CONFINEMENT AND BETA STUDIES IN LOW-q TOKAMAK CONFIGURATIONS

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Abstract

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Tokamak discharges with $1 \lesssim q_\psi \leqslant 2$ have been produced on the Cleo device with pulse durations much longer than the shell time constant, provided the torus is gettered and feedback control of the radial position is used. Using the $\ell = 3$ stellarator windings, it has also been possible to produce discharges with $1 \lesssim q_\psi \leqslant 2$ that are controlled by the magnetic aperture associated with the helical field – a helically assisted low-q tokamak (HALQT). A comparison of confinement properties of several different toroidal configurations reveals that a low-q tokamak achieves the best product of beta and confinement time for Ohmically heated discharges.

1. INTRODUCTION

Reducing the value of the safety factor q at the limiter q_L in a tokamak allows large values of beta to be obtained at relatively low values of the poloidal beta, β_p. Stable operation is predicted for values of q_ψ between 1 and 2 with a conducting shell close to the plasma. Operation at such low values of q_L has been realized on the T6 [1], T11 [2] and Diva [3] devices, all of which had a conducting shell close to the plasma and where the shell time constant was longer than the duration of the plasma. Operation with $q_L < 2$ was also obtained on the Tosca device [4] without a conducting shell, and the authors calculated that the observed speed of rotation of the magnetic structures resulted in the thin vacuum vessel wall acting as a shell. One special feature of such discharges was that they were free from disruptions. This could be particularly important for future operation of large tokamak devices. Confinement has been observed to be only moderately impaired at $q_L < 2$ compared with discharges of $q_L > 2$. No attempt to maximize β in these configurations has yet been reported.

The Cleo device has a major radius of 0.9 m. The minor radius of the vacuum vessel is 0.14 m and the limiter aperture has a radius of 0.13 m. The vacuum vessel

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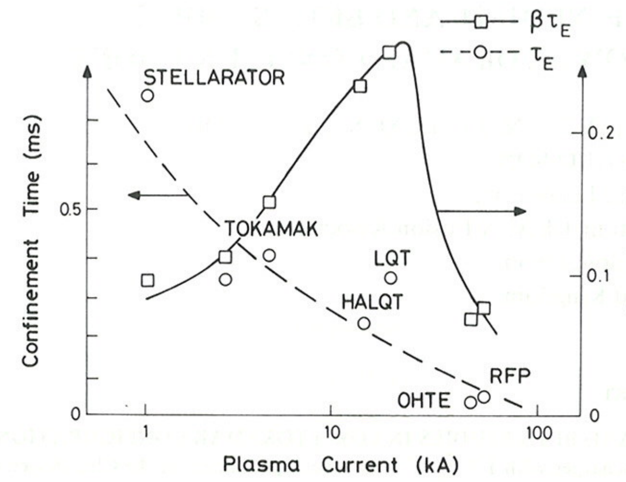

FIG.1. Total energy confinement time and the product $\beta\tau_E$ as a function of plasma current for different toroidal configurations. OHTE is a reversed field pinch with the helical windings controlling the pitch of the magnetic field lines [5].

has two insulating breaks and a diffusion time of about 3.6 ms. The use of precise plasma position control, wall conditioning including titanium gettering, and careful control of the gas puffing has allowed low-q tokamak (LQT) operation ($q_L \gtrsim 1$) at currents previously only accessible by HALQT operation [5]. In addition, the HALQT regime has been extended to somewhat higher currents. LQT and HALQT discharges have been maintained stably for periods up to 10 times the shell diffusion time. The recently reported study of the confinement properties of various toroidal configurations [5], including stellarator, tokamak, HALQT and RFP configurations, has been extended to include these new LQT and HALQT data (Fig. 1). The plasma current has been varied over two orders of magnitude for the different configurations and it was found that the maximum line density, N, scaled with the plasma current such that I/N was about 10^{-14} A·m. A comparison of confinement ($B_\phi = 0.18$ T) was made, based on loop resistance (constant Z_{eff}), line average density and total input power. Though the stellarator was found to exhibit the best energy confinement time (τ_E) under these conditions, namely 0.75 ms, the figure of merit $\beta\tau_E$ was optimum for the low-q tokamak configurations, largely because of the increased density allowed by higher plasma current. High average values of β were readily achieved in the pinches (≈6%), but the confinement was relatively poor (20 μs).

2. HELICALLY ASSISTED LOW-q TOKAMAKS

In the HALQT configuration, a reverse helical transform with high shear allows higher plasma currents to be obtained for a given total rotational transform $\iota_\Sigma = \iota_I - \iota_w$, where ι_I is the rotational transform due to the Ohmic heating current and ι_w is the helical winding transform, all of which are functions of radius. Thus, if the plasma aperture is fixed and the current is limited by a minimum value of q along a field line q_ψ, then the addition of a helical field allows more current to be passed. This current permits higher densities and thus high β values in Ohmically heated discharges. However, the reverse transform associated with the $\ell = 3$ windings reduces the plasma aperture. Field line tracing calculations [6] have been used to determine the position and rotational transform of the last closed flux surface (Fig. 2). For this case the separatrix is on the vacuum vessel wall and q_ψ is 1.35. If the current centroid is moved inwards 1–2 cm, as experimentally observed, then the separatrix just touches the two limiters which are 180° apart toroidally, and q_ψ is then 1.25. The presence of a zero in the rotational transform during the plasma current rise is avoided by raising the helical winding current I_L with approximately the same risetime. If a zero in the transform at the limiter does occur, rapid loss of plasma is observed.

The discharge current can be increased up to ≈15 kA, at which time substantial fluctuations appear which limit the plasma current and lead to a rapid drop

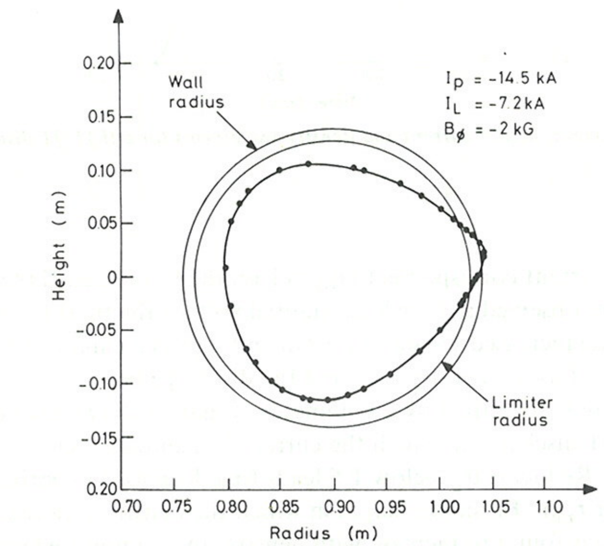

FIG.2. Last closed magnetic flux surface for a HALQT with a plasma current of 14.5 kA, showing the limiter and wall radii. The current in the helical winding, I_L, is 7.2 kA.

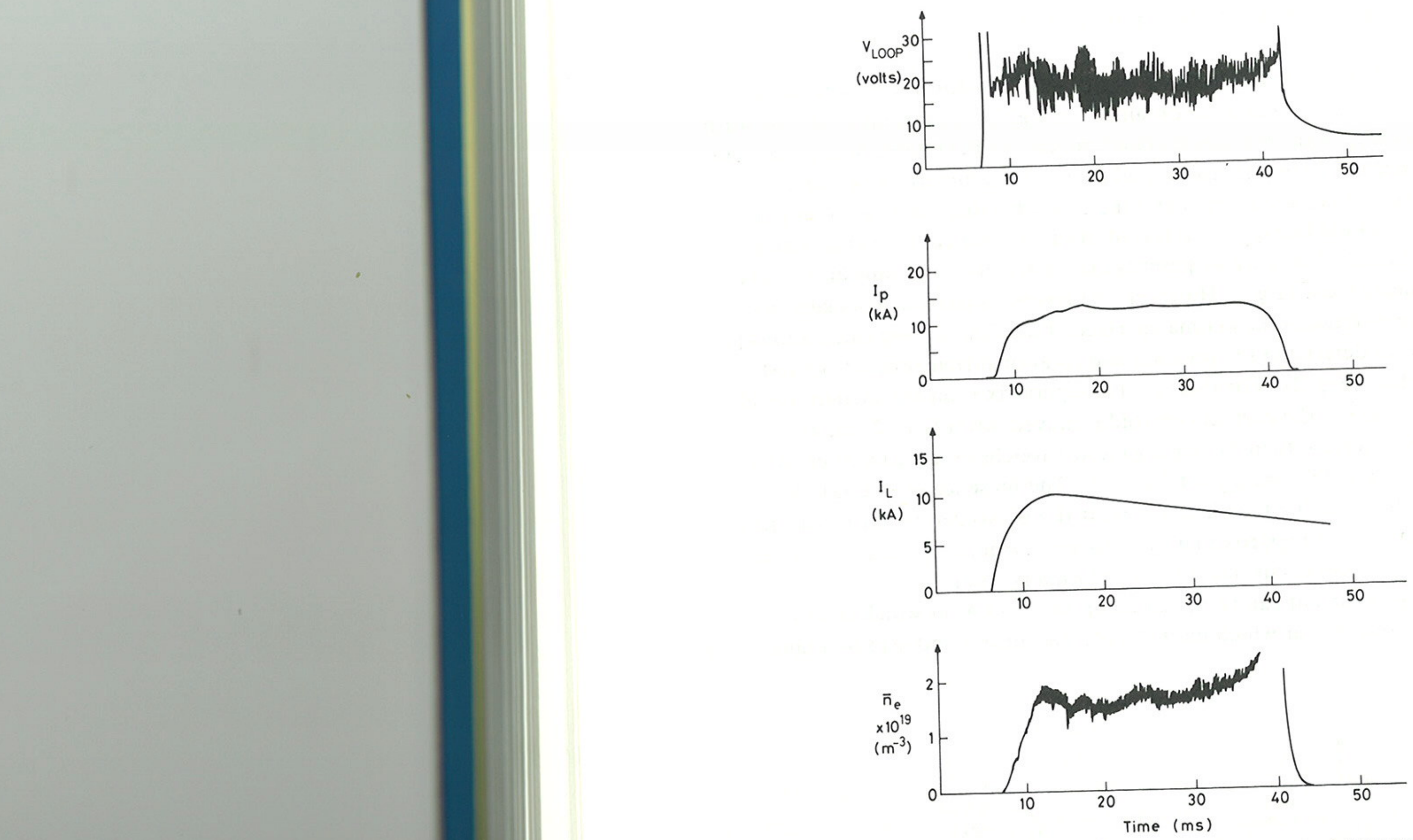

FIG.3. Voltage, current, helical current and density waveforms for a HALQT discharge (B_ϕ = 0.2 T).

in density. This current corresponds to $q_\psi \approx 1$ on the last closed flux surface. No disruptions are observed although substantial voltage fluctuations are seen, due possibly to the increased separation between the plasma and conducting wall. The current falls off as the density rises and the discharge becomes resistive and radiation-dominated, as verified by a bolometer. Figure 3 shows a set of waveforms for such a HALQT discharge in which the current is maintained close to $q_\psi \approx 1$ for about 25 ms. Reducing q_ψ below 1.5 leads to a decrease in confinement time ($180 \rightarrow 130$ μs for τ_{Ee}). From discharges in which the density is raised, the confinement time is found to increase with density up to a point where ion heat conduction becomes significant. The Murakami parameter (nR/B_ϕ) in such discharges is $\leqslant 9$, which is larger than values obtained on Diva or T11. The

maximum density is close to the limiting density given by $I/N \approx 10^{-14}$ A·m. Soft X-ray measurements using aluminium filters to determine the energy distribution show that the central temperature in these discharges is roughly 70 ± 20 eV.

3. LOW-q TOKAMAKS

Using wall conditioning, including gettering, feedback control of the plasma position and careful gas puffing to control the initial density rise, it has been possible to produce discharges with $1 < q_L < 2$ without the assistance of the helical windings. This has been achieved in two ways. The first method is to raise the current in two stages: first to $q_L \approx 2$ and then ramp slowly to $q_L \geqslant 1$. The proximity to $q_L = 2$ is accompanied by a burst of noise on the loop voltage and a drop in density which can be recovered by gas puffing. When the current reaches 17.5 to 18 kA with B_ϕ = 0.2 T, positive voltage spikes appear and the

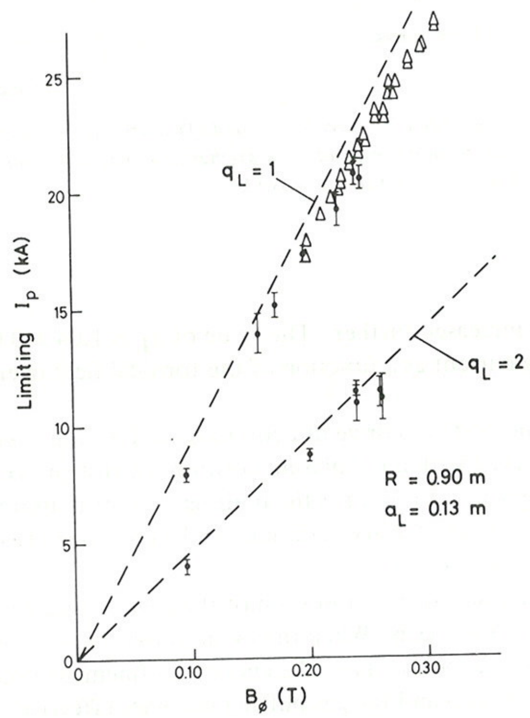

FIG.4. Limiting current as a function of toroidal field. Limiter q values of 1 and 2 are shown. The different points denote discharges with a delayed slow current rise (●) and a single fast rise (△) with feedback control.

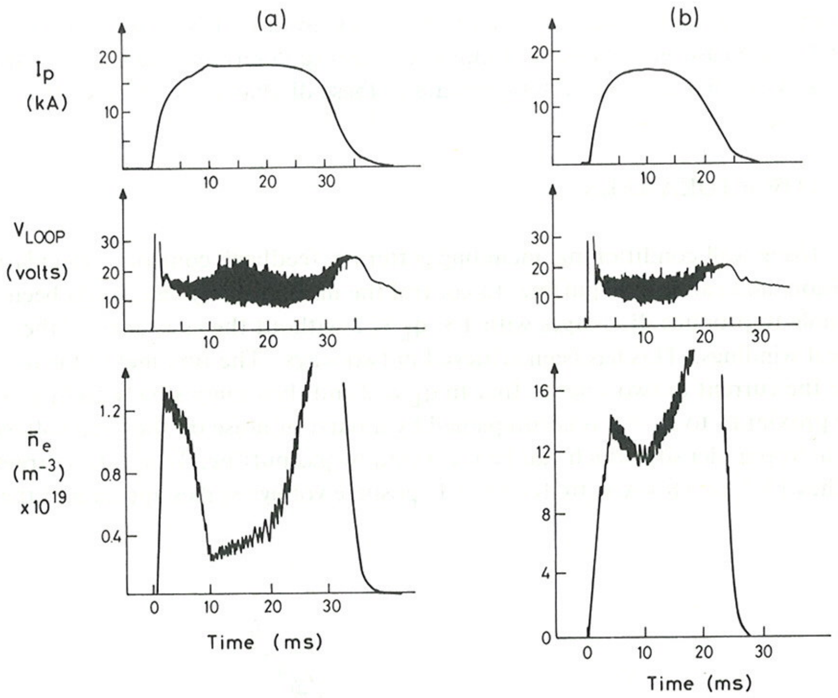

FIG.5. Current, voltage and density waveforms for LQT discharges showing: (a) rapid density pump-out associated with instabilities, and (b) a discharge in which the limiting current is not reached and a steady build-up in density is possible.

current cannot be increased further. The value of q_L is 1.04 ± 0.04. Figure 4 shows this limiting current as a function of the toroidal field over the range 0.1 T to 0.3 T.

The second method is to drive directly to $q_L \gtrsim 1$ as indicated in Fig. 5(a). This is readily achieved with good plasma position control and gettering. Rapid pump-out of the density can occur if the limiting current is approached (Fig. 5(a)), but at smaller currents the density variation can be controlled (Fig. 5(b)) by gas puffing (up to 10^{20} m^{-3}·ms^{-1}).

Discharges can also exhibit saturation of the current and density pump-out at $q_L \approx 3/2$, as shown in Fig. 6. When the mode activity associated with $q_L \approx 3/2$ ceases, as shown on the loop voltage, the energy confinement time improves by more than a factor of two and the gas puffing becomes effective.

In an attempt to optimize the plasma β by Ohmic heating alone, we have used gas puffing to raise the density in these LQT discharges. It is possible to reach line-of-sight average densities of 2×10^{19} m^{-3} at a toroidal field of 0.2 T.

At higher densities, bolometer measurements show that the discharge is radiation-dominated. At lower densities the radiated power is typically 30%. Diamagnetic loop measurements indicate $\beta_p \leqslant 0.4 \pm 0.1$ for $q_L \approx 1.2$. A similar value is obtained using density, electrical conductivity measurements, and ion temperatures calculated by using the Artsimovich formulae. The average value of β reaches 0.6–0.8%. Ideal MHD stability calculations [7] for ballooning modes and kink instabilities indicate that, with wall stabilization, average values of β up to 1% should be possible on this large-aspect-ratio device. The magnetic Reynolds number for such discharges is about 6×10^4, which is large enough to prevent significant damping of the mode spectrum by dissipative effects.

Magnetic probe measurements made near the plasma surface show oscillations that are occasionally linked to periodic activity as might be expected from sawtooth behaviour in such plasmas. The period observed on current, density and soft X-ray monitors is about 300–500 μs. However, the magnetic activity is characterized by irregular bursts of oscillation at a frequency of about 200 kHz with an rms amplitude of about 1% of the poloidal field. From poloidal and toroidal field measurements, this is principally m = 1, n = 1, but with a pronounced ballooning character.

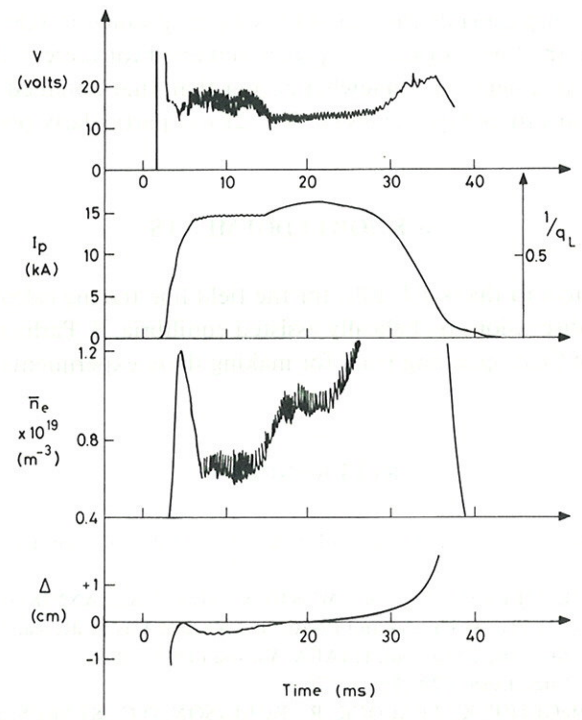

FIG.6. Saturation of current and density pump-out at q ≈ 3/2 in a LQT discharge from 5 ms to 15 ms. △ denotes the plasma displacement; + designates outward movement.

Discharges with $q_\psi < 2$ do not disrupt with the usual tokamak signature of a negative voltage spike (Figs 3, 5 and 6). Disruptions can occur at $q_\psi \approx 2$ during the current decrease at the end of the discharge. This can be avoided, however, by raising the density, which creates strong radiative cooling, thus reducing the MHD activity.

In these high-density, low-field discharges, classical ion heat conduction is substantial: $\tau_{Ei} \gtrsim 500\ \mu s$. If conventional tokamak empirical scaling laws held [8], we would expect $\tau_{Ee} \approx 600\ \mu s$. The equipartition time is less than the confinement time, so $T_i \sim T_e$. Provided the discharges are not operated at rational q_ψ values (1, 3/2, 2), the energy confinement time is within a factor of two of this value (200–350 μs). This degradation factor is similar to that found on T11 and Diva.

4. CONCLUSION

Tokamak discharges with $1 \leqslant q_\psi \leqslant 2$ have been achieved for many shell diffusion times in the Cleo device both with and without the assistance of a helical field. The higher currents attainable in both these configurations allow significantly higher plasma densities and thus higher β values ($\lesssim$0.8%). The highest values of the figure of merit $\beta\tau_E$ were obtained for these configurations even though confinement was somewhat poorer than that obtained for $q_\psi > 2$. Confinement near rational q_ψ values (1, 3/2, 2) was particularly poor.

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DISCUSSION

T. TAMANO: Is there any particular reason why you chose $\beta\tau_E$ as a figure of merit, apart from the fact that large β and τ_E are desirable?

T.N. TODD: Increasing $\beta\tau_E$ represents increasing proximity to the reactor requirements of $n\tau_E \times T$, with $1/B^2$ included as an economy factor which is also of relevance to reactors.

T. TAMANO: Is there any sign that β is the limiting factor for the confinement time?

T.N. TODD: No β limit is seen; β seems to increase with current, so we would at present regard maximum β as a current limit effect.