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ABSTRACT

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 reverse field pinch and OHTE configurations, tokamaks at high and low values of the safety factor and an ℓ=3 stellarator. The plasma current and density vary over two 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, an $\ell=3$ stellarator, a reverse field pinch and an OHTE[1] configuration. This comparison was undertaken at a magnetic field for the different configurations in the region of 1.8 kG. A comparison could have been made at similar densities but this would have required much larger toroidal fields ($\sim$ 10 kG) for the tokamaks and stellarator. On the basis of Larmor radius effects and classical confinement scaling the comparisons were made at comparable total magnetic fields.

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. Nevertheless it is believed from other more detailed measurements of plasma parameters in similar devices that the differences between the configurations would not be modified by more detailed measurements of the gross plasma parameters. Because of the short shell time constant ($\lesssim$ 3.6 ms) on this device, programming of the vertical and toroidal fields was 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 safety factor (or q) 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 waveforms for the tokamak, HALQT, stellarator, RFP are shown in Fig. 2. The OHTE waveforms are similar to the RFP but with a 30% higher loop voltage. All of the discharges were optimised for pulse duration by adjusting the ohmic heating, vertical field control system and gas injection systems. The pinch durations were ultimately limited by the 0.7 V sec swing of the iron core. The longest pulses were limited by vertical field programming error arising from the magnetisation current.

The principal results are tabulated in Table 1. The plasma currents range from 1 to 67 kA and the densities from $2 \times 10^{12} cm^{-3}$ to $8 \times 10^{13} cm^{-3}$. The different maximum attainable densities for these ohmically heated configurations are in agreement with the near universal scaling of current to line density ratio, $I/N = 2.10^{-14}$ A.m. It can be seen from the Table that the different configurations of CLEO are close to this optimum.

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 unlikely to be effective for pinches, in which the field lines at the wall spiral prinicipally poloidally. For the tokamaks the limiters are probably effective and the radius is taken as 13 cm. For the stellarator, helically assisted low q tokamak and OHTE the plasma size is determined by three dimensional field line tracing with the plasma modelled 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 $Z_{eff}=2$. In all cases the torus walls are gettered so it is possible that Z_{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, $\sim$ 1.6. The mean conductivity temperatures vary by only a factor of two for the different configurations. The central temperatures, T_o, 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 formulae is approximately half the electron temperature. The percentage radiated power is significant and varies from 20-40%. The Table shows the electron poloidal beta, average beta and electron energy confinement time. These values are uncertain up to a factor of two, 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 is not far behind with a confinement time which corresponds fairly well 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_I near the separatrix is in the region of unity. It is possible in this case that the average value of beta is $\gtrsim$ 1% including the ions since the equipartition time and energy confinement time are similar. Without the helical field the critical beta value for ideal MHD ballooning mode stability is 0.6% for a q on axis of 1. The two pinch configurations produce high average values of beta, 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 configurations 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 neo-classical correction factors for the other configurations almost cancel this density effect. Thus the neo-classical energy confinement time for the various configurations is almost the same, at $\sim$ 1 ms.

A 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 $\beta\tau_E$ on this device.

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

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TABLE 1

CLEO CONFIGURATION COMPARISONS

B_ϕ = 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	β_θ^e	$\bar{\beta}_e$ (%)	τ_E^e (μs)	τ_{pulse} (ms)
RFP	67	0	4.5	20	14	40	∿40*	80	0.07	3.1	7	3.5
OHTE	67	6.9	6	18	13	36	∿40*	80	0.07	2.8	5	2.5
TOK (high q)	4	0	1	23	13	70	37	2	0.49	0.06	209	16
TOK (low q = 2.5)	6.7	0	0.7	29	13	90	30	5.5	0.60	0.20	372	12
HALQT (q∿1)	11.5	8.5	1	33	10	100	40	17	0.42	0.72	180	15
Stell	1	11.8	3	18	9	56	16	3.5	5	0.07	760	35

*total integrated radiated power through shot.

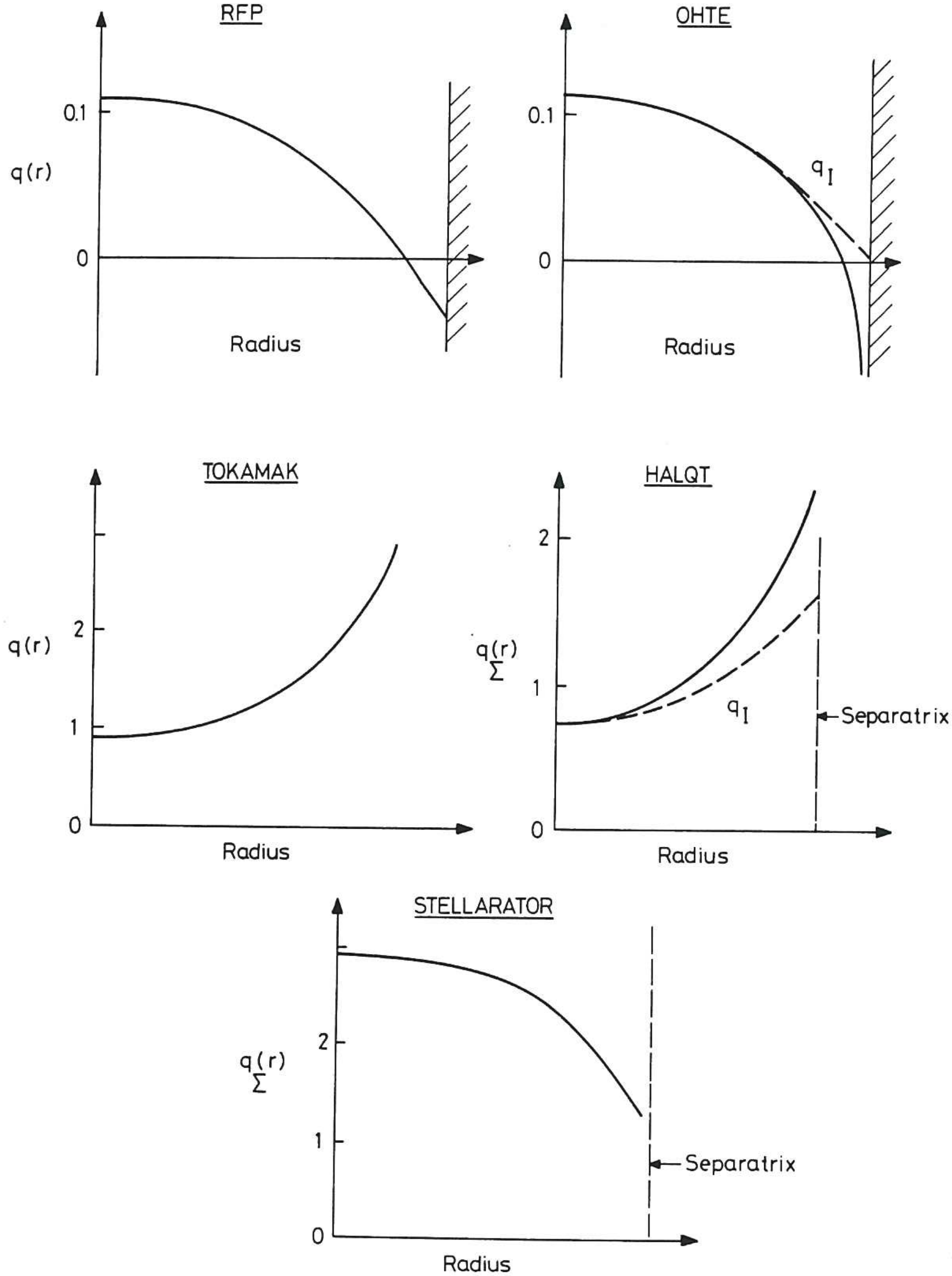

Fig.1 Safety factor or q profiles for five toroidal configurations.
q_I is the safety factor derived from the current distribution alone.

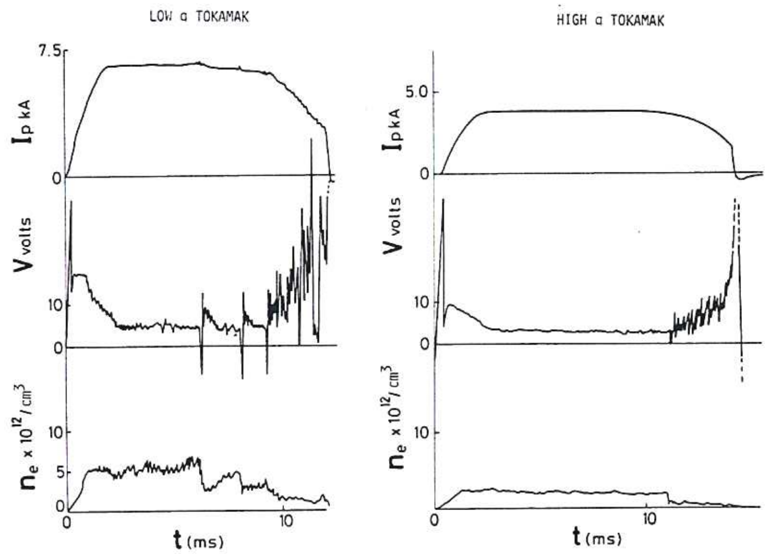

Fig.2(a) Current, voltage and density evolution for a low and high q tokamak.

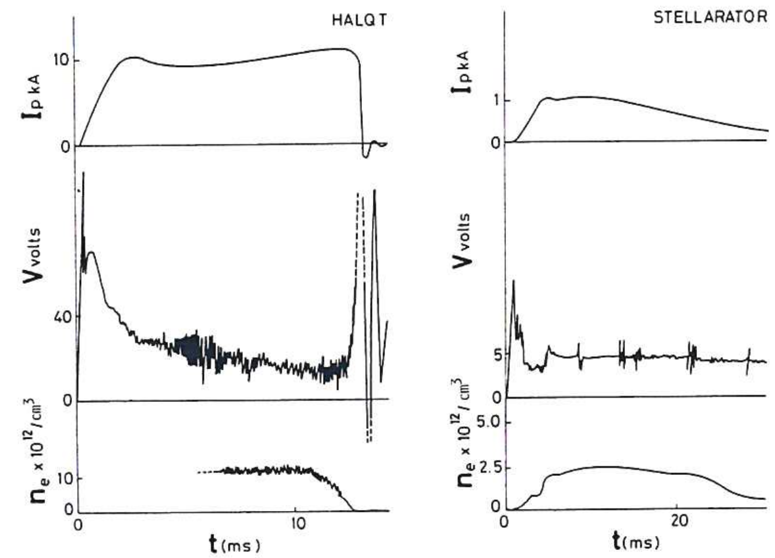

Fig.2(b) Current, voltage and density evolution for a helically assissted low-q tokamak and a stellarator.

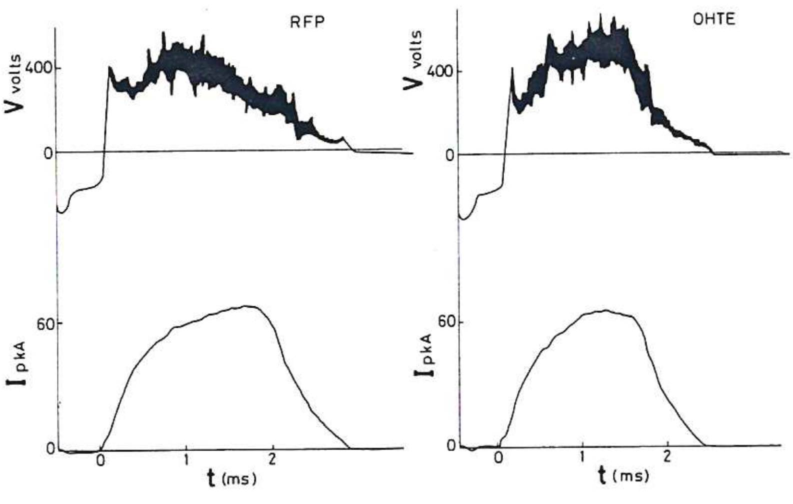

Fig.2(c) Current and voltage waveforms for a RFP and an OHTE, initial toroidal field 500G.