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Abstract

The Extrap T1 device is a high aspect ratio toroidal pinch with the dimensions R/a = 0.5m/0.057m. In the experiments described here, the stainless steel bellows vacuum vessel was surrounded by a resistive shell with a perpendicular field penetration time of 75 μs.

The ULQ discharges, with toroidal currents in the range 20 - 50 kA and pulse lengths up to 2 ms, showed the typical step-wise decay of the plasma current. The current steps corresponded to transitions of the edge q-value across rational values 1/4, 1/3, 1/2, and 1. During a step through a rational q value, there was an increase in the fluctuation activity and a corresponding increase in the plasma resistance. As part of the ULQ studies, discharges with four poloidal field nulls were produced by applying an octupole magnetic field, thus demonstrating that is possible to sustain ULQ equilibria with poloidal field x-points and a magnetic separatrix.

In another study, the transition from ULQ discharges to relaxed state discharges was investigated. When the initial bias toroidal field was reduced so that q was less than about 1/6, which corresponded to a pinch parameter (Θ) of about 0.6, a change in the discharge character was observed. The loop voltage required to sustain a given current increased and stochastic fluctuations were seen. Toroidal flux was generated and relaxed state equilibria developed. For higher Θ, in the range of 1.5 to 2.0, a reversed field pinch could be set up if the toroidal field power supply provided a reversed current in the coils. The plasma resistivity was again lower and the pulse lengths in the RFP mode were up to 1 ms, corresponding to over 10 shell penetration times.

1. Introduction.

In this paper we present the global features of reversed field pinch (RFP) and ultra low q (ULQ) plasmas in the resistive-shell T1 upgraded device. It is well established that RFP discharges are sensitive to the shell boundary conditions [1-5]. In the experiments described here, the shell was resistive and had 12 poloidal gaps. Nevertheless RFP discharges, discharges with $F = 0$ and ULQ discharges were sustained for over 10 shell penetration times. In addition, ULQ discharges with poloidal field x-points, were produced and sustained for many shell penetration times.

The important conditions which determined whether a discharge in the T1 device was an ULQ discharge or an RFP discharge were first the relative initial strength of the toroidal field, as characterized by the pinch parameter, $\Theta = B_\theta(a)/\langle B_\varphi \rangle$, and secondly, the toroidal field circuit conditions. The relaxation effects which characterize the start up of an RFP became strong if Θ exceeded 0.6. Since there was no toroidal-flux conserving shell on the T1 device, reversal of the toroidal field at the edge could be obtained only if the toroidal field coil circuit allowed reversal. If this were the case then RFP operation was achieved. However, when the toroidal field circuit sustained a constant current thus inhibiting reversal, toroidal flux was produced so that the average field was larger than the value at the plasma edge. As a result, the pinch parameter and the reversal parameter, $F = B_\varphi(a)/\langle B_\varphi \rangle$ followed the relation corresponding to a relaxed state even for these ULQ discharges in spite of the fact that the toroidal field coil current was held constant. In this paper we compare ULQ discharges and RFP discharges, in the resistive-shell T1 device, in order to investigate whether the transition from the ULQ mode to the RFP mode can provide information on the relaxation process.

The T1 device has a set of toroidal coils outside the shell which can produce an octupole field. When this octupole field was applied, the resulting discharge equilibria had four poloidal field nulls. For these discharges, the step-wise evolution of q, characteristic for ULQ operation, was not observed. Also, there was evidence that the presence of the four poloidal nulls in the equilibrium suppressed the relaxation process. This is consistent with earlier Extrap T1 experiments where discharges with a four poloidal null magnetic separatrix and an on-axis axis safety factor of $q(0) = 0.1$ were studied. In these discharges, although the toroidal field was weak, the measured equilibria were paramagnetic and in agreement with an anisotropic resistivity [6]. Without the poloidal nulls, for discharges initiated with this weak toroidal field corresponding to $\Theta > 0.6$, the relaxation effects have been very strong.

2. Description of the Extrap T1 Upgrade device

A schematic drawing of the upgraded Extrap T1 device is shown in Fig. 1 and the parameters of the experiment are presented in Table 1. The vacuum liner cross-section is shown in Fig. 2. The stainless steel bellows liner has six toroidal sectors with intervening port sections for pumping and diagnostic access. These port sections have a wall thickness of 0.7 mm and the minor radius of the inside aperture is 55 mm, which is 2 mm less than the inside minor radius of the bellows. There are no other limiters facing the plasma in the interior of the liner. The penetration time for the toroidal field is 50 μs.

The liner fits into a stainless steel shell, 2.5 mm thick, which has 12 poloidal gaps and 2 toroidal gaps, on the inboard and outboard sides at the equatorial plane. The minor radius of the shell is 67.5 mm so the vacuum region between the plasma edge and the shell is 16% of the minor radius. The area of the cut-outs in the shell for port access is about 1.1% of the shell surface area and the total area of the 12 poloidal gaps is 0.7% of the shell area. This shell has a calculated time constant of 75 μs for the penetration of perpendicular fields.

The toroidal coils, or rings, for generating the octupole field which produce the x-point equilibria are located immediately outside the shell. This coil system which is decoupled from the iron core flux, is driven by a separate capacitor bank power supply.

The ohmic heating primary has eight turns which are distributed on the inboard and outboard side of the discharge axis at positions producing the vertical field necessary for a stable equilibrium in pulses longer than the shell penetration time. The capacitor bank power supply for the ohmic heating circuit has three stages with ignitron switching. The maximum available loop voltage for discharge breakdown and initial build-up is about 2 kV and the maximum sustainment loop voltage is about 1 kV, although the experiments described here were carried out with lower loop voltages. The rise time of the plasma current is about 100 μs, which is comparable to the shell penetration time.

The toroidal field coil consists of 48 turns. The different modes of operation are achieved by changing the toroidal field circuit. For ULQ operation the toroidal field current is held constant by using an external circuit with a long time constant. For RFP operation and operation with $F = 0$, a small capacitor bank with minimal inductance is used to produce the initial toroidal field. The half-sine wave period of the TF current pulse is 280 μs. An electrolytic capacitor bank is used to sustain the reversed current for RFP operation.

Breakdown is achieved with this initial loop voltage with the help of a spark electron source. For the experiments described here the filling gas was hydrogen or helium and the filling pressure was in the range of 1 to 10 mTorr. For the typical parameters of plasma current $I_p > 10$ kA and filling pressure less than 3 mTorr, the ratio of current to filling gas line density is greater than $1\times10^{-14}\mathrm{Am}^{-1}$, which has been observed to be necessary to burn through light impurities. Monitors of HeI and HeII line radiation intensity as well as VUV spectroscopy indicate that the electron temperature is in the range 20 to 30 eV. No interferometric measurements of the density have been made but Langmuir probe measurements indicate that the electron density is comparable to the filling density and that the density decrease during the pulse due to pump out of density is less than 50% for the helium plasmas.

3. Ultra-low q discharges.

The ULQ configuration has been described as a self-organized equilibrium which is an intermediate state between the Tokamak and the RFP [7,8]. The speculation is that the equilibrium profiles develop through the combined action of resistive diffusion, which would produce the tokamak type profile, and the MHD relaxation process, which would lead to the Taylor relaxed state of the RFP. Approximately flat q(r) profiles with a local maximum on the axis, then decreasing out to the edge where there is a local minimum, have been proposed. The value of q at the plasma edge is sustained in a window between rational surfaces (i.e. $1/(n+1) < q(a) < 1/n$) where n is typically 1, 2, 3 or 4. The operational parameters of the ULQ discharges for the present experiments in the T1 device are summarized in Table 2.

The loop voltage requirements were high due to the high aspect ratio geometry of the device and the small cross-sectional area. The core flux swing was 0.4 Vs so even these high loop voltages could be sustained for several shell penetration times. Although the plasma currents were not large, in the range 10 to 50 kA, the current densities, in the range 1 to 5 MAm^{-2}, were comparable to typical current densities in present generation RFPs.

Magnetic diagnostics, including toroidal loops at the periphery of the vacuum vessel and m = 1 sine and cosine coils were used to measure the toroidal equilibrium position of the discharge. The shift of the outermost flux surface centre from the geometric axis was less than ±5 mm for the discharges discussed here. In this range there was no observed dependence of plasma resistance on radial displacement, although an increase in resistance was seen if the shift exceeded about 10 mm.

The development of the characteristic step-wise q(a) evolution could depend on the filling pressure [9]. Pulse shapes for various parameters are shown in Fig. 3 for two discharges with different filling pressures. Discharge a) shows a typical ULQ step transition for q between the windows 1/4 < q(a) < 1/3 and 1/3 < q(a) < 1/2. After the transition, the discharge was sustained until the iron core saturated. During the transition of q(a) between windows, the magnetic fluctuation level, seen on the cosine and sine coils, was larger than the level seen while q(a) was sustained in a window. The plasma resistance increased at the transition and then decreased to a lower level during the second q(a) window. The power input at the second window was reduced. A monitor of the H_α radiation showed that ionization occurred within the first 100 μs of the pulse while the current was rising. Discharge b), which was initiated with a lower filling pressure but with other parameters unchanged, exhibited a different development. A larger discharge current resulted and q(a) was in the range 1/5 < q(a) < 1/4 for about 300 μs. The resistance and the C-III radiation decreased in time, and the current increased resulting in a decrease in q(a). The ratio of radiated power to input power decreased substantially indicating burn-through. The fluctuation level increased at the same time, as is characteristic for a transition between windows, however a new quiescent period, corresponding to operation in the window 1/6 < q(a) < 1/5, was not achieved. Operation with q(a) = 1/6 corresponds to a pinch parameter of $\Theta = 0.6$. The fluctuation level was higher and toroidal flux was generated as is characteristic for RFPs during the set-up phase. The plasma resistance increased as the fluctuation level increased. The development of ULQ discharges, with q(a) sustained within windows between rational values, was dependent on the initial parameters of the discharge including toroidal field, filling pressure and OHC bank voltages. For the same toroidal field and filling pressure parameters as for discharge a) above, a decrease in OHC voltages gave discharges where the plasma current decreased smoothly and the resulting q(a) increased without evidence that the discharge development was dependent on the relation between q(a) and rational surfaces.

For ULQ discharges, the plasma current normally decayed in a step-wise fashion with each step corresponding to a transition across a mode rational value. In some cases a coherent oscillation was observed on cosine and sine coils during the stationary periods [10]. As an example, we show in Fig 4 the time evolution of plasma current, loop voltage, safety factor at plasma edge, cosine and sine coil signals indicating position variation (radial and vertical) and the signal from a helium line radiation monitor. After the start-up phase, the current settled into an apparently stable level, for this shot corresponding to an edge q-value in the range $1/4 < q < 1/3$. The current then spontaneously decayed in a step-wise fashion to lower levels with edge q-values in ranges, $1/3 < q < 1/2$ and $1/2 < q < 1$. The current in the lowest level was finally terminated due to the saturation of the transformer core. The current steps were correlated with an increased magnetic fluctuation amplitude, detected by the cosine and sine coils, as well as a momentarily increased line radiation. The magnetic fluctuations were coherent and the frequency was quite constant while q(a) was within a window, but there was a change in the frequency of the fluctuations seen on both coils as q(a) evolved through the windows. Also, there was a $\pi/2$ phase difference in the signals of the two coils indicating a rotating helical $m = 1$ mode structure. The modes producing these fluctuations were global and similar spectra were seen on other magnetic diagnostics at other toroidal positions. The change in frequency of the oscillation at each step transition is possibly explained by a simultaneous change in the helical structure.

The time evolution of plasma resistance versus safety factor at the edge is shown in Fig. 5a, for this shot. The resistance was low during periods when q(a) was sustained within a window between two rational values and increased at the transitions.

Although, for this ULQ operation, the TF circuit did not allow a decrease in the TF coil current, toroidal flux was produced by the discharge. The average toroidal field $\langle B_\varphi \rangle$, measured by a poloidal loop increased during the pulse as the pinch parameter $\Theta = B_\theta(a)/\langle B_\varphi \rangle$, increased. For these ULQ discharges, the time evolution of the RFP parameters F (field reversal ratio) and Θ (pinch parameter), were evaluated and are shown in Fig. 5b. Reference trajectories are plotted for the Bessel function model (BFM) and the polynomial function model (PFM) developed by Sprott [11]. Note that the observed F-Θ trajectory follows the PFM quite well. Furthermore, each of the steps in the current level corresponding to different rational values for q are evident in the F-Θ trajectory. It appears that each allowed current level has a corresponding F-Θ operation point.

Observed current levels usually corresponded to edge q-values near, or slightly above, the mode rational values $q = 1/n$, $n = 1, 2, 3, \ldots$. This behaviour could be explained by the observed plasma resistance. In Fig. 6a. we plot the plasma current as a function of toroidal field for a series of shots with OHC capacitor bank voltages kept unchanged. The resistance, measured during the first flat-top period of the current, showed a marked increase for edge q-values near the mode rational values (Fig. 6b). The increased resistance was coincident with a gradually decreased plasma current as the rational q-value 1/4 was approached from above by lowering the toroidal field in small steps. The plasma current decreased with the toroidal field and the edge q remained around the rational value. For a given OHC voltage, the higher resistance near the mode rational q-value limited the plasma current for a certain range of toroidal field strength. For a sufficiently low toroidal field, the limit was overcome and the next q-window below the rational value was entered. The plasma resistance was here again low and the plasma current higher.

The dependence of plasma resistance on plasma current is shown in Fig. 7. The scaling corresponds to $V_{loop}/I_p \propto I_p^{-1.2}$.

4. Magnetic Separatrix Configuration.

When a sufficiently large octupole field is superimposed on a circular discharge, a magnetic separatrix, defined by four poloidal field nulls, is introduced into the discharge region [12]. The separatrix bounds the plasma discharge in a way analogous to a four null poloidal divertor. In earlier studies on the Extrap T1 device, which was operated with $q < 1$ and with a four poloidal-null separatrix bounding the discharge axis, a flat q profile was observed [6]. In the earlier device the toroidal rings producing the octupole field were inside the vacuum vessel and the current in the rings and the plasma were both induced. In the rebuilt device the rings are outside the vacuum vessel and the strength of the octupole field is controlled by a separate power supply. We have made a preliminary study of ULQ plasmas with the magnetic separatrix configuration in the rebuilt device. Globally stable ULQ discharges were observed in the magnetic separatrix configuration although they had a shorter duration than the conventional ULQ discharges bounded by the liner. The loop voltage requirements were higher for these discharges and the discharges terminated due to saturation of the iron core. The increase in plasma resistance corresponded to the decrease in plasma cross-sectional area. The discharges were globally stable, with q-values in the range from 0.3 to 1, and were sustained for more than 1 ms. These discharges showed no evidence of the characteristic behaviour associated with the step-wise decay of the plasma current observed in ordinary ULQ discharges.

Pulse data for an ULQ discharge with four poloidal nulls is shown in Fig. 8. The time evolution of plasma current, loop voltage, octupole coil current and magnetic x-point radius are shown. The radius of the x-point was calculated assuming that the discharge current was a line current on the geometric axis of the vacuum vessel. The octupole field, which was applied prior to the discharge initiation, clearly affected the plasma current build-up. The current rise was slower compared to discharges without octupole field. The plasma current rose to a value about equal to the current in each toroidal ring for this case. The discharge was presumably initiated along the low field region of the octupole field, near the minor axis. The plasma radius, defined by the separatrix radius, then increased with the plasma current amplitude. After the start-up phase, the plasma current and octupole coil current exhibited similar time dependences resulting in a radially stationary separatrix.

A calculated flux plot corresponding to the experimental case presented in Fig. 8 is shown in Fig. 9. The flux plot was obtained by a numerical solution of the Grad-Shafranov equation assuming vanishing plasma pressure at the separatrix. The plasma boundary, defined by the separatrix, is well separated from the vessel wall.

5. F = 0 discharges

For discharges with the ULQ-type of toroidal field circuit, where the TF-coil current was fixed on the time scale of the discharge, the plasma resistivity increased along with the fluctuation level as the edge safety factor approached $q = 1/\epsilon$ (which corresponded to a pinch parameter Θ of about 0.6). In addition, the plasma self-generation of toroidal magnetic flux became stronger. The increased fluctuation activity and the toroidal flux generation was associated with the RFP dynamo. Sustained ULQ discharges with the pinch parameter Θ exceeding 0.6 were not obtained. In order to achieve discharges with $\Theta > 0.6$ and RFP discharges, the toroidal field circuit was changed to provide a TF coil current pulse which decreased on the time scale of the rising plasma current. The plasma discharge was initiated 150 µs after the start of the B_φ pulse and the discharge current rose in about 100 µs as the TF coil current fell to zero. Pulse data for a case where the toroidal field current was switched off when the current reached zero is shown in Fig. 10. For this case we obtained sustained pinch discharges with $\Theta \approx 1.5$ and $F \approx 0$. The plasma discharge continued for over 1 ms with the TF coil open and toroidal flux was generated during this period. This duration corresponds to over 10 times the vertical field penetration time of the segmented shell. The termination of the discharge current, which was about 15 kA, occurred due to the iron core saturation.

The time-evolution of the parameters F and θ, shown in Fig. 11, were calculated from measurements of the toroidal flux and the toroidal field at the liner. This field at the liner was monitored by coils which measured the toroidal field over 60-degree poloidal sectors, one each on the inboard, outboard, top and bottom of the liner minor circumference. The coils had a 2-mm radial width and lie in the bellows convolution at a minor radius of 60 mm. At this measuring point, fluctuations in the toroidal field were seen and therefore the observed field reversal ratio, F, showed oscillations around zero during the sustainment of the discharge. The pinch parameter, Θ, was about 1.8, but increased to a larger value at discharge termination.

Oscillating fluctuations which were quite regular were seen on the cosine and sine coils. The fluctuations seen on the sine coil and the cosine coil had a phase difference of $\pi/2$. This phase difference was fixed throughout the pulse although the frequency of the oscillations increased during the pulse. Although an analysis of the spectra has not been carried out, these signals suggest that there was an $m = 1$ helical structure, with a fixed toroidal mode structure, that rotated with a varying velocity during the pulse.

Fluctuations with the same frequency were seen on other magnetic diagnostics at different toroidal positions indicating that the helical structure extended over the full toroidal circumference.

The sine and cosine coils were calibrated and the amplitude of the signals are expressed in the figures as a shift, in millimetres, of the discharge axis in major radius horizontally (Δr) or vertically (Δz). For these discharges, if the entire plasma current has a helical structure, then typical signal amplitudes correspond to displacements of the helix of about ±3 mm which is about 5% of the minor radius.

6. RFP discharges

When the reversal stage of the toroidal field circuit was implemented so that the TF coil current reversed, RFP discharges were sustained. An example of a discharge with reversal is shown in Fig. 12. The plasma current, TF coil current and average toroidal field during the pulse show RFP operation. The pulse was sustained for 800 μs which was about 10 shell penetration times. The magnetic fluctuations, observed with cosine and sine coils, were generally irregular, having several frequency components. However in this shot, a slow coherent oscillation appeared around 200 μs after discharge initiation (Figs 12f and 12g). The amplitude remained unchanged for about 300 μs and the radial and vertical displacements were $\pi/2$ out of phase, suggesting a rotating, saturated, helical perturbation. Towards the end of the discharge pulse, the signals became in phase, consistent with a non-rotating mode, and at the same time the perturbation amplitude increased. The discharge termination occurred prematurely, before iron-core saturation, and we speculate that the termination was caused by the growing, wall-locked, mode (as observed in other resistive shell RFP experiments [3]). We note that the plasma current gradually decayed during the pulse and was already low at termination. Most likely, the relatively high loop voltage requirement, for the RFP discharges, was partly due to the short field penetration time of the shell [3, 4].

A graph of F versus Θ during the pulse is shown in Fig. 13. As field reversal occurred in the set-up phase of the discharge, the F-Θ trajectory approached the PFM model curve. At the termination of the discharge Θ increased and the trajectory departed from the model curves.

The difference between the mode spectra for $F = 0$ operation and RFP operation is also evident in discharges where the TF coil current is reversed for the initial part of the shot and then switched to zero during the pulse. When $F < 0$, the sine and cosine signals were in phase indicating that an $m = 1$ kink perturbation was located at the toroidal position of the coils. When F switched to zero, the regular oscillations were again seen with a phase shift of $\pi/2$ between the sine and cosine coil signals.

7. Summary

Ultra-low q discharges, with toroidal currents in the range 20 - 50 kA and pulse lengths up to 2 ms were studied. The time-evolution of the plasma current during an ULQ discharge showed the typical step-wise decay. The current steps corresponded to transitions of the edge q-value across rational values. During a step through a rational q value, there was an increase in the fluctuation activity and a corresponding increase in the plasma resistance. The duration of the interval between a step could be as long as 5 shell penetration times. The discharges were sustained with good toroidal equilibrium position maintained throughout the discharge using an external vertical field. In the ULQ mode the toroidal field circuit had a large inductance which tended to hold the current in the TF-coil constant on the time scale of the discharge. Although the TF coil current was fixed, toroidal flux was generated and the parameters F (reversal parameter) and Θ (pinch parameter) followed the typical RFP F-Θ trajectory (in the non-reversed regime).

A preliminary study of ULQ plasmas with a magnetic separatrix configuration was made. Globally stable discharges, with edge q-values in the range from 0.3 to 1, were sustained for more than 1 ms. There was no evidence of the characteristic step-wise current decay, observed in ordinary ULQ discharges. The magnetically limited discharges had a somewhat higher resistance, in correspondence with the decreased plasma cross-sectional area.

The RFP mode was achieved when the TF power supply provided a reversed current in the toroidal field coil. RFP discharges were sustained for up to 0.8 ms with the reversal parameter in the range $-0.2 < F < -0.1$. In addition to this normal RFP operation, we have run discharges with F = 0. For this case, when the toroidal field current reached zero, the TF circuit opened and the coil current was zero for the remainder of the pulse which could last up to 1 ms.

The magnetic fluctuation spectra observed with m = 1 sine and cosine coils was quite different for the different modes of operation. For ULQ operation and operation with F = 0, the fluctuations observed with m = 1 sine and cosine coils were generally coherent, and the corresponding radial and vertical plasma displacements were $\pi/2$ out of phase, suggesting rotating, saturated, helical perturbations. For RFP operation the fluctuations were more irregular with several frequency components. Sometimes a growing, non-rotating, perturbation was seen. It was followed by a premature discharge termination, possibly caused by the observed mode.

The pulse data can be summarized by comparing the loop voltage requirements for the different modes of operation. In Fig.14, we show a summary curve of the bulk resistivity, including corrections for helicity, versus the pinch parameter. The bulk resistivity is defined in terms of the resistive component of the loop voltage, the plasma current, geometry factors and the helicity factor f. The helicity factor is estimated as a function of Θ using the model proposed by Sprott [11].

The ULQ mode operation was achieved with Θ less than about 0.6. The dependence of resistivity on Θ shows scatter in Fig. 14 due to the strong variations of loop voltage as a function of q(a), which was a result of the dependence on rational surfaces. When the toroidal field was weak so that Θ = 0.6 was approached, the resistivity increased significantly and sustained ULQ discharges could not be produced. However when an RFP type TF circuit was used, which allowed the TF coil current to decrease so that the parameter F was zero or negative, the resistivity was again lower. The resistivity for the RFP mode was slightly lower than for the F=0 mode, when the helicity factor was included.

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References.

1. Goforth, R.R., Carlstrom, T.N., Chu, C., Curwen, B., Grauman, D., Lee, P.S.C., Nilles, E.J., Ohkawa, T., Schaffer, M.J., Tamano, T., Taylor, P.L., Taylor, T.S., *Nucl. Fusion* **26** (1986) 515.

2. Tamano, T., Bard, W.D., Chu, C., Kondo, Y., La Haye, R.J., Lee, P., Saito, M., Schaffer, M.J., Taylor, P.L., *Phys. Rev. Lett.* **59** (1987) 1444.

3. Alper, B., Bevir, M.K., Bodin, H.A.B., Bunting, C.A., Carolan, P.G., Cunnane, J., Evans, D.E., Gimblett, C.G., Hayden, R.J., Hender, T.C., Lazaros, A., Moses, R.W., Newton, A.A., Noonan, P.G., Paccagnella, R., Patel, A., Tsui, H.Y.W., Wilcock, P.D., *Plasma Phys. and Contr. Fusion* **31** (1989) 205.

4. Robertson, S. and Schmid, P., *Nucl. Fusion* **27** (1987) 267.

5. Ho, Y.L., Prager, S.C., *Phys. Fluids* **31** (1988) 1673.

6. Drake, J.R., Brunsell, P., Brzozowski, J., Eninger, J. E., Hedin, E. R., Karlsson, P., Lehnert, B., Li, J., Scheffel, J., Sätherblom, H.E., Tennfors, E. and Wilner, B., *Plasma Physics and Controlled Nuclear Fusion Research 1988* (Proc. of 12th Int. Conf. Nice 1988) *Nuclear Fusion,* Suppl. Vol. 2, p. 751, IAEA, Vienna 1989.

7. Kamada, Y., Fujita, T., Murakami, Y., Ohira, T., Saitoh, K., Fuke, Y., Utsumi, M., Yoshida, Z. and Inoue, N., *Nucl. Fusion* **29** (1989) 713.

8. Taylor, P.L., LaHaye, R.J., Schaffer, M.J. and Tamano, T., *Nucl. Fusion* **29** (1989) 92.

9. Brunsell, P., Brzozowski, J., Bunting, C., Drake, J.R., Hellblom, G., Källne, E., Mazur, S. and Nordlund, P., *Controlled Fusion and Plasma Heating* (Proc. of 17th European Conf. Amsterdam 1990), **14B**, Part II (1990) 610.

10. Drake, J.R., Brunsell, P., Mazur, S. and Nordlund, P., to be published in Proc. of *Workshop on Physics of Alternative Magnetic Confinement Schemes,* Varenna, 15-24 October 1990.

11. Sprott J.C., *Phys. Fluids* **31** (1988) 2266.

12. Brunsell, P., Brzozowski, J., Drake, J.R., Hellblom, G., Li, J., Mazur, S., Nordlund, P, Tennfors, E. and Brynolf, J., to be published in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (Proc. of 13th Int. Conf., Washington, DC, 1-6 October 1990).

Table 1. Parameters of the T1 Device

Vacuum vessel:	major radius	0.5 m
	inside minor radius	57 mm
	bellows wall thickness	0.25 mm
	bellows material	316 L stainless steel
	vertical field penetration time	3 μs
	toroidal field penetration time	50 μs
Shell:	inside minor radius	67.5 mm
	shell wall thickness	2.5 mm
	vertical field penetration time	75 μs
	no of poloidal gaps	12
	no of toroidal gaps	2
Ohmic heating:	iron core flux swing	0.4 Vs
	no of cap. bank stages	3
	no of primary turns	4 or 8
	max initial one turn loop voltage	2 kV
	max sustainment loop voltage	1 kV
Octupole field:	no of coils	8
	coil minor radius	80 mm
Toroidal field:	no of coils	48
	coil minor radius	120 mm

Table 2. Plasma Parameters in ULQ regime.

Plasma current	10 - 50 kA
Current density	1 - 5 MA/m^2
Octupole coil current	0 - 50 kA
Toroidal field	< 0.25 T
One turn loop voltage	200 - 500 V
Conductivity temperature	10 - 20 eV
Discharge duration	1 - 2 ms
Alfvén transit time	≈ 1 μs
Filling gas pressure (H_2 or He)	1 - 10 mTorr

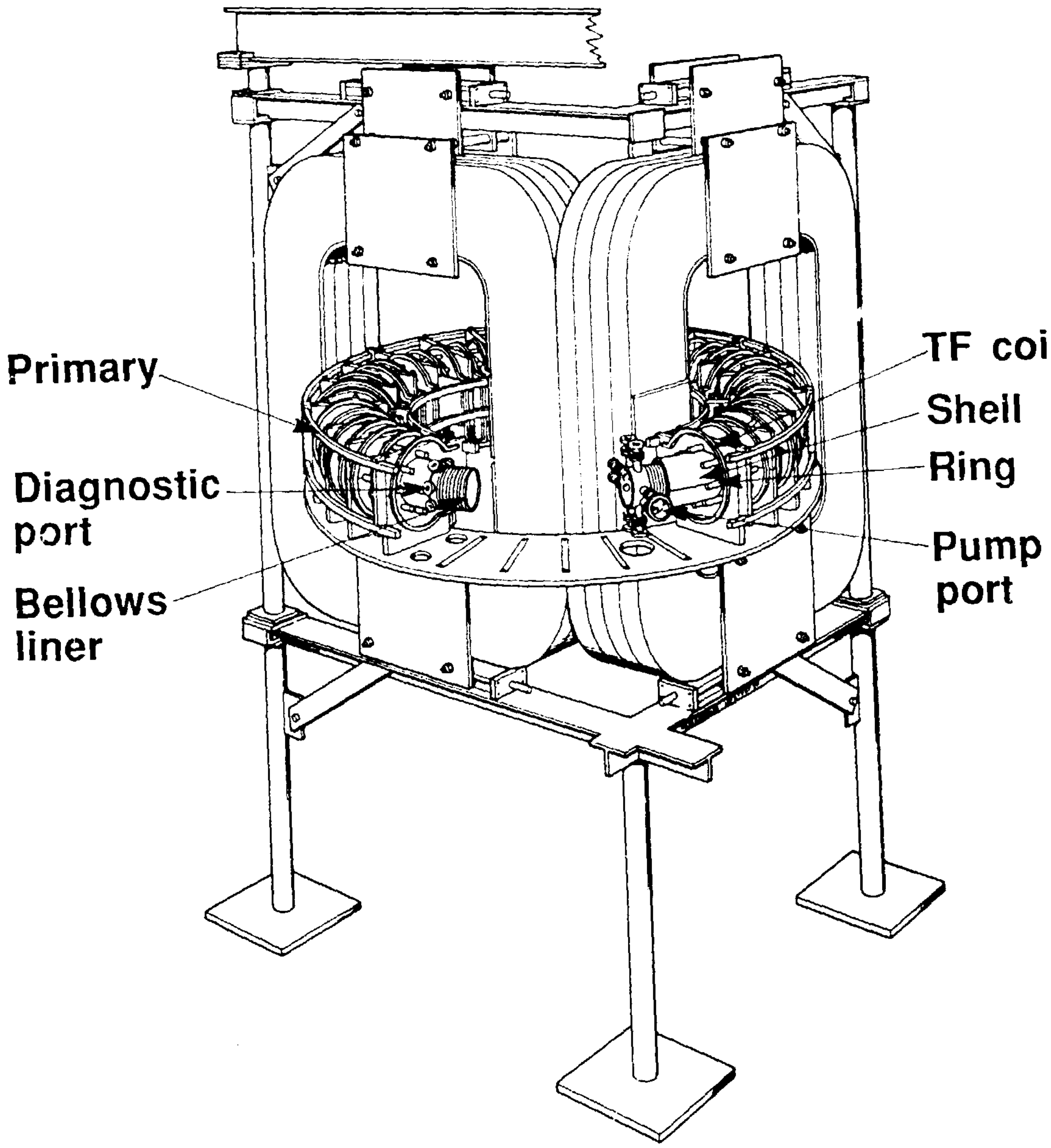

Fig. 1. Schematic drawing of the upgraded Extrap T1 experiment. The device incorporates a stainless steel bellows vacuum vessel located inside the octupole field ring conductors.

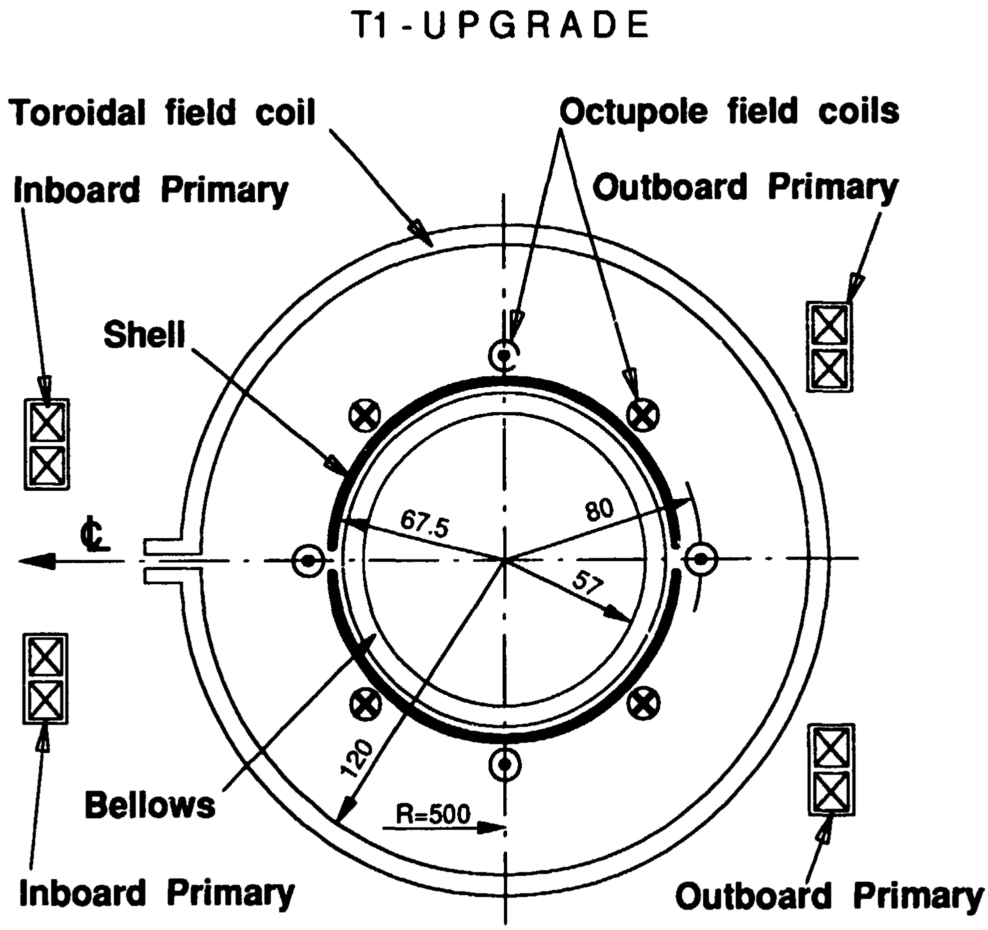

Fig. 2. Cross-sectional diagram of the device showing the bellows vacuum vessel, the resistive shell, octupole rings, toroidal field and primary coils. The primary winding produces the vertical field for plasma toroidal equilibrium control.

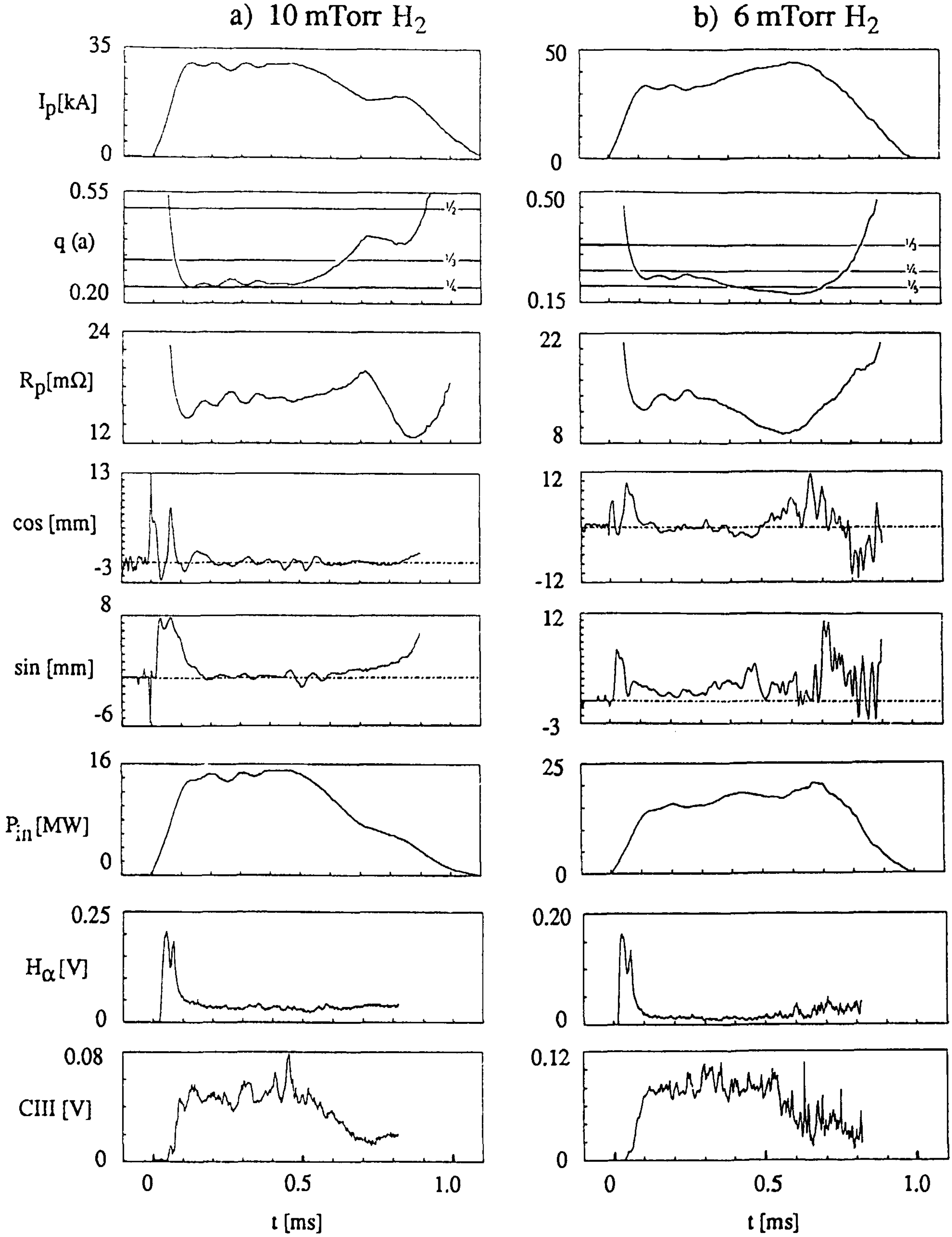

Fig. 3. Pulse forms for two discharges with different filling pressures. a) 10 mTorr H_2: The typical step-wise decay of the plasma current is clearly observed. b) 6 mTorr H_2: Radiation burn-through occurs about 0.5 ms into the discharge resulting in a drop in resistance which causes an increase in plasma current.

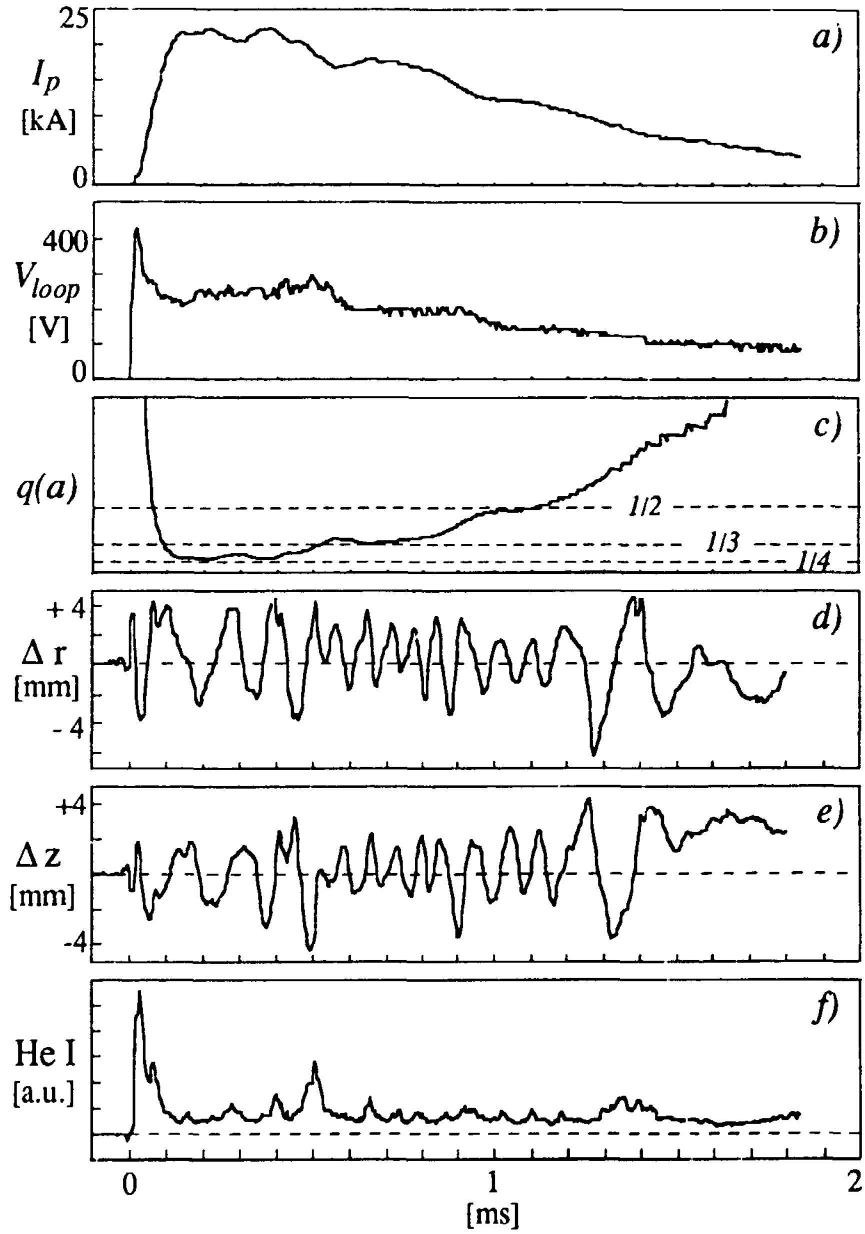

Fig. 4. Pulse forms for an ULQ discharge showing a) plasma current, b) loop voltage, c) safety factor at the liner, d) data from cosine coil showing radial displacement, e) data from sine coil showing vertical displacement and f) HeI line radiation monitor. There is clear correlation between plasma current steps, increased line radiation and frequency changes of the magnetic fluctuations.

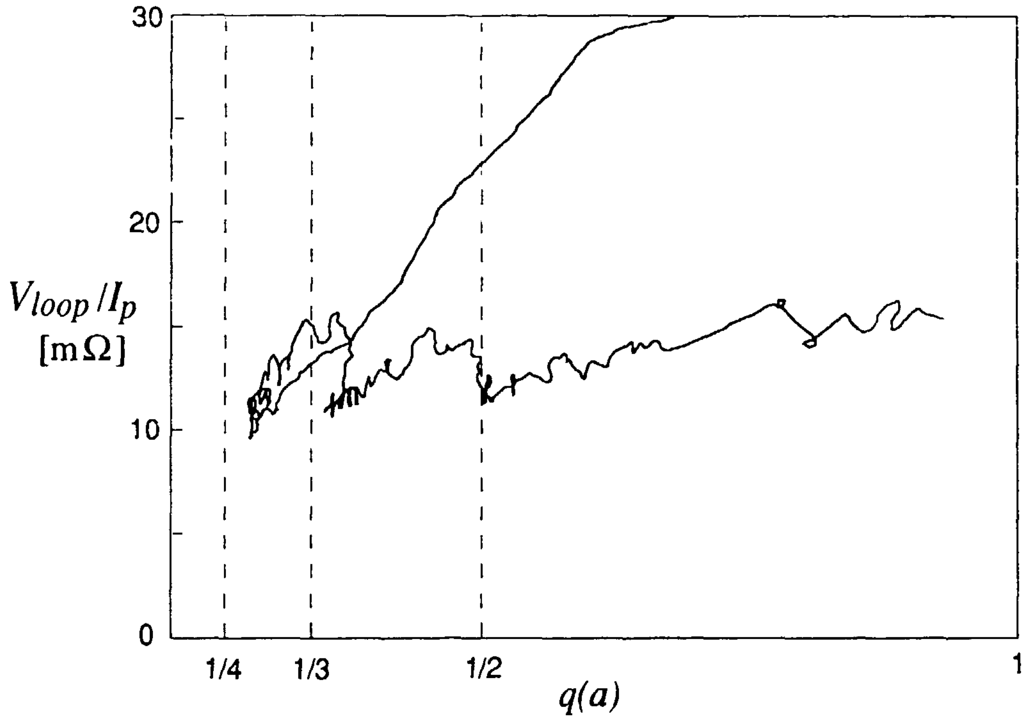

Fig. 5a. Time evolution of plasma resistance V_{loop}/I_p and safety factor q(a) for the ULQ discharge of Fig. 4. The plasma resistance is lower during the constant current periods and increases at the step transitions. (V_{loop} is the resistive part of the loop voltage obtained by subtracting the inductive dI_p/dt contribution from the measured voltage in a toroidal loop).

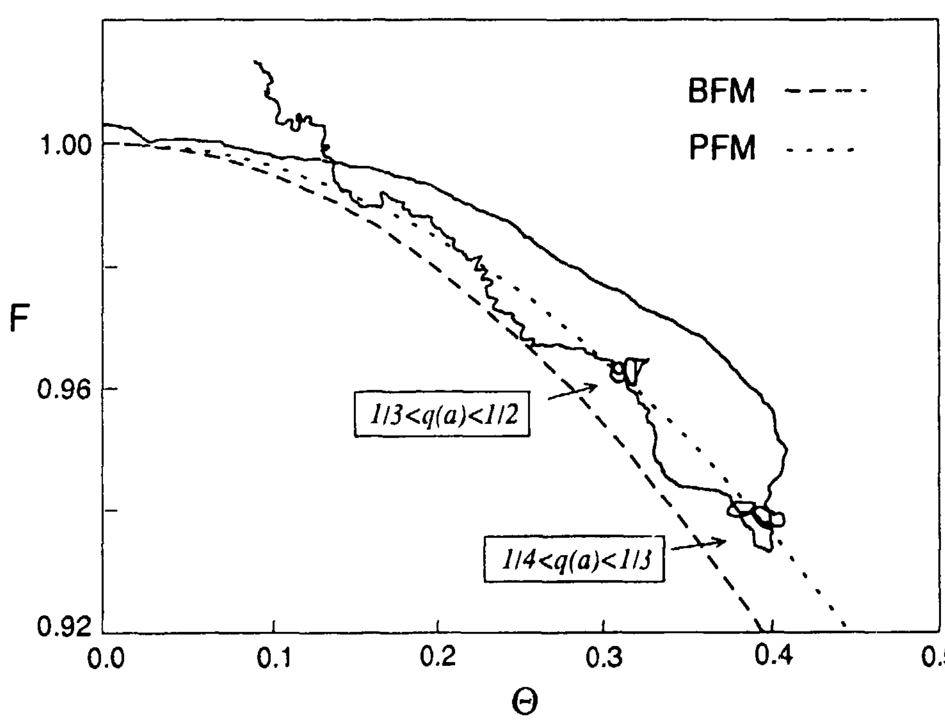

Fig. 5b. Time evolution of RFP parameters F (field reversal ratio) and Θ (pinch parameter) for the ULQ shot shown in Fig. 4. The Bessel Function Model (BFM) and the Polynomial Function Model (PFM) are plotted for reference. The experimental ULQ equilibria are in agreement with the PFM prediction during the two constant current periods.

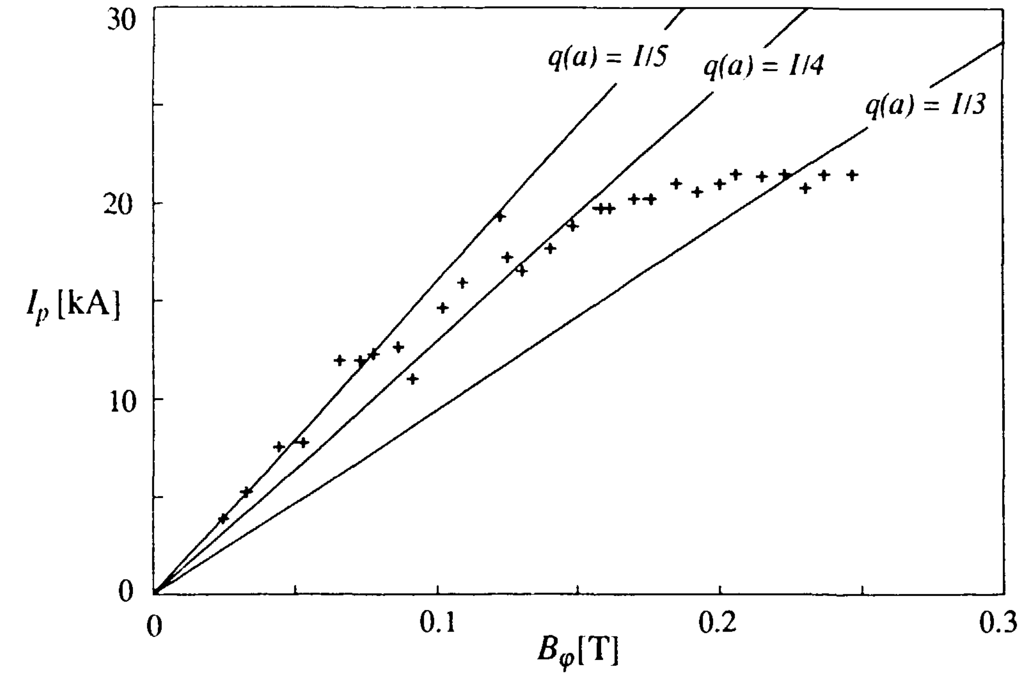

Fig. 6a. Plasma current I_p versus applied toroidal field B_φ for a series of discharges with fixed OHC bank voltages. There is an apparent current limitation at q(a)=1/4 which however is overcome for lower toroidal fields.

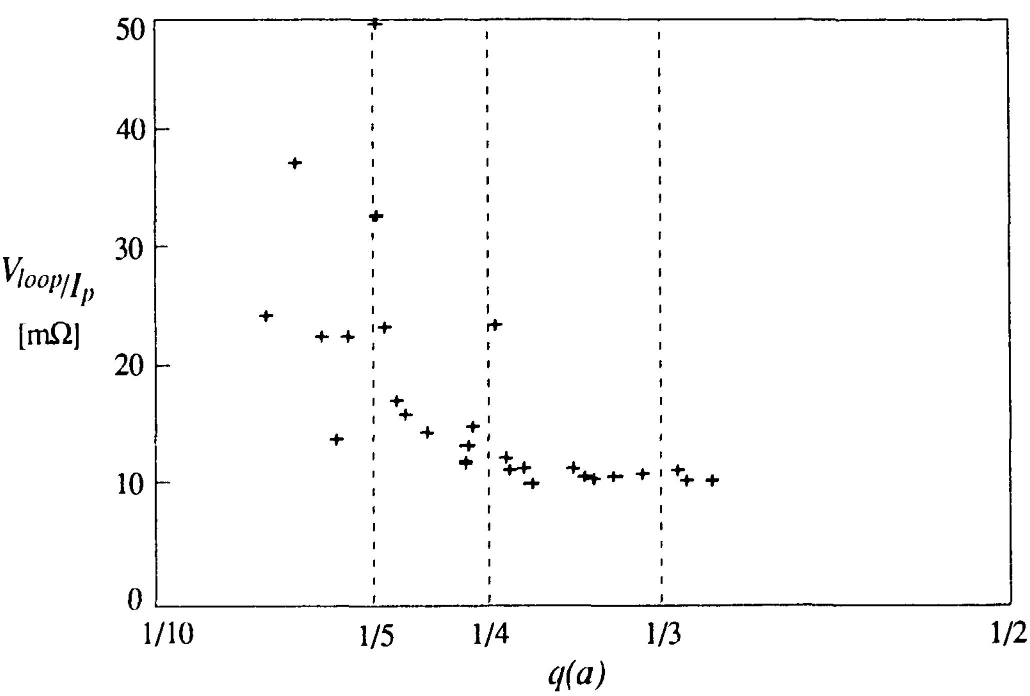

Fig. 6b. Plasma resistance V_{loop}/I_p versus safety factor q(a). There is a markedly increased resistance near the rational values q(a)=1/4 and 1/5, which explains the observed current limitation. The resistive part of the loop voltage, V_{loop}, is measured during the first flat top period of the current (exceeding 300 μs).

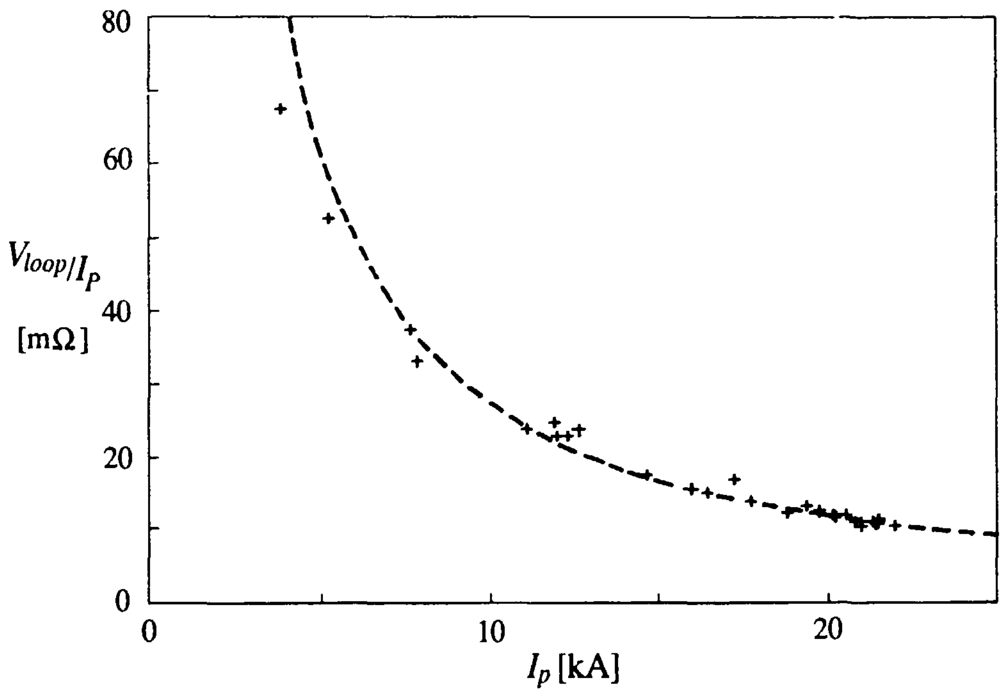

Fig. 7. Plasma resistance V_{loop}/I_p versus plasma current I_p. The curve represents the scaling $V_{loop}/I_p \propto I_p^{-1.2}$. Measured during first flat-top period of the current pulse.

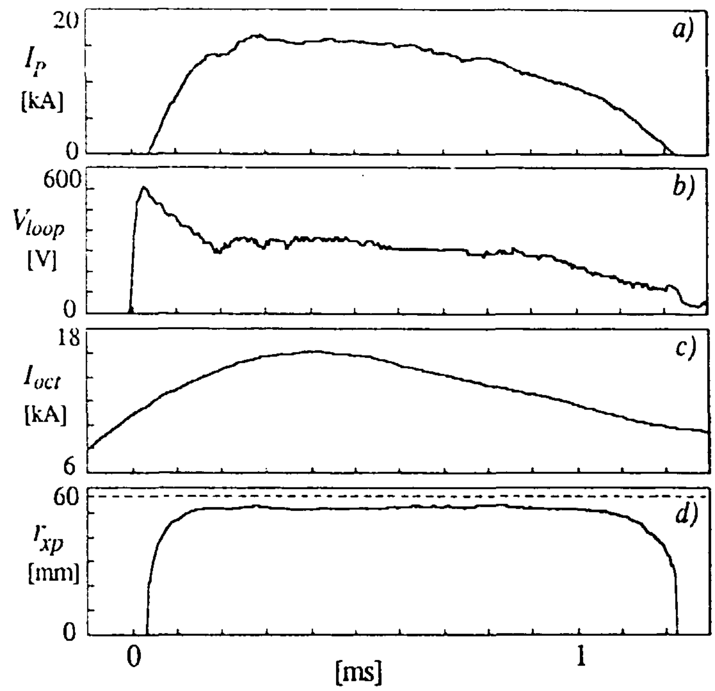

Fig. 8. Pulse forms for a magnetically limited ULQ discharge showing a) plasma current I_p, b) loop voltage V_{loop}, c) octupole coil current I_{oct} and d) magnetic x-point radius r_{xp} (The radius of the liner is drawn for reference). The plasma radius, defined by the separatrix, increases initially with the current amplitude. After start-up, the plasma current and octupole ring current have similar time-dependences, resulting in a stationary separatrix.

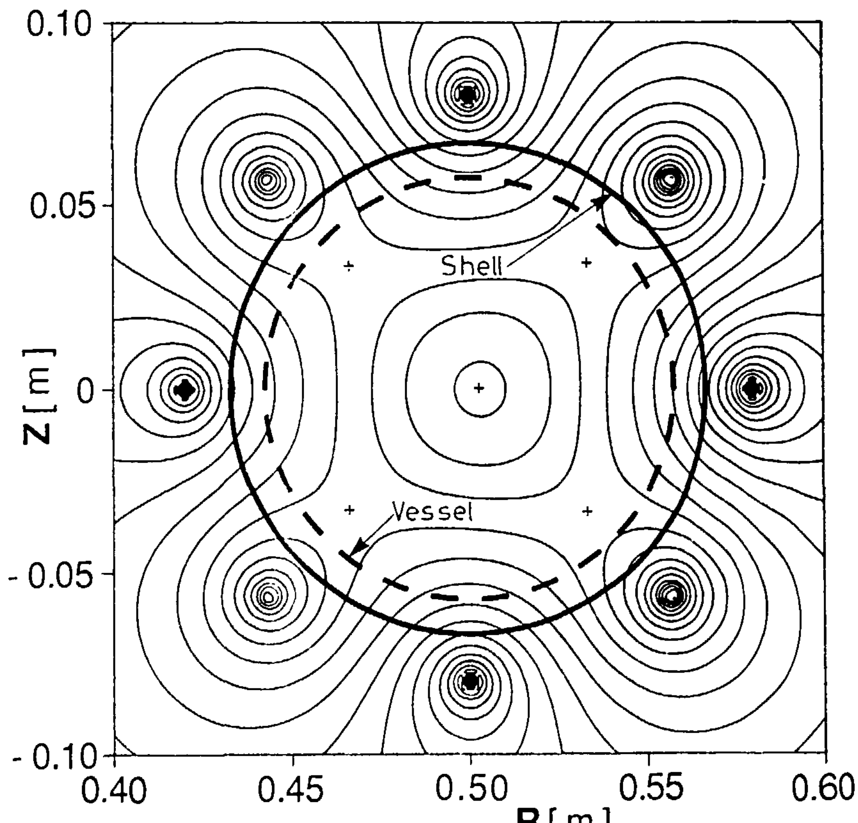

Fig. 9. Calculated flux plot corresponding to the ULQ magnetic separatrix configuration. The parameters are: I_p =15 kA, I_{oct}=15 kA, B_{vert}= -3 mT, β_{pol}=0.5.

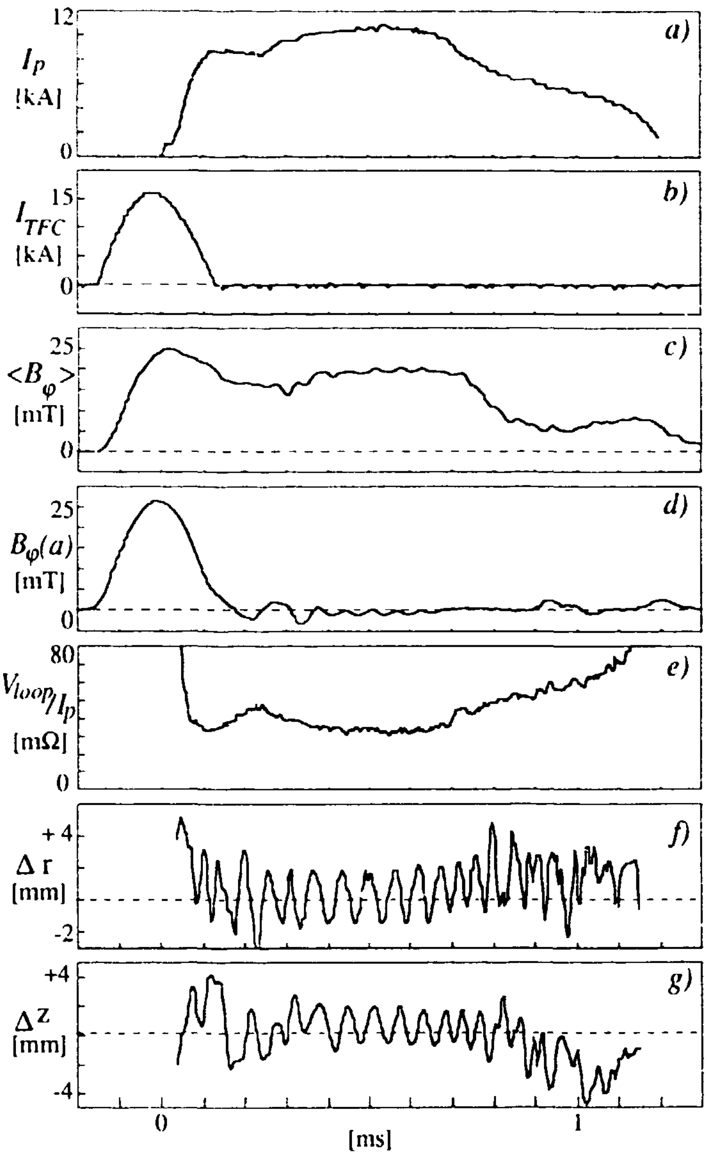

Fig. 10. Pulse forms for a shot with reversal parameter F=0 showing a) plasma current, b) current in the toroidal field coil, c) average toroidal field, d) toroidal field at liner, e) loop voltage divided by plasma current, f) cosine coil signal and g) sine coil signal. A coherent oscillation is observed on the magnetic signals, analogous to that seen in the ULQ case.

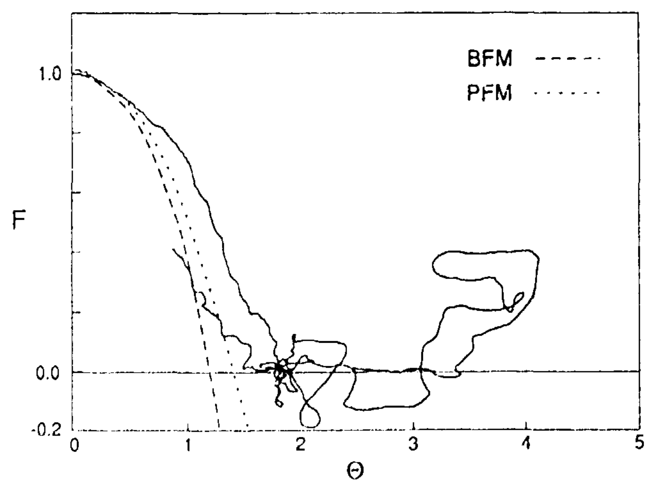

Fig. 11. Curve of field reversal ratio F versus pinch parameter Θ for the F=0 discharge in Fig. 10. The large excursion to high Θ values occurs at discharge termination.

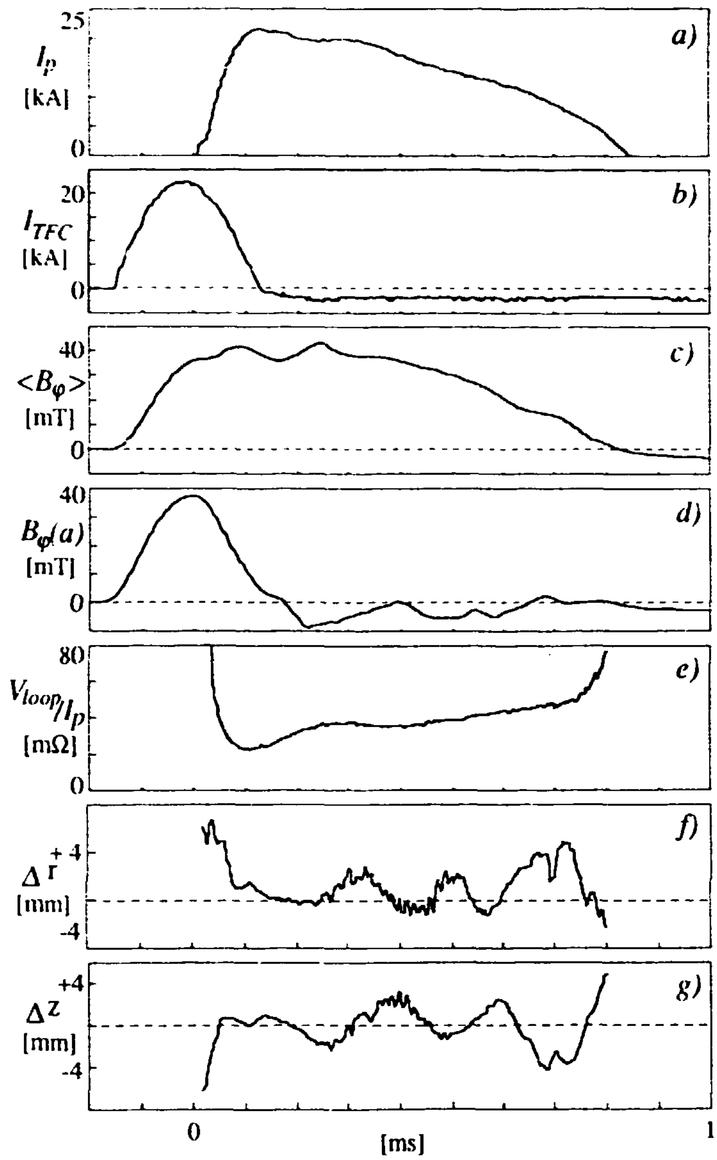

Fig. 12. Pulse forms for a discharge with reversed toroidal coil current showing a) plasma current, b) TF coil current, c) average toroidal field, d) toroidal field at liner, e) loop voltage divided by plasma current, f) cosine coil signal and g) sine coil signal.

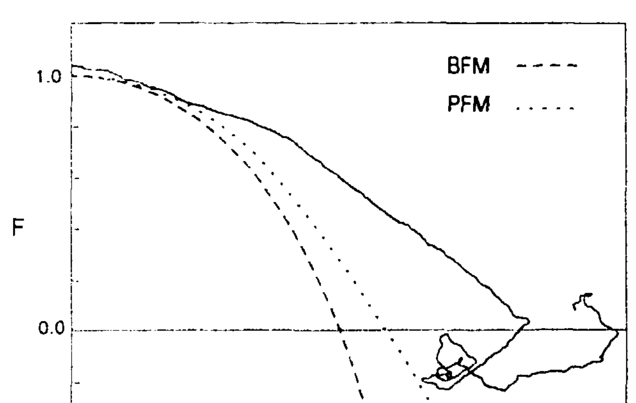

Fig. 13. Curve of field reversal ratio F versus pinch parameter Θ for the RFP discharge shown in Fig. 12.

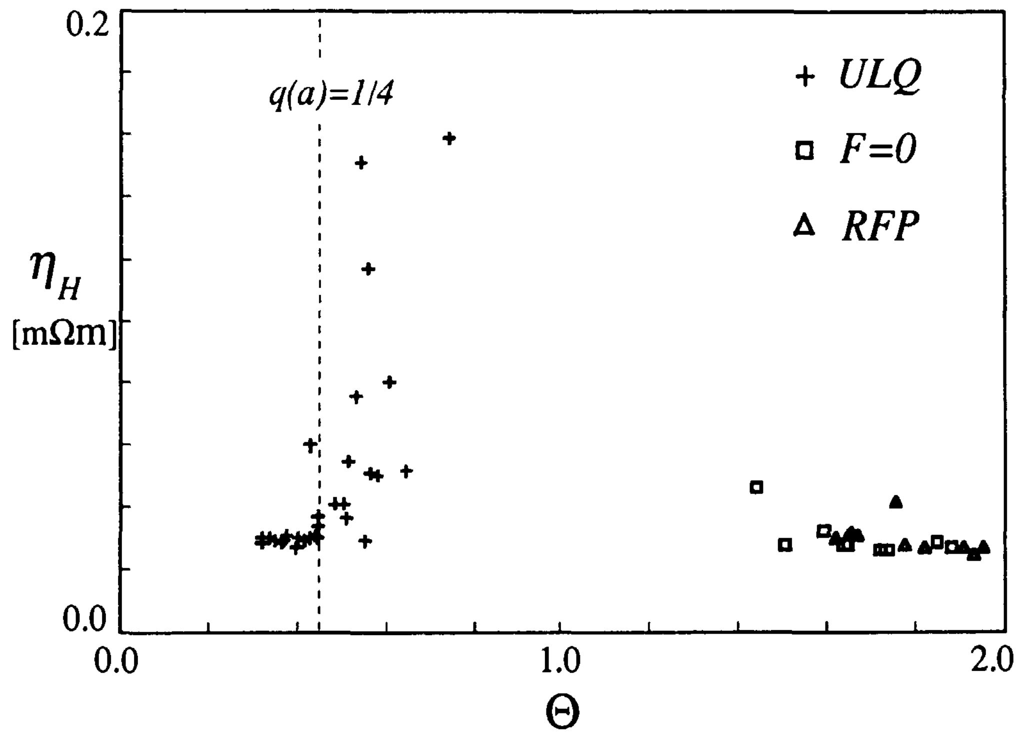

Fig. 14. Summary of resistivity versus pinch parameter for different modes of operation. There is large scatter in the data for the ULQ mode which is due to the strong dependence of resistance on the rational values of the safety factor. The line marked q(a) = 1/4 corresponds to the approximation F = 1.

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ULTRA-LOW q AND REVERSED FIELD PINCH EXPERIMENTS IN EXTRAP T1 WITH A RESISTIVE SHELL

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24 pages, in English

Abstract

The Extrap T1 device is a high aspect ratio toroidal pinch with the dimensions R/a = 0.5m/0.057m. In the experiments described here, the stainless steel bellows vacuum vessel was surrounded by a resistive shell with a perpendicular field penetration time of 75 ms.

The ULQ discharges, with toroidal currents in the range 20 - 50 kA and pulse lengths up to 2 ms, showed the typical step-wise decay of the plasma current. The current steps corresponded to transitions of the edge q-value across rational values 1/4, 1/3, 1/2, and 1. During a step through a rational q value, there was an increase in the fluctuation activity and a corresponding increase in the plasma resistance. As part of the ULQ studies, discharges with four poloidal field nulls were produced by applying an octupole magnetic field, thus demonstrating that is possible to sustain ULQ equilibria with poloidal field x-points and a magnetic separatrix.

In another study, the transition from ULQ discharges to relaxed state discharges was investigated. When the initial bias toroidal field was reduced so that q was less than about 1/6, which corresponded to a pinch parameter (Q) of about 0.6, a change in the discharge character was observed. The loop voltage required to sustain a given current increased and stochastic fluctuations were seen. Toroidal flux was generated and relaxed state equilibria developed. For higher Q, in the range of 1.5 to 2.0, a reversed field pinch could be set up if the toroidal field power supply provided a reversed current in the coils. The plasma resistivity was again lower and the pulse lengths in the RFP mode were up to 1 ms, corresponding to over 10 shell penetration times.

Key words

ULQ, Ultra-low q, RFP, Reversed Field Pinch, Extrap, resistive shell