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SCHOOL OF PHYSICAL SCIENCES

OBSERVATION OF THE REVERSED CURRENT EFFECT

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ABSTRACT

This paper describes an observation of the reversed current effect, and its consequences, in a "stabilized" Z-pinch. Magnetic probe measurements and holographic interferometry were used to follow the development of a reversed current layer and to pinpoint its location in the outer region of the pinched plasma column. The subsequent ejection of the outer plasma layer was observed using fast photography.

1. INTRODUCTION

In 1959, Haines (1959) published a paper in which he theoretically investigated the current density distribution in circular cylindrical conductors of infinite length. He considered the situation where the total axial current, $I_z(t)$, was a specified, though quite general, function of time and showed that, in addition to the normal skin effect, an inverse skin effect (that is, the current density rises towards the centre of the conductor) and a reversed current effect could occur.

These two additional effects, which manifest themselves when $a/\delta \sim 1$ (a - radius of the conductor; δ - normal skin depth = $\sqrt{\frac{1}{\pi f \mu_0 \sigma}}$), are best described by reference to a particular example documented in Haines' paper. In this example, Haines considered the passage of a current pulse, $I_z(t)$, produced by an overdamped discharge of an LCR circuit, through a rigid, cylindrical conductor. His calculated radial distribution of current density, $j_z(r)$, at various times during the passage of the current are shown in Fig. 1 (reproduced from Fig. 2 in Haines, (1959)). At the start of the current pulse the current is confined to the surface of the conductor and one observes the normal skin effect. Later on, when the total current has started to decay, the current density is a maximum in the interior of the conductor (the inverse skin effect) and, finally, towards the end of the pulse, it is observed that the current reverses in the surface layer even though the total current remains positive (the reversed current effect). This latter effect is due to a back emf being induced near the surface of the conductor.

In his analysis, Haines showed that the gradient of the current density at the surface of the conductor is proportional to the rate of change of total current with time; specifically,

$$\left.\frac{\partial j_z}{\partial r}\right|_{r=a} = \left[\frac{\mu_o \sigma}{2\pi a}\right] \frac{dI_z}{dt}$$

Thus, an essential ingredient for observing the reversed current effect is that the total current must decrease with time.

In his paper, Haines drew attention to the fact that if the reversed current effect occurred in a pinched plasma column, the outside layer of the column would experience a force tending to accelerate it in an outward direction. He speculated that in these circumstances, there was a possibility that this outer shell of plasma would perhaps even separate from the main column and be ejected.

There have been a number of experimental observations which could be adduced to the reversed current effect. The occurrence of reversed current in pinched discharges has been reported on a number of occasions (see, for example, Andrianov et al 1958; Komelkov et al 1958). However, none of these papers have reported on a simultaneous detachment of the surface layer of the plasma. Bodin et al (1960) reported on discharge tube wall effects which they said could have been initiated by plasma jetting out from the central pinch. In the best study to date, Kvartskhava et al (1971) have emphasized the importance of the reversed current effect as a phenomenon which can occur over a wide range of circumstances and have presented photographic evidence for its presence in pinched discharges. Their photographs show the outer layer of a Z-pinched plasma column breaking away and moving towards the wall of the discharge vessel. The electromagnetic measurements which accompany the photographs are, however, not so convincing. A convincing experimental demonstration of Haines' conjecture should show the formation, after a period of decreasing total current, of a reversed current layer in the outer region of the pinched plasma column followed by a subsequent ejection of the outer plasma shell.

In this paper we report on a detailed examination of the reversed current effect in a "stabilized" Z-pinch. Firstly, by means of magnetic probe measurements having good spatial resolution we followed the formation of a reversed current layer and, using the holographic interferometry technique (see, for example, Jahoda and Siemon 1972), we established that it was located in the outer layer of the plasma column. Secondly, axially-directed streak and framing photography was used to observe the ejection of the outer plasma layer which resulted.

2. FORMATION AND LOCATION OF THE REVERSED CURRENT LAYER

The "stabilized" pinches were generated in an apparatus of conventional design. The discharge tube consisted of a 10.4 cm inside diameter pyrex tube fitted with 9.5 cm inside diameter, annular stainless steel electrodes at each end. This particular electrode geometry was chosen so that axially-directed photography and interferometry could be made through the end of the apparatus. The distance between the ends of the electrodes was 1.65 cm. Currents flowed through the discharge tube in a coaxial manner; the diameter of the return mesh was 12.6 cm. The discharge tube was located within a solenoid which could provide the required initial bias axial magnetic field.

The filling gas was preionized by means of a single half-sine wave current pulse which was generated by means of an LCR circuit having nonlinear resistive elements. The peak amplitude and duration of this current pulse were 13.6 kA and 11.6 μs, respectively. For the measurements reported in this paper, the main pinch discharge was initiated 100 μs after the end of the preionization current pulse. At that time, interferometry showed the percentage ionization to be about 2%.

The main discharge was powered by means of a conventional crowbarred capacitor discharge. The current waveform of the main discharge is shown in Fig. 2. A peak current of $\sim$ 37 kA was reached in a time of 1 μs following which there was a short period of decreasing current.

The measurements reported here were made on "stabilized" pinches generated in deuterium gas (35 mTorr filling pressure). The value of the initial bias axial magnetic field was 235 gauss. The observations we now describe were made possible by the very good shot-to-shot reproducibility of these discharges.

Measurements of $B_\theta(r,t)$ and $B_z(r,t)$ were made using a miniature magnetic probe. The time variation of each of these components was recorded at a number of radial positions across a diameter of the discharge tube, each position being separated by a distance of 2.5 mm. A sample of the B_θ oscillograms is shown in Fig. 2. One of the most noteworthy features of this set of measurements is the sudden increase in the B_θ signal which occurs in the $r : 2.0 \rightarrow 4.0$ cm range during the time interval $t : 1.6 \rightarrow 2.1$ μsec (the origin of time is taken to coincide with the start of the total discharge current, I_z, which is also shown in Fig. 2).

By cross-plotting it was possible to obtain the radial profiles of $B_\theta(r)$ at a number of times in the $t : 1.6 \rightarrow 2.1$ μsec interval. These are shown in Fig. 3, together with the radial profiles of (rB_θ) and j_z, this latter quantity being derived using the relationship:

$$j_z = \frac{1}{\mu_o r} \frac{\partial}{\partial r} (rB_\theta) \quad .$$

The graphs of Fig. 3 show quite clearly the formation, and subsequent disappearance, of a reversed current layer. At t = 1.8 μsec, for example, the value of the reverse current is 5.5 kA and the value of the forward current is 37.4 kA, giving a nett forward total current of 31.9 kA.

By correlating these current profiles with the total current waveform shown in Fig. 2, we note that the reversed current layer is formed after a short period of decreasing total current.

In order to locate the position of the reversed current layer in the pinched plasma column, a holographic interferogram taken at t = 1.8 μsec, and shown in Fig. 4, was analysed. The resulting radial profile of electron number density, $n_e(r)$ is shown in Fig. 5 together with the t = 1.8 μsec $j_z(r)$ distribution. We see that the reversed current is indeed located within the outermost layer of the plasma and is carried by about 10% of the total electron line density.

For future reference we include in Fig. 5 a plot of the radial profile of $B_z(r)$ at t = 1.8 μsec. We note that the outer layer of the plasma column contains axial magnetic flux.

3. EJECTION OF THE OUTER PLASMA LAYER

The evidence for the ejection of the outer layer of plasma is mainly furnished by axially-directed streak and framing photography (Fig. 6).

The streak photograph shows that starting at approximately 1.7 μsec, the plasma column divides into two coaxial layers, with the outer layer expanding towards the wall of the discharge vessel with a velocity of about 2×10^6 cm/sec. Framing photographs taken at t = 1.7, 1.8 and 1.95 μsec (Fig. 6) confirm that the two coaxial layers are azimuthally symmetric in appearance. In passing we note that a photographic observation of this phenomenon depends heavily on a suitable choice of camera aperture size. We did not search for the optimum aperture size in the present study.

Examination of the streak photograph shows that after a slight expansion, the inner layer is re-compressed. We identify the outer luminous layer with the outer plasma sheath expanding radially under the influence of an outwardly directed $\vec{j} \times \vec{B}$ body force. The time at which the reversed current layer is formed and at which we observe the ejection of the plasma sheath are well correlated.

Some additional, confirmatory evidence for the ejection of the plasma layer came from probe measurements of the B_z component of the magnetic field. As seen from Fig. 5, the outer layer of the plasma column contained axial magnetic flux. The ejected plasma sheath carried this flux with it and its passage past the magnetic probe was clearly seen as a momentary perturbation on the B_z signals.

4. DISCUSSION

In this paper we have described what we believe to be an unambiguous observation of the reversed current effect and its consequences. The formation of the reversed current layer has been documented and its location in the outer plasma layer of the pinch has been pinpointed. The subsequent ejection of the plasma sheath has been observed using fast photography.

A reversed current layer arises in a pinched discharge whenever there is a sufficiently rapid decrease in total pinch current. Negative dI_z/dt values can arise from a number of causes:

(i) The external circuitry may impose a negative value of dI_z/dt, for example, during the second quarter cycle of a capacitor discharge.

(i) During the pinching process, the load inductance increases. If the generator of the axial current is not a constant current source, then the pinch current decreases as a result of this increase in inductance. This is the mechanism which was operable in the present study.

(iii) If, after a pinched plasma column is formed, a new conducting path is formed at the discharge tube wall (the secondary wall-breakdown effect), then the central pinched plasma is decoupled from the external circuit and the total current through it decreases. We note that this is a bootstrap process inasmuch as the formation of the pinch in the first instance can give rise to an ejected sheath of plasma which, in turn, can initiate a secondary wall breakdown.

The above examples should be enough to convince one that the occurrence of the reversed current effect, and its consequences, is perhaps more prevalent in pinch discharge physics than hitherto supposed.

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FIGURE CAPTIONS

Fig. 1. Radial distributions of current density, $j_z(r)$, in a cylindrical conductor of radius 1, at various times during the total current pulse, $I_z(t)$. (Reproduced from Fig. 2, Haines, 1959.)

Fig. 2. Oscillograms of $B_\theta(r,t)$.

Fig. 3. Radial distributions of B_θ, rB_θ and j_z at t = 1.6, 1.7, 1.8, 2.0 and 2.1 μs.

Fig. 4. Holographic interferogram of "stabilized" pinch taken at t = 1.8 μs.

Fig. 5. Radial distributions of j_z, n_e and B_z at t = 1.8 μs.

Fig. 6. Axially-directed streak and framing photographs of the "stabilized" pinch.

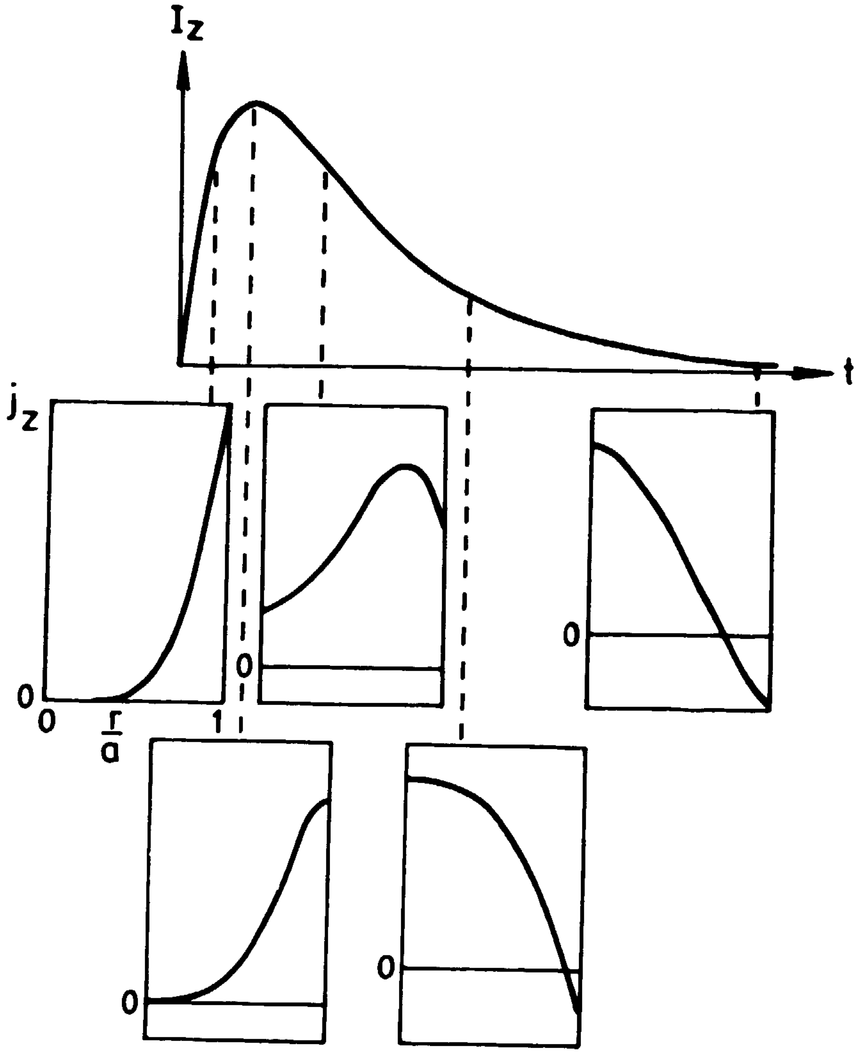
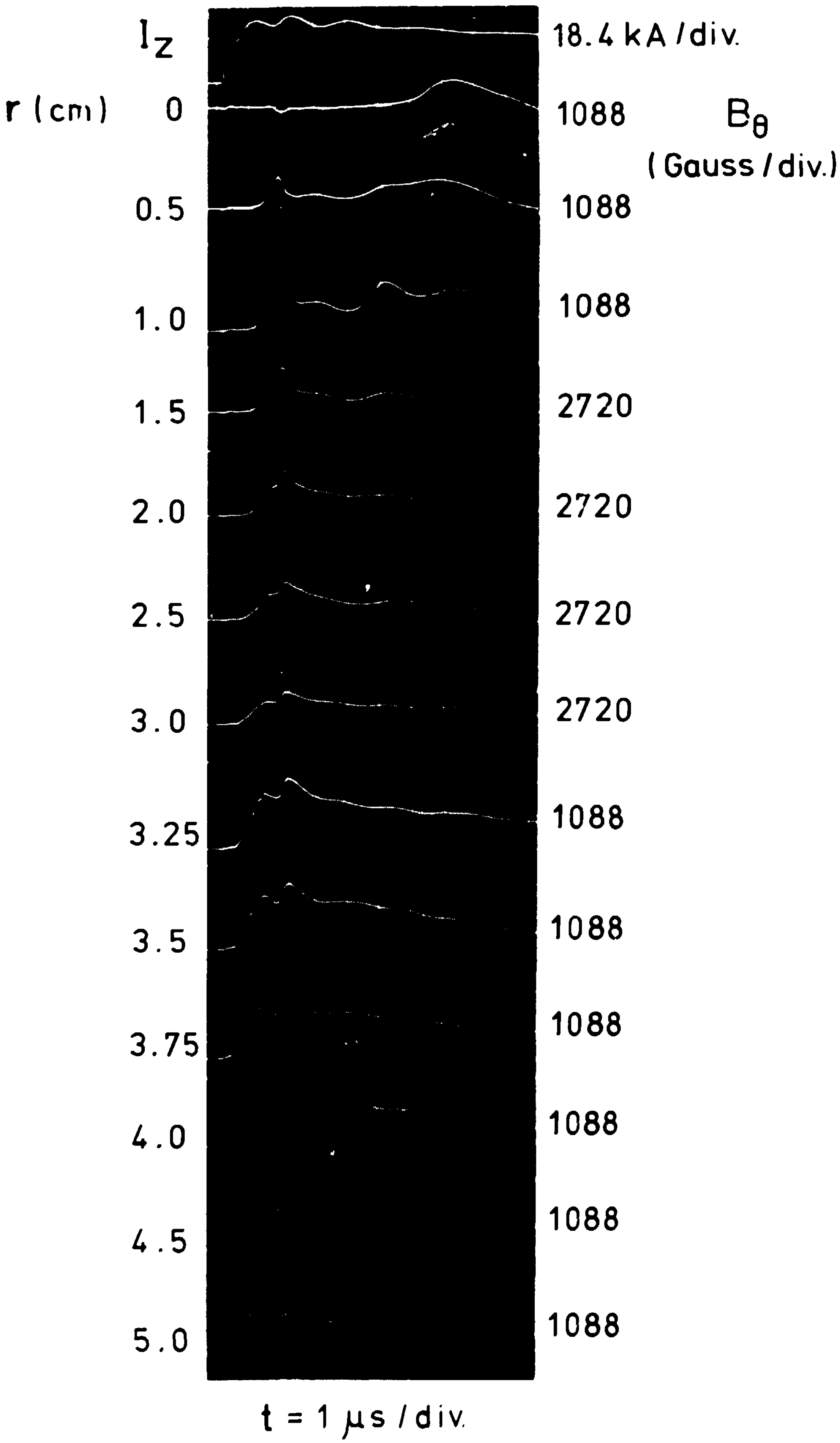
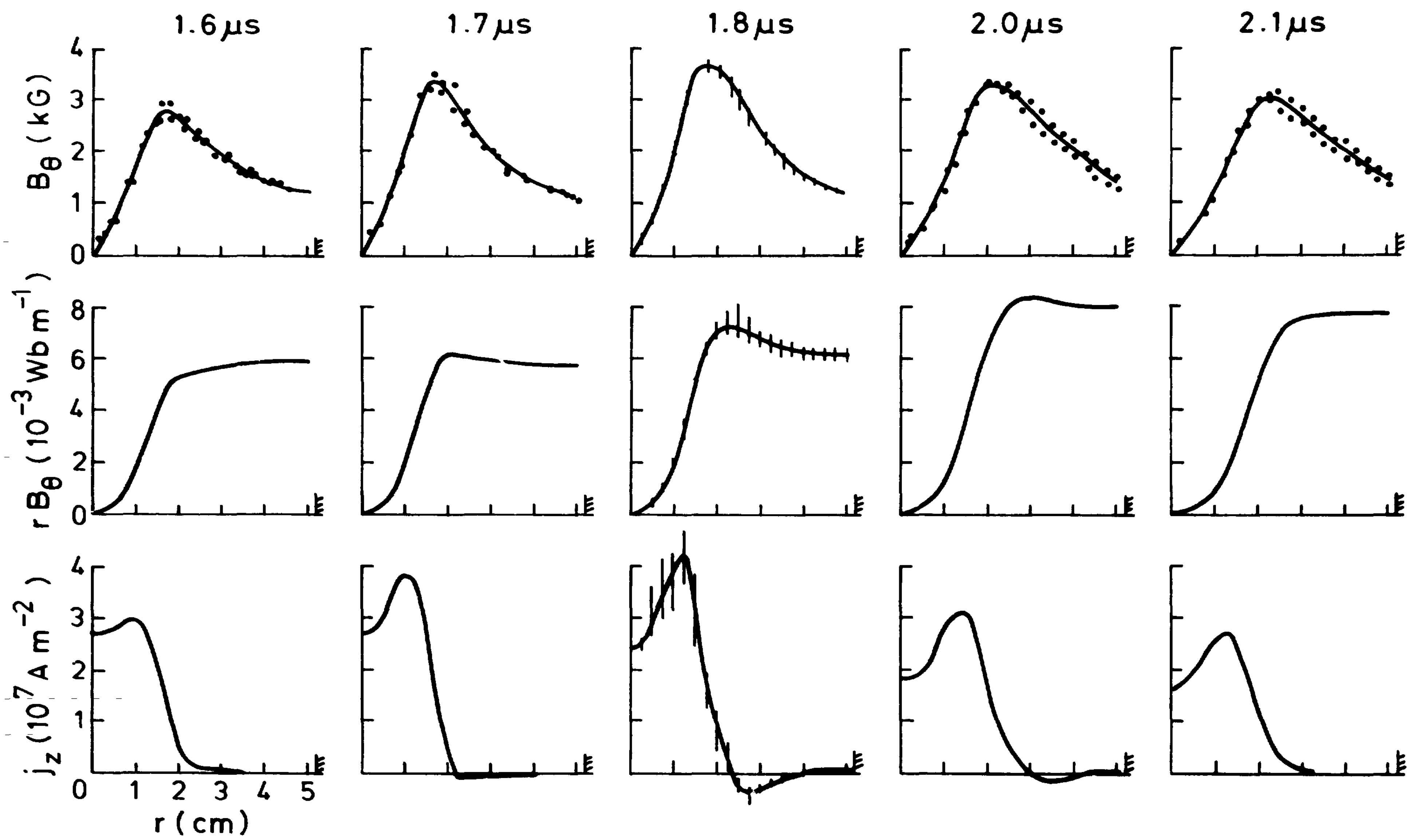


FIG. 1.



I_z
18.4 kA / div.
r (cm)
0
1088
B_θ
(Gauss / div.)
0.5
1088
1.0
1088
1.5
2720
2.0
2720
2.5
2720
3.0
2720
3.25
1088
3.5
1088
3.75
1088
4.0
1088
4.5
1088
5.0
1088
t = 1 μs / div.

FIG. 2.



1.6μs
1.7μs
1.8μs
2.0μs
2.1μs
B$_\theta$ (kG)
r B$_\theta$ (10^{-3} Wb m^{-1})
j$_z$ (10^7 A m^{-2})
r (cm)

FIG. 3.

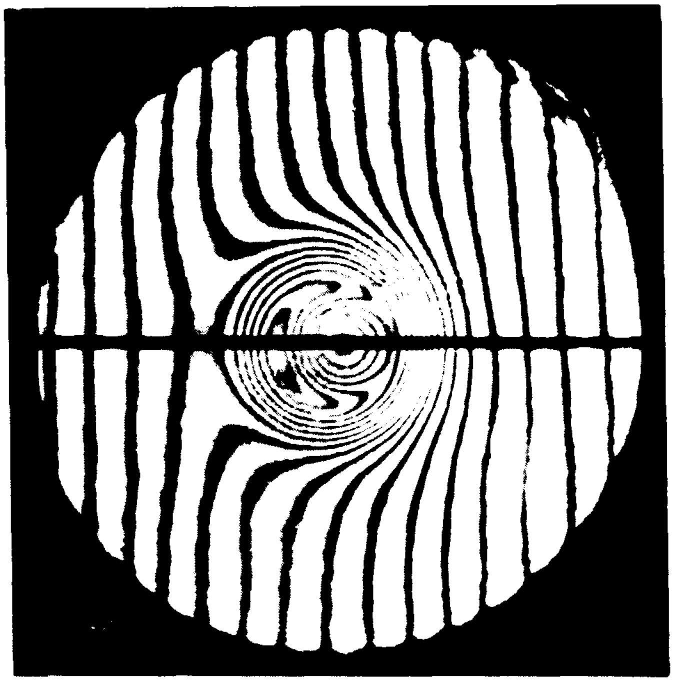
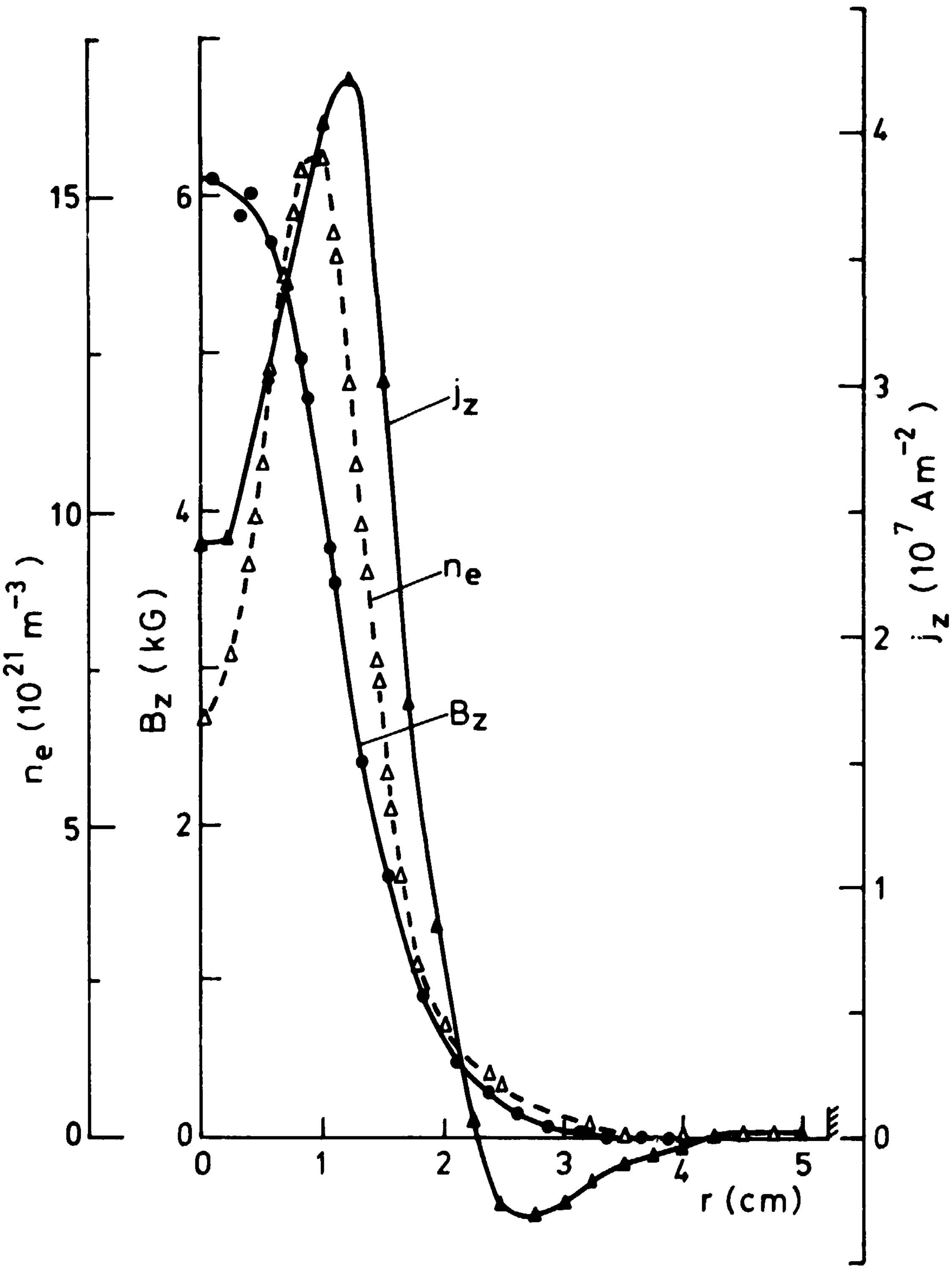


FIG. 4.



15
10
5
0
n_e (10^{21} m^{-3})
6
4
2
0
B_z (kG)
4
3
2
1
0
j_z (10^7 Am^{-2})
j_z
n_e
B_z
0
1
2
3
4
5
r (cm)

FIG. 5.

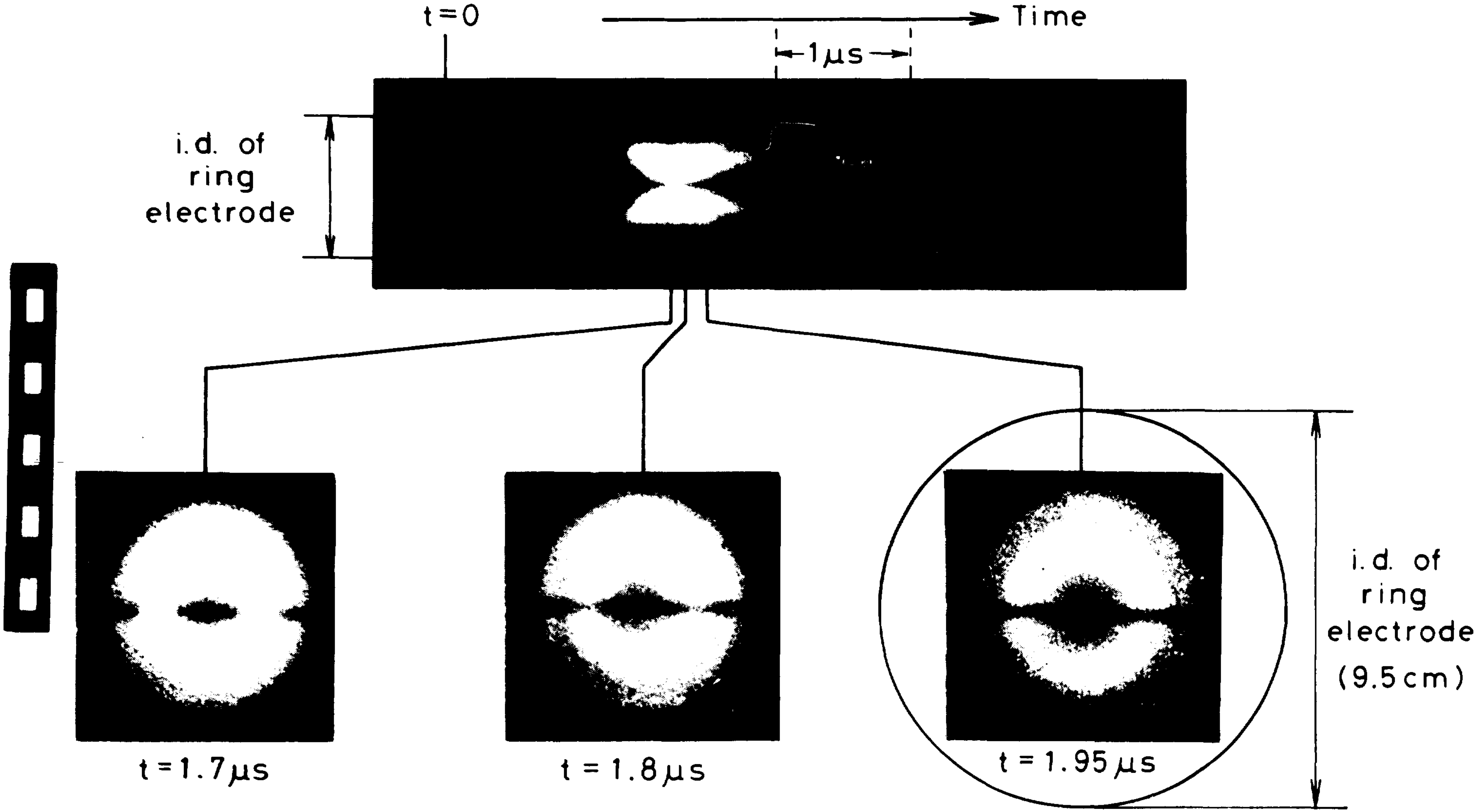

t=0
Time
1μs
i.d. of ring electrode
t=1.7μs
t = 1.8μs
t = 1.95μs
i.d. of ring electrode (9.5cm)

FIG. 6.