Development of a soft x-ray plasma camera with a Fresnel zone plate to image laser produced plasmas

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Abstract. A soft x-ray plasma camera operated at 3.35nm in the water window x-ray region is developed and demonstrated imaging gas jet plasmas of several spices produced with a 10TW Ti: sapphire laser. The plasma camera consists of a 300nm thick Ag/Ti/Si$_3$N$_4$ x-ray band pass filter with bandwidth of 1.43nm to cut visible light and also to reduce colour aberration of the Fresnel zone plate, a Fresnel zone plate with diameter of 1mm and outermost zone width of 300nm, and a soft x-ray CCD camera. The magnification of the plasma camera is 10. The soft x-ray plasma camera powered by a Fresnel zone plate is a very powerful tool to observe laser produced plasmas since it is 1000 times brighter and has 5 times higher spatial resolution comparing ordinary x-ray pinhole camera. The soft x-ray images of helium, nitrogen, argon, krypton, and xenon gas jet plasmas are obtained changing gas pressure from 0.01MPa to 1MPa.

1. Introduction
Soft x-ray microscopes using x-ray wavelength from 2.3 to 4.4nm, which is so called “water window”, are very powerful tools to image wet biological specimens with high spatial resolution of nm level without any artifacts such as drying, fixing, and staining. [1][2][3]. It will make possible to image a flash photograph at a certain moment of moving biological specimens in natural environment [4] and will help to solve functional role of the specimens.

In order to develop x-ray microscopes it is very important to produce bright and uniform soft x-ray source in water window region and also to examine the x-ray source in detail. X-ray pinhole camera is the general diagnostic to image laser produced plasmas [5]. The spatial resolution and the acceptance angle of the x-ray pinhole camera are both limited to the size of the pinhole. In order to obtain higher spatial resolution one the acceptance angle has to be sacrificed.

Fresnel zone plates have long been used and are very powerful tools to image laser-produced plasma x-ray sources with high spatial resolution [6][7]. We have proposed to use a Fresnel zone plate replacing the pinhole and named it as a soft x-ray plasma camera. The advantages of the soft x-ray plasma camera comparing the ordinary x-ray pinhole camera are its large acceptance angle and the high spatial resolution. Both of large acceptance angle and higher spatial resolution are achievable at same time. The disadvantage of using a Fresnel zone plate is that the chromatic aberration of the Fresnel zone plate degrades the spatial resolution. In order to reduce the degradation of spatial resolution a band path filter to select x-rays in water window region is installed and reduces the spectral bandwidth of the x-ray source.

2. Configuration of the soft x-ray plasma camera
The soft x-ray plasma camera is consisted of a Fresnel zone plate, a band path filter, and a back illuminated soft x-ray CCD camera. The magnification of the plasma camera is 10. The focal length and the diameter of the Fresnel zone plate are 90.9mm and 1mm and the outermost zone width is about 300nm. The band path filter is composed of three thin layers of titanium, silver, and silicon nitride and thicknesses of each layer are 100nm. The central wavelength of the band path filter is 3.35nm and bandwidth is 1.43nm in FWHM. The transmission of the filter is about 28% at the peak. As the x-ray detector a back illuminated soft x-ray CCD camera is used and the pixel number and the size are 2048x2048 and 13.5\( \mu \text{m} \), respectively.

Comparing to the ordinary x-ray pinhole camera with a 10\( \mu \text{m} \) pinhole the diameter of the Fresnel zone plate is 100 times larger and that gives 10000 times higher sensitivity. The efficiency of the Fresnel zone plate is about 10% although the efficiency of the pinhole is usually 100%. Total brightness of the soft x-ray plasma camera is 1000 times higher than that of the x-ray pinhole camera and still the spatial resolution of the plasma camera is 5 times better than that of the x-ray pinhole camera. In order to obtain the same spatial resolution by the soft x-ray plasma camera the brightness is reduced to 4%.

3. Characterization of laser plasma x-ray source

The soft x-ray plasma camera is used to characterize water window x-ray plasma sources produced with pulsed laser irradiation onto gas jet plasmas. Several kinds of gas jets such as argon, krypton, nitrogen, and helium are irradiated with 10TW Ti:Sapphire laser and the images of the gas jet plasmas are obtained with the soft x-ray plasma camera. The laser energy and pulse duration on target are 165mJ and 36fs, respectively. The gas pressure is varied from 0.1 to 0.73MPa. Shown in figure 1 is the typical x-ray image of the argon gas jet plasma. There is a large and dim x-ray emission covering

![Figure 1](image1.png)

**Figure 1.** Typical x-ray image of the argon gas jet plasma is shown. The laser propagates from top and right to down and left. The gas jet is placed from 1.5mm away from laser focal spot.

![Figure 2](image2.png)

**Figure 2.** Gas pressure dependence of the x-ray intensities of helium, nitrogen, argon, and krypton gas jet plasmas is shown. X-ray intensity increases as the atomic number of gas species increases and also gas pressure increases.
from laser focal position to the gas jet position and there is also a sharp strong emission at the gas jet position.

The separation of laser focal spot and gas jet position is varied moving gas jet from 0.5 to 2mm and the position of the sharp strong x-ray emissions moves corresponding to the position of gas jet. It is apparent that the sharp strong x-ray emissions are from gas jet plasmas. The size of the gas jet plasma x-ray source is estimated and the lateral size of the gas jet plasma x-ray source is about 80µm and longitudinal size is about 300µm. X-ray intensity is also estimated taking account of the transmission efficiency of the band path filter, diffraction efficiency and the solid angle of the Fresnel zone plate, and quantum efficiency of the soft x-ray CCD camera. The x-ray intensity of the argon gas jet plasma with gas pressure of 0.73MPa is \(8.37 \times 10^8\) (photons/sr mm\(^2\) eV pulse) and is converted to \(3.00 \times 10^{-6}\) J in the water window x-ray region. The conversion efficiency from incident laser energy to the water window x-ray region is calculated to be about 0.0022%.

The x-ray intensities of the gas jet plasma x-ray sources are obtained from various species of gas jet such as argon, krypton, nitrogen, and helium and gas pressure. Shown in figure 2 is the gas pressure dependence of the x-ray intensity of various gas jet plasmas.

4. Summary
In summary a soft x-ray plasma camera with a Fresnel zone plate to achieve high spatial resolution and high sensitivity is developed and used to characterize gas water window x-ray source using gas jet plasmas. The soft x-ray plasma camera is expected 1000 times higher sensitivity and 5 times higher spatial resolution. The soft x-ray plasma camera is operated at the wavelength of 3.35nm and the magnification is 10. The several species of gas jet plasmas such as helium, nitrogen, argon, and krypton are irradiated with a Ti:Sapphire pulsed laser with 136mJ in 36fs pulse duration.

Dependences of the x-ray intensities of the gas jet plasmas on gas species and gas pressure are obtained. X-ray intensity increases as the atomic number of gas species increases and also gas pressure increases. The x-ray energy of the argon gas jet plasma with gas pressure of 0.73MPa is \(3.00 \times 10^{-6}\) J in the water window x-ray region and the conversion efficiency from incident laser energy to the water window x-ray region is calculated to be about 0.0022%.

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