THE TPX SUPERCONDUCTING MAGNET SYSTEM

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***Abstract*--The Tokamak Physics Experiment (TPX) at Princeton will be the first tokamak with an all superconducting magnet system, including both the toroidal field (TF) and poloidal field (PF) coils. The conductors are all cable-in-conduit (CIC) superconductors with a single conduit, similar to those in the International Thermonuclear Experimental Reactor (ITER).**

I. INTRODUCTION

The Tokamak Physics Experiment (TPX), an advanced plasma, steady-state tokamak experiment to be built at the Princeton Plasma Physics Laboratory [1] will be the first entirely superconducting magnet system in the world [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], a much larger burning plasma reactor that will also use internally-cooled, superconducting toroidal and poloidal field magnet systems. TPX is designed to run double-null, high-beta and high-bootstrap-fraction plasmas, as well as single-null plasmas at full current. Because the TPX mission includes the achievement of steady-state and extremely long pulse operation at full parameters, the use of superconducting coils was an obvious choice for the magnet system. The only normal copper coils in the machine are two pairs of four saddle coils about the vertical ports above and below, used for field error correction and a pair of vertical stability coils inside the vacuum vessel.. A cutaway of the tokamak and its coils is shown in Figure 1.

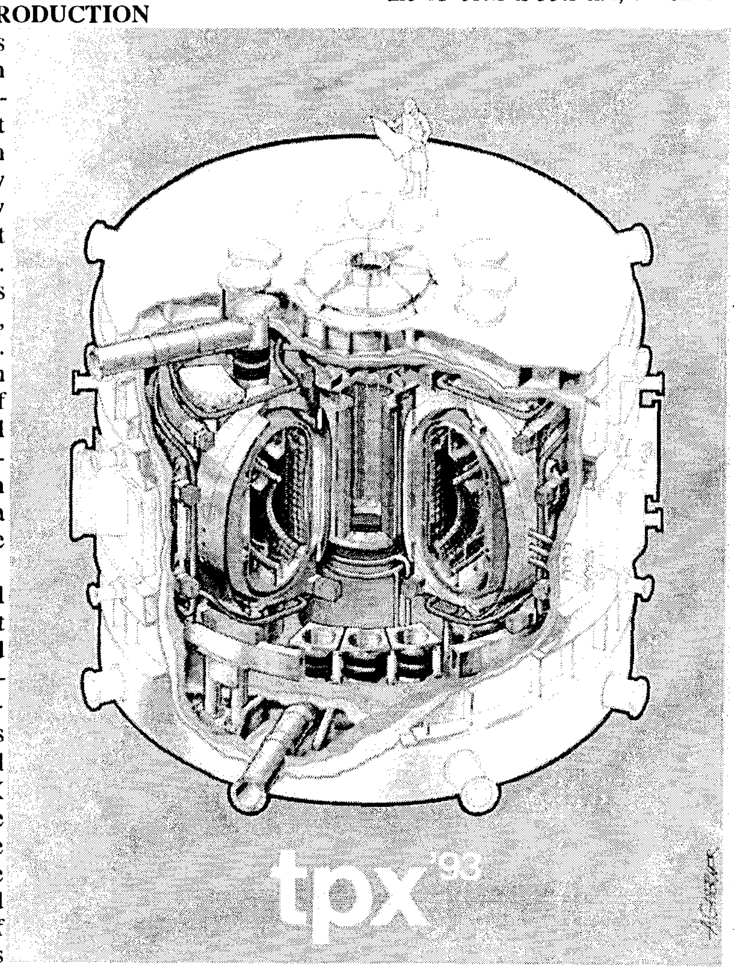

Figure 1: The Tokamak Physics Experiment

The TF system has 16 coils, providing a field of 4 T at a plasma major radius of 2.25 m, with a peak flux density at the TF coils of 8.6 T. The TF coils use Nb_3Sn strands in a 2.4 mm thick Incoloy 908 conduit, like that of the US-DPC coil [4]. The inner conductor dimensions are scaled to the Westinghouse LCP conductor [5] and the cable is also 3^4 x 6. This is larger than the conductor described in the Conceptual Design Review (CDR) [2], because of subsequent increases in the peak field and nuclear heat load. The conductor current in the TF coils is 33.5 kA, which is high enough to allow the TF system to dump 1.0 GJ of stored energy with all coils in series. Each coil is continuously wound without joints. The TF coils are encased and then assembled in two coil welded modules, which are then joined into quadrants with insulating break joints. The out-of-plane structure is a welded and bolted system of webs and gussets between cases and ports.

The PF system has 14 coils, 8 in a central solenoid (CS) stack and 6 outer PF coils. These provide 18 V-s and can sustain steady-state, current-driven 2 MA plasmas. The CS and PF5 coils use Nb_3Sn in an Incoloy 908 conduit, identical to that of the US-DPC [4], while the outer PF coils use NbTi strands in a 316LN conduit. 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 PF support system bolts the outer six coils rigidly to the TF structure, while suspending the central solenoid from the TF coils. The CS can move radially with respect to the TF, achieving axial precompression through bolts and panels on the inside and outside of the CS stack. The quadrant concept and the outer PF supports are shown in Figure 2.

Since the CDR, a number of design changes have been considered, in order to better satisfy the full range of plasma

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shaping flexibility and steady-state deuterium burn requirements. Along with the abovementioned increase in the TF conductor size, these include:

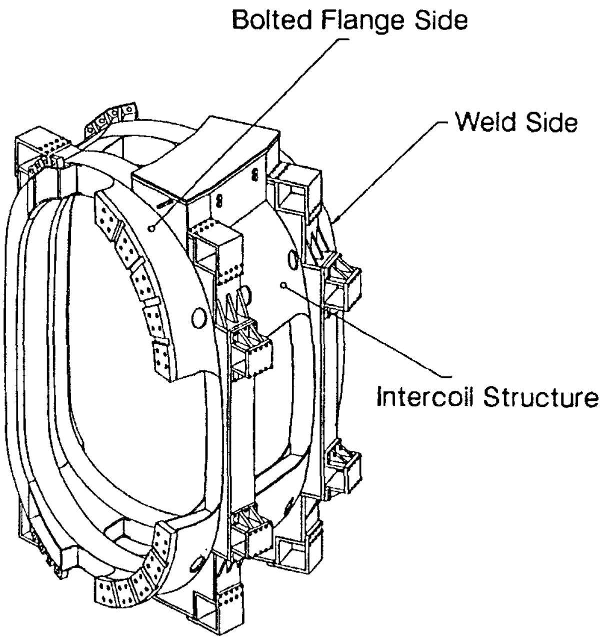

Figure 2: Two TF Coil Assembly with Outer PF Supports

(1) Increasing the height/width ratio of PF5-7 in order to decrease the field at the conductor for a given PF current.
(2) Providing cooling at the high field side of the TF coils.
(3) Adding more cable space for internal sensors, such as insulated voltage snesors.
(4) Moving the TF case closeout weld from the nose to the lower-stress sidewall [6].

Operational Requirements

The TF performance required by the plasma is summarized in Table I.

Parameters	Units	Dimensions
B_t	(T)	4.0
R_0	(m)	2.25
NI	(MAT)	45
Edge $\text{Ripple}_{pk\text{-}avg}$	(%)	0.4

Table I: TF Design Requirements

The combined TF and PF system must initiate, startup, and sustain three reference operating modes: high-current (HC) double-null divertor operation, low-current (LC) double-null divertor,and single-null divertor operation, including enhanced flexibility operating modes in β, l_i, and q_L space as defined in the General Requirements Document [7]. 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 [7] based on the criteria for fatigue life superconductive magnet stability, and protection criteria in the TPX Structural Design Criteria Document [8].
Conductor and structural design criteria are shown in Table II.

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}	$(W/m^2\text{-}K)$	1120
$h_{disturbance}$	$(W/m^2\text{-}K)$	640
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

The TF coil is designed for 6,000 charge-discharge cycles for operation and glow-discharge cleaning. It also allows 2×10^6 s of D-D operation, which should cause a dose rate to the insulation of 3.7×10^6 rads [7]. The TF coil insulation system, including the epoxy and S-glass, should have no measurable damage to insulation shear strength below a dose of 5×10^9 rad.

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.

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

II. TF AND PF CONDUCTOR DESIGNS

All conductors use cable-in-conduit superconductors with cooling by forced-flow supercritical helium. The conductor concept is a modification of the US-DPC wire, which combines a high yield, moderate performance Nb_3Sn composite with tested performance in pulsed fields [4]. The dimensions of the US-DPC conductor are identical to those of the CS coils. The PF5 coils use only the thick outer Incoloy 908 conduit of the US-DPC, in order to fit a larger 375 strand cable of modified US-DPC Nb_3Sn conductor. The PF6-7 conductors are topologically and dimensionally the same as the US-DPC, but use NbTi strands in a 316LN conduit. The Nb_3Sn strands in the central solenoid and in PF5 all have a 3.5:1 ratio, while the NbTi strands are 6:1. The TF conductor is inserted in an Incoloy 908 conduit the same thickness as the

Parameter	Units	TF	CS	PF5	PF6-PF7
Conductor type			Nb_3Sn	Nb_3Sn	NbTi
Conduit type		Incoloy 908	Incoloy 908	Incoloy 908	316LN
Cu/Noncu		2.05:1	3.5:1	3.5:1	6:1
Aconduit	(mm^2)	192	228.6	179.2	228.6
D_{strand}	(mm)	0.78	0.78	0.78	0.78
$n_{strands}$		486	225	375	225
$h_{conduit}$	(mm)	24.0	22.3	22.3	22.3
$w_{conduit}$	(mm)	24.0	22.3	22.3	22.3
$t_{conduit}$	(mm)	2.41	2.41	2.41	2.41
A_{cu}	(mm^2)	158	83.6	139.4	89.6
A_{noncu}	(mm^2)	77	23.89	39.8	17.9
A_{Hecond}	(mm^2)	127	85.5	120.2	85.5
Strand length	(km)	6,781	1,184	604	1,811
Cable length	(km)	16.1	5.06	1.55	3.87
Strand mass	(tonnes)	26.8	4.68	2.39	3.57
Ncoils		16	8	2	4
J_{noncu}	(A/mm^2)	1130@8.6 T, 4.2 K, ε=-0.3	1300 @7.6 T, 4.2 K, ε=-0.3	1850 @ 5.3 T, 4.5 K, ε=-0.3	2075 @ 5 T, 4.2 K
D_{feff} $Loss_{Noncu}$ ($\pm$ 3 T)	(μm) (mJ/cc)	20 460	20 460	20 460	7 150
Coupling time (B=0)	(ms)	30	30	30	30
RRR		75	75	75	150

Table IV: TF and PF Conductor Parameters

US-DPC, but is widened to permit the 3^4 x 6, 486 strand pattern of the Westinghouse LCP coil. [5]. Conductor dimensions are shown in Table IV.

All sixteen TF coils are electrically connected in series. This saves money on the power supply and refrigerator for the 33.5 kA leads, but the primary benefit is that single coil faults don't cause any unbalanced forces. If a TF coil quenches, all coils are dumped through an external nonlinear resistor. The toroidal field magnet performance is listed in Table V.

Parameter	Units	Dimensions
B_{max}	(T)	8.6
I_{cond}	(kA)	33.5
$n_{pancakes}$		12
n_{layers}		7
n_{coils}		16
$n_{turns,system}$		1344
$n_{strands}$		486
$W_{m,TF}$	(GJ)	1.04
$V_{dump,system}$	(kV)	15
$L_{conductor}$	(km)	16.1

Table V: TF Magnet System Major Parameters

III. TF DESIGN DESCRIPTION

The TF coils are assembled in groups of four, forming TF assembly quadrants to facilitate assembly and repair. The TF structure interfaces with the cold mass gravity support structure through a circular ring between the two structures. Each of the PF 6 and 7 coils are rigidly supported at 16 places and PF5 at eight places by attachment to the TF magnet cases. The TF - power supply interface is made near the power supply to reduce the length of room temperature bus. The entire magnet system is inside the cryostat.

The TF structure consists of welded 316LN 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 apiece, along with other tokamak components, are then joined at the intercoil structure parting plane with an insulated break joint, to form a 90^0 module. Insulating sheets are inserted in the TF coil noses between every two coil octant. Compression is ensured in the insulation through bolted flanges at the top and bottom of the TF inside legs. The highest stresses occur in the nose and port region, where the intercoil structure is constrained by the need for large horizontal ports between each TF coil.

Each of the sixteen TF coils is 4-3/4 meters high and 3 meters wide and each coil winding pack weighs 50 tons. There are 84 turns per coil, arranged in 12 pancakes of 7 layers each, with no joints at the transitions between pancakes. Each coil is wound from a single length of conductor, 1008 meters long, and does not have splice joints internal to the coil. This is done by winding the coil radially outward on one pancake and then backwinding radially inward on the next pancake and repeating the process. A three roll bender is used to bend the conductor to the correct radius instead of the usual winding under tension. After heat treatment, each turn is separated and hand insulated, then returned to the plane of the pancake, as shown in Figure 3.

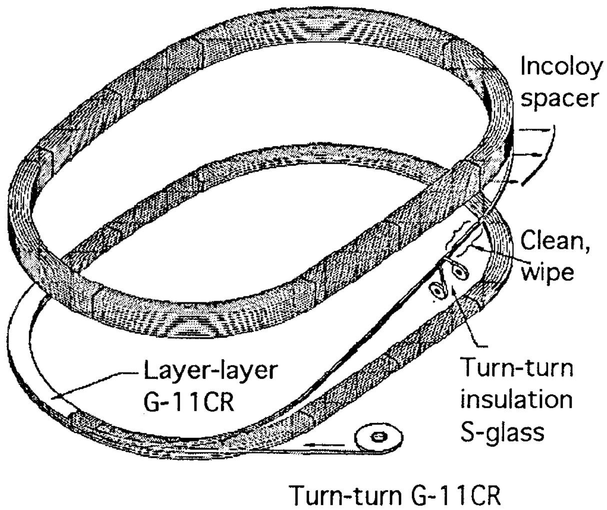

Figure 3: Insulation of Continuous Wound TF Coil

The TF coil is cooled by by forcing supercritical helium through the winding packs and interconnection joints and through 3.0 mm thick Mueller panels mounted on the TF coil cases. The cooling connections to the conduits are on the low field side of the coil at the top. The cooling lines "Tee" into the conductor at the pancake crossovers at both the inlet and outlet.. Helium transverses a pancake to the pancake transition at the high field side and then spirals out through the adjacent pancake. The insulator, filters, instrumentation, and headers for the cooling lines are located at the top of the intercoil structure between coil pairs. The outputs of all the TF hydraulic paths are combined to cool the interconnection joints between TF coils.

The transitions between pancakes and the layer-layer transitions are at the top of the coil. This allows a void free, rectangular winding pack in the inner and outer legs of the coil. Voids caused by the transitions are filled with G-11CR 'S' glass blocks. Between each coil there is an interconnection joint, similar to the US-DPC lap joint, which is particularly appropriate for the steady-state TF coils, because of its low DC resistance of 0.4 nΩ at 30 kA [9]. The 15 interconnection joints are located in the intercoil structure between coils in the coil module, at the bolted structural joint between modules and at the welded structural joint between quadrants. There is a splice joint between the Nb_3Sn conductor and the NbTi/copper bus from the TF coils to the vapor cooled leads.

IV. PF DESIGN DESCRIPTION

The PF system initiates plasma current discharges, ramps the plasma to its flattop current, maintains the plasma current, and ramps down. 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 system provides a range of scenarioes, including the high-current, double-null divertor operation (HC), low-current, double-null divertor operation (LC), and single-null operation [7]. The PF coils also satisfy physics specifications for the field null, electric field, and current ramp-up [7]. The PF coils are designed to provide up to 30,000 pulses at up to 2.0 MA for any combination of these three scenarioes or for their flexibility operating modes [7]. 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 topology of the TPX poloidal field system is the same as that of the ITER CDA [10]. The Central Solenoid (CS) is supported through a single gravity support, coupled to the TF coil structure. The Central Solenoid also prevents axial tension anywhere in the interpancake insulation by the application of mechanical precompression to the stack through an uninsulated spider support structure. The CS stack is connected to the TF cases through a slotted bracket which permits differential radial motion of the two coil systems. The CS assembly is shown in Figure 4.

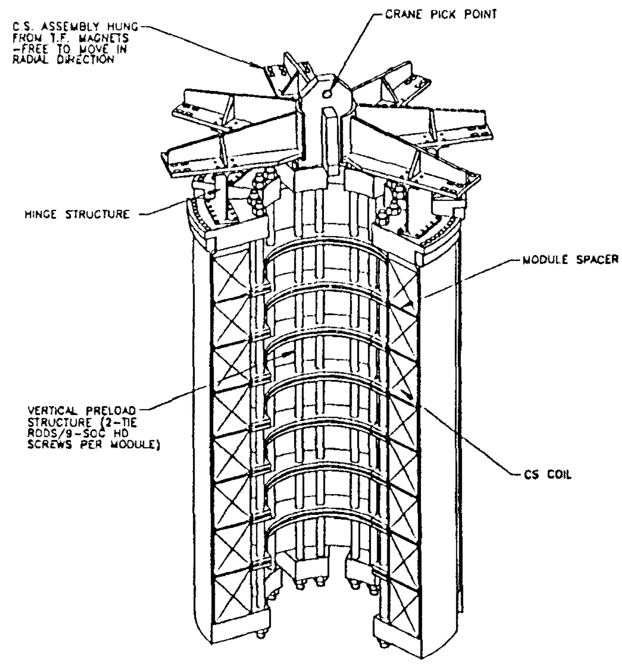

Figure 4: Central Solenoid Assembly

PF5-7 are clamped to the TF cases through bolted brackets and do not permit relative radial motion. The major design parameters of the PF system are listed in Table VI.

Parameter	Units	Value
Ncoils		14
$I_{cond,max}$	(kA)	27
$W_{m,pf,max}$	(MJ)	118
M_{cond}	(tonnes)	50.1
L_{cond}	(km)	14.5
$B_{max,pf}$	(T)	7.5
$V\text{-}s_{swing}$	(Wb)	18.0

Table VI: PF Magnet System Dimensions

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

Coil	R	Z	dR	dZ	nturns	strands
	(m)	(m)	(m)	(m)		
PF1,U+L	0.72	±0.175	0.239	0.334	140	225
PF2,U+L	0.72	±0.525	0.239	0.334	140	225
PF3,U+L	0.72	±0.875	0.239	0.334	140	225
PF4,U-L	0.72	±1.225	0.239	0.334	140	225
PF5,U+L	1.23	±2.2	0.239	0.239	100	375
PF6,U+L	3.78	±2.13	0.239	0.239	100	225
PF7,U+L	4.244	±1.091	0.168	0.192	56	225

Table VII: TPX PF System Dimensions

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

Coil	SC type	Pancakes x Layers	Helium channels	L_{chan}	Pin
	(m)	(m)	(m)	(m)	(MPa)
CS (PF1-4))	Nb_3Sn	14 x 10	7	90.5	0.4
PF5,U+L	Nb_3Sn	10 x 10	5	154.6	0.4
PF6,U+L	NbTi	10 x 10	5	475	0.4
PF7,U+L	NbTi	8 x 7	4	373	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 IX.

Coil	$Icond_{max}$	$Icond_{min}$	$Verm_{max}$	$Vterm_{min}$
	(kA)	(kA)	(kV)	(kV)
PF1,U+L	5.96	-19.7	0.424	-1.62
PF2,U+L	7.97	-13.7	0.35	-1.57
PF3,U+L	18.6	-7.05	0.256	-1.55
PF4,U+L	21.8	-0.718	0.247	-1.523
PF5,U+L	27.0	0.0	0.162	-1.475
PF6,U+L	1.80	-16.8	0.892	-1.55
PF7,U+L	2.45	-14.8	0.615	-1.14

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

Central Solenoid (PF1 to 4) and Poloidal Coil 5

The eight central solenoid PF coils are identical except for the length of the lead stems on the inside diameter. Each winding pack module is a single 633 m length of conductor, wound in 14 pancakes of ten turns each. 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 proposed for the NET CS Model 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 there are only 10 pancakes of 10 turns, wound continuously from a single conductor 773 meters long. The winding packs are unencased and self-supporting against hoop forces. After potting, the winding packs are clamped to the inside frame of the TF coil structure. L-shaped brackets forming open boxes about the winding packs are bolted and keyed 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 eachTF coil structure with L-shaped brackets, like PF5. 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.

V. TF AND PF QUENCH DETECTION

In order to achieve reliable quench detection, several independent sensor types are used, including voltage taps, flow meters, cowound wires, and fiber optic thermometers [12]. There are four candidate voltage sensors. The first are conventional taps connected to the outer conduit in each pancake. Cancellation techniques, such as using a differential signal from two adjacent pancakes or central difference average of three will be used to eliminate the TF and PF noise voltages, from events such as vertical disruptions. The second sensor type is an insulated wire down the center of the TF superconducting cable, through the entire winding pack. The third type are cowound, insulated wires, laid along the conduits, as was done in the US-DPC coil. These would also be tapped every two pancakes. The fourth and potentially most sensitive are cowound and insulated wires along the surface of the cable, extracted every two pancakes. 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.

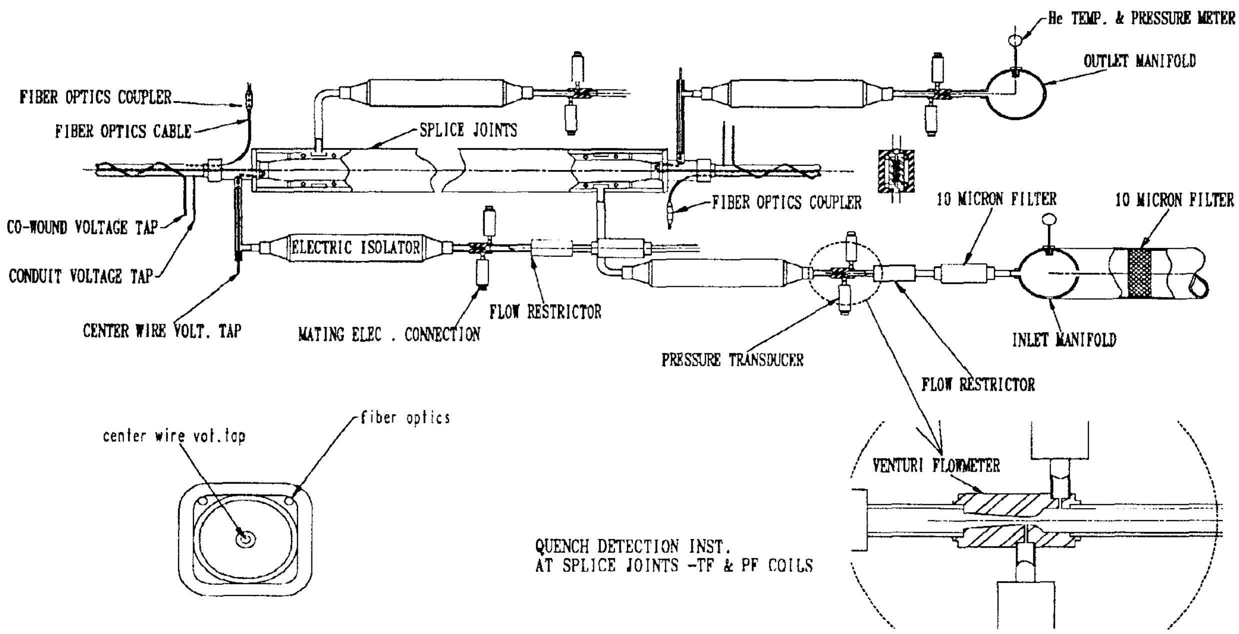

Figure 5: Quench Detection Sensor Concept for TPX

Fiber optic temperature sensors may be cowound continuously with the cable, but will be 'fished out' through the hydraulic inlets and outlets and spliced to optical couplers. Fiber optic cables may be used either as continous interferometric measures of changes in the optical path length or as reflectometers, measuring local temperature changes. Quench detection concepts are shown in Figure 5.

V. 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 are needed 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.

Subcable tests will be conducted at M.I.T. at up to 20 T/s to explore the limits of different conductor design options.. Full scale conductor and joint tests will be done in FENIX. New pulsed coils in the HFTF dewar, capable of 12 T/s ramps will test stability and losses in transverse and longitudinal pulsed fields.

VII CONCLUSIONS

1) The conceptual design of an all-superconducting tokamak has been completed, 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.

4) Design and operation of the world's first all-superconducting tokamak will assist design and operations planning for ITER.

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