# NCSX

# SPECIFICATION

# General Requirements Document (GRD)

**NCSX-ASPEC-GRD-00**

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## 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 WBS identifier

NCSX Vacuum Materials List (to be provided)

NCSX Structural and Cryogenic Design Criteria Document (to be provided)

NCSX Grounding Specification for Personnel and Equipment Safety (to be provided)

NCSX Test and Evaluation Plan (to be provided)

NCSX RAM Plan (to be provided)

## 2.4 Other Documents

TBD

# 3 SYSTEM REQUIREMENTS

## 3.1 System Definition

### 3.1.1 General Description

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.

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.

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

The NCSX MIE Project shall include all equipment required at the start of operations (first plasma), including the support subsystems (central I&C and utility systems) required to support that equipment.

In addition, the NCSX MIE Project shall include the refurbishment and installation of 3 MW of neutral beam heating power.

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

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 |

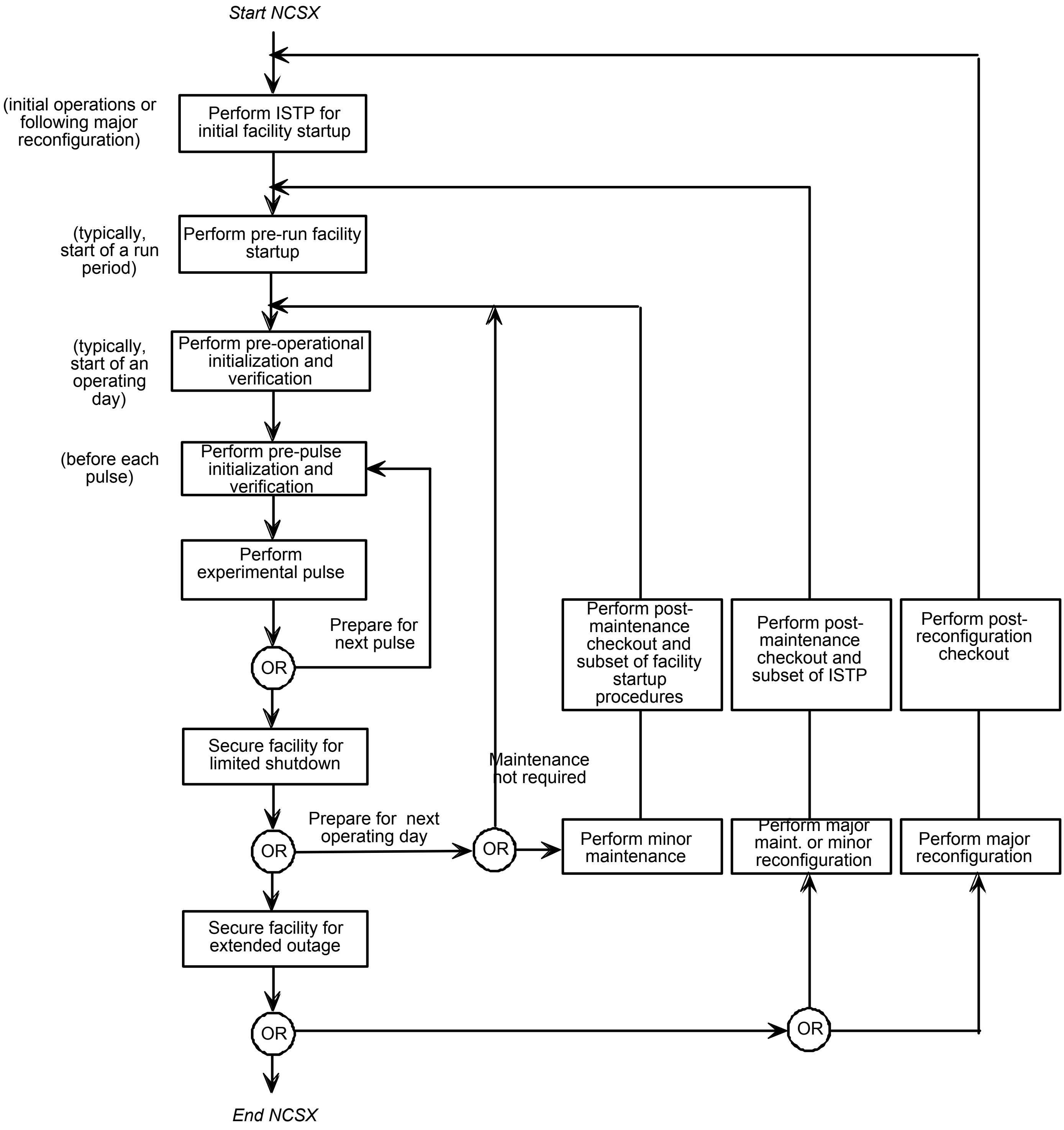

Figure 3-1 NCSX System Functional Flow Diagram

#### 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**

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 less than 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 Coil Cool-down Timeline

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 **(TBR)**.

### 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 operating temperature.

### 3.2.1.2.1.3 Pre-Run Temperatures

The vacuum vessel and all in-vessel components shall be maintained at a minimum temperature of 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 and facility shall produce, through design and the use of baking and wall conditioning, high vacuum conditions with a base pressure of less than or equal to $2 \times 10^{-8}$ torr and a global leak rate of less than or equal to $2 \times 10^{-5}$ torr-l/s at 293K.

b. The base pressure shall be measured with a standard, magnetically shielded, nude ion gauge.

c. The device shall accommodate additional nude ion gauges and at least one fast neutral pressure gauge as future upgrades.

d. 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.

e. 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.

### 3.2.1.2.2.2 Pumping Speed

The device and facility shall be equipped with 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 2600 l/s.

### 3.2.1.2.3 Bakeout

**Background**

The temperature of the vacuum vessel shell will be elevated to a nominal bakeout temperature of 150ºC by circulating high temperature gas in tubes attached to the vacuum vessel shell and ports. Initially, there will be only a few, discrete limiters installed in the vacuum vessel for ohmic operation. However, later in the program, a carbon-based 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. The temperature of the carbon-based liner will be elevated to a nominal bakeout temperature of 350ºC by circulating high temperature gas in tubes attached to the liner assembly. 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 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 bakeout, the temperature of the carbon-based PFCs (to be installed as a future upgrade) shall be maintained at 350ºC±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 **(TBR)** and returned to their pre-pulse operating temperatures within the 24 hours **(TBR)** 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 **(TBR)** and maintained at that temperature indefinitely.

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

#### 3.2.1.2.3.5 Glow Discharge Cleaning (GDC) During Bakeout

The facility shall provide 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 100 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 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 40ºC **(TBR)**.

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 **(TBR)** 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.

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

#### 3.2.1.5 Experimental Operations

##### 3.2.1.5.1 Field Error Requirements

a. Field error correction 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.

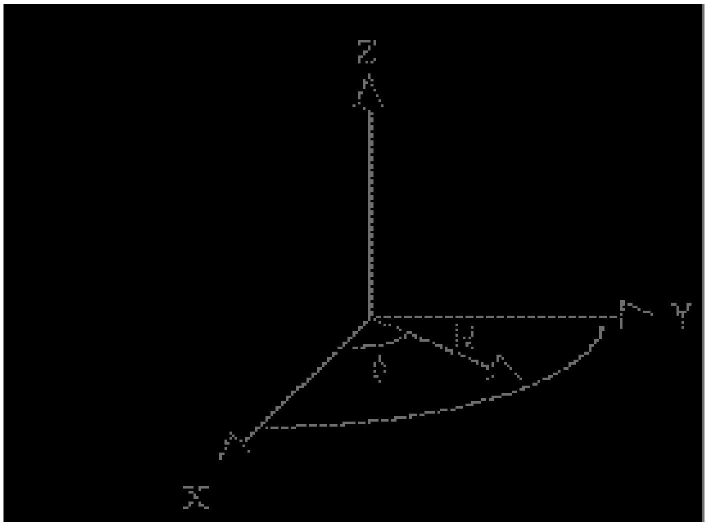

**Figure 3-2 NCSX Coordinate System**

### 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 Initial Ohmic 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 Initial Ohmic Scenario

The Initial Ohmic Scenario is characterized by:

- Ramping the coils to their pre-initiation values at a magnetic field on axis (R=1.4m) of 1.4T. 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 99kA at a rate of 2 MA/s
- Maintaining the plasma current constant for 300ms

### 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 1.9T High Beta Scenario

The 1.9T 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, PF, and modular coil systems and the vacuum vessel will be designed to meet the requirements of all the reference scenarios.

b. Electrical power and cryogenic systems shall be designed and initially configured to meet the requirements of the First Plasma and Initial Ohmic Scenarios and 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 ($\iota(a)$-$\iota(0)$~0.2), 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.

### 3.2.1.5.4 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 be configured with discrete limiters to handle the modest heat loads (less than 350kW) associated with initial ohmic operation. 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. The initial Plasma Facing Component surfaces shall be carbon-based, i.e. graphite or carbon fiber composite (CFC) material. Future upgrades for a 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. Initial configuration. An array of poloidal limiters will be provided for the Initial Operation (Phase 1), Field Mapping (Phase 2), and Initial Ohmic (Phase 3) operation. They will be located on the inboard side of 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 **(TBR)** 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

a. The facility shall be designed for a maximum plasma heating power of 350 kW for 0.3s for the Initial Ohmic Phase of operation.

b. 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

Two of the four beamlines previously used on the PBX-M project will be installed as part of the NCSX MIE Project to provide 3 MW of neutral beam heating power with a minimum of 0.3 s of pulse length. One beam will be configured in the co-direction (the nominal direction of the plasma current) and the other in the counter-direction. 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 (TBR) 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 (TBR) 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 of the diagnostics required for Initial Operation and Field Line Mapping, as identified in Table 3-2, shall be provided.

b. The facility shall be designed to accommodate the remaining diagnostics identified in (as future upgrades).

## Table 3-2 Diagnostic Requirements

| | **research topic** | **essential new measurements** | **new diagnostics** |
|---|---|---|---|
| **1. Initial Operation** | | | |
| | initiate plasma: exercise coil set | plasma current | plasma current Roqowskis |
| | Ip >25 kA | conductivity | flux loops |
| | checkout vacuum diagnostics | plasma position | saddle loops |
| | checkout magnetic diagnostics | plasma stored energy | B-dot probes |
| | initial wall conditioning | | diamagnetic loop |
| | | plasma/wall imaging | fast visible cameras |
| | | line integrated density | 1 mm interferometer |
| **2. Field Line Mapping** | | | |
| | map flux surfaces | vacuum flux surfaces | e-beam probe |
| | verify iota and QA | variable energy trace particles | fluorescent rod probe |
| | | | high dynamic range CCD |
| **3. Initial Ohmic** | | | |
| | initial plasma control, plasma evolution control | electron density profiles | multichord FIR interf./ polarim. |
| | global confinement & scaling, effect of 3D shaping | electron temperature profiles | Thomson scattering |
| | density limit & mechanisms | radiated power profiles | core foil bolometer array |
| | study of Te and ne profiles. | magetic axis position | compact SXR arrays |
| | vertical stability | low (m,n) MHD (<100kHz) | |
| | current-driven kink stability | flux surface topology | |
| | effect of low-order rat. surf. on flux-surface topology | impurity species | visible spectrometer |
| | initial study of effect of trim coils, both signs | impurity concentration | abs. UV spectroscopy |
| | effect of contact location on plasma edge & recycling | Zeff | filtered 1D CCD camera |
| | initial attempts to control plasma contact location | hydrogen recycling | visible filterscopes |
| **4. Initial Aux. Heating** | | | |
| | plasma control with NB heating and CD | | diagnostic neutral beam |
| | test of kink & ballooning stability at moderate beta | ion temperature profile | toroidal CHERS |
| | effect of shaping on MHD stability | toroidal rotation profile | |
| | initial study of Alfvenic modes w/ NB ions | poloidal rotation profile | poloidal CHERS |
| | confinement scaling w/ iota, B, … | radial electric field | MSE polarimeter |
| | local transport measurements, perturb. meas. | iota profile | |
| | test of quasi-symmetry on confinement and transport | fast ion loss | fast ion loss probe |
| | density limits and control with heating | ion energy distribution | neutral particle analyser |
| | use of trim coils to minimize rotation damping | neutron flux | epithermal neutron detector |
| | blip measurements of fast ion conf. and slowing down | first wall surface temperature | compact IR cameras |
| | initial attempts to obtain enhance confinement regimes | high frequency MHD(<5Mhz) | high frequency Mirnov coils |
| | pressure effects on surface quality | | fast tang. x-ray pinhole camera |
| | controlled study of neoclassical tearing using trim coils | | enhanced x-ray tomography |
| | wall coatings with aux. heating | SOL tmperature and density | moveable Langmuir probe |
| | edge and exhaust charact. with aux. heating | neutral pressure | fast neutral pressure gauges |
| | attempts to control wall neutral influx | target Te, ne | plate mounted Langmuir probes |
| | wall biasing effects on confinement | | |
| **5. Confinement & beta push** | | | |
| | stability tests at beta >~ 4% | edge/div. radiated power profile | divertor foil bolometer arrays |
| | detailed study of beta limit scaling | divertor recycling | divertor filtered CCD cameras |
| | detailed studies of beta limiting mechanisms | edge temp. and dens. prof. | fast scanning edge probe |
| | disruption-free operating region at high beta | divertor target surface temp. | fast IR camera |
| | active mapping of Alfvenic mode stability (with antenna) | | divertor thermocouples |
| | enh. conf.: H-mode, hot ion modes, RI mode, pellets | core helium density | He CHERS system (with DNB) |
| | enhanced confinement, rotation effects | | |
| | scaling of local transport and confinement | divertor impurity concentration | divertor UV spectroscopy |
| | turbulence studies | core density fluct. amp. & spec | fluctuation diagnostics TBD |
| | scaling of power or other thresholds for enh. conf. | | |
| | ICRF wave propagation and damping (possible) | | |
| | perturbative RF measurements of transport (possible) | | |
| | divertor operation optimized for power handling | | |
| | trace helium exhaust and confinement | | |
| | scaling of power to divertor | | |
| | control of high beta plasmas and their evolution | | |
| **6. Long Pulse** | | | |
| | long pulse plasma evolution control | more detailed divertor profiles | divertor Thomson scattering |
| | equilibration of current profile | | divertor diagnostics (TBD) |

#### 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 **(TBR)**.

###### 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 D-site experimental power systems. All other electrical power for NCSX will be provided through the C-site experimental power systems.

#### 3.2.2.4 Utility Gas Systems

The facility shall provide gaseous nitrogen and 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 30 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 18 feet wide and 16 feet high.

##### 3.2.3.1.3 Maximum Floor Loading

**TBD**

### 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 **(TBR)** 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

All materials to be used in the stellarator and peripheral equipment inside the cryostat must have a relative magnetic permeability less than 1.02 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 electropolished 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 prior to installation, except when authorized by the project.

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

#### 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 Electrical Grounding

a. A single-point electrical grounding system shall be provided in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety.

b. A ground-loop detection system shall be provided to facilitate maintaining the integrity of the grounding system.

c. Voltage isolation shall be provided between the VV and systems attached to the vacuum vessel, in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety.

d. RF Shielding shall be provided in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety.

### 3.3.3 Nameplates and Product Marking

#### 3.3.3.1 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.

### 3.3.4 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.

### 3.3.5 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.

### 3.3.6 Environmental, Safety, and Health (ES&H) Requirements

#### 3.3.6.1 General Safety

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.

#### 3.3.6.2 Safety Hazards

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

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

##### 3.3.6.2.1 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.

##### 3.3.6.2.2 Controlled Access System

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.

#### 3.3.6.2.3 Toxic Gases

**Background**

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.

**Requirement**

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

#### 3.3.6.2.4 Oxygen Depletion

**Background**

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.

**Requirement**

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.

#### 3.3.6.2.5 Vacuum Implosion

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

### 3.3.6.3 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).

### 3.3.6.4 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.

### 3.3.6.5 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.

### 3.3.6.6 Hazardous Materials

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

#### 3.3.6.7 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.

#### 3.3.6.8 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 $4.6\times10^{16}$ per year in order to limit the neutron dose-equivalent in the control room to 1 rem 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**

| | | | Public Exposure[1] | | Occupational Exposure | |
|---|---|---|---|---|---|---|
| Condition | | P, Probability Of Occurrence In A Year | 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<br>0.01 airborne[3]<br>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 |

---

[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.

### 3.3.7 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.

#### 3.3.7.1 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.

#### 3.3.7.2 Human Environments

##### 3.3.7.2.1 Temperature and Humidity

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

##### 3.3.7.2.2 Ventilation

**TBD**

##### 3.3.7.2.3 Lighting

Adequate light levels shall be provided.

##### 3.3.7.2.4 Emergency Lighting

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

#### 3.3.7.3 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.”

### 3.3.8 System Security

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

### 3.3.9 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

**TBD**

## 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:

a. Examination: 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.

b. Test: 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.

c. Demonstration: 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.

d. Analysis: 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

### Background

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 Confromance Matrix in Appendix C. All other requirements in Section 3 flow down to individual subsytems 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.

### Requirements

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

# 5 NOTES

## 5.1 Definitions

**TBD**

## 5.2 Acronyms

**TBD**

# Appendix A – Technical Data Sheet

## A.1 Coil Set Definition

*The coil set used in this analysis corresponds to the c07r00 coil set. This data in this section (A.1) is provided in order to define the coil geometry on which the technical data in following sections is based. This section does not define requirements for coil geometry.*

### A.1.1 Modular Coil Build

| | M1 | M2 | M3 |
|---:|---:|---:|---:|
| Length_m | 7.35767 | 7.172828 | 6.660598 |
| BundleHeight_mm | 116.6114 | 116.6114 | 116.6114 |
| BundleWidth_mm | 42.2529 | 42.2529 | 42.2529 |
| BundleArea_mm2 | 4927.17 | 4927.17 | 4927.17 |
| BundleArea_m2 | 0.004927 | 0.004927 | 0.004927 |
| EquivRadius_m | 0.056007 | 0.056007 | 0.056007 |
| GroundWrap_mm | 0.762 | 0.762 | 0.762 |
| TurnInsulation_mm | 1.3716 | 1.3716 | 1.3716 |
| InternalSeptum_mm | 0 | 0 | 0 |
| TurnsHigh | 9 | 9 | 9 |
| Turns | 36 | 36 | 36 |
| ConductorLengthPerDP_m | 132.4381 | 129.1109 | 119.8908 |
| ConductorHeight_mm | 10.04429 | 10.04429 | 10.04429 |
| ConductorWidth_mm | 17.62125 | 17.62125 | 17.62125 |
| ConductorArea_mm2 | 176.9929 | 176.9929 | 176.9929 |
| CopperVolumeFraction | 0.785 | 0.785 | 0.785 |
| Area correction | -0.0552 | -0.0552 | -0.0552 |
| CopperArea_mm2 | 131.27 | 131.27 | 131.27 |
| Length correction | 0.058425 | 0.058425 | 0.058425 |
| Resistance correction for helical current path | 0.120264 | 0.120264 | 0.120264 |
| GeometricResistance_m-1 | 12814118 | 12492197 | 11600097 |
| Tstart_K | 85 | 85 | 85 |
| Resistivity_ohm-m | 2.36E-09 | 2.36E-09 | 2.36E-09 |
| InitialResistance_ohms | 0.030193 | 0.029434 | 0.027332 |

### A.1.2 TF Coil Build

*The TF conductor was modeled as a rectangular conductor of uniform thickness and width in each turn.*
*Conductor dimensions correspond to the dimensions of the smallest turn.*

| | **TF** |
|---:|---:|
| Length_m | 8.656783 |
| NumberCoils | 18 |
| TurnsHigh | 6 |
| TurnsWide | 2 |
| Turns | 12 |
| ConductorLengthPerDP_m | 103.8814 |
| BundleHeight_mm | 84.8868 |
| BundleWidth_mm | 100.838 |
| BundleArea_mm2 | 8559.815 |
| BundleArea_m2 | 0.00856 |
| GroundWrap_mm | 0.762 |
| TurnInsulation_mm | 1.2446 |
| PancakeInsulation_mm | 0.762 |
| ConductorHeight_mm | 11.4046 |
| ConductorWidth_mm | 47.752 |
| CornerRadius_mm | 2.5 |
| CornerArea_mm2 | 5.365046 |
| CoolingHoleWidth_mm | 6.84276 |
| CoolingHoleHeight_mm | 19.1008 |
| CoolingArea_mm2 | 120.6538 |
| ConductorArea_mm2 | 418.5736 |
| FillFactor | 1 |
| CopperArea_mm2 | 418.5736 |
| Tstart_K | 80 |
| Resistivity_ohm-m | 1.99E-09 |
| GeometricResistance_m-1 | 4467231 |
| InitialResistance_ohms | 0.008877 |
| Required flexibility_T | 0.5 |
| Current per turn for flexibility_kA | 16.2037 |
| Max current in reference scenario_kA | 7.796296 |

### A.1.3 PF Coil Builds

| | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 |
|---:|---:|---:|---:|---:|---:|---:|
| Rpf_m | 0.219075 | 0.219075 | 0.219075 | 0.521945 | 2.223186 | 2.720467 |
| Rpf_in | 8.625 | 8.625 | 8.625 | 20.549 | 87.527 | 107.105 |
| Zpf_m | 0.239725 | 0.71915 | 1.198575 | 1.583436 | 1.53035 | 0.954075 |
| Zpf_in | 9.438 | 28.313 | 47.188 | 62.34 | 60.25 | 37.562 |
| Length_m | 1.376489 | 1.376489 | 1.376489 | 3.279475 | 13.96869 | 17.0932 |
| TurnsHigh | 18 | 18 | 18 | 10 | 6 | 7 |
| TurnsWide | 4 | 4 | 4 | 8 | 4 | 2 |
| Turns | 72 | 72 | 72 | 80 | 24 | 14 |
| Construction | Helically Wound | Helically Wound | Helically Wound | Helically Wound | Helically Wound | Helically Wound |
| BundleHeight_mm | 428.8188 | 428.8188 | 428.8188 | 248.9052 | 158.9484 | 181.4376 |
| BundleHeight_in | 16.88263 | 16.88263 | 16.88263 | 9.799417 | 6.257811 | 7.143213 |
| BundleWidth_mm | 93.7668 | 93.7668 | 93.7668 | 186.7716 | 93.7668 | 47.2644 |
| BundleWidth_in | 3.691606 | 3.691606 | 3.691606 | 7.353213 | 3.691606 | 1.860803 |
| BundleArea_mm2 | 40208.97 | 40208.97 | 40208.97 | 46488.42 | 14904.08 | 8575.539 |
| BundleArea_m2 | 0.040209 | 0.040209 | 0.040209 | 0.046488 | 0.014904 | 0.008576 |
| GroundWrap_mm | 0.762 | 0.762 | 0.762 | 0.762 | 0.762 | 0.762 |
| TurnInsulation_mm | 1.2446 | 1.2446 | 1.2446 | 1.2446 | 1.2446 | 1.2446 |
| PancakeInsulation_mm | 0.762 | 0.762 | 0.762 | 0.762 | 0.762 | 0.762 |
| ConductorHeight_in | 0.787402 | 0.787402 | 0.787402 | 0.787402 | 0.787402 | 0.787402 |
| ConductorHeight_mm | 20 | 20 | 20 | 20 | 20 | 20 |
| ConductorWidth_in | 0.787402 | 0.787402 | 0.787402 | 0.787402 | 0.787402 | 0.787402 |
| ConductorWidth_mm | 20 | 20 | 20 | 20 | 20 | 20 |
| CornerRadius_in | 0.03937 | 0.03937 | 0.03937 | 0.03937 | 0.03937 | 0.03937 |
| CornerRadius_mm | 1 | 1 | 1 | 1 | 1 | 1 |
| CornerArea_mm2 | 0.858407 | 0.858407 | 0.858407 | 0.858407 | 0.858407 | 0.858407 |
| CoolingHoleDia_in | 0.354331 | 0.354331 | 0.354331 | 0.354331 | 0.354331 | 0.354331 |
| CoolingHoleDia_mm | 9 | 9 | 9 | 9 | 9 | 9 |
| CoolingArea_mm2 | 63.61725 | 63.61725 | 63.61725 | 63.61725 | 63.61725 | 63.61725 |
| ConductorArea_mm2 | 335.5243 | 335.5243 | 335.5243 | 335.5243 | 335.5243 | 335.5243 |
| FillFactor | 1 | 1 | 1 | 1 | 1 | 1 |
| CopperArea_mm2 | 335.5243 | 335.5243 | 335.5243 | 335.5243 | 335.5243 | 335.5243 |
| Tstart_K | 80 | 80 | 80 | 80 | 80 | 80 |
| Resistivity_ohm-m | 1.99E-09 | 1.99E-09 | 1.99E-09 | 1.99E-09 | 1.99E-09 | 1.99E-09 |
| InitialResistance_ohms | 0.001174 | 0.001174 | 0.001174 | 0.003108 | 0.003971 | 0.002835 |
| 1Vs_OH_MAT | 2.515329 | 2.515329 | 1.913926 | 0.962985 | 0.032436 | 0.019286 |

**PF 1-6 conductor dimensions correspond to Outokumpu 8110**

### A.2 Coil Inductance Matrix (Henries)

| | M1 | M2 | M3 | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | TF | Plasma |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **M1** | 4.01E-02 | 9.15E-03 | 4.51E-03 | -9.94E-05 | 1.65E-05 | 6.81E-05 | 2.19E-04 | -4.12E-04 | -5.07E-04 | 1.56E-02 | -2.94E-05 |
| **M2** | 9.15E-03 | 2.99E-02 | 8.37E-03 | 3.99E-05 | -1.86E-05 | -9.13E-06 | -2.29E-05 | -8.13E-05 | -1.13E-04 | 1.20E-02 | -1.94E-05 |
| **M3** | 4.51E-03 | 8.37E-03 | 3.16E-02 | 2.05E-04 | -1.70E-05 | -6.96E-05 | -3.31E-04 | -4.06E-04 | -1.24E-04 | 9.35E-03 | -1.72E-05 |
| **PF1** | -9.94E-05 | 3.99E-05 | 2.05E-04 | 3.04E-03 | 4.79E-04 | 7.21E-05 | 1.47E-04 | 1.68E-04 | 1.19E-04 | 0.00E+00 | 8.92E-06 |
| **PF2** | 1.65E-05 | -1.86E-05 | -1.70E-05 | 4.79E-04 | 2.63E-03 | 4.30E-04 | 3.22E-04 | 1.75E-04 | 1.14E-04 | 0.00E+00 | 6.78E-06 |
| **PF3** | 6.81E-05 | -9.13E-06 | -6.96E-05 | 7.21E-05 | 4.30E-04 | 2.62E-03 | 1.14E-03 | 1.82E-04 | 1.04E-04 | 0.00E+00 | 4.40E-06 |
| **PF4** | 2.19E-04 | -2.29E-05 | -3.31E-04 | 1.47E-04 | 3.22E-04 | 1.14E-03 | 1.53E-02 | 1.14E-03 | 5.89E-04 | 0.00E+00 | 1.82E-05 |
| **PF5** | -4.12E-04 | -8.13E-05 | -4.06E-04 | 1.68E-04 | 1.75E-04 | 1.82E-04 | 1.14E-03 | 1.29E-02 | 3.49E-03 | 0.00E+00 | 4.81E-05 |
| **PF6** | -5.07E-04 | -1.13E-04 | -1.24E-04 | 1.19E-04 | 1.14E-04 | 1.04E-04 | 5.89E-04 | 3.49E-03 | 6.29E-03 | 0.00E+00 | 3.97E-05 |
| **TF** | 1.56E-02 | 1.20E-02 | 9.35E-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** | -2.94E-05 | -1.94E-05 | -1.72E-05 | 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.3 Reference Scenario Data

#### A.3.1 Current Waveforms

*Conductor currents are given in amperes. Maxima for all reference scenarios are shown in blue, minima in red.*

| 320kA 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 | 19318 | 19626 | 17254 | **-22649** | **-22649** | **-15010** | -10205 | 131 | -126 | -1106 | **0** |
| | 0.100 | 19318 | 19626 | 17254 | **-22649** | **-22649** | **-15010** | -10205 | 131 | -126 | -1106 | **0** |
| | 0.206 | 19000 | 17809 | 16092 | 11328 | 11328 | -9479 | **-14892** | 4924 | 4826 | 2191 | **-320775** |
| | 0.306 | 19000 | 17809 | 16092 | 14822 | 14822 | -6821 | -13688 | 5059 | 4964 | 2191 | **-320775** |
| | 0.506 | 19000 | 17809 | 16092 | **21809** | **21809** | -1505 | -11281 | 5329 | 5239 | 2191 | **-320775** |
| Maximum | | 19318 | 19626 | 17254 | 21809 | 21809 | 0 | 0 | 5329 | 5239 | 2191 | 0 |
| Minimum | | 0 | 0 | 0 | -22649 | -22649 | -15010 | -14892 | 0 | -126 | -1106 | -320775 |
| I2t (A2-s) | | 4.14E+08 | 3.93E+08 | 3.28E+08 | 4.55E+08 | 4.44E+08 | 1.57E+08 | 1.53E+08 | 1.59E+07 | 1.19E+07 | 1.36E+08 | |
| tESW (s) | | 1.11 | 1.02 | 1.10 | 0.89 | 0.86 | 0.70 | 0.69 | 0.56 | 0.43 | 28.29 | |

| **1.9T 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 | **21591** | **21935** | **19284** | 1505 | 1505 | 3630 | -2165 | 1183 | 917 | -1236 | **0** |
| | 0.050 | **21591** | **21935** | **19284** | 1505 | 1505 | 3630 | -2165 | 1183 | 917 | -1236 | **0** |
| | 0.094 | **21591** | **21935** | **19284** | 8745 | 8745 | 9139 | 330 | 1292 | 6356 | -1236 | -134176 |
| | 0.189 | 20363 | 20234 | 16774 | 8186 | 8186 | 7845 | -2104 | 2903 | 7478 | **4203** | -199246 |
| | 0.194 | 20363 | 20234 | 16774 | 8204 | 8204 | 7859 | -2098 | 2904 | **7479** | **4203** | -199246 |
| Maximum | | 21591 | 21935 | 19284 | 8745 | 8745 | 9139 | 330 | 2904 | 7479 | 4203 | 0 |
| Minimum | | 0 | 0 | 0 | 0 | 0 | 0 | -2165 | 0 | 0 | -1236 | -199246 |
| I2t (A2-s) | | 4.24E+08 | 4.31E+08 | 3.30E+08 | 2.18E+07 | 2.14E+07 | 2.29E+07 | 3.22E+06 | 4.54E+06 | 1.29E+07 | 2.05E+08 | |
| tESW (s) | | 0.91 | 0.90 | 0.89 | 0.28 | 0.28 | 0.27 | 0.69 | 0.54 | 0.23 | 11.60 | |

| **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 | 21189 | 19725 | 17727 | 1134 | 1134 | 5100 | 3391 | **8499** | -7428 | **-3548** | **0** |
| | 0.100 | 21189 | 19725 | 17727 | 1134 | 1134 | 5100 | 3391 | **8499** | -7428 | **-3548** | **0** |
| | 0.140 | 19318 | 19626 | 17254 | 10053 | 10053 | 9872 | 1063 | 1242 | 5774 | -1106 | -120052 |
| | 0.240 | 18220 | 18104 | 15009 | 9606 | 9606 | 8755 | -1096 | 2686 | 6781 | 3760 | -178272 |
| | 0.440 | 18220 | 18104 | 15009 | 10304 | 10304 | 9287 | -856 | 2713 | 6808 | 3760 | -178272 |
| Maximum | | 21189 | 19725 | 17727 | 10304 | 10304 | 9872 | 3391 | 8499 | 6808 | 3760 | 0 |
| Minimum | | 0 | 0 | 0 | 0 | 0 | 0 | -1096 | 0 | -7428 | -3548 | -178272 |
| I2t (A2-s) | | 4.18E+08 | 3.80E+08 | 3.05E+08 | 5.09E+07 | 5.04E+07 | 4.94E+07 | 4.92E+06 | 4.09E+07 | 4.92E+07 | 1.69E+08 | |
| tESW (s) | | 0.93 | 0.98 | 0.97 | 0.48 | 0.47 | 0.51 | 0.43 | 0.57 | 0.89 | 11.97 | |

| **Initial Ohmic Scenario** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** | **Plasma** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -1.000 | **0** | **0** | **0** | 0 | 0 | 0 | 0 | **0** | 0 | 0 | **0** |
| | 0.000 | 17450 | 16244 | 14598 | 1140 | 1140 | 4356 | 2863 | 7007 | -6109 | -2922 | **0** |
| | 0.100 | 17450 | 16244 | 14598 | 1140 | 1140 | 4356 | 2863 | 7007 | -6109 | -2922 | **0** |
| | 0.149 | 15909 | 16163 | 14209 | 9045 | 9045 | 8714 | 1139 | 1052 | 4786 | -910 | -98867 |
| | 0.249 | 15909 | 16163 | 14209 | 12539 | 12539 | 11372 | 2343 | 1187 | 4923 | -910 | -98867 |
| | 0.449 | 15909 | 16163 | 14209 | 19526 | 19526 | 16688 | **4751** | 1458 | 5199 | -910 | -98867 |
| Maximum | | 17450 | 16244 | 14598 | 19526 | 19526 | 16688 | 4751 | 7007 | 5199 | 0 | 0 |
| Minimum | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -6109 | -2922 | -98867 |
| I2t (A2-s) | | 3.61E+08 | 3.33E+08 | 2.68E+08 | 1.41E+08 | 1.40E+08 | 9.73E+07 | 2.18E+07 | 3.78E+07 | 4.20E+07 | 7.41E+07 | |
| tESW (s) | | 1.19 | 1.26 | 1.26 | 0.37 | 0.37 | 0.35 | 0.97 | 0.77 | 1.12 | 8.68 | |

| 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 | 21189 | 19725 | 17727 | 436 | 436 | 4568 | 3150 | 8472 | -7456 | -3548 | 0 |
| | 0.100 | 21189 | 19725 | 17727 | 436 | 436 | 4568 | 3150 | 8472 | -7456 | -3548 | 0 |
| | 0.140 | 19318 | 19626 | 17254 | 9354 | 9354 | 9341 | 822 | 1215 | 5747 | -1106 | -120052 |
| | 0.240 | 19318 | 19626 | 17254 | 12848 | 12848 | 11999 | 2026 | 1350 | 5885 | -1106 | -120052 |
| | 0.440 | 19318 | 19626 | 17254 | 19835 | 19835 | 17316 | 4433 | 1620 | 6160 | -1106 | -120052 |
| Maximum | | 21189 | 19725 | 17727 | 19835 | 19835 | 17316 | 4433 | 8472 | 6160 | 0 | 0 |
| Minimum | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -7456 | -3548 | -120052 |
| I2t (A2-s) | | 4.34E+08 | 4.03E+08 | 3.40E+08 | 1.45E+08 | 1.44E+08 | 9.97E+07 | 1.96E+07 | 3.83E+07 | 4.60E+07 | 1.02E+08 | |
| tESW (s) | | 0.97 | 1.04 | 1.08 | 0.37 | 0.37 | 0.33 | 1.00 | 0.53 | 0.83 | 8.10 | |

| 1.2T Long Pulse Scenario | t(s) | M1 | M2 | M3 | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | TF | Plasma |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0.000 | 14957 | 13923 | 12513 | 1725 | 1725 | 4304 | 2712 | 6035 | -5207 | -2504 | 0 |
| | 0.100 | 14957 | 13923 | 12513 | 1725 | 1725 | 4304 | 2712 | 6035 | -5207 | -2504 | 0 |
| | 0.128 | 13636 | 13854 | 12179 | 8013 | 8013 | 7666 | 1066 | 912 | 4112 | -780 | -84743 |
| | 0.228 | 12861 | 12779 | 10594 | 7800 | 7800 | 6956 | -423 | 1935 | 4827 | 2654 | -125839 |
| | 1.728 | 12861 | 12779 | 10594 | 13040 | 13040 | 10943 | 1383 | 2138 | 5033 | 2654 | -125839 |
| Maximum | | 14957 | 13923 | 12513 | 13040 | 13040 | 10943 | 2712 | 6035 | 5033 | 2654 | 0 |
| Minimum | | 0 | 0 | 0 | 0 | 0 | 0 | -423 | 0 | -5207 | -2504 | -125839 |
| I2t (A2-s) | | 4.12E+08 | 3.99E+08 | 2.82E+08 | 2.65E+08 | 2.66E+08 | 1.94E+08 | 5.27E+06 | 1.93E+07 | 5.10E+07 | 8.65E+07 | |
| tESW (s) | | 1.84 | 2.06 | 1.80 | 1.56 | 1.57 | 1.62 | 0.72 | 0.53 | 1.88 | 12.28 | |

| Ref. Scenario Summary | | M1 | M2 | M3 | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | TF | Plasma |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum | | 21591 | 21935 | 19284 | 21809 | 21809 | 17316 | 4751 | 8499 | 7479 | 4203 | 0 |
| Minimum | | 0 | 0 | 0 | -22649 | -22649 | -15010 | -14892 | 0 | -7456 | -3548 | -320775 |
| Maximum I2t (A2-s) | | 4.34E+08 | 4.31E+08 | 3.40E+08 | 4.55E+08 | 4.44E+08 | 1.94E+08 | 1.53E+08 | 4.09E+07 | 5.10E+07 | 2.05E+08 | |
| tESW (s) | | 0.93 | 0.90 | 0.91 | 0.89 | 0.86 | 0.65 | 0.69 | 0.57 | 0.91 | 11.60 | |

### A.3.2 Temperature History

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

| **320kA Ohmic** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.700 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 95 | 96 | 92 | 82 | 82 | 81 | 80 | 80 | 80 | 80 |
| | 0.100 | 98 | 100 | 95 | 83 | 83 | 81 | 80 | 80 | 80 | 80 |
| | 0.206 | 102 | 103 | 97 | 83 | 83 | 81 | 81 | 80 | 80 | 80 |
| | 0.306 | 105 | 106 | 100 | 83 | 83 | 82 | 81 | 80 | 80 | 80 |
| | 0.506 | 112 | 112 | 104 | 84 | 84 | 82 | 81 | 80 | 80 | 80 |
| | 2.687 | 123 | 120 | 113 | **85** | **85** | 82 | **82** | 80 | 80 | 81 |
| Dissipated Energy (J) | | 1.96E+07 | 1.77E+07 | 1.29E+07 | **5.79E+05** | **5.63E+05** | 1.86E+05 | **4.90E+05** | 6.50E+04 | 3.45E+04 | 1.22E+06 |
| | | | | | | | | | | | 5.33E+07 |

| **1.9T High Beta** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.850 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 103 | 106 | 97 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.050 | 105 | 108 | 99 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.094 | 107 | 110 | 100 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.189 | 111 | 114 | 103 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.194 | 111 | 114 | 103 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 2.375 | 124 | **124** | 114 | 80 | 80 | 80 | 80 | 80 | 80 | **81** |
| Dissipated Energy (J) | | 2.02E+07 | **2.01E+07** | 1.29E+07 | 2.68E+04 | 2.65E+04 | 2.75E+04 | 9.88E+03 | 1.86E+04 | 3.86E+04 | **1.86E+06** |
| | | | | | | | | | | | **5.53E+07** |

| **1.7T High Beta** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.700 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 98 | 96 | 93 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.100 | 102 | 100 | 95 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.140 | 103 | 101 | 96 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.240 | 107 | 104 | 99 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.440 | 113 | 110 | 103 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 2.621 | 123 | 119 | 111 | 81 | 81 | 80 | 80 | **80** | 80 | 81 |
| Dissipated Energy (J) | | 1.98E+07 | 1.69E+07 | 1.16E+07 | 6.21E+04 | 6.15E+04 | 5.90E+04 | 1.48E+04 | **1.59E+05** | 1.40E+05 | 1.53E+06 |
| | | | | | | | | | | | 5.03E+07 |

| **Initial Ohmic** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -1.000 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 98 | 97 | 94 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.100 | 101 | 99 | 95 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.149 | 102 | 100 | 96 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.249 | 105 | 102 | 98 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.449 | 110 | 107 | 101 | 81 | 81 | 81 | 80 | 80 | 80 | 80 |
| | 2.630 | 117 | 114 | 107 | 81 | 81 | 81 | 80 | 80 | 80 | 80 |
| Dissipated Energy (J) | | 1.61E+07 | 1.41E+07 | 9.82E+06 | 1.74E+05 | 1.73E+05 | 1.18E+05 | 6.86E+04 | 1.47E+05 | 1.18E+05 | 6.56E+05 |
| | | | | | | | | | | | 4.14E+07 |

| **1.7T Ohmic** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.700 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 98 | 96 | 93 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.100 | 102 | 100 | 95 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.140 | 103 | 101 | 96 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.240 | 107 | 104 | 99 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.440 | 114 | 112 | 104 | 81 | 81 | 81 | 80 | 80 | 80 | 80 |
| | 2.621 | **125** | 121 | **115** | 81 | 81 | 81 | 80 | 80 | 80 | 81 |
| Dissipated Energy (J) | | **2.09E+07** | 1.84E+07 | **1.35E+07** | 1.80E+05 | 1.78E+05 | 1.21E+05 | 6.15E+04 | 1.49E+05 | 1.30E+05 | 9.07E+05 |
| | | | | | | | | | | | 5.45E+07 |

| **1.2T Long Pulse** | **t(s)** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -0.400 | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.000 | 88 | 88 | 87 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.100 | 90 | 89 | 88 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.128 | 90 | 89 | 88 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 0.228 | 91 | 91 | 89 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| | 1.728 | 117 | 117 | 105 | 82 | 82 | 82 | 80 | 80 | 80 | 80 |
| | 3.909 | 122 | 121 | 109 | 83 | 83 | **82** | 80 | 80 | **81** | 81 |
| Dissipated Energy (J) | | 1.94E+07 | 1.81E+07 | 1.05E+07 | 3.21E+05 | 3.22E+05 | **2.30E+05** | 1.60E+04 | 7.58E+04 | **1.45E+05** | 7.72E+05 |
| | | | | | | | | | | | 4.99E+07 |

| **Ref. Scenario Summary** | | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Max Final Temperature | | 125 | 124 | 115 | 85 | 85 | 82 | 82 | 80 | 81 | 81 |
| Max Dissipated Energy (J) | | 2.09E+07 | 2.01E+07 | 1.35E+07 | 5.79E+05 | 5.63E+05 | 2.30E+05 | 4.90E+05 | 1.59E+05 | 1.45E+05 | 1.86E+06 |
| | | | | | | | | | | | 5.53E+07 |

### A.3.3 Electrical Power Requirements

Power supply requirements for the 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 seriers in a single circuit except for PF1 and PF2. PF1 and PF2 coils are connected in series in a single circuit.

[2] All coils of the same type have a single CLR connected in series with the coils. The PF1/2 circuit has two CLRs in the circuit. 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 1000MCM cables approximately 750 feet in length. Each circuit will have 1 cable per pole with 2 poles per circuit in the initial configuration. In the upgrade configurations, the M3 circuit will have 2 cables per pole.

[4] TFTR power supply sections (PSS) will be used. Each PSS has an open circuit voltage of 1012.85V and a maximum current of 24kA.

[5] Each circuit has a maximum current rating of 24kA.

[5] NCSX research will pursue the mission in a series of phases, corresponding to the increasing capability of the facility. The planned phases are:
  I. Initial Operation – initial plasma operation and system shakedown
  II. Field-line Mapping – validation of the coil manufacture and assembly
  III. Ohmic – operation with inductive current and ohmic heating only
  IV. Auxiliary Heating – operation with 3MW of NBI, installation of PFC liner.
  V. Confinement and Beta Push – operation with ~ 6MW of auxiliary heating, 2nd generation PFCs
  VI. Long Pulse – plasma and heating pulse lengths of at least 1.1 sec, pumped divertor. Possible further upgrade of heating power.
Electrical power systems shall be designed and initially configured to meet the requirements of First Plasma and the Initial Ohmic Scenario and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

#### A.3.3.1 Initial Power Supply Requirements

| Initial Capability | M1 | M2 | M3 | PF1/2 | PF3 | PF4 | PF5 | PF6 | TF |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Series supplies | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Current direction | + | + | + | + | + | + | + | +/- | + |
| TFTR PSS | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 2 |
| Total TFTR PSS | | | | | | | | | 20 |

### A.3.3.2 Upgrade Power Supply Requirements

*Changes in the capability required are shown in blue*

| **Capability at start of Phase IV** | **M1** | **M2** | **M3** | **PF1/2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|
| Series supplies | **4** | **4** | 2 | 2 | 2 | 2 | 2 | 2 | **4** |
| Current direction | + | + | + | + | + | **+/-** | + | +/- | **+/-** |
| TFTR PSS | **4** | **4** | 2 | **4** | 2 | **4** | 2 | 4 | **8** |
| Total TFTR PSS | | | | | | | | | **34** |

| **Capability at Start of Phase V** | **M1** | **M2** | **M3** | **PF1/2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|
| Series supplies | 4 | 4 | 2 | **4** | 2 | 2 | 2 | 2 | 4 |
| Current direction | + | + | + | **+/-** | **+/-** | +/- | + | +/- | +/- |
| TFTR PSS | 4 | 4 | 2 | **8** | **4** | 4 | 2 | 4 | 8 |
| Total TFTR PSS | | | | | | | | | **40** |

### A.3.3.3 Total Power Requirements

| **Reference Scenario** | **Max Active Power (W)** | **Max Apparent Power (VA)** | **Stored Energy Required (J)** |
|---|---|---|---|
| 350kA Ohmic | 1.09E+08 | **3.39E+08** | **8.79E+07** |
| 1.9T High Beta | **1.09E+08** | 2.73E+08 | 7.94E+07 |
| 1.7T High Beta | 9.79E+07 | 2.74E+08 | 7.45E+07 |
| Initial Ohmic | 6.57E+07 | 1.92E+08 | 6.59E+07 |
| 1.7T Ohmic | 9.77E+07 | 2.97E+08 | 8.10E+07 |
| 1.2T Long Pulse | 7.37E+07 | 2.08E+08 | 7.80E+07 |
| **Maximum** | **1.09E+08** | **3.39E+08** | **8.79E+07** |

## A.4 Cryogenic System Requirements

### A.4.1 Pulsed Heat Loads

Pulsed heat loads for the modular coils calculated on a temperature rise from 85K to 125K in each modular coil.
Pulsed heat loads for the TF and PF coils calculated on the basis of the worst case scenario for each coil.
Total heat loads calculated by summing the above.

| **Pulsed heat Loads** | **M1** | **M2** | **M3** | **PF1** | **PF2** | **PF3** | **PF4** | **PF5** | **PF6** | **TF** |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial Temperature (K) | 85 | 85 | 85 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Max Temperature (K) | 125 | 125 | 125 | 85 | 85 | 82 | 82 | 80 | 81 | 81 |
| Energy Deposited (J) | 2.10E+07 | 2.04E+07 | 1.83E+07 | 5.79E+05 | 5.63E+05 | 2.30E+05 | 4.90E+05 | 1.59E+05 | 1.45E+05 | 1.86E+06 |
| | | | | | | | | | | 6.38E+07 |

| **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 | 0.107717 | 198.7357 | 320.7905 | 805.7325 | 0.001241 | 0.398135 | 398.1353 | 105 | per shot |
| Time between shots (minutes) | 15 | | | | | | | | | | |
| Hours per day | 8 | | | | | | | | | | |
| Full pwr shots per day | 32 | | | | | | | | | 3366 | per day |
| Operating days per week | 5 | | | | | | | | | 16828 | per week |

### A.4.2 Parasitic Heat Loads

Heat leakages to the cold mass calculated on the basis of numbers provided by cognizant engineers based on nominal VV operating temperatures of 40C and bakeout temperatures of 150C with the cold mass at 80K.

| **Normal Operation** | **Heat Load (kW)** | **Flow rate (kg/s)** | **Vol flow rate (m3/s)** | **s/week** | **Volume (m3)** | **(liters)** | **(gallons)** | |
|---|---|---|---|---|---|---|---|---|
| Cryostat gaseous nitrogen circulation | 7.4 | | | | | | | |
| Through cryostat | 3.4 | | | | | | | |
| Through ports | 2.6 | | | | | | | |
| From VV to modular coil shell | 1.4 | | | | | | | |
| Modular coil liquid nitrogen cooling (from VV) | 3.7 | | | | | | | |
| Combined | 11.2 | 0.056189 | 6.97E-05 | 604800 | 42.17631 | 42176.31 | 11142 | per week |
| *VV heating required to maintain VV temperature* | *7.8* | | | | | | | |

| **Bakeout** | **Heat Load (kW)** | **Flow rate (kg/s)** | **Vol flow rate (m3/s)** | **s/week** | **Volume (m3)** | **(liters)** | **(gallons)** | |
|---|---|---|---|---|---|---|---|---|
| Cryostat gaseous nitrogen circulation | 9.6 | | | | | | | |
| Through cryostat | 3.4 | | | | | | | |
| Through ports | 4.0 | | | | | | | |
| From VV to modular coil shell | 2.2 | | | | | | | |
| Modular coil liquid nitrogen cooling (from VV) | 5.7 | | | | | | | |
| Combined | 15.3 | 0.076987 | 9.55E-05 | 604800 | 57.78784 | 57787.84 | 15266 | per week |
| *VV heating required to maintain VV temperature* | *11.9* | | | | | | | |

### A.4.3 Heat Loads For Cooling the Cold Mass from RT to 80K

| | | |
|---|---|---|
| Cold mass | 75000 | kg |
| Cryogen requirements | 0.43 | kg of LN2 per kg of SS assuming evaporation enthalpy only per http://gperinic.home.cern.ch/gperinic/cooldown.htm |
| | 32250 | kg based on evaporation enthalpy only |
| | 10574 | gallons |

### A.4.4 LN2 Delivery Requirements

| | **gallons per truck** | **trucks** | |
|---|---|---|---|
| Pulsed heat loads only | 6500 | 2.6 | per week |
| Parasitic loads only | | | |
| Normal | | 1.7 | per week |
| Bakeout | | 2.3 | per week |
| Cooldown only | | 1.6 | |

# 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 | Initial Ohmic 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 | 1.9T 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 | | | | | | |
| 3.2.1.5.4 | 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***

| **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 | | | Y | | | 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 | | | Y | | | Historically, it takes time to initially eliminate all vacuum leaks and to condition the vacuum vessel adequately for UHV conditions. The PEP requires the following at First Plasma: [1] A base pressure of $2\times10^{-7}$ torr and [2] a maximum global leak rate of $<1\text{x}10^{-4}$ torr-l/s. These values are higher than the ultimate requirements of $2\text{x}10^{-8}$ torr and $2\text{x}10^{-5}$ torr-l/s. |
| 3.2.1.2.2.2 | Pumping Speed | | X | | | | |
| 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 | | | | X | | Upgrade requirement |
| 3.2.1.2.3.3 | Coil Temperatures During Bakeout | | | X | | | |
| 3.2.1.2.3.4 | Bakeout Timelines | | | Y | | | First few bakeouts 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 | | | X | | | |
| 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 | | | | | |
| 3.2.1.4.2 | Pre-Pulse Temperature | | | a | b<br>c | | |
| 3.2.1.5 | Experimental Operations | | | | | | |
| 3.2.1.5.1 | Field Error Requirements | a | | b | | | Part b demonstrated during Field Line Mapping (Phase II) |
| 3.2.1.5.2 | Electrical (Eddy Current) Requirements | | | | X | | |
| 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 | b | | a | | | |
| 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 | |
| 3.2.1.5.3.3.1.2 | Initial Ohmic 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 | 1.9T High Beta Scenario | | | | | X | |
| 3.2.1.5.3.3.1.7 | 320 kA Ohmic Scenario | | | | | X | |

***Key: X = Before First Plasma  Y= After First Plasma***

| **Quality Conformance Matrix** | | **Examination** | **Test** | **Demonstration** | **Analysis** | **Not Applicable** | **Remarks** |
|---|---|---|---|---|---|---|---|
| 3.2.1.5.3.3.2 | Reference Scenario Requirements | | X | | | | All coil systems should be tested at their full circuit ratings prior to First Plasma. (The PEP has less stringent requirements.) Deflections and temperatures should be monitoredd to assure that critical components were behaving as expected.<br>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 Initial Ohmic Scenarios.<br>First Plasma would demonstrate that the integrated requirements for the First Plasma Scenario 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 | | |
| 3.2.1.5.4 | Power Handling | | | | | | |
| 3.2.1.5.4.1 | PFC Configuration | b | | | a<br>c<br>f | | |
| 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 | | | The following inspections and tests will be performed prior to First Plasma:<br>Beamlines will be mechanically installed on NCSX.<br>All cabling and other connections will be installed.<br>Beamline operating vacuum will be achieved.<br>Beamline cryopanels will be cooled down to cryogenic temperatures. |
| 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 | a | | b | c | | |
| 3.2.1.5.7.3 | Pellet Injection | a | | | b | | (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 | a | | | b | | (b) includes future upgrades |
| 3.2.1.5.9 | Instrumentation, Control, and Data Acquisition | | | X | | | The following integrated tests are specified in the PEP:<br>Integrated test of the safety interlock system.<br>Integrated test of the timing and synchronization system.<br>Integrated test of the power supply real time control system.<br>Integrated test of the data acquisition system. |
| 3.2.1.5.10 | Pulse Repetition Rate | | | X | | | |

***Key: X = Before First Plasma  Y= After First Plasma***

| **Quality Conformance Matrix** | | **Examination** | **Test** | **Demonstration** | **Analysis** | **Not Applicable** | **Remarks** |
|---|---|---|---|---|---|---|---|
| 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 | | | 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 | | | |