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Minima in the rate of growth of current accompanied by oscillations are observed in the l=2 ohmically heated WIIb stellarator. By varying the rotational transform of the vacuum field it can be shown that these are related to rational transform near the plasma boundary.

The WIIb stellarator is similar in size and construction to the WIIa stellarator used to study the confinement of barium plasma[1,2]. The major radius is 0.50 m, the vessel internal radius 90 mm, the main magnetic field up to 15kG pulsed, and the lefthanded l=2 helical winding has five field periods, giving a rotational transform, $\iota_0 \leqslant 0.6$ on the axis with very little shear. The vacuum vessel has an insulating gap to allow for ohmic heating. An adjustable limiter consisting of two semicircular tantalum annuli , electrically insulated from the vacuum vessel, is positioned near the gap.

Fig. 1 shows the disposition of the air-cored transformers for ohmic heating. These are of toroidal shape to minimise stray flux. The coupling to the plasma circuit is very weak so that the primary is effectively decoupled from the plasma, and we apply a given voltage to the plasma in contrast to the usual arrangement. The two smaller transformers are intended for preheating, and the larger transformer for quasistationary operation.

In the present experiments only the preheating transformers are used. They are energised from a 30 kJ capacitor bank via ignitrons to give a quarter cosinusoid loop voltage with a peak value of 30V and a duration of 360μs. At this time the bank is crowbarred and the residual loop voltage is initially -5V, slowly decaying. The main magnetic field is adjusted to 4.2kG and the limiter diameter to 130 mm.

Various methods of preionisation were tried, including r.f. applied to ring-shaped electrodes within the vacuum vessel, a hot filament biased to -200V and a plasma gun of the type used on the Proto-Cleo experiment[3], fired both into a vacuum ($p = 10^{-6}$ torr) and into hydrogen gas ($p = 5 \times 10^{-5}$ torr). The highest plasma current and plasma temperature are obtained using the plasma gun fired into a vacuum. The ohmic heating pulse is applied 50μs after the gun injection process, which lasts for 100μs. This timing is found to give maximum induced current. The densities reached are higher than would be expected from the gun alone according to previous experience. It is thought that during the pulse gas is evolved from the walls of the vacuum vessel, which are not yet clean, and ionised within the plasma column.

Diagnostics presently employed are: gap voltage measurement, plasma current measurement by a Rogowski coil inside the vacuum vessel, optical spectroscopy, ruby laser light scattered at 90° for density and temperature, multichannel μ-wave interferometry for density versus time, and detection of X-rays from part of the limiter.

Fig.2 shows the gap voltage, the plasma current I, the X-ray intensity and the integrated electron density along two beams of the 4mm μ-wave interferometer for t_0=0.27. The electron density at the center of the discharge, n, increases to a maximum of 10^{13} cm^{-3} between 80μs and 300μs after current maximum. The electron temperature T_e, measured by the laser diagnostic at current maximum is approximately 10 to 20 eV and the density agrees with $\int ndl$ from the μ-wave interferometer assuming a plasma profile rather flatter than parabolic. Bursts of X-rays are generated at the limiter during current decay, accompanied by small steps in current of 100A. This suggests that a substantial fraction of the plasma current is carried by runaways. The rather low initial value of dI/dt also suggests that the inertial effect of a small number of high energy current carriers is present. If dL/dt=0 at current maximum we can use the gap voltage to calculate the plasma resistance and hence a conductivity temperature. Fig. 3 shows the temperature thus calculated, assuming the ions are singly ionised, for both flat and parabolic current distributions (extreme points on lines) against T_e measured by the scattering of laser light. In general T_e(conductivity) > T_e(laser) which again suggests the presence of a substantial runaway current, especially when T_e is low. In general the reproducibility of the voltage and current is within 5%, while that of the laser-measured n and T_e is poor, 50% from shot to shot. This result probably reflects the variable amount of energy absorbed by the plasma and the runaway electrons respectively, depending on both the initial conditions and the amount of gas evolved from the vacuum wall during the discharge.

The variation in the peak current, I_{max}, with the initial value of the rotational transform on the magnetic axis ŧ_o, is shown in Fig.4. Three regions can be distinguished. At $\text{ŧ}_o=0.0$ I_{max} is nearly zero, i.e. we do not obtain a tokamak-type discharge. This may be related to inaccuracies in the main field or to the poor confinement of the gun-injected plasma. The 2cm thickness of the stainless-steel vacuum vessel should be adequate to allow tokamak equilibrium on our time scale. However an initial $ŧ_0=0.02$ is already sufficient to provide nearly maximum peak current, where the rotational transform produced by the current is 0.2 at the plasma boundary. For $0.05< ŧ_0 <0.25$ I_{max} is nearly constant, and appears to be limited principally by the plasma inductance and the available flux, 0.007Vs, from the preheat transformer. However, as $ŧ_0$ is increased from 0.25 to 0.5, I_{max} decreases linearly towards zero. If we interpret this result as an effect of rational total transform, $ŧ_0+ŧ_j=0.5$, where $ŧ_j$ is the transform due to the plasma current (in the same direction as that of the helical windings in our experiment), then the current produces a transform of 0.1 I, where I is in kA. This corresponds with the transform produced at a radius of 5 cm, that is near the outer boundary of the plasma column , or at any radius within a uniform current distribution with a mean radius of 5cm.

The cause of the limitation of the plasma current can be seen by looking at the dI/dt signal from the Rogowski coil. At $ŧ_0=0.5$, dI/dt has a low mean value accompanied by violent oscillations. Typically these disappear as the driving voltage falls, and the dI/dt trace becomes clean: then I rises slightly to its maximum value. The mean value of dI/dt increases as ŧ_0 is reduced allowing I to rise to the values given in Fig.4. As ŧ_0 is further reduced several regions of instability in the dI/dt signal can be seen separated by more or less stable regions. An example is shown in Fig.5 for $\text{ŧ}_0=0.21$. The regions of instability are quite well defined and are marked by arrows in the figure. Oscillation frequencies in the unstable regions are typically 200kHz, about 5 to 10x the electron diamagnetic drift frequency. Notice that the dI/dt trace becomes much cleaner after current maximum (dI/dt = 0). Minima in dI/dt are also observed after this time. These are not associated with rapid oscillations of the dI/dt signal but with X-rays from the limiter , which are not observed during periods of instability.

In Fig.6 the values of the current at which well-defined instabilities occur like those shown in Fig.5 , are plotted as a function of ŧ_0. The straight lines drawn in Fig.6 correspond to values of $\text{ŧ}_h+\text{ŧ}_j=1/2,\ 1/3,\ 1/4$, where ŧ_h is the transform of the helical field at the limiter ($\text{ŧ}_h=1.12\times\text{ŧ}_0$) and ŧ_j is the transform produced by the plasma current at a mean radius of 5.0cm. There are no fitted parameters. The observed instabilities seem to be convincingly related to these lines. They could only be consistent with rational transform at other radii if the current distribution were nearly uniform; but bell-shaped current distributions should give lines with a different slope when the rational surfaces occur appreciably inside the plasma boundary.

We conclude that instabilities of the plasma current have been observed when the transform near the plasma boundary is rational, whose strength decreases with increasing mode number. The $\iota\!\!\!-=1/2$ instability is sufficiently strong to limit the current attainable. The instabilities do not seem to depend strongly on other plasma parameters such as n and T_e which can vary 50% from shot to shot. Similar phenomena observed in the early B and C stellarator work[4] and in present tokamaks[5] are usually attributed to MHD instabilities; the variation of instability strength with $\iota\!\!\!-$ in WIIb is also reminiscent of these experiments. However the minima in confinement time observed in the similarly constructed WIIa stellarator in experiments with Ba plasma may equally provide an explanation for our results. These are also found to be associated with rational transform at the plasma boundary, and their strength decreases with decreasing $\iota\!\!\!-$.

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FIG.1. The disposition of the ohmic heating transformers in WIIb.

FIG.2. Typical oscillograms of measured parameters during a preheating pulse.

FIG.3. Comparison of conductivity temperature with that measured by the laser diagnostic.

FIG.4. Variation of maximum plasma current with the rotational transform of the vacuum field.

FIG.5. Oscillograms showing instabilities in the plasma current, marked by arrows.

FIG.6. The plasma currents at which instabilities occur as a function of the rotational transform of the vacuum field. The straight lines are calculated as described in the text. For $\iota\!\!\!-_0$ from 0.35 to 0.5 the instability is strongest and occurs from zero to nearly maximum current. There is always some noise on the current trace at low current (see Fig.5), partly caused by interference from the plasma gun and the ignitron switch of the preheat transformer. At $\iota\!\!\!-_0$=0.14 we still see regions of instability but these are very weak and difficult to analyse in detail. They have not all been included in the figure.

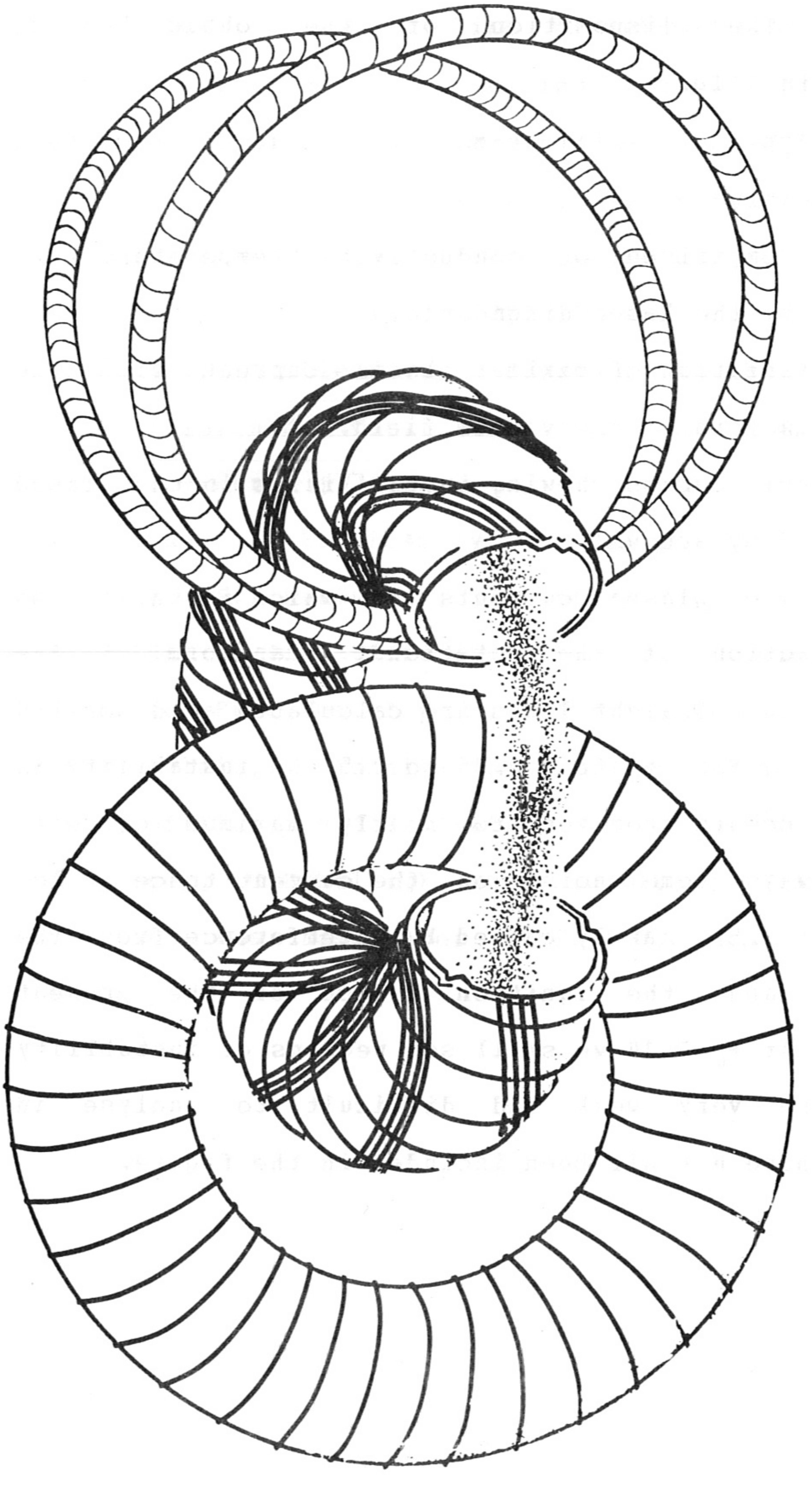

Fig.1

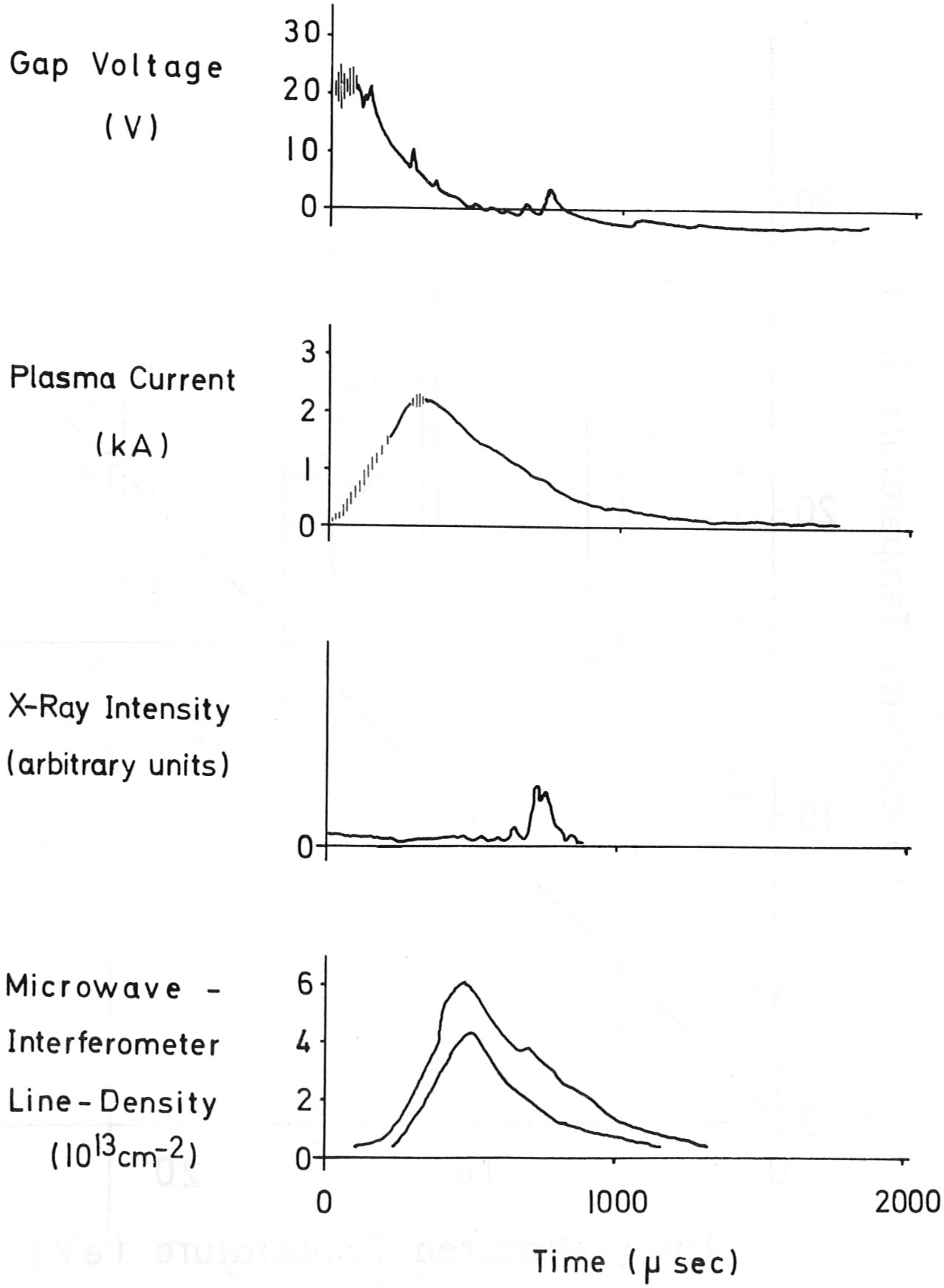
Gap Voltage
(V)
30
20
10
0
Plasma Current
(kA)
3
2
1
0
X-Ray Intensity
(arbitrary units)
0
Microwave -
Interferometer
Line-Density
($10^{13}cm^{-2}$)
6
4
2
0
0
1000
2000
Time (μ sec)

Fig. 2

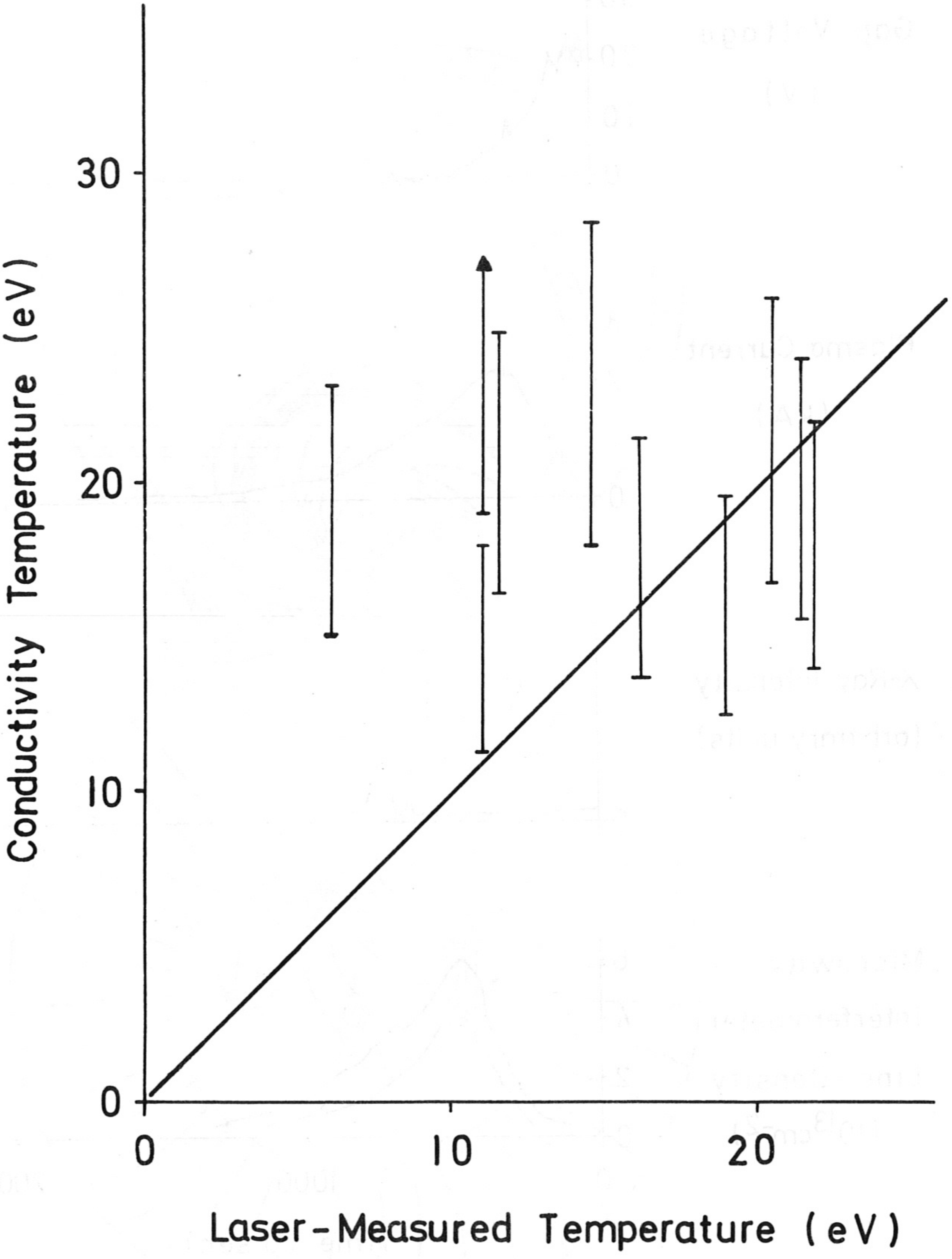
Conductivity Temperature (eV)
30
20
10
0
0
10
20
Laser-Measured Temperature (eV)

Fig. 3

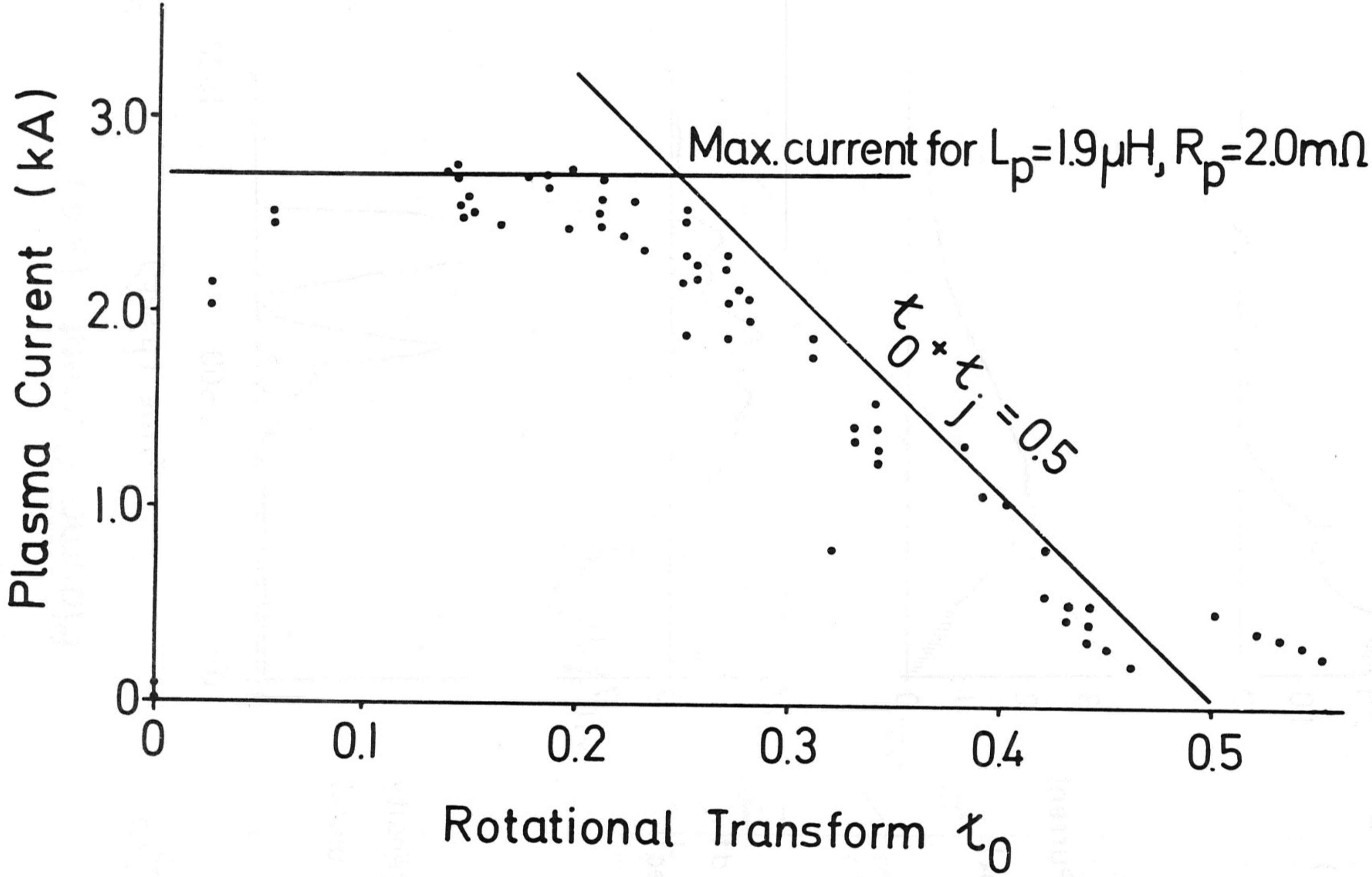
Plasma Current (kA)
3.0
2.0
1.0
0
0.1
0.2
0.3
0.4
0.5
Rotational Transform ι_0
Max. current for L_p=1.9μH, R_p=2.0mΩ
$\iota_0 + \iota_j = 0.5$

Fig. 4

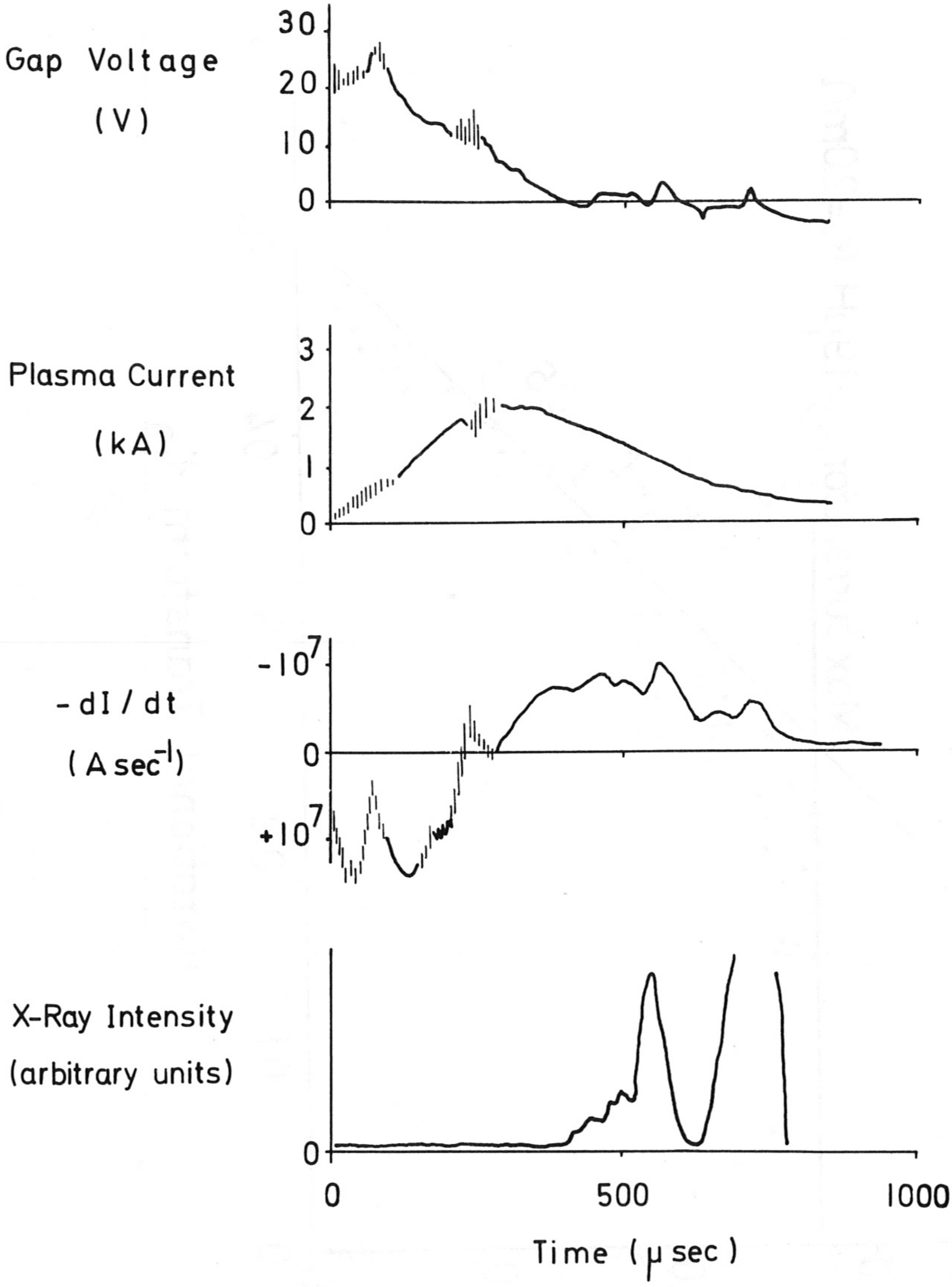
Gap Voltage
(V)
30
20
10
0
Plasma Current
(kA)
3
2
1
0
-dI / dt
(A sec^{-1})
-10^7
0
$+10^7$
X-Ray Intensity
(arbitrary units)
0
0
500
1000
Time (μ sec)

Fig. 5

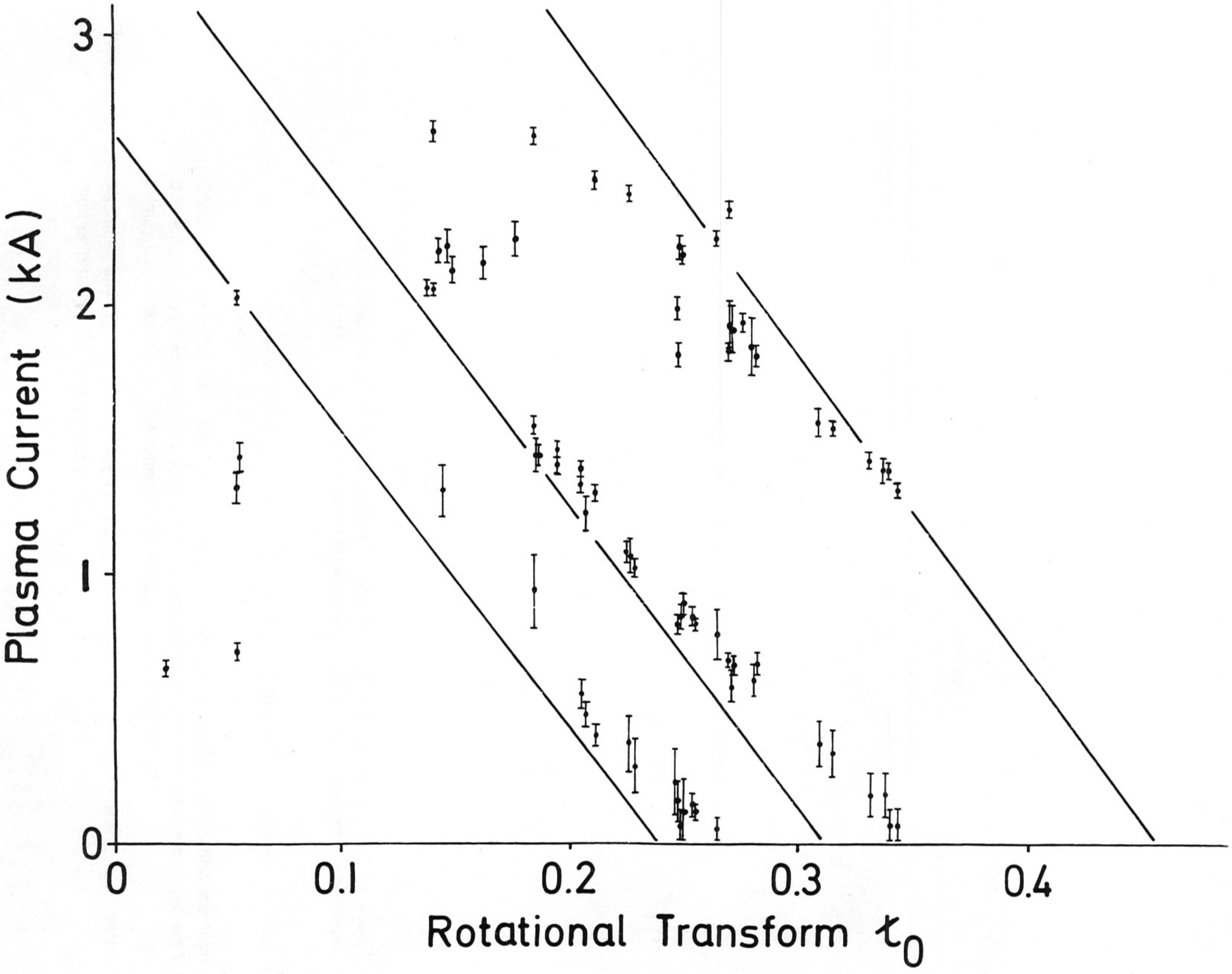
Plasma Current (kA)
3
2
1
0
0
0.1
0.2
0.3
0.4
Rotational Transform ι_0

Fig. 6