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# Spatial coherence measurement of a high average power table-top soft X-ray laser

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**Abstract.** An extraordinarily high degree of spatial coherence from a high average power tabletop 46.9 nm laser was observed in two-pinhole interference experiments. Refractive anti-guiding and gain guiding along a capillary discharge-produced plasma column causes a rapid increase of the spatial coherence with amplifier length. Full spatial coherence was approached with a 36 cm long plasma of very high axial uniformity and a length to diameter ratio exceeding 1000:1.

## 1. INTRODUCTION

The development of advanced light sources at soft x-ray wavelengths is motivated by applications such as high-resolution microscopy, interferometry, lithography, holography, and the possibility of nonlinear science at ultrashort wavelengths. While high average power radiation produced at modern synchrotron radiation (SR) facilities are making important contributions in multiple disciplines of scientific research [1], recent advances in tabletop x-ray lasers [2] and high-order harmonic generation (HHG) sources [3] are helping to greatly increase the peak brightness and make intense short wavelength radiation widely accessible. The degree of spatial coherence of the radiation from a soft x-ray source plays a critical role in many applications. Compared with synchrotron radiation (SR) and high-order harmonic generation (HHG) sources, soft x-ray lasers have substantially higher pulse energy and narrower linewidth. However, to date they have been characterized by rather low spatial coherence [4-6]. Soft x-ray lasers are generally based on amplification of spontaneous emission (ASE) processes in hot dense plasmas, in which the short duration of the gain limits the ASE process to a single pass or double pass through it. From the theory of light source coherence (the van Cittert-Zernike theorem) [7], a high degree of spatial coherence from an ASE-based laser requires that the gain medium has a Fresnel number less than unity. Unless some forms of spatial filtering are used, it is difficult to produce plasma columns with the geometry necessary to fulfill this requirement. Here we experimentally demonstrate that refraction in a plasma with sharp density gradients can reduce the effective transverse source size significantly and result in a much higher spatial coherence. Although theoretical results have suggested that refractive anti-guiding and gain guiding along a long plasma column could result in improved spatial coherence [8-10], in previous experiments the coherence buildup was limited to values significantly below full coherence [5,11]. In present work, we utilized fast capillary discharge excitation to produce plasma columns with both very high axial uniformity and length to diameter ratio exceeding 1000:1. In these conditions strong refractive anti-guiding makes it possible to achieve essentially full spatial coherence with a plasma column length of 36 cm.

## 2. EXPERIMENT SETUP

The laser beam in our experiments is generated by excitation of an Ar-filled capillary channel with a fast discharge current pulse. In this excitation scheme the magnetic force of the current pulse rapidly compresses the plasma to form a dense and hot column with a large density of Ne-like ions [12,13]. Collisional electron impact excitation of the Ne-like ions produces a population inversion between the 3p ($^1S_0$) and 3s ($^1P_1^0$) levels, resulting in amplification at 46.9 nm. The experiments are conducted utilizing aluminum oxide capillary channels 3.2 mm in diameter and up to 36 cm in length, filled with preionized Ar gas at a pressure of ~59 Pa. The plasma columns are excited by current pulses of ~25 kA peak amplitude, with a 10% to 90% rise time of approximately 40 ns. The set up is similar to that used in previous experiments [14,15]. Efficient extraction of energy is obtained by operating the laser in a highly saturated regime. The laser pulse energy increases nearly exponentially as a function of plasma column length, until the beam intensity reaches the gain saturation intensity of 56-78 MW cm$^{-2}$ at a plasma column length of about 14 cm [13]. For longer plasma columns, the laser average pulse energy increases linearly with length from 0.075 mJ for a plasma column 16 cm in length, to 0.88 mJ (> 2×10$^{14}$ photons/pulse) for a plasma column length of 34.5 cm [15]. Average laser powers of 3.5 mW are obtained when operating the laser at a repetition rate of 4 Hz.

The spatial coherence of a quasi-monochromatic light source is characterized by the cross-correlation of fields across the output wavefront, which can be described in terms of the normalized complex degree of coherence $\mu_{12}$ [7]. In a two-pinhole interference experiment, the fringe visibility, defined as $V = (I_{max} - I_{min})/(I_{max} + I_{min})$, where $I_{max}$ and $I_{min}$ are the maximum and minimum intensities of the fringe pattern, as a function of pinhole separation is proportional to the modulus of $\mu_{12}$ [16]. This was demonstrated in experiments by Thompson and Wolf with partially coherent visible light [17]. Similar measurements were conducted recently in SR sources [18]. A variation of this method, a two-slit experiment, had been used in measuring the spatial coherence of both x-ray lasers [19] and HHG sources [20]. The laser used in our experiment has sufficiently high pulse energy for us to perform a two-pinhole interference experiment with a single laser pulse.

The set up used in our two-pinhole interference experiment is shown in figure 1. The pinhole masks consisted of pairs of 10 µm diameter pinholes laser-drilled at selected separations on 12.5 µm thick stainless steel substrates (National Aperture Inc., NH). Measurements were conducted placing the masks at distances of 15 cm and 40 cm from the exit of the capillary. An x-y translation stage was used to position the pinholes with respect to the beam. The interference patterns were recorded with a thermo-electrically cooled, back-thinned charge-coupled device (CCD) having a 1024 × 1024 pixel array (SI-003A, Scientific Imaging Technologies, Tigal, OR). The distance from the pinhole plane to the CCD was 300 cm. This distance was selected to assure that the CCD's spatial resolution (25 µm pixel size) is sufficient to resolve the finest interference fringes, while recording essential features of the pinhole diffraction patterns.

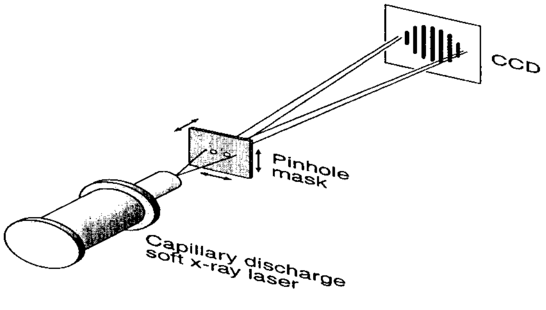

Figure1. Experiment Setup

The interference patterns recorded by the CCD contain an underlying background that is due to spontaneously emitted radiation from the hot plasma. To reduce its effect, we recorded the background after acquiring each interferogram. This was done by increasing the gas discharge pressure to ~130 Pa, which quenches the laser line while maintaining the background emission. Final interferograms were obtained by subtracting the recorded backgrounds from the original interferograms. This procedure also removes thermal "dark counts" of the CCD.

## 3. RESULTS

Comparative interferograms corresponding to increasing capillary lengths of 18, 27 and 36 cm are shown in figure 2, with their corresponding lineouts. A mask with pinhole separation of 200 µm was used in all three measurements. The mask was positioned at a distance of 40 cm from capillary exit. The interferograms consist of two almost entirely overlapped Airy patterns, modulated by the interference

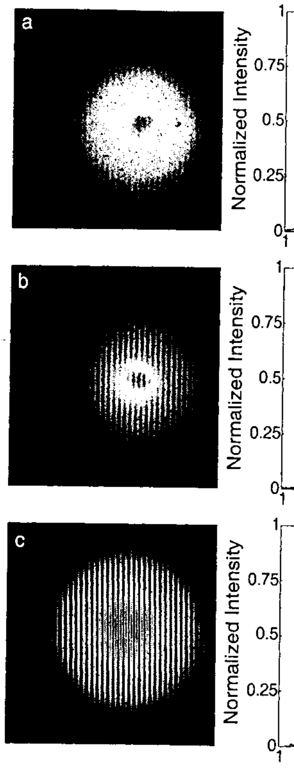

Figure 2. Interferograms and the
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## 4. SUMMARY

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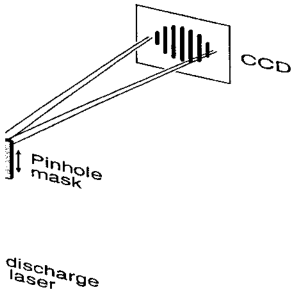

Experiment Setup

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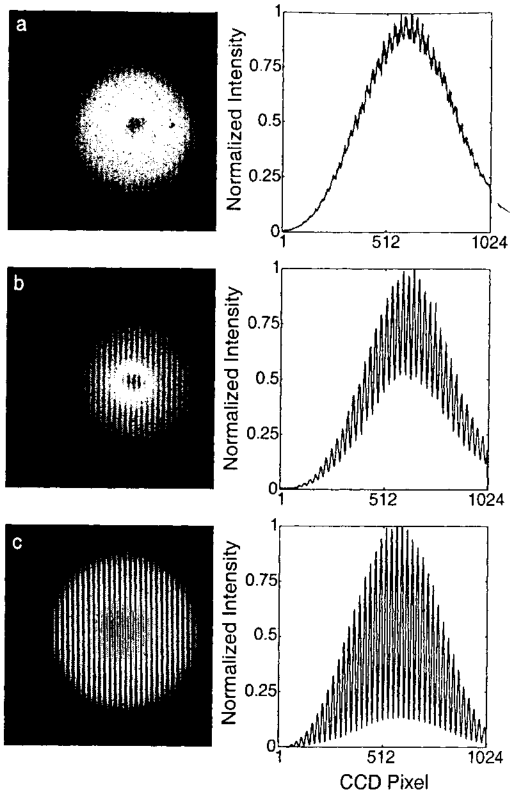

Figure 2. Interferograms and their lineouts showing the coherence buildup of the laser beam with increasing capillary length. The capillary lengths are (a) 18, (b) 27, and (c) 36 cm.

show the obtained interferograms and their lineouts with pinhole separations of 300 and 680 μm. $|\mu_{12}|$, determined from the maximum value of the visibility [22], is equal to 0.8 and 0.55, respectively. Considering the smaller beam size at this position, these results indicate a very high degree of spatial coherence throughout practically the entire laser beam. A more detailed and complete discussion and result of the coherent power and the brightness of this laser is presented in another paper [23].

## 4. SUMMARY

In summary, we have observed an extraordinarily high degree of spatial coherence in high average power soft x-ray laser beams produced by a tabletop device. The results were obtained by single pass laser amplification in a very long capillary plasma column using intrinsic mode between them. The expected coherence buildup with increasing capillary length is clearly observed. The fringe visibility increases from 0.05 for the 18 cm long capillary, to 0.33 for the 27 cm long plasma, and reaches 0.8 for the 36 cm capillary. Assuming a Gaussian profile $|\mu_{12}|$, the coherence radii [21] for the three capillary lengths are 80, 135 and 300 μm, respectively. Although the last number is likely to be significantly underestimated as result of the background error, it is quite clear that the coherence radius scales much faster than linearly with capillary length. This is evidence of refractive mode selection as gain guiding alone provides only a linearly increasing coherence radius [8,10].

At the expense of the effective gain, refraction provides a mode selection mechanism that improves the spatial coherence of soft x-ray lasing. In our case, a coherence radius comparable to the beam size was achieved with 36 cm long capillary length. Evidence of near full spatial coherence requires measurements using pinholes with separation comparable to the beam size. To clarify the point, we positioned the pinholes closer (15.7 cm) to the capillary exit. The spatial profile of the laser beam at this position was previously measured and verified during these experiments by scanning a single pinhole across the beam. Refraction causes a ring-shaped beam profile with a peak-to-peak diameter of approximately 950 μm [15]. Figure 3

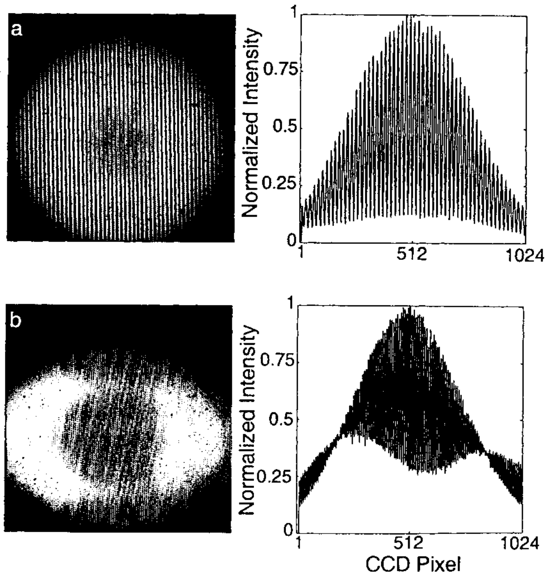

Figure 3. Interferograms and their lineouts obtained with two pinholes located at 15.7 cm from the capillary exit. The pinhole separations are a) 300 and b) 680 microns.

selection mechanisms. The availability of full spatial coherence in tabletop soft x-ray laser beams with high average power and extremely high spectral brightness opens new opportunities in science and technology.

## Acknowledgements

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[21] In this paper, we use coherence radius $R_c$ to characterize the transverse coherence length. The definition of $R_c$ is following the convention of coherence area $A_c$ used in Ref. 16 as $\pi R_c^2 = A_c = \int\int |\mu_{12}(\Delta x, \Delta y)|^2 \, d\Delta x d\Delta y$. Therefore, a Gaussian profile $|\mu_{12}|$ would be $|\mu_{12}(\Delta x, \Delta y)| = Exp\,(-(\Delta x^2 + \Delta y^2)/2R_c^2)$.
[22] The general relationship between fringe visibility $V$ and $|\mu_{12}|$ is $V = \frac{2\sqrt{I^{(1)}I^{(2)}}}{I^{(1)} + I^{(2)}} |\mu_{12}|$, where $I^{(1)}$ and $I^{(2)}$ are the light intensities in the observation plane if only pinhole 1 or 2 is present. In the ideal case $I^{(1)} = I^{(2)}$, $V = |\mu_{12}|$. Generally, difference between $I^{(1)}$ and $I^{(2)}$ will lead to $V < |\mu_{12}|$.
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