# NCSX Specification

# System Requirements Document (SRD) For the Toroidal Field Coils (WBS 131)

**NCSX-BSPEC-131-00**

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# 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 Toroidal Field Coils (WBS 131). It also addresses the design requirements for Local I&C for the TF coils which are part of WBS 134.

## 1.1 Document Overview

This document, the System Requirements Document (SRD) for the TF Coils (WBS 131), 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 "TF coils" refer to the Toroidal Field Coils (WBS 131).**

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

The following documents 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 superseding requirement.

## 2.1 NCSX Documents

- Project Execution Plan (NCSX-PLAN-PEP-XX)
- General Requirements Document (NCSX-ASPEC-GRD-XX)
- Stellarator Core Systems (WBS 1) WBS Dictionary (NCSX-WBS1-XX)
- Structural and Cryogenic Design Criteria (NCSX-CRIT-CRYO-XX)
- Seismic Design Criteria (NCSX-CRIT-SEIS-XX)
- Reliability, Availability, and Maintainability Plan (NCSX-PLAN-RAM-XX)

Note: In the document names above, XX denotes the latest issue.

# 3 SUBSYSTEM REQUIREMENTS

## 3.1 Subsystem Definition

The TF coil system consists of 18 identical, equally spaced TF coils providing a 1/R field at the plasma. The coils operate within the cryostat and are cooled by liquid nitrogen. Each coil consists of a winding with a rectangular cross-section with wedge pieces bonded on each side. The coil 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 TF coils and their environment is depicted in Figure 3-1.

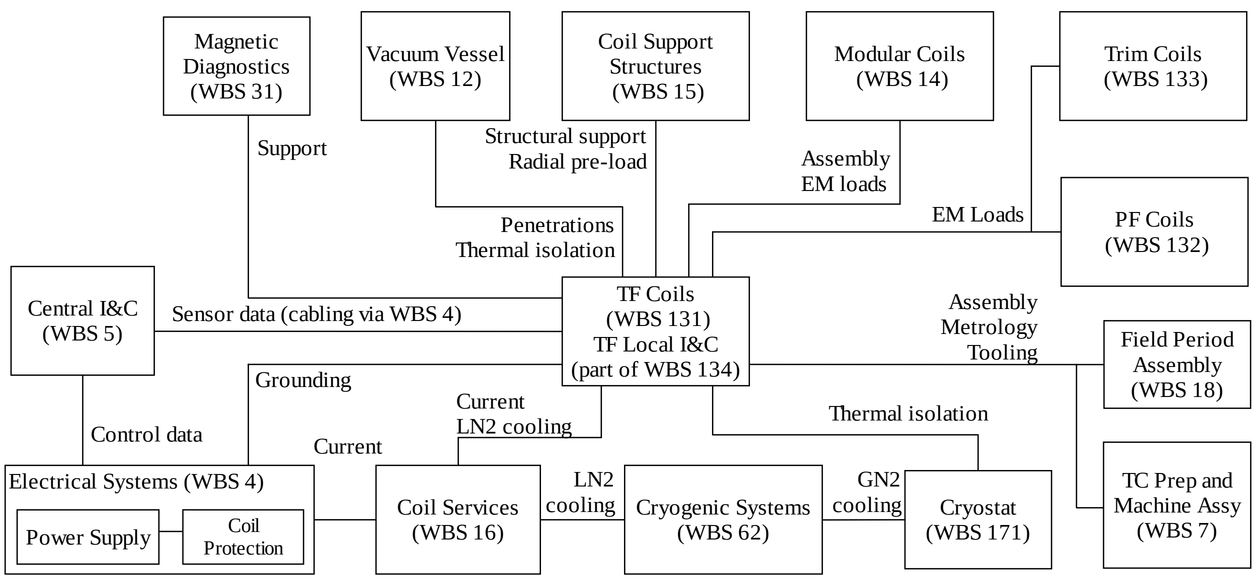


**Figure 3-1 TF coil system functional relationships**

#### 3.1.1.2 Functional Flow Block Diagram

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

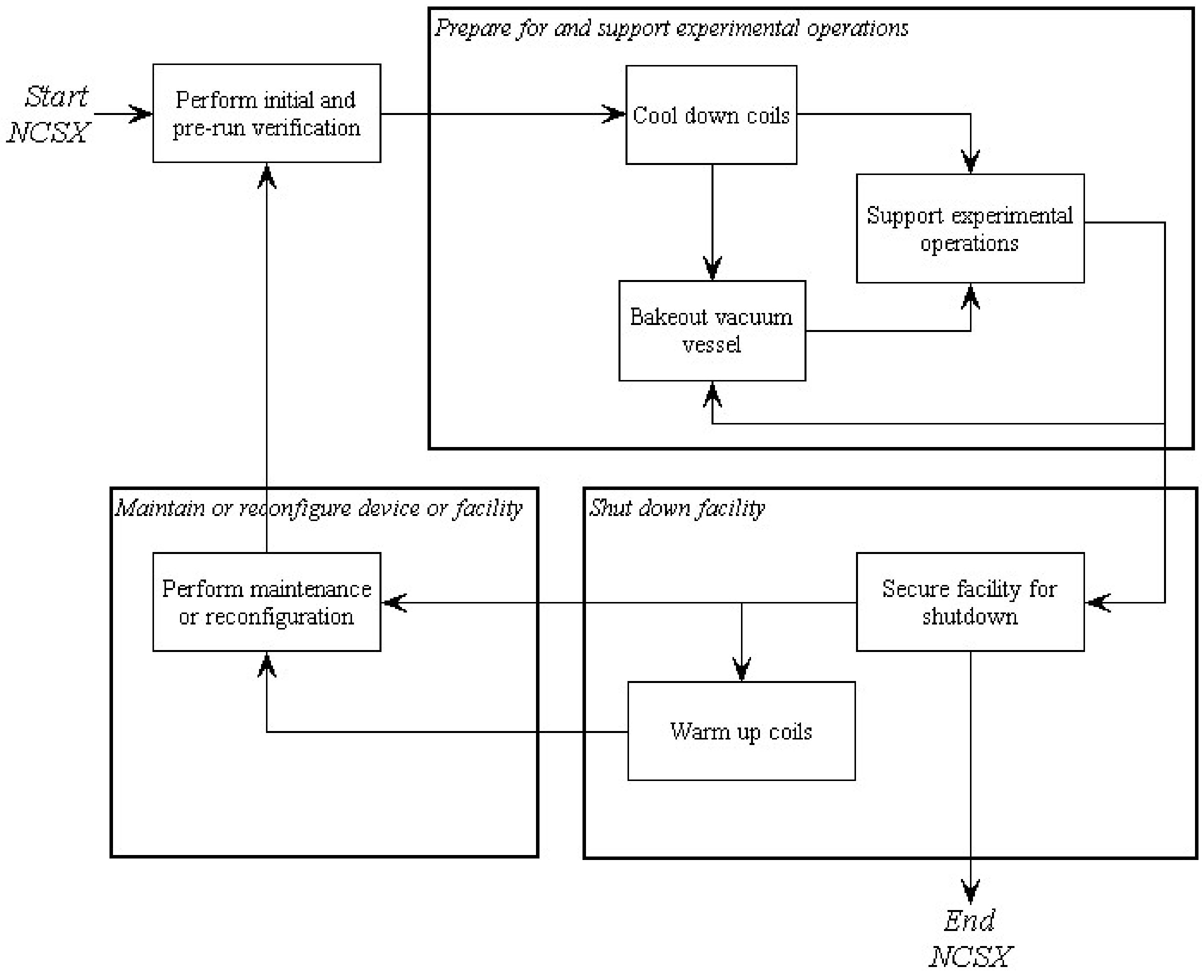


**Figure 3-2 Functional flow block diagram**

### 3.1.2 Interface Definition

#### 3.1.2.1 Vacuum Vessel (WBS 12)

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

b. **Heat leakage**. The TF 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 TF coils to tolerable levels.

#### 3.1.2.2 PF Coils (WBS 132)

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

#### 3.1.2.3 Trim Coils (WBS 133)

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

#### 3.1.2.4 Modular Coils (WBS 14)

a. **EM loads**. The modular coils impose EM loads on the TF coils and vice versa.

b. **Assembly**. The TF coils must slide over the modular coils during field period assembly.

#### 3.1.2.5 Coil Support Structures (WBS 15)

a. **Mechanical support**. The coil support structures provide mechanical support to the TF coils for out-of-plane EM loads and gravity loads.

b. **Radial pre-load**. The coil support structures also provide a radial pre-load to the TF coils.

c. **Geometric position/correction** – The coil support structures will be used to position and correct the TF coil winding geometry at assembly.

#### 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 individual TF coils.

#### 3.1.2.7 Electrical Leads (WBS 162)

The current and voltage required to drive the TF 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 individual TF 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 TF 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 TF Coils, the cryostat does provide thermal isolation from the environment outside the cryostat and containment for the cold, dry nitrogen environment inside the cryostat. The TF Coil is both cooled by the internal LN2 cooling and the external cooling provided by the cryostat. The nitrogen environment inside the cryostat is maintained by the Cryogenic Systems (WBS 62).

#### 3.1.2.10 Field Period Assembly (WBS 18)

The TF coils will have interfaces with the tooling and metrology equipment required for field period assembly, including lifting points and monuments to facilitate position measurements.

#### 3.1.2.11 Magnetic Diagnostics (WBS 31)

Magnetic loops will be incorporated into TF coils.

#### 3.1.2.12 Electrical Power Systems (WBS 4)

a. **DC power**. The current and voltage required to drive the TF 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 individual TF 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 TF Coil System (WBS 131).

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

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

#### 3.1.2.13 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 TF Coil System (WBS 131), 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).

#### 3.1.2.14 Cryogenic Systems (WBS 62)

a. **Liquid nitrogen cooling**. Cryogenic Systems (WBS 62) are responsible for providing liquid nitrogen cooling for the TF 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 TF coils.

#### 3.1.2.15 Test Cell Preparations and Machine Assembly (WBS 7)

The TF coils will have interfaces with the tooling and metrology equipment required for field period 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 Field Line Mapping

The subsystem shall provide the capability to perform field line mapping with current waveforms as specified in the Field Line Mapping Scenario (GRD Section A.3.2) with the TF coils starting at cryogenic temperature (nominally 80K) after completely installing the cryostat. [Ref. GRD Section 3.1.2a]

#### 3.2.1.1.1.3 Design Verification

The subsystem shall be instrumented such that key vacuum vessel 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 TF Coils (WBS 131) 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 Timeline for Coil Cool-down to Cryogenic Temperature

The TF Coils shall be capable of being cooled down from room temperature (293K) to their pre-pulse operating temperature 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 TF coils below 90K shall be provided. The TF coils shall return to their pre-pulse operating temperatures 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 TF coils shall return to a pre-pulse temperature of about 80K, 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 TF 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

##### 3.2.1.2.5.2.1 In-plane perturbations

For in-plane perturbations, the local current centroid for each TF coil shall be located within 3mm of the nominal current centroid on the inboard half[1] of the coil and within 6mm on the outboard half of the coils with the TF coils at the pre-pulse operating temperature and zero current in their installed positions.

##### 3.2.1.2.5.2.2 Out-of-plane Perturbations

For out-of-plane perturbations, the local current centroid for each TF coil shall be located within 3mm of nominal current centroid with the TF 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, PF, and modular coil systems and the vacuum vessel will be designed for a plasma with a nominal major radius of 1.4 m and capability to meet the requirements of all the reference scenarios. Electrical power systems shall be designed and initially configured to meet the requirements of the First Plasma and Field Line Mapping Scenarios and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

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**

The TF coils will be designed to meet the requirements of all the reference scenarios. [Ref. GRD Section 3.2.1.5.3.3.2]

#### 3.2.1.2.6.2 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.

Adequate flexibility can be achieved with the TF coil capabilities developed in response to the reference scenarios plus the requirement for the TF coils to provide a self-field of 0.5T at 1.4m.

[1] The inboard half is defined as the part of the coil extending from the minimum coil elevation to the maximum coil elevation on the inboard (major axis) side of the coil.

**Requirement**

The TF coils shall be designed to provide a self-field of 0.5T at 1.4m with the current waveform defined for the 0.5T TF Scenario defined in Section A.3.2 of the GRD.

#### 3.2.1.2.7 Disruption Handling

The TF 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 TF 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 Discharge Termination

##### 3.2.1.2.9.1 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 TF 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]

##### 3.2.1.2.9.2 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 TF coil power supplies will be bypassed and the TF 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 3.2.1.2.9) 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 TF Coils. [Ref. GRD Section 3.2.1.6]

#### 3.2.1.3.1 Coil Warm-up Timeline

The TF 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 Spacing

There shall be 18 uniformly spaced TF coils.

##### 3.2.2.1.2 Planarity

The nominal TF current centroid location shall lie in the vertical midplane that also defines the toroidal position of the coil in the NCSX assembly

##### 3.2.2.1.3 Up-down Symmetry

The nominal TF current centroid location shall be up-down symmetric.

##### 3.2.2.1.4 Horizontal Alignment

The horizontal midplanes of the TF and modular coils shall be coincident at the pre-pulse operating temperature and zero current.

##### 3.2.2.1.5 Reaction of Loads

###### 3.2.2.1.5.1 In-plane Electromagnetic (EM) Loads

TF coils shall be self-supporting for in-plane EM loads. Net centering forces shall be reacted by wedging of the TF coils in the nose region.

###### 3.2.2.1.5.2 Out-of-plane Electromagnetic (EM) Loads

The Coil Support Structures (WBS 15) shall provide needed support for out-of-plane EM loads.

###### 3.2.2.1.5.3 Gravity Loads

Gravity loads shall be reacted by the Coil Support Structures (WBS 15). The support will be designed to maintain stellarator symmetry, if possible.

##### 3.2.2.1.6 Radial Pre-load

The Coil Support Structures (WBS 15) shall provide the mechanical radial pre-loads required to ensure that the TF coils remain wedged in the nose region.

##### 3.2.2.1.7 Coil Cooling

The coils will be designed with conventional, hollow copper conductor for liquid nitrogen cooling. Peak operating temperatures will be held well below the boiling point of the liquid nitrogen at the minimum coolant pressure to ensure single phase flow.

##### 3.2.2.1.8 Electrical Requirements

###### 3.2.2.1.8.1 Turns per Coil

The TF coils shall be designed with 12 turns per coil. [GRD Section A.1.2]

#### 3.2.2.1.8.2 Circuit Configuration

a. TF coils shall be connected in series.

b. TF coil electrical buswork shall be configured to facilitate connecting the TF coils in three separate circuits, which would preserve stellarator symmetry, as a future upgrade.

#### 3.2.2.1.8.3 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.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**

The TF coils shall be designed to a DVS of 20 kV.

### 3.2.3 System Quality Factors

#### 3.2.3.1 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. The TF 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 TF 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 TF coils.

[Ref. GRD Section 3.2.4.1]

#### 3.2.3.2 Design Life

a. The TF coils shall have a design life of >10 years.

b. The TF 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 TF coils shall be design in accordance with the NCSX Seismic Design Criteria. [Ref. GRD Section 3.3.1.5]

### 3.2.4 Transportability

The TF 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 TF 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 TF 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 TF 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

TF 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 TF 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 TF 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 TF coils shall be provided.
- The TF coils shall not present any uncontrolled safety or health hazard to user personnel.
- The TF 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 TF 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 TF coil specifications**

| Configuration Item | Specification Identifier | Specification Type |
|---|---|---|
| TF Coil Winding | NCSX-CSPEC-131-01-XX | Product specification – forms the basis of the TF coil winding procurement |
| TF Coil Wedges | NCSX-CSPEC-131-02-XX | Product specification – forms the basis of the TF coil wedge piece procurement |

## 3.5 Logistics

### 3.5.1 Maintenance

The TF 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 TF 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:

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

Inspection: 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.

Test: 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

**Background**

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.

**Requirements**

Test methods for each of the performance characteristics in Section 3.2 are identified in the Quality Conformance Matrix in Appendix A – Quality Conformance Matrix.

**APPENDIX A – QUALITY CONFORMANCE MATRIX**

| Section | Characteristic | Analysis | Inspection | Test | Comments |
|---|---|---|---|---|---|
| 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 | | | | |
| 3.2.1.1.1.1 | Initial Verification of Operability | | | X | |
| 3.2.1.1.1.2 | Field Line Mapping | | | X | |
| 3.2.1.1.1.3 | Design Verification | | | X | |
| 3.2.1.1.2 | Pre-Run Facility Startup | | | X | |
| 3.2.1.2 | Prepare for and Support Experimental Operations | | | | |
| 3.2.1.2.1 | Subsystem Verification and Monitoring | | | X | |
| 3.2.1.2.2 | Coil Cool-down | | | | |
| 3.2.1.2.2.1 | Timeline for Coil Cool-down to Cryogenic Temperature | X | | X | |
| 3.2.1.2.3 | Bakeout | | | | |
| 3.2.1.2.3.1 | Coil Temperatures during Bakeout | X | | X | |
| 3.2.1.2.3.2 | Bakeout Cycles | X | | | |
| 3.2.1.2.4 | Pre-Pulse Temperature | X | | X | |
| 3.2.1.2.5 | Field Error Requirements | | | | |
| 3.2.1.2.5.1 | Eddy Current Time Constants | X | | | |
| 3.2.1.2.5.2 | Winding Tolerance | | | | |
| 3.2.1.2.5.2.1 | In-plane Perurbations | | X | X | Test can be used if magnetic method is available |
| 3.2.1.2.5.2.2 | Out-of-plane Perturbations | | X | X | Test can be used if magnetic method is available |
| 3.2.1.2.6 | Plasma Magnetic Field Requirements | | | | |
| 3.2.1.2.6.1 | Reference Scenario Requirements | X | | | |
| 3.2.1.2.6.2 | Flexibility Requirements | X | | X | |
| 3.2.1.2.7 | Disruption Handling | X | | | |
| 3.2.1.2.8 | Pulse Repetition Rate | X | | X | |
| 3.2.1.2.9 | Discharge Termination | | | | |

| Section | Characteristic | Analysis | Inspection | Test | Comments |
|---|---|---|---|---|---|
| 3.2.1.2.9.1 | Normal Termination | X | | X | |
| 3.2.1.2.9.2 | Abnormal Termination | X | | X | |
| 3.2.1.3 | Shut Down Facility | | | X | |
| 3.2.1.3.1 | Coil Warm-up Timeline | X | | X | |
| 3.2.2 | Physical Characteristics | | | | |
| 3.2.2.1 | Configuration Requirements and Essential Features | | | | |
| 3.2.2.1.1 | Number and Spacing | | X | | |
| 3.2.2.1.2 | Planarity | | X | | |
| 3.2.2.1.3 | Up-down Symmetry | | X | | |
| 3.2.2.1.4 | Horizontal Alignment | | X | | |
| 3.2.2.1.5 | Reaction of Loads | | | | |
| 3.2.2.1.5.1 | In-plane Electromagnetic (EM) Loads | X | X | | |
| 3.2.2.1.5.2 | Out-of-plane Electromagnetic (EM) Loads | X | X | | |
| 3.2.2.1.5.3 | Gravity Loads | X | X | | |
| 3.2.2.1.6 | Radial Pre-load | X | X | | |
| 3.2.2.1.7 | Coil Cooling | X | X | | |
| 3.2.2.1.8 | Electrical Requirements | | | | |
| 3.2.2.1.8.1 | Turns per Coil | | X | | |
| 3.2.2.1.8.2 | Circuit Configuration | | X | | |
| 3.2.2.1.8.3 | Voltage Stand-off Requirements | X | | | |
| 3.2.3 | System Quality Factors | | | | |
| 3.2.3.1 | Reliability, Availability, and Maintainability | X | X | | |
| 3.2.3.2 | Design Life | X | | | |
| 3.2.3.3 | Seismic Criteria | X | | | |
| 3.2.4 | Transportability | | X | | |