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Report

THE CLEO-TOKAMAK EXPERIMENT

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THE CLEO-TOKAMAK EXPERIMENT

by

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ABSTRACT

Tokamak discharges have been established without using a thick conducting shell. Currents up to 70 kA and gross stability for up to 80 msec are obtained. No obvious instability or loss is produced when a 48 kW neutral beam is injected tangentially into the plasma.

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1. INTRODUCTION

CLEO is designed as a high shear stellarator. All major components are now complete except for the $\ell = 3$ winding which is in position on its own torus and is awaiting installation into the main assembly. During construction it was decided to use the anticipated interval between completion of the toroidal field and availability of the helical winding to carry out exploratory tokamak experiments. These experiments were designed to investigate two major problems relevant to a future tokamak programme: (a) the gross stability of a tokamak with an iron core but no thick stabilizing shell and (b) the possibility of using neutral beam injection to heat the plasma without provoking excessive loss or instability.

The new systems required for tokamak operation were a large torus and a programmed, profiled transverse field (B_V) system. The torus was welded from commercially available stainless steel octants giving a "lobster-back" torus construction. The B_V was obtained by energizing a suitable winding in series with the primary winding, giving a B_V varying roughly in sympathy with the gas current. A shunt was provided to vary the ratio of B_V to gas current. A separate amplifier controlled winding was provided for feed back control of B_V over a range of $\pm$ 20 G compared to the $B_V \approx 400$ G required for equilibrium at $I_{gas} = 120$ kA ($q = 3$), the response time of $\sim$ 0.5 msec equals the time constant of the 0.5 cm thick stainless steel vacuum vessel.

2. THE APPARATUS

The main parameters are: major radius (R) = 90 cm, limiter radius $a_{lim} \leqslant 18$ cm, $B_{TOR} \leqslant 20$ kG, $I_{q=3} = 120$ kA, available flux swing = 0.8 volt secs. The small available power supply (6 MW) forced the use of liquid nitrogen cooled coils. These individual cryostat coils are slim and give good access to the plasma. There were initial difficulties with the cooling system, possibly due to condensation of impurities into the nitrogen circuit. The system was modified to have extra filters and pressurized interpulse cooling in January 1973 and has operated continuously since that date. The toroidal field coils had their magnetic axes individually determined and were carefully aligned. However, electron beam tests, on the final assembly, revealed a 0.1% horizontal lack of closure in B_{TOR}. Further radial field errors arise due to stray fields from the core. These errors are corrected by a separately energized B_R winding.

The discharge is initiated by a 1.5 kV, 0.035F bank and sustained by up to three 500 V, 0.5 F banks fired in sequence. Transformer turns ratios of 10:1, 12:1 and 16:1 have been used. The insulating gap in the torus is a 2 cm thick alumina ring and there is no liner. The limiter consists of four quadrants of 1 cm diameter molybdenum rod, mounted to form two electrically insulated arcs of radius 18 cm. Preionization filaments giving 5 mA emission are mounted in the top and bottom of the limiter. Additional preionization is provided by a 400 kHz 3 kW R.F. oscillator giving ± 50 V across the gap.

A 50 Hz discharge can be used for mild vacuum baking and cleaning. It is also possible to run at B_{TOR} = 2 kG and 3 shots/min for discharge cleaning. At full field B_{TOR} = 20 kG the minimum interval between shots is 15 mins.

3. NEUTRAL INJECTION SYSTEM

The neutral injector is of the multi-hole electrode type (Fig. 1 and 2), developed from that described by Morgan and co-workers at Oak Ridge. The power supply is capacitor bank driven, and gives a 60 msec pulse on test.

Performance Curves are shown in Fig. 3. The best operation, on test, at 30 kV acceleration voltage gives an 8.5 A current drain on the power supply. 80 kW of this enters an aperture equivalent to CLEO (11 cm diameter at 135 cm) as fast neutrals, 45 kW as 30 keV neutrals originating as H^+, 20 kW at 15 keV (from H_2^+) and 15 kW at 10 keV (from H_3^+). In actual operation on CLEO up to 50 kW of neutrals have been injected. The total particle flow into CLEO from the source, including beam, in test conditions is 10 A (H^+ equivalent) or 1 torr ℓ/sec (H_2). During a 40 msec pulse this would introduce enough particles to increase the usual

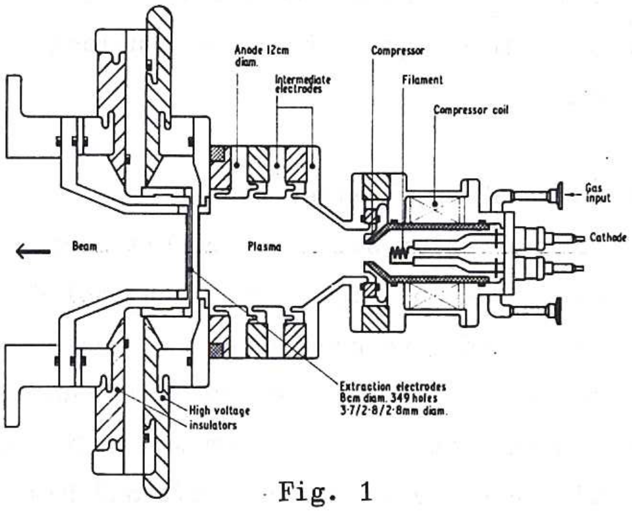


Fig. 1

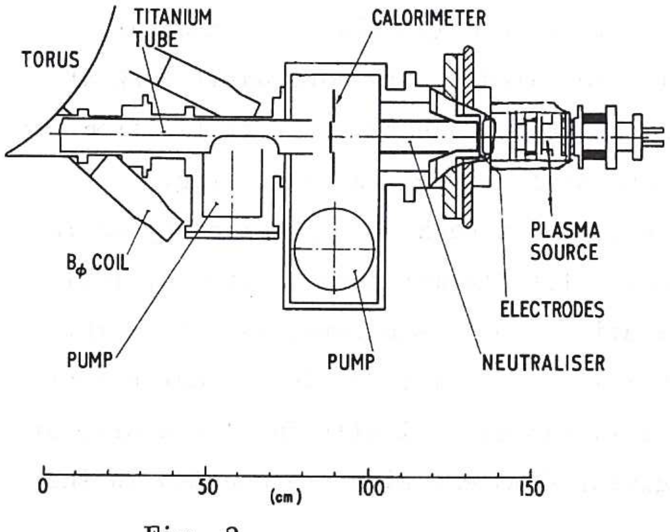


Fig. 2

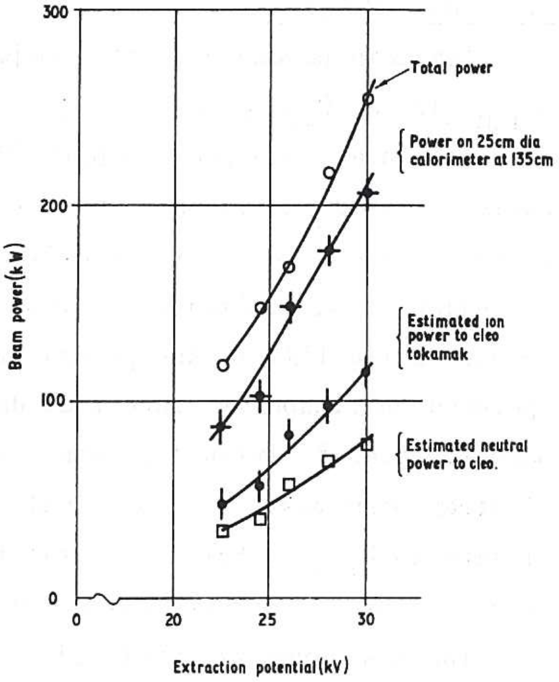


Fig. 3

operating $\bar{n}_e$ ($\sim 10^{13}/cm^3$) by about 50%. If the injection does not provoke any enhanced loss then using empirical scaling from T-3 parameters we would expect the beam to produce a 10% increase in T_e and T_i for $I_{pl} = 80$ kA. At this level neutrals carrying more than 60% of the injected power are expected to be captured in the plasma. With a single beam it is possible that effects will arise due to the imbalance of angular momentum and the generation of injection produced currents. We can if necessary add a second beam line (which exists) to inject in the opposite direction, but for this line only 30 kW of neutrals could be injected and only 45% of this would be captured.

4. RESULTS

The first discharges were obtained at the beginning of September 1972. On first operation the base pressure was $\sim 4 \times 10^{-6}$ torr and currents of 8 kA were obtained with 50 volts around the torus, the conductivity temperature was ~ 5 eV, and the current lasted for about 5 msec.

Using the 50 Hz discharge to give a mild bake at 60 - 100° C for 40 hours improved the base pressure to $\sim 1 \times 10^{-6}$ torr. Higher bake temperatures are not possible because of danger of stresses in the welded torus. After about 500 discharges at ~ 15 kA and 1.5 kG field the base pressure was $\sim 5 \times 10^{-7}$ torr and discharges with $I_{gas} = 38$ kA, $B_{TOR} = 18$ kG, $q_{lim} \approx 6$, $a_{lim} = 15$ cm, $\tau_{pulse} > 40$ msec, $T_\sigma \approx 90$ eV were produced. C III radiation observed at a point remote from the limiter was for early discharges much larger during the pulse than the initial ionization transient but is now much smaller than the initial ionization peak except at the end of the discharge. A radiation thermopile indicates significant emission only at the beginning and end of pulse.

The initial dirty discharges were easy to initiate and relatively well centred for a range of applied B_v and without correction of the B_R error. As cleaning proceeded so it became more difficult to get breakdown and it became essential to apply the correcting B_R and the correct B_v to centre the discharge. The feedback controlled B_v modifies the position of the plasma but is not essential to obtain a centred equilibrium. At small I_{gas} and sufficiently large gain the feed back amplifier can induce as expected, an oscillation of the plasma position; the 1/4 period is about 1 msec somewhat longer than the time constant of the stainless steel vacuum vessel.

Figure 4 shows the discharge behaviour at this stage, the conditions are: $B_{TOR} = 18$ kG, $I_{max} = 42$ kA, $a_{lim} = 15$ cm, $q_{lim} \sim 6$ the external vertical field falls like R^{-m} with m = 0.8. The H_2 working gas is introduced from a fast gas valve. Negative going voltage spikes are evident on the current rise, but subside soon after peak current. The loop voltage drops to ~ 3 V, equivalent to a conductivity temperature of 85 eV (assuming Z = 1 and constant conductivity over the aperture; a parabolic temperature profile would lead to 155 eV on axis.) The discharge is well centred in the up-down direction for the first 15 msecs and is stationary at about R = 90 cm for this time. At later times it moves inwards at about 0.5 cm/msec until the discharge is abruptly terminated at 25 msec when it has displaced about 7 cm in from its initial position. There is strong hard X-ray emission throughout the pulse. The H_β line remote from the limiter shows an intense burst of radiation at the end of the pulse. The density increases throughout the pulse reaching $\bar{n} = 1.4 \times 10^{13}/\text{cm}^3$ which is about five to six times the density observed immediately after the initial transient of H_β.

Figure 5 shows the effect of using the feedback amplifier. At the time when the inward motion begins in Figure 5, the amplifier switches on to produce its maximum output (about 20 G compared to the main B_V of 160 G at this time.) The inward motion is then much reduced, being within 2 cm of the initial position after 40 msec, and the discharge continues for more than 50 msecs. The density reaches a maximum of $\bar{n} = 1.8 \times 10^{13}/\text{cm}^3$ at 30 msecs and this is some 6.5 times the initial density. Attempts to increase the current beyond

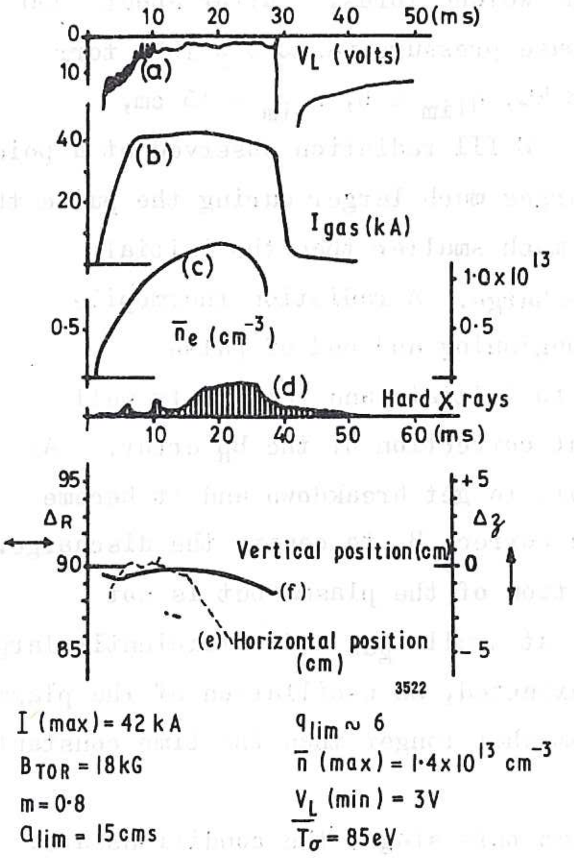


Fig. 4

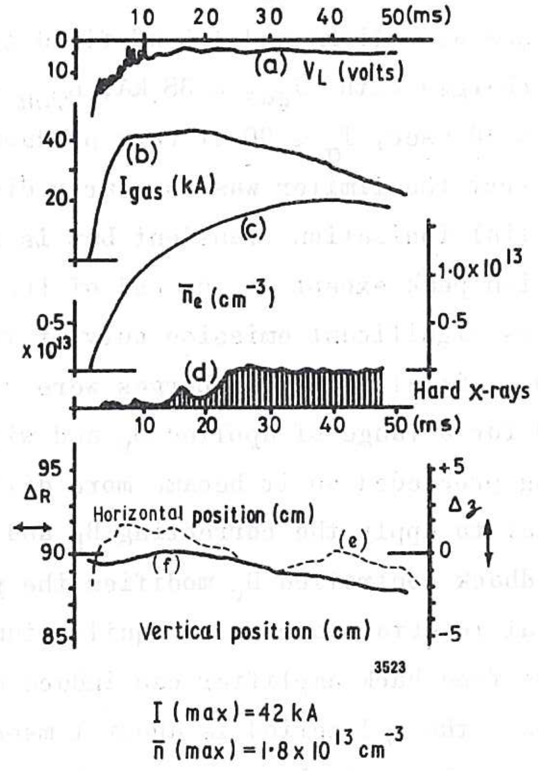


Fig. 5

the value of 42 kA in Figures 4 and 5 provoked large disruptive instabilities. Consequently more extensive discharge cleaning was attempted and after ~ 5000 shots at 15 - 20 kA and B_{TOR} = 2 kG (~ 1000 in Neon, the remainder in Helium) the base pressure dropped to 2 x 10^{-7} torr.

A failure in the vertical field winding at this stage forced us to use a configuration where, by careful positioning of the primary winding, most of the B_v is produced as stray flux from the core. This arrangement results in a field falling with an index $0 < m < 0.6$ depending on the value of the vertical field but typically m = 0.3. This field is significantly non-uniform around the major circumference, being 30% bigger under the core than 90° away. This more gentle gradient of B_v should give better in-out stability and better compensation for changes in β_θ but is nearer to the limit (m = 0) for up-down stability. In fact with the new configuration and careful adjustment of the B_R it is possible, without using the feed back amplifier, to get discharges which are well centred both horizontally and vertically. An example is shown in Figure 6. In this case B_{TORR} = 20 kG, I_{max} = 42 kA, a_{lim} = 18 cm, q_{lim} = 8.5, the loop voltage drops to ~ 2.2 volts corresponding to conductivity temperature of ~ 80 eV and an ohmic power input of 92 kW, there are no disruptive instabilities after the initial rise and the pulse duration can be up to 80 msec.

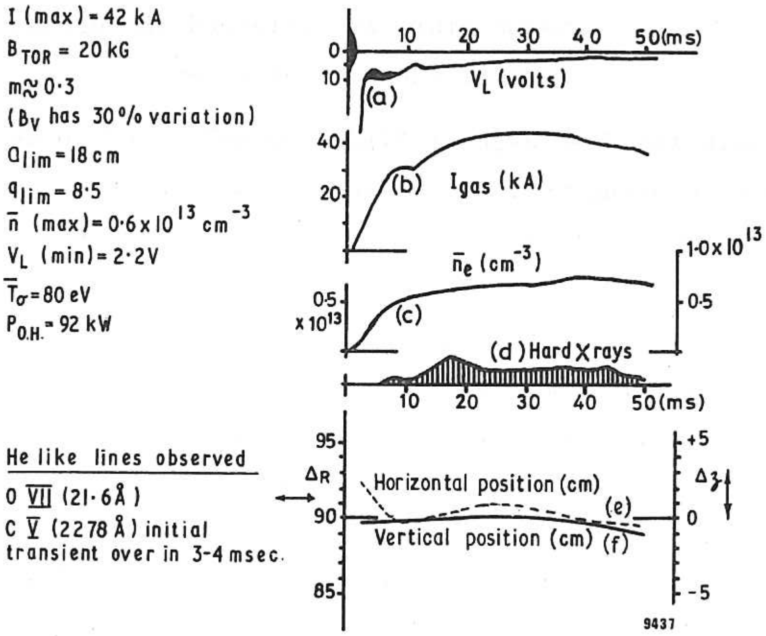
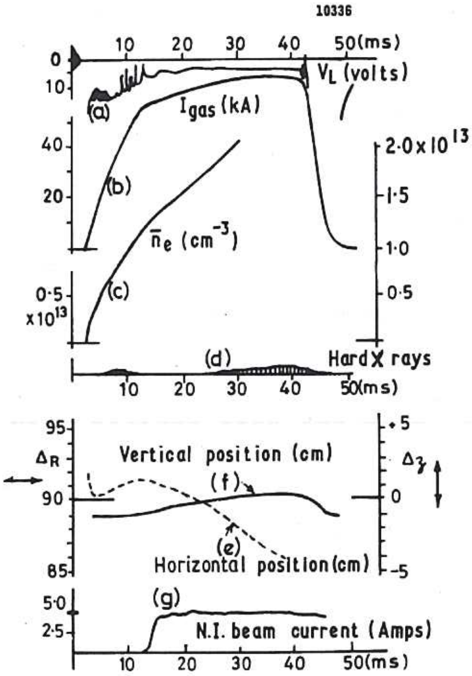


Fig. 6

The density reaches a maximum value of $\bar{n} = 0.6 \times 10^{13}/\text{cm}^3$ about 7 times the initial density. This rather large ratio indicates that there is still a significant influx of material during the discharge. There is strong x-ray emission throughout the pulse. Spectroscopic observations on similar discharges show that the helium-like O VII (21.6 Å) and C V (2278 Å) are excited. The C V line showed an initial transient in the first 3-4 msec of the discharge. These observations suggest that the discharge consist of a high electron temperature (> 100 eV) plasma, rather than a cold plasma with the current sustained by a runaway electron beam.

After some circuit changes higher current discharges have been obtained at higher densities. An example is shown in Fig.7: B_{torr} = 19 kG, I_{max} = 68 kA,

a_{lim} = 18 cm, $q_{lim} \sim 5$, the loop voltage drops to about 3 V and the density rises to $\bar{n} \sim 2 \times 10^{13}/\mathrm{cm}^3$ the hard x-ray emission is much less intense than in Fig.6. The conductivity temperature is about 90 eV and the ohmic power input ~ 200 kW.



I (max) = 68 kA
B_{TOR} = 19 kG
m ≈ 0·3
(B_V has 30 % variation)
a_{lim} = 18 cm
q_{lim} = 5
$\bar{n}$ (max) ~ 2 x 10^{13} cm^{-3}
V_L (min) ~ 3 V
$\bar{T}_\sigma$ = 90 eV
$P_{O.H.}$ = 200 kW
giving: τ_{Ee} = 1·2 msec.
& $\beta_{\theta e}$ = 0·13
If $T_i + T_e \approx$ 360 eV
then τ_E = 5 msec
β_θ = 0·5

H like lines observed
O $\overline{\underline{\text{VIII}}}$ (18·97 Å)
C $\overline{\underline{\text{VI}}}$ (33·74 Å)
(stronger than He like)

Fig. 7

The electron energy replacement time and the value of $\beta_{\theta e}$ deduced from this conductivity temperature are τ_{Ee} = 1.2 msec and $\beta_{\theta e}$ = 0.13. If as is usual in tokamaks the sum of the electron and ion temperatures is higher than the conductivity temperature these values would be increased, thus $T_i + T_e$ = 360 eV would correspond to τ_E = 5 msec and β_θ = 0.5. In these discharges the hydrogen-like spectral series of oxygen (O VIII with principle line at 18.969 Å) and carbon (C VI at 33.736 Å) are excited much more strongly than the helium-like series indicating that a high electron temperature is sustained throughout most of the current pulse.

The neutral injector was fired into the discharge of Fig.7 and delivered 36 kW of neutrals into CLEO with a 24 kV accelerating voltage. Injection was in the favourable direction for containment (parallel to the plasma current) and in these circumstances more than 70% of the beam should be trapped on confined orbits in the plasma. A calorimeter is located at the wall at the place where the beam leaves the plasma. The signal on the calorimeter with plasma present is less than 5% of the signal with no discharge, showing that the plasma does indeed intercept the beam. A neutral particle detector shows that fast ions, ranging from the beam energy downwards, are present in the plasma when the beam is on. A similar discharge with the gas system of the injector operating but no injected beam showed no change in characteristics. In both cases there are no disruptive instabilities after the initial rise and it can be seen that the beam introduces no instabilities or losses strong enough to affect the discharge impedance. Similar results are obtained with injected powers up to 48 kW corresponding to a trapped power which is up to 20% of the ohmic input. 36 kW of neutrals were also injected into a lower current discharge similar to that in Fig.6; again the beam produces no striking differences or indications of gross instability. In this case, however, many of the injected particles are on escape orbits.

5. CONCLUSIONS

5.1 A satisfactory discharge equilibrium for times up to 80 msec ($q = 6$) is obtained by using a space profiled, time varying, external vertical field even though the penetration time of vertical field through the vacuum vessel is only ~ 0.5 msec. When the external vertical field falls as $R^{-0.8}$ use of a feed back controlled vertical field extends the pulse length. With a field falling as $R^{-0.3}$ long pulses are obtained despite the major azimuthal non-uniformity (30%) of the field.

5.2 Unidirectional tangential injection of 48 kW of neutrals into a 68 kA plasma with 200 kW of ohmic input and of 36 kW of neutrals into a 42 kA plasma with 90 kW of ohmic input, did not lead to significant instability or loss.

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