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Current research on reversed field pinches

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In the reversed field pinch (r.f.p.), confinement is provided by the poloidal magnetic field of the plasma current and a toroidal field which has the opposite sign (i.e. is reversed) outside the plasma with respect to its value on the axis. This provides high magnetic shear which favours stability at high β, and this can give confinement with relatively low magnetic fields. The reversed field configuration can be generated spontaneously by the plasma by a relaxation process known as self-reversal. In this paper the basic theoretical and experimental properties of the r.f.p. are discussed briefly and an account given of the latest experiments on Eta Beta II at Padua, which confirmed early observations on Zeta that when the configuration is set up slowly by using the self-reversal process, reduced fluctuations, longer confinement times and ohmic heating to temperatures of about 100 eV are observed.

1. Introduction

The reversed field pinch (r.f.p.) derives from the first system proposed for plasma confinement – the 'pinch effect' (Bennett 1934) – in which the plasma is confined by the poloidal self-magnetic field, B_θ, of the longitudinal (or toroidal) plasma current. In this simple pinch, since $B_\theta \propto r^{-1}$ (r is the plasma radius) the field is stronger close to the plasma than near material conductors so that external forces are reduced; also, the plasma is heated by ohmic heating from the current that provides the confining field.

The first pinch experiments were done in a torus by Cousins & Ware (1951). Simple pinches were found to be highly unstable to m.h.d. modes, as discussed by Kruskal & Schwarzschild (1954). Research continued with fast linear experiments in which electrodes were used in an attempt to reach high temperatures before instabilities developed and with further toroidal experiments in which an additional (toroidal) magnetic field, B_ϕ ($\approx B_\theta$), was applied parallel to the current, and a conducting shell encircling the plasma was used to try to stabilize the discharge. (This is called the 'stabilized pinch.') Instabilities were reduced but not removed and high temperatures were still not obtained.

Two further ways of stabilizing toroidal pinches have developed: tokamak (Bezbatchenko *et al.* 1960; Furth, this symposium), in which $B_\theta \gg B_\phi$ so that the safety factor, $q = aB_\phi/RB_\theta$, is greater than one (a and R are the minor and major radii of the torus), which corresponds to currents below the 'Kruskal–Shafranov limit', and the r.f.p., in which stability is obtained with $B_\phi \approx B_\theta$ but with the use of a specially shaped magnetic field configuration in which the B_ϕ field reverses (Rosenbluth 1958) in the outer regions of the plasma with respect to its value on the axis (figure 1). With reversal the magnetic field vector changes direction rapidly with radius to give high magnetic shear (*ca.* $q^{-1}\,\mathrm{d}q/\mathrm{d}r$) out to the wall. This has an important stabilizing effect, especially for high-β plasma (Suydam 1958), β being the plasma pressure:

magnetic field pressure ratio. Confinement can be obtained with modest magnetic fields and the current is not restricted to values below the Kruskal–Shafranov limit. Calculations (Yeung 1975; Lawson 1977; Bodin *et al.* 1981) indicate that if the energy losses can be made small the plasma can be heated to the ignition temperature of about 5 keV by ohmic heating from the current. Recently a third pinch variant called the spheromak has been proposed (Bussac *et al.* 1979). R.f.p. research is reviewed by Ortolani (1979) and Bodin & Newton (1980).

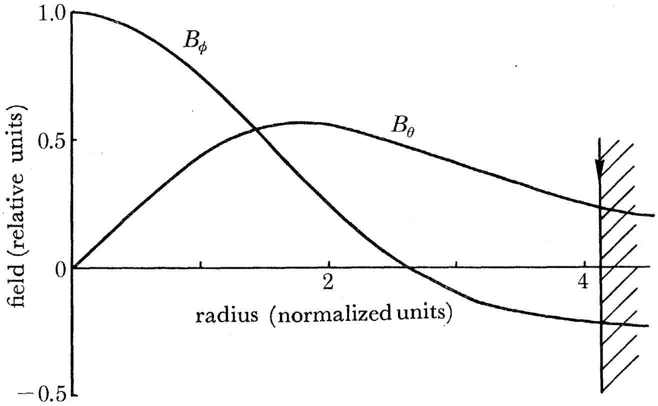

FIGURE 1. Reversed field pinch configuration – this distribution is representative of experimentally observed equilibria and can be stable, on ideal and resistive m.h.d. theory, to kink instabilities with β up to about 20%.

A reversed field can be generated spontaneously by the plasma, as observed in 1958 by Butt *et al.* (1958) and Colgate *et al.* (1958). This 'self-reversal' was explained later by Taylor (1974, 1975*a*, *b*) in terms of plasma relaxation to a state of near minimum energy. In Zeta (Robinson & King 1969) and recently in Eta Beta II (Buffa *et al.* 1979) this spontaneous field reversal resulted in a period of reduced fluctuations and a longer confinement time, and the temperature rose by ohmic heating to about 100 eV. In this paper we review briefly the principles of the r.f.p. and summarize experimental results obtained, with emphasis on the latest results from Eta Beta II.

2. R.F.P. EQUILIBRIA AND SELF-REVERSAL

(*a*) *Formation in experiment by self-reversal*

Similar r.f.p. configurations are generated by field reversal in experiments operating in widely differing conditions. They are described by two parameters, $\theta = B_{\theta\,\mathrm{wall}}/B_{\phi\mathrm{av}} = \mu_0 I/2\pi a B_{\phi\mathrm{av}}$ and the field reversal ratio, $F = B_{\phi\,\mathrm{wall}}/B_{\phi\mathrm{av}}$. The similarity is illustrated by the F–θ diagram in figure 2, where data from four experiments are shown. It is seen that the points lie in a band and that F is a unique function of θ, essentially independent of the initial conditions (pressure, dimensions of apparatus, peak current value and rise-time). Values of θ can extend up to 2.5 (or even more) and during quiescent operation in Eta Beta II the value is typically in the range 1.5–2.5. It is seen that although the points from Eta Beta II follow the general trend there is a tendency for these data to be displaced towards a slightly higher value of θ, an observation yet to be explained fully. The self-reversal mechanism can continue to operate once the distribution is set up and counteracts field diffusion to give a quasi-stationary reversed field configuration which lasts as long as the current is sustained (Bunting *et al.* 1977; Sykes & Wesson 1977).

(*b*) *Theory of relaxed states – equilibrium and stability*

These observations have been interpreted by Taylor as a consequence of the natural tendency of an unstable pinch discharge to relax to a near minimum energy state by a process involving instability and field line reconnection. The observations that the final state depends little on the initial conditions cannot be explained by ideal m.h.d. theory since in this case the final state would be a perfect mapping of the initial one. The essential basis of Taylor's theory is that in a slightly dissipative plasma the final relaxed state is obtained by minimizing the magnetic energy with respect to a single invariant given by $\int_v \boldsymbol{A}\cdot\boldsymbol{B}\,\mathrm{d}\tau$ = constant over the plasma volume, where $\boldsymbol{B} = \nabla\wedge\boldsymbol{A}$, $\boldsymbol{A}$ being the vector potential and $\boldsymbol{B}$ being the field. The final state is force-free and is given by $\nabla\wedge\boldsymbol{B} = \mu\boldsymbol{B}$, where μ is the same on every field line. In a cylinder the solution to this equation is given by Bessel-function fields, $B_\phi = B_0J_0(\mu r)$, $B_\theta = B_0J_1\,(\mu r)$ and $B_r = 0$, where $\mu a \approx 2\theta$; field reversal occurs when $\theta > 1.2$. (This solution is valid when $\theta < 1.56$; at higher values the distributions become helical.) The Bessel function model (B.f.m.) is, therefore, the basic pinch equilibrium, and many of the observed properties of the relaxed state can be interpreted on this basis, including the F–θ behaviour and the appearance of reversal, as seen in figure 2, where the F–θ variation for the B.f.m. is also shown.

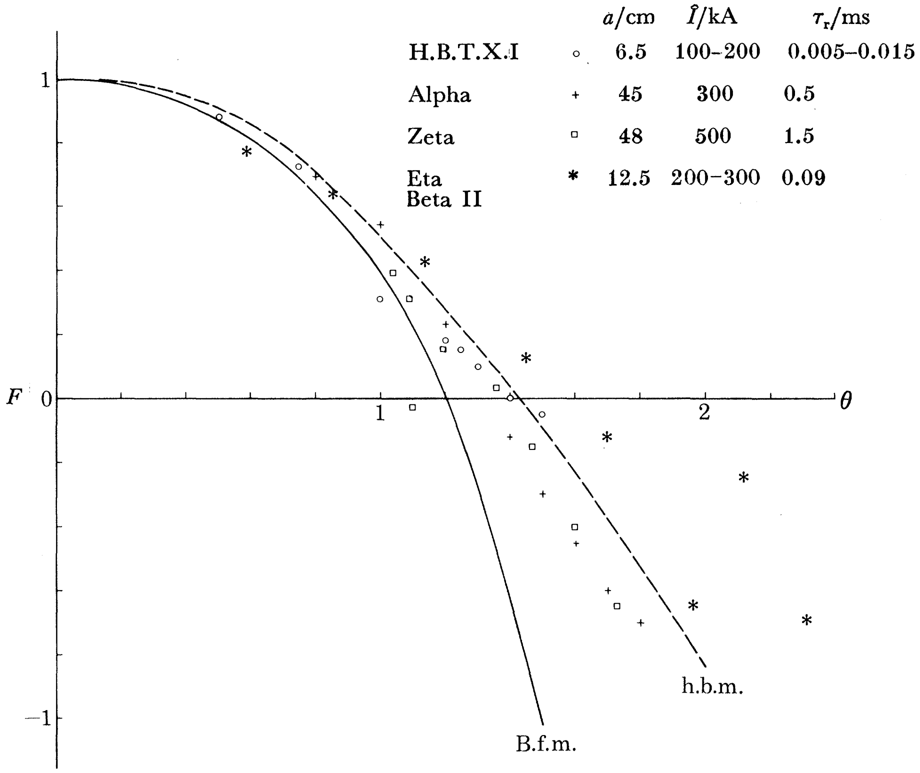

FIGURE 2. The F–θ diagram with points from four experiments operating in widely different conditions ($F = B_{\phi\mathrm{wall}}/B_{\phi\mathrm{av}}$, $\theta = B_{\theta\mathrm{wall}}/B_{\phi\mathrm{av}} = \mu_0 I/2\pi a\, B_{\phi 0}$); the theoretical curves are for Bessel-function fields (B.f.m.) and for a theoretical model (h.b.m.) with relatively high β (up to about 20 %) corresponding better to the distributions found in experiments.

However, the B.f.m. has the property that j/B, where j is the current density, is constant across the plasma whereas in experiment $j \rightarrow 0$ and $j/B \neq$ constant near the walls, so that a true B.f.m. distribution does not exist in practice. There is, however, a second class of equilibria that have higher energy, are not fully relaxed and occur at slightly higher values of θ in which j falls smoothly to zero in the outer regions (figure 1). They are stable (when $\beta = 0$) to all ideal and resistive m.h.d. modes and can, in principle, exist as stationary states.

All these pressureless equilibria have high magnetic shear and with slightly modified fields (Taylor 1975*b*; Robinson 1978) can confine finite-β plasma. They can be stable on ideal m.h.d. theory (Robinson 1969) with β up to about 40%, and stability to resistive tearing (kink) instabilities (Robinson 1978) is possible with β up to about 20%. The F–θ curve for one possible high-β model, the h.b.m., is also shown in figure 2; the experimental data lie in the region of this curve and that for the B.f.m. If these high-β equilibria are also stable to pressure-driven resistive instabilities (g-modes), and current theory (Hosking & Robinson 1979) suggests this may be so for $\beta \lesssim 10\%$, they can exist as stationary finite-β equilibria. If they are unstable to g-modes then whether, theoretically, they will relax to the B.f.m. or one of the other stable zero-β equilibria is a question that cannot currently be answered. It should be noted that although the above considerations include pinch equilibria with $\theta < 1.2$ and no reversal, it can be shown (Robinson 1969) that a reversed field is necessary to obtain stability with a vacuum region outside the plasma and that high β is not possible without reversal.

In experiment the plasma is dissipative with ohmic heating balanced by losses. However, quasi-stationary finite-β (greater than about 10%) equilibria are observed when the time-scale is long enough to allow relaxation to occur, i.e. many poloidal Alfvèn times ($\tau_A = a/V_{A\theta}$, where $V_{A\theta}$ is the Alfvèn speed in B_θ).

(*c*) *Mechanism of self-reversal and relaxation*

Qualitatively a dynamo mechanism acts to drive currents in the poloidal direction which amplify the flux in the core of the plasma; when the plasma is enclosed in a B_ϕ-flux-conserving shell the field in the outer regions can reverse. The simplest mechanism observed (Gowers *et al.* 1977; Bagatin *et al.* 1979) is a single large-amplitude helical kink deformation in which the toroidal current flows in a helix, the solenoidal effect of which gives the required flux amplification. Other possible mechanisms involve the cumulative effect of a number of small-amplitude kink instabilities (Bunting *et al.* 1977) and turbulence (Rusbridge 1977).

The relaxation process depends on the device and on the plasma conditions, particularly on the ratio of the current rise-time to τ_A and on the magnetic Reynolds number, S, defined here as $S = \tau_r/\tau_A$, where $\tau_r = 4\pi a^2/\eta$ ($\eta \propto T_e^{-\frac{3}{2}}$ is the resistivity). The relaxation process involves resistive instabilities (Robinson, this symposium) and is dissipative. It can be shown (Bunting *et al.* 1977) that the associated energy losses become smaller as S, i.e. the temperature, increases.

3. EXPERIMENTS

(*a*) *General*

Experiments fall into two categories. The first, known as 'fast experiments', includes devices with small minor radii ($5 \lesssim a \lesssim 10$ cm), insulating vacuum vessels and fast-rising currents ($50 \lesssim I \lesssim 200$ kA, rise time $\lesssim 10$ μs). The field configuration is generally set up in about one Alfvèn time, before instabilities develop, by fast programming in which the reversed field is driven by controlling the external poloidal current. In the second category, called 'slow experiments', the apparatus is relatively large ($10 \lesssim a \lesssim 50$ cm) and metal bellows vacuum vessels are usually used with peak currents up to about 500 kA. Configurations are set up slowly in many Alfvèn times by self-reversal, with pulse lengths typically greater than 1 ms. The behaviour in these two types of experiments differed, with the exception of observations on relaxed states.

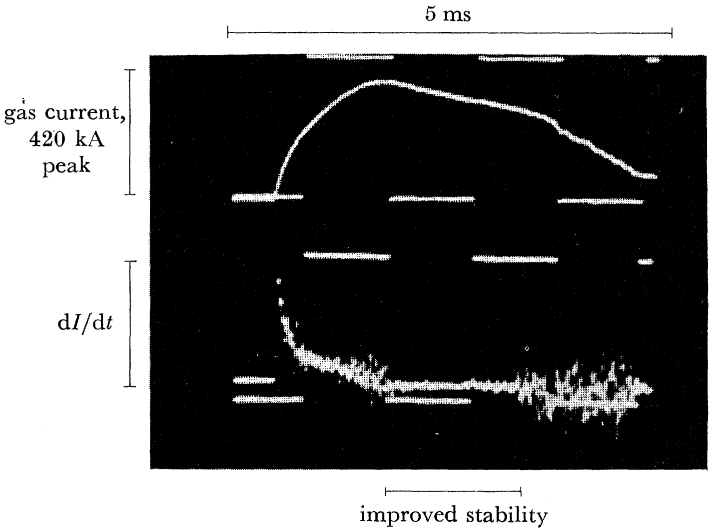

Figure 3. Current (above) and dI/dt waveforms from the Zeta experiment, showing quiescence. (Initial $B_\phi = 0.9$ T; filling pressure = 2 mTorr† D_2.)

(*b*) *Fast experiments*

These include H.B.T.X. I (Carolan *et al.* 1979), Eta Beta I (Bagatin *et al.* 1978), the Z.T. series (Baker *et al.* 1976) at Los Alamos and experiments in Japan (Tamaru *et al.* 1978). Stable distributions could be set up by fast programming with reduced wall contact at $\beta > 50\%$. At low currents ($40 < I < 80$ kA) no unstable fluctuations were found and classical confinement was observed for about 10 µs at temperatures of about 10 eV. As the current was raised, although peak temperatures of more than 100 eV were reached, there were large magnetic field fluctuations accompanied by a rapid fall in temperature to 10–20 eV, with $\delta B/B \approx 10^{-1}$ and an energy confinement time of a few microseconds. The plasma decay time at higher currents was independent of the current, which indicated that the resistance, R, did not fall and, since $R \propto T_e^{-\frac{3}{2}}$, that the electron temperature, T_e, did not increase as the current was raised. The reason for this behaviour is not completely understood but unstable fluctuations driven because β was too high were shown to be important and both ideal and resistive pressure driven modes were identified (Carolan *et al.* 1979); the magnetic Reynolds number was low. Radiation losses were also thought to be important (Buffa *et al.* 1977). Because fast programming enables a range of field configurations to be set up in a controllable fashion for short times many of the theoretical predictions of ideal and resistive m.h.d. stability theory and on self-reversal were checked in low-temperature plasma.

(*c*) *Slow experiments*

An important advance in r.f.p. research was made on Zeta (Robinson & King 1969) in the period 1965–8 (towards the end of its ten-year lifetime) with the observation of a relatively stable period known as the quiet period (q.p.) or quiescence which occurred just after peak current when both B_ϕ and the toroidal electric field, E_ϕ, were reversed in the outer regions.

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† 1 Torr ≈ 133 Pa.

The fluctuations of dI/dt were reduced by a factor of ten or more (figure 3), the temperature increased up to 150–200 eV by ohmic heating and the field fluctuation level in the outer region became small ($\delta B/B \approx 10^{-3}$). The energy confinement time was in the range 3–10 ms with $\beta \lesssim 10\,\%$. This was the first example of prolonged confinement of high-β plasma in a toroidal system and was interpreted as being due to an improvement in the electron confinement in the outer region of the plasma. This observation contrasted sharply with the results subsequently obtained in fast experiments (§ 3 (*b*)).

TABLE 1. ENGINEERING PARAMETERS OF NEXT-GENERATION R.F.P. EXPERIMENTS AND BEYOND

	TPE-IR(M) Sakura-Mura	Eta Beta II Padua	H.B.T.X. IA Culham	Z.T.-40 Los Alamos	R.F.X.† Culham
major radius/cm	50	65	80	114	180
minor radius/cm	10	12.5	26	20	60
peak current, I/MA	0.15	0.2–0.3	0.4	0.6	2.0
rise time/ms	0.5	0.120	0.1–0.8	0.1–0.7	10–50
decay time/ms	≈ 0.5	0.5–3.0	1–5	2–5	120
completion date	operational	operational	early 1981	late 1979‡	

† Designed but not yet approved.

‡ With an insulating liner; a metal bellows liner similar to the others will be fitted early 1981.

(*d*) *New results from Eta Beta II*

(i) *General – parameters of experiments*

Eta Beta II (Buffa *et al.* 1979 and 1981) is the first of a new generation of slow r.f.p. experiments which includes TPE-IR(M) in Japan (Hirano *et al.* 1980), Z.T.-40 at Los Alamos (first operational late 1979) and H.B.T.X. IA (under construction at Culham) whose parameters are given in table 1. Eta Beta II has a toroidal stainless-steel bellows liner with major and minor radii of 65 and 12.5 cm respectively. Peak gas currents up to 300 kA can be reached in 100 μs, driven by a 40 kV, 132 μF capacitor bank. The pulse length can be up to about 1.5 ms. Most experiments have been done at 210 kA rising in 90 μs with 32 kV bank voltage and $B_{\phi \mathrm{av}} \approx 0.3$ T. The filling pressure of the deuterium gas was in the range 3–25 mTorr.

(ii) *Comparison between pinches with and without reversed field*

The properties of a 'stabilized pinch' ($\theta \lesssim 1.2$, no field reversal) were compared with those of a reversed field pinch. The self reversal process in Eta Beta II is aided by letting the B_ϕ-circuit complete a half period of oscillation before it is crowbarred, while the current is initiated at or near the peak of B_ϕ. In this way the plasma only has to drive the reversal inside the liner. The current-rise phase is similar in both pinches (figure 4) but after the current is crowbarred the decay time is always longer in the r.f.p. than in the stabilized pinch. In particular, at the optimum filling pressure of 4–6 mTorr a marked reduction is observed in the fluctations of the dI/dt signal (see figure 4) and the behaviour is very similar to that in Zeta (figure 3).

The substantially longer current decay time in the r.f.p. is interpreted as being due to a lower plasma resistance, which agrees with temperature measurements, showing that although the temperature of about 40 eV at peak current is similar for both pinches, thereafter it increases only in the r.f.p., to double in about 0.1–0.2 ms, while oxygen line radiation (O^{IV}, O^{V}, O^{VI}) is reduced to a negligible value. In the r.f.p. the radiation barrier due to the light elements is overcome and there is a second decay phase characterized by a slow linear decay corresponding to a e^{-1}-time longer than 1.5 ms. During this phase, which lasts up to 0.8 ms, both B_ϕ and E_ϕ are negative, as in Zeta, and the field fluctuation level in the outer region is low ($\delta B/B \approx 10^{-2}$). Finally a relatively fast (10–20 μs) current termination is observed, while B_ϕ and E_ϕ become positive at the wall and the line radiation reappears abruptly.

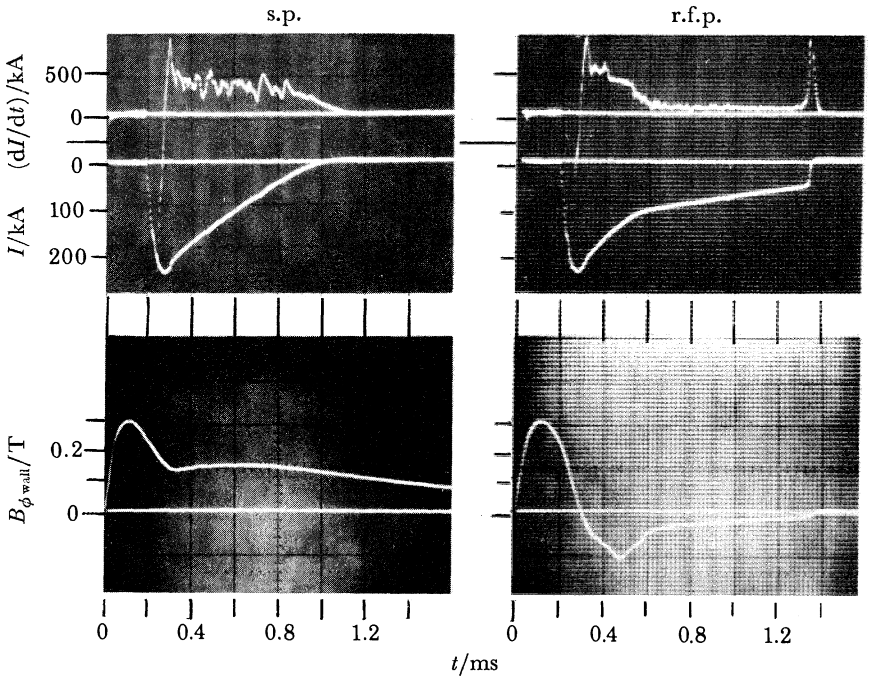

FIGURE 4. Current, dI_ϕ/dt and $B_{\phi\,\mathrm{wall}}$ waveforms from Eta Beta II for a stabilized pinch, s.p. (no field reversal) and a reversed field pinch (initial pressure $\approx$ 6 mTorr D_2).

(iii) *Plasma behaviour at different filling pressures*

High temperatures (50–100 eV) are obtained only when the oxygen impurity is reduced to a small value by extensive conditioning. However, at high filling pressure (greater than 10 mTorr) radiation losses dominate and prevent the temperature increasing above about 40 eV. The observed temperatures and decay times at various filling pressures are compared in figure 5 with the results of an O–D model calculation including the circuit and plasma, with line radiation. Best agreement is obtained for an oxygen content less than about $4 \times 10^{18}\ \mathrm{m^{-3}}$ (i.e. 1 % of 5 mTorr). This oxygen concentration is markedly less than that obtained in the best conditions on Eta Beta I by using a quartz tube and fast programming, where the value was estimated to be $2 \times 10^{19}\ \mathrm{m^{-3}}$. At lower pressures (less than 4 mTorr) turbulent diffusion associated with field fluctuation levels considerably higher than those in the optimum pressure range is thought to be the dominant loss mechanism. This behaviour has been investigated at different currents and can be interpreted in terms of an optimum value of the ratio I/N (N is the electron line density) of about 10^{-14} A m^{-1} (Buffa *et al.* 1981), which is also consistent with similar observations on Zeta.

(iv) *Electron temperature and density measurements*

The electron temperature and density were measured during the current decay phase by Thomson scattering, mostly on the axis, and the integrated density along a diameter was measured by using a helium–neon interferometer. Figure 6 shows that the temperature approaches 75 ± 25 eV at the end of the linear decay phase. After an initial fast rise, T_e remains,

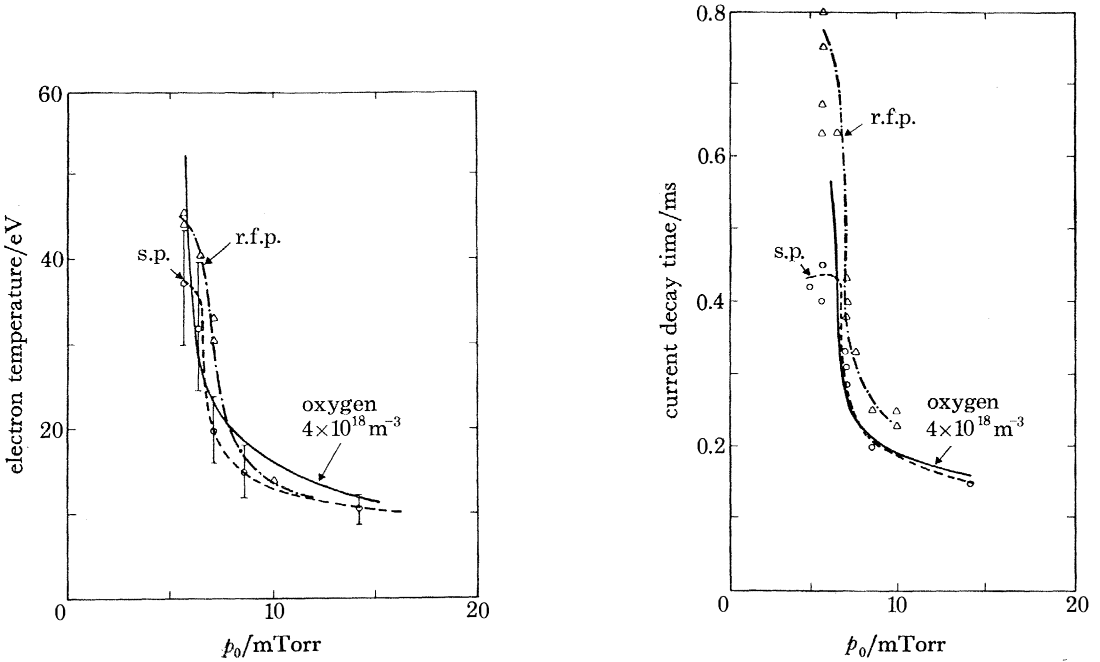

FIGURE 5. Measured temperature and current decay time, and computed values, including the effect of impurities, as function of filling pressures on Eta Beta II. The temperature was measured by Thomson scattering on the axis at the current peak.

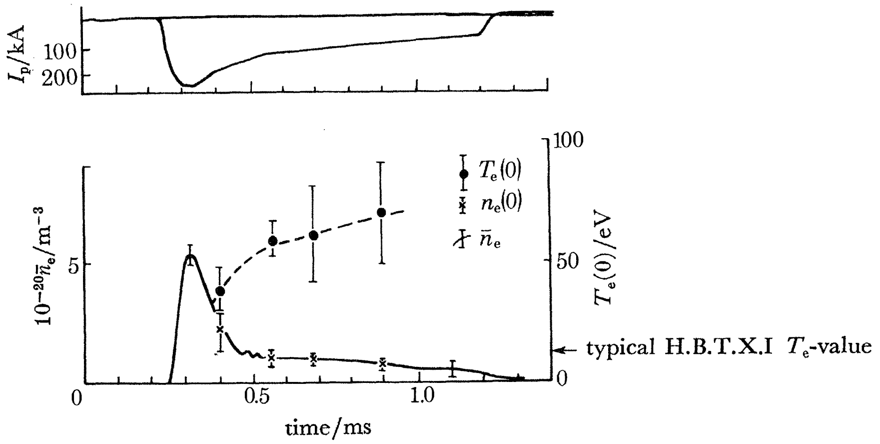

FIGURE 6. Time dependence of the temperature and normalized density on axis, measured by Thomson scattering, and the average line-of-sight density along a diameter, measured by a calibrated interferometer. (The scattering data are normalized to those from the interferometer.) (From Eta Beta II.)

within experimental error, approximately constant or increases slowly during the linear decay phase. In contrast, the density falls sharply just after peak current and thereafter remains approximately constant or decreases slowly.

(*e*) *Discussion of experimental results*

The improved confinement and heating observed in Zeta, Eta Beta II and TPE-IR(M) are a distinguishing feature of slow experiments. Reasons suggested to explain the difference between slow and fast experiments include the following:

(i) The effect of oxygen impurity is less, owing to improved vacuum technology and cleaning in a metal system. Furthermore, only with slow setting-up was the plasma close to the minimum energy F–θ curve, so that it was only weakly unstable during the setting-up phase, which may have given less wall interaction.

(ii) Because of (i) the temperature and magnetic Reynolds number were higher; also, the value of β increases slowly and never becomes excessive. Both these factors can lead to a reduced fluctuation level.

(iii) The stability properties of the field configuration in the outer region of the plasma are better because $E_\phi < 0$ on both Zeta and Eta Beta II; experiments are required to find out if $E_\phi < 0$, which can give higher shear, is a necessary condition for quiescence. Also, the metal liner provides a conductor close to the plasma.

5. CONCLUSIONS

Many of the properties of the r.f.p. have been established experimentally and a theoretical framework has been developed which can account for the main observations, for example the spontaneous generation of reversed field by relaxation (self-reversal). In fast experiments several theoretical predictions, including those on resistive instabilities and self-reversal, have been tested in low-temperature (10 eV), high-β (0.1–0.5) plasma but the confinement is poor except at low currents. When the configuration is set up slowly by self-reversal as in Zeta, Eta Beta II and TPE-IR(M) reduced fluctuations, longer confinement times and ohmic heating to temperatures of about 100 eV are observed. R.f.p. research will be extended in the near future (table 1) on new intermediate-scale experiments at Los Alamos and Culham, while a larger machine designed to study high-β plasma at higher temperatures and in more collisionless conditions, closer to those expected in a reactor, has been designed at Culham in collaboration with Padua and Los Alamos.

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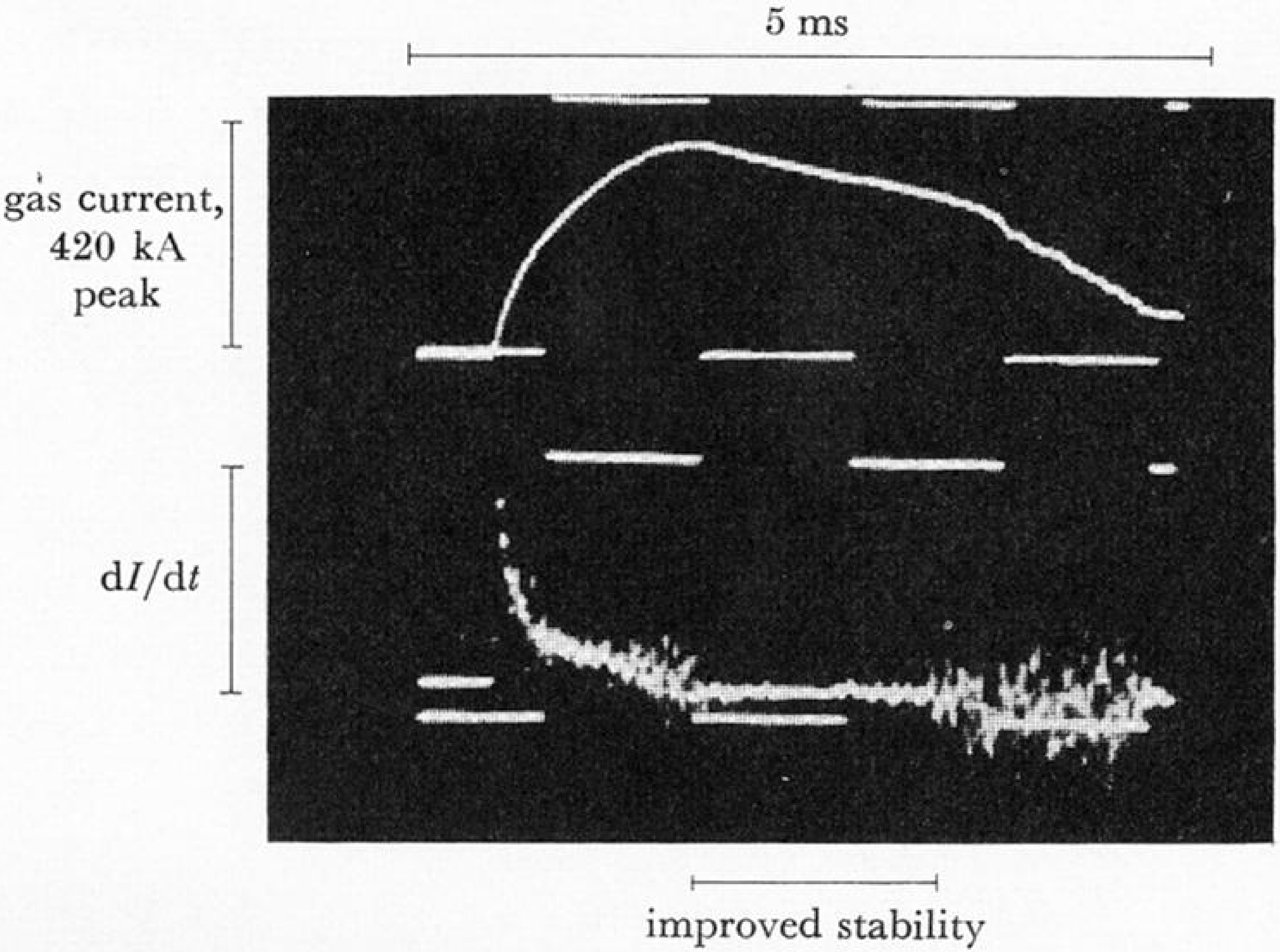

GURE 3. Current (above) and $\mathrm{d}I/\mathrm{d}t$ waveforms from the Zeta experiment, showing quiescence. (Initial $B_\phi = 0.9$ T; filling pressure = 2 mTorr† D_2.)

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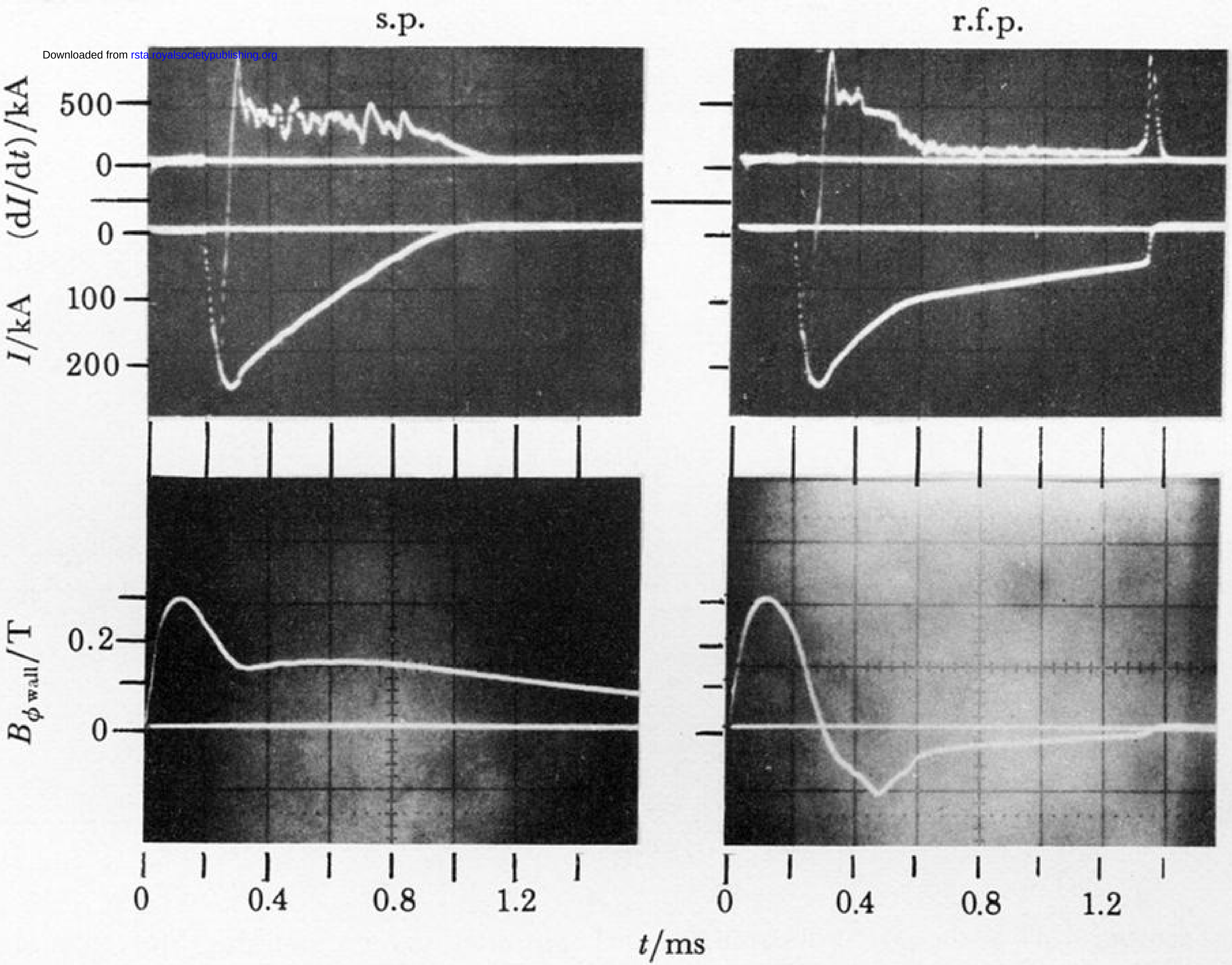

GURE 4. Current, $\mathrm{d}I_\phi/\mathrm{d}t$ and $B_{\phi\,\mathrm{wall}}$ waveforms from Eta Beta II for a stabilized pinch, s.p. (no field reversal) and a reversed field pinch (initial pressure $\approx$ 6 mTorr D_2).