Thus, the experimental data obtained by us are in qualitative agreement with the multifocus model of self-focusing. A quantitative comparison of the experimental data with the theory is difficult, since our experiments showed only the result (the damage to the glass), and not the very process of the self-focusing. Furthermore, we do not know precisely the mechanism of the nonlinearity of the refractive index of the investigated glasses.

We note that the use of laser pulses of rectangular form and variable duration makes it possible to investigate the temporal evolution of the pointlike self-focusing pattern and to ascertain the mechanism of its occurrence in various media.

The authors are grateful to V.N. Shkilev for help in the preparation and performance of the experiments.

[1] S.A. Akhmanov, A.P. Sukhorukov, and R.V. Khokhlov, Usp. Fiz. nauk 93, 19 (1967); 95, 231 (1968) [Sov. Phys.-Usp. 10, 609 (1968); 11, 394 (1968)].
[2] V.V. Korobkin, A.M. Prokhorov, R.V. Serov, and M.Ya. Shelev, ZhETF Pis. Red 11, 153 (1970) [JETP Lett. 11, 94 (1970)].
[3] M.T. Loy and Y.R. Shen, Phys. Rev. Lett. 22, 994 (1969).
[4] A.L. Dyshko, V.N. Lugovoi, and A.M. Prokhorov, ZhETF Pis. Red. 6, 655 (1967) [JETP Lett. 6, 146 (1967)].
[5] A.L. Dyshko, V.N. Lugovoi, and A.M. Prokhorov, Dokl. Akad. Nauk SSSR 188, 792 (1969) [Sov. Phys.-Dokl. 14, 976 (1970)].
[6] R.Y. Chiao, E. Garmire, C.H. Townes, Phys. Rev. Lett. 13, 479 (1964).
[7] V.N. Lugovoi and A.M. Prokhorov, ZhETF Pis. Red. 7, 153 (1968) [JETP Lett. 7, 117 (1968)].
[8] M. Hercher, J. Opt. Soc. Am. 54, 1563 (1964).

CONTINUOUS OPTICAL DISCHARGE

N.A. Generalov, V.P. Zimakov, G.I. Kozlov, V.A. Masyukov, and Yu.P. Raizer
Institute of Mechanics Problems, USSR Academy of Sciences
Submitted 1 April 1970
ZhETF Pis. Red. 11, No. 9, 447 - 449 (5 May 1970)

We report in this communication, the production, for the first time, of a continuously burning hot plasma, maintained by a beam from a cw CO_2 laser. The plasma burns in the center of a gas volume, far from all solid surfaces. This confirms experimentally the feasibility of producing the "optical plasmotron" considered theoretically in [1].

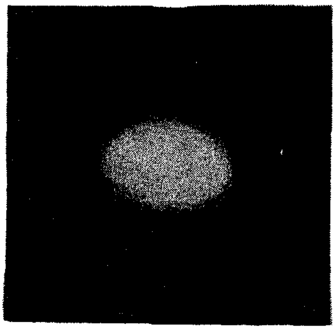
Our work is related to a certain degree to the work of P.L. Kapitza [2], who obtained a free continuous microwave discharge in a resonator. In our case the plasma was maintained continuously at higher frequencies ($\lambda = 10.6\ \mu$).

It is important that the intensity of the light feeding the discharge is lower by two orders of magnitude than the breakdown threshold of the cold gas, and the discharge is ignited in the beam by producing an initial absorbing plasma with the aid of an external source. The possibility of forced ignition of a laser spark at light intensities below the breakdown threshold was noted in [3], where the question of the initiation and the limits of "detonation" of the beam was discussed. Such an ignition was realized in experiments [4] performed with a millisecond pulse from a neodymium laser; these experiments revealed another laser-spark propagation mode, namely "slow burning" of the beam, requiring less power than "detonation."

To maintain the plasma, we used in our experiment the commercial laser "Lund-100," the power output of which was raised by modification to 150 W. The discharge current in the laser was 100 mA, and the beam diameter was 2 cm. The beam passed through a salt window into a steel cell filled with xenon at pressures up to 10 atm, was reflected back by a spherical mirror with f = 2.5 cm, and was focused in the center of the vessel into a circle of 0.1 mm diameter.

The stationary discharge was ignited by breaking down the gas with radiation from another Q-switched CO_2 laser, producing pulses of 10 kW power, 0.3 - 1.5 μsec duration, and repetition frequency 50 - 250 Hz. This laser was used in [5] to investigate the phenomenon of breakdown by infrared radiation.

The beam of the ignition laser passed through another salt window into a cell at right angle to the beam of the plasma-feeding laser, and was focused backwards by a spherical mirror of f = 1.5 cm into a circle of 0.08 mm diameter. The foci of the two mirrors were made precisely coincident, and otherwise no continuous discharge (which always initiated at the focus) could be produced. The breakdown plasma existed for several (up to 10) microseconds following each pulse, and its dimensions were much smaller than the dimensions of the stationary plasma.



The employed ignition system, owing to its relative complexity, is possibly not promising for practical applications. It is, however, very convenient for experimentation. First, periodic ignition can be repeated as long as desired; second, unlike ignition by means of an ordinary discharge, we are guaranteed against the entry of electrode-erosion products into the optical discharge.

After ignition of the stationary discharge by the breakdown plasma, the beam of the breakdown laser could be obstructed, and the discharge continued in exactly the same manner as with the beam uncovered. The discharge was very stable under certain conditions, could last a long time (10 minutes and more), and was terminated in practice either as a result of misalignment of the supply laser (since we were near the very threshold for discharge maintenance under our conditions), or else was terminated on purpose to prevent excessive heating of the cell, which was not cooled.

The plasma emitted blinding white light, and its shape, dynamics (in the case of instability), and brightness distribution could be conveniently examined by projecting the glowing spot on a remote screen. A photograph of the stationary discharge is shown in the figure.

A stable discharge in xenon was observed under the concrete experimental conditions at pressures from 3 to 4 atm. Below 3 atm, the discharge could not be started at all, although the igniting breakdown occurred in a perfectly stable manner, but the supply laser power was insufficient. At 3.5 atm, which was optimal from the point of view of stability, the plasma was more or less symmetrical with respect to the focal point, being stretched out along the beam axis. Its longitudinal dimension was 1 mm and the maximum diameter 0.6 mm. The symmetry is evidence that the plasma does not absorb the laser beam completely.

At higher pressures, starting with 4 atm, the discharge becomes asymmetrical, stretching in the direction of the mirror, opposite to the direction of the supply beam; this is due to the increased opacity of the plasma. Under such conditions, however, the discharge more frequently died out. It is possible that combustion-instability effects arise in this case.

Estimates made with the aid of the formula for the absorption coefficient of infrared laser radiation show that the plasma temperature is approximately 14,000°K (the temperature will be lower in gases having an ionization potential larger than that of xenon).

The described experiment is of fundamental significance in that the question of producing an analogous stable spatially-localized plasma in free air, as well as the question of increasing the plasma dimensions, now reduces essentially only to the question of increasing the power of the supply laser (in our experiment the power was quite modest).

It is important that once the discharge is ignited, it can be moved continuously in space at a sufficiently slow motion of the plasma-feeding beam. The rate of this motion need be only lower than a certain limit dictated by the existence of a "normal discharge propagation velocity," analogous to the flame velocity in ordinary combustion [6].

The results of the measurements and of the theoretical calculations of the phenomenon will be presented in later papers.

The authors are deeply grateful to A.E. Abaliev for much work performed during the course of the experiments. We are also grateful to D.I. Roitenburg for discussions.

[1] Yu.P. Raizer, ZhETF Pis. Red. 11, 195 (1970) [JETP Lett. 11, 120 (1970)].
[2] P.L. Kapitza, Zh. Eksp. Teor. Fiz. 57, 1801 (1969) [Sov. Phys.-JETP 30, 973 (1970)].
[3] Yu.P. Raizer, ZhETF Pis. Red. 7, 73 (1968) [JETP Lett. 7, 55 (1968)].
[4] F.V. Bunkin, V.I. Konov, A.M. Prokhorov, V.B. Fedorov, ibid. 9, 609 (1969) [9, 371 (1969)].
[5] N.A. Generalov, V.P. Zimakov, G.I. Kozlov, V.A. Masyukov, and Yu.P. Raizer, ibid. 11, 343 (1970) [11, 228 (1970)].
[6] Yu.P. Raizer, Prikl. Mat. Teor. Fiz. No. 3, 3 (1968); Usp. Fiz. Nauk 99, 687 (1969) [Sov. Phys.-Usp. 12, No. 6 (1970)].

ION ENERGY BALANCE IN THE PLASMA OF A TOKAMAK MACHINE

L.A. Artsimovich, A.V. Glukhov, and M.P. Petrov
Submitted 6 April 1970
ZhETF Pis. Red. 11, No. 9, 449 - 452 (5 May 1970)

It was shown in [1, 2] that when the ratio of the external magnetic field intensity H_z to the intensity of the field H_ϕ produced by the current flowing in the plasma of a closed Tokamak magnetic trap is large enough, it is possible to produce a macroscopically stable plasma loop that retains well the energy accumulated in it. This has made it possible to heat electrons to a temperature $T_e \sim 1 \times 10^3$ eV and ions to a temperature $T_i \sim 5 \times 10^2$ eV in hydrogen and $T_i \sim 4 \times 10^2$ in deuterium.

The most important research problem performed with the Tokamak is to establish and explain the laws governing the thermal and diffusion processes in the plasma. Let us consider part of this general problem, namely the energy balance of the ionic component. Measurements of the neon temperature by analysis of the energy spectrum of the charge-exchange atoms show that, other conditions being equal, T_i increases with increasing plasma concentration and decreases with increasing ion mass (when the hydrogen is replaced with deuterium). These facts favor the assumption that the ions are heated principally as a result of heat exchange with the electrons in Coulomb collisions. We take this