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Magnetic Design of the KT-2 Tokamak for "Advanced Tokamak" Studies

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Abstract

The magnetic system design of the KT-2 tokamak has been performed at KAERI. Design goal has been set to facilitate the so-called "advanced tokamak" studies, which is essential to secure the economy of the tokamak fusion reactors. Design features include a large-aspect-ratio machine configuration, long-pulse operation capability with heavy plasma shaping, hybrid magnetic field control and machine/in-vacuum structures for MHD stability.

1. Introduction

Since the 80's, worldwide nuclear fusion research has made significant progresses toward a realistic energy option for the future, resulting in the achievement of the scientific breakeven at the Joint European Torus(JET) tokamak in 1993 and other similar large tokamak experiments, and in the completion of the conceptual design of the International Thermonuclear Experimental Reactor(ITER) tokamak reactor for engineering breakeven(i.e. ignition) in 1992. The engineering design of ITER is being carried out as an international joint project among the US, Japan, the European Union, and Russia. The machine is expected to be operational by 2005, and will have an output thermal power of 1.5 GW. The next step after the ITER, being conceptualized as *DEMO*, will then be a commercial power plant.

Meanwhile, in the 90's, a new concept, the so-called *"advanced tokamak"*, has emerged. It was motivated by the prevailing judgement that the first ignition reactor ITER was designed too conservatively to secure the necessary economy for the commercial power plant DEMO, and that therefore it is necessary to improve its economy to the level comparable to that of PWR's. The "advanced tokamak" reactor is expected to achieve this economy through (1) the optimization of natural current (the so-called *"bootstrap current"*) production in a strongly-heated, high-β tokamaks and the incorporation of improved confinement operation techiniques, and hence (2) reducing the power demand for the external current drive to maintain tokamak operation, and thus (3) facilitating a compact steady-state tokamak reactor.

Table 1 exemplifies the impact of an "advanced tokamak" fusion reactor on the economy of fusion power plants[2]. From the table it can be concluded that a *steady-state* fusion reactor, and more importantly, an *"advanced tokamak"* reactor is consistently more economical than pulsed ITER-type conventional reactors both in overall COE and in the capital cost by a factor of 2-4 for all plant sizes, as well as in the required minimum plant size for economy. Similar estimations, although somewhat less optimistic, have been concluded from the design study of the typical, steady-state "advanced tokamak" fusion reactor SSTR by JAERI[3], where an COE of 150% of that of the contemporary PWR's was estimated. All these developments indicate that the fusion research is undergoing a critical transition from science-oriented feasibility studies to engineering-oriented studies for practical and eceonomical energy production.

Table 1. Improved Plant Economy of the "advanced tokamak" fusion reactor[2]

		500 MWe		1000 MWe		2000 MWe	
		conventional	advanced	conv.	adv.	conv.	adv.
Pulsed	COE, \$/kwH*	> 0.3	0.158	0.212	0.105	0.147	0.073
	Capital Cost, B\$	11	4.5	13	5.8	18	7.7
Steady-State (q>3)	COE	0.272	0.149	0.187	0.102	0.133	0.073
	Capital Cost	8.3	4.1	11	5.4	15	7.4

* 1994 US market rate = \$0.15/kwh.

2. KT-2 tokamak project for "advanced tokamak" studies at KAERI

The KT-2 tokamak project at KAERI, being carried out since 1992, aims and is designed for such an "advanced tokamak" study on a realistically medium-sized machine[4]. The most important implementation for that aim is the adoption of the large-aspect-ratio (R/a = 5.6~7.0 >> 1) configuration (see Table 2 below).

It is well known that the large-aspect-ratio(LAR) configuration is preferrable for maximizing the bootstrap current fraction considered essential for advanced tokamak studies, since $I_{bootstrap} \propto A^{-1/2}\ \beta_p \propto A^{1/2}\ \beta_N\ q_a$ where $\beta \leq \beta_N\ (I_p/aB_tq_o)$ or $(\varepsilon\ \beta_p)(\beta/\varepsilon) \leq 0.03(1+\kappa^2)/2q_o^2$ is the Troyon β-limit. In fact, all of the presently available "advanced tokamak" reactor designs have adopted the LAR configuration: TPX[1], ARIES-series[6] of US and JT-60SU, SSTR[3] of Japan. Hence a midsize LAR tokamak with intense heating like KT-2 is considered to be very useful[5] to study many physics and engineering issues for the refinement and the materialization of the "advanced tokamak" concept, as well as to enlarge the validity region of the scaling laws for reactor design with the much awaited data in the LAR zone.

For KAERI, therefore, it is expected that when a synergetic combination of the basic tokamak engineering capability obtained from the previous KT-1 tokamak project with the general nuclear engineering infrastructure, as well as with the domestic plasma research capabilities, is completed through the "advanced tokamak" KT-2 project, a truly competitive fusion energy research program will be established which is comparable to those in the industrialized countries of the west[4,5].

Table 2. KT-2 Machine Specifications

Major/minor radius	R/a	1.4/0.2-0.25	m
Aspect ratio	A	5.6 - 7	
Elongation	κ	1.8	
Triangularity	δ	> 0.5	
Toroidal field	B_t	3	Tesla max.
Number of magnets		16	(water-cooled, possible LN2)
Ripple	δB_t	< 2	% at separatrix
Magnetic field flat top		20	sec @ B_{max},
Plasma current	I_p	500+	kA
Flux swing		9.9	v-s (bipolar) air-core
Current flat-top	t_{ft}	4.2	sec @ I_{max}, OH-only
Density	n_e	$(5\text{-}10) \times 10^{19}$	m^{-3}
Electron(ion) temperature	$T_e(T_i)$	1	keV, OH-only
FWCD/ICRH		1 (>5 by 2001)	MW
NBI/LH/ECRH		total 3	MW (by 2001)
Motor-Generator Power(Stored Energy)		166 (3.0)	MVA(GJ)

3. Magnetic Field System of the KT-2 Tokamak:

3.1 Structural Design of the Toroidal Field (TF) magnet system.

The TF magnets produce the magnetic fields for the confinement of the high temperature fusion plasma. For KT-2, the maximum TF strength is 3 Tesla. During the machine operation, this magnetic field interacts with tokamak plasma current, producing tremendous stresses on the magnet structure. Results from the stress analysis performed with ANSYS for a total coil current of 21 MA-Turn(480 turns) are shown in Figure 1. The results indicate that deformations are acceptable when appropriate provisions are made such as employment of the bucking cylinder or wedging the TF magnets, which have been incorporated in the design. Summarized in Table 3 are the electrical and mechanical properties of the TF magnets.

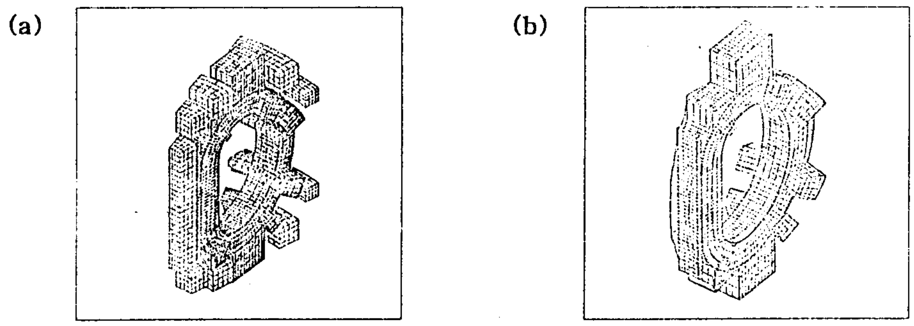


Figure 1. Electromechanical Stress Analysis of a TF magnet during the 21 MA-Turn Operation. (a) FEM cells, (b) deformations.

Table 3. Electrical and Mechanical Properties of the KT-2 TF Magnets

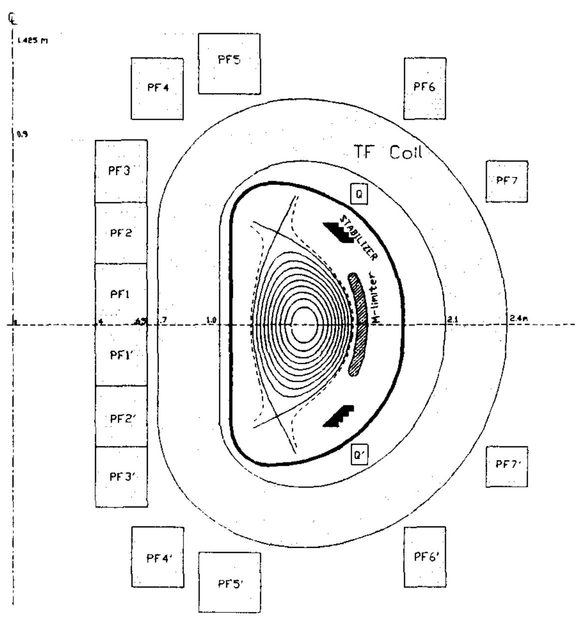
Field strength at R=1.4m :	3.0 Tesla	Overall height/width:	2.2/1.7 m
Total ampere-turn :	21 MAT	Window height/width:	1.6/1.1 m
Total # of turns :	30 X 16 = 480	Weight :	16×3.5=56 tons
Inductance :	58 mH	Flat top voltage :	875 V
Resistance :	20 m Ω	Flat top current :	43.75 kA
Time constant :	2.9 sec	Forcing voltage :	1167 V(α=1.[illegible])
Current density :	15.8 A/mm^2	Plasma flat-top time :	19.5 s
Max. current density :	19.5 A/mm^2	Flat top time :	20 s
Coil c.x. :	30 × 33 cm^2	Rising time :	4.02 s
Packing factor(average) :	0.817	Flat top power :	38.3 MW
Max. temperature rise :	2.2 °C/sec	Max. required power :	51.1 MW
Max. tensile stress :	2 kg.f/mm^2	Start up energy :	126 MJ
Centripetal force :	300 ton.f/coil	Flat top energy :	766 MJ
Compression stress to b.c. :	120 kg.f/cm^2	Ramp down energy :	25.0 MJ
Out-of-plane force(moment):	30 ton.f/coil	Magnetic energy :	56.0 MJ
for B_V = 0.3 T	(60 ton-m)	Total required energy :	917 MJ

3.2. Electrical Design of the Poloidal Field (PF) System.

Since the KT-2 tokamak aims "advanced tokamak" research where effective modification and control of the plasma curremt is essential, it must be capable of extended discharges in the OH mode lasting much longer than the current relaxation time scales. Total of five(5) operation modes have been identified: two OH modes and three auxilliary heated modes[3]. The PF system to facilitate these modes is designed first for a 4-second "OH-baseline" mode at B_t^{max} and I_p^{max}, extendable to >20 sec with a reduced loop voltage when heated as in "5MW-baseline" mode.

The resultant KT-2 PF magnet system is shown in Figure 2 below. The design is developed using an axisymmetric, free-boundary, ideal-MHD equilibrium analysis code FBT[7] which allows the computation of arbitrarily-shaped tokamak equilibria. The design consists of 8-coil sets, connected in up-down symmetry with a total of 16 individually controllable coil modules. There are two pairs of outboard 'ring coils' (PF6,7), two pairs of 'diverter coils' (PF4,5), one pair of 'control coils' (Q), and the central solenoid is divided into 3 pairs of modules(PF1,2,3). They are all

(a) PF magnet system.



(b) PF coil specifications

coil	R_c^* (mm)	Z_c^* (mm)	ΔR_c (mm)	ΔZ_c (mm)	turns	$I_{c.P}$ (kA)	$I_{c.av}^{\#}$ (kA)
PF1, 1'	525	±150	250	300	10x6	25.0	12.0
PF2, 2'	525	±450	250	300	10x6	27.3	14.4
PF3, 3'	525	±750	250	300	10x6	25.0	11.2
PF4, 4'	700	±1150	250	300	10x6	25.0	15.3
PF5, 5'	1050	±1275	300	300	12x6	26.5	17.7
PF6, 6'	2000	±1150	200	300	8x6	13.7	13.2
PF7, 7'	2400	±700	200	200	8x4	8.8	6.1
Q, Q'	1680	±640	80	100	4x2$	20.0	13.0

* Coil center, #for pulse duration of 18 sec,
$ conductor unit-cell size of 20 x 50 mm

(c) Coil insulation standards (units: kV)

	PF1	PF2	PF3	PF4	PF5	PF6	PF7	Q
norm. max. appl. volt.	+1.4 -2.2	+1.5 -2.1	+1.5 -2.1	+4.7 -2.4	+10.2 -2.9	+2.4 -4.4	+3.6 -6.8	+1.9 -4.2
Trans. induced volt. due to disruption	20*	16	15	18	18	10	11	9

* High voltage surge is induced across coil terminals at disruptions for about 2 ms

Figure 2. TF and PF Magnet System of the KT-2 Tokamak.

located outside the TF coils except QQ′ for the simplicity in the construction and the maintenance of the device. QQ′ are inside the TF coils closer to the plasma for a feedback-control of the slower components (<20 Hz) of unstable vertical motions which are left over from the faster (up to 10 kHz) stabilization provided by the in-vessel passive stabilizer bars[8].

The hybrid control scheme is employed for the PF coil system, where the currents for ohmic heating and for shaping/position control flows in the same coil. This is accomplished by fast monitoring the motions of the magnetic flux surfaces with magnetic probes, and feedback-applying the error voltages from the comparison of measured signal with calculated reference signal to the thyristor amplifiers in the PF power supplies(see B. H. Oh, this proceeding). As a result, the coil set has the flexibility to produce a broad spectrum of double-null configurations while maintaining the ability to create single-null configurations by making the current distribution asymmetric (for example, PF1=PF1′=PF2′, PF2=PF3′, Q=-Q′). The coil cross sections are derived from a conductor unit-cell size of 25 x 50 mm including service c.x.(interconductor and other insulation, cooling channel, casing where necessary), and are deduced from the current requirement to meet the plasma scenario of KT-2 tokamak. Standard (chilled) water cooling of the magnets is included for pulse repetition rate of 5-6 shots/hour. Optional LN_2 cooling is being considered for the long pulse operation.

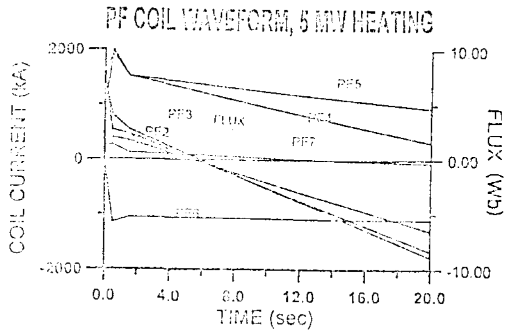
With this PF system, a "design-base" operation scenarios have been obtained from snapshot equilibrium calculations of the KT-2 discharges in two cases, the OH baseline and the 5MW baseline modes. Both scenarios start at the same initial magnetization flux states (5.53 V-sec). Two equilibria are generated for the OH baseline scenario, the "start of flattop"(SOF) and the "end of flattop"(EOF). For the 5MW baseline scenario, three equilibria: the SOF, the "start of heating" (SOH), and the EOF(=EOH). In Table 4 below, design basis parameters for these five equilibria are summarized, along with typical PF coil current waveforms in Figure 3 for the 5MW baseline mode.

These snapshot calculations are being replaced by more detailed and self-consistent MHD-stability calculations with numerical analysis codes like TSC[9] and WHIST[10]. For this high-beta operation mode, the need for accurate profile

Table 4. Computed Discharge Parameters for design-base KT-2 equilibria

	OH baseline		5 MW baseline			5 MW HiBS		
	SOF	EOF	SOF	SOH	EOF (=EOH)	SOF	SOH	EOF (=EOH)
I_p (kA)	500	500	500	500	500	300	300	300
Beta (%)	0.74	0.75	0.74	2.15	2.16	0.41	2.31	2.32
$Beta_p$	0.62	0.62	0.62	1.62	1.59	0.62	3.41	3.39
q_0	0.75	0.73	0.75	2.02	2.03	0.91	1.00	1.01
q_{95}	2.65	2.64	2.65	2.74	2.73	3.18	3.21	3.20
l_i	0.91	0.90	0.91	0.54	0.53	1.04	0.89	0.87
V_{loop}	1.6	1.6	1.6	0.28	0.27	2.2	0.1	<0.1
flux (Vs)	2.32	-4.32	2.32	0.72	-4.38	2.2	0	3.43

Figure 3. Typical PF current waveforms in KT-2



control is evident from the hollow current profiles and the negative shear in this mode (see B.G. Hong *et. al.*, in this conference). In addition, analyses of the RF heating/CD power deposition and thermalization/CD process with a full-wave code will be incorporated in the above, for the two FWCD modes (1MW and 5MW HiBS).

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