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# IMPROVED FUSION PERFORMANCE IN LOW-q, LOW TRIANGULARITY PLASMAS WITH NEGATIVE CENTRAL MAGNETIC SHEAR



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GENERAL ATOMICS

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# IMPROVED FUSION PERFORMANCE IN LOW-q, LOW TRIANGULARITY PLASMAS WITH NEGATIVE CENTRAL MAGNETIC SHEAR*


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The fusion performance in DIII–D low-q single-null divertor discharges has doubled as a result of improved confinement and stability, achieved through modification of the pressure and current density profiles. These discharges extend the regime of neoclassical core confinement associated with negative or weak central magnetic shear to plasmas with the low safety factor ($q_{95} \sim 3$) and triangularity ($\delta \sim 0.3$) anticipated in future tokamaks such as ITER. Energy confinement times exceed the ITER–89P L–mode scaling law by up to a factor of 4, and are almost twice as large as in previous single-null cases with $3 \leq q_{95} \leq 4$. The normalized beta [$\beta$ (aB/I)] reaches values as high as 4, comparable to the best previous single-null discharges, with no confinement deterioration. The peak fusion power gains of $Q_{DD} = 1.0 \times 10^{-3}$ and D–D neutron rates of $1.4 \times 10^{16}$ s$^{-1}$ are more than double the previous maximum values for single-null discharges. Although high triangularity allows a larger plasma current, the fusion gain in these low triangularity plasmas is similar to that of high triangularity double-null plasmas at the same plasma current. These results are encouraging for advanced performance operation in ITER and for D–T experiments in JET.


## Introduction

Plasmas with negative central shear (NCS) may represent an attractive regime for advanced performance operation in ITER, as well as for D–T fusion experiments in existing devices such as JET. Weak or negative magnetic shear, in combination with E×B flow shear, is predicted to stabilize microinstabilities which may be responsible for energy transport. Indeed, there is clear evidence from DIII–D[1–3] and other tokamaks that transport can be reduced to near-neoclassical levels in a central region of negative magnetic shear. This core "transport barrier," accompanied by a reduction in fluctuation amplitude, results in high central pressure.

Stability to long wavelength magnetohydrodynamic (MHD) modes at high beta is necessary to utilize the improved energy confinement in NCS discharges. Calculation and experiment show that the beta limit is sensitive to the plasma profiles and discharge shape. Highly triangular double-null NCS plasmas in DIII–D with strongly peaked pressure profiles disrupt at $\beta_N = \beta \,(I/aB)^{-1} \approx 2$ while discharges with broader pressure profiles reach $\beta_N \lesssim 5$, consistent with MHD stability calculations. However, the improvement in $\beta_N$ with broadening of the pressure profile is calculated to be small for circular cross-section discharges. The highest fusion performance in DIII–D[4] has been achieved in high triangularity discharges with a relatively broad pressure profile and weak central magnetic shear, consistent with calculated stability limits.

The purpose of the experiments described here was to determine whether a core transport barrier occurs in NCS plasmas with a lower triangularity, single-null configuration similar to JET or ITER,


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whether stability at high beta can be maintained with relatively low triangularity, and whether these properties extend to the low values of safety factor ($q_{95}$ ~3) anticipated in future tokamaks such as ITER. The results will provide input for development of high performance scenarios with negative shear in JET.[5]

## Plasma Formation

The experiments were carried out in DIII–D plasmas similar, except in size, to those planned for "advanced tokamak" experiments in JET. The cross-sectional shape of the DIII–D plasma (Fig. 1) closely reproduces a JET model equilibrium, with elongation $\kappa \approx 1.8$ and triangularity $\delta \approx 0.3$. The aspect ratios differ slightly, with A = 2.75 in DIII–D and A = 3.2 in JET. Figures 1 through 3 describe a 1.8 MA discharge with an edge safety factor $q_{95} \approx 3.5$, but 2.0 MA discharges with $q_{95} \approx 3.0$ were also operated with no special difficulty.

Negative central shear profiles are formed by using low-power neutral beam heating during the plasma current rise to slow the penetration of inductive current,[6] as shown in Fig. 2(a). The q-profile in DIII–D is determined from MHD equilibrium fits which include motional Stark effect (MSE) measurements of the internal magnetic field at the locations shown in Fig. 1. A plasma current ramp rate dI/dt ≈ 0.7 to 1 MA/s is used in both DIII–D and JET, representing a change in safety factor $dq_{95}/dt$ about twice as fast in DIII–D as in JET. Assuming classical current density diffusion and the same electron temperature in both cases, similar q-profiles should result at the same edge safety factor $q_{95}$,since the smaller radius of DIII–D is compensated by the more rapid time evolution.

As the heating power increases in the current flattop, an internal transport barrier forms, producing a strong rise in central pressure. Although initially the plasma remains in L–mode, the global energy confinement is about 1.4 times the prediction of the ITER–89P L–mode scaling,[7] as seen in Fig. 2(c). In this phase, a region of negative shear (dq/dr < 0) extends over a normalized minor radius $0 < \rho < 0.5$, as shown in Fig. 3(a). Profiles of electron density measured with Thomson scattering and

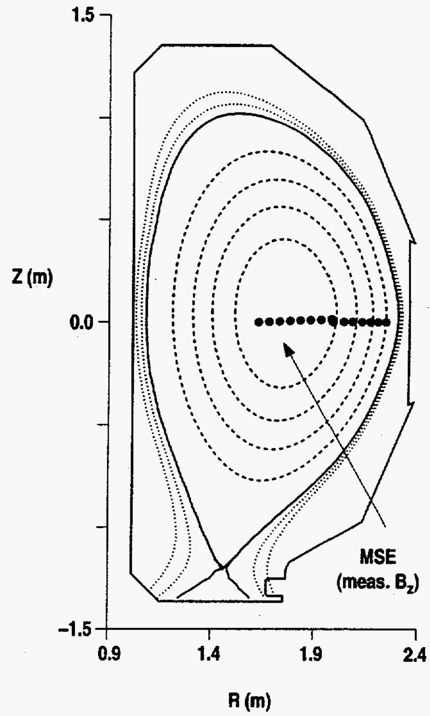


Fig. 1. Cross-section of single-null negative central shear plasma. (Discharge 88964, $I_P$ = 1.8 MA, $B_T$ = 2.1 T).

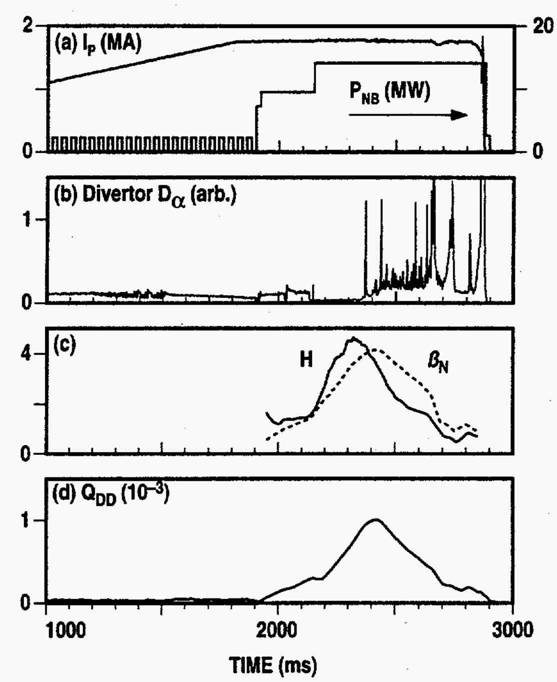


Fig. 2. Time evolution of single-null negative central shear plasma (discharge 88964): (a) plasma current and neutral beam power, (b) $D_\alpha$ emission, (c) energy confinement quality ($H = \tau_E/\tau_{ITER-89P}$) and normalized beta [$\beta_N = \beta\ (I/aB)^{-1}$], and (d) fusion power gain $Q_{DD} = P_{fus}/P_{in}$.

several $CO_2$ laser interferometer chords, ion temperature measured with charge exchange recombination spectroscopy, and electron temperature measured with Thomson scattering and electron cyclotron emission, shown in Fig. 3, all exhibit strong gradients in the region of weak or negative shear.

Uncontrolled peaking of the pressure profile often leads to disruptions at relatively low beta. Here, an additional increase in beam power at t = 2150 ms ensures an H–mode transition, indicated by the drop in $D_\alpha$ emission in Fig. 2(b), which broadens the pressure profile (Fig. 3) before a stability limit is reached. The confinement quality factor $H = \tau_E/\tau_{ITER-89P}$ rises to a maximum of ~4, as does the normalized beta $\beta_N$ [Fig. 2(c)], and the fusion power gain $Q_{DD}$ [Fig. 2(d)] reaches a maximum of $1.0 \times 10^{-3}$ at the end of the ELM-free H–mode phase.

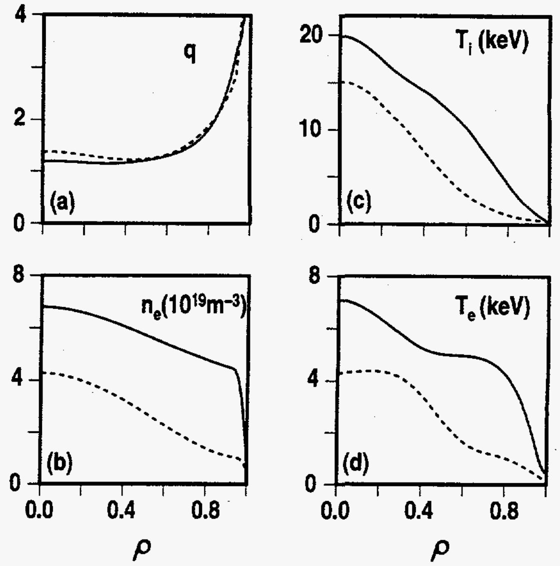


Fig. 3. Profiles of single-null negative central shear plasma during L–mode (broken lines) and H–mode (solid lines): (a) safety factor, (b) electron density, (c) ion temperature, and (d) electron temperature. (Discharge 88964, t = 2.1 and 2.4 s.)

### Plasma Performance

The energy confinement in these discharges is significantly better than in other, comparable single-null discharges, as shown in Fig. 4. The H factor in previous low triangularity single-null discharges reaches a maximum of about 3, and diminishes as $q_{95}$ decreases below 4, while the present NCS discharges reach values up to 4, almost twice as large as in previous single-null cases with $3 \leq q_{95} \leq 4$. The improved confinement has resulted in stored energies as high as 3.0 MJ, greater than in any previous low triangularity single-null plasma. Stability limits are similar to those in previous low triangularity single-null discharges, with values of normalized beta up to 4. However, it is noteworthy that even at the highest $\beta_N$ there is no degradation of energy confinement (see Fig. 5).

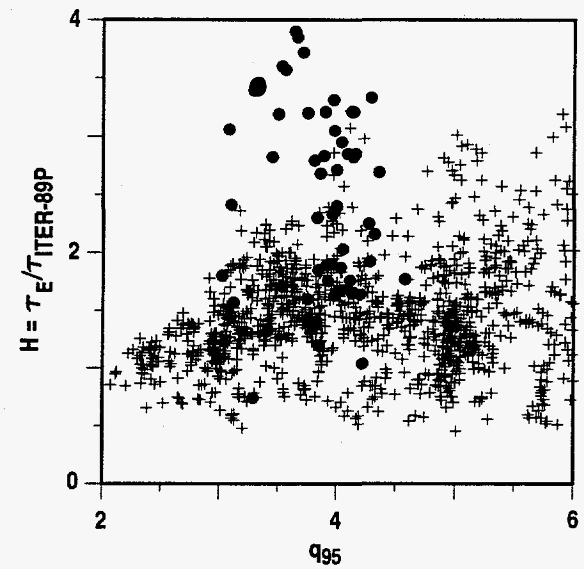


Fig. 4. Energy confinement quality ($H = \tau_E/\tau_{ITER-89P}$) versus $q_{95}$ for low triangularity single-null NCS plasmas (solid circles) compared to the DIII-D confinement data base of single-null plasmas with $1.5 < \kappa < 2$ and $\delta < 0.5$ (crosses).

The combination of internal transport barrier, H–mode edge transport barrier, and stability at high beta leads not only to high global energy confinement but also to higher fusion power gain than in single-null divertor discharges with conventional q profiles. The peak fusion power gains of $Q_{DD} = 1.0 \times 10^{-3}$ (obtained in 1.8 and 2.0 MA discharges) and D–D neutron rates of $1.4 \times 10^{16}\ s^{-1}$ (at 2.0 MA) are more than double the previous maximum values for single-null discharges.

The fusion performance of these low triangularity single-null discharges is comparable to that of the best high triangularity double-null plasmas[4] at the same plasma current. This is consistent with the observation that the two cases have similar normalized energy confinement (H). Since fusion power density varies roughly as the square of the plasma pressure and the energy confinement time scales with the plasma current, the fusion power gain is expected to vary approximately as $Q \sim P_{in} \tau_E^2 \sim P_{in} I_P^2$. As shown in Fig. 6, the measured $Q_{DD}$ does increase as $I_P^2$, with similar values for high and low triangularity discharges. However, the maximum plasma current is smaller for low triangularity plasmas, restricting them to a smaller maximum fusion power and fusion power gain.

## Conclusions

The fusion performance in DIII–D low-q single-null divertor discharges has doubled as a result of improved confinement and stability, achieved through modification of the pressure and current density profiles. These discharges extend the regime of neoclassical core confinement associated with negative or weak central magnetic shear to plasmas with the low safety factor ($q_{95} \sim 3$) and triangularity ($\delta \sim 0.3$) anticipated in future tokamaks. These results are encouraging for advanced performance operation in ITER and for D–T experiments in JET.

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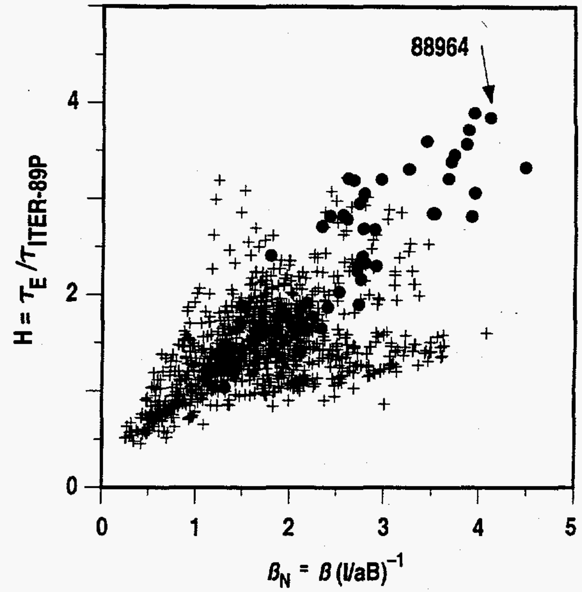


Fig. 5. Energy confinement quality (H) versus normalized beta ($\beta_N$) for low triangularity single-null NCS plasmas (solid circles) compared to the DIII–D confinement database of single-null plasmas with $1.5 < \kappa < 2$ and $\delta < 0.5$ (crosses).

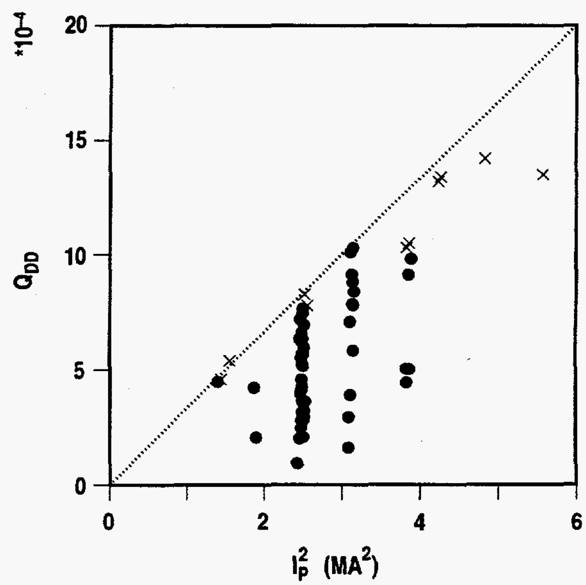


Fig. 6. Fusion power gain ($Q_{DD} = P_{fusion}/P_{in}$) versus plasma current squared, for low triangularity single-null NCS plasmas (solid circles) and high triangularity double-null NCS plasmas (crosses).