Elongated high-temperature, dense plasma produced by a high-power-laser heating of a capillary discharge

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A novel method for producing a high-density, high-temperature plasma medium in which light amplification in the soft x-ray region may occur is described. A cold dense plasma is produced by a slow electrical capillary discharge and subsequently heated by a high-power laser pulse.

Various designs for producing a soft x-ray laser require a large homogeneous plasma (with a scale length of at least 100 μm, having a density of the order of 10^{20} cm^{-3}. Such plasmas allow propagation along a gain direction without substantial refraction.[1] A number of methods for producing low-density gradient plasmas have been investigated. These include exploding foils,[2] dextran foams,[3] carbon fibers,[4] gas-puff Z-pinch method,[5] and a magnetically confined plasma.[6]

In this paper we report the production of a large, high-density, high-temperature plasma by combining a high-power laser with a capillary electrical discharge. A low-temperature, high-density plasma produced by passing a slow electrical discharge through a flat capillary filled with an appropriate element is heated by a 20-GW Nd:glass laser pulse focused to a line. The laser beam is synchronized with the discharge so that it reaches the plasma when the plasma has emerged a few hundred microns from the capillary.

The energy required for the creation of the initial plasma is stored in a capacitor and switched into a flat capillary which acts as a resistive element. The obtained dense, low-temperature plasma[7] (of the order of a few electron volts) expands along the capillary. This expansion is followed by wall ablation. The power which is dissipated in the discharge controls the amount of wall material which is ablated into the capillary volume. Thus by properly choosing the discharge power and the volume of the capillary, the required plasma density can be obtained. For plasma densities between 10^{20} cm^{-3} and critical, the 1.06-μm Nd laser absorption is mainly due to inverse bremsstrahlung. For a homogeneous plasma, the absorbed energy will be approximately evenly distributed over a distance which is of the order of the inverse bremsstrahlung optical depth. Thus the plasma conditions of high temperature and density can be maintained during the laser-pulse duration over distances of several hundreds of microns. In such plasmas favorable conditions for population inversion in lasing schemes based on collisional excitation may be obtained.

The plasmas-producing capillary and the illumination geometry are shown in Fig. 1. The capillary, which measures 1 cm long by 1 cm high by 0.2-mm separation and which is electrically connected to a 60-μF capacitor charged to 2.5 kV, is triggered by a third electrode. The discharge current which reaches its peak 4 μsec after initiation is monitored by a Rogowsky coil. The whole setup rests on an XYZ stage, the center of which is positioned in the line focus of an $f/20$ cylindrical lens. The Soreq Nuclear Research Center 20-GW Nd: glass laser[8] is focused to a line 8 mm long by 0.2 mm wide, giving 1.2×10^{12} W/cm^{-2} approximately 0.3 mm above the capillary exit. The size of the high-temperature plasma is measured by means of two perpendicular x-ray pinhole cameras, and its x-ray spectrum—by a spatially resolving RAP flat crystal spectrometer and the amount of the laser energy transmitted through the plasma—by a calorimeter. The visible light which is emitted from the plasma is recorded by a video camera and a photodiode. The latter also monitors the time delay between the initiation of the discharge and the arrival of the laser pulse.

In most of our experiments the capillary was filled with Teflon [$(CF_2)_n$]. The discharge current from such an experiment, as measured by the Rogovsky coil, is shown in Fig. 2(a). Figures 2(b) and 2(c) show the visible light emitted by the plasma as measured by a photodiode. In case (b), which corresponds to a capillary discharge with no laser action, no x-ray radiation was observed. Case (c), corresponding to a combined action of capillary discharge

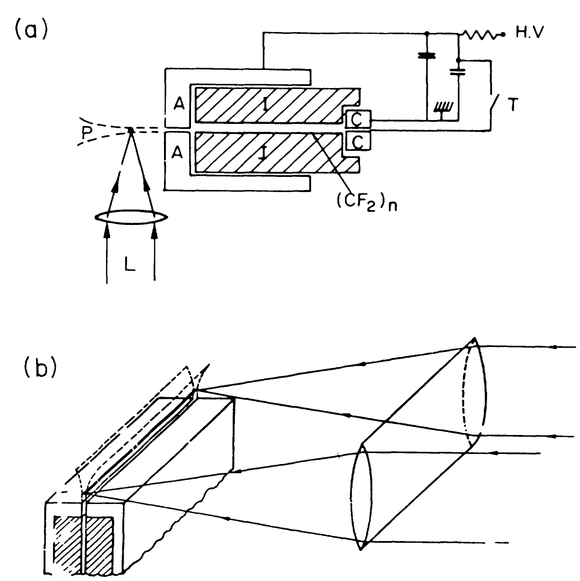

FIG. 1. The plasma producing capillary (a) and the illumination geometry (b): A—anode, C—cathode, I—insulator, $(CF_2)_n$—teflon, T—trigger, P—plasma, L—laser light.

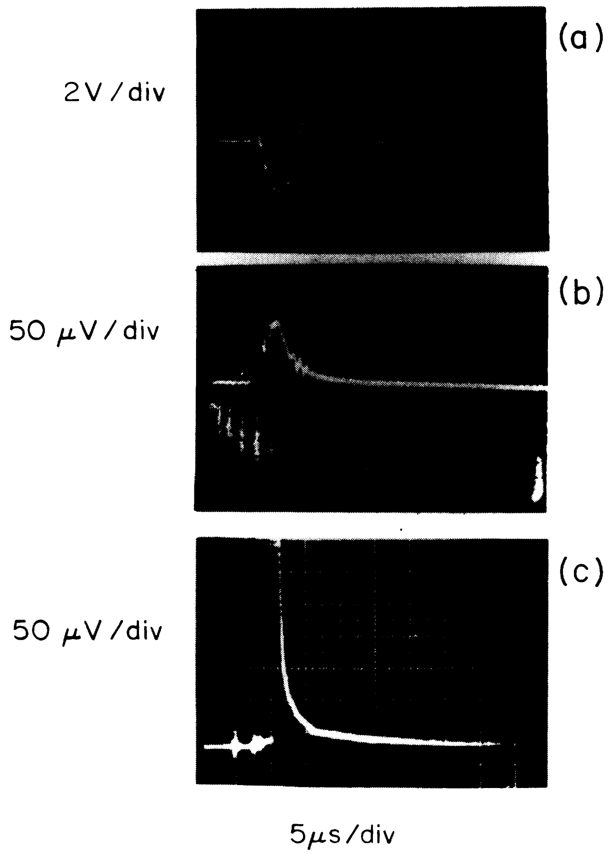

FIG. 2. The discharge current driving the capillary (a) as recorded by the Rogovsky coil and the visible light output from a capillary discharge with (b) and without (c) laser action as recorded with a photodiode.

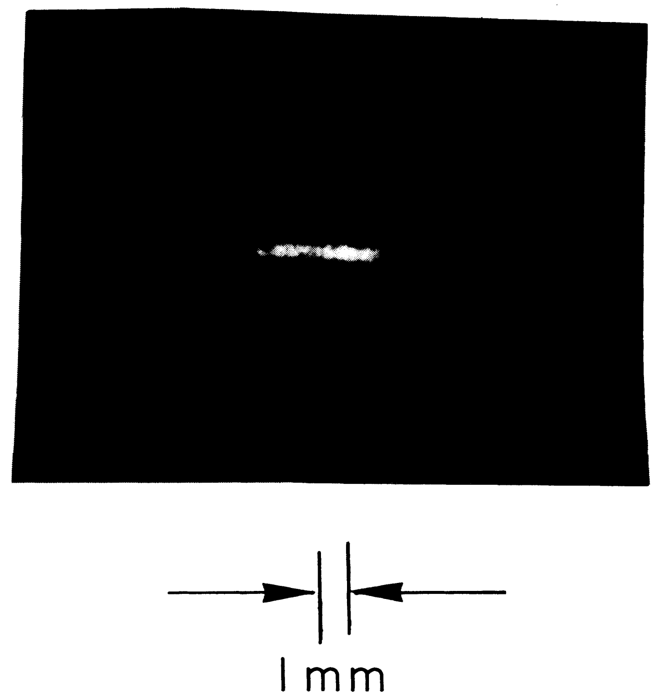

FIG. 3. An x-ray pinhole photograph of the hot dense plasma.

and laser operation, shows a much larger optical signal. In addition strong x-ray radiation emitted by the high-temperature plasma was also observed. The pinhole photographs (one of which is shown in Fig. 3) indicate that the plasma is 8 mm long and 0.4 mm wide.

The x-ray spectrum of the heated plasma recorded by a RAP flat crystal spectrometer is shown in Fig. 4. The observed spectral range is 12.5 to 17 Å. Lines of Li-like

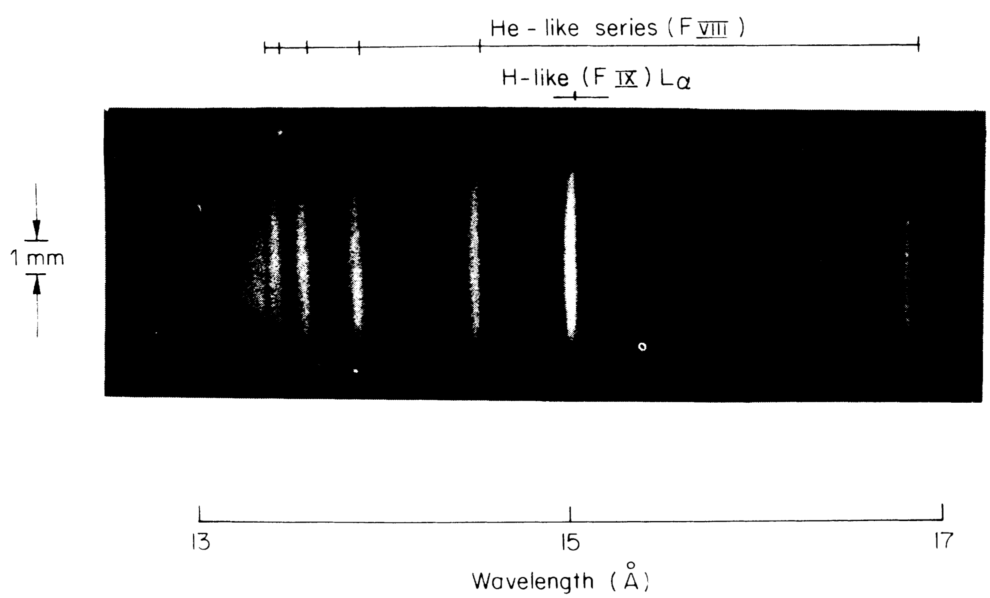

FIG. 4. An x-ray spectrum of the dense and hot plasma obtained when combining laser action and capillary discharge.

(satellites), He-like, and H-like fluorine appear in the spectrum. The line identification was done following Ref. 9. These lines include $1s^2$-$1snp$ transitions with the principal quantum number as high as eight. Assuming that Stark broadening is dominant, an electron density of about $N_e \sim 10^{20}$ cm^{-3} was obtained from the relation[9] $n = 1.7 \times 10^3\ Z^{2/5} N_e{}^{-2/5}$ where Z is the mean nuclear charge, N_e the electron density, and n the principal quantum number of the last member of a particular series which is still clearly observable. An average electron temperature of about 250 eV was derived from the intensity ratio of the H-like and the He-like lines, assuming coronal ionization equilibrium, and using approximate cross sections for ionization and recombination from Ref. 10, and excitation cross sections from Ref. 11.

In order to derive the plasma dimensions, a 1.5-mm-wide slit was placed between the plasma and the spectrometer crystal to provide spatial resolution perpendicular to the laser axis. This enabled us to obtain an additional estimate of the plasma dimensions from the length of the spectral lines and their width. The thus measured plasma dimensions of 8×0.4 mm are in agreement with the pinhole camera results. In addition, the measured line intensities, which are fairly uniform along the entire length of the line, indicate that the plasma is fairly uniform along its long dimension. The pinhole pictures confirm this fact.

The measured amount of the transmitted laser light showed that only 5% of the light was found in a 5° cone. Since the deposition of the laser energy into the discharge plasma is due to inverse bremsstrahlung, for an electron density below critical, the reflection of the laser light from the plasma may be ignored.

Thus, using the inverse bremsstrahlung coefficient[12] and taking into account the plasma dimensions and the amount of transmitted energy, we again find a density of about 10^{20} cm^{-3}. Additional corroboration of the estimated values of electron temperature and density is obtained from the presence of H-like lines in the spectrum of the plasma. In a plasma undergoing ionization, the appearance of H-like ions requires that the ionization time be shorter than the laser-pulse length. The time required to ionize fluorine up to the H-like stage can be estimated[13] from $\tau_H \sim (N_e S_{He})^{-1}$, where N_e is the electron density and S_{He} is the electron impact ionization rate coefficient from He-like to H-like stages. Using $N_e \sim 10^{20}$ cm^{-3} as derived above and S_{He} values from Lotz,[14] an electron temperature of higher than 250 eV is obtained.

We have developed a new method for the creation of high-density, high-temperature elongated plasma. This plasma is obtained by heating by means of a high-power laser a cool plasma obtained from an electrically discharged capillary. The major advantage of the method proposed here is the separation between the process of creating a high-density plasma and the way by which this plasma is heated. This separation provides the possibility of employing the conditions which are optimal for population inversion production. The electron density is simply controlled by varying the electrical energy supplied to the capillary while the temperature is controlled by varying the laser intensity. The plasma density that can be achieved by the proposed method is limited by the pressure that the capillary can withstand, and densities as high as 10^{22} cm^{-3} have been obtained.[7] The temperature can be raised by using a more powerful laser. It scales as laser flux by the power of 4/9. In addition the very same scheme can also be used in order to obtain controlled plasma regions which are essential for spectroscopy experiments dealing with plasma modeling.

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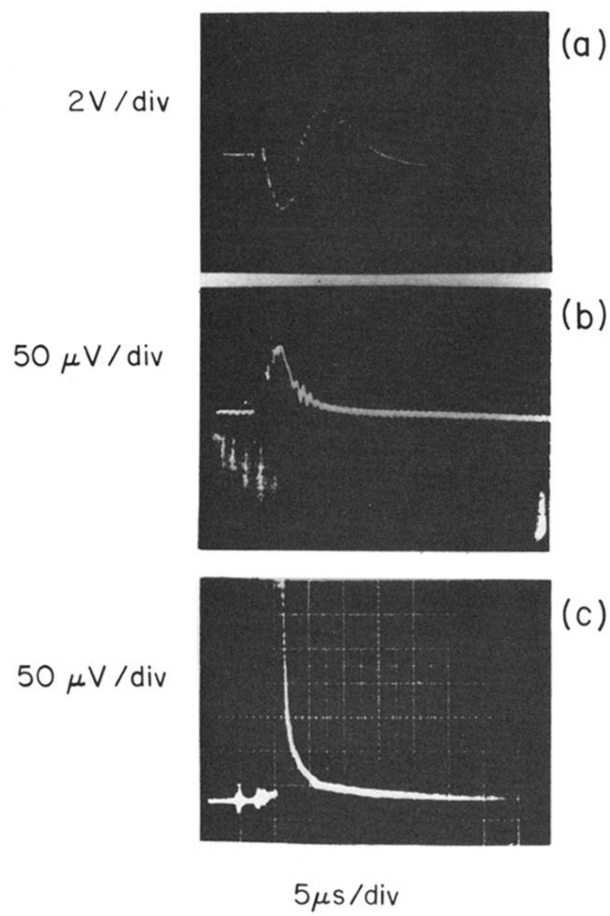

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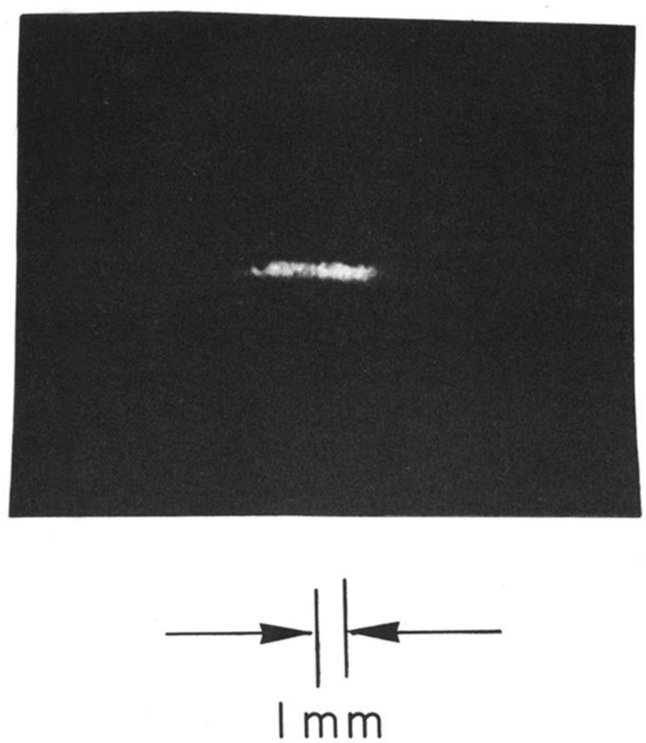

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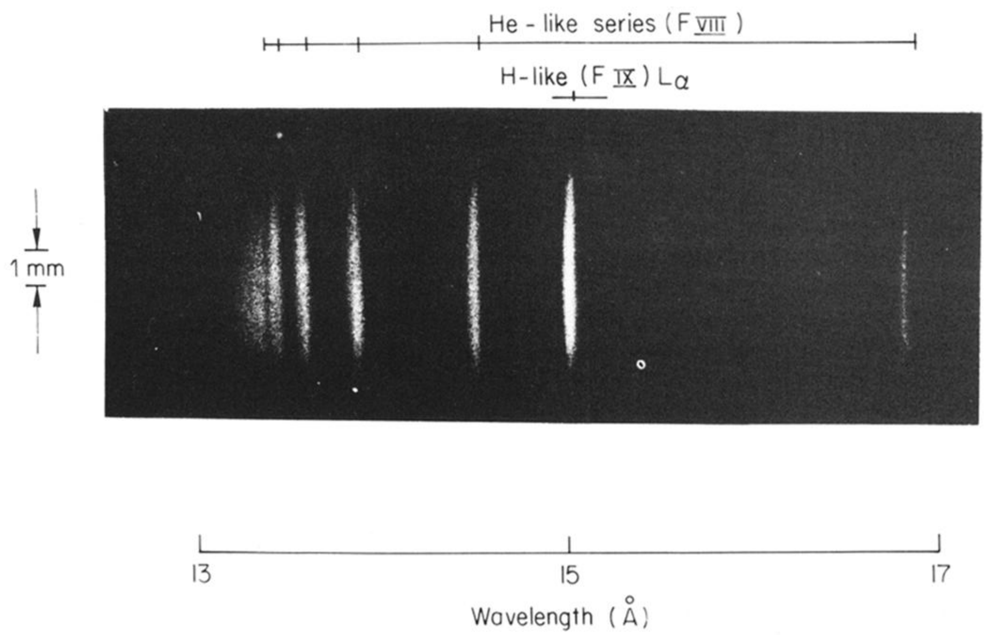

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