9. THE QPS FACILITY

9.1. Introduction

The proposed Quasi-Poloidal Stellarator, QPS, is a small, low aspect ratio, concept exploration experiment with a non-axi-symmetric, poloidally symmetric magnetic configuration. The nominal QPS design parameters are <R> = 0.9 m, <a> = 0.35 m, B = 1 T, and 0.5-s pulse length. The facility consists of the stellarator core, the plasma heating, diagnostics and data acquisition systems, the power supplies and cooling systems, and the test cell.

The stellarator core consists of the modular coil set that provides the primary magnetic field configuration, auxiliary coils including vertical field, toroidal field and an ohmic heating solenoid, machine structure, and a vacuum vessel, as shown in Figure 9.1-1. The modular coils represent the most difficult part of the facility design and fabrication. The coil set has two field periods with 8 modular coils per period. Due to symmetry, only four different coil geometries are required. Several fabrication options are under consideration, but the baseline concept uses flexible copper cable conductor wound on a form and vacuum impregnated with epoxy. The coil form also provides the support features that allow the coils to be connected into an integral structure.

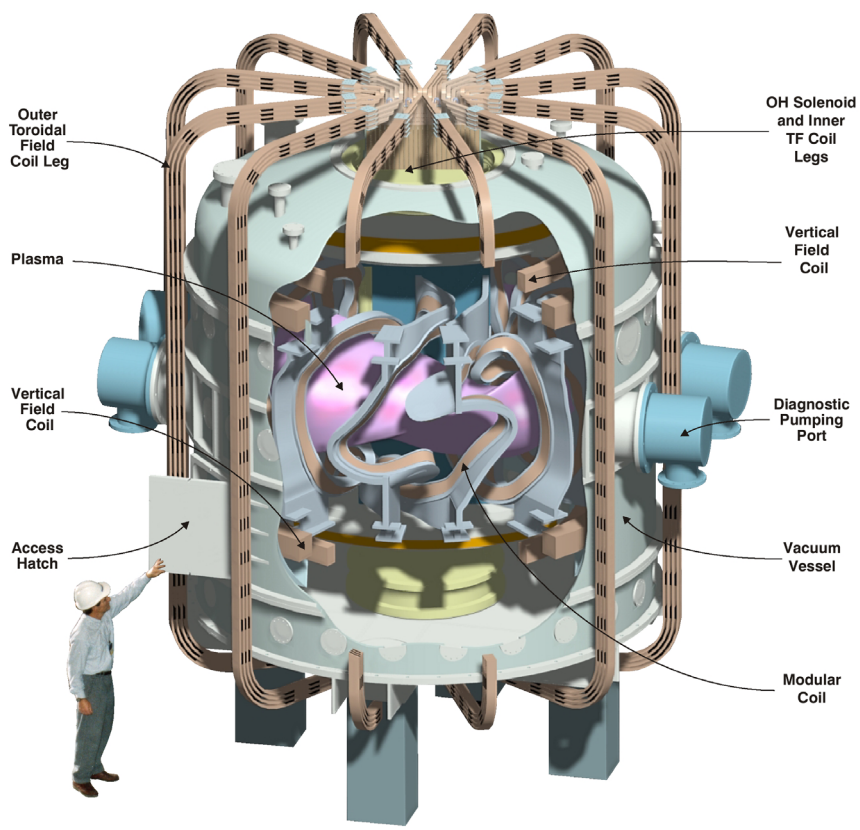


Figure 9.1-1 The QPS facility stellarator core

The vacuum vessel is an existing, external "bell-jar, with the modular coil set and vertical field coils in the same vacuum region as the plasma. This approach has been commonly used for small experiments, such as the H1 device in Australia. The coils must be canned for compatibility with the vacuum, but inside the vessel there is good access between the modular coils for plasma diagnostics and heating.

The QPS device would be located in a new building in the 7600 area of ORNL (near the X-10 site). Existing long pulse plasma heating systems (0.6 MW ECH, 3 MW ICRF), power supplies (>40 MW), de-mineralized water system, and other equipment are available for this experiment.

The QPS device is estimated to require 4 years from start of design to first plasma. Status of the engineering design and analysis are described in the following sections.

9.2. General approach

QPS is a small concept exploration experiment intended to investigate a compact stellarator configuration with quasi-poloidal symmetry. The coil set consists of modular stellarator coils, 3 pairs of vertical field (VF) coils, an ohmic heating (OH) solenoid, and a set of toroidal field (TF) coils. The nominal device parameters are listed in Table 9.1. The concept exploration mission imposes some additional constraints on the QPS device, which include:

Minimum cost
Short schedule (~ 4 years for first plasma)
Maximum flexibility, including access for diagnostics and heating
Maximum use of existing facilities and equipment

Table 9.1 QPS General Design Parameters and Requirements

Parameter	Value
Major radius, R_o	0.9 m
Minor Radius, a	0.35 m
Aspect ratio, R_o/a	2.6
Toroidal field at R_o, B_o From modular coils From TF coils	 1 T +/- 0.15 T
No. of Field Periods	2
No. of Modular Coils	16
Plasma current, I_p	<70 kA
Flattop Pulse length	~0.5 s
Auxiliary drive power, P_{aux}	1-3 MW
Coil resistive power, P_{res}	$\leq$ 50 MW
Total s.s. heat removal, P_{cool}	$\leq$ 2 MW

9.3. Determination of Device Parameters

The QPS device parameters (magnetic field, pulse length, average major radius, auxiliary coil sets, and heating power, are set by a combination of physics and practical considerations, including mechanical constraints, available equipment, and cost. Here we describe the reason for these choices.

Average magnetic field on axis $\langle B_{axis} \rangle = 1$ T. The available high-power plasma heating systems are designed for 1-T operation. Restricting the magnetic field to 0.5 T would preclude use of the 0.6-MW 53.2-GHz ECH system, which is resonant at the second electron cyclotron harmonic at $B = 0.95$ T, or use of the 1.2-MW 28-GHz ECH at the fundamental resonance at $B = 1$ T. The cutoff density varies as B^2, so there is a factor of 4 difference in the density achievable with ECH between operation at $B = 0.5$ T and $B = 1$ T. The "maximum" useful density with ion cyclotron range of frequency (ICRF) heating or electron Bernstein wave (EBW) heating is related to the Sudo density "limit" $n_{Sudo} = 2.5[PB/Ra^2]^{1/2}$. This density "limit" is nominally the density at which the stored energy no longer increases with increasing density, however, the best results are obtained at densities up to twice this value in LHD. The combination of power availability and operating density make a significant difference in the plasma parameters expected with the standard stellarator confinement scaling, ISS-95 [R],

$$\tau_E^{ISS95} = 0.079 a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4},$$

Confinement times up to ~2.5 times this value are now obtained on W 7-AS and LHD.

Flat-top pulse length $t_{flat\text{-}top} = 0.5$ s. The current waveform and flat-top time are determined by the coil parameters, the power supply, and the coil heating from a base temperature. Figure 9.3-1 shows the modular coil current waveform for different coil temperature ranges. About 1 s is required to reach $B = 1$ T with the existing power supplies and about 0.75 s is required for ramping the current back to zero, so very little is saved by having a short flat-top time. A flat-top time of ~0.5 s is needed to allow time for eddy currents in conducting structures (the aluminum vacuum tank and the coil cases) and plasma currents (bootstrap and Ohmic) to come to equilibrium and to keep the temperature rise in the modular coil conductor to a reasonable value. The coil temperature rise and the plasma heating systems allow long-pulse operation at half field.

Average major radius $R = 0.9$ m. Since the machine cost increases with size, we set the major radius at the minimum value compatible with the QPS physics goals and engineering constraints. The limiting factor is the minimum distance needed between the modular coils so coils do not overlap. The minimum distance between the filamentary coils, $\Delta_{c\text{-}c}$, is determined by the coil optimization discussed in Sect. 4.3, but the minimum distance between actual coils is determined by the width w and radial depth d_r of the finite-cross-section modular coils. Both the width and the depth are important because of the twist of the coils, so the diagonal length d of the winding pack is the relevant scale. The optimum aspect ratio of the coil cross section, $\mathcal{A}_c = d_r/w$ and

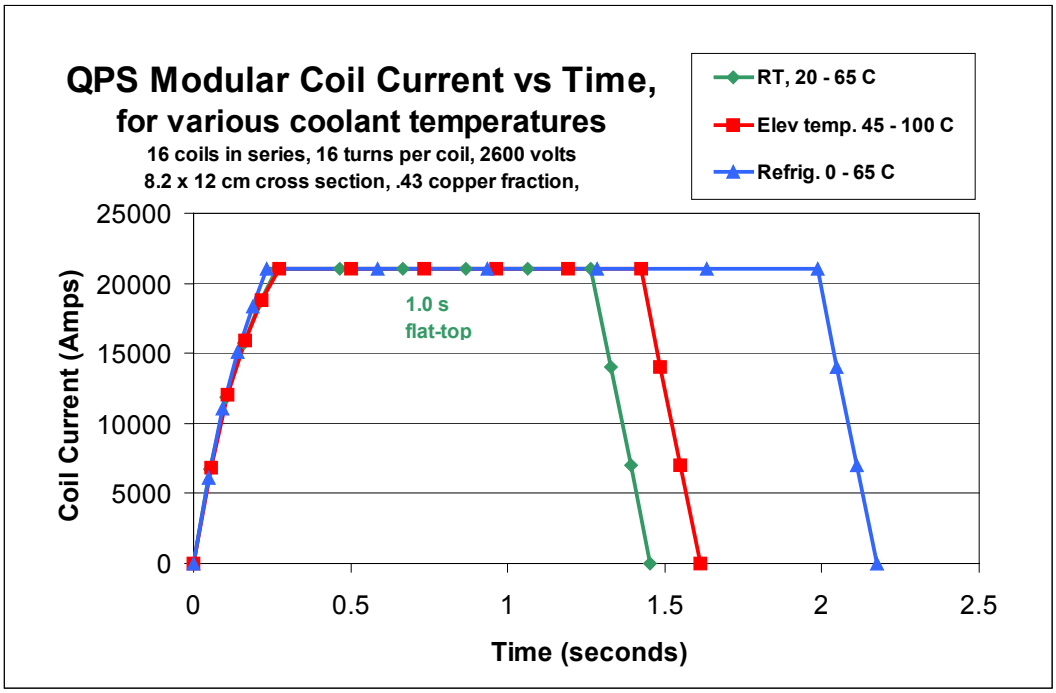


Figure 9.3-1. Modular coil current flat-top time depends on the initial temperature of the coils.

hence d, is set by engineering constraints. Here $d = [R\langle B\rangle(1 + \mathcal{A}_c^2)/(2\mathcal{A}_c N_{coils} j)]^{1/2}$ where N_{coils} is the number of modular coils and j is the current density in kA/cm^2 averaged over the coil winding pack.

For a given coil geometry, $\Delta_{c\text{-}c}/R = K$ is a constant and the minimum value of R is set by

$$R_{min} = d/(\Delta_{c\text{-}c}/R) = \langle B_{axis}\rangle(1 + \mathcal{A}_c^2)/(2\mathcal{A}_c N_{coils} K^2 j) \propto 1/K^2 j.$$

The fact that $R_{min} \propto 1/K^2$ is the reason why we have put emphasis on increasing $\Delta_{c\text{-}c}/R$ in the design of the modular coil set. More effort will be placed on shaping the modular coil cross section and orienting the winding pack where the modular coils come closest to each other. Once R has been reduced to the point that adjacent modular coils touch, as in the reference QPS design, further reduction in R can only be reduced by increasing j.

<u>Coil current density j and coil operating temperature</u>. Only about 44% of the modular coil cross section is occupied by the winding; the rest is structure and winding form. The maximum value of j is set by the allowable coil temperature and power supply limits. Figure 9.3-2 shows the required start temperature for the QPS modular coils for three conditions: a peak temperature of 65 C (limit for room-temperature-cured epoxy), 100 C, and the 2600-V limit for the power supplies. The maximum practical current density in the conductor is ≈8.4 kA/cm^2 (only about 44% of the modular coil cross section is occupied by the winding; the rest is structure and winding form). Higher current density requires operation of the coils below room temperature.

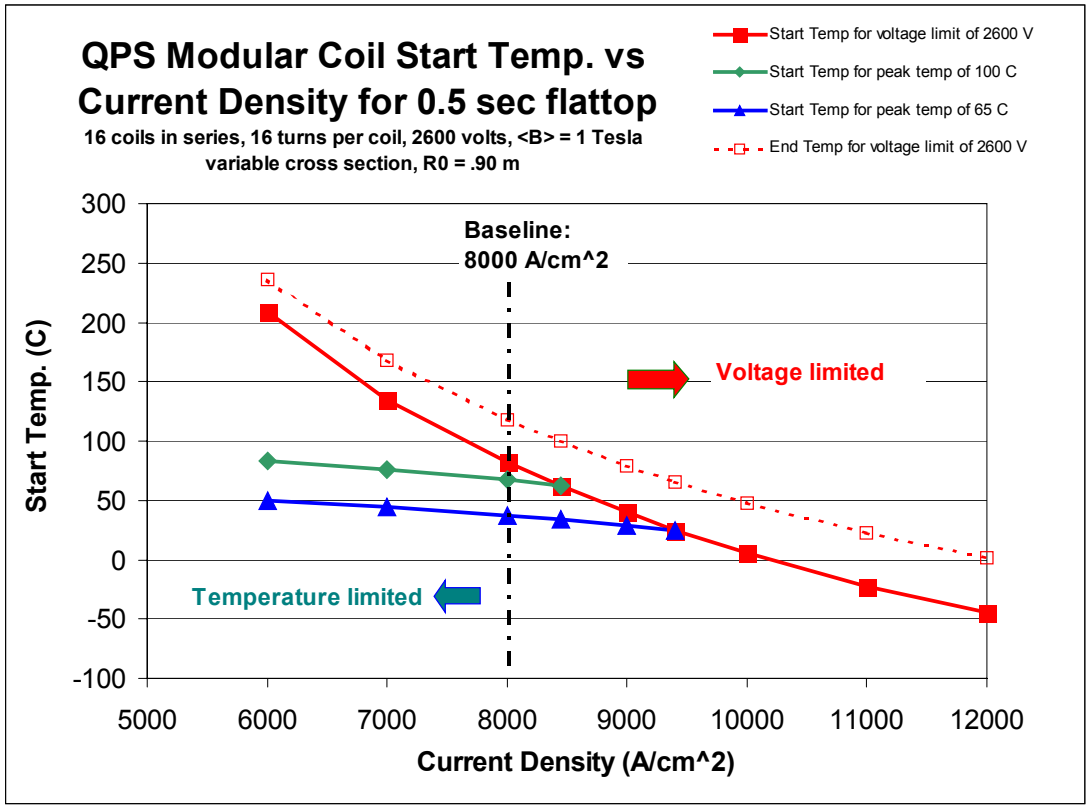


Figure 9.3-2 Operating temperature and power supply constraints for the QPS

As discussed in Chapter 10, even a 20 C temperature difference (start temperature of 0 C) results in a large differential collection of condensables on the coils, which would come off into the plasma during a discharge. The benefit in current density is small, ~5%, and a costly vacuum liner would be required. Lowering the temperature to get a significant increase in current density requires thermal insulation to reduce the heat loss in addition to the vacuum liner. The most cost effective solution is to operate with room-temperature coils, which limits the current density to ≈8.4 kA/cm^2. Lower current density, which would ease the construction of the coils, would result in a larger *R* and more cost.

Heating power: 0.5 MW initially, increasing to 3 MW. The existing ECH systems provide 1.2 MW at 28 GHz and 0.6 MW at 53.2 GHz. The ECH power will be phased in started with 0.5 MW (two sockets) and increasing to 1 MW (four sockets) after initial operation. The existing ICRF systems provide 2 MW at 6--20 MHz and 1.5 MW at 40-80 MHz. A reasonable goal is 2 MW of ICRF power in the second stage of operations.

External vacuum vessel. A large existing vacuum tank is chosen as the QPS vacuum vessel. While an internal vacuum vessel is the more conventional approach for maintaining good vacuum conditions, it has several serious drawbacks for application to QPS. Because the shape of the inner bore of the modular coils changes dramatically (from bean-shaped to comma-shaped to triangular) in half a field period, an internal vacuum vessel must have a similarly contorted

shape. However, in this approach, it is necessary to allow sufficient space between the vacuum vessel and the modular coils to allow the modular coils to slide over an interior vacuum vessel during assembly. The modular coils cannot be jointed because of the current density required. Because the shape of a modular coil differs from the vacuum vessel over most of a field period, extra space must be allowed between the vacuum vessel and the coil bore, which reduces significantly the space between the plasma and the vacuum vessel. In addition to the complex coil assembly process, the many sections of an interior vacuum vessel must be welded together, which presents difficulties for the last sector that is welded, and the ports must be welded to the vacuum vessel after the modular coils are installed. The ports would severely limit access for heating, diagnostics, and in-vessel components such as divertor plates, and it is not possible to have personnel access into an internal vacuum vessel in the QPS case. Care must be taken in the fabrication and welding of an internal vacuum vessel to ensure that the permeability of the vacuum vessel remains low and that there are no leaks due to the many welds. This results in an expensive vacuum vessel and extra cost in the assembly process.

In contrast, the existing external vacuum vessel allows assembly of the modular coil set without the constraint of an interior vacuum vessel, as illustrated in section 9.7, and allows maximum access to all parts of the interior of the vacuum tank for installation of in-vessel components such as divertor plates, ICRF antennas, diagnostics, etc. The extremely good access is important for diagnostics in taking advantage of various sightlines through the plasma and access to the different sectors of a field period through the large open areas between the modular coils. The large interior volume allows large-area gettering for high effective pumping speeds. The external vacuum tank approach has been used successfully on a number of experiments.

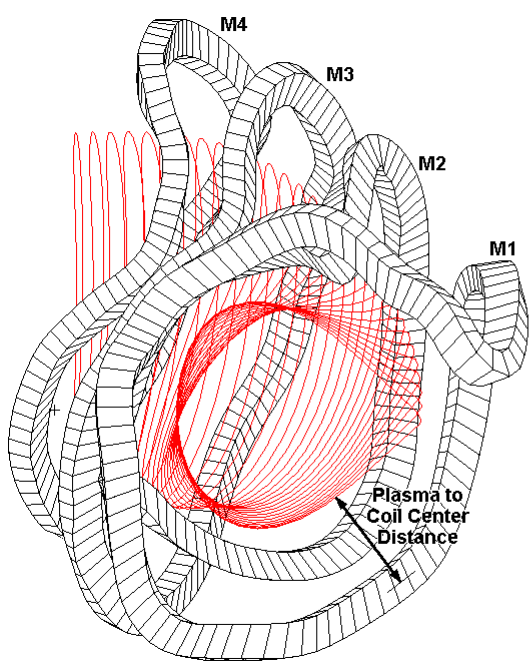
There are also some disadvantages with this approach. Because the coil sets are inside the vacuum tank, they must be vacuum canned, and it is more difficult to bake the in-vacuum components and maintain good vacuum quality. However, various standard techniques can be used to ensure adequate vacuum quality, as discussed in Chapter 10.

9.4 Modular Coil Set

The modular coil set consists of two field periods with 8 modular coils per period. Due to symmetry, only four different coil shapes are required. . The coil winding geometry, generated using physics optimization codes, must be expanded from a single filament path to a solid model geometry with a finite cross section capable of carrying the required current. This is accomplished with a code that orients the cross section to be approximately normal to the outermost plasma surface, but optimizes the twist of the coils for better coil-to-coil nesting. For QPS, the winding surface is not a simple offset from the plasma surface, but is generated as part of the coil optimization procedure and ranges well away from the plasma in some locations. Figure 9.4-1 illustrates the plasma to coil distance variation.

The finite cross section modular coil set with plasma is illustrated in Figure 9.4-2, and the modular coil parameters are listed in Table 9.4-1.

Table 9.4-1 Modular Coil Parameters



Coil	Minimum Coil Center to Plasma Distance (cm)	Maximum Coil Center to Plasma Distance (cm)	Average Distance (cm)	Max/Min Ratio
M1	20.4	42.5	30.5	2.1
M2	13.7	37.2	24.1	2.7
M3	14.3	40.5	26.3	2.8
M4	14.9	35.8	25.3	2.4

Figure 9.4-1 Distance from QPS flux surface to coil winding center

Parameter	Value
No. of Field Periods	2
No. of Modular Coils	16
Toroidal field at R_o, B_o	1 T
Current per coil	337 kA
Average winding length	5.07 m
Winding cross section	~100 cm^2
Copper packing fraction in cable	70 %
Winding accuracy	+/- 1 mm
Coil circuit resistance (all coils, bus and power supply)	91 m-ohm
Coil circuit time constant (all 16 coils)	0.2 s
Coil resistive power, P_{res}	~ 45 MW

This coil set geometry is preliminary but has relatively good engineering properties. One of the

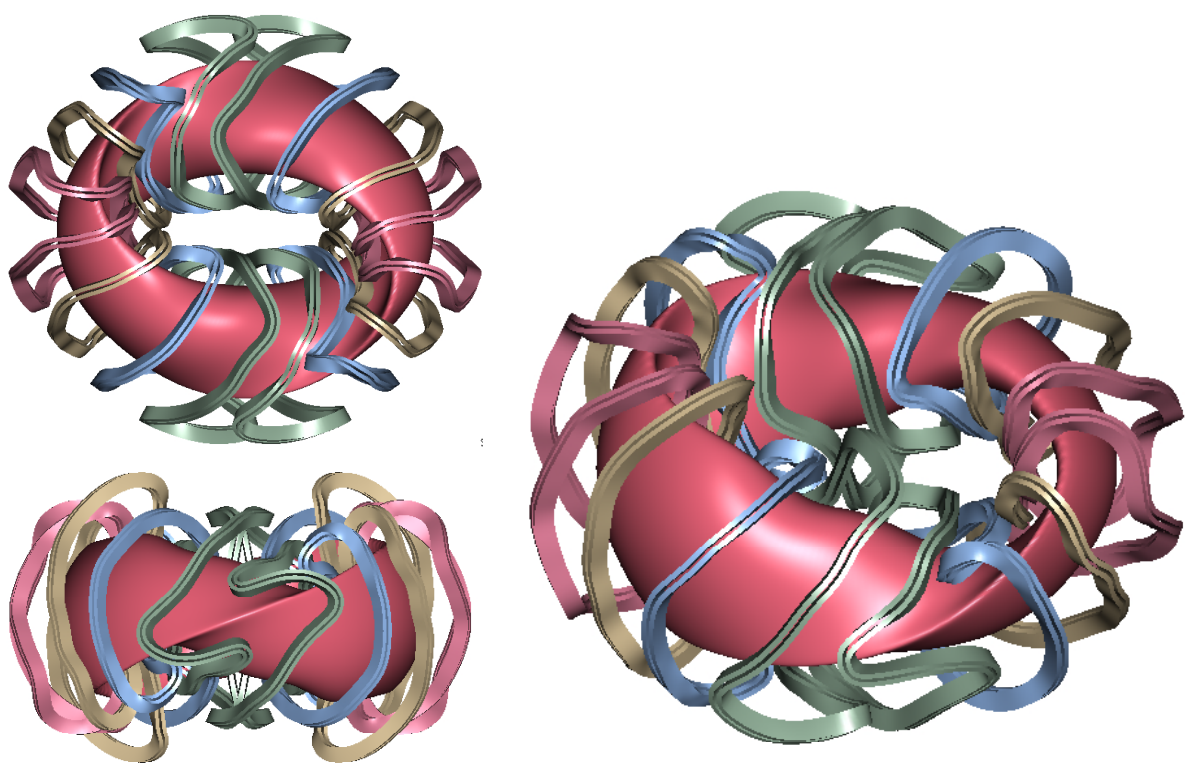


Figure 9.4-2 QPS finite cross-section coil winding geometry

most important properties is sufficient bend radius to avoid "kinking" of the cross section. This problem is often not apparent for the filament models of the coils, but can appear when finite cross sections are modeled. In addition to "kinking", there are constraints associated with interference between adjacent coils as well as limits on the proximity of the coil to the plasma. Space must be provided for the coil structure, winding cross section, tolerance, and vacuum enclosure. Additional space may be needed in certain areas to accommodate FW structures. As the design progresses, a number of iterations will be necessary to ensure that the physics performance goals and engineering constraints are both satisfied. Most of these engineering constraints have already become part of the coil winding path optimization process. Figure 9.4.3 compares the winding shape for each of the four coil types.

Several fabrication options are under consideration for the modular coils, but the baseline concept uses flexible, copper cable conductor wound on a form and vacuum impregnated with epoxy. The coil form also includes the support features that allow the coils to be connected into an integral structure. The primary support feature is a contoured "I-beam" shape that follows the shape of the coil winding. The windings are laid up by hand on either side of the "I-beam" web, as shown in Figure 9.4-4.

The winding form structure is fabricated as a casting. Due to the complexity of the shape, the pattern geometry must be tested and iterated to obtain a net accuracy within 5mm of the true shape anywhere in the section. At this point the casting is stress relieved in a fixture and re-measured. Reference points are located, and all the structural interface features are machined. Instead of making the winding cavity undersized and contour machining it to the required size and accuracy, the cavity would be 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 these would be accurately positioned in the casting. The space between the winding pattern and the structure would be filled with an epoxy grout. The pattern

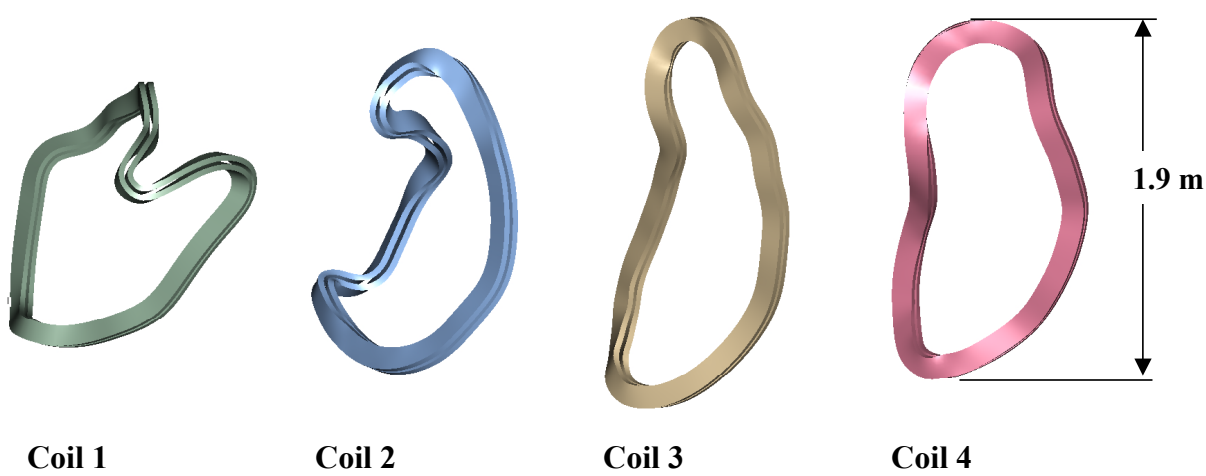


Figure 9.4-3 Modular coil shapes

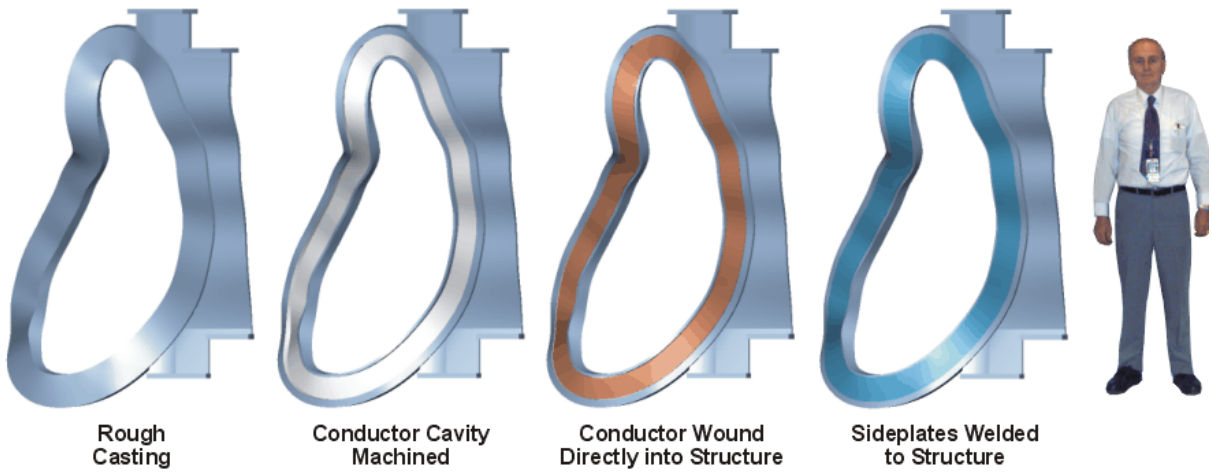


Figure 9.4-4 Winding and cast structure for modular coil

would be removed leaving a very accurate, molded winding cavity. This idea is illustrated in Figure 9.4-5. In some areas, where the windings are very close together, there may not be room for the epoxy grouting. In these areas the web of the I-beam would be locally machined to exact size. Of course, a fully machined winding cavity would be considered if the cost were favorable.

The preferred option for the conductor is a flexible cable design. A typical design would consist of a standard braided cable of fine copper wire (36 gage, for example) that would be pulled through a "turks head" into a rectangular cross section. The conductor would be wrapped with fiberglass tape and hand wound into the winding cavity of the coil form. Once a single layer of conductor is in place a series of chill plates are installed and the second layer of conductor is wound into place. 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 is impractical for the turn lengths needed for QPS. Gas cooling is used to avoid electrical failure modes common to water cooled coils.

After winding is complete, the final geometry is verified and the assembly is vacuum pressure impregnated with epoxy to complete the insulation system. 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 up to 75% can be assured, although 80% is theoretically possible. The design is based on a packing fraction of 70%. A second disadvantage is that the conductor has little inherent strength, and

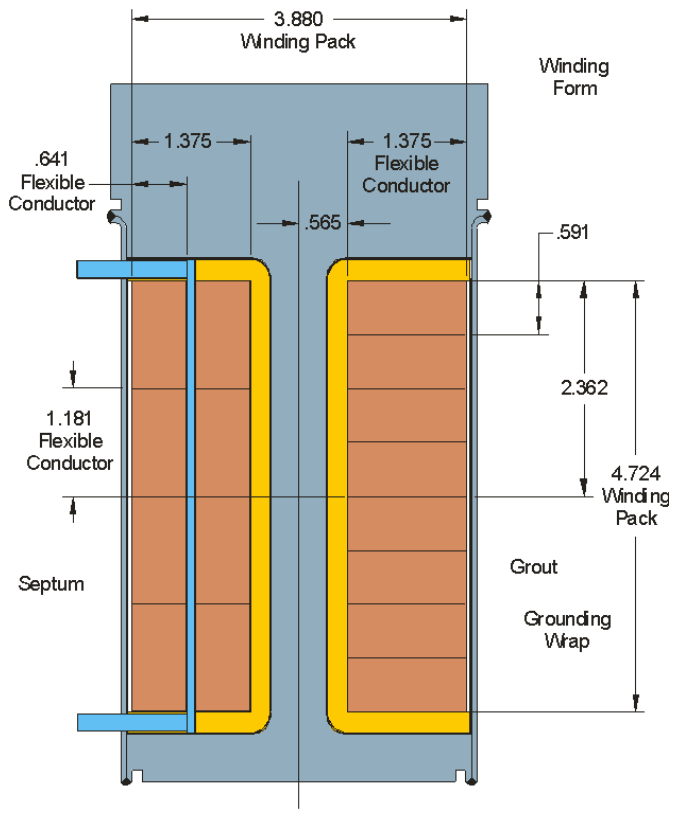


Figure 9.4-5 Modular coil winding cross section

must be almost continuously supported by the integral coil structure. Other winding options, such as a "dry cable": design with no epoxy impregnation, have been considered but these would require significant R&D to provide confidence that conductor motion would not cause fatigue failure. It is very unlikely that a winding using all solid conductor would be feasible due to the highly contoured winding path. Finally, this system requires a slightly compliant layer between the outside of the coil and the winding form to accommodate relative thermal expansion.

After the winding pack is completed, thin side sheets are welded in place to provide a high-vacuum "can" for the windings. This step must come after the epoxy impregnation to allow vacuum leak checking of the can and to avoid contamination of the winding during welding. Some development will be required to insure that no distortion of the coil occurs during the welding process. In local areas requiring reinforcement, intermittent ribs are bolted to the flanges of the "I-beam" as structural retainers for the windings.

The modular coil windings will be cooled with room temperature gas, but additional performance may be possible by using refrigerated gas below room temperature. Figure 9.4-6 illustrates the dependence of pulse length on coolant schemes, including cryogenic cooling, and on current density. The current density in the copper for the modular coils is a function of number of turns, packing fraction of the cable, insulation thickness, and chill plate thickness.

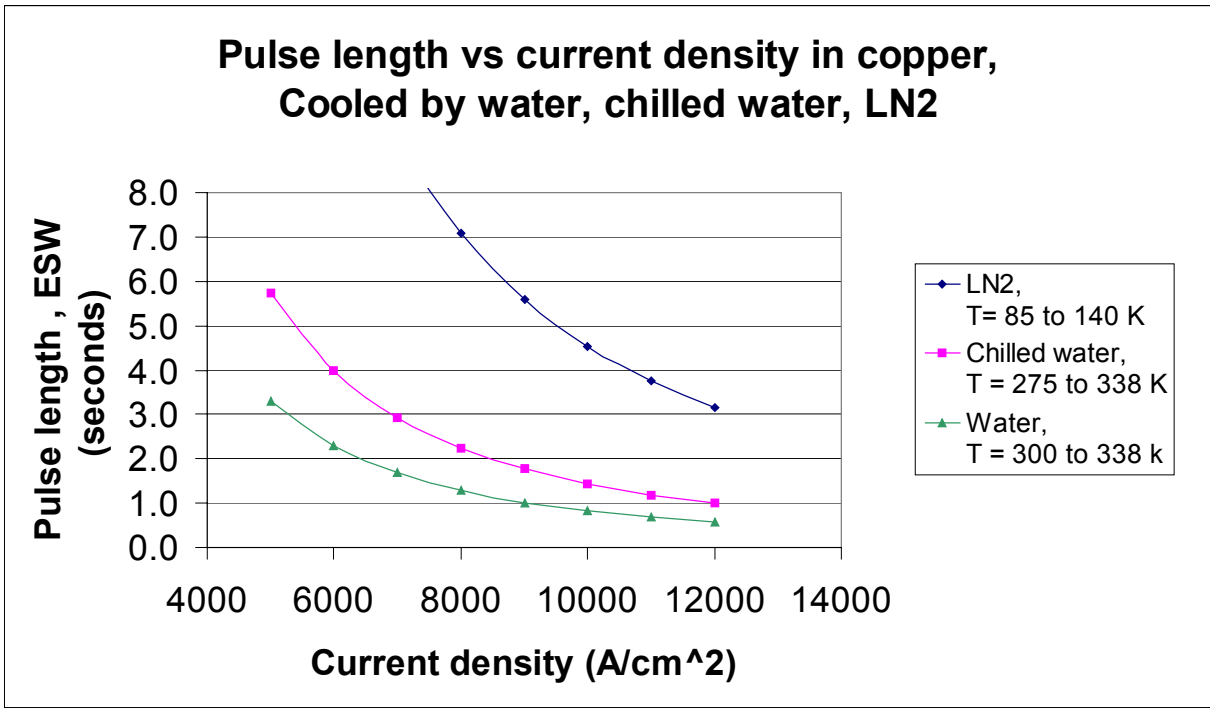


Figure 9.4-6 Pulse length vs current density in copper for various coolants

Figure 9.4-7 shows the range of current density as a function of number of turns and copper packing fraction. The design point is 16 turns with a cable packing fraction of 70%, yielding a net current density of about 8 kA/cm^2.

The modular coils are powered in groups of four by a set of existing solid state power supplies. The goal is to allow the current in any set of four coils can be independently controlled from 0 to 125% of the nominal value. The pulse length depends on the operating temperature of the coil set, the current density in the copper, and the voltage available from the power supplies. The basic electrical characteristics of the modular coils are listed in Table 9.4.2. Since the coils are located in a vacuum, they can be operated over a wide range of temperatures. As illustrated in Figure 9.3-1, reducing the temperature only slightly below room temperature can have a marked effect on the flattop time, and taking the coils to cryogenic temperatures enables flattop times of several seconds. The total power as a function of current density is shown in Figure 9.4.8.

The coil leads will consist of commercial coaxial conductor routed through vacuum conduit, where the coil sets will be connected in groups of four. Cooling gas will flow through the conduit to supply the coils. The coil return gas will flow through a separate pipe.

Table 9.4-2 Electrical parameters for modular coil set

Parameter	Coil 1	Coil 2	Coil 3	Coil 4
Single turn length, m	5.97	4.93	4.82	4.57
No of turns	16	16	16	16
Max current / turn, kA	21.1	21.1	21.1	21.1
Resistance at RT, m-ohms	6.2	5.1	5.0	4.7
Circuit resistance, m-ohms	26.5	22.2	21.8	20.7

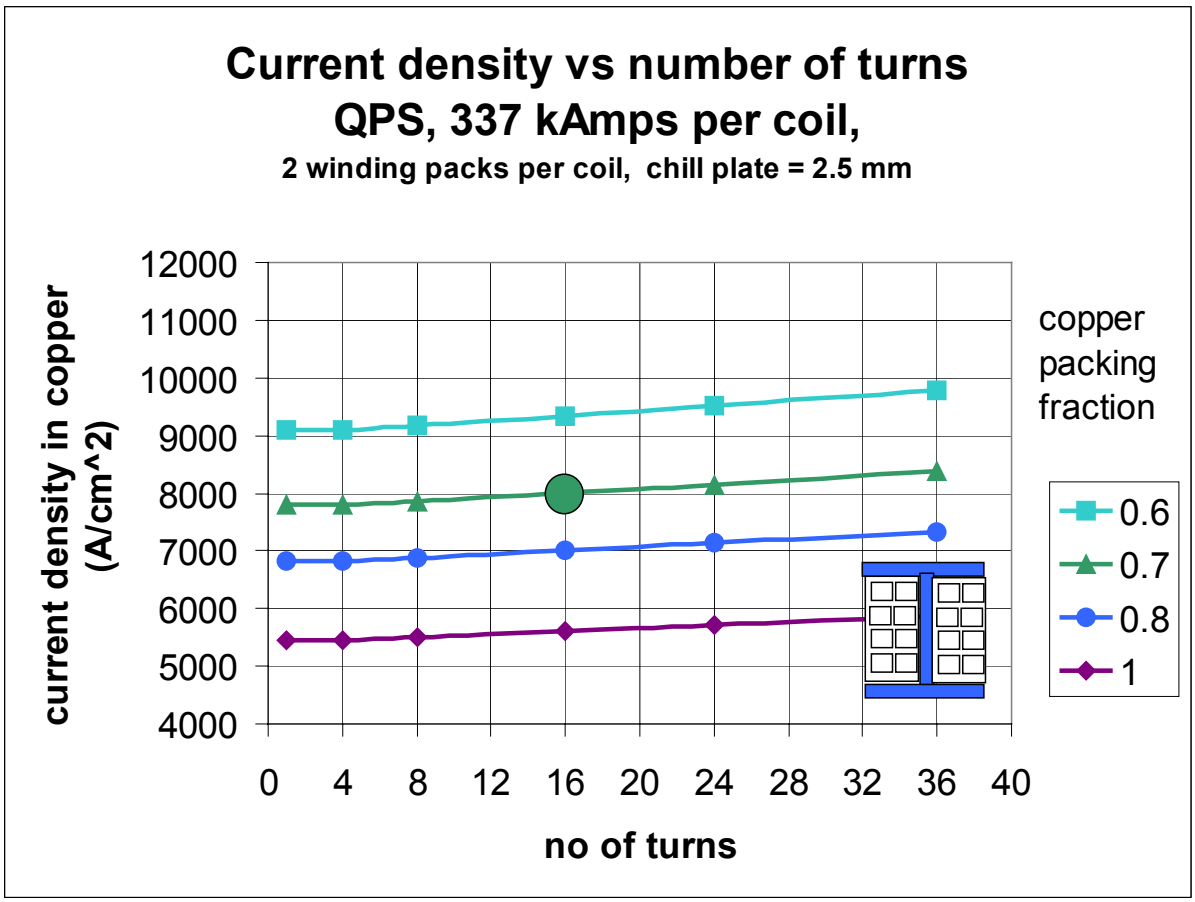


Figure 9.4-7 Current density vs number of turns for various values of packing fraction in copper

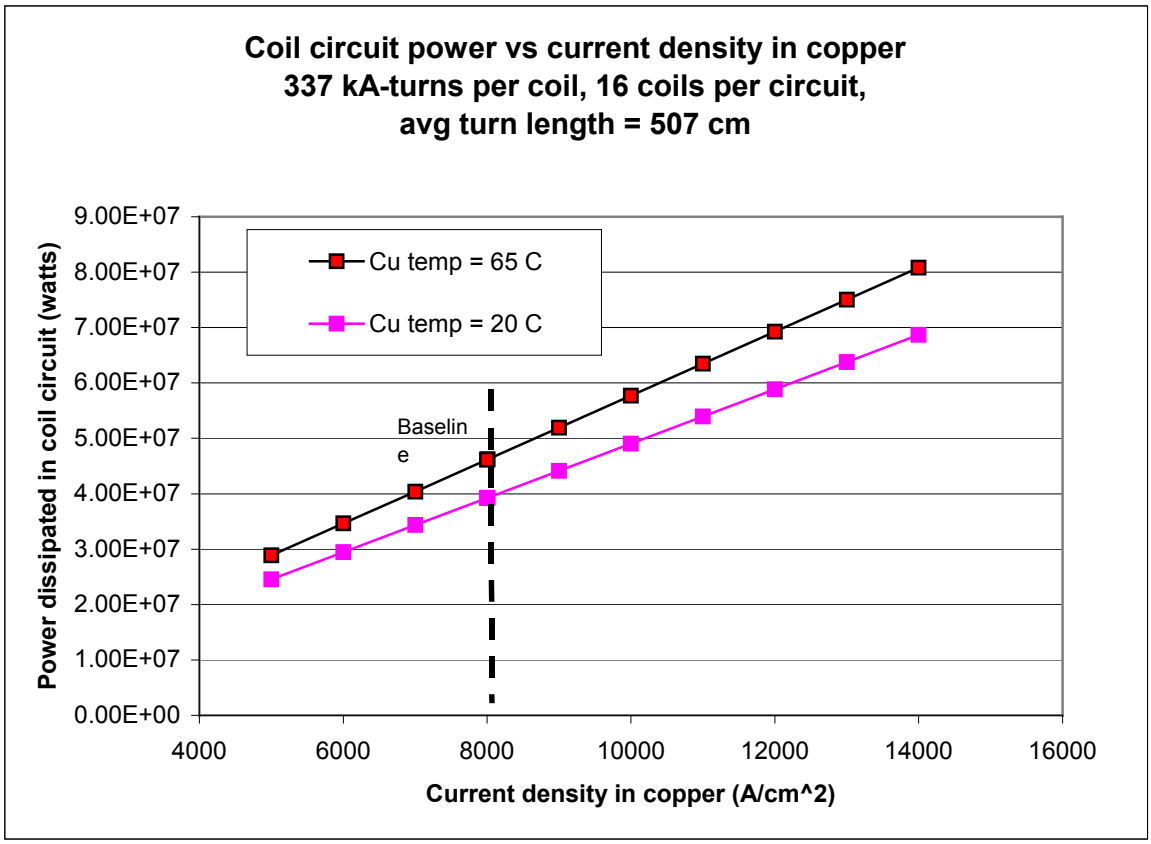


Figure 9.4-8
Modular coil resistive power vs current density for two operating temperatures
16 coils, average turn length = 5.07 m

9.5 Auxiliary coils: OH, VF, and TF coils

Three pairs of vertical field (VF) coils, an ohmic heating (OH) solenoid, and a set of toroidal field (TF) coils are provided in addition to the modular coils to reduce errors and for enhanced experimental flexibility. As shown in Figure 9.5-1, all these coils are located outside the modular coil set. The OH solenoid and inner legs of the TF coil set are contained in a centerstack assembly that occupies the center of the bell jar vacuum vessel. This arrangement allows these coils to operate in air, eliminating the need for vacuum electrical feed-throughs and separate vacuum jackets. The inner and mid VF coils will require vacuum jacketing because they are located inside the main vacuum vessel.

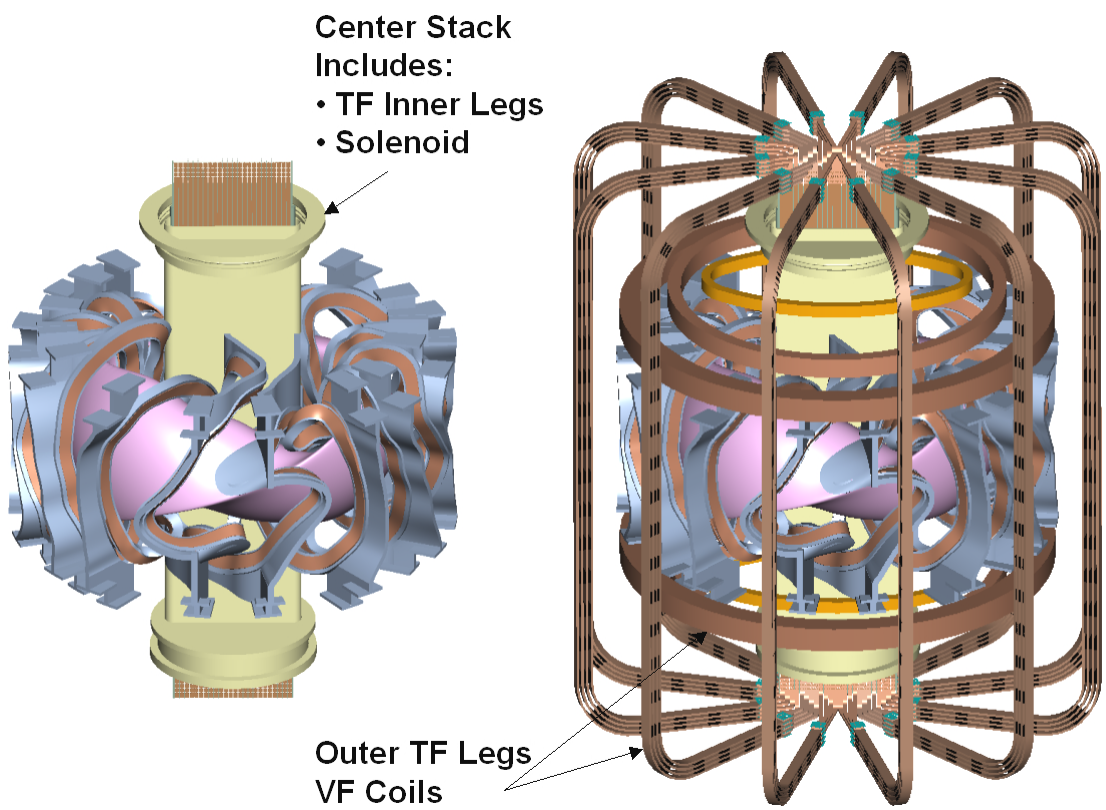


Figure 9.5-1 Auxiliary coil illustration

VF coils and OH solenoid

The OH solenoid and mid VF coils are new coils, while the outer two pairs of coils are re-used from the ATF experiment. The mid VF coil is configured in an elliptical shape to better match the plasma shape, but this shape has not been finalized. The coils are standard hollow copper construction, and are sized to match existing power supplies as closely as possible. Table 9.C-1 lists the VF coil design parameters. No fast control coils are provided.

Table 9.5-1 VF coil parameters

Parameter	PF1, PF2 OH coils	PF3 Mid VF	PF4 Outer VF-A	PF5 Outer VF-B
Current/coil, MA-turns	1.28	0.1	0.1	0.22
Radius , avg– (a x b), m	0.10 x .9	0.75 x 1.5	1.33	1.69
Height, m	+/- .25, .75	1.27	1.23	1.04
Winding width, dr, cm	3.1	8	10.7	17.5
Winding height, dz, cm	4 x 50	10	16.4	19.6
Gross current. density, A/cm^2	4225	1800	570	642
No. Of turns	4 x 45	8	16	24
Current per turn, A	14340	12500	6250	9200
Resistive voltage/circuit, V	~400	27	116	99
Resistive power/circuit, MW	5.7	0.29	0.32	0.92
Approx. Wt./coil, tons	0.23	0.13	0.9	2.3

The OH solenoid must provide the required flux and must fit within the racetrack-shaped opening in the center of the modular coil set. The TF coil center legs occupy the same opening, so the solenoid is wound around the outside of the TF coil legs. One of the constraints on the modular coil design was to provide sufficient space for the solenoid, which is a tradeoff between current density in the solenoid windings and required flux. Figure 9.5-2 shows that for a flux requirement of +/- 0.15 V-s and current density of `4500 A/cm^2, the clear opening through the modular coils and structure must be at least 140 mm. The solenoid design is evolving, and the final capability will depend both on the geometry and the details of the power supply matching.

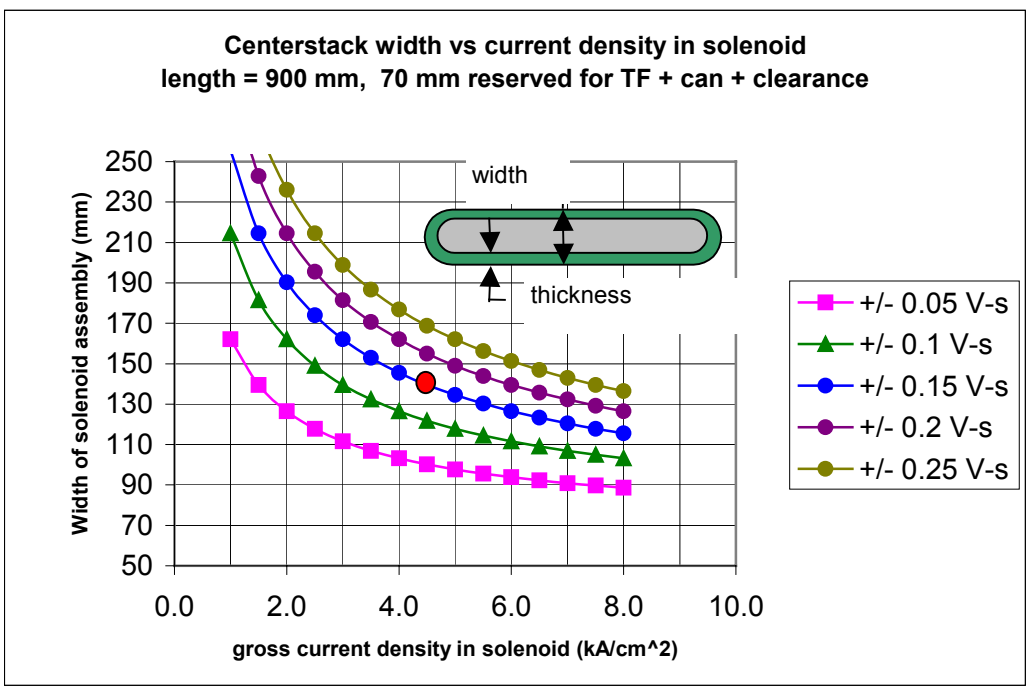


Figure 9.5-2
OH solenoid capability as a function of centerstack width and current density in the windings.

Toroidal Field Coils

In addition to the VF coils there is set of toroidal field (TF) coils. The TF coils consist of a set of straight inboard turns that thread through the bore of the solenoid and a set of outer legs that return outside the "bell jar" vacuum vessel. All of the TF conductors are thus completely located outside the vacuum space. The inboard turns consist of straight copper conductor with internal cooling holes for water cooling, and the outboard turns are simply rolled copper buss-bars. To facilitate installation and removal of the bell jar dome, the coils are jointed at the top and bottom of the centerstack. A set of semi-permanent jumpers connect the flat centerstack with the radially spaced outer return legs. The crossovers and feed buss are at the bottom of the centerstack. Figure 9.5-3 illustrates the TF coil set and relation to the plasma and bell jar.

The existing power supplies and cooling system are adequate to drive the TF set to an average field on axis of +/-0.15 Tesla. The TF coil current will be controlled independently from the modular coils. Table 9.5-2 lists the TF coil parameters.

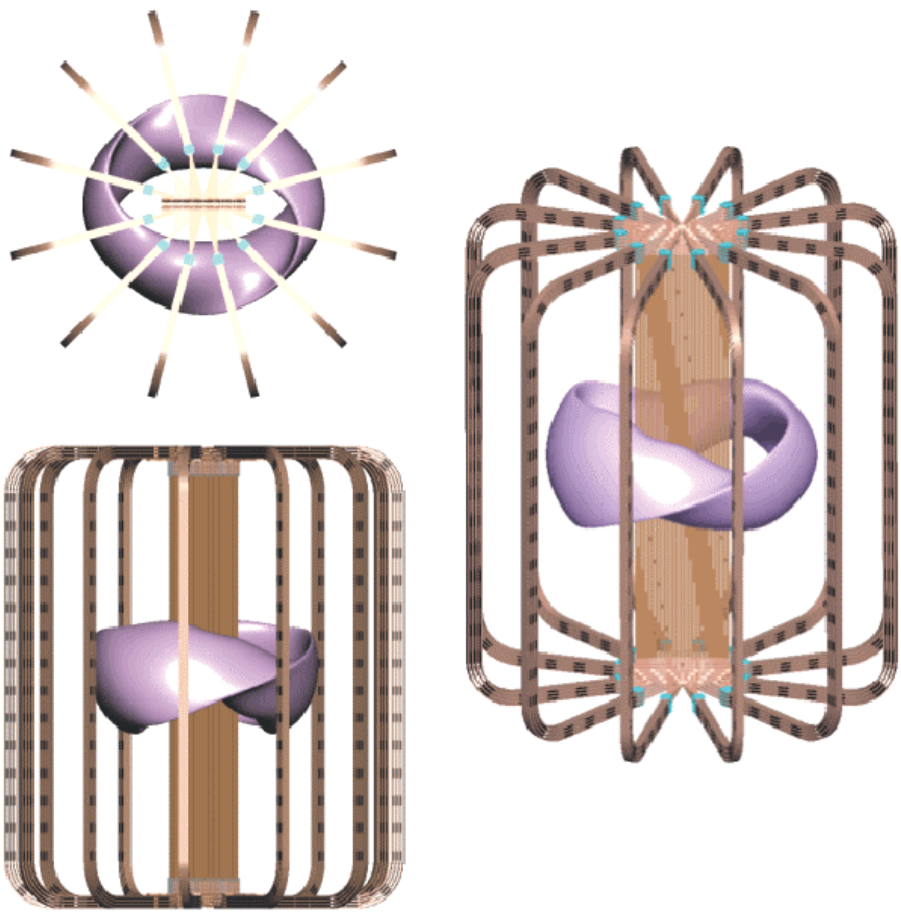


Figure 9.5-3
TF Coil geometry relative to plasma

Table 9.5-2 TF Coil parameters

Parameter	Value	Remark
Field capability	+/-0.15 T	Field at 0.90 m
No. of outboard return legs	12	Bundle of 4 turns each
Total number of turns	48	
Current per turn	14 kA	At full field
Circuit voltage at full current	191 V	All turns in series
Power at full current	2.7 MW	
Temperature rise in centerstack	~ 2.5 C/s	

9.6 Structural concept

General description

The support structure is composed of two basic systems. The primary structure is formed by the set of modular coil winding forms, VF coil structural rings and shear panels, which are bolted together at assembly into an integrated structure. The secondary structure consists of the external vacuum vessel and pedestal support columns, which provide the base for the machine as well as the support system for TF coil return legs.

The modular coil structure is shown in Figure 9.6-1. The modular coils are directly attached, via the vertical web structures and flanges, from coil to coil and from coil to the VF coil ring structures, to form an integrated structure that reacts centering loads and twisting moments. The details of this structure are still being developed, but the intent is to take advantage of the coil form castings to provide most of the features necessary for both winding and reacting the forces in the coils. The centering load will be taken as a compressive hoop load in the vault formed by the modular coil set. The torque produced by the out-of-plane forces acting on the modular coils will be transmitted between coils via the cast bridging structure at the inner and outer perimeter of the coil vertical webs and to the PF rings. Any net torque will be carried between the upper and lower VF rings and bridging structure via two large shear panels on the outer perimeter of the outer VF ring structure. A pair of vertical shear plates is also located in the bore of the machine. The bore is very crowded, so the inner shear plates have openings corresponding to the innermost regions of coils 1 and 2.

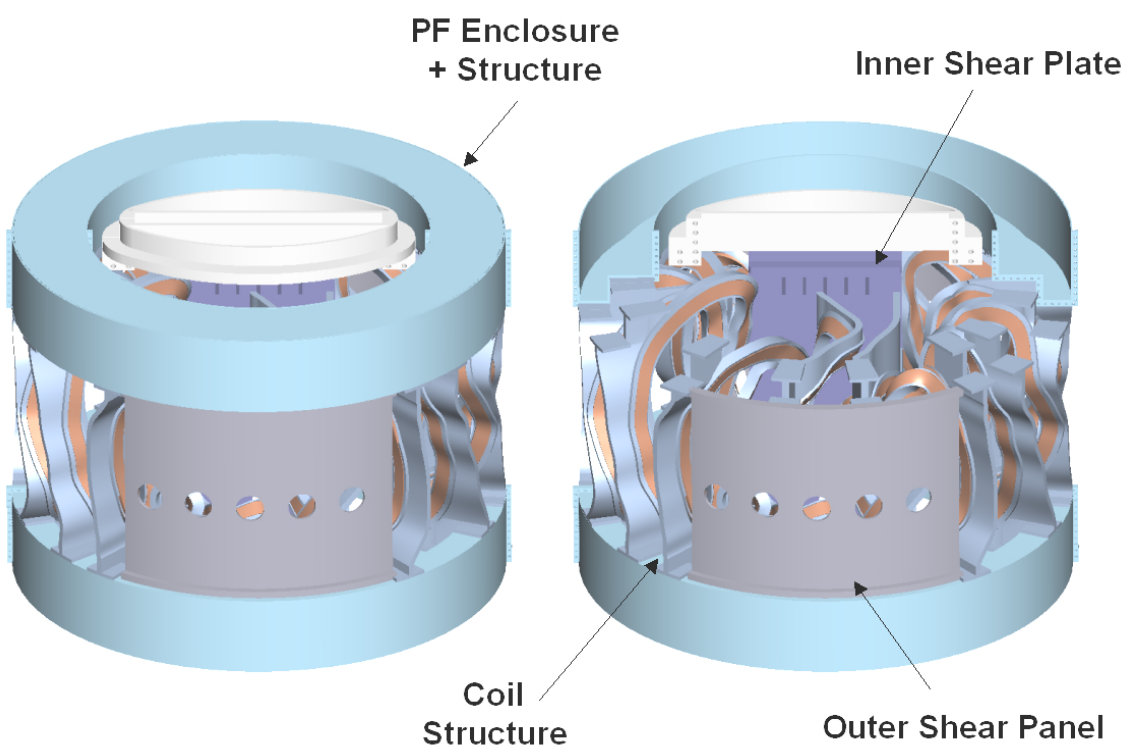


Figure 9.6-1 Support structure system

Magnetic field and force analysis

The magnetic fields and forces were calculated using the MAGFOR program, which handles the complicated modular coil winding geometry with 20 node iso-parametric bricks. A model was constructed that includes the modular coils, the TF centerstack turns, the VF coils, and the plasma. The calculated fields for the nominal 1 Tesla operating case are shown in Figures 9.6-2 and 9.6-3. As shown in the figures, the maximum field at the modular coil conductor is only 2.1 T, about twice the average field on axis. The peak field in the other coils is significantly lower.

The forces on the coil set are rather complicated, because in addition to the nominal centering force there are large vertical loads on each of the coils. The vertical forces balance out in total but cause substantial local loading on the structure. The net forces are illustrated in figure 9.6-4

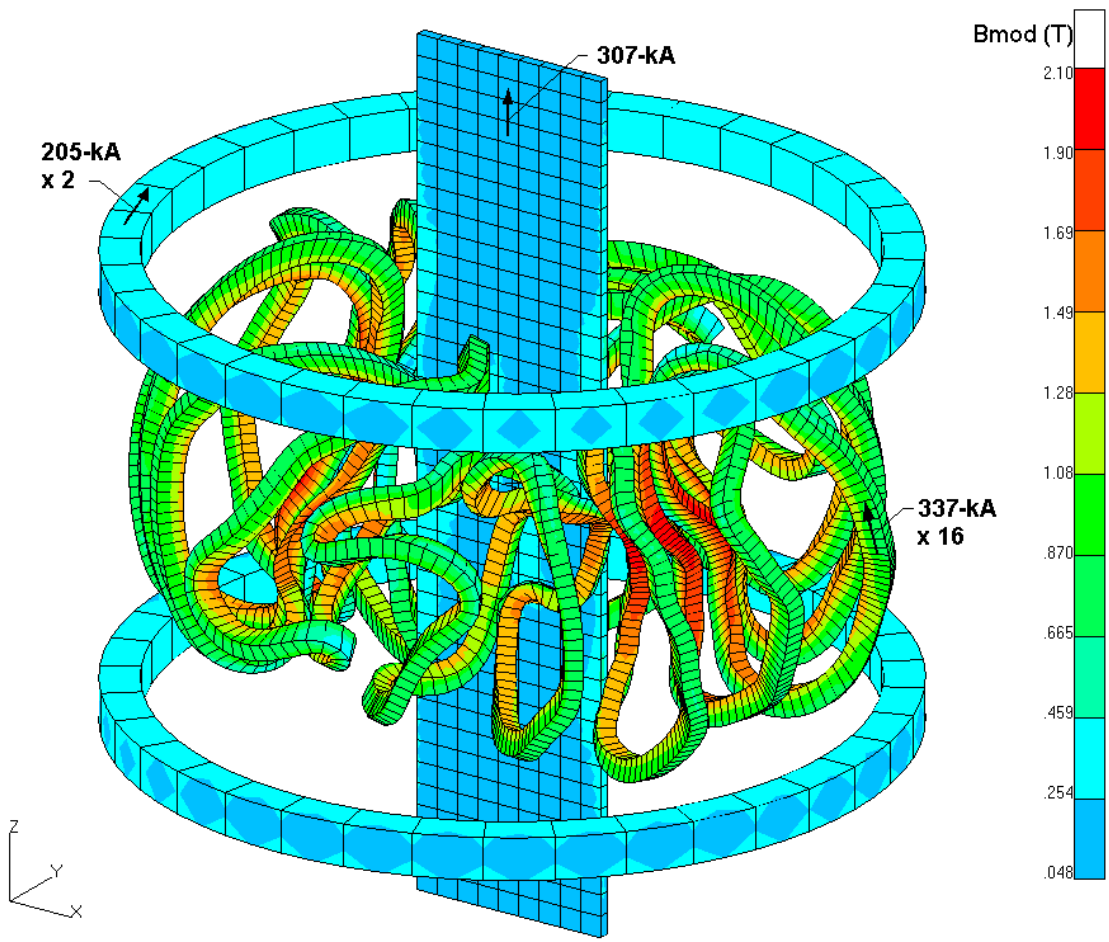


Figure 9.6-2 Electromagnetics model and field contours at the nominal 1 Tesla operating scenario

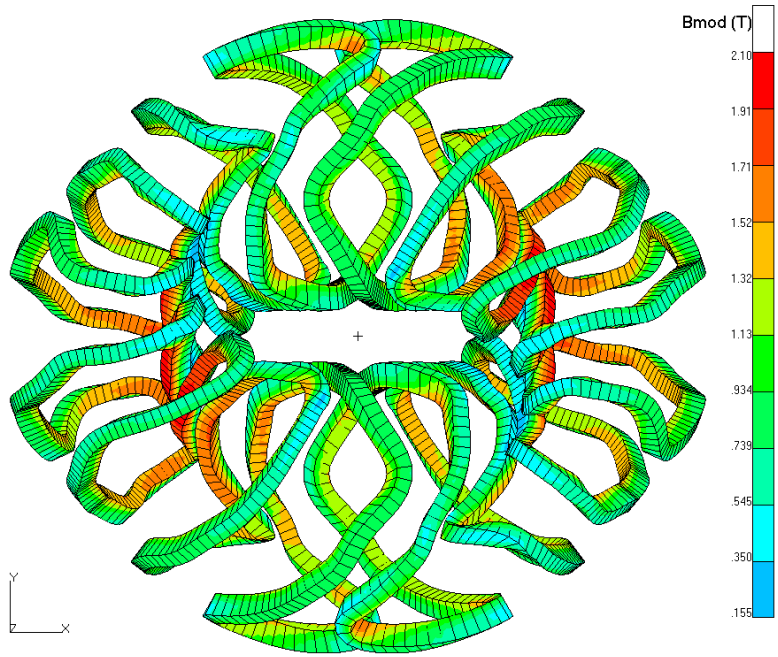


Figure 9.6-3 Field contours at modular coil surface

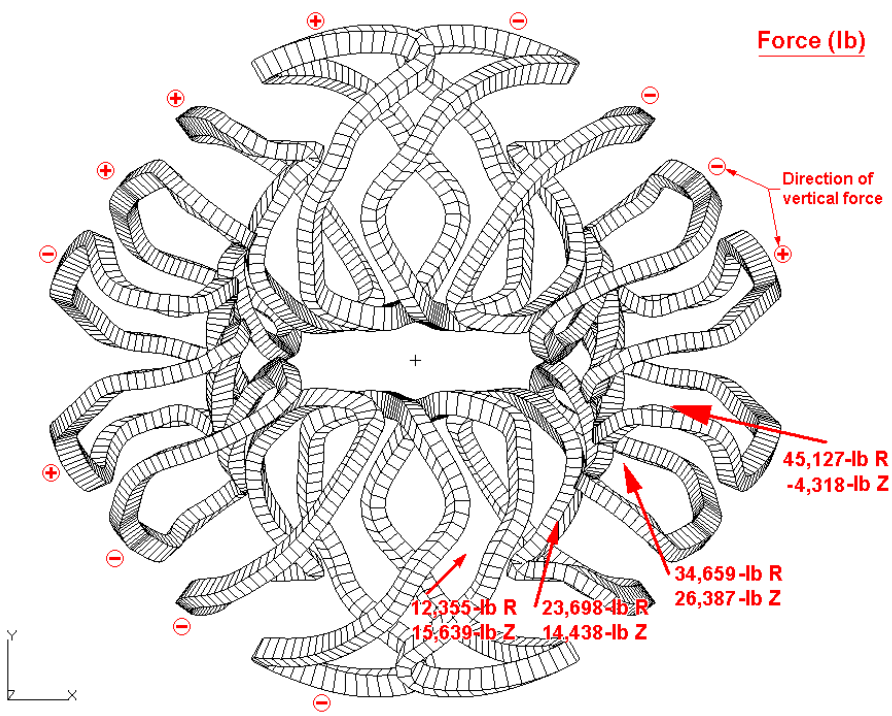


Figure 9.6-4 Net force acting on modular coils

The force distribution on the modular coil windings were also calculated, and these are plotted as a function of winding perimeter in Figure 9.6-5. As expected, the forces peak on the inboard region. The force plot represents the total running load on the pair of winding packs for a given coil. In general, the loads on the two winding packs are toward the structural web for most loading conditions and in most locations. However, in a few regions around sharp curves the outside winding pack will tend to pull away from the coil form structure. In these regions a reinforcing band may be required to retain the winding.

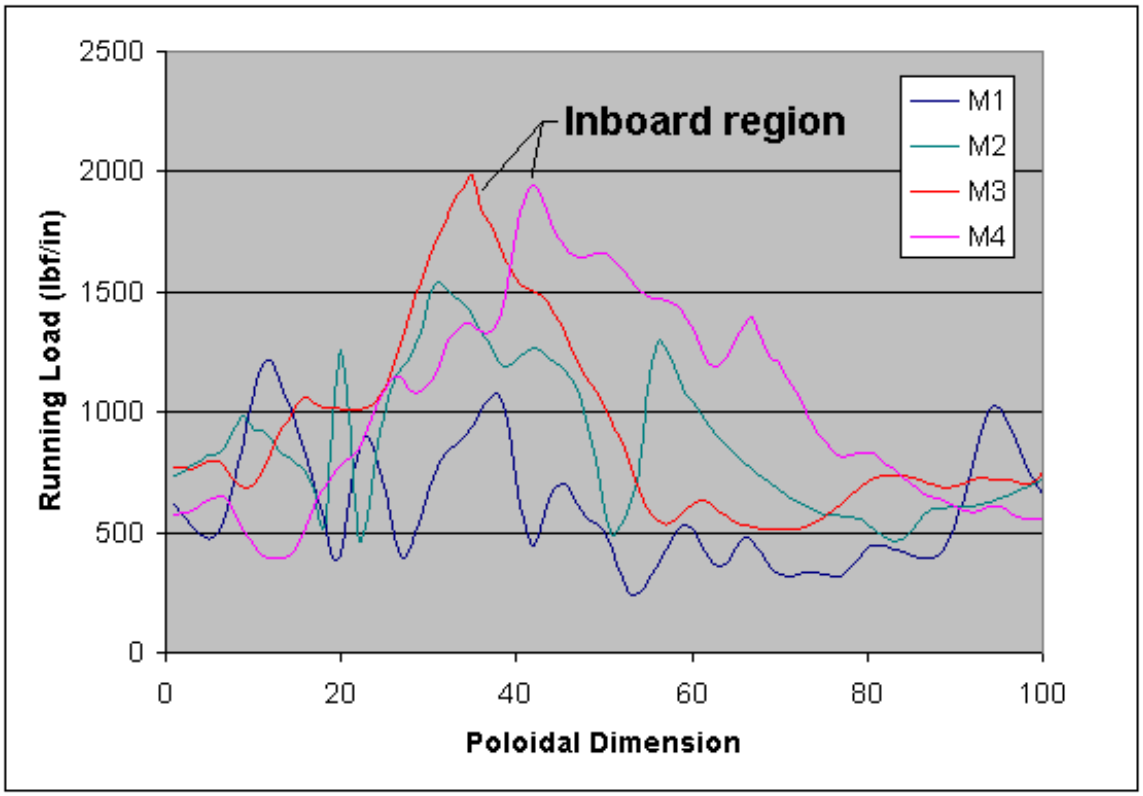


Figure 9.6-4 – Distribution of force on the four types of modular coils per unit length vs a normalized poloidal location

Structural design studies and analysis

A preliminary finite element structural analysis has been performed using electromagnetic loads for the nominal operating scenario: 1 Tesla from the modular coils, 0.15 T from the TF coils and the nominal currents in the outer VF coils. The finite element model includes the I-beam cast structure and a series of constraints that simulate various methods of supporting the coils. The winding stiffness was not included in the analysis. The structure was modeled with plate and beam elements, and the analysis was performed using the ANSYS Finite Element Code.

The most successful system of constraints was to tie the coils together directly with shear panels. This is very difficult to do in practice because the complex geometry does not lend itself to planar bolted joints. However, it is possible to obtain a simple reference surface by providing a ring structure around the VF coils. A vacuum enclosure is needed around the VF coils in any event, and it may be possible for this enclosure to double as the backbone of the structural system.

The results for a moderately interconnected structure are illustrated in Figures 9.6-6 through 8. For the nominal load case, this support structure will deflect approximately 1 mm and experience Von Mises stress due to torsion and bending of less than 100 MPa (14 ksi) in most general regions. There are some localized areas, however, that experience stresses over 200 Mpa. The structure has not been optimized, but it should be relatively easy to locally reinforce the casting to reduce both the stresses and deflections. The goal will be to reduce all the stresses to less than 100 Mpa and keep the deflections to less than 1 mm for the final structural configuration.

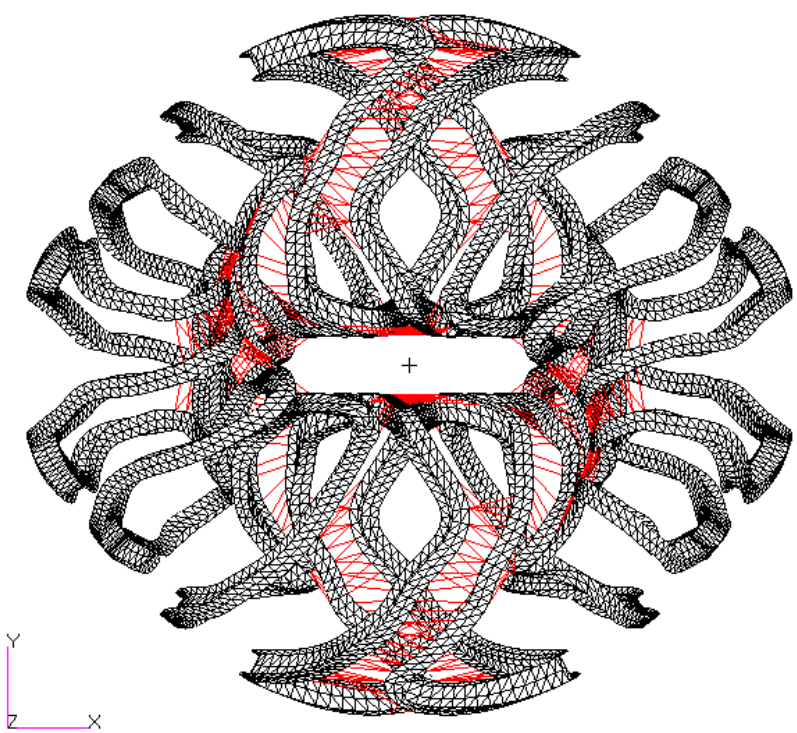


Figure 9.6-6 Analysis model with beams representing coil-to-coil structure

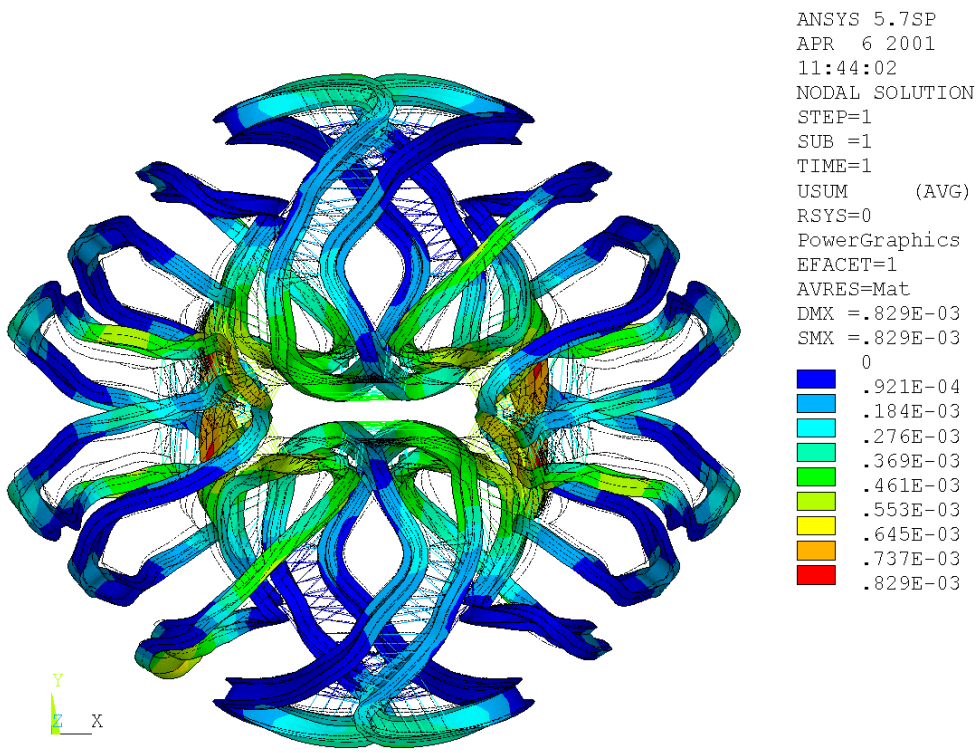


Figure 9.6-7 Deflections for structure with intercoil support

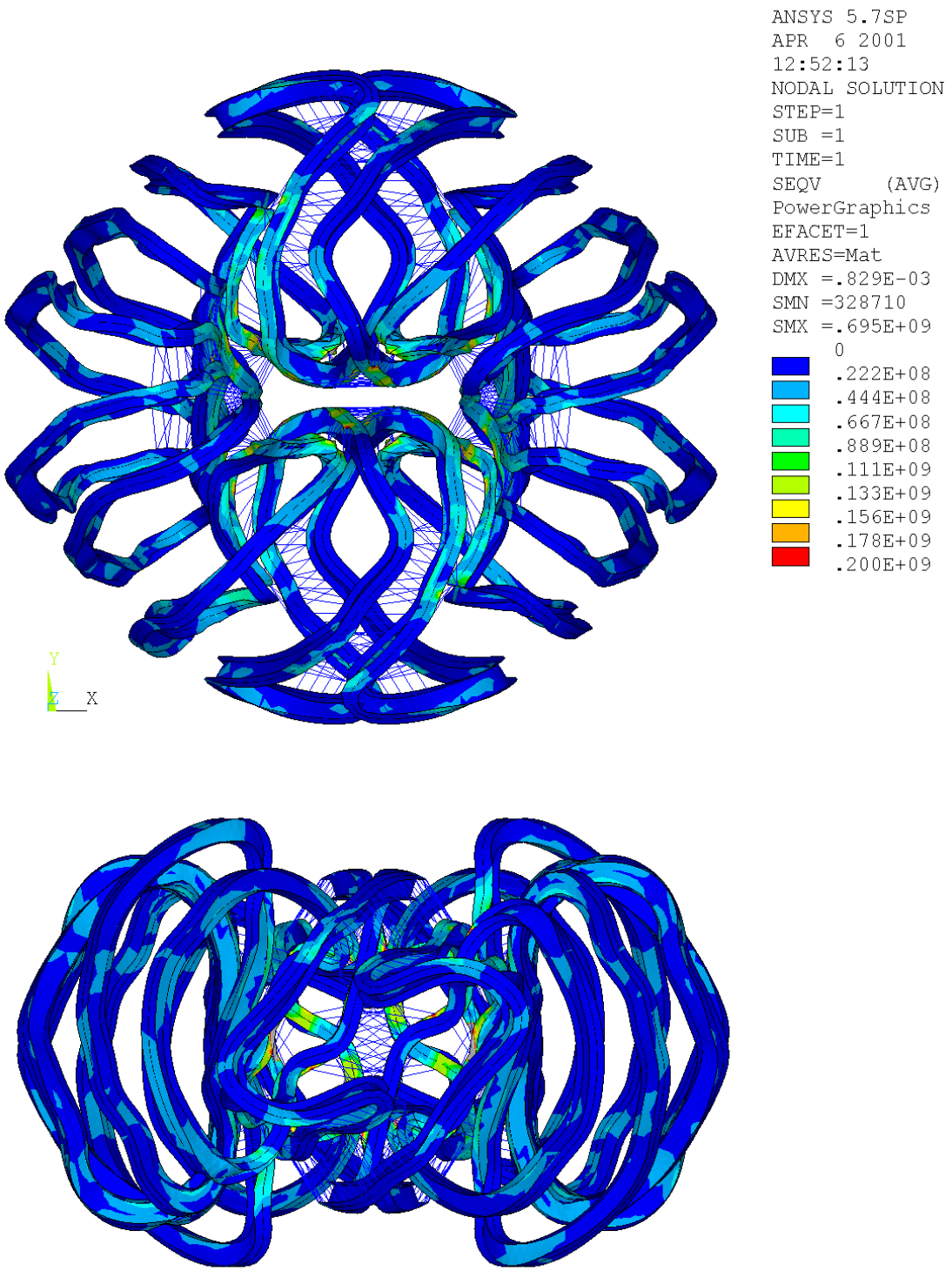


Figure 9.6-8 Modular coil Von Mises stresses at 1 Tesla

9.7 Vacuum system and PFCs, (external vessel, pumping, wall conditioning and power and particle control)

The QPS vacuum vessel is a large, existing bell jar. The vessel has numerous ports and is divided into a reinforced flat base, a lower spool piece, a middle spool piece and a dished head. The head and base are made from 300 series stainless steel, but the spool pieces are fabricated from aluminum. The vessel is illustrated in Figures 9.7-1 and 2. To improve the vacuum quality, the large seal surfaces will be re-worked to accommodate double o-rings with interstitial pumping. Thermal insulation blankets and heaters will also be added to provide a bakeout capability with a temperature goal of 100 to 150 C. The temperature limit will be based on the differential thermal expansion of the vessel head and spool pieces and on the temperature limit of the solenoid winding in the centerstack The basic vessel parameters are listed in Table 9.7-1.

Table 9.7-1 Vacuum Vessel Parameters

Baseline material	6061 Aluminum and 304l ss
Nominal outer radius	1.9 m
Max height	4.9 m
Thickness	1.3 to 2.5 cm
Inside surface area	~75 m2
Enclosed volume	~45 m3
Bake out temperature	150 C
Operating temperature	20-100 C
Thermal growth during bake out	0.3 cm radial

Studies are under way to assess the effect of the aluminum spool pieces on the ability to quickly ramp the current in the vertical field coils. It may be advantageous to procure new, stainless steel vessel sections to replace the aluminum sections. The cost of the new sections will be partially offset by eliminating the need to refurbish and modify the seals on the existing vessel.

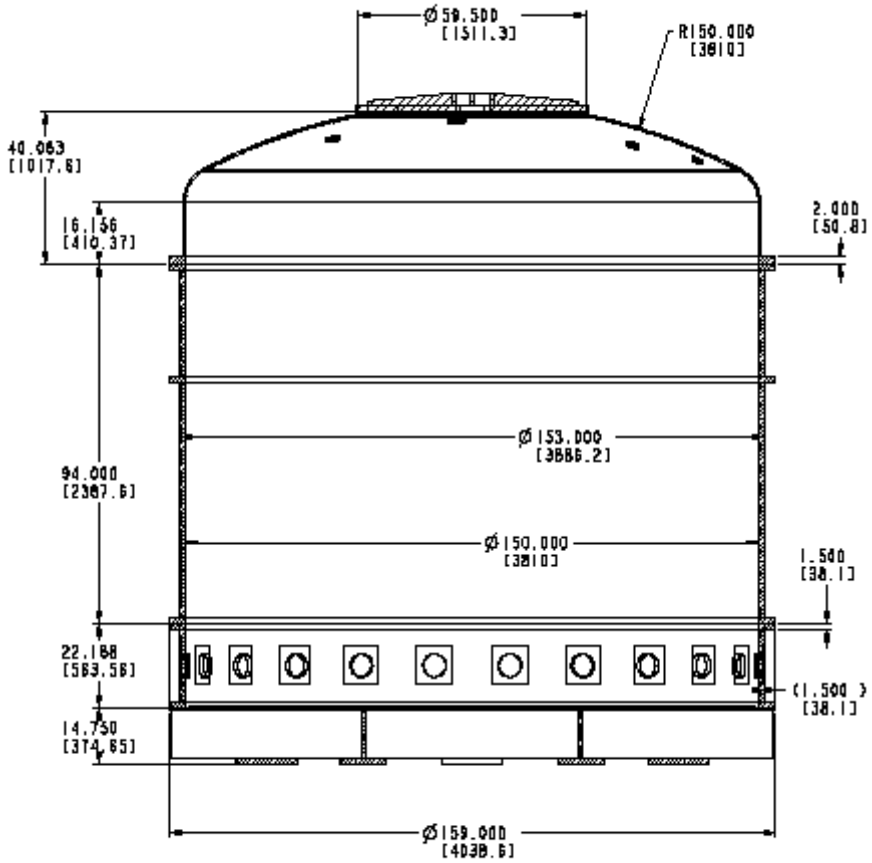


Figure 9.7-1 Vacuum tank and dimensions

Vacuum Pumping and wall conditioning

The vacuum boundary is given by the existing aluminum bell jar. The vacuum conditions will be determined by the out-gassing rate of the bell jar, all internal components, and the leak rate. The vacuum seals are viton o-rings and are bake-able up to 150° C. The centerstack casing may be limited to 100C due to the difficulty of isolating this structure from the solenoid coils. To reduce the leak rate as much as possible, the main seals are differentially-pumped double seals. Applying a mild fore-vacuum to the space between the seals, will reduce the leak-rate by orders of magnitude. Hence, the targeted leak-rate of $Q_{leak}<10^{-5}$ Torr-l/s should be achieved easily. Any graphite surfaces such as the divertor baffle plates should be baked at 300 ^{o}C to drive out the water.

The out-gassing rate of Al can be as favorable as that of stainless steel; for Al with conventional surface cleaning and baking at 150° C, out-gassing rates of $<10^{-9}$Torrl/sm^{-2} have been achieved [1]. Assuming a surface area of 75 m^2 for the bell jar and doubling it for other in-vessel surfaces, will result in total out-gassing rates of $1.5\text{x}10^{-7}$ Torr-l/s. The base pressure will be provided by a set of turbo-molecular pumps with 1000 L/s effective pumping speed. That will provide a base vacuum of $<10^{-8}$ Torr based on the leak rate and $1.5\text{x}10^{-10}$ Torr based on the out-gassing rate.

The pumping will be accomplished through the large, 22 inch ports located on the midplane of the vessel. Each of the four ports will be equipped with a spool piece that can accept an existing 25 cm turbomolecular pump with its isolation valve. A microwave screen will be required over the pump opening to prevent damage from the ECH system.

If necessary, large area titanium pumping can be activated in the top of the bell jar. This area will be baffled so that the titanium is prevented from reaching the walls of the main discharge chamber. Transient pumping speeds of $\sim 10^5$ l/s can be achieved. This pump can be activated if either the partial pressure of impurity gases gets too high or if the pressure of neutral hydrogen increases to the point that density control becomes a problem.

Wall conditioning will include glow-discharge cleaning in hydrogen for chemical cleaning of the surfaces with chemically reactive atomic hydrogen and in helium for physical scrubbing and hydrogen depletion of the surfaces. For uniform glow discharges, two or more electrodes will be installed. Surface modifications by film deposition such as boronization or other techniques is foreseen for the main plasma chamber. Boronization will be installed with the more benign Trimethylboron (as opposed to the highly toxic and pyrophoric Diborane).

Limiters, Divertors and First Wall

There are no plans for a separate first wall structure on QPS, only local baffles in the form of divertor structures near the ridgeline of the plasma. The basic concept is illustrated in Figure 9.7-2 – 3. As shown in the figures, symmetrical baffles would be placed between the coils and the plasma in the region where most of the particle losses are expected. The baffles would be coated with boron carbide rather than carbon to avoid the need for a high temperature bakeout. Additional limiter or baffle structures can be provided as upgrades later in the QPS program.

The modular coils, which represent the closest approach to the plasma, are operated at or above room temperature as described in section 9.3. In order to reduce gas evolution from the coil surfaces, it may be possible to retrofit low-Z or low-Z- coated covers over the plasma facing side of the coils that can be independently heated. This upgrade would also be useful to allow the coil operating temperature to be reduced.

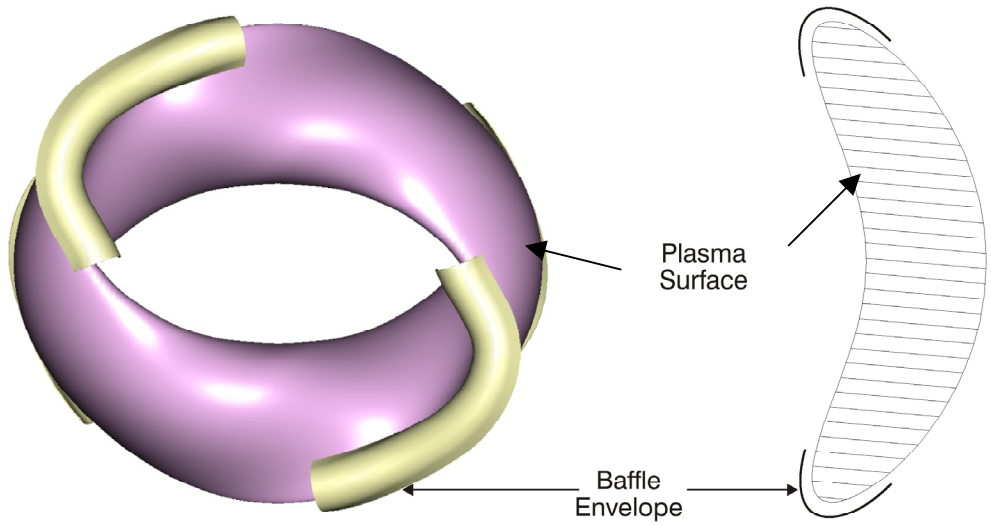


Figure 9.7-2 Divertor baffles relative to plasma

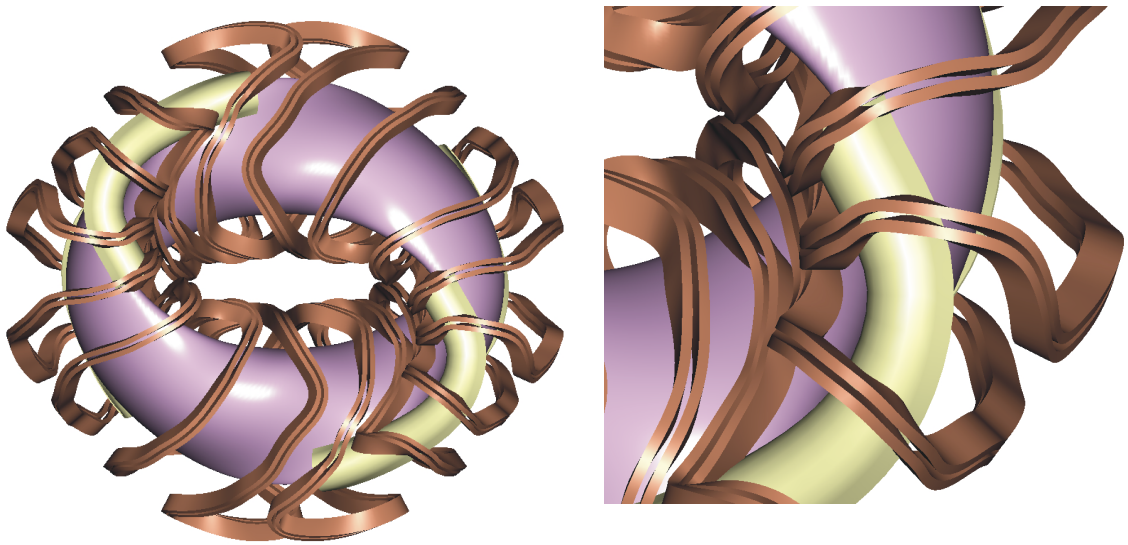


Figure 9.7-3 Divertor baffles relative to coils

9.8 Diagnostic and heating access

Access to the plasma for heating and diagnostics is extraordinarily good for QPS because the only constraints are associated with the external vacuum vessel and the modular coil structure. Port locations and sight lines do not have to be determined a priori, and there are no long, port duct extensions to constrict viewing angles. Antennas and launchers can be mounted inside the vacuum region free from the typical port limitations. Figure 9.8-1 illustrates the plasma view through the large 22-inch ports.

In order to save cost, gate valves will not be used for the major port openings, but some individual diagnostics applications that require a retractable configuration may need to use a gate valve. Reentrant ducts will be used where needed.

Diagnostics that need to be replaced will require a vacuum opening. This can be done by letting the vessel up to dry nitrogen for short periods or waiting until the next general opening if the diagnostic does not present a leak problem.

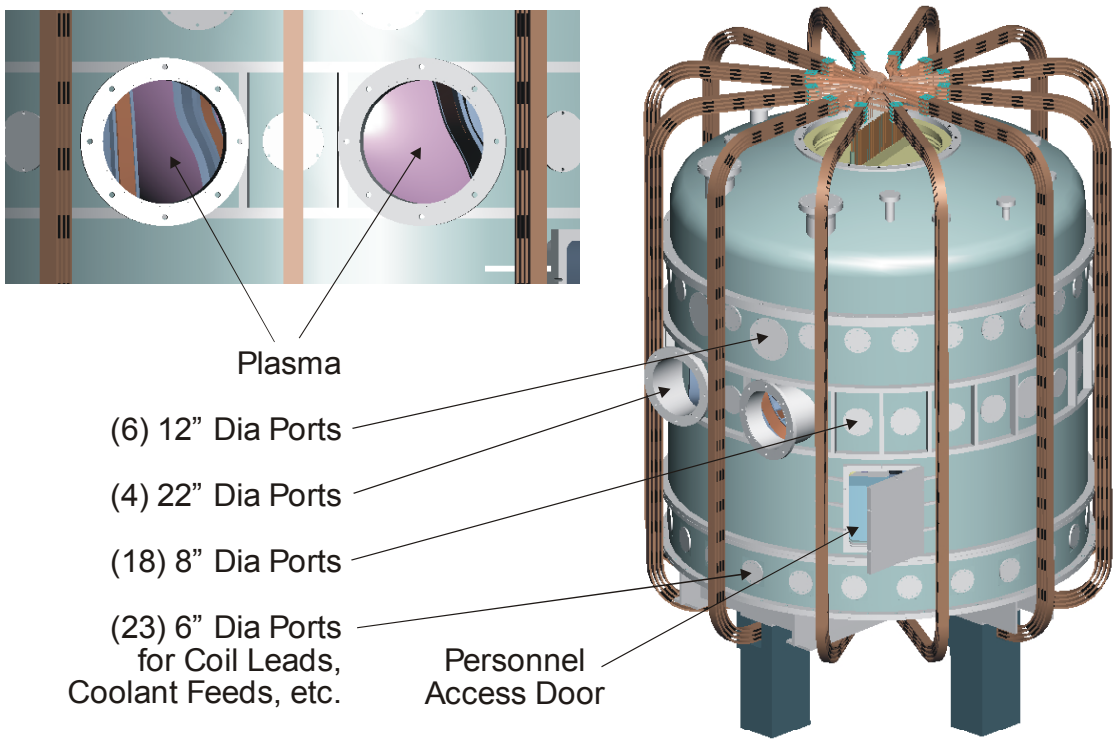


Fig 9.8-1 Diagnostic access through external vessel ports

Maintenance access

Maintenance inside the vacuum vessel can be accomplished in three ways: By reaching through the ports in the vessel, by entering the vessel through the large man way, or by removing the vessel lid. These approaches are illustrated in Figure 9.7-2

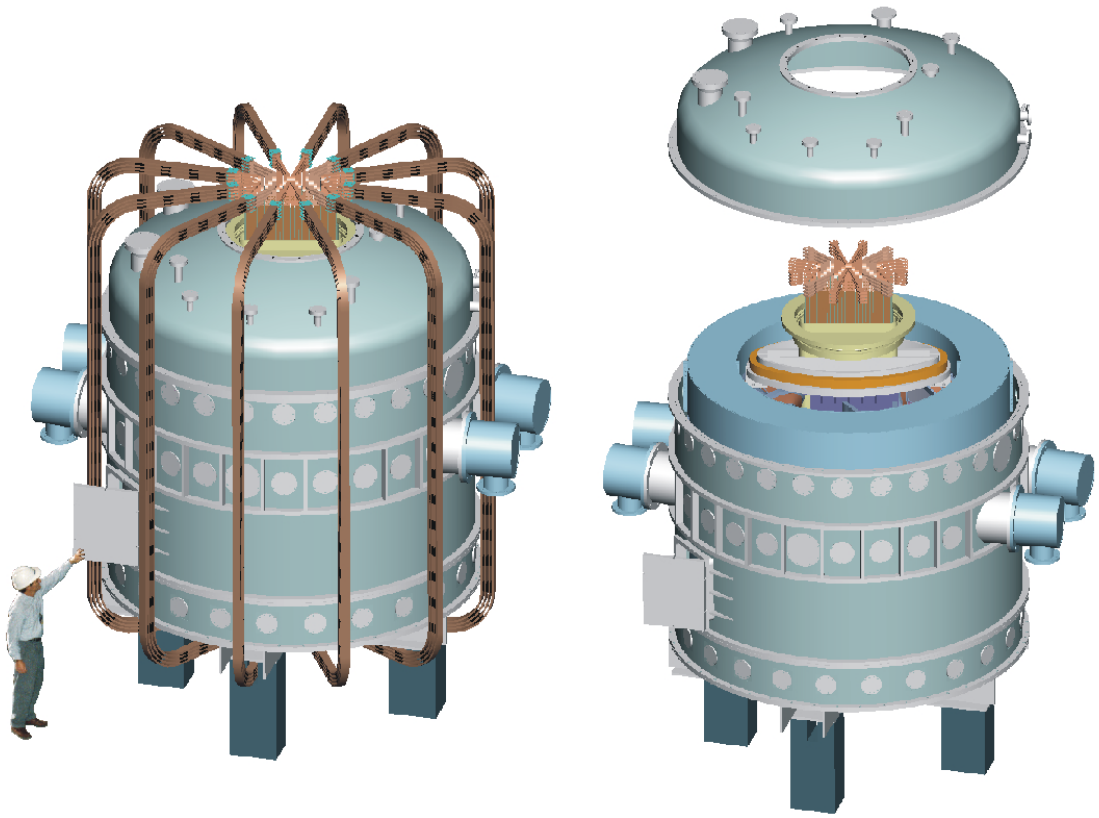


Fig 9.8-2 Maintenance access via man way or by removing vessel dished head

9.9 Machine Assembly

Device Location

There are presently two possible locations for the QPS experiment, one at the ORNL site and the other at the Y-12 National Security Complex. Both locations would be equivalent in terms of capability and infrastructure. The current plan calls for the QPS device to be located in the 7600 area of the Oak Ridge National Laboratory (near the X-10 site) in a new facility to be constructed in FY 2003. The location is shown in Figures 9.9-1 and. 9.9-2. The infrastructure is described in detail in Appendix C of this proposal. The device will be mounted above a pit to provide better access for diagnostics and utility routing and to avoid carbon steel reinforcing in the concrete pad. A safety enclosure (75' x 50') will surround the device and a new control room (50' x 25') will be located adjacent to the enclosure.

Two 20- ton capacity cranes are available for device assembly and maintenance. The total estimated weight of the QPS device is about 60 tons, as described in Table 9.9-1

Table 9.9-1 Component quantities and weights

Component	Quantity	Est. wt., each (tons)	Total weight (tons)
External vacuum vessel	1		10.7
Base		1.5	
Lower Ring		1.1	
Mid Section -		4.7	
Head		3.4	
Modular coil assemblies (avg, with associated cast structure)	2	5.8	11.6
OH Solenoid, PF-1 ,2	4	.25	1.04
Elliptical VF coil, PF-3	2	0.25	0.5
Outer VF coil, PF-4	2	0.9	1.8
Outer VF coil, PF-5	2	2.3	4.6
Outer ring structure	2	2.6	5.1
Elliptical coil structure	2	.8	1.6
Inner shear panels	2	.9	1.8
Outer shear panels	2	.8	1.6
TF Coils			
Inner leg assembly	1	1.4	1.4
Outer legs and jumpers	12	0.5	6.5
Centerstack casing	1	3.0	3
leads, local bus, misc clamps	1	1.0	1.00
Base support pedestals	3	1.0	3
Grand Total, stellarator core			56.8

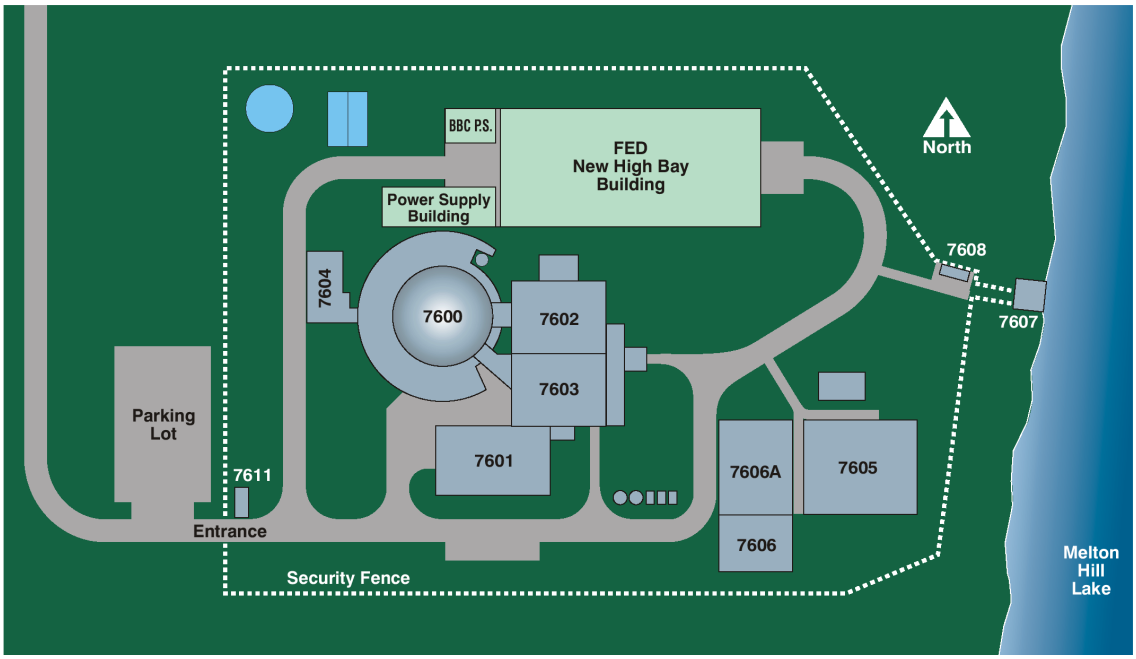


Figure 9.9-1
Plan view the new Energy Sciences Research Building in the 7600 area of the Oak Ridge National Laboratory, near the X-10 site

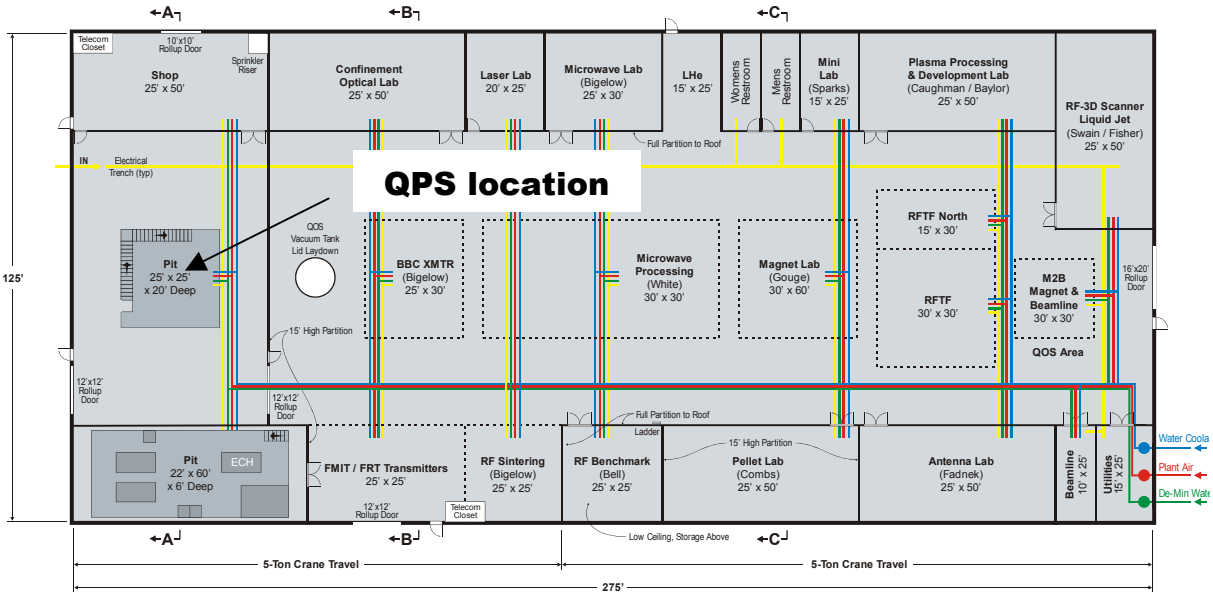


Figure 9.9-2 Plan view of QPS location in the new building

Alternate Device Location

As an alternate to the new facility described above, the QPS device could be located in Building 9201-2 at the Oak Ridge Y-12 National Security Complex, between columns 16 – 19 and columns D – F. This location is shown in Figure 9.9-3. This location would also take advantage of existing facilities and equipment, which minimizes the cost and schedule for the project. The device would be mounted on the reinforced concrete pad that was built for ATF and would utilize the existing ATF safety enclosure and control room. Two 20- ton capacity cranes are available for device assembly and maintenance.

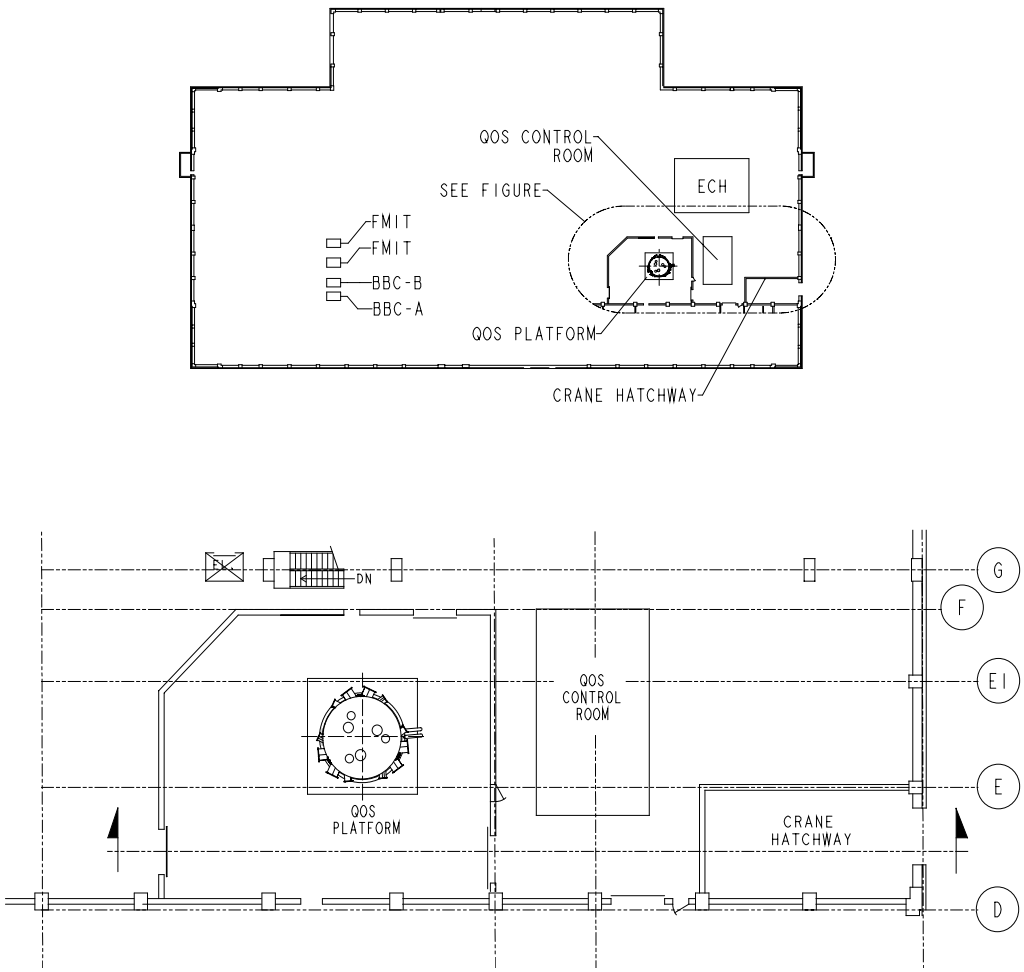


Figure 9.9-3 Alternate location for QPS at the Y-12 National Security Complex

Machine Assembly Sequence

The QPS stellarator core will be assembled to the extent possible at an outside vendor's site and installed on the reinforced concrete pad in the ATF area. Assembly at the vendor's site helps insure the accuracy of the completed system, since problems will be identified in a place where they can be more easily remedied. It also puts more of the responsibility for quality with the fabricator. However, due to the large weight of the completed stellarator core, only subassemblies of the machine can be handled for subsequent final assembly. While the total weight of the modular coil assembly may just be under the crane limitations, a fully integrated assembly must include the centerstack and this component definitely puts the total weight over the limit.

The present plan calls for the complete modular coil set to be pre-assembled, aligned, and all holes match reamed at the vendor site, then split apart into the two field periods. These would be shipped and reassembled on site.

The main assembly steps both on and off-site are listed below and illustrated in Figures 9.9-4 through 9.9-6

Machine Assembly steps at Vendor's site

Set up measurement and alignment datums
Prepare half period coil/vessel sub-assemblies (Figure 9.9-4)
Align and pre-fit two half period assemblies around centerstack
Disassemble and ship two field period subassemblies to assembly site

Remaining Machine Assembly to be done on-site

1 Install and level pedestal attachment features on pad
2. Install vacuum tank base
3. Pre-positions lower outer and mid VF coils (PF-3,4,5)
4. Install centerstack on base
5. Install lower TF turns
6. Install / align coil field period sub-assemblies on vessel base (Figure 9.9-5)
7. Install upper, outer and mid PF coils and support ring covers (Figure 9.9-6)
8. Connect cooling lines to gas manifold around base
9. Perform coolant leak check
10. Connect buswork to coil leads
11. Perform low current electrical check
12. Install vacuum tank spool piece, dished head, and outer TF coil legs (Figure 9.9-7)
13. Leak check vacuum vessel
14. Install machine diagnostics and I&C
15. Perform pre-operational checkout and coil tests
16. Install auxiliary heating systems
17. Install plasma diagnostics

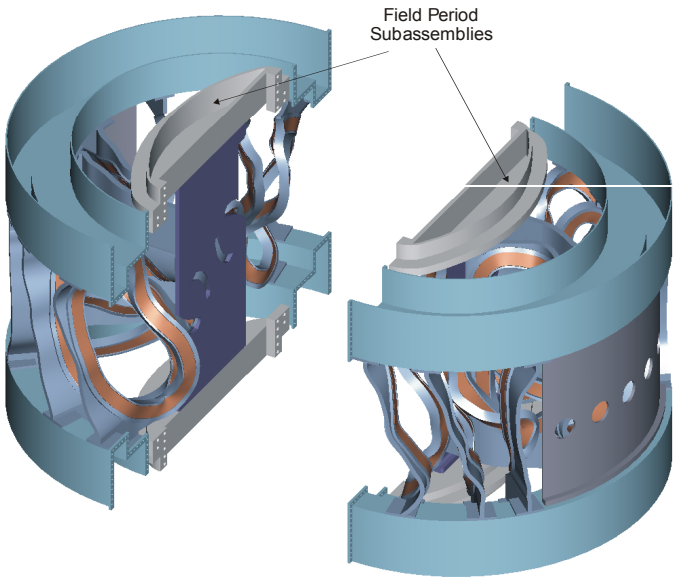


Figure 9.9-4 Assembly of modular coil field periods with structure: pre-assemble / fit up two field periods, then disassemble into single period subassemblies for shipment to site

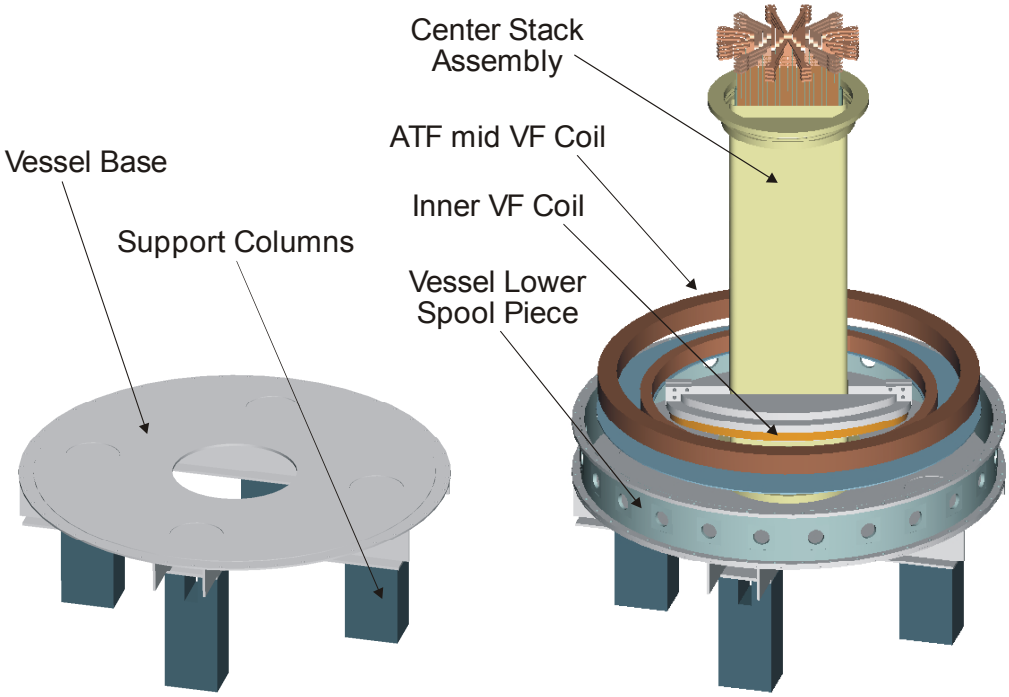


Figure 9.9-5 Install base and pre-position lower VF coils

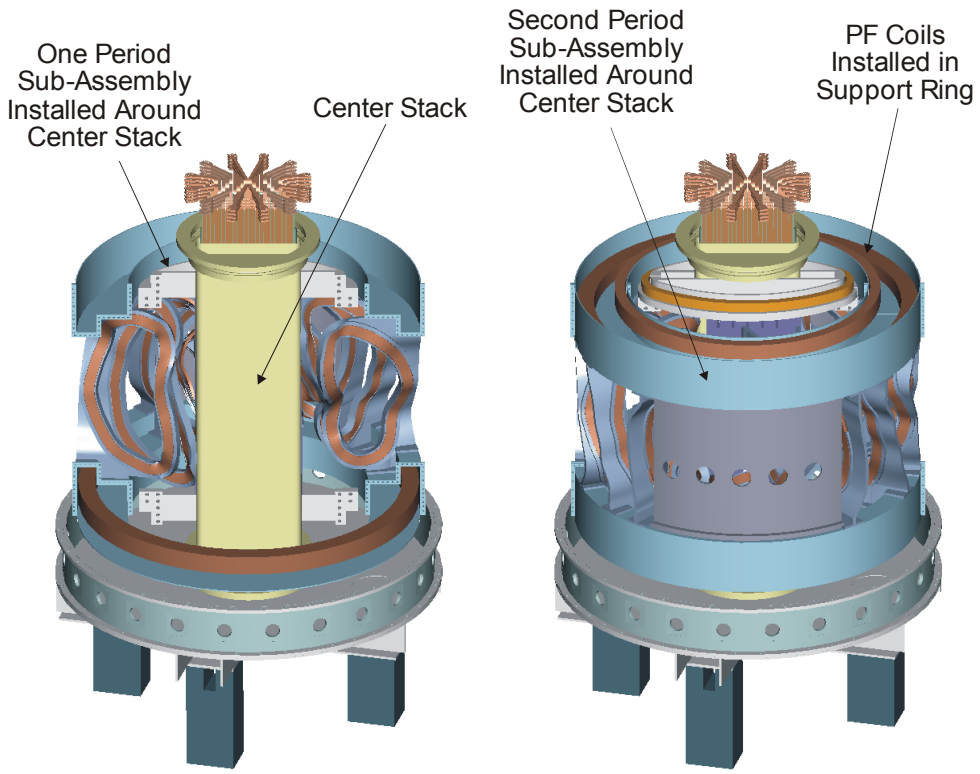


Figure 9.9-6 Install centerstack, two field periods and upper VF coils
Route all leads/cooling through lower spool piece

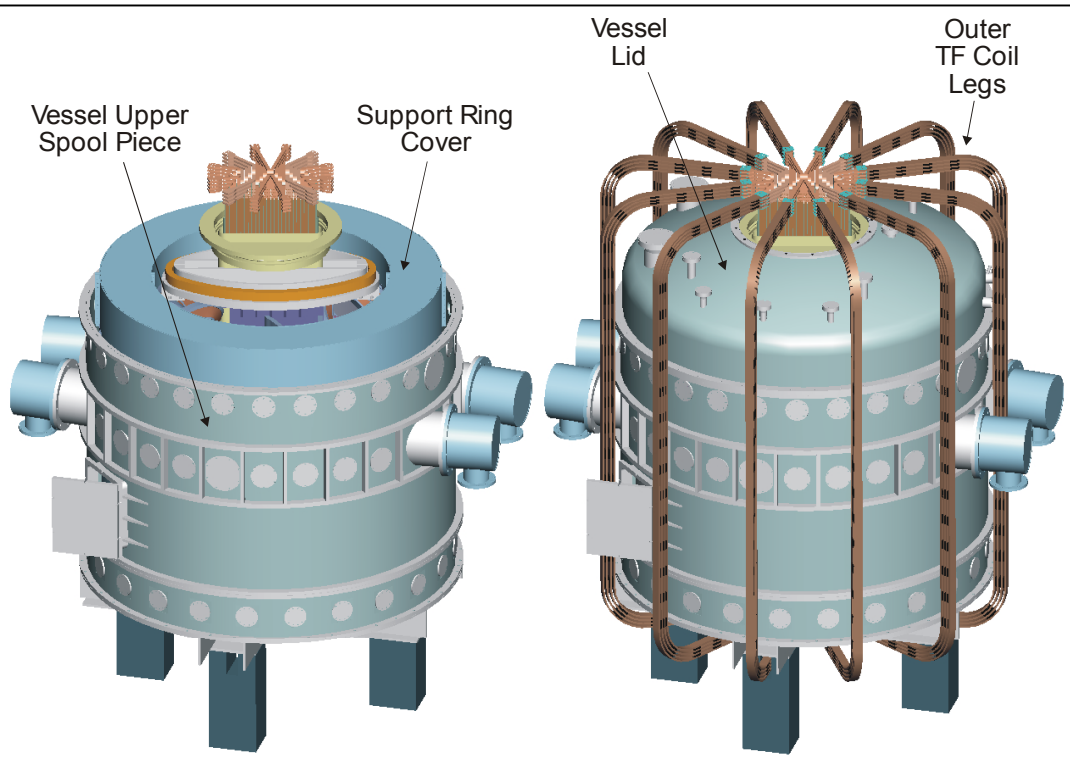


Figure 9.9-7 Install main spool piece, TF legs, upper head

9.10 Ancillary Systems

The following sections describe the ancillary systems, which include the device support facilities such as the coil power supplies and water cooling system, as well as experimental support systems and facilities such as the diagnostics and control room. The QPS device has been conceived to take advantage of as many existing facilities and systems as possible.

Power Supplies

Existing power supplies owned by ORNL's Fusion Energy Division were evaluated to determine their compatibility as magnet power supplies for the coils as proposed for the QPS device. Power supply voltage and current ratings were matched to the amp-turn requirements of the modular coil set, the OH solenoid and the three pairs of vertical field coils to determine a satisfactory number of turns for each coil. The power supplies included in this study were the Advanced Toroidal Facility's (ATF) helical field power supply and ATF's three vertical field power supplies, and six power supplies on standby from the Large Coil Test Facility (LCTF). Table 9.10-1 summarizes the power supply capabilities and coil assignments

Table 9.10-1 Coil Power Supply Assignments

Coil Set	Power Supply
Modular Coils, 4 groups of 4 coils	Existing ATF helical field power supplies, 4 each 650 V open circuit voltage, 30 kA pulsed current
OH solenoid, PF-1,2 2 pairs of solenoid coils in series	Existing ATF VF coil power supply 625 V, 15kA pulsed
Elliptical PF coils PF-3 1 pair of coils in series	Existing LCTF power supplies x 2 12 V, 25 kA
Outer PF coils, PF-4,5 2 pairs of coils	Existing ATF VF coil power supply 625 V. 10 kA pulsed rating (PF-4 is powered alternately or in series with another coil set)
TF coils 1 circuit, 48 total turns in series	Existing ATF VF coil power supply 625 V. 15 kA pulsed rating

Modular Field Coils

The ATF helical field power supply consists of 8 modules that are presently connected to operate at 62.5 kA on a continuous duty cycle. This system is readily compatible with the modular field coils consisting of 4 circuits of 4 coils each.. The buswork must be modified to provide separate connections to each power supply module.

Vertical Field coils and OH solenoid

Each of the three pairs of OH / vertical field coils will be driven by separate power supplies. The ATF VF coil supplies match the OH and outer VF loads well and will be used by these circuits. The mid VF coil requires lower voltage and can be accommodated by two of the LCTF low voltage power supplies. The LCTF power supplies would have to be relocated and installed near the QPS device.

Toroidal Field Coils

The toroidal field coils will be driven by a single ATF VF coil supply. This limits the toroidal field to about +/- 0.15 T. Further optimization of the coil design is planned to better match the capability of this power supply.

Cooling system

Cooling for the QPS will be provided by an existing demineralized water system located in the 7600 area of ORNL, either directly for water cooled components or through a helium gas heat exchanger. The water system consists of a closed-loop demineralized water facility with a nominal summer continuous cooling capacity of >2 MW. The system has the capability to supply 750 GPM at 60 psi.

The coil gas cooling system will utilize an existing compressor rated at 200 horsepower to compress gas to 100 psi. The compressor skid has an integral heat exchanger through which the gas is circulated.

As shown in Table 9.10-1, the QPS magnets and ancillary systems have an equivalent continuous thermal load of ~ 600 KW. The QPS will require about 400 gpm for a differential inlet

Table 9.10-1 QPS Device Cooling Requirements

System	Cooling Load (kW)	
	Peak	Avg.*
Modular coils	48,700.	82.
VF coils	2,600.	4.
Ancillary equip., power supplies, etc. (est.)	15,000.	500.
MACHINE TOTAL	65,300.	~ 600.

*Assumes 1 second ESW pulse every 10 minutes

and outlet temperature of 10 F. The water will be distributed to the helium compressor, power supplies, gyrotrons, and other ancillary equipment. Inlet and outlet ring headers will distribute the cooling gas from the heat exchanger to the 16 Modular coils (two circuits each) and the 5

pairs of VF coils (one circuit each). Each cooling circuit for the magnets will be connected to the headers outside the vacuum vessel. The lines will incorporate a manual flow control and shutoff valve, a flow indicator and inlet and outlet thermocouples. The flow indicators and temperatures from the thermocouples will be monitored in the control room.

9.11 Schedule

Schedule Estimate

The QPS schedule is based on an engineering estimate of design, fabrication, assembly and installation times for the major components and systems. The intent was to establish the schedule logic, identify the critical path, and make a first estimate of the total time required. Based on the best estimate so far, it appears possible to reach first plasma approximately four years after start of Title I design. This assumes that the conceptual design is completed and the funding profile is not a constraint.

The summary estimate is shown in Figure 9.11-1.

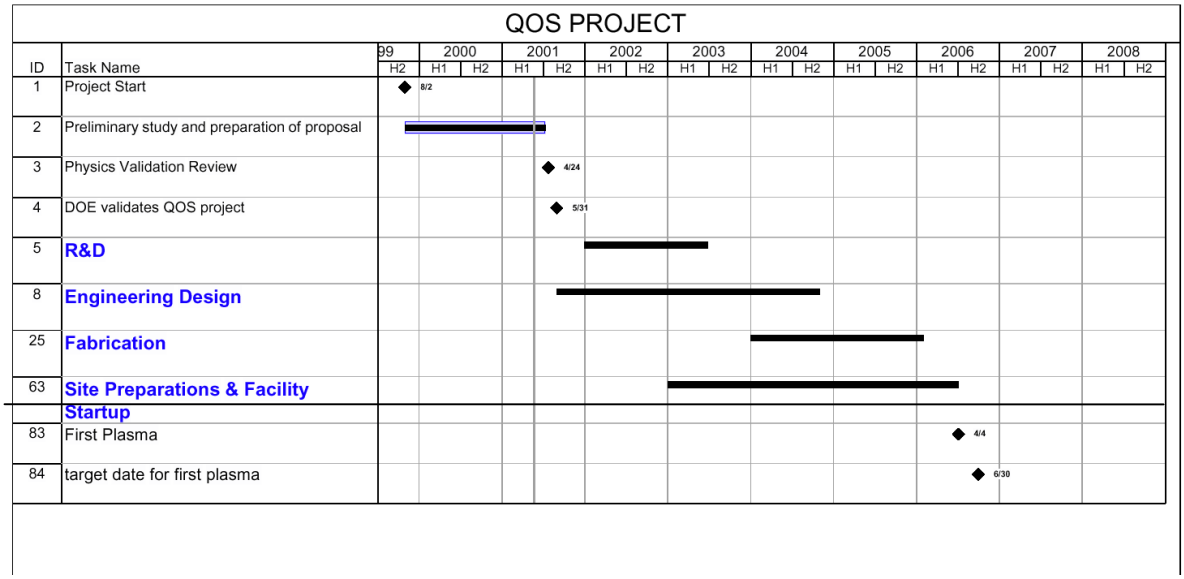


Figure 9.11-1 Overall project schedule

9.12 Summary

A systematic study of the QPS facility has been completed, including pre-conceptual design of the stellarator core, identification of ancillary equipment and infrastructure requirements, and an estimate of the construction cost and schedule. The design is based on a two field period configuration with 8 modular coils per period. The average major radius is 0.9 m and the average minor radius is 0.35 m for an aspect ratio of 2.6. For experimental flexibility, an ohmic heating solenoid and 3 other pairs of vertical field coils are provided, as well as a set of toroidal field coils producing +/- 0.15 Tesla. The coils and associated structure will be located inside an existing "bell jar" vacuum vessel, avoiding the need to fabricate a complex internal vessel.

The QPS experiment will be located in a new building planned for the 7600 area of the ORNL X-10 site. The existing Fusion Energy Division infrastructure, including power supplies, cooling systems, experimental enclosure, control room, etc. will be moved or duplicated at the new facility.

Some of the remaining issues associated with design and construction of the stellarator core include:

- Optimizing the coil set geometry to increase the space between coils and the bend radius of the winding path while minimizing the local twist of the cross section.
- Casting the modular coil forms within a tolerance of +/- 5 mm.
- Preparing an accurate winding cavity by grouting and/or machining and winding the coils within the acceptable geometric tolerance of +/-1.0 mm.
- Vacuum "canning" the coils without causing distortion.
- Providing a structural support concept that maximizes access to the plasma and minimizes deflection of the coil set
- Performing a tradeoff study between re-using the existing aluminum vacuum vessel sections and buying new stainless steel sections. This relates both to vacuum quality and to the long time constant of the aluminum shell.