Spectroscopically pure metal vapor source for highly charged ion spectroscopy and capillary discharge soft x-ray lasers

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We describe a compact, pulsed metal vapor source used for the production of dense plasma columns of interest for both soft x-ray laser research and spectroscopy of highly ionized plasmas. The source generates spectroscopically pure cadmium vapor jets in a room-temperature environment by rapidly heating an electrode with a capacitive discharge. In the configuration described herein, the metal vapor jet produced by the source is axially injected into a fast (up to 15 kA/ns), high current (up to 200 kA peak) capillary discharge to generate highly ionized cadmium plasma columns. Spectroscopic analysis of the discharge emission in the 12–25 nm spectral range evidences the dominance of Cu-like (CdXX), and Ni-like (CdXXI) lines and shows strong line emission at 13.2 nm from the 4d\(^1\)S\(_0\)−4p\(^1\)P\(_1\) laser transition of Ni-like Cd. Hydrodynamic/atomic physics simulations performed to describe the dynamics of the plasma column and compute the optimum discharge conditions for laser amplification are discussed. © 2008 American Institute of Physics.

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I. INTRODUCTION

Fast capillary discharge excitation is a very successful working principle that has enabled the development of a new generation of compact and efficient soft x-ray lasers.\(^1\)–\(^6\) Tabletop Ne-like Ar lasers operating at 46.9 nm have produced the highest average power reported to date for a tabletop soft x-ray laser, 3.5 mW,\(^5\) and have been successfully utilized in a number of applications.\(^6\) Strong laser amplification in discharge-pumped capillary lasers has also been attained at slightly longer wavelengths in Ne-like S and Ne-like Cl.\(^3,4\) However, some applications require shorter lasing wavelengths. Of particular interest is the possibility of using discharge-created plasmas to achieve lasing around 13.5 nm, a wavelength relevant to metrology tasks related to extreme ultraviolet lithography.\(^7\) Scaling of the collisional laser scheme to this spectral region can be accomplished by excitation of Ni-like Cd ions (CdXXI), which can provide amplification at 13.2 nm in the 4d\(^1\)S\(_0\)−4p\(^1\)P\(_1\) transition. A gain-saturated, high repetition rate Ni-like Cd laser has been demonstrated in plasmas created by heating a Cd target with a powerful picosecond tabletop laser.\(^8\) The use of fast capillary discharge excitation can potentially result in a more compact and efficient 13.2 nm laser, capable of producing higher laser pulse energy. However, the generation of such discharge-pumped soft x-ray laser gain medium requires the presence of a substantial density of high purity metal vapor into a capillary channel at the time of the onset of the main excitation discharge.

In this paper, we present a room-temperature pulsed source that produces high purity metal vapor using a compact and relatively simple design. Its applicability to soft x-ray laser research is shown by results from experiments where highly ionized cadmium plasma columns are created using the vapor source in combination with a fast, high power capillary discharge.

The production of capillary plasmas from solid materials in a repetitive way can be achieved by either ablation of the material from the capillary walls or injection of the material into the capillary. Several attempts to produce discharge-pumped plasmas for soft-x-ray amplifiers from solid elements have utilized direct ablation of the material from the capillary walls.\(^9\)–\(^13\) In the case of plasmas for collisionally excited lasers, our group has previously used excitation of ablated material from capillary channels for the identification of line emission at wavelengths corresponding to the \(J = 0 – 1\) laser transition in Ne-like ions from elements heavier than argon.\(^14\) However, as most of the materials of interest are electrically conductive on their pure form, they have to be transformed into insulators by either using compounds such as oxides, nitrides, and hydrides, or binding them with an insulating material, such as epoxy resin. As an example, for our previous experiments with calcium and titanium, the capillary channels were drilled on cylinders made by either
pressing CaH$_2$ powder to high pressures or binding TiH$_2$ and CaH$_2$ with epoxy resin. Unfortunately, both methods introduce into the plasma undesirable elements that reduce the laser gain. Instead, as in the case of gaseous targets, the lasing material can be pulse injected into the capillary channel of the laser. We have successfully used this technique for the demonstration of lasing in Ne-like sulfur at 60.8 nm. In those experiments, the lasing material was produced by ablation of the wall of a separate sulfur capillary channel with a relatively slow current pulse. The sulfur vapor produced by this secondary discharge was injected into the main capillary channel and subsequently excited by a fast current pulse to generate a narrow plasma column with the necessary conditions for amplification. Ablation of material from an auxiliary capillary channel, however, presents some of the same challenges faced by direct ablation of the laser capillary walls, especially the fact that the capillary has to be made out of an insulating compound.

The concept of using an auxiliary capillary has been lately extended to include an exploding wire inside the secondary channel as a source of metal plasmas, as described in Ref. 15. For the particular case of titanium, the authors reported the generation of single-shot plasma jets with ion densities of about $3 \times 10^{17}$ cm$^{-3}$. Recently, a scheme using exploding wires in water was also proposed as a potential approach to the generation of plasmas for soft x-ray amplification. Titanium plasmas have also been generated using a capillary discharge where the metal plasma is produced by laser ablation of a solid target and injected into a capillary tube. Initial investigation based on this approach using alumina capillaries resulted in plasmas dominated by aluminum and oxygen ablated from the walls. In later experiments, the use of a series of titanium rings for the generation of the metal vapor resulted in plasmas with higher titanium content.

To overcome the limitations of single-shot operation and the problems associated with plasma impurities, we have designed a new discharge scheme where the desired material is injected by a secondary discharge placed on the same axis as the capillary channel. In this paper, we describe this metal vapor source and discuss its application to the generation highly ionized Cd plasma columns of interest for atomic spectroscopy and soft x-ray laser generation at 13.2 nm. The following section discusses the design and characterization of the vapor source. Section III discusses its use in combination with a fast capillary discharge to create highly ionized Cd plasma columns, and Sec. IV discusses the discharge conditions required for strong laser amplification.

II. METAL VAPOR SOURCE SETUP AND CHARACTERIZATION

Figure 1 shows a schematic diagram of the metal vapor source coupled to the channel of a high power capillary discharge. The metal vapor source consists of a capacitor-driven discharge that takes place between a cathode electrode and a grounded, hollowed metal electrode serving as both the anode for the metal source and the ground electrode for the capillary discharge. The separation between the electrodes was designed to be 3 mm. The metal vapor is produced by ablation of a cathode insert made of the material of interest, for example, cadmium. The metal insert, which is collinear with the capillary axis, has a hole on axis for the escape of the radiation generated in the capillary discharge plasma. In the experiments described below, we used an insert of high purity (99.99+ %) Cd (Ref. 19) pressed into a stainless steel holder that provided both support and electrical contact. The insert is ablated by a relatively slow current pulse produced by discharging a 1 $\mu$F capacitor through a pressurized spark gap. Current pulses with a first period length of about 22 $\mu$s and peak currents of up to 8 kA can be obtained charging the capacitor up 15 kV. Ablation is restricted to the surface of the insert by a polycrystalline capsule tightly fitted to the tip of the cathode. To generate the highly ionized plasma column in the capillary channel, the metal vapor source is triggered such that the ablated vapor expands and fills the channel a few microseconds before the initiation of the main discharge pulse. In this design, the metal vapor source is shielded from the main discharge's high current pulse by the ground electrode, which consists of a stainless steel embodiment with a molybdenum insert that minimizes the sputtering of the electrode by the high current pulses.

The cadmium injection discharge was first characterized in a separate vacuum chamber. A 4 cm long quartz capillary
channel was attached to the ground electrode to simulate the capillary channel of the main discharge. The quartz capillary allowed us to study both the radiation emitted by the Cd plasma and the propagation of the cadmium vapor into the capillary. The light emitted by the discharge in the spectral range between 300 and 700 nm was analyzed using a 0.67 m focal length spectrometer provided with a 1200 l/mm grating. The instrument was calibrated using a mercury lamp. Figure 2 shows a typical spectrum of the plasma created by only firing the metal vapor source. Notice that the lines of atomic cadmium (Cd I) completely dominate the spectrum, without any significant impurity lines. A coarse estimate of the metal vapor density in the column for the case of 15 kV charging voltage discharges was derived from measurements of the extent and thickness of metal coatings deposited by the discharge on a glass slide located at the end of the quartz capillary. Measuring the thickness of the deposit with an alpha-step probe, and using the density of solid cadmium to estimate the mass of metal deposited, the metal vapor density on a 5 mm diameter, 2.5 cm long capillary channel was estimated to be of the order of $1 \times 10^{17}$ cm$^{-3}$, corresponding to a linear mass density of $2 \times 10^{16}$ cm$^{-1}$. Since the density of the film is likely to be lower than the density of solid cadmium, and some deposition will occur between the generation of the metal vapor and the initiation of the capillary discharge, this estimation represents just an upper limit for the metal vapor density at the onset of the main excitation pulse. Figure 3 shows a typical current trace and the time-dependent, spectrally integrated intensity emitted by the plasma as observed near the open end of the quartz capillary. For the conditions of this shot, the intensity of the emitted light peaks approximately 4 $\mu$s after the peak of the first half-cycle of the current, and ablation is not observed to be significant beyond the first half-cycle of the current pulse. The time evolution of the spectrally integrated light emission was also measured at several positions along the quartz capillary by displacing it with respect to a fixed 1 mm wide slit. Near the electrode, the spectrally integrated light emission is observed to peak very shortly (~1 $\mu$s) after the first current peak. Measurements of the time of peak light emission at
various positions along the capillary axis permitted to estimate the expansion velocity of the cadmium vapor along the capillary axis. The average expansion velocity along the capillary axis was measured to be up to 1.8 ± 0.2 cm/μs.

### III. GENERATION OF HIGHLY IONIZED Cd PLASMA COLUMNS USING A HIGH POWER CAPILLARY DISCHARGE

Radial compression of the metal vapor column described above by a fast, high current capillary discharge can, in principle, create small diameter plasma columns with plasma densities in excess of $1 \times 10^{20}$ cm$^{-3}$, and a degree of ionization reaching the Ni-like stage. To generate such dense, highly ionized plasma columns, we used a three-stage pulsed power generator that has been described elsewhere. The first stage, which produces a current pulse that is subsequently shortened by the two following stages, consists of a conventional eight-stage Marx generator that for the present experiment was operated at an erected voltage of ~650 kV. The Marx generator is used to charge in about 1 μs the second pulse compression stage, consisting of a 26 nF coaxial water-dielectric capacitor. In turn, this water capacitor is discharged through a self-breakdown spark gap pressurized with SF$_6$ gas to charge the third and final stages in about 75 ns. The third stage consists of two radial water-dielectric transmission lines arranged in a Blumlein configuration. The capillary channel is located on the axis of this radial Blumlein. The fast current pulse that excites the capillary plasma is produced by discharging the Blumlein transmission line through an array of seven synchronously triggered SF$_6$ spark-gap switches equally distributed along the outer diameter of the water transmission line. The very rapid switching of the Blumlein transmission line produces current pulses with amplitudes of up to 200 kA and risetimes of less than 15 ns through the capillary load (see Fig. 4). To aid the formation of a stable plasma column, the material in the capillary channel was preionized with a current pulse of 20–40 A and 10 μs duration immediately preceding the fast discharge pulse. Initial studies of hot, dense argon plasmas generated with this high power capillary discharge showed that the setup can produce dense plasma columns with electron temperatures in excess of 250 eV and electron densities of about $1 \times 10^{20}$ cm$^{-3}$.

The evolution and stability of Cd plasma columns were studied using a soft x-ray pinhole camera equipped with a microchannel plate (MCP) charge coupled device (CCD) detector. The camera had a magnification of 2.76×, and gating of the MCP allowed images of the plasma column with ~3 ns temporal resolution. A combination of a 1 μm thick carbon and a 0.2 μm thick aluminum filters was used to limit the response of the camera to photons with wavelengths between 45 and 100 Å, and below 25 Å. This allows differentiating the hotter regions of the plasma from the colder regions that emit longer wavelength radiation. Figure 5 consists of a sequence of end-on images of the plasma column, showing the evolution of the soft x-ray emitting region of the Cd plasma in a 2.5 cm long, 5 mm diameter polycrystalline capillary. These pinhole camera measurements show the onset of significant soft x-ray emission occurring about 27 ns after the initiation of the current pulse, with a rapid increase of the intensity in the following few nanoseconds. The diameter of the soft x-ray emitting region achieves a minimum of 250–350 μm at 32–34 ns after the onset of the current. Shortly afterward, the emitted soft x-ray intensity rapidly decreases. The plasma columns are observed to have a good degree of symmetry, comparable to that observed in the plasma columns of the Ne-like Ar laser, until the time of maximum compression. Although later in time the plasma becomes asymmetrical, these late nonuniformities should not be of concern for soft x-ray laser development, as they appear after the time of interest for laser amplification.

End-on spectra of the capillary discharge plasma were obtained using a 2.2 m grazing incidence spectrometer provided with a 2400 1/mm gold-coated diffraction grating. A time resolution of about 5 ns was obtained by gating a microchannel plate-intensified CCD detector. Spectra taken on the 23–25 nm region were observed to be dominated by lines from Ni-like (CdXXI) and Cu-like (CdXXX) ions, with all the CdXXI lines corresponding to 4p–4s transitions. The spectral region between 15.8 and 18.4 nm shows numerous 4d–4p Ni-like Cd lines, as well as Cu-like Cd lines. As an example, Fig. 6 shows a spectrum within this region, for wavelengths spanning from 17.2 to 18.4 nm. Assisted by calculations performed using the Slater-Condon method with generalized least squares fits of the energy parameters, we were able to identify $3d^94p−3d^84d$ and $3d^94d−3d^84f$ CdXXI lines in spectra from this region. Figure 7 shows a spectra corresponding to the 12.7–13.7 nm region, obtained from a 5 mm diameter capillary excited by a 173 kA current pulse. Strong line emission observed at 13.162 ± 0.010 nm, which is assigned to the $4d^93s^54p^12P_1$ Ni-like Cd. This measured wavelength agrees well with a previously reported wavelength 13.166 ± 0.015 nm for this laser line. The fact that the soft x-ray line spectra of the highly ionized
FIG. 5. Sequence of end-on pinhole images of the soft x-ray emitting region of a cadmium plasma column created in a 5 mm diameter capillary. The images were acquired using a 1 μm thick carbon filter and a 0.2 μm thick aluminum filter. The discharge current pulse is shown as a reference, and the timing of each image respect to the initiation of the current pulse is indicated.

FIG. 6. End-on spectrum of a Cd capillary column covering the 17.2–18.4 nm region. The spectrum was obtained from a plasma column formed in a 5 mm diameter capillary by a current pulse with peak amplitude of approximately 180 kA.
plasmas produced by this fast capillary discharge have a lower background than those typically produced by laser-created plasmas makes them particularly interesting for the study of the energy level structure of highly charged ions. Note that plasma columns of other elements can be generated by selecting different materials for the source cathode insert. An example is shown in Ref. 23, which reports the assignment of numerous lines of Ni-like Ag using the discharge described here with a silver insert.

These experimental observations were complemented by the results of hydrodynamic/atomic physics model simulations conducted using the code RADEX. Figure 8 illustrates computed results corresponding to a 190 kA cadmium discharge in a 5 mm diameter capillary with an initial Cd density of $2 \times 10^{16}$ cm$^{-3}$, well within the range of densities that the metal vapor source is able to generate. The graphs of the evolution of the computed plasma parameters show the dynamics of a cylindrical shock wave, driven toward the axis of the capillary by the Lorentz force and the thermal pressure in the skin layer near the walls. The electron temperature plot [Fig. 8(a)] shows a heat wave moving ahead of the hydrodynamic shock wave, preheating the plasma in front. When the heat wave reaches the axis, the maximum of the current density switches to the center of the capillary. When the hydrodynamic shock wave reaches the axis of the capillary several nanoseconds later [see Fig. 8(b)], the temperature rapidly increases, ionizing plasma up to and beyond Ni-like stage [Figs. 8(c) and 8(d)]. The electron density is calculated to reach a maximum value of $(1-2) \times 10^{20}$ cm$^{-3}$ needed to obtain high gain values. It is interesting to notice that both the calculation and the experiment show the formation of a concave radial profile that could potentially guide the laser beam in both the current and future laser designs. The concave axial density profile is formed when the plasma front starts to expand after reaching the axis and achieving maximum compression. At this time, two counterstreaming plasma fronts, the part reflected on axis and the incoming plasma, collide with each other roughly keeping pressure balance. The central part of plasma column keeps a higher temperature and hence smaller density, due to larger Joule heating and resonance line opacities, while the incoming plasma cools faster due to smaller radiation trapping caused by the macroscopic Doppler shift in the slope of density profile where plasma decelerates. This causes the peak density to occur off axis, resulting in a concave profile. The concave profile becomes less pronounced in the calculations when line radiation, a major energy loss in high-Z plasmas, is excluded. In this case, the electron density only reaches a value of about $5 \times 10^{19}$ cm$^{-3}$. Radiation also substantially cools the plasma from about 550 down to 350 eV, but conditions are still far from radiation collapse.

IV. PROSPECT FOR STRONG LASING AT 13.2 nm

A remaining question is the possibility of demonstrating strong lasing at 13.2 nm utilizing capillary discharge excitation. The basic strategy for achieving optimal conditions for soft x-ray laser action in capillary discharges typically takes into account the following considerations. First, in order to ensure a high utilization efficiency of the driver energy and a high compression, the time of plasma collapse on axis should, in principle, approach the end of electric current pulse. However, aside from obtaining the high compression of the core needed to reach the necessary electron density, the electron temperature must reach a value between 25% and 50% of the ionization potential to effectively excite the ions. Lasing with Ni-like Cd ions requires achieving temperatures of 300–400 eV (the ionization potential of CdXXI is approximately 900 eV), which implies substantially larger driving currents relative to the previously realized 46.9 nm Ne-like Ar soft x-ray laser, and also higher compression densities. However, the temperature does not increase as much as could be expected from the increased adiabatic heating, due to enhanced radiation losses that grow as the square of the electron density.

Plasma heating can be more efficiently achieved if the plasma collapse on axis takes place at a slightly earlier time, when the axial electric current density still has a large value. In this case, both Joule heating and the kinetic energy of the accelerated plasma, transformed into thermal energy, combine to boost the electron temperature at the time of collapse. These requirements define the optimum time of collapse to

![Graph of axial spectrum of a Cd discharge for the 12.7–13.6 nm region, obtained from a 5 mm diameter capillary excited by a 173 kA current pulse. The time delay with respect to the beginning of the current pulse is 29 ns. The strong line emission observed at 13.16 ± 0.010 nm corresponds well with the previously measured wavelength 13.166 ± 0.015 nm of the 4d$^1$S$-4p^1$P$^0$ laser line of Ni-like Cd (Ref. 9). The presence of several other 4d-4p Ni-like Cd lines shown in Fig. 5 supports the identification of this line as the laser line.](image-url)
be approximately 0.6–0.8 of electric pulse width (measured at the base). Second, this optimum time of collapse, in turn, defines the maximum values of the initial Cd vapor pressure for a given capillary radius. For discharges with 30–35 ns pulse width, such as those produced by the generator used in our experiments, the range of optimal initial vapor densities is approximately (2–5) \times 10^{16} \text{ cm}^{-3}. An increase of the vapor pressure beyond this value results in a slower plasma compression and hence smaller temperature at the time of collapse. In the opposite case of smaller pressures, the compressed column becomes too narrow, collapses too quickly, and does not utilize the electrical driver energy efficiently.

Figure 9 shows the value of the gain for the 13.2 nm line of Ni-like Cd as a function of peak current and initial vapor density. For these calculations, the capillary diameter was chosen to be 5 mm and all other discharge parameters were kept constant. This two-variable optimization computation shows that, in principle, it is possible to obtain high gain using high currents in the range of 300–400 kA. Figure 9 also shows that at the maximum drive current of 200 kA achieved in our experiments, substantial gain can only be obtained for relatively low initial vapor densities, as re-
quired to reach a sufficiently high electron temperature. At these conditions, the compressed plasma column becomes quite narrow, and refraction is too large for the laser radiation to propagate a sufficiently long distance for strong amplification. Computations estimate that at these excitation conditions the gain in the 13.2 nm line of Ni-like Cd is 1–3 cm–1.

The clean line spectra with relatively small continuum component produced by these highly ionized metal vapor capillary discharge plasmas are also of significant interest for the assignment of lines corresponding to highly charged ions.

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V. CONCLUSIONS

In summary, we have demonstrated a discharge-based metal vapor source that can produce high purity vapor suitable for the generation of hot and dense capillary plasmas of interest for both spectroscopy of highly ionized ions and soft x-ray laser development. The source metal vapor was used to generate Cd vapor columns that were compressed by a fast high current capillary discharge to generate very dense and highly ionized plasma columns. The results from soft x-ray imaging diagnostics show that the fast plasma compression results in well-behaved plasma columns with good axial symmetry up to the time of maximum compression. Analysis of the radiation from Cd plasmas in the spectral region spanning from 12 to 25 nm shows that the cadmium vapor can be ionized to the Ni-like ionization stage. Spectra of the discharge around 13 nm reveal strong line emission at 13.162 ± 0.010 nm, corresponding to the 4d 1S0 → 4p 1P1 laser transition of Ni-like Cd. This identification is supported by the simultaneous observation of other Ni-like Cd lines.