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A HIGH CURRENT HALL ACCELERATOR

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ABSTRACT

A high-current two-stage DC Hall accelerator is investigated in order to determine its possible application in controlled thermonuclear fusion work. Detailed measurements are made on the electrical characteristics of the device for currents of up to ~ 3 kA and potential differences of up to ~ 1 kV. It is shown that the impedance of the device, and consequently the energy of the accelerated plasma, increases directly with B_r over the range investigated. The output of accelerated plasma also increases with B_r and maximum values of ~ 500 A equivalent are obtained.

The presence of a rotating cathode spot is shown by means of high speed framing photographs. An important characteristic of the device is its flexibility, the total number of particles produced depending on the duration and magnitude of the gas feed and current pulse. The output of the device is compared with fusion reactor requirements and the way in which it could be scaled up to meet these requirements is considered.

1. INTRODUCTION

A high current two stage DC Hall accelerator is investigated in order to determine its possible application in controlled thermonuclear fusion work. Much of the work on Hall accelerators has been in the space vehicle propulsion field, [1,2,3], the aim being to achieve a relatively high exhaust velocity with high overall efficiency and not to use energy in producing unwanted ionisation and heating. For this reason argon or cesium plasmas have been used.

In the fusion field hot, highly ionised hydrogen or deuterium plasmas at high densities are required. Efficiency is not of paramount importance in the filling of experimental magnetic traps but obviously becomes more important at reactor levels. However, even in the latter case if the device has to produce only the 'start up' plasma a relatively low efficiency $\sim 10\%$ could probably be tolerated.

The Hall acceleration of plasma has been investigated by M.G. Haines [4,5] and applied directly in the Polytron experiment as a means of improving the containment in multiple cusp geometry [6,7]. However, little work has been done on the use of Hall accelerator devices as a means of providing an external source of plasma for fusion experiments. A.I. Morozov [8] has described experiments on a device similar to but much larger than that reported in this paper but little detailed information is available on its performance.

In this paper a detailed experimental investigation of the Hall accelerator is described and discussed. The possibility of scaling up the device to provide the 'start up' plasma for a fusion reactor is considered, as well as possible ways of improving its efficiency. A brief description of some of the work is given in [9].

2. THE ACCELERATOR

The device examined here has about one half the linear dimensions of that in [8]. It consists essentially of two radial magnetic field sections in an annular channel, the fields being generated by a solenoidal winding on the inner iron core as shown in Fig.1. The average value of these magnetic fields can be varied up to ~ 1000 gauss. A unidirectional current pulse is supplied by a 10 kV 45 kJ capacitor bank connected as a ten section delay line. Hydrogen gas is fed into the device from a fast acting gas valve with a plenum volume of 0.30 cc situated behind the anode ring. The latter helps to distribute the gas uniformly around the annulus in addition to carrying the total gas current.

The operation of the device may be explained in broad physical terms as follows. The axial electric and radial magnetic fields set up in the annulus are such that the Larmor radius of the ions is greater than a stage length while that of the electrons is smaller. The ions can therefore move relatively unimpeded through the system, while the electrons, which are prevented from moving directly towards the anode by the radial magnetic field, move in an azimuthal direction as a result of the crossed electric and magnetic fields. This drift of electrons constitutes a Hall current j_θ which interacts with the radial magnetic field B_r to produce a $j_\theta \times B_r$ magnetomotive force acting in the same direction as the initial electric field. In addition the plasma should be effectively collisionless $\omega_e \tau_e > 1$ where ω_e and τ_e are the electron gyro frequency and collision time respectively.

An essential feature of this device is that it is in principle capable of continuous operation so that the quantity of plasma produced is limited only by the power supply and technological problems such as cathode erosion, cooling, etc.

In addition the ions are accelerated through a background of electrons so that the space charge limitation of the normal ion source is avoided.

3. EXPERIMENTAL OBSERVATIONS

(i) Initial conditions

In order to determine the rate at which gas enters the accelerator and also the way in which the pressure varies in space and time a fast ionisation gauge was set up which could be moved along the guide tube and into the accelerator. The gauge was calibrated at a series of static pressures in a separate system in which the pressure was measured with a trapped Vacustat. Pressure time curves were then recorded on an oscilloscope and from these pressure-distance curves were obtained at a series of times. These are shown in Fig.2.

It is noted that the device can only be triggered satisfactorily when the delay between firing the fast acting valve and the main condenser bank ignitron is $\geqslant 500\ \mu s$. This is the time at which the gas pressure at the cathode rises to ~ 10 mtorr. In addition the minimum breakdown voltage is 5kV.

It is convenient experimentally to use a resistance in series with the accelerator in order to limit the current to the desired value. In operation a voltage in excess of that required for breakdown is applied. When breakdown occurs the voltage falls to a value determined by the impedance of the device under the conditions of operation.

The accelerator and its power supply are allowed to float so that any probes in the apparatus do not act as partial cathodes thus ensuring that all the electrons required to neutralise the accelerated ions are obtained from the cathode.

(ii) Electrical Characteristics

Typical voltage and current waveforms are shown in Fig.3. The current remains relatively constant for a time $\sim$ 1.5 ms and then decays to zero, giving a total pulse length of $\sim$ 5 ms.

The volt-ampere characteristics of the device are shown in Fig.4. The negative slope of this characteristic must be due to heating effects.

On Fig.5. is shown the variation of impedance with B_r. At low currents the impedance is directly proportional to B_r whereas at high currents there is some departure from linearity due to the additional ohmic heating at the higher values of B_r.

This dependence of impedance on B_r is largely due to the effectiveness of B_r in controlling the backleakage of electrons. At low values of B_r the Larmor radius of the electrons will be greater than the stage length. Under these circumstances no Hall current flows and the major part of the gas current is carried by electrons; the impedance is therefore low. As B_r is increased the Hall current develops, a greater proportion of the gas current is carried by the ions; and the impedance increases.

This is substantiated by measurements on the variation of output with B_r, which, as can be seen in Fig.6 has the same form as the impedance - B_r curve at the same current. Hence the output is directly proportional to the impedance over the range investigated. It should also be noted that as the impedance increases with B_r there is a corresponding increase in potential difference across the device. As the energy of the ions in the output plasma is related to this potential difference we have a very simple method of control.

(iii) Ion Energy Distribution

A multigrid probe was used for measuring both the magnitude of the output and its ion energy distribution. The probe used is basically similar to that described by M.V. Nezlin [10]. The electrodes were connected as follows, E1. the outermost electrode is earthed, this acts as a screen and attenuator, E2. at - 240V repels the electrons and collects ~ 80% of the ions passing through E1. This ion current is monitored and provides a measure of the total ion current. It also provides a means of normalising the collector current for shot to shot variations when determining the energy distribution, E3. is the analysing grid to which a positive potential is applied. It transmits only ions with energies greater than the applied potential, E4. is at - 360V and provides an electrostatic screen preventing secondary emission electrons escaping from the collector, E5. is the collector plate and is connected to earth via a 5 kΩ measuring resistance.

The energy distribution is obtained by varying the potential applied to E3 and plotting the change in collector currents as a function of this potential. By differentiating this curve we obtain the actual energy distribution. Typical distribution curves are shown in Fig.7. The full line shows the initial distribution and this exhibits two maxima at ~ 350 eV and ~ 700 eV respectively.

The existence of these two maxima is considered to be related to the two stages in the accelerator. Ions created in the first stage form the high energy peak, while ions created in the second stage form the lower energy peak. This broad distribution can only be produced as a result of ionisation taking place throughout the volume. This must be so initially as the annulus in full of gas at the time of breakdown. Later in the pulse when this gas is ionised and accelerated out of the system, fresh gas entering is ionised mainly near the anode and accelerated through the full potential difference across the device. The dashed curve on Fig.7 shows the distribution after 400 μsec. This has a single maximum at an energy related to the potential differences at that time.

The divergence of the output from this type of accelerator operating in the collisionless regime depends largely on the trajectories of the ions. If we consider an idealised case in which the two radial magnetic fields sections are sharply defined and have uniform intensity then ions created near the anode will traverse an orbit which is part of a cardiod in the first stage. These ions will then enter the second stage with a finite velocity and proceed along a trochoidal orbit oppositely directed to that in the first stage. Such ions will suffer little total deviation. Ions created between the two stages will be accelerated to intermediate energies and will traverse the maximum total flux. They will therefore suffer the maximum deviation. On this basis we would expect to find ions at or near maximum energy travelling in a near axial direction, while the ions of intermediate energy will tend to be concentrated in the outer regions of the ejected plasma. This may explain the shape of the initial energy distribution. It is estimated that the divergence initially has a maximum of $\sim \pm 20^{0}$ (½ angle) for typical operating conditions, while later in the pulse the collimation should be better.

Measurements of the change in plasma density with distance from the accelerator are reasonably consistent with this divergence.

The form of the angular energy distribution discussed above is substantiated by the following evidence: If we compare the ion energy distribution obtained with this accelerator at a distance of one metre with that obtained by Morozov et al. [8] on their accelerator at a distance of 2.5 metres we find that in the former the lower energy hump is the larger while in the latter the high energy hump is the larger. Although these devices are of different size the above argument applies to both. This difference in the observed distribution is consistent with the idea that the highest energy particles travel near the axis so that the greater the distance from the accelerator the greater the proportion of fast particles. Further evidence which supports this is given in the next section.

(iv) The neutral particle detector

Energy distribution measurements were also made using a neutral particle detector of the type described in [11]. This consists essentially of a collimator, a He charge exchange cell, charged particle deflector plates, followed by an ion detector. Neutral particles entering the apparatus undergo charge exchange in the helium cell, the charged particles produced are selectively passed between the deflecting electrodes and enter the ion detector. The deflector plates themselves constitute a discriminator while the ion detector can be used for more accurate discrimination of the particles passed by the deflector plates. The system can also be used as a charged particle detector simply by evacuating the charge exchange chamber.

This apparatus was set up at a distance of $\sim$ 3 metres from the accelerator. The neutral particle distribution obtained showed a maximum at $\sim$600 eV with a spread of energies up to 1800 eV. The charged particle distribution however showed a broad maximum at $\sim$1200 eV with a spread of energies up to $\sim$4 keV (see Fig.8). This provides further evidence for the change in energy distribution with distance and angle discussed earlier.

It should be noted that the multigrid probe described in Section 3(iii) has an acceptance angle of $\pm 70^{o}$ compared with $\pm \frac{1}{2}^{o}$ for the neutral particle detector. Hence the distribution obtained from the latter is not truly representative of the output. The broad spread of energies observed in this small axial sample suggests the existence of an acceleration process additional to the Hall acceleration mechanism.

The presence of oscillating azimuthal electric fields crossed with the radial magnetic fields could very well provide the mechanism for this. Such oscillations are reported by G.S. Janes in [12] and E.C. Lary et al in [13]. In order to reconcile the charged particle peak at 1200 eV with the 600 eV neutral peak it is considered that the particles arriving at the detecting system consist mainly of H_2^+. This would produce

H_1^0 atoms at half their original energy on neutralisation. It is proposed therefore that the 600 eV neutrals were produced by charge exchange of 1200 eV H_2^+.

(v) Cathode phenomena

The presence of a large rotating cathode spot is shown by the use of a high speed framing camera. Its direction and velocity of rotation was also established with the aid of a streak camera. Typical framing and streak pictures are shown in Fig.9. If we determine the frequency of rotation with respect to time we find that it decreases from $\sim$ 180 kc/s initially to $\sim$ 100 kc/s after $\sim$ 2ms. In addition we also find that the frequency falls with increasing B_r. This shows that the frequency of rotation is a function of the electric and magnetic fields. A careful examination of these field directions at the cathode showed that the cathode spot moves in the same direction as the E/B drift in this region. The exact value of the electric field at the cathode is not known but in any case it is unlikely that the ions will achieve the full E/B drift velocity as they only traverse part of their Larmor orbit. The observed rotation frequency is $< \frac{1}{10}$ th of that calculated on the basis of the E/B drift in the annulus.

This spot probably provides the bulk of the electrons for neutralising the accelerated ions as they pass the cathode. In addition it supplies the backleakage electrons some of which ionise the incoming gas.

(vi) The Hall current

If we consider the question as to whether or not this device genuinely operates as a Hall accelerator we can make several tests. Firstly, a reversal of the magnetic field should simply reverse the direction of the electron drift in the two stages and make no difference to its operation. This was tried experimentally and shown to be so, the only difference being a reversal in the direction of rotation of the cathode spot. Secondly, a reversal of the electric field should reverse the direction of the ion current thus driving the ions towards the closed end of the accelerator. The ions would then no longer be able to escape from the accelerator. This again was shown to be so. In addition the impedance of the device increased and the current pulse was considerably prolonged which is consistent with ions being retained in the accelerator.

A further experiment was performed which demonstrates the effect of the Hall current. By inserting a set of three radial quartz baffles into the annulus of the accelerator the azimuthal Hall current is prevented from flowing. The effect of this is to build up an azimuthal electric field in each sector. This electric field crossed with the radial magnetic field tends to drive the electrons towards the anode. A larger proportion of the current is then carried by the electrons and the impedance should be decreased. In the limit if the Hall current is stopped completely the impedance should fall from that for the transverse magnetic field case to that for the parallel magnetic field case. Experimentally the reduction in impedance was to $\sim \frac{1}{3}$rd of normal. What is more striking is that the output from the device fell to less than 1% of its usual value. This is very strong evidence that most of the current is now being carried by electrons rather than by the ions. It also shows that the presence of the Hall current is essential to the operation of the device as an accelerator.

After about one hundred shots had been fired in this condition the quartz baffles were removed and examined. Clearly defined regions of erosion were observed which must have been produced by the limited azimuthal electron Hall current bombarding the baffles. These regions of erosion are on opposite sides of the quartz blades in the two stages and are on the side which would be struck by the electrons. This implies that a limited Hall current must have flowed in each section, presumably as fresh gas was ionised, in order to set up and maintain the azimuthal electric field.

The regions of erosion on the quartz baffle are shown in Fig.10. It will be noted that the Hall current in the first stage occurs near the outer wall while in the second stage it is near the inner wall. This is considered to be a result of the opposite slope in the two radial magnetic field sections, see Fig.1. Other forces on this Hall current act in the same direction in the two stages. These forces are firstly that due to the distortion of the radial magnetic field by the azimuthal field of the axial current; this produces an inward force in both stages, and secondly, the partial radial confinement of the electrons as a result of the outward force due to the magnetic field gradient balanced by a negative charge on the outer wall of the annulus.

(vii) Efficiency

The overall efficiency has been measured with a calorimetric probe. For typical conditions, I_g 2800A and B_r 600 gauss, a value of $\sim$ 16% is obtained integrated over the whole pulse. However as the output is proportional to the impedance we would expect to obtain an efficiency of $\sim$ 20% at the maximum attainable value of B_r.

4. DISCUSSION & CONCLUSIONS

The results obtained show that the accelerator can produce $\sim$ 500 amperes equivalent of plasma with ion energies of up to $\sim$ 1 keV.

The impedance and the energy of the ions in the output plasma are a function of B_r.

The output is proportional to the impedance and its divergence is initially $\sim \pm 20^0$ with the particles of intermediate energy suffering the greatest divergence.

The overall efficiency has values of up to $\sim$ 20%. If we consider how these characteristics compare with reactor requirements, take the case of a stellarator reactor as described by R. Carruthers et al in [14]. The volume of plasma required to fill such a reactor is $\sim 2 \times 10^8$ cc and the density is $\sim 3 \times 10^{14}$ cm^{-3}. Hence the total number of particles is $\sim 6 \times 10^{22}$. The accelerator described in this paper working at $\sim$ 3 kA would produce plasma at a rate of 3×10^{21} ions/sec. On the basis of an injection time of 1 sec it would provide $\sim \frac{1}{20}$ th of the reactor requirement providing that the plasma could be efficiently injected into the reactor system.

It should be emphasized that the accelerator described is a small experimental device and that the output could easily be increased by scaling up the dimensions and increasing the current. The energy of the ions in the output could be increased by increasing the intensity of the radial magnetic field. This would at the same time probably lead to an increase in efficiency. It may also be possible to improve the collimation by an adjustment of the magnetic fields.

While the results obtained suggest that a device of this type can be scaled up to produce the quantity of plasma required to fill a fusion reactor further investigation is necessary in order to determine whether or not it can produce plasma at 10 - 20 keV and densities in the region of 10^{15} cm^{-3}.

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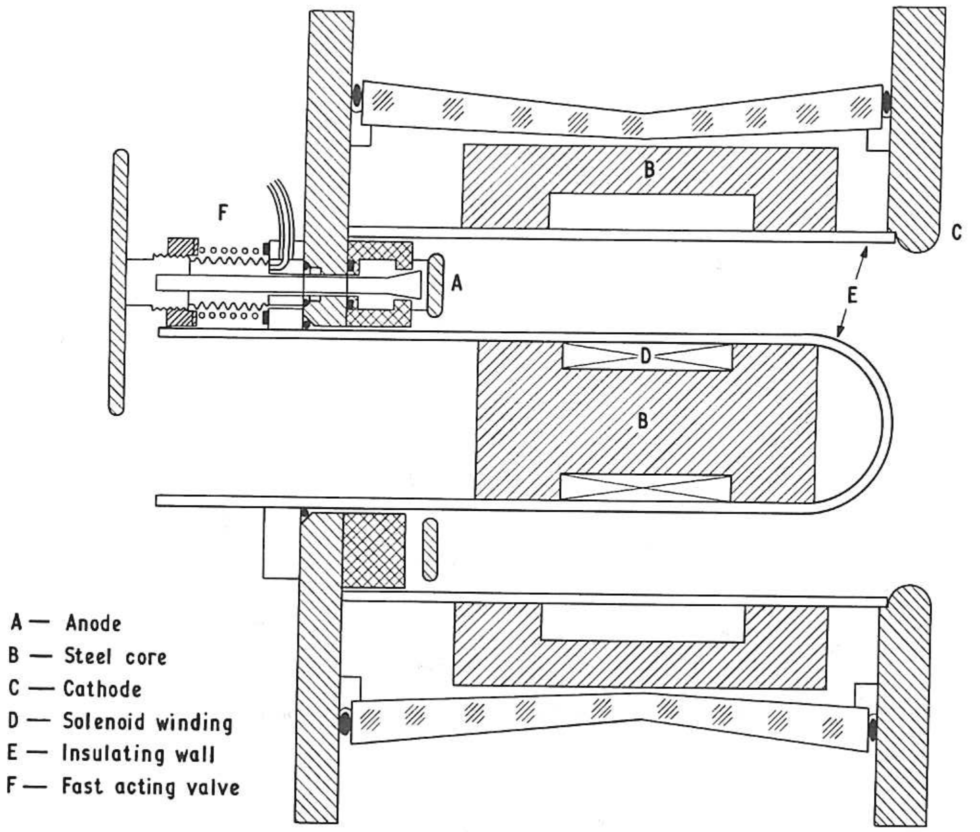


Fig. 1 Diagram of the accelerator (CLM-P 216)

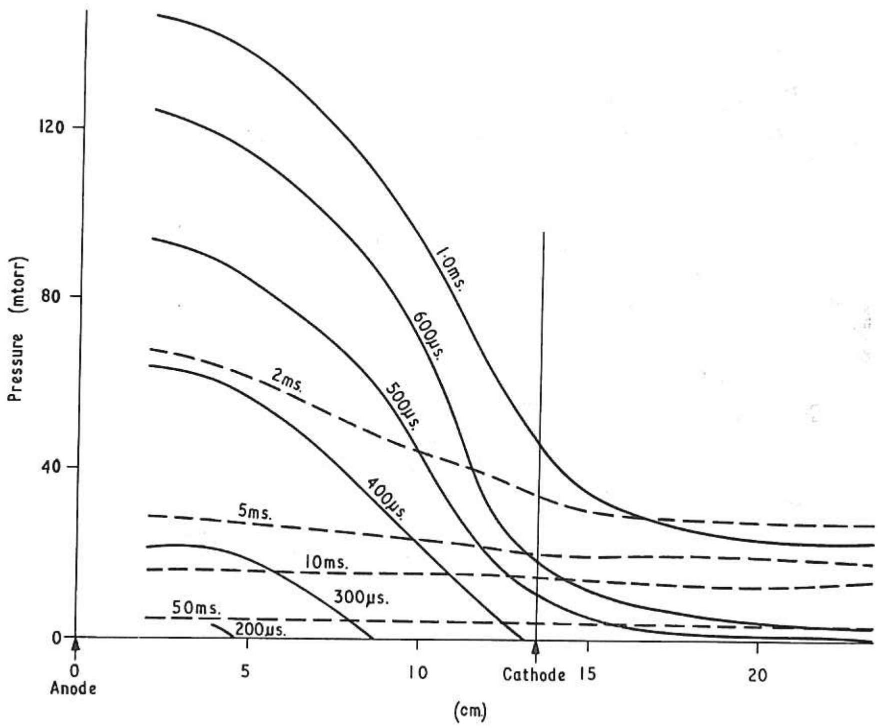
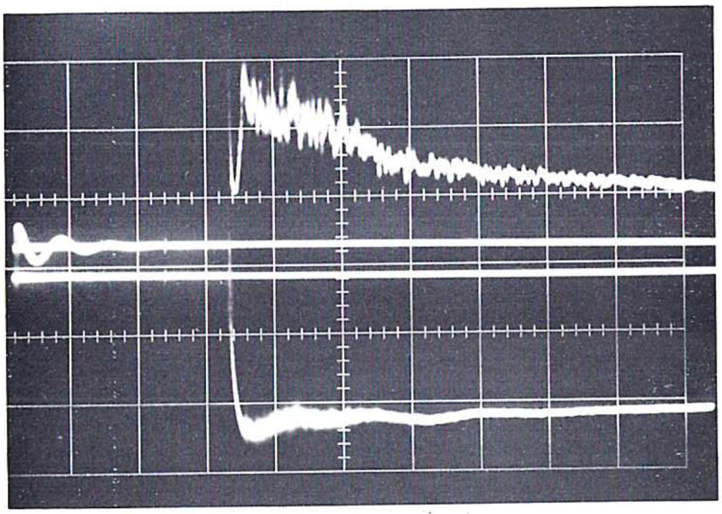


Fig. 2 (CLM-P 216)
Variation of pressure distribution in the accelerator at various times after operating the gas valve

Volts

(a)

Amps



500 V/div

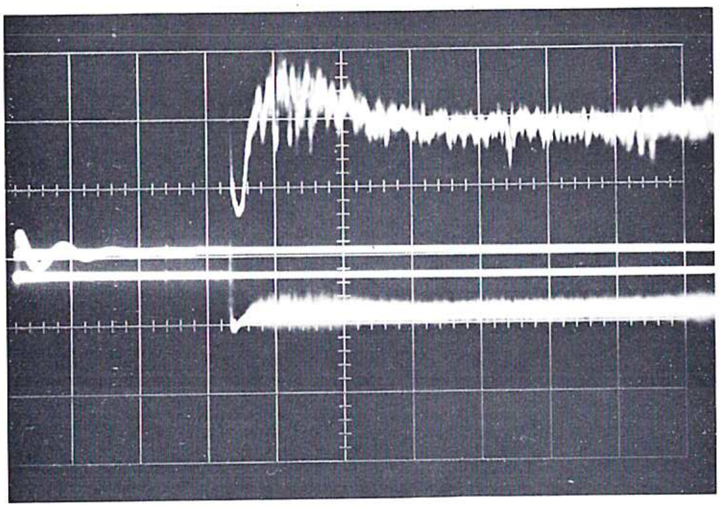
1200 A/div

200 μsec/div

Volts

(b)

Amps



500 V/div

1200 A/div

200 μsec/div

Fig.3 (CLM-P 216)

Voltage and current waveforms (a) high current, (b) low currents

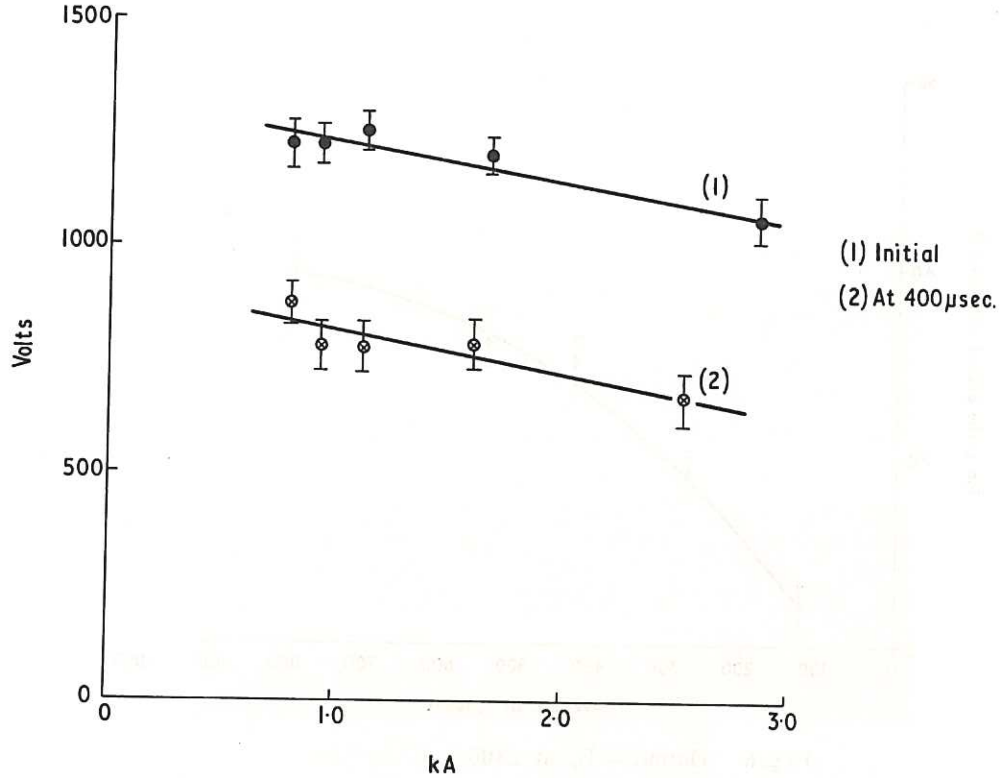


Fig. 4 (CLM-P 216)
Volt-ampere charactersitics. Average B_r 600 gauss

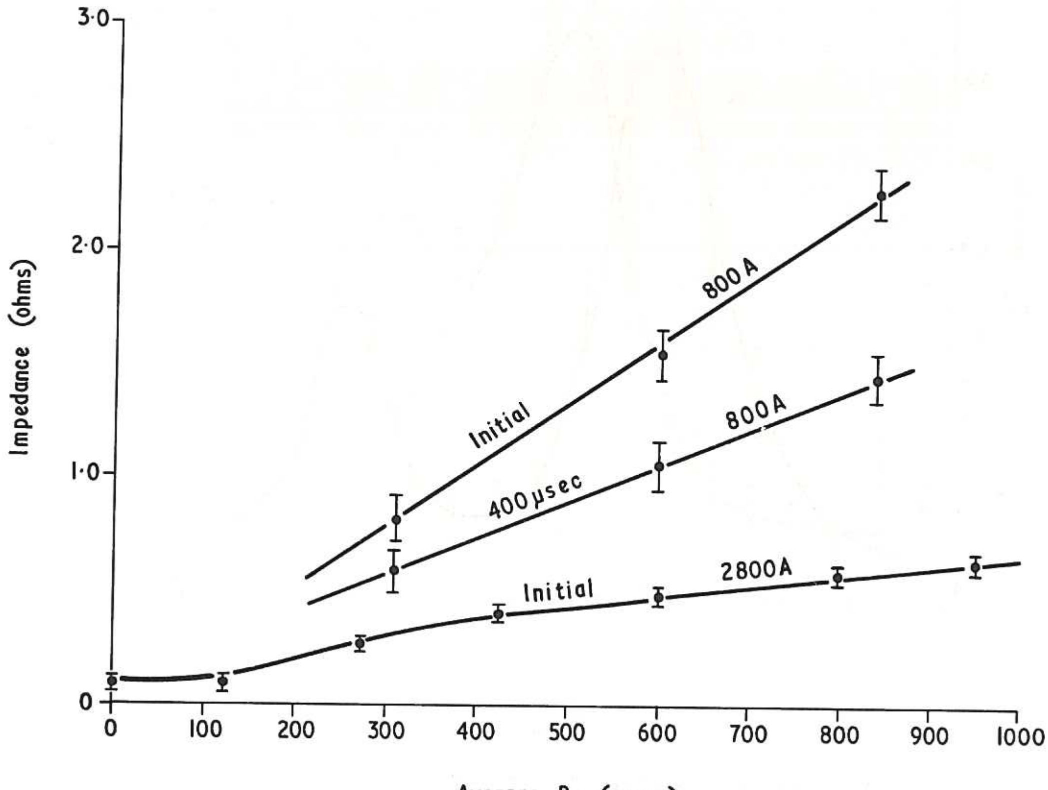
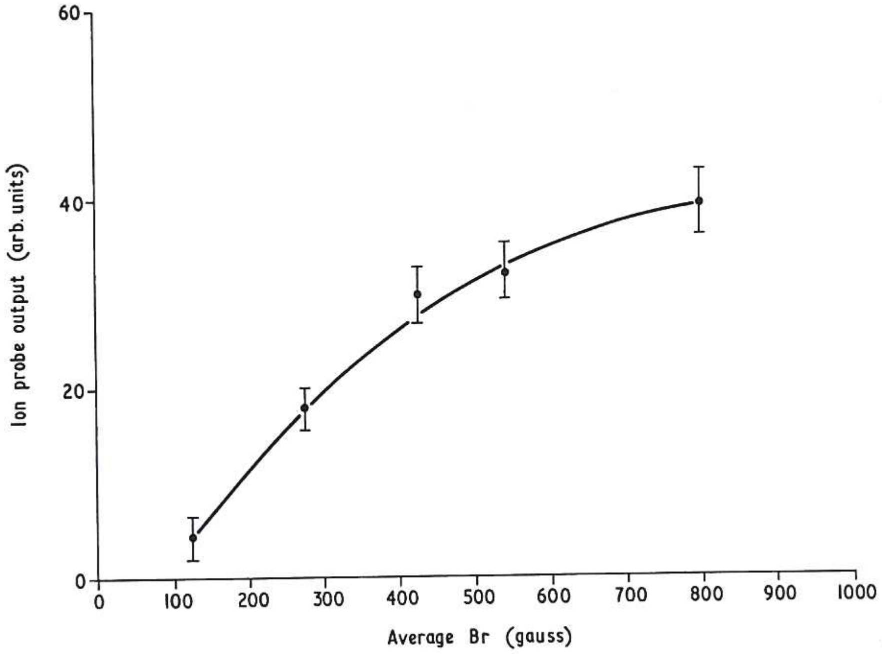


Fig. 5 Impedance — B_r (CLM-P 216)



Fi g. 6 Output – B_r at 2800 A (CLM-P 216)

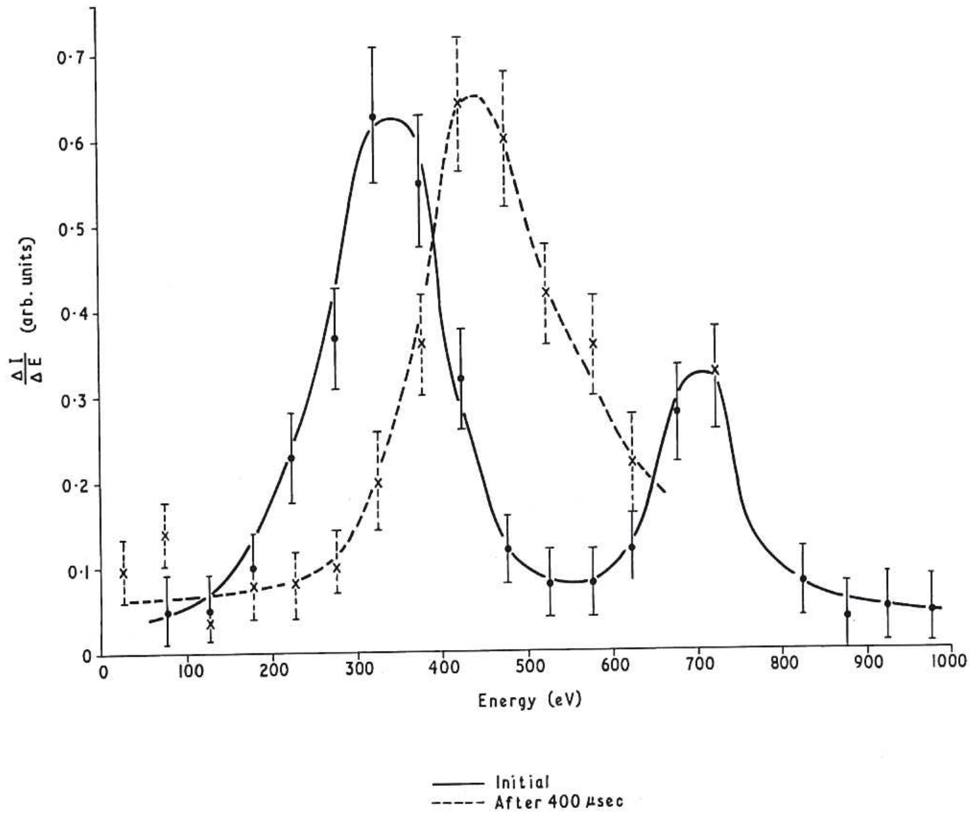
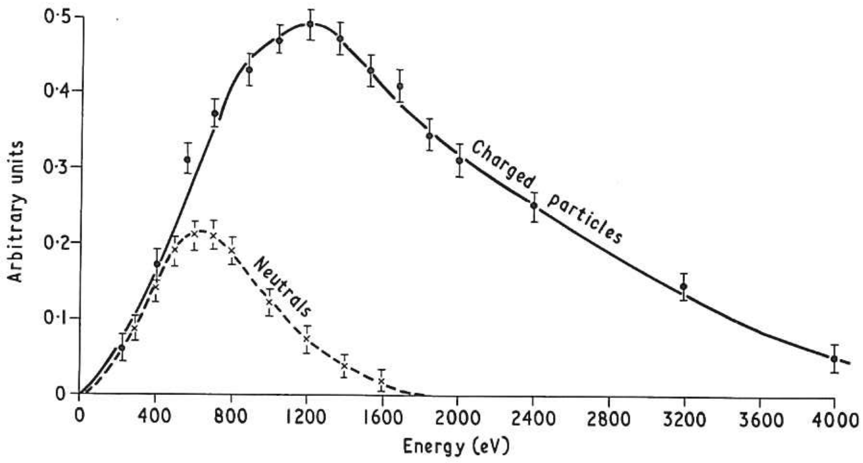


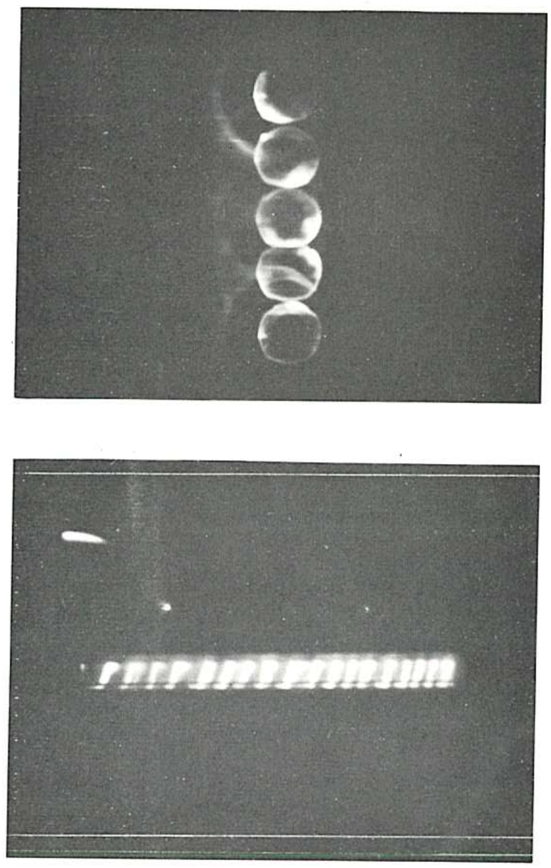
Fig. 7 Energy distributions from multigrid probe (CLM-P 216)



NPD results. 2800A
Average Br. 600gauss

Fig. 8 Energy distributions from neutral particle detector (CLM-P 216)

(a)



50 nsec exposure

1 μsec inter-frame delay

(b)

100 μsec streak →

Fig. 9 (CLM-P 216)

(a) Framing pictures taken on axis; (b) Streak picture side view. I_g 2800 amp. B_r 600 gauss

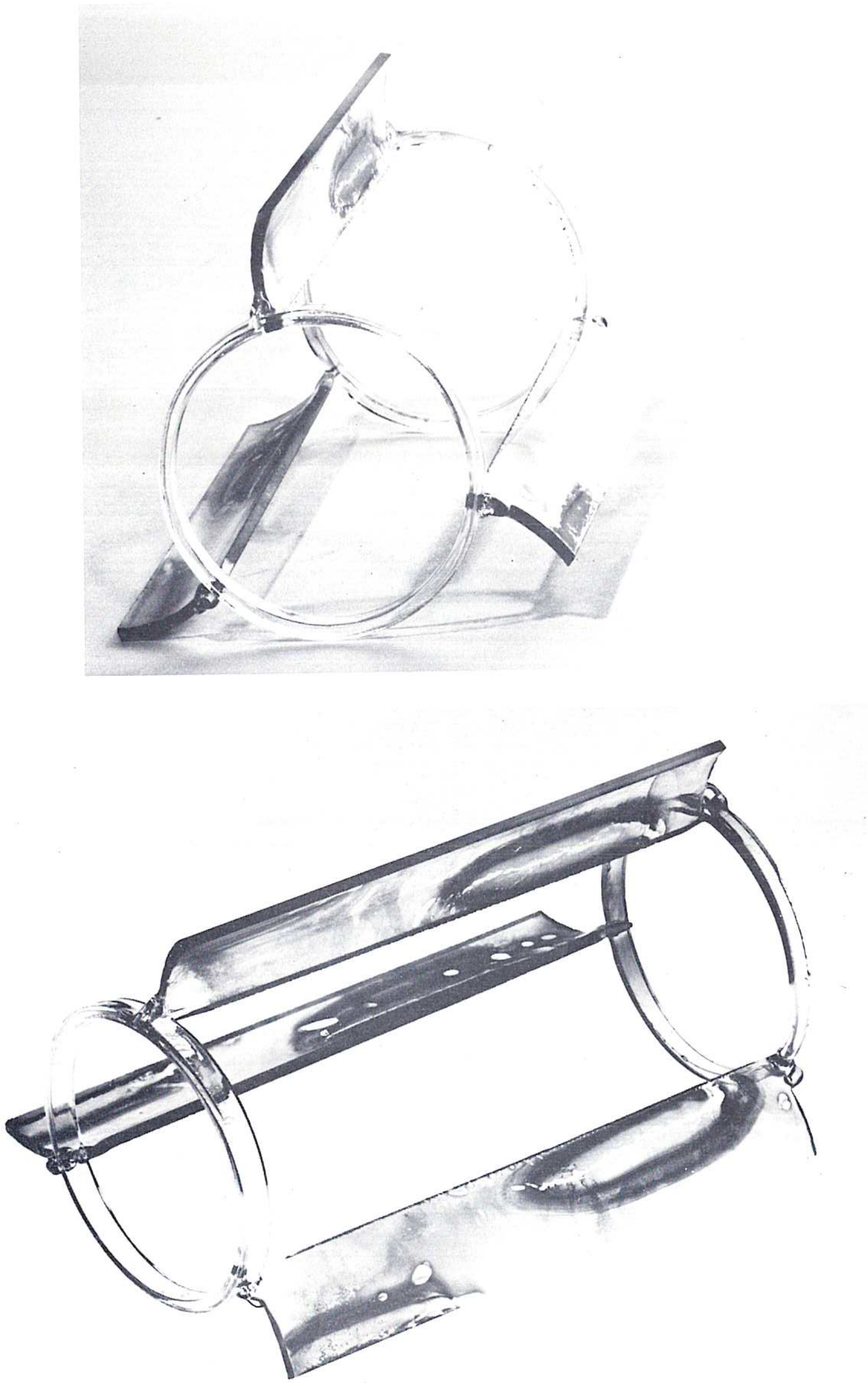


Fig. 10 Quartz baffles after approx. 100 shots (CLM-P 216)