

## OPTICAL TOMOGRAPHY OF PLASMAS

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New experimental set-ups for optical tomography on the basis of holographic interferometry are presented which allow the determination of the local refractive index of inhomogeneous phase objects, such as plasmas. The tomographic reconstruction procedures require subfringe resolution of the interferograms which can be achieved by the application of heterodyne techniques. These interferograms are evaluated using the algorithms of Fourier transformation. Using in addition resonance interferometry, the capability of optical tomography in plasmadiagnostics for the determination of particle densities of certain atoms is demonstrated.

### INTRODUCTION

One of the main difficulties in plasma diagnostics is the lack of sufficient symmetries of the distributions of plasma parameters in discharges to be investigated, a fact which makes the evaluation of data difficult. In order to overcome these problems the authors applied the well-known methods of computerized tomography in medicine to the field of optical holographic interferometry, where especially Vest [1] and his co-workers have given essential contributions.

For transparent objects, such as plasmas, an angular observation range of  $180^\circ$  is sufficient. The quality of the reconstruction of the spatial refractive index distribution depends obviously on the number of projections, their accuracy and the actually covered angular range. There exist different tomographic reconstruction algorithms which are to be preferred, if any of the above mentioned conditions is

not fulfilled satisfactory. In general, it can be stated that the more highly resolved projections over a large angular scale are needed, the more the structure of the investigated phase object turns out to be complicated and asymmetric.

Since in many cases the fringe shifts caused by the investigated plasmas are comparatively small (subfringe domain), it was desirable to improve the sensitivity of the method by applying a heterodyne technique facilitating the use of Fast Fourier Transformation formalisms (FFT).

The relatively complex algorithm for the evaluation of the heterodyned interferograms and the succeeding tomographic reconstruction procedures make it necessary to find a way for testing the data reduction process as well as the experimental method. This was performed using a new arrangement for optical tomography on the basis of holographic interferometry in order to investigate an inhomogeneous convective flow of hot air with known temperature distribution [2].

In diagnosing plasmas frequently there exists special interest in the spatial distribution of the number densities of certain atoms or ions in distinguished states. The availability of tunable dye-lasers leads to resonant interferometric techniques, which allow to determine such selective particle densities. In the following chapters the experimental arrangements used are roughly described and some results are presented.

## TEST OF THE METHOD

Since the use of computerized tomography for optical data has not been frequently reported on in literature, it seemed to be desirable to test as well the suitability of the designed experimental arrangement as the accuracy of the tomographic reconstruction procedure. Therefore the local refractive index of the asymmetric phase object to be measured by optical tomography should have been also determined in an independent way. A possibility to do this was to generate a stabilized convective flow of hot air emerging out of an elliptical orifice of an oven and to measure the temperature distributions in cross-sections of it in different heights above the orifice. These temperature data correspond to certain values of the refractive index and therefore can be compared to the values found by optical tomography.

A fundamental requirement for the application of optical tomography is the need of projection data over a large angular scale, the best would be over 180 degrees. Another question of importance is the fact, how many different projections would be sufficient for a reliable resolution of a phase object of given extent and spatial structure. A detailed discussion of these problems can be found in the book of Herman [3].

A general problem being typical for plasmadiagnostics is that such phase objects do not show too much variation of the index of refraction in many cases. Only a few fringes or even less than one can be expected to be formed by the phase objects in the holographic interferograms. This is a very important fact especially in the investigation of different types of so-called low temperature

plasmas. Unfortunately one needs very accurate input (projection) data for the tomographic reconstruction process, otherwise this procedure would not lead to reliable results. As a solution of this last point an application of heterodyne holographic interferometry is very useful.

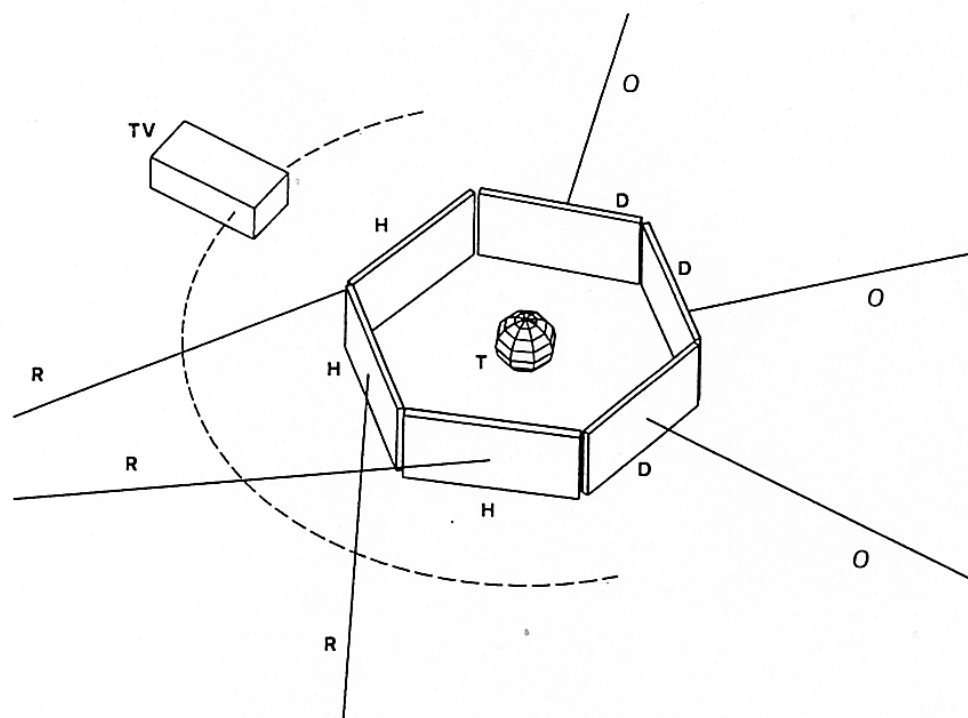


Fig. 1. Hexagonal plate holder: O object beam, R reference beam, H holographic plate, D diffusing screen, T test section (phase object), TV camera movable along a semicircle.

Fig. 1 gives a sketch of the important part of our experimental arrangement in order to demonstrate our solution of the points mentioned above. It consists of an hexagonal plate-holder for three diffusing screens and three opposite holographic plates. In this way an observation of the phase object over nearly 180 degrees can be performed, which is made possible by using these diffusing screens in order to enlarge the angle of observation [4]. The diffusing screens are hit by three object beams which are scattered by the micro structure of these screens. The scattered laser light then penetrates the phase object in different directions and reaches the corresponding holographic plates afterwards.

All of the three object beams can be tilted in a defined way by rotating one single mirror. Doing so between the two exposures in the applied double exposure technique, a vertical fringe system of constant and more or less high spatial frequency can be superposed to the low frequency fringes originating from the phase object to be investigated. This process is known as optical heterodyning and it allows an analysis of the interferograms by FFT algorithms thus yielding the required subfringe resolution of the phase distortion. In this way projection data with sufficient accuracy are provided for the tomographic reconstruction procedure.

After development the holographic plates are repositioned in the plate holder and the interferograms are stored using a TV camera and a video frame store. The data reduction procedure is described in a recently published paper [2]. Fig. 2 gives a comparison between the tomographically evaluated and the directly measured temperature values (dots) for an elliptical orifice limiting the convective flow of hot air. The small straight vertical lines link corresponding points.

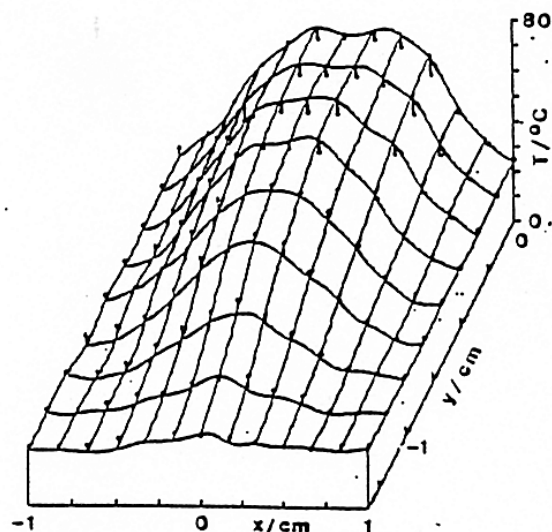


Fig. 2. Tomographically evaluated temperature distribution for one half of a horizontal cross section through a vertical inhomogeneous flow of hot air and comparison to directly measured values (dots, obtained by scanning a point-like NTC detector across the plane to be investigated)

19 different projections in form of evaluated phase distortions caused by the phase object were used for the computerized tomographic reconstruction of the temperature field via the determined refractive index distribution. The total angular range of observation covered was about 155 degrees. For the tomographic reconstruction the so-called convolution method (sometimes also called 'filtered backprojection') was used [2,3]. The comparison in Fig. 2 shows for the worst case a disagreement of 9 °C. So the quality of reconstruction resulting of this test was encouraging us to apply the method in plasma diagnostics.

In Fig. 3 the temperature profile of the convective air flow is given for an egg-shaped orifice. In addition another tomographic reconstruction technique has been used, the Algebraic Reconstruction Technique (ART). The advantage of this reconstruction method is that it gives also reliable results, if only a small number of projections are available. Furthermore this procedure leads in general to better smoothed data.

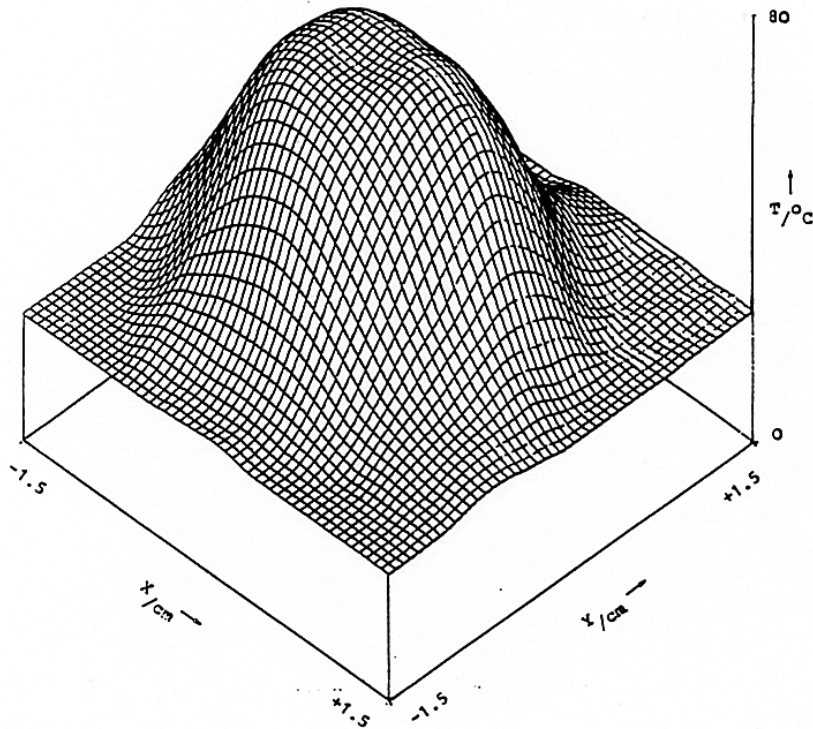


Fig. 3. Temperature profile within a cross-section of a convective flow of hot air emerging out of an orifice of egg-shaped geometry.

## APPLICATION TO PLASMA DIAGNOSTICS

### Optical Tomography of a High Frequency Discharge

For a first application to plasma diagnostics, a plasma was chosen that showed not too much self-radiation to avoid blurring of the interferograms. This condition could be satisfied using a capacitively coupled high frequency discharge in the same optical arrangement as given in Fig. 1. The electrodes had an elliptical cross-section (principal axes being 20 mm and 10 mm), the separation between the

electrodes was 3 mm, the current was 150 mA at a pressure of 0.45 bar of a mixture of helium and argon (in a composition of 4 : 1). The discharge was operated at a frequency of 40 MHz. A cross-section of this plasma in the middle position between the electrodes has been tomographically investigated. Fig. 4 shows the result. Due to a higher temperature inside of the plasma the index of refraction is decreasing there.

#### Tomographic Determination of the Sodium Ground State Number Density in a DC-Discharge by Resonant Holographic Interferometry

As commonly known from elementary dispersion theory, the refractive index changes very much in the spectral vicinity of strong optical transitions, especially in the case of resonance lines. Interferometric methods using this behaviour belong to the group of resonant techniques. Our subject was a dc glow discharge in neon of 25 mbar seeded with sodium atoms. The anode was a small rod of copper, the flat cathode consisted of a so-called sodium intercalation compound ( $C_{64}Na$ ; electrode gap: 4 mm; discharge current: 30 mA).

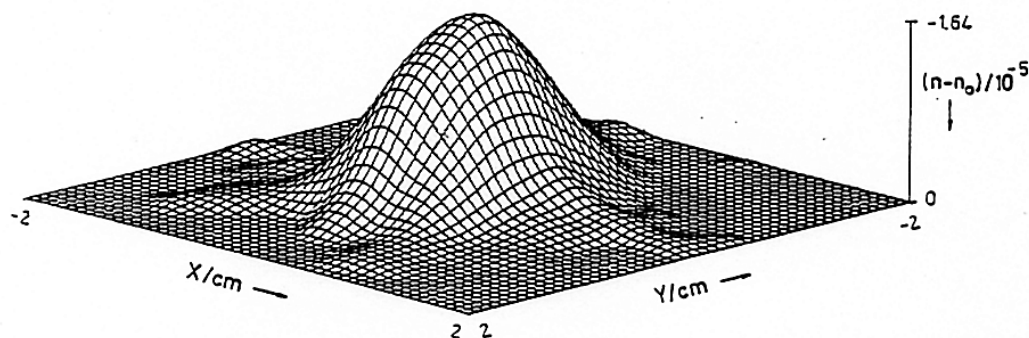


Fig. 4. Tomographic reconstruction of the index of refraction of a capacitively coupled helium-neon high frequency discharge operated at 40 MHz between electrodes of elliptical geometry. The maximum fringe shift caused by the discharge was 7/10 of a fringe.

A condition that must be fulfilled, if particle densities of a certain atomic species are to be determined by resonant interferometry, is the knowledge of the line profile which is characteristic for the considered transition. An actively stabilized cw ring dye laser (FWHM approx. 10 MHz) was used to record the lineshape of the sodium  $D_2$ -line, which was performed by tuning the laser through the frequency range of the line and recording the fluorescence signal. Special care has been taken on the fact that the laser intensity had to be chosen low enough so that the population of the upper levels in the plasma atoms remains negligible.



The flat cathode with the carbon-sodium intercalation compound had a triangular profile in order to introduce a pronounced asymmetry. First the lineshape was recorded, controlled by etalon markers. Afterwards double exposure resonant heterodyne holographic interferograms were taken. At least two exposures were made, each close to the region of the both extrema of the corresponding refraction curve. The phase shifts for different directions of observation, which were analysed with subfringe accuracy, were used as projections for the tomographic reconstruction algorithms.

The knowledge of the dispersion in the spectral region of the sodium D<sub>2</sub>-line combined with the tomographically evaluated refractive index distributions led to the determination of the local number densities of ground state sodium atoms. The procedure of data reduction is relatively complex [5] and cannot be discussed in this paper. Fig. 5 is a 3-D sketch of the used experimental set-up for the production of the holographic interferograms, showing another arrangement of diffusing screens and holographic plates than used for the examination of the convective heat flow described above.

In Fig. 6 the results of this investigation are presented in form of a particle density distribution as well as in the form of a contour map. These results should demonstrate the possibility of the determination of spatially resolved particle density distributions and show the applicability of the tomographic reconstruction techniques and resonant methods and the advantages of heterodyne interferometry in the case of comparatively small changes of refractive index.

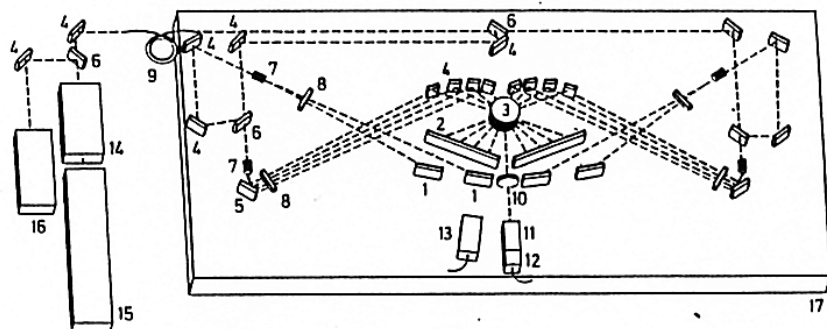


Fig. 5. Set-up for the determination of atomic particle densities by using heterodyne resonance holographic interferometry and optical tomography. 1 holographic plate holders, 2 diffusing screens, 3 plasma, 4 mirrors, 5 rotatable mirrors, 6 beam splitters, 7 beam expanders, 8 cylindrical lenses, 9 optical fibre, 10 lens, 11 monochromator, 12 multiplier, 13 TV camera, 14 actively stabilized cw dye laser, 15 argon ion pump laser, 16 marker etalon, 17 vibrationally isolated table (7 tons).

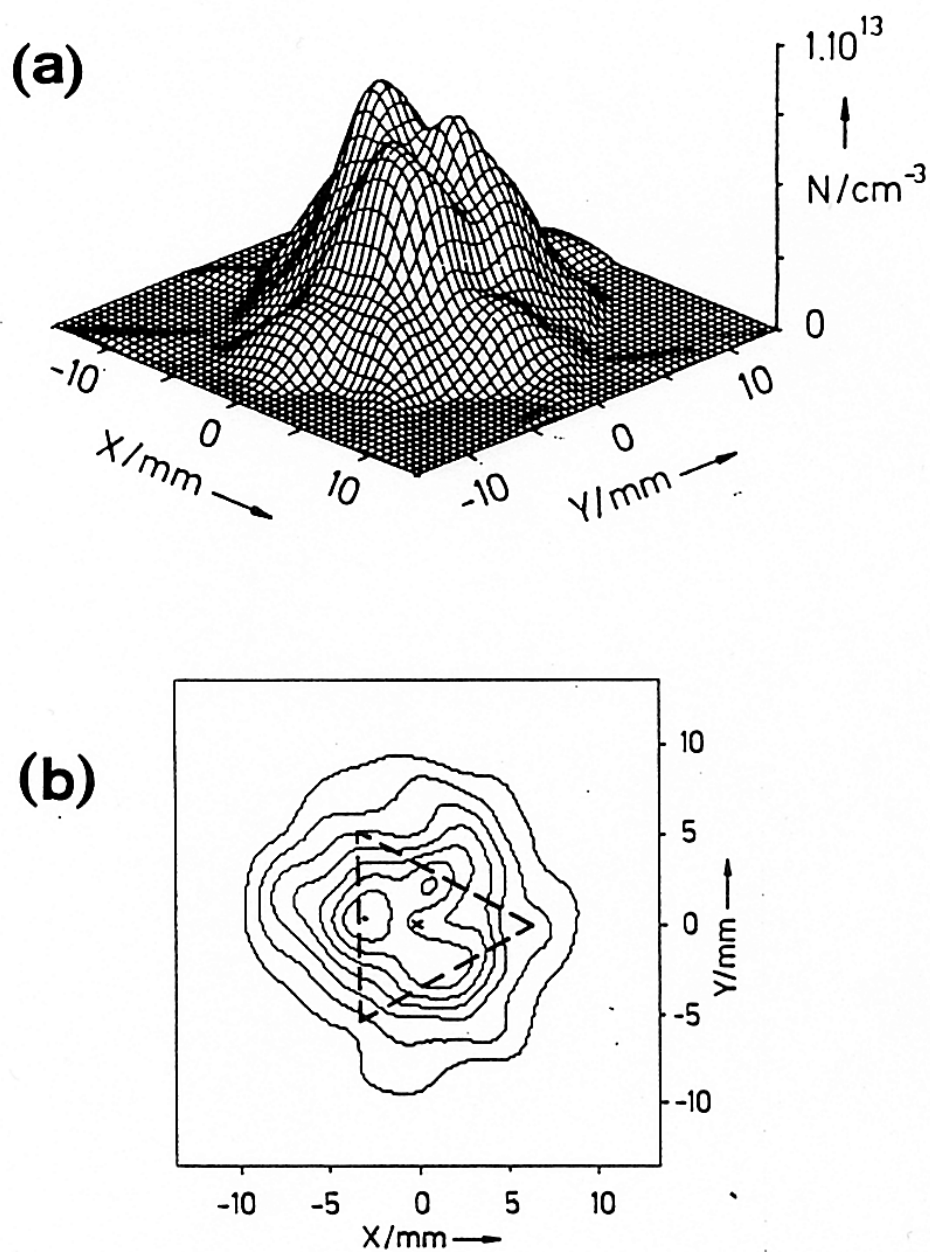


Fig. 6. Distribution of sodium ground state number density across a horizontal plane halfway between the electrodes in the investigated dc glow discharge. (a) 3-D plot, (b) contour map. The difference between two contour lines corresponds to a particle density of  $4.10^{12} \text{ cm}^{-3}$ . The shape of the sodium seeded cathode is indicated by the dashed triangle.



## The Influence of Ray Bending on Tomographic Reconstruction in Resonant Holographic Interferometry

The use of resonant holographic interferometry brings about the possibility that the probe beams of laser light might be deflected because of gradients that exist in inhomogeneous plasmas, an effect being enhanced by the strong change of the refractive index in the spectral vicinity of the investigated optical transition. The fundamental question to be answered is, how a ray bending of certain amount influences the tomographic reconstruction procedure. These procedures generally assume a straight propagation of the laser beams through the phase object. If a remarkable ray bending occurs, new algorithms have to be found which take these effects into account.

Corresponding investigations are currently carried out in our laboratories and first results show that for our plasmas investigated so far by using optical tomography, these effects can be neglected with respect to the accuracy that is achieved for our data reduction procedure and our experimental conditions. Nevertheless we try to realize experimental conditions which cause noticeable ray bending effects in order to analyze the questions above and to be able to modify the reconstruction technique accordingly.

So in conclusion it can be summarized that optical tomography combined with heterodyne (resonant) holographic interferometry establishes as a suitable tool for the investigation of plasmas with asymmetric distribution of the refractive index. The applicability of the method for the selective determination of particle densities was demonstrated, a fact that opens the experimental field of the investigation of technically relevant plasmas which show usually poor symmetries.

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