Studies of AM He Atomic Magnetometer for Fusion Plasmas*)

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Amplitude modulated helium atomic magnetometers (AM He AOM) are proposed as a new method, which allows spatially resolved magnetic field measurement in the inner regions of burning plasmas without heating beams nor impurity atoms. In order to understand the fundamental properties of AM He AOM, we have developed a prototype, and Helium discharge lamp as well as its power supply has been also elaborated as a light source. 1083 nm AM emission was successfully obtained in the frequency range between 40 kHz and 500 kHz. We have performed an exploratory experiment of test magnetic field measurement with the developed AM He AOM. For the test magnetic fields: 2.6 μT and 5.0 μT, possible signs of magnetic field have been observed.

Keywords: atomic magnetometer, optically pumped magnetometer, optically driven spin precession, burning plasma diagnostics, magnetic turbulence

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1. Introduction

An atomic magnetometer (AOM), also called as an optically pumped magnetometer, has ultra-high sensitivity, which is comparable to SQUID, and can work without cryogenic cooling or under radiation environment. Therefore AOM is employed for space magnetometry or detection of biomagnetic fields [1]. In this paper a new application of AOM for fusion plasmas is suggested.

The detailed measurement of magnetic field is above all fundamental in fusion research, and various approaches, as represented by the Faraday rotation and motional stark spectroscopy techniques, have hitherto been extensively developed.

An atomic magnetometer, in particular, amplitude modulated helium atomic magnetometer (AM He AOM) allows spatially resolved magnetic field measurements even in the inner regions of burning plasmas, where helium ions are produced from the D-T fusion reaction and part of them exist as meta stable ^{4}He (2^3S_1) atoms suggested as probing targets in this work. Accordingly neither heating beam nor impurity atoms is necessary. The principle of AM-AOM is following.

Atomic magnetometers take advantage of the transmission property of light through spin polarized atoms; alkali atoms and helium atoms are often employed. Magnetic moments of these atoms precess around the magnetic field direction and its frequency is f_L called as Larmor frequency or Zeeman transition frequency, which equals γB. Here γ is gyromagnetic ratio and Table 1 shows γ values of He and alkali metals. γ is determined by nuclear spin momentum and 28 GHz/T for ^{4}He [2]. These precessions change their refractive indices periodically at the frequency f_L and modulate transmitted light property. The maximum modulation is obtained when precessions are synchronized, which leads to resonant properties of the transmission rate. In the case of AM He AOM, these synchronized precessions are produced through the optically pumping whose intensity modulated at f_L and this process is illustrated in Fig. 1. Target atoms in a glass cell absorb injected circularly polarized light together with its angular momentum, which modifies their magnetic moments to point in a certain direction (left in Fig. 1). When amplitude of the injected light is modulated at the frequency f_L, intensity of these modification as well as absorption is also

Table 1 Values of magnetic ratio for He, Rb and Cs.

Element	^{4}He	^{85}Rb	^{87}Rb	^{133}Cs
γ [GHz/T]	28.0	4.67	7.00	3.50

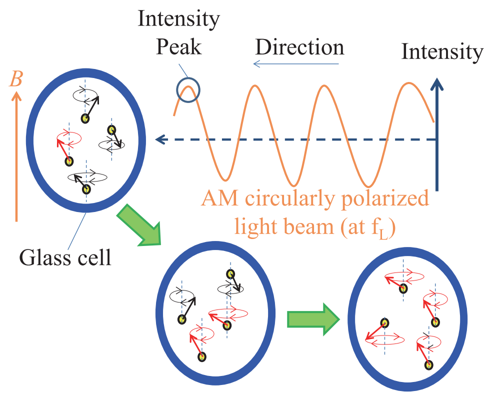

Fig. 1 Phase modulation of Larmor precessions through light absorption is maximized when intensity peak of AM light beam injects to the cell. After several peaks inject, in-phase precessions are produced.

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modulated at the same frequency, and accordingly in-phase precessions are produced. The basic principle herein employed is referred to as Bell and Bloom techniques [3].

Figure 2 shows a schematic of the AM He AOM system. The pump and probe beams are injected into a He discharge cell in which probing targets, meta stable ^{4}He (2^3S_1) atoms, are produced. The wavelength of these light beams is 1083 nm (He D1 line). An amplitude of pump beam is modulated at frequency f_{pump} and circularly polarized for the spin-polarization of the He atoms, whilst the probe beam is only circularly polarized. When f_{pump} equals the Larmor frequency f_{L} ($= \gamma B$), Larmor precessions of He atoms in the discharge cell are synchronized and the resonant property is detected in terms of transmission rate. From the resonant frequency, magnitude of the magnetic field at the cell is evaluated. In order to understand the fundamental properties of the proposed AM He AOM, we have developed the prototype and conducted exploratory experiments of measuring test magnetic fields.

2. Experimental Setup

Our prototype of AM He AOM is shown in Fig. 3. For simplifying the setup, single beam configuration has been adopted, with which magnitude of the magnetic field on the beam pass can be measured. As a light source for this prototype, He discharge lamp and its power supply have been designed and elaborated in the lab and it produces AM light emission (discussed in detail later). Collimated beam from the light source is injected into He discharged cell (probing targets) after circularly polarized. The transmitted light intensity is detected by a photo diode amplifier circuit. Furthermore the signal is amplified with Lock-in amplifier whose reference is synchronized with the frequency of amplitude modulation. He discharge cell is installed inside a magnetic shielded box made of PC permalloy (μ = 20000 H/m), which is a cube of 150 mm side length and 1.5 mm thick. This shielded box decreases low frequency (< 20 Hz) magnetic noise produced by the surrounding electronics from 30.6 μT to 0.94 μT (these are RMS values and measured by Gauss Meter DSP425). Inside the box, a helmholtz coil which generates test magnetic field is also fixed as shown in Fig. 4. This test magnetic field is perpendicular to a beam direction, which maximizes resonant signals [4].

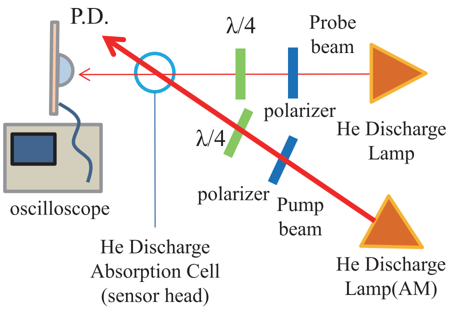

Fig. 2 Schematic of AM He AOM System, which can measure absolute magnitude of magnetic field at the cross point of two beams.

3. Development of a Light Source

A hollow cathode type He discharge lamp shown in Fig. 5 (left) has been developed in the lab. During discharge, oxygen is released from the surface of an Al hollow cathode, and it degrades He D1 emission intensity through the Penning effect shown below [5].

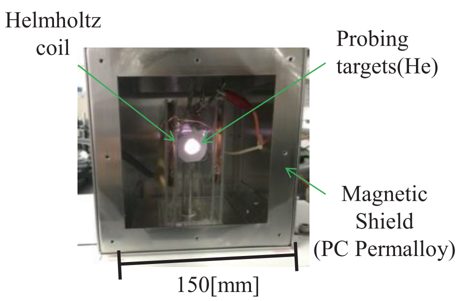

Fig. 4 Arrangement inside the magnetic field.

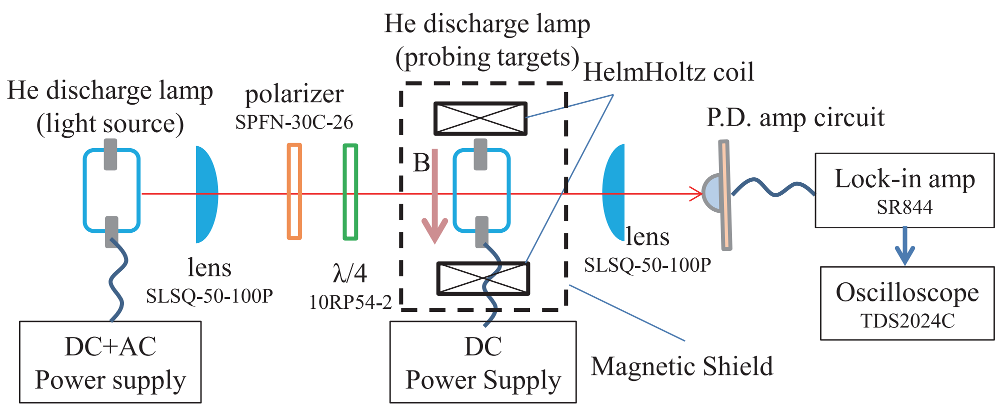

Fig. 3 Schematic of Experimental setup. In measuring magnetic field, high frequency Lock-in amplifier, SR844 is employed. In order to investigate the property of the light source, instead of SR844, light chopper and low frequency Lock-in amplifier, SR510, are utilized for evaluating DC light intensity.

$$\mathrm{He} + \mathrm{electron} \rightarrow \mathrm{He}^*(2^3\mathrm{S}, 2^1\mathrm{S}) + \mathrm{electron},$$
$$\mathrm{He}^*(2^3\mathrm{S}, 2^1\mathrm{S}) + \mathrm{O}_2 \rightarrow \mathrm{He} + \mathrm{O}^* + \mathrm{O}^+ + \mathrm{electron}.$$

For extending a lifetime of the discharge lamp, an oxygen absorber (Fe) is enclosed inside the lamp as shown in Fig. 5 (right). Cooling this absorber with Liquid nitrogen is also adopted aimed at improving the efficiency of oxygen absorption. These techniques have improved the lamp's lifetime successfully as indicated in Fig. 6 (left).

In a preliminary experiment, emission intensities of different diameter lamps (12, 18, 30 mm) were evaluated. As depicted in Fig. 6 (right), smaller diameter lamp had the larger emission intensity. Therefore 12 mm diameter lamp has been adopted as a light source.

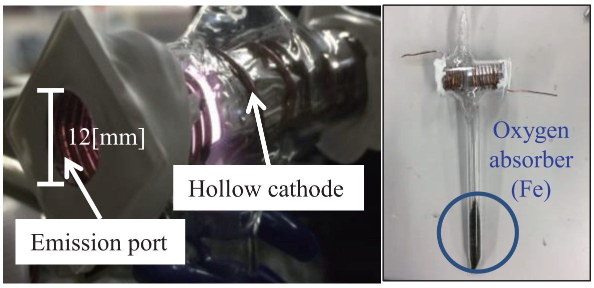

Fig. 5 (left) A manufactured hollow cathode lamp. (right) An oxygen absorber inside the discharge lamp.

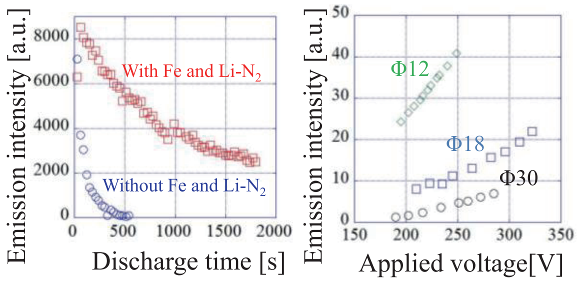

Fig. 6 (left) Time development of 1083 nm emission intensity, which was measured with NIR2b-14. (right) Comparison between emission intensities of different diameter lamps: 12, 18, 30 mm.

Power supply of the discharge lamp has been also designed and built. The circuit diagram is shown in Fig. 7. This power supply can produce frequency tunable AC voltage with DC voltage offset which is high enough to discharge the lamp. Fig. 8 (left) shows the output waveform at 100 kHz. The input rectangular signal from the function generator, whose amplitude is 8 V, is amplified to about 80 V with the emitter amplifier circuit. Figure 8 (right) indicates AM emission intensity of this light source. The intensity was measured in the optical system shown in Fig. 3 with the Lock-in amp, SR844. Though the intensity decreases in high frequency region possibly due to the restriction of discharge process, frequency tunable AM He D1 emission has been successfully obtained in the frequency range between 40 kHz and 500 kHz.

Whilst AC component of the injected light into a helium discharge lamp (probing targets) synchronizes spin precessions of atoms, DC component destroys these syn-

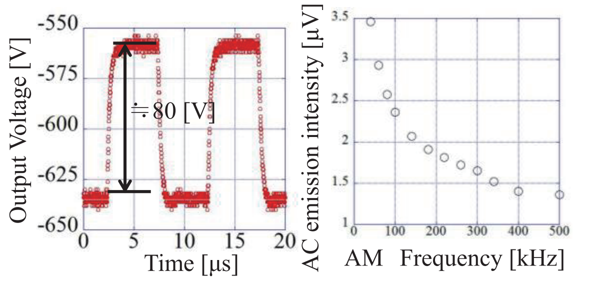

Fig. 8 (left) The output waveform of the developed DC+AC power supply at 100 kHz. (right) AC emission intensity versus frequency.

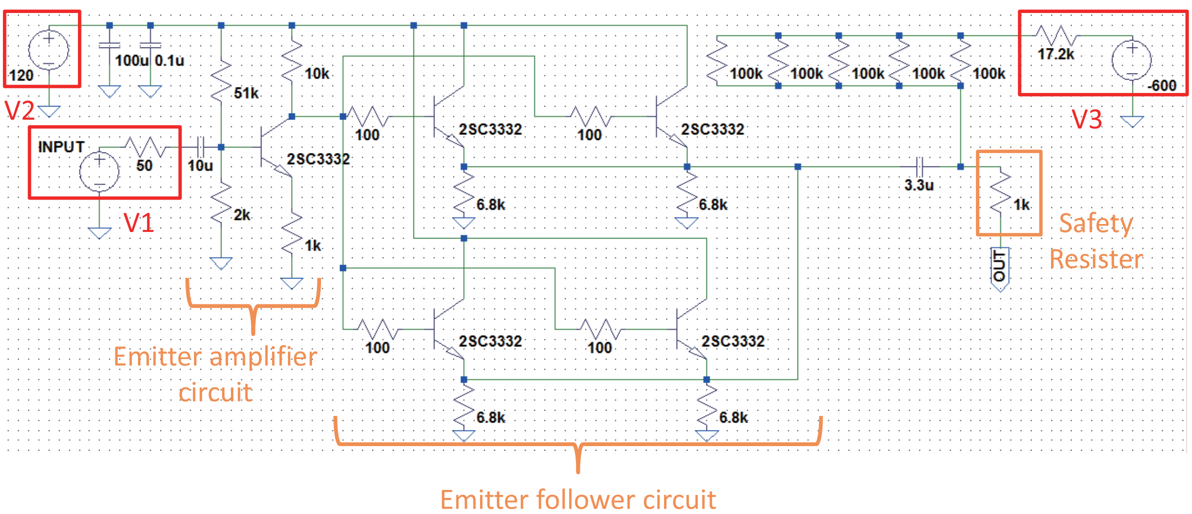

Fig. 7 Circuit diagram of the developed DC+AC power supply depicted with LT-SPICE. V1 is a function generator, E3612A and V2 is a DC power supply, 33120A. V3 is a double voltage rectifier circuit manufactured in the lab.

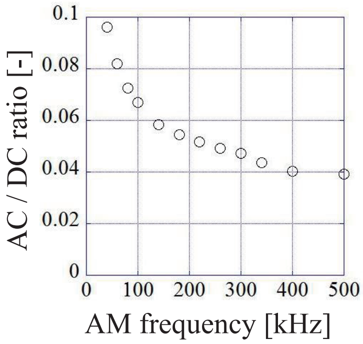

Fig. 9 AC/DC ratio versus AM frequency.

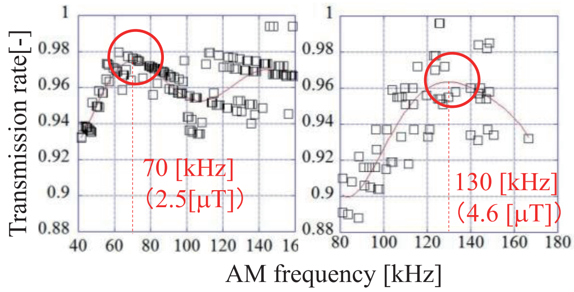

Fig. 10 Transmission rate versus AM frequency.

chronized precessions. Therefore higher ratio of AC to DC component (AC/DC ratio) is required for improving resonant signals. The AC/DC ratio for the developed light source was calculated from AC emission intensity depicted in Fig. 8 and DC emission intensity, which was measured in the optical system shown in Fig. 3 with the light chopper and the Lock-in amp, SR511. As shown in Fig. 9, our developed light source has an about 7% AC/DC ratio at 100 kHz.

4. Results of Magnetic Field Measurement

With the developed AM He AOM prototype, we have performed an exploratory experiment of test magnetic field measurement. The sweep rate of AM frequency is fixed at 1/3 kHz/s. In the experiment, transmitted light intensity is measured for activated probing targets (discharged absorption cell) together with non-activated targets, and transmission rate is calculated from these values.

Figure 10 shows the transmission rate versus AM frequency. Around 70 kHz (left) and 130 kHz (right), these signals seem to have their peaks, which correspond to 2.5 μT and 4.6 μT respectively. These values roughly equal to magnitude of test magnetic field: 2.6 μT (left) and 5.0 μT (right). Consequently possible signs of magnetic field have been observed with the developed prototype. The left signal has another peak around 140 kHz. However this is presumably a noise related with instability of the discharge lamps.

5. Summary and Discussion

Amplitude modulated helium atomic magnetometers (AM He AOM) are proposed as a new method to measure magnetic field in burning plasmas. In order to understand fundamental properties of AM He AOM, the prototype has been developed in the lab. With the developed tunable frequency AM light source, whose wave length is 1083 nm (He D1 line), AM light emission has been successfully obtained between 40 kHz and 500 kHz, and its AC/DC ratio is about 7%.

An exploratory experiment with test magnetic field has been conducted. Through this measurement, possible signs of magnetic field have been observed for a few micro tesla test fields: 2.6 μT and 5.0 μT. These resonant signals are degraded possibly due to impurity atoms, in particular, oxygen which is released from electrodes in a helium discharged lamp. Therefore we suppose that the non-electrode absorption cell, which takes advantage of inductively coupled helium plasma, is effective for improving the signal quality.

For application to fusion plasmas, the amount of probing targets (He atoms) in the core must be considered. Most of helium atoms produced from D-T reaction exist as ions in the inner regions due to extremely high temperature of burning plasmas. Therefore the quantitative relation between probing target's density and signal intensity of AM He AOM should be investigated in order to examine possibility of this application. In addition to that, since hitherto AOM is generally employed for relatively small magnetic fields measurement (under dozens of micro tesla), research toward measurement of a few tesla magnetic fields, which corresponds to confinement magnetic fields, with AM He AOM is also required.

[1] D. Budker and D.F. Jackson Kimball, *Optical Magnetometry*, Chp.15, 16 (Cambridge university press, Cambridge, 2013).
[2] I.M. Savukov *et al.*, Phys. Rev. Lett. **95**, 063004 (2005).
[3] W.E. Bell and H.L. Bloom, Phys. Rev. Lett. **6**, 280 (1961).
[4] V. Schultze *et al.*, Optics Express **20**, 13 (2012).
[5] M. Kogoma, J. Plasma Fusion Res. **79**, 10 (2003).