NCSX

System Requirements Document (SRD)

for the

Poloidal Field Coil System (WBS 132)

NCSX-BSPEC-132-00

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Record of Revisions

Revision	Date	ECP	Description of Change
Rev. 0		-	Initial issue

TABLE OF CONTENTS

Table of Figures

Table of Tables

1 SCOPE

The National Compact Stellarator Experiment (NCSX) is an experimental research facility that is to be constructed at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the understanding of 3D plasma physics for fusion and basic science.

A primary component of the facility is the stellarator core, an assembly of four coil systems that surround a highly shaped plasma and vacuum chamber. The four coil systems include the modular coils, the poloidal field (PF) coils, the toroidal field (TF) coils, and the external trim coils. These coils provide the magnetic field required for plasma shaping and position control, inductive current drive, and error field correction.

This specification addresses the design requirements for the Poloidal Field Coils (WBS 132). It also addresses the design requirements for Local I&C for the PF coils which are part of WBS 134.

1.1 Document Overview

This document, the System Requirements Document (SRD) for the PF Coils (WBS 132), is the complete development specification for this subsystem. Performance requirements allocated to this subsystem in the system specification, the General Requirements Document (NCSX-GRD-XX), have been incorporated in this document. **In this document, the term "the system" refers to the overall device and facility and the terms "the subsystem" and "PF coils" refer to the Poloidal Field Coils (WBS 132).**

The specification approach being used on NCSX provides for a clear distinction 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.

1.2 Incomplete and Tentative Requirements

Within this document, the term "TBD" (to be determined) indicates that additional effort (analysis, trade studies, etc) is required to define the particular requirement. The term "TBR" (to be revised) indicates that the value given is subject to change.

2 APPLICABLE DOCUMENTS

NCSX-ASPEC-GRD	NCSX General Requirements Document
NCSX-CRIT-CRYO	NCSX Structural and Cryogenic Design Criteria Document
NCSX-CRIT-SEIS	NCSX Seismic Design Criteria Document

3 REQUIREMENTS

3.1 Subsystem Definition

The PF coil system consists of an assembly of solenoid coils and three pairs of ring coils. Initially, the solenoid assembly will contain two existing coils which were originally used on the National Spherical Torus Experiment (NSTX). On NSTX, these coils were named PF1AU and PF1AL where the U and L designate upper and lower respectively. The solenoid assembly will be upgraded, replacing the PF1AU and PF1AL with three pairs of identical coils during experimental operation. The ring coils (PF4U/L, PF5U/L, and PF6U/L) are designed for operation throughout the life of NCSX. All of the PF coils operate within the cryostat and are cooled by liquid nitrogen. The coils will be equipped with local I&C (as required).

3.1.1 Subsystem Diagrams

3.1.1.1 Functional Relationships

A block diagram of the PF Coils and their environment is depicted in Figure 3-1.

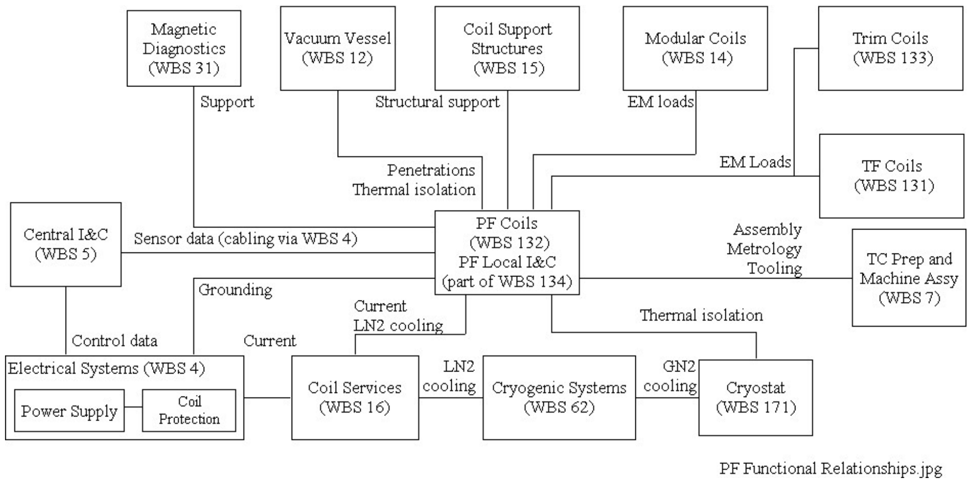

Figure 3-1 PF coil system functional relationships

3.1.1.2 Functional Flow Block Diagram

A functional flow block diagram (FFBD) is provided in Figure 3-2.

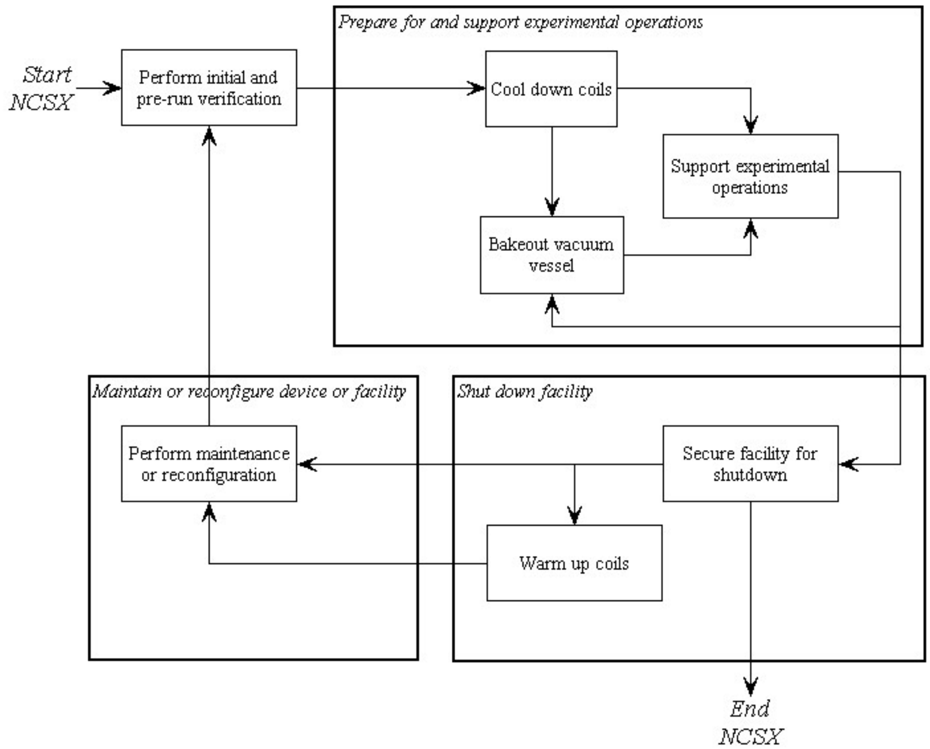

Figure 3-2 Functional flow block diagram

3.1.2 Interface Definition

3.1.2.1 Vacuum Vessel (WBS 12)

a. **Proximity**. The vacuum vessel port extensions pass close by the PF coils. Although there is no physical contact between the PF coils and VV port extensions, they are all inside the cryostat and clearances must be maintained under all operating conditions.

b. **Heat leakage**. The PF coils operate at cryogenic temperature whereas the VV port extensions operate at temperatures up to 150C. The port extensions are thermally insulated to reduce heat leakage to the PF coils to tolerable levels.

3.1.2.2 TF Coils (WBS 131)

TF coils impose EM loads on the PF coils and vice versa.

3.1.2.3 Trim Coils (WBS 133)

Trim coils impose EM loads on the PF coils and vice versa.

3.1.2.4 Modular Coils (WBS 14)

The modular coils impose EM loads on the PF coils and vice versa.

3.1.2.5 Coil Support Structures (WBS 15)

The coil support structures provide mechanical support to the PF coils.

3.1.2.6 LN2 Distribution System (WBS 161)

Liquid nitrogen for coil cooling is supplied from the Cryogenic Systems (WBS 62) to the LN2 Distribution System (WBS 161), which in turn supplies the liquid nitrogen to the PF coils.

3.1.2.7 Electrical Leads (WBS 162)

The current and voltage required to drive the PF coils is supplied from the Electrical Power Systems (WBS 4) to the Electrical Leads (WBS 162), which in turn supplies the direct current (DC) power to the PF coils.

3.1.2.8 Coil Protection System (WBS 163)

The Coil Protection System (WBS 163) includes all the activities required to develop the coil protection logic and specification of coil protection parameters, including PF coils. The Coil Protection System (WBS 163) does not include any hardware or software.

3.1.2.9 Cryostat (WBS 171)

Although there is no physical contact between the Cryostat (WBS 171) and the PF Coils, the cryostat does provide thermal isolation from the environment outside the cryostat and containment for the cold, dry nitrogen environment inside the cryostat. PF coils are cooled by the internal LN2 cooling. The nitrogen environment inside the cryostat is maintained by the Cryogenic Systems (WBS 62).

3.1.2.10 Magnetic Diagnostics (WBS 31)

Magnetic loops will be incorporated into the PF coils.

3.1.2.11 Electrical Power Systems (WBS 4)

a. **DC power**. The current and voltage required to drive the PF coils is supplied from the Electrical Power Systems (WBS 4) to the Electrical Leads (WBS 162), which in turn supplies the direct current (DC) power to the PF coils.

b. **Coil protection**. Electrical Power Systems (WBS 4) provide coil protection via parameters measured in the power supply circuitry based on parameters provided by Coil Protection System (WBS 163) activities. Electrical Power Systems (WBS 4) also provides coil protection via permissives and trip signals provided by Central I&C (WBS 5) in response to the output from sensors included in the local I&C within the PF Coil System (WBS 132).

c. **Grounding**. Electrical Power Systems (WBS 4) are responsible for providing single point grounds for the PF coils.

d. **I&C sensor leads –** The connecting cables between the PF coil I&C sensors and the Central I&C system (WBS 5) will be supplied by Electrical Power Systems (WBS 4).

3.1.2.12 Central I&C (WBS 5)

Central I&C (WBS 5) is responsible for taking the output from the sensors (e.g. strain gauges, resistance temperature detectors, and thermocouples) provided in the local I&C in the PF Coil System (WBS 132), processing those signals, displaying and storing the data, and providing permissives and trip signals for coil protection to Electrical Power Systems (WBS 4) in accordance with the coil protection logic and parameters specified by the Coil Protection Systems (WBS 163).

3.1.2.13 Cryogenic Systems (WBS 62)

a. **Liquid nitrogen cooling**. Cryogenic Systems (WBS 62) are responsible for providing liquid nitrogen cooling for the PF coils via the LN2 Distribution System (WBS 161).

b. **Gaseous nitrogen cooling**. Cryogenic Systems (WBS 62) are responsible for providing the gaseous nitrogen cooling within the cryostat required to cool and maintain the external temperature of the PF coils.

3.1.2.14 Test Cell Preparations and Machine Assembly (WBS 7)

The PF coils will have interfaces with the tooling and metrology equipment required for final machine assembly.

3.1.3 Major Component List

There are no major components for which additional development specifications are planned.

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Perform Initial and Pre-run Verification

3.2.1.1.1 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 subsystem pre-operational test procedures (PTPs) and 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 (NCSX-PLAN-PEP-01). A subset of the ISTP will be conducted before the start of a run.

3.2.1.1.1.1 Initial Verification of Operability

The subsystem shall provide the capability to perform subsystem PTPs and support a comprehensive ISTP, to verify, prior to plasma operation that the system is properly configured, functioning correctly, and can be operated safely. [Ref. GRD Section 3.2.1.1]

3.2.1.1.1.2 Design Verification

The subsystem shall be instrumented such that key performance parameters (stresses, deflections, temperatures, etc.) can be measured and compared to calculated values to assure that the subsystem is performing consistent with the design intent prior to First Plasma.

3.2.1.1.2 Pre-Run Facility Startup

Background

Pre-run facility startup includes all activities required to verify safe operation of the NCSX subsystems 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 PTP and ISTP activities referred to in Section 3.2.1.1.1.1.

Requirement

The subsystem shall support the capability to perform a controlled startup of the facility, and verify that the subsystem is properly configured, functioning correctly, and can be operated safely. [Ref. GRD Section 3.2.1.2]

3.2.1.2 Prepare for and Support Experimental Operations

3.2.1.2.1 Subsystem Verification and Monitoring

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. Pre-pulse initialization and verification activities cover those activities required prior to the start of each pulse (plasma discharge). The PF Coils (WBS 132) should be monitored to verify that the subsystem is functioning correctly and configured properly at the start of an operating day and prior to the start of each pulse.

Requirement

The subsystem shall provide the capability to verify that the subsystem is properly configured, functioning correctly, and can be operated safely prior to the start of an operating day and prior to the start of each pulse (plasma discharge). [Ref. GRD 3.2.1.3 and GRD 3.2.1.4]

3.2.1.2.2 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 about 80K. The coils are located in a dry nitrogen environment that is provided by the cryostat, which surrounds the coils. 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 no more than 150 cool-down and warm-up cycles between room temperature and operating temperature over the lifetime of the machine.

3.2.1.2.2.1 Coil Cooling

a. The coils will be designed with conventional, hollow copper conductor for liquid nitrogen cooling with a maximum operating pressure of 150 psig, a minimum operating pressure of 60 psig, and a nominal inlet temperature of 80K.

b. Peak coil temperatures shall be less than 92K assuming a starting temperature of 85K to avoid the potential for 2-phase flow. (The saturation temperature at 60 psig is approximately 94.4K.)

3.2.1.2.2.2 Timeline for Coil Cool-down to Cryogenic Temperature

The PF Coils shall be capable of being cooled down from room temperature (293K) to their pre-pulse operating temperature (<85K) within 96 hours with the vacuum vessel at room temperature (20°C). [Ref. GRD Sections 3.2.1.2.1.1 and 3.2.1.2.1.3]

3.2.1.2.3 Bakeout

Background

The temperature of the vacuum vessel shell will be capable of being elevated to a nominal temperature of 150ºC for vacuum vessel bakeout operations and to a nominal temperature of 350ºC to support bakeout of an in-vessel carbon-based liner (to be installed as an upgrade) at that temperature. Initially, there will not be any limiters installed in the vacuum vessel for first plasma or field line mapping. However, later in the program, the liner will be installed inside the vacuum vessel with a surface area that is a substantial part of the vacuum vessel surface area to absorb the high heat loads and to protect the vacuum vessel and internal components. The capability to bake the vessel with the cryo-resistive coils at cryogenic temperature is required.

3.2.1.2.3.1 Coil Temperatures during Bakeout

The capability to bakeout the vacuum vessel with the PF Coils below 90K shall be provided. The PF Coils shall return to their pre-pulse operating temperatures (<85K) within the 24 hours following completion of bakeout. [Ref. GRD Section 3.2.1.2.3.3]

3.2.1.2.3.2 Bakeout Cycles

The device shall be designed for at least 1000 bakeout cycles over the life of the machine. [Ref. GRD Section 3.2.1.2.3.6]

3.2.1.2.4 Pre-Pulse Temperature

The PF Coils shall return to a pre-pulse temperature of less than 85K, so as to prevent overheating during repeated operation, with a vacuum vessel shell temperature in the range of 40ºC to 210 C. [Ref. GRD Section 3.2.1.4.2]

3.2.1.2.5 Field Error Requirements

Background

Field errors are a major concern in the design of NCSX. The fundamental global requirement is that 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). To implement this requirement, external trim coils have been provided for field error correction. The PF Coils will be fabricated and assembled to tight tolerances which are calculated to introduce acceptably low field errors after deflections due to EM loads are taken into account.

3.2.1.2.5.1 Eddy Current Time Constants

The time constant of the longest-lived eddy current eigenmode shall be less than 20 ms. [Ref. GRD Section 3.1.5.2c]

3.2.1.2.5.2 Winding Tolerances

The local current centroid for each PF coil shall be located within 3 mm of the nominal current centroid with the PF coils at the pre-pulse operating temperature and zero current in their installed positions.

3.2.1.2.5.3 Leads and Transitions

The toroidal flux in island regions due to winding perturbations in leads and transitions shall not exceed 1% of the total toroidal flux in the plasma (without compensation).

3.2.1.2.6 Plasma Magnetic Field Requirements

3.2.1.2.6.1 Reference Scenario Requirements

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 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. The PF ring coils will also be designed to meet the requirements of all the reference scenarios. The PF solenoid assembly will be designed to meet the requirements of the First Plasma Scenario and shall be capable of being replaced with an upgraded solenoid assembly to meet the requirements of other reference scenarios. Electrical power systems shall be designed and initially configured to meet the requirements of the First Plasma and Field

Line Mapping Scenarios and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

Reference scenario definitions are provided in Section 3.2.1.5.3.3.1 of the GRD. Reference waveforms of engineering parameters such as coil currents, voltages, power dissipation, etc. are derived from the scenario specifications and are documented in Appendix A of the GRD.

Requirement

c. The PF ring coils (PF3-6) will be designed to meet the requirements of all the reference scenarios. [Ref. GRD Section 3.2.1.5.3.3.2]

d. The PF solenoid assembly will be design to meet the requirements of the First Plasma Scenario.

e. The PF solenoid assembly shall be capable of being replaced with an upgraded solenoid assembly which meets the requirements of all the reference scenarios.

3.2.1.2.6.2 Vertical Position Control

The upper and lower PF5 coils shall be capable of being powered independently (with a differential current of up to 1 Kamp-turn) in order to effect plasma vertical position control.

3.2.1.2.7 Disruption Handling

The PF Coils shall be designed to withstand electromagnetic forces due to major disruptions characterized by instantaneous disappearance of the plasma at the maximum plasma current of 320 kA [Ref. GRD Section 3.2.1.5.5]

3.2.1.2.8 Pulse Repetition Rate

The PF Coils shall be designed for pulses to be initiated at intervals not exceeding 15 minutes when constrained by cool-down and 5 minutes otherwise. [Ref. GRD Section 3.2.1.5.10]

3.2.1.2.9 Voltage Stand-off Requirements

Background

Voltage standoff requirements are based on an assumed Maximum Operating Voltage (MOV) which is greater than or equal to the maximum voltage from the number of series power supply sections identified in Section A.2.3.4 of the GRD. A Maintenance Field Test Voltage (MFTV) is derived by multiplying the MOV by two and adding 1 kV. A Manufacturing Test Voltage (MTV) is derived by multiplying the MFTV by 1.5. A Design Voltage Standoff (DVS) is derived by multiplying the MTV by 1.5. Based on the D-site circuit configuration presented and the PDR, the MOV is 4kV.

Requirements

a. PF1-3 coils shall be designed to a DVS of 20kV and subjected to a MTV of 13.5kV.

b. PF4-6 coils shall be designed to a DVS of 11kV and subjected to a MTV of 7.5kV.

c. PF1A coils shall be subjected to a MTV of 5kV.

3.2.1.2.10 Discharge Termination

3.2.1.2.10.1 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

During a controlled shutdown, the PF coil currents will be driven to zero by the power supplies according to the pre-programmed current waveform. [Ref. GRD Section 3.2.1.5.11.1]

3.2.1.2.10.2 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

During an abnormal termination, the PF coil power supplies will be bypassed and the PF coil currents will go to zero on the natural decay times of the coil circuits. [Ref. GRD Section 3.2.1.5.11.2]

3.2.1.3 Shut Down Facility

Background

Facility shutdown involves the shutdown of NCSX equipment following the termination of a discharge (per Section 3.2.1.2.10) 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 PF Coils. [Ref. GRD Section 3.2.1.6]

3.2.1.3.1 Coil Warm-up Timeline

The PF Coils shall be capable of being warmed up from operating temperature (80K) to room temperature (293K) within a period of 96 hours. [Ref. GRD Section 3.2.1.6.1]

3.2.2 Physical Characteristics

3.2.2.1 Configuration Requirements and Essential Features

3.2.2.1.1 Number and Location

3.2.2.1.1.1 Initial System Configuration

The system shall initially be configured with one pair of existing coils in the solenoid assembly (PF1AU and PF1AL) and three pairs of ring coils (PF4-PF6). The locations of the current centroids and nominal builds are shown in Figure 3-3.

3.2.2.1.1.2 Upgraded Solenoid Assembly

The locations of the current centroids and nominal builds for the coils with the upgraded solenoid assembly are shown in Figure 3-4.

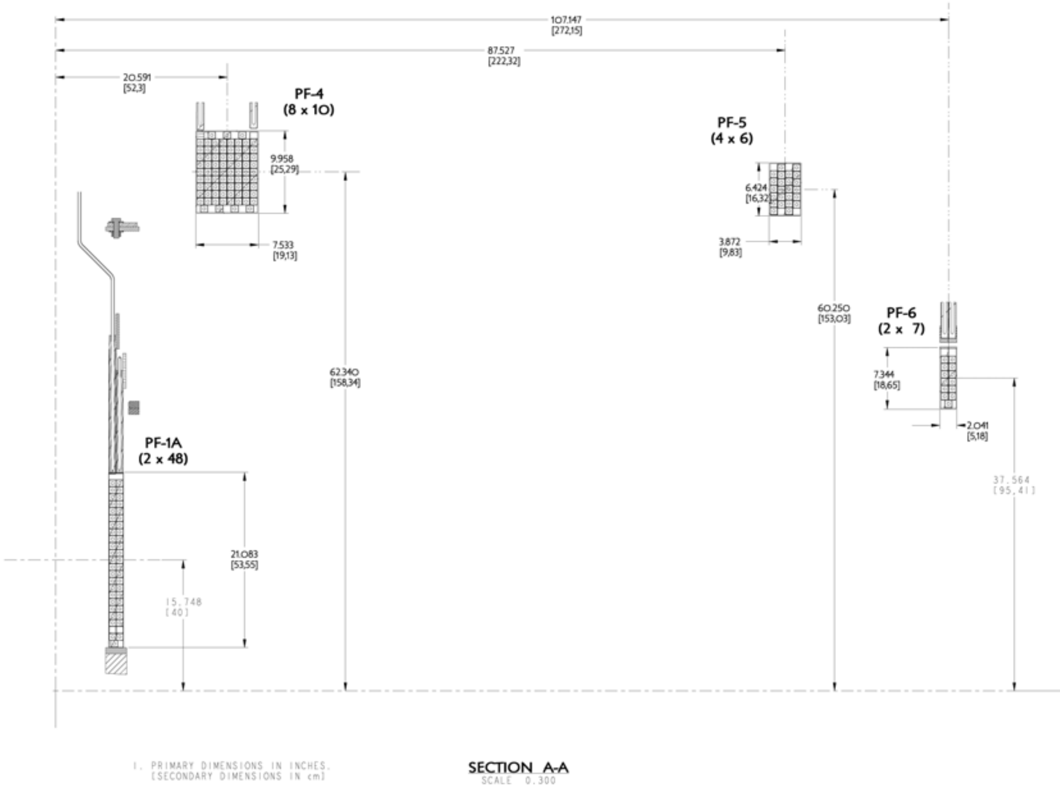

Figure 3-3 PF coil geometry with PF1A coils

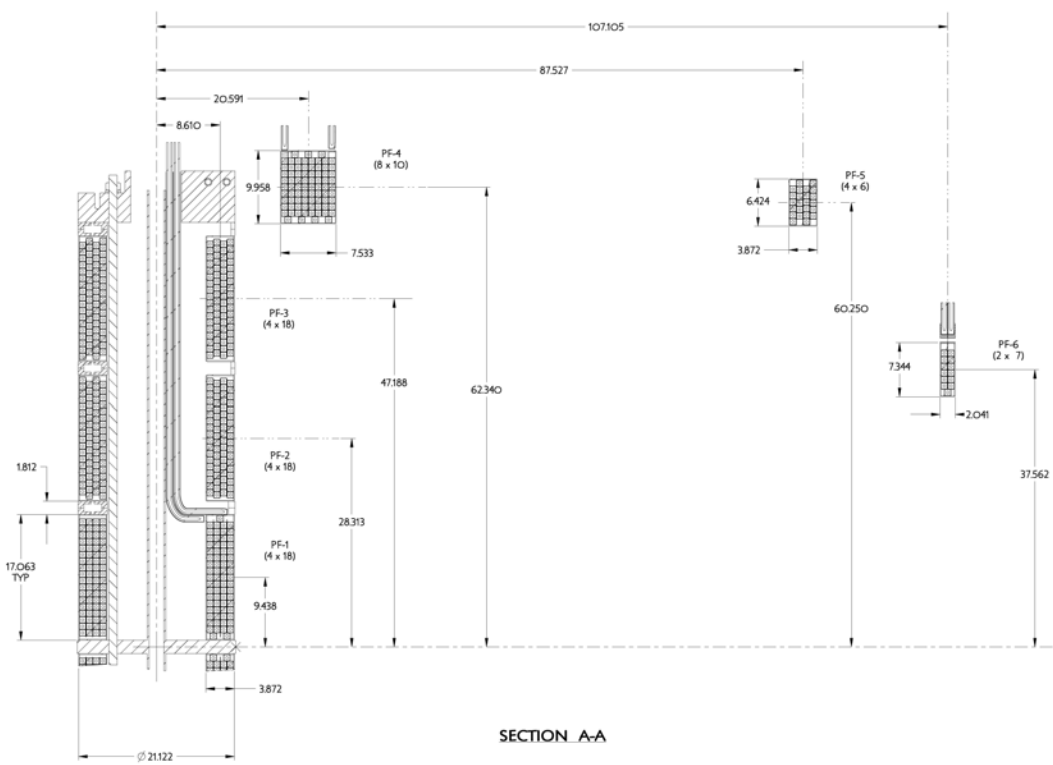

Figure 3-4 PF coil geometry with upgraded solenoid assembly

3.2.2.1.2 Symmetry and Alignment

PF coils shall be up-down symmetric with respect to the horizontal mid-plane of the modular coils and aligned with the major axis of the modular coil assembly in the installed condition at the nominal pre-shot operating temperature.

3.2.2.1.3 Coil Supports

The ring coils (PF4-6) and solenoid assemblies will be mounted to the Coil Support Structures (WBS 15).

3.2.2.1.4 Electrical Requirements

3.2.2.1.4.1 Turns per Coil

The PF coils shall be designed with the number of turns shown in Figure 3-3 and Figure 3-4. [GRD Section A.1.2 and A.2.1]

3.2.2.1.4.2 Circuit Configuration

3.2.2.1.4.2.1 Initial Circuit Configuration

a. Upper and lower PF coil pairs (PF1A, PF4, and PF6) shall be connected in series.

b. The upper and lower PF5 coil pair shall be configured to facilitate powering the coils independently, i.e. with different currents.

3.2.2.1.4.2.2 Circuit Configuration with Upgraded Solenoid Assembly

a. Upper and lower PF1 and PF2 coil pairs shall be connected in series (in a future upgrade).

b. The upper and lower PF3 coil pair shall be connected in series (in a future upgrade).

3.2.3 System Quality Factors

3.2.3.1 Reliability, Availability, and Maintainability

<u>Background</u>

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. The PF Coils shall incorporate reliability and maintainability features in the design that are consistent with achieving a high (greater than 95%) operational availability.

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

c. The PF Coils shall be capable of being disassembled and reassembled to permit replacement of any part or machine reconfiguration that would require disassembly.

d. Provisions for lifting, e.g. lifting eyes, other sling attachment provisions, or equivalent provisions, shall be made in the design of the PF Coils.

[Ref. GRD Section 3.2.4.1]

3.2.3.2 Design Life

a. The PF Coils shall have a design life of >10 years.

b. The PF Coils shall be designed for the following maximum number of pulses 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.

[Ref. GRD Section 3.2.4.2]

3.2.3.3 Seismic Criteria

Background

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.” The NCSX Seismic Design Criteria provides an NCSX-specific interpretation of those requirements

Requirement

The PF Coils shall be design in accordance with the NCSX Seismic Design Criteria. [Ref. GRD Section 3.3.1.5]

3.2.4 Transportability

The PF Coils and components shall be transportable by commercial carrier via highway, air, sea, or railway. [Ref. GRD Section 3.2.5]

3.3 Design and Construction

3.3.1 Materials, Processes, and Parts

3.3.1.1 Magnetic Permeability

All materials (including weld materials) used in the PF Coils must have a relative magnetic permeability less than 1.02 unless otherwise authorized by the Project. [Ref. GRD Section 3.3.1.1]

3.3.1.2 Structural and Cryogenic Criteria

The PF Coils shall be designed in accordance with the NCSX Structural and Cryogenic Design Criteria. [Ref. GRD Section 3.3.1.3]

3.3.1.3 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. [Ref. GRD Section 3.3.1.4]

3.3.1.4 Metrology

The PF Coils shall provide features (e.g., fiducial markers) to facilitate accurately measuring and locating components relative to the magnetic field for the life of the machine. [Ref. GRD Section 3.3.1.6]

3.3.2 Electrical Grounding

PF coils will not have a ground plane surface. PF Coils shall be connected via a single point ground provided by the Electrical Power Systems (WBS 4) where appropriate. [Ref. GRD Section 3.3.2]

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. The labels for the PF Coils will be in the vicinity of the leads for ease of identification of lead polarity and winding direction. [Ref. GRD Section 3.3.3.1]

3.3.4 Workmanship

During PF coil 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. [Ref. GRD Section 3.3.4]

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. [Ref. GRD Section 3.3.5]

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 PF Coils shall be provided.
- The PF Coils shall not present any uncontrolled safety or health hazard to user personnel.
- The PF Coils shall be designed such that degradation of epoxy shear strength over the life of the coil will not result in catastrophic failure of the winding, i.e. the coil windings will not unravel at the free ends where the leads are attached.

[Ref. GRD Section 3.3.6.1]

3.3.6.2 Personnel Safety

The PF Coils 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). [Ref. GRD Section 3.3.6.3]

3.3.6.3 Flammability

The use of flammable materials shall be minimized. [Ref. GRD Section 3.3.6.4]

3.4 Documentation

3.4.1 Specifications

Specifications shall be developed for the configuration items shown in Table 3-1.

Table 3-1 PF coil specifications

Configuration Item	Specification Identifier	Specification Type
Solenoid Structural Assembly	NCSX-CSPEC-132-01	Product specification – forms the basis for procuring the solenoid structural assembly
PF Ring Coils	NCSX-CSPEC-132-02	Product specification – forms the basis for procuring or fabricating the PF ring coils (PF4-6)
Solenoid Assembly	NCSX-CSPEC-132-03	Product specification – forms the basis for assembling and testing the completed solenoid assembly

3.5 Logistics

3.5.1 Maintenance

The PF Coils 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 Standardized Parts

Standardized parts shall be used in all coil systems (including the PF Coil System) to the extent practicable. Specifically, standardization shall be considered for electrical leads, coil I&C, co-wound flux loops, and epoxy formulation.

4 QUALITY ASSURANCE PROVISIONS

4.1 General

This section identifies the methods to be used for verification of requirements in Section 3.2 of this specification. General definitions of basic verification methods are outlined in Section 4.2 Verification of subsystem requirements will require additional testing in operational or near-operational environments.

4.2 Verification Methods

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

<u>Analysis</u>: Verification of conformance with required characteristics by calculation or simulation, including computer modeling based on established material or component characteristics.

<u>Inspection</u>: Verification of conformance by measuring, examining, testing, and gauging one or more characteristics of a product or service and comparing the results with specified requirements.

<u>Test</u>: Verification by physically exercising a component or system under appropriate loads or simulated operating conditions, including measurement and analysis of performance data.

4.3 Quality Conformance

This section establishes the specific evaluation criteria for verification of the subsystem performance requirements in Section 3.2. In general, all requirements shall be verified under operational or near-operational conditions as possible given test constraints.

4.3.1 Performance

4.3.1.1 Perform Initial and Pre-run Verification

4.3.1.1.1 Initial Facility Startup

4.3.1.1.1.1 Initial Verification of Operability

Initial verification of operability (ref. Section 3.2.1.1.1.1) shall be assured by inspection of the subsystem PTPs and the ISTP.

4.3.1.1.1.2 Design Verification

a. The adequacy of the design to determine key performance parameters (ref. Section 3.2.1.1.1.2) shall be assessed during final design.

b. Functionality shall be tested during integrated systems testing.

4.3.1.1.2 Pre-Run Facility Startup

a. The adequacy of the design to support a controlled startup of the facility (ref. Section 3.2.1.1.2) shall be assessed during final design.

b. Functionality shall be tested during integrated systems testing.

4.3.1.2 Prepare for and Support Experimental Operations

4.3.1.2.1 Subsystem Verification and Monitoring

a. The adequacy of the design to verify that the subsystem is properly configured, functioning correctly, and can be operated safely prior to the start of an operating day and prior to the start of each pulse (ref. Section 3.2.1.2.1) shall be assessed during final design.

b. Functionality shall be tested during integrated systems testing.

4.3.1.2.2 Coil Cool-down

4.3.1.2.2.1 Coil Cooling

a. The ability to withstand the maximum operating pressure specified in Section 3.2.1.2.2.1 shall be verified by analysis during final design and by testing following coil manufacture.

b. The ability to meet the maximum temperature specified in Section 3.2.1.2.2.1 shall be demonstrated by [1] analysis during final design, [2] testing upon manufacture to measure key parameters such as coil resistance, and [3] by testing during integrated systems testing.

4.3.1.2.2.2 Timeline for Coil Cool-down to Cryogenic Temperature

a. The ability to cool down the PF coils is the required time (ref. Section 3.2.1.2.2.2) shall be verified by analysis during final design.

b. The actual cool down time shall be demonstrated during integrated systems testing.

4.3.1.2.3 Bakeout

4.3.1.2.3.1 Coil Temperatures during Bakeout

The ability to bakeout the vacuum vessel with the PF coils below 90K shall be verified by analysis during final design (ref. Section 3.2.1.2.3.1).

4.3.1.2.3.2 Bakeout Cycles

The ability to accommodate the required number of bakeout cycles (ref. 3.2.1.2.3.2) shall be verified by analysis during final design.

4.3.1.2.4 Pre-Pulse Temperature

a. The ability to return to the specified pre-pulse temperature (ref. Section 3.2.1.2.4) shall be verified by analysis during final design.

b. The ability to return to the specified pre-pulse temperature shall be demonstrated during integrated systems testing.

4.3.1.2.5 Field Error Requirements

4.3.1.2.5.1 Eddy Current Time Constants

Time constants for PF coil system eddy currents will be verified by analysis during final design (ref. Section 3.2.1.2.5.1)

4.3.1.2.5.2 Winding Tolerances

Achieved winding tolerances will be determined by inspection of the coil upon manufacture and upon installation (ref. Section 3.2.1.2.5.2).

4.3.1.2.5.3 Leads and Transitions

Field errors due to winding perturbations in leads and transitions (ref. Section 3.2.1.2.5.3) shall be verified by analysis during final design.

4.3.1.2.6 Plasma Magnetic Field Requirements

4.3.1.2.6.1 Reference Scenario Requirements

a. The ability of the PF coils to meet the Reference Scenario requirements in Section 3.2.1.2.6.1 shall be demonstrated by analysis during final design.

b. Coil performance shall be monitored during integrated system testing to verify that the structural performance is consistent with expectations.

4.3.1.2.6.2 Vertical Position Control

The capability of the upper and lower PF5 coils to be powered independently per Section 3.2.1.2.6.2 shall be verified by analysis during final design.

4.3.1.2.7 Disruption Handling

The ability of the PF Coils to withstand electromagnetic forces due to major disruptions per Section 3.2.1.2.7 shall be verified by analysis during final design.

4.3.1.2.8 Pulse Repetition Rate

The ability of the PF Coils to meet the pulse repetition rate specified in Section 3.2.1.2.8 shall be verified by [1] analysis during final design, [2] testing upon manufacture to measure key parameters such as coil resistance, and [3] by testing during integrated systems testing.

4.3.1.2.8.1 Voltage Stand-off Requirements

a. The design voltage standoff (ref. 3.2.1.2.9) for the PF Coils shall be determined by analysis during final design.

b. The ability to accommodate the manufacturing test voltage (ref. 3.2.1.2.9) shall be verified by test following coil manufacture.

4.3.1.2.9 Discharge Termination

4.3.1.2.9.1 Normal Termination

Normal termination (ref. 3.2.1.2.10.1) will be demonstrated during integrated systems testing.

4.3.1.2.9.2 Abnormal Termination

Abnormal termination (ref. 3.2.1.2.10.2) will be demonstrated during integrated systems testing.

4.3.1.3 Shut Down Facility

Controlled shutdown of the PF Coils (ref. Section 3.2.1.3) will be demonstrated during integrated systems testing.

4.3.1.3.1 Coil Warm-up Timeline

The capability to warm up the PF Coils in the required time period (ref. Section 3.2.1.3.1) shall be demonstrated during integrated systems testing.