Comparison of Confinement in Different Toroidal Configurations

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The CLEO device has been used to compare the confinement properties of a variety of Ohmically heated toroidal configurations at the same magnetic field. These include RFP and OHTE configurations, conventional tokamaks, a novel helically assisted low-q tokamak, and an $l = 3$ stellarator. The plasma current and density vary over 2 orders of magnitude for the different configurations. The stellarator exhibits the best energy confinement time, τ_E, but the tokamak achieves the best $\beta\tau_E$ product.

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The CLEO device (major radius 90 cm, minor radius 9–14 cm) has been used to compare the confinement properties of various toroidal systems, namely tokamaks, including the helically assisted version, an $l = 3$ stellarator, a reverse field pinch (RFP), and an OHTE[1] configuration. Two clear advantages in the use of one machine to make such comparisons are the constancy of (i) sources of field errors such as core limbs, shell gaps, and portholes, and (ii) limiter, wall materials, and surface conditioning. On the basis of Larmor-radius effects and classical confinement scaling it is reasonable to make comparisons at a similar total magnetic field, a value of 1.8 kG being used here.

The comparison was made using electrical diagnostics for the conductivity temperature T_σ, interferometric measurements for density, and bolometry for radiation losses. This permits estimates to be made of the average electron temperature, average electron beta, and electron energy confinement time. These values will be minimum ones because of the nature of the methods used to make the comparison. The differences between the various configurations are such that the trend of the results would not be altered even by quite large errors in, e.g., Z_{eff} and $\bar{a}$ (effective minor radius). Because of the short shell time constant ($\lesssim 3.6$ ms) on this device, programmed vertical and toroidal fields were necessary to control the plasma position and ensure toroidal flux conservation. Gettering was used throughout and in each case the deuterium-gas puffing rate was adjusted to produce the maximum attainable density without any obvious transfer to radiation-dominated phenomena.

The different q (safety factor) profiles for the various configurations are shown in Fig. 1. The helically assisted low-q tokamak (HALQT) should be noted in that it uses a reverse helical transform to permit higher values of plasma current or lower q and thereby attains higher values of density and beta. Typical current and voltage wave forms for each configuration are shown in Fig. 2. All of the discharges were optimized for pulse duration by adjusting the Ohmic heating, vertical field control system, and gas injection systems. The pinch durations were determined by the 0.7-V·s swing of the iron core. The longest pulses were limited by vertical field programming error arising from the magnetization current.

The principal results are tabulated in Table I. The plasma currents range from 1 to 67 kA and the densities from 2×10^{12} to 8×10^{13} cm^{-3}. The different maximum attainable densities for these Ohmically heated configurations are in agreement with the near-universal scaling of current to line density ratio, $I/N \sim 2\times10^{-14}$ A·m, as can

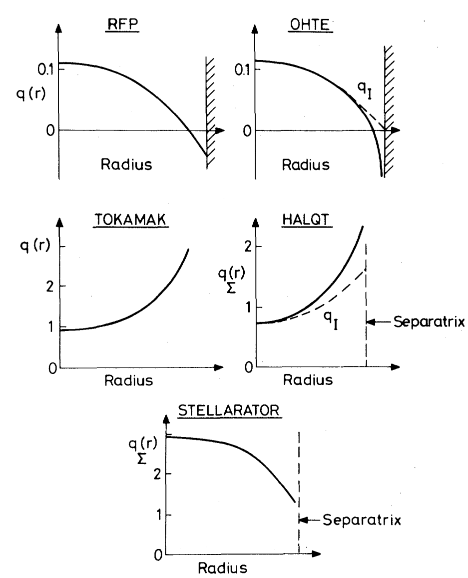

FIG. 1. Safety factor or q profiles for five toroidal configurations. q_I is the safety factor derived from the current distribution alone.

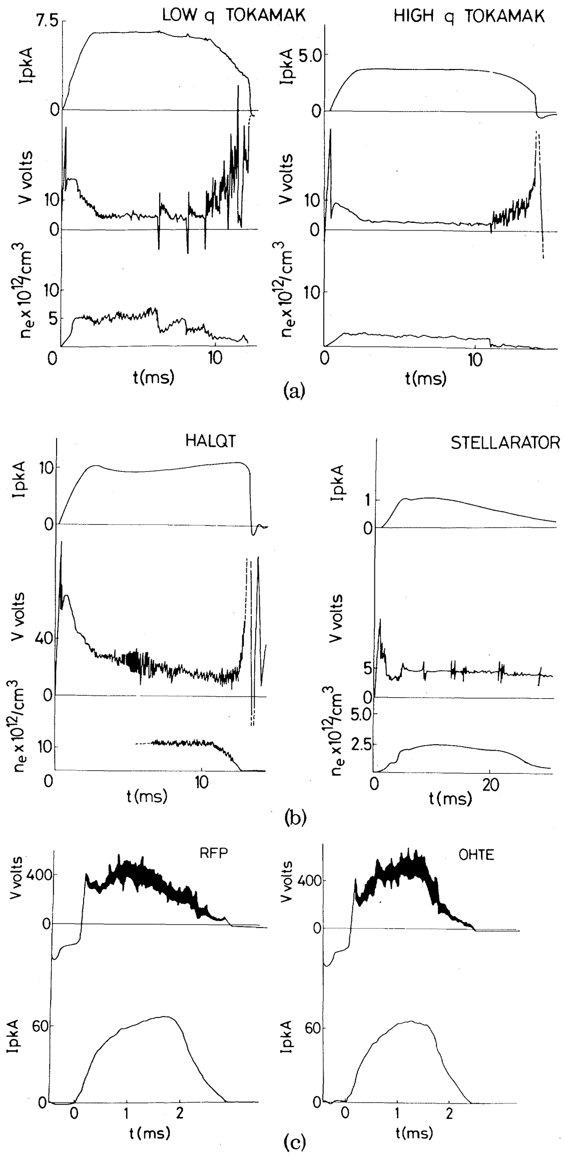

FIG. 2. (a) Current, voltage, and density evolution for a low- and high-q tokamak. (b) Current, voltage, and density evolution for a helically assisted low-q tokamak and a stellarator. (c) Current and voltage wave forms for a RFP and an OHTE, initial toroidal field 500 G.

be seen from the table.

The radius of the RFP configuration is taken as the wall radius, 14 cm, even though there are two limiters of 13 cm radius. This is because at these modest temperatures the limiters are ineffective for pinches, in which the field lines at the wall spiral principally poloidally. For the tokamaks the limiters are probably effective and the radius is taken as 13 cm. For the stellarator, HALQT, and OHTE the plasma size is determined by three-dimensional field-line tracing with the plasma modeled as a single current filament carrying the plasma current, together with an appropriate vertical field to ensure the positional equilibrium of the current channel. The effective aperture radius derived from the shape of the surface of the last closed field line for the stellarator, HALQT, and OHTE is ~9, 10, and 13 cm, respectively. The mean conductivity temperature is derived from the measured impedance allowing for the plasma size and assuming $Z_{\rm eff}=2$. In all cases the torus walls are gettered so it is possible that $Z_{\rm eff}$ is nearer to 1. For the pinch discharges an additional factor of 4 has been used to correct for the current distribution[2] associated with a pinch parameter, θ, ~1.6. The mean conductivity temperatures vary by only a factor of 2 for the different configurations. The central temperatures, T_0, are estimated from temperature distributions measured elsewhere in the various configurations. In no case does the temperature exceed 100 eV. The central ion temperature predicted using the Artsimovich formulas is approximately half the electron temperature. The percentage radiated power is significant and varies from (20 to 40)%. The table shows the electron poloidal beta, average beta, and electron energy confinement time. These values are uncertain up to a factor of 2, because the radial energy distribution has not been measured.

The stellarator exhibits the best confinement time but with a small value of beta. This result is borne out by other investigations of stellarator devices.[3] The value of beta would have been higher with an $l=2$ stellarator as the stability properties would then have permitted higher currents and densities. The low-q tokamak has a confinement time which agrees with that predicted from empirical scaling laws. The HALQT has a lower confinement time, which appears to be similar to that obtained on other low-q tokamak devices when $q \lesssim 1.5$.[4] Here the q_l near the separatrix is in the region of unity. It is possible in this case that the average value of β is $\gtrsim 1\%$ (including the ions since the equipartition time and energy confinement time are similar) although without the helical field the critical β value for ideal magnetohydrodynamic ballooning mode stability is 0.6% for a q on axis ~1. The two pinch configurations produce high average values of β, possibly up to 6% depending on the ion component, but with rather short energy confinement time, <15 μs. This is a factor 20–40 worse than the other con-

TABLE I. CLEO configuration comparisons. B_φ(axis) ≈ 1.8 kG; D_2 gas.

	I_p (kA)	I_L (kA)	R(mΩ)	T_σ	$\bar{a}$	T_o	radiated power %	$\bar{n}_e$ $10^{12}/cm^3$	I/N 10^{-14}A.m	β_θ^e	$\bar{\beta}_e$ (%)	τ_E^e (μs)	τ_{pulse} (ms)
RFP	67	0	4.5	20	14	40	∼40[a]	80	1.3	0.07	3.1	7	3.5
OHTE	67	6.9	6	18	13	36	∼40[a]	80	1.5	0.07	2.8	5	2.5
TOK (high q)	4	0	1	23	13	70	37	2	3.7	0.49	0.06	209	16
TOK (low q = 2.5)	6.7	0	0.7	29	13	90	30	5.5	2.2	0.60	0.20	372	12
HALQT (q∼1)	11.5	8.5	1	33	10	100	40	17	2.1	0.42	0.72	180	15
Stell	1	11.8	3	18	9	56	16	3.5	1.1	5	0.07	760	35

[a]Total integrated radiated power through shot.

figurations and represents a very severe anomalous loss process. Because the classical confinement time at constant field and temperature scales inversely as the density it might be thought that this could account for the poor confinement of the pinch as it has a much higher density; however, the neoclassical corrections factors for the other configurations almost cancel this density effect. Thus the neoclassical energy confinement time for the various configurations is almost the same, at ~1 ms.

This comparison of the confinement properties of different toroidal configurations, namely the RFP, stellarator, and tokamak, reveals that the stellarator possesses superior confinement while the pinch obtains high beta but with poor confinement. The tokamak confinement is a factor 2 or 3 down on the stellarator, depending on the safety factor, but it produces the optimum combination of $\beta\tau_E$ in this device.

We would like to thank the CLEO team for their invaluable assistance in these experiments.

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[3]D. V. Bartlett *et al.*, in *Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, 1980* (International Atomic Energy Agency, Vienna, 1981) Vol. I, p. 173.

[4]V. M. Leonov *et al.*, in Ref. 3, Vol. I, p. 393.