mapping Scenarios. The PF coil system shall be capable of being upgraded to meet the requirements of all other reference scenarios.

3.2.1.5.3.4 Flexibility Requirements

Background

NCSX is designed to be a flexible, experimental test bed. To ensure that changes in equilibria can be accommodated, several dimensions have been identified over which changes in equilibria must be accommodated.

Flexibility requirements have been established for a toroidal magnetic field of 1.7T. Greater flexibility exists at lower field levels.

The NCSX Project will provide coil currents in technical data files required for each equilibrium at the extremes in flexibility space.

3.2.1.5.3.4.1 Quasi-axisymmetry Flexibility

The coils shall be designed and the power systems shall be upgradeable to vary quasi-symmetry by varying the effective ripple from the reference value to 10 times the reference value.

3.2.1.5.3.4.2 External Iota Flexibility

The coils shall be designed and the power systems shall be upgradeable to vary the rotational transform from -0.2 to +0.2 **(TBR)**, relative to the reference profile, while holding the global shear ($\iota(a)-\iota(0)\sim0.2$), plasma current (175kA), and toroidal magnetic field (1.7T at R=1.4m) constant.

3.2.1.5.3.4.3 Shear Flexibility

The coils shall be designed and the power systems shall be upgradeable to vary the shear by varying the global shear (equal to $\iota(a)-\iota(0)$) by -0.2 to +0.2 **(TBR)**, relative to the reference value, while holding the central iota (0.4), plasma current (175kA), toroidal magnetic field (1.7T at R=1.4m) constant

3.2.1.5.3.4.4 Beta Limit Flexibility

The coils shall be designed and the power systems shall be upgradeable to be capable of reducing the kink stability beta limit to 1% from its reference value of ~4%.

3.2.1.5.3.4.5 Radial and Vertical Position Flexibility

The coils shall be designed and the power systems shall be upgradeable to be capable of varying the radial position of the magnetic axis by ±16 cm relative to the nominal position, and the vertical position by ±2 cm relative to the midplane. **(TBR)**

(Note that this applies only to the coils and power supplies and does not imply any requirement on the Plasma Facing Components.)

3.2.1.5.3.5 Equilibrium Control

Feedback equilibrium control systems for radial and vertical plasma position control shall be provided (as a future upgrade).

3.2.1.5.3.6 Breakdown Loop Voltage

a. The coils and power supplies shall be designed to be capable of producing a loop voltage of 3 V for plasma breakdown under dirty plasma conditions.

b. The power supplies shall be upgradeable to be capable of producing a loop voltage of 5 V.

3.2.1.5.3.7 Power Supply Ripple

The power systems shall be designed with low enough voltage and current ripple so as not to interfere with magnetic diagnostic measurements or plasma equilibrium control.

3.2.1.5.3.8 Coil Current Measurements

Coil currents shall be continuously measured during a pulse with an accuracy of 0.1% of the peak power supply current.

3.2.1.5.4 Power Handling

Background

PFCs serve the following functions: a) Provide for limiter operation, b) Provide for divertor operation including power handling, neutral recycling, and density control, and c) protect the vacuum vessel and in-vessel components from particle and radiation heat loads from the plasma (including energetic ions) and from the shinethrough of neutral beams through the plasma.

Initially, the device will not be configured with any PFCs. Upgrades to the PFC system will be incrementally made in response to experimental program needs to provide all of the functions above.

3.2.1.5.4.1 PFC Configuration

a. Coverage. The capability to expand the coverage by the PFCs (as a future upgrade) to 100% shall be provided.

b. Materials. Future upgrades for a carbon fiber composite (CFC), lithium, tungsten, or molybdenum liner shall be accommodated. Materials used inside the vacuum vessel shall, unless otherwise authorized by the project, be compatible with lithium, in order to facilitate the use of a lithium liner as a possible future upgrade. The vacuum vessel and support system must be capable of supporting the weight of all in-vessel components, including upgrades, and maintain their alignment (including tungsten and molybdenum liner upgrades).

c. Poloidal limiters. The capability to accommodate an array of graphite or CFC poloidal limiters (as a future upgrade) shall be provided on the v=0.5 cross section.

d. Divertor capability. The capability to accommodate a divertor (as a future upgrade) shall be provided.

e. Divertor pumping. The capability to configure the divertor (as a future upgrade) with a slot, permitting neutral particles passage into a plenum that is actively pumped (with a cryopump or titanium getter pump), shall be provided.

f. Electrical biasing. The capability to electrically bias regions of the plasma boundary up to 1000 V relative to each other and the vacuum vessel (as a future upgrade) shall be provided.

g. Armor. The capability to add armor to protect the vacuum vessel, port extensions, and in-vessel components from neutral beam shinethrough and from fast ions lost from the plasma (as future upgrades) shall be provided.

3.2.1.5.4.2 Maximum Plasma Heating Power

The capability to accommodate (as a future upgrade) heat loads associated with up to 12MW of plasma heating power for 1.2s (including 6MW of neutral beam injection) shall be provided.

3.2.1.5.4.3 Maximum Component Surface Temperature

The maximum surface temperature for carbon-based PFCs shall not exceed 1200˚C.

3.2.1.5.5 Disruption Handling

The facility shall be designed to withstand electromagnetic forces due to major disruptions characterized by instantaneous disappearance of the plasma at with a maximum plasma current of 320 kA.

Note: Instantaneous decay is assumed for simplicity and is conservative for EM load calculations. Induced voltage effects due to disruptions are ignored because of the relatively low plasma current and continuous vacuum vessel in NCSX.

3.2.1.5.6 Plasma Heating

3.2.1.5.6.1 Neutral Beam Heating

3.2.1.5.6.1.1 Initial Neutral Beam Heating Complement

One beamline previously used on the PBX-M project will be installed as part of the NCSX Fabrication Project to provide 1.5 MW of neutral beam heating power with a minimum of 0.3 s of pulse length. The beam will be configured in the co-direction (the nominal direction of the plasma current) The tangency radius shall be inside the magnetic axis for the nominal 1.7T high beta equilibrium and located such that the beam does not intercept the inboard first wall.

3.2.1.5.6.1.2 Ultimate Neutral Beam Heating Complement

The facility shall be designed to accommodate future neutral beam heating upgrades up to 6 MW of power and up to 1.2 s of pulse length using the four (4) beamlines previously used on PBX-M in two possible configurations: a) 2 co- and 2 counter-directed beamlines and b) 3 co- and 1 counter-directed beamlines.

3.2.1.5.6.2 Ion Cyclotron Heating (ICH)

a. The facility shall be designed to accommodate 6 MW of ICH (as a future upgrade) with a pulse length of 1.2s and frequency of 20-30 MHz.

b. The facility shall be designed to accommodate three sets of launchers on the inboard side, one at each of the three v=0.5 cross-sections.

3.2.1.5.6.3 Electron Cyclotron Heating (ECH)

The facility shall be designed to accommodate 3 MW of ECH (as a future upgrade) with a pulse length of 1.2s and frequency of 70-140 GHz.

3.2.1.5.7 Plasma Fueling

3.2.1.5.7.1 Fuel Species

The facility shall be designed to be fueled with hydrogen (H), deuterium (D), helium (He), or other non-corrosive gases.

3.2.1.5.7.2 Gas Injection

a. The device and facility shall have a programmable gas injection system capable of injecting any one or a combination of the fuel species specified in Section 3.2.1.5.7.1.

b. The system shall provide one injector per period (total of 3), each with a maximum flow rate of at least 50 torr-l/sec.

c. The system shall have the capability to accommodate as future upgrades:

  - Up to four injectors per period (inboard, outboard, and top and bottom divertors).
  - One outboard and one inboard supersonic injector per period.
  - One inboard injector per period for either gas or pellets.
  - Feedback on real-time density measurement.

3.2.1.5.7.3 Pellet Injection

a. The facility shall incorporate guide tubes to accommodate pellet launch from the inboard (high-field) side of the plasma.

b. The device and facility shall be designed to accommodate (as a future upgrade) a single pellet injector capable of repetitively injecting H or D pellets.

3.2.1.5.8 Plasma Diagnostics

3.2.1.5.8.1 General Diagnostics Requirements

Diagnostic measurements of the plasma parameters that are: a) critical to the research goals of NCSX and b) necessary for plasma control and operational purposes shall be provided.

3.2.1.5.8.2 Diagnostics Implementation

a. All magnetic trapped sensors (e.g., those located between the coils and vacuum vessel or co-wound with the coil), magnetic diagnostics, and signal processing electronics needed to measure plasma current, a fast visible camera, and field mapping apparatus (e-beam, fluorescent probe, camera) shall be provided.

b. The facility shall be designed to accommodate the additional diagnostics identified in Table 3-2 as future upgrades.

Table 3-2 Diagnostic Requirements

Research program phase/measurement	**Diagnostic technique**
1. Initial Operation (B=0.5 T, room temperature)	
Plasma current	Rogowski coil
Wide-angle image of plasma/wall	Visible camera (1)
2. Initial Field Line Mapping (no plasma)	
Vacuum flux surfaces	E-beam, fluorescent probe & CCD camera
3. 1.5 MW Initial Experiments (1.5 MW NBI, B=1.2 T, cryogenics, minimal PFCs)	
Boundary position and shape	Saddle loops, flux loops, B probes, V3FIT
Total stored energy	Diamagnetic loop
Wide-angle image of plasma/wall	Visible cameras with filters (2)
Core T_e	Basic Thomson scattering or filtered SXR diodes, and x-ray crystal spectrometer
n_e profile	FIR interferometer/polarimeter
Core T_i	X-ray crystal spectrometer
Total P_{rad}	Wide angle bolometer
Low m,n MHD modes (<100 kHz)	Compact soft x-ray arrays (8 20-channel arrays)
Magnetic axis position	Compact soft x-ray arrays & 3-D EFIT
Impurity identification	Visible spectrometer
VB, H_α & carbon line emission	Visible filterscopes
PFC temperature	Compact IR camera
4. 3 MW Heating (3 MW NBI, full PFCs, B=2.0 T, 350 C bake)	
T_e profile	Full Thomson scattering system
T_i, v_θ profiles	DNB & CHERS
Rotational transform profile	DNB & MSE, FIR inter./polar., V3FIT
Higher m,n MHD modes	Additional soft x-ray arrays (8 20-channel arrays)
High-frequency MHD (<5 MHz)	High-frequency Mirnov coils
Flux surface topology	Tangential SXR camera
Impurity concentrations	Absolute VUV spectroscopy
Z_{eff} profile	Thomson scattering detector system
P_{rad} profile	Core bolometer array
Fast ion loss	Fast ion loss probe, IR camera
Ion energy distribution	Neutral particle analyzer
Neutron flux	Epithermal neutron detector
SOL n_e and T_e	Movable Langmuir probe
Edge neutral pressure	Fast pressure gauges
5. Confinement & β push (3 MW NBI & 6 MW NBI or RF, divertor)	
Core n_e fluctuations	Fluctuation diagnostic (HIBP and/or BES)
Core helium density profile	DNB & He CHERS
Divertor P_{rad} profile	Divertor bolometer arrays
Divertor plate temperature	Fast IR camera & thermocouples
Target T_e & n_e	Plate-mounted Langmuir probes
Divertor recycling	Divertor filtered 1-D CCD camera
Divertor Impurity concentrations & flows	Divertor VUV spectroscopy
6. Long pulse (Existing heating & 3 MW long pulse NBI or RF)	
Divertor T_e & n_e profiles	Divertor Thomson scattering

3.2.1.5.9 Instrumentation, Control, and Data Acquisition

a. The NCSX facility shall have a flexible instrumentation, control, and data acquisition (central I&C) system that allows for coordination of operations and the acquisition, archiving, and display of all pertinent information.

b. Archiving of data shall be done in a way that enables the data be retrieved with widely available cross-platform software.

c. Archived data shall be protected from loss or destruction by maintaining multiple copies, including off-site storage.

3.2.1.5.10 Pulse Repetition Rate

The facility shall be designed for pulses to be initiated at intervals not exceeding 15 minutes when constrained by coil cool-down, Plasma Facing Component cool-down, or glow discharge cleaning (GDC) and 5 minutes otherwise.

3.2.1.5.11 Discharge Termination

3.2.1.5.11.1 Normal Termination

Background

Normal termination includes all system actions necessary to shutdown the plasma and associated subsystems at the conclusion of a pulse in preparation for the next pulse.

Requirement

The NCSX system shall provide the capability to perform a controlled shutdown of the plasma and associated subsystems at the conclusion of a pulse.

3.2.1.5.11.2 Abnormal Termination

Background

Abnormal termination consists of all system responses necessary to remove conditions that occur during experimental operations that could cause significant damage to the NCSX system or cause injury to personnel.

Requirement

The NCSX system shall provide the capability to shut down the plasma and associated subsystems if a condition occurs during experimental operation that could cause significant equipment damage or cause injury to personnel.

3.2.1.6 Facility Shutdown

Background

Facility shutdown involves the shutdown of NCSX equipment following the termination of a discharge (per Section 3.2.1.5.11) in preparation for a brief (overnight or weekend) or extended (between run periods) shutdown.

Requirement

The NCSX system shall provide the capability to perform a controlled shutdown of the facility.

3.2.1.6.1 Coil Warm-up Timeline

The cryo-resistive coils (TF, PF, and modular coils) shall be capable of being warmed up from operating temperature (80K) to room temperature (293K) within 96 hours.

3.2.1.6.2 Vacuum Vessel Venting

Provisions shall be made to vent the vacuum vessel in preparation for a vacuum opening.

3.2.2 External Interface Requirements

3.2.2.1 Shelter

NCSX will be sited at C-site at PPPL. The NCSX Test Cell will be the same test cell first used for the C-Stellarator and subsequently used for the PLT and PBX-M tokamaks. It is assumed that the NCSX Test Cell, basement, and adjoining rooms utilized by the NCSX Project will be received equipped with proper:

- Shelter from the environment (roofing and walls)
- Lighting
- Environmental (temperature, humidity, and air exchange) control
- Fire suppression

3.2.2.2 Water Systems

It is assumed that the facility water systems to be used by NCSX will be received in a fully operational condition. The NCSX Project will be responsible for adding cooling loops as required for NCSX subsystems.

3.2.2.3 Electrical Power

Electrical power for the TF, PF, and modular coils will be provided through the C- or D-site experimental power systems. All other electrical power for NCSX will be provided through the C-site power systems.

3.2.2.4 Utility Gas Systems

The facility shall provide compressed air as utility services to the core machine and diagnostics for general use such as venting the vessel to atmospheric pressure and actuating valves and shutters.

3.2.3 Physical Characteristics

3.2.3.1 Test Cell Compatibility

Background

NCSX will be sited in an existing test cell. NCSX equipment shall be designed to be within the lift capacity of the existing overhead crane, fit through the existing door, and be within existing floor loading limitations.

3.2.3.1.1 Maximum Lift

The maximum lift required to assemble, maintain, and disassemble NCSX shall not require an overhead crane capacity exceeding **45** tons.

3.2.3.1.2 Maximum Dimensions

Each assembly entering and leaving the test cell must be able to fit through a rectangular door that is 17’6” feet wide and 16 feet high.

3.2.3.1.3 Maximum Floor Loading

3.2.3.1.3.1 Test Cell Floor Loading

The maximum floor loading in the Test Cell shall not exceed 4,500 pounds per square foot on the concrete floor of the building and 150 pounds per square foot on the penetration covers.

3.2.3.1.3.2 Platform Floor Loading

The maximum floor loading on the platform surrounding the machine is 250 pounds per square foot.

3.2.4 System Quality Factors

3.2.4.1 Reliability, Availability, and Maintainability

Background

The overall objective is to provide a device with high operational availability, meaning that the number of plasma discharges achieved in a run period is a large percentage (greater than 75%) of the number planned after the initial shakedown and commissioning phases of the facility. Bottoms-up reliability predictions are difficult to perform and have large uncertainties for first-of-a-kind experimental devices such as NCSX. Therefore, quantitative RAM requirements on NCSX will be few. Rather, NCSX will rather rely on sound engineering practice to assure high availability in NCSX, which has been the tried-and-true approach on similar scale fusion devices. Sound engineering practices include:

- Applying design principles that promote reliability (e.g., employing an adequate factor of safety on mechanical and electrical stresses, avoiding unnecessary complexity, using proven design approaches and well characterized materials, etc.)
- Optimizing designs for reliability and maintainability through systematic evaluation of design options,
- Performing failure modes, effects and criticality analysis (FMECAs) for RAM design improvement and verification, and
- Employing peer reviews as a mechanism to enhance the design process.

The NCSX RAM Plan defines the processes that will be used by the Project to achieve a device with high availability.

Requirements

a. NCSX shall incorporate reliability and maintainability features in the design that are consistent with achieving a high (greater than 75%) operational availability after the initial shakedown and commissioning phases of the facility.

b. The device and components internal to the vacuum vessel shall be designed for installation and maintenance by personnel entering and working inside the vacuum vessel.

c. The facility shall include a work platform surrounding the device to provide access to the device and diagnostic equipment.

d. Provisions for recovery shall be made for every credible failure mode.

e. The stellarator core shall be capable of being disassembled and reassembled within one year to permit replacement of any part or machine reconfiguration that would require disassembly.

f. Assemblies that exceed two man manual lift limits shall include provisions for lifting eyes or other sling attach provisions.

3.2.4.2 Design Life

a. The facility shall have a design life of >10 years when operated per the reference scenarios defined in Section 3.2.1.5.3.3.1.

b. The facility shall be designed for the following maximum number of pulses when operated per the reference scenarios defined in Section 3.2.1.5.3.3.1 and based on the factors for fatigue life specified in the NCSX Structural and Cryogenic Design Criteria Document:

- 100 per day;
- 13,000 per year; and
- 130,000 lifetime.

3.2.5 Transportability

All assemblies and components shall be transportable by commercial carrier via highway, air, sea, or railway. All system elements that are unsuitable, due to operational or functional characteristics, for normal transportation methods by highway, air, or railway shall be identified.

3.3 Design and Construction

3.3.1 Materials, Processes, and Parts

3.3.1.1 Magnetic Permeability

a. All materials to be used in the stellarator and peripheral equipment inside the cryostat must have a relative magnetic permeability not to exceed 1.02 unless otherwise authorized by the Project.

b. Bulk materials used outside the cryostat but within the NCSX Test Cell must have a relative permeability not to exceed 1.05 unless otherwise authorized by the Project.

c. Welds and attaching hardware, e.g. nut and bolts, outside the cryostat but within the NCSX Test Cell must have a relative permeability not to exceed 1.20 unless otherwise authorized by the Project.

3.3.1.2 Vacuum Compatibility

a. The vacuum vessel interior and all in-vessel metallic components shall be polished to a 32 micro-inch finish prior to installation, except when authorized by the project.

b. The vacuum vessel interior shall be degreased and cleaned prior to installation. All in-vessel components shall be made of vacuum compatible materials and degreased and cleaned. They shall be vacuum baked and degassed at a bakeout temperature exceeding the maximum operating temperature prior to installation, except when authorized by the project.

c. All in-vessel materials shall be approved by the PPPL Vacuum Materials Committee for vacuum compatibility.

d. The system shall be designed for high vacuum compatibility: All appendages, ports and diagnostics that are not to be left open permanently to the vacuum vessel shall have their own pumping system and conditioning capabilities to maintain required conditions when opened to the vacuum vessel. All systems and components either in vacuum or with a vacuum interface should be designed to preclude trapped volumes and virtual leaks. The system shall be designed to allow for leak checking and repair of leaks on the vacuum vessel.

3.3.1.3 Structural and Cryogenic Criteria

NCSX stellarator systems shall be designed in accordance with the NCSX Structural and Cryogenic Design Criteria.

3.3.1.4 Corrosion Prevention and Control

Materials, processes, and protective surface treatments or finishes shall be provided to ensure that equipment capability during its service life is not degraded due to corrosion. Where possible, contact between dissimilar metals shall be avoided.

3.3.1.5 Seismic Criteria

NCSX systems shall be designed in accordance with seismic design and evaluation criteria for Performance Category 1 (PC1) facilities, per DOE-STD-1020-2002, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities.”

3.3.1.6 Metrology

The NCSX device shall provide features (e.g., fiducial markers on the coils and vacuum vessel) to facilitate accurately measuring and locating components relative to the magnetic field for the life of the machine.

3.3.2 Nameplates and Product Marking

3.3.2.1 Labels

Equipment and any parts of that equipment to be used by personnel shall be identified with appropriate labels. Labels shall indicate clearly and concisely the function and purpose of the item being labeled. Hierarchical labeling shall be used to facilitate component location on control panels. The terminology used for equipment, procedures, and training materials shall be the same for each case. Label design shall be consistent to promote simplicity and avoid clutter. The use of abbreviations and acronyms shall be minimized. Permanent labels shall be attached to the specific component or equipment in such a manner that environmental conditions or usage by personnel will not remove or destroy the label. Temporary labels shall be used only when necessary and shall not obscure other information or equipment. If a temporary label is to designate a device that is out of service, the label shall be applied so that it prevents the use of that device. Labeling shall be legible and conform to human visual capabilities and limitations in regard to physical characteristics.

3.3.3 Workmanship

During NCSX fabrication and finishing, particular attention shall be given to freedom from blemishes, defects, burrs, and sharp edges; accuracy of dimensioning radii of weld fillets; making of parts; thoroughness of cleaning; quality of brazing, welding, riveting, painting, and wiring; alignment of parts; and tightness and torquing of fasteners.

3.3.4 Interchangeability

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement parts without degrading the specified performance of the parent item.

3.3.5 Environmental, Safety, and Health (ES&H) Requirements

3.3.5.1 General Safety

a. When utilized within its intended use and within specified environments, the safe operation, test, handling, maintenance and storage of the system hardware and software shall be provided.

b. The system shall not present any uncontrolled safety or health hazard to user personnel.

c. The system shall detect abnormal operating conditions and safeguard the NCSX system and personnel.

3.3.5.2 Safety Hazards

3.3.5.2.1 Radiation Monitoring

For plasma operations (and depending on experimental plans and operational experience), fixed and/or portable gamma and neutron radiation monitors may be set up at various locations inside and outside the NCSX Test Cell. Locations for these monitors will be determined by the PPPL Health Physics organization, in conjunction with the NCSX organization.

3.3.5.2.2 Controlled Access System

a. A controlled access system (CAS) shall protect against inadvertent entry into the NCSX Test Cell when electrical, magnetic, mechanical, toxic, or radiation hazards exceed allowable limits.

b. The CAS shall be upgradeable to allow controlled access periods of at least five (5) minutes in the NCSX Test Cell between shots without impacting a 15-minute pulse repetition rate.

3.3.5.2.3 Toxic Gases

<u>Background</u>

Toxic gases such as tri-methyl boron (TMB) are sometimes used to perform GDC. Potential hazards can be controlled by selecting GDC gases with reduced toxicity, minimizing the gas inventory (through the use of small storage containers and compact distribution systems), implementing controls to shut down the flow of such gases in the event that the glow discharge is extinguished, and venting the effluent from the plasma chamber in a manner that there is no risk to personnel safety.

<u>Requirement</u>

Safeguards shall be implemented regarding the use of toxic gases for GDC to mitigate potential safety hazards.

3.3.5.2.4 Oxygen Depletion

<u>Background</u>

The cryostat is filled with cold (80K), dry nitrogen gas and maintained at a pressure slightly above atmospheric to prevent moisture from leaking into the cryostat. Excessive leakage of nitrogen gas represents a possible mechanism for oxygen depletion in the vicinity of the cryostat. The air in the test cell should be constantly exchanged and oxygen levels monitored to ensure personnel safety.

<u>Requirement</u>

a. The air in the NCSX Test Cell shall be exchanged once per **TBD** hours when the cryostat is pressurized with dry nitrogen.

b. Oxygen levels in the vicinity of the cryostat shall be monitored and alarmed to detect excessive leakage of nitrogen from the cryostat.

c. The cryostat shall be carefully air purged, monitored, and certified safe before cryostat panels are removed and personnel are allowed to enter.

3.3.5.2.5 Vacuum Implosion

Vacuum windows of 4 inches diameter or greater shall incorporate protection from accidental vacuum implosion.

3.3.5.3 Personnel Safety

The system shall meet all applicable OSHA requirements in accordance with 29CFR1910. The system shall limit personnel exposure to hazardous materials to below their OSHA permissible exposure limit (PEL).

3.3.5.4 Flammability

a. The use of flammable materials shall be minimized.

b. Components containing flammable materials, fluids or gases shall be designed to minimize the possibility of leaks and spills.

3.3.5.5 Fire Suppression

A fire suppression system shall be provided for the NCSX system, which meets the requirements of DOE O 420.1 and PPPL ESHD-5008.

3.3.5.6 Hazardous Materials

Radioactive and hazardous waste shall be handled in accordance with federal, state, and local standards.

3.3.5.7 Electrical Safety

a. Electrical apparatus and systems shall be designed so that two simultaneous failures of high voltage (>600 V) barriers or a single failure of a low voltage barrier would have to occur to endanger workers performing work processes.

b. Designs shall comply with the requirements of PPPL-ES&HD-5008, Section 2.

3.3.5.8 Radiological Design Objectives

Background

NCSX is being situated in the test cell previously used for the PBX-M experiment. It is expected that NCSX will produce fewer neutrons than PBX-M produced in its peak years. The plan is to reconfigure the shield walls to provide about the same level of shielding that was provided for PBX-M and to administratively limit deuterium (D) operation to keep personnel exposure within radiological limits. It is anticipated that annual DD neutron yields would be limited to approximately 2.3×10^{16} per year in order to limit the neutron dose-equivalent in the control room to 500 mrem per year.

Requirement

Deuterium (D) operation shall be administratively limited to keep personnel exposure within the radiological limits and design objectives of Table 3-3.

Table 3-3 Radiological Limits and Design Objectives

Condition		P, Probability Of Occurrence In A Year	Public Exposure[1]		Occupational Exposure	
			Regulatory Limit (rem per yr)	Design Objective (rem per yr)	Regulatory Limit (rem per yr)	Design Objective (rem per yr)
Routine Operation[2]	Normal Operations	P~1	0.1 total 0.01 airborne[3] 0.004 drinking water	0.01 total	5	1
Accidents[4]	Anticipated Events	$1>P\geq10^{-2}$	0.5 total (including normal operation)	0.05 per event		
	Unlikely Events	$10^{-2}>P\geq10^{-4}$	2.5	0.5	ref[5]	ref[5]
	Extremely Unlikely Events	$10^{-4}>P\geq10^{-6}$	25	5[6]	ref[5]	ref[5]
	Incredible Events	$P<10^{-6}$	NA	NA	NA	NA

3.3.6 Human Engineering

Human factors technology shall be considered in the design, operation, and maintenance of the NCSX system. The criteria and requirements provided in this section are applicable to the design of the work environment and human-machine systems at NCSX facilities. These criteria shall apply to new construction and to retrofitting of existing facilities. These criteria shall be considered for upgrading existing facilities where cost-benefit or risk-tradeoff analyses indicate justification for such expenditures.

3.3.6.1 Anthropometry

Equipment that is to be used by personnel shall be designed or selected to accommodate the fifth to ninety-fifth percentile of the user population for stand-up and sit-down consoles and other work stations, for accessibility of equipment and instrumentation, for furniture and equipment layout, and for traffic flow.

3.3.6.2 Human Environments

3.3.6.2.1 Temperature and Humidity

Temperature and humidity for human environments shall be maintained within **TBD** limits.

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[1] Evaluated at the PPPL site boundary.

[2] Dose equivalent to an individual from routine operations (rem per year unless otherwise indicated)

[3] Compliance with this limit is to be determined by calculating the highest effective dose equivalent to any member of the public at any off site point where there is a residence, school, business, or office.

[4] Dose equivalent to an individual from an accidental release (rem per event)

[5] See Reference 4, Section 10, Item 10.1302 for exposure limits for emergency situations.

[6] For design basis accidents (DBAs), i.e., postulated accidents or natural forces and resulting conditions for which the confinement structure, systems, components, and equipment must meet their functional goals, the design objective is 0.5 rem.

3.3.6.2.2 Ventilation

TBD

3.3.6.2.3 Lighting

Adequate light levels shall be provided.

3.3.6.2.4 Emergency Lighting

Emergency lighting systems shall be provided as required by NFPA 101.

3.3.6.3 Protective Equipment

The facility shall be designed to ensure worker access to appropriate protective equipment as prescribed in ESHD 5008, "PPPL Environment, Safety, and Health Directives."

3.3.7 System Security

The system shall provide security features with the capability to protect against unauthorized access and use of the NCSX system.

3.3.8 Government Furnished Property Usage

TBD

3.4 Documentation

N/A

3.5 Logistics

3.5.1 Maintenance

The system shall be maintained using, to the extent possible, standard/common tools and existing multi-purpose test equipment. Use of new/special tools and the number of standard/common tools shall be minimized through maximum commonality of fasteners, clamps, adapters, and connectors.

3.5.2 Supply

The NCSX system shall use the existing PPPL material system.

3.5.3 Facilities

Maximum use shall be made of the existing facilities and equipment at PPPL. Modifications and new facilities shall be constructed only where existing facilities are not adequate to house, store, maintain, operate, or test NCSX equipment.

3.6 Personnel and Training

Background

The principles of Integrated Safety Management shall be followed in executing the NCSX project. The guiding principles are line management responsibility for safety, clear roles and responsibilities, competence commensurate with responsibilities, balanced priorities, identification of safety standards and requirements, and hazard controls tailored to work being performed. To assure competence commensurate with responsibilities, training shall be provided.

Requirement

Training shall be provided as required to assure competence commensurate with responsibilities.

3.7 Characteristics of Subordinate Elements

Background

In this section, the performance characteristics defined in Section 3.2.1 are allocated to the subsystem level. These allocated characteristics provide the basis for defining performance characteristics in subsystem specifications.

Requirements

Allocated subsystem performance characteristics are defined in the Characteristics Allocation Matrix in Appendix B.

4 VERIFICATION OF REQUIREMENTS

4.1 General

This section identifies the methods to be used for verification of requirements in Section 3 of this specification. General definitions of basic verification methods are outlined in Section 4.2. System requirements will be allocated in part or total to lower-level NCSX element specifications as outlined in Section 4.3. Verification and qualification of individual components will be conducted in accordance with individual specifications. Verification of system requirements will require additional testing in operational or near-operational environments. Detailed planning for verification of all system requirements will be documented in the NCSX Test & Evaluation Plan.

4.2 Inspection Verification Methods

Verification of qualification shall be by examination, demonstration, test or analysis. Definition of examination, demonstration, test and analysis is as follows:

<u>Examination</u>: Examination is an element of inspection consisting of investigation, without the use of special laboratory appliances, procedures or supplies and services to determine conformance to those specified requirements which can be determined by such investigations. Examination is generally non-destructive and includes but is not limited to, simple physical manipulation, gauging and measurement, visual, auditory, olfactory, tactile, gustatory and other investigations.

<u>Test</u>: Test is an element of inspection denoting the determination of the properties or elements of supplies or components thereof by technical means, including functional operation and the application of established principles and procedures. The analysis of data derived from test is an integral part of the inspection element and shall not be confused with “Analysis” below.

<u>Demonstration</u>: Demonstration is an element of inspection that, although technically a variation of test, differs from “Test” above, by directness of approach in the verification of a requirement and is accomplished without the use of elaborate instrumentation or special equipment. Thus, operation of a representative configuration item (CI) in or near its use environment would be defined as a demonstration rather than a test.

<u>Analysis</u>: Analysis is an element of inspection in the form of a study resulting in data that is intended to verify a requirement when an examination, test, or demonstration cannot feasibly be employed to verify the requirement. Such data may be a compilation or interpretation of existing data, analysis, design solutions, and lower-level inspection results.

4.3 Quality Conformance

<u>Background</u>

This section establishes the specific evaluation criteria for verification of the system requirements in Section 3. Each of the performance characteristics in Section 3.2.1 is associated with a verification method in the Quality Conformance Matrix in Appendix C. All other requirements in Section 3 flow down to individual subsystems and will be verified at a level below the system level. In general, all requirements shall be verified under operational or near-operational conditions as possible given test constraints.

<u>Requirements</u>

Test methods for each of the performance characteristics in Section 3.2.1 are identified in the Quality Conformance Matrix in Appendix C.

APPENDIX A – TECHNICAL DATA SHEET

A.1 Initial Operation

A.1.1 Coil Set Definition

A.1.1.1 Current Centroid Locations

Coil centroids are defined by the TBD coil set.

A.1.1.2 Turns per Coil

	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	Plasma
Turns	22	22	20	48	80	24	14	12	1

A.1.2 Coil Inductance Matrix (Henries)

	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	Plasma
MA	1.42E-02	3.42E-03	1.53E-03	-1.84E-05	1.34E-04	-2.51E-04	-3.10E-04	9.52E-03	-1.79E-05
MB	3.42E-03	1.04E-02	2.84E-03	3.56E-06	-1.31E-05	-5.10E-05	-7.07E-05	7.34E-03	-1.20E-05
MC	1.53E-03	2.84E-03	9.29E-03	3.15E-05	-1.84E-04	-2.26E-04	-6.86E-05	5.19E-03	-9.57E-06
PF1A U+L	-1.84E-05	3.56E-06	3.15E-05	8.13E-04	8.56E-05	7.90E-05	5.48E-05	4.17E-21	4.06E-06
PF4 U+L	1.34E-04	-1.31E-05	-1.84E-04	8.56E-05	1.50E-02	1.14E-03	5.91E-04	-7.18E-20	1.73E-05
PF5 U+L	-2.51E-04	-5.10E-05	-2.26E-04	7.90E-05	1.14E-03	1.28E-02	3.48E-03	1.52E-18	4.26E-05
PF6 U+L	-3.10E-04	-7.07E-05	-6.86E-05	5.48E-05	5.91E-04	3.48E-03	6.23E-03	5.07E-19	3.46E-05
TF Coils	9.52E-03	7.34E-03	5.19E-03	4.17E-21	-7.18E-20	1.52E-18	5.07E-19	5.27E-02	1.51E-06
Plasma	-1.79E-05	-1.20E-05	-9.57E-06	4.06E-06	1.73E-05	4.26E-05	3.46E-05	1.51E-06	2.68E-06

A.1.3 Reference Scenario Data

A.1.3.1 Reference Equilibria (amp-turns per coil)

Equlibrium ID	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	Plasma
8	2.00E+05	2.00E+05	1.82E+05	0.00E+00	0.00E+00	0.00E+00	0	0	0
9	2.00E+05	2.00E+05	1.82E+05	0.00E+00	0.00E+00	0.00E+00	0	0	-26000

A.1.3.2 Current Waveforms

Conductor currents are given in amperes. ***Maxima are shown in blue*** **,** ***minima in red.***

0.5T First Plasma Scenario	**Time**	**MA**	**MB**	**MC**	**PF1A U+L**	**PF4 U+L**	**PF5 U+L**	**PF6 U+L**	**TF Coils**	**Plasma**
Start	-1.900	**0**	**0**	**0**	**0**	**0**		**0**		**0**
Modular coils at full current	0.000	**9115**	**9115**	**9115**	**0**	**0**		**0**		**0**
Start Ip ramp	0.050	**9115**	**9115**	**9115**	**0**	**0**		**0**		**0**
SOF	0.120	**9115**	**9115**	**9115**	17872	3016		234		**-26068**
EOF	0.130	**9115**	**9115**	**9115**	**19083**	**3220**		**250**		**-26068**
End of discharge	4.130	**0**	**0**	**0**	**0**	**0**		**0**		**0**
Max		9115	9115	9115	19083	3220		250		0
Min		0	0	0	0	0		0		-26068
I2t(A2-s)		1.45E+08	1.45E+08	1.45E+08	3.09E+08	8.79E+06		52983		0
tESW(s)		1.75	1.75	1.75	0.85	0.85		1		0

Field Line Mapping Scenario	**Time**	**MA**	**MB**	**MC**	**PF1A U+L**	**PF4 U+L**	**PF5 U+L**	**PF6 U+L**	**TF Coils**	**Plasma**
Start	-0.250	**0**	**0**	**0**	**0**	**0**		**0**		0
Modular coils at full current	0.000	1823	1823	1823	**0**	**0**		**0**		0
Start Ip ramp	0.050	1823	1823	1823	**0**	**0**		**0**		0
SOF	0.150	1823	1823	1823	**0**	**0**		**0**		0
EOF	10.150	1823	1823	1823	**0**	**0**		**0**		0
End of discharge	13.150	**0**	**0**	**0**	**0**	**0**		**0**		0
Max		1823	1823	1823	0	0		0		0
Min		0	0	0	0	0		0		0
I2t(A2-s)		3.60E+07	3.60E+07	3.60E+07	0.00E+00	0.00E+00		0		0
tESW(s)		10.85	10.85	10.85	0.00	0.00		0		0

Summary		**MA**	**MB**	**MC**	**PF1A U+L**	**PF4 U+L**	**PF5 U+L**	**PF6 U+L**	**TF Coils**	**Plasma**
Max	0	9115	9115	9115	19083	3220		250		0
Min	0	0	0	0	0	0		0		-26067.71
I2t(A2-s)	0	1.45E+08	1.45E+08	1.45E+08	3.09E+08	8.79E+06		52983		
tESW(s)	0	1.75	1.75	1.75	0.85	0.85		1		

Equivalent square wave times (tESW) for the coils calculated on the basis of the maximum coil current

A.1.3.3 Temperature History

Coil temperatures are in Kelvin. *Maxima are shown in blue.*

0.5T First Plasma Scenario	Time	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	
	-1.900	85	85	85	85	85		85		
	0.000	86	86	86	85	85		85		
	0.050	86	86	86	85	85		85		
	0.120	87	87	87	85	85		85		
	0.130	87	87	87	85	85		85		
	4.130	88	88	88	89	85		85		
Dissipated Energy (J)		1.41E+06	1.38E+06	1.16E+06	2.60E+05	3.27E+04		1.79E+02		4.25E+06

Field Line Mapping Scenario	Time	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	
	-0.250	85	85	85	85	85		85		
	0.000	85	85	85	85	85		85		
	0.050	85	85	85	85	85		85		
	0.150	85	85	85	85	85		85		
	10.150	86	86	86	85	85		85		
	13.150	86	86	86	85	85		85		
Dissipated Energy (J)		3.38E+05	3.31E+05	2.78E+05	0.00E+00	0.00E+00		0.00E+00		9.47E+05

Summary		MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	
Max Final Temperature		88	88	88	89	85		85		
Max Dissipated Energy (J)		1.41E+06	1.38E+06	1.16E+06	2.60E+05	3.27E+04		1.79E+02		4.25E+06

A.1.3.4 Circuit Characteristics and Requirements

A.1.2.4.1 Circuit Resistance and Bus Inductance

		MA	MB+MC	PF1A U+L	PF4 U+L	PF6 U+L
Initial coil resistance (mΩ)		9.275	16.682	0.795	3.712	3.387
Bus resistance (mΩ)		4.355	3.414	2.619	11.058	5.997
Initial loop resistance (mΩ)		13.629	20.096	3.414	14.770	9.384
Bus inductance (μH)		4.250	4.250	4.250	4.250	4.250

A.1.3.4.2 Circuit Inductance (μH)

	MA	MB+MC	PF1A U+L	PF4 U+L	PF6 U+L	Plasma
MA	14232.4	4948.6	-18.4	133.9	-310.3	-17.9
MB+MC	4948.6	25405.0	35.1	-197.0	-139.3	-21.6
PF1A U+L	-18.4	35.1	817.7	85.6	54.8	4.1
PF4 U+L	133.9	-197.0	85.6	15029.5	590.6	17.3
PF6 U+L	-310.3	-139.3	54.8	590.6	6230.5	34.6
Plasma	-17.9	-21.6	4.1	17.3	34.6	2.7

A.1.3.4.3 Power Supply Assignments and Ratings

		MA	MB+MC	PF1A U+L	PF4 U+L	PF6 U+L
Power supply assignments		R10	2R5(P)	R20	R5+PEI(S)	R5
		DF	T1, T2	IF	T3, PEI	T4
Nominal circuit pulsed current rating (A)		10000	10000	20000	5000	5000
OC voltage (V)		229.58	344.37	575.3	894.55	344.37
Equivalent resistance (Ohms)		0.00458	0.00632	0.004135	0.01808	0.01272

A.1.3.4.4 Power Supply Requirements

		MA	MB+MC	PF1A U+L	PF4 U+L	PF6 U+L
Max I2t (A2-s)		1.45E+08	1.45E+08	3.09E+08	8.79E+06	5.30E+04
tESW (s)		1.45	1.45	0.77	0.35	0.00
Required DC rating (A)		402	402	586	99	8

DC ratings were calculated based on a 15 minute pulse repetition rate.

Equivalent square wave times (tESW) for the power supplies calculated on the basis of the power supply current rating

A.1.4 Pulsed Cryogenic Heat Loads

Pulsed heat loads calculated on the basis of the worst case scenario for each coil.

A.1.4.1 Maximum Temperature and Energy Deposition

Pulsed heat Loads	MA	MB	MC	PF1A U+L	PF4 U+L	PF5 U+L	PF6 U+L	TF Coils	
Initial Temperature (K)	85	85	85	85	85	85	85	85	
Max Temperature (K)	88	88	88	89	85	85	85	85	
Energy Deposited (J)	1.41E+06	1.38E+06	1.16E+06	2.60E+05	3.27E+04	0.00E+00	1.79E+02	0.00E+00	4.25E+06

A.1.4.2 LN2 Consumption During Pulsed Operation

Max LN2 Consumption		Tsat (K)	Psat (MPa)	hfg (kJ/kg)	Mass per pulse (kg)	Density (kg/m3)	(m3/kg)	Volume (m3)	(liters)	(gallons)
Per shot		78	0.10936535	198.3014	21.42446644	805.735	0.001241	0.02659	26.5899656	7.0 per shot
Time between shots (minutes)	15									
Hours per day	8									
Full pwr shots per day	32									224.8 per day
Operating days per week	5									1123.9 per wk

A.2 Full Operating Capability

A.2.1 Coil Set Definition

A.2.1.1 Current Centroid Locations

Coil centroids are defined by the c08r00 coil set.

A.2.1.2 Turns per Coil

	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
Turns	22	22	20	72	72	72	80	24	14	12	1

A.2.2 Coil Inductance Matrix (Henries)

	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
M1	1.50E-02	3.42E-03	1.53E-03	-6.07E-05	1.01E-05	4.16E-05	1.34E-04	-2.52E-04	-3.10E-04	9.54E-03	-1.79E-05
M2	3.42E-03	1.12E-02	2.84E-03	2.44E-05	-1.14E-05	-5.58E-06	-1.40E-05	-4.97E-05	-6.89E-05	7.35E-03	-1.19E-05
M3	1.53E-03	2.84E-03	9.76E-03	1.14E-04	-9.45E-06	-3.87E-05	-1.84E-04	-2.26E-04	-6.88E-05	5.19E-03	-9.55E-06
PF1	-6.07E-05	2.44E-05	1.14E-04	2.99E-03	4.82E-04	7.20E-05	1.47E-04	1.67E-04	1.18E-04	0.00E+00	8.92E-06
PF2	1.01E-05	-1.14E-05	-9.45E-06	4.82E-04	2.58E-03	4.33E-04	3.22E-04	1.75E-04	1.14E-04	0.00E+00	6.78E-06
PF3	4.16E-05	-5.58E-06	-3.87E-05	7.20E-05	4.33E-04	2.57E-03	1.14E-03	1.81E-04	1.04E-04	0.00E+00	4.40E-06
PF4	1.34E-04	-1.40E-05	-1.84E-04	1.47E-04	3.22E-04	1.14E-03	1.52E-02	1.14E-03	5.90E-04	0.00E+00	1.82E-05
PF5	-2.52E-04	-4.97E-05	-2.26E-04	1.67E-04	1.75E-04	1.81E-04	1.14E-03	1.28E-02	3.49E-03	0.00E+00	4.81E-05
PF6	-3.10E-04	-6.89E-05	-6.88E-05	1.18E-04	1.14E-04	1.04E-04	5.90E-04	3.49E-03	6.24E-03	0.00E+00	3.97E-05
TF	9.54E-03	7.35E-03	5.19E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.90E-02	1.51E-06
Plasma	-1.79E-05	-1.19E-05	-9.55E-06	8.92E-06	6.78E-06	4.40E-06	1.82E-05	4.81E-05	3.97E-05	1.51E-06	2.68E-06

A.2.3 Reference Scenario Data

A.2.3.1 Reference Equilibria (amp-turns per coil)

Equlibrium ID	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma		Comment
1	7.63E+05	7.10E+05	6.38E+05	0.00E+00	0.00E+00	3.05E+05	2.40E+05	2.03E+05	-1.05E+05	-4.26E+04	0		iota>0.5
2	6.95E+05	7.06E+05	6.21E+05	0.00E+00	0.00E+00	1.60E+05	-1.92E+05	2.42E+04	1.07E+04	-1.33E+04	0		iota<0.5
3	6.95E+05	7.06E+05	6.21E+05	0.00E+00	0.00E+00	1.60E+05	-1.92E+05	2.05E+04	7.53E+04	-1.33E+04	-120000		120kA, zero beta
4	6.59E+05	6.54E+05	5.43E+05	0.00E+00	0.00E+00	1.05E+05	-3.54E+05	5.58E+04	9.00E+04	4.53E+04	-179000		179kA, full beta
5	6.82E+05	6.40E+05	5.78E+05	0.00E+00	0.00E+00	-1.30E+06	-1.50E+06	1.07E+05	6.12E+04	2.62E+04	-320000		320kA, zero beta
6	6.69E+05	6.44E+05	5.57E+05	0.00E+00	0.00E+00	-1.14E+05	-2.09E+05	-3.27E+05	2.60E+05	3.77E+04	-160000		160kA, zero beta
7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E+05	0		0.5T TF

A.2.3.2 Current Waveforms

Conductor currents are given in amperes. Maxima are shown in blue, minima in red.

1.7T Ohmic Scenario	t(s)	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
	-0.700	**0**	**0**	**0**	0	0	0	0	0	0	0	**0**
	0.000	34673	32277	31908	**-23438**	**-23438**	-14478	-4495	7293	**-8195**	**-3548**	**0**
	0.100	34673	32277	31908	**-23438**	**-23438**	-14478	-4495	7293	**-8195**	**-3548**	**0**
	0.140	31611	32115	31058	-14475	-14475	-9334	-7030	135	4932	-1106	-120052
	0.240	31611	32115	31058	-10963	-10963	-6531	-5907	309	5041	-1106	-120052
	0.440	31611	32115	31058	-3941	-3941	-924	-3661	657	5257	-1106	-120052
Maximum		34673	32277	31908	0	0	0	0	7293	5257	0	0
Minimum		0	0	0	-23438	-23438	-14478	-7030	0	-8195	-3548	-120052
I2t (A2-s)		1.19E+09	1.11E+09	1.05E+09	3.30E+08	3.31E+08	1.36E+08	2.24E+07	2.79E+07	4.56E+07	1.07E+08	
tESW (s)		0.99	1.07	1.03	0.60	0.60	0.65	0.45	0.52	0.68	8.52	

1.7T High Beta Scenario	t(s)	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
	-0.700	**0**	**0**	**0**	0	0	0	0	0	0	0	**0**
	0.000	34673	32277	31908	-14660	-14660	-7469	-1688	**7728**	-7924	**-3548**	**0**
	0.100	34673	32277	31908	-14660	-14660	-7469	-1688	**7728**	-7924	**-3548**	**0**
	0.140	31611	32115	31058	-5697	-5697	-2325	-4223	570	5203	-1106	-120052
	0.240	29814	29625	27016	-6146	-6146	-3461	-6371	2009	6213	3760	-178272
	0.440	29814	29625	27016	-5444	-5444	-2901	-6147	2044	6235	3760	-178272
Maximum		34673	32277	31908	0	0	0	0	7728	6235	3760	0
Minimum		0	0	0	-14660	-14660	-7469	-6371	0	-7924	-3548	-178272
I2t (A2-s)		1.15E+09	1.04E+09	9.44E+08	1.25E+08	1.26E+08	3.59E+07	2.70E+07	3.25E+07	4.87E+07	1.75E+08	
tESW (s)		0.95	1.00	0.93	0.58	0.58	0.64	0.67	0.54	0.78	12.38	

2T High Beta Scenario	t(s)	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma
	-0.850	**0**	**0**	**0**	0	0	0	0	0	0	0	**0**
	0.000	**37190**	**37783**	**36538**	-14615	-14615	-9054	-7498	460	453	-1301	**0**
	0.050	**37190**	**37783**	**36538**	-14615	-14615	-9054	-7498	460	453	-1301	**0**
	0.097	**37190**	**37783**	**36538**	-6931	-6931	-2919	-5041	660	6114	-1301	-141238
	0.192	35075	34852	31783	-7540	-7540	-4319	-7595	2348	7300	4424	-209732
	0.197	35075	34852	31783	-7522	-7522	-4305	-7589	2349	**7300**	4424	-209732
Maximum		37190	37783	36538	0	0	0	0	2349	7300	4424	0
Minimum		0	0	0	-14615	-14615	-9054	-7595	0	0	-1301	-209732
I2t (A2-s)		1.28E+09	1.27E+09	1.15E+09	1.41E+08	1.40E+08	5.74E+07	5.20E+07	2.24E+06	1.20E+07	2.36E+08	
tESW (s)		0.93	0.89	0.86	0.66	0.65	0.70	0.90	0.41	0.23	12.06	

1.2T Long Pulse Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**	**Plasma**
	-0.500	**0**	**0**	**0**	0	0	0	0	0	0	0	**0**
	0.000	24475	22784	22523	-14066	-14066	-8241	-2380	5271	-5708	-2504	**0**
	0.100	24475	22784	22523	-14066	-14066	-8241	-2380	5271	-5708	-2504	**0**
	0.128	22314	22670	21923	-7747	-7747	-4616	-4172	218	3558	-780	-84743
	0.228	21045	20911	19070	-7961	-7961	-5336	-5656	1239	4274	2654	-125839
	1.728	21045	20911	19070	-2694	-2694	-1131	-3972	1500	4436	2654	-125839
Maximum		24475	22784	22523	0	0	0	0	5271	4436	2654	0
Minimum		0	0	0	-14066	-14066	-8241	-5656	0	-5708	-2504	-125839
I2t (A2-s)		1.12E+09	1.07E+09	9.04E+08	1.05E+08	1.05E+08	3.61E+07	4.33E+07	1.36E+07	4.45E+07	9.20E+07	
tESW (s)		1.86	2.06	1.78	0.53	0.53	0.53	1.35	0.49	1.37	13.05	

320kA Ohmic Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**	**Plasma**
	-0.600	**0**	**0**	**0**	0	0	0	0	0	0	0	**0**
	0.000	31611	32115	31058	-22763	-22763	**-15953**	-9680	**-122**	66	-1106	**0**
	0.100	31611	32115	31058	-22763	-22763	**-15953**	-9680	**-122**	66	-1106	**0**
	0.206	31091	29143	28966	11386	11386	-9008	**-15155**	5050	4730	2191	**-320775**
	0.306	31091	29143	28966	14897	14897	-6205	-14032	5224	4838	2191	**-320775**
	0.506	31091	29143	28966	**21919**	**21919**	-598	-11786	5572	5054	2191	**-320775**
Maximum		31611	32115	31058	21919	21919	0	0	5572	5054	2191	0
Minimum		0	0	0	-22763	-22763	-15953	-15155	-122	0	-1106	-320775
I2t (A2-s)		1.10E+09	1.02E+09	9.66E+08	4.18E+08	4.04E+08	1.49E+08	1.50E+08	1.71E+07	1.15E+07	1.40E+08	
tESW (s)		1.10	0.99	1.00	0.81	0.78	0.59	0.65	0.55	0.45	29.19	

0.5T TF	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**	**Plasma**
	-0.800										0	
	0.000										16204	
	0.100										16204	
	0.200										16204	
	0.300										16204	
	0.500										16204	
Maximum											16215	
Minimum											0	
Current direction											1.00E+00	
I2t (A2-s)											4.05E+08	
tESW (s)											1.54	

Summary		**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**	**Plasma**
Maximum		37190	37783	36538	21919	21919	5217	1584	7728	7300	16215	0
Minimum		0	0	0	-23438	-23438	-15953	-15155	-122	-8195	-3548	-320775
Max I2t (A2-s)		1.28E+09	1.27E+09	1.15E+09	4.18E+08	4.04E+08	1.49E+08	1.50E+08	3.25E+07	4.87E+07	4.05E+08	
tESW (s) at max current		0.93	0.89	0.86	0.76	0.74	0.59	0.65	0.54	0.73	1.54	

A.2.3.3 Temperature History

Coil temperatures are in Kelvin. Maxima for all reference scenarios are shown in blue.

1.7T Ohmic Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.700	85	85	85	85	85	85	85	85	85	85
	0.000	93	92	92	88	88	86	85	85	85	85
	0.100	96	94	94	88	88	86	85	85	85	85
	0.140	97	95	95	88	88	86	85	85	85	85
	0.240	99	98	97	89	89	86	85	85	85	85
	0.440	104	103	102	89	89	87	85	85	85	85
	3.621	113	111	109	89	89	87	85	85	86	86
Dissipated Energy (J)		1.62E+07	1.44E+07	1.13E+07	4.87E+05	4.88E+05	1.94E+05	8.28E+04	1.32E+05	1.55E+05	1.22E+06
											4.47E+07

1.7T High Beta Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.700	85	85	85	85	85	85	85	85	85	85
	0.000	93	92	92	86	86	85	85	85	85	85
	0.100	96	94	94	86	86	85	85	85	85	85
	0.140	97	95	95	86	86	85	85	85	85	85
	0.240	99	97	97	86	86	85	85	85	85	85
	0.440	103	102	101	86	86	85	85	85	85	85
	3.621	112	109	106	86	86	85	85	**85**	**86**	86
Dissipated Energy (J)		1.54E+07	1.33E+07	9.81E+06	1.78E+05	1.79E+05	5.03E+04	1.00E+05	**1.54E+05**	**1.65E+05**	2.01E+06
											4.13E+07

2T High Beta Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.850	85	85	85	85	85	85	85	85	85	85
	0.000	98	99	98	86	86	86	85	85	85	85
	0.050	99	101	99	86	86	86	85	85	85	85
	0.097	101	102	101	86	86	86	85	85	85	85
	0.192	104	105	104	86	86	86	85	85	85	85
	0.197	104	105	104	86	86	86	85	85	85	85
	3.378	**115**	**115**	**112**	87	87	86	86	85	85	87
Dissipated Energy (J)		**1.79E+07**	**1.73E+07**	**1.26E+07**	2.01E+05	1.99E+05	8.06E+04	1.93E+05	1.05E+04	4.04E+04	2.74E+06
											5.13E+07

1.2T Long Pulse Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.500	85	85	85	85	85	85	85	85	85	85
	0.000	87	87	87	86	86	85	85	85	85	85
	0.100	89	88	88	86	86	85	85	85	85	85
	0.128	89	88	88	86	86	85	85	85	85	85
	0.228	90	89	89	86	86	85	85	85	85	85
	1.728	107	106	102	86	86	85	85	85	85	85
	4.909	111	110	105	86	86	85	85	85	85	86
Dissipated Energy (J)		1.48E+07	1.37E+07	9.29E+06	1.49E+05	1.49E+05	5.05E+04	1.61E+05	6.41E+04	1.51E+05	1.05E+06
											8.88E+05

320kA Ohmic Scenario	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.600	85	85	85	85	85	85	85	85	85	85
	0.000	90	91	90	87	87	86	85	85	85	85
	0.100	93	93	92	88	88	86	85	85	85	85
	0.206	95	95	95	88	88	87	86	85	85	85
	0.306	97	97	96	88	88	87	86	85	85	85
	0.506	102	101	100	89	89	87	86	85	85	85
	3.687	110	108	107	**90**	**90**	**87**	**87**	85	85	86
Dissipated Energy (J)		1.46E+07	1.29E+07	1.01E+07	**6.25E+05**	**6.03E+05**	**2.13E+05**	**5.69E+05**	8.09E+04	3.86E+04	1.61E+06
											0.00E+00

0.5T TF	**t(s)**	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
	-0.800										85
	0.000										86
	0.100										86
	0.200										86
	0.300										86
	0.500										87
	4.287										**88**
Dissipated Energy (J)											**4.79E+06**
											4.79E+06

Summary		**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
Max Final Temperature		115	115	112	90	90	87	87	85	86	88
Max Dissipated Energy (J)		1.79E+07	1.73E+07	1.26E+07	6.25E+05	6.03E+05	2.13E+05	5.69E+05	1.54E+05	1.65E+05	4.79E+06
											5.13E+07

A.2.3.4 Electrical Power Requirements

Upgrade Power Supply and Cabling Requirements and Modeling Assumptions

Other than for the First Plasma and Field Line Mapping Scenarios, it is assumed that DC power will be brought over from D-site.

Power supply requirements for these reference scenarios have been calculated based on the following assumptions:

[1] All coils of the same type (e.g. all M1 coils) are connected in series. All coils in the same circuit are connected in series.
Circuit configurations are defined in the table below.

[2] All coils of the same type have a single CLR connected in series with the coils. Each CLR has an inductance
of 267 micro-H and a resistance of 100 milli-ohms.

[3] DC power will be carried from D-site to the test cell via cables approximately 750 feet in length (each way).
Required DC current ratings and cables per pole in each circuit are defined in the table below.
An inductance of 132 micro-Henries per cable pair (supply and return) was assumed.

[4] TFTR power supply sections (PSS) will be used. Each PSS has an open circuit voltage of 1012.85V and a maximum current of 28kA.
When operated in parallel, the maximum rated current is reduced by 10%.

[5] Required DC ratings are based on a pulse repetition time of 15 minutes.

Ultimate capability required	1.7T Ohmic 1.7T Hi Beta 2T Hi Beta 1.2T Long Pulse 320kA	M1	M2	M3	PF4	PF6	TF	PF1/2	PF3	PF5U	PF5L	
128 MW	Max I2t (A2-s)	1.28E+09	1.27E+09	1.15E+09	1.50E+08	4.87E+07	4.05E+08	4.04E+08	1.49E+08	3.25E+07	3.25E+07	
380 MVA	tESW (s)	0.93	0.89	0.86	0.65	0.73	1.54	0.74	0.59	0.54	0.54	
94 MJ	Required DC rating (A)	1193	1190	1128	409	233	670	670	407	190	190	
	Cables per pole	2	2	2	1	1	1	1	1	1	1	26 Cables
	Series PSS per branch	2	2	2	2	2	4	4	2	2	2	40 PSS
	Branches	2	2	2	1	2	2	2	1	1	1	
	Branch configuration	Parallel	Parallel	Parallel		Anti-parallel	Anti-parallel	Anti-parallel				

A.2.4 Pulsed Heat Loads

Pulsed heat loads calculated on the basis of the worst case scenario for each coil.

A.2.4.1 Maximum Temperature and Energy Deposition

Pulsed heat Loads	**M1**	**M2**	**M3**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**TF**
Initial Temperature (K)	85	85	85	85	85	85	85	85	85	85
Max Temperature (K)	115	115	112	90	90	87	87	85	86	88
Energy Deposited (J)	1.79E+07	1.73E+07	1.26E+07	6.25E+05	6.03E+05	2.13E+05	5.69E+05	1.54E+05	1.65E+05	4.79E+06
										5.13E+07

A.2.4.2 LN2 Consumption During Pulsed Operation

Max LN2 Consumption		**Tsat (K)**	**Psat (MPa)**	**hfg (kJ/kg)**	**Mass per pulse (kg)**	**Density (kg/m3)**	**(m3/kg)**	**Volume (m3)**	**(liters)**	**(gallons)**	
Per shot		78	0.109365352	198.301405	258.4629516	805.735019	0.001241103	0.320779097	320.7790968	85	per shot
Time between shots (minutes)	15										
Hours per day	8										
Full pwr shots per day	32									2712	per day
Operating days per week	5									13559	per wk

A.2.4.2 LN2 Delivery Requirements

	Gallons per Truck	6500	**Trucks**	
Pulsed heat loads only				
Max pulsed heat loads			2.09	per week
Field line mapping			0.05	per week
First Plasma			0.02	per week
Parasitic loads only				
Normal			2.12	per week
150C Bakeout			2.86	per week
350C Bakeout			3.52	per week
Cooldown only			1.63	

APPENDIX B – CHARACTERISTIC ALLOCATION MATRIX

Characteristics Allocation Matrix

		11 - In-Vessel Components	12 - Vacuum Vessel Systems	13 - Conventional Coils	14 - Modular Coils	15 - Structures	17 - Cryostat and Base Support Structure	21/23 - Fueling and Wall Conditioning	22 - Torus Vacuum Pumping	24 - Ion Cyclotron Heating System	25 - Neutral Beam Injection System	26 - Electron Cyclotron Heating System	3 - Diagnostics	4 - Electrical Power Systems	5 - Central I&C Systems	61 - Water Cooling Systems	62 - Cryogenic Systems	63 - Utility Systems	64 - Helium Bakeout System	7 - Test Cell Preparation and Machine Assy
3.2.1	Performance Characteristics																			
3.2.1.1	Initial Facility Startup	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.2	Pre-Run Facility Startup	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.2.1	Coil Cool-down																			
3.2.1.2.1.1	Coil Cool-down Timeline			X	X	X	X										X			
3.2.1.2.1.2	Cool-down and Warm-up Cycles			X	X	X	X										X			
3.2.1.2.1.3	Pre-Run Temperatures	X	X					X		X		X	X						X	
3.2.1.2.2	Vacuum Requirements																			
3.2.1.2.2.1	Base Pressure	X	X					X	X	X	X	X	X							
3.2.1.2.2.2	Pumping Speed		X						X											
3.2.1.2.3	Bakeout																			
3.2.1.2.3.1	Vacuum Vessel Bakeout Temperatures		X																X	
3.2.1.2.3.2	Carbon-based Plasma Facing Components (PFCs) Bakeout Temperatures	X	X																X	
3.2.1.2.3.3	Coil Temperatures During Bakeout			X	X	X	X										X			
3.2.1.2.3.4	Bakeout Timelines	X	X					X	X	X		X	X						X	
3.2.1.2.3.5	Glow Discharge Cleaning (GDC) During Bakeout	X	X					X	X	X	X	X	X						X	
3.2.1.2.3.6	Bakeout Cycles	X	X					X	X	X		X	X						X	
3.2.1.3	Pre-operational Initialization and Verification	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.3.1	Plasma Chamber Conditioning																			
3.2.1.3.1.1	Boronization	X	X					X	X	X	X	X	X							
3.2.1.3.1.2	Lithiumization	X	X					X	X	X	X	X	X							
3.2.1.4	Pre-pulse Initialization and Verification	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.4.1	Glow Discharge Cleaning (GDC) Between Pulses	X	X					X	X	X	X	X	X						X	
3.2.1.4.2	Pre-Pulse Temperature	X	X					X	X	X		X	X						X	
3.2.1.5	Experimental Operations																			
3.2.1.5.1	Field Error Requirements	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.5.2	Electrical (Eddy Current) Requirements	X	X	X	X	X	X	X		X		X	X							X
3.2.1.5.3	Plasma Magnetic Field Requirements																			
3.2.1.5.3.1	Coordinate System	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.5.3.2	Magnetic Field Polarity	X	X	X	X	X	X	X		X	X	X	X	X	X					
3.2.1.5.3.3	Reference Scenarios																			
3.2.1.5.3.3.1	Reference Scenario Specifications																			
3.2.1.5.3.3.1.1	First Plasma Scenario	X	X	X	X	X								X			X		X	
3.2.1.5.3.3.1.2	Field Line Mapping Scenario	X	X	X	X	X								X			X		X	
3.2.1.5.3.3.1.3	1.7T Ohmic Scenario		X	X	X	X								X			X		X	
3.2.1.5.3.3.1.4	1.7T High Beta Scenario		X	X	X	X								X			X		X	
3.2.1.5.3.3.1.5	1.2T High Beta Long-Pulse Scenario		X	X	X	X								X			X		X	
3.2.1.5.3.3.1.6	2T High Beta Scenario		X	X	X	X								X			X		X	

Characteristics Allocation Matrix		11 - In-Vessel Components	12 - Vacuum Vessel Systems	13 - Conventional Coils	14 - Modular Coils	15 - Structures	17 - Cryostat and Base Support Structure	21/23 - Fueling and Wall Conditioning	22 - Torus Vacuum Pumping	24 - Ion Cyclotron Heating System	25 - Neutral Beam Injection System	26 - Electron Cyclotron Heating System	3 - Diagnostics	4 - Electrical Power Systems	5 - Central I&C Systems	61 - Water Cooling Systems	62 - Cryogenic Systems	63 - Utility Systems	64 - Helium Bakeout System	7 - Test Cell Preparation and Machine Assy
3.2.1.5.3.3.1.7	320 kA Ohmic Scenario		X	X	X	X								X			X		X	
3.2.1.5.3.3.2	Reference Scenario Requirements		X	X	X	X								X			X		X	
3.2.1.5.3.4	Flexibility Requirements																			
3.2.1.5.3.4.1	Quasi-axisymmetry Flexibility		X	X	X	X								X					X	
3.2.1.5.3.4.2	External Iota Flexibility		X	X	X	X								X					X	
3.2.1.5.3.4.3	Shear Flexibility		X	X	X	X								X					X	
3.2.1.5.3.4.4	Beta Limit Flexibility		X	X	X	X								X					X	
3.2.1.5.3.4.5	Radial and Vertical Position Flexibility		X	X	X	X								X					X	
3.2.1.5.3.5	Equilibrium Control			X									X	X	X					
3.2.1.5.3.6	Breakdown Loop Voltage			X	X	X								X						
3.2.1.5.3.7	Power Supply Ripple												X	X						
3.2.1.5.3.8	Coil Current Measurements												X	X						
3.2.1.5.4	Power Handling																			
3.2.1.5.4.1	PFC Configuration	X	X					X	X	X			X						X	
3.2.1.5.4.2	Maximum Plasma Heating Power	X	X							X	X	X							X	
3.2.1.5.4.3	Maximum Component Surface Temperature	X																		
3.2.1.5.5	Disruption Handling	X	X	X	X	X														
3.2.1.5.6	Plasma Heating																			
3.2.1.5.6.1	Neutral Beam Heating																			
3.2.1.5.6.1.1	Initial Neutral Beam Heating Complement										X			X		X	X			X
3.2.1.5.6.1.2	Ultimate Neutral Beam Heating Complement										X			X		X	X			X
3.2.1.5.6.2	Ion Cyclotron Heating (ICH)		X							X				X		X				X
3.2.1.5.6.3	Electron Cyclotron Heating (ECH)											X		X		X				X
3.2.1.5.7	Plasma Fueling																			
3.2.1.5.7.1	Fuel Species							X	X	X	X	X								
3.2.1.5.7.2	Gas Injection							X												
3.2.1.5.7.3	Pellet Injection	X	X					X												
3.2.1.5.8	Plasma Diagnostics																			
3.2.1.5.8.1	General Diagnostics Requirements												X							
3.2.1.5.8.2	Diagnostics Implementation												X							
3.2.1.5.9	Instrumentation, Control, and Data Acquisition														X					
3.2.1.5.10	Pulse Repetition Rate	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.5.11	Discharge Termination																			
3.2.1.5.11.1	Normal Termination	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.5.11.2	Abnormal Termination	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.6	Facility Shutdown	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3.2.1.6.1	Coil Warm-up Timeline			X	X	X	X										X			
3.2.1.6.2	Vacuum Vessel Venting		X						X											

APPENDIX C – QUALITY CONFORMANCE MATRIX

Key: X = Before First Plasma Y= After First Plasma
X(a)=Before First Plasma for Part a of the requirement

Quality Conformance Matrix		**Examination**	**Test**	**Demonstration**	**Analysis**	**Not Applicable**	**Remarks**
3.2.1	Performance Characteristics						
3.2.1.1	Initial Facility Startup			X			
3.2.1.2	Pre-Run Facility Startup			X			
3.2.1.2.1	Coil Cool-down						
3.2.1.2.1.1	Coil Cool-down Timeline			X			First few cooldowns should be closely monitored to assure that temperatures are tracking expected values and that no unanticipated thermal stresses are being imposed. Ultimate demonstration after First Plasma.
3.2.1.2.1.2	Cool-down and Warm-up Cycles				X		
3.2.1.2.1.3	Pre-Run Temperatures			X			
3.2.1.2.2	Vacuum Requirements						
3.2.1.2.2.1	Base Pressure	X(b)	X(a)	Y(a)			Historically, it takes time to initially eliminate all vacuum leaks and to condition the vacuum vessel adequately for UHV conditions. The VVSA shall be tested during the assembly process (prior to First Plasma) to assure that the VVSA is sufficently leak-tight to support achieving the ultimate base pressure and leak rate requirements. Demonstration of achieving the ultimate requirements will take place after First Plasma.
3.2.1.2.2.2	Pumping Speed		X(b)		X(a)		
3.2.1.2.3	Bakeout						
3.2.1.2.3.1	Vacuum Vessel Bakeout Temperatures			X			.
3.2.1.2.3.2	Carbon-based Plasma Facing Components (PFCs) Bakeout Temperatures			Y	X		Upgrade requirement
3.2.1.2.3.3	Coil Temperatures During Bakeout			X			
3.2.1.2.3.4	Bakeout Timelines		X	Y			First few bakeouts (prior to First Plasma) should be closely monitored to assure that temperatures are tracking expected values and that no unanticipated thermal stresses are being imposed. Ultimate demonstration after First Plasma.
3.2.1.2.3.5	Glow Discharge Cleaning (GDC) During Bakeout			Y	X		Upgrade requirement
3.2.1.2.3.6	Bakeout Cycles				X		
3.2.1.3	Pre-operational Initialization and Verification			X			
3.2.1.3.1	Plasma Chamber Conditioning						
3.2.1.3.1.1	Boronization				X		Upgrade requirement
3.2.1.3.1.2	Lithiumization				X		Upgrade requirement
3.2.1.4	Pre-pulse Initialization and Verification			X			
3.2.1.4.1	Glow Discharge Cleaning (GDC) Between Pulses				X		Upgrade requirement
3.2.1.4.2	Pre-Pulse Temperature			X(d)	X(a) Y(b) Y(c)		
3.2.1.5	Experimental Operations						
3.2.1.5.1	Field Error Requirements	X(a)	X(b)	Y(b)			Part b addressed in component testing prior to First Plasma to ensure that individual elements would not compromise the requirement. Part b demonstrated after First Plasma, when power supplies for the field error correction coils are available.
3.2.1.5.2	Electrical (Eddy Current) Requirements		X(b)		X(a) X(c) X(d) X(e) X(f)		
3.2.1.5.3	Plasma Magnetic Field Requirements						
3.2.1.5.3.1	Coordinate System					X	
3.2.1.5.3.2	Magnetic Field Polarity	X(b)		X(a)			
3.2.1.5.3.3	Reference Scenarios						

Key: X = Before First Plasma Y= After First Plasma
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Quality Conformance Matrix		**Examination**	**Test**	**Demonstration**	**Analysis**	**Not Applicable**	**Remarks**
3.2.1.5.3.3.1	Reference Scenario Specifications						
3.2.1.5.3.3.1.1	First Plasma Scenario					X	
3.2.1.5.3.3.1.2	Field Line Mapping Scenario					X	
3.2.1.5.3.3.1.3	1.7T Ohmic Scenario					X	
3.2.1.5.3.3.1.4	1.7T High Beta Scenario					X	
3.2.1.5.3.3.1.5	1.2T High Beta Long-Pulse Scenario					X	
3.2.1.5.3.3.1.6	2T High Beta Scenario					X	
3.2.1.5.3.3.1.7	320 kA Ohmic Scenario					X	
3.2.1.5.3.3.2	Reference Scenario Requirements		X				Part a - All coil systems should be tested to the lesser of their full ratings and their power supply capability prior to First Plasma. (The PEP has less stringent requirements.) Deflections and temperatures should be monitored to assure that critical components were behaving as expected. Part b- Electrical power (including real time control) and cryogenic systems should be tested prior to First Plasma to show that those systems were operating at their rated capacity which would meet the requirements of the First Plasma and Field LIne Mapping Scenarios. Field Line Mapping and First Plasma would demonstrate that the integrated requirements for the Field Line Mapping and First Plasma Scenarios were met. Demonstrations for other scenarios would occur in later phases of operation.
3.2.1.5.3.4	Flexibility Requirements						
3.2.1.5.3.4.1	Quasi-axisymmetry Flexibility				X		
3.2.1.5.3.4.2	External Iota Flexibility				X		
3.2.1.5.3.4.3	Shear Flexibility				X		
3.2.1.5.3.4.4	Beta Limit Flexibility				X		
3.2.1.5.3.4.5	Radial and Vertical Position Flexibility				X		
3.2.1.5.3.5	Equilibrium Control				X		
3.2.1.5.3.6	Breakdown Loop Voltage				X		
3.2.1.5.3.7	Power Supply Ripple				X		
3.2.1.5.3.8	Coil Current Measurements			X			
3.2.1.5.4	Power Handling						
3.2.1.5.4.1	PFC Configuration				X		
3.2.1.5.4.2	Maximum Plasma Heating Power				X		
3.2.1.5.4.3	Maximum Component Surface Temperature				X		
3.2.1.5.5	Disruption Handling				X		
3.2.1.5.6	Plasma Heating						
3.2.1.5.6.1	Neutral Beam Heating						
3.2.1.5.6.1.1	Initial Neutral Beam Heating Complement	X	X				The following inspections and tests will be performed prior to First Plasma: - The beamline shall be mechanically installed on NCSX. - All cabling and other connections shall be installed. - Beamline operating vacuum shall have been achieved. - Beamline cryopanels shall be leak-checked. - Power system refurbishment will be complete. - A source shall be leak-checked. - Control systems shall be installed sufficient to begin subsystem testing.
3.2.1.5.6.1.2	Ultimate Neutral Beam Heating Complement				X		
3.2.1.5.6.2	Ion Cyclotron Heating (ICH)				X		
3.2.1.5.6.3	Electron Cyclotron Heating (ECH)				X		
3.2.1.5.7	Plasma Fueling						
3.2.1.5.7.1	Fuel Species			X			
3.2.1.5.7.2	Gas Injection			X(a) X(b)	X(c)		

Key: X = Before First Plasma Y= After First Plasma
X(a)=Before First Plasma for Part a of the requirement

Quality Conformance Matrix		**Examination**	**Test**	**Demonstration**	**Analysis**	**Not Applicable**	**Remarks**
3.2.1.5.7.3	Pellet Injection	X(a)			X(b)		Part b is a future upgrade
3.2.1.5.8	Plasma Diagnostics						
3.2.1.5.8.1	General Diagnostics Requirements					X	
3.2.1.5.8.2	Diagnostics Implementation	X(a)			X(b)		Part b includes future upgrades
3.2.1.5.9	Instrumentation, Control, and Data Acquisition			X			The following integrated tests are specified in the PEP: Integrated test of the safety interlock system. Integrated test of the timing and synchronization system. Integrated test of the power supply real time control system. Integrated test of the data acquisition system.
3.2.1.5.10	Pulse Repetition Rate			X			
3.2.1.5.11	Discharge Termination						
3.2.1.5.11.1	Normal Termination			X			
3.2.1.5.11.2	Abnormal Termination			X			
3.2.1.6	Facility Shutdown			X			
3.2.1.6.1	Coil Warm-up Timeline		X	Y			First few warmups should be closely monitored to assure that temperatures are tracking expected values and that no unanticipated thermal stresses are being imposed. Ultimate demonstration after First Plasma.
3.2.1.6.2	Vacuum Vessel Venting			X			