Review of Controlled Thermonuclear Research at A.E.I. Research Laboratory

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At temperatures of several hundred million degrees, in deuterium, the energy generated by nuclear reactions will exceed the radiation loss. This fact suggested to one of us (G.P.T.), in 1946, that useful power might be generated from such reactions, provided that the loss of energy to the walls could be sufficiently reduced by magnetic fields. Experiments were begun at Imperial College, London, in February 1947, to produce very large currents in a low-pressure gas discharge. The containment of the gas was to be achieved by the pinch effect and a toroidal discharge tube was used to eliminate end losses. Currents in the range $1 \times 10^4$ to $2 \times 10^4$ amp were induced in the gas by discharging a condenser of maximum energy 400 joules through a primary winding coupled with the gas. These experiments were the first to demonstrate a marked pinch effect in a gas discharge, although inertial effects caused the contracting discharge to overswing and expand again, followed by further contractions and expansions.

In order to achieve temperatures of several million degrees and demonstrate a thermonuclear reaction it was clear from the Bennett relation, $2NkT = I^2$, that currents of the order $10^5$ amp were required. $(N$ is the total number of particles per unit length of the discharge, $k$ Boltzmann’s constant, $T$ the temperature and $I$ the current.) When, however, the condenser energy was increased in 1950 to 18,000 joules, serious crazing and evaporation of the small Pyrex glass discharge tubes occurred and it became necessary to develop superior materials to contain the large currents. At this juncture thermonuclear research was made secret by the Government and, because of the undesirability of conducting secret research at a university, the staff and apparatus were moved to the Associated Electrical Industries Research Laboratory, Aldermaston, in 1951. In the development of suitable discharge tubes, quartz and porcelain were tried, but it soon became apparent that only metals could withstand the heat pulse involved. With metal tubes, a new problem was encountered; arc breakdown occurred across the gap which must be left in the tube to avoid a short-circuit. This arc breakdown has been the main problem in the development of metal discharge tubes. In addition, as the research was extended to currents of longer duration the fundamental problem of the discharge instability was encountered. Most of the research at A.E.I. has been directed towards solving these two main problems, namely the arc breakdown and the discharge instability.

**DEVELOPMENT OF METAL DISCHARGE TUBES**

The quartz and porcelain discharge tubes used had tube diameters 3–5 cm and torus diameters 20–30 cm. With pulsed oscillographic currents of amplitude about $3 \times 10^4$ amp and frequency 20 kc/s, the quartz tube was found to vaporise appreciably after 5 microseconds and the porcelain after about 20 microseconds. A simple calculation showed that these times were consistent with most of the heat generated in the gas being passed rapidly to the tube walls and the walls vaporising when their surfaces approached boiling point. The time for which a given surface can withstand a heat flux of $q$ calories cm$^{-2}$ sec$^{-1}$ is given by:

$$t = \frac{X}{\pi \rho s}$$

(1)

where $\lambda = \frac{\pi \theta_0 K \rho s}{4}$, and $\theta_0$ is the boiling temperature, $K$ the thermal conductivity, $\rho$ the density and $s$ the specific heat. On this basis, the most suitable materials for the discharge wall are those having high values of the quantity $\lambda$. Unfortunately, most electrically insulating materials have a low value of $\lambda$ because of their poor thermal conductivity. The only exceptions are a few oxides and, in particular, beryllia, but these are very difficult to fabricate. The other materials having high values of $\lambda$ are electrical conductors and of these the metals with high $\lambda$ are the most suitable.

The first metal tube was made in 1951 of aluminium and had two gaps. In preliminary experiments satisfactory discharges of several thousand amperes were obtained with about 100 volts per turn. At higher currents and voltages serious arc breakdown occurred across the gaps, causing a short-circuit of the discharge and melting the metal at the gaps. The first step taken to prevent arc breakdown was to increase the number of gaps to reduce the gap voltage. A series of multi-gap tubes was developed, culminating in 1955 in a large...
Study of the Discharge in a Metal Torus

Kruskal and Schwarzschild\(^5\) showed theoretically that a self-constricted discharge is inherently unstable. There are many modes of instability but probably the most important is that known as the "wriggle" instability which causes any slight kinks in the discharge filament to grow in amplitude. It was first observed in the United Kingdom in 1953.\(^6\) If such an instability develops in a metal tube the eddy currents induced in the walls produce magnetic fields which tend to prevent the wriggle developing, and it was originally hoped that this effect would control the instability. However, in experiments with a glass torus, surrounded by a metal sheath, high speed photography showed that stability was retained for current values only slightly in excess of the currents giving rise to instability in the absence of a metal sheath. At high currents the discharge appeared to wriggle over the whole tube. A simple analysis shows that eddy current forces will not balance the instability forces arising from short wave instabilities until the wriggle approaches very near the wall.

As so little was known of the properties and, in particular, the wavelength of the wriggling discharge in a metal tube, it was agreed with AERE that a study should be made of the phenomenon, especially as the decision had been taken to construct ZETA at AERE, in which some instability was expected to occur. The discharge tube used initially was a four-gap aluminium torus with tube bore 30 cm and mean diameter 105 cm. Coupling between the primary and the gas was aided by a four-ton iron core and the primary was wound on the core to reduce its stray magnetic field in the discharge regions. The condenser bank, which was discharged through an eight turn primary by a spark-gap switch, had a maximum energy storage of 66,000 joules. In practice, however, the energies used were limited to about 6000 joules because, with greater energy inputs, arcing occurred at all the gaps, resulting in a short-circuit of the discharge. The current pulse time was about 1 millisecond. A rotating mirror camera

Various metals have been compared in these tests and, in particular, copper was found to arc less than aluminium. Because of this and the fact that copper has a larger value of \(\lambda\), copper liners were used in Sceptre III to cover the aluminium near the gaps. This enabled over 40,000 discharges with currents from 50,000 to 200,000 amp to be passed without arc damage seriously interrupting research. Similar operations without the copper liners lead to serious damage of the aluminium after only several hundred discharges.

Considerable progress has been made in understanding the dynamic behaviour of the arc spots in the presence of a high-current discharge. The arc spots undergo retrograde motion due to the self-magnetic field of the discharge. This effect causes the arcs to travel along the discharge tube and enter the gaps, and it is in the confined space of the gaps that serious arc damage occurs. Most of the damage is on the anode side of a gap. Further details of this work are given in a separate paper.\(^3\)

64-gap torus with tube diameter 30 cm and torus diameter 100 cm, in which currents up to \(8 \times 10^4\) amp were produced (see Fig. 1). At currents much less than the maximum and an applied voltage corresponding to only 10 volts per gap, appreciable arc breakdown still occurred at some of the gaps. The discharge was very unstable and wriggle velocities up to \(10^7\) cm sec\(^{-1}\) were observed. The instability caused serious bombardment of the tube wall and may well have caused local enhancement of the gap voltages, but, when a high temperature plasma is adjacent to a metal surface, an arc can form independently of applied voltages.\(^4\)

Since 1955 a considerable amount of work has been done to understand the nature of arc breakdown in order to find ways of preventing it. Investigations have been made of the role of the surface condition in glow-to-arc transitions in the hope of finding a suitable material or surface treatment with which transitions did not occur. Success has been achieved in greatly reducing the amount of arc breakdown on small test electrodes immersed in the plasma of a 1000-amp hydrogen ring discharge. The electrodes were "conditioned" by allowing arc discharges to form on their surfaces under controlled conditions, a process similar in some respects to that widely used in the manufacture of certain types of electronic tubes. With all the metals tried the probability of a ring discharge resulting in arc formation, which was initially unity, was found to decrease with the number of discharges. For example, in the case of copper and up to 4000 volts applied between test electrodes of 10 sq. cm area, the probability could be reduced from near unity to about 0.01 in some 100 flashes. Careful chemical cleaning or baking in vacuo reduced the number of arcs required to condition a surface but no treatment was found to obviate the need for 'conditioning'.

A simple analysis shows that eddy current forces will not balance the instability forces arising from short wave instabilities until the wriggle approaches very near the wall.
THERMONUCLEAR RESEARCH AT A.E.I.

Figure 2. Racetrack torus with "Pepper-Pot" section.
Internal bore of tubing, 12 in.

was used to photograph the discharge as seen through a slot running across the discharge tube, and by viewing the discharge from two directions at right angles, a two dimensional, time-resolved record of the discharge was obtained. Current and voltage oscillograms were also recorded and the apparatus provided time correlation between the streak photographs and the electrical waveforms.

In order to obtain information regarding the third dimension, parallel to the tube axis, and in particular to determine the wriggle wavelength, further experiments were carried out with two straight sections, 60 cm long, inserted in the torus and making it race-track in shape. The sections were square in cross section and one, known as the "Pepper-Pot", had an array of holes perforated in two of its sides as shown in Fig. 2. The holes were 1.3 cm in diameter and were spaced 2.5 cm apart in both directions. They were drilled in such a way that their axes converged on a focus at the position of the camera lens. Photographs were taken first with an image converter camera giving single-frame microsecond exposures, and secondly with a Courtney-Pratt lenticular plate camera giving multiple-frame photography with exposure and framing times both 10 microseconds.

Very little success has been achieved in photographing hydrogen discharges because of the very rapid discharge movement and the low light level involved. Because of this most of the work has been done with argon discharges. The currents studied have been in the range 5000-20,000 amp and the main results can be summarised as follows. At the low electric fields used (0.3 to 1.0 v cm⁻¹), the discharge forms as a constricted filament near the centre of the tube and no pinch effect oscillations occur. The discharge has no kinks at this stage but these soon develop and the discharge filament becomes approximately sinusoidal in shape. The sine wave grows in amplitude with time and in addition moves along the tube with a velocity of the same order of magnitude as the rate of growth in amplitude. Figure 3 shows two sample image converter photographs of the racetrack section taken during the development of the instability, and the graphs in Fig. 4 give the magnitude of the wriggle growth velocity in the radial direction and its variation with the applied electric field for different argon pressures. In addition to the development of the instability, the width of the discharge channel is increasing during this period, and measurements of current and gas resistance suggest that the gas kinetic pressure is increasing more rapidly than the confining magnetic pressure.

For a given set of experimental conditions the time of initial onset and rate of growth of instability were found to repeat accurately from one pulse to another. The wriggle wavelength was about 40 cm in all cases.

10 µsec after initiation of discharge

Figure 3. Development of wriggling in a metal torus.
"Pepper-Pot" section. Argon discharge

Each photograph shows two images of the discharges. The lower image in each case is for the direct view of the discharge and the upper image is photographed via the mirror as shown in Figure 2.
and only the rate of growth varied with pressure and current. In other words it was the same mode of instability appearing first each time and, for fixed conditions, the time of onset and position of the instability did not vary. These results suggest that the particular mode observed is due to departures from perfect toroidal geometry in the torus rather than to fundamental properties of the discharge.

The wriggle amplitude continues to grow until the discharge is apparently touching the tube wall. At the lower currents studied, the discharge thereafter wriggles in a confused and random manner throughout the remainder of the pulse and other modes of instability may well be present. At currents greater than about $1.2 \times 10^4$ amp, and after the discharge has reached the walls, streak photographs show bars of light extending across the tube width which last about 10 microseconds and appear at random intervals. At still higher currents (greater than about $1.5 \times 10^4$ amp) this "Barring" effect occurs for only a short period in the pulse and is then followed by an abrupt and permanent reduction in the light emitted by the gas, although the oscillograms show a marked simultaneous increase in current. It is believed that the effect is due to short-circuiting arcs having formed at all the gaps at this instant. All these effects—the growth of wrigging, the barring, the reduction in light intensity and the sudden increase of current—are shown in Fig. 5 which shows simultaneous streak photograph and current oscillogram records for an argon discharge.

Prior to the short-circuiting arcs occurring at all the gaps, local intermittent arcing can take place at some gaps independently of others, and the barring phenomenon (which will be referred to later, since it appears on all records of hydrogen discharges in ZETA and Sceptre) is believed to be associated with this arcing. An arc produces a local burst of gas and metal vapour which will lead to a region of high gas pressure moving along the tube.

Study of the Discharge in Applied Magnetic Fields

Before the observation of the discharge instability in 1953, a few experiments had been carried out in which toroidal magnetic fields were applied parallel to the discharge. These fields were intended to maintain the containment of charged particles during the periods around the current zeros in the case of oscillatory discharge currents. Apart from a reduction in the constriction of the discharge and a lowering of gas resistance no marked effects were observed. Since 1953 many experiments employing magnetic fields have been performed with a view to stabilizing the discharge channel.

Some of the earlier experiments with steady magnetic fields have been described already. In particular, a toroidal magnetic field, $B_\theta$ applied to currents of a few thousand amperes in a glass torus was found to destroy the pinch effect. This occurred even when the magnetic field was applied after the discharge had constricted. In many cases the photographs showed sharp-edged light and dark regions travelling across the discharge tube. The velocity of these bands appeared independent of magnetic field and had the magnitude to be expected for an acoustic type magnetohydrodynamic wave.

In other work with an alternating toroidal magnetic field, Miles confirmed the results of Bickerton of AERE that circulating currents induced in the $\theta$ direction suppressed wriggling. It was found, however, that the discharge sat near the outer wall of the torus for part of a half cycle of the alternating magnetic field and at other times near the inner wall. In an analysis of this type of discharge, Liley showed that such an effect could be explained by taking account of the gradient of $B_\theta$ and the phase angle between $B_\phi$ and the $\phi$ currents in the gas. This work was not pursued.

![Figure 4. Wriggle growth velocities for different pressures in Argon vs. applied electric field](image)

![Figure 5. Streak photograph and oscillograms of Argon discharge showing barring and major arcing](image)
however, since the results showed that very large reactive powers were required in order to produce toroidal magnetic fields capable of controlling large gas currents.

In 1956 Bickerton showed that a stable discharge could be obtained with a steady toroidal magnetic field when combined with a metal torus.8 Experiments, therefore, were carried out with a steady magnetic field applied to the discharge in the four sector aluminium torus described in the previous section. In this work, \( B_\phi \) was again found to increase the gas current, the increase being as much as five times in the case of low pressure hydrogen. The current range studied was from 5000 amp to about 30,000 amp. With argon, the streak photographs were similar to those with glass tubes. The amount of constriction of the discharge when it first becomes visible is progressively reduced by increasing \( B_\phi \), and in all cases the transverse wave motion has again been observed at this point. The discharge subsequently expands and fills the whole tube. With hydrogen at the lower currents, photographs show a diffuse discharge filling the whole tube with some diagonal streaks, suggesting a helical instability. At the higher currents these diagonal streaks are observed only at the beginning of the pulse; at later times the streak photographs have a turbulent appearance with intermittent bars similar to those already mentioned. The effect of \( B_\phi \) is to increase the number of bars and make them more marked in appearance.

In 1957 the “Pepper-Pot” racetrack sections were fitted to this torus and, after the experiments without magnetic field, coils were added to extend the study to discharges with \( B_\phi \). It was at this time that the first results were obtained with ZETA at AERE9 and these indicated: (i) that at high currents in a metal torus with \( B_\phi \), a stable discharge with trapped field was obtained and (ii) that the amount of arcing in the presence of such a discharge was very much reduced, compared with similar currents in the absence of \( B_\phi \). These results gave encouragement to studying higher currents in the racetrack torus, and it was found that in spite of the tube’s having only eight gaps, large gas currents could be obtained in the presence of \( B_\phi \) without arcs short-circuiting the discharge. Currents of \( 10^8 \) amp were obtained with the full condenser energy.

With argon, the appearance of the discharge is markedly different under these conditions (Fig. 6). The discharge forms initially over the whole tube, contracts to a minimum diameter and then expands again, and over this time the discharge has a more clearly defined edge. After the discharge has expanded to the walls the streak photographs become confused for a time and then seem to indicate a sharp-edged constricted discharge with bars superimposed on it. The two phenomena are not independent since marked sideways perturbations occur in the sharp-edged channel at the time of each bar. These excursions of the channel, however, are limited in amplitude and the channel does not touch the tube wall. The constriction of the channel is less the higher the initial gas pressure and the higher \( B_\phi \).

With hydrogen the photographs in most cases show only the bars, but in a few cases a sharp-edged core has been observed. With colour films this core is blue, whereas the bars are mainly red. Some streak photography was carried out with hydrogen, using a line of holes along the length of the “Pepper-Pot” and this showed that the bars were travelling along the tube. The direction of motion was that of the electron drift velocity in the discharge for most of the pulse, but changed to the opposite direction towards the end of the pulse. The velocity appeared independent of \( B_\phi \) and gas current and was always in the range \( 10^6 \) to \( 2 \times 10^6 \) cm sec\(^{-1}\).

Following the work of Ramsden at AERE,9 measurements were made of the ion temperature from the Doppler broadening of oxygen (O\(^+\)) impurity lines, since these were from the most highly ionised atoms observed in the discharge. Voigt profiles were used to correct the line contours for instrumental broadening and, by the middle of October 1957, broadening corresponding to temperatures more than \( 10^8 \)°K were recorded.

**EXPERIMENTS WITH SCEPTRE**

Following Bickerton’s observation of stability in a metal tube with \( B_\phi \), the work of Bickerton, Liley and others led to the understanding of the part played by trapped magnetic fields in such discharges. A detailed analysis by Tayler10 gave the conditions necessary for stability which are now well known. As a result several experiments were proposed at the end of 1956, at AERE and AEI, all incorporating this method of stabilisation but with different heating mechanisms. Liley suggested that adequate heating of the gas could

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\( \ddagger \) Sceptre: Stabilised Controlled (E) Pinch Thermnuclear Reaction Experiment.
be achieved by ohmic heating due to both the $\theta$ and $\phi$ gas currents, aided by the adiabatic compression of the gas during contraction.

Two small tubes (Sceptre I and Sceptre II) based on this idea were in construction in 1957 when the large racetrack torus yielded the promising results described above. It was decided to rebuild this large torus without the racetrack sections and its primary was adapted to produce higher currents. This apparatus was renamed Sceptre III.

Figure 7 shows a photograph and Fig. 8 a plan diagram of Sceptre III. The torus is made of aluminium tubing with a bore of 30 cm and a wall thickness of 1.2 cm. The eight porcelain insulators at the gaps are protected by eight pairs of interlaced copper liners, and double vacuum gaskets made from indium wire are used throughout. Quartz-covered slits—one in the vertical plane and one horizontal—allow observation of the discharge. The primary has been placed near the torus to reduce the leakage inductance which is now an important factor because of the low impedance of a stabilised discharge. It consists of four separate windings, of eight turns each, and is wound as uniformly as possible over the surface of the torus so that the local magnetic fields of the primary current cancel in the discharge space.

The toroidal magnetic field is produced by 102 layer-wound coils placed around the torus perimeter beneath the primary, and at pumping and viewing ports the field is maintained constant by compensating coils. The maximum $B_\phi$ is 1000 gauss. The condenser bank with maximum energy 66,000 joules and maximum voltage 30 kv is discharged through the primary by means of a spark gap switch.

The gas used so far with Sceptre III has been almost exclusively deuterium and all the results given below refer to this gas. The pressure range has been $4 \times 10^{-4}$ to $4 \times 10^{-3}$ mm Hg. Work has been done with the primary connected to give transformer turns ratios of 8:1, 16:1 and 24:1.

Experimental Results

Conditioning Effect

The behaviour of Sceptre III shows a conditioning effect. Following a period with no discharges, and particularly after the apparatus has been dismantled and re-assembled, the first few pulses show a high gas resistance,§ with a high level of radiation from the impurities oxygen and nitrogen, and no neutron emission is detected. With further discharges the impurity level of oxygen and nitrogen and the gas resistance decrease, though the copper and aluminium impurity increases. The degree of ionisation of the oxygen atoms increases and the lines become broader. The current waveform changes in shape and, after a time, exhibit the characteristic changes of slope referred to below. Simultaneously, neutrons are detected and, with further discharges, their number increases. Lastly, the voltage observed across the gaps in the torus shows more fluctuations under the neutron producing conditions.

After a period of repeated discharges the various parameters reach steady values and the results listed below refer to this "conditioned" state.

Current and Voltage Oscillograms

In Fig. 9, peak gas current is plotted as a function of magnetic field for several condenser voltages with the eight turn primary and for one voltage with the sixteen turn primary. The length of the current pulse is proportional to the number of primary turns and the decrease in peak current with the number of turns is

§ In some cases the first two or three discharges showed very high currents which were believed to be due to short-circuit arcs occurring at all the gaps.
due to the increased damping that results. There is a slow increase of current with increase in pressure.

Figure 10 shows sample oscillograms for voltage, current and rate of change of current. The current waveforms have a characteristic shape. When the current reaches a certain critical value there is a fairly abrupt change in $\frac{dI}{dt}$ and a corresponding change when the current returns to this value. The value of this current corresponds to a self-magnetic field $B_\phi$ at the discharge tube wall equal to the applied magnetic field $B_\Phi$. The waveforms are consistent with the gas having a kinetic pressure low compared with the magnetic pressure and with at least some of the discharge plasma filling the whole tube until the critical current is reached, then constricting and trapping most of the $B_\phi$ flux, and finally expanding to the walls when the current returns to this value. This behaviour is to be expected since, with trapped $B_\phi$, there is an outward pressure of $B_\phi^2/8\pi$ which must be exceeded by $-Z\phi^2/8\pi$ before pinching can occur.

A considerable amount of information can be obtained from simple inductance measurements. First, before the discharge leaves the wall, and assuming the discharge is stable, the leakage inductance of the gas is given by:

$$L_1 = 4\pi R \ln (\frac{d}{a} + \gamma)$$

(2)

where $R$ is the major radius of the torus, $2a$ is the width of the discharge and $d$ is the distance of the primary turns from the centre of the discharge. The factor $\gamma$, associated with the magnetic field within the discharge, will be zero for an infinitely thin skin current and will rise to unity for a uniform current density across the discharge. Measurement of $L_1$ will yield therefore a measure of $\gamma$ since the other components can be calculated. Unfortunately, the method is rather inaccurate since the $\gamma$ component is only a small fraction of the total inductance.

Secondly, when the current exceeds the critical value at which the discharge leaves the wall, assuming $B_\phi$ to be completely trapped and the kinetic pressure to be small compared with the $B_\phi$ magnetic pressure, the rate of change of inductance leads to an effective increase, of $4\pi R$, in the inductance of the discharge. This follows from (a) the circuit equation,

$$L_1 \frac{d^2I}{dt^2} + I \frac{dL_1}{dt} + R_g I = V,$$

(3)

where $I$ is the measured gas current, $R_g$ the "effective" gas resistance and $V$ the volts per turn, and (b) from the discharge pressure balance relationship,

$$B_\phi = \frac{2I}{a} = \alpha \frac{b^2}{a^2} B_{\phi 0},$$

(4)

where $2b$ is the diameter of the discharge tube, $B_{\phi 0}$ the applied field and $\alpha$ the fraction of $B_\phi$ flux trapped, and where $\alpha$ is assumed near unity.

This yields

$$\frac{dI}{I} = -\frac{1}{a} \frac{da}{dt},$$

and hence

$$\frac{dL_1}{dt} + \frac{dL_1}{da} \frac{da}{dt} = \frac{4\pi R \frac{dI}{dt}}{I}.$$  

(5)

Equation (3) then becomes

$$L_2 \frac{dI}{dt} + R_g I = V,$$

(6)

where

$$L_2 = L_1 + 4\pi R.$$  

(7)
A measurement of the change of $dI/dt$ at the critical current yields the change of effective inductance. If the measured increase in inductance is $\beta \pi R$, then $\beta$ should equal unity if the above assumptions are correct.

Lastly, from Eqs. (2) and (4) we have

$$L_2 = 4\pi R \left[ \ln \left( \frac{2I_d}{\pi B_0} \right) - \ln a + \frac{\gamma}{4} + \delta \right]. \quad (8)$$

$L_2$ has been measured at peak current from the ratio $(dV/dI)/(dI/dt)$ (on the assumption $dR/dt \approx 0$) and, since all other quantities are known in Eq. (8), a value can be obtained for $\alpha$.

Table 1 shows a sample set of experimental results obtained for $V/I$, at peak current, and the quantities $\alpha$, $\beta$ and $\gamma$ for the eight turn primary. For this set,

<table>
<thead>
<tr>
<th>( B_0 ) (gauß)</th>
<th>( V/I ) (ohms)</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( \delta )</th>
</tr>
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<td>200</td>
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<td>0.45</td>
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<td>1.30</td>
<td>0.8</td>
<td>0.82</td>
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</table>

the kinetic pressure is known to be appreciably less than the magnetic pressure and the simple results just derived can be used. For kinetic pressures comparable with the magnetic pressures, as with the sixteen turn primary, a more exact analysis must be applied. The values of $\alpha$ indicate that the discharge is trapping most of the $B_0$ magnetic field. The values of $\beta$ are near unity and confirm the assumptions made in the above analysis. The values of $\gamma$ are the least accurate of the three since they involve measuring a small increment in the inductance. The values of skin depth corresponding to these values of $\gamma$ are shown in the sixth column of the table as fractions of the discharge tube radius. The inductance and hence $\gamma$ have not been measured at the beginning of the first half cycle because the gas resistance is unknown and likely to be large at this point. The high value of the ratio $V/(dI/dt)$ before the discharge leaves the wall indicates either a high gas resistance or high inductance.

The measurements of $V/I$ at peak $I$ cannot be directly taken to be a measure of gas resistance. This is because resistance associated with eddy currents in the torus walls and arcs must be accounted for in the ratio $V/I$, while any component of $dI/dt$ which is not in phase with the current will also be included in this ratio.

Streak Photography

The predominant feature of the streak photographs is the "bars" which are observed in all cases with deuterium and hydrogen discharges. During the "conditioning" of the discharge a sharp-edged core is also observed which is blue in colour, whereas the bars are mainly red. With the decrease in impurity content which results from conditioning, this core becomes invisible. Its continued presence is indicated by the more sensitive detection of the light from highly ionised impurity atoms described below.

Spectroscopic Measurements

The spatial and temporal variation of the intensity of impurities lines has been studied by combining a photomultiplier with a monochromator. This work indicates that the oxygen O\textsuperscript{V} light comes mainly from a narrow core at the centre of the discharge, with a diameter from $\frac{1}{3}$ to $\frac{1}{4}$ of the tube diameter. On the other hand, O\textsuperscript{IV} has minima at the centre of the discharge and is otherwise fairly uniform across the tube.

At a condenser voltage of 25 kv and a pressure of $1.4 \times 10^{-3}$ mm Hg, the intensity distributions have been obtained for different $B_0$. At 250 gauss the waveforms exhibit considerable fluctuations, suggesting some instability of this central core, and in this particular case the O\textsuperscript{IV} intensity is a maximum at a radius of about 4 cm and is less at the centre. At higher fields the waveforms show only small fluctuations and the intensity has a sharp maximum in the centre. The oscillograms indicate that the O\textsuperscript{IV} light appears shortly after the change of slope on the current waveforms and has a maximum intensity at about peak currents; at all times it comes mainly from the central core of the discharge.

Measurements have also been made of the Doppler broadening of the O\textsuperscript{V} lines using a Hilger medium quartz spectrograph. In one case the line profile was checked to be Gaussian down to $\frac{1}{3}$ of the peak intensity. This shape is consistent with the oxygen ions having a Maxwellian distribution of velocities and the temperature indicated by the line broadening. It
is not proof of the temperature, however, since a random instability could have velocities which, when averaged over time, give a Maxwellian distribution.

On the assumption that the broadening is wholly due to thermal motion, the ion "temperatures" have been calculated. The line breadth measurements come from photographic exposures for the whole duration of the current pulse and for many discharges. The "temperatures" therefore are to some extent average values, but the time variation of O\textsubscript{v} intensity weights the average in favour of temperature at peak currents. Figure 11 shows a graph of ion "temperature" against applied magnetic field B\textsubscript{ф}. With the eight-turn primary the ion "temperatures" were found to decrease with increasing condenser voltage over the range studied (11-20 kv) but with sixteen turns it increases with increasing voltage.

**Nuclear Measurements**

Neutrons and protons from the D(d,n) and D(d,p) reactions respectively have been observed from the discharge, and X-rays of energies up to 300 kev are also present, mainly in an intense pulse at the beginning of the current cycle. The neutrons appear shortly after the change of slope on the current waveform and are emitted in a continuous manner throughout the rest of the current pulse and also part of the way into the second half cycle. Figure 12 shows examples of the variation of neutron yield with time; in each case it is for one flash of the discharge. The neutron yield is seen to continue in each case beyond the current zero into the second half cycle of the current. Some delayed counts are expected to be due to capture gamma rays in the scintillation counter, but the number of observed counts at the current zero and afterwards is too great to be explained in this way. There is a real neutron emission at these times.

Nuclear plates, shielded by thin metal foils to reduce fogging by light and very soft X-ray, have been exposed to the discharge: proton tracks, of length corresponding to an energy of 3 Mev, have been observed. The energy spectra of the protons observed at 30\textdegree, 90\textdegree and 150\textdegree to the direction of current flow in the discharge have been measured. Significant differences in the mean proton energies have been observed. (A provisional value for the difference between the energies at 30\textdegree and 150\textdegree is 0.17 ± 0.04 Mev.) These indicate that at least some of the protons are due to nuclear reactions involving deuterons accelerated preferentially in the direction of current flow. The statistical accuracy of the results is not yet high enough to exclude the possibility that some of the protons may be of thermonuclear origin. The proton energy measurements confirm that these arise from the D(d,p) reaction and since their yield is in agreement with the measured neutron yield, the origin of the neutrons is also confirmed as being the D(d,n) reaction. From the direction of the proton tracks it can be deduced that these originate near the centre of the torus rather than from the walls.

Four indium activation counters have been positioned around the outer walls of the torus at roughly 90° intervals, and the induced activities measured. These were constant within the statistical accuracy of the results, which is 10%, indicating that the neutron yield did not vary appreciably round the torus.

Figure 13 shows two examples of the variation of neutron yield with time; in each case it is for one flash of the discharge. The neutron yield is seen to continue in each case beyond the current zero into the second half cycle of the current. Some delayed counts are expected to be due to capture gamma rays in the scintillation counter, but the number of observed counts at the current zero and afterwards is too great to be explained in this way. There is a real neutron emission at these times.

Nuclear plates, shielded by thin metal foils to reduce fogging by light and very soft X-ray, have been exposed to the discharge: proton tracks, of length corresponding to an energy of 3 Mev, have been observed. The energy spectra of the protons observed at 30°, 90° and 150° to the direction of current flow in the discharge have been measured. Significant differences in the mean proton energies have been observed. (A provisional value for the difference between the energies at 30° and 150° is 0.17 ± 0.04 Mev.) These indicate that at least some of the protons are due to nuclear reactions involving deuterons accelerated preferentially in the direction of current flow. The statistical accuracy of the results is not yet high enough to exclude the possibility that some of the protons may be of thermonuclear origin. The proton energy measurements confirm that these arise from the D(d,p) reaction and since their yield is in agreement with the measured neutron yield, the origin of the neutrons is also confirmed as being the D(d,n) reaction. From the direction of the proton tracks it can be deduced that these originate near the centre of the torus rather than from the walls.

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 Since this has served as a yardstick with which to compare experimental results, it is of interest to summarize the theory of ohmic and adiabatic heating, as developed by Liley. The more recent experimental results, given above, and further theoretical considerations have brought to light several serious discrepancies which cast doubt on these conclusions. The main discrepancies can be summarized as follows.

1. Although no electron temperatures have been measured yet, what evidence there is indicates an electron temperature less than the measured ion "temperature". The weakness of the O\(^{14}\) lines relative to O\(^{16}\) and O\(^{17}\) suggests that the electron temperature is not greater than 10\(^{4}\) K. The apparent high gas resistance also suggests an electron temperature less than this value.

2. There is a marked discrepancy in many cases between the ion "temperature" and the "temperature" deduced from the neutron yield, and the nuclear plate experiments indicate that at least some of the protons, and consequently some of the neutrons, are of non-thermonuclear origin.

3. In some cases, if all the gas which is initially present in the discharge is at the temperature indicated, the kinetic pressure would exceed the magnetic pressure \(B_0^2/8\pi\) and the discharge should not be constricted. The current waveforms, however, give evidence that the discharge is constricted.

The following conclusions can be drawn from the results.

First, it is reasonable to conclude that both the Doppler broadening and neutron yields give upper limits for the true deuterium temperature. From this it follows that in some cases all of the neutrons
observed are produced by non-thermonuclear processes. For example, in Fig. 11 at 25 kv and 600 gauss, the Doppler broadening indicates a temperature of $1 \times 10^6$ °K at which the thermonuclear reaction rate is undetectable, but nevertheless a large yield was obtained. Second, the evidence indicates an electron temperature appreciably greater than $10^5$ °K but less than $10^6$ °K. The deuterium ion temperature may be less than $10^5$ for an initial pressure of $1.4 \times 10^{-3}$ mm Hg this energy is sufficient to raise all the original particles to the temperature $3 \times 10^7$ °K, it must be concluded that most of the energy is being lost from the discharge or shared with impurities.

Despite these many uncertainties, however, there is one outstanding achievement indicated by the results, and particularly by the study of O⁺ light, and this is that a stable discharge was achieved for several hundred microseconds.

ACKNOWLEDGEMENTS

The authors wish to point out that this paper describes the work of a team of scientists and engineers whom it was their pleasure to direct. The nuclear physics measurements were made by members of the Nuclear Physics Section of this Laboratory.

The authors would also like to acknowledge the close co-operation with the Atomic Energy Research Establishment, Harwell, and, since 1956, the stimulus of exchange of information with the United States. Most of the work was carried out under a contract with the Atomic Energy Authority.

REFERENCES

4. J. L. Craston et al., The Role of Materials in Controlled Thermonuclear Research, P/34, Vol. 15, these Proceedings.

Mr. Ware presented Paper P/3, above, at the Conference and added the following remarks:

With reference to the spectroscopic study of light from highly ionised oxygen, Fig. 14 shows intensity profiles for the O⁺ light at different times during the discharge pulse. There are some high frequency fluctuations on the intensity oscillograms, but the light, and this is particularly by the study of O⁺ light, and this is that a stable discharge was achieved for several hundred microseconds.

The line broadening was found to be the same for both directions. The results also indicated a shift of the broadened line when viewed tangentially. The O⁺ particles have a directed velocity parallel to the positive gas current from $10^6$ to $2 \times 10^6$ cm/sec.

Magnetic measurements have been made with a small probe inserted into the discharge. Figure 15 shows typical $B_\phi$ and $B_\psi$ profiles for peak current and the conditions shown. The $B_\phi$ profile shows that the discharge has an edge outside which there is either zero or a small negative current density. The $B_\phi$ profile shows that the applied magnetic field is trapped by the discharge, and in addition extra $B_\phi$ is produced within the discharge so that $B_\phi$ outside the discharge extends.

Table 2. Proton Energy Measurements in Sceptre

<table>
<thead>
<tr>
<th>$B_0$ field, gauss</th>
<th>Peak gas current, ka</th>
<th>Deuterium pressure, µ</th>
<th>Nominal angle of observation</th>
<th>Number of proton tracks</th>
<th>Relative mean proton energy, MeV</th>
<th>Energy shift $E_{20^\circ} - E_{135^\circ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>1.8</td>
<td>45°</td>
<td>56</td>
<td>$3.07 \pm 0.03$</td>
<td>$0.16 \pm 0.04$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>135°</td>
<td>40</td>
<td>$2.91 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>140</td>
<td>1.4</td>
<td>45°</td>
<td>204</td>
<td>$3.07 \pm 0.02$</td>
<td>$0.23 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td>42</td>
<td>$3.00 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>135°</td>
<td>145</td>
<td>$2.84 \pm 0.02$</td>
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</tr>
</tbody>
</table>
is negative. The oscillograms show substantial fluctuations.

With reference to the measurement of proton energies, Fig. 16 shows histograms of the proton energies for $B_0$ fields of 500 and 1000 gauss. The discharge conditions and detailed results are tabulated in Table 2. In this work the protons studied were those emitted at angles of 45°, 90° and 135° with respect to the positive gas current.