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Translation

PHENOMENA ACCOMPANYING THE FORMATION OF A DENSE PLASMA FOCUS DURING THE IMPLOSION OF A NON-CYLINDRICAL Z-PINCH

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PHENOMENA ACCOMPANYING THE FORMATION OF A DENSE PLASMA FOCUS DURING THE IMPLOSION OF A NON-CYLINDRICAL Z-PINCH

by

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ABSTRACT

Investigations were continued of the central region of a discharge in deuterium in a pinch device with a metal chamber of larger volume than that used previously. The velocities of the plasma sheath (up to 4×10^7cm/sec) were determined by means of streak photographs and also by a new technique based on the modulation of the X-ray emission from the electrode. Both the quantity (over 10^{14}) and hardness (100 - 300 keV) of the γ - quanta increase with a decrease in the initial pressure, whereas the neutron emission shows the opposite behaviour and has a maximum at $p = 1.2$ Torr. Neutron time-of-flight measurements showed that despite the anisotropy observed in the axial direction the number of neutrons is practically independent of the degree of anisotropy. Simultaneously, with an accuracy better than 5%, complete isotropy of the neutron intensity was observed, which is not in accord with the conventional (target) model of their generation. To explain the observed facts a moving "boiler" mechanism is proposed. The neutron yield and the soft X-ray intensity were stabilized and increased by a 2% addition of xenon to the deuterium. The energy content at the focus of the pinch, estimated from the damage to the electrode surface, was approximately 100 kJ cm^{-3}, or $nT = 10^{23} - 10^{24}$eV cm^{-3}. At a temperature of (1 - 3)keV characteristic of similar discharges[1,3], such an energy content corresponds to a density of $(1 - 3) \times 10^{20}cm^{-3}$ or a pinch radius smaller than 0.5 mm.

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This paper reports on the further progress of investigations of the non-cylindrical convergence of a z-pinch in a chamber with metal walls. The principle of operation and the development of the discharge have been described in detail in reference (1). Subsequently considerable attention has been paid to the study of the processes associated with the formation, structure and dynamics of the plasma sheath. This cycle of investigations, presented in a paper given at the VIIth Ionization Conference, Belgrade, was carried out in view of the importance of the initial phase of the discharge, which has a considerable effect on the parameters of the plasma focus obtained during the implosion.

The main phase of the discharge, i.e. the constriction of the sheath toward the axis under the influence of electrodynamic forces, is characterised by formation of a shock wave and transition to supersonic motion. Simultaneously with the formation of the shock wave, which plays a stabilising part during the motion, a type of constriction peculiar to this investigation, associated with the non-cylindrical nature of the pinch ("rosette" type of constriction), begins to appear. In contrast to the "snowplow" model, where the quantity of gas increases continually because of the piling-up of the particles, in this case one observes ejection of gas increasing with time, which leads to a significant increase in the radial velocity of the sheath. The most complete solution of the one-dimensional problem of a converging cylindrical wave in a plasma taking into consideration the structure of the wavefront (i.e. consideration of the dissipative processes, the finite conductivity and so forth) relating to pinches, is given by V.F. Dyachenko and V.S. Imshennik(2). The experimentally observed curvature of the sheath is essentially a 2-dimensional effect which cannot be treated by this theory. To explain the nature of the velocity increase it is necessary to assume that the loss of mass is proportional to the velocity of the shock wave front. In this case, a considerable volume (over ¾) of matter is lost at the instant of convergence of the sheath, which permits acceleration of the remaining small part of the plasma sheath to large velocities (2.5 - 4) $\times 10^{-7}$ cm/sec. The process described is, in some respects, similar to a "shepherds crook" type wave motion.

Fig.1 shows schematically the discharge chamber, consisting of a copper box (3) and the positive electrode (5) of dia. 480 mm introduced through a porcelain insulator (4).

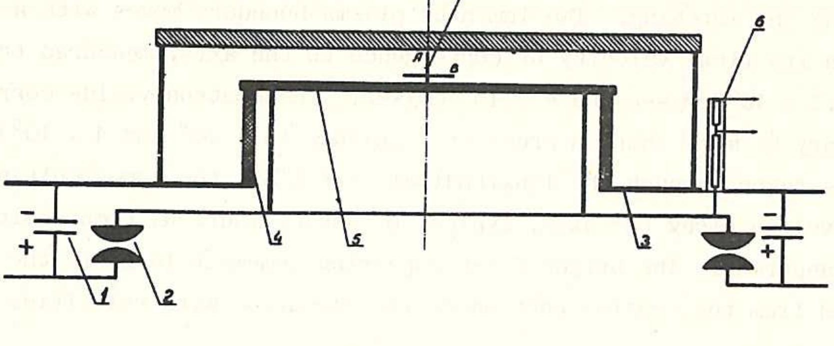

Fig. 1

(CLM-Trans 7)

Discharge chamber, schematic; (1) capacitor bank C = 180 μF; (2) ring-shaped vacuum spark gap; (3) body of chamber (cathode); (4) porcelain insulator; (5) internal electrode (anode) diameter 480 mm; (6) voltage divider; (7) cruciform slit ('A' and 'B')

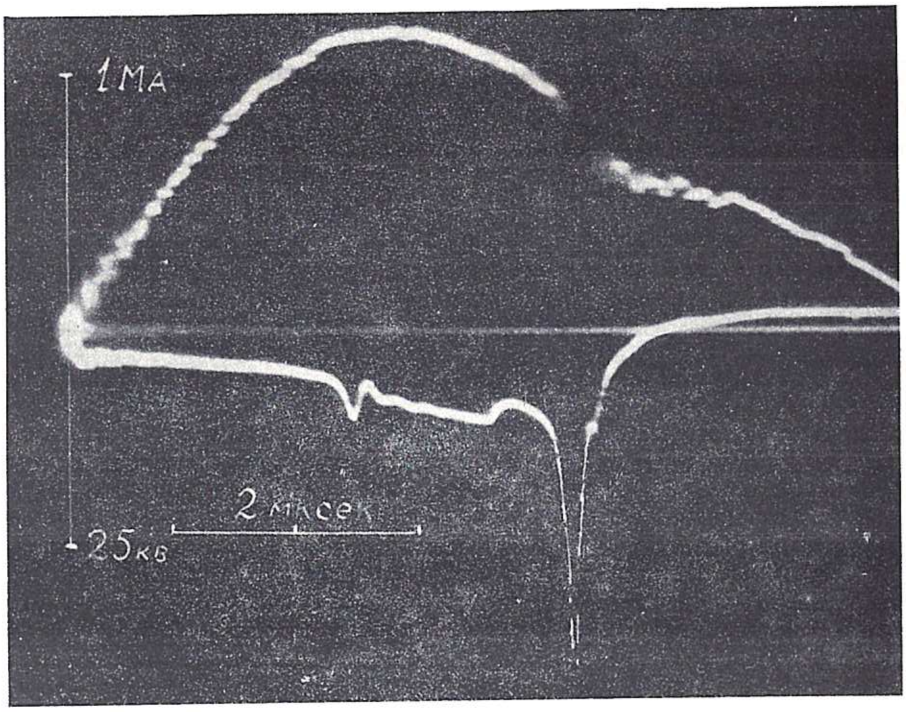

Fig. 2 (CLM- Trans 7)
Current and voltage oscillograms, p = 1 Torr deuterium, u_0 = 24 kV

A capacitor bank (1) of capacitance 180 μF at a working voltage of 16-26 kV, was discharged into the chamber through a ring-shaped vacuum spark gap (2) . The chamber was filled with deuterium to a pressure of 0.3 - 1.5 Torr. The current through, and the voltage across, the chamber were displayed on an oscilloscope screen (Fig.2) by means of a Rogowski coil and a resistive voltage divider (6) respectively.

The motion of the plasma sheath near the moment of implosion was studied by means of streak photographs taken at a velocity of 16 km/sec. Figs.3 and 4 show two typical streak photographs obtained through the longitudinal ("A") and the transverse ("B") slit ("7" on Fig.1) combined by means of a simple optical system. The longitudinal slit is situated in the plane passing through the chamber axis; the transverse slit is parallel to the electrode surface, separated from it by a distance of 0.8 cm. When examining these combined photographs it is necessary to take into account the time lag of 0.04 μsec occurring in the optical path during the matching. The luminous plasma boundary moves with a considerable acceleration, and its final velocity of convergence to the axis, measured from Fig.3 and 4, equals 3.2×10^7 cm/sec and 4×10^7 cm/sec. The neutron yields corresponding to these discharges vary by more than an order of magnitude (3×10^8 and 4×10^9). On the streak photographs taken through the longitudinal slit ("A") the non-simultaneous convergence of the envelope along the axis, typical of non-cylindrical compression of a pinch, is distinctly apparent. The bright flash appearing somewhat later is the glow of copper vapour released from the central portion of the electrode with velocities exceeding 4×10^6 cm/sec.

Fig.5 is an analagous streak photograph with better spatial resolution, obtained through the vertical slit alone. The first luminous band ("a" on Fig.5) corresponds to the appearance of the leading front of the shock wave at the camera axis. The convergence of the magnetic piston (current sheath) seems to give rise to a second less intense

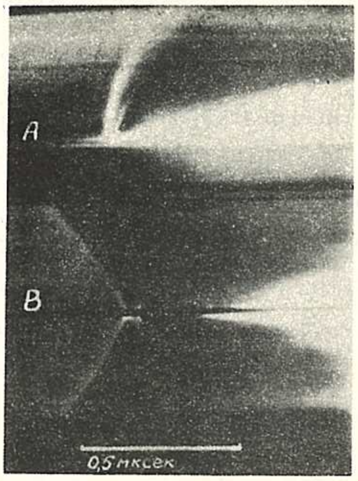

Fig. 3 Streak photographs (CLM-Trans 7)
('A') longitudinal; ('B') transverse slit

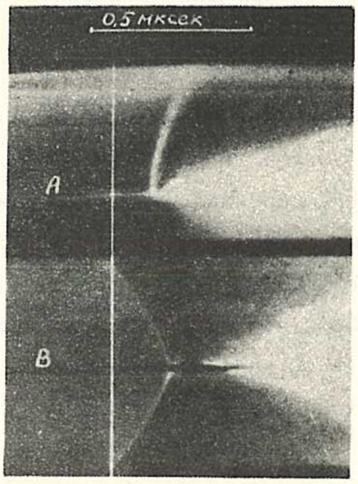

Fig. 4 Streak photographs (CLM-Trans 7)
('A') longitudinal; ('B') transverse slit

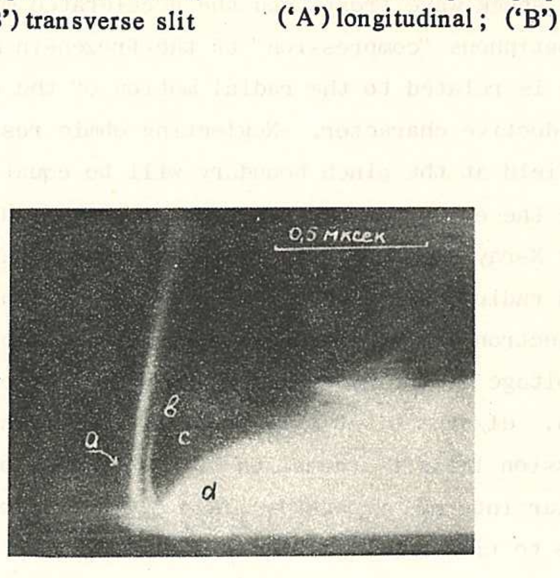

Fig. 5 (CLM-Trans 7)
Streak photographs taken through the longitudinal slit
(a) convergence of shock wave
(b) convergence of current sheath
(c) region, coinciding in time with neutron emission
(d) glowing electrode vapour

flash ("b"). The line spectrum is "burnt out" and the main radiation power is transferred to the continuum, situated in the ultraviolet and soft X-ray regions. The faintly luminous region ("c") in the optical waveband coincides, in its time of existence, with the observed neutron pulse.

There is always some question as to the correct interpretation of the boundary of the bright front observed in photographs of fast pinches. By taking simultaneous streak photographs and high speed shadow photographs it was shown that the boundary of the bright region coincides with large gradients of electron density. The shadow photographs were obtained by the usual Schlieren technique by transmitting a pulsed Q-spoiled ruby laser beam through the discharge. The exposure time of 70 nsec was found to be sufficiently short adequately to register the motion at large radii, but too long to allow study of the final compression stage.

The current sheath (skin-layer) has a complex structure which is related to the high conductivity behind the shock wave front, and the accelerated motion of the magnetic piston, leading to a continuous "compression" of the frozen-in magnetic field. The electric field in the skin-layer is related to the radial motion of the current carrying layer, and is essentially of an inductive character. Neglecting ohmic resistance, the strength of the longitudinal electric field at the pinch boundary will be equal to V_r/cH_φ . At a velocity of $(2 - 4) \times 10^7$ cm/sec the energy of the electrons accelerated in this field is sufficient to give rise to intense X-ray emission. The hardness of the radiation due to the inverse dependence on the pinch radius during the final compression stages, reaches a value of several hundred kilo-electron volts. Here it is necessary to bear in mind that there is some decrease of the voltage at the discharge gap due to the term $L\frac{dI}{dt}$, (L being the inductance of the pinch, $dI/dt < 0$ at this phase of the discharge). The rapid voltage increase during compression leads to formation of a secondary breakdown which shunts the discharge gap (a peculiar internal crowbar). This makes it impossible to measure the voltage which continues to rise in the pinch constricting itself in the central region of the chamber.

Under certain discharge conditions the velocity of the plasma sheath along the electrode surface could be measured by a new technique, based on recording the X-ray bremsstrahlung. For this purpose the central part of the positive electrode was built up of alternate copper and aluminium rings 0.5 cm wide forming a periodic structure of 1 cm pitch. During the motion of the current layer the intensity of the bremsstrahlung is modulated due to the different Z for aluminium and copper. Oscillographic records of the signals, obtained from a photomultiplier with a plastic scintillator arranged above the vessel, are reproduced in Figs.6 and 7, and correspond to sheath velocities of 1 and 3×10^7 cm/sec respectively. The intensity of the X-ray emission from the electrode is fairly high. When the focus of compression is located immediately at the electrode surface, integral fluxes in excess of 10^{14} quanta per pulse were measured. The X-ray yield increases as the initial pressure in the chamber decreases. For the neutron yield the opposite relationship is found. The intensity of the neutron radiation reaches a maximum at $p = 1.2$ Torr, whereas the X-ray intensity at this pressure is several times smaller compared with its value at $p = 0.5$ Torr. As the pressure decreases the hardness of the X-ray quanta

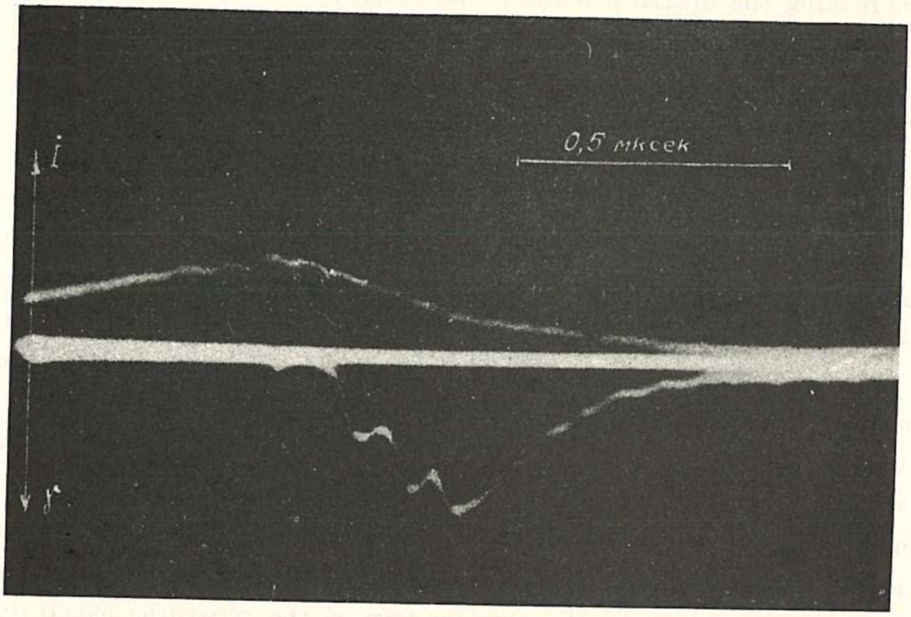

Fig. 6

(CLM-Trans 7)

X-ray emission from electrode, modulated by motion of current sheath (sheath velocity 10^7 cm/sec)

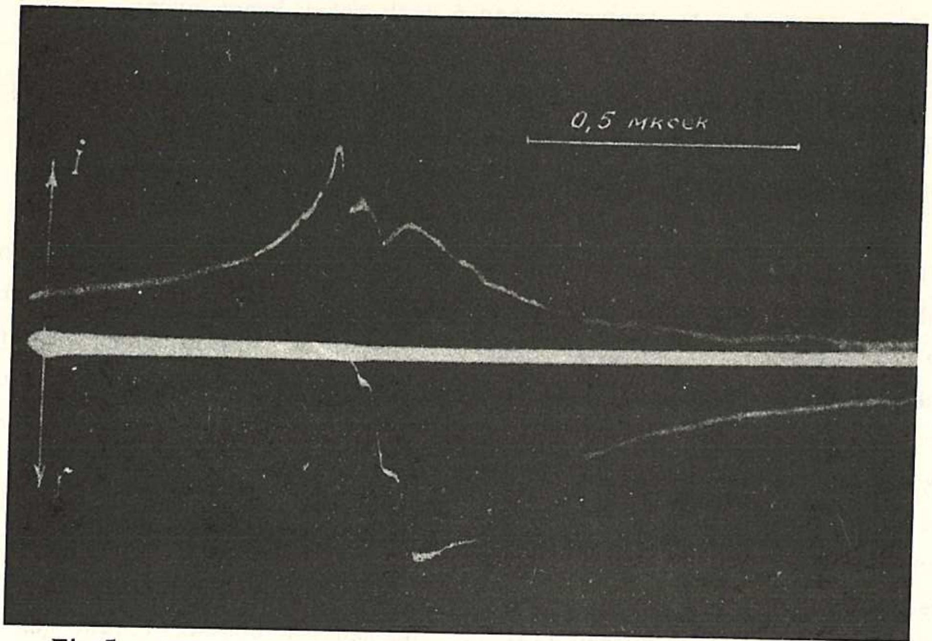

Fig. 7

(CLM-Trans 7)

X-ray emission from electrode, modulated by motion of current sheath (sheath velocity 3×10^7 cm/sec)

increases. Thus, the mean hardness at $p = 1$ Torr and 0.7 Torr is 125 keV and 230 keV respectively. If a cavity is made in the central part of the anode (see reference (1)) thereby increasing the distance between the discharge focus and the metal surface, the intensity of the hard X-ray emission decreases by several orders. It would seem that in this case the energy of the fast electrons is converted into magnetic bremsstrahlung.

The smallest size of the plasma region corresponding to a maximum compression was determined, as in reference (1) and (3), by means of a pinhole camera. The diameter of the region emitting soft X-ray quanta was found to be less than 0.6 mm, which is similar to the earlier values. On those rare occasions when the shadow photographs were obtained at the "stationary" moment of compression the region bounded by the electron density gradient does not exceed 1 mm. A small (~2% particles) addition of xenon to the deuterium considerably increases the intensity of the soft X-ray emission from the volume as recorded by the pinhole camera. By contrast to the discharges in cylindrical chambers[4,5] where a few tenths of a per cent of oxygen, argon or xenon suppressed the neutron yield to the background value, in a discharge of the present type one usually observes even an increase of the yield by several times. This appears to be related to the increase of the final velocity of convergence due to the slowing down of the remaining particles of the sheath in an upward and lateral direction. However, the increase in the neutron yield does not contradict L.A. Artsimovich's suggestion that there may be an additional increase of the deuteron temperature due to energy exchange with heavy xenon atoms.

The high intensity and great stability of the neutron yield in conjunction with the satisfactory localisation in space allowed measurements of the angular and energy distribution of the neutrons to be made.

If there is an angular dependence of the energy spectrum of the neutrons, then it must imply a predominant direction of the motion of the fast deuterons participating in the $D(d,n)He^3$ reaction. The technique generally used for analysing the spectra is by measuring the track lengths of the recoil protons in thick nuclear emulsions[6]. The presence of a shift in the velocity of the reaction products (in particular, the neutrons) may be verified by using time-of-flight analysis. Two photomultipliers with plastic scintillators were arranged so that one was situated exactly at the axis on the cathode side at a distance of 15.15 metres, the other in the equatorial plane of the chamber at the same distance. Measures were taken for protection from scattered neutrons and γ-quanta. The direct X-ray emission was attenuated by a lead filter. The neutron time-of-flight was about 0.7 μsec, separated by a large margin from the X-ray and neutron pulses on the oscillograms. For a total neutron yield of 2×10^9, the scintillators with these dimensions and at this position produced a light flash due to approximately 10^2 recoil protons. The accuracy in measuring the different flight times made it possible to detect a shift in the neutron velocities of up to 1.5% or a variation of the neutron energy by about 3% (74 keV).

The recordings of the neutron pulses showed that among a statistically large number of experiments a velocity shift of the neutrons was sometimes observed in an axial direction (Fig.8a). The maximum shift measured from either the displacement of the maximum or the shift of the leading edge of the pulse corresponds to a variation of the neutron energy $\Delta E_n \simeq 280$ keV. Generally the shift is much smaller and it often falls outside the limit of accuracy of the measurement (Fig.8b). For the whole group of experimental data the energy E_d of the accelerated deuterons calculated by considering the conventional "target" model of the (D-D) reactions lies within the limits of 5-65 keV. When taking into account that in the expression for (σv) the deuteron energy enters into the exponent, the neutron yield recorded in these cases should have varied by approximately two orders. Experimentally, however, the fluctuations of the neutron count are practically independent of the shift in the neutron velocity. At the same time the neutron yield is directly related to the final radial velocity (Figs.3 and 4). The appearance of the shift in the neutron velocity is well correlated only with the increase in the hard X-ray emission (compare the first pulse of Figs.8a and 8b).

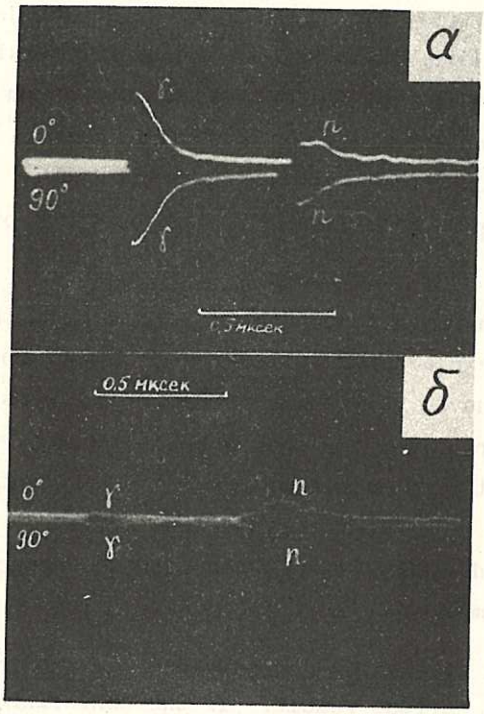

Fig. 8 (CLM-Trans 7)
Longitudinal and transverse X-ray and neutron emission (a) large velocity anisotropy (2.8×10^9 neutrons); (b) negligible velocity anisotropy (2.2×10^9 neutrons/pulse)

The angular distribution of the neutron intensity in the laboratory system of coordinates (target model) is made up of the anisotropy in the differential cross section in the centre of mass system and of the transformation of the solid angles during the transition from the moving to the fixed system. For the measured maximum deuteron energy $E_d \simeq 70$ keV the intensity in the axial direction should exceed by about 60% the neutron radiation intensity in the transverse direction. Two identical β-counters, determining the artificial radioactivity of silver, were placed at a distance of 56 $\pm$ 0.5 cm from the centre of the positive electrode surface. In this case also the counters were shielded from the scattered radiation. In a series of several hundred measurements complete isotropy in the intensity of the absorbed neutron radiation was found (with an accuracy better than 5%).

These experimental observations can be accounted for by considering, instead of the traditional "target" model of the reactions, a moving "boiler" model. In the former case a deuteron at rest is struck by an accelerated particle with energy E_d. The neutron energy E_n measured in the direction of acceleration is determined by the value of E_d, which also enters into the expression for the anisotropy in the intensity:

$$\sqrt{E\alpha} = \sqrt{3(2E_n - Q} - \sqrt{2E_n} \qquad \ldots (1)$$

In this expression $Q = 3.25$ MeV which is the energy liberated in the reaction $D(d,n)He^3$.

The special features of the second model will be clear by considering the following simple picture: the interaction between two deuterons in the centre of mass system is determined by their thermal energy T_i, and the total system moves with a velocity corresponding to the energy E_d' for each deuteron. Then we have

$$\sqrt{E_\alpha'} = \sqrt{2E_n} - \sqrt{{}^3/_2\, Q} \qquad \ldots (2)$$

It is easily seen that in the second case the same shift in the neutron energy is produced by considerably smaller energies E_d'. A comparison of these two models calculated from (1) and (2) is shown in the following table:

ΔE_n	E_d	E_d'
100 keV	7.5 keV	2 keV
200 keV	28 keV	7.5 keV
300 keV	64 keV	17 keV

ΔE_n is defined as the difference between the neutron energies measured in, and perpendicularly to, the direction of "acceleration".

In the moving "boiler" model only the term containing the transformation of the solid angles enters into the calculation of the anisotropy. For $E_d' = 20$ keV the intensity difference is of the order of several per cent. (The anisotropy in the differential cross sections will be negligibly small, i.e. is determined by T_i, for which was assumed $T_i \ll E_d'$. On the other hand, when not considering two particles but a "boiler" then, even when $T_i \sim E_d'$, the anisotropy vanishes due to the randomness of the collisions). From such a scheme it follows logically that the integral neutron yield is independent of E_d', i.e. of the velocity of the "boiler".

To make the moving "boiler" model compatible with the effects taking place during the convergence of the current sheath it is necessary to explain the collective motion of the plasma focus along the axis. This motion may occur due to very large pressure gradients along the axis in the case of a non-cylindrical constriction, and should be enhanced by the conical nature of the implosion. In some cases it is possible to observe experimentally the consequences of the impact of the plasma jet on the upper lid of the chamber (cathode). The effect of the jet is weakened if the distance between the cathode surface and the central position of the focus is large (7-8 cm).

The impact of a plasma with large energy content against a metal surface located in the immediate vicinity of the focus leads to a highly curious result. If the convergence of the discharge takes place close to the anode whose central portion is in the form of a plate of reduced thickness, one observes damage* to the material on the outer side of the electrode.

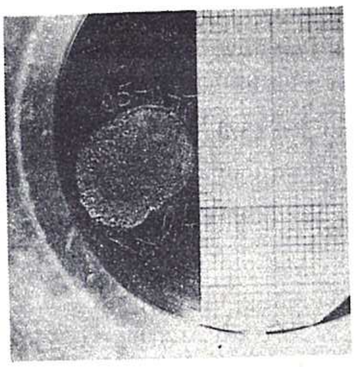

Fig. 9 (CLM-Trans 7)
Photograph of electrode damage
(verb : rear-end splitting-off)

Thus, on a 6 mm Dural plate one observes a damage area of approximately 12 mm dia. and depth 0.6 mm (Fig. 9). The duration of the pressure pulse causing the damage (about 0.1 μsec) is determined from the depth of the damage and the velocity of sound in the metal. The amplitude of the pressure can be estimated from the pulse strength of Dural ($\sim 8\times10^3$ kg/cm^2) taking into account the geometrical factor which leads to a reduction in pressure in the ratio of the damage area to the area of contact with the compression focus (a near-spherical

* Verbatim: "rear-end splitting-off".

wave propagates in the metal). This ratio exceeds 10^2 when assuming a pinch diameter of 1 mm. Under these assumptions the plasma pressure at the instant of maximum compression must be greater than 10^6 atmospheres, which corresponds to an energy content of roughly 100 kJ/cm^{-3}, or $nT \simeq 6 \times 10^{23}$ eV cm^{-3}. More exact calculations, using experiments to determine the velocity of the removed material, give $nT \simeq 10^{24}$ eV cm^{-3}. (The pulse pressure from the electron impact, calculated from the intensity of the hard x-radiation, can be neglected in this case).

The magnetic field necessary to balance the plasma pressure must be of the order of (3-5) $\times 10^6$G. Such a magnetic field, taking a current at the instant of convergence of about 700 kA, corresponds to pinch radii smaller than 0.5 mm. The existence in the discharge of regions with a magnetic field of this magnitude requires verification by some special method for the direct measurement of the fields, but is not inconsistent with the minimum dimensions of the focus region as determined by the pinhole camera and from the shadow photographs. At such small radii the current density attains a value larger than $10^8 A/cm^2$ and so the significant contribution made by joule heating towards the energy content of the pinch becomes a very real effect.

The special measurements of the temperature made in reference (1) and (3) were not repeated in the present case; as followed from the radial velocity, it was of the same order as, or slightly higher than, these. At a temperature $T_i = T_e = (1-3)$ keV, the above energy content of the plasma corresponds to a density $n_i = n_e = (1-3) \times 10^{20}$ cm^{-3} and ensures neutron yields up to 10^{10} neutrons/pulse. Consistent yields of $10^9 - 10^{10}$ at an emission time of $(0.1 - 0.3) \times 10^{-6}$ sec were observed in the experiments described here.

The authors would like to take this pleasant opportunity to express their gratitude to L.A. Artsimovich, V.S. Imshennik, B.I. Kogan and Yu.A. Kolesnikov for frequent fruitful discussions and critical comments.

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