15. Complex Interferometry

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Introductory Notes

Practically immediately after the construction and successful functional demonstration of the first laser at the beginning of the 1960s, researchers in various fields of science have started enthusiastic discussions on possible applications of this revolutionary invention. The basic possibility of transferring a large amount of energy into a small volume in a very short time could not be missed by scientists dealing with the problem of a **controlled thermonuclear reaction** – at that time performed by a method of heating the plasma kept together by means of strong magnetic fields in devices of a **tokamak** type. When the originally expected success in this field did not materialize quickly enough, an alternative idea of using lasers to reach the desired aim seemed to be most welcome. The fundamental importance of this research is based on the fact that in case of its success, the problem of searching for practically inexhaustible energy source would be solved once and for all.

Joint worldwide research in the interaction of intensive laser radiation with solid targets, which started in the way described above, gradually brought to light a number of various physical processes influencing the efficiency of energy transfer into inner target regions. A suitable fuel placed inside the targets (frozen layers of deuterium and/or tritium) has to be stimulated by an outer energy supply to release energy of thermonuclear origin by heating it to a temperature of the order of 100 million degrees Celsius. Therefore, it was necessary first to understand these processes as well as possible, in order to minimize their negative consequences. The necessary condition for starting a chain reaction is a high degree of compression of the obtained hot plasma. However, this is considerably impeded by various kinds of instabilities.

The need for detailed research in the dynamics of processes taking place in plasma under these extreme conditions required the **development of a number of new diagnostic methods**. One of them originating from laser plasma study is a method of **complex interferometry**, which is being reviewed in this chapter.

To complete the above survey it should be added that even the new alternative way to a thermonuclear reaction controlled by lasers has not been very smooth. After the initial enthusiasm in the course of the last four decades, the research community felt periods of deep scepticism and, as well as cautious optimism. Only recently the research in both branches has hopefully seemed to develop more quickly, as seen in present activities aiming at constructing immense experimental facilities, both for the research in thermonuclear **magnetic confinement** fusion (ITER – being prepared) and the alternative so-called **inertial confinement**. In this latter case the consequences of enormous energy densities transported into the target by means of lasers are faced only by inertial forces (NIF and LMJ – being constructed).

Development of the Method, its Principles and Applications

One of the interesting physical phenomena in the process of interaction of intensive laser radiation with solid targets is known as so-called **fountain effect**. First, a certain number of electrons in the arising plasma are accelerated in the direction *away* from the target. Then, due to electrostatic field influences, these electrons return and penetrate into the target where their kinetic energy is converted into X-rays, among others. The electron trajectories in plasma are considerably influenced by a very strong magnetic field (~100 T), which is generated spontaneously, especially by crossed gradients of plasma density and temperature ($\nabla n \times \nabla T$).

This magnetic field has a toroidal structure with its maximum at a certain distance from the plasma symmetry axis, and causes the division of the returning electrons roughly into two groups. Electrons of the first group succeed in returning into the target near the symmetry axis, like through a funnel, while electrons of the other group are forced away from the axis as far as behind the magnetic field maximum. As a result, they impinge on the target in a ring of a certain radius (hence the name of this phenomenon). This fountain effect can be verified experimentally by detection of characteristic X-ray radiation emitted from the target rear coated with a layer of material suitable for this purpose.

To study the efficiency of energy transfer into regions of dense plasma and the target itself, it is very important to understand the mechanisms responsible for the fountain effect. It also requires a sufficient detailed knowledge of topology and size of spontaneously generated magnetic fields in as large a plasma region as possible, for computer simulations show that these magnetic fields can continue expanding inside the target (their intensity being increased even by an order of magnitude) and thus influence considerably the energy transfer process.

Experimental detection of spontaneous magnetic fields in laser plasma is very difficult, because it is necessary to measure the profiles of physical variables in objects, whose dimensions are in fragments of millimetres and time duration in nanoseconds or shorter. That is why the laboratories trying to carry out these measurements in the first half of the1980s could easily be counted on fingers of one hand. However, the results of these measurements were more or less qualitative, proving the existence of such fields. Maximum values were stated only approximately, without any serious attempt to obtain their quantified spatial distribution. This was absolutely insufficient for the needs mentioned above. What was then the main cause of the difficulties?

To **study the presence of a magnetic field in plasma**, the Faraday phenomenon of rotation of the plane of polarization of the probe beam is most frequently employed. The rotation angle θ (in degrees) is given by the expression

$$\theta \,|\, 1.51\lambda_p^2 \,|\frac{nB\,dl}{10^{23}(1\,4\,n/n_{kp})^{1/2}}\,,$$

where λ_p denotes the probe beam wavelength (in σm), B represents the component of the magnetic field in the direction of beam propagation (in Tesla), n_{cp} denotes so-called *critical plasma density* for the used probe beam wavelength (in cm^{-3}), and n the local plasma density value in places of beam propagation (in cm^{-3}).

It is obvious from the above-mentioned expression that obtaining the rotation angle itself is not sufficient for magnetic field reconstruction, because rotation of the plane of polarization depends on plasma density profiles as well. Consequently, it is necessary to measure also the plasma density distribution. This is carried out by the method of interferometric measuring of phase shift between the probe and reference beams. Only these two quantities combined together can then provide the required profiles of a magnetic field. This can occur only on condition that the tested plasma is axially symmetrical which permits the application of the **Abel inverse transformation** for the reconstruction of the sought variables (plasma density and magnetic field profiles) from integral expressions (phase shift or rotation angle).

An example of a typical procedure in reconstructing the magnetic field profile is a pair of experimentally obtained data (*interferogram* and *polarigram*), which was always used as a base for such analyses in the past (Fig. 43).

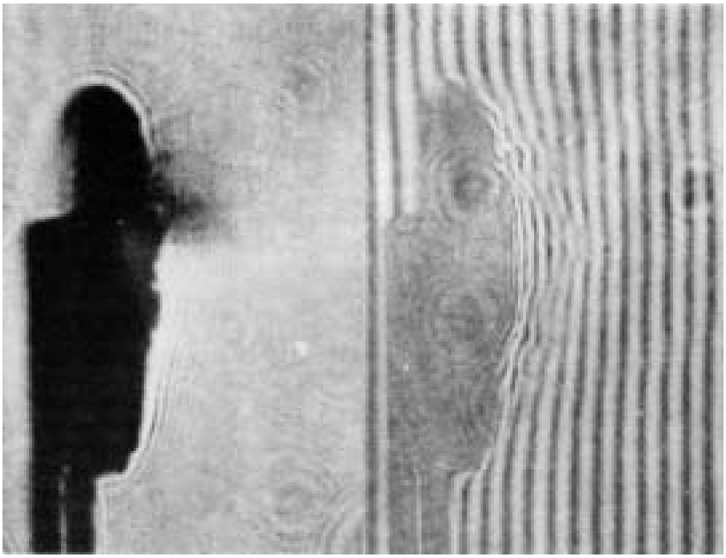

Fig. 43: Example of an interferogram and polarigram obtained simultaneously

After the *rotation angle* and *phase shift* reconstructions it is first necessary to use the *Abel inversion* to find the profiles of values *nB* and *n* respectively. The required profiles of the magnetic field *B* are then obtained by division of the two quantities mentioned above in each point of space. In this division, it is very important for both files of two-dimensional data to coincide in space, i.e. single elements of matrices should represent the same space coordinates, which is not an easy task, not to mention the necessity of maintaining the same imaging (enlargement).

No wonder that the typical reconstructed profile of the magnetic field obtained on the basis of the data mentioned in Fig. 43 was as follows. [1]

It is obvious that the data in Fig. 44 can hardly be used for the purposes mentioned above. They are definitely not the needed two-dimensional field profiles within the whole plasma region. Therefore, it was necessary to design, test and apply a new diagnostic method, which could not only prove the existence of these fields, but also provide the subsequent quantitative analysis of experimental data with maximum spatial resolution in the whole region of laser-produced plasma, where the fields would have non-negligible values.

Eventually, great efforts in this sphere led to the development of a method called complex interferometry. Details concerning this effort can be found in [2], description of the method itself in [3] and [4]. It will only be

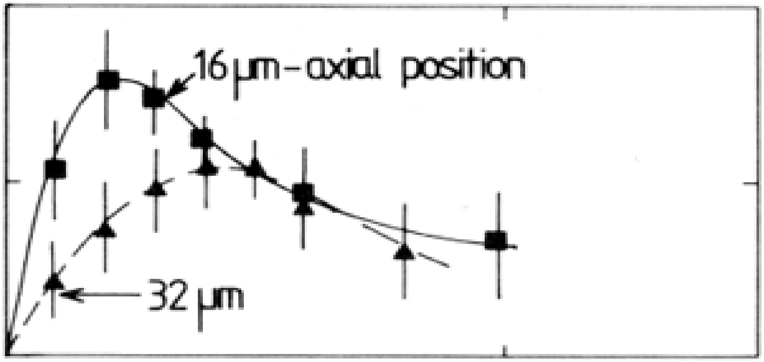

Fig. 44: Example of the reconstruction of radial distribution of the spontaneous magnetic field in two different cross-sections, including error bars

stated here that unlike *classic interferometry*, this is an absolutely *general* diagnostic method, treating an interferogram not as an object with *one* degree of freedom (the *change in* interference fringe *shape*), but using *two more* degrees of freedom (mostly ignored in the past): the change in interference fringe intensity in the direction *along* the fringes, and the decrease in interference fringe contrast (in *dynamic* processes). Thus, it is possible to record as many as *three* physical quantities into *one* data object (complex interferogram) and then to analyze them. Physical quantities, which are to be encoded into the respective degrees of freedom, are determined by arranging the experimental set-up. Examples of computer generated and experimentally obtained complex interferograms are shown in Fig. 45.

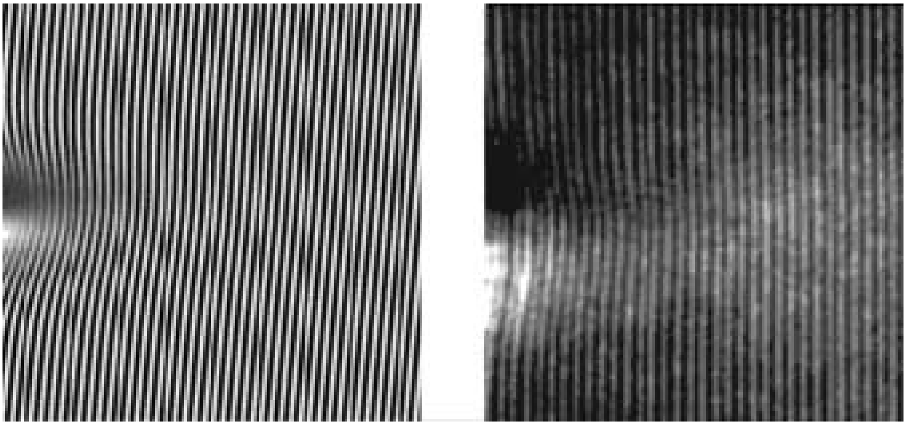

Fig. 45: Examples of *complex interferograms* – computer generated (left) and obtained by an experiments (right)

In addition, it should be pointed out here that the term *complex interferometry* does not only mean experimental equipment itself, for the application of which there are certain requirements to be met. Its inherent part also consists of *sophisticated algorithms* for computer analysis necessary for making effective use of *all three* degrees of freedom. It also includes very *fast* and potentially very **precise numeric methods of calculating the Abel inversion**, which play a key part in the process of reconstruction of physical values encoded into an interferogram [5].

To conclude, it can be stated that it was the initial unavailability of the necessary software that caused a considerable delay in using this universal method more widely within the scientific community. However, the recent state of the art has become much better due to transferring the software into the Microsoft Windows platform. The user interface presenting examples of some analyses is shown in Fig. 46.

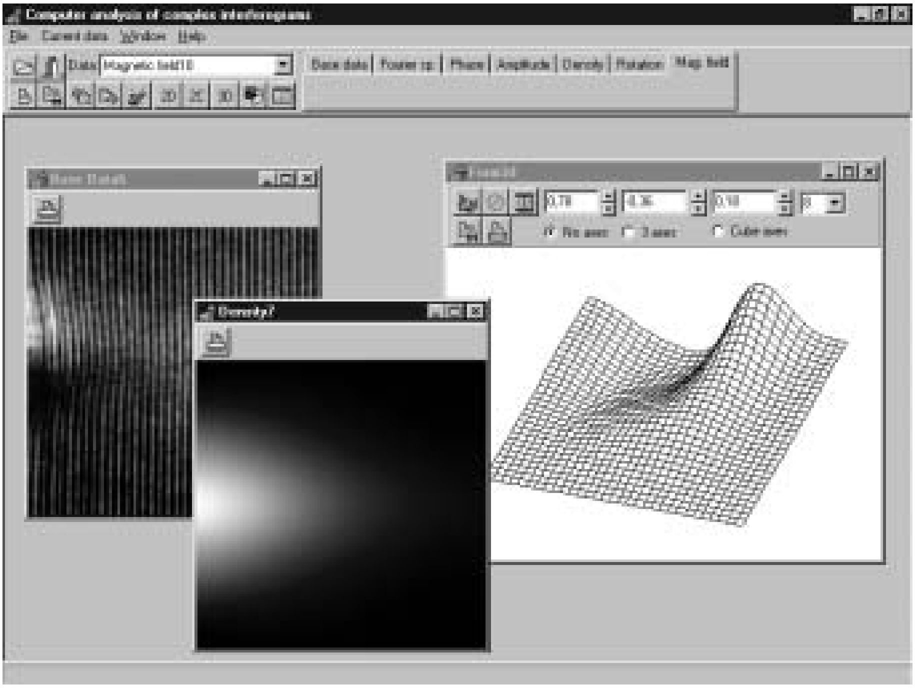

Fig. 46: Example of a user graphic interface of a program analysing *complex interferograms*. The interface contains images of a complex interferogram, reconstructed density profiles (2D) and a spontaneous magnetic field (3D).

References:

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