Development of High-Order Harmonic Light Spectrometer for Observation of Strong Magnetic Field Generated by Fast Electrons in Laser-Plasma Interactions

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(Received: 9 September 2008 / Accepted: 25 November 2008)

Measurement of magnetic field is one of critical parameters for Fast ignition in inertial confinement fusion research. Not only that the field inside plasma affects the transport of fast electrons generated in intense laser pulse-plasma interactions, but also that measurement of the field is one of good tools for investigation the current of fast electrons, resulting in estimation of conversion efficiency from laser light to nuclear energy. In order to measure the magnetic field, we developed a 2-dimensional and VUV spectrometers to measure sideband of high-order harmonics created via cyclotron motion of bulk electrons. The preliminary experimental results will be also discussed.

Keywords: Magnetic field, Cyclotron frequency, Fast electrons, Bundled fiber.

1. Introduction

Magnetic field plays an important role in plasma physics. In Tokamak or Helical devices geometry of magnetic field is so essential to confine the plasma. In addition, there are several mechanisms to create magnetic field inside plasma themselves such when density and temperature gradient become orthogonal ($\nabla n \times \nabla T$). In the area of inertial confinement fusion, magnetic field is also created due to Weibel instability, thermal instability, and Rayleigh-Taylor instability have been proposed in high dense region [1]. These magnetic fields would affect fast electron transport inside plasma such as pinching or bending, so that it is also important to measure such magnetic fields.

For the fast ignition in inertial fusion research, fast electrons generated by an ultra-intense laser propagate into the high dense plasma to core. In order to understand its behavior inside the plasma, so many measurements are proposed and carried out such as observations of $k\alpha$ emission and transition radiation using just planer target, not long scale plasma. In recent publications, measurement of magnetic fields, could be created by fast electrons themselves, is also effective to investigate the propagation directly in the dense plasma [2]. The magnetic fields inside plasma could be measured with sidebands of high-order harmonics (HH) shifted by scattering at cyclotron-electrons in magnetic field with cyclotron frequency [3].

In order to measure the self-created magnetic fields, we performed a side band measurement of high-order harmonics developing a two type of spectrometers. One is a 2-dimensional spatial resolved spectrometer using a bundle-fiber array to observe the magnetic field at the target surface via reflected high-order harmonics. The other is Rowland-type spectrometer to achieve extreme high resolution in wavelength for measurements of magnetic field created by fast electrons themselves deeply inside plasma. The center wavelength of the detector is set to 10th order (105 nm for 1μm light) harmonics, which can propagate into solid dense plasma, and ranged from 7th to 17th high harmonics at the same time. The spectrometer has a 90 μm spatial resolution for 10th order high harmonic on the Rowland circle, which can measure the magnetic field lower than 20 Mega Gauss with 1 MG resolution. Here we report the construction of these spectrometers and preliminary experimental results.

2. Construction of bundle-fiber spectrometer

In the laser-plasma interactions, the mechanism to generate high-order harmonics is known as a vibration mirror model [4]. When the laser field is strong enough to nonlinear effect, the vibration oscillation becomes to be included a high-order motion. The high-order harmonics can be generated via the interaction of incident laser light and this high-order oscillation. If the harmonics cannot penetrate solid dense plasma, this light reflected to backside. Because the solid dense plasma corresponds to critical density of about 10th order harmonics, the side band measurement of lower-order (2 or 3) harmonics from the target surface direction exhibits the magnetic field around the target surface.

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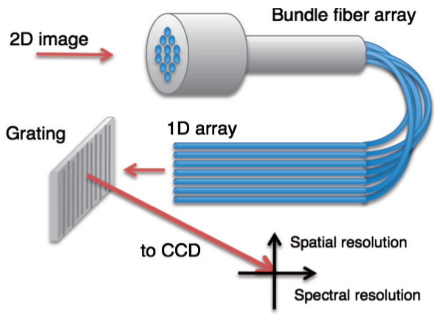

Fig. 1 Construction of bundle fiber spectrometer.

Also in order to observe spatial dynamics of magnetic field, we developed a 2-dimensional spectrometer using bundle fiber. Figure 1 shows the construction of this detector. A 2-dimensional image is observed at the bundled fiber array. At the end fibers are separated and aligned again in line. The exit light from the lined fiber array enters slit of spectrometer, so that we can observe the spatial resolved spectrum in 2-dimension. Our detector has 10×10 channel step-index SiO_2 fiber at the incident surface. Each fiber is 100 μm diameters and 500 mm length with transportation loss is less than 8dB for visible light. The detectable magnetic field is up to 4.6 MGauss with 40 kGauss resolutions.

3. Construction of VUV Spectrometer

The spectrometer consists of mainly two parts, spectrometer and light detector. As a spectrometer construction, we choose a Rowland-type setup, which uses spherical grating and mirrors, to achieve high spectral resolution compared with a planer grating (Czerney-Turner / Littrow type), and reduce fabrication cost and alignment difficulty when off-axis mirror is used (Wadsworth-type).

Figure 2 shows an overview of spectrometer setup. The incident light is reflected to grating via two spherical mirrors of which focal length is adjusted with the distance from the source. The light is at first focused on the Rowland circle and then diffracted at the grating. Finally the light is focused again onto the detector at the Rowland circle. In order to estimate the spectral resolution (spatial resolution) on detector surface, we performed a ray-trace calculation. In the results, the line spread at 10th harmonics

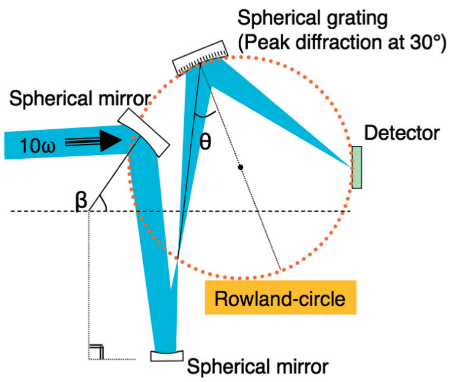

Fig. 2 Overview of setup of Rowland-type spectrometer.

signal is about 90μm assuming a point source. In the previous experiments in laser plasma interactions, the magnetic field of which strength is from 10 [5] to 80 [6] MGauss is observed. These magnetic fields corresponds to 250 μm and 2.5 mm dispersion between sideband and main light at the detector position, which are able to distinguish clearly. The detectable magnetic field is ranging from 7 MGauss to a few hundred MGauss with 1 MGauss resolution.

As a VUV (vacuum ultra-violet) / XUV (extreme ultra-violet) light detector, we use two type of detector: one is phosphors, which are usually used in a deep UV region (λ>120 nm) for plasma display panel, are used coupled with the charge coupled device (CCD). The phosphor films are fabricated by coagulation sedimentation method and are experimentally evaluated the luminous fluorescent characteristics from the rear side of the films. The second is an imaging plate which has enough sensitive to X/VUV rays.

We used two types of phosphor, P1-G1S and KX-501A, made by KASEI OPTORONICS INC., which emit green and blue light absorbing a UV light. Because there are no data for conversion efficiency to VUV light (less than 100 nm), we performed calibration experiments using monochromatic VUV light from synchrotron radiations at UVSOR, IMS, Japan. At first, we observed emission spectra changing the incident light wavelength from 10 to 300 nm, but no changes on peak wavelength and spectral width are observed.

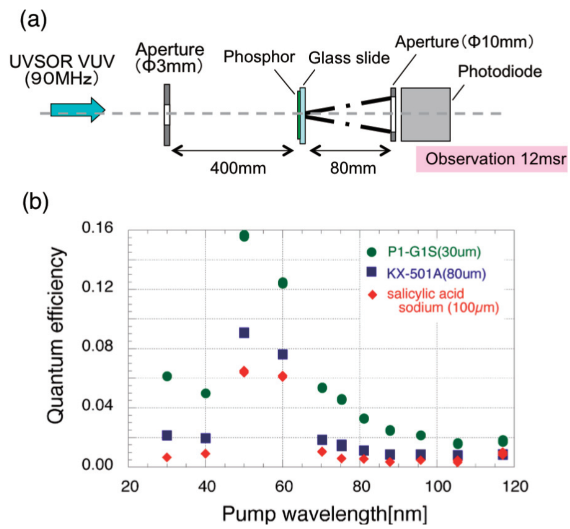

Fig. 3 (a) Experimental setup. (b) Quantum efficiency as a function of incident light wavelength.

Figure 3(a) shows an experimental setup and the results. The first aperture is set to define the incident light intensity. The escaped light is irradiated onto the phosphor on the transparent glass slide. Generally, there is no direction for fluorescence, so that we set an aperture again in front of Photodiode in order to know the observed cross section. The VUV light from the synchrotron has a high repetition rate (90MHz). On the other hand, the fluorescence decay time is order of μsec. So we need to consider pile-up effect of fluorescence for conversion efficiency. Fig. 3(b) indicates the obtained conversion efficiency for different incident light wavelength. As a comparison, the result of salicylic acid sodium has also shown in the same figure. In the results, P1-G1S has highest conversion efficiency among these three phosphors. Because the signal is observed from rear side, one could suspect that difference on the thickness of phosphors affect this result. Each thickness is the thinnest sample we can make with sufficient surface flatness. We also observed the dependence of thickness on signal intensity, resulting in no change between 50 and 80 μm for KX-501A and 30% reduction from 30 to 60 μm for P1-G1S. From these results, P1-G1S indicates a few times larger conversion efficiency than salicylic acid sodium and good light converter. Note that the bump at 50 nm is not difficult to explain from the established model such as Interband Auger process [7]. However because the peak shows same wavelength for different phosphors, there is a possibility due to Ba ions used for solution as settling process and need the verifications. Taking into account of light intensity of high order harmonics in intense laser plasma interactions, these phosphors has an enough efficiency to observe harmonics with mlux sensitivity CCD.

4. Preliminary Experimental Results

Using a 2-dimensional spatial resolved spectrometer, we performed a preliminary experiment to measure the magnetic field at the target surface. The experiment is conducted at PW CPA Nd:glass laser system in Institute of Laser Engineering, Osaka University. The laser energy is about 500J and pulse width is 0.5 ps with 70μm spot diameter, resulting in laser focus intensity of 10^{19} W/cm^2 at best. As the target, we used a thick gold plane (0.1 mm) and laser irradiates on this target with 25° incidence angle with p-polarization direction.

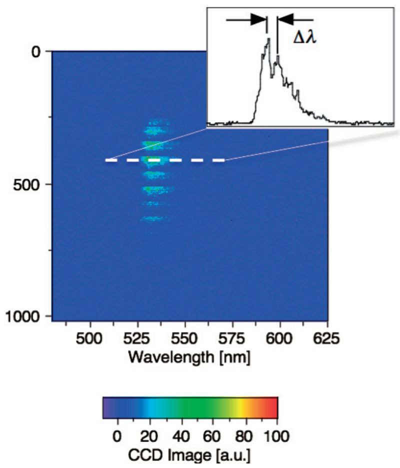

Fig. 4 Typical experimental result for 2-D spatial resolved spectrometer.

Figure 4 shows a typical experimental image of 2ω harmonics taken with spectrometer. At this time the laser energy is 336 J, resulting in 2.62×10^{18} W/cm^2. Each line aligned vertically indicates a spectrum for each channel. The line profile of one channel is also shown in inset of the figure. The line shape clearly exhibits regularly modulation on the spectrum, which represents exactly side-bands of 2ω light. The spectral and spatial resolutions of this image are 0.7 nm and 5 μm.

From this modulation, we can estimate magnetic field for each channel. The cyclotron frequency can be written by the spectral shift, $\triangle\lambda$, as

$$\omega_{ce} = \frac{2\omega_0}{\lambda_0/2}\Delta\lambda, \qquad (1)$$

for $2\omega_0$ light. On the other hand, the definition of cyclotron frequency is

$$\omega_{ce} = \frac{eB}{m_e C}. \qquad (2)$$

Figure 5 shows (a) the spatial light intensity of back scattered $2\omega_0$ light and (b) the magnetic field strength at the same position calculating form eqs.1 and 2. Fig. 5 (a) represents laser focus pattern showing peak intensity near the center. Considering fast electrons generated at the laser spot, an azimuthal magnetic field could be generated around the fast electrons according to Ampère's law [8]. In Fig. 5 (b) the azimuthal magnetic field is cleary displayed around the center part, where the magnetic field is relatively low.

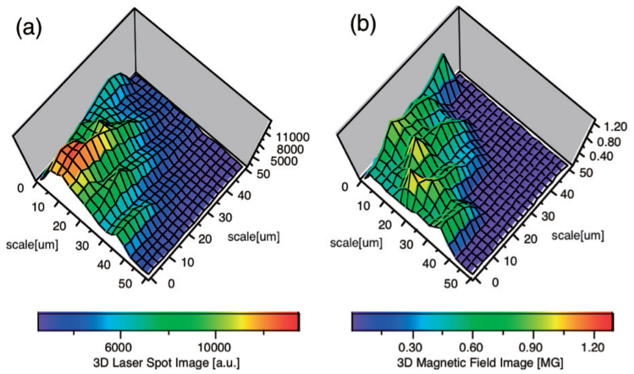

Fig. 5 (a) A 2-dimensional image of Back-scattered light. (b) Calculated magnetic field pattern from the cyclotron frequency.

We also performed similar experiment at GMII 30TW laser system at ILE. Table 1 shows the summary of these experiments. Observed magnetic fields are comparable to other experiments [5,6,9].

Table 1 Summary of the observed magnetic field.

	Laser Intensity [W/cm^2]	$\Delta\lambda$ [nm]	Max. B-field [MG]
GMII	8.81×10^{17}	2.12	0.818
PW	2.62×10^{18}	3.21	1.24

5. Summary

In order to measure the magnetic field, we developed a 2-dimensional and VUV spectrometers to measure sideband of high-order harmonics created via cyclotron motion of bulk electrons. A 2-D spectrometer utilizes bundled fiber array in order to achieve spectral and 2-dimentional space resolutions for back scattered relatively lower-order harmonics.

On the other hand, for measurement of magnetic field inside plasma, we also developed a VUV spectrometer using a Rowland-type setup in order to achieve high spectral resolution. As a light detector, we use phosphors and measure the conversion efficiency from VUV to visible light using a synchrotron X-ray source, resulting in enough efficiency to measure 10th order high-harmonics generated in laser plasma interactions.

Finally, we performed preliminary experiments of back-scattered 2nd harmonics at ILE, Osaka University. Using a two different intense laser system, the observed magnetic fields were order of MGauss in both cases. This result is consistent with previous publications. We now plan to conduct an experiment to measure the magnetic field inside plasma using the VUV spectrometer at GMII laser system at ILE.

6. References

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