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PLASMA PHYSICS

TOKAMAK STARTUP WITH ELECTRON CYCLOTRON HEATING

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ABSTRACT

Experiments are described in which the startup voltage in a tokamak is reduced by ~ 60% by the use of a modest amount of electron cyclotron resonance heating power for preionization. A 50% reduction in volt-second requirement and impurity reflux are also observed.

One important technological difficulty with a tokamak fusion reactor is the high toroidal voltage required to initiate the discharge when the temperature (and hence conductivity) is low and energy losses are dominated by line radiation from low-Z, partially-stripped impurities.[1] One possible means for reducing the loop voltage is the use of electron cyclotron resonance heating (ECRH) to produce a plasma of modest conductivity prior to the onset of ohmic heating.[2] ECRH has the added advantage of initializing the discharge in a local region away from the walls so that one might expect reduced impurity reflux from the walls during the early stages of the discharge when the plasma is poorly confined.

ECRH has been used previously for plasma production in a purely toroidal field,[3] and for bulk heating in tokamaks.[4] We report here the first systematic study of the magnitude of the loop voltage reduction that can be achieved in a tokamak by such a technique. Similar studies are underway in the ISX tokamak at Oak Ridge.[5]

The experiments were performed on the Tokapole II device,[6] a tokamak with a four-node poloidal divertor (Fig. 1). The device was operated at toroidal fields of ~ 3 to 6 kG on axis so that readily available microwave sources at 9 and 16 GHz with nominal output powers of ~ 10 kW for ~ 1 msec could be used. The ECRH preionization is applied prior to the ohmic heating voltage (Fig. 2) when the magnetic field is purely toroidal; thus the ECRH resonance zone is a vertical cylinder with radius adjustable via the toroidal field strength. The wave is launched vertically from a waveguide located at the midcylinder so as to insure propagation of the extraordinary wave when the cyclotron resonance zone is on the large major radius side of the midcylinder. A previous report described ion saturation current measurements and visible light measurements made on this ECRH plasma alone with no ohmic heating ($n \sim 10^{10}$ cm^{-3}, $kT_e \sim 10$ eV) showing that the plasma density profile is strongly peaked at the electron cyclotron resonance position, but extends to the outer wall consistent with the fact that no equilibrium exists with a purely toroidal field. Electric field measurements show a vertical electric field which gives rise to an outward $\vec{E}\times\vec{B}$ drift, consistent with the observed outward motion of the plasma. An x-ray detector consisting of a thin aluminum-coated plastic scintillator with photomultiplier located on the midcylinder shows a dramatic increase in x-rays when the cyclotron resonance lies exactly on the midcylinder.

The effect of primary interest is the reduction in the startup toroidal loop voltage. ECRH is observed to reduce the voltage at the machine center by ~ 60% (20 volts to 8 volts) as shown in Figure 2. The reduction lasts for about 300 μsec with negligible effect on plasma parameters after ~ 1 msec. Measurement of the spatial profile of the loop voltage using a probe (described in reference 6) indicates that the voltage reduction decreases gradually with radius, and monotonically goes to zero at the wall (Fig. 3). The ECRH does not change voltage at the wall (the gap voltage) simply because it is fixed by the external circuitry. The gap voltage decays sinusoidally in time; thus the same gap voltage is applied with and without ECRH in order to obtain the same plasma parameters late in time in both cases.

The relevant location at which to evaluate voltage reduction is where the plasma current flows. Spatial profiles of plasma current measured with a small Rogowski coil (2 cm diameter) show that for the first 200 μsec the plasma has a very broad peak at the minor axis (Fig. 4). Measurements made with a 1/4 inch paddle probe[6] are almost identical. Thus the startup loop voltage has, on the average, been reduced by roughly a factor of two at the location of the plasma. This is indeed equivalent to a gap voltage reduction in a typical tokamak that starts up with a fast gap voltage spike.

At about 300 μsec after the ohmic heating is applied, the current profile develops a distinct peak roughly midway between the minor axis and the wall. This is most likely caused by the inhomogneity of the applied electric field which rises monotomically from the center to the wall. By about 1.5 msec the central current channel has fully evolved, and the plasma current has a maximum on the central magnetic axis. This behavior is virtually identical with and without ECRH preionization, except for earlier startup with preionization.

As the ECRH power is only a small fraction of the ohmic input (which is ~ 100 kW at startup) the loop voltage decrease is <u>not</u> due to trading ohmic power for ECRH. Furthermore, the loop voltage reduction is not a sensitive function of the ECRH power level (in the range ~ 1-10 kW). It is most likely a more subtle (and less costly) effect due to the creation of a higher conductivity, more localized, startup plasma. The current is allowed to rise more rapidly (see Figure 2) and at a lower voltage. In addition, the impurity radiation is reduced by as much as 50% for the first millisecond,[7] perhaps due to the more localized startup, and the total volt-seconds consumed up to the time of peak plasma current (~ 1000 μsec) is reduced by 50%.

In another series of experiments, a comparable amount of second harmonic ICRH power was applied during startup. In that case, there was no initial loop voltage reduction, but the ohmic discharge was observed to start somewhat earlier.

In conclusion it has been shown that a modest amount of ECRH power applied just before the onset of ohmic heating in a tokamak can significantly reduce the required loop voltage, volt-second consumption, and impurity radiation.

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REFERENCES

1. R.J. Hawryluk and J.A. Schmidt, Nuclear Fusion 16, 775 (1976).

2. Y-K.M. Peng, S.K. Borowski, and T. Kammash, Nuclear Fusion 18, 1489 (1978).

3. A.J. Anisimov, N.I. Vinogradov, and P.B. Poloski, Sov. Phys.-Tech. Phys. 18, 459 (1973); 20, 626 (1975) 20, 629 (1975).

4. V.V. Alikaev et al., Fiz. Plasmy, 390 (2976) [Sov. J. Plasma Phys. 2, 212 (1976)].

5. R.M. Gilgenbach et al., Phys. Rev. Letters 44, 647 (1980).

6. D.E. Lencioni, University of Wisconsin Ph D Thesis (Physics), (1969).

7. A.P. Biddle, R.N. Dexter, R.J. Groebner, D.J. Holly, B. Lipschultz, M.W. Phillips, S.C. Prager, and J.C. Sprott, Nucl. Fusion 9, 1509 (1979).

FIGURE CAPTIONS

Fig. 1 Poloidal magnetic flux plot as calculated by an MHD equilibrium code. The four current-carrying internal rings provide the divertor field. The flux plot has been experimentally verified through internal magnetic probe measurements.

Fig. 2 Loop voltage on minor axis, current and electron density versus time during startup with and without ECRH preionization.

Fig. 3. Percentage by which loop voltage is reduced by ECRH versus position. Resonance held fixed at 4 cm from axis. Data taken at 200 μsec.

Fig. 4 Spatial profiles of plasma current density during tokamak startup, taken with a small Rogowski coil.

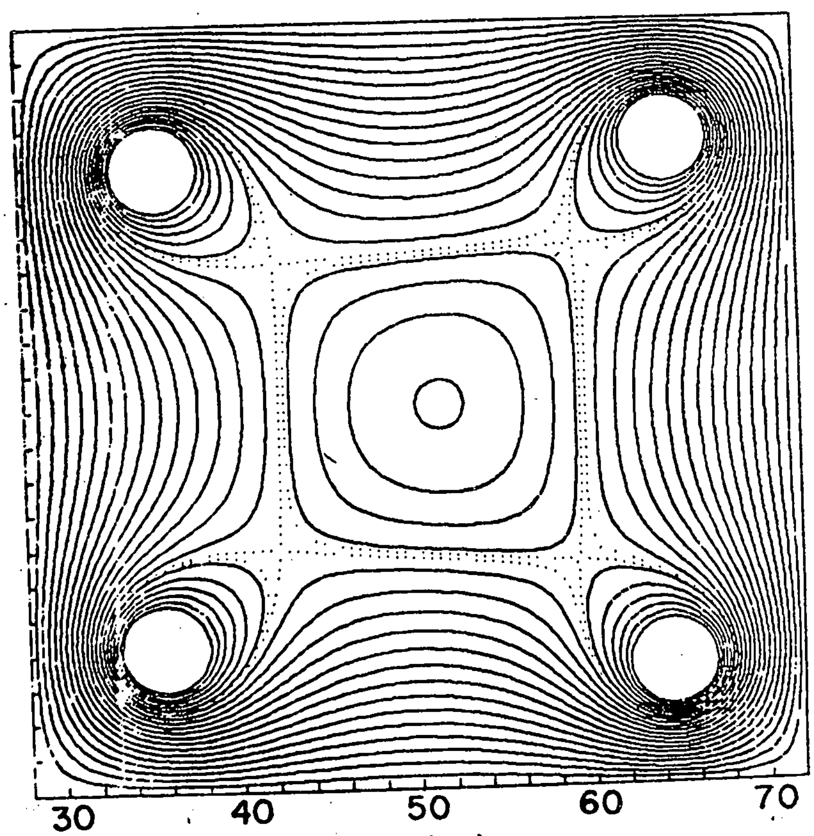
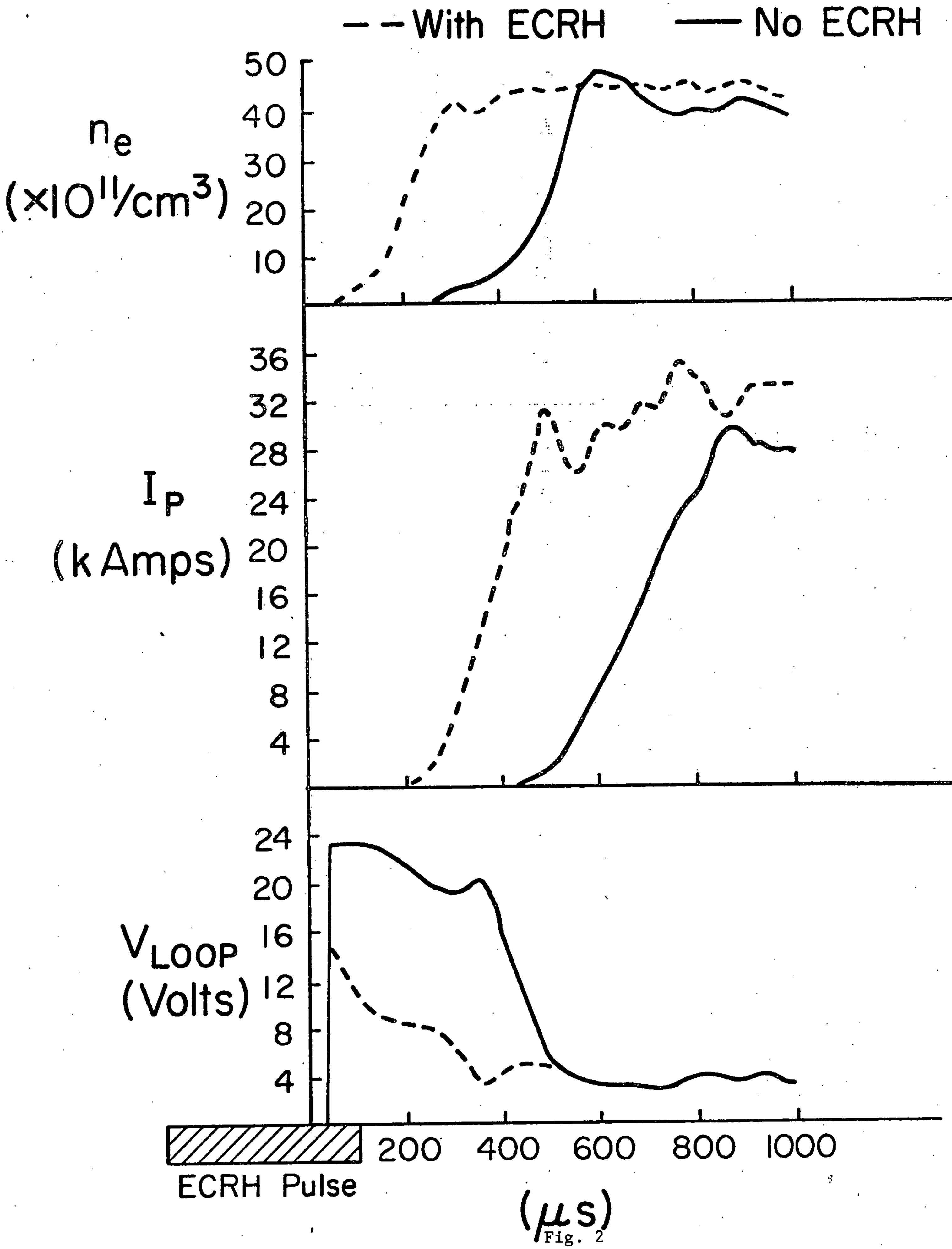


Fig. 1



- - With ECRH
— No ECRH
n_e ($\times 10^{11}$/cm^3)
50
40
30
20
10
I_P (k Amps)
36
32
28
24
20
16
12
8
4
V_{LOOP} (Volts)
24
20
16
12
8
4
ECRH Pulse
200
400
600
800
1000
(μs)

Fig. 2

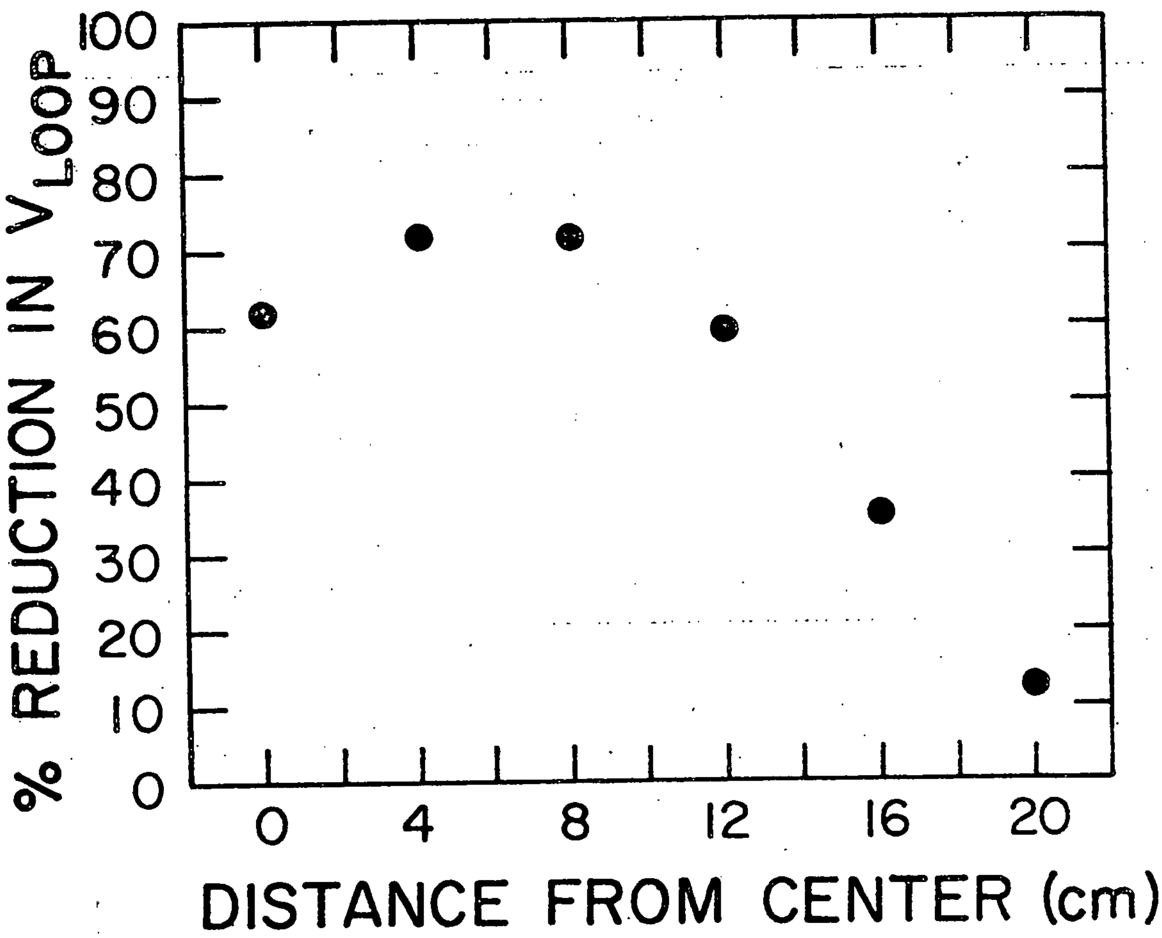

% REDUCTION IN V_{LOOP}
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
DISTANCE FROM CENTER (cm)

Fig. 3

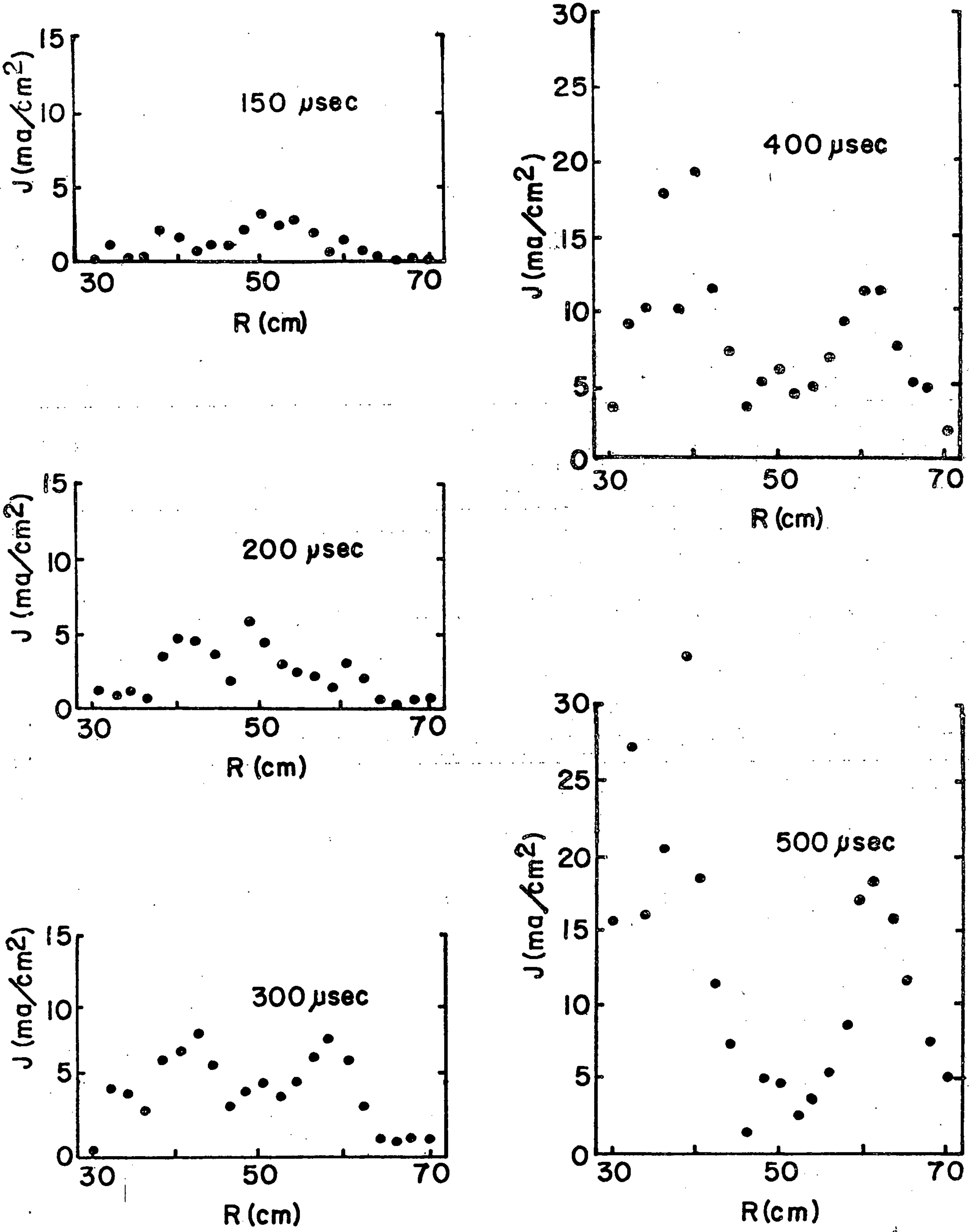

150 μsec
200 μsec
300 μsec
400 μsec
500 μsec
J (ma/cm2)
R (cm)
0
5
10
15
20
25
30
50
70

Fig. 4

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