# Complex interferometry application for spontaneous magnetic field determination in laser-produced plasma

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## Introduction

Generation of spontaneous magnetic fields (SMF) is one of the most interesting phenomena accompanying the interaction of intense laser radiation with matter. SMF above 1 MG may significantly change plasma transport coefficients and thereby affect the plasma density and temperature distributions, absorption of laser radiation and, ultimately, the value of ablation pressure. In context of the inertial confinement fusion ICF, in particular in those related to the fast ignition concept, the knowledge about distribution of spontaneous magnetic fields generated in compressed plasma and their influence on emission of the fast electrons is necessary from the point of view of implementation of this concept.

The various methods of recording and investigating the SMF have been developed, however the most reliable and efficient is the method based on the magnetooptic Faraday effect. The main advantage of this method is that it provides the information about magnetic fields distribution in the entire area of investigated plasma. Nevertheless it is difficult to implement and requires several conditions to be fulfilled. The basic requirement is that interferometric and polarimetric measurements should be perform simultaneously. According to the formula describing the Faraday effect at the cylindrical symmetry:

$$\theta(y) = 5.24 \cdot 10^{-17} \cdot \lambda^2 \int_y^R \frac{B_\theta(r) n_e(r) dr}{\sqrt{r^2 - y^2}}, \qquad (1)$$

information about the magnetic field distribution ($B_\varphi$), can be obtained based on electron density distribution ($n_e$) from interferometric measurements and the distribution of the Faraday rotation of the polarization plane $\varphi(y)$ from polarimetric measurements.

A unique diagnostic tool for the laser plasma research, in particular for studies of SMF and electron density distributions, is the two-channel polaro-interferometer, Fig. 1, irradiated with femtosecond Ti:Sa laser working at the wavelength of 808 nm with the pulse duration about 40 fs.

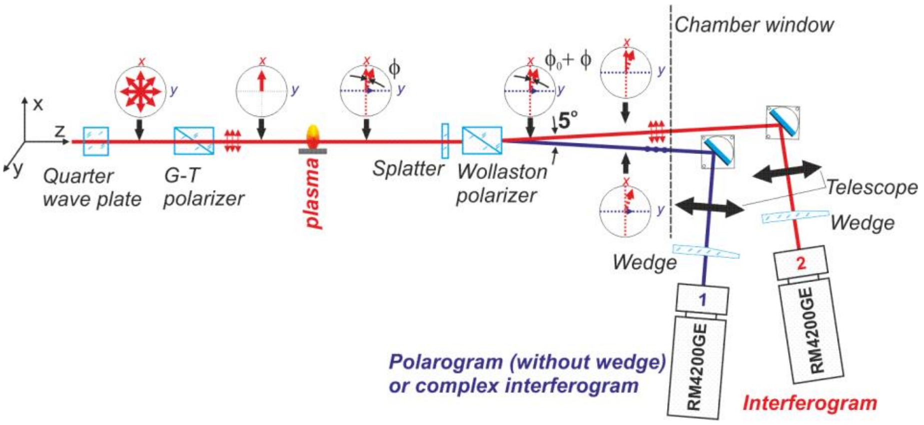


Fig. 1 The scheme of the polaro-interferometer

This system consists of two independent channels which provide a possibility to measure the magnetic fields in two ways, dependent on the optical configuration of the polarimetric channel. In the first case, a polarogram and an interferogram are recorded in each channel and the magnetic field distribution in plasma is calculated on the basis of Faraday rotation angle and electron density distributions.

At the second measurement option, instead of the polarogram, a complex interferogram is registered via initial rotation of the polarization plane using a wedge added in the polarimetric channel. Information about the magnetic field distribution can be obtained directly with amplitude-phase analysis of an interferogram. The amplitude modulation is represented by intensity changes of interferometric fringes, while the shift of interferometric fringes corresponds to the phase modulation.

The system operating at the first option of SMF measurements was successfully applied for the first time in experiment at Prague Asterix Laser System (PALS). Results from these measurements and their method of analysis have been published in paper [1].

This paper concerns the first investigations which are realized with using two-channel polaro-interferometer working in the complex interferometry option. Both the software for analyzing complex interferograms and the preliminary SMP measurements performed during the PALS experiment, are presented.

In comparison to classical polaro-interferometry, the complex interferometry seems to be more reliable because it allows to obtain information about the magnetic field directly from phase-amplitude analysis of a complex interferogram. In this option the polarogram and interferogram are represented by one image – complex interferogram. It should be emphasized that although the basis of interferometry is known and published [2], there is quite a lack of papers in which the results of the SMF measurements obtained with this method are presented.

**Methodology determination of SPM by the complex interferometry**:

The intensity of the complex interferogram may be described by the following formula:

$$I(y,z,t) = A_p{}^2(y,z,t)f(t) + A_r{}^2(y,z,t)f(t) + \\ 2A_p(y,z,t)A_r(y,z,t)\cos[2\pi(\omega_0 y + \nu_0 z) + \varphi(y,z,t)]f(t) \tag{2}$$

The φ(y,z,t) represents phase shift between a probe and a reference part of diagnostic beam, $A_p$ and $A_r$ are the amplitudes of a probe and a reference beams respectively, $\omega_0$ and $\nu_0$ are the spatial frequencies in the horizontal and vertical directions and f(t) is a temporal profiles of the pulse. In order to determined SMF, phase shift φ(y,z) and $A_p/A_r$ ratio need to be defined from the complex interferogram. Those quantities are encoded in two function: visibility v (y,z) and background b(y,z):

$$v(y,z) = A_r(y,z)\cdot A_p(y,z)\cdot q(y,z)exp[i\varphi(y,z)] \tag{3}$$

$$b(y,z) = A_r{}^2(y,z) + A_p{}^2(y,z)$$

which can be obtained by performing Fourier transform of given interferogram. The quantities q(y,z) in the first equation represents the modifying function. The visibility corresponds to the left or right lobe of the spectrum and it is defined by shifting of the selected lobe to the center of the spectral plate and performing the inverse Fourier transform. Similarly the background is obtained, however in this case the middle lobe is selected.

Once the v(y,z) and b(y,z) functions are provided, the phase shift φ(y,z) and $\gamma = A_p/A_r$ ratio may be calculated according the following equations:

$$\varphi(y,z) = arctan\frac{Im[v(y,z)]}{Re[v(y,z)]} \tag{4}$$

$$\gamma(y,z) = \sqrt{\frac{2\cdot b_p(y,z)}{p\cdot b_r(y,z)} - 1}$$

where *p* is a ratio between the energies of the sygnal and reference beam, and the indexes p and r correspond to the probe and reference beam relatively.

The angle of the polarization plane rotation is calculated as follow:

$$\theta(y,z) = \arcsin(\gamma(y,z)\cdot\sin\theta_0) \tag{5}$$

The $\theta_0$ is an initial angle of the rotation of the polarizers.

Having determined distributions: φ(y,z) and θ(y,z), next step is to transform both functions with the Abel integral equation [1]. Then, the spontaneous magnetic fields distribution is computed according the following formula [1]:

$$B_\varphi(r,z) = \frac{1.7\cdot 10^3}{\lambda}\cdot\left[\frac{rf_B(r,z)}{f_n(r,z)}\right] \tag{6}$$

where: *$f_B(r,z)$*- the distribution function of the angle of the polarization plane rotation which is calculated by abelization of θ(y,z)/y and

*$f_n(r,z)$* - the distribution function of the phase which is calculated by abelization of φ(y,z).

**Software testing:**

Basing on the presented methodology, the software for a complex interferogram analysis was developed and tested on the computer generated synthetic interferogram, which was created according to the equation (2). The assumed phase and amplitudes ratio γ distribution are described by following formulas:

$$\varphi(y,z) = 25\exp[-0.1y^2 - (z-5)^2]$$

$$\gamma(y,z) = 1 - (exp[-0.1y^2 - (z-4.5)^2] - exp[-0.1y^2 - (z-5.5)^2]) \tag{7}$$

The functions $\varphi(y,z)$ and $\gamma(y,z)$ are presented in Fig3a.
The obtained synthetic interferogram and its spectrum provided by Fourier transform are shown in Fig.2.

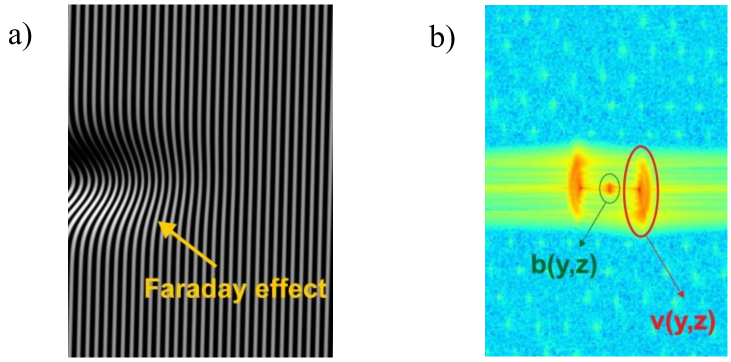
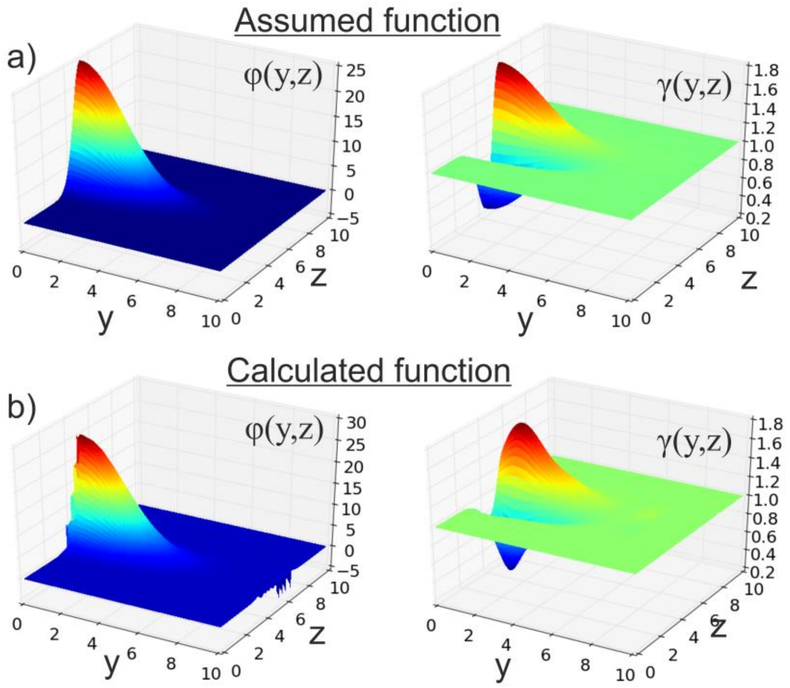


Fig 2 The synthetic complex interferogram (a) and the Fourier transform spectrum (b).

According to the methodology described in the previous paragraph, phase and amplitude distributions were calculated from visibility and background functions (v(y,z), b(y,z)). Figure 3 shows the comparison of the calculated phase and amplitude distributions (b) with the ones assumed.


Assumed function

Calculated function

Fig. 3 The comparison of the assumed distributions of the phase and amplitudes ratio (a) with the ones calculated with the elaborated software (b).

Both the shape and the value of the assumed phase and amplitude distributions are satisfactorily reproduced by the developed software. Some accuracy of the reproduction occurs on the edges of the matrixes due to numeric errors.

**Experimental results:**

An exemplary complex interferogram, presenting interaction of 1st harmonic PALS iodine laser ($\lambda$=1.315 μm) of energy ~270 J, with planar massive Cu target, is presented in Fig. 4a. To achieve maximal sensitivity of the polaro-interferometer, the measurements were carried out with initial rotation of a polarizer, $\varphi_o=-2^o$, what created asymmetry of intensity distribution in a interferogram, which demonstrates azimuthal geometry of SPM. Fourier spectrum, obtained from the interferogram with presented method of analysis, is presented in Fig.4b. Results of phase-amplitude analysis is illustrated in Fig. 5a and compared with those obtained with classic method [1] with no significant difference between both methods.

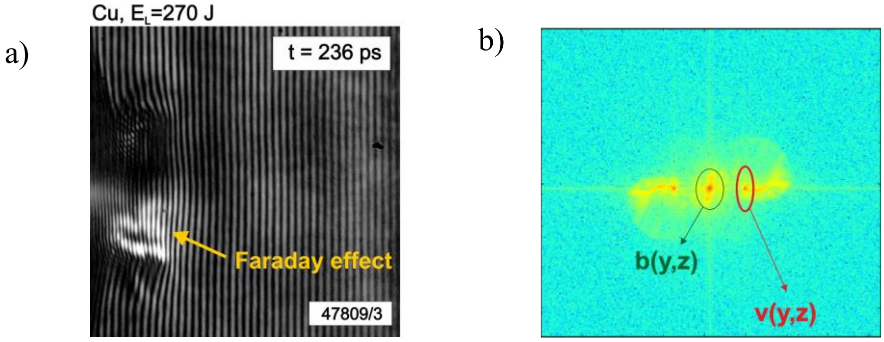


Fig 4 The real complex interferogram (a) and the Fourier transform spectrum (b).

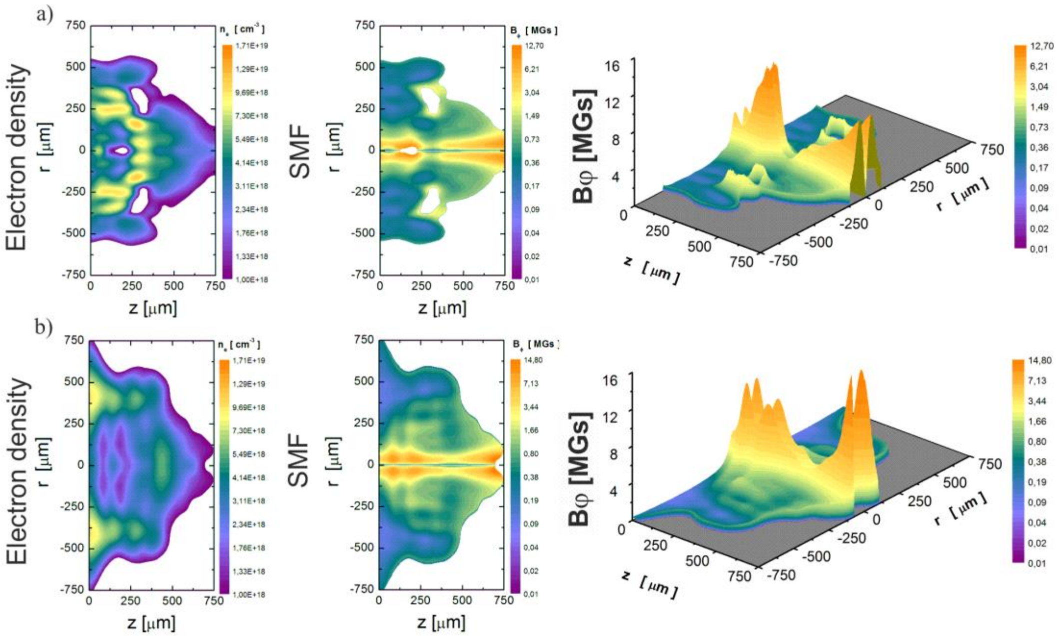


Fig. 5 The electron density and SMF calculaded with classical method (a) and by the phase-amplitude analysis program from complex interferogram (b).

## Acknowledgement

This paper was supported by the Access to the PALS RI under the EU LASERLAB IV project (Grant Agreement No. 654148), by the Ministry of Education, Youth and Sports of the Czech Republic, Grant No.: LM2015083 (PALS RI) and ELI: Extreme Light Infrastructure project CZ.02.1.01/0.0/0.0/15008/0000162, and by the Czech Science Foundation, project P205/11/P712. The work was also partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the years 2016-2017

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