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Very low-q_a discharge experiments in the SINP tokamak*

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Abstract : Stable very low-q_a discharges have been obtained in the SINP Tokamak. The discharge duration increases with applied voltage. We have obtained a scaling for current rise in terms of neutral gas filling pressure. MHD activities in high-q_a = 2.12 and very low-q_a = 1.12 discharges are presented.

Keywords : Very low-q_a discharges, fast current rise, conducting shell, MHD activities.

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1. Introduction

Extensive theoretical and experimental progress has been made in the research of toroidal magnetic confinement of high temperature plasmas since 1950's [1]. Tokamaks with high energy confinement times have proved to be most stable amongst the generation of toroidal systems.

Tokamaks' operation is limited by a figure of merit called the edge safety factor (q_a). In terms of the tokamak parameters it is defined as $q_a \approx \frac{a^2 B_T}{R I_p}$ where a is plasma minor radius, R is the plasma major radius, B_T is the toroidal magnetic field and I_p is the plasma current. Most tokamaks are operated at $q_a > 2$ and attempts to lower $q_a < 2$ have only resulted in major disruptions whereby the entire plasma energy is dissipated in a few tens microseconds [2]. Tokamaks are also governed by another figure of merit called the Toroidal Beta ($B_T = \frac{\eta k T_e}{B_T^2/8\pi}$, which is the ratio of the plasma pressure to the magnetic fields pressure. According to Troyon's scaling $B_T \propto \frac{1}{q_a}$. Hence lowering q_a not only enables operation at higher currents but also increased the toroidal beta.

Mirnov and Semenov [3] carried out some experiments in which they could surpass the mode rational surface barriers by a fast current. Following this idea, we were able to

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obtain very low-$q_a q_a << 2$ discharges using fast current rise rates in combination with the closely fitted conducting shell in the SINP Tokamak. Having obtained these discharges, we investigated some of the MHD properties of these very low-q_a discharges.

In this paper, we present in brief, the experimental set up in Section 2, the results and discussion in Section 3 and the conclusions in Section 4.

2. Experimental set up

The above experiments were performed in the SINP Tokamak with the following parameters :

Major radius (R_0) = 30 cm
Minor radius (a) = 7.5 cm
Plasma current (I_p) = 20 - 40 KA
Toroidal field = 4.5 kG
Base pressure = $1 - 3 \times 10^{-7}$ Torr
Operating/filling pressure = Hydrogen $3 - 4 \times 10^{-4}$ Torr.

The power supply is a of capacitive storage scheme. The capacitor is initially charged to a desired value and then discharged into the coils cither due to toroidal field, Joule heating or vertical field.

The main diaghostics deployed for these experiments were the Rogowski coil to measure plasma current and the loop voltage coil to measure the toroidal electric fields.

3. Results and discussion

There are several ways of obtaining a very low-qa discharge. As seen from the expression for edge safety factor

$$q_a \approx \frac{a^2 B_T}{R I_p},$$

major radius R is a fixed parameters and there ate three variables a (minor radius), B_T (toroidal field), I_p (plasma current) which can be changed to lower q_a value. The low-q_a experiments obtained by varying the toroidal filed keeping a and I_p fixed have already been reported [4], and those obtained by varying a will be reported elsewhere. In the present set of experiments we shall report on low-q_a experiments carried out by keeping a and B_T fixed and varying I_p. This was done by varying the Capacitor Bank voltage of the Joule heating coils.

Figure 1 shows a plot of plasma current and loop voltage obtained by charging the Joule heating capacitor bank to 2.0 kV. Since the toroidal field was set to 4.5 KG and plasma minor radius to 7.5 cm, we could obtain a q_a of 2.12 at the peak of plasma current. As observed from both the plasma current and the loop voltage, the discharge tends to highly unstable and disruptive as expected when a tokamak is oprated at $q_a < 2$. The behaviour of the discharge during the soft disruptions is similar to those observed in other devices like expansion of the plasma column followed by the inward acceleration of the plasma which gives rise to the negative voltage spike.

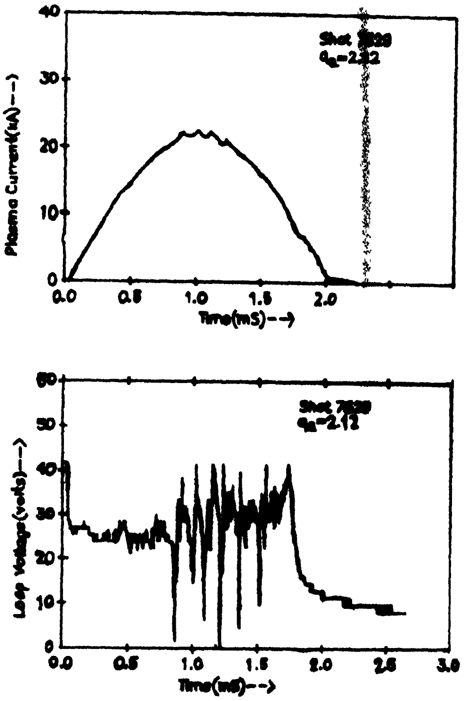


Figure 1. Hign $q_a = 2.12$ discharge. Plot of plasma current (top) and loop voltage (bottom).

We gradually raised the secondary loop voltage which changed the $I_p(t)$ profile quite considerable. This is shown in Figure 2. One remarkable feature of this results is that the peak current not increases (q_a decreases accordingly) but the duration of the discharge also increases. Besides this the flat top nature of the current also increases, signifying increased stability of the discharge. Figure 3 shows a plot of plasma current and loop voltage for the maximum toroidal electric field of 90 volts, and we could raise above this voltage. The maximum current in this discharge > 30 kA and the q_a at peak current is about 1.12. Comparing this discharge with that in Figure 1 shows that the very low-q_a discharge is more stable than the high $q_a = 2.12$ discharge. The soft disruptions in Figure 1 are completely absent. Hence we have been able to eliminate or suppress disruptions by operating at low-q_a values. The loop voltage of $q_a = 1.12$ discharge is also different from the $q_a = 2.12$ discharge. The disruptive features of the latter are completely absent, but besides this the $q_a = 1.12$ discharge exhibits a very pronounced turbulence in the loop voltage signal. This has been attributed to current driven MHD turbulence, and a consequence of this is anomalous ion heating which shall be reported elsewhere.

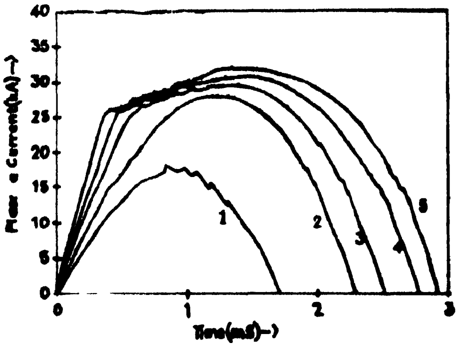


Figure 2. Plots of plasma current for different applied loop voltages (1) 40 volts. (2) 50 volts. (3) 60 volts. (4) 70 volts. and (5) 90 volts.

Setting up phase :

Now the next question is the setting up of the very low-q_a discharges. It was pointed out by Mirnov and Semenov [3] that with a fast current rise (without quantifying how fast) one could surpass the mode rational surface barrier and obtain lower-q_a values. Thus, Mirnov and Semenov [3] could surpass the $q_a = 3$ surface and obtain a $q_a \approx 1.5$ discharge but not below. TFR Group [2] also attempted a fast current rise but could never operate below $q_a \approx 2$. Yoshida *et al* [5] were the first to present a scaling for current rise to surpass the $q_a = 2$ surface and attain lower q_a values. It appears that the current rise time should be 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.

We shall now derive the relation between B_T and T_2 (time taken to cross the $q_a = 2$ surface) as follows :

$$q_a = \frac{a\,B_T}{R\,B_p}\,, \tag{1}$$

B_p is the poloidal magnetic field generated by the plasma current I_p

$$B_p = \frac{\mu_0\, I_p}{2\pi\, a} \tag{2}$$

$$\frac{4\pi \times 10^{-7}\, I_p}{2\pi\, a}$$

$$B_p = \frac{2 \times 10^{-7}\, I_p}{a} \tag{3}$$

Substituting (3) in (1) we get

$$q_a = \frac{5 \times 10^6 \, a^2 \, B_T}{R \, I_p} \tag{4}$$

Differentiating (4) w.r.t. *t* We get

$$\frac{dq_a}{dt} = \frac{5 \times 10^6 \, a^2 \, B_T}{R \, I_p} \times \frac{1}{I_p} \frac{dI_p}{dt}, \tag{5}$$

$$\frac{dq_a}{dt} = q_a \cdot \frac{1}{I_p} \cdot \frac{dI_p}{dt}. \tag{6}$$

Multiplying and dividing RHS of (6) by $\frac{5 \times 10^6 \, a^2 \, B_T}{R}$

We get

$$\frac{dq_a}{dt} = q_a \left(\frac{5 \times 10^6 \times a^2 B_T}{R \, I_p} \right) \left(\frac{R}{5 \times 10^6 \times a^2 B_T} \right) \frac{dI_p}{dt}, \tag{7}$$

$$\frac{dq_a}{dt} = q_a^2 \bullet \frac{R}{5 \times 10^6 a^2 \bullet B_T} \bullet \frac{dI_p}{dt}. \tag{8}$$

If $q_a = 2$, and $dt = T_2$

$$\frac{1}{T_2} = \frac{2R}{5 \times 10^6 \; a^2 \, B_T} \bullet \frac{dI_p}{dt}, \tag{9}$$

$$T_2 = \frac{5 \times 10^6}{2} \, \frac{a^2}{R} \, B_T \left(\frac{dI_p}{dt} \right)^{-1}, \tag{10}$$

$$T_2 = 2.5 \times 10^6 \, \frac{a^2}{R} \bullet B_T \left(\frac{dI_p}{dt} \right)^{-1}_{q_a} = 2 \tag{11}$$

$$\frac{T_2(S)}{B_T(T)} = 2.5 \times 10^6 \, \frac{a^2}{R} (i_p)^{-1}_{q_a} = 2. \tag{12}$$

Converting T_2 into MS on LHS we get

$$\frac{T_2(mS)}{B_T(T)} = 2.5 \times 10^9 \, \frac{a^2}{R} . \; (\dot{i}_P)^{-1}, \tag{13}$$

$$\frac{T_2}{B_T}(mS/T) = 2.5 \times 10^9 \, \frac{a^2}{R} (i_p)^{-1}_{q_a} = 2 \;\; (\mathrm{S/Amp}). \tag{14}$$

By varying the filling pressure we were able to obtain a scaling for plasma current rise in terms of neutral pressure as

$$\dot{I}_p > 2.2 \times 10^6 / \text{prefill pressures (m Torr)} \tag{15}$$

for the SINP tokamak.

MHD activities :

High q_a discharges :

Comparison of Figures 1 and 3 shows that the MHD activities should also be different. The former is quite unstable, being dominated by soft disruptions during which current does not terminate abruptly but recovers again. But it has all the features of a major disruption as in other devices, like expansion of the plasma column followed by plasma acceleration towards the inner wall. The loss of energy appears as a negative going voltage spike on the loop voltage.

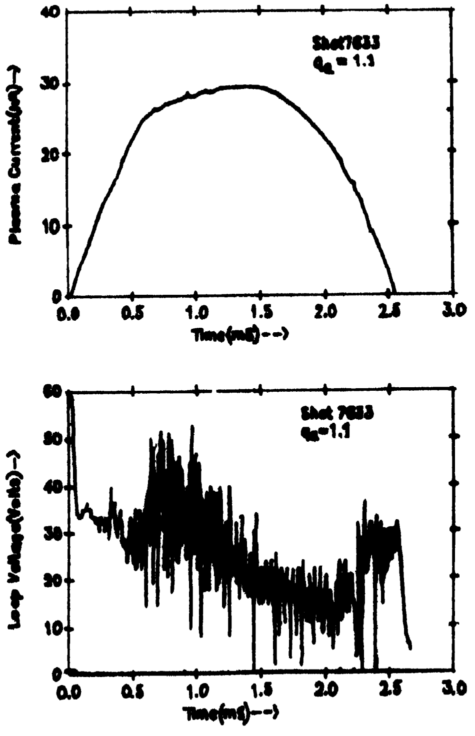


Figure 3. Very low q_a = 1.12 discherge. Plot of plasma current (top) and loop voltage (bottom).

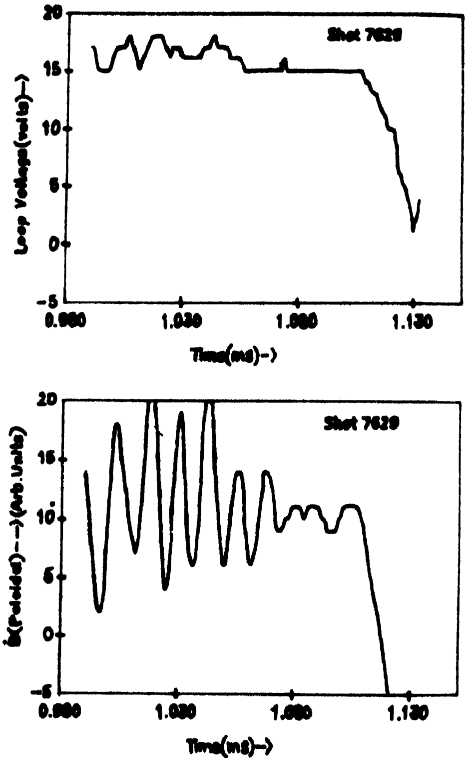
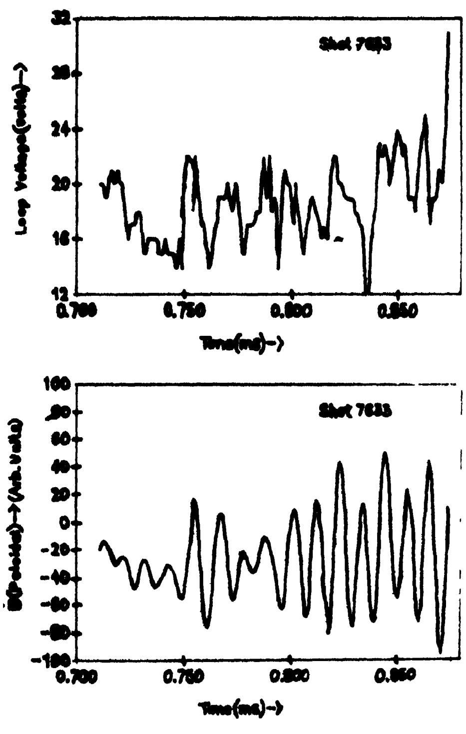


Figure 4. Top : Expanded view of the characteristics of loop voltage for soft disruptions. Bottom : Magnetic activity preceeding the soft disruptions. Locked mode activity is observed just prior to the disruption.

This is shown in Figure 4 where a negative going voltage spike is observed at the disruption phase. The poloidal magnetic probe exhibits an oscillating MHD followed by a finite period which is devoid of oscillations and then the loss of magnetic energy. The absence of oscillations indicate the presence of a locked mode activity. The MHD mode is the m = 2 mode which locks to a m = 1 perturbation before the final crash.

Very low-qa discharges :

As compared to the $q_a = 2.12$ discharge, the MHD activity is different in very low-q_a discharges. In the first instance there is no disruption in the very low-q_a discharges. In Figure 3, during the current rise phase, we observe an inflection point in the current and there is also an increase on the loop voltage signal. This occurs when q_a is either 1.5 or 2. In the former it could be an an $m/n = 3/2$ mode and in the latter an $m/n = 2/1$ mode. Since both the modes are responsible for current termination in tokamaks, it is plausible that in Figure 3 the inflection in plasma current is caused by the $m/n = 3/2$ mode. A growing mode is observed by the poloidal magnetic prior to the inflection point but it does not result in current termination. Hence it appears that we have successfully suppressed major disruptions by operating at low q_a values.



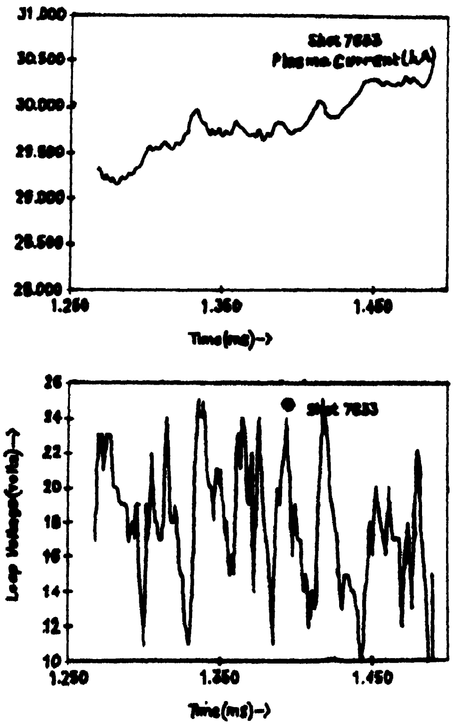


Figure 5. Top : Characteristic feature of the loop voltage at the inflection point of plasma current for a very low q_a discharge. Bottom : Magnetic activity preceeding the inflection point for the very low q_a discharge. Growing mode is observed prior to the inflection point in the plasma current.

Figure 6. Sawteeth observed on the loop voltage (bottom) for the very low q_a discharge.

DIVA Group [6] had observed sawteeth on the loop voltage when operated at $q_a < 2$. We also observed sawteeth on the loop voltage in our very low-q_a discharges as seen in Figure 5. In contrast to this we observed only sharp spikes at the instants of disruptions in q_a

≈ 2.1 discharges. More detailed calculations are being carried to investigate the characteristics of these sawteeth oscillations.

4. Conclusions

We have observed very low-q_a discharges with relative ease as compared to other tokamaks [6-9]. In the above devices extensive conditioning of vacuum vessel had to be carried out, and in some of them external helical coils had to be used to obtain low q_a discharges. In the SINP Tokamak none of these schemes had to be deployed. It appears that with a fast current rise assisted by a conducting shell is adequate to obtain very low-q_a discharges. Another added fact is that our very low-q_a discharges are very stable and the discharge duration also increases with increase in applied voltage.

We have obtained a scaling for the plasma current rise in terms of the prefill pressure.

More detailed investigations are being planned to study the nature of the current profiles and the anomalous effects associated with these very low-q_a discharges.

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