Pramana - J. Phys., Vol. 39, No. 2, August 1992, pp. 181-191. © Printed in India.

Ultra low q_a discharge experiments in the SINP tokamak

A N SEKAR IYENGAR, S K MAJUMDAR, J BASU, R K PAUL, R PAL and S CHOWDHURY

Saha Institute of Nuclear Physics, Sector I, Block - AF, Bidhan Nagar, Calcutta 700064, India

MS received 13 May 1991; revised 4 June 1992

Abstract. Operation of most tokamaks in limited by q_a, the edge safety factor, which is usually about 2–3. In the SINP tokamak we have been able to obtain discharges with q_a values as low as 0·8. In this paper we describe our results on the setting up processes and the MHD activity associated with these ultra low q_a discharges.

Keywords. Edge safety factor; ultra low q_a; classical diffusion; MHD relaxation; $q(r)$ profiles; low Z impurities.

PACS No. 52·55

1. Introduction

Since 1950 extensive theoretical and experimental progress has been achieved in the toroidal magnetic confinement of high temperature plasmas (Kadomtsev *et al* 1990). The tokamaks with high energy confinement times and reverse field pinches with high toroidal beta (beta $= \beta_T =$ plasma pressure/magnetic field pressure $= 8\pi n_e/B_T^2$), where n_e is the plasma density and kT_e is the electron temperature, B_T is the toroidal magnetic field), have proved to be the most stable systems amongst the present generation of toroidal systems. Though they can be produced in the same toroidal device, they differ in the ratio of the poloidal magnetic field B_P, to the toroidal magnetic field B_T. In the case of tokamaks $B_P/B_T < 1$ while in reverse field pinches this ratio is > 1. This ratio is usually expressed in the form of a figure of merit called the safety factor q_a where a is the plasma minor radius. In cylindrical approximation q_a is generally expressed in terms of the dimensions of the torus and the magnetic field ratios by the relation $q_a = aB_T/R_O B_P$ where R_O is the major radius of the torus and $B_P = \mu_0 I_P/(2\pi a)$, where I_P is the plasma current. The edge safety factor q_a is also related to the other important figure of merit β_T which according to Troyon's scaling (Troyon *et al* 1984) is given by $\beta_T = ca/R_O q_a$, where c is a constant. Thus one can obtain a higher β_T by lowering q_a, leading to a higher current density at a given toroidal magnetic field, which is essential for a viable compact reactor. This fact has motivated research activities on low q_a operation of the tokamaks.

Tokamaks are usually operated at $q_a > 3$ to avoid major disruptions but some authors claim to have obtained ultra low q_a discharges even at $q_a \approx 1·5$ (Berlizov *et al* 1981). A better classification of the toroidal devices has been provided on the basis of current profiles by Yoshida *et al* (1987), which is as follows: $q_a > 2$ are conventional tokamaks, $1 < q_a < 2$ are very low q_a tokamaks and $0 < q_a < 1$ are called ultra low

q_a configurations. In the conventional and very low q_a tokamaks $dq(r)/dr > 0$ while in ultra low q_a configurations $dq(r)/dr < 0$ in the major part of the plasma and $dq(r)/dr$ may be > 0 at the periphery. Reverse field pinches also have $dq(r)/dr < 0$ but $q(r) < 0$ at the periphery. It has been shown that tokamaks are dominated by classical diffusion (Grad and Hogan 1970), but during sawteeth oscillations and major disruptions they exhibit MHD relaxation type of behaviour while reverse field pinches are completely dominated by MHD relaxation (Taylor 1974).

Extensive numerical simulation has been carried out (Yoshida *et al* 1987; Kusano *et al* 1988 and Murakami *et al* 1988) to determine the dynamics and stability of the ultra low q_a configuration. It was shown that the ultra low q_a configurations is located between the tokamak and RFP and exhibits characteristics of both kinds: diffusion and MHD relaxation. So besides technological advantages, study of ultra low q_a discharges would enhance our understanding of the MHD processes in magnetic confinement systems.

Mirnov and Semenov (1971) carried out some experiments in which they could surpass the mode rational surface barriers by a fast current rise. Following this idea we were able to obtain stable low q_a discharges < 2 using fast current rise rates in combination with the closely fitted conducting shell in the SINP tokamak. An interesting feature of our results is that the ultra low q_a discharges exhibit a more stable equilibrium than the high q_a discharges.

We describe briefly the experimental set up and the diagnostics in § 2. The results and discussion are presented in § 3 and conclusion in § 4.

2. Experimental set up

The experiments were performed in the SINP tokamak with plasma major radius $R_O \approx 30{\cdot}0$ cm, minor radius $r \approx 7{\cdot}5$ cm. A 50 turn ohmic heating coil wound around the central limb of an iron core form the primary and the plasma current $(I_p) \approx 20$–30 kA serves as the secondary of the transformer system. The stainless steel vacuum vessel is surrounded by an aluminium conducting shell with a time constant of 13 mS (without cuts). The vacuum system was initially evacuated by a turbo molecular pump to a base pressure of 1–3×10^{-7} Torr and was filled with hydrogen before the discharge to a pressure of 3–4×10^{-4} Torr. Capacitor banks were used to power the toroidal, vertical and the Joule heating coils.

The main diagnostics deployed for these expriments were the Rogowski coil, loop voltage coil, $\cos\theta/\sin\theta$ coils and the Mirnov coils (Huddlestone and Leonard 1965; Equipe 1978; Miyamoto 1980). The Rogowski coil was used to measure the plasma current and the $\cos\theta/\sin\theta$ coils to measure the position of the plasma column. The toroidal electric field was measured using the loop voltage from which one can also obtain a rough estimate of the plasma resistivity temperature when $dI_p/dt \approx 0$. The Mirnov coils or the B_θ coils were used to obtain the various modes of the instabilities generated in the plasma.

3. Results and discussion

3a. *Preliminary results*

The toroidal magnetic field was raised to the desired peak value in about 7 mS. Gas puffing was initiated about 300 mS before the initiation of the discharge. When the pressure attains the required value, the stored energy in the capacitor was discharged into the ohmic coils, which serves as the primary. Induced voltage in the secondary ionizes the neutrals and also raises the plasma current to the desired value.

We did not have either low temperature Taylor discharge cleaning or glow discharge cleaning and had to resort to baking the vacuum vessel for about 8 to 10 h at 120°C for cleaning it. After this we fired about 30 to 40 low power tokamak discharges with TF = 1·5 kgauss and plasma currents 1–2 kA. Low Z impurities (oxygen, carbon) which will be present on the surfaces exposed to the plasma are largely but not completely removed by extensive running of tokamak discharges. Since we could obtain the low q_a discharges without extensive cleaning, we concentrated more on repeatability and reproducibility rather than on the role of impurities, as suggested by Morris (1985).

Under this condition, we set the toroidal field to about 8 kgauss and the primary voltage at 4·5 kV. This produced a secondary voltage (loop voltage) of about 90 V, which ionized the neutrals and increased the plasma current to about 27 kA. Figure 1

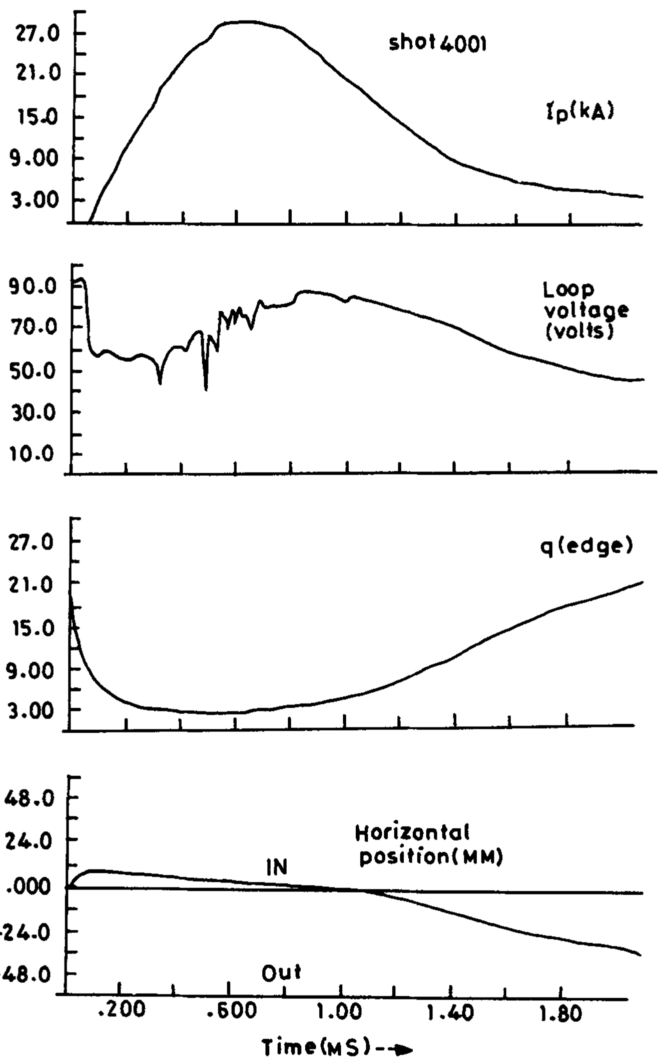

Figure 1. Plasma current I_p, loop voltage V_{loop}, $q_a(t)$, and horizontal position for $q_a = 2{\cdot}8$ discharge.

shows a plot of plasma current I_p loop voltage time evolution of q_a and horizontal position for the same discharge. The q_a value estimated at the peak of I_p is about 2·8. In this paper we have followed the usual convention of defining q_a in its cylindrical approximation as mentioned in § 1. The value of q_a with the toroidal corrections has been derived by Cheetham *et al* (1985) and since the error involved in using q_a(cyl) is $< 10\%$ we have used the cylindrical approximation throughout the paper.

Negative going spikes are observed in the loop voltage signal during the rise phase of plasma current when the rational surfaces are formed and which have been associated with the transformation of a hollow profile into a flat/peak profile through the double tearing modes in the current rise phase (Stix 1976; Granetz *et al* 1979). The q_a values at the instant of the spikes are 4 and 3. We do not observe the spikes at $q_a = 5$, 6 etc. The loop voltage after reaching a minimum once again begins to increase in some discharges with high filling pressure.

Keeping the primary voltage constant we gradually lowered the toroidal field in steps till we could obtain a minimum q_a value of 0·8. By reducing the toroidal field further below 1·5 kgauss we could not strike a discharge. Figure 2 shows a plot of

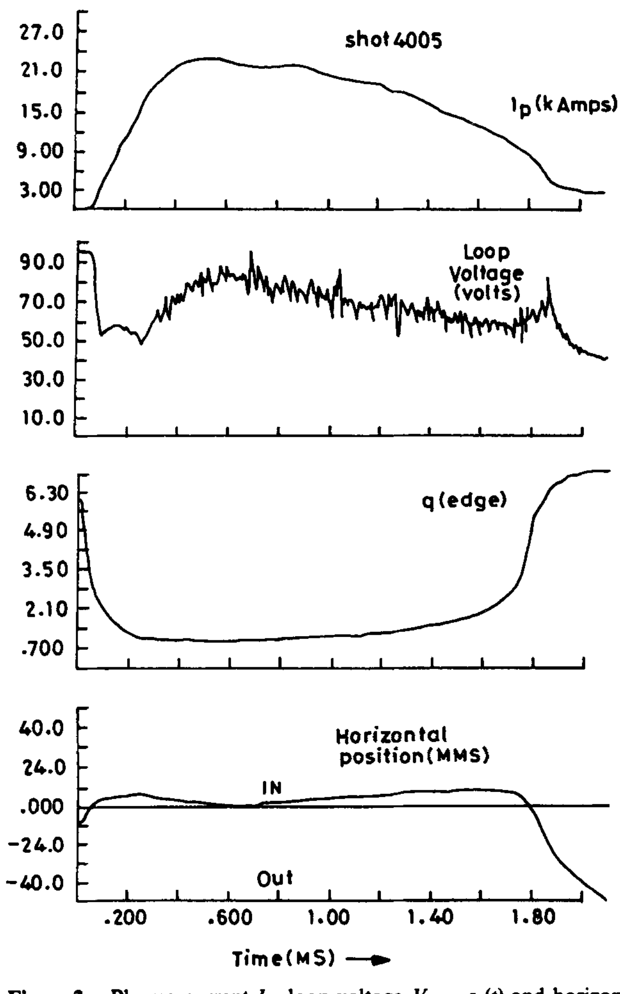

Figure 2. Plasma current I_p, loop voltage V_{loop}, $q_a(t)$ and horizontal position for $q_a = 0{\cdot}8$ discharge.

plasma current I_p, loop voltage, time evolution of q_a and horizontal position for the $q_a \approx 0{\cdot}8$ discharge at a toroidal field of 2·0 kgauss. Comparing the two discharges of figures 1 and 2 we find a remarkable change in the current and loop voltage signals. The current in figure 1 corresponding to a $q_a \approx 2{\cdot}8$ discharge decays quite rapidly. On the contrary the low $q_a \approx 0{\cdot}8$ discharge current decay is slower by a factor of 2·5 than the high q_a, discharge and exhibits a stepwise behaviour as it decreases, like in other ultra low q_a discharges (Taylor *et al* 1989; Kamada *et al* 1989).

The negative going loop voltage spikes which are seen in the high q_a (figure 1) discharges are absent in the ultra low q_a discharge, which indicates that MHD relaxation associated with tearing modes are eliminated. Similar observations were made in other tokamaks (Berlizov *et al* 1981; McGuire 1979; DIVA 1980). But the loop voltage signal of the ultra low q_a discharge exhibits a turbulent feature and hence a different type of MHD behaviour more similar to reverse field pinches and could lead to ion heating (Yoshida 1990a). Figure 3 is a plot of plasma current at different q_a values. The plots show that the plasma current decay time progressively gets slower as q_a is lowered. This observation coupled with the absence of negative spikes shows that the plasma stability improves as the discharges tend towards ultra low q_a configuration.

Since stability is also related to the position of the plasma column, we compared the plasma column position in the high q_a and low q_a discharges. It is observed as shown in figure 1 that in the $q_a \approx 2{\cdot}8$ discharge, the plasma column initially moves outwards towards the centre and gradually continues to drift outwards till the end of the discharge. But in figure 2 of the ultra low q_a discharge the plasma column

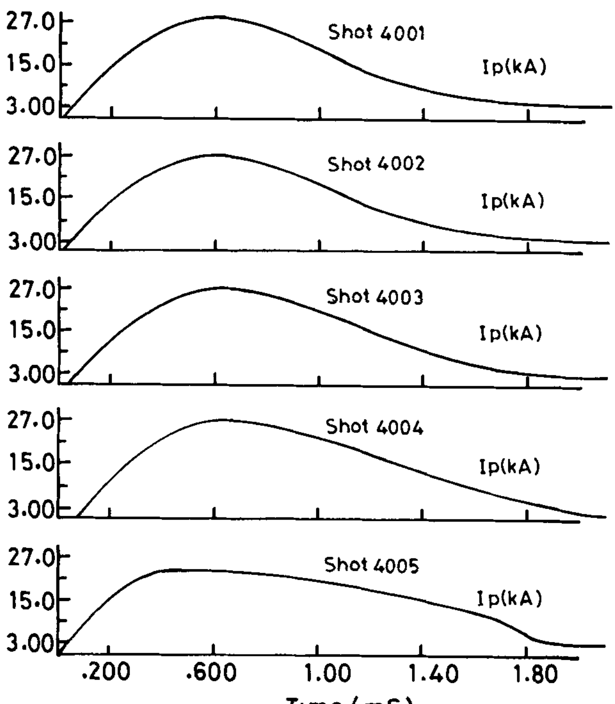

Figure 3. Plasma current I_p for different q_a discharges. Shot 4001 $q_a = 2{\cdot}8$, shot 4002 $q_a = 2{\cdot}29$, shot 4003 $q_a = 1{\cdot}5$, shot 4004 $q_a = 1{\cdot}11$, shot 4005 $q_a = 0{\cdot}8$.

moves outwards towards the centre bit is again pushed back towards the inside and thereby improving the stability. This observation also explains why the decay of plasma current is slower and hence more stable in the ultra low q_a case than in the high q_a discharge.

3b. *Self organization of plasma*

The next interesting aspect of ultra low q_a equilibrium configuration is the self organization phenomena wherein plasma current decreases not in a continuous fashion but by a stepwise behaviour and thus avoid the major rational values of $q_a = 1, 1/2, 1/3, 1/4$ ... etc. It does this by MHD relaxation process whereby an $m = 1$ mode is triggered which raises the central q value (q_0). As a result the profile is modified from a hollow profile to a paramagnetic profile with $dq(r)/dr < 0$ throughout the minor radius. Beyond a certain stage, classical diffusion sets in and changes it to a tokamak like profile. After this the profile continues in this mode till the end of the discharge.

Kusano *et al* (1988) carried out a numerical simulation and observed that if the growth time of the instability is shorter than the resistive diffusion time, then the MHD activity would lead to a shift of the plasma which thereby increases the central q value (q_0) and later classical diffusion would modify this profile to a monotonically increasing profile.

We also observe a self organization type of behaviour in our ultra low q_a discharges wherein plasma current remains at $q_a \approx 0{\cdot}8$ for a certain duration and exhibits a stepwise behaviour as it decreases to a lower value. This is shown in figure 4 where a growth of MHD activity is seen before the second step. The growth time of this $m = 1, n \geqslant 1$ mode measured with a poloidal magnetic probe (B_θ) is about 50 μS which is quite low compared to our resistive diffusion time scales (approximately 250 μS at

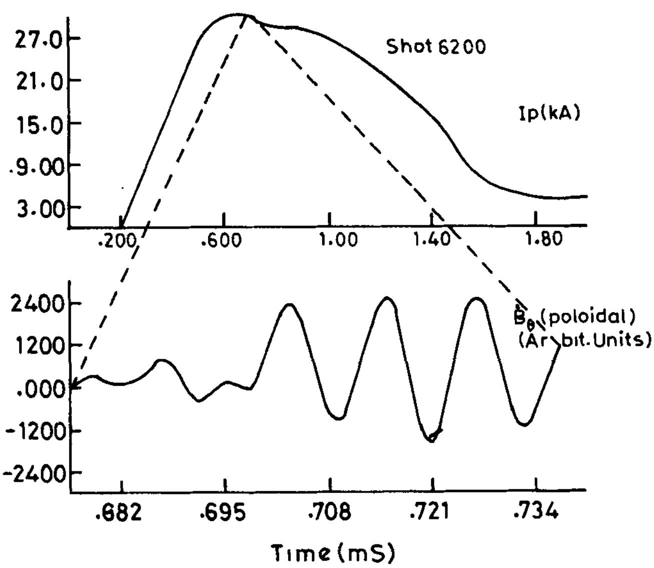

Figure 4. Plasma current I_p decreasing with a step in ultra low q_a discharges (top). Plot below exhibits growth of MHD activity (obtained with B_θ probe), before plasma current settles down to another quasi equilibrium state.

a modest Z_{eff} value of 2). Hence as observed in numerical simulations and experiments (Kusano *et al* 1988; Murakami *et al* 1988; Itami *et al* 1988) it is likely that we started with a $dq(r)/dr < 0$ profile with $n > 1$ (since the q_a value in our ultra low q_a discharge lies between $1/2 < q_a < 1/1$) which is reduced to $n = 1$ by $m = 1$, $n = 1$ global kink instability via MHD relaxation. Following this classical diffusion modifies the profile to a tokamak profile with $dq(r)/dr > 0$. In many experiments (Taylor *et al* 1989; Robinson and Todd 1982a, b) only a paramagnetic profile with $dq(r)/dr < 0$ and not a hollow profile was observed like those in the ramped up discharges on Repute I. It was also shown by Yoshida *et al* (1986) that the hollow profile first gets modified to a paramagnetic profile due to MHD relaxation of the $m = 1$, $n > 1$ mode, and finally evolves into a tokamak like profile due to classical diffusion. Since we did not have the internal magnetic probes we could not obtain the $q(r)$ profiles for these experiments. However we can make an approximate estimate of the central q value (q_0) from the relation:

$$q_0 \approx \{1 + 2(1 + \varepsilon/2)^2 \varepsilon^2/q_a^2\}^{1/2} q_a \tag{1}$$

where $\varepsilon = a/R_0$ is the inverse aspect ratio obtained by Murakami *et al* (1988) for an ultra low q_a configuration from a force free equilibrium model. This value yields a central q value $q_0 \approx 0{\cdot}9$ which indicates that our $q(r)$ profile could be a flat profile across the major part of the plasma and decreasing towards the edge. The broad current profile can also enhance stability, since broadening of the current profile at fixed total current effectively moves the current channel closer to the conducting wall and thereby providing stability.

Our results of low q_a discharges at $q_a \approx 0{\cdot}8$ are quite contrary to the DIVA (1980) results where they observed that the plasma became unstable at low $q_a \approx 0{\cdot}8$ discharges. DIVA mentioned that their ultra low q_a becomes unstable, no detailed results are presented, since they were contended with stable discharges $q_a > 1$ the entire analysis is also concentrated to this phase. DIVA had a tear drop shaped conducting shell inside the vacuum and hence the plasmas were non circular as reported in the paper. DIVA had conjectured that the unstable nature of the discharge could be due to a growing $m = 1$, $n = 1$ mode associated with a sudden rise in loop voltage. This is possible since, as discussed in § 3b, the $m = 1$, $n = 1$ modes are responsible for profile modification and accompanying reduction of I_p. In our experiment these modes seem to grow about 50 μS after I_p reaches the peak value. But if these modes are activated even before I_p reaches peak value as in DIVA, it is impossible to maintain a stable discharge. It has been shown by Murakami *et al* (1988) that a hollow profile is necessary to maintain discharges with $q_a < 1$. But an $m = 1$ mode destroys the profile and renders it to a tokamak like profile. This is perhaps what is happening to DIVA. We guess that because of the peculiar shape of the conducting shell it is unable to stabilize the mode in spite of its thickness being four times larger than ours.

3c. *Setting up and stability of ultra low q_a discharges*

Now the next question to be answered is the setting up of the ultra low q_a discharges. It was pointed out by Mirnov and Semenov (1971) that with a fast current rise one could surpass the mode rational surface barrier and obtain lower q_a values. Thus Mirnov and Semenov (1971) could surpass the $q_a = 2$ surface and obtain a $1 \leqslant q_a \leqslant 2$ discharge. But they were not able to obtain lower q_a. TFR Group (1985) also attempted a fast current rise but could never operate below $q_a \approx 2$. Yoshida *et al* (1990b) were the first to present a scaling for current rise to surpass the $q_a \approx 2$ surface and attain lower q_a values. It appears that the current should cross the rational surface barriers in a time faster than the growth time of the $m = 2$, $n = 1$ mode which has been detrimental to tokamak operation below $q_a < 2$ to attain discharges with q_a value at the peak < 2. From the experimental observations as in figure 5 the typical growth time of the MHD activity ranges from 30 to 50 μS. Theoretical estimates for the growth times [White (1986)] of an ideal, marginally unstable $m = 1$, $n = 1$ mode (since this mode prevents stable ultra low q_a configurations) given by the relation

$$\tau(\text{growth time}) = (R/a)^2 * S_\theta^{1/3} * \tau_{\theta a}$$

where R/a is the aspect ratio, S_A is the poloidal Reynold's number and $\tau_{\theta a}$ is the poloidal Alfven (MHD) time scale, is also about 50 μS. This agrees quite well with the experimentally observed results. The current rise times to cross the mode rational surfaces in our experiments are larger than the MHD instability growth times but smaller than the resistive diffusion time scales. It is probable that the modes cannot grow to very large amplitudes in such a short time scale due to some nonlinear stabilization processes, presence of a conducting plasma in the periphery ($T_e = 10$ eV), conducting wall etc. It has also been pointed out by White (1986) that in the initial stages of the discharge when I_p is increasing, magnetic islands are observed to develop to a large size if the current is increased slowly than if it is raised quickly. This is because conditions favourable to large island growth are not satisfied on a fast time scale.

Hence we believe that a combination of both fast current rise and a conducting shell is essential to obtain ultra low q_a discharges. In our case it is the combination of fast current rise rate of about $\approx$ 40–50 MA/s, to surpass the mode rational surface barriers and the conducting shell to stabilize the possible MHD modes that has enabled us to obtain ultra low q_a discharges. Extensive theoretical work has been carried out to determine the range of stable operation of tokamaks with a conducting shell (Shafranov 1970; Bateman 1976; Robinson 1971; Pogutse and Yurchenko 1981). Detailed stability analysis of the ultra low q_a discharge would require extensive numerical computation which is not possible here. But the role of the conducting shell in improving the stability of our ultra low q_a discharge (without position feedback) can be clearly seen from figure 2 wherein the plasma equilibrium is restored after an initial displacement. This does not happen in the high q_a discharge (figure 1) where the plasma column is seen to drift outwards continuously. This also explains why the plasma current decay time is 2·5 times slower in the ultra low q_a discharge as compared to the high q_a discharge. The broad current profile (as estimated from equation 1), can also be beneficial to the stability of the ultra low q_a discharges, since broadening the current profile at fixed total current effectively moves the current channel closer to the conducting wall and thereby providing stability (Friedberg 1987). On the other hand the high q_a discharge would have a tokamak (parabolic)-like profile resulting in moving the high current channel away from the conducting wall and hence lesser stability.

In ultra low q_a discharges resistive tearing modes (like $m = 2$, $n = 1$, $m = 3$, $n = 2$, $m = 1$, $n = 1$) which are responsible for current disruption in the high q_a discharges of tokamaks, do not play a significant role (Mcguire 1979) since the resonant surfaces no longer exist in the plasma which is a necessary criterion. But ideal kink modes

($m = 1$, $n = 1$) which lead to a displacement of the plasma column can be stabilized with a conducting wall (Bateman 1976). This is clearly seen in our ultra low q_a discharges where the initial displacement of the plasma column is restored but not so in the high q_a discharge. Murakami *et al* (1988) derived a condition for stability of an ultra low q_a discharge against single resonant $m = 1$, ideal kink instability in the presence of a conducting shell which is given by

$$(1 - nq_a) > n^2 \varepsilon^2 (1 - x_s)^2 \tag{2}$$

where n is the toroidal mode number and $x_s(r_s/a)$ is the location of the resonant surface. For our value of $q_a \approx 0{\cdot}8$, $n = 1$, $\varepsilon = a/R = 0{\cdot}25$ we find that

$$1{\cdot}7 > (1 - x_s)^2 \tag{3}$$

which is satisfied for all x_s varying from 0 ot 1 (edge of the torus) and hence the ultra low discharge in our experiment is quite stable.

Only two tokamaks had attempted to lower q_a by fast current rise (Mirnov and Semenov 1971; TFR 1985) but they did not have a conducting shell, and hence the former could not obtain discharges less than $q_a \approx 1{\cdot}5$, and the latter could operate at just about $q_a \approx 2{\cdot}0$. Hence from our observations it is quite clear that it is essential to have a fast plasma current rise rate and a conducting shell to obtain stable ultra low q_a discharge.

From our experiments it also appears that extensive cleaning is not necessary to obtain ultra low q_a discharges. Power balance analysis by Kamada *et al* (1989) shows that it is the metal impurities which may be more harmful than the low Z impurities like oxygen and carbon. Even after extensive cleaning and carbonisation they were able to only decrease the loop voltage by a factor of 2 at peak plasma current but not the total current. Hence they could only increase the plasma temperature but not reduce q_a value at the edge. In our case as mentioned earlier we concentrated on repeatability and reproducibility than on the role of impurities. In this connection it is interesting to note that according to Berlizov *et al* (1981) light impurities like oxygen may be beneficial rather than harmful in low q_a discharges. It was observed in their experiment that the light impurities leaving the plasma were cooled quite effectively in the edge region and thereby minimizing wall sputtering whereas with the removal of light impurities the discharge became unstable due to wall sputtering.

5. Conclusions

We have been able to obtain ultra low q_a discharges with $q_a \approx 0{\cdot}8$ that are more stable than high $q_a \approx 2{\cdot}8$ discharges. This has been possible by fast current rise and with a conducting shell which stabilizes the harmful ideal and resistive modes. The absence of the negative loop voltage spikes indicate that operating at ultra low q_a values is an efficient way of controlling the destructive tearing modes and hence avoid current disruptions. The equilibrium is also better in the ultra low q_a discharge as compared to the high q_a discharge. Self orgnization behaviour with a growing MHD instability has been observed in the ultra low q_a discharges wherein plasma current falls in steps after attaining the peak value.

While the other experiments resorted to extensive wall conditioning like gettering or external magnetic fields we have been able to obtain stable ultra low q_a discharges with a moderately clean machine after the usual low power tokamak discharge cleaning. Profiles may also be playing a crucial role and hence the construction of internal magnetic probes are in progress for these measurements. Investigation of anomalous ion heating due to turbulence in ultra low q_a discharges is in progress and the role of edge plasmas in these low q_a discharges and effects of additional cleaning systems are planned as part of the future work.

Acknowledgments

We would like to thank P S Bhattacharjee, A Bal, S Bose and S S Sil for the technical assistance provided in operating the tokamak and the other group members for the discussions and encouragement. One of the authors (ANSI) would like to thank Drs D C Robinson, T N Todd, P L Taylor and Z Yoshida for their useful comments and suggestions, and Profs P K Kaw, P I John, Y C Saxena, A Sen and S K Mattoo for discussions during his visit to IPR.

References

Bateman G 1976 *MHD Instabilities* (Cambridge, Massachussets, USA: The MIT Press)
Berlizov A B *et al* 1981 *Plasma physics and Cont. Nuclear Fusion Research* (Proc. 8th IAEA Conf., Brussels) Vol 1 23
Cheetham A D, Hamberger S M, How J A, Kuwahara H, Morton A H and Sharp L E 1985 ANU-PRL/PP85/10
DIVA Group 1980 *Nucl. Fusion* **20** 271
Equipe T R F 1978 *Nucl. Fusion* **18** 647
Friedberg J 1987 *Ideal magnetohydrodynamics* (New York: Plenum Press)
Grad H and Hogan J 1970 *Phys. Rev. Lett.* **24** 1337
Granetz R S, Hutchinson I H and Overskei D O 1979 *Nucl. Fusion* **19** 1587
Huddlestone R H and Leonard S L 1965 *Plasma diagnostic techniques* (London: Academic Press)
Itami I, Hattori K, Fujita T, Murakami Y, Yoshida Z and Inoue N 1988 *Nucl. Fusion* **28** 1535
Kadomtsev B B, Troyon F S, Watkins M L, Rutherford P H, Yoshikawa M and Mukhovatov Y S 1990 *Nucl. Fusion* **30** 1675
Kamada K, Sato T, Murakami Y, Ohira T, Saitoh K, Fuke Y, Utsumi M, Yoshida Z and Inoue N 1989 *Nucl. Fusion* **29** 713
Kusano K, Sato T, Yamada H, Murakami Y, Yoshida Zk and Inoue N 1988 *Nucl. Fusion* **28** 89
McGuire K M 1979 *Relaxation processes in toroidal pinch experiments* D. Phil, University of Oxford
Mirnov S V and Semenov I B 1971 *Sov. Phys. Tech. Phys.* **33** 1134
Miyamoto K 1980 *Plasma Physics for nuclear fusion* (Cambridge, USA: MIT Press)
Morris A W 1985 *Large scale instabilities in tokamaks*, D. Phil, University of Oxford
Murakami Y, Yoshida Z and Inoue N 1988 *Nucl. Fusion* **28** 449
Pogutse O P and Yurchenko E I 1981 *Plasma Physics* (ed.) B B Kadomtsev (Moscow: Mir Publishers)
Robinson D C 1971 *Plasma Physics* **13** 439
Robinson D C and Todd T N 1982a Culham Report CLM-R 166
Robinson D C and Todd T N 1982b *Phys. Rev. Lett.* **48** 1359
Robinson D C 1989 Private Communication
Shafranov V D 1970 *Sov. Phys. Tech. Phys.* **15** 175
Stix T H 1976 *Phys. Rev. Lett.* **36** 521
Taylor J B 1974 *Phys. Rev. Lett.* **33** 1139
Taylor P L, La Haye R J, Schaffer M J, Tamano T, Inoue N, Yoshida Z and Kamada K 1989 *Nucl. Fusion* **29** 5

TFR Group 1985 Internal Report EUR-CEA-FC-119
Troyon F S, Gruber T, Saurenman H, Semenzato S and Succi S 1984 *Plasma physics and controlled fusion* **26** 209
White R B 1986 *Rev. Mod. Phys.* **58** 183
Yoshida Z, Ishida S, Itami K, Murakami Y, Nihei H, Morikawa J and Inoue N 1986 *J. Phys. Soc. Jpn.* **55** 550
Yoshida Z, Kusano K and Inoue N 1987 *Phys. Fluids* **30** 2465
Yoshida Z 1990a Private Communication
Yoshida Z, Murakami Y, Morimoto H, Matsui J, Nagahara D, Takeji S and Inoue N 1990b *Nucl. Fusion* **30** 762