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RESEARCH REPORT

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Abstruct

Reversed-field pinch (RFP) operation on STP-3(M) proved that the adition of a quasistational vertical field $B_\perp$ together with large reduction of irregular magnetic field at the shell gap could remarkably improve properties of the plasma confinement. Here,the gaps of a thick shell is wholely covered with the single primary coil having a shell shape. The measured field error at the gap is as small as 7.5 % of the poloidal field. The application of $B_\perp$ sets the plasma at a more perfect equilibrium. In this operation, the plasma resistivety much decreased by a factor 2 and the electron tempareture rose up to 0.8 keV.

In a reversed-field pinch(RFP) [1], global equilibrium of the plasma column has been provided primarily by a thick conducting shell. When the discharge duration of an RFP becomes much longer than the time constant of the conducting shell, it is required to maintain an equilibrium by the externally applied vertical field [2]. However,the use of a conducting shell seems to be a wise choice for the purpose of obtaining an RFP of good quality in the present stage of RFP research.

A conducting shell should have its toroidal gap for permeating the induced toroidal electric field for current drive. It has been recognized that local field errors caused by the shell current at the gaps have a strong unfavorite influence on an RFP operation, causing a significant deterioration of the discharge characteristics [3]. Therefore,efforts have been made for the reduction of field errors at the shell gap, including a particular structure of the gap (e.g.,tapered gap [4]), an application of magnetic field locally at the gaps [5-7],and so on. Trim coils have been used in the HBTX-1A with preprogrammed current waveform for the coils for matching the vertical field components inside and outside of the shell [5]. In ZT-40M, field errors have been compensated using saddle coils at the gap with feedback-controlled coil currents [6]. And, as a results, it has been demonstrated clearly that, with a careful compensation of field errors at the gap, control of the average plasma posistion by a quasistasionary (DC) vertical field has improved discharge characteristics [5,7,8]. This efforts have been made, however, only for the conventional structure of the shell: a single shell surrounding the plasma. Hereafter we will refer to this structure as the single-shell (SS) structure.

The RFP device STP-3(M)[9] has a shell structure called "double shell" (DS) which is composed of the inner thick shell and the outer shell working as a primary coil for exciting the plasma current. This Letter describes favourite properties of this DS structure, of which the error fields at the gaps can be small enough without the help of external field compensation. In practice, the radial magnetic field at the gap of the inner shell in this device is an order of magnitude smaller than in SS, and, as a results, RFP discharges could be operated successfully without external compensation of local field errors. In adition, application of a DC vertical field brought drastic rise of plasma parameters because of better setting of the plasma equilibrium.

Prior to describing the experiments in STP-3(M), for the help of discussion, we will give a brief review on the experiments in TPE-1RM15 [7], in which the effect of the compensation of field errors at the shell gap on the discharge characteristics has been systematically demonstrated. In TPE-1RM15, three vertical field sets are equipped: quasistationary (DC) vertical field, B_v^{dc}, for the control of plasma position, pluse vertical field, B_v^{P}, for canceling B_v^{dc} at the breakdown phase, and control vertical field, B_v^{c}, applied locally at the shell gap for compensating the field errors. The current waveform for B_v^{c} was preprogrammed to be similar shape to the current Ip. Figure 1 shows the dependence of the current waveform on B_v^{c} which is proportional to the charging voltage of the bank Vcv [7]. All other conditions were kept at constant. The figure clearly indicates that, without B_v^{c}, the discharge terminated quite rapidly in the current rise phase. It is probably due to the disturbance by field errors: for example, average radial field at the shell gap $\overline{B}_r$ just before the current termination, at Ip of $\sim$40 kA, was $\sim$0.7 kG [10] which was comparable to, or, slightly larger than the poloidal field at the plasma surface. The figure also indicates that, as B_v^{c} was raised up the maximum current increased and at the optimum B_v^c the discharge duration reached its design value of $\sim$7 ms. Excess application of B_v^c has deteriorated the discharge characteristics.

Figure 2 gives the cross sectional view of DS structure in STP-3(M) and the setting position of DC vertical field coils. The copper inner shell of 1.1 cm thick is covered with the 2.1 cm thick one-turn primary coil. The inner shell has two 6 mm wide gaps, separated by 180° toroidally each other. It should be noted effectively no gap is present in the outer shell because the poloidal circuit is shortened through the external circuit during the operation. The poloidally averaged radial magnetic field $\bar{B}_r$ measured beneath the gap of inner shell was 75 G at the plasma current of 50 kA, so that the ratio $(\bar{B}_r/B_\theta(a) = 7.5\,\%$, where $B_\theta(a)$ is the poloidal field at the plasma surface. Here, Br was estimated from the gap flux measured with a saddle coil under the assumption that the current does not diffuse into the shell but flows only at the edge of the shell gap. This level of error field is an order of magnitude lower than in the TPE-1RM15 without B_v^c. And, as a result of optimization, a high-current density $(j \gtrsim 8\ \mathrm{MA/m^2})$ operation with moderate duration (3 ms) has been realized in STP-3(M) without external compensation of field errors [9].

Dependance of the current waveform on DC vertical field $B_\perp$ in STP-3(M) is given in Figure 3, which should be compared with Figure 1 for SS. It may be emphasized again that no local compensation of field errors has been applied in STP-3(M). The DC vertical field was turned on 0.3 sec prior to the start of discharge. No preprogramming of $B_\perp$ has been made at the breakdown phase. Due to mismatching in the waveforms of Ip and $B_\perp$ at the earlier phase, the plasma current rise became slower with increasing $B_\perp$. The discharge duration was prolonged much by applying $B_\perp$, through experiments in other devices have not indicated such a clear dependence of Ip on $B_\perp$ as observed in STP-3(M). The reason is probably attributed to the level of degradation of axi-symmetry by field errors.

Reduction of $\overline{B}_r$ in the DS structure can be treated qualitatively (or semi-quantitatively) by the following simple model for the conducting shell [11,12]. Field errors (mainl $\overline{B}_r$) are produced by a poloidal dipole current at the gap. Firse, consider an sufficiently thin conducting shell with majior radius R and minor radius b (thin shell approximation). Then, the poloidal current $I_\theta^s(\theta)$ at a small toroidal gap of the shell can be expressed as follows,

$$I_\theta^s(\theta) = - \frac{I_p b}{2\pi R}\left[\log\left(\frac{8R}{a}\right) + \Lambda - \frac{1}{2} - \frac{4\pi R}{\mu_0 I_p} B_\perp\right] \sin\theta, \qquad (1)$$

where $\Lambda = \beta_p + li/2 - 1$, with poloidal beta ($\beta_p$) and normalized internal inductance per toroidal unit length(li). When the plasma is surrounded by coaxial double shell, using the thin shell approximation again, the poloidal current at the small gap of the inner shell $I_\theta^d(\theta)$ is given as follows [12],

$$I_\theta^d(\theta) = - \frac{I_p b_1}{2\pi R}\left[\log\left(\frac{b_1}{a}\right) + \Lambda + \frac{1}{2} + \frac{b_2^2}{b_2^2 - b_1^2}\log\left(\frac{b_2}{b_1}\right) - \frac{4\pi R}{\mu_0 I_p} B_\perp\right]\sin\theta, \qquad (2)$$

where b_1 is the minor radius of the inner shell and b_2 that of the outer shell. For the parameters of STP-3(M), the poloidal current for the inner shell of DS reduces to about 30 % of that for SS. In the actual situation for DS, the image current induced on the outer shell is opposite to the gap current and resultant error field is of quadrapole. This field decreases faster as going into the confinement region than the dipole error field in SS case. Thus, the field errors in DS is expected to be smaller than the estimated amount (30 %),which is semi-quantitatively in agreement with the experiments.

Field errors are also correlated with averaged plasma position is clearly demonstrated as shown in Figure 4. In the figure, time behavior of Ip, horizontal displacement of the plasma column Δ_h , and $\overline{B}_r$ is shown,(a) without and (b) with DC vertical field. In a discharge without a control of the plasma position, Δ_h is about 5 mm throughout the discharge, because the penetration time of the inner shell with respect to the vertical field is about 100 ms and is much longer than the discharge duration. Since the gap flux is produced primarily by a dipole current, which is essentially a poloidal return current (at the gap) of the toroidal image current flowing in the shell, time behavior of $\overline{B}_r$ is approximetely similar to that of Ip. The value of $\overline{B}_r$ is about 75 G at Ip of 50 kA.

Figure 5 shows the dependence of $\overline{B}_r$ on the vertical field $B_\perp$ in normalized form. All the quantities were estimated at 0.4 ms into the discharge, at the maximum plasma current without $B_\perp$ relative to the poloidal field at the wall $B_\theta(a)$ is 7.5 % without $B_\perp$: it then decreases linearly with $B_\perp$. We may conclude, therefore, that the field errors in DS structure is an order of magnitude smaller than in SS.

A remarkable effect of DC vertical field on the global discharge parameters has been observed in STP-3(M). Dependance of the plasma resistance, Rp=Vl/Ip, on the plasma current Ip is show in Figure 6, with and without $B_\perp$. When no vertical field is applied, resistance does not depend on Ip, remaning the value 1.0 - 1.2 mΩ. On the contrary, when $B_\perp$ is applied, resistance increases (approximetely linearly) with Ip. In paticular, for modererate-current discharge (Ip: 70 - 100 kA), resistance decreases to half of that without $B_\perp$.

Under these optimum conditions with respect to vertical field, horizontal displacement of the plasma column becomes almost zero, as shown in Figure 4. In other words, resistance is minimazed when the current channel becomes coaxial with the liner.

Effect of the vertical field on the confinement properties should be adressed here. Figure 7 shows the dependance of central electron temperature Te(0) measured by Tomson scattering on Ip in discharges with and without the vertical field. As mentioned previously, without $B_\perp$, central temperature increases linearly with Ip [9]. This linear dependence holds for discharges with $B_\perp$. Te(0) became twice as large as that without $B_\perp$ for the same value of Ip. The maximum Te(0) attened so far is 0.8 keV at the plasma current of 130 kA. The scaling coefficient, Te(0)/Ip is as large as 6.2 eV/kA and does not degrade in high-current density regime ($j < 5.3$ MA/m^2). This result may support the favorable scaling for an RFP in high-current density regime.

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Figure Captions

Fig. 1. Dependence of current waveform on the control vertical field B_v^c observed in TPE-1RM15. Reproduced from ref. 7.

Fig. 2. Cross sectional view of the double-shell structure in STP-3(M), along with the poloidal windings for quasistationary vertical field.

Fig. 3. Dependence of current waveform on the quasistationary vertical field $B_{\perp}$.

Fig. 4. Time behavior of the plasma current I_p, horizontal displacement Δ_h, and average radial magnetic field at the shell gap B_r, in a discharge, (a) without, and (b) with optimum, vertical field $B_{\perp}$.

Fig. 5. Dependence on the vertical field $B_{\perp}$ of the average radial field at the shell gap B_r in normalized form.

Fig. 6. Dependence of the plasma resistance R_p on the plasma current I_p, with and without the vertical field $B_{\perp}$.

Fig. 7. Dependence of the central electron temperature $T_e(0)$ on the plasma current I_p, with and without the vertical field $B_{\perp}$.

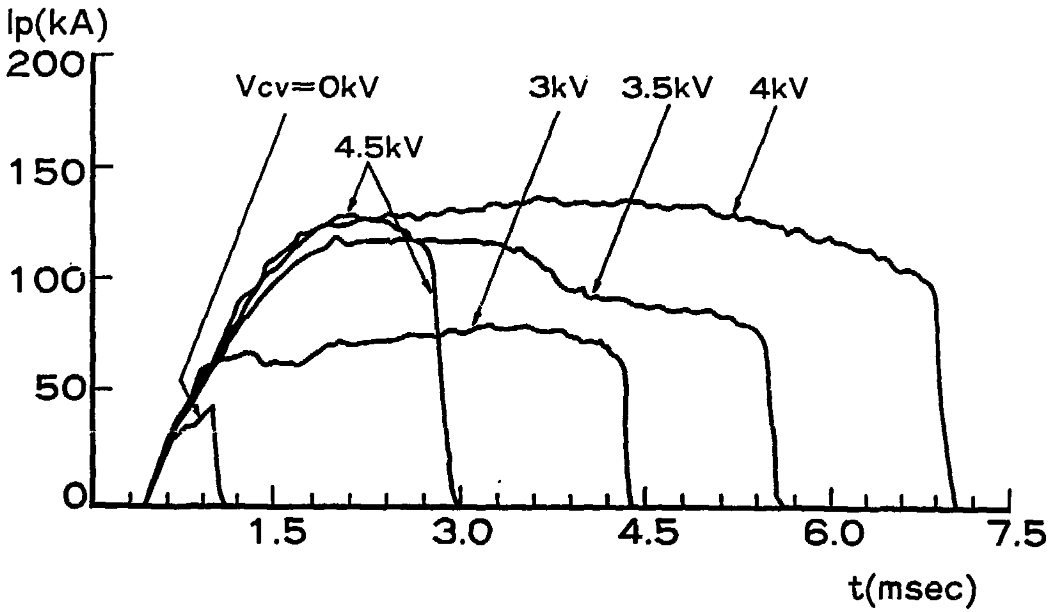

Ip(kA)
200
150
100
50
0
Vcv=0kV
4.5kV
3kV
3.5kV
4kV
1.5
3.0
4.5
6.0
7.5
t(msec)

Fig. 1

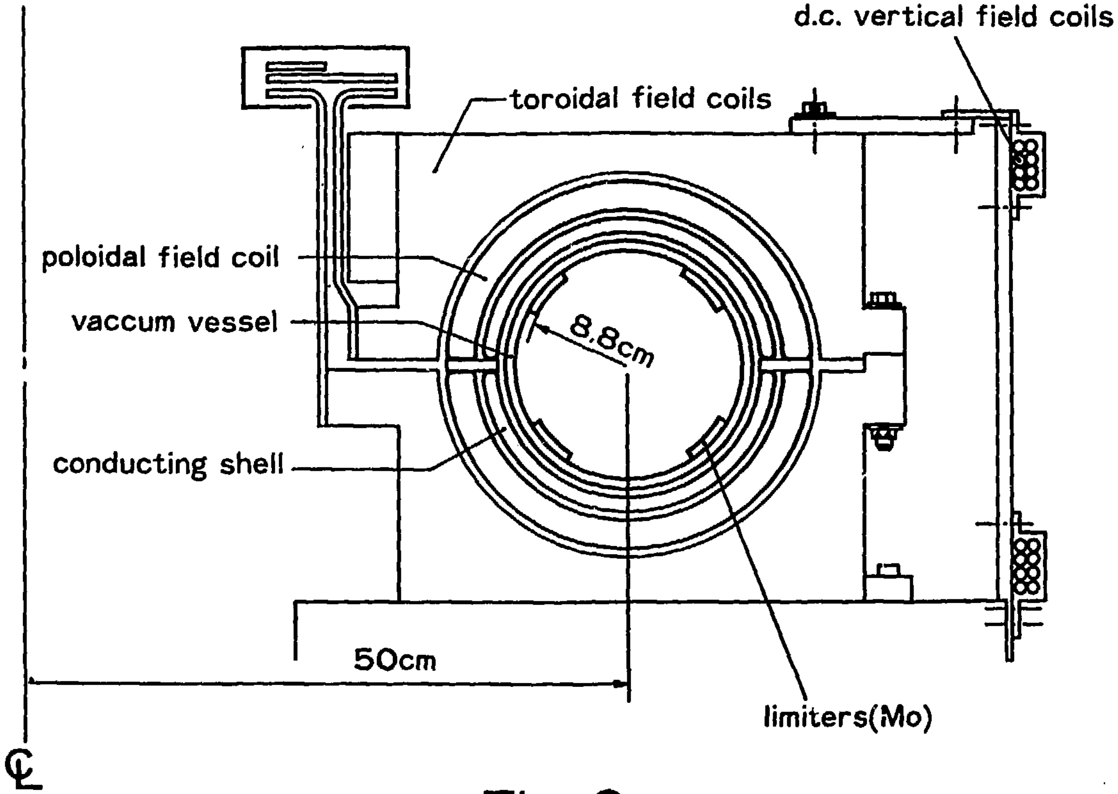

d.c. vertical field coils
toroidal field coils
poloidal field coil
vaccum vessel
8.8cm
conducting shell
50cm
limiters(Mo)
℄

Fig. 2

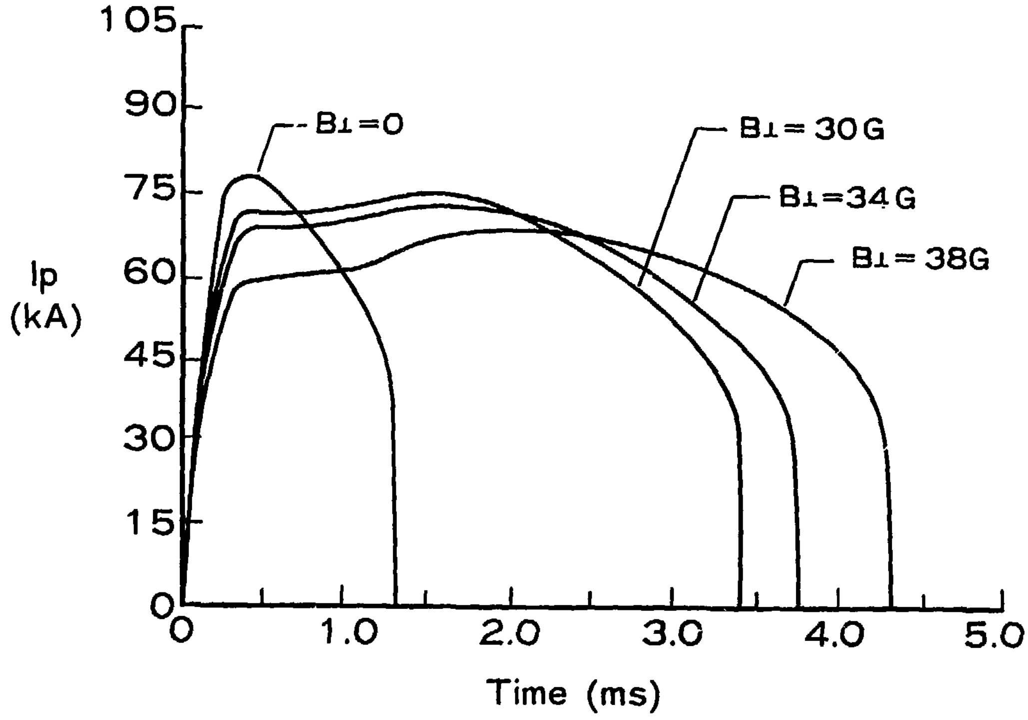
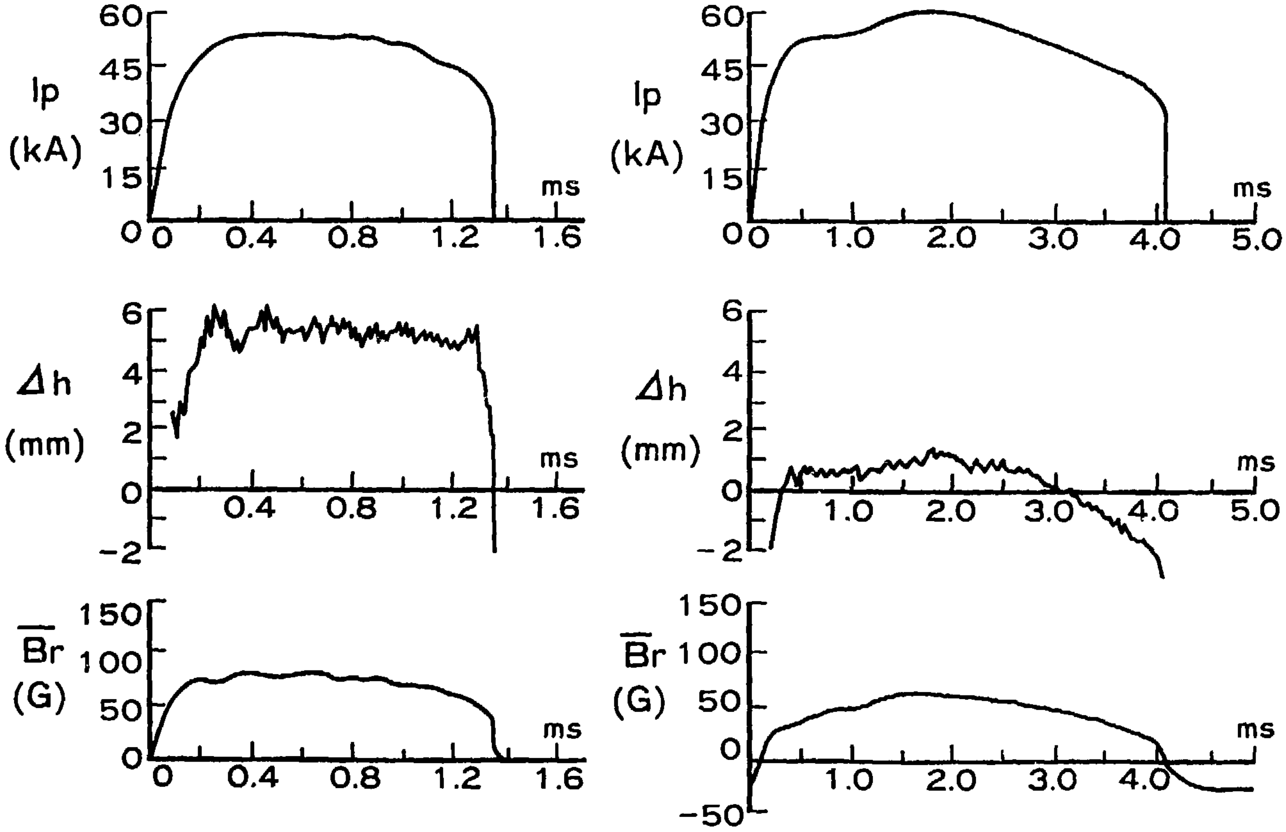

105
90
75
60
45
30
15
0
Ip
(kA)
0
1.0
2.0
3.0
4.0
5.0
Time (ms)
B⊥=0
B⊥= 30G
B⊥=34G
B⊥= 38G

Fig. 3


Ip
(kA)
60
45
30
15
0
0
0.4
0.8
1.2
1.6
ms
Δh
(mm)
6
4
2
0
−2
0.4
0.8
1.2
1.6
ms
$\overline{Br}$
(G)
150
100
50
0
0
0.4
0.8
1.2
1.6
ms
Ip
(kA)
60
45
30
15
0
0
1.0
2.0
3.0
4.0
5.0
ms
Δh
(mm)
6
4
2
0
−2
1.0
2.0
3.0
4.0
5.0
ms
$\overline{Br}$
(G)
150
100
50
0
−50
1.0
2.0
3.0
4.0
ms

(a)

(b)

Fig. 4

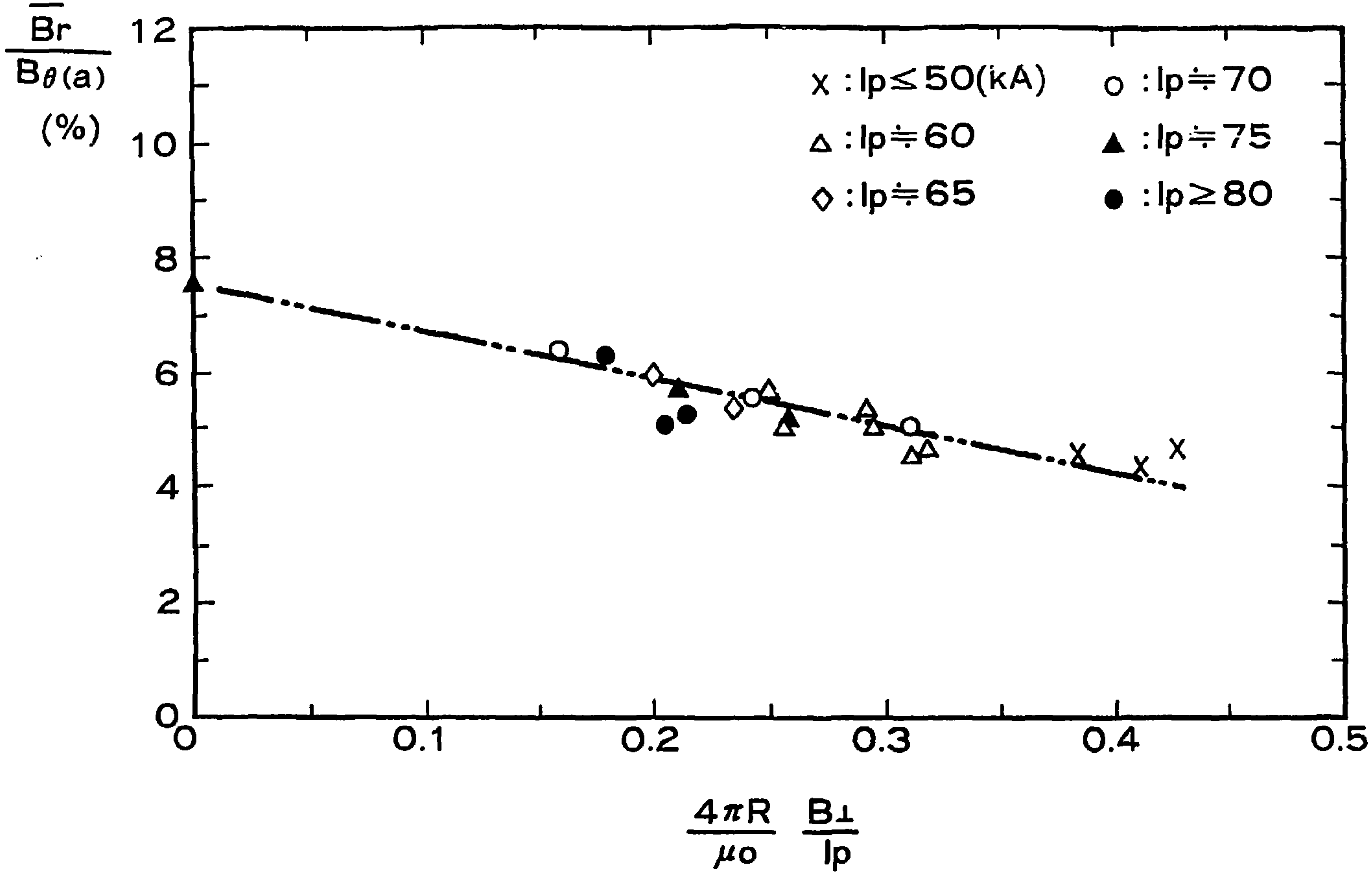
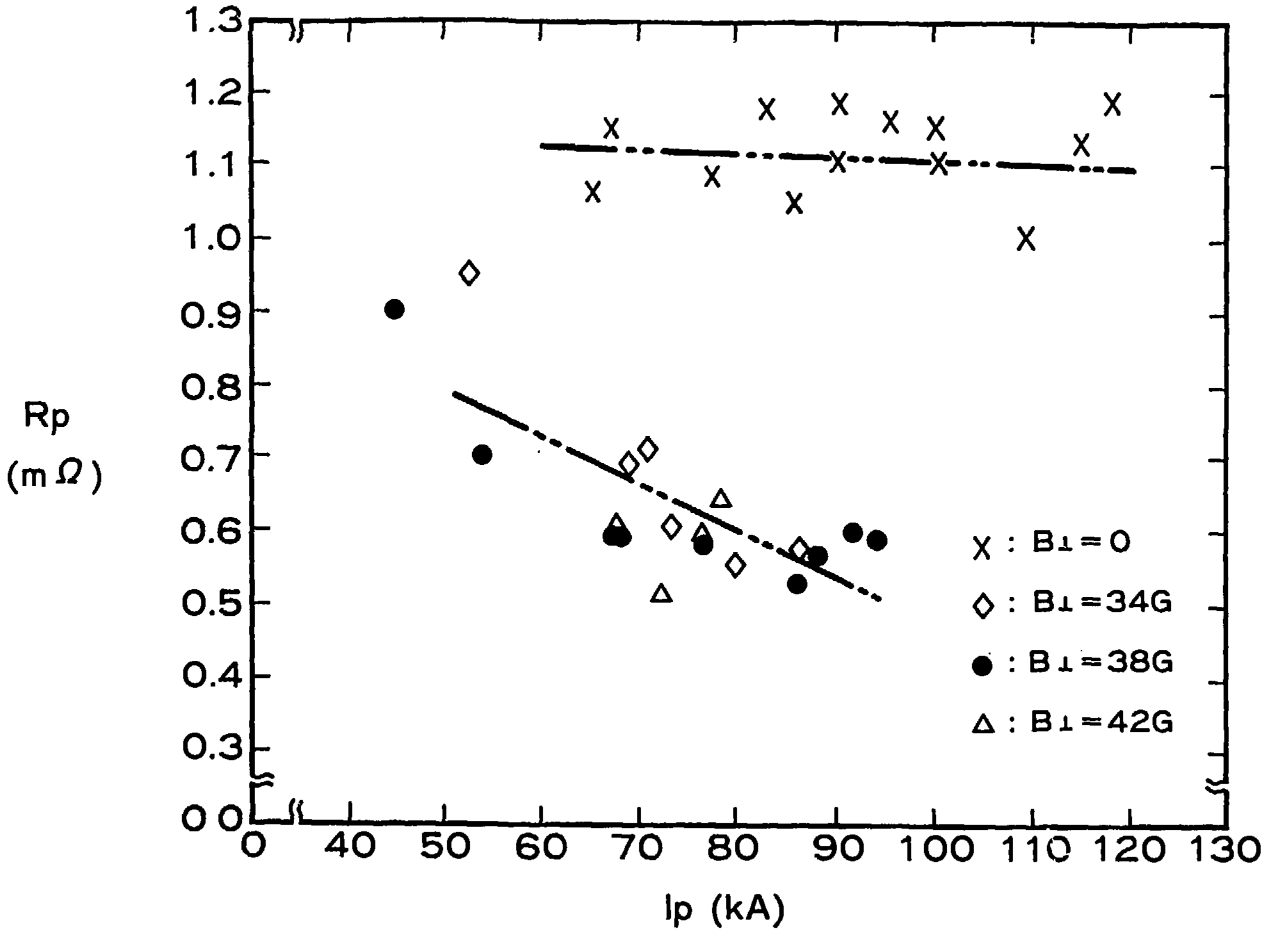

$\frac{\overline{Br}}{B_\theta(a)}$ (%)
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
$\frac{4\pi R}{\mu_0} \frac{B_\perp}{I_p}$
x : Ip≦50(kA)
○ : Ip≒70
△ : Ip≒60
▲ : Ip≒75
◇ : Ip≒65
● : Ip≧80

Fig. 5


Rp
(mΩ)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.0
0
40
50
60
70
80
90
100
110
120
130
Ip (kA)
X : B⊥ = 0
◇ : B⊥ = 34G
● : B⊥ = 38G
△ : B⊥ = 42G

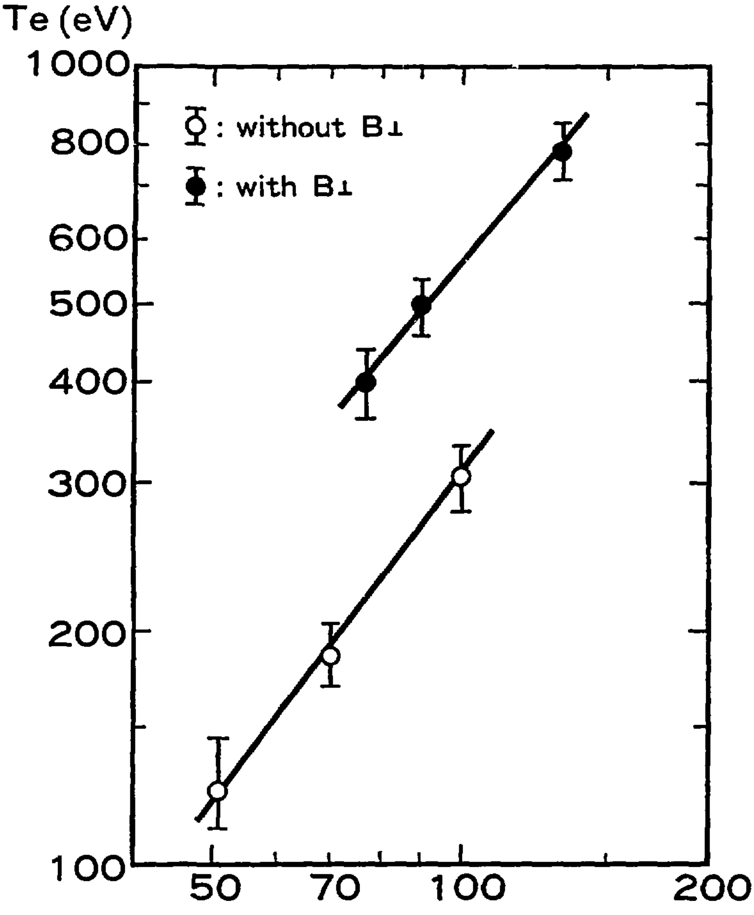

Te (eV)
1000
800
600
500
400
300
200
100
50
70
100
200
Ip (kA)
○ : without B⊥
● : with B⊥

Fig. 7