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EFFORTS TO STABILIZE THE m = 2 HELICAL INSTABILITY IN ATC

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I. Introduction

Helical perturbations of quasi-steady currents in toroidal discharges have long been known to enhance the radial transport of energy and particles(1), the more so the lower the azimuthal mode number m. In tokamaks, modes with m = 2,3,4 and toroidal mode number n = 1 (hereafter designated m/n) are easily observable(2,3), but in general it is possible to pass rapidly through regimes where modes with $m \geq 3$ are unstable, so that special efforts to stabilize these modes are not likely to become necessary. The 2/1 mode, on the other hand, (and a forteriori the 1/1 mode) even when it does not lead to a disruptive instability(4,5), still has a deleterious effect on plasma confinement and its control is a worthwhile goal of tokamak research. On ATC(6) the control problem has been approached in three ways: searching for a stable window between the 2/1 and 1/1 modes, feedback control (stabilization), and control by the imposition of a D.C. helical quadrupole poloidal magnetic field ($m_o = 2$, $n_o = 1$, plus higher harmonics). Results obtained with the last two methods were described previously(7), but we shall review them here for the sake of completeness.

II. Feedback Stabilization Experiments

The design and use of ATC for radial compression experiments made it impossible to use helical quadrupole control windings, the

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ideal configuration, and instead eight toroidal half-loops were interconnected in such a way as to generate poloidal fields having $m_o = \pm 2$, $n_o = 1$ components. Four magnetic pickup coils were spaced 90^o apart on the midplane and oriented to minimize their mutual inductance to the control circuit. Fig. 1 shows the arrangement of the loops and Fig. 2 a cross-section of ATC. Opposite coils were connected in pairs in order to cancel the $n = 0$ component of poloidal field, and the resulting signals were then added in suitable proportion to obtain a signal shifted by an arbitrary amount from a reference phase tied to the mode. The feedback amplifier was capable of 0.5 MW output, and, after phase compensation, had 90^o phase shift at 22 kHz, about three times the frequency of the usual saturated $m = 2$ mode as it is observed in ATC. Overall loop gain was only about 0.5-2 at the limiter radius, however, so that no very strong effect on the mode was to be expected. For small mode amplitudes the gain limit was set by the residual coupling between pickup coils and control loops; for saturated modes it was set by the amplifier power.

The main result of the feedback experiment is given in Fig. 3. It is interesting because on the whole it conforms to what one would expect for a single unstable wave; i.e., it suggests a so-called dissipative rather than a reactive unstability. There is nonetheless considerable departure from the ideal single-wave model, and indeed, subsequent experiments in which the feedback loop was opened and the amplifier driven by an oscillator demonstrated the excitation of modes fixed with respect to the control loops. Hence to obtain better results it appears essential to have a purer helical quadrupole control winding than was used in our experiment, and it may also be necessary to generate a rotating rather than a stationary wave. Furthermore, attainment of higher loop gain and earlier mode detection will necessitate development of a non-magnetic sensing system, such as the x-ray technique described in Ref. 8.

III. Control by pulsed fields

The second approach to the problem of controlling the m = 2 mode grew out of a series of mode locking experiments performed by driving the open feedback loop(7), and involved application of a current pulse of up to 10 ms duration to a set of control loops outside the vacuum vessel. (The loops inside the vessel that were described above could not withstand the electro-mechanical forces.) Concurrently similar experiments were performed on the Pulsator tokamak(9), with more encouraging results than we obtained. The chief difference in the experiments seems to be in the control winding, which in the case of Pulsator is an $m_o = 2$, $n_o = 1$ helical quadrupole. We found that a quadrupole field approximately the strength of the plasma perturbation field would stop the rotation of the mode, but usually without quenching its amplitude. Nor were we able to delay the onset of the disruptive instability; to the contrary, insofar as a statistically significant result could be obtained at all, it was that a disruption was brought on somewhat sooner with the control field pulsed on.

A very clear example of the suppression of mode rotation rather than of the mode amplitude is given in Fig. 4, which illustrates the growth of the 2/1 instability - the poloidal mode number was established by a different set of magnetic pickups - before a disruption, with and without control field. The initiating event was the intentionally caused outward drift of the plasma into the outer limiter. Evidently the only observed difference in plasma behavior in the two cases is the presence or absence of mode rotation before the disruption sets in.

Under certain conditions it was nevertheless possible to suppress the mode, as shown in Fig. 5. Here the mode continues to rotate, but the amplitude in the course of 10 ms is reduced at least 10 fold. One necessary condition is certainly that the mode be only midly unstable: Fig. 5-a shows, for example, that with control field off the plasma suffers no serious harm by way of a disruption. As the following section will show, there can be little doubt that vacuum vessel wall conditions, plasma density, current distribution, and so on, all have an interconnected role in determining the development of the instability, but we are not yet able to be more precise.

IV. Search for stable operating range between 2/1 and 1/1 modes

When the ATC vacuum vessel is partially coated with titanium sublimated from a source which is positioned inside the vessel in between shots, a much smaller rise in density is observed than is normally the case.[10] A characteristic of such discharges is that they can sustain considerably larger currents than in the ungettered case. In particular, as is shown by Figs. 6b and 6f, a 2/1 mode may first grow and then diminish again, while the current continually increases. Such behavior is to be expected for a kink mode, which should become stable when the resonant layer (where $q = m/n$) has moved far enough outside the plasma.[11] And, indeed, if the toroidal field is increased (cf. 6-a), or the plasma current lowered somewhat (cf. 6-e), the mode continues unabated to the end of the discharge. Nevertheless, the relatively quiescent period following the diminution - if not the disappearance - of the mode, does not persist for longer than at most 10 msec in ATC. Furthermore, the mode which reappears is not, as might reasonably be expected, a 1/1 mode or even a 3/2, but again a 2/1. A possible explanation is a change in the current profile, but so far attempts to measure the temperature profile by means of Thomson scattering have not been able to cope with the poor reproducibility and low density of such discharges.

The significance of these results is that they strengthen the possibility that the consequences of a 2/1 mode are a strong function of the wall properties of the vacuum vessel and not of the density, per se. In particular, if by appropriate control of the gas flux from the walls it should be possible to moderate the effect of 2/1 or 3/1 modes to the point where they do not lead to disruptions, the worst properties of such modes would already have been overcome. It should also be noted that there is some similarity between our results and those obtained earlier on the T-6 Tokamak.[12] In fact, in that case, where the stabilizing effect of a conducting wall was studied, it was possible to obtain even lower q discharges but also, like ours, for only short intervals of a few milliseconds.

V. Conclusion

Our experiments have shown that there is no difficulty about interacting with a 2/1 mode in ATC, and that given sufficient gain and a harmonic-free control winding the probability of stabilizing it is good. Control by steadily applied, DC quadrupole fields, on the other hand, on the basis of experiments with ATC as well as

Pulsator, would seem at this juncture to have a small chance of success. Finally, the high currents achieved in gettered discharges offer the possibility that if control of wall emission can be achieved - e.g., with a divertor - we may simultaneously achieve a measure of control of the 2/1 and higher modes.

References

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Figure Captions

Fig. 1 Diagram of internal control loops and sensors.

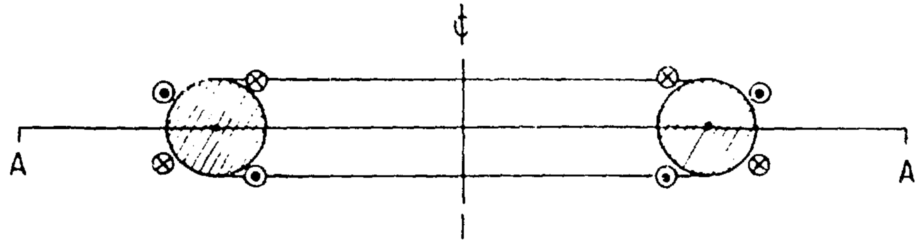
Fig. 2 Cross-section of ATC. Internal control loops consisted of those marked FB and of Breakdown Loops.

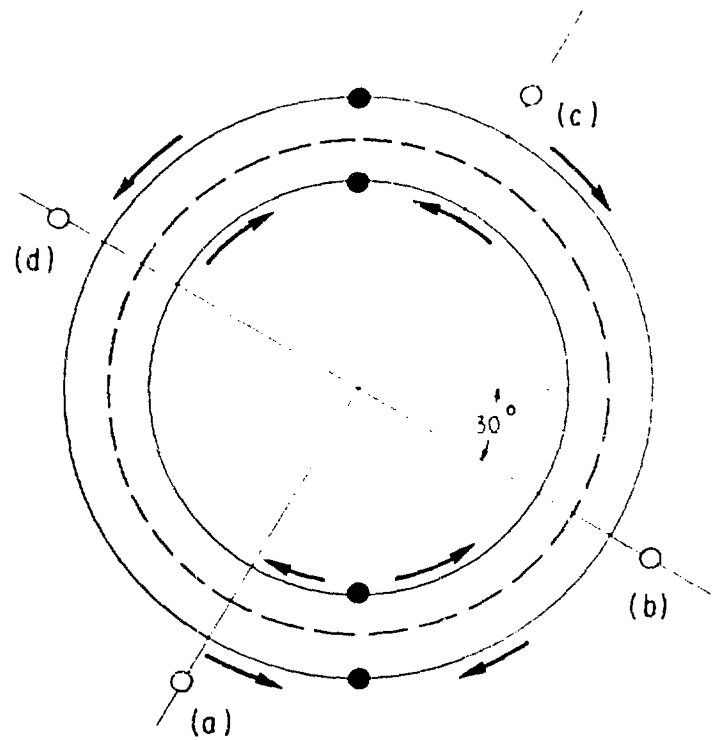
Fig. 3 Mode frequency and amplitude changes as function of feedback-loop phase shift. Curves are least square fits of sinusoids to data.

Fig. 4 Demonstration that control field stops rotation of mode but not its growth. (a) Without, and (b) with control field. $\dot{B}_\theta$ signals (integrated) come from magnetic pickups on midplane, 90^o apart in toroidal azimuth.

Fig. 5 Mode stabilization by pulsed quadrupole control field.
5(a): zero control field
5(b): with control field
a, b, c and e: baselines for loop voltage (1V/cm), magnetic pickup signal, plasma current (20kA/cm), and control field, respectively.

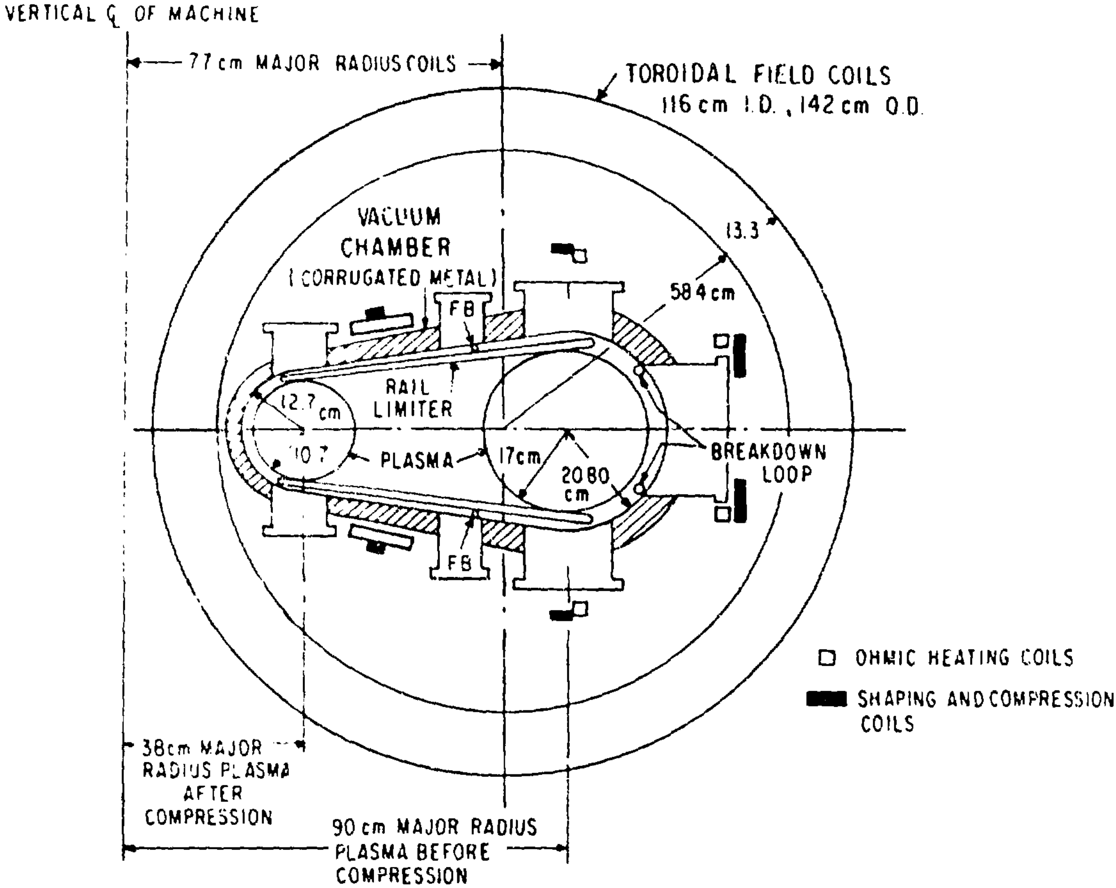
Fig. 6 High-current, Ti-gettered discharges. Note that e, f, g are for same B_ϕ but different currents. Values of q at edge of current channel [q (plasma)] for e, f, g are based on Thomson scattering T_e profiles. The same radius is assumed to apply in remaining cases. Terms "onset" and "end" refer to 2/1 instability, which stops at progressively lower currents as B_ϕ is lowered (a, b, f, c, d). The subsequently resurging fluctuations are also predominantly 2/1.





SECTION AA'

NOTE : $\left.\begin{array}{ll} \tilde{B}_\theta(\text{ANTINODE}) & = \tilde{B}_\theta(b) - \tilde{B}_\theta(d) \\ \tilde{B}_\theta(\text{NODE}) & = \tilde{B}_\theta(a) - \tilde{B}_\theta(c) \end{array}\right\}$ SENSORS



ADIABATIC TOROIDAL COMPRESSOR (ATC)

FEEDBACK STABILIZATION

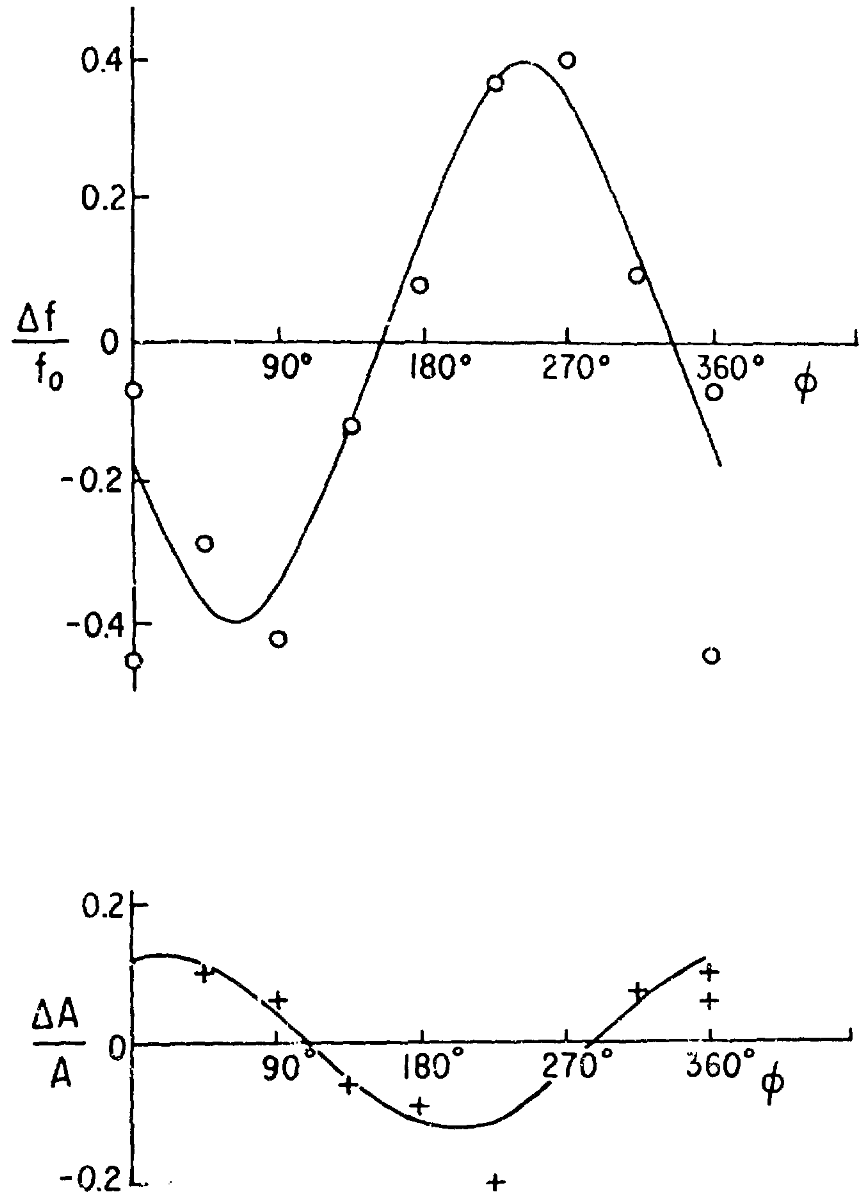
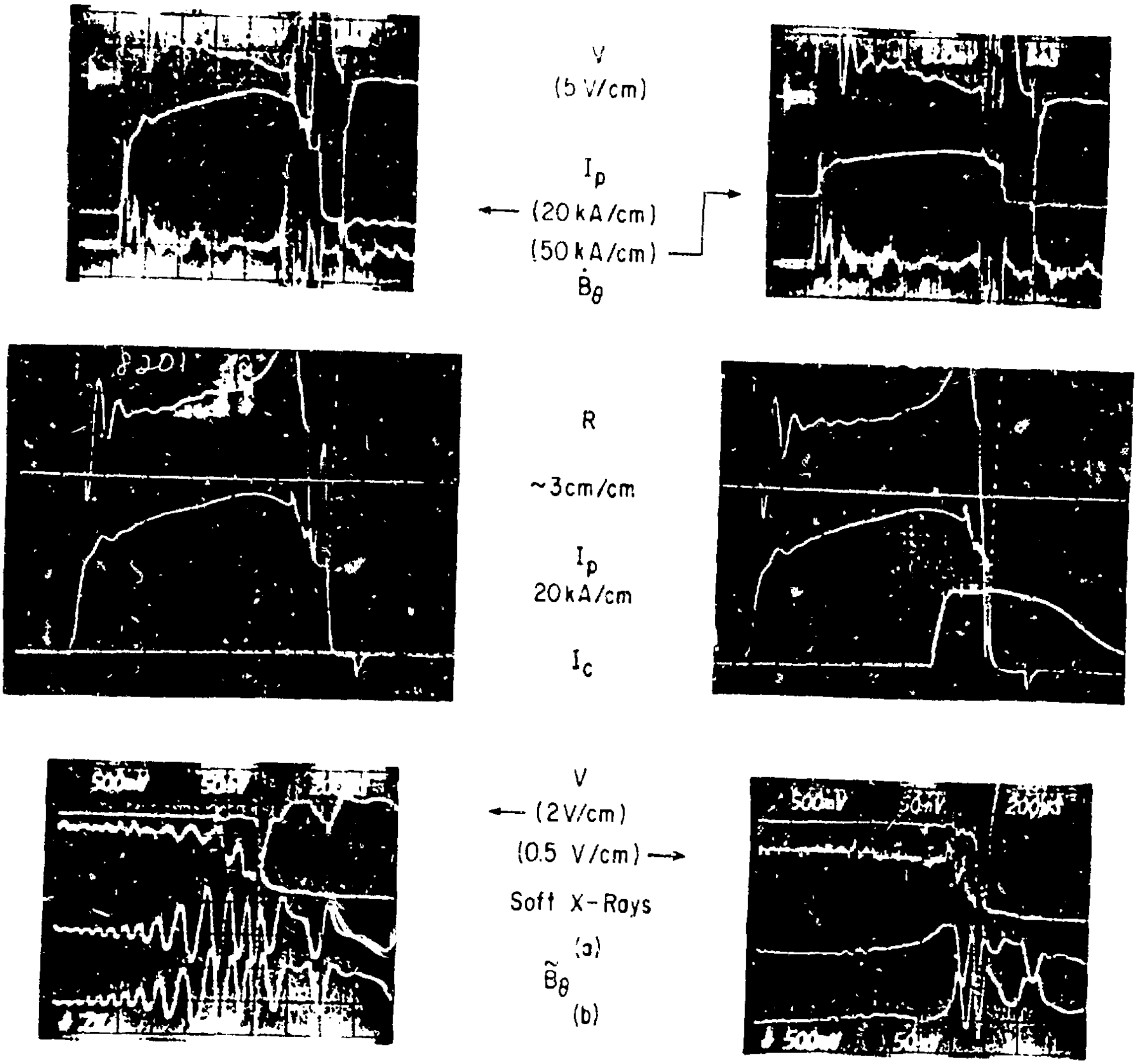


Fig. 3



V
(5 V/cm)
I_p
(20 kA/cm)
(50 kA/cm)
$\dot{B}_\theta$
8201
R
~3cm/cm
I_p
20 kA/cm
I_c
500mV
50mV
V
(2V/cm)
(0.5 V/cm)
Soft X-Rays
(a)
$\tilde{B}_\theta$
(b)

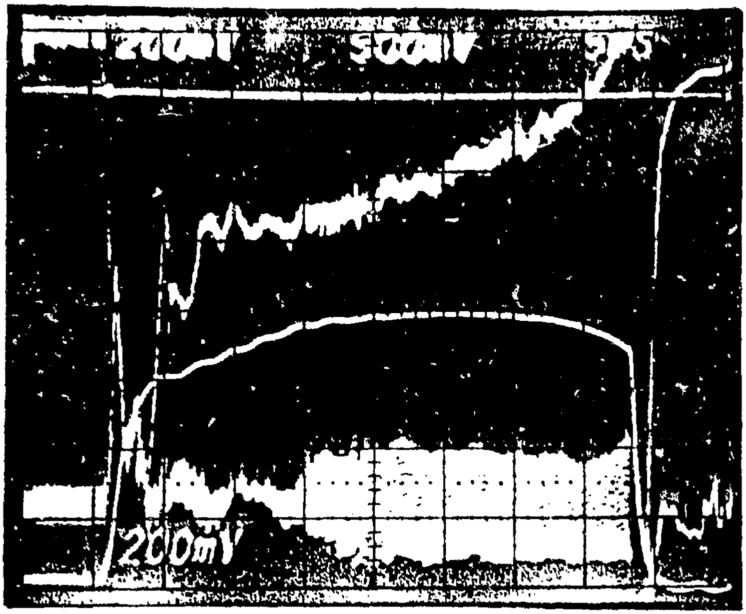
(a)

(b)

a
e

(a)

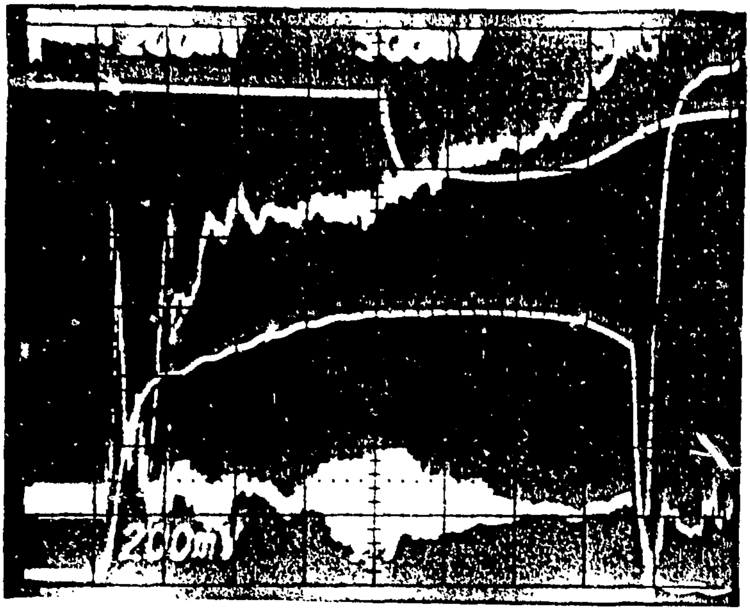
b
c



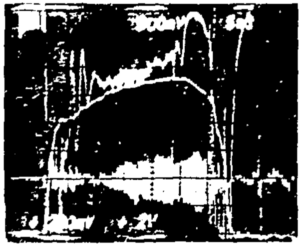
a
e

(b)

b
c



a



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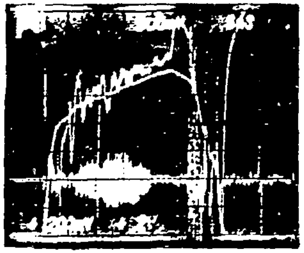

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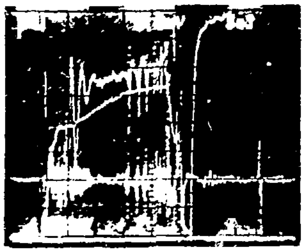
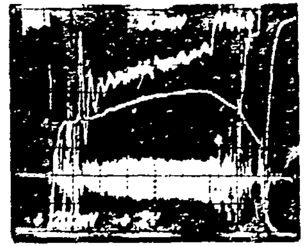


d

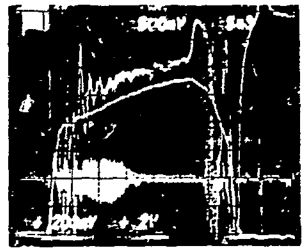
STABILITY OF ATC PLASMA

	B_ϕ - kG	I_p - kA		q (LIMITER)		q (PLASMA) at Max. I_p
		ONSET	END	ONSET	END	
a	17.5	96	>110	3.1	< 2.7	2.1 (est.)
b	15.5	88	114	3.0	2.3	1.8 (est.)
f	14	< 80	102	>2.9	2.3	1.7
c	11	< 80	90	>2.3	2.0	1.3 (est.)
d	8	< 75	84	> 1.8	1.6	1.1 (est.)
e	14	< 80	>100	>2.9	<2.3	1.8
f	14	< 80	102	>2.9	2.3	1.7
g	14	< 80	103	>2.9	2.3	1.6

e



f



g

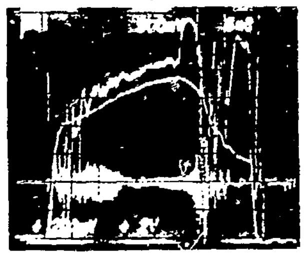


Fig. 6