

STUDY OF PLASMA IN MAGO CHAMBER BY OWN NEUTRON RADIATION

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1. INTRODUCTION

Paper [1] was the first to publish results of research into plasma heating in plasma chamber MAGO obtained in experiments using explosive magnetic generators (EMG). This paper presents results of experimental research into MAGO chamber operation using DT and DD - reaction neutron spectra measurement with the time-of-flight method. A possible interpretation of obtained new results is also given.

OBJECT: The MAGO chamber used for the experiments is a fairly compact device (Fig.1): a hollow copper thick-wall cylinder 200 mm in inner diameter and 165 mm in length

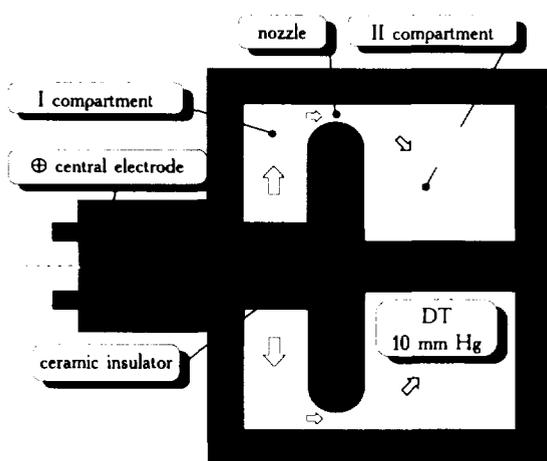


Fig. 1. Scheme of plasma chamber MAGO.

with a central electrode 60 mm in thickness separating the internal chamber space into two compartments (25 and 80 mm in height) connecting to each other with a narrow annular nozzle whose minimum width was 12 mm.

The vessel of the chamber with the central electrode constitutes a coaxial, short-circuited turn. The internal space of the chamber is filled with DT or DD - gas. At the chamber inlet the central electrode is separated from the vessel with ceramic insulator 20 mm in outer radius. Initial gas pressure in the chamber is 10-20 mm Hg. In the chamber initial magnetic field was preliminary created through gradual increase of electric current in

the short-circuited turn up to 1.5 - 2.2 million amperes. Then the current abruptly, during 1-3 microseconds, increased up to 8-10 MA. Our experiments used explosive magnetic current sources with a current pulse generation unit (the stored energy is up to - 10 MJ).

During the abrupt current growth, according to the theoretic model, in the first chamber compartment where the insulator is located volume gas discharge occurs. Under action of ponderomotive forces low-temperature plasma begins to flow out of the first chamber compartment to the second through the narrow nozzle. At the nozzle outlet the plasma flow becomes supersonic and at the second chamber inlet a collisionless shock wave is generated. It is in this wave that kinetic energy of the plasma flux is converted to energy of chaotic ion movement. Later on the plasma which is already heated descends to the central electrode and is compressed with magnetic field and heavy insulator vapors which follow the DT plasma. In the hot plasma thermonuclear reactions take place and stop in some time by virtue of hot plasma mixing with cold plasma and insulator vapors. In the chamber specially designed for the above-described process scheme $5 \cdot 10^{13}$ neutrons are obtained in a pulse of - 2 μ s duration.

In addition to these two parameters, the experimental data of the chamber involve information from current and light pickups, data of electron density obtained using

interferometry and data of plasma X radiation spectrum, there is the source image obtained in DT neutrons [1,2]. The neutron source is composed of two parts: 10% - the nozzle region; 90% - the central volume of the second chamber compartment. Mean energy of emitted neutrons in various directions is practically constant and close to 14.1 MeV.

2. RESEARCH TECHNIQUE

From the standpoint of plasma diagnostics, the MAGO chamber is not a very convenient device. The experiment is explosive, fragmental, the neutron source is voluminous, occupying practically the whole volume of the second chamber compartment; the neutron generation process duration, 2 μ s, does not allow to use verified measuring techniques both for pulsed and continuous systems.

Under these conditions it was suggested that plasma ion temperature should be measured using the differences in DT and DD - reaction rate dependencies on ion temperature.

Deuterium-tritium mixture of 50/50% ratio as a most productive in the number of generated neutrons was usually used in the high-temperature plasma experiments. The dominant reaction in this mixture is the D and T nuclei reaction, $D(T,n)He4+17.6$ MeV. DD and TT type reactions concurrently proceed, however, on the background of TD they are practically insignificant. Among the reactions attended with neutron radiation the reaction $D(D,n)He3+3.27$ MeV is the closest by reaction rate.¹ When plasma ion temperature is 3 keV the DD reaction rate is 128 times less than the DT rate. Taking into consideration less detector sensitivity to DD neutrons, on the oscillograms for equicomponent DT plasma the DD pulse amplitude appears 850 times lower than from DT neutrons. At this ratio in the DT 50/50% experiments the DD pulse is completely lost in scattered neutrons from the DT reaction and is practically invisible.

To secure the possibility of measurements, it was suggested that the ratio of the number of nuclei in the D and T - mixture should be changed in order to obtain *equal amplitudes* of pulses from DD and DT neutron detectors. Simultaneous DD and DT recording was intended to be made with scintillation plastic detectors with neutron pulse separation by time of flight.

Oscillograms with three pulses of approximately equal amplitudes from gamma quanta and DT and DD neutrons were expected in the experiment. The principal experiment result should have been the measured ratio of DT and DD pulse areas appropriately recalculated to the reaction rate ratio and, eventually, to plasma temperature.

A feature of the reaction rate-temperature ratio dependence used is its nonuniqueness. With increasing temperature the ratio increases, reaches its maximum at 14 keV and then decreases. Thus, the experiment may result in ambiguity. For example, when the measured ratio is 120 the temperature may be both 3 and 35 keV.

3. EXPERIMENT RESULTS

Fig. 2 gives the oscillogram obtained in the experiment. The experiment was made on DT mixture with the ratio of the number of nuclei, T:D, 1:991. The ratio error was 0.15%.

On the oscillogram: the first pulse is gamma; the second is DT neutrons, energy 14.1 MeV; the third is DD neutrons, energy 2.45 MeV.

The measured integral ratio of DT and DD reaction rates was 139.

¹ Hereinafter by the DD reaction rate is meant $\langle\sigma v\rangle_{dd}$ for the neutron channel, by the DT reaction rate $\langle\sigma v\rangle_{dt}$

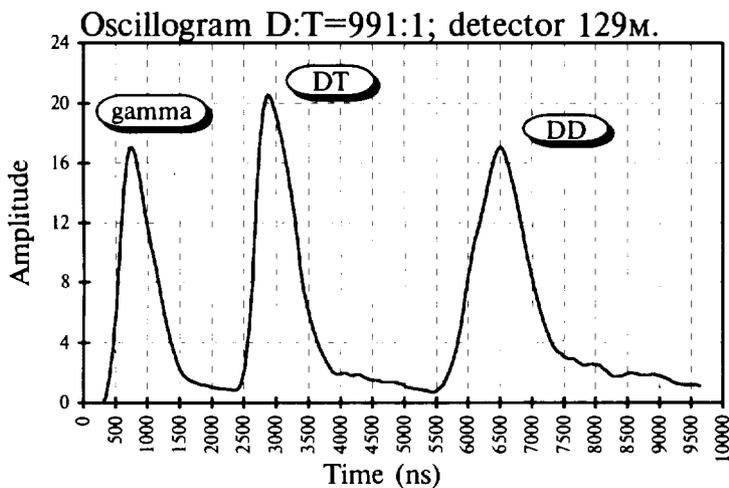


Fig. 2. Oscillogram obtained in the experiment with the nuclei ratio T:D of 1:991.

broadening. The hypothesis can be easily verified: transfer the gamma pulse to the time equal to the time of neutron delay relative to γ quanta on the base of 129 m and superpose this on the

Comparison DD and gamma by time of flight.

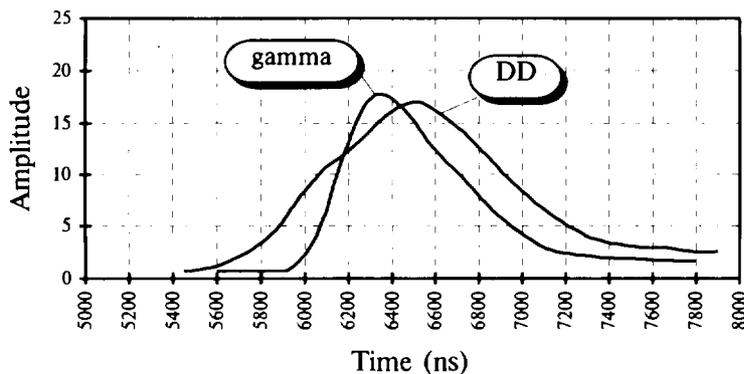


Fig. 3. Result of gamma pulse and DD-pulse superposition in time .

neutron pulse: the result of the superposition is given in Fig. 3.

Scattered neutron radiation can only lag behind the primary. So, all the leading pulse elements can not result from scattering. It becomes fairly evident that we are dealing with more energetic ions than it seemed. An attempt to describe the observed DD pulse broadening with temperature dispersion results in the plasma temperature estimate of ~ 35 keV. This estimate is in good agreement with the measured reaction rate ratio. The ratio 139 approximately corresponds to 30 keV of plasma temperature .

Thus, we are brought as if into the second, descending half of the reaction rate-temperature rate ratio dependence, provided, of course, we try to retain the temperature notion itself. In the described experiment the direction to the detectors was 75 degrees to the chamber axis (almost perpendicular). This direction was not chosen premeditated. The question, that was occur just after first looking to results, is: what will we see along the axis of the chamber? It was the main goal of shot 2.

SHOT '2.

Fig. 4 gives the neutron pulse oscillogram in experiment '2 recorded by a detector 129 m off, located in the direction along the chamber axis. That time the experiment was made on pure deuterium.

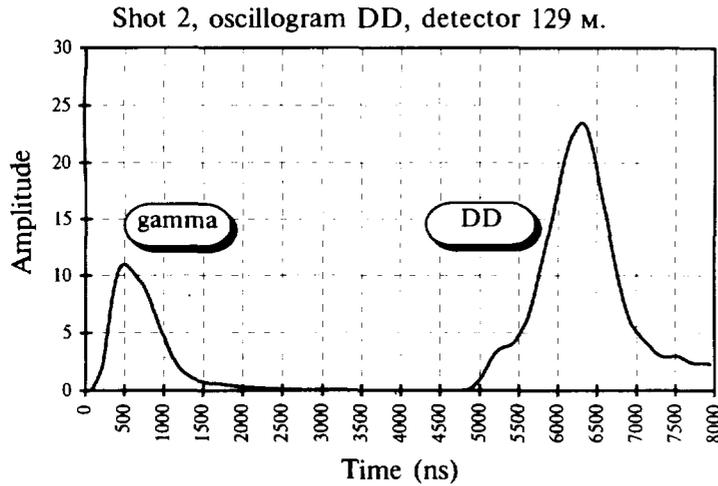


Fig. 4. Oscillogram obtained in the pure deuterium experiment .

MeV neutrons with the neutrons generated in the chamber nozzle. To generate a neutron of 3 MeV energy at collision with an immovable deuteron, the deuteron should be of 170 keV energy or the neutrons should be emitted in flow of material moving at a velocity of $2.3 \cdot 10^8$ cm/s.

Energetic dispersion for the bulk of the neutrons is the same as in the first experiment.

4. INTERPRETATION OF RESULTS

The obtained new results may be treated differently. There is no complete unanimity among the authors of this paper, but as one of possible options, the proposed interpretation of the results is admitted by everybody.

The DD pulse broadening found in the experiments, at first sight, is contradictory to theoretic representations and MHD computations of plasma chamber operation [1] where characteristic temperatures of ion plasma components are several keV. An important fact accounting for this contradiction is that the shock wave where plasma is heated is collisionless (CSW) and ion distribution in hot plasma is not necessarily Maxwellian when ion relaxation times are large (which is the case in our experiments, particularly for the fastest ions) Only for the Maxwellian distribution the distribution of relative ion velocities and the distribution of mass centers of colliding ions are independent, therefore, despite the fact that the principal contribution to the number of DD reactions is made by the most energetic ions, the mass center distribution determining the neutron spectrum broadening depends only on ion temperature. The situation changes if we have an ion spectrum with a larger fraction of fast ions as compared to the Maxwellian distribution. In this case the fastest ions making the main contribution to the DD reaction will also determine the neutron spectrum broadening. At equal mean ion energy the neutron spectrum can be broadened much more than for the Maxwellian spectrum.

Consider our plasma from this standpoint. In paper [3] ion distribution by relative velocities was obtained using numerical simulation for a perpendicular CSW with the Alfvén-Mach number $M=2.6$ which may be considered as representative for CSW in our chamber. This distribution is given in Fig. 5. For comparison the same figure gives distributions by relative velocities for two particles obtained for one-particle Maxwellian distribution

$$\frac{df}{dv} \sim v^2 \exp\left(-\frac{v^2}{v_0^2}\right)$$

The measured results were still more surprising. In Fig. 4 at the neutron pulse front a protruding "nose" of neutrons of considerably higher energy (3 MeV) is clearly seen. The quantitative estimate of the fraction of these neutrons is 10%. The estimate correlates with the 10%- estimate of the number of neutrons generated in the chamber nozzle by the results of neutron source image processing in the DT gas experiments [1]. It would be logical to relate the 3

and for one-particle ion distribution reducing for high velocities according to the power law

$$\frac{df}{dv} \sim \begin{cases} \frac{v^2}{\left(1 + \frac{v^2}{v_0^2}\right)^2} & , v < v_{\max} \\ 0 & , v > v_{\max} \end{cases} \quad (1)$$

where $m_i v_{\max}^2 = 20 \bar{\epsilon}$ ($\bar{\epsilon}$ - mean ion energy equal for all three distributions; at the numerical simulation ion velocities had only two components perpendicular to the magnetic field)

Comparison of these curves shows that the ion distribution obtained at the numerical simulation severely differs from the Maxwellian, contains a "tail" of fast ions and is fairly well described using distribution (1)

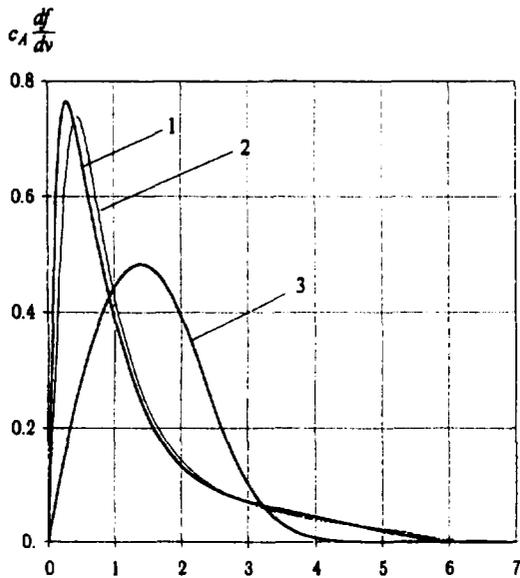


Fig. 5. Ion distribution by relative velocities v/c_A behind the front of the perpendicular CSW with the Alfvén-Mach number $M=2.6$ (c_A - Alfvén sound speed). 1 - distribution obtained in numerical simulation [3], 2 - distribution for power law (1), 3 - Maxwellian distribution.

In order to find out if distribution (1) with reasonable temperature values (since distribution (1) is not Maxwellian, by temperature we mean the measure of average energy, i.e. for the velocity distribution isotropic in space $T \equiv 2/3 \bar{\epsilon}$) can lead to the DD pulse broadening observed in the experiments, numerical computations of DD neutron yield at a given ion distribution type were made. In doing so the following effects were taken into consideration: actual dependence of the DD reaction cross section on energy [4], impact on energy of neutrons emitted in various directions, velocities of mass centers of colliding ions and their relative velocities, and device smearing of neutron pulses detector.

As for the "nose" in the second experiment, to account for this, one is forced to assume presence of a small amount of plasma moving along the axis z at a velocity of $-2 \cdot 10^8$ cm/s. We suggested that these neutrons are generated in the nozzle region in plasma flowing at large velocities near the internal electrode-anode (where, according to our calculations, plasma is rarefied and, hence, moves at a high velocity which can also be promoted by the Hall effect [6]) This plasma is heated due to friction on the electrode and/or due to development of turbulence resulting from the Kelvin-Helmholtz instability caused by large velocity difference across the nozzle. Thus, it was believed that some small fraction of neutrons, α , at the forward pulse front is generated in plasma moving at a velocity of u from collision of ions which have isotropically distributed velocities u relative to the plasma with cold ions of the main flow. An explanation for existence of such large plasma flow velocities is not provided in the MHD-computations of plasma chamber operation. One of possible hypotheses which might lead to so large velocities suggests presence of low-density residual deuterium plasma which remains in the first compartment after outflow of the bulk of the plasma and flows after the bulk of the plasma at higher velocities.

Taking into consideration all of the above, we assumed that in both the experiments $\alpha=0.06$, $u=2.2 \cdot 10^8$ cm/s, maximum ion "temperature" is 5.5 keV, ion distribution for the main pulse, $1-\alpha=0.94$, is described with distribution (1), and the time history of temperature for both the experiments is shown in Fig.6. (for comparison the figures also present the initial non-broadened neutron distributions vs the times of DD- neutron arrival at the pickups).

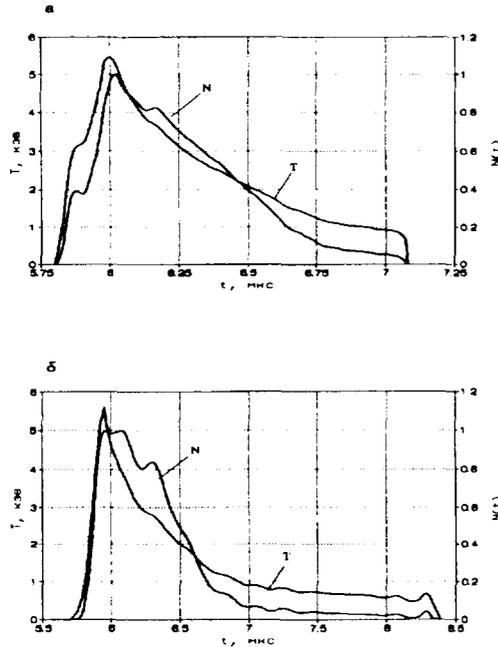


Fig. 6. Ion "temperature" T vs time in experiments No.1(a),No.2(b). Initial non-broadened neutron distributions Ntt vs times of DD-neutron arrival at the pickup are also given.

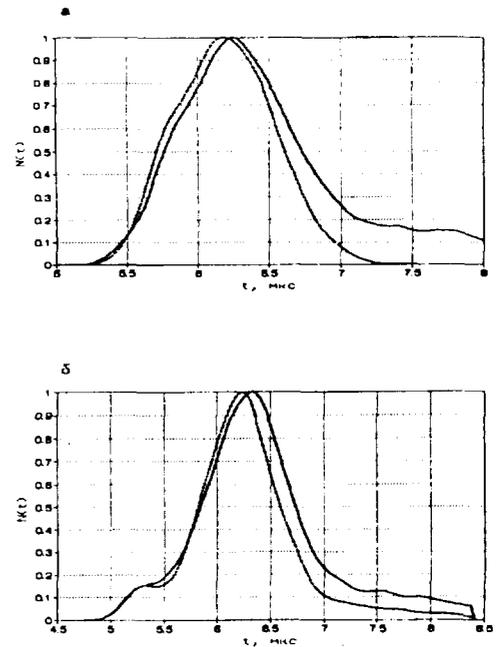


Fig. 7. DD-pulses vs time in the experiments (solid line) and computations (dotted line), (a) experiment No.1, (b) - experiment No.2.

The obtained time dependence of DD-pulses is shown in Fig.7., for comparison the same figures give the experimental curves of DD-pulses. From the figures it is seen that the forward fronts of the obtained pulses are in good agreement with the experiment.

CONCLUSION

Using the time-of-flight technique for the MAGO chamber, even though the generated neutron pulse is of large duration, is still worthwhile on DD and, possibly, on DT. Using this technique proved surprisingly productive. The obtained neutron pulse dispersion was an order of magnitude superior to the expected values. A certain fraction of neutrons of pronounced energy anisotropy was also detected. About 10% of neutrons escaping ahead, along the chamber axis have a considerable excess in energy. Unfortunately, it was yet impossible to verify that the anisotropy fact is not coincidental for the two above-described experiments. To confirm this, an experiment is required with simultaneous measurement of spectra along the chamber axis and in the perpendicular direction.

The obtained results provide a basis for planning special diagnostic experiments on neutron spectra recording with the time-of-flight method. Evident therewith becomes the need of separate study of the nozzle region and the central chamber region in two perpendicular directions. It is possible to separate temporal processes from dispersive only using a great number of detectors on flight bases of 50-300 m.

The measured results for spectra of neutrons generated in DT and DD reactions may be basically explained if one assumes that the ion plasma component produced in a CSW in the MAGO chamber has the non-Maxwellian distribution by velocities at characteristic mean ion energies on the order of several keV.

The obtained results provide information about ion distribution behind the front of the perpendicular CSW with the characteristic Alfvén-Mach numbers of $M \sim 3$.

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