Cooling of optical-field-ionized plasmas

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Time-resolved investigations of soft-x-ray radiation from helium and oxygen plasmas produced by optical-field ionization in an intense laser field are performed. The possibility of rapid cooling of these plasmas by metal pieces is studied. It is shown that the time duration of the radiation components produced by three-body recombination pumping can be significantly reduced in the vicinity of metal surfaces. Soft-x-ray lasing at 37.4 nm in O III ions with a gain-length product $GL \simeq 4.4$ is demonstrated. [S1063-651X(99)15102-X]

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I. INTRODUCTION

Intense ultrashort-pulse laser systems can produce strongly nonequilibrium plasmas by optical-field ionization (OFI) of gaseous (or cluster) media. In a previous paper [1] we demonstrated possibilities to manipulate the plasma parameters and the temporal structure of the line emissions by varying the pump laser frequency and polarization. It is well known that to achieve amplification on soft-x-ray transitions to the ion ground states, a rapid recombination and thus very low electron temperatures are necessary. Unfortunately, in many cases the initial electron temperatures of OFI plasmas are too high to provide efficient recombination pumping of the upper laser level. Therefore, additional cooling mechanisms for OFI plasmas are necessary.

The idea of cooling laser produced plasmas by metal pieces is very old and has been successfully applied in [2], where the first soft-x-ray laser with recombination pumping has been demonstrated. It is natural to ask whether the same idea can be used for cooling of OFI plasmas. The OFI plasma can be produced very close to a metal surface in a small well-defined volume determined by the focusing optics. In this case the estimated cooling time due to thermal conduction (see below) could be of the order of 100 ps.

In previous experiments we demonstrated amplification on the $2p3s(^3P)-2p^2(^3P)$ transition in O III ions at 37.4 nm [3]. In these experiments the laser focus was positioned very close to the metal surface of the gas injecting nozzle. Several attempts of other groups to repeat our observations in a pure gaseous medium (far from solid surfaces) have failed [4,5]. It appears that in the pure gaseous medium the initial electron temperature of the OFI oxygen plasma is not sufficiently low for a fast recombination and an inversion to the ground state. Additional cooling of this plasma is required. In [3] cooling via thermal conduction to the metal nozzle has been responsible for successful observation of amplification in O III ions.

In this paper experimental investigations of OFI plasma cooling by metal pieces are performed. It is shown that a very rapid recombination can be achieved for He^{2+} and O^{3+} ions. Experimental results reported in [3] are confirmed. In Sec. II, possibilities of cooling OFI plasmas by thermal conduction are discussed. In Sec. III, the experimental setup is described. In Sec. IV, results of the experimental observations and further explanations are given.

II. THERMAL CONDUCTION COOLING

The transport of large energy fluxes in nonstationary nonequilibrium inhomogeneous plasmas is a very complex topic. Many theoretical efforts [6,7] have been devoted to understanding the mechanisms responsible for the inhibition of a free-electron heat flux and the role played by nonlocal transport effects. In recent experiments [8], nonlocal electron heat transport in ps-pulse laser produced plasma in clustering gases has been studied. It has been found that a semiempirical formula for the nonlocal energy transport suggested in [6] is in good agreement with the experimental data. We think that for a further progress in this field investigations of cooling dynamics of OFI plasmas will be very important.

By focusing ultrashort-pulse laser radiation into a gaseous (or cluster) medium, OFI plasmas can be produced very close to a metal surface. This allows to realize a plasma-metal contact with well defined initial plasma parameters. Since the electron mean free path is density dependent, by varying the gas (plasma) density the transition from the classical diffusive heat flux to the free-streaming behavior can be studied. This offers a way for direct measurements of the nonlocal heat conductivity.

Neglecting hydrodynamic motion and density gradients, the short-time scale evolution of the electron temperature T_e in the OFI plasma can be described by

$$\frac{\partial T_e}{\partial t} = -\frac{2}{3N_e}\frac{\partial q}{\partial z}, \tag{1}$$

where z is the direction perpendicular to the metal surface, N_e is the electron density, $q=-\kappa \partial T_e/\partial z$ is the electron heat flux, and κ is the thermal conductivity.

The expression for the classical diffusive thermal conductivity is given by [9]

$$\kappa \simeq 14 b(Z) N_e v_e^2 \tau_{ei}, \tag{2}$$

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$$\tau_{ei}=\frac{3}{4\sqrt{2\pi}}\frac{m_e^{1/2}T_e^{3/2}}{N_e\Lambda e^4 Z}, \tag{3}$$

where $\tau_{ei}\simeq 3\times 10^5(T_e/1\ \text{eV})^{3/2}/(N_e Z\Lambda)$ is the characteristic time for electron-ion collisions, $v_e=\sqrt{T_e/m_e}$ is the electron thermal velocity, $b(Z)\simeq(1+3.3/Z)^{-1}$ is a dimensionless correction factor taking into account electron-electron collisions that become important for small values of ion charges Z, and Λ is the Coulomb logarithm.

Collisionless heat transport is usually described by simply limiting the value of the maximum energy flux which can be carried by Maxwellian electrons $q_m=(3/2\sqrt{2\pi})N_e v_e T_e \simeq 0.6 N_e v_e T_e$. Calculations and available experimental data (see [9], for example) show that the heat flux tends to saturate at a lower value $q_f=fN_e v_e T_e$, where $f\sim 0.1$ is the so-called flux limit. For the transition region the heat flux is usually approximated by $q_t=q/(1+q/q_f)$. In a more accurate modelling a semiempirical formula [6] for the nonlocal energy transport is used.

In our estimates of the OFI plasma cooling rate we consider a cylindrical plasma column placed in a close contact with a metal surface. For the diffusive regime of the electron heat transport, the cooling time $t=t_c$ can be defined from the condition that the electron heat propagation length $l=\sqrt{2Dt}$, where $D\simeq 9b(Z)v_e^2\tau_{ei}$ is the electron thermal diffusivity, becomes equal to the OFI plasma diameter $2r$. This gives

$$t_c\simeq\frac{2r^2}{D}=\frac{2}{9b(Z)}\left(\frac{r}{v_e}\right)^2\nu_{ei}, \tag{4}$$

where $\nu_{ei}=1/\tau_{ei}$ is the effective electron-ion collision frequency. For the collisionless heat flux the cooling time is

$$t_c\simeq\frac{3}{2}\frac{r}{fv_e}. \tag{5}$$

The maximum value of these two expressions gives an estimate of the cooling time. For the typical parameters, $r\simeq 20\ \mu\text{m}, v_e\sim v_{at}\simeq 2\times 10^8$ cm/s, as it follows from Eq. (5), the cooling time is of the order of 100 ps.

Note that for soft-x-ray lasing to the ion ground states, the cooling time should be of the order of the radiative lifetime of the upper level $t_c\sim A^{-1}$. For the $2p3s(^3P)-2p^2(^3P)$ transition in O III ions, which is investigated in this paper, A^{-1} is approximately 260 ps.

The electron distribution function produced by optical field ionization in a linearly polarized laser field is strongly anisotropic in directions $\parallel$ and $\perp$ to the laser field with $T_e^{\parallel}\gg T_e^{\perp}$ (see [1] for details). Therefore, one could expect that the electron heat flux and the corresponding cooling rate will be different when the polarization vector of the laser field is directed perpendicular or parallel to the metal surface. In spite of the fact that with the time resolution of our detection system (see below) we were not able to observe any difference in the cooling rate between these two cases, in our experiments the polarization vector has been always chosen perpendicular to the metal surface. In this case the expected cooling rate is maximum.

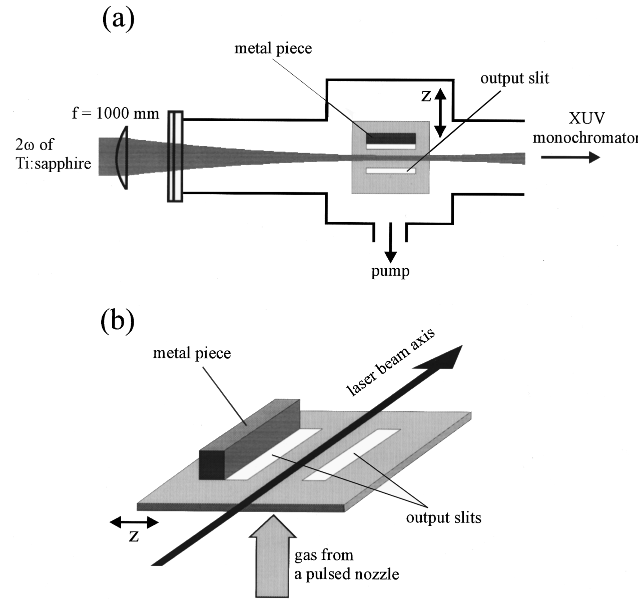

FIG. 1. Experimental setup (a) and the nozzle (b) used for time-resolved investigations of thermal conduction cooling of OFI plasmas.

III. EXPERIMENTAL SETUP

The experimental setup that has been used for investigations of optically field-ionized (OFI) helium and oxygen plasmas is shown in Fig. 1. The plasmas are produced by focusing of frequency-doubled (400 nm) Ti:sapphire laser pulses with a $f=1000$ mm lens into gas jets. The pulse energy and pulse duration used in our experiments are 50 mJ and 150 fs.

Helium and oxygen gas is injected into the vacuum chamber (10^{-5} Torr) by a pulsed nozzle (General Valve Corporation, model Iota One), with an opening time of about 1 ms. The experiments are performed at backing pressures of 0.1–1.5 bar, which correspond to particle densities of 10^{17}–10^{18} cm^{-3} in the interaction region.

To study the possibility to cool OFI plasmas by metal pieces, a nozzle consisting of two slits parallel to the pump laser direction is used, as shown in Fig. 1(b). Each slit has a length of 2 mm and a width of 0.2 mm. At the edge of the left slit an aluminum piece is mounted. The distance from the laser focus to the metal surface is varied by moving the nozzle perpendicular to the beam direction (see Fig. 1).

Time-resolved soft-x-ray spectra are obtained in the direction of beam propagation with a grating monochromator (Jobin Yvon, LHT 30, 550 lines/mm platinum grating, angle of incidence 19°) equipped with a fast microchannel plate (MCP) detector having a temporal resolution of about 2 ns. The signals are recorded by a digitizing oscilloscope (Tektronix, model TDS 620B, 2.5 GS/s, 500 MHz) and averaged over 50 laser shots. A narrow central part of the laser beam is blocked in front of the focusing lens to protect our monochromator from the direct laser radiation. The shadow produced by this 2-mm beam block reduces the laser intensity on the entrance slit of the monochromator by two orders of magnitude.

To investigate amplification on the $2p3s(^3P)-2p^2(^3P)$ transition in O III ions ($\lambda=37.4$ nm), the nozzle shown in

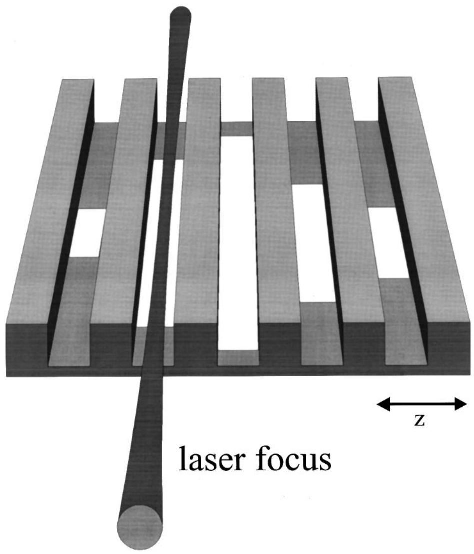

FIG. 2. Nozzle used for plasma-length variation and gain measurements.

Fig. 2 is used. This nozzle has five output slits with a width of 0.2 mm and lengths ranging from 1 mm to 5 mm. Every slit is located inside a channel with a depth of 0.2 mm. The laser focus can be positioned inside these channels, which provides possibilities for cooling of OFI plasmas via rapid heat conduction into the metal. By moving the nozzle perpendicular to the laser beam axis the interaction length can be varied. This nozzle and the nozzle described above have been manufactured at the Laser Zentrum Hannover with a fs-laser system [10].

IV. RESULTS AND DISCUSSION

In this section results of the experimental investigations of possibilities to cool OFI plasmas by metal pieces are discussed. Time-resolved studies of helium and oxygen plasmas are performed with the experimental setup shown in Fig. 1. The plasma is produced by focusing of frequency-doubled Ti:sapphire laser pulses with an energy of 50 mJ into gas jets expanding into the vacuum through 0.2×2 mm slits, as shown in Fig. 1(b). The pump laser intensity in the focus is estimated to be $I_0\simeq2\times10^{16}$ W/cm^2, which is high enough to produce a fully ionized He plasma and ionize oxygen to OIV stage.

Figure 3 shows four oscillograms of the He II Lyman-α emission at 30.38 nm. In Fig. 3(a) the plasma is produced in a gas ejected from the right slit [see Fig. 1(b)]. One can clearly distinguish between a fast and a slow component in the time-resolved line emission. As discussed in our previous paper [1], the fast and the slow components are generated due to electron collisions and three-body recombination, respectively. The position of the fast component coincides with the laser pulse within the time resolution of our detection system (2 ns).

The oscillogram shown in Fig. 3(b) is recorded when the OFI plasma is produced at the edge of the left slit close to the metal surface [see Fig. 1(b)]. In this case the fast and slow components can not be distinguished anymore. Due to the thermal cooling, the recombination component becomes very fast, with a rise time below the resolution limit of our detector.

Close to the metal surface, it is reasonable to expect that the gas density profile will be changed. A density increase near the wall could also increase the recombination rate. To discard this effect as a possible explanation of the signal observed in Fig. 3(b), the backing pressure of the gas injecting nozzle is varied. In Figs. 3(c,d) the plasma is produced again in a gas ejected from the right slit. Four and eight times higher backing pressures than in Fig. 3(a) are used. As can be seen, the peak strength of the recombination component becomes much higher than in Figs. 3(a,b) and follows the quadratic dependence on the particle density. But still the fast component signal can be clearly observed. This is very different from the signal behavior shown in Fig. 3(b), where the cooling is present. These observations provide irrefutable

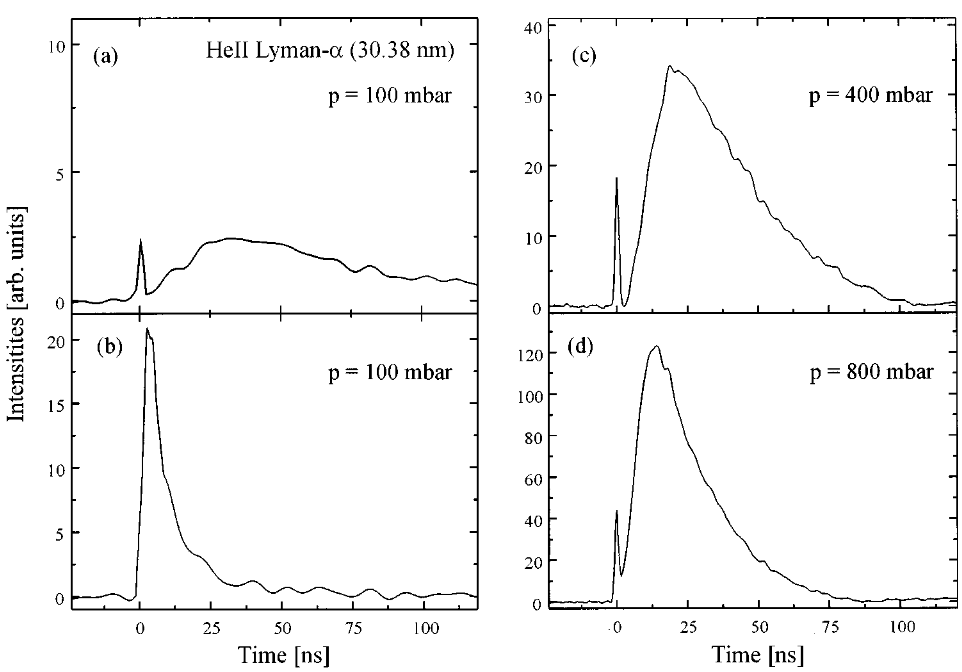

FIG. 3. Oscillograms of the He II Lyman-α line emission from the plasmas produced in a gas ejected from the right slit (a,c,d) and from the left slit (b).

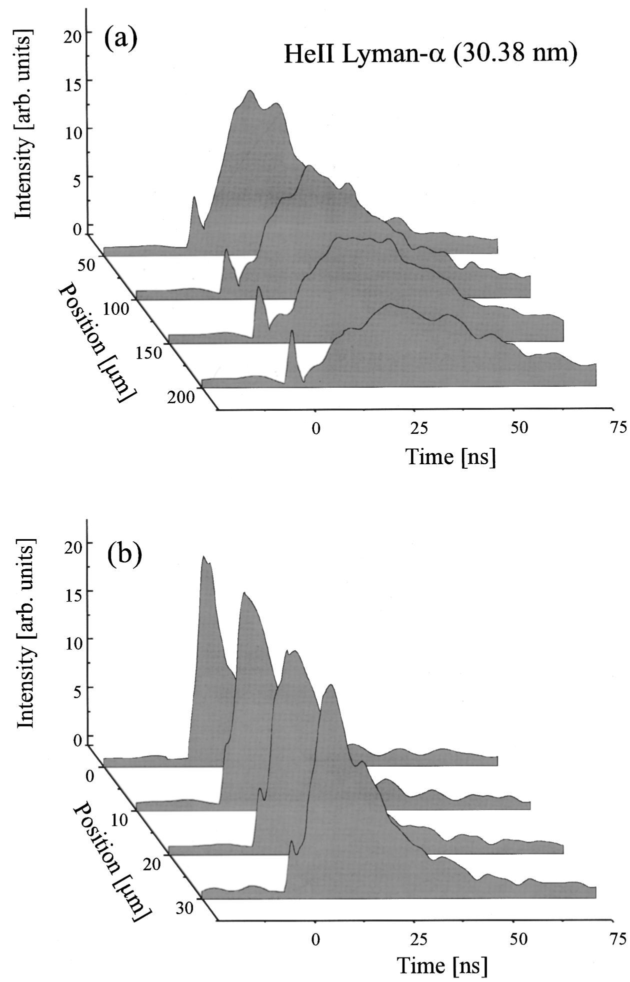

FIG. 4. Temporal evolution of the He II Lyman-α line emission at different distances from the metal wall.

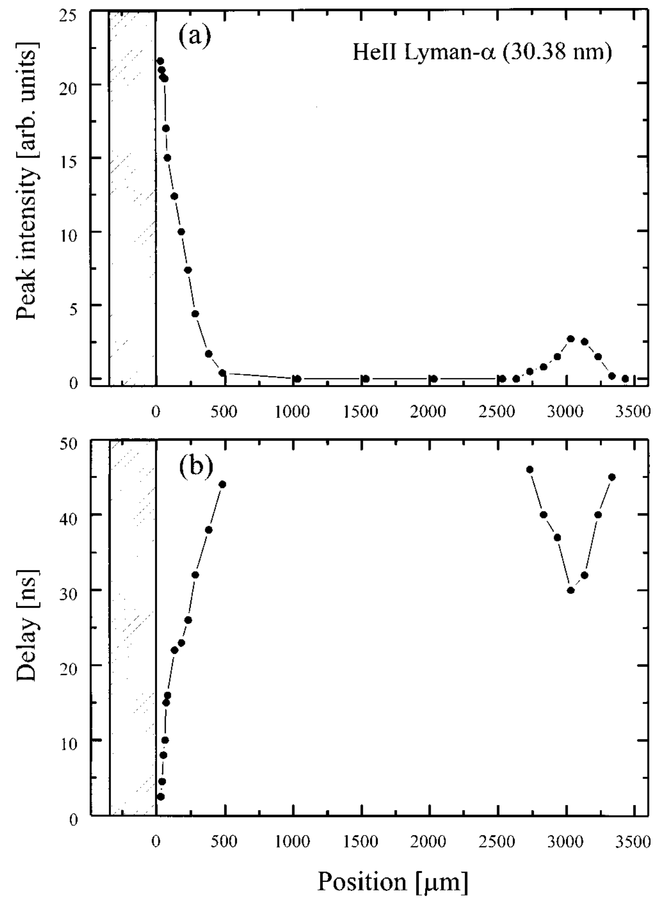

FIG. 5. Peak intensity (a) and delay between the fast and slow components (b) as a function of the focus position. The position of the metal piece is marked by a box.

evidence that the effect is due to the thermal conduction cooling.

In Fig. 4 the OFI plasmas are produced in the left jet. To study the temporal dynamics of the Lyman-α line emission and the importance of thermal cooling the position of the focus is moved towards the metal piece. In Fig. 4(a) the focus position is moved in steps of 50 μm (starting from 200 μm) and in Fig. 4(b) in steps of 10 μm. The change in the intensity of the recombination component can be clearly seen.

In Fig. 5 the peak intensity of the recombination component of the He II Lyman-α emission (a) and the delay between the fast and slow components (b) is plotted versus the focus position. The position of the metal piece is marked by a box. The center of the right slit is located at a distance of about 3000 μm from the metal surface. As can be seen in Fig. 5(a), the intensity of the recombination component is strongly enhanced by a factor of 10 in the vicinity of the metal surface compared to the signal generated from the right slit. When the focus is in the middle of the right slit the minimum delay between the fast and the slow components that can be reached (at a backing pressure of 600 mbar) is approximately 30 ns. This position corresponds to the highest particle density. On the edges of the right slit the delay increases [see Fig. 5(b)], since the particle density and three-body recombination rate become smaller. The delay is dramatically reduced when the OFI plasma is produced closer to the metal wall, as can be clearly seen in Fig. 5(b).

Analogous investigations are performed with OFI oxygen plasmas. The temporal behavior of the $2p3s(^3P) - 2p^2(^3P)$ line emission in O III ions at 37.4 nm is studied. Typical signals are shown in Fig. 6. In Fig. 6(a) the plasma is produced in the gas ejected from the right slit and in Fig. 6(b) in the gas ejected from the left slit, close to the aluminum piece. It is remarkable, that in both cases there is no fast emission component in the O III line emission. This can be explained by the much lower initial electron temperature of the OFI oxygen plasma compared to the helium plasma. The electrons are not hot enough to excite the $2p3s(^3P)$ state in O III ions. A significant change in the intensity can be observed due to the influence of the metal piece. The peak intensity is increased by a factor of more than 10. The delay between the slow component and the laser pulse reduces from 10 ns in the free gas jet to the resolution limit of our detection system when the focus position is close to the metal surface.

In Fig. 7 the peak intensity of the O III line emission and the delay of the recombination component are illustrated as a function of the focus position. The dramatic increase of the peak intensity of the recombination component in the vicinity of the aluminum surface can be clearly seen in Fig. 7(a). Thermal conduction cooling results in a strong reduction of

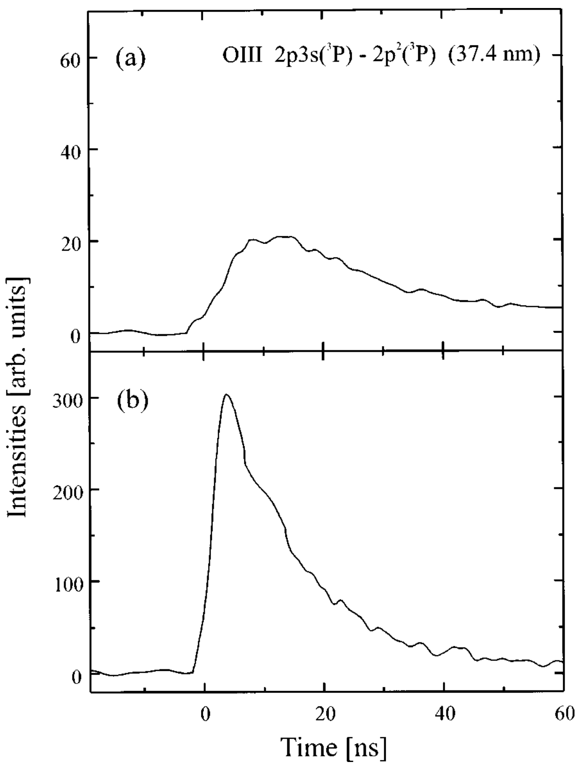

FIG. 6. Typical time evolutions of the O III line emission at 37.4 nm without (a) and with (b) the influence of thermal conduction cooling.

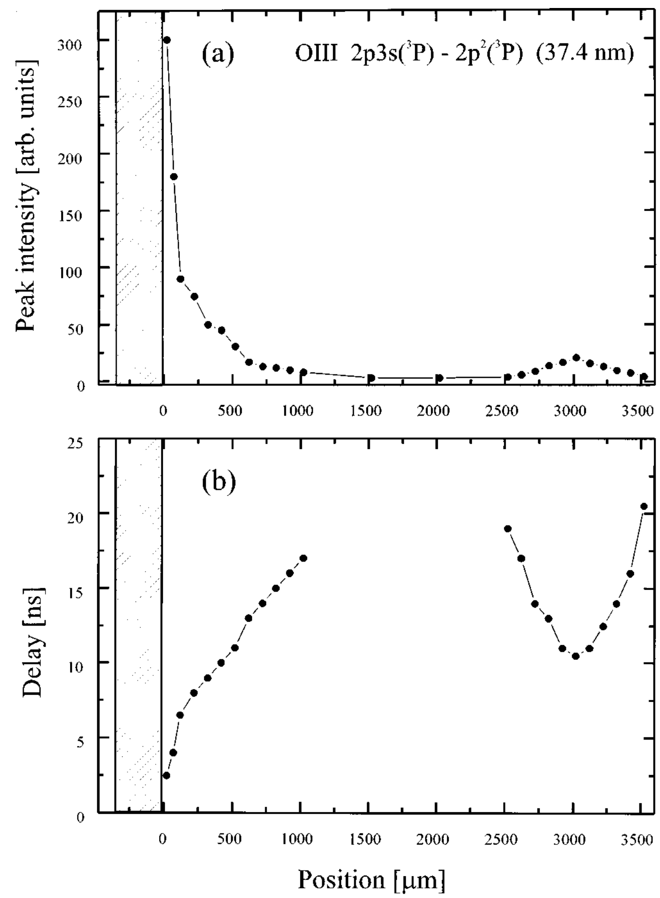

FIG. 7. Peak intensity (a) and delay of the slow component (b) as a function of the focus position.

the delay [see Fig. 7(b)]. Starting from a value of about 17 ns at a distance of 1200 μm from the wall the delay falls below the resolution limit.

To investigate amplification on the $2p3s(^3P)-2p^2(^3P)$ transition in OIII ions, which has been previously observed in [3], the nozzle shown in Fig. 2 is used. The plasma length is varied by positioning the laser focus inside the different channels. In all cases the plasma is surrounded by metal walls from both sides which allows effective thermal conduction cooling. In Fig. 8 results of the variation of the plasma length for the $2p3s(^3P)-2p^2(^3P)$ transition in O III ions (filled squares) are shown. In this figure the peak intensity of the recombination component is plotted versus the plasma length. A nonlinear growth of the O III $2p3s(^3P)-2p^2(^3P)$ signal is observed. The solid line represents a Linford fit [11]. The gain coefficient that can be estimated from the data is $G=11\ \mathrm{cm}^{-1}$, which provides a gain-length product $GL\simeq 4.4$. The thermal conduction cooling can be switched off by moving the focus out from the metal channels. In this case the observed signal (dotted line in Fig. 8) grows linearly with the plasma length.

These results demonstrate the importance of additional thermal conduction cooling of OFI oxygen plasmas for the observation of amplification. It should be noted that the alignment of the laser focus inside the channels is very crucial due to their small sizes. The channels can be easily destroyed during positioning of the laser focus. Therefore, reproducibility of the gain measurements is not very high. With several nozzles different results have been obtained. The measured gain coefficients vary from values of 8 cm^{-1} up to 14 cm^{-1}.

V. CONCLUSION

The possibility of rapid cooling of OFI plasmas by metal pieces has been demonstrated. The OFI plasma can be produced in a gaseous medium very close to the metal surface. This allows to realize a plasma-metal contact with well-defined initial plasma parameters. Investigations of the temporal evolution of this plasma offer a way for direct mea-

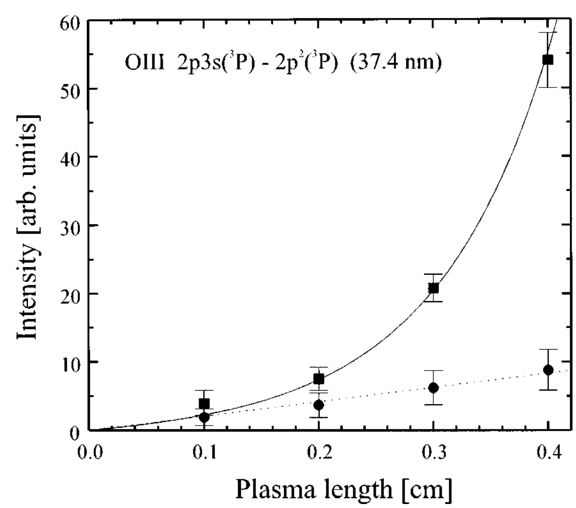

FIG. 8. Dependence of the O III line emission signal at 37.4 nm on the plasma length when the focus is located inside the channels (filled squares) and outside of the channels (filled circles).

surements of the nonlocal heat conductivity.

A very important aspect of the demonstrated thermal conduction cooling of OFI plasmas is related to the development of recombination type soft-x-ray lasers. In many cases the initial electron temperature of the OFI plasma is too high. In our previous experiments [3], reporting amplification on the $2p3s(^3P)-2p^2(^3P)$ transition in O III ions at 37.4 nm, cooling via thermal conduction to the metal nozzle has already been involved. These results have been confirmed with an improved nozzle design. Soft-x-ray lasing at 37.4 nm with a gain-length product $GL\simeq 4.4$ has been achieved. Further improvements can be expected by the use of metal capillaries filled with oxygen gas.

ACKNOWLEDGMENTS

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