Chapter 3 - Engineering Design

Development of the NCSX engineering design was an iterative process that involved:

- Defining physics requirements and design criteria,
- Developing the stellarator core configuration,
- Developing cost estimates and scaling algorithms, and
- Exploring design alternatives.

The NCSX design is built around the 3-period reference plasma configuration, scaled to a major radius of 1.4 m. A cut-away view of the stellarator is provided in Figure 3-1. The machine parameters are presented in Table 3-1. The plasma is surrounded by a vacuum vessel with an internal liner of molded carbon fiber composite (CFC) panels that are bakeable to 350ºC. The design features 21 modular coils, 21 TF coils, and 4 pairs of PF coils located symmetrically about the horizontal midplane. The coils are pre-cooled to 80K. A cryostat encloses all of these coils. The modular coils, TF coils, and vacuum vessel are assembled in 120° segments. Each segment features ports for heating, pumping, diagnostics, and maintenance access.

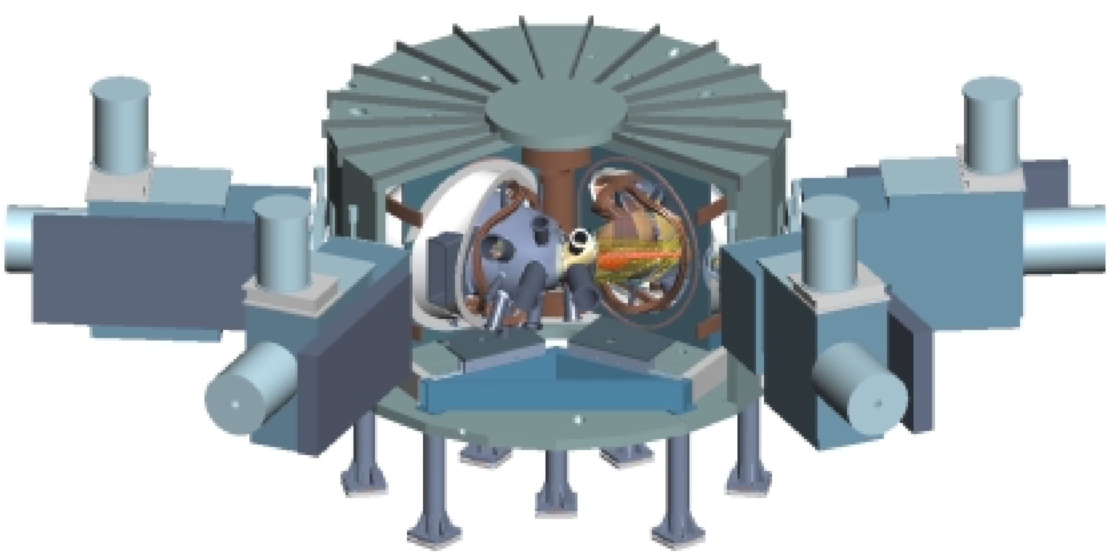
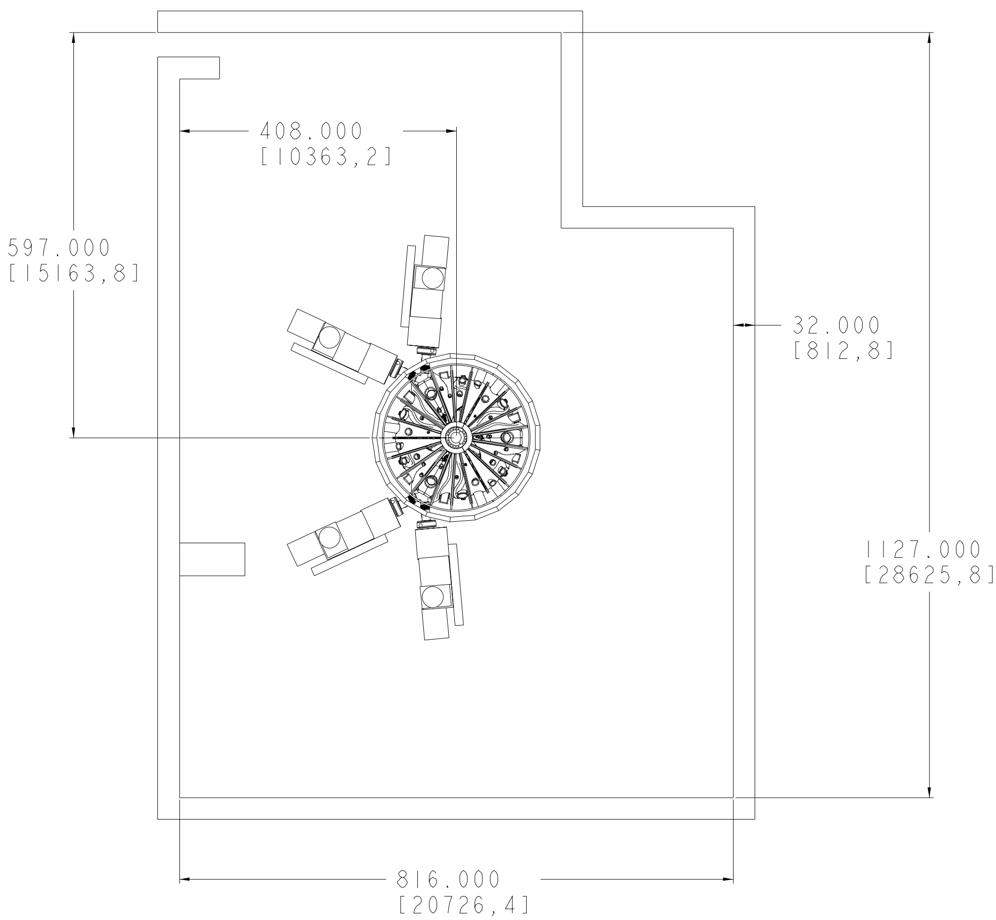


Figure 3-1 NCSX machine configuration

NCSX will be assembled in the combined PBX/PLT test cell following removal of the PBX device. Figure 3-2 shows a plan view of NCSX inside the test cell. This location is well suited to NCSX. The test cell provides ample space for the device along with adequate crane capacity. The PBX/PLT computer and control rooms, which are contiguous to the test cell, will be refurbished and utilized. Many systems formerly used on PBX including the neutral beam (NB), vacuum pumping, power supplies, and water systems will be reused. Power supplies located at D-site will also be used.

Table 3-1 NCSX machine parameters

Major radius	m	1.4
Aspect ratio		4.4
Volume	m3	3.0
Surface Area	m2	23.9
Maximum plasma current	kA	420
Maximum toroidal field	T	2



Dimensions are in inches (millimeters)

Figure 3-2 Plan view of NCSX in combined PBX/PLT test cell

3.1 Stellarator Core

The stellarator core is a complex assembly of four magnet systems that surround a highly shaped plasma. The coils provide magnetic field for plasma shaping and position control, inductive current drive, and field error correction. The vacuum vessel and plasma facing components are designed to produce a high vacuum plasma environment with access for heating, pumping, diagnostics, and maintenance. The entire system is surrounded by a cryostat to permit operation of the coils at liquid nitrogen temperature. Figure 3-3 shows a cutaway view of the stellarator core assembly.

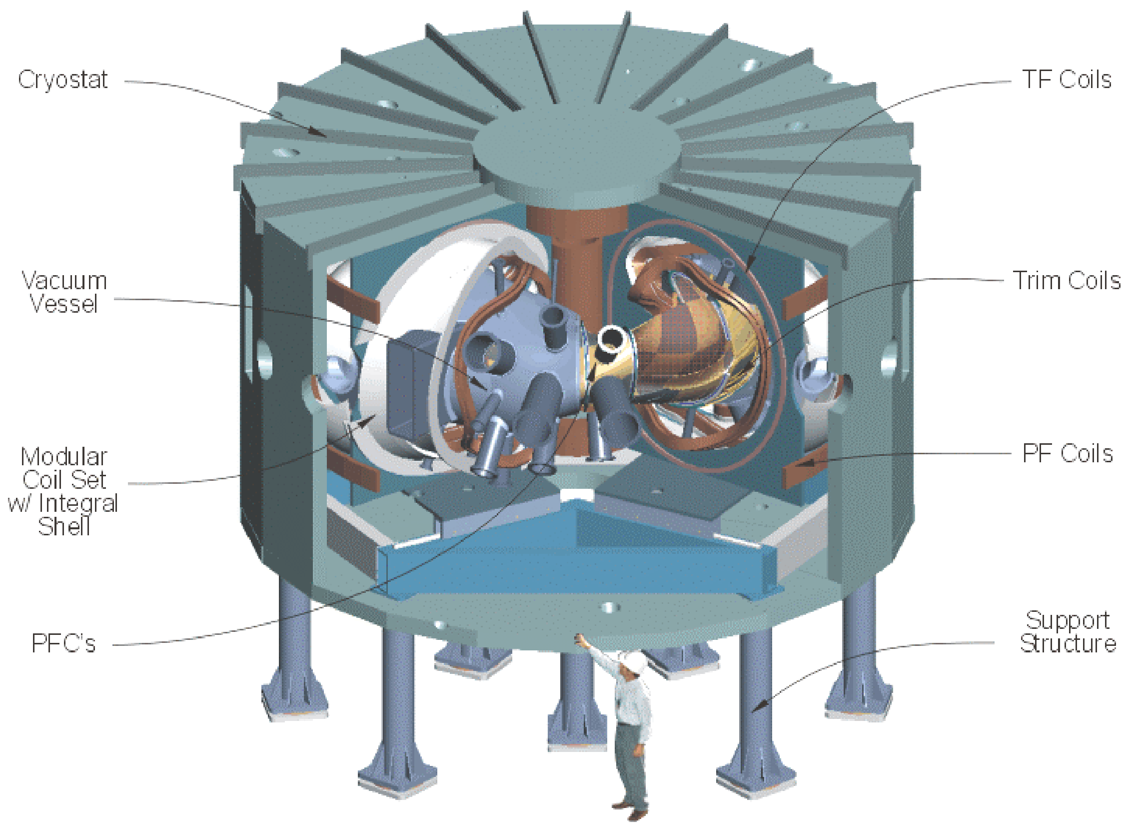


Figure 3-3 NCSX stellarator core

3.1.1 Plasma facing components

The baseline design utilizes a contoured liner, shown in Figure 3-4, constructed of molded carbon fiber composite (CFC) panels mounted on a frame of poloidal rings. When the full complement of panels is installed, they will shield the entire interior surface of the vessel. The plan is to stage the installation of the liner, with very limited wall coverage during initial operation, and the addition of the remainder of the liner

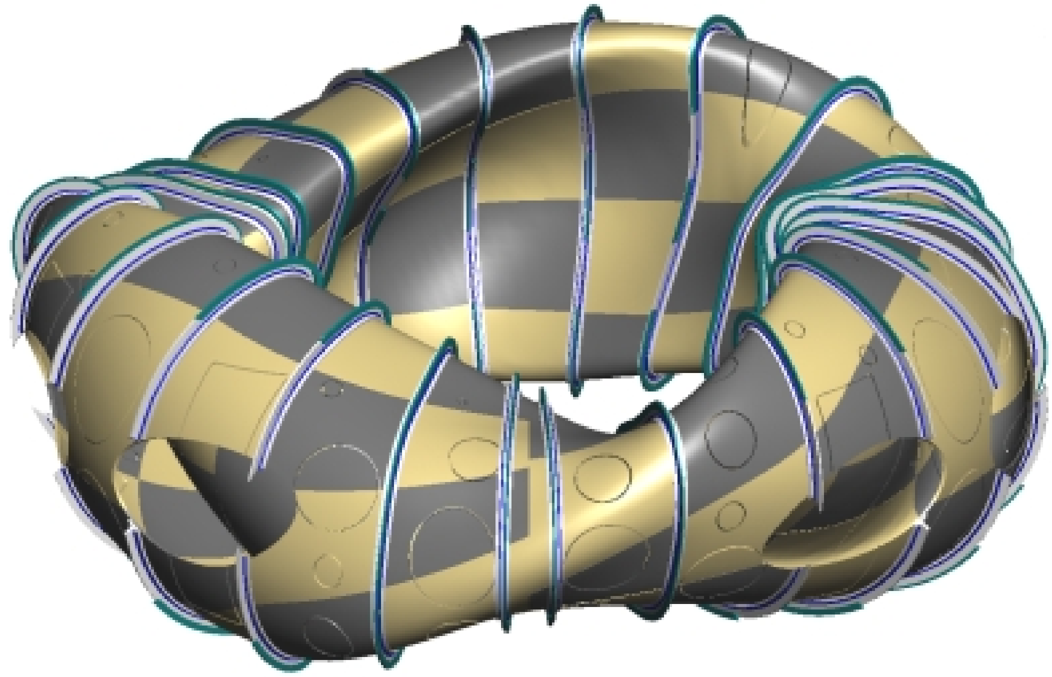


Figure 3-4 Internal liner with full complement of formed panels

during later operation. Having an independently supported, bakeable liner avoids the need to design the vacuum vessel and the in-vessel components mounted on the vessel for baking at 350ºC and reduces the heat loads to the cold mass during bakeout. The liner is baked at 350ºC while maintaining the vessel at 150ºC. Radiation heat loads to the vacuum vessel and in-vessel components are reduced by thermal shields mounted on the backside of the panels. During normal operation, the liner will have a lower pre-shot temperature in the range of 20ºC to 150ºC.

The molded panels form a continuous shell around the plasma with penetrations for diagnostics, heating, and personnel access. This shell serves many functions. It provides a high heat flux surface in the regions of sharp curvature where the heat flux from the plasma is expected to be highest. It can act as a belt limiter on the inboard midplane. On the lower half of the shell, it will absorb the power deposited by the beam ions that are promptly lost from the plasma. On the outboard side, the shell serves as armor to protect the vacuum vessel and in-vessel components from heat loads due to neutral beam shinethrough. The shell also protects in-vessel components mounted on the vessel, e.g., trim coils and magnetic diagnostics, from heat loads from the plasma.

The continuous shell allows great flexibility in plasma shaping because any surface that the plasma impinges on can act as a limiter and be resistant to damage from plasma heat loads. The properties of the CFC panels will be tailored to the local heat loads. More expensive panels with high thermal conductivity will be used in regions of higher heat loads. Less expensive panels with modest thermal conductivity will be used in regions of lower heat loads.

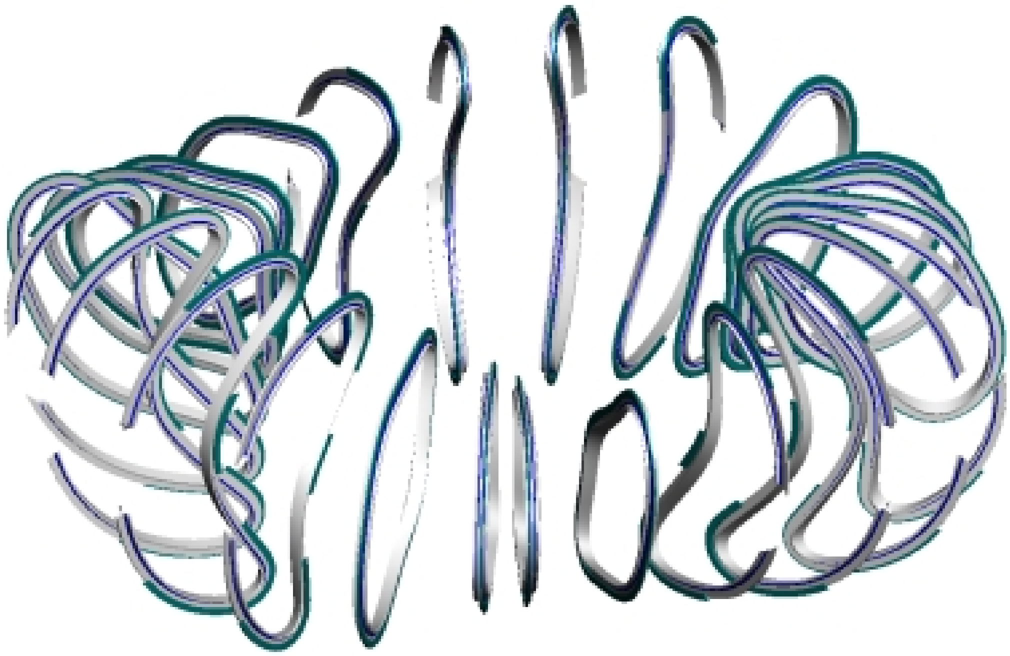


Figure 3-5 Support structure for formed panels

The panels are attached to 24 stainless steel ribs, which are traced to provide heating for the carbon liner during bakeout and cooling between shots. They also serve as thermal isolation members that maintain alignment of the liner during thermal cycling. For initial operation, there will be very limited wall coverage with CFC panels. The 24 ribs will act as a set of poloidal limiters. U-shaped sheet metal clips will protect rib surfaces not covered by CFC panels. The plasma facing surfaces of these clips are flame coated with boron carbide or other low-Z material. Figure 3-5 shows the general arrangement of the panel ribs. Bake out of the liner is provided by circulating heated gas through the tracing on the mounting ribs. The tracing also serves to remove the heat deposited in the PFCs during normal operation. Helium gas will be the working fluid for heating and cooling.

In the present design, the plasma-facing surface is located 2 cm off the nominal plasma surface on the inboard side and 10 cm on the outboard side. During conceptual design, options for expanding the plasma-facing surface away from the plasma and adding a baffled region at the tips of the plasma (akin to a divertor in a tokamak) will be investigated.

3.1.2 Vacuum vessel

The vacuum vessel is a complex, three-period structure with a geometry that repeats every 120º toroidally. The geometry is also mirrored every 60º so that the top and bottom sections of the first (0º to 60º) segment can be flipped over and serve as the corresponding sections of the adjacent (60º to 120º) segment. Table 3-2 lists the main vacuum vessel parameters.

Table 3-2 Vacuum vessel parameters

Physical parameters	
Material	Inconel 625
Thickness	0.95 cm (3/8 in)
Time constant	<10 ms
Inside surface area (without ports)	27.6 m^2
Inside surface area (with ports)	57.6
Enclosed volume (without ports)	8.69 m^3
Enclosed volume (with ports)	11.0 m^3
Weight with ports (without PFC's)	5375 kg
Operating parameters	
Liner bakeout temperature	350ºC
Vessel bakeout temperature	150ºC
Vessel operating temperature	20ºC
Heating pulse duration (max)	1.2 seconds
Cool down time between shots	
Short pulse operation	5 minutes
Long pulse operation	15 minutes

The vessel will be baked to 150ºC and operate at 20ºC. The vessel is maintained at temperature by helium gas circulated through tracing lines attached to the vessel exterior. The vessel is insulated on its exterior surface to provide thermal isolation from the modular coils, which operate at cryogenic temperature. When the vessel is being baked at 150ºC, the conductive heat loss through 2 cm of insulation to the cryogenic system will be 21 kW. Conductive heat losses drop to 13 kW during normal operation. In conceptual design, the insulation thickness will be increased where space allows, substantially reducing the conductive heat loss.

Inconel 625 is the material chosen for the vessel shell. It was selected over stainless steel primarily because of its low permeability and high electrical resistivity. The electrical resistivity of Inconel 625 is 70% higher than for 304SS. Higher resistivity results in a shorter vessel time constant, which is beneficial for plasma current profile control.

Using Inconel avoids the permeability issues associated with stainless steel. Stainless steel is prone to have elevated permeability when subject to severe cold working or when welded. Furthermore, the regions of elevated permeability are not necessarily uniform from one period to the next. Non-uniform regions of elevated permeability are a concern because they are a potential source of field errors.

The device will be fabricated in three subassemblies that are bolted together, complete with the vacuum vessel, modular coils, and TF coils. The ports will already be installed. The preliminary port configuration may be seen in Figure 3-6. Several sizes of radial and vertical ports are used to best utilize the limited access between modular coils. The large neutral beam ports are designed to permit personnel access into the liner for final assembly of the three vessel subassemblies and maintenance of diagnostics and liner panels. Most of the ports must be welded onto the three liner sub-assemblies after installation of the modular coils and prior to final assembly. Port stubs are provided on the vessel to permit the modular coils to slip on first, followed by welding of the port extensions from the outside using an automatic pipe welder inserted down into the port extensions.

The vessel will be supported from the modular coil structure via hangers for ease of adjustment and to minimize heat transfer between the two structures. Significant thermal growth must be accommodated when the modular coils are cooled to cryogenic temperatures or when the vacuum vessel is heated for bakeout.

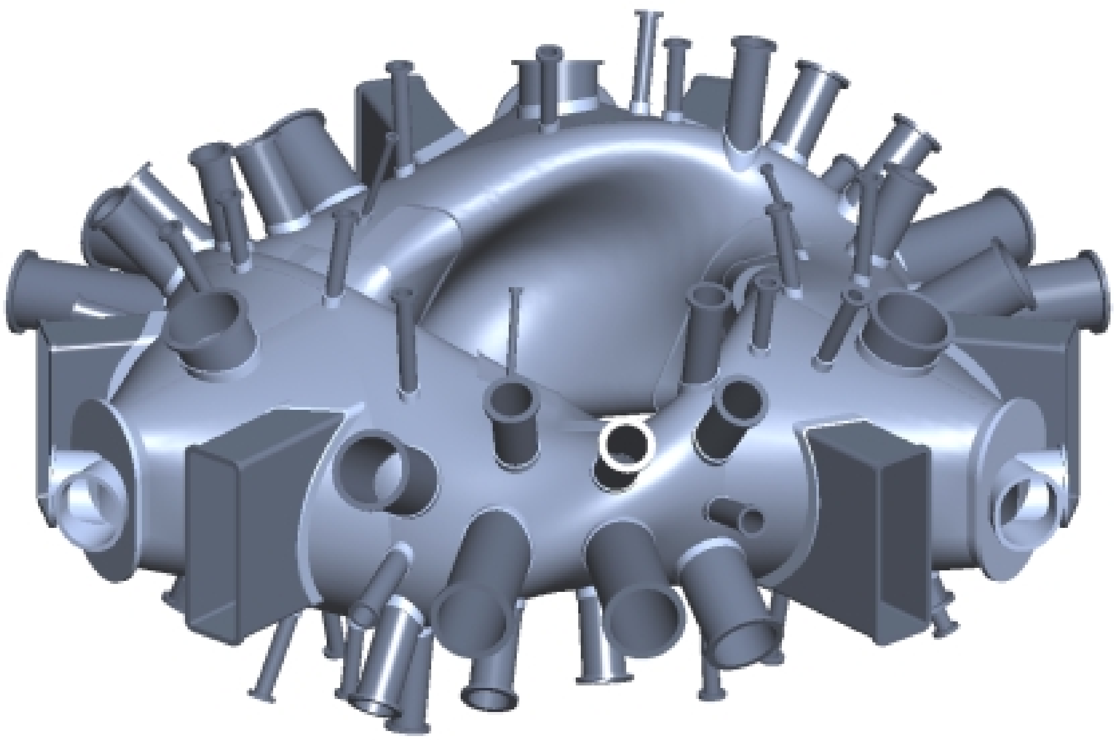


Figure 3-6 Vacuum vessel with port extensions

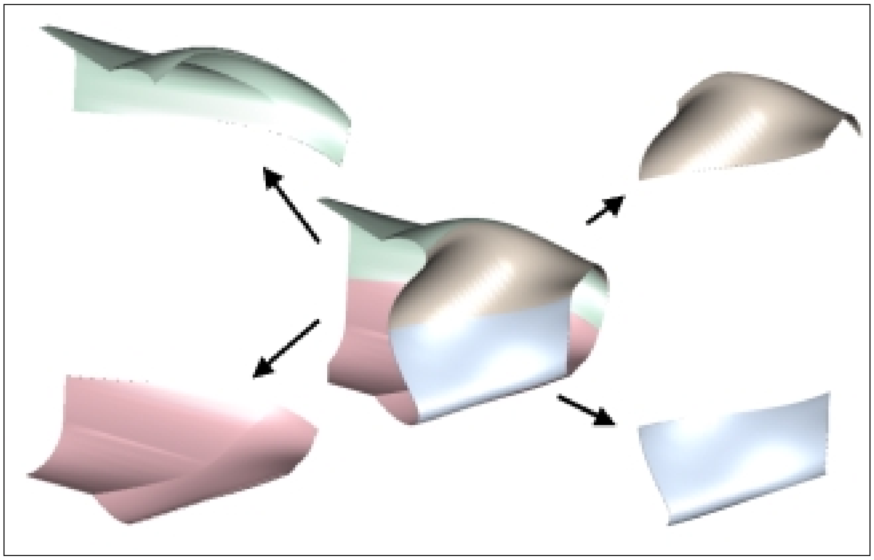


Figure 3-7 Vacuum vessel shell segmentation

Fabrication is a significant challenge, since the vessel has a contour closely conforming to the plasma on the inboard side. The vessel shell may be formed by pressing, explosive forming, or possibly casting sections of the vessel and welding them together to form the finished shape. Embossments can be incorporated to locally strengthen the wall thus permitting thinner gauge material and fewer piece parts and seams. The pressing option presently being explored is hydrostatic rubber forming. In this process, a male die is used in conjunction with a thick rubber platen that roughly approximates the contour of the liner. This reduces the tooling requirements since both male and female dies are not required. Segmentation of the vessel is driven by assembly requirements and inherent fabrication limitations. Fabrication by pressing requires the panel sections to be removable from the tooling dies. This requirement must mesh with the desire for half-period segments. The result is that the number and geometry of poloidal segments is dictated by the die contour. A first cut at the segmentation indicates that the half period can be formed with as few as three poloidal sections, but more probably four as shown in Figure 3-7. For practicality, die size limitations may require more sections than this.

After each field period of the shell is constructed and port stubs welded in place, coolant tracing is installed on the outside surface on approximately 20 cm centers. To minimize distortion of the vessel, these lines are not skip welded or brazed, but are attached by clips and compression gaskets, bolted to the vessel, on approximately 15 cm centers.

The final assembly requires a precise fit. To accomplish this, the welding of the field period sections to their respective end flanges is done with the components all pre-assembled on a fixture into a complete torus. This forces a good fit during the final field assembly.

The next assembly step is installation of the port extensions. This requires that the vacuum vessel be placed inside the modular coils, by sliding the coils over each end of the vessel subassembly. The port extensions are then slipped into the port stubs and welded on from inside. The three sub-assemblies (periods), complete with coils, are bolted internally into a final torus at the oblate (wide) sections. The torus sections are provided with internal, machined end flanges that provide a double o-ring, bolted assembly. The o-rings will be metal or Viton. The space between the seals will be differentially pumped. The alternative, welding the period sections together, would be very difficult. There is also no access from the outside to reach an external weld joint. Achieving quality welds by welding on the inside would be very difficult due to the tight space constraints and contorted geometry inside the vessel. A bolted joint facilitates pre-installation of in-vessel components and assembly of the vacuum vessel. Figure 3-8 illustrates three segments being brought together to complete assembly of the vacuum vessel. The bolted joint feature also makes disassembly possible for major modifications of the device in the future.

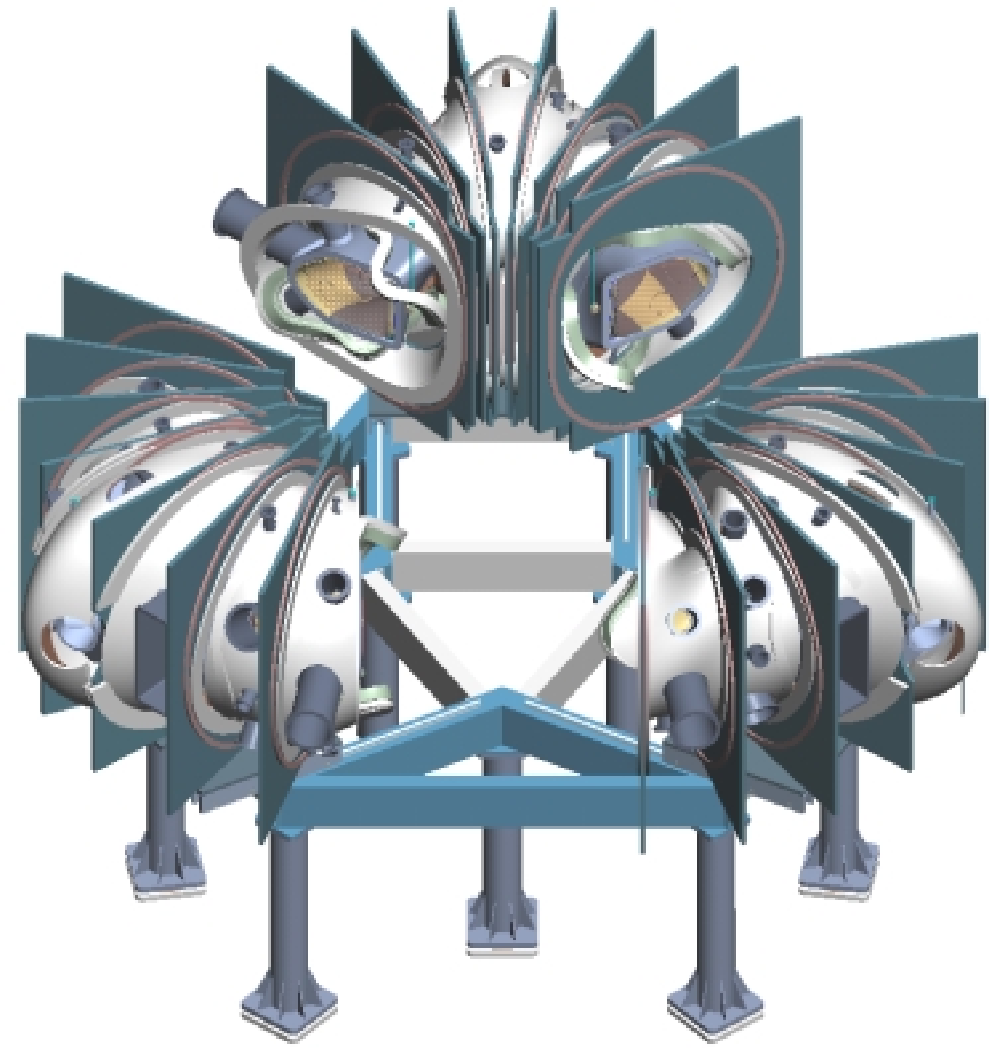


Figure 3-8 Final assembly of vacuum vessel

3.1.3 Modular coils

The modular coil set consists of three field periods with 7 coils per period, for a total of 21 coils. Due to symmetry, only four different coil shapes are needed to make up the complete coil set. The coils are connected electrically with 4 circuits in groups of 3 or 6, according to type. Each circuit is independently powered to provide maximum flexibility. The maximum toroidal field at 1.4 m produced by the modular coils with a flattop of 0.5s is 1.7 T. The toroidal field on axis can be raised to 2 T by energizing the TF coils, which can add ±0.3 T to the field generated by the modular coils.

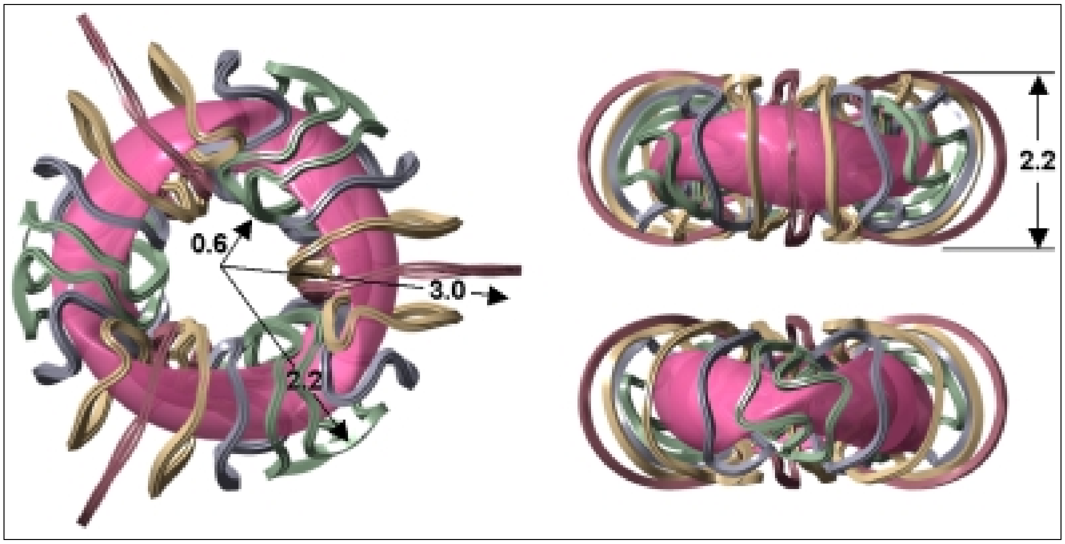


Figure 3-9 General arrangement of modular coil set

The modular coils are pre-cooled to 80K because of the high current density in the coils. In order to avoid two-phase flow in the cooling tubes or excessively high pressures, the windings are cooled with helium gas. Heat is removed from the helium gas through a heat exchanger with liquid nitrogen on the secondary side. The modular coil structure is cooled directly with liquid nitrogen vapor.

Figure 3-9 shows the general arrangement of the coil set. It may be seen that the outer leg of the coil on the v=0 symmetry plane is pulled out for neutral beam access. The other coils are wrapped more tightly around the plasma. The coils on either side of the v=0.5 symmetry plane (60º away from the v=0 symmetry plane) exhibit the largest toroidal excursion and are the most difficult to fabricate. Table 3-3 summarizes the main

Table 3-3 Modular coil parameters

Parameter	Unit	Value	Remarks
Number of field periods		3	
Number of modular coils		21	
Number of turns per coil		32	
Maximum toroidal field at 1.4 m	T	1.7	Modular coils only
	T	2.0	Modular plus TF coils
Winding length along winding center	m	6.0-7.6	
Winding cross-section	cm^2	67	
Winding accuracy	mm	±1	

modular coil parameters.

The winding center for each modular coil is specified through a physics optimization process that emphasizes both plasma properties and geometric constraints, such as coil-to-coil spacing (a key factor determining the current density) and minimum bend radius. From this data, a cross-section is developed that is normal to the winding surface, except in regions where there are sharp bends or the coils are very close together. Twisting in these areas has been adjusted so as to avoid crimps and maximize the available conductor space. A study of the effect of finite-build coils on plasma reconstruction indicates that these small coil adjustments do not significantly affect the plasma properties.

The design concept uses flexible, copper cable conductor. The primary advantage of the flexible cable design is low cost, both to purchase the conductor and to wind it. The primary disadvantage is the loss of copper area compared to a solid conductor. A packing fraction of only 75% can be assured, although 80% is theoretically possible. The design is based on a packing fraction of 70%. The conductor is purchased as a round cable that has been compacted into a rectangular cross-section. Turn-to-turn insulation is then applied. Even after compaction, the conductor is flexible and easy to wind. A picture of the conductor before and after compaction is provided in Figure 3-10. Once wound, the conductor is vacuum impregnated with epoxy. The epoxy fills the voids within the cable conductor so the winding pack becomes a monolithic copper-glass-epoxy composite.

Table of Conductor Parameters

Parameter	Unit	Value
Maximum current	kA	20.3
Pulse length (ESW)	s	~1
Repetition rate	min	10
Total number of cycles	-	130,000
Conductor width	mm	16
Conductor height	mm	13
Max continuous length	m	130
Copper strand size	AWG	36
Conductor packing fraction	%	70-75
Insulation thickness	mm	0.8
Insulation rating	kV	> 3
Minimum bend radius	cm	> 4

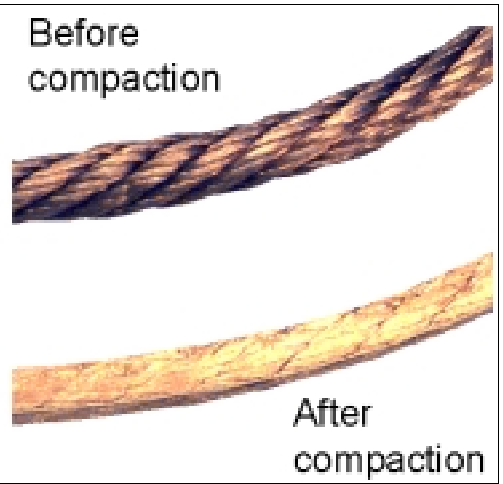


Figure 3-10 Cable conductor

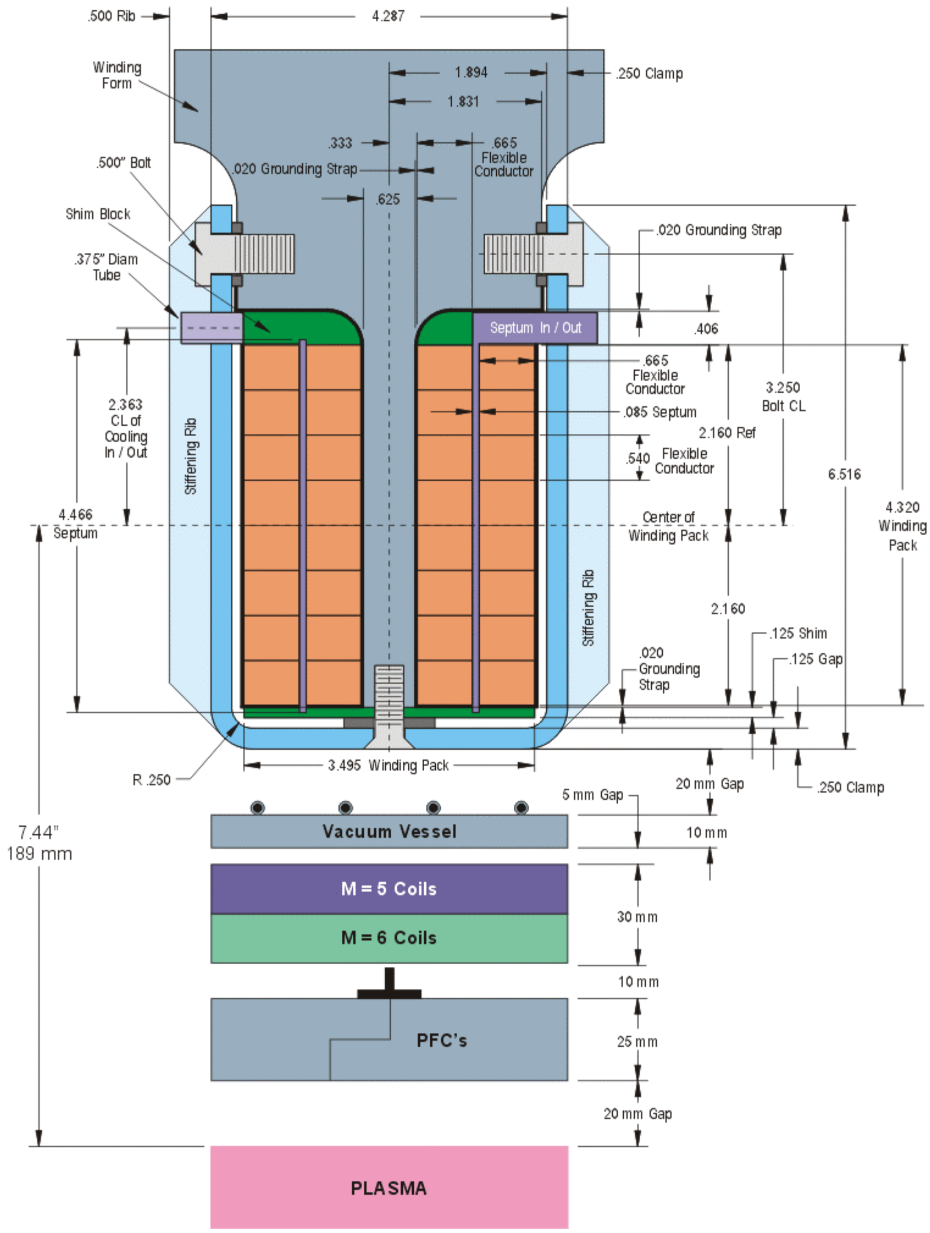


Figure 3-11 Modular coil cross-section

The cross-section dimensions of each coil are 10.9 cm x 16.5 cm, as shown in Figure 3-11. Within this envelope is a 16 mm thick, tee-shaped member that supports two multi-turn winding packs. Each winding pack is a double-layer pancake with 8 turns per layer. A crossover between layers occurs at the top of the tee. The leads extend from the bottom of the winding pack in a coaxial arrangement. Between the layers there is a thin plate through which gas cooling flows. The winding packs are clamped in place by discrete u-shaped brackets that provide support in areas where the electromagnetic force is away from tee structure.

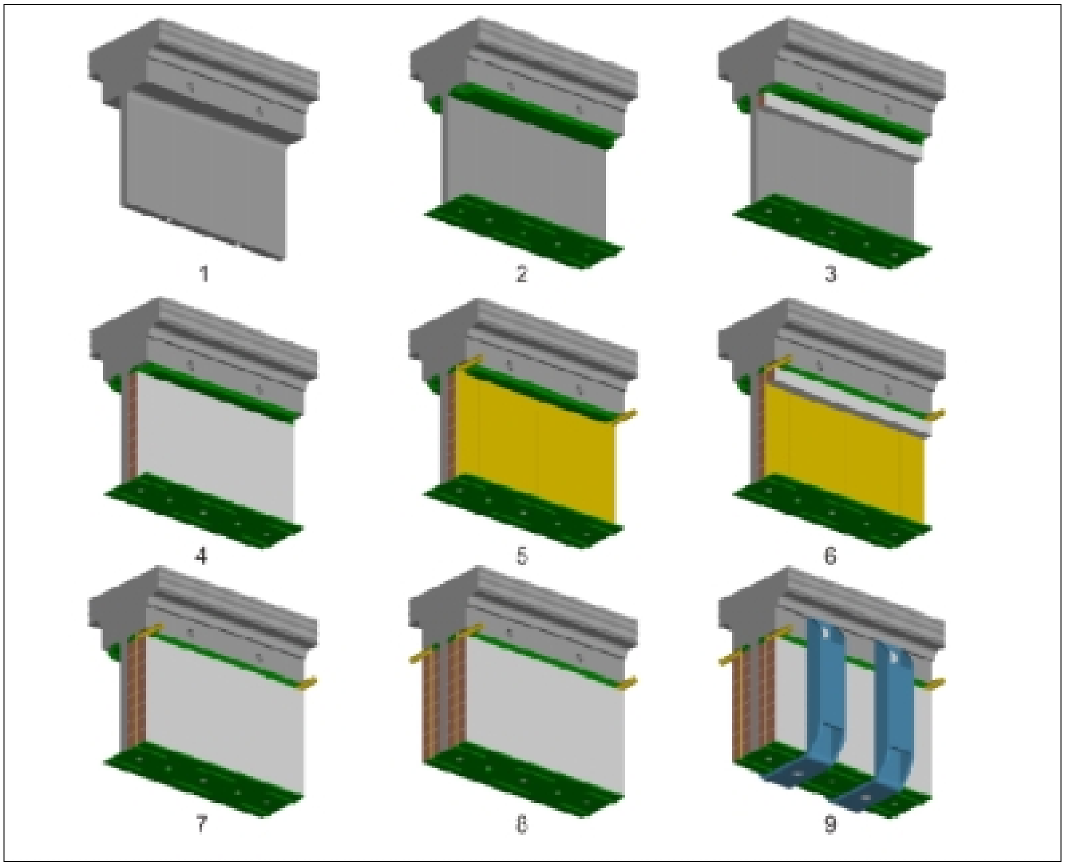


Figure 3-12 Coil winding process

In order to avoid unwanted field errors, the position of the winding current center must be tightly controlled. The true position tolerance (TPT) for the winding current center is ±1 mm. In order to achieve this tolerance, the conductor will be wound on a precision surface on each side of the structural tee, which is part of the winding form. The winding process is illustrated in Figure 3-12. The conductor is wound in a double pancake on each side of the tee. When the first pancake has been wound, a chill plate is placed against the first pancake. The chill plates consist of a copper sandwich containing a serpentine cooling passage with inlet and outlet pipes for the gas cooling. The chill plates avoid the need for cooling the conductor internally, which would reduce the achievable current density. Then the second pancake is wound. After winding is complete, the final geometry is verified and the assembly is vacuum pressure impregnated with epoxy to complete the insulation system. Support brackets are then installed. An illustration of a completed modular coil in the winding form is shown in Figure 3-13.

The winding form is fabricated as a casting. Due to the complexity of the shape, the pattern geometry will likely be developed through several iterations by a pattern maker. In order to minimize machining, the as-cast part must be within 5 mm of the true

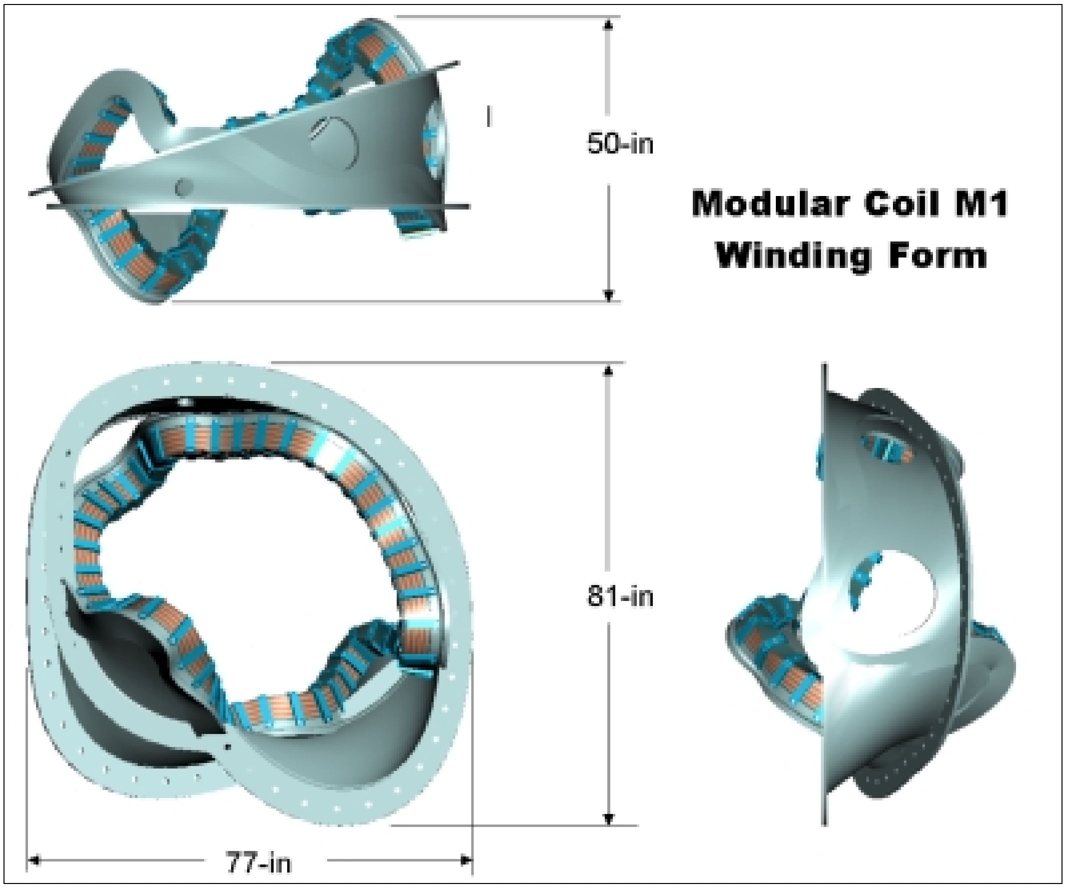
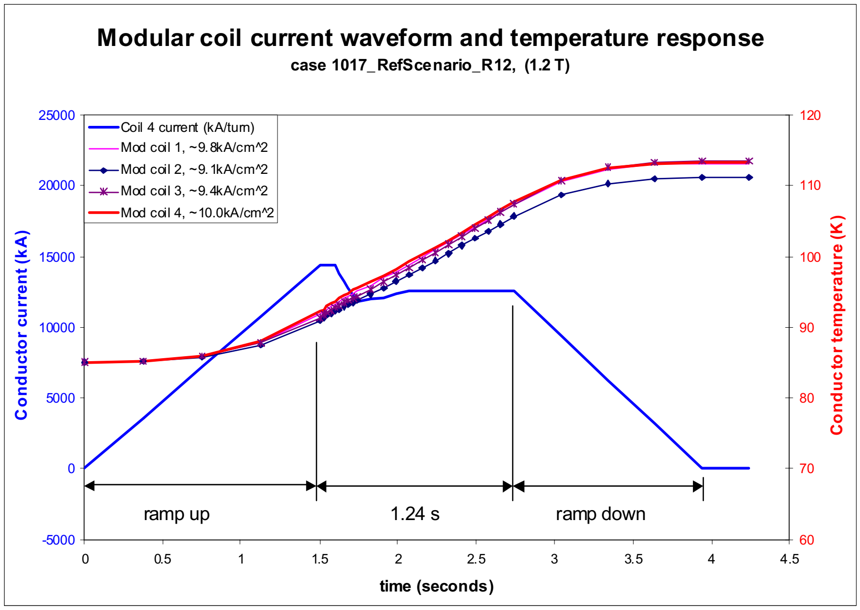


Figure 3-13 Completed modular coil in the winding form

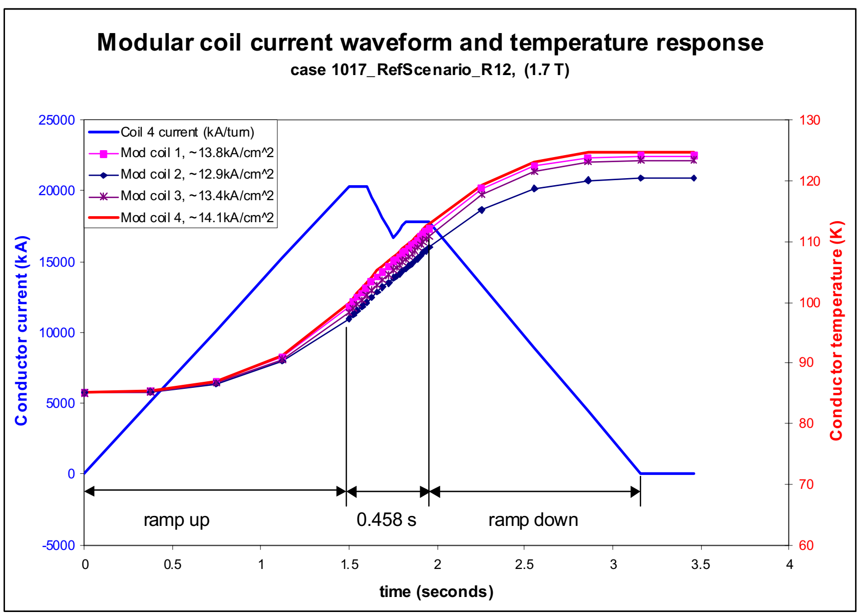
shape anywhere in the section. After stress relieving in a fixture, the casting would be re-measured and have all structural interface features machined.

Instead of making the winding cavity undersized and contour machining it to the required size and accuracy, it is proposed to make the cavity *oversized* in most areas. A very accurate, multi-part set of patterns would be created using rapid prototyping techniques (such as stereolithography or laminated object modeling) and accurately positioned in the casting. The space between the winding pattern and the structure would be filled with an epoxy grout. The pattern would be removed leaving a very accurate, molded winding cavity. In some areas, where the windings are very close together, there may not be room for the epoxy grouting. In these areas the structural tee would be locally machined to exact size. Of course, a fully machined winding cavity would be considered if the cost was favorable.

The modular coil windings will be cooled with helium gas at 80K. Figure 3-14 illustrates the current waveforms and temperature response of the modular coil windings for the two reference scenarios: 1.2 T with a 1.2 s flattop and 1.7 T with a 0.45 s flattop. The temperature rise in the 1.7T scenario is the higher of the two. The temperature rise is 26 K at the end of flattop and 36 K at the end of the pulse. The allowable temperature



1.2 T



1.7 T

Figure 3-14 Modular coil current waveforms and temperature response

rise will be determined by thermal stress considerations. A limit of 40 K has been imposed pending more detailed analysis and testing.

The temperature rise in an adiabatic copper coil is governed by the current density, equivalent square wave time (ESW), and initial temperature. In the 1.7 T reference scenario, the highest copper current density in the modular coils is 14 kA/cm^2, with an ESW of 1.2 s. Lower current density would translate into longer flattop times and perhaps higher toroidal field capability. Analysis indicates that cooldown within 15 minutes can be accomplished by cooling by gaseous helium at 80 K.

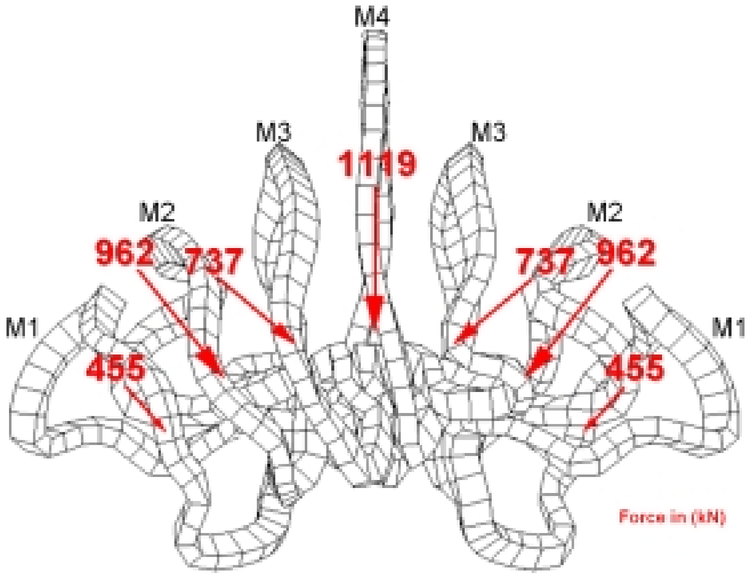
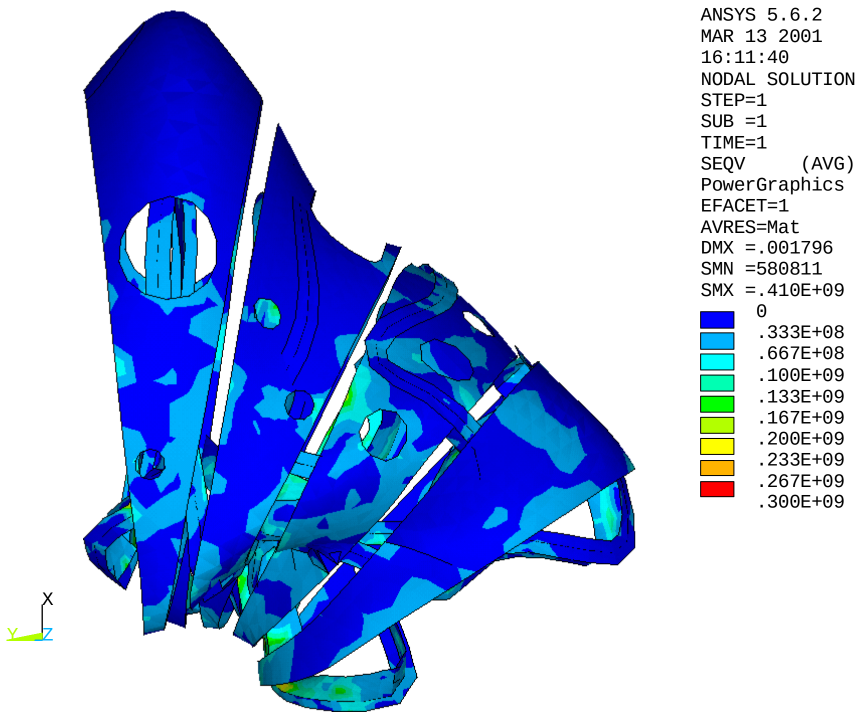


Figure 3-15 Net radial forces on modular coils

A preliminary analysis of the stresses in the coil structure has been completed. The structure has been evaluated for a “worst case” operating point, which occurs when the modular and PF coils are at their largest currents (based on the 1.7 T reference scenario) and the TF coils are providing an additional 0.3 T. The magnitude and direction of the net forces on the modular coil forces are shown in Figure 3-15. The stresses are calculated using a finite element model of the shell and web structures, with all the modular coil loads applied to the midpoint of the coil web structure. In this way the global response of the shell as well as the local bending in the web due to lateral loads can be determined. The TF coil loads are applied to the radial plates, which in turn are connected to the appropriate regions of the modular coil shell.

As shown in Figure 3-16, the analysis results indicate the stress in the structural shell is between 50-100 MPa throughout most of the structure. There are some areas in the inboard “trough” region that peak around 200 MPa. The stresses in the web portion of the structural tee are between 60 and 120 MPa, with very localized peaks up to 300 MPa due to bending. The allowable stress for membrane plus bending is about 180 MPa for a typical cast austenitic alloy.

Although the peak stresses from this first analysis exceed the allowable limit in localized areas, the shell thickness and shape can be optimized to reduce these localized stresses. The primary reason for selecting the shell concept for structural support is to have a robust structure that can be easily optimized to reduce stress peaking. At the same time, there is maximum flexibility for providing local holes and cutouts for diagnostic and heating access.



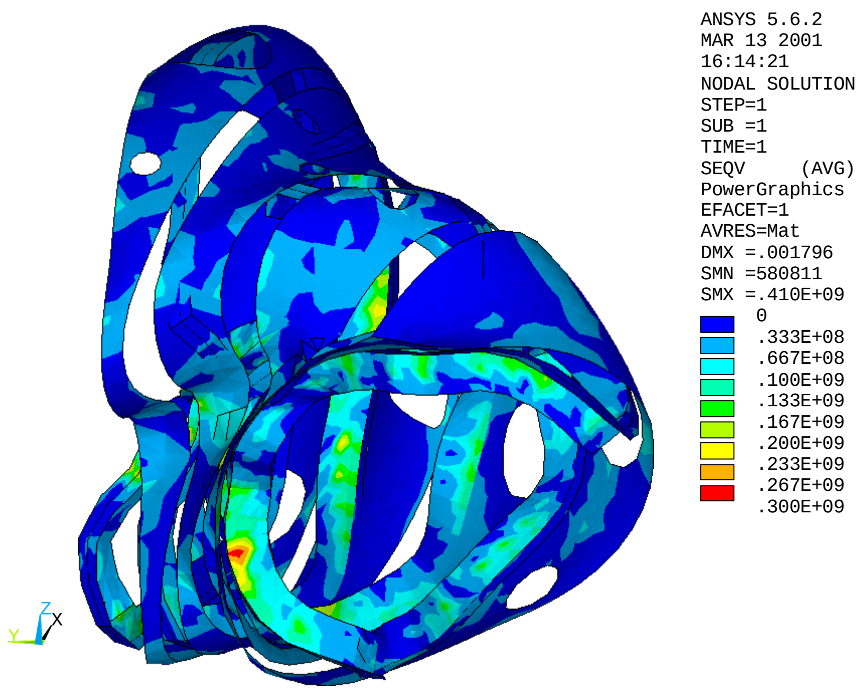


Figure 3-16 Stress pattern in modular coil structure for "worst case" operating loads (1.7 T from modular coil set, peak PF currents, 0.3T from TF coil set)

There are a number of improvements that will be sought in conceptual design. These include:

- Lowering the copper current density for longer flattop times and higher field capability,
- Reducing the number of modular coils for improved access and reduced cost, and
- Modifying the winding shape to make it easier and less expensive to manufacture.

Contracts will be placed with potential vendors to conduct manufacturing studies and provide feedback on how the coil design should be changed to improve fabricability and reduce cost.

3.1.4 Toroidal field coils

A set of toroidal field coils is included to provide flexibility in the magnetic configuration. Adding or subtracting toroidal field is an ideal "knob" for lowering and raising iota. There are 21 identical, equally spaced coils providing a 1/R field at the

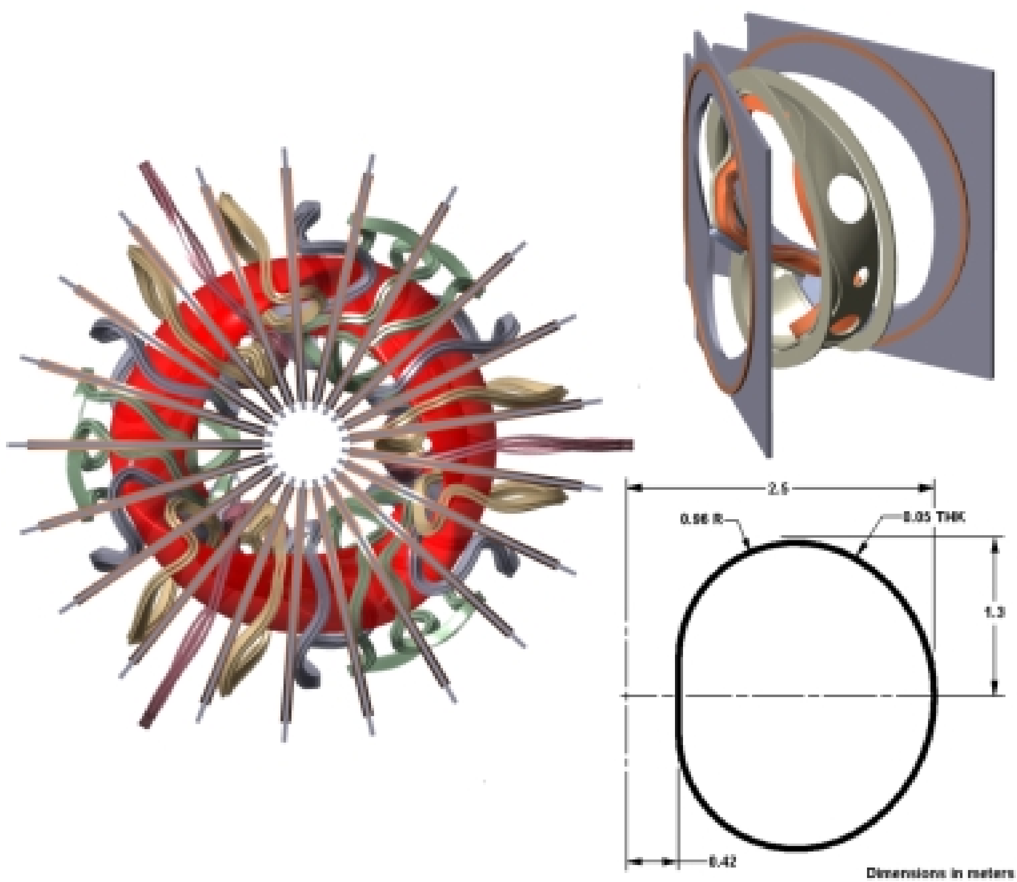


Figure 3-17 TF coil geometry and support

Table 3-4 TF coil parameters

Parameter	Unit	Value	
Number of TF coils		21	
Number of turns per coil		6	
Maximum toroidal field at 1.4 m	T	±0.3	TF coils only
Maximum current per turn	kA	17	
Winding length along winding center	m	9.5	
Winding cross-section	cm^2	21	
Maximum copper current density	kA/cm^2	9.6	

plasma. The TF coils are mounted on flat, radial plates that are bolted between adjacent modular coil winding forms. In addition to supporting and locating the TF coils, the radial plates provide structural support to the modular and PF coils. The TF coils are located at these radial locations for symmetry and to avoid introducing additional obstructions to access. All of the coils are connected in a single circuit. Each coil consists of a pair of windings, one on either side of radial support plates as shown in Figure 3-17. The windings are split about the plate for structural, magnetic, and geometric symmetry, for improved accuracy, and for ease of mounting. The coils are wound from hollow copper conductor and insulated with glass-epoxy. They operate at the same temperature as the modular coil set - nominally 85K (cooled by 80 K helium) - and are connected in series. The leads consist of coaxial conductor to minimize field errors. The nominal TF coil parameters are listed in Table 3-4.

The modular coils were designed for the reference plasma configuration *in the absence of TF coils*. TF coils were added for flexibility. Design studies are being conducted to determine if the design of the modular coils could be improved by assuming a background 1/R field when designing modular coils for the reference plasma configuration.

The 1/R nature of the TF field was adopted based largely on precedent in other stellarators, which were largely high aspect ratio, many field period designs. The magnetic axis in these machines could be approximated by a circle, the shape of a field line in a 1/R field. However, in a low aspect ratio, 3-period stellarator like NCSX, it is not clear that a 1/R background field is optimal with a highly non-circular magnetic axis. In conceptual design, a study will be performed to optimize the field distribution from the TF coils.

3.1.5 Poloidal field coils

A set of poloidal field coils is provided for inductive current drive and plasma shape and position control. The basic coil geometry is shown in Figure 3-18. The coil set consists of two inner solenoid pairs (PF 1 and PF 2), a mid coil pair (PF 3) and an outer coil pair (PF 4). Coil pairs are symmetric about the horizontal midplane. The coils are of

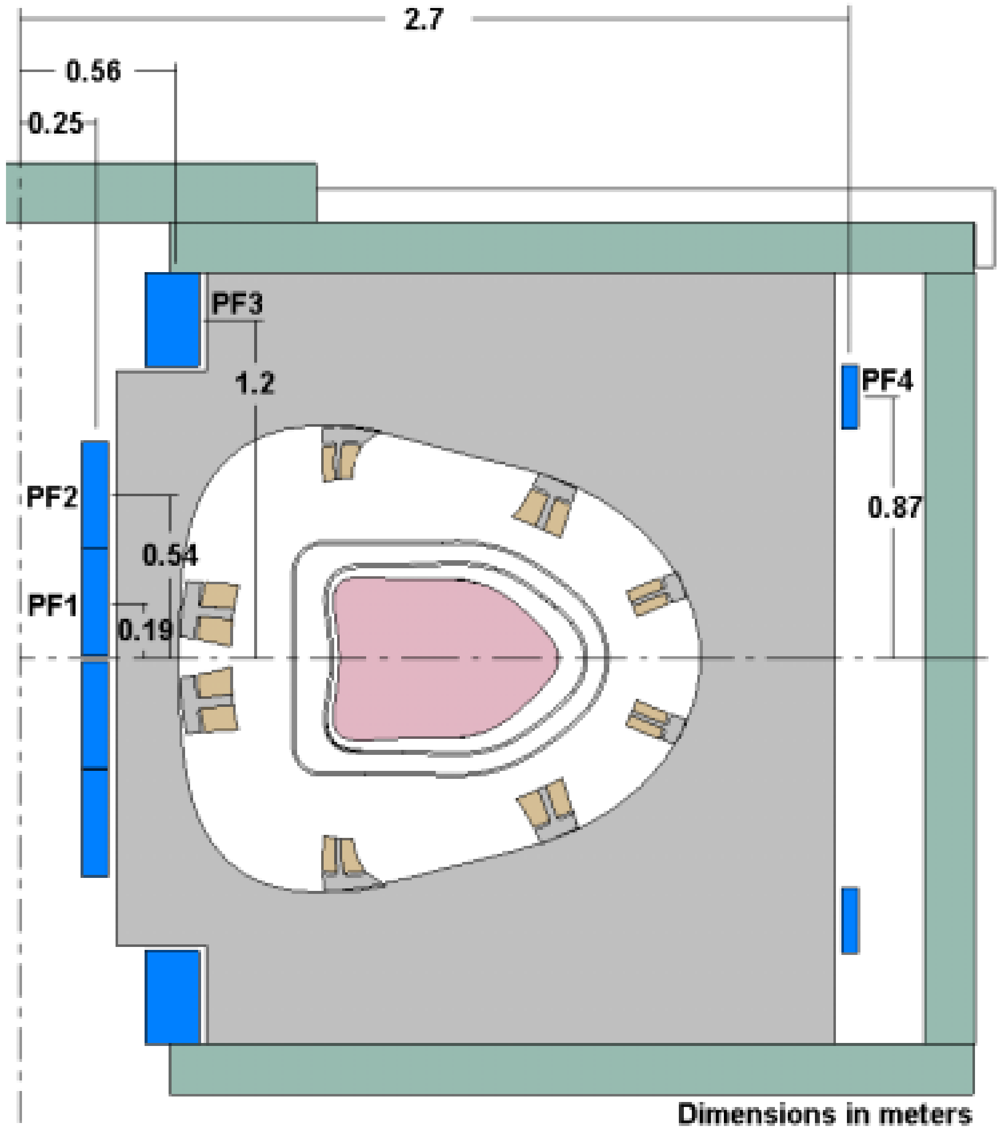


Figure 3-18 PF coil layout

conventional construction, wound from hollow copper conductor and insulated with glass-epoxy. The PF coils operate at the same temperature as the modular and TF coil sets - nominally 85K (cooled by 80 K helium). The leads consist of coaxial conductor to minimize field errors. PF coil parameters are listed in Table 3-5. The coils are supported via adjustable clamps to the radial support plates.

Upper and lower PF coils in a given pair are connected in series. Thus, there are four independent electrical circuits. The PF coils, when independently driven, provide much flexibility for plasma shaping and position control. With an OH (nullapole) distribution in the PF coils, the coil set can provide 1.5 Wb (single swung) or 3 Wb (double swung). This capability should be adequate, even for the maximum plasma

Table 3-5 PF coil parameters

Parameter	Unit	Total	PF 1	PF 2	PF 3	PF 4
Winding radius	m		0.25	0.25	0.556	2.745
Winding elevation	m		±0.188	±0.543	±1.155	±0.868
Winding width, dr	cm		9.02	9.02	17.88	5.41
Winding height, dz	cm		35.4	35.4	31.16	21.16
Number of turns per coil			76	76	80	12
Volt-seconds [a]	Wb	3				

[a] OH (nullapole) current distribution in PF coils, double swung

current of 420 kA, provided that the coil currents required for shaping are not too extreme.

The present design features four pairs of PF coils. This is the minimum number that might be acceptable for performing all of the required functions. During conceptual design, PF coil requirements for the full range of flexibility space will be investigated, including reproduction of the desired physics properties and surface quality. As a result of those investigations, the number and placement of the PF coils may change.

As with the TF coils, the modular coils were designed for the reference plasma configuration in the absence of PF coils. PF coils were added for flexibility and for inductive current drive. In conceptual design, studies will be conducted to determine if the design of the modular coils could be improved by taking advantage of the PF coils when designing modular coils for the reference plasma configuration. Studies will also be conducted to determine if the design could benefit by allowing the PF coils to be non-circular and non-planar.

3.1.6 Trim coils

Trim coils are provided to mitigate field errors, in particular the errors on m=5 and m=6 resonant surfaces. The coils are configured in a saddle geometry as shown in Figure 3-19, and are located inside the vacuum vessel on the inboard and outboard regions of the v=0 (bean-shaped) plasma cross-section based on a study to determine where the coupling with the plasma was best. The m=5 coils are on a surface that is offset 63 mm from the plasma on the inboard and 143 mm from the plasma on the outboard side. The m=6 coils are in a layer offset 15 mm farther out from the plasma. The present coil geometry interferes slightly with the beam lines near the outboard midplane, so the geometry of the saddle coils will have to be adjusted slightly during conceptual design.

The coils should require less than 10 kA-turns per coil. To provide this, five turns are envisaged in a 5 cm x 1 cm winding pack. Since the coils are located in the vacuum vessel, they must be vacuum tight (canned). High temperature electrical insulation will

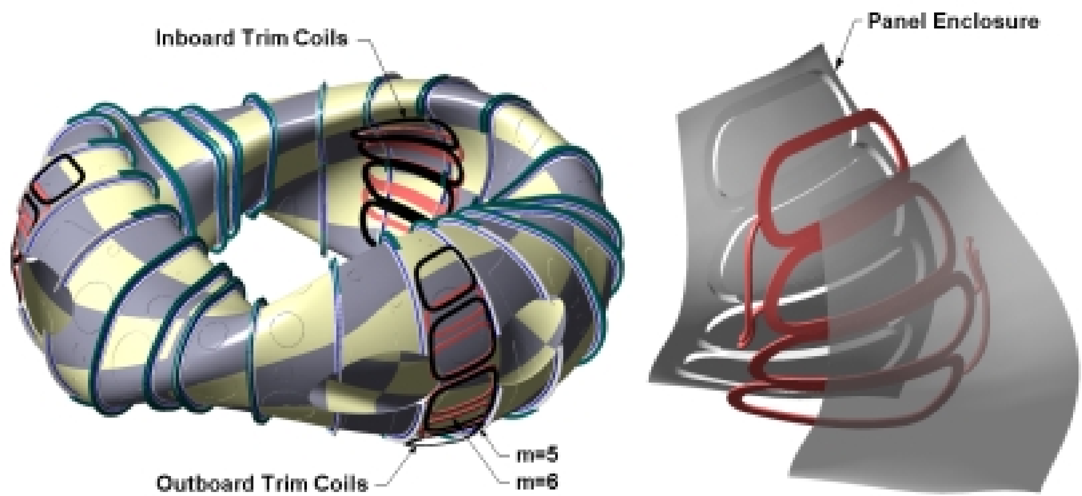


Figure 3-19 Trim coil configuration

be required. The present concept for the coils is to provide a formed and embossed stainless steel panel into which the four saddle coils would be wound, with a second panel seam welded over the coils to provide the vacuum closure. Special tooling will be required to provide an accurate, contoured shape. The completed panels can be fully supported by the vacuum vessel on the inboard side, but will cantilevered from the top and bottom on the outboard side.

There are six panels (3 periods, each with an inboard panel and an outboard panel) for the m=5 resonance and six for the m=6 resonance. Coaxial leads from each panel will be routed to the outside through continuous conduit. There, the coils in each group will be connected in series and connected to power supplies in the ESAT building at C-site.

To date, only the trim coils for symmetry preserving field errors have been investigated. In addition, it is anticipated that trim coils for symmetry breaking field errors, e.g., n/m=½ and n/m=⅔ resonant errors, might be desirable. The design of these trim coils will be investigated during conceptual design.

3.1.7 Machine support structure

The machine support structure consists of the base columns, support beams, and radial support plates. These components provide mounting points for all the other components and support the gravity and seismic loads on the device. The base columns and support beams are illustrated in Figure 3-20. The columns are tall enough to provide headroom under the machine. Rails mounted on top of the columns provide a means of assembling the machine in three field periods. The columns will be covered with thermal insulation to provide a long conduction path for reducing heat leakage to the machine.

The radial support plates provide a set of interface planes for the modular coils as well as convenient support structure for accurately locating and mounting the TF and PF

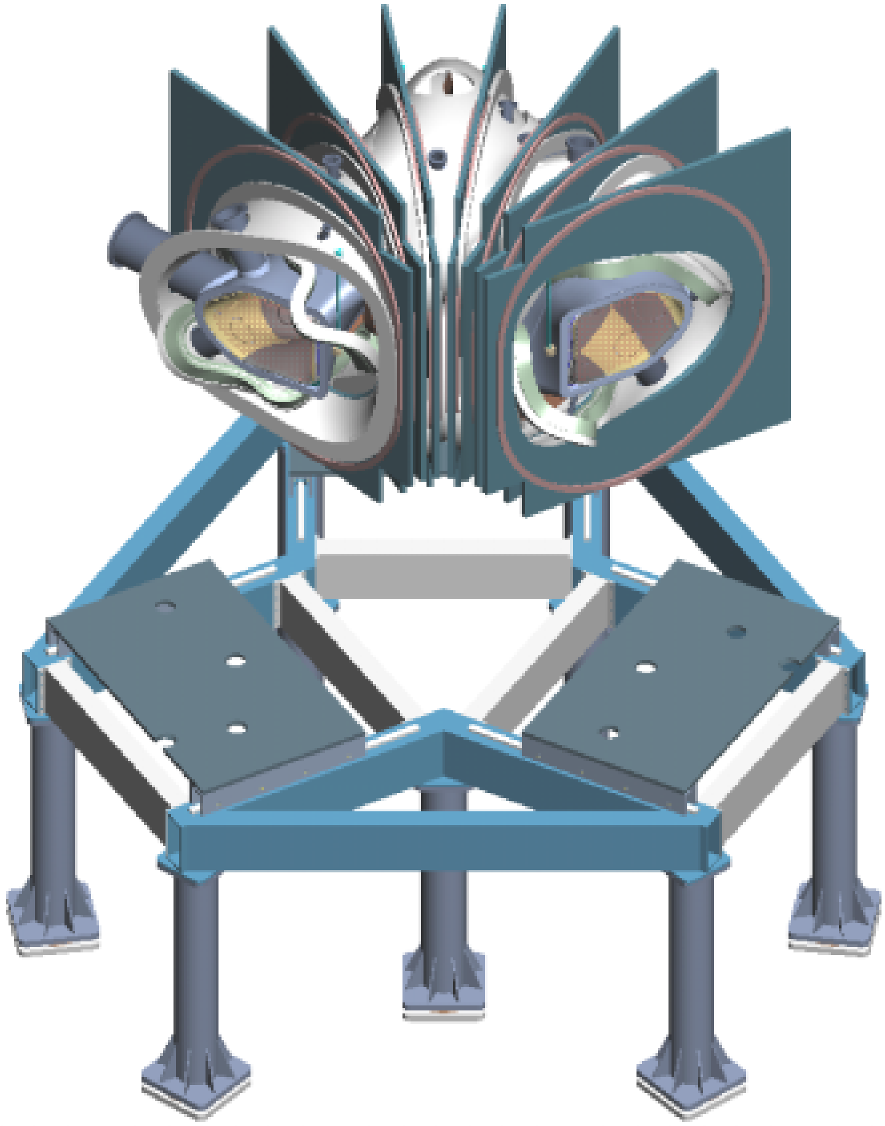


Figure 3-20 Support structure

coils. Shims can be used if necessary between the support plates and the modular coil structure for minute adjustments in coil position and to avoid tolerance buildup of the whole assembly. Adjustable brackets will provide the interface between the support plates and the PF coils to accurately align the coils with respect to the modular coils and TF coils. Since large ring coils are often out-of-round, these brackets will also serve to bring the coils into an acceptably round shape.

3.1.8 Cryostat

Since the coils and structure operate at cryogenic temperatures, a cryostat is provided for thermal isolation. The cryostat must also seal the coil space from the outside air to prevent condensation on the cold surfaces and to provide a means for

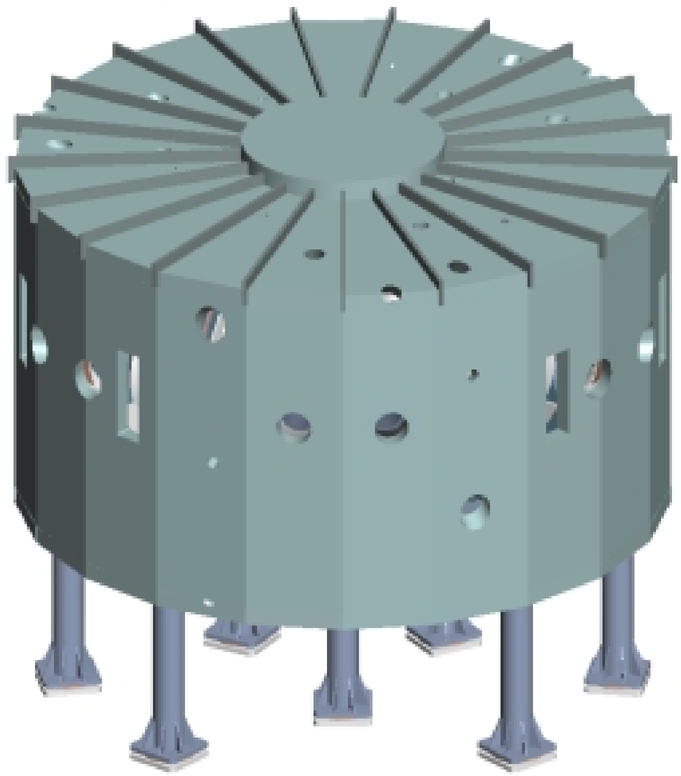


Figure 3-21 Cryostat configuration

circulating dry nitrogen inside the cryostat to cool down and maintain the temperature of the interior structures.

The baseline concept consists of a simple frame and panel design covered with urethane insulation as illustrated in Figure 3-21. The frame consists of fiberglass channels mounted along the edges of each of the radial TF coil support plates. Fiberglass panels are attached to the frame to form a surface for the urethane. Fiberglass dams are positioned around each vacuum vessel port, coil lead, or utility penetration. A flexible silicone rubber boot is used to provide a seal. Urethane is then sprayed on the fiberglass panels using a commercial process typically used for large stationary cryogenic tanks. The exterior surface of the urethane is then sprayed with a butyl rubber coating for an additional gas seal and to provide a durable surface. For access to interior components, a few removable panels (including the top and bottom central openings) would be provided, but in general, the urethane would simply be removed and a hole cut in the panel where access is desired. The hole would be repaired by patching the panel and re-foaming. This process is analogous to accessing plumbing by cutting holes in a sheet rock wall.

The urethane insulation is approximately 8 inches thick, which provides good thermal isolation for the cold components (~ 2 kW heat leak), but is probably not sufficient to prevent condensation on the outside of the cryostat. For this reason, heaters and blowers will be used to control the outside surface temperature and prevent condensation. Flexible insulation must also be stuffed around the penetrations outside the boots.

3.2 Access and Maintenance

3.2.1 Diagnostic access

Port locations were defined based on available space between modular coils, trim coils, PF and TF coils, and structure, and are shown in Figure 3-22. Table 3-6 shows the size and total number of ports. The sizes and numbers of ports appear well matched to our needs for diagnostic access. However, the all-important task of matching the view angle to the geometric requirements remains to be done in conceptual design. A description of the NCSX diagnostics can be found in Chapter 12.

3.2.2 Access for plasma heating

The requirement for neutral beam access is to be able to accommodate two of the PBX-M neutral beams in the initial configuration. These beams must be oriented for tangential injection with one co-injected beam and one counter-injected beam. In addition, the device must be able to accommodate the two remaining PBX-M neutral beams as a future upgrade. One of these beams must be oriented for tangential co-

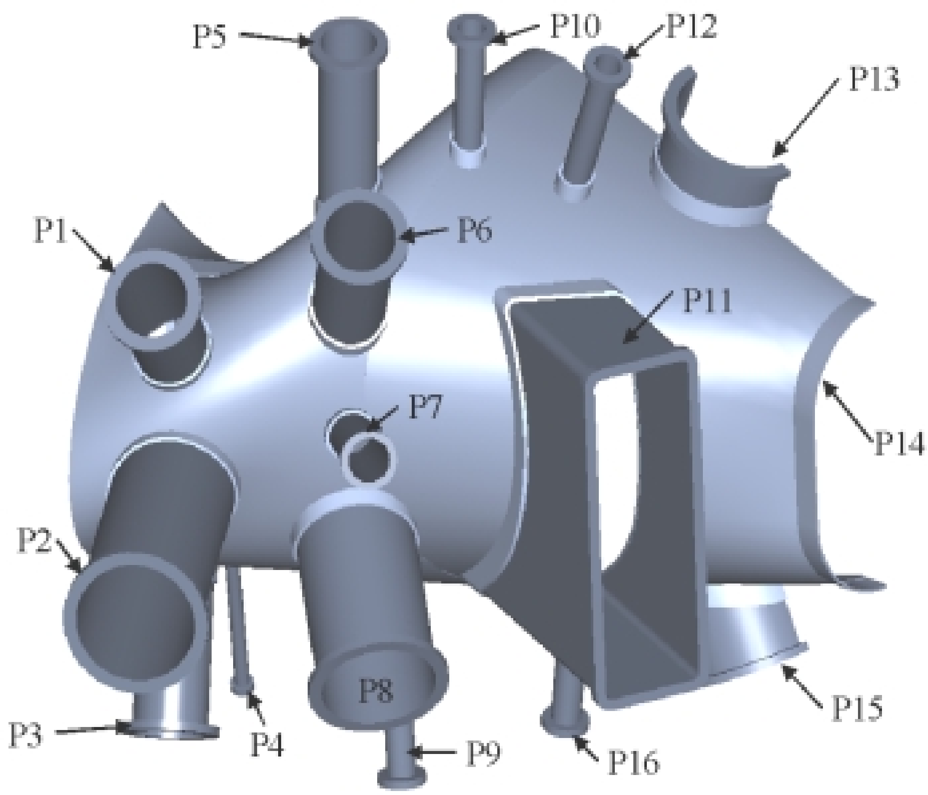


Figure 3-22 Vacuum vessel with ports for diagnostic access

Table 3-6 Port sizes and numbers

Port ID	Port size (inside diameter in inches)	Number of ports per half period	Total number of ports
P1, P3, P6	8.0	3	18
P2, P8	13	2	12
P4	1.5	1	6
P5	6.0	1	6
P7	4.5	1	6
P9, P10, P12, P16	3.0	4	24
P11	36 X 12	1	6
P13, P15	14.5	2	6
P14	31 X 20	1	3
Total			87

injection. The other beamline must be capable of being oriented for either tangential co- or counter-injection.

The neutral beams will be injected through a port centered on the v=0 (bean-shaped) cross-section. The outer leg of the modular coil has been moved to accommodate tangential injection. Figure 3-23 shows the device configured for two co- and two counter-injected neutral beams. If the fourth beamline was configured for co-injection, it would be located at the remaining v=0 plane.

NCSX is being designed to accommodate 6 MW of ion cyclotron resonant frequency (ICRF) heating in addition to neutral beams. The leading candidate for ICRF heating is a 20-25 MHz system that employs a combline antenna inboard of the plasma at the v=0.5 (the oblate or bullet-shaped cross-section). This size of the antenna is approximately 10 cm deep x 50 cm wide x 50 cm tall. This option is attractive because of the physics advantages derived and because it makes use of existing RF sources at PPPL. Design studies are currently underway to accommodate this plasma heating option.

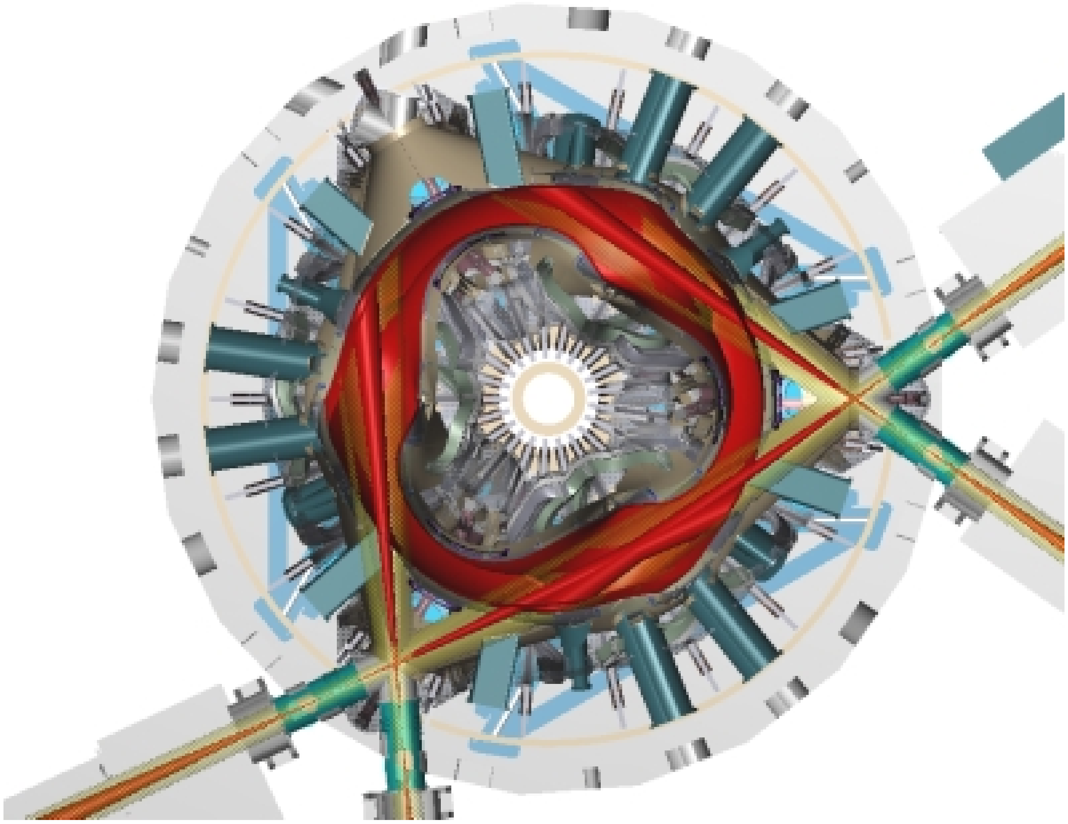


Figure 3-23 Plan view showing neutral beam access

3.2.3 Personnel access

Personnel access requirements for different stages of fabrication and operation were considered. Several of the requirements are listed below:

- During manufacture – measure, inspect, assemble, and install components
- During field period subassembly – weld/inspect ports; leak check and repair welds; install trim coils, magnetic diagnostics, and PFC's
- During final assembly of vessel – connect vessel segments; clean, leak check, and inspect; complete installation of in-vessel components
- After final assembly of vessel – maintenance and reconfiguration of internal components

Port access is limited because of the modular coils, PF coils, TF coils, and structure supporting the modular coils. The three large ports through which the neutral beams are injected are adequate for personnel access. These ports have an opening of 32 inches tall by 20 inches wide. Plan and elevation views are provided in Figure 3-22.

These ports have ample size for allowing personnel access into the vacuum vessel. However, they are less than ideal because the outboard trim coils are located in

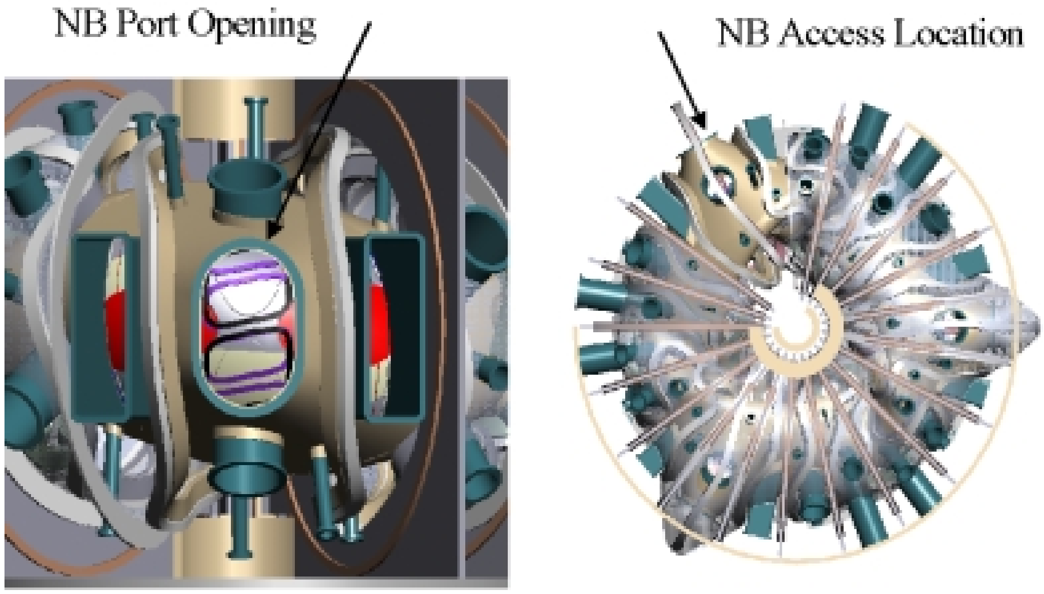


Figure 3-24 Elevation and plan views of personnel access port

front of them, blocking immediate access into the vessel interior. The trim coils and molded panels in front of the trim coils would likely have to be removed to allow entry into the vessel interior. Although in the initial configuration only one of the three ports would have neutral beams installed, it is anticipated that ultimately two or perhaps all three would have equipment installed that would block ready access to the vessel interior. For this reason, alternative routes for personnel access (perhaps through the ports adjacent to the neutral beam ports, which are also large enough to permit personnel access) will be investigated during conceptual design. In addition, NCSX engineers will work with PPPL machine technicians to incorporate features inside the vacuum vessel to improve maintainability.

3.3 Machine Assembly

Machine assembly includes all activities in the assembly of the individual field periods (one-third segments of the overall machine) plus the overall machine assembly. These activities can be divided into three areas, which include:

- Planning and oversight
- On-site pre-assembly
- Test cell and basement assembly activities

3.3.1 Planning and oversight

A Construction Manager will be appointed and will be responsible for planning and supervising all assembly activities in the NCSX test cell and test cell basement. Engineering will support field activities. The oversight and planning responsibilities will also include the pre-assembly of the three field periods in the TFTR test cell. A full time

Construction Safety Representative along with Industrial Hygienist and Quality Control will support all field activities.

Special tooling will be designed and fabricated to support the field period and machine assembly activities. This tooling will include lifting, assembly and alignment fixtures and jigs.

A platform will be designed and fabricated which will surround the NCSX device and provide support for diagnostics and improve access to the machine. This platform will be modular in design, similar to the NSTX platform, allowing for fabrication of standard parts and minimizing costs during future expansion.

3.3.2 On-site pre-assembly

The vacant TFTR test cell will be utilized for the assembly of the three field periods. The area has sufficient floor space, crane capacity, and electrical power to allow for the assembly of all three field periods in parallel. The area will also have a line from the NSTX helium bakeout system so that the individual vacuum vessel sections can be baked to 150ºC.

The modular and TF coils will be completely pre-assembled at the factory for fit-up, inspection, and testing prior to shipping. They will then be delivered to the assembly area. The Inconel vacuum vessel will be delivered in three sections plus the port extensions.

Each field period is comprised of one third of the Inconel vacuum vessel, TF and modular coils, PFC support rings, trim coils and in-vessel diagnostics. The TF and modular coils will first be assembled over the vacuum vessel (VV) segment. The vacuum vessel will then be supported (hung) from the modular coil structure. Once assembled, the port extensions will be welded onto each VV segment. PFC support rings will then be installed inside of the vacuum vessel to support the PFCs. In the initial configuration, these rings will be covered with low-Z tiles with minimal coverage of molded CFC panels.

The vacuum vessel segment will then be baked out to 150ºC and a vacuum leak check will be performed to verify the integrity of the newly welded port extensions. Following the leak check, some of the in-vessel diagnostics along with the trim coils will be installed. The field period is now ready for delivery to the NCSX test cell.

3.3.3 Test cell and basement assembly activities

The plan is to pre-assemble as many components as possible outside of the test cell. This will minimize congestion in the NCSX test cell and should decrease the assembly schedule. The machine components will be delivered to the NCSX test cell and unloaded using the 30 Ton overhead crane.

The general assembly plans are to first install and level the machine support columns. This will be followed by installing the lower support ring segments (with a fiberslip surface) and lower cryostat floor. Prior to delivering the field periods, the lower PF 3 and PF 4 coils will be positioned onto the top of the support rails.

Each of the three field periods will be delivered and positioned onto the lower support rails, which allow the field periods to be moved radially together for final fit up. The three field periods will then be carefully slid together and their vacuum vessel segments bolted together using either a Helicoflex or Viton seal.

The vacuum pumping duct will then be connected to the vessel so that the pre-operational test procedures (PTP) for pumpdown can be performed. These tests will verify the integrity of the vacuum boundary. Once these tests have been completed, the remaining components can be assembled. The lower PF 3 and PF 4 coils will be raised into position followed by the installation of the upper PF 3 and PF 4 coils. The solenoid assembly (with the PF 1 and PF 2 coils) will then be placed in position.

The remaining elements of the cryostat will then be assembled. Bus and cable runs, water-cooling lines, helium gas lines along with the liquid nitrogen lines will also be installed and connected at this time.

The machine platform will be installed in stages around the machine. Once the major machine components have been installed, the platform will quickly grow around the device to make access easier and to support auxiliary lines that will interface with the machine. In conjunction with the platform installation lighting, fire detection and fire suppression systems will be installed under the platform.

The final installations will include the neutral beams and external diagnostics, which will be installed following the completion of the platform. The radiation shield wall that surrounds the delivery area will be completed once all of the major elements of the machine have been delivered to the test cell.

3.4 Neutral Beam Heating

NCSX will re-use two of the four PBX-M neutral beamlines in its initial configuration. NCSX will be able to accommodate the other two as an upgrade. Prior to clearing the test cell, the four beamlines will be relocated to the Neutral Beam Power Conversion building at D-site for refurbishment. Upon completion of the machine assembly, two beamlines will be installed on the machine.

The beamlines will re-use existing support subsystems (power, vacuum, cryogenic, water, air, instrumentation, control, diagnostic, and computer archiving subsystems). These subsystems have not been maintained since PBX-M was last operated in FY93. In order to startup these subsystems, maintenance, repair, and integrated subsystem testing must be performed.

There is concern about starting up the neutral beam accel power rectifier and modulator. This equipment was designed in the 1970’s and is based on 1950’s technology. It is difficult to impossible to procure spares. Starting up two of the beamlines by cannibalizing parts from the accel power supplies for the unused beamlines appears feasible. However, the long-range plan is to use a modern accel power supply for the third and fourth beamlines and ultimately, for the first two as well.

3.5 Fueling, Vacuum Pumping, and Conditioning

Fuel gas can be puffed into NCSX using the legacy PBX-M gas puffing system, which includes a hydrogen purification system. The legacy PBX-M pellet injection system will be installed later, as an upgrade after first plasma. Special guide tubes will be installed for injection from the high field side during the initial machine assembly.

NCSX will also re-use the torus vacuum pumping system from PBX-M. This system consists of:

- 4 Leybold Heraeus TMP 1500 turbo-molecular pumps (TMPs)
- 4 Model 1398 belt driven backing pumps
- 1 Kinney KT 500 belt driven roughing pump

The four TMPs will initially be mounted on the two neutral beam drift ducts. A new Residual Gas Analyzer (RGA) will be installed. Routine scheduled maintenance has not been performed on these systems since CY93 and will be required prior to startup. The legacy controls will be replaced with a PLC based system.

NCSX will also provide capability for wall conditioning with glow discharge cleaning (GDC) and boronization using Trimethylboron (TMB).

3.6 Electrical Power

Electric power systems includes all work required to supply AC power to all NCSX systems. The largest component of the work is the supply of controllable DC power to the modular, TF, and PF magnets. Preliminary design studies considered many approaches, including the following:

Option 1: Use of C-site MG sets and C-site Robicon AC/DC converters;

Option 2: Relocation of existing Transrex AC/DC converters from D-site to C-site, and supply of power to same via new AC transmission from D-site to C-site;

Option 3: Procurement of new AC/DC converters for C-site, and supply of power to same via new AC transmission from D-site to C-site;

Option 4: Use of existing Transrex AC/DC converters at D-site with DC transmission from D-site to C-site:

a) Segregated completely from NSTX, no shared power supplies

b) Use of C-site MG and Robicon equipment where possible

c) Sharing of power supplies with NSTX

After careful study, Option 4c was identified as the most cost effective and technically attractive option. It was determined that sufficient D-site power supplies were available, with some sharing with NSTX, such that all of the three reference scenarios (the Day One, 1.2T, and 1.7T reference scenarios) can be supplied with the baseline design. Switchover of systems shared between NSTX and NCSX can be accomplished in a matter of minutes, but must be limited to, nominally, one operation per day in order to

Table 3-7 Ratings of the AC/DC converter systems

Circuits	Full Load Current (kA)	No-Load Voltage (kV)	Comments
M1, 2, 3, 4	+24	+/-2	Each circuit independently controllable; shared with NSTX TF
PF1	+/-24	+/-8	Shared with NSTX OH
PF2	+/-24	+/-2	
PF3	+24	+/-2	
PF4	+24	+/-2	
TF	+/-24	+/-2	
Trim1,2,3,4	+5	+/-0.3	

limit the number of times that the isolating switches are cycled. Ratings of the AC/DC converter systems supplied are provided in Table 3-7.

3.7 Central I&C and Data Acquisition

Central I&C and Data Acquisition provides the global man-machine interface for all facility and physics subsystems such as:

- High energy subsystems
- Safety systems
- Facility timing and synchronization system
- Power conversion feedback control systems
- Cooling systems
- Diagnostic systems
- Auxiliary heating subsystems

The Experimental Physics and Industrial Control System (EPICS) will be the software base for this function. Also provided will be a convenient interface to the data acquisition and data management systems, allowing the acquisition, display, analysis, archival, and restoration of NCSX shot data. The MDSplus software from MIT will be used for data acquisition functions. This work package will also provide the physical control room environment, which will include the workstations and furniture for physics, engineering, and operations staff.

The communications backbone will be an extensive TCP/IP network infrastructure running at a minimum of 100Mbps. All NCSX facilities and physics subsystems will use this common communications highway. Several classes of networks will be deployed which will provide varying degrees of security depending on the importance of the connected subsystems. A new timing and synchronization system, with the flexibility of the old TFTR system, will be designed and deployed for all machine timing requirements. All instrumentation will be based on modern PC technology and the PCI bus in the form of Compact PCI (CPCI), PXI, and some VME. All the instrumentation electronics and computers required for diagnostic subsystems will also be provided.

3.8 Site and Facilities

3.8.1 Site preparation

Site preparation includes all activities associated with the preparation of the NCSX test cell and those areas that will be required to support the operation of the NCSX device, including:

- Facility modifications outside of the test cell
- Preparation of the test cell
- Seismic reinforcement of the test cell shield walls.

3.8.1.1 Facility modifications outside of the test cell

The vacant PBX/PLT control rooms will become the home of the new NCSX control room. The existing facilities will be cleared. All of the wiring systems will be electrically safed, followed by the removal of wiring, cables, trays, control consoles, etc. Both the ceiling and raised floor will also be discarded and replaced, including new lighting and electrical panels throughout the control room. The adjacent PBX computer room will also be cleared and the walls separating the computer and control rooms removed. Once the walls have been reconfigured and the ceiling and floor replaced, the control room will be refurbished.

Other areas outside of the test cell, which will be modified, include the 2nd floor of the D-site FCPC building and the vacant TFTR test cell. A great deal of activity will occur in the 2nd floor of the FCPC building at D-site. It is from this area where the power required by the NCSX coil systems will originate. The 2nd floor presently houses a number of occupied offices plus the vacuum prep laboratory. The laboratory will remain in its present location. However, the offices along with the personnel will have to be relocated. The office walls will be removed. Twenty 6" diameter penetrations will have to be added through the FCPC concrete floor along with a large weatherproofed wall penetration for the exiting power cables.

The field period assemblies will be assembled in the vacated TFTR test cell at D-site. The facility already has sufficient floor space, lighting, power and crane capacity. However, it will be necessary to bakeout each of the vacuum vessel segments during the assembly of the field periods. The NSTX Helium Bakeout System will be utilized for bakeout. It will be necessary to extend the bakeout lines approximately 100 feet to the field period assembly area.

3.8.1.2 Preparation of the NCSX test cell

The NCSX test cell is the location of the combined PLT and PBX test cells at C-site. The PLT device has already been removed, but the PBX machine along with its diagnostics and neutral beams, remains intact. The area will first be electrically safed by

PPPL or electrical contract personnel. Major electrical components such as panels and circuit breakers will be salvaged for future use on NCSX. The bulk removal of the cables and trays will be performed later as part of a bulk removal operation. Prior to bulk removal of the PBX device, all lead and hydraulic fluids will be removed. There is presently approximately 16,000 pounds of lead shielding which will be removed by PPPL personnel along with all of the hydraulic fluids from pumps along with the TF hydraulic joint clamps.

Once these operations have been completed, the PBX device along with remaining diagnostics, bus systems, coils, structure, vacuum vessel, cables, and trays will be removed by a contract salvage firm. Preliminary indications are that the contractor will perform these activities at no cost to PPPL, as was done for PLT.

The existing radiation shield walls between the PLT and PBX test cells will be removed, which will increase the size of the NCSX test cell. Additional shielding around the delivery high bay area will also be removed to expedite the removal of the PBX device along with assembly of the NCSX.

3.8.1.3 Seismic reinforcement of the test cell shield walls

Once the PLT and PBX test cells have been cleared, and prior to starting the assembly of NCSX, the remaining shield walls will need to be seismically reinforced. It may also be necessary to increase the height of the shield walls on the East, West and South walls to reduce shine associated with operations. The shield wall surrounding the delivery area will be completed once the major components for the NCSX device have been delivered.

3.8.2 Heating, cooling, and utility systems

The vacuum vessel is bakeable to 150ºC with a nominal operating temperature of 20ºC. Inside the vacuum vessel is a stand-alone liner that ultimately will be covered with molded CFC panels. The liner is bakeable to 350ºC with a nominal operating temperature in the range of 20ºC to 150ºC. The vacuum vessel and liner will be connected to helium systems capable of independently controlling their temperature. This requires that the systems have both a heating capability (for bakeout and to maintain the temperature during standby operation) and a cooling capability (to remove heat deposited by the plasma between pulses).

Cooling water is required by numerous systems, including:

- Neutral beams
- Vacuum pumping
- Diagnostics
- Vacuum vessel and liner heating and cooling systems

Each of these cooling loops will be connected to the existing C-site water system.

3.8.3 Cryogenic systems

The modular, TF, and PF coils on NCSX are located within a common cryostat and pre-cooled to liquid nitrogen temperature (80K) before operation. A liquid nitrogen supply system is provided to remove heat from the structure and from the nitrogen environment within the cryostat. The coils within the cryostat will be cooled by helium gas. The helium gas will be pre-cooled to 80K in a liquid nitrogen heat exchanger.

The liquid nitrogen system is a once through system. Upon vaporization, the nitrogen exhaust will be heated and vented to the atmosphere. A 15,000-gallon tank will be installed at C-site for storage of liquid nitrogen. If required, a second 15,000-gallon tank can be installed at a later date.

3.8.4 Utility systems

Compressed air, gaseous nitrogen, and vacuum venting systems will be provided in the NCSX test cell. Manifolds will encircle the machine to provide access to these systems at each bay. The vacuum vent will connect to the vacuum pumping system, which is in the basement beneath the experiment.