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EXPERIMENTAL INVESTIGATIONS INTO THE INTERACTION OF HIGH-POWER LASER RADIATION WITH A PLASMA IN MISHEN'-1 AND MISHEN'-2 DEVICES

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In recent years many laboratories have been conducting systematic research in compression and heating of matter under the effects of high-power laser pulses. The goal of these investigations is to elucidate the optimum conditions for conducting controlled thermonuclear reactions in an ultradense substance. A considerable portion of the information on this question has been obtained as a result of numerical calculations, the real accuracy and reliability of which is limited by two factors. First, the actual hydrodynamic model of the laser target is approximate due to the scantiness of our data on equations of state and transfer coefficients in certain ranges of density and temperature, and also due to a lack of clarity in the question of anomalous absorption of light. Second, the majority of the calculations has been conducted on one-dimensional models, which are a rough approximation due to the instability of compression. Two-dimensional calculations are associated with considerable difficulties, and three-dimensional calculations with the current state of computer technology are in principle impossible.

An idea of the accuracy of numerical calculations can be formed by comparing the results of a calculation with an experiment. Scheduled and partly initiated experiments are intended to verify theoretical predictions with respect to degree of compression, temperature, stability, and the dependence of these characteristics on the degree of satisfaction of the conditions imposed on laser pulse parameters. We have conducted calculations of experimentally measurable quantities, based on analytical and numerical models. The analytical models are used for evaluating the optimum pulse shape depending on the state equation, density profile, and other target characteristics. The research shows that almost adiabatic compression is unstable in relation to one-dimensional perturbations, with one of the modes of instability corresponding to a transfer of the moment of collapse. Short-wave instability of the Taylor type. Linear analysis shows that the most rapidly developing mode of this instability is stabilized at the expense of a broadening of the boundary between the dense nucleus and the plasma corona. Under these conditions instabilities with wavelength on the order of the dimensions of a compressed drop prove to be dangerous. It has been possible to obtain an accurate solution of the three-dimensional problem of the development of instabilities disrupting symmetry and transforming a sphere into an ellipsoid. The simplest spherical variant of this model has been studied by many authors (cf., for instance, [1]) and is in good agreement with numerical calculations. Our accurate solution shows that the small deviation from sphericity for degree of compression n rises approximately by a factor of $\sqrt{n}$. The most rapid compression occurs along the shortest axis of the ellipsoid , and in the extreme case the ellipsoid is transformed into a disc, and compression becomes planar.

Numerical calculations have been carried out for a one-dimensional, two-temperature hydrodynamic model. The influence of the pulse shape on the degree of compression and temperature has been studied. Compression stability relative to an approximation of an "ideal pulse" [2] has been shown as piecewise-linear. An example of temperature and density distribution is shown in Fig. 1. (Compression occurs with symmetric two-sided irradiation of a flat target. The pulse shape is shown at the top, and energy is $2 \cdot 0.5$ kJ. Distributions correspond to a moment in time of 11.65 nsec.) All variants of the numerical calculations were developed for laser pulse parameters and conditions which can be realized in the Mishen'-2 (Target-2) apparatus.

The Mishen'-2, designed for conducting experiments in the study of compression of a substance that is being subjected to irradiation by time-programmed laser pulses, consists of a laser system with an active element of neodymium glass, a vacuum interaction chamber with devices for attaching the target and a focusing lens, and a diagnostic apparatus. Figure 2 shows an optical diagram of the laser system. The input generator and the pulse shaping device are similar to those described in detail in [3] (the Mishen'-1 apparatus). The diameter of the light beam at the opening of the input generator is 3 mm, beam divergence is close to diffraction (radiation of a single transverse mode), and the energy in pulses lasting 30-50 nsec is ∿0.1 J. Two sequentially located Pokkel's* cells are employed in the shaping device; the voltage to these cells is supplied from a cable generator. Switching is accomplished with a high-pressure discharger with laser ignition. In the amplification output stages active elements with a 40×240-mm^2 rectangular cross-section having the shape of a crosstie (crosstie length ∿700 mm) are used. The appropriate pumping regime, use of light sources with extremely close lamp packing, and correct selection of the grade of glass [4] make it possible to obtain at the output of a light source with three parallel crossties short light pulses with overall energy of 1-2 kJ for a divergence of each of the three parallel beams on the order of 10^{-4} rad. A comparison of the two possible systems for surveying the light beam through three channels – reflector and refractor – unequivocally results in selection of the latter. One of the drawbacks of the reflector system (it is shown in the upper part of Fig. 2) has to be the presence in it of a cylindri-

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* Tr. note: unable to verify this name.

cal telescope and mirrors with large reflecting surfaces. Manufacture of a cylindrical telescope of high quality is associated with specific technical difficulties. The wave front after the beam has passed through the telescope, as a rule, proves to be highly distorted. As regards large-size mirrors, the durability of reflective coatings presently in existence is not sufficient, and the maximum allowable energy densities for them are substantially lower than for active elements.

Active elements with rectangular cross-sections (dimensions given in Fig. 2) are used in a pre-amplification system in two stages. A magneto-optical shutter (a Faraday cell) is used to protect the input generator, shaping unit, and first amplifying stages from radiation reflected by the target which passes through the laser system in the reverse direction and is amplified in the output stages. Trays with a nitrobenzene solution of a dye possessing non-linear optical properties are located between the amplification stages. Similar optical isolators make it possible to considerably increase the energy contrast of the system. When a value of contrast exceeding 10^4 is attained, the energy released on the surface before the arrival of the main pulse proves to be lower than the sublimation energy, and premature vaporization of the target substance is avoided.

The design of the interaction chamber takes into consideration the possibility of symmetrical irradiation of the target from two opposite directions. A special alignment mechanism makes it possible to move the target along three coordinate axes with 5-μm precision without disturbing the vacuum within the chamber. Quartz peep holes are used for conducting optical measurements. Table 1 gives the characteristic parameters of the laser pulses and results of preliminary experiments conducted on the Mishen'-2.

Investigations of the mechanisms of radiation absorption in a plasma corona take on special importance in an examination of the question of the possibility of realizing high compression of matter in models with irradiation of a target by programmed laser pulses. Data obtained by a number of authors [3,5,6] attest to the abnormal absorption of radiation and non-linear interaction processes at high power densities $\sim 10^{13}$-10^{14} W/cm^2. It can be expected that the velocity distribution function of plasma electrons in the absorption band will in this case prove to be considerably non-equilibrium. Increasing the fraction of fast electrons relative to the Maxwellian distribution will prevent compression of the target nucleus due to substance heating and from this standpoint is highly undesirable. Valuable information on non-linear processes taking place during interaction between high-power radiation and plasma evidently can be obtained by analyzing the spectrum of scattered radiation. Similar measurements were initiated on the Mishen'-1 around 18 months ago. Up to now it has been possible to conduct a rather large series of experiments, the results of which in our opinion are of definite interest.

The laser system of the Mishen'-1 apparatus generates pulses lasting 4-8 nsec with energy of $\sim$100 J. The rise time of a square pulse is $\sim$1 nsec. The output diameter of the light beam equals 45 mm (active elements with circular cross-section sequentially increasing diameters of 15, 20, and 45 mm were used). Massive solid targets of Al, LiD, and

$(SD_2)_{17}$ were placed in a vacuum chamber. The light beam is focused on the target surface by a spherical lens with a focal length 15 cm. A special attachment made it possible to shift the target in the direction of the optical axis (precision of the movements not worse than 5 μm) without disrupting the vacuum within the chamber.

A camera obscura with an aperture closed by thin metal foil was used to record the space distribution of the sources of X-ray radiation and to evaluate the dimensions of the focal spot. The diameter of the aperture shaping the image is 30 μm. The smallest diameter of the focal spot, determined both according to the image of the flame in the X-rays and from independent measurements with the aid of an Ne-He laser operating on a wavelength of 1.15 μm, equaled 60 μm. Thus, at a maximum energy of 50 J introduced into the plasma the power density in the focal plane of the lens reached $2\text{-}3 \cdot 10^{14}$ W/cm^2.

The shape and energy of the incident laser pulse and the pulse reflected into the aperture of the focusing lens were recorded in each experiment. The temperature of the resulting plasma was estimated from measurements of soft X-ray radiation by the traditional filter method. Three scintillation detectors measured the intensity of the X-radiation that had passed through various aluminum and beryllium foils. The detectors contained ELU-F type photomultipliers (FEU) possessing a high amplification factor and high value of output current ($\leqslant 5$ A in the linear region). Signals from the photomultiplier were fed to the plate of a six-rayed oscillograph BLOR-02. The time resolution of the whole measurement channel, taking into account the de-excitation time of the scintillator, is not worse than 1.5 nsec. The spectral composition of the incident and reflected light in the infrared region was analyzed with the aid of a standard diffraction spectrograph with linear dispersion of 20 Å/mm. Another spectrograph with an output image converter providing $\sim 10^3$ light intensification was used for studying the scattered light spectrum on wavelengths from 5000 Å to 7500 Å. The time characteristics of scattered light on frequencies $2\omega_0$ and $3/2\ \omega_0$ (ω_0 is the working frequency of an Nd laser) were analyzed with the use of a monochromator and an ELU-F photomultiplier. Radiation scattered by the plasma on frequencies ω_0 and $2\omega_0$ into the aperture of the focusing lens and in directions 45° and 90° to the axis of the beam incident on the target was recorded.

The power density on the target surface was changed both with a change in pulse energy over the 5-50-J range and by moving the target in respect to the focal plane of the lens.

The experiments were conducted in two operating regimes of the input generator. In the first variant, when the Q factor modulator was a Pokkel's* cell and the resonator was formed by two mirrors, the radiation spectrum is rather broad, 20-30 Å. If a stop is used as a 30% mirror at the output, then fine lines whose width does not exceed 1 Å are clearly evident on the background of the continuous spectrum. Line spacing is ~ 5 Å, and the number of observed lines varies from three to six or seven. In the second variant the Q factor modulating element was a passive shutter on the dye with non-linear optical properties, and both resonator mirrors were replaced with

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* Cf. footnote, p. 4.

stops. The generation spectrum in this case consists of a single line with width $\leqslant 1$ Å. It should be immediately noted that within the limits of accuracy of the measurements neither the reflection factor nor the width of the lines of scattered radiation on wavelengths $2\omega_0$ and $3/2\omega_0$ nor the measured electron temperature of the plasma was changed during the transition from one generator operating regime to another. (Naturally, the character of the spectral distribution of the reflected radiation in the vicinity of the working wavelength of the laser was changed.)

We shall now examine in more detail the main results of these experiments.

In the spectrum of radiation reflected into the aperture of the lens under specific focusing conditions $2\omega_0$ and $3/2\omega_0$ lines were recorded. (A diffraction spectrograph with an output image converter was used in these measurements.) The evaluations show that maximum radiation intensity on frequencies $2\omega_0$ and $3/2\omega_0$ amounts to not more than 10^{-3}-10^{-4} of the intensity of the light scattered on the base frequency at the same solid angle. The intensity of these lines is not changed when the target is moved along the optical axis. The distributionsof intensity depending on the location of the target in relation to the focal plane of the lens have a bell shape, while the maxima for the $2\omega_0$ and $3/2\omega_0$ lines correspond to different positions. The greatest radiation intensity on frequency $2\omega_0$ occurs when the beam is focused on the target surface, and the intensity of the $3/2\omega_0$ line rises when the target is removed from the lens and peaks when the distance from the target surface to the focal plane of the lens is ~ 300 μm. Reducing the energy contrast leads to an abrupt drop in the $2\omega_0$ line intensity. The $3/2\omega_0$ line is less sensitive to both the energy contrast of the radiation incident on the target and focusing conditions.

The line shape of $2\omega_0$ is asymmetric, and a broadening of 10-15 Å in the direction of longer wavelengths is observed for all operating regimes of the input generator (a continuous generation spectrum with half-width ∿40 Å – one narrow line and several narrow lines spaced at 4-5 Å intervals).

The line shape of $3/2\omega_0$ is symmetric, and the line width at half height equals 30-40 Å. Figure 3 shows a spectrogram obtained by focusing a 5-nsec pulse with energy of 25 J on the surface of a target made of deuterated polyethylene. To identify the lines, the spectrum of a pulsed Xe lamp was obtained on the same film. Photomicrograms of spectra in the vicinity of the wavelengths in which we are interested are presented below. The line widths of $2\omega_0$ and $3/2\omega_0$, and also the dependences of their intensity on focusing conditions and the energy of the primary laser beam are practically unchanged when the polyethylene target is replaced by targets made of lithium and aluminum deuteride.

Investigations of the time path of radiation on wavelengths $1/2\lambda_0$ and $2/3\lambda_0$, conducted with the use of a monochromator and ELU-F photomultiplier, showed that the shape of the corresponding pulses is similar to the shape of a laser pulse. (The intensity of lines $1/2\lambda_0$ and $2/3\lambda_0$ rises more steeply, but the insufficient time resolution of the apparatus used did not permit accurate measurements and reliable phasing of the observed pulses with the pulse incident on the target).

The photoelectric method also was used to study the angular distribution of radiation on the $2\omega_0$ frequency. For this purpose, the luminous fluxes scattered at equal solid angles into the aperture of the focusing lens and at angles of 45° and 90° to the optical axis were recorded simultaneously in a single experiment. Figure 4 shows polar diagrams for radiation scattered on the base frequency (ω_0) and on frequency $2\omega_0$.

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Figure captions

Fig. 1	Temperature and density distributions with two-sided irradiation of a planar target. (Results of numerical calculation.)
Fig. 2	Optical diagram of laser system. a) Reflector variant of separating a light beam; b) Refractor variant of separating a light beam.
Fig. 3	a) Spectrogram of radiation scattered by plasma into the aperture of a lens; b) Photomicrogram of line shapes $2\omega_0$ and $3/2\omega_0$.
Fig. 4	Polar diagrams of radiation scattered by a plasma a) on frequency ω_0; b) on frequency $2\omega_0$.

Table I

Parameters of laser beam and preliminary results obtained on the Mishen'-2 device

Output dimensions of beam	3 parallel beams, each with a rectangular cross-section 40×240 mm^2
Duration of pulse	4-8 nsec
Energy	1 kJ
Divergence of beam	$2 \cdot 10^{-4}$ rad.
Energy contrast	10^4
Diameter of focal spot	300 μm
Maximum power density on target	$3 \cdot 10^{14}$ W/cm^2

Fig. 1

Temperature and density distributions with two-sided irradiation of a planar target. (Results of numerical calculation.)

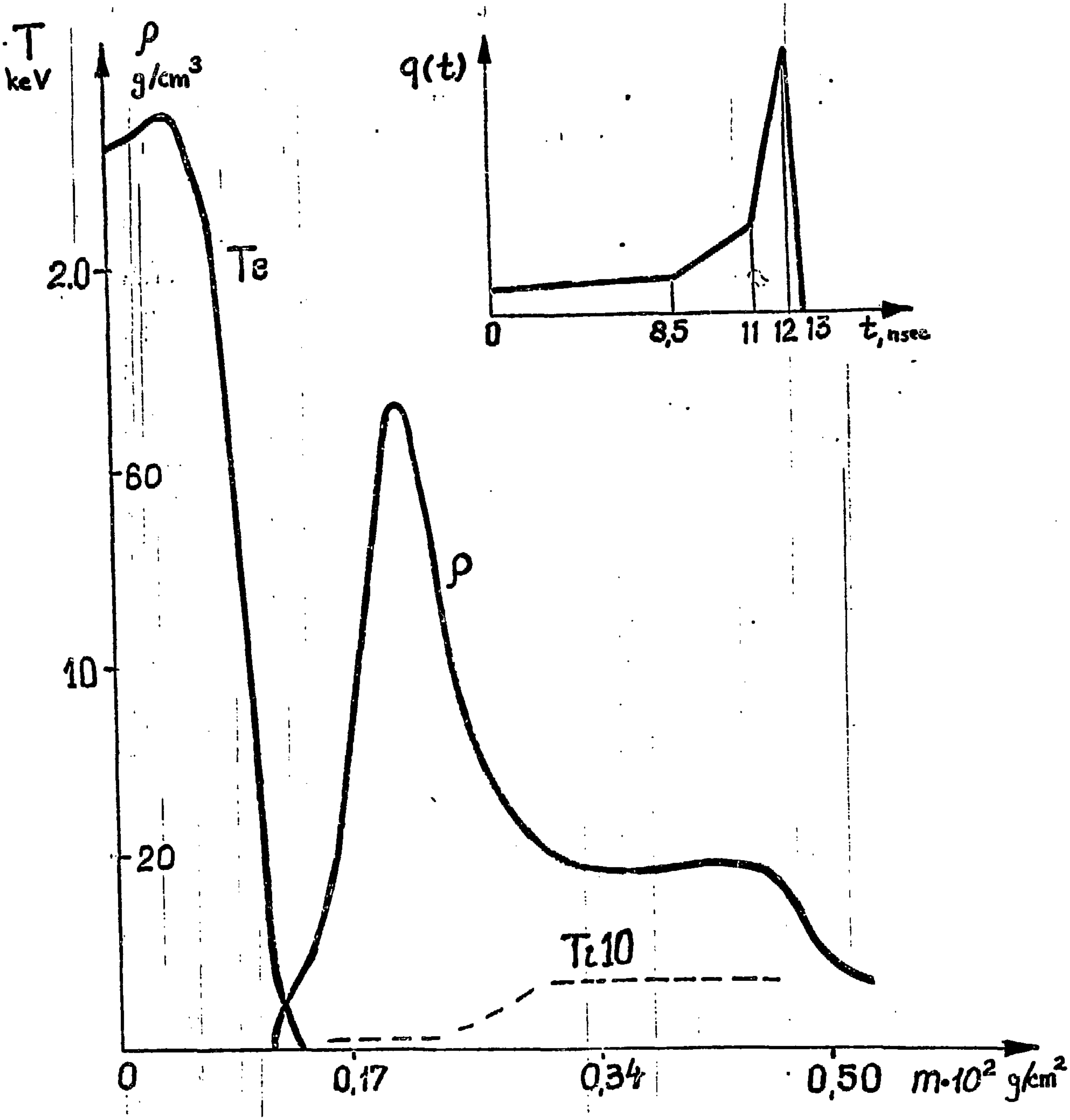
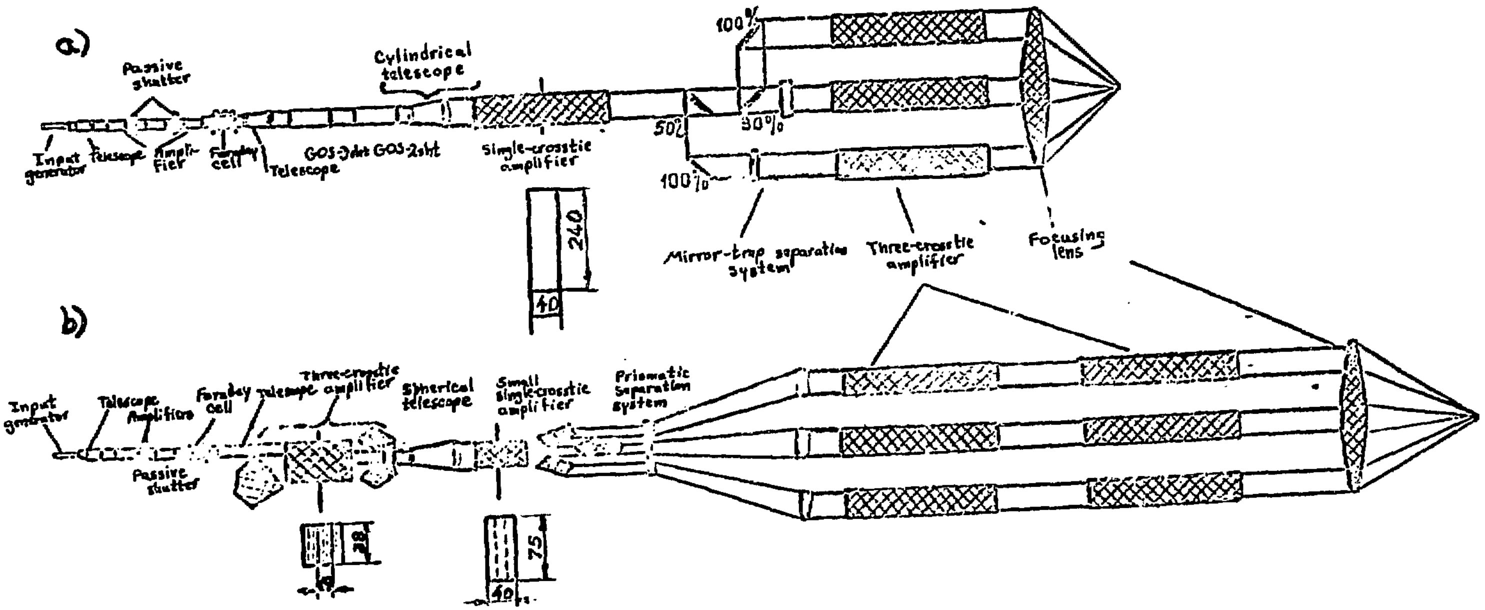


Fig. 2

MISHEN' II

("Target II")



OPTICAL DIAGRAM OF LASER SYSTEM

a) Reflector variant of separation of light beam.
b) Refractor variant of separation of light beam.

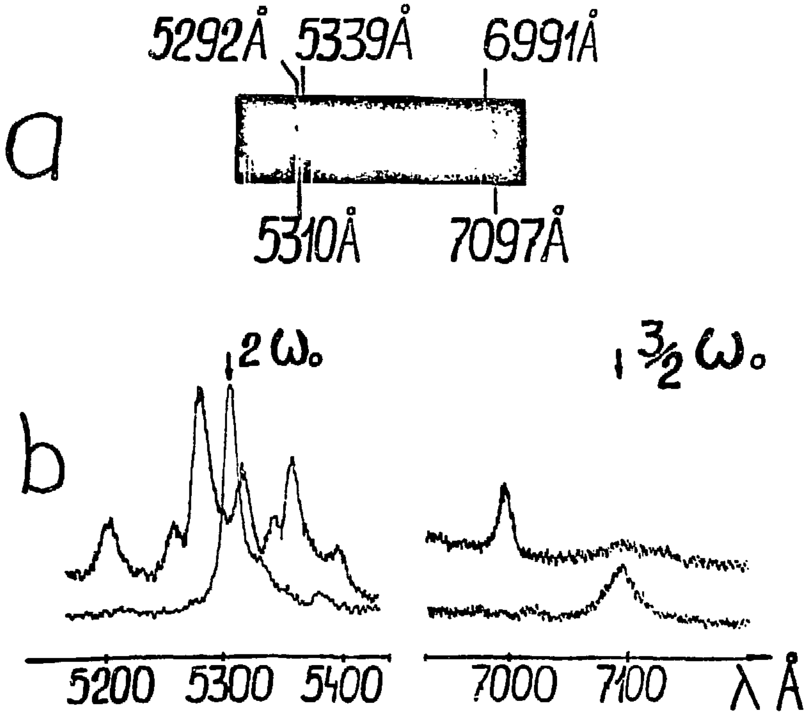


Fig. 3. a) Spectrogram of radiation scattered by plasma into lens aperture;

b) Photomicrogram of line shapes $2\omega_0$ and $3/2\omega_0$.

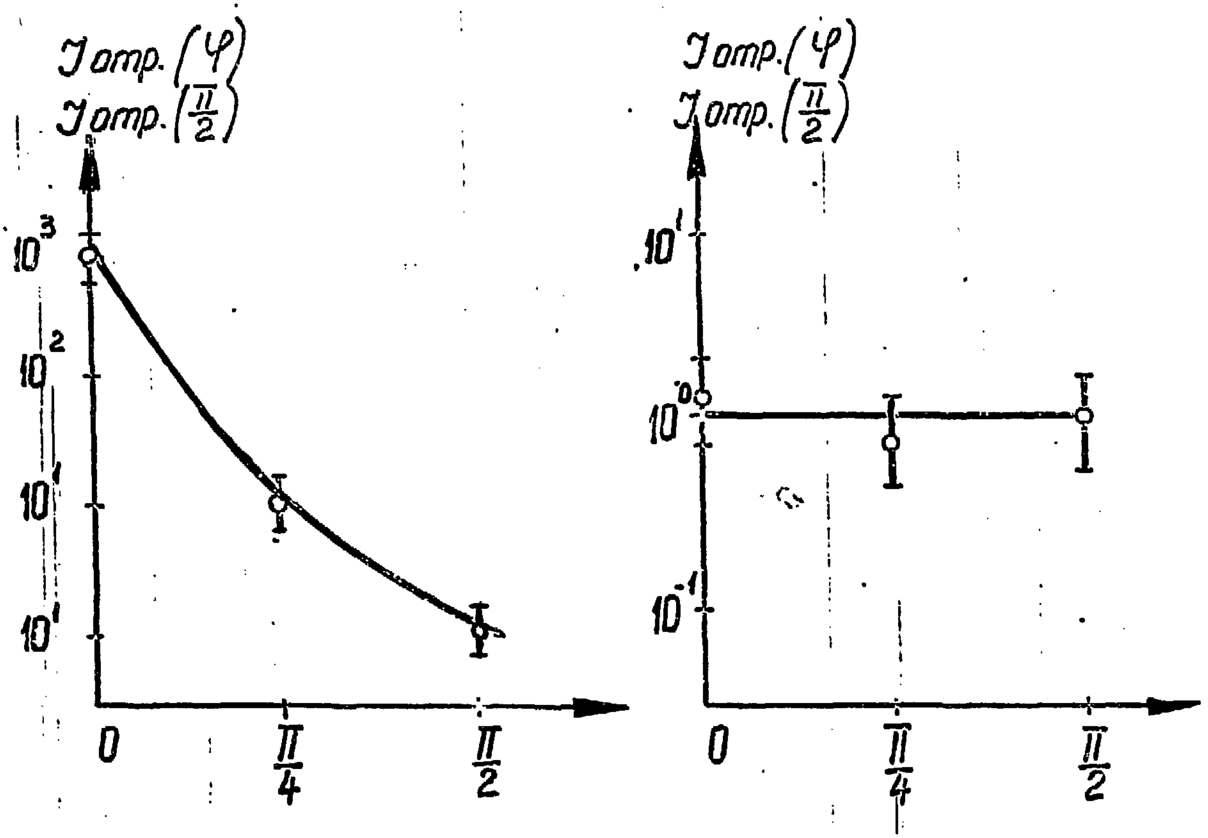


Fig. 4

Polar diagrams of radiation scattered by a plasma

a) on frequency ω_0

b) on frequency $2\omega_0$.