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ELECTRICAL BREAKDOWN IN BEAMS OF CONDENSED HYDROGEN AND CONDENSED NITROGEN IN HIGH VACUUM

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Abstract—Beams of hydrogen and nitrogen clusters are produced by expanding hydrogen or nitrogen gas out of a Laval-nozzle cooled by liquid hydrogen or liquid nitrogen respectively. The beams are passed through a pair of parallel annular electrodes with a spacing of 22 cm. The electrodes are connected to a 0·1 μF capacitor which is charged to voltages between 10 and 20 kV. Electrical breakdown in these beams is achieved by injection of electrons. The behaviour of the resulting plasma column was studied by magnetic probe and image converter measurements.

1. INTRODUCTION

SOME time ago we suggested using beams of very cold deuterium or deuterium–tritium clusters, held together by van der Waals forces, for the directed introduction of the nuclear fuel into the highly evacuated reaction chambers of nuclear fusion devices (BECKER, 1959; BECKER, KLINGELHÖFER and LOHSE, 1960).

Initially, an attempt was made, to cause spontaneous electrical breakdown along beams of hydrogen and nitrogen clusters respectively in high vacuum. However, no signs of breakdown could be observed, even with applied voltages up to 35 kV. Under the conditions applied, electrical breakdown would have been expected below 1 kV with a gas of the same density but consisting of single uncondensed molecules.

Electrical breakdown has been achieved by the injection of electrons into the beams in a manner which is discussed below (BECKER and KLINGELHÖFER, 1964).

2. EXPERIMENTAL ARRANGEMENT

Although only the isotopes of hydrogen are of interest for nuclear fusion experiments, most of the development work was carried out with beams of nitrogen clusters since the liquid nitrogen required to produce these beams is much easier to handle than liquid hydrogen. The results were always checked with beams of hydrogen clusters. Hydrogen and nitrogen beams were produced by using a system consisting of a liquid hydrogen or liquid nitrogen-cooled Laval nozzle fitted with an electromagnetic fast-acting valve. On energizing the valve, pulsed beams of a few milliseconds duration could be obtained. The cryostat containing the beam-producing system and the vacuum apparatus have been described previously (BECKER, KLINGELHÖFER and LOHSE, 1962).

The pressure in the high vacuum chamber was held below 2×10^{-6} mm Hg. The electrical arrangement is shown schematically in Fig. 1. Two circular aluminium electrodes, with 22 cm diameter and 22 cm separation are mounted inside the vacuum chamber below the collimator of the beam-forming system. The electrodes have central apertures to allow the condensed beam to pass through with adequate clearance. The upper electrode (earth electrode) is in metallic contact with the whole apparatus. The two electrodes are connected to a capacitor (0·1 μF, 25 nH) outside the apparatus by a coaxial line.

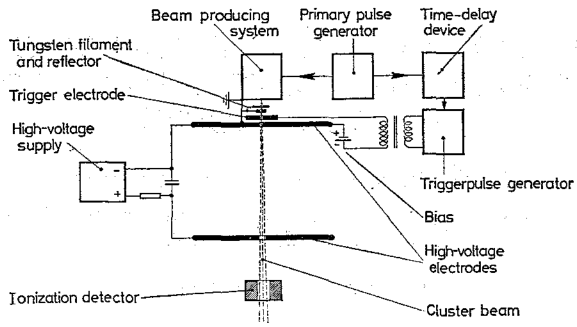


FIG. 1.—Schematic view of the arrangement for triggering an electrical discharge in cluster beams in high vacuum.

The system for the injection of electrons (details see Fig. 2) into the condensed cluster beam is built in the space between the collimator and the earth electrode. The electron-emitting filament is directly heated and consists of a 40 $\mu \times 1$ mm tungsten ribbon, which is bent into the form of a ring, whose diameter is a few tenths of a millimeter larger than the beam. The distance between the earth electrode and the tungsten filament is 0·5 mm. A mica-insulated-stainless steel reflector is mounted directly above the tungsten filament.

The tungsten filament and the reflector are at earth potential. To avoid continuous electron flow to the positive high-voltage electrode a negative bias of ≈ -80 V is applied on the trigger electrode (see Figs. 1 and 2). This electrode can be pulsed positive by means of the trigger-pulse generator. An ionization detector is used to determine the exact timing of the beam pulse, and the trigger pulse with the high-voltage capacitor uncharged.

The primary pulse generator energizes the fast-acting valve and simultaneously triggers a delay circuit which operates the trigger-pulse generator after a variable time delay. The delay time is adjusted so that the trigger pulse is applied as soon as the condensed beam has reached a steady-state condition between the high-voltage electrodes (Fig. 3). Within a time of less than a microsecond after the application of the trigger pulse, the trigger electrode falls to earth potential. This indicates that a

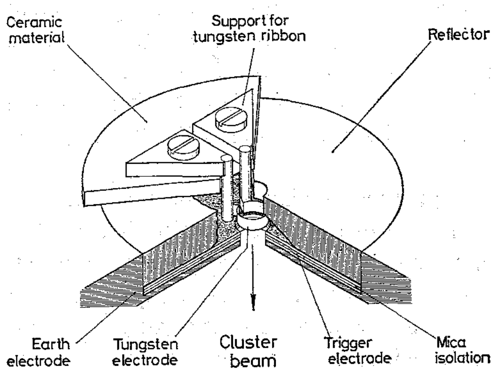


FIG. 2.—Isometric view of the system for injection of the electrons.

predischarge takes place in the space between the trigger electrode and the earth electrode. This predischarge does not occur in the presence of the electron beam but in the absence of the cluster beam. Following this predischarge, the main discharge between the high-voltage electrodes fires after a time lag of about 5 μsec with a jitter of $\approx \pm 8\%$. Simultaneously, the luminous beam shown in Fig. 4 is observed.

3. TIME DEPENDENCE OF THE DISCHARGE

3.1 *Magnetic probe measurements*

The positions of the magnetic probes used to investigate the time dependence of the discharge are shown in Fig. 5(a). Probe 1 encircles the cluster beam or a metal rod which can be substituted for the beam for calibration. Probe 2 measures the rate of change of the total discharge current outside the vacuum chamber.

The traces Figs. 5(b) and 5(c), which were taken with the same oscilloscope deflexion sensitivity, are approximately the same in the time interval between the first

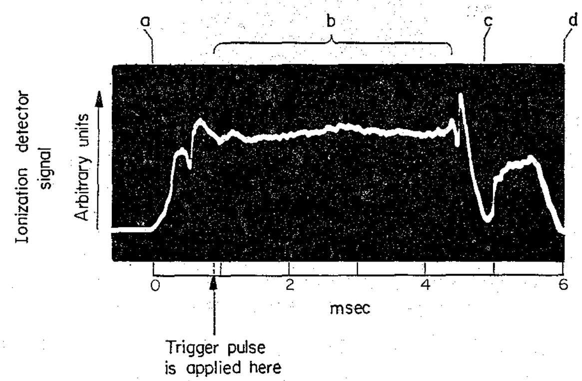


FIG. 3(a–d).—Oscillogram of the ionization detector signal. The horizontal display is triggered by the primary pulse generator. The trace shows the various phases of beam formation, delayed by the time of flight between the nozzle and the detector.
(a) Nozzle open.
(b) Steady-state beam conditions.
(c) Valve spindle bounces.
(d) Nozzle is closed.

crossing of the abscissa and about one microsecond after firing of the main discharge. The initial rise time in Fig. 5(b) is slower and the first crossing of the abscissa occurs later than in Fig. 5(c)* because the discharge in the cluster beam starts with lower conductivity than that in the metal rod.

Thus the oscillograms show that the discharge current is restricted to the region encircled by probe 1 within about the first microsecond after breakdown. After the first microsecond the signal from probe 1 [see Fig. 5(b)] and thus the proportion of discharge current passing through the loop decreases very rapidly. Even after the signal from probe 1 [Fig. 5(b)] has become small, however, the signal from probe 2 [shown in Fig. 5(d)] indicates that the discharge is still continuing. It may thus be assumed that after about 1 μsec the diameter of the current-carrying region exceeds

* The fast-changing signal within the first quarter period in Fig. 5(c) was not recorded by the photographic material.

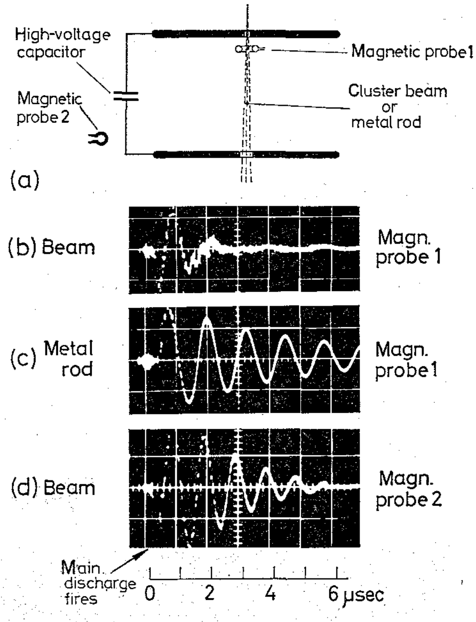
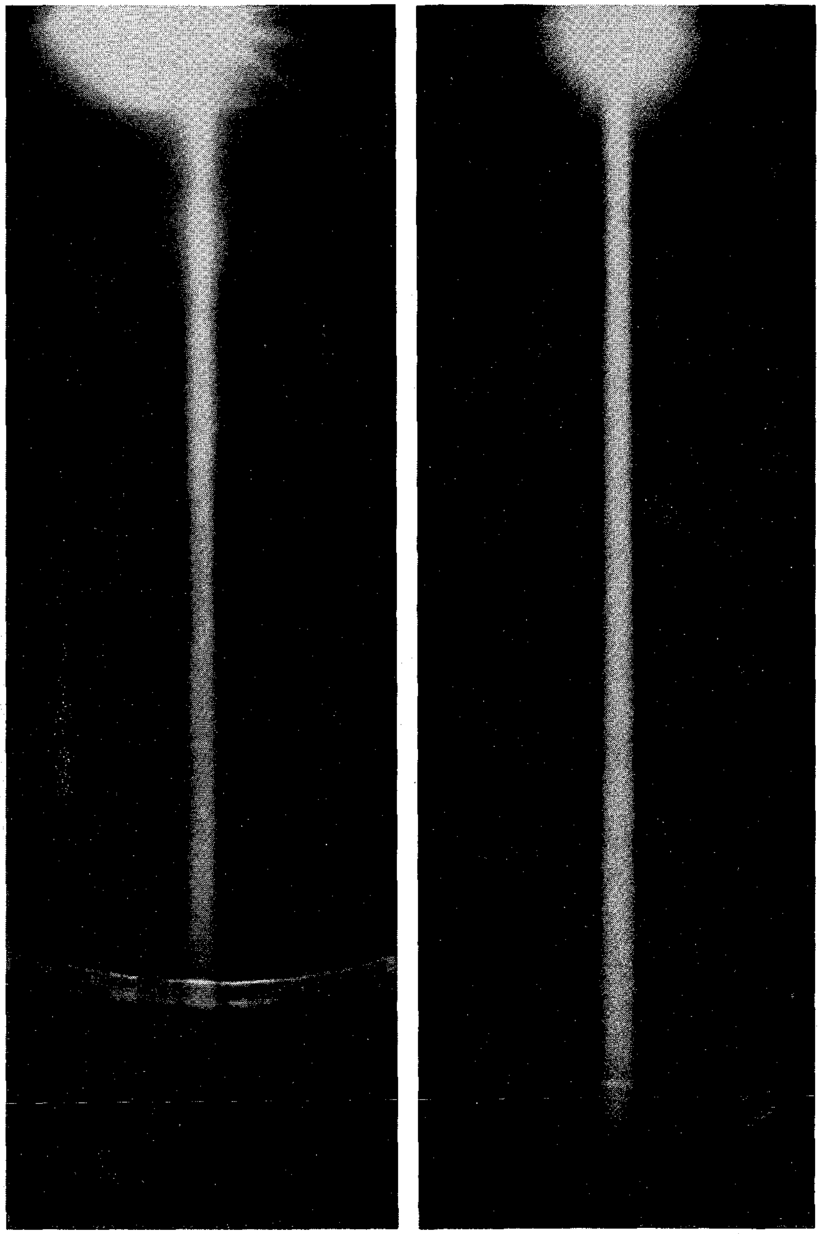


FIG. 5(a–c).—Schematic view of the arrangement of magnetic probes 1 and 2 [Fig. 5(a)]. The oscillograms 5(b) and 5(d) show the probe signals for a discharge along a beam of nitrogen clusters (probes 1 and 2 respectively).
Oscillogram 5(c) shows the signal of probe 1 when encircling a metal rod instead of the beam. In this case the discharge was fired by a spark gap. In the first quarter period after breakdown the photographic material did not record the fast-changing signal. The high-voltage capacitor was charged to 12 kV.

the inner diameter of probe 1 (27 mm), the mean radial velocity with which this region expands being about 10^6 cm/sec. The reduction of the period with increasing time, as seen from oscillogram 5(d) can also be explained by the radial expansion of the current-carrying region in the condensed cluster beam, since such expansion reduces the inductance of the discharge circuit. Although the electric field between the high-voltage electrodes is considerably distorted by the presence of probe 1, which is at earth potential, the shape of the luminous column remains unaffected. Thus the discharge path appears to be largely independent of the spatial electric field distribution and the discharge takes place only in the region of the beam.

3.2 *Image converter measurements*

Time-resolved photography of the beam was undertaken using an STL image converter, the sweep being started by the trigger pulse after a time delay chosen to match the mean time-lag for the occurrence of breakdown. Figure 6 shows a smear picture of the cross section of the luminous column, in which the start of the image converter sweep and the moment of breakdown in the beam accidentally coincided within the accuracy of measurement. The time interval between the start of the image-converter sweep and breakdown in the beam varies statistically within the jitter time for the occurrence of the breakdown. The mean time interval in question was determined by observing the signal from the external magnetic probe used for measuring the rate of change of the total discharge current. The time base of the oscilloscope was synchronized with the start of the image converter sweep. The



(a) (b)

FIG. 4(a, b).—Time-integrated photography of the luminous column.
(a) Discharge in a beam of hydrogen clusters.
(b) Discharge in a beam of nitrogen clusters.

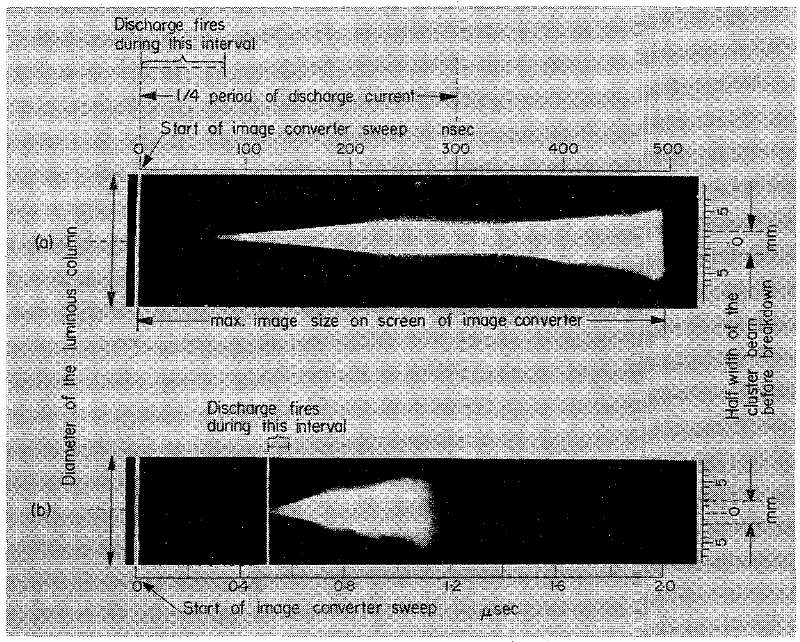


FIG. 6(a, b).—Smear-picture of the diameter of the luminous column in a beam of nitrogen clusters.
(a) Speed of the image converter: 10 cm/μsec.
(b) Speed of the image converter: 2·5 cm/μsec.

possible error in timing inherent in this method of working is indicated at the top of Fig. 6(a).

The smear picture in Fig. 6(a) is limited at about 500 nsec after exposure by the maximum image size on the screen of the image converter. In the smear picture in Fig. 6(b), the writing speed of the image converter was made 1/4 of the speed used for Fig. 6(a). Figure 6(b) also demonstrates a case in which the start of the image converter sweep did not coincide with the initiation of the discharge, although the sweep delay time was the same as that used for Fig. 6(a). It can be seen from Fig. 6(b) that the diameter of the luminous column increases by about 12 mm in 600 nsec; this corresponds to an average expansion velocity of the column of about 10^6 cm/sec, which agrees with the radial expansion velocity of the current-carrying region. The agreement between the values for the radial expansion velocities measured by the magnetic probes and by the image converter shows that the current is largely limited to the luminous plasma column. It can be seen from Fig. 6(b) that the diameter of the plasma column at the first current maximum of the discharge is about 5 mm. The maximum discharge current of about 5 kA determined from the magnetic probe measurements, corresponds to a current density at the time of maximum current of ≈ 25 kA/cm^2.

4. DISCUSSION OF THE RESULTS

The results show that it is possible to cause a discharge in a condensed cluster beam in high vacuum which converts the beam into a transient locally restricted plasma column. Unlike the plasma columns produced by normal pinch discharges, the columns produced by condensed beams are in contact with the electrodes only, and not with the wall of the discharge tube. Since it is known that the impurities in normal discharges are introduced mainly from the wall it may be expected that the columns produced with condensed beams would contain considerably smaller amounts of impurities.

Spectroscopic measurements still under way indicate that the plasma column is essentially free from impurity radiation, except in regions near the electrode, a fact of vital interest in thermonuclear experiments.

The technique described in this paper could be used, for example, for the production of thin-walled cylindrical plasma sheaths as required for a hollow dynamic pinch (LINHART 1960; MAISONNIER *et al.*, 1965).

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