Proceeding of the Korean Nuclear Society Spring Meeting
Cheju, Korea, May 1996

KT-2 Poloidal-Field (PF) System Design

J.M. Han, K.W. Lee, B.G. Hong, C.K. Hwang, B.J. Yoon, J.S. Yoon, Y.D. Bae, W.S. Song, S.K. Kim, S.R. In, S.H. Jeong, B.H. Oh, H.J. Choi, K.H. Im, M.H. Joo, D.H. Chang and Z. Liu*
Korea Atomic Energy Research Institute
** Institute of Plasma Physics, China*

Abstract

KT-2 poloidal-field (PF) system is designed to cope the up-down symmetric double-null (DN) and asymmetric single-null (SN) discharges with typical plasma parameters, in which three sets of "design-basis" scenarios - the ohmic heating (OH), the 5MW and the high bootstrap (HIBS) baseline modes - are applied. The power and energy demand for each cases are also deduced. The peak power and the maximum energy requirements for the KT-2 magnet system, incorporating the PF and the toroidal-field (TF) coils, are proven to be 123MW and 1601MJ, respectively when it is driven in DN configuration. The KT-2 PF system is capable of achieving the machine mission of creating a 500kA heated plasma with a current flattop of $\geq$20 seconds.

I. KT-2 PF System Overview

The layout of the major components of the KT-2 poloidal field (PF) system is shown in Fig. 1.[1-5] Most PF coils locate outside the toloidal field (TF) magnet for simplicity of construction and maintenance of device. The PF coils are geometrically arranged in an up-down symmetric configuration. The coil set has the flexibility to produce a broad spectrum of up-down symmetric double-null (DN) configurations while maintaining the ability to create up-down asymmetric single-null (SN) shapes by making the coil current distribution asymmetric. There are two pairs of outboard "ring coils" [PF6,6', PF7,7'], two pairs of "diverter coils" [PF4,4', PF5,5'] and the central solenoid is divided into 3 pairs of modules [PF1,1', PF2,2', PF3,3']. Thus, a 7-coil up-down symmetric connection is the nominal arrangement, and up to 14 individually controllable coil modules are available.

The external PF coils have two major functions: to provide the flux linkage (or volt-seconds) to build up and sustain the plasma current, and to control the plasma shape and position as well as details of the divertor sweep.

In addition to the external PF coils, there are two smaller up-down symmetric pairs of internal coils, say, [Q,Q'] coils are between the vacuum vessel and TF magnet, [D,D'] coils are inside the vacuum vessel. Q and Q' coils have three major functions. First, they provide the fast time scale vertical control of the wall stabilized axisymmetric instability. Second, they also provide control of the radial plasma position on the fast time scale, enabling the plasma to recover, for example, from a minor disruption or to have its position adjusted relative to the radio-frequency antenna, as edge plasma parameters change. Third, they are used to adjust the poloidal field strength and gradient during the initial plasma breakdown. D and D' coils is to modulate the X-points as well as to reduce the PF4(4') and PF5(5') coil duties. The geometric specifications of the PF coils are summarized in Table 1.

Fig. 1. PF coil layout of the KT-2 tokamak.

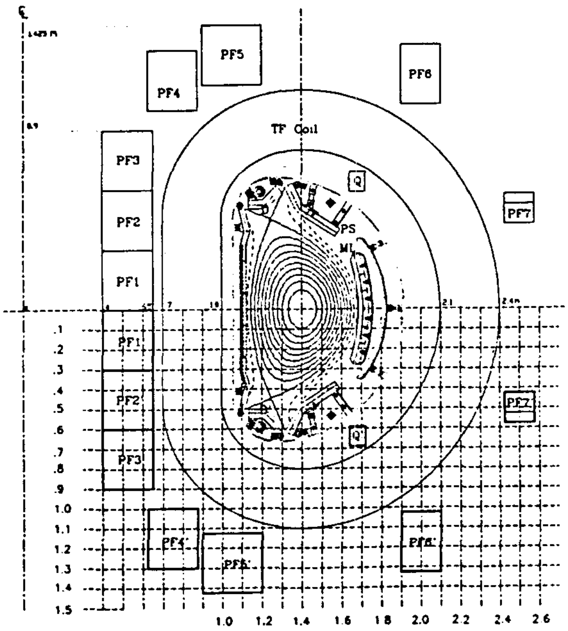

Table 1. PF coil set of the KT-2 tokamak.

coil	Rc(mm)	Zc(mm)	ΔRc(mm)	ΔZc(mm)	turns
PF1, 1'	525	±150	250	300	(10 x 6)/ea
PF2, 2'	525	±450	250	300	(10 x 6)/ea
PF3, 3'	525	±750	250	300	(10 x 6)/ea
PF4, 4'	750	±1150	250	300	(10 x 6)/ea
PF5, 5'	1050	±1275	300	300	(12 x 6)/ea
PF6, 6'	2000	±1175	200	300	(8 x 6)/ea
PF7, 7'	2500	±500	150	150	(8 x 3)/ea
Q,Q'(-Q)	1680	±640	80	100	(4 x 2)/ea
D, D'	1190	±590	ϕ_0=60	ϕ_i=20	1 /ea

The hybrid control scheme is employed for the PF coil system, where the currents for ohmic heating and shape/position control flows in the same coils. The fast vertical motion in highly elongated plasmas as in KT-2 is primarily suppressed by a set of passive stabilizing conductor(PS in fig.1) and vacuum vessel. The active control coil set Q,Q' takes care of the slower components left behind.

In tokamak fusion research there are two paths being followed which should lead to a working fusion reactor. One path, the one taken by ITER EDA[6], extrapolates experimental results from existing tokamaks. This leads to large machines that have large plasma currents and a pulsed operation. Other approaches, commonly referred to as advanced tokamak scenarios, try to find ways to operate the fusion tokamak in steady state.[7,8] The advanced tokamak experiments must have their current driven non inductively. From an economic point of view it is advantageous to have a large fraction of the current driven by the high bootstrap (HIBS) effect. In this paper, hereby we also introduce a concept of 'advanced tokamak scenario' appropriate to the typical KT-2 parameters through HIBS operation mode analysis.

II. PF Scenarios of the KT-2 Tokamak

The design of the PF system starts from the definition of a small set of "design-basis" scenarios. The design basis scenarios imply three types of fiducial discharges, the ohmic heating (OH) baseline, the 5MW baseline, and the high bootstrap (HIBS) modes. The OH and 5MW baseline scenarios are both referenced to B_0=3T of field and I_p=500kA of plasma and having the same initial magnetization flux state (ψ_M=5.46 for DN and ψ_M=5.71 for SN). In HIBS mode of B_0=2T and I_p=300kA, plasma initiates at the magnetization flux state of ψ_M=2.05 for DN and ψ_M=1.46 for SN.

The flexibility of the PF system has been generated through the equilibria and stability analysis aiming specified physics goal. It is to compute PF coil current distributions, and then check the consistent with engineering constraints and the plasma guidelines. The results in terms of coil current distributions, poloidal magnetic fields and plasma shapes, are applied to the stability test, the divertor and limiter design, and the coil and power system design. Given the coil distribution, reference MHD equilibria for KT-2 are computed using the free boundary MHD equilibrium code (FBMEC)[9]. The plasma shape is chosen to have elongation, κ =1.8 and triangularity, δ=0.6. A set of equilibria are adopted for the OH baseline scenario, corresponding to the "start of flattop" (SOF) and the "end of flattop" (EOF). For the 5MW and HIBS baseline scenarios, the equilibria are set to three fiducial flux states: the SOF, the "start of heating" (SOH), and the EOF(=EOH). The fiducial equilibria are used to set up the nominal PF coil current waveform of each design-basis. The major parameters of the OH baseline and the 5MW baseline modes are summarized in Table 2.1 and those of the HIBS mode are in Table 2.2 in which the bootstrap current fraction is calculated in the TSC code.[10]

Table 2.1 Major parameters of KT-2 for the OH and the 5MW baseline modes.

Major radius	1.4 m
Minor radius	0.25 m
Aspect ratio	5.6
Elongation	1.8
Triangularity	0.6
Plasma current	500 kA
Toroidal field	3 T

Table 2.2 Major parameters of KT-2 for the HIBS mode.

Major radius	1.4 m
Minor radius	0.25 m
Aspect ratio	5.6
Elongation	1.8
Triangularity	0.6
Plasma current	300 kA
Toroidal field	2 T
Bootstrap current fraction	80 %

The MHD stability of these equilibria are analyzed using MHD stability code GATO[9,11]. The stability are fully analyzed in reference [11[which indicates that both DN and SN plasmas stable for n=0 axisymmetric and n=1 kink mode, and also for the internal stabilities provided profiles meet $q_0 \geq 1$.

The discharge duration of a normal conductor tokamak with intensive auxiliary plasma heating and/or high bootstrap current fraction of ~ 80% (Table 2.2) is subject to restricted mainly due to the temperature rise of TF magnets rather than the limited capacity of poloidal flux swing. If discharge starts at an magnetization level optimized to minimize the temperature rise of coils for a given plasma scenario, the pulse length can be extended. A code (subroutine TEMCOIL in PFCOIL code[4]) was developed to get the optimized initial flux state of a PF-coil set. The design basis for the DN configurations are summarized in table 3 and the resulting coil currents in snapshot equilibria of each mode of table 3 are in Table 4. Prior to breakdown, the ohmic heating transformer will be charged to provide the initial poloidal flux.

Table 3. The KT-2 operation modes with the DN configurations.

state \ coil	OH			5MW				HIBS			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
B_0 (T)	3			3				2			
I_p (kA)	500			500				300			
β_p		0.47	0.47		0.47	1.68	1.68		0.51	2.23	2.23
β_T (%)		0.53	0.53		0.53	1.89	1.88		0.47	2.09	2.09
β_N (%)		0.8	0.8		0.8	2.82	2.82		0.78	3.5	3.5
q_0		1.0	1.0		1.0	1.0	1.0		1.06	3.05	3.05
q_{min}										2.40	2.40
q_{95}		2.82	2.82		2.82	2.92	2.93		3.11	3.47	3.47
l_i		0.84	0.84		0.84	0.82	0.82		0.88	0.50	0.50
A(m^2)		0.32	0.32		0.32	0.32	0.32		0.32	0.31	0.31
V(m^3)		2.72	2.73		2.72	2.73	2.73		2.73	2.65	2.65
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20

Table 4. PF coil current (NI in kA) in the KT-2 operation modes with the DN configurations.

state \ coil	OH (3T/500kA)			5MW (3T/500kA)				HIBS (2T/300kA)			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
1,1'(kA)	1506	301	-2041	1506	301	70	-1142	565	-214	129	129
2,2'	1536	598	-2196	1536	598	11	-1415	577	-52	-665	-665
3,3'	1511	1041	-2172	1511	1041	259	-1378	567	160	-755	-755
4,4'	1048	1586	224	1048	1586	1183	474	393	722	603	603
5,5'	1325	1681	299	1325	1681	1443	711	497	740	1235	1235
6,6'	0	-847	-1140	0	-847	-754	-889	0	-487	-835	-835
7,7'	94	119	-21	94	119	-31	-108	35	23	95	95
Q	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
Q'	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
D,D'	10	10	10	10	10	10	10	5	5	5	5
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20
flux(Wb)	5.46	2.46	-6.51	5.46	2.46	0.66	-4.0	2.05	0.05	-0.7	-0.7
V_{loop}(V)	-6	-1.8	6.2	-6	-1.8	-0.25	3.81	-4	-0.25	0	0.67

The above temperature rise analysis of each PF coil versus magnetization level for a given PF system scenarios inform the optimal magnetization level and makes it possible to minimize the overall temperature of PF coils. The maximum temperature rise of PF coil is shown to be 44°C for the 5MW baseline and 42.6°C for the HIBS in DN discharge.

The bootstrap current is proportional to the pressure gradient. And also it is apparent that the high poloidal beta is essential to get large bootstrap current fraction. Since the pressure gradient has a maximum somewhere off axis it can also be seen that the current profiles of advanced tokamak scenarios will in general be non-monotonic. The non-monotonic current profiles give rise to inverted safety factor profiles with negative shear region. [see HIBS modes in Table 3 and 5, and Ref. 1-5, 7-9]

Table 5. The KT-2 operation modes with the SN configurations.

state \ coil	OH			5MW				HIBS			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
B_0 (T)	3			3				2			
I_p (kA)	500			500				300			
β_p		0.47	0.47		0.47	1.70	1.70		0.47	2.25	2.25
β_T (%)		0.54	0.55		0.54	1.93	1.92		0.44	2.08	2.08
β_N (%)		0.83	0.83		0.83	2.9	2.9		0.73	3.5	3.5
q_0		1.17	1.16		1.17	1.13	1.10		1.29	3.22	3.22
q_{min}										2.41	2.41
q_{95}		2.61	2.56		2.61	2.75	2.79		2.91	3.19	3.19
l_i		0.79	0.79		0.79	0.77	0.77		0.79	0.51	0.51
A(m^2)		0.31	0.31		0.31	0.31	0.31		0.31	0.31	0.31
V(m^3)		2.69	2.65		2.69	2.71	2.73		2.69	2.69	2.69
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20

In Table 5, the design basis parameters for the SN configurations are summarized. By a comparison of Table 3 and Table 5, we show a magnitude of the volume and the cross-section area of DN and SN same roughly. Typical coil currents for the KT-2 tokamak with the SN configurations are listed in Table 6. For the SN, the maximum temperature rise of PF coil set is 38°C for the 5MW baseline and is 38.6°C for the HIBS.

Table 6. PF coil current (NI in kA) in the KT-2 operation modes with the SN configurations.

state \ coil	OH (3T/500kA)			5MW (3T/500kA)				HIBS (2T/300kA)			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
1,1′(kA)	1575	476	-1974	1575	476	102	-1165	403	-324	-148	-148
2,3′	1578	1147	-1986	1578	1147	497	-1003	404	-39	-466	-466
3	1578	784	-1917	1578	784	374	-1022	404	-209	-308	-308
2′	1606	564	-2105	1606	564	71	-1309	411	-320	-988	-988
4	1096	1094	-49	1096	1094	805	215	280	364	6	6
4′	1096	1621	162	1096	1621	1165	406	280	602	421	421
5	1385	1279	-145	1385	1279	907	172	354	409	231	231
5′	1385	1828	113	1385	1828	1361	509	354	679	955	955
6	0	-138	-821	0	-138	-221	-565	0	-215	-55	-55
6′	0	-994	-839	0	-994	-595	-567	0	-491	-760	-760
7	98	-205	37	98	-205	-184	-61	25	-74	-293	-293
7′	98	-202	-278	98	-202	-116	-364	25	-8	138	138
Q	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
Q′	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
D,D′	10	10	10	10	10	10	10	5	5	5	5
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20
flux(Wb)	5.71	2.83	-6.30	5.71	2.83	0.91	-3.72	2.45	0.45	-1.27	-1.27
V_{loop}(V)	-5.76	-1.83	6.0	-5.76	-1.92	-0.25	3.54	-4	-0.25	0	1.23

III. Power and Energy Requirements

Given the coil current distribution, voltage, power and energy for KT-2 are computed using the PFCOIL code[2]. In double-null configuration, most of the PF coil sets (PF1=PF1',....., PF2=PF2', D=D') run in series only except for the Q and Q' coils which are driven by it's own power supply independently to maintain average bias current level for the equilibrium in addition to the control current. Typical power demands for the KT-2 tokamak with the DN configurations are summarized in Table 7.

Table 7. Voltage, power and energy requirements in the KT-2 operation modes with the DN configurations.

state / coil	OH (3T/500kA)			5MW (3T/500kA)				HIBS (2T/300kA)			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20
P_{PF}(MW)	35	46	79	35	46	14	31	5	16	23	21
P_{TF}(MW)	63	44	44	63	44	44	44	63	44	44	44
P_{Total}(MW)	98	90	123	98	90	58	75	68	60	67	65
E_{PF}(MJ)	124	133	313	124	133	150	570	18	20	65	408
E_{TF}(MJ)	150	172	392	150	172	216	1030	150	172	304	1030
E_{Total}(MJ)	274	305	705	274	305	366	1600	168	192	369	1438
$V_{PF}(kV)_{peak}$	0.45	-1.65	-0.86	0.45	-1.65	-0.57	-0.56	0.17	-0.98	-0.58	-0.51
$V_{TF}(kV)_{peak}$	1.43	1.01	1.01	1.43	1.01	1.01	1.01	1.43	1.01	1.01	1.01

In single-null configuration, except PF1=PF1', PF2=PF3' and D=D', the other coil sets are the independent circuits. Typical power demands for the KT-2 tokamak with the SN configurations are listed in Table 8.

Table 8. Voltage, power and energy requirements in the KT-2 operation modes with the SN configurations.

state / coil	OH (3T/500kA)			5MW (3T/500kA)				HIBS (2T/300kA)			
	EOM	SOF	EOF	EOM	SOF	SOH	EOF	EOM	SOF	SOH	EOF
time(sec)	0	0.5	5.5	0	0.5	1.5	20	0	0.5	3.5	20
P_{PF}(MW)	41	24	51	41	6	14	21	3	5	12	12
P_{TF}(MW)	63	44	44	63	44	44	44	63	44	44	44
P_{Total}(MW)	104	68	95	104	50	58	65	66	49	56	56
E_{PF}(MJ)	145	146	251	138	139	138	372	9	8	30	231
E_{TF}(MJ)	150	172	392	150	172	216	1030	150	172	304	1030
E_{Total}(MJ)	295	318	643	288	311	354	1402	159	180	334	1261
$V_{PF}(kV)_{peak}$	-0.7	-1.02	-0.36	-0.6	-0.95	0.22	-0.23	-0.34	-0.49	-0.28	-0.25
$V_{TF}(kV)_{peak}$	1.43	1.01	1.01	1.43	1.01	1.01	1.01	1.43	1.01	1.01	1.01

IV. CONCLUSIONS

- PF scenarios have been developed for the DN and the SN KT-2 options, satisfying physics and engineering constraints.

· A typical factor for the reference design of the KT-2 magnet system is the temperature rise of the uncooled PF coils.

· The KT-2 PF system is capable of achieving the machine mission of creating a 500kA heated plasma with a current flattop of ≥20 seconds.

· The peak power and energy requirements for the DN KT-2 PF system are 79MW and 570MJ, respectively.

· The maximum power and energy requirements for the DN KT-2 magnet system, including the PF and the TF coils, are 123MW and 1601MJ, respectively.

· The peak power and energy requirements for the SN KT-2 PF system are 51MW and 372MJ, respectively.

· The maximum power and energy requirements for the SN KT-2 magnet system, including the PF and the TF coils, are 104MW and 1402MJ, respectively.

· From the above results, we have known the peak power and energy requirements for the SN PF system is less than those for the DN PF system.

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