

Determination of Temperature in a Toroidal Theta Pinch Discharge with an Image Converter Camera*

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With an image converter camera, developed at the Instituut voor Plasma-Fysica, streak pictures have been made of toroidal Θ -pinch discharges in helium at pressures ranging from 0.01 to 0.06 torr. The discharges are produced by a capacitor bank of 2.5 kJ. From the pictures the acceleration of the outward drifting plasma column and the drift time (1 to 2 μ s) have been measured. From these quantities the mean plasma temperature after the compression has been determined. The temperature depends on the pressure and varies from about 5×10^5 °K at 0.01 torr to 10^5 °K at 0.06 torr. These results are compared with temperatures calculated from the irreversible heating during the compression. From spectroscopical measurements of the intensities of He II $\lambda=4686$ Å and He I $\lambda=5015$ Å the electron temperature is estimated and the assumption of complete ionization is checked.

In the course of experimental work on various pinch configurations, e. g. alternating pinches¹ and screw pinches², a study of the toroidal Θ -pinch³ has been made as this discharge configuration might be used as an initial stage for a more complicated configuration.

It is well-known that the Θ -pinch in toroidal geometry cannot be in equilibrium because of the inhomogeneous B_z -field. The outward motion limits the confinement time, but gives on the other hand a method to determine the mean temperature since the outward acceleration is proportional to the temperature³⁻⁵.

In the measurements described in this paper the outward acceleration, and thus the temperature, is determined from streak pictures. The temperatures resulting from these drift measurements are compared with values calculated from the irreversible heating during the compression.

1. Experimental Arrangement^{1, 3}

The experiments are carried out in a quartz torus with major and minor diameters of $2R=0.32$ and $2r_1=0.08$ m respectively. The torus is surrounded by metal shells. The gaps between the shells are covered

with overlapping metal strips. Around the tube two helical coils with opposite pitch are wound, each consisting of 10 parallel wires making 4 turns in the Θ -direction and one in the z -direction. Each coil is connected with a 7.5 μ F, 18 kV capacitor by a low-inductance plate system with a built-in triggered spark gap. In case of a Θ -pinch the spark gaps are fired simultaneously; the frequency of the discharge is 90 kHz. The torus is shown in Fig. 1. One of the strips covering the

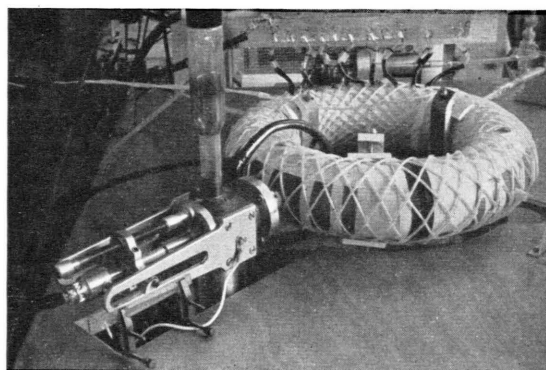


Fig. 1. Torus and helical windings.

azimuthal gaps between the metal shells has two rows of holes ("pepperpot") and acts as the slit through which the streak pictures are made (see Fig. 1). The pictures are taken with a 45° mirror, so that plasma motions in the equatorial plane can be seen.

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¹ P. C. T. VAN DER LAAN and L. H. TH. RIETJENS, Nuclear Fusion Suppl. Part 2, 693 [1962].

² L. H. TH. RIETJENS, P. C. T. VAN DER LAAN, and C. BOBELDIJK, Bull. Amer. Phys. Soc. (II) 9, 335 [1964].

³ P. C. T. VAN DER LAAN, Rijnhuizen Report 64—16 [1964].

⁴ P. C. T. VAN DER LAAN, Plasma Physics (J. Nucl. Energy, Part C) 6, 559 [1964].

⁵ U. GROSSMANN-DOERTH, W. LOTZ, F. RAU, E. REMY, and G. WOLF, Laborbericht Max-Planck-Institut PMI-PA-9/63 (2nd Ed., 1964).



2. Camera⁶

The image converter camera, developed at the Instituut voor Plasma-Fysica, can be used both as a streak camera with a writing speed, adjustable in steps from 0.5 to 25 mm per microsecond, and as a framing camera (1 or 2 pictures) with an exposure time, adjustable from 0.2 to 100 microseconds. The delay time after triggering and the interval between two frames can be varied from 0.1 to 100 μ s. The linearity of the writing speed is checked with the aid of two sparks, which are fired with a certain delay. The light of the sparks is both photographed with the image converter and measured by a photomultiplier (see Fig. 2). The departure from linearity is less than 2% for the writing speeds 5 and 10 mm per microsecond.

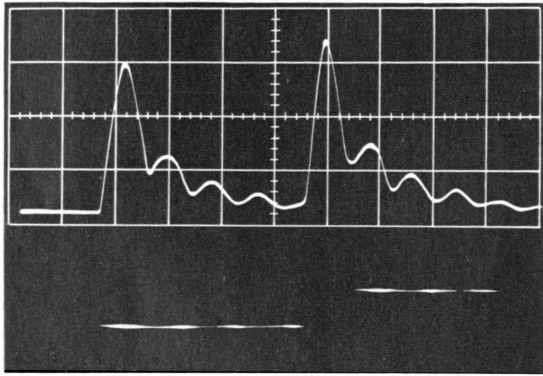


Fig. 2. Streak picture of two sparks taken with the image converter (writing speed 10 mm/ μ s) compared with an oscillogram of the emitted light (time scale 0.5 μ s/div.).

3. Drift Measurements

The measurements have been made on a discharge in helium, preceded by a pre-ionizing rf pulse; an additional pre-discharge has been used for the measurements in the first half period. Typical results of streak pictures at several pressures are shown in Figs. 3 and 4*. From the pictures it can be seen that after the compression the plasma column shows radial oscillations and an outward motion, which is faster at lower pressures.

A theoretical description of the motion of a plasma column in a curved magnetic field is given in Refs. 3-5. On the basis of a magnetohydrodynamic model it can be shown that the outward acceleration, a , is given by:

$$a = 2 k T (1 + Z) / (m_i R) \quad (1)$$

where k is BOLTZMANN's constant, Z is the effective charge number of the ions, m_i is the ion mass and T is the mean of the ion temperature, T_i , and the electron temperature, T_e , defined by:

$$(1 + Z)T = T_i + Z T_e. \quad (2)$$

All the temperatures are averaged over the cross section of the plasma column.

Formula (1) is valid for an arbitrary current and field distribution and shape of the cross section of the plasma column with the only assumption that no appreciable transverse accelerations are present. In case T is constant during the time in which the column moves over a distance equal to the tube radius r_1 , the drift time, t_D , can be found from:

$$t_D = \{m_i R r_1 / [k T (1 + Z)]\}^{1/2} \quad (3)$$

The temperature T can be found both from a and t_D . The acceleration a is given by the second time derivative of the curve which represents the motion of the centre of the plasma column on the streak picture. In practice this curve was approximated by a parabola, which gives a time-averaged value for the acceleration and thus for the temperature.

It is also possible to derive a time-averaged temperature from the drift time; the time in which the centre of the column moves to the wall of the torus. If we assume that the drift starts at the end of the compression stage, the temperature found from equation (3) will be too high, because the initial outward velocity of the column is neglected. On the other hand, if the drift is assumed to begin at the start of the compression, we will find a too low temperature since during the compression the temperature is low. The theory is not well applicable during the compression stage since large transverse accelerations are present. From the two values of t_D an interval is found, which should include the temperature of the pinched column.

In Fig. 5 the temperatures are plotted as a function of the pressure. A pre-discharge was used for the measurements in the first half period; for the measurements in the second half period only rf pre-ionization was used. Complete ionization of the helium has been assumed ($Z = 2$).

To explain the measured temperatures and the variation of the temperature with pressure, the energy gained by the ions in the first compression

⁶ A. M. VAN INGEN and A. B. STERK, Rijnhuizen Technisch Rapport TEC 63/003 [1963].

* Fig. 3, 4 see page 196 a.

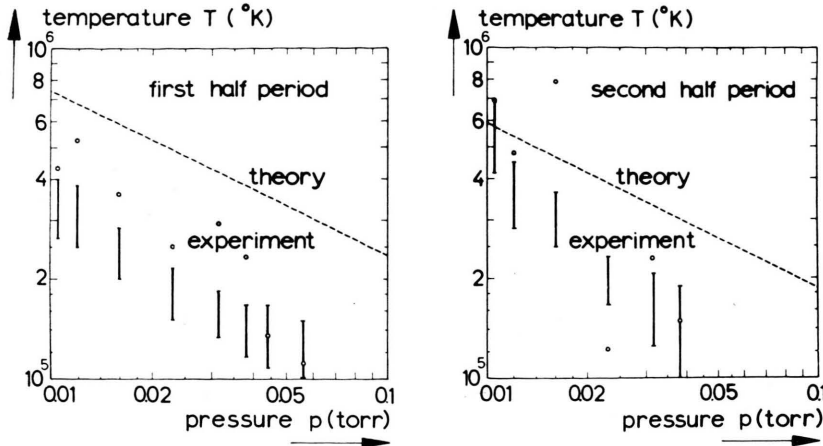


Fig. 5. Temperatures of a Θ -pinch in helium as a function of pressure. From a measurement of either the acceleration (circles) or the drift time (intervals) a value of $T_i + Z T_e$ averaged over the cross section and an interval of time, is derived. The theoretical line ($T \propto p^{-1/2}$) gives the temperature attained in the compression stage calculated on the basis of the free particle model.

has been calculated. If the "free particle model" is used, the ion temperature, after thermalization in the column is, according to KEVER⁷ (in GIORGI units):

$$T_i = \frac{4 r_1 (dB/dt)}{9 k} \left(\frac{m_i}{n_{i0} \mu_0} \right)^{1/2} \quad (4)$$

where dB/dt is the rate of rise of the vacuum magnetic field (in the experiment $dB/dt = 4.6 \times 10^5$ Wb pro m^2 sec) and n_{i0} is the initial ion density. The temperature found from equation (4) has been plotted in Fig. 5 with T equal to $\frac{1}{3} T_i$ ($Z=2$). Since the outward acceleration is proportional to $T_i + Z T_e$, the exchange of energy between ions and electrons does not influence the value of a . A calculation of the "equipartition time" given by SPITZER⁸ shows that the ion and electron temperatures can be expected to be equal; however, at low pressures (< 0.01 torr) the equipartition time increases to about $1 \mu s$.

As can be seen from Fig. 5 the predicted variation of the temperature with pressure ($T \propto p^{-1/2}$) is in reasonable agreement with the measured temperature variation. In absolute value the measured temperatures are too low; if radiation losses are taken into account a better agreement might be expected. Anyway, the results indicate that an important fraction of the kinetic energy of the plasma is supplied by the irreversible heating during the compression.

4. Spectroscopical Measurements

The spectral lines He I $\lambda = 5015 \text{ \AA}$ and He II $\lambda = 4686 \text{ \AA}$ have been measured at a pressure of 0.023 torr. Shortly after the compression in the

second half period the intensity of He II $\lambda = 4686 \text{ \AA}$ reaches a maximum value and thereafter it drops off with a decay time of about $0.3 \mu s$ until a quasi-stationary value. The disappearance of the ionic light suggests that singly ionized helium is ionized in about $0.3 \mu s$. Assuming the electron density $n_e = 10^{16} \text{ cm}^{-3}$ and taking into account step-wise excitation this would correspond with $T_e \cong 2 \times 10^5 \text{ }^\circ\text{K}$. When He II $\lambda = 4686 \text{ \AA}$ has reached its quasi-stationary value, the intensity ratio of He I $\lambda = 5015 \text{ \AA}$ and He II $\lambda = 4686 \text{ \AA}$ is 0.04 which, for $n_e = 10^{16} \text{ cm}^{-3}$ gives $T_e \cong 0.4 \times 10^5 \text{ }^\circ\text{K}$ according to calculations⁹ for a bounded isothermal and homogeneous helium plasma in a steady state. This last value is probably a lower estimate due to the presence of a region of cold neutral helium gas around the plasma column. For $n_e = 10^{16} \text{ cm}^{-3}$ the same calculations yield a percentage of doubly ionized helium, that varies from 89% for $T_e = 0.64 \times 10^5 \text{ }^\circ\text{K}$ to 98% for $T_e = 1.3 \times 10^5 \text{ }^\circ\text{K}$ and thus Z from 1.9 to 2, so that the assumption $Z=2$ is quite reasonable.

Conclusions

The analysis of the outward drift in a toroidal Θ -pinch yields values of the mean temperature of the plasma. For discharges in helium these temperatures are compared with values calculated from the irreversible heating during the compression according to the free particle model. An agreement within about a factor two is obtained.

The assumption of complete ionization is confirmed by spectroscopical measurements.

⁸ L. SPITZER, Physics of fully ionized Gases, 2nd Ed., Interscience, New York 1962, p. 135.

⁷ H. KEVER, Nuclear Fusion Suppl. Part 2, 613 [1962].

⁹ R. MEWE, to be published.

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Interferometrische Untersuchungen an elektromagnetisch beschleunigten Stoßwellen

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The phenomena of shock waves generated electromagnetically in T-tubes were studied with a MACH-ZEHNDER interferometer. The measurements were made in hydrogen at initial pressures from 2.5 to 10 mm Hg. Shock velocity varied between Mach 6 and Mach 20. It was found that there are two fronts: the luminosity front due to the discharge plasma and the non-luminous shock front in front of this. The distance between the shock front and the luminosity front decreases with increasing velocity. At $v_s \triangleq$ Mach 20 the luminosity front reaches the shock front. Shock fronts are always plane. The density decreases directly behind the shock front. The shock waves thus formed cannot be described with the RANKINE-HUGONIOT equations. At small velocities, the density jump is 6, at higher velocities the gas is dissociated. The refractive index of atomic hydrogen can be measured. Simultaneously the selection of the computational method used to describe the shock conditions in hydrogen can be justified. Precursor effects have no influence, relaxations could not be seen.

In verschiedenen Arbeiten über elektromagnetische Stoßwellen kommen die Autoren zu unterschiedlichen Erklärungen der auftretenden Phänomene. Einige Veröffentlichungen besagen, daß das beobachtete Plasma im wesentlichen aus stoßwellen-aufgeheiztem Gas besteht^{1,2}. Eventuelle Abweichungen von den durch die RANKINE-HUGONIOT-Gleichungen bestimmten Plasmametern werden dem Einfluß von Precursor- oder Relaxationseffekten zugeschrieben. Andere Autoren beschreiben das leuchtende Plasma als im Elektrodenraum durch die Entladung aufgeheiztes Gas³⁻⁶. Durch elektromagnetische Kräfte wird es aus dem Elektrodenraum herausgeschleudert und läuft dann in Verbindung mit einer Stoßwelle durch das Rohr. Dabei wird das Entladungsplasma manchmal als „Kolben“ aufgefaßt, der das im Rohr befindliche Gas vor sich herschiebt. Abweichungen der Plasmagrößen von den durch die stationäre

RANKINE-HUGONIOT-Theorie berechneten Werten werden z. B. bei BREDERLOW⁴ damit erklärt, daß der Kolben das Gas nicht vollständig aufammelt, also teilweise durchlässig ist.

Wie BREDERLOW und andere, so konnte auch CORMACK⁷ bei seinen Untersuchungen feststellen, daß dem leuchtenden Entladungsplasma eine nichtleuchtende Erscheinung vorauseilt, die als Stoßwelle gedeutet werden sollte. Er fand ferner, daß die Leuchterscheinungen in dem von ihm untersuchten Bereich nur vom Entladungsplasma herrühren, und daß die Leuchtfrent sehr diffus und nicht reproduzierbar ist.

Die im folgenden beschriebenen interferometrischen Messungen sollten die CORMACKSche Arbeit fortsetzen und klären, ob es sich bei diesen nichtleuchtenden „Erscheinungen“ tatsächlich um Stoßfronten handelt. Darüberhinaus sollten diese Phänomene auch quantitativ erfaßt werden.

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³ M. CLOUPEAU, Phys. Fluids **6**, 679 [1963].

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⁵ P. JEANMAIRE, H. KLINGENBERG u. H. REICHENBACH, Z. Naturforschg. **18 a**, 318 [1963].

⁶ H. F. BERG, K. L. ECKERLE, R. W. BURRIS u. W. L. WEISE, Astrophys. J. **139**, 751 [1964].

⁷ G. D. CORMACK, Z. Naturforschg. **19 a**, 934 [1964].