POLOIDAL FIELD SYSTEM FOR THE TOKAMAK PHYSICS EXPERIMENT

Joel H. Schultz, R.D. Pillsbury, Jr., A. Radovinsky, P.W. Wang, Massachusetts Institute of Technology
J. Citrolo Princeton Plasma Physics Laboratory
R.J. Bulmer, D. Lang, T. O'Connor, D. Slack, J. Zbasnik
Lawrence Livermore National Laboratory
L. Myatt, Stone and Webster

***Abstract*--The Tokamak Physics Experiment (TPX) at Princeton will be the first tokamak with an all superconducting poloidal field (PF) magnet system. The conductors are all cable-in-conduit (CICC) superconductors with a single conduit, similar to those in the International Thermonuclear Experimental Reactor (ITER). 10 of the PF coils use Nb3Sn superconductor while 4 of them use NbTi. High noise initiation and disruptions demand the use of an advanced quench detection system.**

I. INTRODUCTION

The Tokamak Physics Experiment (TPX], a steady-state tokamak experiment to be built at the Princeton Plasma Physics Laboratory [1] will be the first tokamak in the world with a superconducting poloidal field (PF) magnet system [2]. All of the TPX magnets will use internally-cooled, cabled superconductors. TPX will thus be an important precursor of ITER, the International Thermonuclear Experimental Reactor [3]. Because the TPX mission includes steady-state and extremely long pulse operation at full parameters, the use of superconducting coils was an obvious choice for the magnet system. The PF system has 14 coils, 8 in a central solenoid (CS) stack and 6 outer PF coils, providing 18.8 V-s. The TPX PF system will provide advanced shaping for double-null, high-beta and high-bootstrap-fraction plasmas, as well as single-null plasmas at a full plasma current of 2.0 MA. An isometric view of the TPX PF system is shown in Figure 1.

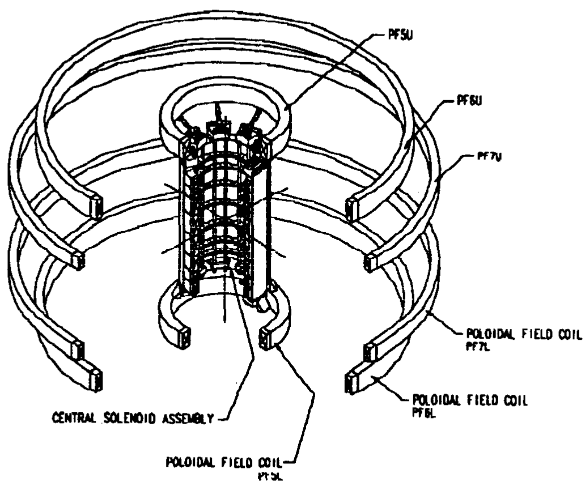

Figure 1: Isometric View of TPX PF System

A conceptual magnet design was completed and reviewed (CDR) in 1993 [4]. Since then, more detailed calculations of machine loads and requirements have necessitated changes in both the toroidal field (TF) and PF magnet systems [5], and an Engineering Change Proposal has been submttted. This paper describes the ECP design. A contract was awarded to complete preliminary design and R&D of the PF system to an industrial team headed by Westinghouse Electric Corporation, and including Northrup-Grumman and Everson Electric.

Manuscript received Oct 17, 1994. This work was supported by the US Department of Energy.

Major PF system design parameters are listed in Table I.

Parameter	Units	Value
Ncoils		14
$I_{cond,max}$	(kA)	27
$W_{m,pf,max}$	(MJ)	113.5
M_{cond}	(tonnes)	45.4
L_{cond}	(km)	15.6
$B_{max,pf}$	(T)	6.0
$dB/dt_{initiation}$	(T/s)	16
$V\text{-}s_{swing}$	(Wb)	18.8

Table I: PF Magnet System Dimensions

II. REQUIREMENTS

The magnet system must initiate, startup, and sustain three reference operating modes: high-current (HC) double-null, low-current (LC) double-null, and single-null divertor operation, including enhanced flexibility operating modes in β, l_i, and q_L space as defined in the TPX General Requirements Document [6]. The PF coils also satisfy physics specifications for the field null, electric field, and current ramp-up [6]. It is required to maintain a desired radial position, shape and size to within ± 1 cm, to control collector strike points and vertical instabilities. The PF coils can run 10 consecutive 1,000 s HC or LC pulses at 75 minute intervals in a 24 hour period or 36 consecutive 100 s pulses at 20 minute intervals in a 24 hour period. The PF coils provide 30,000 pulses at up to 2.0 MA for any of the reference and enhanced flexibility operating modes specified in the GRD, based on the criteria for fatigue life, stability, and protection in the TPX Structural Design Criteria Document [7]. Table II lists key conductor and structural design criteria.

Parameter	Units	Allowable
$f_{critical}$		0.6
$T_{margin/headroom}$	(K)	1.0/2.0
$E_{margin/headroom}$	(mJ/cc)	300/600
h_{I^2R}	$(W/m^2\text{-}K)$	1000_{Nb3Sn} 600_{NbTi}
$h_{disturbance}$	$(W/m^2\text{-}K)$	600
Allowable Stress S_M		< 2/3 yield < 1/2 tensile < 1/3 weld tensile
$P_{Memb}<1.0\ S_M$	$P_{Local\ Membrane}<1.5\ S_M$	$P_{Local\ Membrane+Bending}<1.5\ S_M$

Table II: TPX Superconductor and Structural Design Criteria

1051-8223/95$04.00

The coils are designed to remain superconducting and to recover without quench during all modes of normal operation, from all disturbances, including disruptions occurring at any time. The coils are capable of dumping all of their energy at any time without exceeding allowable voltage or temperature limits. The TF insulation systems must satisfy all protection and electrical integrity requirements, as shown in Table III.

Parameter	Units	Allowable
$V_{terminal}$	(kV)	15
$T_{hotspot}$	(K)	150
$t_{detection,max}$	(s)	1
$E_{insulation}$	(kV/mm)	2.5epoxy 8.0kapton
$E_{tracking}$	(V/mm)	80

Table III: Insulation and Protection System Allowables

III. PF DESIGN DESCRIPTION

All conductors use cable-in-conduit superconductors with cooling by forced-flow supercritical helium. The CS and PF5 coils use Nb_3Sn in an outer Incoloy 908 conduit, identical to that of the US-DPC [8], while the outer PF6-7 coils use NbTi strands in a 316LN conduit. While the two conductor types use different materials, they have the same cable and conduit geometries. The Nb_3Sn strands in the central solenoid and in PF5 all have a 3.5:1 ratio, while the NbTi strands are 5:1. All of the PF conductors have 360 strands, 240 superconducting composite and 120 pure copper strands, 1 in each triplet.

The PF coils are symmetric about the equator to provide nominal double null operation, but they are also capable of supporting single-null operation with unbalanced currents. The topology of the TPX poloidal field system is the same as that of the ITER CDA [9]. The PF support system bolts the outer six coils to the TF structure, while suspending the central solenoid from the TF coils. The Central Solenoid (CS) is supported through a single gravity support, coupled to the TF coil structure. The CS stack is connected to the TF cases through a turnbuckle support structure, connected to the TF cases, that permits differential radial motion of the two coil systems. The Central Solenoid also prevents axial tension anywhere in the interpancake insulation by the application of mechanical precompression to the stack The CS top support structure achieves the axial precompression through bolts and panels on the inside and outside of the CS stack. The CS assembly is shown in Figures 1, 2, and 3.

Closed loop cooling by supercritical helium is required for cooling of the coils, buswork, and structure. The coils are capable of being cooled down after a coil dump within 12 hours. The entire assembly is capable of being cooled down from 293 K to 4 K within 10 days.

Since the CDR, a number of design changes have been proposed, in order to better satisfy the full range of plasma shaping flexibility and steady-state deuterium burn requirements. These include:

(1) The radius of the central solenoid was increased by 10 cm when improvements in the vacuum vessel plumbing allowed an increase in PF volt-seconds and a decrease in TF peak field without increasing the tokamak major radius.

(2) The height/width ratio of the PF coils was increased in order to decrease the field at the conductor for a given PF current.

(3) The central solenoid design was changed so that the eight CS modules are no longer identical. CS modules are still symmetric about the machine equator.

(4) More cable space for internal sensors, such as insulated voltage sensors, was added.

(5) The conductor design was changed from 225 superconducting strands in PF1-4 and PF6-7, to 360 strands in all of the PF coils. The inner tube containing the US-DPC size cable was removed, in order to accommodate the larger number of strands. The reason for doing this was to be able to add 120 pure copper strands. When MHD flexibility points were added to the HC and LC scenarios considered at the CDR, several of the PF coils exceeded allowables for power balance and protection. Pure copper strands were added in order to reduce the cost impact and because the copper/noncopper ratios of the composite conductors was already high.

(6) The bolt-in-slot slip plane for the support of the CS off the TF structure was replaced by a linkage. The CS supports were "shaved" in order to allow space for the linkage and TF case growth.

(8) A radial slip plane was added to PF5 in order to eliminate insulation shear due to the differential contraction on cooldown of the PF5 coil and the TF support structure. PF6 and PF7 have a smaller cooldown shear stress and are still clamped to the TF structure, but a recent finite element stress analysis indicates that PF6 and PF7 may also require radial slip planes [10].

(7) The PF6 continuous winding length increased from 2.3 km to 2.8 km. This places the feasibiliy of using a continuous winding in all coils in question, so that intermediate joints are now being considered for PF6 and PF7, depending on cabler capabilities.

Other changes from the CDR that are currently under consideration are the use of joint/instrumentation boxes for PF5-7, the elimination of a polyimide insulation option for the interturn strips and interlayer sheets, and a decrease in the copper/nonopeer ratio of PF6-7, in order to accommodate the neutron-gamma heating from long-pulse D-D experiments.

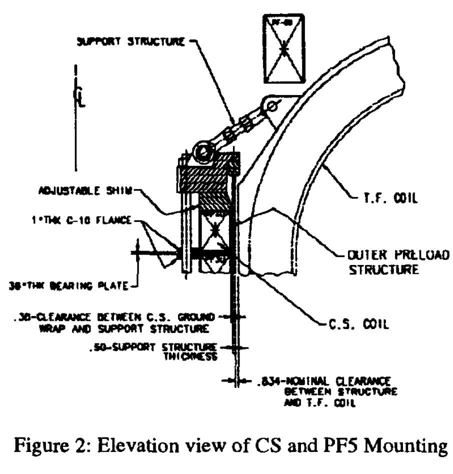

Figure 2: Elevation view of CS and PF5 Mounting from TF

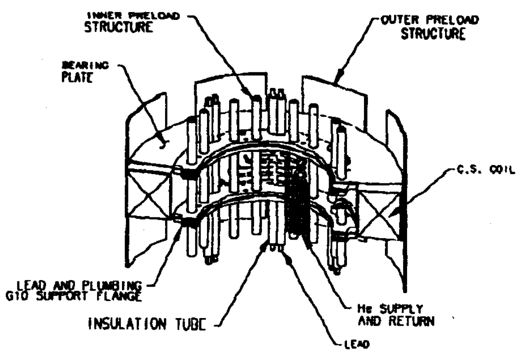

Figure 3: CS Precompression with lead and coolant supports

Central Solenoid (PF1 to 4) and Poloidal Coil 5

All eight of the central solenoid PF coils have 6 layers. The eight identical modules of the CDR CS required 10 layers. An optimization of the PF system with an MHD solver and simple cost model showed significant savings over the CDR design with 8 identiical modules. A jointless solenoid design is used without any fittings on the outer circumference of the modules in order to avoid a large gap between the CS and the TF coils in a small machine. The coils are wound in a continuous spiral using a roll bending technique similar to that of the TF coil. The pancake transitions are gentle spirals, with no jogs, on both the inside and outside diameters. There is a transition splice at the bottom of the central solenoid assembly from the Nb_3Sn lead stems to the NbTi bus. Hydraulic inlet and outlet fittings alternate pancakes on the inside radius of each module. The helium flows through a double pancake before exiting the coil. Each fitting is a Tee with split flow at the conductor.

The CS is hung from the TF structure and is allowed to move in the radial direction. Cooling lines are connected to manifolds located at the bottom of the CS assembly through electric isolators, similar to those used in the POLO Coil [11]. The vertical and radial size of the lines and headers permit vertical removal of the central solenoid, while satisfying the crane height restrictions of the TFTR test cell. The CS-power supply interface is made at the cold to warm current leads, near the power supplies to reduce the length of room temperature bus.

PF5, upper and lower, use Nb_3Sn composite strands and Incoloy 908 single conduits. The PF5 windings are similar to the CS coils except that they are at the higher radius of 1.2 m and sit directly on the TF structure. The winding packs are unencased and self-supporting against hoop forces. After potting, the winding packs are mounted on a radial slip plane to the inside frame of the TF coil structure. L-shaped brackets forming open boxes about the winding packs are bolted and keyed with springs to the TF structure at 8 places. The leads are in the inside diameter. The cooling paths of PF5 are identical to the paths of the CS coils, and the insulation system on PF5 is identical to the insulation of the central solenoid. PF5 upper is removed vertically without tokamak disassembly.

Poloidal Field Coils 6 and 7

PF6 and PF7, upper and lower, are superconducting cable-in-conduit conductors, using NbTi composite strands and 316LN double conduits. The windings are continuously wound without joints. The winding packs are unencased and self-supporting against radial hoop forces. After potting, the winding packs are clamped to the outside frame of the TF coil structure with L-shaped brackets. After disassembly of the support structure, PF6 upper and PF7 upper and lower can be removed vertically without tokamak disassembly. The leads for both coils are located on the outside diameter of the coil bundle. Each supercritical helium flowpath is comprised of a double coil pancake. The helium feedthroughs are located on the outer transitions between pancakes.

IV. PF SYSTEM DIMENSIONS

The overall dimensions of the TPX PF coils are shown in Table IV.

Coil	R	Z	R_1	R_2	Z_1	Z_2
--	(m)	(m)	(m)	(m)	(m)	(m)
PF1,U+L	0.810	±0.251	0.738	0.882	±0.012	±0.490
PF2,U +L	0.810	±0.706	0.738	0.882	±0.515	±0.898
PF3,U+L	0.810	±1.042	0.738	0.882	±0.922	±1.161
PF4,U +L	0.810	±1.306	0.738	0.882	±1.186	±1.425
PF5,U +L	1.213	±2.350	1.117	1.309	±2.159	±2.541
PF6,U+L	3.758	±2.144	3.687	3.830	±1.905	±2.383
PF7,U+L	4.297	±1.113	4.225	4.369	±0.946	±1.281

Table IV: TPX PF System Dimensions

The hydraulic circuits of the PF winding packs are described in Table V.

Coil	SC type	Pancakes x Layers	n_{turns}	L_{chan}	Pin
	(m)	(m)	(m)	(m)	(MPa)
PF1,U+L	Nb_3Sn	20 x 6	120	61.1	0.4
PF2,U+L	Nb_3Sn	16 x 6	96	61.1	0.4
PF3,U+L	Nb_3Sn	10 x 6	60	61.1	0.4
PF4,U+L	Nb_3Sn	10 x 6	60	61.1	0.4
PF5,U+L	Nb_3Sn	16 x 8	108	122	0.4
PF6,U+L	NbTi	20 x 6	120	283	0.4
PF7,U+L	NbTi	14 x 6	84	324	0.4

Table VIII: PF Coil Hydraulic Circuit Description

The electrical requirements for the PF coils for the nominal 2.0 MA Double-Null HC scenario are shown in Table VI. The voltages listed are for an individual upper or lower coil.

Coil	$Icond_{max}$	$Icond_{min}$	$Vterm_{max}$	$Vterm_{min}$
	(kA)	(kA)	(kV)	(kV)
PF1,U+L	7.79	-24.6	0.25	-1.85
PF2,U+L	24.1	-13.4	0.19	-1.53
PF3,U+L	24.1	-5.6	0.12	-0.93
PF4,U+L	24.4	-0.54	0.214	-0.81
PF5,U+L	26.2	0.0	0.31	-2.77
PF6,U+L	1.2	-14.2	0.66	-2.82
PF7,U+L	1.4	-10.9	1.21	-2.37

Table VI: Peak Current and Voltage on PF Coils, HC Scenario

V. PF QUENCH DETECTION

In order to achieve reliable quench detection, several independent sensor types are used. The design philosophy is to use two independent, high signal-noise, nonrepairable sensor types (fiber optic thermometers and cowound voltage sensors) and two moderate signal-noise, repairable sensor types (flow meters and voltage taps) [12], [13]. Cancellation techniques, such as using a differential signal from two adjacent double pancakes or central difference averaging of three double pancakes will be used to eliminate the TF and PF noise voltages, from events such as vertical disruptions. Active and passive coil influence matrices will be used for further noise reduction of signals from routine operation. Two possible cowound sensor types are an insulated wire down the center of the TF superconducting cable or cowound and insulated wires along the surface of the cable. Sensors are terminated every two pancakes and extracted at the joint regions. Insulated cowound sensors can also double as heaters for coil testing.

Flow meters will be used in each hydraulic inlet and outlet line. Strain gauge bridges should be relatively insensitive to pulsed fields and oscillations due to large flow reversals. Fiber optic cables will be terminated every 2 pancakes with sputtered-gold reflectors. Changes in the optical path length will be measured by Michelson interferometers. Injection of dual light signals with different light and strain sensitivities will be used to cancel the effects of mechanical strain.

VI. R&D SUMMARY AND PLANS

The R&D program includes routine small sample testing, dummy cabling and jacketing, conductor bending, practice windings, and practice impregnations and cures. The dielectric strength of the insulation system will be tested in mockups of the lead, hydraulic joint, and electrical isolator area under different partial helium pressures, in order to test the integrity of the boot and insulation wrap designs under the probable condition of small helium leaks into vacuum.

Prototyping experiments have begun for new quench detection techniques, such as fiber optic temperature sensing, coaxial insulated voltage sensors and distributed pressure sensors. Quench detection R&D is being coordinated with the US Home Team research activities for ITER.

Strand tests will be conducted at several laboratories on samples from two TF prototype billets, four Nb_3Sn PF prototype billets, and 1 NbTi billet. Subcable tests will be conducted at M.I.T. at up to 25 T/s to explore the limits of different conductor design options.. Full scale conductor and joint tests will be done in the new 1J facility at MIT. The conductor-and-joint samples under test for both the DC and pulsed testing will be provided by Livermore.

VII CONCLUSIONS

1) The conceptual design of an all-superconducting tokamak PF system has been completed, and engineering change proposals submitted, allowing both pulsed ohmic and steady-state deuterium burns at full operating parameters.

(2) The CIC conductors take advantage of tested designs and the ITER conductor development program.

3) The R&D program addresses the issues of reliable quench detection and high dB/dt during initiation and disruptions.

REFERENCES

[1] W. Reiersen, "The Engineering Design of TPX", 15th IEEE Symp on Fus Eng, Hyannis, MA, Oct 1993

[2] J.H. Schultz et al, "The TPX Superconducting Magnet System," 15th IEEE Symp on Fus Eng, Hyannis, MA, Oct 1993

[3] R.J. Thome, "Program Overview for the International Thermonuclear Experimental Reactor," IEEE Magnet Technology Conference, MT-13, Victoria, Sept 1993

[4] W. Reiersen, TPX: Tokamak Physics Experiment: Conceptual Design Overview," TPX No.91-930319-PPPL/WReiersen-02

[5] J. Zbasnik et al, "TPX Magnet System Status," 18th Symp on Fus Tech, Karslruhe, Ger, Aug 1994

[6] W. Reiersen, ed., "TPX General Requirements Document," March 15, 1993

[7] P. Heitzenroeder, I. Zatz, J.H. Schultz, "Development and implementation of the TPX structural and cryogenic design criteria," 15th IEEE Symp on Fus Eng, Hyannis, MA, Oct 1993

[8] M.Steeves et al, "Test results from the Nb3Sn US-Demonstration Poloidal Coil", Adv Cryo Eng, 37A, 345, Plenum, June 1991

[9] ITER Magnet Design Unit, J.Miller, ed., **ITER MAGNET SYSTEM**, ITER Doc. Series No 26, IAEA, Vienna 1990

[10] R. Leonard Myatt, "3-D Stress Analysis of the TPX Toroidal Field Coil Support Structure," this conference

[11] G. Schenk et al, "High voltage insulation and tests of cryogenic components for the superconducting model coil POLO," 15th Symp on Fus Tech, 1552, Utrecht, Neth, Sept 1988

[12] J.H. Schultz et al, "Superconducting magnet protection system for the Tokamak Physics Experiment," IEEE Magnet Technology Conference, MT-13, Victoria, Sept 1993

[13] J.H. Schultz et al, "Novel Quench Detection Methods for the Superconducting Magnets in ITER and TPX" , Karslruhe, Ger, Aug 1994