THE DETERMINATION OF DEUTERIUM PLASMA DENSITY BY MEANS OF A TRITIUM ION BEAM

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A method is developed for probing a deuterium plasma with a tritium beam; neutrons from the T+D reaction are registered. The method is applied to the investigation of density changes in the plasma of a toroidal discharge within a weak magnetic field; the initial density of the working gas is found to increase. The experiments indicate that the observed increase of plasma density is due to gas liberated from the chamber walls during the discharge.

ONE of the most important plasma parameters, determining its properties to a great extent, is the ion density. However, most of the present methods of studying plasmas are limited, often determining plasma densities only indirectly and usually within a very limited range. New methods of studying plasmas are therefore needed.

If a beam of accelerated ions or atoms traverses a plasma, and the secondary particles produced in collisions with the plasma particles are registered, the plasma density along the beam path can be determined. A first step in this direction is the utilization of nuclear reactions to determine the total density of plasma nuclei (the combined density of ions and neutral particles). Such measurements are of decided interest in apparatus where density changes of a highly ionized plasma can be expected. By combining the use of nuclear reactions with other methods (such as charge exchange of ion beams etc) information can be obtained regarding the degree of ionization and the component densities of a plasma. The present article is concerned only with the utilization of nuclear reactions to determine the total density of nuclei in a deuterium plasma.

DESCRIPTION OF THE METHOD

The most suitable reaction for investigating a deuterium plasma is $D(t,n)He^4$, which has a maximum cross section ~ 5 barns for ~ 160-keV tritons. In this reaction ~ 14-MeV neutrons and ~ 3.5-MeV α particles are produced. It was early decided to utilize the neutrons for the purpose of registering the reaction. This method affords the advantage that the detector can be placed outside the housing of the plasma vessel. The high energy of neutrons from the T+D reaction makes it easy to distinguish them from various forms of noise and background, including neutrons from the D+D reaction.

The experimental arrangement is shown in Fig. 1. A narrow beam of accelerated tritium ions or atoms traverses a vessel filled with deuterium plasma, whose density is indicated by the number of neutrons formed in the $D(t,n)He^4$ reaction. Of course, only the mean density along the entire beam path is determined in this manner; the density distribution can be obtained by shifting the position of the beam throughout the cross section of the plasma.

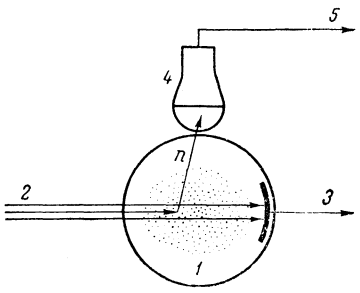

FIG. 1. Experimental arrangement. 1 – deuterium plasma, 2 – triton ion beam, 3 – measurement of beam current, 4 – neutron detector, 5 – to counter.

The number of registered neutrons is given by

$$N = knl\sigma\eta\Omega J\tau,$$

where n is the mean density of deuterium nuclei along the beam path, l is the length of the beam path in the plasma, σ is the reaction cross section, η is the detector efficiency, Ω is a geometrical factor, J is the triton current of the beam, τ is the time during which neutrons are registered, and k is a proportionality factor.

In our apparatus $l = 20$ cm, $\tau = 600$ μsec, $\eta\Omega = 10^{-3}$, and n is of the order 10^{14} cm^{-3}. With these parameters and with 160-keV tritons ($\sigma = 5 \times 10^{-24}$ cm^2) ~ 40 neutrons/mA are regis-

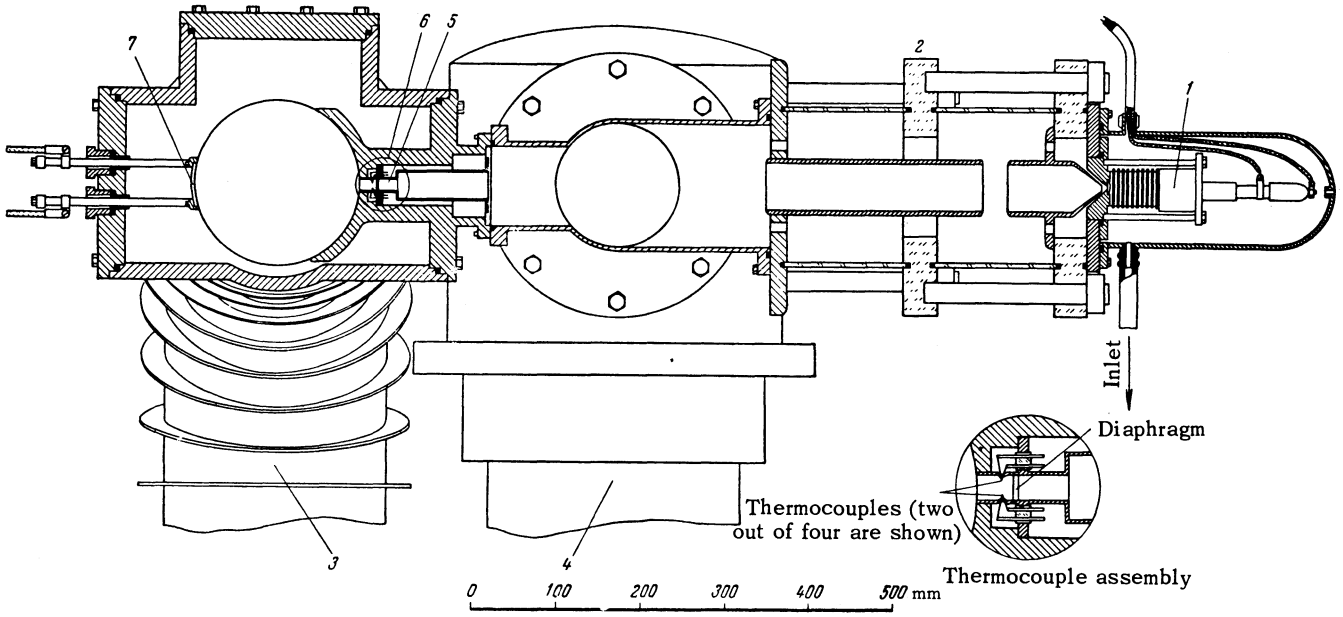

FIG. 2. Cross section of apparatus. 1 – source, 2 – accelerating tube, 3 – discharge chamber, 4 – diffusion pump, 5 – separating channel, 6 – thermocouple assembly, 7 – current collector.

tered in each pulse (during the time τ). The data indicate that for a 1-mA triton current the statistical accuracy of the mean density measurement is about 15—20% for a single pulse.

EXPERIMENTAL APPARATUS

The technique of probing a plasma with a beam of accelerated ions was developed using a toroidal discharge chamber with a weak longitudinal magnetic field. The principal diameter of the torus was 750 mm, the inside diameter of the discharge chamber was ~ 210 mm, the longitudinal magnetic field was 200—700 Oe, the maximum energy stored in the battery of condensers was 35 kilojoules, and the maximum discharge current was 100 kA.

Figure 2 is a cross section of the main part of the apparatus. The accelerating tube 2 (with the ion source 1) is connected to one of the side ports of the discharge chamber 3. The distance between the center of the discharge chamber and the emission aperture of the ion source was about one meter. The accelerating tube was evacuated by a VA-2000 diffusion unit 4. The toroidal discharge chamber was evacuated independently; between this chamber and the accelerating tube there was inserted a separating channel 5 with a diaphragm (channel length 40 mm, channel diameter 13 mm, and diaphragm diameter 10 mm) which provided for a pressure difference between the discharge chamber (~ 10^{-3} mm Hg) and the tube (~ 10^{-5} mm). The current was measured and the ion beam was adjusted by means of an assembly 6 of four thermocouples mounted in front of the channel exit to the discharge chamber.

Definite requirements are imposed on the ion source by the reaction $D(t,n)He^4$. For safety the tritium flow must be minimal. We investigated several types of pulsed tritium sources. A "titanium source"[1] utilizing tritium-saturated titanium disks was found to be most suitable. With this source the tritium ion current entering the toroidal discharge chamber (through the 10-mm diaphragm located one meter from the source) was about 10 mA; the tritium flow was ~ 5×10^{-4} cm^3 per pulse.

The control system provided for a delay between the triggering of the source and that of the discharge chamber. Neutrons were registered with a solid organic scintillator (~ 500 cm^3) and a FÉU-1B photomultiplier. The pulse-height discriminator registered neutrons from the T+D reaction, distinguishing them from possible neutrons arising in a D+D reaction. Also, by means of a time delay pulse selector[2] we registered on the oscilloscope screen a curve of the neutron yield vs. time (the time channel widths were 20, 60, and 120 μsec); the total number of neutrons during an ion pulse was also registered.

The resolving time of the circuit was ~ 50 nsec; this prevented counting losses in the most heavily loaded channels. As a control, the total number of neutrons was registered using a PS-10000 scaler with two additional sections that improved its re-

solving time to 0.16 μsec; the scaler was gated only during ion pulses.

It was necessary that the tritium beam, after traversing the discharge chamber, should strike a surface having no deuterium or tritium contamination; otherwise neutrons would be emitted from the surface. The utilized clean surface was a stainless steel collector 7 (Fig. 2) heated by an electric current which raised its temperature as high as ~ 1000°C. This collector was used for control measurements of the tritium ion beam current in the absence of discharges in the toroidal chamber.

As already stated, the determination of the plasma density required measurement of the tritium ion current in a beam traversing the plasma. In most instances we could confine ourselves to relative measurements of the current (even for absolute measurements of the deuterium plasma density). This was possible because the number of neutrons generated when the tritium ion beam passed through the plasma could be compared with the number of neutrons generated in the absence of a discharge within the plasma chamber; the static deuterium pressure in the chamber was measured very accurately.

The ion current was determined from the heating of a thermocouple junction placed in the path of the beam; in addition, the signal from the collector monitored the shape of the ion pulse. The control measurements showed that with a well-regulated and aged source both the heating of the junction and the shape of the ion pulses remain constant during a series of pulses.

A study of the composition of the ions emitted by the pulsed "titanium source" showed that the tritium ion content of the beam varies during a pulse, reaching an almost constant level about 500—1000 μsec after the start of the pulse. The triggering of the ion source and the initiation of the discharge in the toroidal chamber were separated by a corresponding delay.

TESTING OF APPARATUS

In order to test the operation of the entire apparatus we measured the neutron yield for various deuterium pressures in the toroidal chamber (without discharges). Figure 3 shows the number of registered neutrons (for a constant integral current in the ion beam pulses) as a function of the deuterium pressure in the chamber. The experimental points are the averages for ten pulses. The spread of the neutron count in separate pulses was

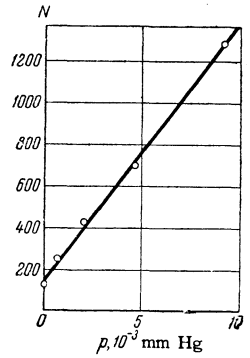

FIG. 3. Neutron yield against deuterium pressure.

~ 15%, somewhat exceeding the statistical spread. The pressure dependence of the neutron yield is linear, indicating regular operation of the apparatus. The straight line does not pass through the origin because some neutron background is present, mainly as a result of interaction between the tritium beam and the deuterium absorbed in the walls and in the collector. We checked the variation of the amount of deuterium absorbed in the toroidal chamber walls with both the number of preliminary hf ionization pulses and the number of pulsed main discharges.

Figure 4 shows the increase of the neutron background (without heating of the collector) as a function of the number of 1-sec hf ionization pulses, and also as a function of the number of the main discharges (discharge current 80 kA, longitudinal magnetic field 300 Oe, and pressure 2×10^{-3} mm).

The neutron yield following a single hf ionization pulse increases 2—3% over the neutron yield from the gas filling the chamber; following one of the main discharges the increase is ~ 10%. This indicates that the walls absorb 10% and 40%, respectively, of all deuterium in the working space before a discharge. It should be noted that these results pertain to the start of operation with deuterium following prolonged aging of the apparatus with hydrogen.

As already stated, in order to remove the absorbed gas the collector was heated to ~ 1000°C, thus practically eliminating the neutron background.

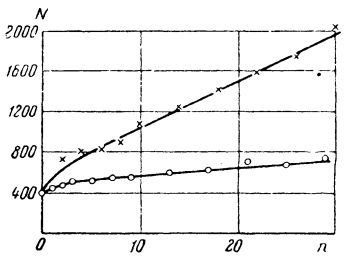

FIG. 4. Variation of the amount of deuterium absorbed by cold chamber walls: o – dependence on the number of hf ionization pulses; × – dependence on the number of discharges (N – number of neutrons; n – number of pulses).

MEASUREMENT OF DEUTERIUM PLASMA DENSITY

The deuterium plasma density was measured in the toroidal discharge chamber described above. The discharge duration in the chamber was ~ 600 μsec; the length of the current pulse from the ion source was ~ 2000 μsec. Discharge initiation in the chamber was delayed 500—1000 μsec after the beginning of the source-current pulse, thus providing for a maximum constant tritium ion flux. Measurements were made in the chamber when filled with deuterium and also, as a control, when filled with hydrogen. All measurements were performed alternately with and without discharges in the toroidal chamber. The screen of the dual-beam oscilloscope was photographed to register the neutron yield in 120-μsec time channels and the discharge current in the toroidal chamber.

A number of control runs were performed in order to confirm that the discharge in the toroidal chamber did not generate noise in the neutron-registering apparatus. In the first run γ quanta emitted by Co^{60} were registered both with a discharge in the toroidal chamber and without a discharge (with the ion source switched off). The corresponding oscillogram is seen in Fig. 5a, which shows that the γ count does not vary during a discharge; this indicates that the discharges did not affect the registering apparatus.

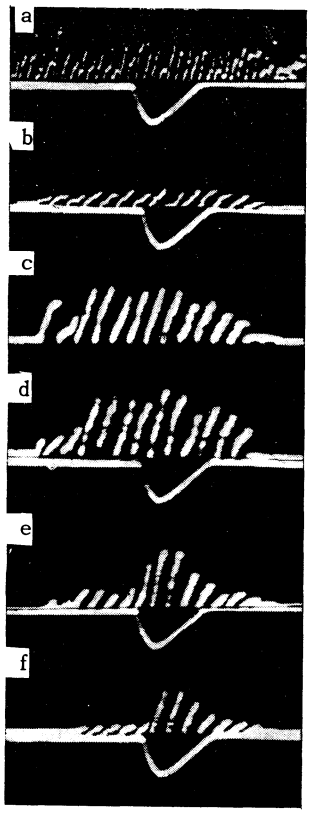

FIG. 5. Oscillograms. a – γ-quantum count, b-f – neutron yields under different operating conditions and discharge currents. The scale of the neutron yields is reduced to one-third in oscillograms e and f. The trace time was 2.5 msec.

In the second control run the registering apparatus was tested by operating the plasma apparatus with hydrogen following prolonged aging in a hydrogen atmosphere. The neutron yield, shown in oscillogram 5b, indicates that under these conditions the discharge has no appreciable effect on the yield of neutrons (which, as previously mentioned, result from the presence of deuterium and tritium in the chamber walls and in an incompletely outgassed collector plate).

Oscillogram 5c shows the neutron yield without a discharge when deuterium was admitted into the apparatus. In this case the neutron yield is determined mainly by the T+D reaction in gaseous deuterium in the chamber (with only a small background from the walls). Oscillogram 5d shows the neutron yield during one of the first discharges in deuterium (in a "clean chamber") following cleaning of the chamber by prolonged aging in hydrogen. In this case also the pattern of the neutron yield during discharges is not appreciably changed. Oscillogram 5e shows the neutron yield from a discharge in deuterium after 30 discharges had occurred. It is seen here that the neutron yield during the discharge (with subtraction of the background) is almost three times greater than the

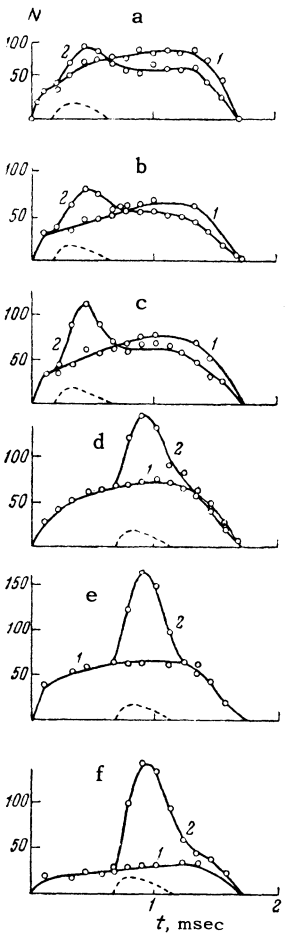

FIG. 6. Analysis of oscillograms. Solid curves – neutron yield in toroidal chamber: 1 – without discharge, 2 – with discharge. Dashed curves – discharge current.

yield from gaseous deuterium in the absence of a discharge (oscillogram 5c).

The analysis of the oscillograms represented by Fig. 6 shows the entire transition from 5c and 5d to 5e. Each graph is based on several successive measurements (curves 1 without discharges and curves 2 with discharges). The discharge count and the corresponding measurements began after several discharges in deuterium as soon as an increase of the neutron yield associated with a discharge became noticeable.

The neutron yield during a discharge increases continuously with the number of preceding discharges up to a total of 34 discharges; this is shown in Fig. 7. It should be noted that when the discharge chamber is operated with deuterium the neutron yield decreases immediately after a discharge compared with the yield in the absence of a discharge; this is especially clear in the oscillograms obtained with a delay of ~ 500 μsec between the starts of the current pulse and the discharge. In the operation with hydrogen the reverse occurs—following a discharge the neutron yield is somewhat greater than before; this appears in Figs. 5f and 6f, which show the neutron yield during a discharge in hydrogen following 34 discharges in deuterium. These graphs also show that the absolute increase of the neutron yield during a discharge in hydrogen agrees with the yield increase following discharges in deuterium (Figs. 5e and 6e).

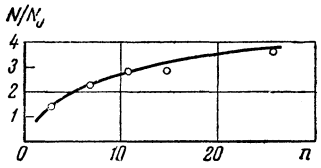

FIG. 7. Relative increase of neutron yield during discharge against the number of preceding discharges in deuterium.

In order to determine whether the increase of the neutron yield is associated with a shift of the ion beam during a discharge, which would make it impinge on an unheated wall that is increasingly contaminated with deuterium (from one discharge to the next), an experiment was performed with a neutral beam of fast tritium atoms. This neutral beam was produced by subjecting a tritium ion beam to charge transfer in a stream of air; residual ions were deflected by a magnet. The magnitude of the neutral atom flux, estimated from the reading of a point thermocouple and from the neutron background, was about 40% of the initial ion flux. Measurements with the neutral beam were performed with discharges in the toroidal chamber containing hydrogen following its operation with deuterium; the results are shown in

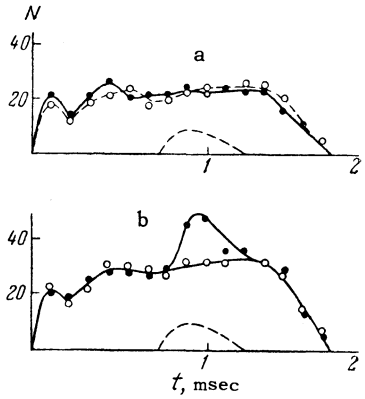

FIG. 8. Neutron yield from measurements with a neutral beam. o – without discharge, • – with discharge.

Fig. 8. In case a no air stream was used, there is no neutral beam, and background neutrons from the deflected ion beam are registered. In case b the ions undergo charge exchange in the air stream. The increase of the neutron yield during a discharge agrees quantitatively with the result obtained when an ion beam is used.

CONCLUSION

A technique has been developed for determining the density of a deuterium plasma by means of a tritium beam. The variation of the plasma density in the toroidal discharge chamber has been measured provisionally. The results indicate that the increase of the neutron yield during a discharge results from increased density of deuterium nuclei in the plasma along the ion beam path. At the start of the operation with deuterium, when the walls of the discharge chamber were "clean," i.e., not containing deuterium, the deuterium density was not increased during a discharge. This indicates the absence of appreciable (within experimental accuracy limits) compression of the plasma in the toroidal chamber during a discharge. In connection with subsequent discharges the walls absorb more and more deuterium, part of which enters the chamber during a discharge and thus increases the plasma density. At the end of a discharge a still larger amount of deuterium is driven into the walls; this accounts for the reduced neutron yield following a discharge. As a result, after a few tens of discharges the liberation of deuterium during a discharge increases the deuterium density several fold.

When a discharge now occurs in hydrogen, deuterium is liberated from the walls and replaced with hydrogen. A portion of the liberated deuterium remains in the chamber following a discharge; this accounts for the increased neutron yield following a discharge in hydrogen as compared with the neutron background.

These conclusions agree with data on the absorption of the working gas by the walls when a discharge occurs. The observed increase of deuterium density in the plasma during a discharge in the toroidal chamber can therefore not be attributed to compression of the plasma.

More detailed information regarding the dynamics of the processes associated with changes of plasma density must await the performance of similar experiments in which a plasma is probed at different points of the discharge-chamber cross section.

[1] Afanas'ev, Knyazyatov, and Fedorov, Atomnaya énergiya **13**, 135 (1962), Soviet J. Atomic Energy **13**, 734 (1963).

[2] V. G. Brovchenko and Yu. D. Molchanov, PTÉ No. 6, 74 (1961).

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