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***Abstract*—The Tokamak Physics Experiment (TPX) will be the first Tokamak using superconducting magnets for both the poloidal and toroidal field. It is designed for advanced Tokamak physics experiments in steady-state and long-pulse operation. The TPX superconducting magnets use an advanced cable-in-conduit conductor (CICC) design similar to that developed in support of the International Thermonuclear Experimental Reactor (ITER). The toroidal field magnets provide 4.0 T at 2.25 m with a stored energy of 1.05 GJ. The poloidal field magnets provide 18.0 V-s to ohmically start and control long burns of a 2.0 MA plasma.**

I. INTRODUCTION

The Tokamak Physics Experiment (TPX) facility is key to the United States Magnetic Fusion Energy Development Strategy, providing improvements in the Tokamak concept, as well as resolving key issues in the design and operation of steady-state reactors and plasmas [1], [2].

TPX has received initial DoE approval and will be built at the Princeton Plasma Physics Laboratory (PPPL). It is designed to run double-null, high-beta, and high-bootstrap fraction plasmas, as well as single-null plasmas at reduced parameters. Because the mission includes the achievement of steady-state and extremely long-pulse operation at full parameters, the use of superconducting coils to provide both toroidal and poloidal fields was an obvious candidate for the magnet system. The higher current densities of the superconducting magnet system led to its selection over a much larger resistive magnet design. The only normal copper coils in the machine are internal to the vacuum vessel and, coupled with internal passive plates, control plasma vertical instabilities, while permitting plasma initiation.

The selection of an entirely superconducting coil system is significant for the world fusion program. TPX will be the first Tokamak with a superconducting poloidal-field system. It will also be the first Tokamak in which all the coils use high-current, Cable-In-Conduit Conductors (CICC), as called for by the preliminary ITER designs. The topology of the superconducting magnet system is similar to those of NET [2] and the ITER CDA [4] magnets. The overall Tokamak configuration is shown in Fig. 1, and a reference set of major parameters and dimensions developed at the time of the Conceptual Design Review in March 1993 is listed in Table 1. The details presented here may change, as the preliminary design of the superconducting magnets is still in progress. Early next year, a major part the design effort will be transferred from the national laboratories to industrial partners who will eventually build the magnets.

II. TOROIDAL-FIELD SYSTEM

The TF system provides 4.0 T at the nominal 2.25-m plasma operating point. It consists of sixteen coils in cases with welded intercoil structures. Each coil consists of six double pancakes with a total of 84 turns. The conductor is based on that developed for the US-DPC magnet [5] to benefit from prior manufacturing, research, and development. The toroidal-field conductor allows modest helium fractions, and hydraulic diameters, improves the reliability of coil protection and reduces the cost of the cryogenic refrigerator. An 11 kW refrigerator presently at LLNL will be modified and moved to PPPL for TPX use. The 33.5-kA conductor current is also a good match to existing power supplies at the PPPL site, requiring no additional rectifiers [1] and thereby achieving some cost reduction. Finally, a 33.5-kA conductor is a good trade between the desires to keep the current low (to minimize lead losses) and to keep dump and initiation voltages low (thereby avoiding arcs). Toroidal-field magnet characteristics are listed in Table 2.

The individual superconducting strands consist of a high-yield, relatively high-performance Nb_3Sn composite with a high critical temperature. The 0.78-mm diameter strands are cabled in a 90 x 5 pattern and inserted in a 2.4-mm

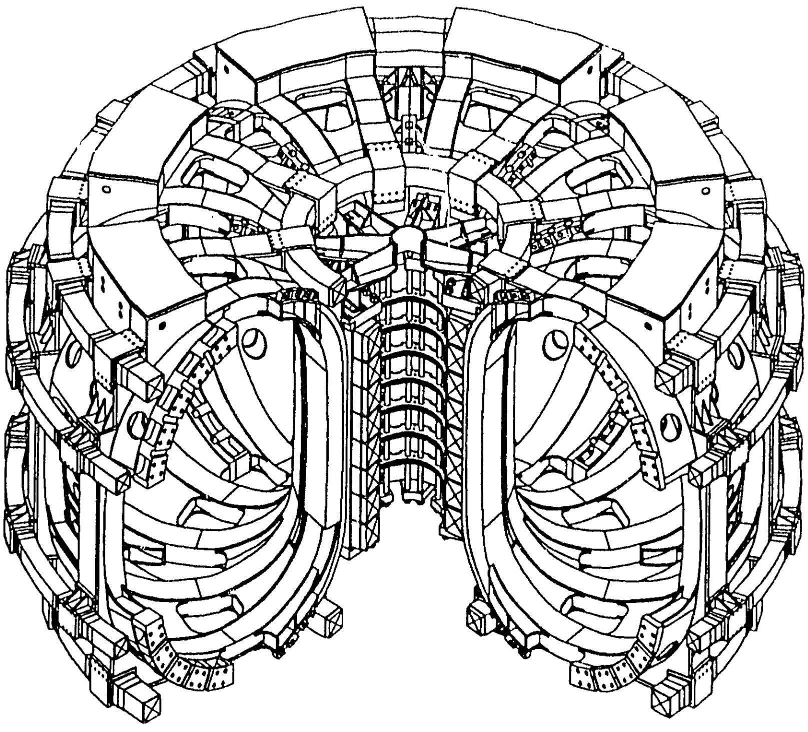

Fig. 1. TPX Superconducting Magnet System

thick Incoloy 908 conduit. To reduce costs and minimize the number of joints, each TF coil is made from a single ~1000 m piece of conductor. Cooling is provided to each double pancake at the top outside radius of the winding. The TF Coil is wound and then reacted to form the Nb_3Sn. The TF coil pack is shown in Fig. 2.

The conductor concept is a modification of the US-DPC wire, which combines relatively low cost with tested performance in pulsed fields. All strands are identical in the reference design, but an R&D program, focused on current transfer, is qualifying a "hybrid" cable design, where some triplets of strands in the TF coil contain one pure copper wire. If successful, it will provide a higher copper/noncopper ratio for coil protection during a dump of the TF systems and reduce the total conductor strand cost. Transient power balance between Joule heating and heat transfer to the local helium reservoir will allow recovery of quenched superconducting strands to assure stable operations.

While the pancakes are wound, steel or Incoloy 908 shims will be inserted as place-holders for the magnet insulation. The Nb_3Sn coils are then heat treated without any insulation in the winding pack. After heat treatment, specially designed tooling is used to separate the turns in the pancakes. Each turn is wound with 0.4-mm thick S-glass tape. The turns are returned to the plane of the pancake and 0.8-mm thick glass-reinforced polyimide strips are inserted between turns and pancakes. The coils are then epoxy

TABLE 1
TPX Tokamak Parameters

Parameter	Units	Value
R_o	(m)	2.25
a	(m)	0.5
k		2.0
B_t @ R_o	(T)	4.0
I_p	(MA)	2.0
height	(m)	5.33
diameter	(m)	8.73

TABLE 2
TF Magnet Performance

Parameter	Units	Dimensions
B_{max}	(T)	8.9
I_{cond}	(kA)	33.5
$n_{pancakes}$		12
n_{layers}		7
n_{coils}		16
$n_{turns, system}$		1344
$n_{strands}$		450
$E_{m, TF}$	(GJ)	1.05
$V_{dump, system}$	(kV)	15.0
$l_{conductor}$	(km)	16.1

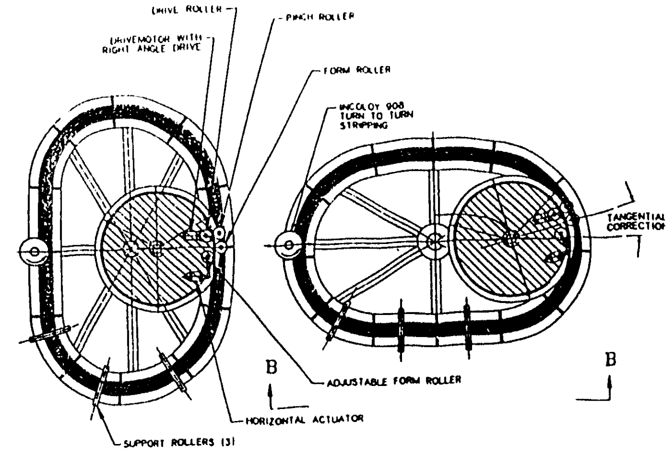

Fig. 2. TF Coil Winding Concept for TPX Superconducting magnets, showing feed spool and conductor forming tooling.

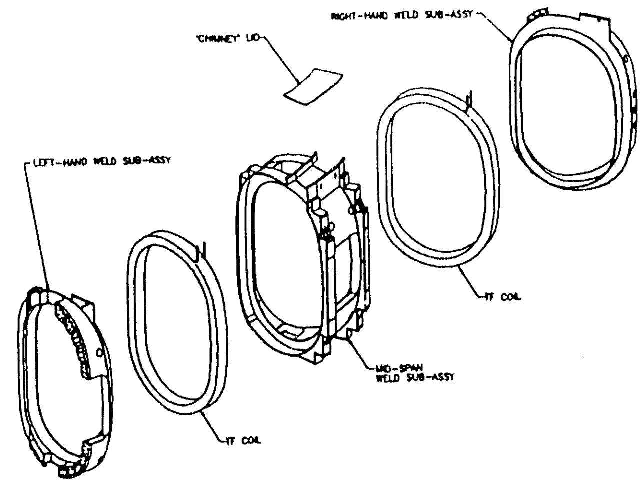

Fig. 3. TPX Module consisting of two coils, case and internal structure

impregnated under vacuum and pressure, and ground plane insulation is applied. Good contact between the windings and the cases of the TF coils is provided by high glass-content epoxy, injected under pressure when the coil is installed in the cases.

The TF structure consists of welded 316 LN or 304 LN cases with thickened noses at the inside leg to support centering loads in wedging. A pair of coils is combined into a welded TF assembly with a central structural weldment and two identical closure welds. Two assemblies of two TF coils each, along with other Tokamak components, are then joined at the intercoil-structure parting plane with an insulated break joint, to form a 90° module. Figure 3 shows a two-coil assembly.

Stresses in the winding packs and cases have been calculated for in-plane and out-of-plane loads at the plasma end of burn (EOB). The highest stresses occur in the port region, where the intercoil structure is constrained by the need for large horizontal ports between each TF coil, and in the nose region, where the radially inward magnetic forces are accommodated with the wedged structure. In the preliminary design, the peak stress is 490 MPa in the port region and 560 MPa in the nose region. The stresses occur in very small areas.

As in the present ITER design, the requirement of quench detection within 1 s has been adopted. Quench detectors will include a combination of conventional methods, such as voltage taps, internal or external to the sheath, and pressure/flow monitors, and experimental instrumentation. The goals of a quench detection R&D program include the development of an insulated, co-wound conductor through the center of each cable and a fibre optic temperature sensor.

A possible joint for the TF is the one developed for the US-DPC joint. It should be effective for the steady-state TF coils because of its low DC resistance of 0.4 nΩ at 30 kA, but will have to be shortened somewhat due to space constraints.

III. THE POLOIDAL-FIELD SYSTEM

The TPX poloidal field system consists of 14 coils and is symmetrical about the vertical midplane and permits both single- and double-null operation. The Central Solenoid (CS) is suspended from the TF-coil structure. An uninsulated support structure, consisting of rods on the inside and panels on the outside of the CS coil, prevents axial tension in the interpancake insulation and provides mechanical precompression to the stack. The CS is connected to the TF cases through a sliding connection that permits differential radial motion of the two coil systems. Coils PF 5–7 are supported by brackets attached to the TF cases.

The PF conductors are similar to those of the TF, using cable-in-conduit superconductors with cooling by forced-flow supercritical helium. A trade study showed that, in contrast to the TF winding pack which prefers a high current density, the PF coils are optimized with a lower average current density to avoid the field concentration of a point source. Major dimensions of the PF system are listed in Table 3. The conductor and winding concept are similar to those shown in Fig. 2 for the TF.

The PF-coils design uses all superconducting cables and strands. However, if current-transfer experiments are successful, the PF cable designs may also be replaced by hybrid cables with one pure copper strand in some triplets, in order to improve cost and protection. The Nb_3Sn composite strands in the CS and PF 5 have a 3.5:1 copper/noncopper ratio, while the Nb-Ti strands are 5:1. Since the PF design is relatively low field, none of the coils see more than 7.5 T. A trade study was performed to examine the cost/performance issues in using Nb-Ti strands, instead of Nb_3Sn. Nb-Ti was more cost effective only in the outer ring coils, PF 6 and PF 7. Therefore, ternary Nb_3Sn is used in PF 1–PF 5 and Nb-Ti in PF 6 and PF 7. With the present design, the lead losses in the PF system are a third of the total refrigeration load, while the initiation voltages never exceed 15 kV or ± 7.5 kV to ground.

TABLE 3
PF Magnet System Dimensions

Parameter	Units	Dimensions
$I_{cond, max}$	(kA)	27
$n_{strands}$ PF1-4&6-7 PF 5		225 375
W_m	(MJ)	118
M_{cond}	(tonnes)	50.1
l_{cond}	(m)	14.5
$B_{max, PF}$	(T)	7.5
$V\text{-}s_{swing}$	(Wb)	18.0

A central solenoid is a novel design having all coil terminations on the inner diameter. This feature minimizes the gap between CS and the TF, and thereby maximizes the volt second - flux swing - capability, important features for small Tokomaks. The CS consists of eight modules to provide flexibility for a variety of physics operating modes. Each module is continuously pancake wound with no interpancake joints, as illustrated by Fig. 2 for the TF coils. Specially designed tooling will be used in order to wind the pancakes radially inward and outward. The coils are fabricated with leads that extend to the service area below the Tokamak. The vertical and radial size of the lines and headers permit vertical removal of the central solenoid without removing any other coils. Hydraulic inlet and outlet fittings follow the US-DPC concept at alternating pancakes on the inside radius of each module. Each hydraulic line is connected through an electric isolator, similar to those proposed for the NET CS Model Coil[7], to vertically removable headers below the CS assembly. The PF cooling requirements are modest in TPX because of the long pulses, and the cooling system may be designed so that helium can move from the inlet to the outlet of a channel in less than one operating cycle. The central solenoid assembly, lead and hydraulic circuit configuration are shown in Fig. 4.

The Nb-Ti PF coils are wrapped with S-glass tape, during winding. Continuous strips of polyimide are co-wound along with them, and polyimide disks are inserted between pancakes. After winding all subsequent insulation, including impregnation, ground wrap, and fittings use the same system as the Nb3Sn coils.

IV. SUMMARY

The TPX magnet system is designed to provide steady-state operation for advanced Tokamak physics experiments with modest machine and operating costs. The TF and PF magnets are based on demonstrated CIC-conductor concepts and also include new features that enhance the performance of superconducting magnets in Tokamak applications. Operational experience with an all superconducting Tokamak in plasma startup, disruption handling, and quench detection will be of value to ITER and subsequent Tokamak reactors.

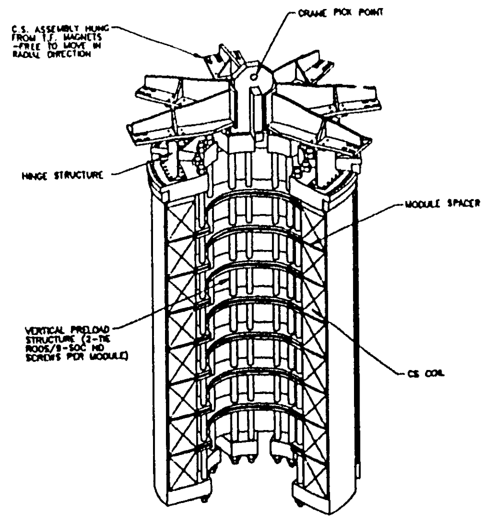

Fig. 4. Central Solenoid Assembly

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