Construction of Plasma Micro-Undulator by Laser Interference and Resonant Photoionization

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Abstract

An electrostatic plasma micro-undulator was formed experimentally using a combination of laser interference and resonant photoionization techniques. Plasma micro-undulator of this type are expected to be applied as compact and short-wavelength insertion devices. Stable microscopic interference fringes were obtained using a prism as an optical device for interference, and atomic vapor was resonantly ionized by this interfered laser beam. As a result, an emission from plasma corresponding to interference fringes, with periodic length of about 300 μ m, was observed. Thus, formation of a plasma micro-undulator was demonstrated by these techniques.

1 Introduction

A plasma micro-undulators are a focus of attention, because they are capable of radiating short-wavelength synchrotron radiation without increasing electron beam energy. An electrostatic plasma micro-undulator is of particular interest in view of its ability to form an undulator with microscopic periodic length of 10 to 100 μ m. In a plasma micro-undulator of this type, an interaction between a relativistic electron beam and a periodic ion-ripple leads to synchrotron radiation. One of the technical problems is how to form a microscopic ion-ripple, and some methods have been proposed.[1], [2]

Ikehata, Suzuki et al. proposed a combination of laser interference and resonant photoionization techniques.[3] Since neutral gas is ionized by a interfered laser beam, a pattern of an plasma-ripple formed by these techniques corresponds to that of interference fringes. Features of these techniques are that it is easy to control periodic length and density of the plasma-ripple, and it is possible to form an plasma-ripple with great regularity. [3] However, formation of a plasma micro-undulator by these techniques has not been demonstrated previously.

The present report describes the experimental apparatus and results respecting the construction of the plasma micro-undulator.

2 Techniques for Formation of Plasma Undulator[3]

A schematic of an electrostatic plasma micro-undulator is shown in Figure 1. As a relativistic electron beam crosses a periodic plasma-ripple obliquely, relativistic electrons remove electrons in a plasma-ripple from an orbital path of electron beam, because a relativistic electron is heavier than an electron in a plasma. As a result, an ion-ripple remains on a beam orbit. Then, a periodic electrostatic field acts on an electron beam as an undulator force.

For example, as a relativistic electron beam, with energy of about 50 MeV, crosses a plasma-ripple, with periodic length of about 20 μ m, it radiates a soft X-ray with wavelength of about 1 nm.

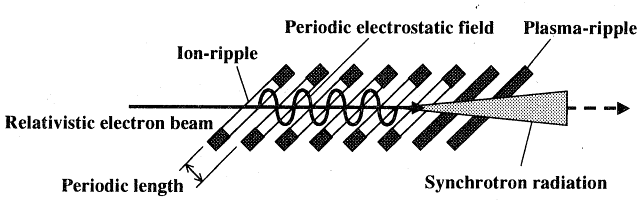


Figure 1. Electrostatic plasma micro-undulator

Figure 2 shows the combination of laser interference and resonant photoionization techniques for formation of a plasma micro-undulator.

Neutral atomic vapor is generated by heating, a laser ablation, etc. Interference fringes are composed of two laser beams with whose wavelength the neutral atoms are resonant, and they are irradiated neutral atomic vapor. Then, neutral atoms are ionized at a position such that the two laser beams are made stronger within an interference region and a plasma-ripple is formed.

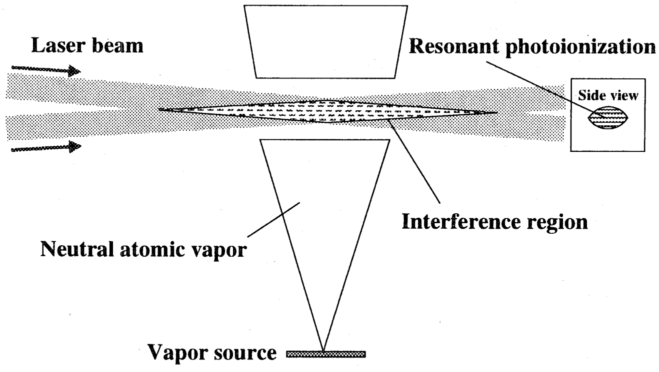


Figure 2. Combination of laser interference and resonant photoionization techniques

3 Experimental Apparatus

3.1 Vapor Source[3]

It is necessary that the shape of an ion-ripple be kept during the interaction between a relativistic electron beam and an ion-ripple. Because A velocity of a heavy ion be low, neodymium (Nd) was selected as a vapor source. The ionization scheme for Nd has been developed at the wavelength of 441.96 nm.

A laser ablation capable of generating pulsed high density vapor was used as a method of vaporization.

3.2 Optical Devices for Interference

Periodic length of laser interference fringes is affected by vibration of optics devices. In order to avoid this influence, a prism was used as an optical device for interference. A laser beam is divided into two beams by a prism, and they form interference fringes as shown in Figure 3.

Two prisms, with the prism angle of 3.2 and 0.54 degrees, were prepared for interference fringes, with periodic length of 17 and 100 μ m, by wavelength of 441.96 nm. Figure 4 shows the observed interference fringes formed by two prisms using a continuous wave He-Ne laser with wavelength of 632.8 nm. The periodic length of the interference fringes was stable, and about 25 and 150 μ m, respectively. These results mean that periodic length of the fringes is about 17 and 100 μ m in the case of laser wavelength of 441.96 nm. Accordingly, it was confirmed that a prism was able to form stable interference fringes with any periodic length.

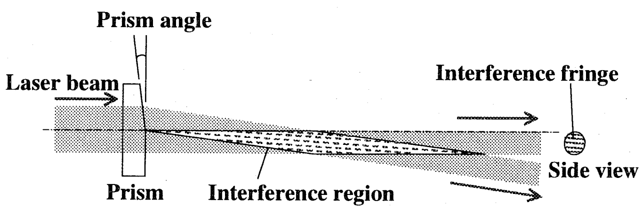
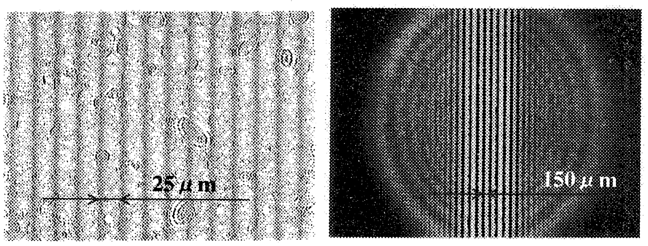


Figure 3. Interference fringes by prism



(a) 3.2 degrees (b) 0.54 degrees

Figure 4. Observed interference fringes

3.3 Experimental Apparatus

The experimental apparatus is shown in Figure 5. The apparatus mainly consisted of the vacuum chamber, the lasers for an ablation and a resonant photoionization, and the prism. On the side of the vacuum chamber, a port was arranged for each incident beam. A Nd target was set up horizontally in the vacuum chamber and irradiated by the laser for an ablation at an incident angle of about 50 degrees. Then, Nd atomic vapor was generated in the vertical direction of the target and irradiated by the laser for an ionization. A SHG-YAG laser and a Ti-sapphire laser were used for an ablation and an ionization, respectively. The pulsed energy of each laser was approximately 100 mJ and 1mJ.

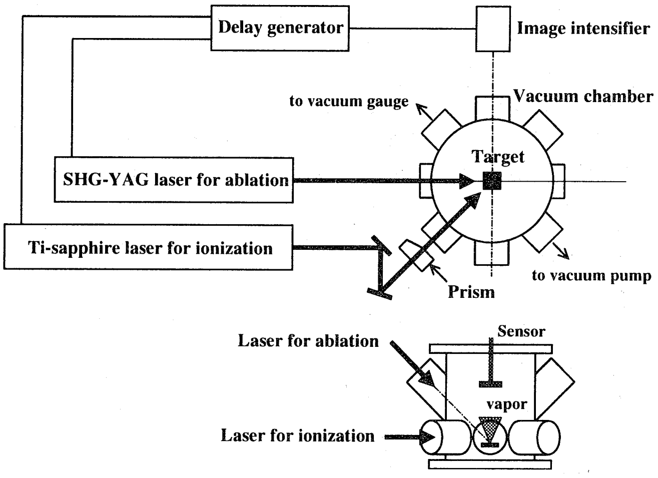


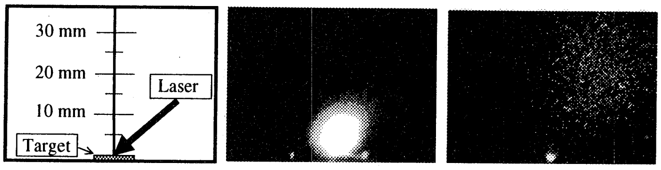
Figure 5. Experimental apparatus

The experimental procedure was as follows. The shape of an emission from Nd particles generated by an ablation was observed, and an irradiated position and time for an ionization and periodic length of a plasma micro-undulator were determined. The number of Nd particles was measured with sensors set up at several points above a target to measure deposition thickness. An emission from a plasma micro-undulator was observed. An image intensifier with a high-speed gate was used to observe an emission.

4 Experimental Results

4.1 Observation of Emission from Nd Particles by Ablation

Figure 6 shows the observed emission from Nd particles at 1 or 4 μ s after the target is irradiated. From these results, the Nd particles moved in the vertical direction of the target as they extended and the velocity of the center was approximately 5000 m/s. The intensity of emission remarkably decreased at 4 μ s after the irradiation. In order to observe an emission from a plasma micro-undulator, it is desirable that intensity of emission by an ablation be lower. Therefore, the irradiated position and time for an ionization were determined to be 25 mm above the target and 4 μ s after the irradiation for the ablation. From the Nd particles velocity, the periodic length of the plasma micro-undulator was decided to be about 300 and 500 μ m.



(a) 1 μ s (b) 4 μ s

Figure 6. Observed emission from Nd particles by ablation

4.2 Measurement of the Number of Nd Particles by Ablation

Figure 7 shows the measured distribution of Nd particles generated by the ablation per laser pulse. This distribution was approximately proportional to $\cos^{10}\theta$, and it was confirmed that the number of Nd particles was about 6×10^{14} n/pulse from the estimation by an integration of this distribution.

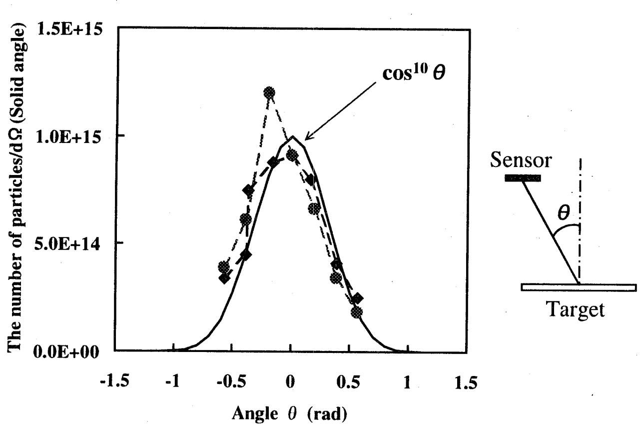


Figure 7. Measured distribution of Nd particles by ablation

4.3 Observation of Emission from Plasma Micro-Undulator

The formation of the plasma micro-undulator was demonstrated by the combination of laser interference and resonant photoionization techniques.

Figure 8 shows the pattern of emission from Nd particles within the interference region with the periodic length of about 300 and 500 μ m, as discussed section 4.1. It was confirmed that the pattern of emission by the resonant photoionization corresponded to that of the interference fringes.

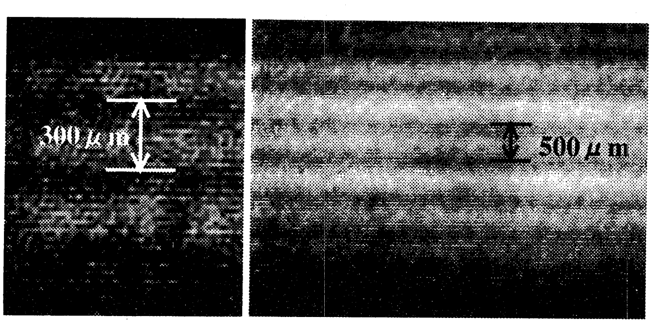


Figure 8. Observed emission from plasma micro-undulator

5. Discussions

The plasma density and the K parameter, which have an important bearing on the properties of a plasma micro-undulator, were estimated.

The results shown in Figure 6 indicate that the volume of Nd particles generated by the laser ablation was expanded to several tens cm^3 at several μ s after the laser irradiation. And the number of particles generated per laser pulse was 6×10^{14} n/pulse. Then, the density of Nd particles was estimated to be the order of 10^{13} cm^{-3}. Assuming that efficiency of a resonant photoionization was about 10 %[3], the density of the obtained plasma micro-undulator was estimated to be of the order of 10^{12} cm^{-3}.

A K parameter of an electrostatic plasma micro-undulator is described by the following equation [4]

$$K=\frac{n_0 e^2 \lambda_u^2}{8\pi^2 \varepsilon_0 m c^2} \qquad (1)$$

where n_0 is the plasma density, e is the elementary electric charge, λ_u is the periodic length of the undulator, ε_0 is the dielectric constant in vacuum, m is the rest mass of electron, and c is the light velocity in vacuum. Using Equation (1), λ_u=300 μ m, and $n_0=10^{12}$ cm^{-3}, the K parameter was estimated to be 4×10^{-5}. In a practical undulator the parameter is more than 0.1. Accordingly, it is necessary to increase the plasma density by using high-power lasers for the ablation and the ionization, and reducing the period after the irradiation for the ablation so that the microscopic plasma-ripple is capable of acting as an undulator.

6. Conclusions

Using the prism for the interference, the fringes were obtained stably with the periodic length of 20 μ m.

The emission from plasma corresponding to the interference fringes, with the periodic length of 300 μ m, was observed by the irradiation of the interfered laser beam. Accordingly, the formation of the plasma micro-undulator was demonstrated by the combination of laser interference and resonant photoionization techniques.

In future work we intend to increase the plasma density and then demonstrate a plasma micro-undulator with an electron beam for a synchrotron radiation.

References

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