THE KSTAR SUPERCONDUCTING MAGNET SYSTEM

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***Abstract*--The Korean Superconducting Tokamak Advanced Research (KSTAR) at the Korea Basic Science Institute in Taejon will be the first tokamak with an advamced all superconducting magnet system, including toroidal field (TF), poloidal field (PF) , and Field Error Correction (FEC) coils. The conductors are all cable-in-conduit (CICC) superconductors with a single conduit, similar to those in the International Thermonuclear Experimental Reactor (ITER).**

I. INTRODUCTION

The Korean Superconducting Tokamak Advanced Reactor (KSTAR), an advanced plasma, steady-state tokamak experiment to be built at the Korean Basic Science Institute will have an superconducting magnet system. All of the KSTAR magnets will use internally-cooled, cabled superconductors. KSTAR will thus be an important precursor of ITER, the International Thermonuclear Experimental Reactor [1], a much larger burning plasma reactor that will also use internally-cooled, superconducting toroidal and poloidal field magnet systems. The magnet system is based on that of the cancelled Tokamak Physics Experiment [2]. KSTAR is designed to run double-null, high-beta single-null plasmas at full current. Because the KSTAR mission includes the achievement of extremely long pulse operation at full parameters, the use of superconducting coils is an obvious choice for the magnet system. An isometric of the tokamak and its coils is shown in Figure 1.

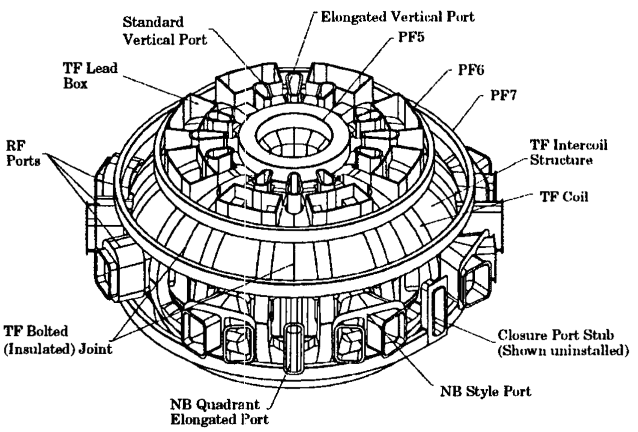

Figure 1: KSTAR general arrangement with magnet system

The TF system has 16 coils, providing a field of 3.5 T at a plasma major radius of 1.8 m, with a peak flux density at the TF coils of 7.5 T. The TF coils use Nb_3Sn strands in a 2.8 mm thick Incoloy 908 conduit. The cable pattern is 3^4 x 6 of 486 ITER HP-I strands. The conductor current in the TF coils is 35.2 kA, which is high enough to allow the TF system to dump 470 MJ 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 with insulating break joints. The out-of-plane structure is a welded system of webs and gussets between cases and ports.

The PF system has 13 coils, 7 in a central solenoid (CS) stack and 6 outer PF coils. These provide 13.6 V-s and can sustain 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 [3], while the outer PF coils use NbTi strands in a 316LN conduit. The PF coils are symmetric about the equator. The PF support system bolts the outer six coils 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.

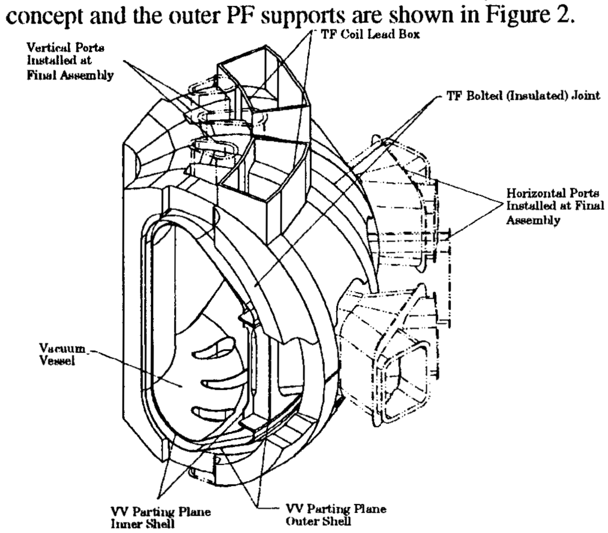

Figure 2: TF Coil Quadrant Assembly with PF Supports

Operational Requirements

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

Table I: TF Design Requirements

Parameters	Units	Dimensions
B_t	(T)	3.5
R_0	(m)	1.8
NI	(MAT)	31.5

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The combined TF and PF system must initiate, startup, and sustain a reference operating mode, and be capable of single-null divertor operation, including enhanced flexibility operating modes in β, l_i, and q_L space as defined in the KSTAR Physics Requirements Document (PRD) [4]. The PF coils provide pulses at up to 2.0 MA for any of the reference and enhanced flexibility operating modes specified in the PRD, based on the criteria for fatigue life superconductive magnet stability, and protection criteria in the TPX Structural Design Criteria Document [5]. Conductor and structural design criteria are shown in Table II.

Table II: KSTAR Superconductor 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-K)	1120
$h_{disturbance}$	(W/m^2-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

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.

Table III: Insulation and Protection System Allowables

Parameter	Units	Allowable
$V_{terminal}$	(kV)	15
$T_{hotspot}$	(K)	150
$S\text{-}N_{detection,min}$	(s)	10:1
$E_{insulation}$	(kV/mm)	2.5epoxy 8.0kapton
$E_{tracking}$	(V/mm)	80

II. TF AND PF CONDUCTOR DESIGNS

All conductors use cable-in-conduit superconductors with cooling by forced-flow supercritical helium. The CS and PF5 coils use a thick outer Incoloy 908 conduit, identical to that of the US-DPC, in order to fit a larger 360 strand cable of ITER HP-I conductor [1]. The PF6-7 conductors are topologically and dimensionally the same as the CS, but use NbTi strands in a 316LN conduit. The Nb_3Sn strands in the central solenoid and in PF5 all have a 1.5:1 ratio, while the NbTi strands are 3.5:1. The TF conductor is inserted in a larger Incoloy 908 conduit to permit the 3^4 x 6, 486 strand pattern of the Westinghouse LCP coil. [6]. Conductor dimensions are shown in Table IV.

Table IV: TF and PF Conductor Parameters

Parameter	Units	TF	PF1-5	PF6-7
Conductor		Nb_3Sn	Nb_3Sn	NbTi
Conduit		Incoloy908	Inco 908	316LN
Cu/Noncu		1.5:1	1.5:1	3.5:1
$A_{conduit}$	(mm^2)	233	179.2	179.2
D_{strand}	(mm)	0.81	0.81	0.81
$n_{strands}$		486	360	360
$n_{custrands}$		162	120	120
$h_{conduit}$	(mm)	25.65	22.3	22.3
$w_{conduit}$	(mm)	25.65	22.3	22.3
$t_{conduit}$	(mm)	2.86	2.41	2.41
A_{cu}	(mm^2)	179.1	132.7	154.1
A_{noncu}	(mm^2)	65.1	48.25	26.8
A_{Hecond}	(mm^2)	133	111.4	111.4
Lstrand	(km)	3194	1625.8	1563
Lcable	(km)	9.86	6.78	7.33
Mscstrand	(tons)	13.4	6.844	7.5
Ncoils		16	9	4
J_{noncu}	(A/mm^2)	540	544.2	641.8
D_{feff} E_{Noncu} (± 3 T)	(μm) (mJ/cc)	28 600	28 600	10 220
nτ (B=0)	(ms)	60	60	60
RRR		100	100	100

All sixteen TF coils are electrically connected in series. This saves money on the power supply and refrigerator for the 35.2 kA leads, but the primary benefit is that neither quench dumps nor single coil faults cause unbalanced forces. If a TF coil quenches, all coils are dumped through an external nonlinear resistor. TF magnet performance is listed in Table V.

Table V: TF Magnet System Major Parameters

Parameter	Units	Dimensions
B_{max}	(T)	7.5
I_{cond}	(kA)	35.2
$n_{pancakes}$		8
n_{layers}		7
n_{coils}		16
$n_{turns,system}$		896
$W_{m,TF}$	(MJ)	470
$V_{dump,system}$	(kV)	3.0

III. TF DESIGN DESCRIPTION

The TF coils are assembled in groups of welded octants, and bolted into 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. PF6-7 are supported at 16 places by attachment to the TF magnet cases and PF5 at 8 places. The entire magnet system is inside the cryostat.

The TF structure consists of welded 316LN cases with thick noses at the inside leg to support centering loads in wedging. Two coils are combined into a welded assembly with a central structural weldment and two identical closure welds. TF octants are joined at the intercoil structure parting planes with precision bolted joints. Insulating sheets are inserted in the TF coil noses between octants. Compression is ensured in the insulation by terminating the sheets below the separation regions. The highest stresses occur in the nose and port regions, where the intercoil structure is constrained by the need for large horizontal ports between each TF coil.

The sixteen TF coils are 4.2 m high and 3 m wide. There are 56 turns per coil, arranged in 8 pancakes of 7 layers each, with no joints at the transitions between pancakes. Each coil is wound from a continuous 616 m length of conductor. This is done by winding the coil radially outward on one pancake and then backwinding radially inward on the alternate pancakes. A three roll bender is used to bend the conductor to the correct radius without 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.

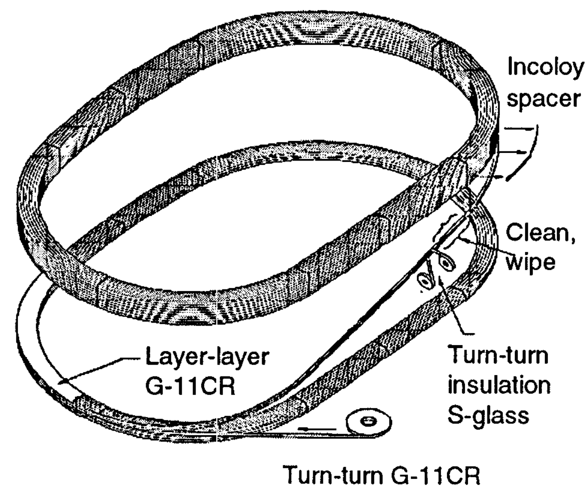

Figure 3: Insulation of Continuous Wound TF Coil

The TF coil is cooled by forcing supercritical helium through the winding packs, joints and cases. The cooling connections to the conduits are on the low field side of the coil at the top. Cooling stubs "Tee" into the conductor at the pancake crossovers at both the inlet and outlet. The insulator, filters, instrumentation, and headers for the cooling lines are located at the top of the intercoil structure between coil pairs. A helium inlet at the center of each intercoil joint splits to cool the joint halves and the adjacent winding pack cooling channels. Intercoil stucture is cooled separately.

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. The 15 intercoil joints are located in the structure between coils in an octant, and at the bolted structural joints between octants.

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 radial position, shape and size. The PF system provides a range of scenarioes, achieving plasmas with $0<\beta<5$ %, $0.4<li<1.3$, and $\kappa\leq 2.0$. The PF coils also satisfy physics requirements for the field null and electric field, during startup [4]. The PF coils are designed to provide up to 50,000 pulses at up to 2.0 MA for any combination of operating modes. The PF coils can run 50 consecutive 20 s pulses at 15 minute intervals.

The Central Solenoid (CS) is supported through a single gravity support, coupled to the TF coil structure. The CS support also prevents axial tension anywhere in the interpancake insulation by precompression of the stack with bolts and panels The CS stack is connected to the TF cases through a centering mount which permits differential radial motion of the coil systems. PF5-7 are bolted to the TF cases through mounts permitting relative radial motion. The major design parameters of the PF system are listed in Table VI.

Table VI: PF Magnet System Dimensions

Parameter	Units	Value
Ncoils		13
$I_{cond,max}$	(kA)	26.5
$W_{m,pf,max}$	(MJ)	86.8
M_{wp}	(tonnes)	45.4
$B_{max,pf}$	(T)	7.8
$V\text{-}s_{swing}$	(Wb)	13.6

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

Table VII: KSTAR PF System Dimensions

Coil	R	Z	dR	dZ	nturns	strands
	(m)	(m)	(m)	(m)		
PF1	0.55	0.0	0.255	0.972	360	360
PF2,U+L	0.55	± 0.685	0.255	0.399	144	360
PF3,U+L	0.55	± 0.988	0.255	0.207	72	360
PF4,U~L	0.55	± 1.244	0.255	0.303	108	360
PF5,U+L	1.04	± 2.3	0.4	0.4	256	360
PF6,U+L	3.03	± 1.92	0.15	0.35	84	360
PF7,U+L	3.915	± 1.095	0.15	0.35	84	360

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

Table VIII: PF Coil Hydraulic Circuit Description

Coil	SC type	Pancakes x Layers	Helium channels	L_{chan}	Pin
				(m)	(MPa)
PF1	Nb_3Sn	40x9	10	122.8	0.4
PF2,U+L	Nb_3Sn	16x9	4	122.8	0.4
PF3,U+L	Nb_3Sn	8x9	2	122.8	0.4
PF4,U+L	Nb_3Sn	12x9	3	122.8	0.4
PF5,U+L	Nb_3Sn	16x16	8	104.4	0.5
PF6,U+L	NbTi	14x6	7	114.3	0.5
PF7,U+L	NbTi	14x6	7	147.6	0.5

The electrical requirements for the PF coils for the worst-case scenario and flexibility requirements are shown in Table IX.

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

Coil	$Icond_{max}$	$Icond_{min}$	$Verm_{max}$	$Vterm_{min}$
	(kA)	(kA)	(kV)	(kV)
PF1	16.3	-26.45	0.346	-0.90
PF2,U+L	22.36	-25.5	0.12	-0.514
PF3,U+L	22.8	-13.1	0.06	-0.896
PF4,U+L	25.7	-25.3	0.08	-0.748
PF5,U+L	26.26	0.0	0.334	-0.751
PF6,U+L	0.76	-17.2	0.263	-0.792
PF7,U+L	1.71	-14.1	0.607	-1.21

Central Solenoid (PF1 to 4) and Poloidal Coil 5

The 7 central solenoid PF coils have 9 layers and are stacked with identical radii Pancakes and lengths are listed in Table VIII. Jointless windings are 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. All splices from from the Nb_3Sn lead stems to the NbTi bus are at the bottom of the central solenoid assembly. Hydraulic inlet and outlet fittings alternate on the inside radius of each module. The helium flows through four pancakes before exiting the coil. Each fitting is a welded 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 POLO [7]. 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 conduits. The PF5 windings are similar to the CS coils. 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 two pancakes long, 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 conduits. The windings are continuously wound without joints. The winding packs are self-supporting against radial hoop forces, but encased against TF ripple-induced bending. 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. 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, redundant sensor are used, capable of very high signal-noise ratios [8]. There are two types of internal sensors. The first is a cowound insulated wire in the centers of the final stages of each cable. The second is a fiber optic temperature sensor, internally terminated as a Michelson interferometer, cowound through the center of the cable. Both of these sensor concepts have been demonstrated in the ITER QUELL experiment [9].

Flow meters will be used in each hydraulic inlet and outlet line. Advanced flow meter concepts such as optical Fresnel drag [9] may be needed to cope with rapid transients, high dynamic range, and clutter in the joint areas.

VI CONCLUSIONS

1) The magnet system conceptual design allows 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) Design and operation of an advanced all-superconducting tokamak will assist design and operations planning for ITER.

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