National Spherical Torus Experiment

NSTX CENTER STACK UPGRADE

GENERAL REQUIREMENTS DOCUMENT

NSTX_CSU-RQMTS-GRD

Revision 6

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NSTX GENERAL REQUIREMENTS DOCUMENT

RECORD OF CHANGES

Revision	Date	Description of Change
First Issue	3/30/09	
1	2/9/10	Modified WBS and associated sections to include RWM; 2.2.3 “Ohmic Heating (OH) Coil”: revised OH flux requirement; Changed “Machine Protection System (MPS) to “Digital Coil Protection (DCP) in various sections; added section 2.6 “Design Criteria”; added 3.1.3.3 “Center Stack Assembly”; 3.1.3.4 “Coil Bus Runs” and 3.1.3.5 “Resistive Wall Mode (RWM) Coils”; In 3.3.5 “General Power Systems Integration” added failure probability requirement; In 3.6 “Central Instrumentation and Control (I&C) System” added sections d. and e.; updated figures 2.2-1, 2.2-2, 3.1-3 and Table 3-1 to reflect latest CSC dimensions
2	6/15/10	Modified 2.9.b and 3.5.3.d to reflect PF5 power supply current rating above 24kA as an upgrade. Added “& SS” after VV in 3.1.2.a and 3.1.2.b.
3	12/15/10	Modified section 3.1.1.e to call specifically for graphite PFC materials.
4	9/15/11	Modified section 2.4.b and Table 2.4 to clarify interpretation of pulse spectrum and revise total number of pulses to more realistic number.
5	6/14/12	Renumbered section 2.7, re-wrote section on magnetic permeability. Revised sections related to inner PF coil usage (2.2.4. 2.9, 3.1.3.1). Included requirement to anticipate 4kV CHI operation in section 2.9 and 3.2.2. Modified list of circuits to be bipolar in section 3.5.3. Modified section 3.5.4 to include requirement to connect CHI PS to inner PF coils. Modified section 3.6 to include PSRTC capability for all new inner PF coils as part of baseline. Added statement in 3.1.1.f that ohmic heating from plasma deposited on PFCs may be ignored. Minor change to Table 3-1 based on design point checking.
6	7/30/15	In section 2.9, limited combined CHI and OH operation voltage to not exceed 6 kV, listed issues to be addressed for 4kV CHI operation.
6	8/3/15	Limits on TF and OH structural (friction) interactions defined in section 2.2.5

NSTX GENERAL REQUIREMENTS DOCUMENT

TABLE OF CONTENTS

TABLE OF CONTENTS

1 Introduction

The NSTX is the world's highest performance ST research facility and is the centerpiece of the U.S. ST research program. Since starting operation in 1999, NSTX has established the attractiveness of the low-aspect-ratio tokamak ST concept characterized by strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature.

The purpose of the NSTX Center Stack Upgrade (NSTX_CSU) project is to expand the NSTX operational space and thereby the physics basis for the next-step ST facilities. The plasma aspect ratio A (= ratio of major radius R_0 to minor radius a) of the upgrade is increased to 1.5 from the original value of 1.26, which increases the cross sectional area of the center stack by a factor of 3 and makes possible higher levels of performance and pulse duration. The new center stack will provide a toroidal magnetic field at the major radius R_0 of 1 Tesla (T) compared to 0.6T in the original NSTX device, and will enable operation at plasma current I_p up to 2 Mega-Amp (MA) compared to the 1MA rating of the original device. A summary comparison of the NSTX_CSU versus the original NSTX device is given in Table 1-1

Table 1-1 - Summary of Machine Parameters

	NSTX	NSTX_CSU
R_0 [m] [1]	0.8540	0.9344
A [2]	1.266	1.500
I_p [MA]	1.0	2.0
B_t [T]	0.6	1.0
T_{pulse} [s]	0.5	5.0
$T_{repetition}$ [s]	600	2400
R_{center_stack} [m]	0.1849	0.3148
$R_{antenna}$ [m]	1.5740	1.5740

[1] R_0 is the plasma major radius defined here as the midpoint, on the midplane, between the inboard side of the last closed flux surface of an x-point plasma located 5cm outboard of the center stack and the outboard side of the last closed flux surface of the x-point plasma located 7cm inboard of the HHFW antenna guard.

[2] A is the aspect ratio defined here based on the plasma chamber major radius located at the midpoint, on the midplane, between the outboard surface of the center stack PFCs and the inboard surface of the HHFW antenna guard, divided by one-half of the distance, on the midplane, between the outboard surface of the center stack PFCs and the inboard surface of the HHFW antenna guard.

This General Requirements Document (GRD) defines the overall engineering requirements for the Center Stack Upgrade as well as those specific to each major element of the Work Breakdown Structure (WBS) as established by the original project and given in Table 1-2.

Table 1-2 NSTX WBS

1	**Torus Systems**
1.1	Plasma Facing Components
1.2	Vacuum Vessel & Support Structure
1.3	Magnet Systems
2	**Plasma Heating & Current Drive Systems**
2.1	High Harmonic Fast Wave (HHFW)
2.2	Coaxial Helicity Injection (CHI)
2.3	Electron Cyclotron Heating (ECH)
2.4	Neutral Beam Injection (NBI)
3	**Auxiliary Systems**
3.1	Vacuum Pumping System
3.2	Coolant Systems
3.3	Bake-out Heating System
3.4	Gas Delivery Systems
3.5	Glow Discharge Cleaning System
4	**Plasma Diagnostics**
5	**Power Systems**
5.1	AC Power Systems
5.2	TF Power Conversion System
5.3	PF/OH/RWM Power Conversion System
5.4	CHI Power Conversion System
5.5	General Power Systems Integration
6	**Central Instrumentation and Controls (I&C)**
6.1	Control System
6.2	Data Acquisition System
7	**Project Support and Integration**
7.1	Project Management. & Integration
7.2	Project Physics
7.3	Integrated Systems Tests
8	**Site Preparation and Assembly**
8.1	Site Preparation
8.2	Torus Assembly & Construction

Criteria given in the last revision of the GRD[3] for the original NSTX Project shall still apply except where superseded by information contained herein.

Information contained herein is as specific possible concerning parameters which are unlikely to change during the design process. However, many parameters will be developed as part of the design process and cannot be specified herein. Accordingly, the latest design details are given at http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html.

[3] NSTX General Requirements Document, NSTX-RQMTS-GRD-018, Rev. 2, December 8, 1998

2 General Engineering Requirements

Requirements which apply generally to the upgrade, rather than specific WBS elements, are contained in this section.

2.1 Scope

2.1.1 Replacement of Center Stack Assembly

a. The entire Center Stack Assembly (CSA) shall be removed from the existing NSTX device and replaced, including the following parts:

- Toroidal Field (TF) inner leg bundle including flags, hubs, and flexible connectors
- Ohmic Heating (OH) coil
- Poloidal Field (PF) coils PF1A Upper, PF1A Lower, and PF1B
- Center Stack Sensors
    - Rogowski Coils
    - Mirnov Coils
    - Flux Loops
    - Langmuir Probes
    - Thermocouples
- Microtherm thermal insulation
- Inboard Gas Injection piping and nozzle
- Center Stack Casing (CSC)
- Plasma Facing Components (PFC) associated with CSC including the Inboard Divertor (IBD)
- Pedestal which supports Center Stack Assembly from floor

b. Various components which interface directly with the CSA shall be modified as necessary fit the new CSA including (but not limited to) the following parts:

- TF, OH, PF1A Upper (PF1AU), PF1A Lower (PF1AL), and PF1B Lower (PF1BL) coil electrical leads
- Coaxial Helicity Injection (CHI) electrical leads
- Water cooling lines to TF, OH, PF1AU, PF1AL, and PF1BL leads
- Cables and connectors associated with CSA sensors
- Supply piping for heating and cooling of CSC and IBD
- Supply piping for inboard gas injection

2.1.2 Modification of NSTX Device for Extended Performance

a. Various parts of the NSTX device shall be evaluated and modified as necessary in order to operate at higher field, higher current, and longer pulse length including (but not limited to):

- TF outer leg supports
- PF coil supports
- Vacuum vessel (VV)
- Internal hardware including Passive Plate (PP) supports and Outboard Divertor (OBD)

b. Various parts of the NSTX device shall be modified as necessary in order to provide geometric fit with new or modified parts associated with the upgrade.

c. Parts not listed in a. and b. above shall be retained and/or unmodified if possible.

2.1.3 Modification of Supporting Subsystems and Equipment

All supporting subsystems and equipment shall be evaluated and modified as necessary in order to operate at higher field, higher current, and longer pulse length including (but not limited to):

- Internal hardware including Passive Plate supports and Inboard Divertor
- Auxiliary Systems
  - Vacuum pumping systems
  - Cooling water systems
  - Gas Injection systems
  - Bakeout systems
- Diagnostic systems
- Electrical power systems
- I&C systems

2.2 Performance

2.2.1.1 Plasma Current

2.2.1.2 Nominal Plasma Current Waveform

Nominal plasma current (I_p) waveform for engineering design purposes shall consist of linear ramp-up from zero to 2MA at a rate of 2MA/sec, flat top (constant 2MA) with duration up to

5.0 sec, and linear ramp-down from 2MA to zero at a rate of 4MA/sec. Total duration 2/2 + 5 + 2/4 = 6.5 sec.

2.2.1.3 Plasma Shape

For engineering purposes the nominal plasma cross section is approximated by a wall-limited plasma whose r, z coordinates are described by the following equations:

$$r(\theta) = R_0 + a * \cos(\theta + \delta * \sin(\theta))$$

$$z(\theta) = \kappa * a * \sin(\theta)$$

where:

R_0 = major radius (m)
a = minor radius (m)
A = aspect ratio = R_0 /a
κ = elongation
δ = triangularity
θ = poloidal angle

Two cross sections are described. The cross section defining the 100% flux surface is descriptive of the full size of the plasma chamber, approximately equal to the shape of the plasma if limited by the walls. The 95% flux surface is most relevant to physics operations and corresponds approximately to the last closed flux surface for X-point plasmas. Data for the two cross sections is given in Table 2-1.

Table 2-1 - Plasma Dimensions

	95%	100%
R_0 [m]	0.9344	0.9450
A	1.6405	1.5000
A	0.5696	0.6300
R_0-a [m]	0.3648	0.3150
R_0+a [m]	1.5040	1.5750
Inboard midplane gap [m]	0.0500	0.0000
Inboard midplane hardware [m]	0.3148	0.3150
Outboard midplane gap [m]	0.0700	0.0000
Outboard midplane hardware [m]	1.5740	1.5750
Elongation κ	2.5000	2.5000
Triangularity δ	0.6000	0.6000

The nominal major radius R_0 is based on the 95% flux surface. The nominal aspect ratio A is based upon the 100% flux surface. Plasma cross sections along with outline of plasma facing surfaces is given in the Figure 2-1.

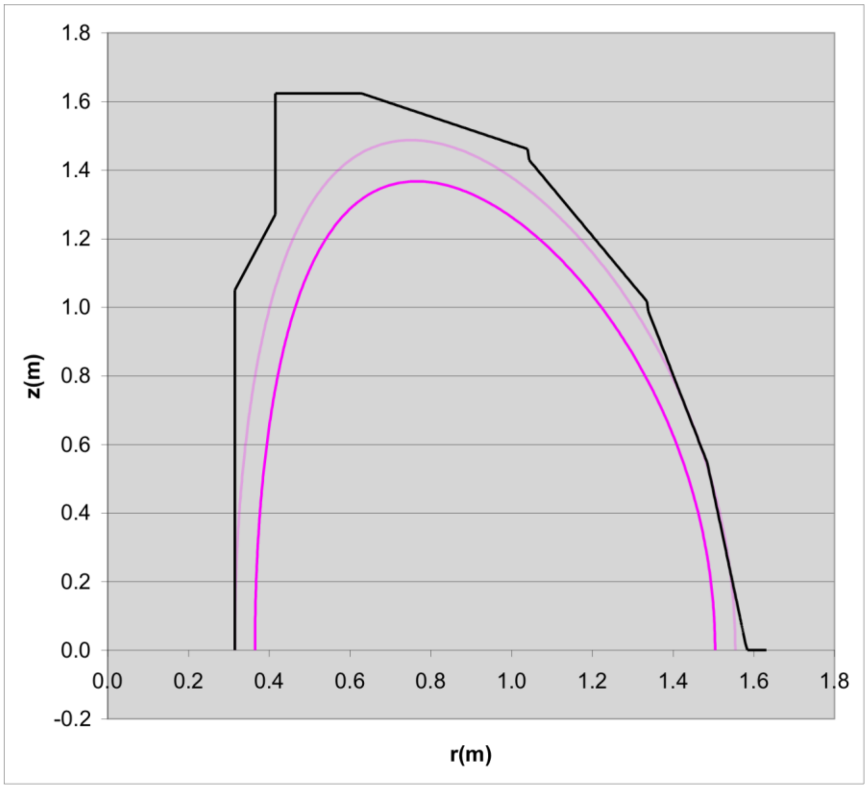

Figure 2-1 - 95% and 100% Cross Sections and Plasma Facing Surfaces

2.2.1.4 Plasma Disruption

Plasma facing components, internal hardware (PP, OBD), CSC, VV, and RF antennae shall be designed to withstand forces due to plasma disruption. Induced current flow in these structures shall be calculated based on the disruption cases described in the following section. Forces shall be calculated based on the induced current flow calculated from the disruption scenario, plus the halo current, crossed with the worst case field at each location which causes the magnitude of the force to be maximized at that location. Worst case poloidal fields shall be determined based on the full available range of current in each PF coil contributing to the field at the location of interest, subject to the constraint that the polarities of the currents in the PF coils shall be consistent with plasma equilibrium and shape control.

Two disruption modes shall be assessed. The first mode is induction due to current quench where the plasma position is fixed and no halo currents are included. The second mode is induction due to plasma motion (e.g. Vertical Displacement Event, VDE) with halo current included. Current flow in conducting structures, crossing with the background toroidal and poloidal fields, produces inward forces in the first mode, and outward forces in the second.

For each mode, various disruption cases shall be analyzed as specified in Table 2-2 and depicted in Figure 2-2. The centered plasma is assumed circular at R_0 and with minor radius a in accordance with the baseline plasma geometry. The four offset cases are designed to simulate worst case conditions where the plasma has moved such that induced and halo current effects are maximized on the relevant structures. For the displaced plasma models the plasma center is equidistant from the halo current entry/exit locations (which are centered on the relevant structures) and is located such that, with a minor radius a/2, the plasma is tangent to a line segment connecting the entry and exit locations.

Table 2-2 - Plasma Disruption Specifications

	Centered	Offset, Midplane	Offset, Inboard	Offset, Central	Offset, Outboard
Center of plasma (r,z) [m]	0.9344	0.5996	0.7280	0.8174	1.0406
	0.0000	0.0000	-1.1376	-1.1758	-0.8768
Minor radius of plasma [m]	0.5696	0.2848	0.2848	0.2848	0.2848
Current Quench					
Initial plasma current [MA]	2	2	2	2	2
Linear current derivative [MA/s]	-1000	-1000	-1000	-1000	-1000
VDE/Halo					
Initial plasma current	2	0	0	0	0
Final plasma current [MA]	0	2	2	2	2
Linear current derivative [MA/s]	-200	200	200	200	200
Halo current [MA]	n.a	20%=	35%=	35%=	35%=
		400kA	700kA	700kA	700kA
Halo current entry point (r,z) [m]	n.a	0.3148	0.3148	0.8302	1.1813
		0.6041	-1.2081	-1.5441	-1.2348
Halo current exit point (r,z) [m]	n.a	0.3148	0.8302	1.1813	1.4105
		-0.6041	-1.5441	-1.2348	-0.7713

For the current quench mode, five cases shall be assessed by simulating the linear decay of current at the rate specified for the five locations. For the VDE/Halo mode, four cases shall be assessed. In each case the current in the centered plasma shall be decreased as indicated while the current in the offset plasma shall be increased as indicated to simulate plasma motion. Forces due to induced currents shall be added to forces due to halo currents.

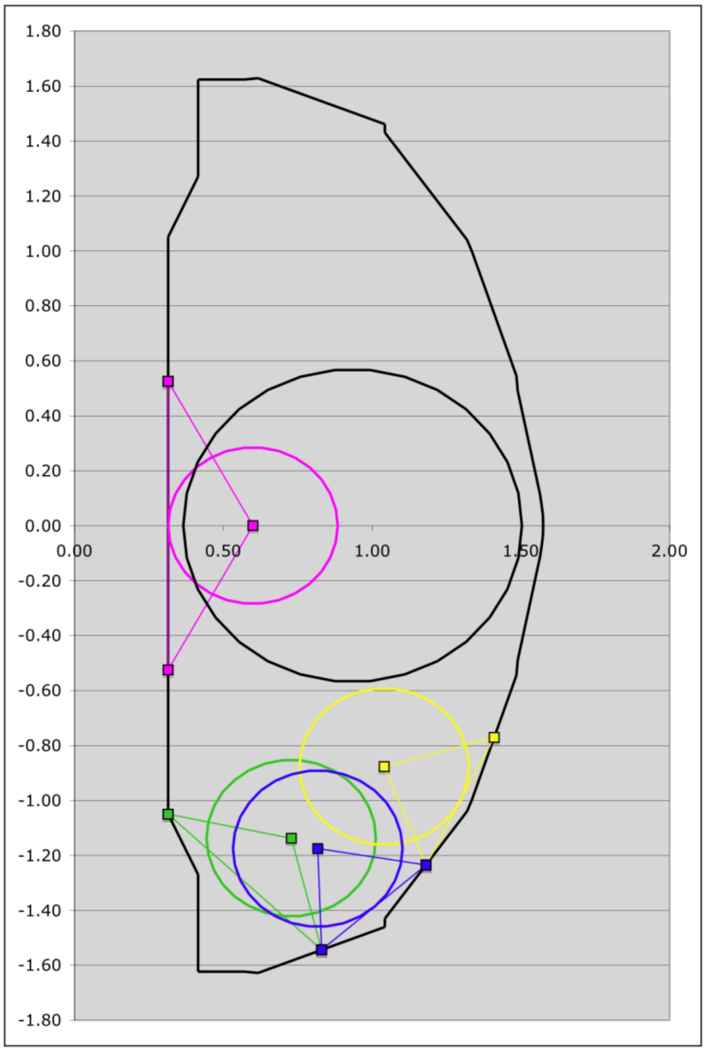

Figure 2-2 - Location of Disrupting Plasmas & Halo Current Entry/Exit Points

Current and field directions (referring to Figure 2-2) shall be as follows:

- Plasma current Ip into the page (counter-clockwise in the toroidal direction, viewed from above)

- Halo current exits plasma and enters the structure at the entry point, exits the structure and re-enters the plasma at the exit point (counter-clockwise poloidal current, in the view of the figure)

- Toroidal field into the page (clockwise in the toroidal direction, viewed from above)

For the halo currents a toroidal peaking factor of 2:1 shall be assumed in all cases. Thus the toroidal dependence of the halo current is $[1 + \cos(\phi - \phi_0)]$, for $\phi = 0$ to 360^o where ϕ is the toroidal angle.

2.2.2 Toroidal Field (TF) Coil

Toroidal field (B_t) shall be 1.0T at R_0=0.9344m, maintained constant for the full 6.5s duration of plasma current based on the nominal I_p waveform given in section 2.2.1.2.

2.2.3 Ohmic Heating (OH) Coil

OH coil shall provide loop voltage for plasma initiation, ramp-up, and sustainment.

a. Plasma initiation

Plasma initiation requirements are based upon breakdown at the radius of the CSA. Metric to be satisfied is $E_\phi B_\phi / B_{perp} \geq 4.2$kV/m, where is E_ϕ is the toroidal electric field, B_ϕ is the toroidal magnetic field (a.k.a. B_t), and B_{perp} is the magnitude of field error at the breakdown region. Conditions for breakdown shall be satisfied over a range of B_t from 60% to 100% of nominal. Field error B_{perp} shall be assumed 1mT and duration of breakdown voltage shall be 20ms. Corresponding loop voltage at breakdown radius R=0.3148m with B_t=0.6T at R_0 and B_{perp} =1mT is V_{loop}= 4.2 volts.

b. Plasma ramp-up

OH coil shall supply, after the plasma initiation phase, sufficient flux swing to ramp I_p to 2MA without reaching its zero crossing. Required ramp-up flux swing is 0.7 Wb, to be assumed for engineering purposes delivered in accordance with the nominal I_p waveform given in section 2.2.1.2.

c. Plasma sustainment

Operation of the OH coil following the plasma ramp up phase, including a second swing, shall be possible within its thermal and stress limits. Based on NSTX flux consumption results and confinement projections, the ohmic flux required for sustaining 2MA plasmas with partial induction for 5s is estimated to be 1.2Wb. The total flux swing requirement (initiation + ramp-up + sustainment) for 2MA and 5s flat-top plasma is therefore 2.0Wb.

2.2.4 Poloidal Field (PF) Coils

The PF coils shall provide field nulling for plasma initiation and shall provide equilibrium and shape control during sustainment.

a. Field nulling

PF coils PF1CU, PF1CL, PF3U, and PF3L shall be capable of bipolar operation and for engineering purposes shall be rated to supply 25% of their rated ampere-turns in the form of a linear ramp waveform beginning at t=-0.5 sec, prior to plasma initiation at t=0 sec.

b. Equilibrium and shape control

For engineering purposes, all PF coils shall be capable of supplying 100% of their rated ampere-turns in the form of a linear ramp-up, flat top, and linear ramp-down waveform synchronized with the I_p waveform given in section 2.2.1.2.

c. Polarity, controllability, and simultaneity

All upper and lower PF coil pairs, with the exception of the PF4's and PF5's, shall have separate control of the current in the upper and lower coils. For maximum shape flexibility, PF1A, PF1B, PF1C, PF2, PF3, PF4 coils may require (not necessarily symmetric) bipolar current capability.

d. For engineering purposes, the nominal design requirement for all components and systems shall be based on the assumption that any combination of PF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with Ip=0 or ≠ 0, shall be allowable. Coil current polarities shall be consistent with plasma equilibrium and shape control, i.e. PF1A and PF2 coil currents nominally in the same direction as I_p, and PF5 coil current in the opposite direction. In the event that this design requirement cannot be satisfied without significant cost impact and/or technical risk, exception may be taken. In this case:

- the design requirement may be reduced from the assumption of maximum possible currents to the PF/OH current distributions derived from the range of plasma equilibria specified by the physics requirements. The derivation shall be based on the nominal equilibria currents but adjusted for the post-disruption current distribution using simple flux conservation.

- the relationship between the design-driving quantity and the PF/OH currents and the plasma current shall be determined and described by an algorithm to be used in the control software and in real-time coil protection systems including the existing Analog Coil Protection (ACP, limited to instantaneous current and duration) and a new Digital Coil Protection (DCP, including capability of programmable algorithms) system (see section 3.5.5) as appropriate.

2.2.5 TF- OH Interaction

The OH shall be maintained at a temperature higher than the TF to avoid frictional interactions between the two coils. In some instances this will require initial preheat of the OH. In others, control of the scenario will be required. This requirement shall be included in the DCP.

2.3 Auxiliary Heating

Auxiliary heating shall consist of High Harmonic Fast Wave (HHFW) Radio Frequency (RF) and Neutral Beam Injection (NBI).

a. HHFW

For engineering purposes HHFW shall be assumed to deliver a maximum of 4MW to the plasma for a pulse duration up to 5s using the existing HHFW system.

b. NBI

For engineering purposes each NBI beam line shall be assumed to deliver a maximum power to the plasma as indicated in Table 2-3.

Table 2-3 – NBI Power To Plasma per Beam Line

Pulse length (sec)	Power to Plasma (MW)
5	5.0
4	5.4
3	6.0
2	6.8
1.5	7.5
1.25	8.2

1	9.0

c. Total Combined Heating Power

The initial total combined heating power will be that deliverable from the HHFW plus one NBI beamline. However, a second beamline may be added as a future upgrade (see section 2.9). Therefore all components of the CSA shall be, or shall be upgradeable, to handle the heating power deliverable from the HHFW plus two NBI beamlines. Thus the nominal 5s heating will be 4+5=9MW initially with one beamline and then 4+2*5=14MW eventually with two beamlines.

2.4 Pulse Duty

a. Duty Cycle

Pulse length requirement is given in Section 2.2.1.2. At the full rated pulse length, the repetition period shall be 2400 sec, but upgradeable to 1200 sec. However, operation at reduced pulse length shall be possible with the constraint that $T_{pulse}/T_{repetition} \leq 5/2400$, and 5/1200 following the future upgrade to 1200 sec repetition period.

b. Number of Pulses

For engineering purposes, the number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of 20,000 pulses based on the pulse spectrum given in Table 2-4 which allows for pulsing at various duty cycles coordinated per section 2.4 a.

Table 2-4 - NSTX CSU Pulse Spectrum

Performance	60%	75%	90%	100%	
B_t	0.6	0.75	0.9	1	T
I_p	1.2	1.5	1.8	2	MA
$T_{pulse}=T_{flat\_Ip}$ (sec)					Total pulses
3	200	1800	1200	1000	4200
3.5	200	1800	1200	1000	4200
4	200	1800	1200	1000	4200
4.5	200	1800	1200	500	3700
5	200	1800	1200	500	3700
				Total	20000

2.5 Field Errors

To avoid locked modes from non-axisymmetric fields due to features of the new CSA (including those from coil misalignment, bus work, coil feeds, coil cross-overs, and magnetic materials), the m=2 n=1 component of the vacuum error field (at the q=2 surface) attributable to the new CSA shall be ≤ 1 gauss.

2.6 Design Criteria

2.6.1 General Design Guidelines

Table 3.1-1 of the original NSTX Project GRD is given below and shall apply to the center stack upgrade.

Table 2-5 - General Design Guidelines

Operating Condition	**Description**	**P, Probability Of Occurrence In A Year**	**General Design Guidelines**
Normal Events	Events that are planned to occur regularly in the course of facility operation	P=1	Provide safe and reliable operation
Anticipated Events	Events of moderate frequency which may occur once or more in the lifetime of a facility	$1>P\geq10^{-2}$	The facility should be capable of returning to operation without extensive corrective action or repair
Unlikely Events	Events which are not anticipated but which may occur during the lifetime of a facility	$10^{-2}>P\geq10^{-4}$	The facility should be capable of returning to operation following potentially extensive corrective actions or repairs, as necessary
Extremely Unlikely Events	Events which are limiting faults and are not expected to occur during the lifetime of a facility but are postulated because of their safety consequences	$10^{-4}>P\geq10^{-6}$	Facility damage may preclude returning to operation
Incredible Events	Events of extremely low probability of occurrence or of non-mechanistic origin	$P<10^{-6}$	Not considered in the design

2.6.2 Failure Modes and Effects Analysis (FMEA)

The FMEA which was prepared for the original NSTX Project and maintained during the NSTX operational era shall be reviewed and updated[4] including:

- Changes attributable to the center stack upgrade
- Additional table entries
    - Failure probability
    - Failure consequence

Failure probabilities shall be quantified based on engineering judgment per the General Design Guidelines Table 2-5. Failure consequences shall be quantified based on engineering judgment per Table 2-6.

Table 2-6 - Failure Consequence Categories

Consequence	**Criteria**
Minimal	Time to correct/repair < 1 week and Cost < $10K
Minor corrective action (not extensive)	Time or Cost greater than entry above, and Time to correct/repair < 1 month and Cost < $100K
Extensive corrective action	Time or Cost greater than entry above, and Time to correct/repair < 12 month and Cost < $5000K
Irreparable facility damage	Time or Cost greater than entry above or other factor preventing future use of facility

2.6.3 Structural Design Criteria

All features of NSTX shall be designed in conformance with the NSTX Structural Design Criteria document NSTX-CRIT-0001.

2.7 Material Selection

2.7.1 Magnetic Permeability

[4] "Procedure to Update NSTX Failure Modes And Effects Analysis (FMEA) Document", 71_091211_CLN_01, 12/11/9

For purposes of material selections and acceptance[5], magnetic materials shall be divided into four categories: welds, fasteners, bulk material, and magnetic shields.

Table 2-7 presents permeability guidelines based on the location of objects which may reside either inside the outer TF (OTF) legs (R<OTF) or outside (R>OTF). Any non-conformances must be approved by the NSTX Upgrade Project so that an inventory of such materials can be maintained.

Table 2-7 - Magnetic Permeability Guidelines

	Large Toroidally Localized[4]		Toroidally Symmetrical		Toroidally Symmetrical Arrays[3]	
	R<OTF	R>OTF	R<OTF	R>OTF	R<OTF	R>OTF
Welds	2.0	3.0	2.3	3.0	2.3	3.0
Base Material	1.04[4]	1.2	1.1	1.2	1.1	1.2
Machined Components	1.2[1]	1.4	1.2	1.4	1.2	1.4
Fasteners ≤5/8”	316SS or 304SS[2]	316SS or 304SS	316SS or 304SS[2]	316SS or 304SS	316SS or 304SS[2]	316SS or 304SS
Fasteners >5/8”	Inconel	316SS	316SS or 304SS[2]	316SS or 304SS	316SS or 304SS[2]	316SS or 304SS
Magnetic Shields	Each evaluated individually					
	[1] Large machined/formed components mounted on the vessel should be annealed before installation to reduce their bulk permeability to the minimum possible. [2] 304SS fasteners should generally be avoided on NSTX for installations inside the TF boundary, and their use should be approved. [3] Here, array refers to an installation with more than 8 objects equally spaced in toroidal angle. [4] If a toroidally localized object weighs less than 1.5 kg, see Figure 2-1 for allowable bulk permeability.					

Welds: Welds are generally regions of higher permeability, but also have small volume. For toroidally localized installations inside the TF boundary, welds on NSTX-U may have a bulk permeability up to μ_R=2.0; small isolated locations up to 3 may be tolerated. Proper choice of weld wire can aid in meeting this requirement. Toroidally symmetric welds or arrays of welds inside the TF boundary may have permeabilities up to 2.3. Welds outside the TF boundary may have permeabilities up to 3.0.

Fasteners: Small fasteners on NSTX-U should, in general, be made from 316 (or other low permeability material); here, small is defined as 5/8” thread diameter or below. Other more magnetic alloys of stainless steel (304, 18-8) shall not be used without approval. If quantities of specialized

[5] “General Magnetic Permeability Guidelines for NSTX-U”, Rev. 3, S. Gerhardt, May 10th, 2012

hardened bolts (or others with elevated permeability) are used whose weight exceeds ~1 kg in a localized installation, then approval shall be required. Inconel fasteners should be considered for these installations where possible.

Magnetic Shields and other high μ_R materials: Magnetic shields are devices designed to exclude the magnetic field from a volume containing some sensitive instrument; they typically have relative permeability levels exceeding 1000, and often exceeding 10,000. All magnetic shields must be reviewed by the magnetic material committee for both i) forces on the shields, and ii) perturbations to the plasma. Based on past NSTX and present DIII-D practice, the field perturbation at the nearest point on the plasma surface from these shields shall be less than 1 G.

Bulk Permeability: It has recently become more difficult to procure 316 stainless steel base material with low permeability (μ_R<1.02). In light of this trend, general guidance for base material is as follows.

For material outside the TF boundary, the relative permeability for base material shall be beneath μ_R=1.2. The permeability of machined components may be up to 1.4.

For material inside the TF boundary, the following guidance is given:

- For discrete, large toroidally localized installations on or inside the vessel, every reasonable effort shall be made to keep the final bulk permeability beneath μ_R=1.04. Here, “large” is defined as exceeding ~1.5 kg. Annealing and shot peening are techniques that can be used to reduce the permeability, provided that base material of sufficiently high quality has been procured. Smaller toroidally localized installations can have somewhat higher permeabilities, as indicated by the curves in Fig. 1.

- For toroidally symmetric objects inside the TF, bulk permeability up to μ_R=1.1 is acceptable. If discrete objects are installed in toroidally symmetric arrays, the target μ_R values can also be raised to 1.1.

- It is anticipated that there shall be some permeability increases in the vicinity of machining or other metal working. These shall not exceed μ_R=1.2. Annealing or other techniques should be considered to eliminate this permeability increase once the machining is finished.

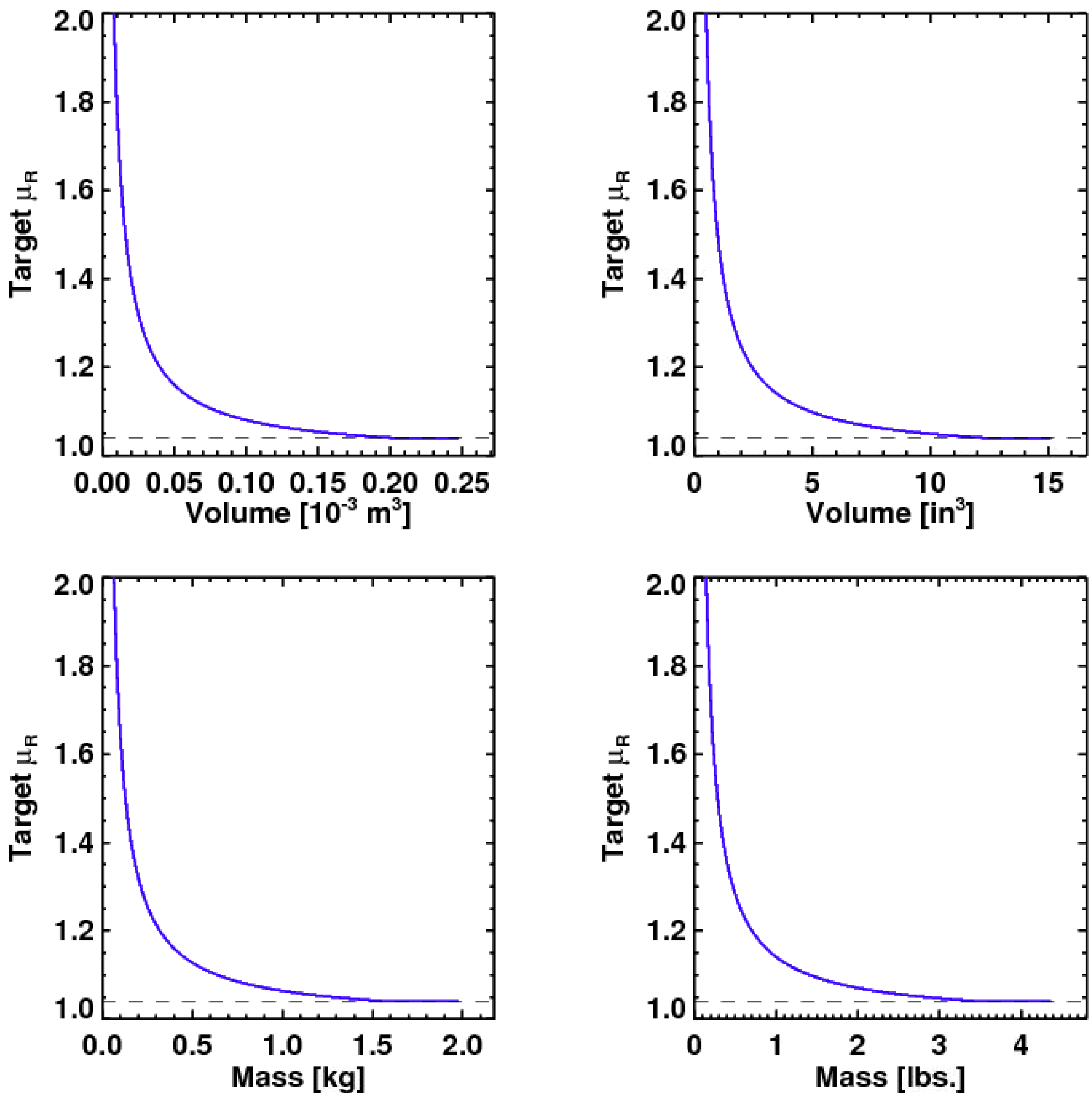

Figure 2-3: Target μ_R and object sizes that result in a 1 G midplane separatrix magnetic perturbation, for a typical NSTX-Upgrade equilibrium and object position of Z=0, R=1.65. Masses greater than 1.5 kg have a target base material permeability of 1.04.

2.7.2 Materials Inside Vacuum Vessel

a. All materials utilized within the primary vacuum boundary shall be on the PPPL Vacuum Committee approved list, or shall be approved by the committee.

b. All materials utilized within the primary vacuum boundary shall be designed to withstand the anticipated temperatures during plasma operation. Note that the vacuum vessel shall be baked out at a temperature of 150^{o}C, and internal plasma facing components including the CSC, IBD, OBD, and PPs shall be baked out at 350^{o}C.

2.8 General Electrical Isolation Requirements

a. All instrumentation shall be isolated via optical and/or magnetic (isolation transformer) means prior to exiting the test cell boundary. The isolation shall be rated to withstand a one minute DC hipot test at 5kV.

b. All ancillary components which are in mechanical contact with the vacuum vessel shall be electrically isolated from the vacuum vessel. The isolation shall be rated to withstand a one minute AC hipot test at 2 kV AC rms.

c. Conducting loops formed by metallic structures within a radius of 3 meters from the centerline of the torus shall be broken by insulating breaks. The insulation shall be rated to withstand a one minute AC hipot test at 2 kV AC rms.

2.9 Future Upgrades

a. This GRD provides the baseline requirements for the NSTX Center Stack Upgrade and provides additional information concerning other future upgrades.

b. Other future upgrades consist of scope which is contemplated at present but may or may not be undertaken, depending on the evolution of the experimental program and the budgetary constraints. In order to minimize the life cycle cost of the NSTX program and make optimum use of the facility, the design of NSTX Center Stack Upgrade shall not preclude the future upgrades, and shall facilitate the future upgrades whenever possible and cost effective. Future upgrades presently contemplated, and provisions to be included in the Center Stack Upgrade, are as follows:

- Reduction of Repetition Period

  - Sufficient ampacity and cooling to reduce repetition period to 1200 sec from 2400 sec

- Addition of Second Neutral Beam Injection (NBI) Line

  - AC input power capacity shall be consistent with additional NBI

- Power handling of CSC and IBD PFCs shall be consistent with additional heating power

- Upgrade of PF5 power supply to permit operation of PF5 circuit beyond 24kA rating of single power supply branch (see section 3.5.3).

- 4kV CHI operations

  - Any new features or components added to NSTX as part of the Center Stack Upgrade Project shall accommodate future upgrades to 4kV CHI operations. See Section 3.2.2.b for more detail.
  - For a combined CHI and OH operation, the combined voltage of CHI and OH shall not exceed 6 kV.

3 WBS Subsystem Requirements

Requirements for individual WBS subsystems are given in this section.

3.1 Torus Systems (WBS 1)

3.1.1 Plasma Facing Components (WBS 1.1)

a. The surfaces of the CSA which face the plasma shall be axisymmetric and up/down symmetric about the midplane (z=0) and shall be divided into four sections depicted as line segments in Figure 3-1 with nominal dimensions given in Table 3-1.

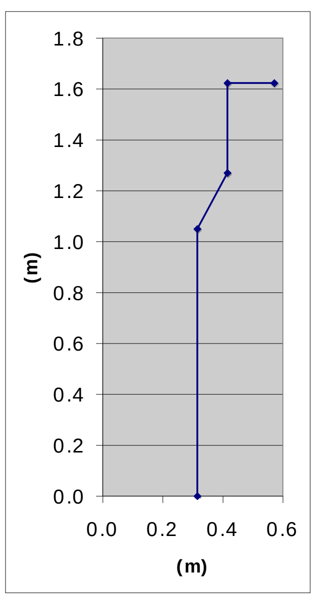

Figure 3-1 - Line Segments Defining Plasma Facing Surfaces

Table 3-1 - Dimensions of Line Segments Defining Plasma Facing Surfaces

	Start point		End point	
	r(m)	z(m)	r(m)	z(m)
Center Stack First Wall (CSFW)	0.3148	0.0000	0.3148	1.0500
Center Stack Angled Section (CSAS)	0.3148	1.0500	0.4150	1.2700
Inboard Divertor Vertical Section (IBDVS)	0.4150	1.2700	0.4150	1.6234
Inboard Divertor Horizontal Section (IBDHS)	0.4150	1.6234	0.5715	1.6234

b. The plasma facing surface of the CSC first wall PFCs which are vertically oriented (CSFW, CSAS, IBDVS) shall be curved, not faceted, with curvature corresponding to the outer radius.

c. The CSC PFC tiles shall include overlapping edges to prevent line-of-sight between plasma and metallic backing structures.

d. The CSC PFC tiles shall consist of carbon-based materials designed to absorb the heat, particle, and radiation flux from the plasma and heating systems, to minimize the influx of impurities to the plasma, and to withstand the electromagnetic forces associated with plasma disruption.

e. All CSC PFCs will be designed using high-grade graphite material. The PFCs and mounting hardware shall be designed to withstand the heat loads due to plasma operation with Single Null (SN) and Double Null (DN) divertor configurations. The heat flux deposited on the PFCs will be controlled by the NSTX physics program (e.g., advanced divertor operations) and will be maintained within allowables based on the choice of materials, geometry, and cooling. Allowables resulting from the design will be provided. Nominal heat and power flux widths on the PFCs, in the absence of advanced divertor operations, are shown in Table 3-2.

f. Heat flux on the divertors shall be assumed to impinge over a region beginning at the strike point and ending at a distance of equal to the power flux width (λ) given in Table 3-2. The peak heat flux given in Table 3-2 occurs at the strike point. The heat flux along the power flux width shall be assumed equal to $q(x) = qpeak * \varepsilon\text{-}x/\lambda$ where $x = 0$ occurs at the strike point.

Table 3-2 - Heat Flux and Power Flux Width on PFCs

	CSFW	IBDAS, IBDVS	IBDHS
Single Null Divertor, T_{pulse}= as determined to be allowable			
Average Heat Flux q_{avg} [MW/m^2]	0.1	4.0	9.8
Peak Heat Flux q_{peak} [MW/m^2]	0.2	6.3	15.5
Power Flux Width λ [m]	n.a.	0.3	0.3
Double Null Divertor, T_{pulse}=5.0s			
Average Heat Flux q_{avg} [MW/m^2]	0.1	1.6	5.2
Peak Heat Flux q_{peak} [MW/m^2]	0.2	2.5	8.3
Power Flux Width λ [m]	n.a.	0.3	0.3

g. The average power load to the PFCs and VV will exceed that typical of the existing NSTX operation and is summarized in Table 3-3. Ohmic heating from the plasma is negligible and may be ignored.

Table 3-3 – Pulsed and Average Power Loss

Case	Paux (MW)	Tpulse (sec)	Trep (sec)	Pavg (kW)
Existing NSTX practice, typ.	4 RF	1	300	13
NSTX CSU baseline heating, upgraded rep rate	4 RF+5NBI = 9	5	1200	38
NSTX CSU upgraded heating, upgraded rep rate	4 RF+2*5NBI = 14	5	1200	58
NSTX CSU baseline heating, upgraded rep rate	4 RF+5NBI = 9	5	2400	19
NSTX CSU baseline heating, baseline rep rate	4 RF+2*5 NBI = 14	5	2400	29

h. The IBDVS and IBDAS shall be equipped with active cooling as necessary to remove the heat between pulses at the upgraded rep rate such that no thermal ratcheting occurs on these surfaces. The design of the cooling shall assume that the full average power given in Table 3-2 is to be removed from either the upper (above midplane) or lower (below midplane) surfaces as if deposited by SN operation.

i. PFCs shall be designed to accommodate 350°C bakeout and helium glow discharge cleaning mode.

3.1.2 Vacuum Vessel (VV) & Support Structure (SS) (WBS 1.2)

a. The VV & SS shall be designed to withstand all loads during normal operation due to dead weight, vacuum, thermal, normal electromagnetic, and disruption electromagnetic.

b. The VV & SS shall be designed to withstand all loads during bakeout due to dead weight, vacuum, and thermal.

c. The CSC shall be mechanically connected to, but electrically isolated from, the upper and lower domes via ceramic insulators, so as to complete the vacuum boundary but allow for a 2kVDC potential difference between the center stack casing and the remainder of the vacuum vessel for CHI. Insulation shall be designed to withstand a test voltage of 2E+1=5kV.

d. Four toroidally symmetric connection points shall be provided at the top and bottom of the CSC. Connections shall be sized to carry the current during CHI operations as well as the return of the current during bakeout heating of the center stack casing.

3.1.3 Magnets (WBS 1.3)

3.1.3.1 Poloidal Field (PF) Magnets

a. The PF magnets shall consist of a new OH solenoid, new inner PF coils, and existing outer PF coils connected in independent circuits as listed in **Table 3-4**.

b. OH and PF coil locations, geometries, number of turns and current scenarios shall be established as part of the design evolution. Geometry and location of existing PF coils shall remain as-is.

Table 3-4 - PF Coils and Circuits

Designation	Source
OH	New
PF1AU	New
PF1AL	New
PF1BU	New
PF1BL	New
PF1CU	New
PF1CL	New
PF2AU, PF2BU	Existing
PF2AL, PF2BL	Existing
PF3AU, PF3BU	Existing
PF3AL, PF3BL	Existing
PF4BU, PF4CU & PF4BL, PF4CL	Existing
FP5AU, PF5BU & PF5AL, PF5BL	Existing

c. Structural design of OH and PF coils and their supports shall accommodate any combination of PF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with $Ip=0$ or $\neq 0$ except where this is judged impractical and special exception is taken. See 2.2.4.d .

d. Cooling for the OH and PF coils shall be provided consistent with a 1200 sec repetition period, or a 2400 sec repetition period upgradeable to a 1200 sec repetition period.

e. Electrical insulation design for the OH and PF coils, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. For the PF coils, E shall correspond to the maximum power supply line-to-line DC voltage. For the OH coil, E shall correspond to the maximum power supply line-to-line DC voltage plus the 2kVDC CHI voltage which appears, in effect, on the CSC.

f. The OH lead shall utilize a coaxial design to minimize net force and field error.

g. Structural support of the OH coil shall allow for axial thermal expansion while ensuring that the coil remains centered when subject to electromagnetic loads.

h. The surface of the new OH coil shall be provided with a ground plane of sufficient conductivity to serve as an electrostatic shield while limiting induced currents. Suitable ground plane leads shall be provided for a ground connection on both the upper and lower ends of the coil.

i. All aspects of the OH and PF coil design shall be compatible with NSTX operation with plasma current and toroidal field in either ϕ direction.

3.1.3.2 Toroidal Field (TF) Magnet

a. The TF magnet shall consist of a new 36 turn inner leg connected in series with the existing 36 outer legs.

b. Heating and structural design shall be based on a toroidal field (B_t) of 1.0T at R_0=0.9344m, maintained constant for the full duration of plasma current based on the nominal I_p waveform given in section 2.2.1.2.

c. Cooling shall be provided consistent with a 1200 sec repetition period, or a 2400 sec repetition period upgradeable to a 1200 sec repetition period.

d. Electrical insulation design for the TF inner legs, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. E shall correspond to the maximum power supply line-to-line DC voltage plus the 2kVDC CHI voltage which appears, in effect, on the CSC and all TF structural elements associated therewith.

e. The TF lead shall utilize a coaxial design to minimize net force and field error.

f. The TF turn-to-turn transitions shall include features to minimize stray field due to net toroidal turn. Alternatively it may be demonstrated that the field error due to turn-to-turn transitions can be nullified to a magnitude less than 1 gauss anywhere between R_0-a $\leq r \leq R_0$+a, z=0.

g. Structural support of the TF coil shall allow for axial thermal expansion while ensuring that the coil remains centered when subject to electromagnetic loads.

h. All aspects of the TF coil design shall be compatible with NSTX operation with plasma current and toroidal field in either ϕ direction.

3.1.3.3 Center Stack Assembly

The Center Stack Assembly consisting of the TF inner legs, inner PF coils, Center Stack Casing, and inboard PFC tiles shall be completely replaced via the upgrade (refer to 2.1.1).

3.1.3.4 Coil Bus Runs

Thermal and structural capacity of coil bus runs shall be assessed based on upgrade ampacity requirements and modified if required.

3.1.3.5 Resistive Wall Mode (RWM) Coils

No changes are required to the RWM coils, unless the higher level of fields and forces requires structural improvements.

3.2 Plasma Heating & Current Drive Systems (WBS 2)

3.2.1 High Harmonic Fast Wave (HHFW) (WBS 2.1)

No changes to HHFW system are required (nominal operating requirement 6MW/5s). However, disruption currents and forces shall be evaluated based on the increased plasma current associated with the NSTX CSU upgrade and corrective measures taken to improve the structure, if necessary.

3.2.2 Coaxial Helicity Injection (CHI) (WBS 2.2)

a. In the same manner as the original NSTX configuration, the new CSC and inner wall of the bore of the machine, including the IBD plates, shall be electrically isolated from the outer VV to permit the biasing of this structure with respect to the VV, to drive a poloidal component of plasma current.

b. Electrical isolation shall be rated for 2E+1 with E=2kV, thus 5kV. However, all new features and components associated with the Upgrade Project shall be upgradeable to accommodate future 4kV CHI operations. Systems to be assessed and possibly upgraded for 4kV CHI operation include (among others): plasma current Rogowski ground-wall insulation, flux loops on the OH ground plane and associated lead blocks, CHI insulators and flange bushings, and isolation transformers for racks.

c. The PFCs which form the electrodes from which the CHI current flows shall be designed to dissipate the local power generation due to the CHI current, during normal and fault conditions, and shall be designed to withstand the electromagnetic forces due the fault current deliverable by the CHI power supply system.

3.2.3 Electron Cyclotron (EC) Pre-ionization (WBS 2.2)

The EC system provides microwave RF power in the electron cyclotron range of frequencies for pre-ionization. Although the location of the resonance will move outboard due to increased B_t in the upgrade, the expectation is that sufficient free electrons will drift to the null region such that the benefit to plasma initiation will still be realized. Therefore no changes are required to the EC system.

3.2.4 Neutral Beam Injection (NBI) (WBS 2.4)

No changes to existing NBI system are required (nominal operating requirement 80kV/5.33MW/5s).

3.3 Auxiliary Systems (WBS 3)

3.3.1 Vacuum Pumping System (VPS) (WBS 3.1)

No changes to the VPS are required.

3.3.2 Cooling Water Systems (CWS) (WBS 3.2)

a. The CWS shall provide cooling water to the TF coils with exact configuration and flow/pressure requirements to be determined as part of the design process. All cooling paths shall be individually monitored and interlocked for flow.

b. The CWS shall provide cooling water to the new OH and PF coils with exact configuration and flow/pressure requirements to be determined as part of the design process. All cooling paths shall be individually monitored and interlocked for flow. Note that the initial requirement involves the same number of coils as the original NSTX. However, three new coils (PF1BU, PF1CU, PF1CL) will be added as an upgrade and will require cooling at that time.

c. No changes to the cooling of the existing outer PF coils is required.

3.3.3 Bakeout System (WBS 3.3)

a. The helium-based and water-based heating/cooling systems for the internal hardware and outer VV do not require modification. However, it may be necessary to operate these systems during plasma operations in the cooling mode, to be determined as part of the design process. See section 2.3.

b. A new power supply shall be supplied to heat the CSC using DC current during bakeout in case the existing power supply does not match the new voltage, current, and power requirements. This needs to be determined as part of the design process.

3.3.4 Gas Delivery System (GDS) (WBS 3.4)

a. The GDS shall be modified if necessary to provide the required gas injection for plasma pulses with duration up to 5s.

b. New gas transport tubing and nozzle shall be provided for inboard gas injection, to be installed under the CS PFCs as with the existing configuration.

3.3.5 Glow Discharge Cleaning System (GDC) (WBS 3.5)

No changes are required to the existing GDC system.

3.4 Plasma Diagnostics (WBS 4)

a. All diagnostics on the existing CSA will need to be replaced. Wiring associated with diagnostics on the new CSA shall fit within the capacity of the existing cables and connectors.

b. New I_p Rogowski coils will be required. Groundwall insulation shall be designed to withstand a hipot test of 2E+1 = 5kV based on the CHI potential of E = 2kV.

c. All diagnostics on the CSA and elsewhere shall be compatible with Bt=1T, Ip=2MA operation. Modifications shall be made where necessary.

3.5 Power Systems (WBS 5)

3.5.1 AC Power Systems (WBS 5.1)

a. No changes to the AC power systems are required unless necessitated by reconfiguration of magnet power supplies.

b. AC power to the experimental loads consisting of the magnet power supplies and NBI shall be supplied by one MG set. Exact load requirements in terms of peak active and reactive power, and total deliverable energy per pulse will be developed as part of the design process.

3.5.2 TF Power Conversion System (WBS 5.2)

a. TF power supplies shall supply current to the TF coils to produce a toroidal field (B_t) ≤ 1.0T at R_0=0.9344m, maintained constant for the full 6.5s duration of plasma current based on the nominal I_p waveform given in section 2.2.1.2. Corresponding flat top current is 129.8kA.

b. Baseline repetition period shall be 2400s, upgradeable to 1200s as specified in section 2.4.

c. Waveforms for current rise and fall, including L/R decay in case of a fault, shall be coordinated with design of the TF coil in terms of heating.

d. Detailed parameters of the electrical load and power supply voltage requirements will be developed as part of the design process.

e. Redundant measurements of TF current shall be provided with accuracy of 0.2% (magnitude of DC measurement error at full rated flat top current).

f. Current during flat top shall be regulated to within 0.5%.

g. Bus links or other means shall be provided in order that the current in the TF magnets can be driven in either direction. The polarity reversal procedure shall require 4 hours or less.

h. No-load disconnect switches shall be provided to isolate the TF power supply system from the connections to the TF magnets. In addition, no-load grounding switches shall be provided to ground the terminals of the connections to the TF magnets. These switches shall be interlocked with test cell access control.

i. The TF Power Conversion System shall include protection to avoid the delivery of current which would overheat the TF magnets, assuming that their coolant conditions are nominal.

3.5.3 PF/OH/RWM Power Conversion Systems (WBS 5.3)

a. The OH and PF power supplies shall provide a variable current in the OH and PF magnet circuits during an NSTX plasma discharge.

b. The OH, PF1C, PF2, and PF3 circuits shall be bipolar (current supplied in both directions during a pulse).

c. Baseline repetition period shall be 2400s, upgradeable to 1200s as specified in section 2.4.

d. Detailed parameters of the electrical load and power supply requirements will be developed as part of the design process. Requirements are given in the design point specifications (http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html). All baseline power supply ratings shall be compatible with the design point except the PF5 power supply current may be limited to 24kA which is the capability of the existing PF5 power supply consisting of a single branch. The addition of the second branch shall be an upgrade option (see section 2.9).

e. Redundant measurements of each OH and PF coil currents shall be provided with accuracy of 0.2% (magnitude of DC measurement error at full rated current).

f. Bus links or other means shall be provided in order that the connection between the power supplies and coils can be established in either direction. The polarity reversal procedure shall require 4 hours or less.

g. No-load disconnect switches shall be provided to isolate the OH and PF power supply systems from the connections to the magnets. In addition, no-load grounding switches shall be provided to ground the terminals of the connections to the magnets. These switches shall be interlocked with test cell access control.

h. The OH and PF power supply systems shall include protection to avoid the delivery of current which would overheat the magnets, assuming that their coolant conditions are nominal.

i. No changes are required to RWM power supplies

3.5.4 CHI Power Conversion System (WBS 5.4)

No changes are required to the existing CHI power supply system. However, it shall be possible to select the connection of the CHI AC/DC converter to either 1) the CHI electrodes or 2) one of the inner PF coils.

3.5.5 General Power Systems Integration (WBS 5.5)

The existing Rochester Instruments System (RIS) protection system shall be replaced by a new Digital Coil Protection (DCP) system. The DCP shall include the following features:

- Protection against instantaneous over-current and $\int i^2(t)dt$ limits in each coil circuit (same functionality as existing RIS)
- Simulation of heating and cooling of each coil using the coil currents as input, and protection against over-temperature
- Simulation of various design-limiting quantities based on algorithms using the coil currents as input, and protection against design limits (see section 2.2.4 d)

The DCP shall be designed and implemented such that its probability of failure is “Extremely Unlikely” per Table 2-5.

3.6 Central Instrumentation & Control (I&C) System (WBS 6)

a. The Central I&C system shall provide the same functionality as existing except for the change in pulse length and repetition period. To accommodate the full interval of coil current rise and fall the time interval of real time control of the plasma and power supplies shall be extended to 10s. Nominal repetition period in this mode of operation shall be 2400s, upgradeable to 1200s as described in section 2.4.

b. The baseline set of individually controlled power supply circuits is the same as the existing NSTX device. However, feedback control of individual branches of the TF converter will be necessary, adding to the number of measurements and feedback loops to be managed by the real time control. The details of this requirement will be determined during the design process.

c. With the addition of the PF1BU, PF1CU, and PF1CL circuits, the real time power supply control shall be expanded to include these three additional measurement and feedback loops.

d. Other control, monitoring, and data recording-analysis-management services provided by Central I&C, which includes some diagnostics, shall be upgraded to accommodate a 5 second plasma.

e. The time required for post-shot data acquisition and the presentation of between-shots analysis shall be comparable to the pre-upgrade time.

3.7 Project Support and Integration (WBS 7)

3.7.1 Project Physics (WBS 7.2)

NSTX Project Physics shall be responsible for the specification of all Plasma Control hardware and software modifications.

NSTX Project Physics shall provide input to the design process in areas which are directly related to plasma behavior including the following.

- Location and geometry of new PF coils
- PF coil current scenarios
- PF coil voltage requirements
- Plasma disruption modeling parameters

4 ES&H Requirements

4.1 General Guidelines

The design, manufacture, fabrication, construction, installation, test, operation, maintenance, modification, and eventual decontamination and decommissioning of the NSTX including all features associated with the Center Stack Upgrade shall be accomplished in a manner that will protect personnel, visitors, the public, property and the environment from injury. Pursuant to this policy, the NSTX CSU project shall:

- Comply with all applicable Federal, State, Local, and PPPL ES&H regulations;
- Assess and minimize the risks inherent in the NSTX program;
- Actively encourage ES&H awareness on the part of NSTX personnel and visitors.

In particular, NSTX shall be designed and operated in accordance with DOE Orders and PPPL Environment, Safety and Health Directives. In the event of conflicts between DOE Orders and PPPL Environment, Safety and Health Directives, DOE Orders shall take precedence.

4.2 Seismic Requirements

The seismic design criteria outlined in the GRD of the original NSTX Project shall apply. Analysis[6] shall be updated to account for the new CSA.

4.3 Radiological Design Objectives

The radiological design criteria outlined in the GRD of the original NSTX Project shall apply. The NSTX CSU will not significantly alter the radiological performance of NSTX and therefore no additional analysis is required.

[6] NSTX Seismic Design Analysis Report, 71-990611-JHC-01, June 11, 1999

List of Acronyms

A	Aspect ratio of plasma
a	Minor radius of plasma
AC	Alternating current
Bt	Toroidal field
CHI	Coaxial helicity injection
CSA	Center stack assembly
CSAS	Center stack angled section
CSC	Center stack casing
CSFW	Center stack first wall
CSU	Center Stack Upgrade
CWS	Cooling water system
DC	Direct current
DCP	Digital coil protection
DN	Double null
EC	Electron cyclotron
ES&H	Environmental Safety & Health
GDC	Glow discharge cleaning system
GDS	Gas delivery system
GRD	General Requirements Document
HHFW	High harmonic fast wave RF heating
IBD	Inboard divertor
IBDHS	Inboard divertor horizontal section
IBDVS	Inboard divertor vertical section
Ip	Plasma current
MA	Mega amp
MW	Mega watt
NBI	Neutral beam injection
ND	Natural divertor
NSTX	National Spherical Torus Experiment
NSTX_CSU	NSTX Center Stack Upgrade
OBD	Outboard divertor
OH	Ohmic Heating

PF	Poloidal Field
PFC	Plasma facing component
PP	Passive plate
R0	Major radius of plasma
RF	Radio frequency
RIS	Rochester Instruments Systems protection device
RWM	Resistive Wall Mode
SN	Single null
ST	Spherical Torus
T	Tesla
TF	Toroidal Field
VPS	Vacuum pumping system
VV	Vacuum vessel