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16. Abstract

The physical principles underlying the use of radiating plasmas for the optical pumping of lasers are described. Particular consideration is given to the properties of radiating plasma, radiation selectivity, the dynamics, equilibrium and stability of radiating plasmas, the radiative Reynolds number, and experimental results on radiating discharges.

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HIGH-POWER RADIATING PLASMA

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One of the most widespread methods of laser pumping is optical pumping, the essence of which consists of irradiation of an active medium with light of a broad spectrum, which is usually noncoherent and created by a heat source (i.e., heated

*Numbers in the margin indicate pagination in the foreign text.

to a high temperature by an ionized gas). The energy of this radiation is stored in an active laser medium in the form of the excitation of its atoms and molecules, and then coherently emitted in a narrow spectral band in the course of a regulated time interval. Such is the mode of operation of ruby and neodymium lasers (the most widespread in laboratory studies), powerful lasers based on gases which dissociate or ionize under the effect of light, lasers on solutions of complex organic compounds (dyes), and many others.

The more powerful the optical pumping, the more powerful and more diverse the lasers themselves may be, insofar as one may utilize a broader class of substances as the active medium. Powerful sources of optical radiation are also necessary for the study of photochemical processes, the interaction of radiation with matter, simulation of processes in cosmic plasma, the study of the physics of explosions and shock and heat waves, and in many other problems.

In the middle of the 1960's, on the initiative of N. G. Basov, powerful sources of optical radiation began to be systematically studied in several of the largest scientific insti- /31
tutions of our country, including the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR, the M. V. Keldysh Institute of Applied Mathematics of the Academy of Sciences of the USSR, the Moscow State University im. M. V. Lomonosov, the Moscow Higher Technical School im. N. E. Bauman, and others. This was an example of the purposeful consolidation of the efforts of many institutes to solve this major scientific and technical problem[1].

Physically, the problem of creation of similar sources of radiation seemed quite complex, since, as compared with the

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[1]Editor's Note — The cycle of studies "Physics of Strong-Current Radiating Discharges" (A. F. Aleksandrov, E. A. Azizov, B. L. Borovich, A. I. Zakharov, N. P. Kozlov, F. A. Nikolaev, N. N. Petrov, I. V. Podmoshenskiy, Yu. S. Protasov, Yu. P. Popov, V. B. Rozanov and A. A. Rukhadze) was awarded the State Prize of the USSR in 1981.

existing sources, it would be necessary to increase the intensity of their radiation in the prescribed range of the spectrum by hundreds and thousands of times, retaining, or even increasing, their effectiveness (i.e., the ratio of the useful portion of the radiation to the total radiation), to advance into the short-wave region of the spectrum, encompassing the ultraviolet, and even the vacuum ultraviolet, regions, and also increase the radiated energy by hundreds and thousands of times.

High-temperature plasma, generated in powerful strong-current self-constricted discharges, which are known in the physics of controlled thermonuclear synthesis by the name of pinch-discharges, could serve as a source of radiation with such extreme parameters. However, a thermonuclear pinch-discharge is unstable, and its lifetime is no more than a millisecond. Is it impossible to lengthen this time?

What is more, although such a discharge also radiates in the short-wave region of the spectrum, radiation plays a minor role in the energy balance of the discharge as a whole, and is dispersed in a broad spectral region; therefore, it is little-effective as a pumping source. Is it impossible to considerably increase its effectiveness?

The three basic characteristics of a radiation source — intensity, pulse duration and effectiveness — are usually associated by the dependence which proves disadvantageous in the given case, namely: an increase in the intensity of luminescence is achieved by an increase in the plasma temperature, and is accompanied by a decrease in the duration of the luminescence and the effectiveness of the source. Such a dependence has been fully demonstrated in studies of thermonuclear pinch-discharges.

How could one resolve the indicated contradictions, and combine all of the necessary properties in a single object?

In the present article, we will set forth the physical principles and solutions, found in the course of the indicated studies, and having made it possible to create sources of optical radiation which possess the necessary, and in a number of cases extreme, characteristics.

Properties of Radiating Plasma

We will examine some characteristics of plasma, which we are using for the analysis of the above-indicated problem. We agree to discuss sources with a radiation energy of 10^5 joules and a radiation pulse duration of 10^{-4}-10^{-3} seconds. Let the source plasma temperature reach several tens of thousands of degrees (the electron-volt is a convenient unit for the measurement of temperature: 1 ev=11,600 K=11.6 kK), and the density — 10^{18} cm^{-3}. These numbers, although conditional, are sufficiently close to the parameters of "good" sources, and to those which were realized under laboratory conditions. A cubic centimeter of hydrogen plasma, with the indicated density and at a temperature of 2 ev, contains 3.5 joules of energy. Thus, if we want to emit 10^5 joules of energy in a hypothetical process, in which such plasma is first heated to the indicated temperature, and then, radiating, cools off, we should prepare the plasma with a volume of about 10^5 cm^3, with linear dimensions of about 50 cm. As in any heated gas, a pressure equal, in our case, to roughly 7 atmospheres, exists in this plasma, and this pressure forces the gas to expand, with the rate of expansion exceeding by two-three times the speed of sound in plasma, and is about 50 km/sec. Being left to itself, our plasma will disintegrate within 10^{-5} seconds, and we should ascertain whether it would be able to radiate any amount during this time, or if all the energy reserves would change into kinetic energy of dispersion. It turns out that the radiation composes a negligibly small portion.

We will examine another approach. Let the volume of the plasma be a working body, into which the energy is introduced constantly, for example, because of Joule heating (i.e., heating by an electric current), and drawn off by radiation, so that the inherent reserves of energy in the plasma are roughly constant. It is common knowledge that, at a plasma temperature T, the radiation from a unit of its surface may not exceed the radiation from the surface of a black body, which is determined by the Stefan-Boltzmann law (see Fig. 1). A flow of energy from the surface of a black body is given by the formula: /32

$$S\ [W/cm^2] = 10^5 T^4\ [ev],$$

and the distribution along the spectrum — by the universal Planck function. Thus, with T=2 ev and a time of radiation of 10^{-4} seconds, we need a source with a cross-section area of only 100 cm^2 in all. This evaluation seems attractive, but many questions remain unclear, among which the most important are: can we eliminate the effect of movement (dispersion) of the plasma, and will the spectrum of the radiation be close (similar) to the spectrum of radiation of a black body?

How does actual plasma radiate? For the problems we are examining, the most important mechanisms of radiation are braking radiation and photorecombination radiation (see Fig. 2). During the braking process, the electron radiates, and then its trajectory of movement in the field of the nucleus changes, the electron undergoes negative acceleration — it brakes (hence the name — braking radiation). The second process is associated with the capture of an electron on one of the free energy levels of the ion; with such capture — photorecombination — the photon is liberated. The radiation, concentrated in individual spectral lines, plays a minor role in the energy balance under the conditions we are examining. Radiation of a small volume of plasma obeys Kirchhoff's law, namely: the intensity of emission of photons of various energies is proportional to the product of the universal Planck function, which describes the distributuion of radiation in the spectrum of a black body, by the coefficient of absorption of photons with a given energy in the plasma. The radiation of a large volume of plasma is made up of the radiation of small volumes, with regard for the possibility of absorption of part of the radiation in the plasma. The boundary between the concepts of "small" and "large" volumes of plasma is determined from comparison of the linear dimensions of the plasma and the length of absorption of the photons — magnitudes which are inverse to the coefficient of absorption. As a result, the spectrum of radiation of the plasma looks roughly like that shown in Figure 1. The plasma is called optically impervious (or dense) if its radiation is close to the radiation of a black body; if the flow of radiation from the surface of the plasma is appreciably less than in a black body, then it is said that the plasma is optically transparent.

The total flow of radiation of a black body, as has already been stated, increases proportional to the fourth degree of temperature, and the total flow of radiation of optically transparent plasma increases considerably more weakly — proportional to the temperature in a degree from 1/2 to 3/2, as a function of the composition of the plasma — because of the fact that the energy practically does not radiate in individual sections of the spectrum. As we have already said, the effectiveness of the pumping source is determined by the ratio of the "useful" portion of the radiation, which excites the active medium of lasers, to the total energy of the radiation. The useful portion of the energy, as a rule, is concentrated in a narrow range of the spectrum; therefore, with a change in temperature, this portion changes roughly linearly with the change in temperature. From here, it follows that, in optically dense plasma, the effectiveness will decrease with an increase in temperature, while in optically transparent plasma, it may remain constant. Thus, a possible means of solution of the problem of a simultaneous increase in both the intensity of luminescence and the effectiveness of the source consists of the creation of conditions when the plasma, being optically transparent, radiates selectively, i.e., in a certain range of of the spectrum.

We have ascertained that the movement of plasma is an unfavorable factor (which decreases the radiation time); consequently, it is necessary to confine the plasma — with a wall, a gas medium or a magnetic field. However, plasma destroys a wall, penetrates a gas medium, and seeps through a magnetic field. The characteristic time of such a process, in order of magnitude, is equal to the distance to which the plasma penetrated as a result of the instabilities occurring in it, divided by the speed of sound in the plasma. During the study of thermonuclear pinches, it was found that this time is considerably less (by 100 times) than the necessary radiation time. However, it turned out that the effect of high-power radiation on the movement of the plasma itself it cardinal, and it was as if the radiation suppresses the instabilities, decreases the seepage of the plasma through the magnetic field, and creates a damping cushion between the plasma and the wall or the gas medium.

Strictly speaking, these two positions — the necessity of selective radiation and consideration of the effect of radiation on the dynamics and stability of the plasma — were also the basic physical results of our studies. Next, we will examine in slightly more detail how these two factors are physically realized in the actual plasma of powerful discharges. /33

Selectivity of Radiation

From the examination of Figure 1, it follows that, in that part of the spectrum in which the coefficient of absorption is great and the plasma is optically dense, the radiation is close to the radiation of a black body, and the flow of energy of the radiation is great. In that part of the spectrum where the coefficient of absorption is small, and the plasma is optically transparent, appreciably less energy is radiated. Would it be impossible to realize the conditions when the radiation would be concentrated in some relatively narrow region of the spectrum? The example given in Figure 1 corresponds to the radiation of the plasma of multi-electron atoms, metal atoms for

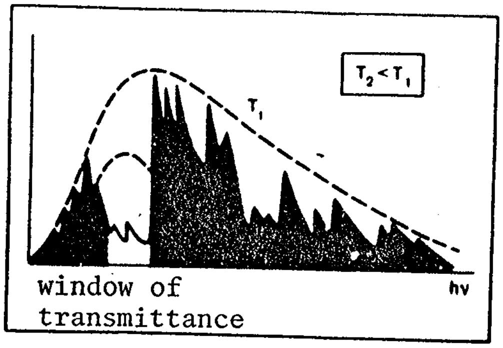

Fig. 1. Spectra of radiation of a black body (Planck function) at temperatures T_1 and $T_2 < T_1$ (dotted line), and plasma of multi-discharge ions (colored curve).

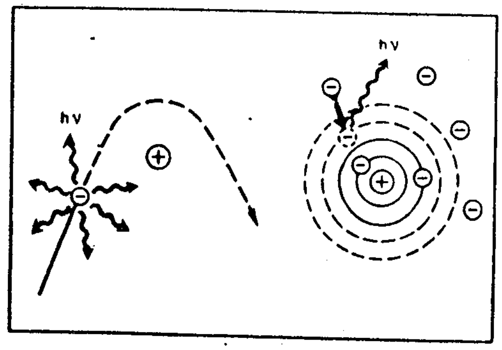

Fig. 2. BRAKING PROCESS: electron is braked in the field of the nucleus, moves along a curved trajectory, and emits photons (on the left).

PHOTORECOMBINATION: free electron is captured by the nucleus on a free level, and, in this case, the photon is emitted (on the right).

example, in which the state of the ions, which leads to radiation of the corresponding photons, is found for any part of the spectrum. However, in a number of elements, the structure of the energy levels is such that the difference in energies between adjacent levels is very great. For example, in lithium, the energy, required for ejection of a single electron from the atom (first potential of ionization), is equal to 5.4 ev, and the second — already 75 ev, while in beryllium, the second and third potentials of ionization are equal to 18.2 and 153.8 ev, respectively. There are also other possibilities, upon which we will not dwell here.

We will use the example of lithium to examine the form of radiation to which such a structure of the levels will lead. For radiation, as we have ascertained, it is necessary that the matter be ionized (that free electrons exist) — then there is the possibility for both braking and photorecombination radiation.

With low heating output of the plasma and low temperatures (below 0.5 ev), ionization is small, and the lithium plasma radiates in the infrared region. With an increase in the heating output of the plasma, the temperature increases, and, in the temperature range of 2-5 ev, all of the atoms are ionized once. In the 1-2 ev range of the spectrum (visible light), both the braking and the photorecombination processes make a contribution to the radiation. In the 3-10 ev range (ultraviolet and vacuum ultraviolet), the radiation has a purely braking nature; the coefficient of absorption, optical density and intensity of the radiation decrease sharply with an increase in the photon energy (inversely proportional to the energy of the photons in the third stage); therefore, lithium plasma practically does not radiate in this region, and the radiation is concentrated in the long-wave range. With a plasma temperature above 5 ev, twofold ionization of the lithium begins, and the photorecombination process into the basic state of a twofold ion becomes possible, accompanied by radiation of very rigid quanta with an energy exceeding 75 ev (mild X-ray radiation).

The appearance of the spectrum of the radiation depends on the density and dimensions of the plasma. If the density of the /34 particles is so great that the plasma is optically dense throughout the spectral interval, then the spectrum of radiation is close to the spectrum of a black body. If the particles are few, and the plasma is optically dense only in those spectral regions in which the coefficient of radiation is great, then, in these very same regions, the intensity of radiation is close to the intensity of radiation of a black body, and considerably less in adjacent regions. Presented in Figure 3 are the different spectra of radiation of lithium and neon plasma, as a function of the temperature

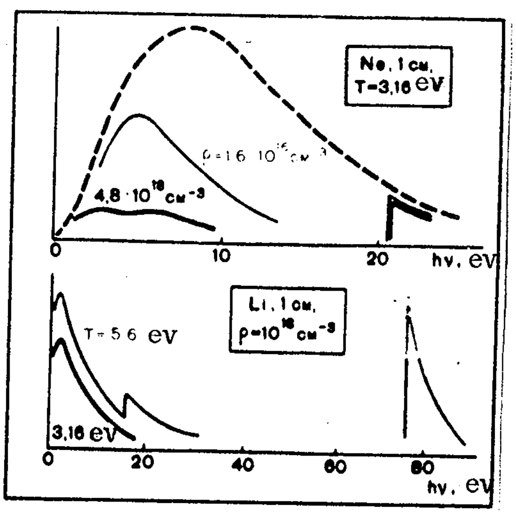

Fig. 3. Spectrum of radiation of layers of neon plasma (top) 1 cm thick at a temperature T= 3.16 ev and particle density (atoms and ions) of $1.6 \cdot 10^{19}$ and $4.8 \cdot 10^{18}$ cm^{-3}, and lithium plasma (bottom) 1 cm thick with a density of 10^{18} cm^{-3} at a temperature of 3.16 and 5.6 ev. Dotted line — spectrum of black body at temperature of 3.16 ev.

and density of the particles.

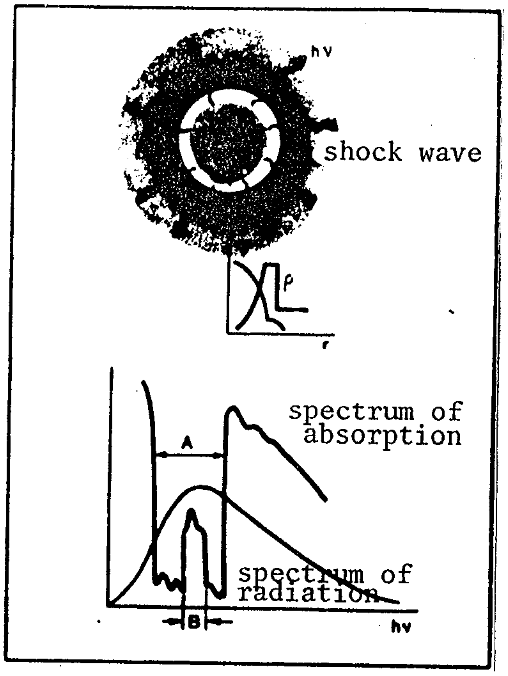

Fig. 4. Radiating discharge in a gas, view from the end (top); T—temperature, ρ—plasma density. GAS-DYNAMIC SELECTIVITY (bottom): radiation, liberated into the gas outside the transmittance window A, is absorbed by the gas, heats it, and may be re-radiated, including in the transmittance window A and in the region of excitation (activation) of the atoms B.

Thus, one may point out the conditions under which the plasma will radiate in a relatively narrow region (5-10 times narrower than the entire potential region of its radiation), with an intensity close to the maximum possible. Under these conditions, the effectiveness of laser pumping (i.e., the ratio of the energy, radiated by the plasma in the band of absorption of the active medium of the laser, to the total radiated energy) may exceed the effectiveness of the non-selective irradiation by 10-30 times.

It proved impossible to increase the effectiveness of pumping with selective irradiation, not only utilizing the differences in the spectral properties of the plasma radiation, but also because of the differences in the spectra of transmission of the gas media. We will visualize a plasma cloud, radiating in a broad spectral range, surrounded by a cold gas medium (Fig. 4). The coefficient of absorption of the gas medium is great everywhere, with the exception of a relatively narrow spectral region (transmittance window), and the spectral band of pumping of the laser is located inside the transmittance window of the gas medium, i.e., its width is less than the width of the transmittance window. The photons, emitted by the plasma in the transmittance window, pass through the gas medium, and part of them is absorbed in the laser matter. The photons, emitted outside the transmittance window, are absorbed by the gas medium, they heat it, and are converted into plasma, which again radiates similar photons. Thus, the radiation outside the band of pumping of the laser is not lost, and may make a contribution to the increase in effectiveness of the pumping.

Dynamics, Equilibrium and Stability of Radiating Plasma

For purposes of optical pumping, the plasma should exist for a sufficiently long time: in this case, the dimensions of the source and the spectral characteristics of the radiation should not change substantially during the pumping process. Of course, the concept of "a long time" is quantitatively determined for each concrete physical case in its own way, but it is clear that the lifetime of the plasma should exceed the time of development of instabilities in it. /35

We will examine the equilibrium state of the simplest variant of a radiation source — a cylindrical column of plasma. Having made the heating output and the radiation flow equal to one another, as well as the pressure of the plasma and the magnetic field, we obtain that the density and dimensions of the plasma column are equal to 10^{18}-10^{19} cm^{-3} and 1-3 cm, respectively. A plasma temperature, equal to 20-30 kK, and a radiation spectrum are obtained from here. The time of radiation of this plasma column is determined by the energy reserves in the feed source.

Why then do the instabilities not disrupt this plasma configuration? After all, from studies of thermonuclear plasma discharges, it is well known that such a structure — a pinch-discharge — is rapidly destroyed, as a result of the effect of force instabilities. The term "force" indicates the cause of the instability — it is impossible to compensate for the magnetic force with the force of the plasma pressure with the smallest deviation of the plasma volume from equilibrium. The effect of one of the power instabilities is most simply illustrated by the following discussion (Fig. 5). We will assume

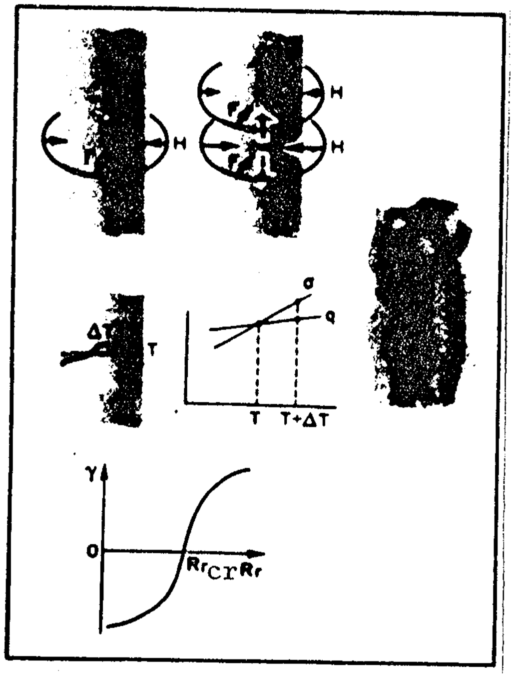

Fig. 5. CONSTRICTION (top): J—current; H—magnetic field; F—magnetic force, which constricts the plasma. On the left, this force is constant along the height of the discharge, and on the right, in the constriction zone, the force F is considerably greater than outside the constriction. П—plasma, issuing from the constriction zone.

SUPERHEATING INSTABILITY (in the middle). With a random jump in temperature ΔT, the equilibrium is disrupted: heating, proportional to the conductivity σ, becomes greater than the cooling, proportional to the radiation flow q. On the right is depicted the discharge which is subjected simultaneously to superheating and force instabilities; the dark and light threads correspond to the hot and cold regions of the plasma. The dependence of the increment of increase of the perturbations (exponent) γ on the Reynolds radiative number (below) is: stable region $Rr<Rr_{ii}$, unstable region $Rr>Rr_{ii}$.

that the radius of the plasma cylinder at a single point decreased, as compared with the equilibrium radius —a "constriction" occurred. Because of the possbility of issuing of plasma along the axis of the cylinder, the pressure of the plasma is maintained at the point of constriction, and the magnetic pressure increases, since the previous current will flow along a conductor of lesser cross-section. The occurring increase in magnetic pressure will bring about a further decrease in the cross-section of the plasma, and so on, so that, at the very end, this process will lead to breaking of the current. The time of development of this catastrophic instability turns out to be on the order of the dimensions of the plasma, divided by the speed of sound, i.e., 10^{-6} seconds. This is 100-1000 times less than is necessary for pumping of lasers. Other similar instabilities bend and twist the plasma pinch.

However, experiments convincingly show that constrictions do not develop in radiation discharges. As a result of the development of the theory of such discharges, it was established that, in them, the process of the transfer of energy and the energy balance are not determined by the particles of the plasma — electrons and ions, as takes place in thermonuclear discharges, but by radiation, generated by these very same particles. In order to note this difference from thermonuclear plasma, such plasma is called radiation plasma. However, we would note that, in radiating discharges, the pressure is determined, as before, by the particles. It turned out that the conditions of equilibrium (i.e., the equality of the heating output of the plasma and the radiation flow from it, and the equality of the magnetic and plasma pressures) lead to the /36 existence around the central dense and hot column of an extended zone of sparse, but still sufficiently hot, conducting plasma — the so-called corona. In thermonuclear discharges, the basic mechanism of transfer of energy is electron thermal conductivity. By equalizing the temperature and density of the plasma along the cross-section of the column, this conductivity lead to the existence of a sharp discharge boundary. Therefore, all of the plasma was involved in the constriction process, which lead to narrowing of the cross-section, and, in the final analysis, to breaking of the current and destruction of the discharge. In radiating discharges, the extended corona does not permit a concentration of current in any narrow area; therefore, an instability of the constriction type is absent in them.

Another widespread type of instability in plasma is the superheating instability. For the examined volume of plasma, at the existing temperature, let the condition of equality of the heating output and the flow of radiation be fulfilled. If the temperature changes randomly to a small magnitude ΔT, then the condition of thermal equality may be disrupted, since the heating output and the flow of energy usually depend differently on the temperature (see Fig. 5).

Another cause of the superheating instability is associated with the movement of small volumes of plasma. We will examine this case. Let the temperature in some volume of plasma, which was in a state of equilibrium until now, increase to a magnitude ΔT. As a result, the pressure increases in this volume, the plasma will expand, and its density will decrease. This will lead to a decrease in the flow of radiation, which is proportional to the density. The heating output, determined by the conductivity of the plasma, increases with an increase in the temperature, and practically does not depend on the density. As a result, in the examined volume, the energy imbalance will be intensified, and the initial fluctuation in temperature will increase. The process, which we have examined, takes place more easily if the region, covered by the fluctuation, is small (since it expands more rapidly); therefore, the probable picture of the development of the discharge consists of its breakdown into "threads" — hot and cold regions, extended along the current, in which the processes develop independently. Each of the threads is also subjected to force instabilities, which bend and twist it. As a result of competition between superheating and force instabilities, a complex picture of heterogeneous, pulsating, one might say turbulent, radiating plasma should appear. And such a picture was actually observed in the experiment.

Through comparison of the experimental and theoretical data, yet another important circumstance was noted. It turned out that the higher the optical density of the discharge, the closer its spectrum of radiation was to the spectrum of radiation of a black body, and the more homogeneous the plasma, and the better the theoretical predictions of the dimensions, density and temperature of the discharge coincided with the results of the measurements. With a decrease in the optical density, the discrepancy between the theory and the experiment became more appreciable. One might say that a transition was observed in the radiating plasma of the discharge — as a function of its optical density — from an easily predicted homogeneous stable (laminar) state to an unstable (turbulent) state.

Radiative Reynolds Number

The passage of a laminar flow of a liquid along a pipe into a turbulent flow, with an increase in the rate of the flow, is well known in hydrodynamics. Utilized for the quantitative characteristics of this passage is a dimensionless parameter, having received the name Reynolds number. In 1883, the English scientist O. Reynolds, in studying the flow of a liquid with colored streams in transparent pipes, showed that, with an increase in the rate of the flow, beginning with some value of it, the nature of the flow changes suddenly — from a layered laminar flow, it is transformed into an irregular, random, complicated flow — a turbulent flow. In this case, the law of resistance to movement along the pipe changes, i.e., the macroscopic characteristics of the flow change. The dimensionless Reynolds number $Re=vL/\nu$ is made up of three important magnitudes, which determine the flow: the rate v, the pipe diameter L, and the kinematic viscosity ν. The critical value of the Reynolds number, at which the indicated passage takes place, is equal to approximately 2000, which, with a pipe diameter of 1 cm, corresponds to a rate of flow of water of roughly 30 cm/sec.

Through the study of the movement of current-conducting liquids and gases, located in a magnetic field, it turned out that there exists a dimensionless parameter[2], called the magnetic Reynolds number Rm. It characterizes a similar passage /37 from the flow, in which the magnetic field has a regular nature, into the flow with an irregular field, and is determined by magnitudes which are important for the flow of a conducting liquid — the conductivity σ, the rate v, and the characteristic dimension L: $Rm=\sigma vL/c^2$ (c=the speed of light).

With all the outer dissimilarity of the magnitudes of Re and Rm, they reveal a profound qualitative similarity. These numbers characterize the ratio of the parameters, inherent to the local movement of elementary volumes of liquid, to the parameters which reflect its total integral movement as a whole,

[2] It was introduced by the well-known Swedish physicist S. Lundquist in 1952.

with the flow becoming turbulent with large values of these numbers. The Reynolds number is determined by the relationship between the forces of inertia and the forces of viscosity. The forces of inertia reflect the local nature of the movement (each volume of liquid strives to move independently), while the forces of viscosity lead to the establishment of some average flow. The magnetic Reynolds number is the ratio of the rate of displacement of the magnetic field, together with the volume of plasma, to the rate of its diffusion. In this case as well, the former parameter characterizes the tendency for movement of the magnetic field, along with the given volume of liquid, independent of the rest of the medium, and the latter parameter — the tendency for averaging of the field throughout the volume.

What then takes place in radiating plasma? In an optically thin (i.e., transparent for natural radiation) plasma, a superheating instability develops, because of the impossibility of compensating for the increase in heating by the radiation in the volume, where random fluctuation of the temperature took place. The force instabilities, which act especially rapidly in small volumes of plasma, bend and confuse the hot and cold regions. As a result, adjacent volumes begin to behave independently — the temperature, plasma density, current density and magnetic field fluctuate, and change irregularly from point to point. With a large optical thickness of the plasma (impervious for at least part of the natural radiation), the natural radiation is accumulated throughout the volume of the discharge. Therefore, in the balance of energy for the volume encompassed by the fluctuation, it is necessary to take into account the admission of energy from the radiation which exists in the plasma. It turns out that the presence of this radiation basically changes the behavior of the plasma: fluctuations do not have the opportunity to develop, and some average distributions are established in the plasma, which depend on the field of radiation, a contribution to which is made by all the volumes of the examined plasma.

Thus, the volumetric radiation, with which each volume of plasma radiates independently, could be a local characteristic in the given case. Radiation from the surface of the plasma, related to a unit volume, may be considered an integral characteristic. It is made up of radiation of individual volumes, with regard for absorption and re-radiation of the photons. This absorption and re-radiation promotes equalization of the forces throughout the volume of the plasma, and thereby hinders its "turbulization". One may imagine the photons in the form of microprojectiles, which fly through the plasma and shoot down all the irregularities.

The radiative Reynolds number $Rr = l_{\varphi}/L$, as the relationship of the average (along the spectrum) length of the free path of the photons l_{φ} to the dimesnions of the plasma L (i.e., its average optical thickness), was first introduced by us in 1969[3]. With this determination, it is similar to the Knudsen number, known in gas dynamics, which characterizes the degree of rarefication of a gas (the path of molecules figures in the Knudsen number, instead of the path of photons).

In the cited discussions, the plasma is essentially viewed as a two-component medium, consisting of particles and photons. The introduction of the radiative Reynolds number is a reflection of this circumstance. Thus, in magnetic radiating plasma, one should speak of three Reynolds numbers: standard, magnetic and radiative. If one notes that plasma, generally speaking, is a multicomponent medium, and consists of electrons, ions of different sorts and neutral particles, then it will become clear that one may introduce a large number of dimensionless parameters, similar to the Reynolds number. In essence (this is known from /38
the theory of non-isothermic plasma with an electron temperature which appreciably exceeds the temperature of the ions, when the transfer processes, specifically heat transfer, are determined by the electrons, and the inertia — by the plasma ions), the

[3]Rozanov, V. B., Rukhadze, A. A., "Strong-Current Radiating Discharges. A Survey Report", in the collection: Tr. IX Mezhdunar. konf. po ionizovannym gazam, Bucharest, 1969; Preprint FIANa, Moscow, 1969, No. 132.

variations and stability of such plasma strongly depends on the electron thermal conductivity. In thermonuclear plasma, α-particles and neutrons play an important role in the energy balance, and, in such plasma, one may discuss the necessity of introducing the corresponding Reynolds numbers, and, in the plasma of stars, one may think of the neutron Reynolds number, and so on.

However, we will return to the stability of the radiating plasma. The number $Rr = l_*/L$ also characterizes the degree of rarefication of the plasma, but with respect to the photons of the natural radiation. In this connection, the radiative Reynolds number takes on a new, extremely important property — with its change from infinity to zero, the intensity of the radiation in the plasma increases from zero to an equilibrium value, determined by the well-known Planck formula. This property distinguishes photons from all other particles, and, in the problem of stability of radiation discharges, it is the most important circumstance.

In order to see how the radiative Reynolds number affects the stability of the plasma, it is necessary to trace the evolution of its small perturbation. It is simplest to do this by examining the equation of energy balance. Omitting the intermediate calculations, we will say that the solution of the equation for temperature perturbations has an exponential nature, with the exponent depending on Rr. With $Rr \to \infty$ (optically transparent plasma), this indicator is positive, and the perturbation may develop and grow — this is the case of unstable plasma. With $Rr \to 0$ (optically dense plasma), it is negative, the perturbations attenuate, and the plasma is stable. A shift in the conditions takes place with $Rr_{cr} \approx 1.5-2$ (see Fig. 5). More detailed analysis shows that, if the plasma loses from 10 to 30% of its total radiative energy under conditions close to the conditions of a black body (i.e., with an optical thickness near to one for this part of the photons), this ensures its stable state and, accordingly, a prolonged time of life and radiation.

The superheating instability of the plasma, which leads to turbulence, is manifested in different physical phenomena. Ionization turbulence of weakly ionized plasma with a current is known, for example, plasma in MHD-converters of thermal energy into electrical energy. Under actual conditions of MHD-plasma, the radiation does not make a substantial contribution to the energy balance, and, therefore, $Rr \gg 1$; the electron thermal conductivity is also not substantial, because of the effect of the magnetic field, and, as a result, such plasma is usually strongly turbulent.

Superheating ionization instability, in the form of contraction of the current into narrow channels (current contraction), is observed with breakdown of the high pressure gases, and with the independent and dependent discharges often utilized in powerful gas lasers. These discharges take place in a mixture of inert gas and an easily ionized admixture. If ionization of the mixture takes place primarily because of collisions of electrons with the atoms of the admixture, this discharge is unstable with respect to the contraction. If the ionization bears a staged nature (excitation of the atoms of the inert gas takes place via an electron impact, and the atoms of the admixture are then ionized with their photodecomposition), then this discharge is stabilized. The fact that the radiation of the excited atoms "carries away" the perturbations of temperature to great distances (to the length of the free path of the photodecomposition quanta) also equalizes the conditions throughout the volume of the discharge.

Among the other phenomena, one may note the instability of the current layer, and the reclosing of the force lines of the magnetic field in the Earth's magnetosphere, which is evidently associated with the decrease in the contribution of the natural radiation of the conical-spherical plasma. It is possible that the granulization structure of the solar photosphere is also associated with the development of a superheating instability, which is only suppressed at great depths (greater than 10^4 km), where the radiative thermal conductivity smooths the conditions in the solar plasma.

Experimental Studies of Radiating Discharges

In the previous sections, we briefly described the basic trends and results of the theoretical studies. In the laboratories, we carried out numerous experiments, developed diagnostic methods, and measured the different characteristics of powerful radiating discharges. In this section, we will set forth the basic results of experiments, related to the most interesting /39 types of discharges — direct, inverse and multichannel pinches, expanding discharges in a dense gas, and dynamic plasma discharges in magnetic plasma compressors.

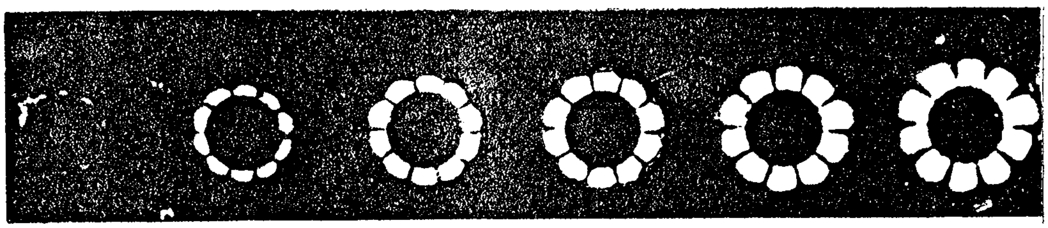

Fig. 6. Frame-by-frame photographing of 10-channel discharge (inverse pinch, view from the end). On the left —initial stage, on the right—developed stage, with the entire process occupying 50 μsec. The individual channels and the total shock wave, which surrounds the discharge, are clearly visible.

First, several words on how the plasma in various devices is created. There are three basic methods: rupture of the conductor (thin wire); electrical breakdown and subsequent discharge in the gas which fills the chamber; erosion, vaporization, heating and ionization of the substance of the dielectric wall of the chamber, with subsequent discharge in the product plasma. The first method makes it possible to create plasma from metals (lithium, tungsten and so on), the second is used in the case of molecular and inert gases, and the third is characteristic for dynamic plasma discharges.

In pinch-discharges (i.e., cylindrical discharges, in which the plasma is held by the natural current's magnetic field), we measured the highest effectiveness of transfer of the energy of the feed source to radiation — 100% in the quasistationary stage (all of the introduced energy was radiated), and up to 70% integrally during the entire process. In these discharges, in order to create plasma, various substances were tested — lithium, neon, aluminum, copper, lead, tungsten, cadmium and other materials, and the radiation spectra were measured — from that near to the spectrum of a black body to various types of optically transparent selective radiation. In the case of lithium, we observed precisely such selectivity, which was described in the previous section (Fig. 3). The effectiveness of radiation in the given band of the soft region of the spectrum increased by 3-5 times in this case, as compared with the black body variant. Selective radiation was obtained in the region of photorecombination of two-fold ionized lithium, with a quantum energy of 75 ev (wavelength of approximately 18 nm). In the case of neon, we observed selective radiation, associated with recombination on the basic level. The problem of stability of the radiating plasma was studied experimentally on direct pinch-discharges.

The inverse pinch-discharge received its name because the radiating plasma in it forms a cylindrical shell, along which the current flows in a single direction, and the entire plasma current, or part of it, returns in the opposite direction along a special massive conductor, located on the axis of the cylinder. This configuration is of interest, in connection with its higher stability, as compared with the direct discharge. The fact is that, in the inverse discharge, part of the magnetic field is predetermined by the central current, and, consequently, is not subject to fluctuations, which, in the final analysis, increases the stability. In the inverse pinch, the surface of the plasma is great, and may radiate a large amount of energy; however, the plasma temperature in it is usually lower than in the direct discharge. Shown in the photograph (Fig. 6) are the sequential stages of the inverse pinch, formed by the rupture of several wires. The photograph demonstrates the stable development of the discharge.

The expanding discharge in a dense gas proved to be an ideal source of pumping for gas lasers, operating on the principle of photodissociation of type SF_6I molecules (so-called photodissociation iodine laser). For photodissociation, as a result of which iodine is split off in an excited state, quanta with an energy of about 4.4 ev were required. Transparent materials of the type of glass, and even quartz, absorb such quanta. Thus, the separation of the pumping source from the laser medium lead to a substantial decrease in effectiveness. The efficiency was found in the accomplishment of the discharge in the same gas medium. These /40 discharges were studied; it turned out that they are related to the optically dense discharges, and the radiation ensures their stable development, with the role of the magnetic field being small in them; therefore, they expand. However, the rate of expansion proved to be low, and the time of radiation was sufficiently great. This fact required explanation, since the temperature of the plasma and the radiation flow were great (plasma temperature of 50-60 kK), and this did not agree with the low rate of movement (about 1 km/sec; we would recall the evaluation of the rate of expansion of hydrogen plasma: 50 km/sec), and the change in the molecular composition of the gas did not provide an explanation for this effect. It turned out that the discharge has a complex structure — it consists of a hot core (heat wave), surrounded by a shock wave, which is disseminated through the laser medium. The temperature of the substance in the shock wave is actually small (several thousand Kelvin), and corresponds to the indicated rate of expansion, and the radiation is provided by the hot core.

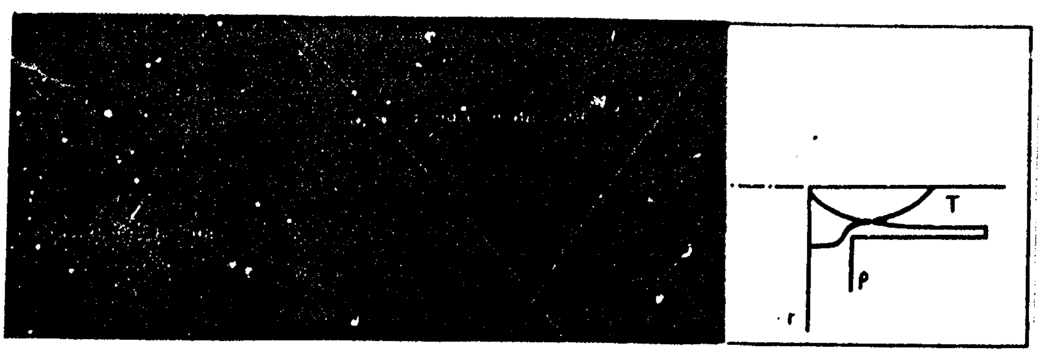

Fig. 7. Photochronograph and structure of individual discharge channel in gas. On the right — profile of temperature T in discharge, and jump in density ρ close to the front of the shock wave.

Measured in this type of discharge was the effect of gas-dynamic selectivity, described above, and powerful lasers are created, which have found the most widespread use, including for thermonuclear studies. Given in Figure 7 is a photochronograph of such a discharge. The discharge was photographed from the side through a narrow slot; because of movement of the image on the recording film, one may continuously trace the entire process of development of the discharge. A shock wave, a radiating central portion, and even weak contraction of the discharge by the magnetic field in the later stage of its development are evident.

In plasma-dynamic discharges, the plasma is first accelerated by the magnetic field. The accelerated plasma in the magnetic field moves along such a trajectory that its bunch, having originally had the shape of a roll, is compressed to a nearly spherical formation, which is dense and hot. With the collisions of plasma streams, the kinetic energy is changed into heat, and then, in a spherical bunch-focus — into radiation. In the flight stage, the plasma streams may also be heated by the current. Insofar as not all of the velocity is damped in the focus, it is a dynamic formation — as if the plasma passes through this bunch. In this type of discharge, the separation of the stages of primary access of energy from the feed source (through the magnetic field) and the liberation of energy in the dense radiating plasma with collision of the plasma streams are important. Such gas-dynamic access of the energy, prescribed by external conditions (rate and density of streams), without making it possible to develop with superheating and force instabilities, leads to dynamic stability of the focus, and ensures a higher rate of introduction of energy into the plasma, as compared with electrical heating. By varying the material and amount of the plasma, the rate of the streams and the magnetic field, one may regulate the temperature and density of the plasma, the spectrum of radiation, and its other parameters. Based on plasma-dynamic discharges, sources of pumping are created, as well as lasers which operate in a mode of repeating pulses, and high selectivity of the radiation is achieved, right up to the region of energies with quanta of 50-100 ev, with an effectiveness 20-30 times higher than in the case of a black body. The rates of the plasma flows are 30-100 km/sec /41 during the formation of the plasma focus.

We would note that, in discharges which have been spoken about in the present section, radiating surfaces with an area of about 1 m^2 are accomplished, and the radiation energy was tens and hundreds of kilojoules.

Theoretical predictions play an extremely important role in the program of studies of various discharges, and searches for optimal solutions of multiparametric systems. However, in such complex dynamic systems, the analytic approach proves insufficient. Therefore, in the early stage of the studies, the problem of the numerical simulation of the processes in strong-current discharges, including radiation, was posed. Without having the possibility here of telling about all aspects of the study, we would only note that the developed programs made it possibly not only to quantitatively describe and predict the phenomena in radiating plasma and carry out a broad search for optimal variants of units, but also created a serious mathematical base for the next generation of programs. This was one of the first examples in our country of numerical simulation of the most complex processes in dense radiating plasma of strong-current discharges.

A lack of space unfortunately does not permit us to also tell of the developed diagnostic methods; we would only note that many methods were developed first, and are now widely used in laboratories.

The fundamental studies of the physics of strong-current radiating discharges, posed and carried out in our country, have created bases for a new prospective division of science — the physics of dense radiating plasma and magnetic fields. As is often the case, the practical requirements (creation of optical pumping sources) initiated studies of an in-depth fundamental plan, having, in turn, provided a basis for broad and diverse applications.

Here is a very brief list of applications of the new sources of radiation and the new scientific results. Photodissociation lasers on atomic iodine were created, including a powerful laser with short pulses for thermonuclear studies; lasers on electron transitions of S_2, XeO, I_2, HgBr and XeF molecules have been produced; lasers on solutions of complex organic compounds (dyes) and photodissociation lasers, operating in a repeating pulse mode, which are convenient in practice, have also been created. Optical radiation of the front of a divergent discharge is widely utilized in photochemistry for determining the rates of reactions of atoms, molecules and radicals in basic and excited states. High-power radiating plasma is a very effective ultraviolet source for lithography, in microelectronics, and for determining the optical properties of metals under conditions close to the solid body—liquid phase transition. The criteria of stability, which take into account radiation, are used in studies of reclosing of force lines of a magnetic field in the magnetospheres of stars and planets, and the created difference schematics (having received the name of completely conservative — in these schematics, in addition to the laws of conservation, a number of physical relationships are precisely fulfilled) and mathematical programs are utilized for numerical simulation of various physical processes. Also created were standard sources of strong shock waves and brightness in the ultraviolet region of the spectrum. Powerful optical sources have gone beyond the limit of physical laboratories, and even in medicine, they have proved useful — for ultraviolet sterilization of operating instruments.

Many of the indicated studies are not only practically important, but are also interesting from the general physical point of view, and one would be able to tell of them individually on the pages of the journal "Priroda".

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