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SOME ASPECTS OF BRITISH FUSION RESEARCH

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Culham Laboratory,
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SOME ASPECTS OF BRITISH FUSION RESEARCH*

by

R.S. PEASE

ABSTRACT

A brief review of British controlled fusion research with particular reference to pinch, hard-core and cusp geometries.

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1. INTRODUCTION

British research on controlled fusion began in the late 1940s from the stimulus and ideas of Craggs and Chadwick at Liverpool, Thonemann and Tuck at Oxford, and G.P. Thomson at London. All these groups were interested in high temperatures that might be obtained in gas discharges, especially if the currents were high enough to produce magnetic containment by the pinch effect. Craggs and his group were the first to attempt to detect neutrons from thermonuclear reactions in a high current arc discharge - hopefully but in vain(1). The work of Thomson and Thonemann produced early experimental data on the pinch effect(2,3,4); and this work culminated in the construction of large pinch devices, Zeta at Harwell(5) and Sceptre(6) at the A.E.I. Laboratories, Aldermaston, in 1957/58.

The basic features of the performance of these devices were described nearly three years ago at the Geneva Conference. It was apparent that much work was needed to elucidate the principal plasma phenomena occurring. It was clear that containment of kinetic energy of the plasma by the magnetic field was poor and that radical improvements were likely to be needed before good containment was obtained. We have pursued the studies of pinch effect since then and I will be saying something of our progress on this front.

We have also, however, started studies of plasma containment in other magnetic field configurations. Figure 1 shows some of the principal geometries available. I shall mention two of them. The first is the unpinch (or hard core) geometry suggested for its stability properties simultaneously by Bickerton in England and Colgate and Furth in America. The importance of this geometry is that it is stable on hydromagnetic theory and is closely related to the pinch; so that comparative studies of pinch and unpinch geometry might reveal much of importance. The second is cusp geometry, suggested by Grad and Tuck in the U.S., and also in Russia. It is not only thought to be stable under a wide variety of hydromagnetic conditions but is also a geometry in which the containing currents are normal to the magnetic field - a condition in which the plasma is not liable to a variety of further instabilities.

This work is all part of the programme being carried out at Harwell. However, I must also mention that there are, of course, sizeable groups at the A.E.I. Laboratories, at the A.W.R.E. Aldermaston, and at Imperial College, London. The A.E.I. Laboratories are studying containment in pinch and a toroidal version of the hardcore geometry; the A.W.R.E. Group are studying mirror geometry, with both shock heating and injection methods; and the Imperial College group are using pinch and mirror geometries. Even if I were qualified to speak for them, I shall not have time to describe the very interesting work they are doing.

2. PINCH CONTAINMENT

The stabilized pinch geometry in its simple idealised form is shown in Figure 2. The geometry is variable in that the compression of the stabilizing field B_z can be varied. In the limit of very high B_z, the B_z itself contains the hot plasma and the geometry becomes akin to that of a Stellerator. In the limit of very low B_z, the geometry becomes that of the unstabilised pinch, known from early days to be grossly unstable. Another variable parameter is the thickness of the skin current carrying region at the plasma surface. This thickness can be small compared to the radius of the plasma if fast rising currents and large bore tubes are used; or the skin can be fully diffused, as in Figure 2b. This thickness also affects the theoretical stability. Indeed the theoreticians have suggested depressingly restrictive conditions for pinch stability. The present state of their calculations suggests that we must have small values of compression (say approximately three times in the radius) within the metal walls of the torus, that the skin must be less than 12% thick(7), and in addition we must add a reversed B_z outside the pinch plasma as shown in Figure 2(8). These conditions are not obtained in Zeta; but if we could prove experimentally that this was the main reason for poor containment, we should be well satisfied; and we could proceed to the next stage.

But the actual position is more complicated. The most significant single observation of Zeta reported in our Geneva paper was of the energy containment time. The current pulse of Zeta provides not only the magnetic containing fields, but also heats the gas. The rate of heating is obtained from the current and voltage measurements. Suppose it is W per unit volume; if all is well, this energy goes into thermal motion of the gas and thus creates a pressure $^2/_3$ Wt at a time t after the completion of ionization. But this pressure cannot exceed some fraction β of the containing magnetic field $H^2/8\pi$ where β could conceivably be as much as 1, but is most unlikely to be so without grossly violating stability conditions. Both H^2 and W are related to the current, and the measurement reduces to that of the resistance of the discharge. This gives us an energy containment time $t_c = \frac{4}{3}\beta/\Omega$ where Ω is the resistance of the unit length of the discharge (in absolute emu). Taking out observed figure and $\beta = \frac{1}{3}$ gave $t_c \simeq 100$ μ sec. compared to a discharge pulse that lasts 2-3 msec.

Clearly, the form in which this energy reaches the walls is an important piece of information obtainable by direct experiment. However, there were, at the time of Geneva, various suggestions and apparently conflicting observations of various groups of workers. Thus Colgate suggested that fast electrons carried the energy to the walls(9) while others suggested it could be all radiated; we ourselves thought only 10% was radiated. Investigation by Gibson and co-workers(10) has now clarified the position on Zeta. The total energy lost in radiation is shown in Figure 3. This confirms the low proportion radiated at the low pressures originally used in Zeta and show how it rises to approximately 100% at about $5\mu D_2$ initial pressure or by adding impurities. Both calculation and collaterial experimental evidence strongly suggests that the radiation is line radiation from impurities of oxygen, nitrogen and carbon which are unavoidable in the present machine. Fast electrons ($\gtrsim$ 1 keV) are only found as a source of serious energy loss at the end of the discharge pulse and in association with an abrupt termination of the current. The measurements show that the majority of the magnetic and kinetic energy in the discharge tube just before the end of the current pulse, is carried to the walls by a large flux of fast electrons of around 8 keV energy. This is normally a small proportion of the total energy to be accounted for during the total pulse.

In the normal low pressure range, the lost energy is due to the plasma crossing the lines of force and reaching the walls. The evidence from Gibson and Mason's work is largely the detection of a plasma close to the walls with a density and energy capable of transmitting the energy to the walls. Moreover, electrical field fluctuations of a magnitude and frequency which could be associated with the plasma diffusion has been found. More striking evidence is provided by the spectroscopic analysis of the life-history of the impurity ions in the plasma. Extensive analysis by Burton and Wilson(11) of the duration of emission from different ion species, have provided measurements of the physical containment time of ions and electrons, and of the injection of cold gas from the walls. The containment time found for the original Zeta type conditions is about 100μ sec, in good agreement with the energy containment time quoted above. These containment times vary in the way shown in Figure 4 with mass density of the initial plasmas and energy input, and are independent of the charge and mass of the tracer ions used.

Shown in figure 5 is a further deduction from the analysis, a plot of the amount of plasma per unit length of discharge as a function of time throughout the discharge pulse. The loss of plasma proceeds at a fairly constant rate throughout the pulse, but the injection rate of cold gas varies throughout the pulse so that there is a rise in the total amount of gas in the plasma at the middle of the pulse. A striking feature of these results is that when the plasma line density falls to a value of 6×10^{16} cm^{-1}, regardless of magnetic field configuration, the abrupt termination of current occurs. The value of 6×10^{16} cm^{-1} multiplied by the mean X-ray energy observed is within a factor of 2 of the magnetic energy in the discharge. Moreover this line density is calculated to be close to the critical one for the onset of strong fluxes of runaway electrons with consequent electrostatic instabilities. Owing to the minimum in the curve of N against time it is possible to obtain the abrupt cessation of current early in the pulse, and a large proportion of the total energy must be dissipated by runaway electrons in this condition and may account for Colegate's measurements. These pump-out observations are now confirmed by spot checks of microwave transmission, and also by measurements in the extreme infra red range by Harding and Roberts.

As might be expected from the energy loss measurements, when the discharge is radiation cooled, plasma does not escape so rapidly, and indeed at the highest pressures both optical analysis and the measurement of particle densities at the walls indicate that the particle containment time approaches 1msec, the pulse duration or thereabouts. However, the plasma is undoubtedly much cooler under these circumstances and our attempts to raise the temperature without increasing plasma loss have not so far been successful.

Thus we are now satisfied that we know the main forms of energy loss. But we do not understand the diffusion mechanism by which the plasma gets to the walls across the lines of force. There are a variety of physical mechanisms possible, and we hope to identify these not only by direct experimental study, but also by relating them to other anomalous phenomena such as the high ion "temperature" (ion energies observed correspond to temperatures in the range $1-5 \times 10^{6}$ °C; electron temperatures are $2-4 \times 10^{5}$ °C). One such possibility is hydromagnetic instability of the configuration.

In the case where there is initially a well-defined skin current, the diffusion of the skin is undoubtedly anomalously rapid. Measurements of Rusbridge and Lees(12) (Figure 6) show a characteristic diffusion time decreasing with electron temperature, in direct contradiction with classical binary collision theory, and this time constant instead appears to be related to the energy per unit mass of the plasma in much the same way as the particle containment time. Such rapid diffusion might well follow from the fine skin instabilities first suggested by Suydam(13) and by Rosenbluth(8), which, on hydromagnetic theory, will occur in the absence of a reverse external B_z. If so, perhaps an effective pinch containment system could be set up, using reversed external B_z. A direct investigation of this possibility was the main motivation of the now cancelled I.C.S.E. experiment. This question of hydromagnetic stability and its effects have been studied extensively in the next experiment to be discussed.

3. EXPERIMENTS IN UNPINCH GEOMETRY

In these experiments(14), Dr. Reynolds and his co-workers set out to compare the hydromagnetically stable unpinch geometry with the unstable pinch geometry. Figure 7 shows the unpinch apparatus. Straight tubes 70 cm. long by 30 cm. bore were used with currents of about 100 kA at pressures of 100μ of D_2. Magnetic search coils provided evidence of instability by showing fluttering of the induced voltage and unreproducibility from shot to shot. In both experiments the traces show fluttering. Although it has been very difficult to establish experimentally the proportion of the fluttering which is due to experimental imperfections of the apparatus - end effects from the electrodes and effects of magnetic search coil on the plasma - it seems unlikely that fluttering in the unpinch represents an instability not predicted by simple hydromagnetic theory. A similar conclusion has been reached from parallel experiments by Colgate and Furth(15).

The present importance of the work is that it has been stimulated re-examination of the theory, and very recently Bickerton(16) and Jukes(17) have developed complementary theories of the stability of the plasma including the effects of finite electrical conductivity. So far such effects have been treated only with very simple models; but they suggest that finite conductivity of the plasma will give rise to instabilities. These ideas may well account for the plasma instability observed, but we await unarguable experimental proof. They may also reflect on the instabilities observed in Zeta and on those observed in rather special circumstances in similar discharges(18). If experimentally confirmed, this result suggests further restrictive conditions on the parameters of a power producing pinch-based thermo-nuclear reactor. Many of these restrictions arise from possible instability mechanisms due to currents flowing along the magnetic lines of force. The idea that such instabilities are the source of many of the confinement difficulties is also supported by the poor containment reported by ohmically heated stellerators, and by the good containment obtained by Dr. R.F. Post at the University of California with mirror geometry, both results being in defiance of simple hydromagnetic theory. For this reason we have placed emphasis on the experiments in cusp geometry, described below.

4. EXPERIMENTS IN CUSP GEOMETRY

At Harwell Dr. T.K. Allen and co-workers have built, and are now experimenting with, a shock pre-heated high compression cusp. The apparatus is outlined in Figure 8. The tube dimensions are 20 cms bore x 60 cms long. The shock pre-heat is provided by the discharge of 4 kilo-joules in $1\frac{1}{2}$ microsecond (quarter cycle) into single turn coils at the ends of the tube. The shock waves travel axially down the tube, collide in the centre, and the resulting plasma is caught and compressed in the rising cusp fields produced by the discharge of about $\frac{1}{2}$ M.joule into the cusp field coils with a $\frac{1}{4}$ period of about $12\frac{1}{2}$ μ sec. The results to be expected from this compression arrangement obviously depends a great deal on the initial state of the plasma, and Dr. Allen has started by conducting extensive experiments on the pre-heat shocks and the timing of these relative to the cusp field rise. One of the difficulties is the complexity of the shock phenomena itself. Framing camera pictures indicate, under some conditions, the presence of a fast front moving at 3×10^7 cm/sec, followed by a slow front at 5×10^6 cm/sec. At present spectroscopic and streak camera measurements suggests that the initial plasma has electron density $n_e \sim 1 - 5\,10^{15}$ cm^{-3} and electron temperature $Te \simeq 6$ eV with essentially 100% ionisation. The initial plasma occupies a volume of about 2 litres.

The observations on the compressed and trapped plasma are preliminary but exhibit at least one phenomenon which may turn out to be of importance. Framing camera pictures taken on our apparatus suggest that during the compressional phase, instabilities can occur. These instabilities are thought to be of the Raleigh-Taylor type predicted by Grad(20). They are supposed to arise from excessive acceleration of the plasma. The theoretical expression for stability is:

$$\frac{\overset{\text{il}}{B^2}}{4\pi R} > \rho \frac{d^2x}{dt^2}$$

$\frac{d^2x}{dt^2}$ = plasma acceleration

R = radius of curvature of field lines

ρ = density

Experimentally, the instabilities shown in the present apparatus are much less severe in light gases such as hydrogen and arise most easily in the early stages of the cusp field when both the radius of curvature of the lines of force and the acceleration are large. It seems possible that these instabilities are limited in amplitude and do not directly produce poor containment; but such instabilities may lead to excessive penetration of the plasma and field, and prevent the formation of a sharp plasma - magnetic field boundary, which will confuse experimental analysis. If these results are confirmed they suggest there is a restriction on shock heating and trapping of the plasma in a cusp, which may conflict with the need to obtain a high density, high temperature plasma quickly before the plasma escapes through the cusp apices.

5. CONCLUSIONS

We do not at present see from our own work any rapid path to the goal of a controlled thermonuclear reactor. Experimental observations are insufficiently in line with theoretical predictions to provide reliable extrapolation of results from any one apparatus to a significantly different one. Each experiment has at present to be analysed in substantial detail before reliable conclusions can be drawn. This process is rather slow, mostly because of the difficulties in making detailed observations on the highly tenuous and mobile plasmas. At present the pinch approach remains apparently feasible as an ultimate thermonuclear reactor. However, our work is governed not so much by the immediate attainment of the ultimate objectives, as by the need to obtain reliable experimental observations and understanding. In doing so, we believe that we will learn a great deal of interest in magneto-plasma physics which will have direct application to cosmic plasmas. Such results will, I hope, be not without interest to aspiring astronauts.

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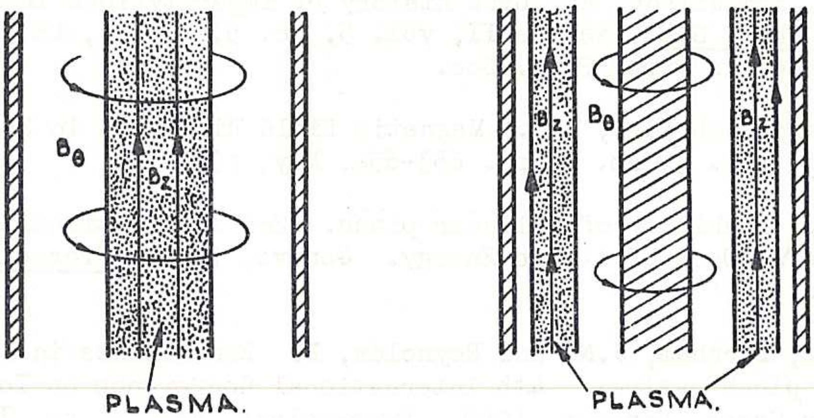
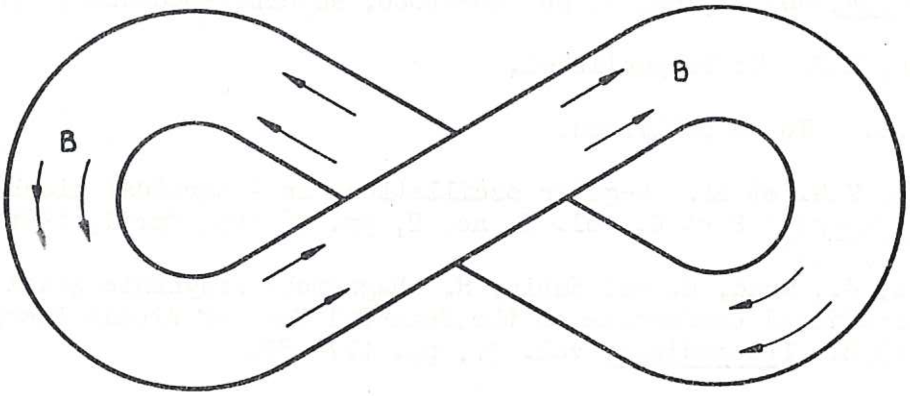
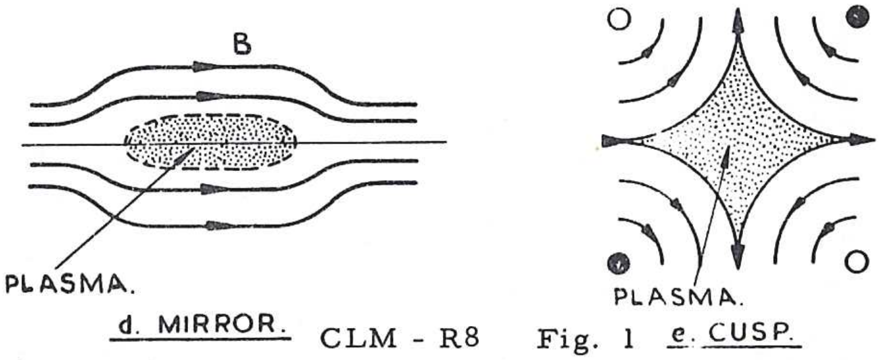


a. STABILISED PINCH.

b. HARD-CORE.

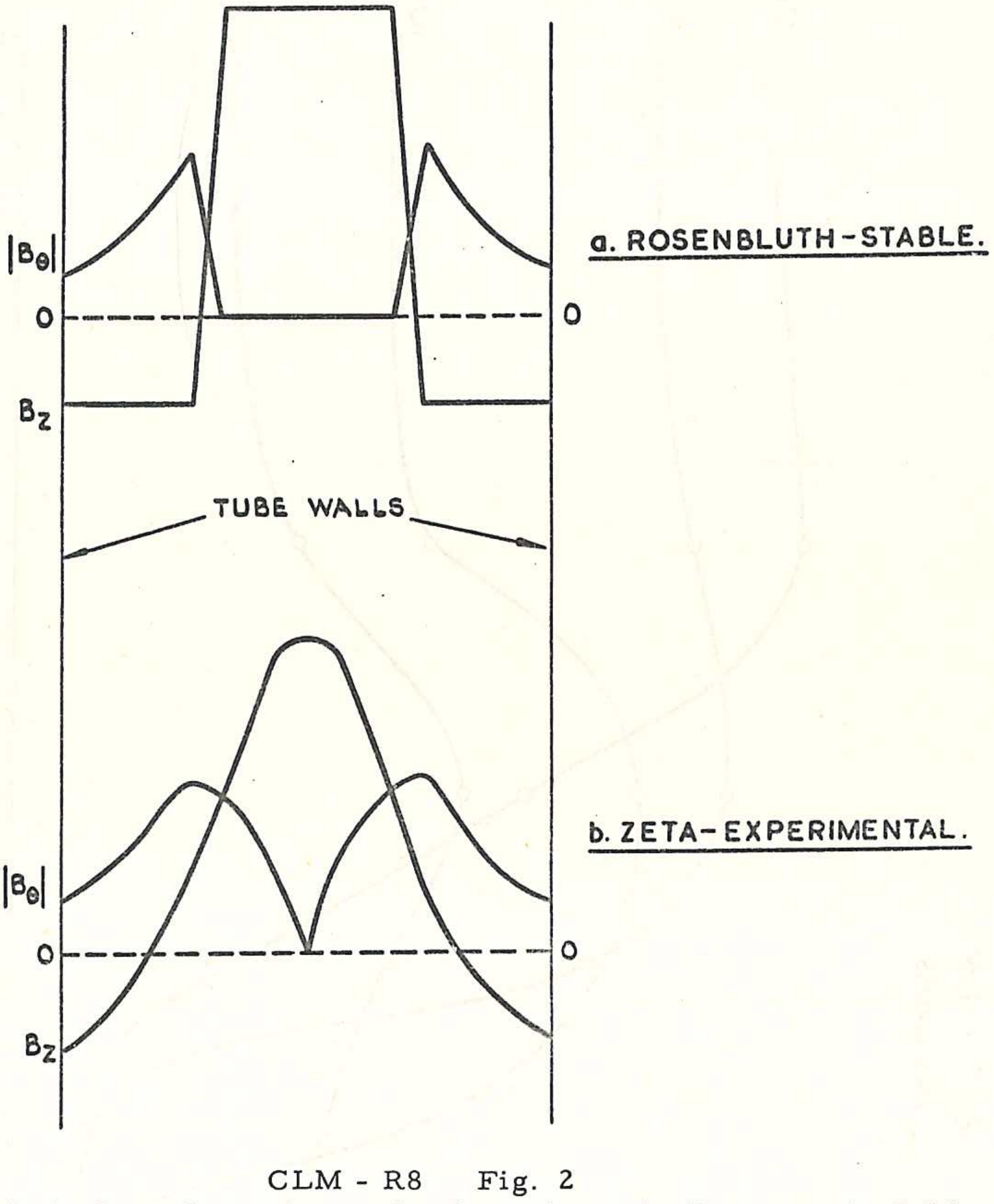


c. STELLARATOR.



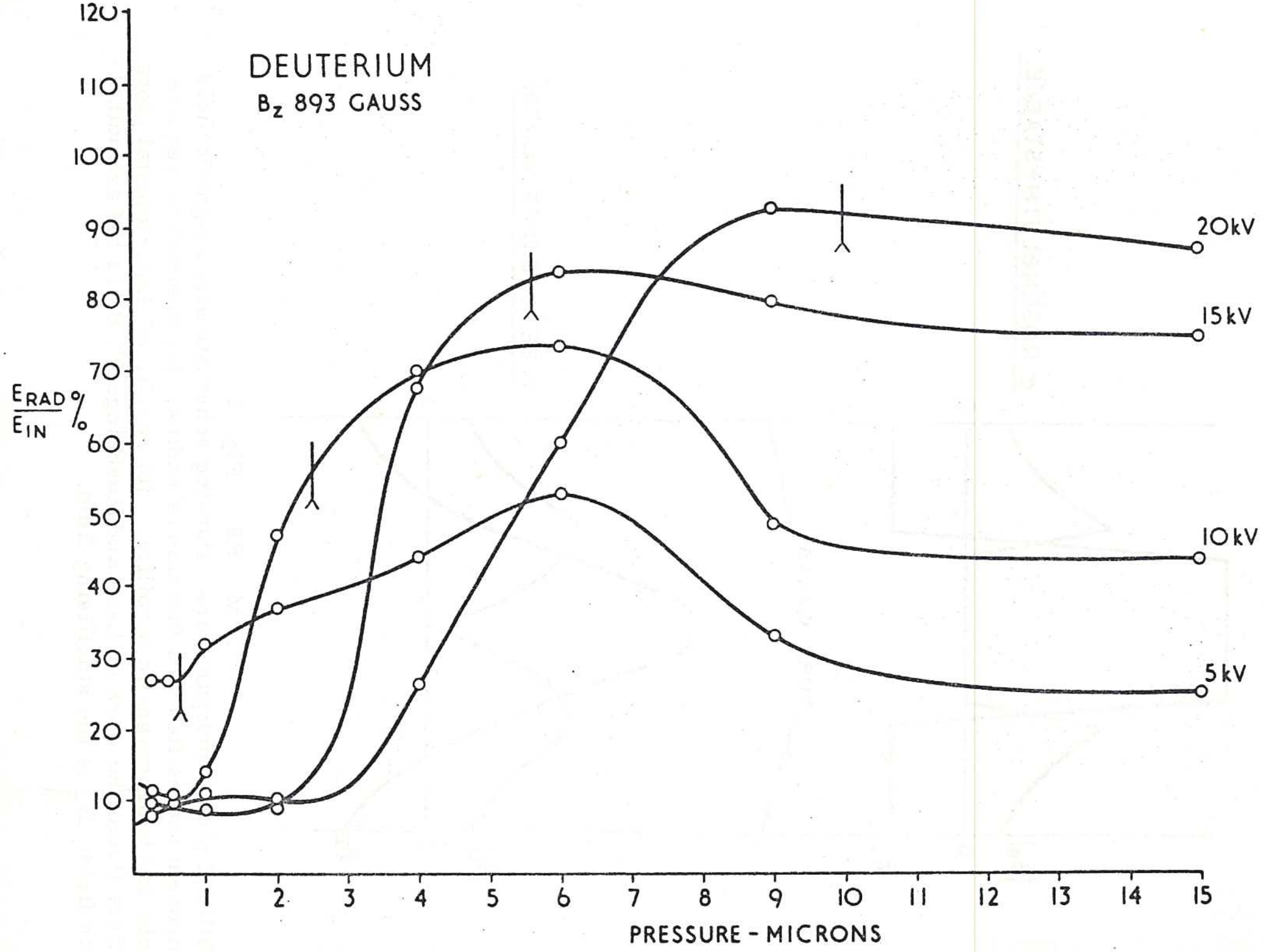
d. MIRROR. CLM - R8 Fig. 1 e. CUSP.

The main containment geometries under study for controlled fusion work



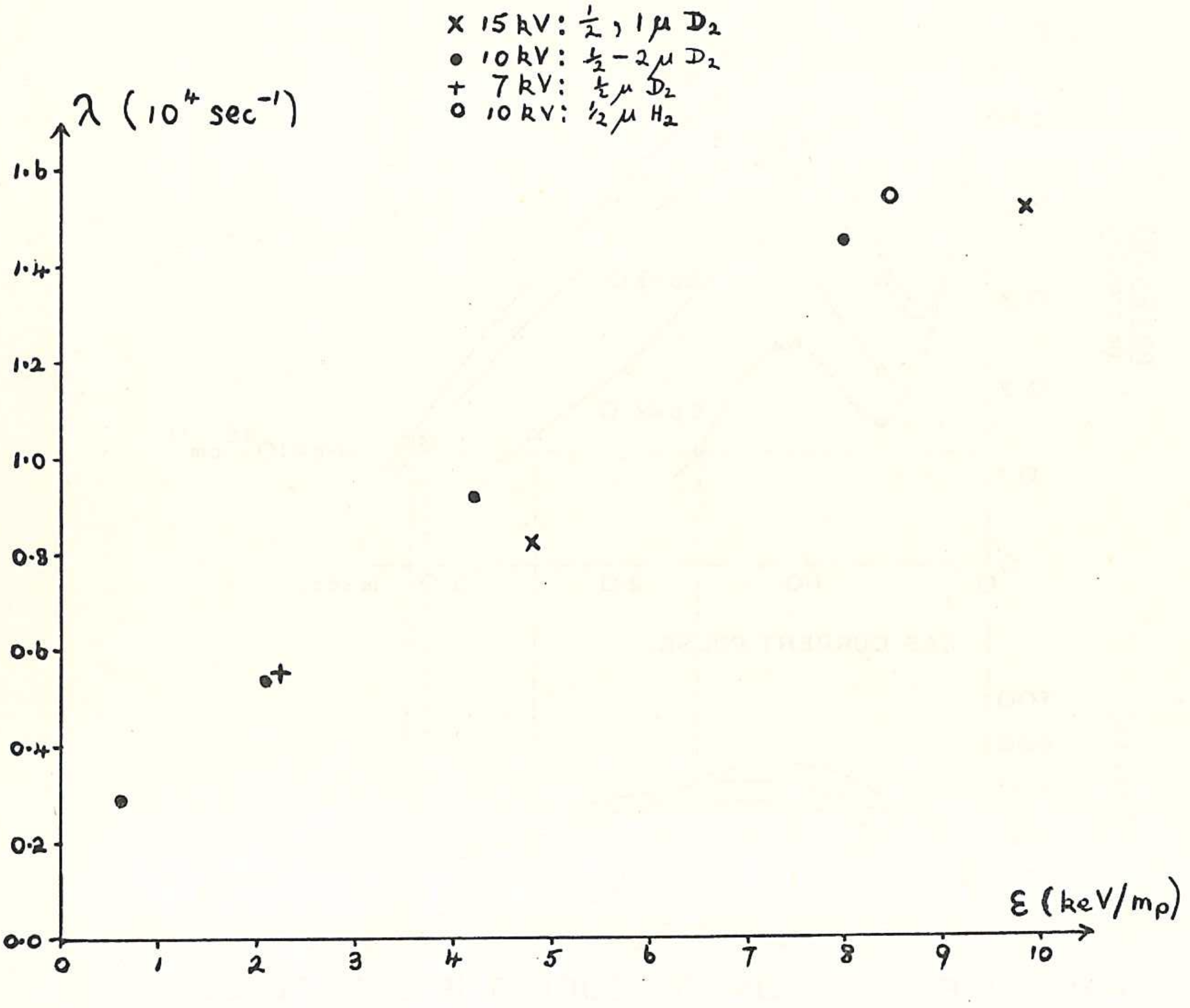
CLM - R8 Fig. 2

Stabilised pinch configurations, showing schematically magnetic field component intensities as a function of radius; (a) theoretical requirements for hydromagnetic stability; (b) results of experimental plots on Zeta (from the work of Lees and Rusbridge(5)) B_θ is the azimuthal pinch field; B_z is the stabilising field.



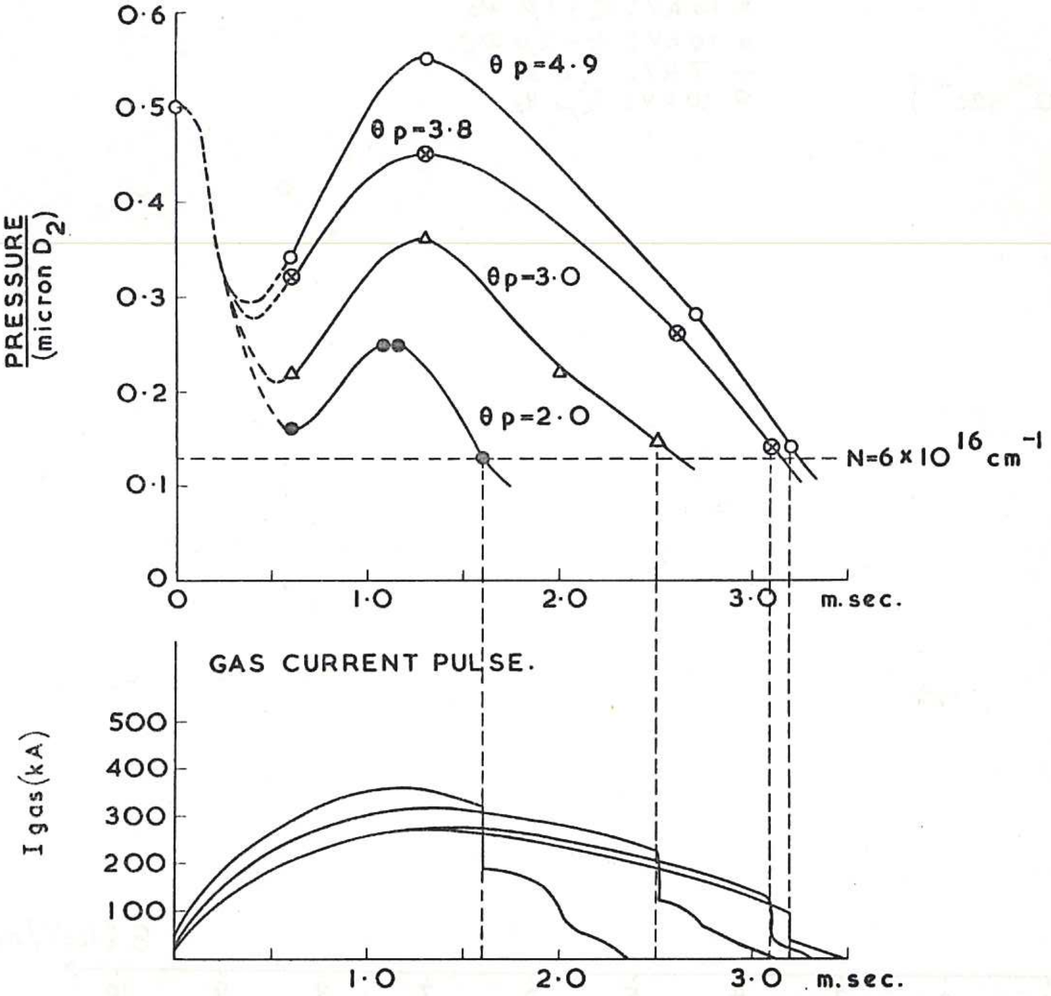
CLM - R8 Fig. 3

Proportion of energy input radiated by the plasma, as a function of initial pressure of deuterium and capacitor bank voltage (Gibson and Mason(10))



CLM - R8 Fig. 4

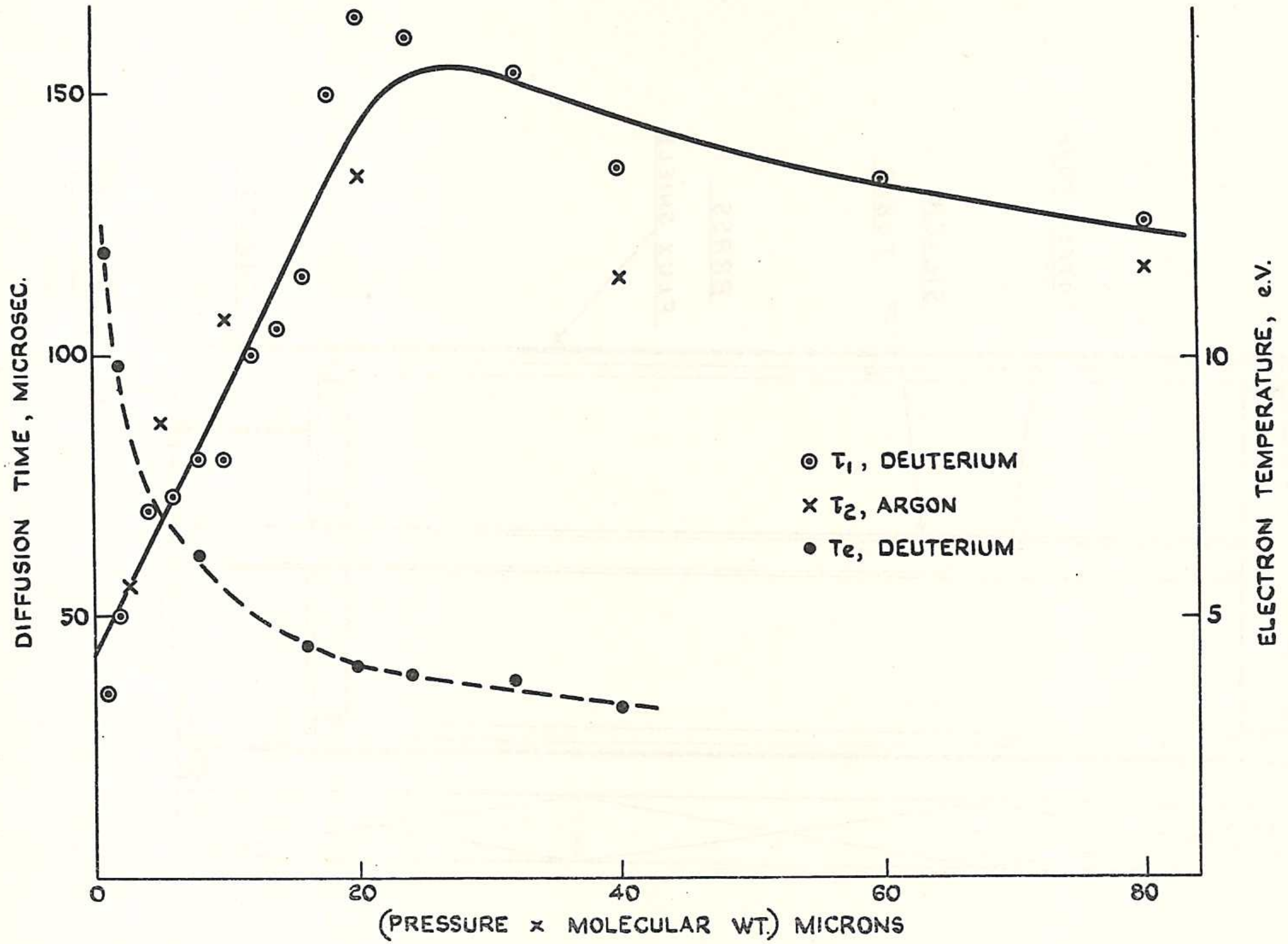
Observed ion loss rates found by spectrographic analysis. The fraction of ions lost per second, λ, is plotted against energy input per unit mass of the gas initially present, ε ; ε is in keV per proton mass. The reciprocal of λ is the ion containment time. (Burton and Wilson$^{(11)}$)



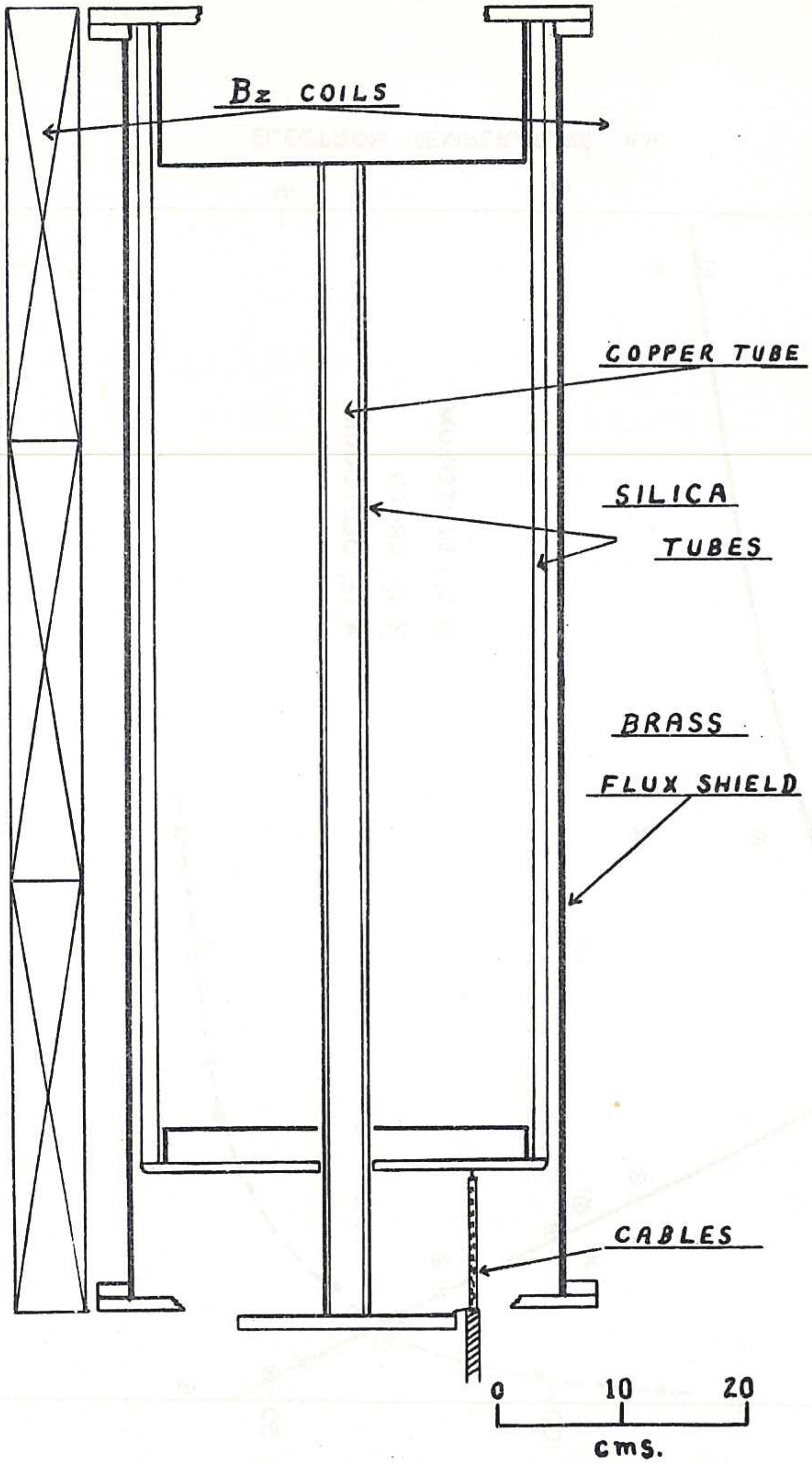
PRESSURE VARIATION THROUGH THE ZETA PULSE.

CLM - R8 Fig. 5

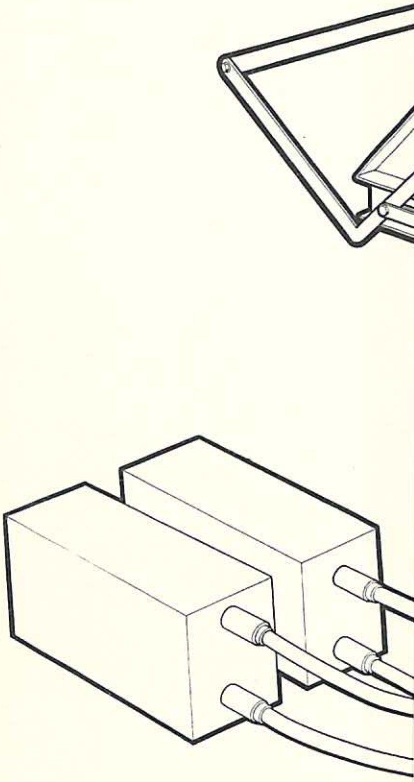
Pump out curves, showing the amount of plasma in the tube, as a function of time throughout the pulse. The amount of plasma is expressed in terms of the initial pressure (0.5 microns). The curves are plotted for different values of the ratio θ_ρ of the confining field B_θ to the initial B_z stabilising field

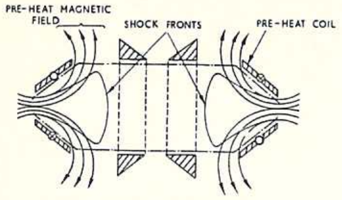


CLM/R 8. FIG. 6. DIFFUSION OF THE SKIN CURRENT IN ZETA, AS A FUNCTION OF INITIAL MASS OF GAS. (LEES AND RUSBRIDGE (12)). AT LOW PRESSURES, THE DIFFUSION TIME DECREASES, WHILE THE ELECTRON TEMPERATURE INCREASES.

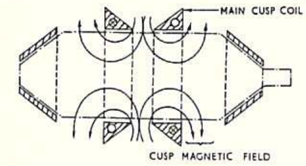


CLM - R 8 Fig. 7
Diagram of the unpinch apparatus used by Reynolds and co-workers(14) in stability studies

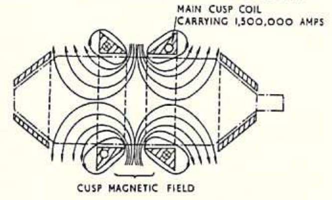



PRE-HEATING BY SHOCK WAVES

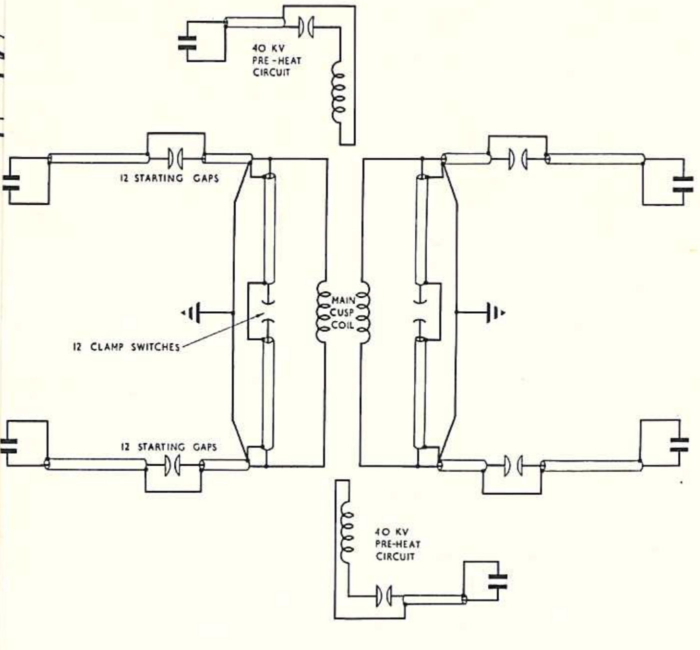
THE CURRENT IN THE PRE-HEAT COILS REACHES 150,000 AMPS IN ONE MICROSEC. THE RESULTING MAGNETIC FIELD PPODUCES SHOCK WAVES WHICH MOVE RAPIDLY TOWARDS THE CENTRE OF THE TUBE.


COLLISION OF SHOCK WAVES AND BEGINNING OF MAIN COMPRESSION

THE SHOCK WAVES MEET AT THE CENTRE OF THE TUBE AND PRODUCE A HOT GAS AT ABOUT 100,000°K COMPRESSION BY THE MAIN CUSP MAGNETIC FIELD THEN COMMENCES


FINAL COMPRESSION OF PLASMA

THE CURRENT IN THE MAIN CUSP COIL REACHES 1,500,000 AMPS IN 18 MICROSECS., THE CORRESPONDING CUSP MAGNETIC FIELD BEING ABOUT 200,000 GAUSS EQUIVALENT TO A PRESSURE OF 10 TONS/SQ. IN. OR 1,600 ATMOSPHERES. THE PLASMA TEMPERATURE IS EXPECTED TO REACH ABOUT 2,000,000° K



BASIC CIRCUIT DIAGRAM

CLM - R8 Fig. 8

usp Geometry Apparatus - The upper part of the apparatus consists two large metal collector plates, into which cables from the main apacitor bank are connected. The current flows from them to the two ain cusp coils in the centre. The lower units are capacitors and witches for the shock preheat