JAERI-M
91-049

CONTROL OF THE PLASMA CONFIGURATION IN ITER

March 1991

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編集兼発行　日本原子力研究所
印　　刷　㈱原子力資料サービス

Control of the Plasma Configuration in ITER

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(Received February 22, 1991)

Control of the plasma configuration in ITER is investigated. Multivariable noninteracting control method is proposed as one of the possible control algorithms for the plasma shape control. The relation between the control variables and the poloidal magnetic field coil currents is essential for investigating a feedback matrix gain, and is estimated for an ITER plasma. Control of the horizontal position of a plasma is investigated at the early buildup phase just after the breakdown. Poloidal field coil power supplies of 20kV and the installation of invessel coils are recommended to obtain the vertical magnetic field required for the plasma current rampup rate of 1MA/s.

Keywords: Control of the Plasma Configuration, ITER, Horizontal Plasma Position, Plasma Current Rampup, Plasma Current, Null Point, Tokamak

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ITERにおけるプラズマ形状制御

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（1991年2月22日受理）

ITERにおけるプラズマ形状制御について評価している。まず，プラズマ形状制御アルゴリズムとして多変数非干渉制御法を提案するとともに，フィードバック・マトリックスゲインを導出する上で重要な，ポロイダル磁場コイル電流と制御変数の関係式を評価した。次に，着火直後の早い時期におけるプラズマ水平位置制御について検討を行ない，1 MA／Sのプラズマ電流立上げを得るには，20 kVのポロイダル磁場コイル電源と真空容器内設置コイルにより，垂直磁場を立ち上げる必要のあることを示した。

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Contents

目次

1. Plasma Shape Control

1.1 Control Variables

In ITER, two control loops are designed for the plasma shape control1). Slow control loop will be performed by superconductor PF (Poloidal magnetic Field) coils with the characteristic frequency of $\leq \sim 0.3$Hz to control the plasma current and the plasma shape. Fast control loop will be performed by normal conductor invessel coils with the characteristic frequency of 5~10Hz to control the vertical plasma position to stabilize the positional instability due to the highly elongated plasma of $\kappa = \sim 2.0$. In this paper slow control loop is discussed mainly, in which I_p, R_{out}, R_{in}, Z_p, R_n and Z_n are selected as the control variables. Definition of them are presented in Fig.1. Plasma current I_p must be controlled to be the required value according to the operational scenario. R_{out} and R_{in} are the horizontal locations of the outside and inside outermost plasma surface at the same vertical height with the plasma current axis. Each of R_{out} and R_{in} determines the clearance between the plasma outermost surface and the first wall, that should be the reasonable value to get the divertor performance and to decrease the erosion of the first wall caused by the charge exchange. Furthermore, R_{out} should be controlled to get the nice coupling between a plasma and a launcher of LHW. R_{in} should be controlled to get a clearance of $> \sim 10$cm in order to avoid the touch of a plasma to the first wall in a inward horizontal shift caused by a minor disruption. Control of Z_p is necessary to equalize the heat load onto two divertor plates, that are settled at the top and bottom of the first wall. Low frequency component of the invessel coil current I_{in}, that will be used for the fast control of Z_p, should be decreased to get the control margin of Z_p. Thus the minimization of D.C. in I_{in} is also the control objective of the slow control loop of Z_p. R_n and Z_n are the horizontal and vertical location of a null point, that should be controlled to guide the separatrix lines onto the divertor plate. ITER has a double null divertor configuration. Thus locations of two null points should be controlled. Swing of the separatrix lines on the divertor plate is also required to decrease the heat flux effectively. These requirements on the slow control loop are summarized in Table 1.

1.2 Noninteracting Control Method

6(+2) control variables should be controlled by ITER hybrid poloidal coil system consist of 14 coils. Then the control system inevitably becomes a multivariable one. In JT-60, the application of the noninteracting control method was investigated to swing the separatrix line on the divertor plate with keeping the configuration of a bulk plasma2), and was found out to be the powerful control method. Thus this control algorithm is re-examined for the control of the plasma current and the plasma shape in ITER.

Basic equations, that are necessary to investigate a feedback matrix gain of the noninteracting control method is presented as follows.

1)Circuit equation of a plasma current I_p.

$$L_p\dot{I}_p+\mathbf{M}_{pc}^{t}\mathbf{I}+\eta_p I_p=0 \tag{1}$$

Where **I** is a vector of PF coil currents, $\mathbf{M}_{pc}$ is a vector of the mutual inductance between a plasma current and PF coil currents, and η_p is the resistivity of a plasma current.

2)Circuit equation of PF coil currents **I**.

$$\mathbf{M}\dot{\mathbf{I}}+\mathbf{M}_{pc}\dot{I}_p+(\partial\mathbf{M}_{pc}/\partial\mathbf{x})I_p\dot{\mathbf{x}}+\mathbf{RI}=\mathbf{E} \tag{2}$$

Where **E** is the control voltages of PF coil power supplies, and **R** is a diagonal matrix of the resistivity of PF coils. When the proportional control with the compensation of the resistivity drop is adopted, **E** becomes,

$$\mathbf{E} = \mathbf{RI} + \mathbf{RG_x}I_p(\mathbf{x}^{ref}\text{-}\mathbf{x}) + \mathbf{RG_p}(I_p^{ref}\text{-}I_p) \tag{3}$$

Where **x** is the vector of control variables (R_{out}, R_{in}, Z_p, R_n and Z_n), and $\mathbf{x}^{ref}$ is the reference values of them. $I_p{}^{ref}$ is the reference value of the plasma current. $\mathbf{G_x}$ is a matrix gain of the plasma shape, and $\mathbf{G_p}$ is a diagonal matrix gain of the plasma current..

3)The relation between the displacements of control variables $\delta\mathbf{x}$ from the equilibrium state and that of PF coil currents $\delta\mathbf{I}$ as,

$$\delta\mathbf{I}=\mathbf{A}I_p\delta\mathbf{x} \tag{4}$$

Where following relations are assumed.

$$\mathrm{I}=\mathrm{I}_0+\delta\mathbf{I} \tag{5}$$

$$\mathbf{x}=\mathbf{x}_0+\delta\mathbf{x} \tag{6}$$

$\mathbf{I}_0$ and $\mathbf{x}_0$ are the equilibrium states of $\mathbf{x}$ and $\mathbf{I}$. The relation of eq.(4) is essential to get a matrix feedback gain as described later. The state equation of $\mathbf{x}$ can be presented as,

$$\mathbf{x}=\mathbf{B}(\mathbf{I}/I_p)+\mathbf{C} \tag{7}$$

Where $\mathbf{B}$ and $\mathbf{C}$ are constant matrices. The relation of eq.(7) can be obtained statistically from the database of the equilibrium conditions3). Then matrix $\mathbf{A}$ can be investigated as,

$$\mathbf{A}=\mathbf{B}^{-1} \tag{8}$$

Firstly the feedback control gain of I_p is estimated from equations of (1)~(3) with the assumption of $\mathbf{x}=\mathbf{x}^{ref}$. The displacement of a plasma current is considered as,

$$I_p=I_{p0}+\delta I_p \tag{9}$$

Where dI_{p0}/dt is zero, but $d\mathbf{I}_0/dt$ is not zero. The control speed of I_p is much faster than the decay time of a plasma current. Thus the resistive drop of a plasma current can be ignored in the time scale of the control. Then the relation between δI_p and $\delta\mathbf{I}$ becomes,

$$\delta I_p=-L_p^{-1}\mathbf{M}_{pc}{}^t\,\delta\mathbf{I} \tag{10}$$

This equation means that the voltsecond is supplied by $\mathbf{M}_{pc}{}^t\delta\mathbf{I}$. Thus $\delta\mathbf{I}$ is the required currents to obtain δI_p without changing $\mathbf{x}$ (the plasma shape). Plasma equilibrium code can be used to get the different coil currents sets of $\mathbf{I}_1$ and $\mathbf{I}_2$, that makes the same plasma configuration. When $d\Phi$ is the difference in the influx of voltsecond supplied by these PF coil currents, the relation of δI_p and $\delta\mathbf{I}$ becomes,

$$\delta\mathbf{I}=(L_p/d\Phi)(\mathbf{I}_1-\mathbf{I}_2)\delta I_p=\mathbf{A}_p\delta I_p \tag{11}$$

From the equation of (10) or (11), $\mathbf{A}_p$ can be investigated. Then the state equation of I_p becomes,

$$(\mathbf{M}\mathbf{A}_p+\mathbf{M}_{pc})\delta\dot{I}_p=\mathbf{R}\mathbf{G}_p(I_p^{ref}-I_p) \tag{12}$$

If we select the control frequency f_p of a plasma current, the feedback gain $\mathbf{G}_p$ multiplied by $\mathbf{R}$ becomes,

$$\mathbf{RG}_p=(\mathbf{MA}_p+\mathbf{M}_{pc})2\pi f_p \tag{13}$$

Secondly the matrix gain of the plasma shape can be derived from equations of (1)~(3) with the assumption of $I_p=I_p^{ref}$. Then the state equation of $\delta\mathbf{x}$ can be obtained as that of a plasma current,

$$(\mathbf{MA}_x+\partial\mathbf{M}_{pc}/\partial\mathbf{x})I_p\delta\dot{\mathbf{x}} =\mathbf{RG}_p(\mathbf{x}^{ref}-\mathbf{x}) \tag{14}$$

Where matrix $\mathbf{A_x}$ can be obtained by the usage of the code to analyze the equilibrium plasma configuration. Each control variable is displaced with keeping the other ones fixed and with the same plasma current and the influx of voltsecond. To get the unique solution of $\mathbf{A_x}$, some restrictions on the coil currents is required$^{1)}$, because the number of control variables is smaller than that of coils. When Δx is displacement of one control variable, and ΔI_x is the displacement of coil currents, the required $\delta \mathbf{I_x}$ for $I_p\delta x$ is,

$$\delta \mathbf{I} = (\ \Delta I_x\ /(I_p\Delta x)\ )\ I_p\delta x \tag{15}$$

This relation can be obtained for each control variables. Then $\mathbf{A_x}$ can be estimated as,

$$\mathbf{A_x}=\Delta\mathbf{I_x}\ /(I_p\Delta\mathbf{x}) \tag{16}$$

When we select a diagonal matrix $\mathbf{f_x}$ as the characteristic frequency of control variables, the matrix gain multiplied by a diagonal matrix of resistivity $\mathbf{R}$ becomes,

$$\mathbf{RG_x}=(\mathbf{MA_x}+\partial\mathbf{M}_{pc}/\partial\mathbf{x})2\pi\mathbf{f_x} \tag{17}$$

Then we define new control variables of $\delta\mathbf{X}$ and matrix $\mathbf{M}_p$ and $\mathbf{A}$ for getting the combined formulation of the plasma current and the plasma shape.

$$\delta\mathbf{X} = (I_p\delta\mathbf{x},\ \ \delta I_p) \tag{18}$$
$$\mathbf{M}_p = (\partial\mathbf{M}_{pc}/\partial\mathbf{x},\ \ \mathbf{M}_{pc}\,) \tag{19}$$
$$\mathbf{A} = (\mathbf{A_x},\ \mathbf{A}_p{}^{V}) \tag{20}$$

$$\mathbf{f} = (\mathbf{f}_x, \ \mathrm{f}_p) \tag{21}$$

Where $A_p{}^V$ in eq.(20) is a vector format modified from a diagonal matrix of $\mathbf{A}_p$. Then the feedback gain of the plasma current and the plasma shape **G** becomes,

$$\mathbf{RG}=(\mathbf{MA}+\mathbf{M}_p)2\pi\mathbf{f} \tag{22}$$

Each element of $\mathbf{M}_p$ is <~20% of **MA**, so $\mathbf{M}_p$ can be ignored in the first approximation. In ITER, only two elements of $\mathbf{M}_{pc}$ (PF6 and PF7) are ~50% of **MA**, and the other elements are below 20%. **RG** is easily calculated from matrix **A**. Thus quantitative estimation on the required voltage of the coil power supply can be possible by eq.(22) with the selection of the control frequencies. **RG** is a matrix of n x m. Where n is the number of PF coils and m is that of control variables. An example of matrix **A** is presented in Table 2. Each magnetic field pattern produced by PF coil currents for each control variable, that is same with each vector of matrix **A** of Table 2, is presented in Fig.2. The determination procedure of matrix **A** decides the applicability of it. If **A** is obtained from large database as eq.(7), rather wide range of plasma shape can be controlled by one matrix gain. If **A** is obtained from eq.(16), the range of the applicability is limited in small plasma parameters and the estimation of matrix **A** is required for small changes in plasma parameter. However it may be possible to calculate matrix **A** in a real time owing to the very slow control frequency.

The effect of eddy currents, that flow in the machine components (e.g. vacuum vessel, cryostat), is not included explicitly in the investigation of a matrix gain presented above, because the feedback control frequency is usually selected to be lower than the characteristic frequency of eddy currents. If it is selected to be too high, it becomes unstable owing to the time delay caused by the shielding effect of eddy currents. Thus the optimum control frequency should be investigated by a simulation code, that includes the effect of eddy currents.

This noninteracting control algorithm is planned to be applied to JT-60U. Thus the experimental experiences in JT-60U will contribute largely to the design of ITER plasma control system.

2. Control of the Horizontal Plasma Position

In ITER, plasma current is planned to be raised with dI_p/dt=1MA/s just after the break down as presented in Fig.3. During this phase, plasma touches the inboard side of

$$\mathbf{f} = (\mathbf{f}_x,\ \mathrm{f}_p) \qquad (21)$$

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In ITER, plasma current is planned to be raised with $dI_p/dt=1MA/s$ just after the break down as presented in Fig.3. During this phase, plasma touches the inboard side of the first wall in the reference scenario$^{4)}$. For getting the stable current rampup, plasma horizontal position should be controlled to be almost the same value to maintain the power density of the joule heating. However there are limits on the rampup rate of vertical magnetic field B_Z inside the vacuum vessel.

2.1 PF Coil Voltage

Voltage of PF coils at the early rampup phase just after the plasma initiation should be controlled as,

$$\mathbf{E} = \mathbf{MA}_p(d\Phi/dt) + \mathbf{MA}_V(dB_Z/dt) + \mathbf{M}_p(dI_p/dt) \qquad (23)$$

First term of eq.(23) is the supply of the magnetic flux to raise the plasma current. $\mathbf{A}_p$ is a coil current vector to produce 1 voltsecond at r=4.5m. $d\Phi/dt$=-15.6V is required in ITER. The second term is the buildup of the vertical magnetic field. A_V is a coil current vector to produce 1 Gauss at R=4.5m and Z=0.0m. Shafranov magnetic field of -300Gauss is required at t=0.5 s to get 0.5MA with R_p=4.5m, a_p=0.8m, Z_p=0m, β_p=0.01, l_i=0.79. Then dB_Z/dt=-600Gauss/s is required. The third term comes from the coupling with a plasma current. The resistivity drop of **RI** is small and is neglected in eq.(23). Table 3 presents the comparison of the coil voltages obtained from the above estimation with the reference ones. Good agreement is obtained between them.

2.2 Restrictions on B_Z Rampup

Restrictions on coil voltages at the early rampup phase can be summarized as follows.

1) B_Z produced by oneturn voltage

When oneturn voltage is supplied, error field of B_Z is produced by eddy currents that flows in the vacuum vessel and the cryostat. 235Gauss (at 4.5m) is produced at t=0.5 s with the oneturn voltage of 15.6V$^{4)}$. Then the required dB_Z/dt is {-300 (Shafranov) - 235 (Component) } / 0.5s = -1070 Gauss/s.

2) Shielding effect of the eddy currents against the B_Z penetration

The shielding effect of eddy currents against the penetration of the vertical magnetic field generated by PF coils or invessel coils are investigated by a simulation code with the linear rampup of coil current as presented in Fig.4(a) and (b). Time evolution of the percentage of B_Z produced inside of the vacuum vessel compared to B_Z generated by coils is investigated as presented in Fig.4(c). Only about 30% penetration is obtained at t=0.1 s.

3) Limit on coil voltage

Maximum rampup rate of B_Z is limited to be 2000Gauss/s due to the available coil voltage of 20kV from the design of PF coils without including the shielding effect of eddy currents. Then dB_Z/dt in the vacuum vessel (R=4.5m) is reduced by the shielding effect of eddy currents as follows,

	% of penetration	dB_Z/dt
t=0.1s	31%	-620Gauss/s
t=0.2s	41%	-820Gauss/s
t=0.3s	47%	-940Gauss/s
t=0.4s	51%	-1040Gauss/s
t=0.5s	55%	-1100Gauss/s

Thus the required B_Z of -1070Gauss/s is obtained at t=0.5s.

4) Horizontal plasma shift

For getting the stable plasma current rampup, small plasma minor radius is required in order to get high power density of the joule heating. However a plasma shifts to the outside ~1.0m just after the plasma initiation owing to the insufficient B_Z as presented in Fig.5.

2.3 Possible solutions

Possible solutions to get the required B_Z is as follows,

1)De-block of PF6 coil into two coils

1.3x-2000Gauss/s can be generated by this de-blocking of PF6, because coil voltages of PF4 and PF7 are already 15kV and can be raised from 15kV to 20kV (20kv/15kV=~1.3). Then -800Gauss/s can be added at R=4.5m, t=0.1 s, and the outward plasma shift can be decreased to be 0.3~0.6m.

2)Invessel coils

Invessel coils installed at R=9.1m and Z=±2.6m produces 45Gauss at R=4.5m with 30kAT, n_{index} of that is about 0.0. With 1kV power supply, control speed of -

3600Gauss/s can be obtained at t=0.1s. Thus coil current of 100kAT increases the controllability of B_Z with producing 150Gauss.

4)Decrease of plasma current rampup

If the plasma current rampup rate can be lowered as <1.0MA/s, it can decrease the oneturn voltage and rampup rate of B_Z. Then it can drop the requirement on the maximum coil voltage of PF coils. Thus the systematic study to decrease the current rampup rate is required. Additional heating may be the useful method to get the stable current rampup.

Furthermore, feedback control or feedforward control of vertical magnetic field is useful to get the stable plasma initiation and current rampup. For this purpose, the second term of left hand side of eq.(23) should be modified as $\mathbf{MA}_V\,(\alpha I_p)$. Where α is the constant.

3. Conclusions

Plasma control related to the plasma configuration in ITER is investigated.

In the plasma shape control, multivariable noninteracting control method is proposed as one of the possible control algorithms with the derivation of a matrix gain of that. The relation between the control variables and the poloidal magnetic field coil currents is essential to obtain the matrix gain, and is estimated for an ITER plasma. This control algorithm is planned to be examined in JT-60U, that will contribute to the design of the ITER control system.

Control of the horizontal plasma position is investigated at the early buildup phase just after the breakdown. Plasma current rampup speed of 1.0MA/s requires fast buildup of B_Z. Thus 20kV power supply of PF coils and installation of invessel coils with 30-100kAT are required. Thus experiments to get the stable ramp-up with <1.0MA/s should be examined to ease these requirements.

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Furthermore, feedback control or feedforward control of vertical magnetic field is useful to get the stable plasma initiation and current rampup. For this purpose, the second term of left hand side of eq.(23) should be modified as $\mathbf{M}\mathbf{A}_V\,(\alpha I_p)$. Where α is the constant.

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Table 1 Requirements on Control Variables in the slow control loop

Control Variables	Required Range	Control Issue	Ref.	Time Issue
R_{out}	±2cm	CX erosion	1)	~1s
		RF coupling	2)	
R_{in}	±2cm	CX erosion	1)	~1s
		disruption survivability	3)	
Z_p	±(0.5-1)cm	divertor heat load(~20%)	4)	~1s
$(R_x, Z_x)^U$ $(R_x, Z_x)^L$	±2cm	divertor heat load location	5)	~1s
I_p	±0.1MA	plasma performance	6)	~1s

1)Large clearance of ~15cm between the separatrix and the first wall is required to decrease the CX erosion.

2) n_e of $0.5 \sim 4.5 \times 10^{18}/m^3$ is necessary for the coupling of LHW(5~6GHz)

3)>~10cm is necessary to avoid the contact of plasma to the inner side of vacuum wall at a disruption.

4)In the double null condition, the allowable Z_p displacement depends on the profile of the radial power flow outside the separatrix line. Short decay length of 0.5cm is expected. Thus power fluctuation of 20~30% on the divertor plate may be produced by ~3mm separation of separatrix at the midplane. This requires the very precise control of Z_p with ~3mm.

5)To keep the separatrix line on the divertor plate (±2cm displacement of null point moves the striking point at most ±8cm on the divertor plate)..

6)Soft-landing at the emergency shut-down is ~-400kA/s

Table 2　Matrix of A (kAT)

Controlled plasma is in the SOFT phase {I_p=22MA, R_p/a_p=6.0/2.15m, β_p/l_i=0.6/0.65}.Unit of R_{out}, R_{in}, Z_p, R_n and Z_n is [cm], and that of I_p and I_{in} is [kA].

	Rout	**Rin**	**Rn**	**Zn**	z_p+cI_{in}	**Ip**
1U	-7.159E+01	2.475E+01	2.800E+01	-4.590E+00	-2.300E+01	1.453E+00
2U	-7.159E+01	2.475E+01	2.800E+01	-4.590E+00	-2.300E+01	1.453E+00
3U	3.477E+02	-4.604E+01	-2.010E+02	-1.530E+00	-5.530E+01	1.533E+00
4U	5.193E+01	2.178E+01	-9.200E+00	-7.776E+01	-6.220E+01	1.559E+00
5U	-1.287E+02	5.673E+01	1.412E+02	-1.485E+02	-1.190E+01	7.860E-01
6U	1.664E+02	-1.266E+02	4.400E+00	1.451E+02	-3.360E+01	6.480E-02
7U	-1.039E+02	9.119E+01	-1.040E+01	-7.929E+01	3.360E+01	5.700E-03
1L	**same with above**				2.300E+01	**same with above**
2L					2.300E+01	
3L					5.530E+01	
4L					6.220E+01	
5L					1.190E+01	
6L					3.360E+01	
7L					-3.360E+01	

Table 3　Voltages of PF coils (kV)

Comparison of the PF coil voltages estimated from eq.(23) and the reference ones in the early rampup phase

	MA_p ($d\Phi/dt$)	MA_V (dBz^{eq}/dt)	M p (dIp/dt)	TOTAL	Reference Voltages at t=0.1-0.6s[kV]
PF1	-5.691	-0.033	0.705	-5.019	-5.015
PF2	-5.682	-0.917	0.437	-6.162	-6.132
PF3	-5.613	-3.851	0.232	-9.233	-9.481
PF4	-4.993	-4.063	0.126	-8.930	-9.114
PF5	-7.673	-1.803	0.203	-9.273	-8.964
PF6	-3.905	-5.803	0.772	-8.941	-9.849
PF7	-2.373	-4.956	0.655	-6.674	-6.250

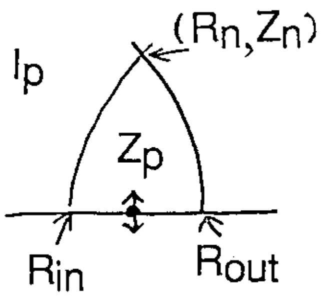


Fig.1　Control variables in the ITER plasma shape control.

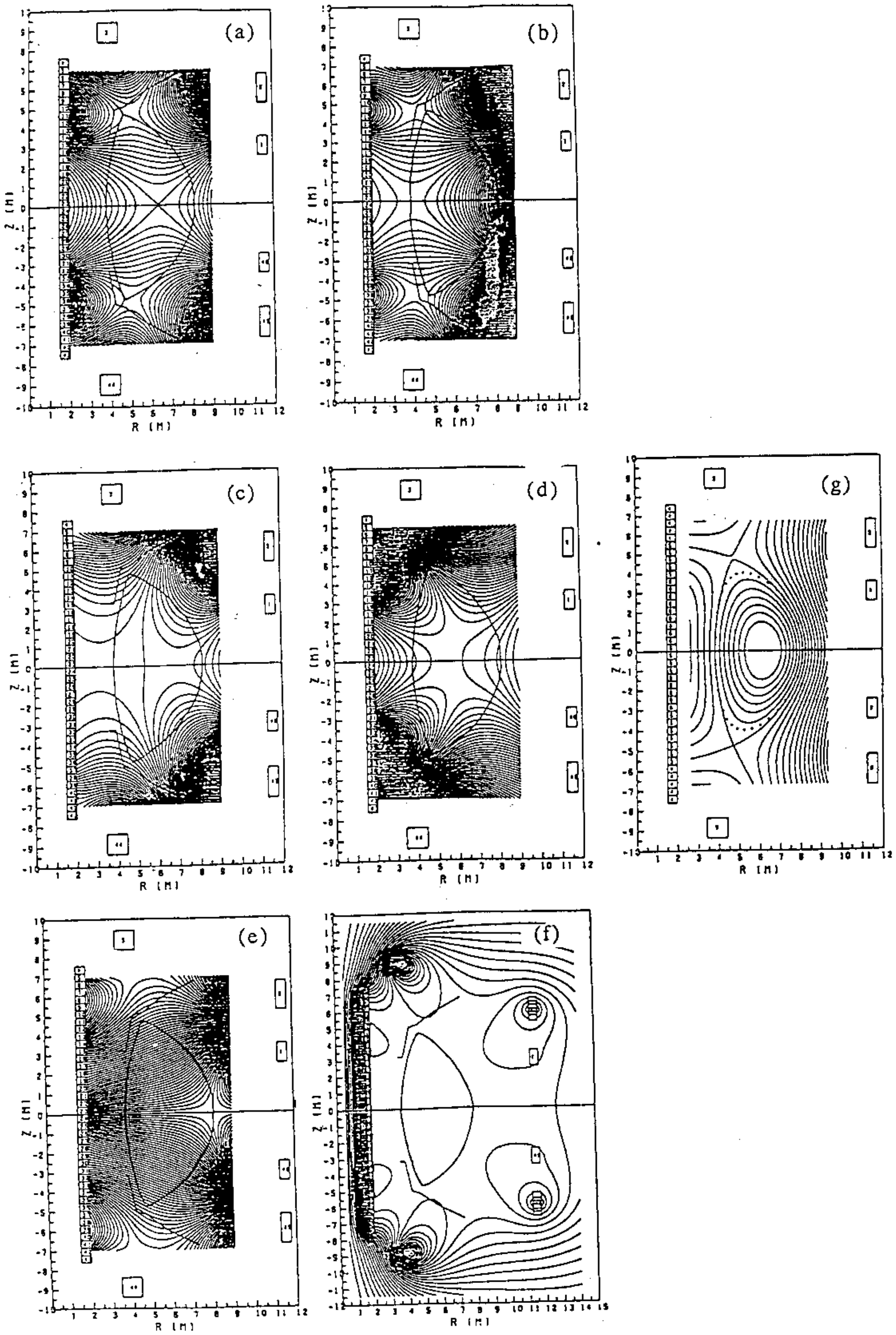


Fig.2 Magnetic field pattern
(a)R_{in}, (b)R_{out}, (c)Z_n, (d)R_n, (e)Z_p, (f)I_p, (g)Reference plasma configuration. Plasma parameters of (g) is same with that of Table 2.

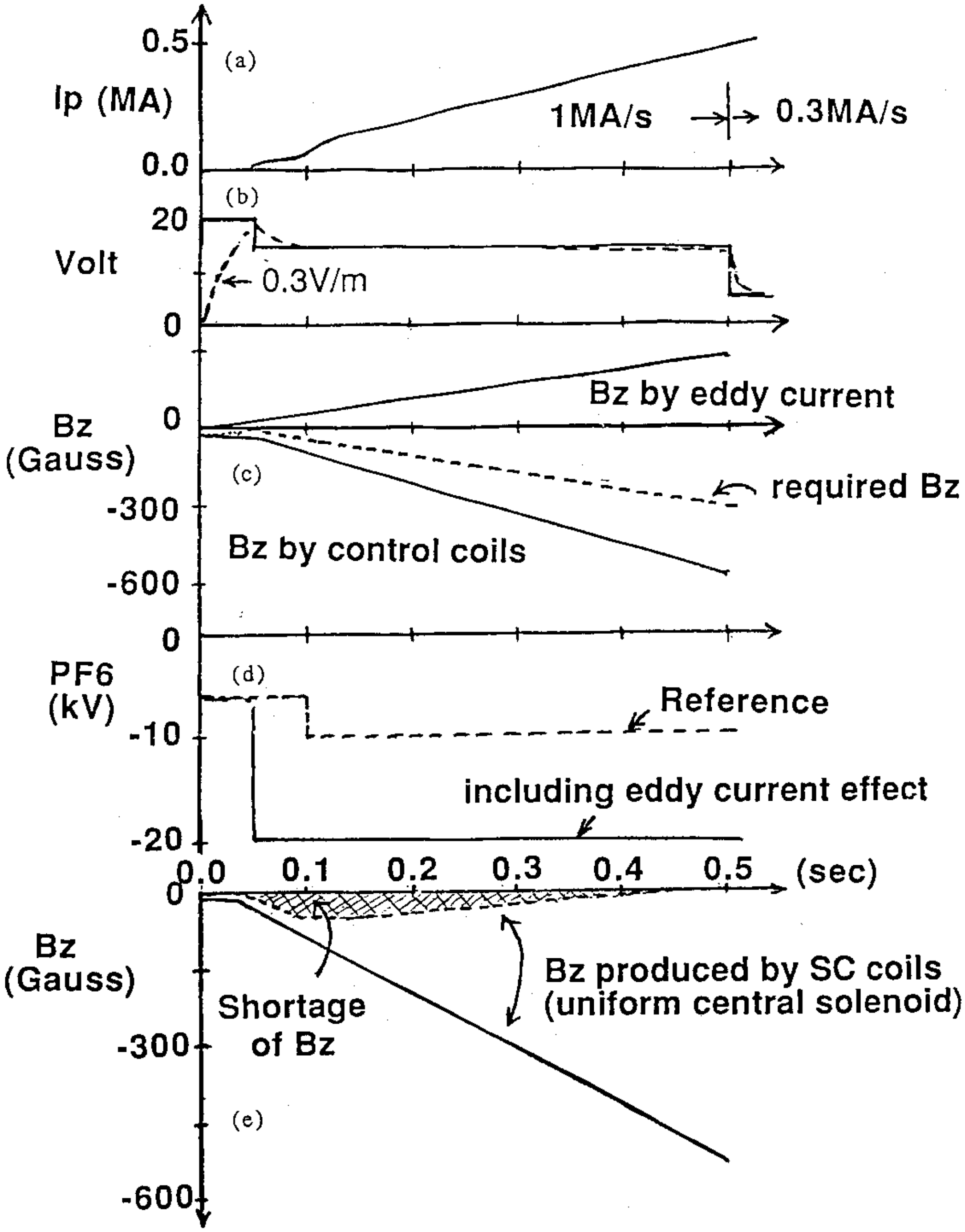


Fig.3 General view of the plasma initiation and current rampup with 1MA/s. (a)plasma current, (b)loop voltage, (c)B_Z generated by eddy currents and PF coils, (d)voltage of PF6 coil (-10kV is the reference design value without including the eddy current effect), (e)comparison of the required B_Z and produced B_Z.

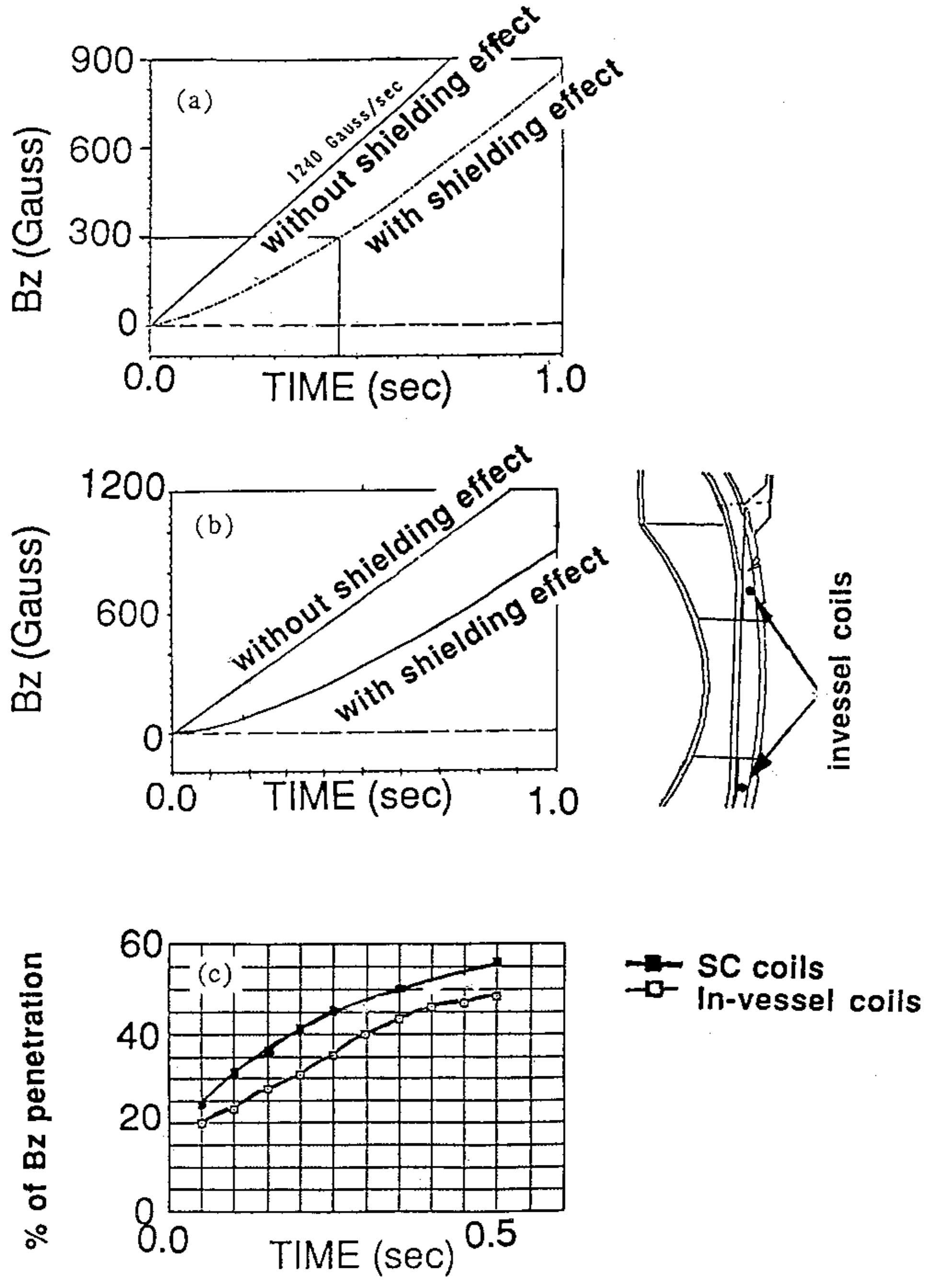
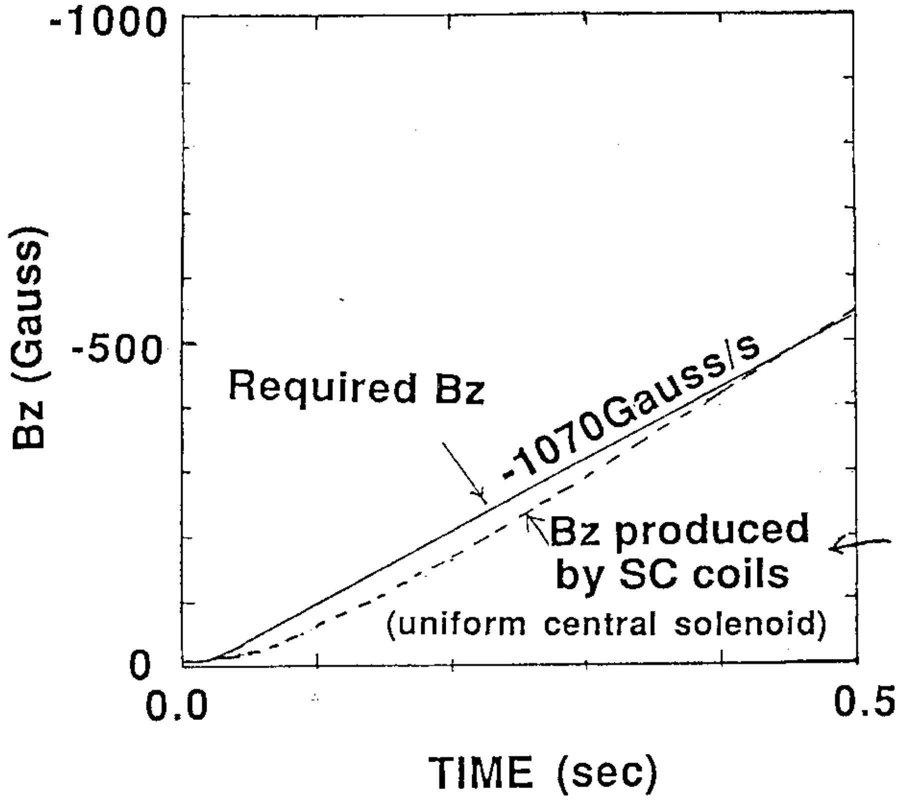


Fig.4　Shielding effect of eddy currents against the penetration of B_Z

Penetration of of the vertical field with the linear rampup generated by (a)PF coils and (b)invessel coils installed at R=9.1m, Z=±2.6m. (c)percentage of the penetrated B_Z compared with the generated B_Z.



PF1	-0.664kV
PF2	-3.880kV
PF3	-13.85kV
PF4	-14.52kV
PF5	-7.507kV
PF6	-19.45kV
PF7	-16.39kV

	dBz/dt	(dBz/dt)/(dBz^{req}/dt)	ΔR from 4.5m
t=0.1sec	-620Gauss/s	57%	+1.4m
t=0.2sec	-820Gauss/s	77%	+0.6m
t=0.3sec	-940Gauss/s	88%	+0.3m
t=0.4sec	-1040Gauss/s	97%	+0.1m
t=0.5sec	-1100Gauss/s	103%	-0.1m

Fig.5 Required B_Z and produced B_Z.
Plasma shifts largely to the outside at t=~0.1 s owing to the shortage of B_Z.