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Production and Stability of High-Beta DIII-D Discharges With Reversed Magnetic Shear*

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Plasma configurations with reversed magnetic shear have been proposed for steady-state tokamak operation [1, 2] since the plasma profiles can be made consistent with good confinement, high bootstrap current fraction, and stability at very high beta. The stability of reversed magnetic shear discharges with beta up to 11% has previously been demonstrated in DIII-D [3]. Reversed magnetic shear (RMS) refers to a safety factor profile, $q(\rho)$, which is a non-monotonic function of minor radius, ρ. The magnetic shear $S \equiv (\rho / q)\, dq/d\rho$ is negative within the plasma core and positive at the edge. When $S < 0$, short wavelength ballooning modes are stable, and the toroidal current density peaks near the radius of minimum safety factor, q_{min}. This off-axis current maximum can be aligned with the non-inductive bootstrap current generated by the pressure gradient, reducing the requirements for external current drive. Stabilization of long wavelength external kink modes at high beta requires a nearby conducting wall, and this effect has been demonstrated in DIII–D experiments [4, 5].

In this paper, we describe high confinement and high beta DIII–D discharges having strongly reversed magnetic shear. These discharges differ from previously reported RMS plasmas [3, 6–9] since high-quality measurements of the internal magnetic field now permit clear documentation of the central shear reversal region in high beta plasmas with enhanced confinement. Additionally, these RMS discharges are produced in DIII–D with power plant-relevant ion temperatures $T_i(0)$ up to 20 keV, at Troyon-normalized beta ($\beta_N \equiv \beta / (I / aB)$ [% m T/MA]) up to 4, high central safety factor with $q(0)$ often exceeding 10 while $q_{min} \sim 2$, and with or without the improved edge confinement characteristic of H–mode operation.

Discharges with strongly reversed magnetic shear are produced by early neutral beam injection (NBI) during the initial current ramp of low density plasmas. Figure 1 illustrates the timing of two comparable high β, high confinement discharges: one with early NBI producing strongly reversed magnetic shear and the other with delayed NBI producing a high-β VH–mode with a monotonic q profile. The early NBI both increases the electron temperature and induces a rapid toroidal plasma rotation within the plasma core. To maintain low density during early NBI, the H–mode transition was delayed until 1.6 s by a vertical shift of the plasma's position in the direction opposite to the ion gradient-B drift. The increased electron temperature and low resistivity slows the inward diffusion of the inductively driven current, and the rapid central toroidal flow may contribute to the stabilization of double tearing modes associated with anomalous current penetration.

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In DIII–D, RMS is characterized by strong central peaking of the ion temperature. Fig. 2 compares the profiles of the two discharges shown in Fig. 1 at times of nearly equal stored energy. The q-profile is determined from the profile of the local magnetic field pitch angle measured with a 16-channel motional Stark effect (MSE) diagnostic [10], and profiles of ion temperature and toroidal flow velocity V_ϕ are measured using a 32-channel charge exchange recombination spectroscopy system. The central region of RMS extends outward to approximately $\rho \leq 0.5$, where ρ is normalized to the minor radius. As shown, $q(0) \sim 10$, $T_i(0) \sim 20$ keV, $V_\phi(0) \sim 500$ km/s, and these values are significantly larger than the central values measured in the comparable VH–mode discharge. Outside the region of RMS, the profiles of both discharges are similar except for the larger rotational shear in VH–mode [11]. Near the outer edge of the reversed magnetic shear region, very large gradients occur. These large gradients of T_i and V_ϕ are observed whenever RMS is produced in low-density discharges, regardless of the edge confinement properties. High-β_N RMS discharges have been madewith edge transport characterized by L–mode, H–mode free of edge localized modes (ELMs), and ELMing H–mode transport.

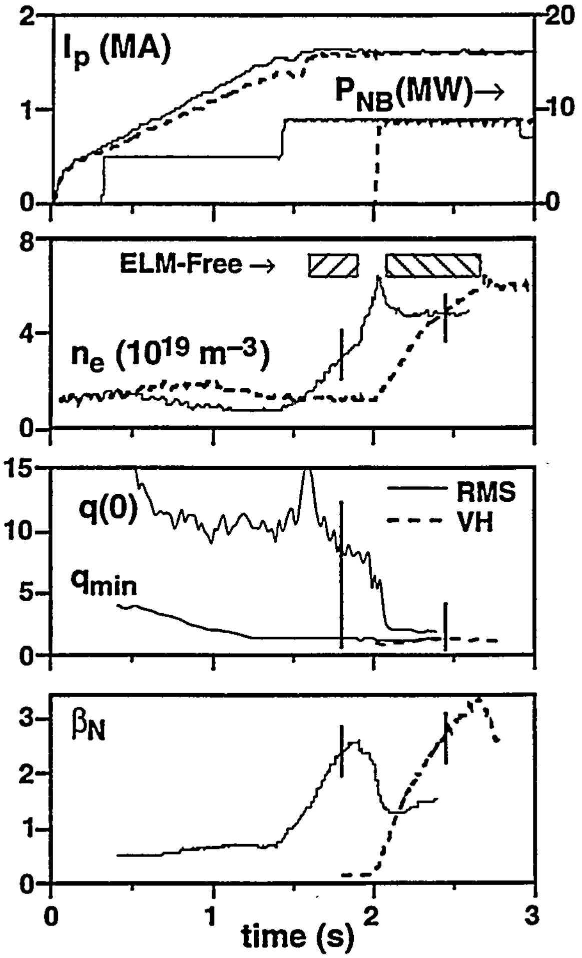

Fig. 1. Strongly reversed magnetic shear is produced with early NBI into low-density target plasmas. Solid line indicates RMS discharge 83721. Dotted line indicates a comparable VH-mode discharge 83710. Vertical lines indicate time-slices shown in Fig. 2.

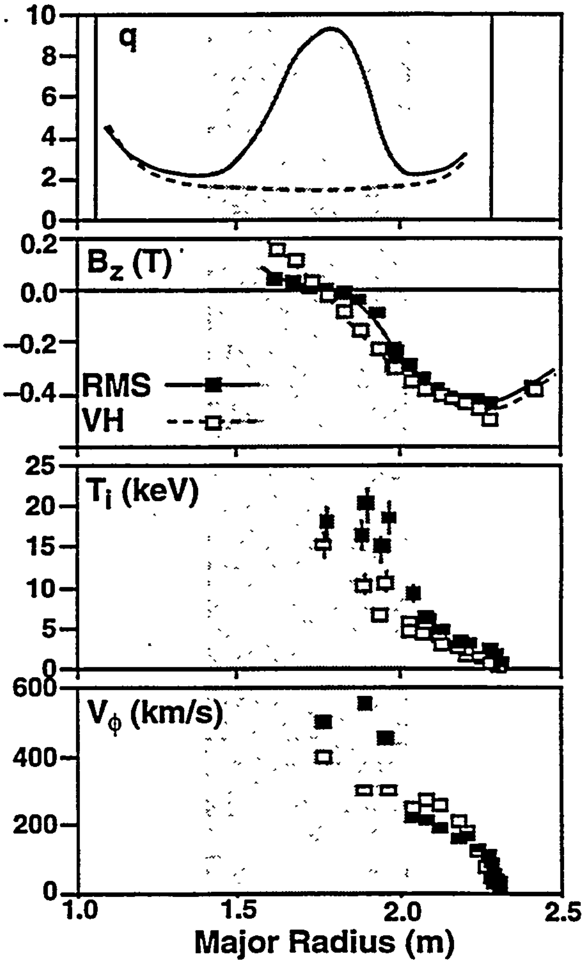

Fig. 2. RMS is associated with steep gradients of the ion temperature and toroidal rotation. Profiles of discharges shown in Fig. 1 are compared at times of equal stored energy: RMS discharge 83721 (t = 1.8 s) and VH–mode discharge 83710 (t = 2.46 s).

The RMS discharge having the highest peak value of $\beta_N \sim 4$ is shown in Fig. 3. In this discharge, the toroidal field was reduced to 1.6 T (in Fig. 1, the toroidal field was 2.1 T), and the initial value of $q(0)$ was only slightly larger than q_{min} — indicating an initially weak reversal of the central magnetic shear. Beginning near $t \sim 1$ s and during the L–mode phase, $q(0)$ rises and the central ion temperature increases with little change in the temperature for $\rho > 0.5$ illustrating the formation of a steep ion temperature gradient. The region of increased pressure coincides with the central 30% of the plasma volume which has reversed magnetic shear, and a corresponding increase in the global energy confinement time, τ_E, occurs. At $t = 1.3$ s, the ELM-free H–mode phase begins producing an overall improvement in plasma confinement. At $t = 1.4$ s, an internal event leads to a rapid reduction of $q(0)$ and a corresponding reduction in central T_i. A further increase in beam-injected power is used to increase $\beta_N \sim 4$ although the presence of ELMs reduces global confinement.

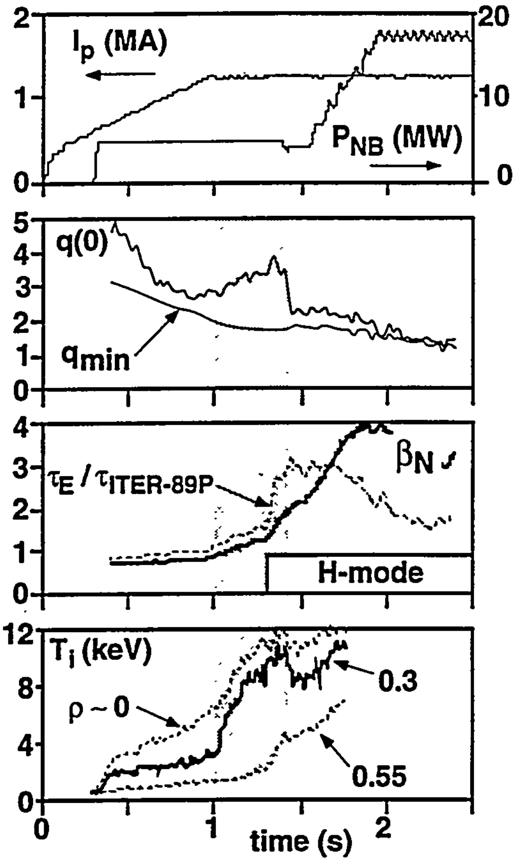

Fig. 3. Record high β_N discharge with reversed magnetic shear (84736). Between 1.0 s $< t < 1.4$ s, $q(0)$ increases with time further reversing the central magnetic shear and leading to the formation of a large T_i gradient. near $\rho \sim 0.5$.

Many high beta RMS discharges had little or no MHD activity. However, in some cases there was a clear correlation between the onset of MHD and time intervals when q_{min} slowly decreased in time and passed through a low order rational value, $q_{min} \sim 5/2, 2/1, 3/2$. In these cases, internal low n activity was often observed momentarily destroying the enhanced central ion confinement. When q_{min} decreased further, the internal activity ceased and the enhanced central confinement was restored. Internal MHD was avoided by proper discharge timing, for example by initiating H–mode earlier in time which broadened the current profile.

MHD instabilities which terminate the high-β_N phases of RMS discharges appear to be related to the production of a large bootstrap current density near the edge of the plasma and not to profile features directly related to RMS. For the discharges studied, the high β_N phase began shortly after the start of the ELM-free phase of the H–mode. This significantly improved edge confinement and produced large edge pressure gradients at low collisionality. Large gradients of pressure and current are also observed at the edges of VH–mode discharges, and the instabilities observed at high β_N for both VH–mode [12] and RMS discharges are similar. A low-n, ideal edge kink having a rapid growth time, < 50 μs, usually initiates the collapse of high-β_N operation. These low-n modes are spatially localized and cause an immediate loss of energy from the plasma edge followed by a slower loss from the core. Since these modes are edge localized, they are dominated by poloidal harmonics which are not easily wall-stabilized. Detailed stability calculations performed on RMS equilibria reconstructed from data prior to observation of an $n = 2$ edge kink confirm this interpretation.

To further increase the beta of RMS discharges, the edge pressure gradient must be kept below the usual values of ELM-free H-mode. Figure 4 illustrates an RMS discharge with an L-mode edge which achieved high central beta, $\beta(0) \sim 11\%$, upon application of increased NBI. In this discharge, the edge pressure gradient was more than ten times smaller than those found in the discharges shown in Fig. 1, while the sharp central gradient allowed by RMS created peaked pressure, $\beta(0)/\langle\beta\rangle \sim 4.1$, with more than double the stored energy expected during L–mode. The strong central peaking of the plasma density and T_i produced a fusion rate more than 1.5 times the rates measured for discharges like those in Fig. 1, where $\beta(0)/\langle\beta\rangle \leq 2.6$. Future experiments will attempt to reach higher β_N by reducing the edge pressure gradient during RMS and by producing profiles more compatible with wall stabilization.

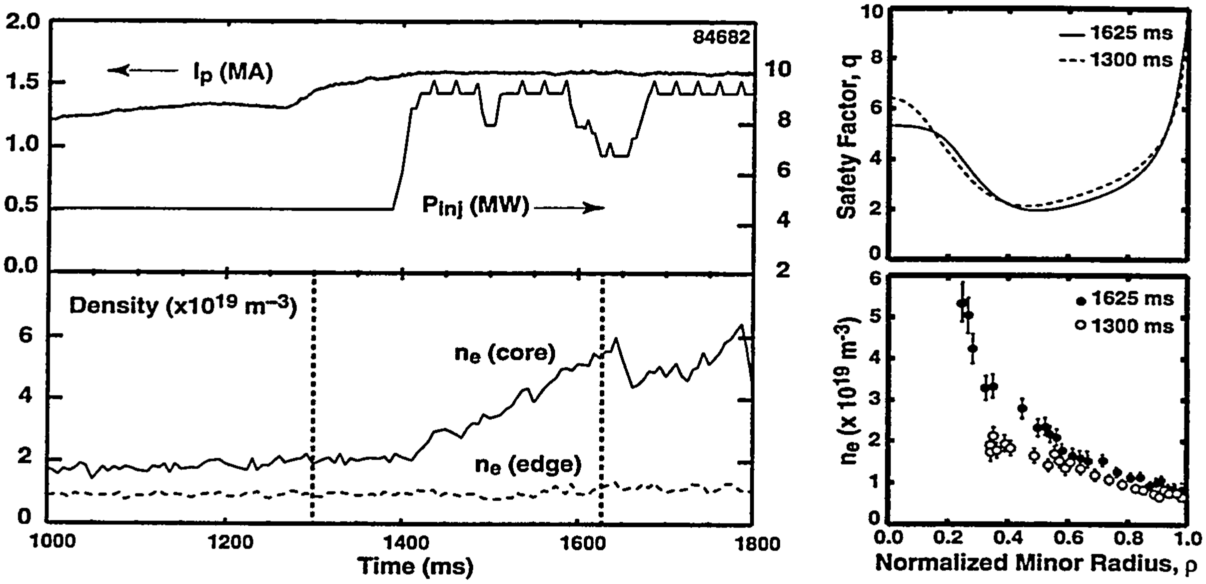

Fig. 4. Formation of a peaked density profile in a discharge with strong RMS and an L-mode edge immediately following increased NBI. Dashed lines indicate two time slices used for profile comparison.

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