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Supershot Performance with Reverse Magnetic Shear in TFTR

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1. Introduction

Discharges with large regions of reversed magnetic shear and good energy and particle confinement have been produced in the Tokamak Fusion Test Reactor (TFTR).[1] Negative magnetic shear has been predicted to improve transport by stabilizing some classes of magnetohydrodynamic instabilities such as ballooning and resistive tearing modes, and also some microinstabilities. It is also desirable for good bootstrap current alignment. The stability is dependent upon q(0), the minimum value of q (q_{min}), and the location of the q_{min} surface [normalized minor radius $(r/a)_{qmin}$ or major radius R_{qmin}], as well other parameters which are as yet unknown. Several techniques have been developed to control the q profile on TFTR and are described in section 2. High-performance discharges are created by injecting more than 18 to 25 MW of neutral beam power into a reversed-shear target plasma. Such a discharge is described in section 3.

Heating of the plasma during a rapid plasma current increase is necessary to produce a reversed-shear current profile. Heating raises the plasma temperature which increases the current diffusion time and slows penetration of the plasma current to the center of the plasma. The most efficient method is to start the heating as early as possible during a "prelude" phase during the initial current ramp. The current ramp alone is insufficient, as shown in Fig. 1.

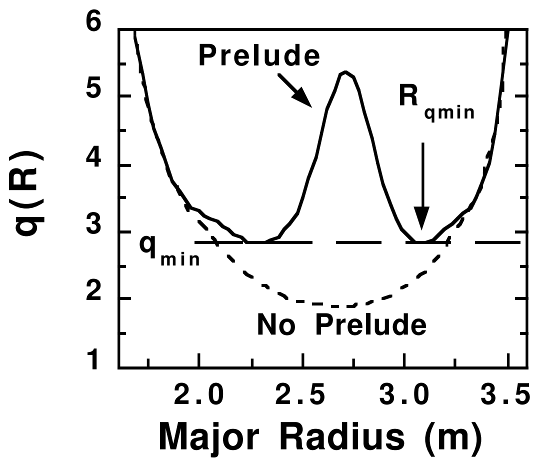

Fig. 1: The measured q profile at 2.55 sec for discharges with and without prelude heating.

The prelude heating can be from tangential neutral beams (NB), as shown in Fig. 2(c), or from ICRF. The preferred "prelude" phase of the discharge has P_{nb} = 5 MW beginning at about 0.55 sec and increasing to 8 MW at 1.0 sec with P_{co} = 6 MW and P_{ctr} = 2 MW. The plasma current rises at a rate of 1.6 MA/sec for the first half second. The ramp rate is then decreased to 0.4 MA/sec until the desired plasma current of 1.6 MA is reached at 2.0 sec. The plasma major radius is approximately the final value of 2.60 m at 0.1 sec. The toroidal field reaches its full value of 4.6 T at 2.60 m at 0.0 sec.

Profiles of the magnetic-field pitch angles in TFTR are measured by a motional-Stark-effect polarimeter with good spatial and temporal resolution.[2] The equilibria are then reconstructed with the VMEC free-boundary equilibrium code[3] which determines the values of q_{min} and $(r/a)_{qmin}$ with accuracies of 10% and 5%, respectively.

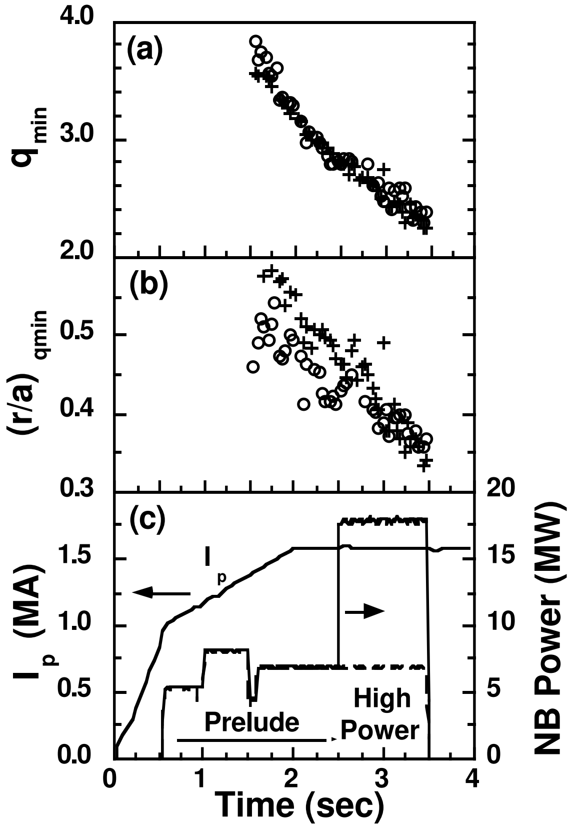

Fig. 2: qmin (a) and $(r/a)_{qmin}$ (b) for discharges with (o) and without (+) a high-power phase starting at 2.5 sec. The plasma current and neutral-beam heating waveforms are shown in (c).

2. q-Profile Control

Control of the q profile has been achieved by optimizing the plasma startup, prelude start time, the NB directionality during the prelude heating phase, and the plasma current ramp rate. It has been observed that high levels of MHD activity during the prelude phase can lead to very rapid current penetration even with early neutral-beam injection. The resulting plasmas have lower values of q(0) and no regions of reverse shear. Details of the plasma startup such as current ramp rate, time at which the current ramp rate changes, major radius evolution, and value of q(a), have been optimized to avoid such MHD.

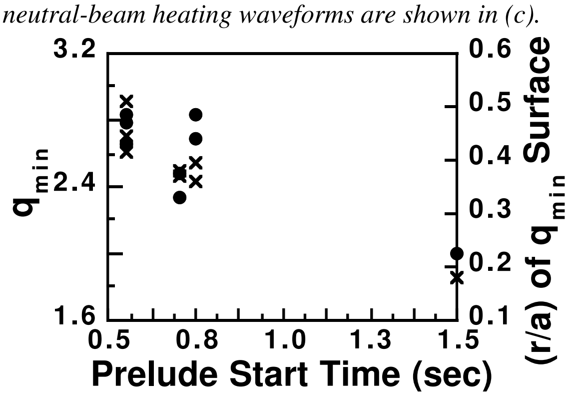

Fig. 3: Delaying the prelude heating start time decreases q_{min} (•) and the size of the region with reverse shear (x) at the start of the high-power heating phase.

Shear reversal over half the plasma minor radius at the start of the heating phase has been obtained by very early beam injection as shown in Fig. 3. Delaying the prelude heating decreases the size of the reverse shear region. The value of q_{min} also decreases at 2.55 sec (the start of the high-power phase) from q_{min} = 2.8 to 2.0 as the prelude start time is delayed from 0.55 to 1.5 sec. Also, q(0) decreases from about 6 to about 2. The prelude start time has little affect on the rate at which the shear reversal region shrinks or q_{min} decreases. Further control of $(r/a)_{qmin}$ and q_{min} can be achieved by varying the start time of the high-power heating phase, as shown in Fig. 2.

The q profile is also affected by the direction of the injected neutral-beam power during the prelude. For example, unidirectional NB injection would lead to strong beam-driven currents while injection with equal amounts of power in the direction of the plasma current (co-injection) and counter to the plasma current (ctr-injection) would minimize the beam-driven current. Experiments which varied the amount of co- and ctr-injected power during the prelude phase are shown in Fig. 4. The largest values of $(r/a)_{qmin}$ are created by predominantly co-injection. However, co-only injection of 8 MW during the prelude caused the discharge to disrupt. It is not yet clear whether pure co-injection of less than 8 MW raises q_{min} more than does a co-fraction of ≈ 0.5.

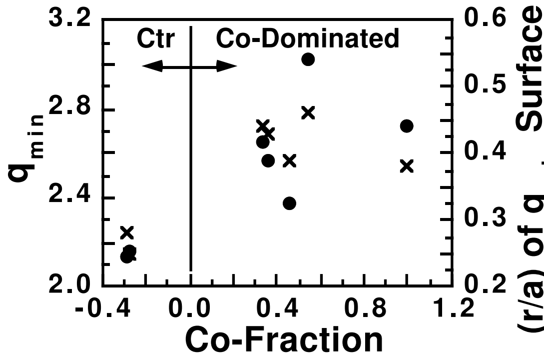

Fig. 4: Co-dominated NB injection during the prelude phase increases q_{min} (•) and the region of reverse shear (x). Co-Fraction is defined as $(P_{co} - P_{ctr})/P_{nb}$.

Increasing the current ramp rate from the nominal 0.4 MA/sec after 0.5 sec modified the q profile and its evolution. Discharges with faster ramp rates reached the final current earlier in time than 2.0 sec. Comparisons at 0.16 sec after a plasma current of 1.6 MA was reached showed that a 20% faster ramp rate increased both the size of the reverse shear region and q_{min}. Both quantities were reduced at the fixed time of 2.55 sec, however. Because q_{min} and $(r/a)_{qmin}$ decrease at a predictable and reproducible rate during the discharge, a range of values can be accessed by varying the time of high-power injection.

Figure 5 displays the wide range of q profiles, as parameterized by q_{min} and $(r/a)_{qmin}$, produced during the high-power phase of reversed-shear discharges through the techniques described here. Modest independent control of $(r/a)_{qmin}$ and of q_{min} has been demonstrated. During the discharge, lower values of q_{min} and $(r/a)_{qmin}$ are reached since both quantities continue to fall during a discharge. Future experiments are intended to develop methods that change the relationship between these quantities and to create larger regions of reversed shear with controlled values of q_{min}. Raising the plasma current from 1.6 MA, increasing the plasma current ramp rate, and beginning beam injection as early as 0.3 sec will be explored. It will also be important to

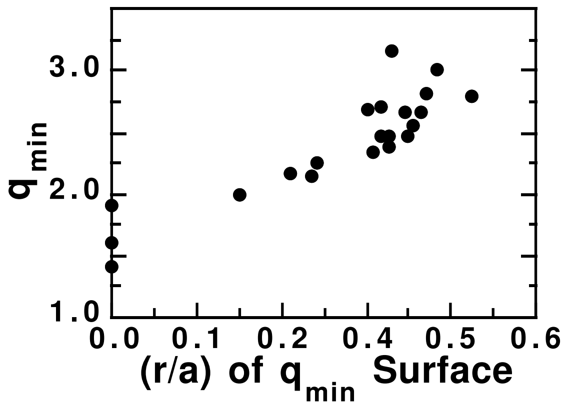

Fig. 5: The q profile control techniques described in this paper have accessed these q profiles. Data is shown at the start of the high-power phase.

develop techniques such as mode-conversion current drive (MCCD)[4] or lower-hybrid current drive (LHCD) to hold q_{min} and $(r/a)_{qmin}$ constant during a discharge.

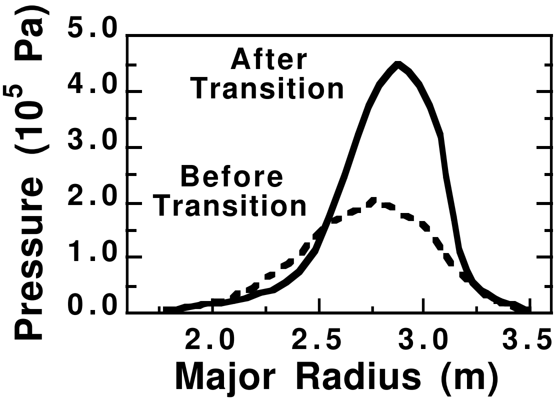

Fig. 6: The pressure at the center of the plasma is greatly increased when the discharge enters the R/S mode.

3. High Performance

High performance discharges were created by injecting up to 25 MW of NB power when the values of q_{min} and $(r/a)_{qmin}$ reached the desired values, typically at 2.5 sec. The values of q(0), q_{min} and $(r/a)_{qmin}$ decreased during the discharge at a predictable rate, Fig. 2. High-power injection did not strongly affect the evolution of any of these quantities.

When an observed P_{nb} threshold of 18 to 25 MW was surpassed, the discharge entered the reversed shear confinement mode (R/S mode) with drastically reduced particle and energy transport in the core of the plasma.[1] Figure 6 shows that the pressure in the center of the plasma was like that of a typical TFTR supershot before the R/S transition occurred during the high-power phase. After the transition, the pressure and pressure peaking factor $[p(0)/\langle p\rangle]$ increased greatly. The increased central pressure reflects an increased central particle density caused by a dramatic decrease in both the electron and ion particle diffusivity. The global energy confinement time also increased

The plasma performance of the reverse shear plasma during the prelude phase was already similar to that of the supershot mode. Both have high electron and ion temperatures, high ratio of T_i/T_e, peaked density profiles, and energy confinement enhancement greater than 2 compared to L-mode scaling. When the plasma made the transition into the R/S mode, performance was further improved.

Most of the discharges reaching the R/S mode have disrupted due to MHD instabilities. The driving mechanism has not yet been determined unequivocally. However, the MHD activity was only observed outside $(r/a)_{qmin}$ which is significantly outside the location of the peak pressure gradient. There was no activity observed in the core of the plasma. In contrast, the disruption stability of standard TFTR supershots is limited by MHD instabilities in the plasma core at the peak of the pressure gradient.

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