A continuous kilohertz Cu Kα source produced by submillijoule femtosecond laser pulses for phase contrast imaging

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We report a continuously operated Cu Kα x-ray source produced by a commercial kilohertz submillijoule femtosecond laser system. The source has an x-ray conversion of $\sim 4 \times 10^{-5}$ into Kα line emission at 8.05 keV. The microplasma x-ray source has a size of 8 μm (full width at half maximum) produced by focusing 260 μJ laser pulses on a moving Cu-wire target. An average photon flux of $\sim 1.1 \times 10^{10}$ photons/sr/s is obtained using the above laser pulses. The source has been used to record phase contrast images of test samples. This compact x-ray source can serve as a low cost operating system for phase contrast imaging in clinical applications. © 2008 American Institute of Physics. [DOI: 10.1063/1.3046727]

Recently there has been a renewed interest in x-ray phase contrast imaging of biological samples due to the availability of monochromatic high spatial coherence sources produced by femtosecond laser produced plasmas,1–7 micro-focus electron x-ray sources,8–11 and micropinch plasmas12 in the range of a few keV to a few tens of keV photon energies. The femtosecond produced plasma x-ray sources have unique properties, which make them very suitable for the above application. For example, they have high spatial coherence due to small source size, short duration, high peak brightness, and tunable spectral range.1–7 In particular, phase contrast x-ray imaging technique has been studied for the recording of high contrast images of biological samples.1–11 This technique provides superior contrast in the image, which is not visible in conventional absorption images, especially for weakly absorbing samples.1–11 Many of the earlier studies have been performed using synchrotron x-ray sources, which have excellent temporal and spatial coherence, high flux, and variable x-ray spectral range.13 However, a synchrotron facility is a very expensive and huge machine and is difficult to be realized in clinical applications.

Alternatively different micro-x-ray sources have been explored, viz., micro-focus x-ray tube5 and plasma focus devices.12 The tube based sources have limitations on x-ray spectral range and x-ray flux due to heat loading on the anode3 and have more continuum emission, which results in more undue radiation exposure to the sample. Although the plasma focus devices can provide large single-shot exposure, they are noisy, operate at low repetition rate, and require high maintenance. With the availability of kilohertz femtosecond laser systems, a high repetition rate x-ray source can be realized.13–20 Many studies have been reported on phase contrast imaging using femtosecond laser based x-ray sources.1–5 All these studies have been carried out using laser systems having relatively large laser pulse energy ranging from a few tens of millijoules to hundreds of millijoules on target. The typical x-ray conversion of the laser light to x-rays ranges from $10^{-6}$ to $10^{-4}$ depending on various experimental conditions and x-ray spectral range.20–23 As these lasers have high pulse energy, they are more prone to frequent optical damage and thus high maintenance and operating cost. The high pulse energy also restricts their operation to below 100 Hz or so. Furthermore, the large pulse energy generates more continuum bremsstrahlung emission, which interferes with high contrast imaging. On the other hand, a low energy laser based source can be more durable, operate at high repetition rate, and generate a lower continuum emission due to less heating of bulk high density plasma.4 However, they typically do not exhibit as good an x-ray conversion efficiency5–10 as Cu Kα conversion efficiency scaling with laser energy approximately to the 1.5 power in this intensity range.4 Recently, we have demonstrated a kilohertz Cu Kα source produced by submillijoule laser pulses20 where the x-ray conversion to Cu Kα x-ray emission was comparable to that using millijoule laser pulses.21–23 The higher conversion efficiency was achieved by optimizing the laser intensity and prepulse on a solid rotating copper target.20,24 An optimized scale length of less than a wavelength has been demonstrated in a recent study because of the transition from resonance absorption to vacuum heating in this intensity regime.1 However, the copper disk source was limited in operating time to a few tens of minutes due to a limited supply of fresh solid target surface for the laser firing at a kilohertz repetition rate. In this paper we present a continuously operating kilohertz x-ray source based on Cu-wire target, which can be continuously fed through a spool, thus allowing much longer operating time. The source has a similar high conversion efficiency of $\sim 4 \times 10^{-5}$ with x-ray emission scaling to the 1.9 power of laser energy in the range of 60–335 μJ. This source has been used for recording x-ray phase contrast images of test samples demonstrating that a submillijoule laser based x-ray source can be used in phase contrast imaging and has the potential to be employed in clinical imaging applications.

The micro Cu Kα source is produced by focusing 130 fs [full width at half maximum (FWHM)] Ti:sapphire laser pulses from a commercial laser system (Spectra Physics, Hurricane model) operating at 800 nm. A 10× microscope objective is used to focus the laser pulses of $\sim 260 \mu$J onto a moving Cu-wire target to an intensity of $\sim 4 \times 10^{14}$ W/cm². The copper wire has a diameter of 250 μm and is continuously spaced on a motorized drive through a guide. This micro-x-ray source has been characterized in our...
earlier work\textsuperscript{20} when a solid copper target was used instead of the current Cu-wire target. The wire target source has a high conversion to x-rays similar to that of the solid target observed in our earlier study, and the spectrum is similar to that shown there.\textsuperscript{20} An x-ray conversion of about $\sim 4 \times 10^{-3}$ is measured for a laser pulse energy of 260 $\mu$J on the wire target at a laser repetition of 1 kHz. The somewhat increased x-ray conversion efficiency in the present case is attributed to slightly higher laser energy on the target and an increase in the prepulse level to $8 \times 10^{-4}$ in the experiment. The x-ray flux is found to vary from shot to shot with a standard deviation of 35%. This may be due to variation in the wire target surface caused by material porosity and scratches. The Cu-wire target displacement in the direction of the laser beam was measured to be within a range of $\pm 5$ $\mu$m. The variation in the laser intensity may also contribute to the variation of the x-ray flux. An average x-ray photon flux of $1.1 \times 10^{10}$ photons/sr/s is measured for the above laser irradiation. A source size of $\sim 8$ $\mu$m (FWHM) was previously measured by the knife-edge technique, as reported in Ref. 20. A moving clear plastic tape, 30 $\mu$m thick, is located between the target and the focusing objective to protect the objective lens from debris deposition. In operation it was found that the objective still required cleaning with acetone every several hours of operation due to buildup of contaminant deposits on the surface.

Figure 1 shows the setup used in the present experiment. X-rays from the source are transported out of the plasma vacuum chamber (pressure $\sim 0.1$ torr) via a 75 $\mu$m thick Mylar window. An Andor x-ray charge coupled device (CCD) camera (model: DO 420BN) with 26 $\mu$m pixel size has been used to record the phase contrast images of the object. It is mounted in a small vacuum chamber evacuated to a pressure $\sim 10^{-5}$ torr by a turbomolecular pump and oil free roughing pump to avoid oil contamination on the CCD camera. This chamber also has a Mylar film (50 $\mu$m thick) entrance window for the x-rays. The CCD is covered with a 15 $\mu$m thick Ni foil to allow exposure primarily by $K\alpha$ emission. The camera is cooled to $-20$ °C to reduce the dark counts.

The x-ray source has been used to record the phase contrast images of a number of test objects. Inline phase contrast imaging geometry has been used in the present experiment as it is quite convenient for clinical applications of the source. The object was kept in air outside the plasma source chamber for recording the phase contrast images, providing convenience in operation. Images were recorded at a magnification of 4.32. The source-to-object and object-to-detector distances were 31 and 103 cm, respectively. Well-defined samples such as optical glass fibers and Mylar films were used to characterize the image quality. The plastic coated glass fiber used in the imaging tests has an outer diameter of 200 $\mu$m for the plastic jacket and an inner diameter of the glass fiber of 125 $\mu$m. Figure 2(a) shows the phase contrast images of glass fibers mounted in a cross geometry. This was recorded for an exposure of 10 min. This corresponds to an x-ray flux of $\sim 5.8 \times 10^9$ photons/cm$^2$/s on the CCD detector. The left vertical fiber does not have a plastic jacket on it. Figure 2(b) shows the line profile across the fiber. Contrast enhancement at the interfaces of glass fiber, plastic jacket, and air is clearly seen in the profiles. Both the horizontal and vertical fibers have similar profiles and fringe intensity modulation, thus confirming equal coherence of the source in both the directions. Similarly, sheets of Mylar film of 50 and

![FIG. 1. Experimental setup.](image1.png)

![FIG. 2. (a) Phase contrast image of glass fibers recorded for an exposure of 10 min. (b) Intensity line out across the fiber with cladding. (c) Phase contrast images of Mylar foils recorded for an exposure of 15 min. (d) Intensity line out across the Mylar foil edges.](image2.png)
25 μm thicknesses were imaged. The two films were placed close to each other with a gap between them. Figure 2(c) shows the image of Mylar film edges recorded using an exposure of 15 min corresponding to an x-ray photon flux \( \sim 10^7 \) photons/cm\(^2\). The intensity modulation due to the film edges is clearly seen in the phase image [Fig. 2(d)], which would otherwise not be seen in the absorption image due to low absorption of the films for the keV x-rays. The intensity profile across the fringes at the Mylar foil edges is in reasonable agreement with the previously measured source size of 8 μm (FWHM).

Finally a phase contrast image of a microscopic biological specimen, namely, a mosquito, was recorded. The mosquito was kept at the exit window of the plasma chamber (Fig. 1). This arrangement facilitates the imaging of the biological samples in vivo condition. Figure 3 shows the image of the mosquito recorded with an exposure of 15 min. The corresponding x-ray photon flux was \( \sim 9 \times 10^6 \) photons/cm\(^2\). The fine details of the internal structure of the mosquito are clearly visible in the phase contrast image. The CCD counts in the images recorded for various exposures are consistent with the x-ray flux estimated from the pin diode signals. An x-ray conversion of \( \sim 2.4 \times 10^{-5} \) is derived from the recorded CCD counts in the above image.

In conclusion we have demonstrated a kilohertz Cu Ka x-ray source based on a commercial submillijoule femtosecond Ti:sapphire laser. The source has an x-ray conversion efficiency of \( \sim 4 \times 10^{-5} \) into Cu Ka x-ray emission and has been used in recording in-line phase contrast images of various test samples. A source size \( \sim 8 \) μm (FWHM) has been measured and is consistent with the contrast seen in the phase contrast images. Further, one can easily vary the x-ray spectral range of the present source by using a wire target of a different atomic number. Such a compact durable kilohertz x-ray source may be of potential interest for clinical application of phase contrast imaging of biological samples.

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