INSTITUTE OF PLASMA PHYSICS

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END EFFECTS ON THE n = 2 ROTATIONAL INSTABILITY IN THE REVERSED FIELD THETA-PINCH

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RESEARCH REPORT

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Further communication about this report is to be sent to
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Abstract

It is observed that n = 2 rotational mode which appears in the field reversed configuration created by a θ-pinch can be stabilized if the ejected plasmas from the ends are guided out to the far ends of the apparatus by long axial solenoidal fields. This is understood from the fact that endshorting becomes no longer possible before the ejecting plasma tips reach to the ends. Measurement of plasma rotations just outside the separatrix suggests that both preferential diffusion loss and endshorting play a very important role for the n = 2 mode.

It has been demonstrated in many places[1-3] that the field reversed configuration (FRC) can be created by a reversed field θ-pinch and high temperature plasmas are stably confined for many Alfvén transit time before it is broken up by the $n = 2$ rotational instability. Many experiments show that the grossly stable time τ_s of FRC is a function of filling pressure,[4] magnetic field strength,[5] and a species of used working gas.[6] In this letter we describe that τ_s is largely affected by the end conditions of the plasma.

The experiments have been done using the STP-L device of which schematic drawing is shown in Fig.1. The STP-L has two peculiar equipments; the one is the long plasma guiding coils attached at both ends of the θ-pinch coils, and the other is the staging system for the θ-pinch discharge. The plasma guiding coils generate uniform axial plasma guiding field (GF) of 0.5 T by which the plasmas ejected from the θ-pinch coil is guided out to the end of the appartus. The qualtz discharge tube has the inner bore of 10 cm and the total length of 8.5 m. The working D_2 gas is puffed at the center of the θ-pinch coil by the two specially designed fast acting gas valves of which muzzles also serve as the electrodes of small coaxial plasma guns. Thanks to electron supplies from these guns a pre-ionization rate by an usual ringing θ-discharge has been raised up to about 50 %. Since D_2 gas is injected at the center of the coil its density distribution along the axis shows transient character as is shown in Fig.2. Here the volume averaged gas density or pressure $\overline{P}$ is employed as a measure of filling gas density. In the present experiment we selected $\overline{P}$ to 8.6 mtorr and always fire the main discharge when the expanding gas front reaches to the ends of the θ-pinch coil (1 msec delay). Therefore we can expect that the hot plasma created in the θ-pinch coil expands into the vacuum along GF up to the ends of the apparatus. During the expansion the hot plasma is said to be completely floated up from the wall. Another special feature of the STP-L is that it equips staging system in which the decoupling of the fast capacitor bank from super-fast one is done by 25 μm thick ion cores. A typical example of the field waveform of the θ-pinch is given in Fig.3, where the super-fast bank is charged to 60 kV while the fast bank to 20 kV. As is seen in Fig.3 this operating voltages generate axial field of 0.25 T and 1 T with the rise time of 0.2 μsec and 2.4 μsec in sequence. The strength of the negative bias field is fixed to 5.5×10^{-2} T because higher field spoils the ionization rate at the moment. Owing to rapid rise of the field by the superfast system magnetic probe measurements show that FRC can be formed in 200 nsec from the start of the main discharge.

Under the fixed operating conditions stated above we studied how GF affects the behavior of FRC. A typical example of streak photographs with and without GF is given in Fig.4. The pictures are taken at the place 20 cm off from the center of the θ-pinch coil. We can see that GF delays the development of the $n = 2$ rotational mode to about 10 μsec. The time evolutions of temperatures and densities of FRC are shown in Fig.5. Here the ion temperatures are obtained by Doppler broadening of 227.1 nm CV line, electron temperatures on the axis by Thomson scattering, and the line integrated electron densities by CO_2 laser interferometry, where error bars originates from shot to shot reproducibility. We confirmed that the total temperatures deduced from the equilibrium relation[8] of $\langle\beta\rangle = 1$ agree fairly well with the sum of ion and electron temperatures given in Fig.4.

As can be seen the difference of the plasma parameters between the two operation, with and without GF, is within 15 %. In accordance with the observed plasma parameters in Fig.5, separatrix radii r_s obtained by excluded flux signals along the axis evolve as shown in Fig.6. Therefore we can say that the plasma parameters of FRC with and without GF become approximately the same before the n = 2 rotational mode appears. It has been discussed theoretically that the n = 2 rotational mode is closely connected to the rotation of FRC. Therefore if the rotation is important for the instability there must appear some differnece in the rotation of the plasma between the two operation. We observed the rotation by a similar directional probe described in ref.(7). It is confirmed that the insertion of the probe does not disturb FRC seriously if it is placed outside the separatrix (r_s = 18 mm). The results are given in Fig.7 where the tip of the plasma is located at r = 20 mm and 25 mm on the plane of 20 cm from the center of the θ-pinch coil. As is seen completely different features appear between the two operation. Without GF the plasma just outside the separatrix rotates in the positive direction of ion diamagnetic current, and is gradually spun up to the n = 2 deformation. On the other hand, with GF it rotates in the negative direction of electron diamagnetic current in the early phase while later on the sign is changed to opposite one and a small scale n = 2 deformation is seen (Fig.4). In order to check this probe measurement the ejecting plasma into GF was observed by a streak camera. A typical example of a streak photograph at the plane of 48 cm from the end of θ-pinch coil is given in Fig.8. We can see that the front of the ejecting plasma is highly deformed and rotating in negative direction until it reaches to the end. The streak photographs of which slit is along z axis in GF's section show that the pitch of the deformation is very long so that we may say that the expanding plasma into GF is deformed and rotates as a rigid body. Therefore it is very reasonable to say that the plasma just outside FRC is rotating in the same direction to the plasma in GF. This may be suggesting that the probe measurements give correct informations at least qualitatively.

If we adopt Barnes and Seyler's model[8] for FRC rotation, a clear explanation of the directional probe measurements becomes possible. As is known their model claims that particles are lost through separatrix with preferred angular momentum, which results FRC to rotate in positive direction. If the plasma is completely floated up from the boundaries as in the case of operation with GF, the conservation of net angular momentum makes the plasma outside the separatrix to rotate in negative direction. We know that if the end of a θ-pinch plasma is in contact with a wall of the apparatus the short circuit effect drives the positive rotation. Observed reduction of negative probe currents from 15 μsec in the operation with GF may show that end shorting begins to be effective since it is observed that the tip of the expanding plasma into GF reaches to the end at about 12 μsec. On the other hand in the case of the operation without GF, endshorting must take place at the end of the θ-pinch coil, so that since it must be important from very early phase of the discharge we do not observe any negative signals.

The above scenario may be the most probable explanation of the probe signals in Fig.7. Consequently it can be said that the observed delay of the n = 2 rotational mode with GF can be ascribed to the fact that end shorting is not possible until the tip of the ejecting plasma reaches to the ends of the apparatus. In the present operation it is noted that the amount of the loss of initially trapped particles in FRC before the n = 2 mode develops is estimated to be about 70 % for the operation without GF while it increases up to 90 % with GF. In conclusion of this letter we can say that not only the preferential diffusion but also the end shorting is required for the grobal rotation of the plasma, which is the necessary condition that the n = 2 rotating mode grows up.

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Figure Captions

Fig.1 Schematic drawing of STP-L.

Fig.2 Puff injected transient D_2 gas distributions along the main θ-pinch discharge tube.

Fig.3 Field waveform of STP-L.

Fig.4 Streak photographs with and without GF at $z = -20$ cm.

Fig.5 (a) Time evolutions of temperatures with and without GF.

○ : ion temperatures with GF,

● : ion temperatures without GF,

△ : electron temperatures with GF,

▲ : electron temperatures without GF.

(b) Time evolutions of line integrated electron densities through FRC diameter at $z = 20$ cm. ○ : with GF,

● : without GF.

Fig.6 Time evolution of separatrix profile obtained from excluded flux signals along the axis. ○ : with GF, ● : without GF.

Fig.7 Ion currents by the directional probe. The positive direction denotes that of ion diamagnetic current.

Fig.8 A streak photograph of the ejecting plasma into GF at the plasma of 48 cm from the end of the θ-pinch coil.

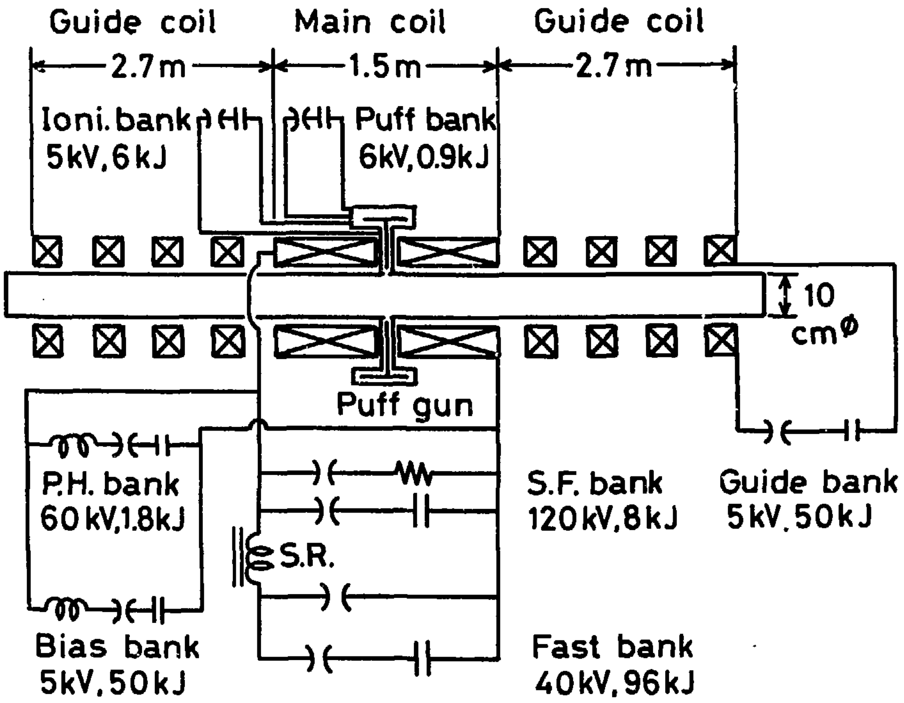

Guide coil
Main coil
Guide coil
2.7m
1.5m
2.7m
Ioni. bank
5kV, 6kJ
Puff bank
6kV, 0.9kJ
10 cmφ
Puff gun
P.H. bank
60kV, 1.8kJ
S.F. bank
120kV, 8kJ
Guide bank
5kV, 50kJ
S.R.
Bias bank
5kV, 50kJ
Fast bank
40kV, 96kJ

Fig.1

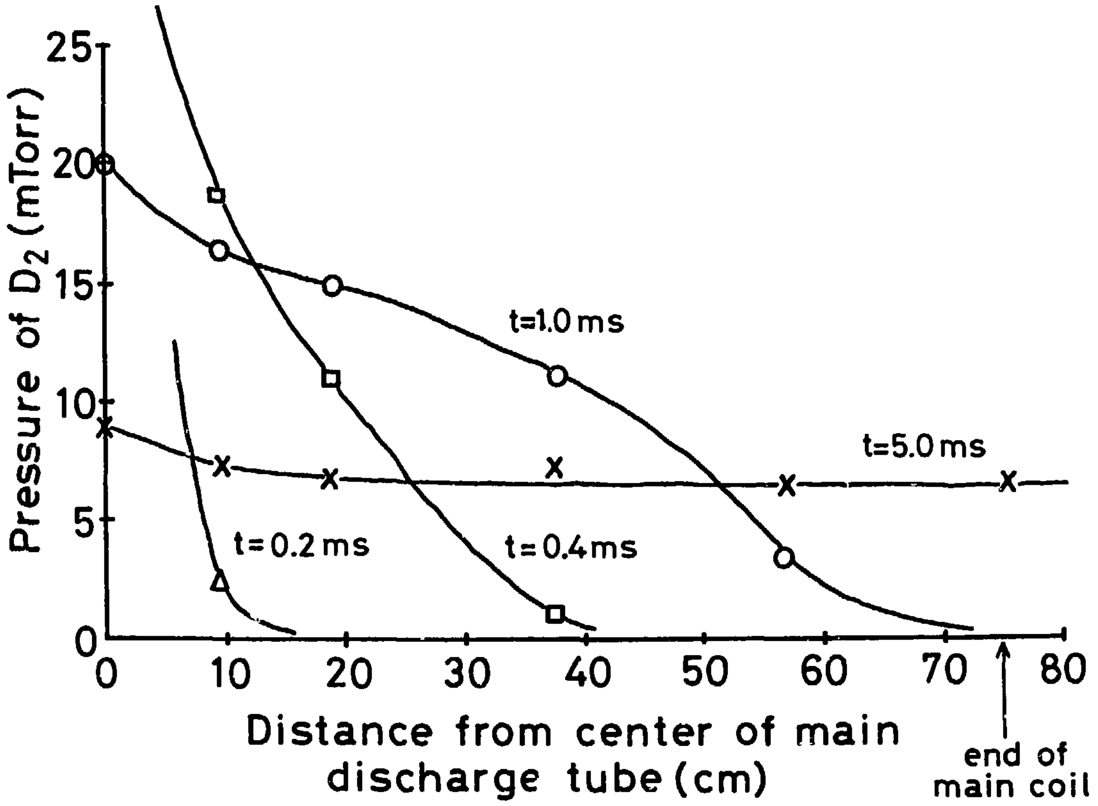

Pressure of D_2 (mTorr)
0
5
10
15
20
25
t=1.0 ms
t=5.0 ms
t=0.2 ms
t=0.4ms
0
10
20
30
40
50
60
70
80
Distance from center of main discharge tube (cm)
end of main coil

Fig.2

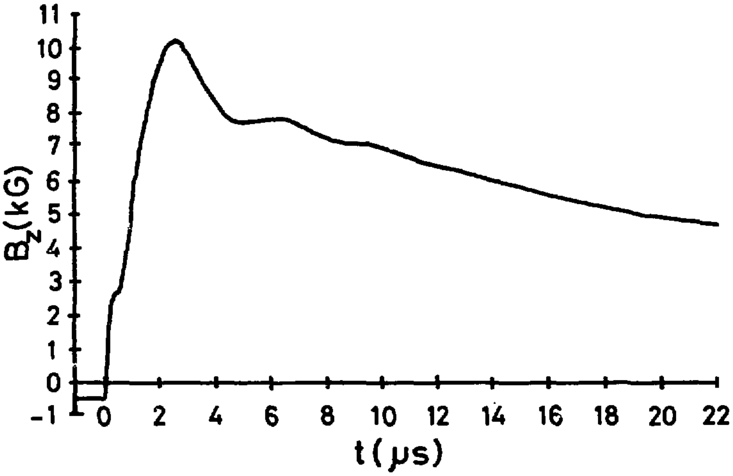


Fig.3

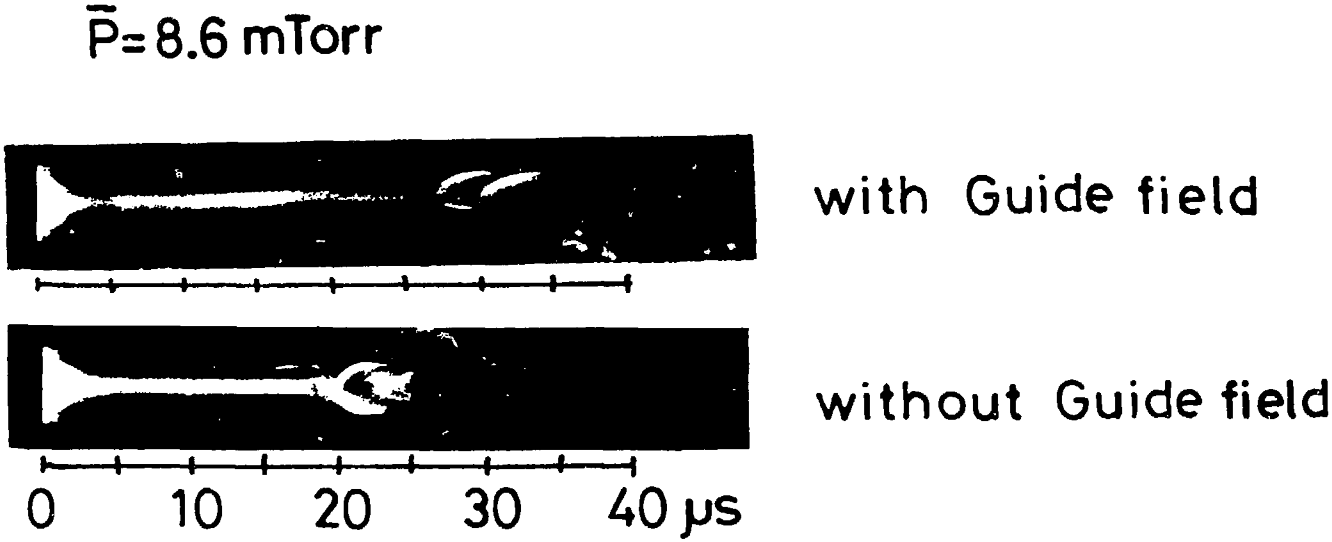

$\bar{P}$= 8.6 mTorr
with Guide field
without Guide field
0
10
20
30
40 μs

Fig.4

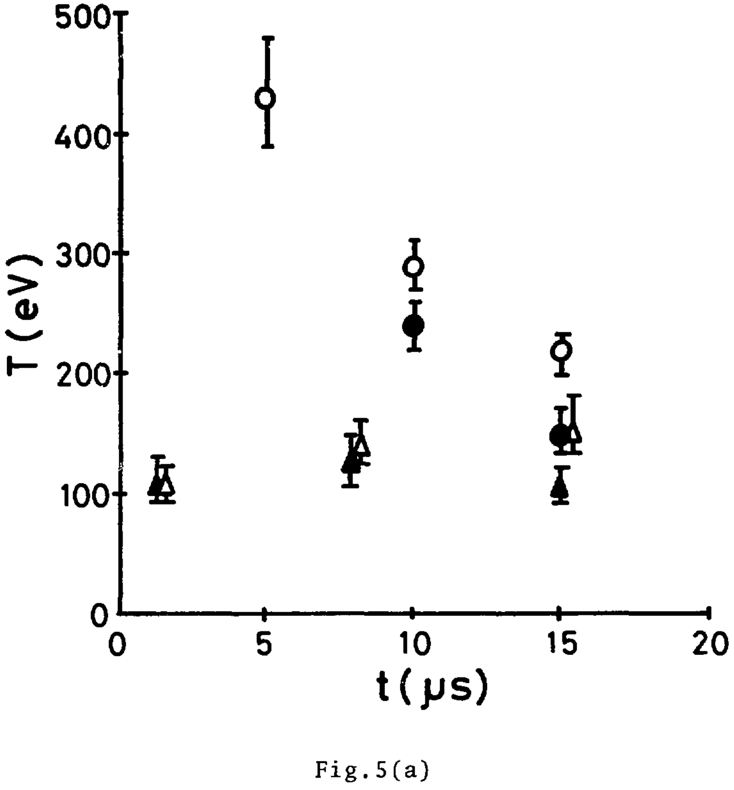
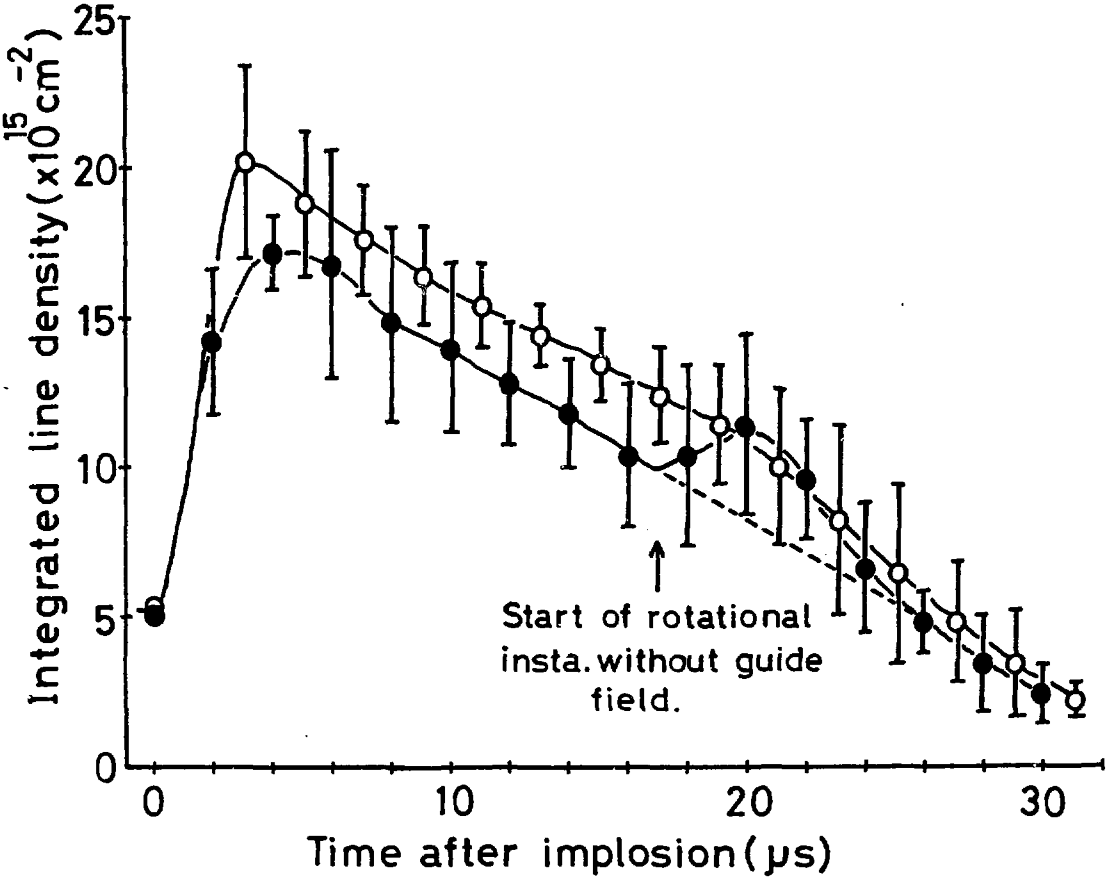


Fig.5(a)



Integrated line density ($\times 10^{15}$ cm^{-2})
0
5
10
15
20
25
Time after implosion (µs)
0
10
20
30
Start of rotational insta. without guide field.

Fig.5(b)

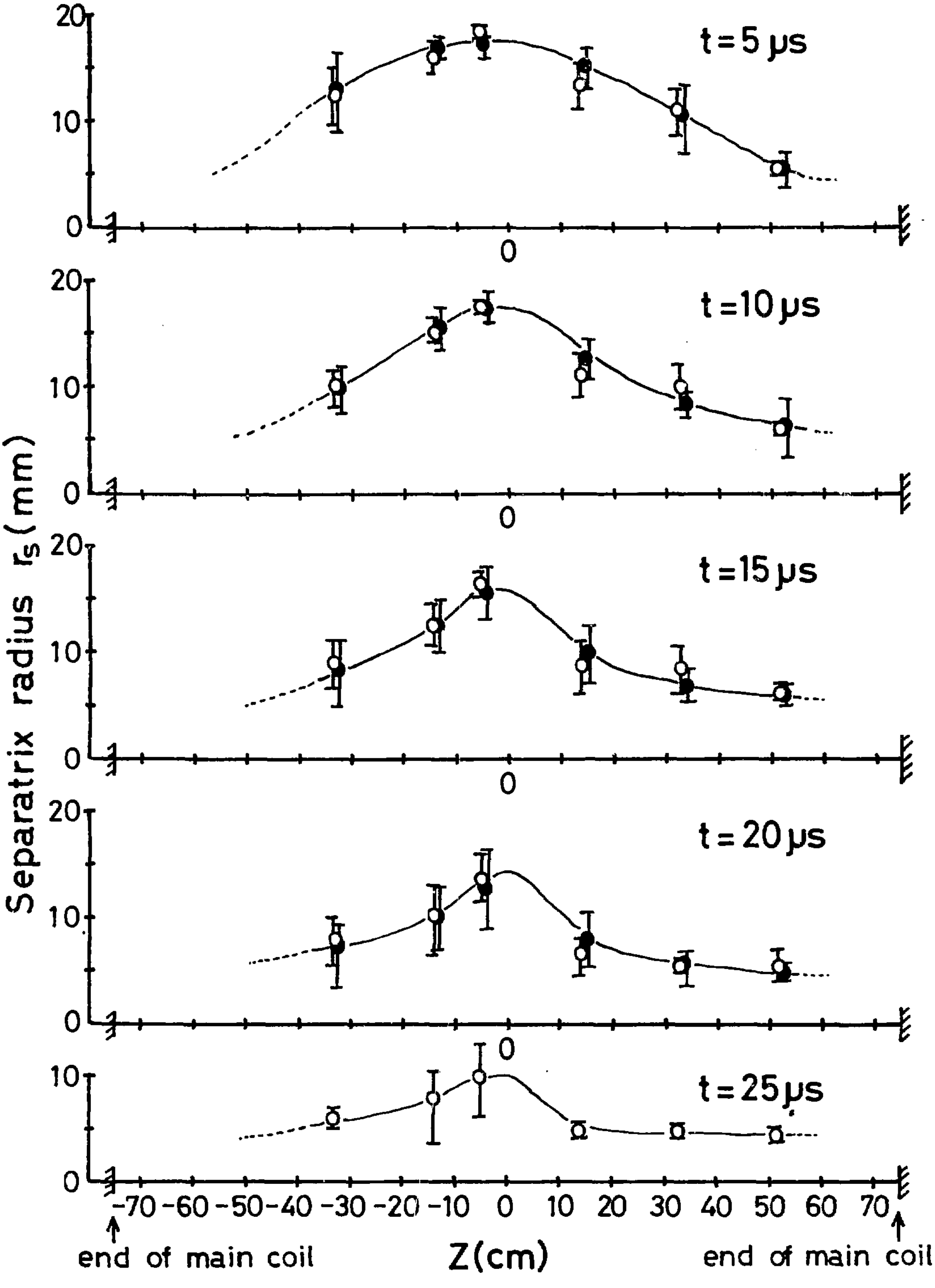
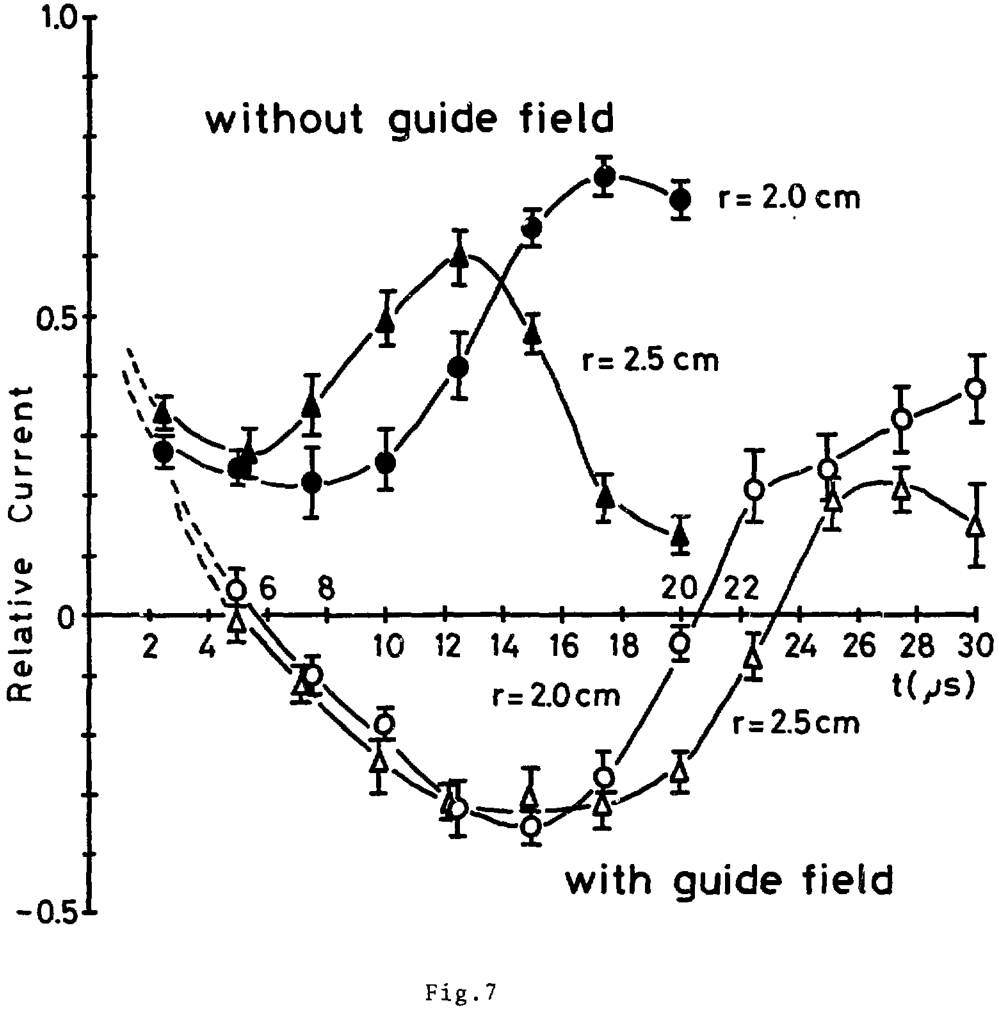

Separatrix radius r_s (mm)
t = 5 μs
t = 10 μs
t = 15 μs
t = 20 μs
t = 25 μs
20
10
0
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
Z(cm)
end of main coil
end of main coil

Fig.6



1.0
0.5
0
-0.5
Relative Current
without guide field
r = 2.0 cm
r = 2.5 cm
with guide field
r = 2.0 cm
r = 2.5 cm
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
t(μs)

Fig.7

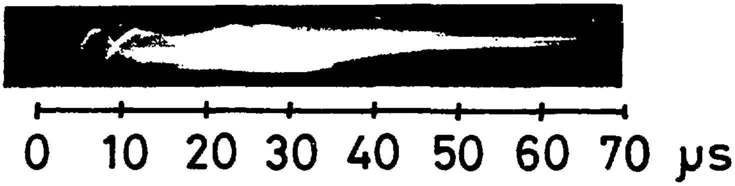


Fig.8