High speed, multichannel image capturing systems with nanosecond time resolution

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1. Introduction

Different images are very often obtained while studying the plasma. These images must be recorded using non-standard cameras of a special design, and processed to obtain readable physical results, for example the distribution of plasma radiation or plasma density, velocity of the object under test, etc. If some of these results are compared with another ones, it is desirable to make all the "photographs" done in the same time, because the phenomena in the plasma are rather nonrepeatable. Additionally, the exposures must be sufficiently short to avoid the effect of "fast moving object" appearing on the images.

In the past, the images of plasma were registered on the photographic film and then they were processed using manual or semi-automatic methods. This was an additional source of errors if the data were used in the final computation of plasma parameters. Recently, the rapid progress in the automatic image capturing is observed. The image acquisition systems become more and more sofisticated and they are able to fulfil all the specific needs of high speed photography, particularly in the plasma diagnostics.

In the cheap image acquisition systems the ordinary TV frame grabbers and CCD cameras are widely used. Unfortunately, the TV resolution may be insufficient in some applications. In such cases the cameras and frame grabbers with enhanced resolution must be used. In advanced applications the high resolution CCD cameras with built-in frame grabbers and digital output become the more popular, but expensive tools.

Of course, if the image is not created by visible light, but for example by infrared radiation, electrons, ions or X-rays, then it must be converted to the form easily registered by the image acquisition system. In such case an image converter must be placed on the input of the visible light camera to solve this task. Such device, being of electrooptical character, enables even shortening of exposure time, synchronization with external events, precise gating to suppress the noise, etc. The systems with such features were developed by the authors and were used in optical diagnostics of plasma focus device located in the Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw. They also were tested in other experiments, for example in investigation of laser-created plasma.

Two different versions of automatic image acquisition system were developed. In the first version the commercial frame grabbers (Visionetics VFG-512) with 10-channel programmable multiplexer (made by Imal Ltd) were used. In the second version the autonomic, four-channel system mod. IM 1024TDV, developed originally by Imal Ltd, was applied. The imaging equipment is described in details in next sections.

2. Investigated phenomena

The plasma focus device (PF) belongs to the family of dynamic, nonlinear Z-pinches. It produces hot and dense plasma by means of magnetic compression. The characteristic lifetime of the dense pinch region is about of 100 ns. Characteristic velocities of this object reach up to 10^7 cm/s. The PF device is a powerful source of electromagnetic radiation ranging from X-rays to microwaves, high energy ions and electrons, and fusion neutrons (if deuterium is used as the working gas).

The possible applications of the PF device are as follows:

- In plasma physics: studying the states of high energy density, turbulent phenomena and non-equilibrium processes;
- As the source of neutrons: material testing, reactor blanket studies, pulse neutronography and activation analysis;
- As the X-ray source: lithography in VLSI technology, X-ray microscopy and spectroscopy, material studies.

Generally, the PF device consists of the set of two coaxial electrodes which are partially separated by an insulating sleeve and located in the vacuum chamber filled with gas at a pressure of a few torrs. The electrodes are connected to the pulse current generator. Usually the bank of fast capacitors is used as the the source of energy. An overall view of the PF-150 device installed in the IPPLM is presented in Fig. 1.

After the electrical breakdown near the insulator, the created plasma sheath is accelerated during its move towards the open ends of the electrodes. In the final stage of the acceleration phase the hot and dense region (so called plasma column or plasma focus) is created as the result of the collapse of the plasma sheath on the axis of symmetry of the electrodes. The thickness of the plasma sheath during this phase equals to about 3 mm and the collapse velocity reaches quickly the values ranging from 10^6 cm/s to $2 \cdot 10^7$ cm/s. All these processes appear in nanosecond time scale.

Hence, very good spatial and temporal resolution is required to measure the plasma parameters with appropriate accuracy. The exposure time of the camera must be shortened at least to 1 ns to record the image of such fast-changing object. Additionally, the phenomena in the PF device are rather nonrepeatable from shot to shot, so that is why the entire information must be acquired within the single discharge. This requires recording of a sequence of images showing consecutive stages of the single PF discharge.

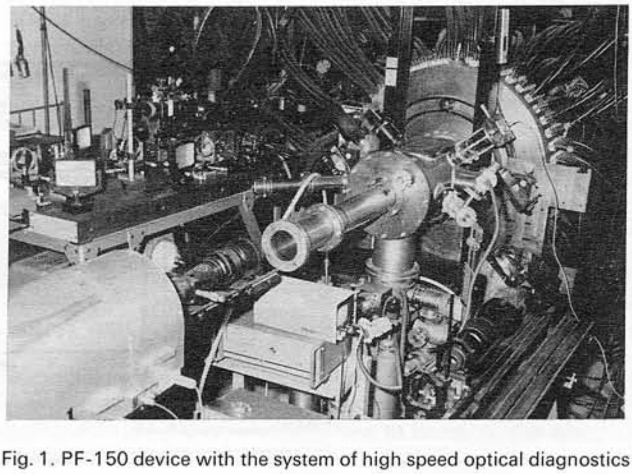

Fig. 1. PF-150 device with the system of high speed optical diagnostics

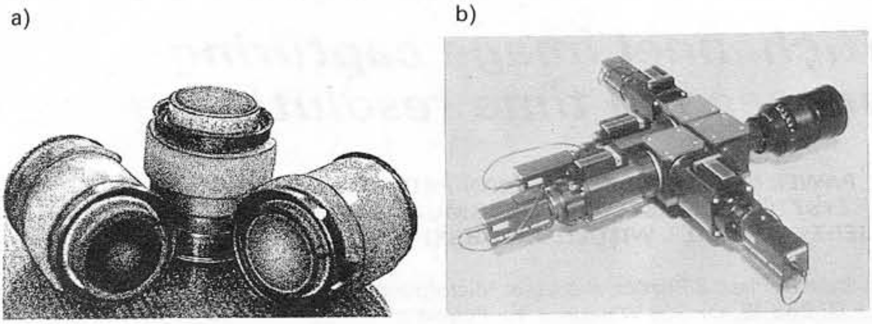

Fig. 2. a) Image converter tubes used as primary image sensors, b) Four-frame camera built on the basis of high speed image converter tubes

The system for optical diagnostics of plasma is designed mainly to investigate the fine structure of the plasma sheath generated in the PF-150 plasma focus device. We have investigated this structure to derive the spatial distribution of electron density, electron temperature and magnetic field. To measure these parameters the laser interferometry, the high-speed photography and the Faraday rotation method were used simultaneously.

3. Measuring system

The system was developed in the Plasma Focus Department of the IPPLM [1]. Image acquisition hardware was made by Imal Ltd. The cameras with image converter tubes (ICC) are used as the primary image sensors (see Fig. 2). The ICCs are gated by synchronizing voltage pulses of about 1 ns duration and 15 kV amplitude [2]. The images are recorded by CCD TV cameras operating in CCIR standard. Each TV channel has its own video digitizer and frame buffer and each image is digitized with resolution of $512 \times 512 \times 8$ bits. We decided to use the TV standard because of the lower costs. However, we plan to build the system of high speed photography using fully digital cameras with improved spatial resolution. Of course, the ICCs used in such system will be also of improved generation.

In the first series of experiments [3] all digitizers were connected to the ten-channel multiplexer controlled by PC/AT-compatible computer (see Fig. 3a). At present we use the new version of hardware, manufactured by Imal Ltd. It consists of four digitizers and four frame buffers, operating independently (see Fig. 3b).

The measuring set-up consists of the following parts:

- a pulsed ruby laser of 100 mJ energy and 1 ns pulse duration, applied here as the light source for the inteferometer and polarimeter, and also for triggering the spark-gaps in the synchronization system;
- an optical system for expanding and shaping the laser beam for the interferometer and polarimeter;
- a Mach-Zehnder interferometer which ensures also the registration of the shadow images;
- a polarimeter for measuring the Faraday rotation angle;
- an electrooptical frame camera (with four independently triggered and exposed image converters), allowing to choose a spectral range of registered radiation by means of optical filters placed in the light path;
- a multichannel image capturing and processing system, containing of multiplexed frame grabbers, CCD cameras and a PC/AT compatible controller;
- a synchronization system enabling proper time relationships between all diagnostics and PF discharge.

All diagnostic sub-systems used in the experiment should be carefully aligned in space relatively each to other with accuracy better than 0.1 mm, because the data processing is based on the assumption of spatial identity of observation directions. Moreover, because of fast changing of the parameters being investigated, the images and electrical signals should be recorded precisely in the same moment, with accuracy at least 1 ns. If these conditions are fulfilled then it is possible to minimize measuring errors.

A special system of the synchronization was used because of short characteristic times in the investigated phenomena (a few nanoseconds range) and their nonrepeatability. It allows each diagnostic device to be switched on in the desired moment with accuracy better than 1 ns. Two main functional parts may be distinguished in the synchronization system: the first one is used for the rough synchronization and the second for the fine adjusting of the time interval between the operation of each diagnostic device. The synchronization system together with the software ensures all the images to be captured in desired moment.

The rough synchronization was achieved by means of standard electronic delay lines and triggers connected to the PF operating system. They operate with an accuracy not greater than 10 ns. To enhance this accuracy and to obtain the proper timing of the whole arrangement, the electrooptical and strictly optical devices in synchronization system were used. They were the laser-triggered spark-gaps and the optical delay lines. It was also accomplished a tight correlation between the moment when the diagnostic laser beam passes through the plasma and the moment when the electro-optical camera is opened. For these purposes the laser-triggered spark-gap is used in the frame camera HV supply unit.

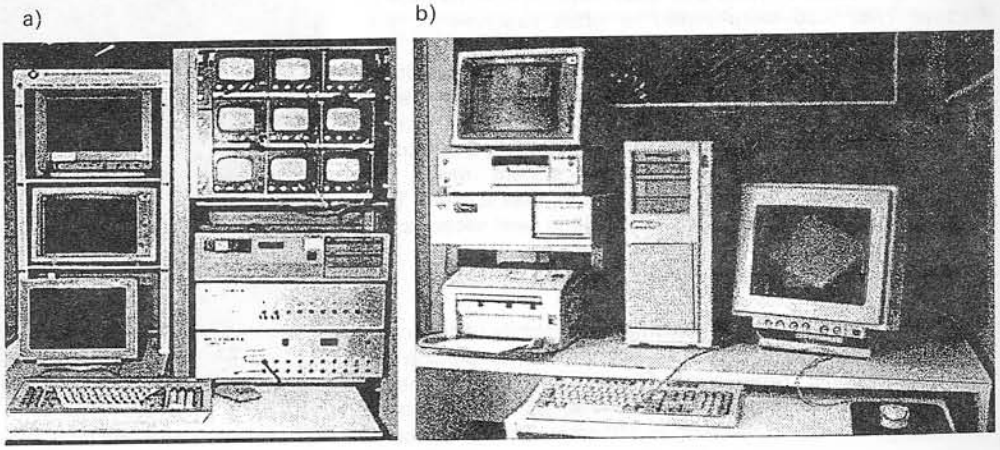

Fig. 3. View of automatic image acquisition systems used in the experiments: a) ten- channel system, b) four-channel system

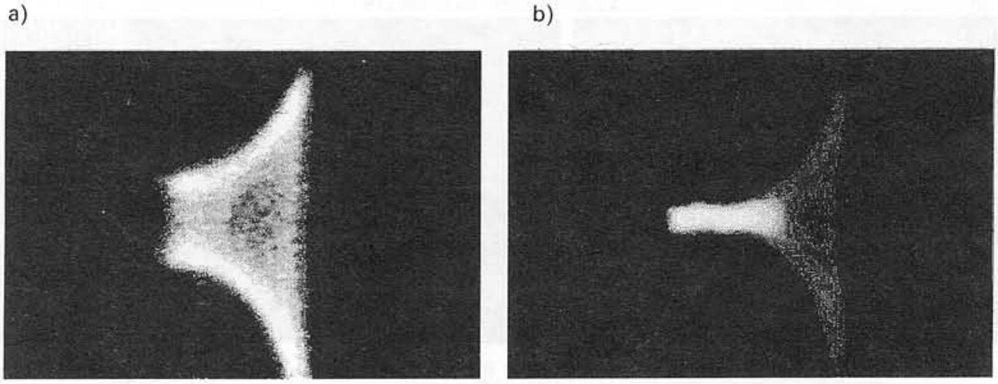

Fig. 4. Registered images of the plasma sheath and plasma column in the PF-150 device: a) plasma before the collapse on the electrode axis, b) after the collapse

The accuracy of time delay between the moment when the camera registers the image and the probing beam of the interferometer passes through the plasma was verified by means of a special optical system, consisting of a series of beam splitters. One part of diagnostic laser beam was splitted out and multiplicated to create a series of light spots on the selected converter of the frame camera. Spatial position of the spots and their number determines the time interval between interferogram and camera image, if the positions of each beam splitter and distances between particular components are known. Such system allows to determine the times within the range from −6 ns to +6 ns with the accuracy better than 1 ns.

In the experiment we measured that the time jitter in synchronization circuit was quite satisfactory. About 81% of discharges have been observed within the measuring range of the system and 48% of total number of events are fully useful for later data processing by the methods described below. As an example of results you can see in Fig. 4 the images of plasma column registered by the system. Each image was registered with exposure time about 1.5 ns.

4. Automatic image capturing and processing system

The image acquisition plays the main role in the experiment. The first version of the imaging hardware with ten-channel multiplexer has been described earlier [3]. Here we present the IM 1024TDV frame grabber.

The frame grabber is designed to digital recording of four monochrome CCIR TV images coming from four TV cameras (in parallel mode) or from a single TV camera (in serial mode of operation). In parallel mode of operation the system grabs images in all channels simultaneously. In serial mode the subsequent TV frames are digitized and then they can be recorded. The grabber is controlled by PC/AT compatible computer using ISA bus interface. The IM 1024TDV system consists of:

- four video inputs for parallel operation, each with its own analog-to-digital flash converter;
- a separate video input for serial operation, with a flash analog-to-digital converter and a programmable real time video processor;
- four blocks of dual port video memory organized as four 8-bits arrays of 512 × 512 size, used as frame buffers;
- four blocks of graphic overlay memory, each of them consisting of 4-bits array of 512 × 512 size, used as a separate planes to display text, graphics etc.;
- 24-bits colour look-up tables (LUT) to convert gray scale into colours on the video monitor, when applicable;
- a video monitor with RGB inputs, displaying in real time either the image from selected channel or four images from all channels;
- synchronization circuits, generating all synchronizing pulses needed in digital image conversion and in synchronization with external events;
- four programmable supply units for controlling the gain in TV cameras and four regulated 12 V DC supply units for these cameras.

The software for IM 1024 TDV system operates under MS-DOS. It is well-known that computerized image processing requires fast computer and is memory-hungry. In our case the Compaq ProSignia microcomputer is used to control the system. It has 16 MB of RAM and 486DX2 processor with 66 MHz clock. The software was developed by Imal and IPPLM. Imal's software package is an universal set of procedures for controlling the grabber and image processing. It is menu-driven and includes disk operation, image filtering, LUT manipulation, contrast enhancement, morphological manipulation, histogram, intensity distribution etc. The images from video memory can be written to disk file using TIFF or BMP formats or as a raw set of bytes. This package is very convenient for medical and biological applications.

In plasma experiments it is required that images should be processed using different and more sofisticated methods. For this purpose the software package called MULTIM was developed in the IPPLM. This package is based on the earlier versions, used in ten-channel system. Main problem in the processing of plasma images is noise filtering, that is why MULTIM consists of wide range of different filters, including median and other rank filters, and filters based on two-dimensional Fourier transform (low pass, high pass, band pass, band stop and homomorphic). The special kind of filtering in spatial frequency domain is also used as the method for computing phase distribution in interferometry (this is described below).

The application of MULTIM package in Fourier analysis of the captured image is shown in Fig. 5. In the same figure it is shown also the image improvement after processing by a series of digital filters operating in spatial domain.

5. Measurements and data processing

As we have just mentioned, the main diagnostics in the system is the laser interferometry. That is because of the electron density distribution is connected with other plasma parameters. The electron density is computed from interference pattern registered as a side-on interferogram. The plasma sheath during the investigated phase on the PF phenomenon has a good axial symmetry, hence only one direction of observation may be used. In such case the well-known Abel integral equation [4] is quite good approximation. The Abel transform combines an electron density profile $n_e(r)$ with a fringe shift $s(x)$ measured over the entire interferogram.

The method based on Faraday effect, i.e., on the rotation $\theta(x)$ of polarization plane of the laser beam passing through the plasma with azimuthal magnetic field profile $B(r)$, is used to determine the radial distribution of this field. The Abel transform is applied here again, due to side-on observation geometry, but the formula is a little different. To obtain the magnetic field distribution $B(r)$ it is necessary first to compute the electron density and then to solve the Abel equation again.

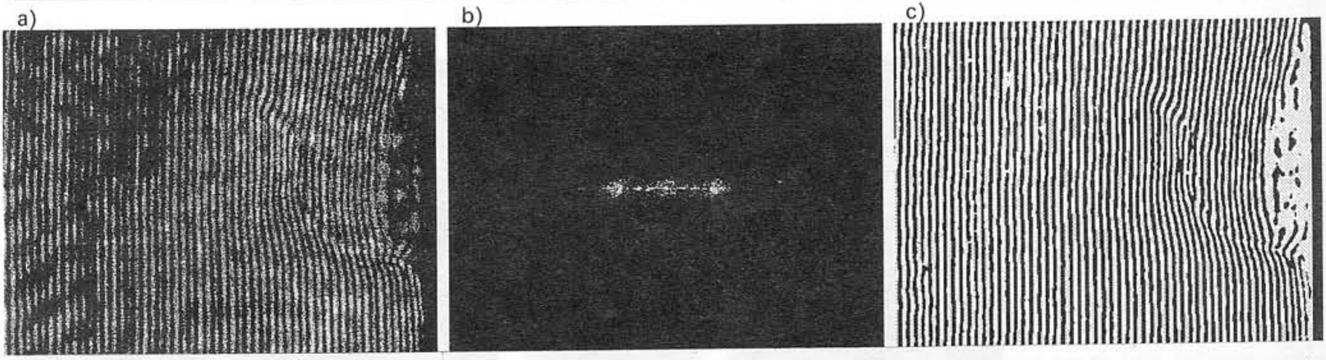

Fig. 5. Two-dimensional Fourier transform applied to the interferogram registered by means of image acquisition system: a) original image of laser-created plasma, b) its Fourier transform shown in logarithmic intensity scale, c) image improved by computer processing

Computing the electron temperature profile $T_e(r)$ is more complicated than determining the electron density or even the magnetic field. Electron temperature of the plasma is not simply connected with the electron density. It can be derived from intensity I of plasma radiation, but the final formulas depend on the plasma model taken into account [5]. However, it is possible to find a relationship between the electron temperature T_e and the relative intensity of plasma radiation I, measured within a narrow band spectrum cut out from the continuum. It is convenient to write that dependence in terms of rather artificial coefficient n_e^2/I.

Such approach is applied in our works. To determine the actual value of the electron temperature $T_e(r)$ in each point inside the plasma sheath we must have at least one arbitrary located point, where the temperature value is known (e.g., either from other independent measurement or from model considerations). Some details of the method are given in one of our papers [6]. Of course, the relative intensity of plasma radiation $I(r)$ is first converted by Abel transform and then combined with electron density.

There is a great variety of methods applied for solving of Abel equation. We have tested some of them and found the most suitable ones for our purposes. All these methods are based on polynomial approximation of the input data [7]. If the automatic image capturing system is applied than will be more convenient to use another technique, based on Fourier transform. For example, the algorithm for automatic Fourier analysis of interferograms was proposed by Takeda et al [8]. The method was extended by other authors [9] even to reconstruction of phase-amplitude images and solving of Abel equation [10]. Such method is applied in MULTIM software package.

All authors of above mentioned papers have considered the images registered on a photographic film and then digitized by microphotometer. They had to develop special methods to minimize errors involved by non-linear response of the film. In our case such errors are neglible because we have used a CCD chip as the imaging detector. Even digitizing the image being registered on the film it is possible to correct the film characteristics by simple setting of the contents of a look-up table in the frame-grabber memory. Such feature is very powerful, because it gives on the output an immediately converted image, e.g., negative, positive, with logarithmically scaled intensity and so on.

In the experiments with PF-150 device the interferogram, the plasma sheath photograph and the "Faraday pattern" were registered in the same PF discharge during the collapse phase. Exposure time of each image was equal to about of 1 ns, and the photographs were done in time intervals measured from a moment when the derivative of total device current had its minimum. The maximum compression of the plasma near the central electrode face (electron density equals then to $2 \cdot 10^{19}$ cm^{-3}) appears also for the time assumed as the moment $t=0$. A series of interferograms showing the plasma column collapse and magnetohydrodynamic instabilities is shown in Fig. 6.

One of the most interesting problems in the physics of the plasma-focus phenomenon is why significant differences of the total neutron yield are observed in discharges with practically the same plasma velocity, density distribution, etc. We suppose that the reason is in differentiated fine structures of the plasma sheath during the collapse phase of these discharges. The results of investigation aimed at explanation of this phenomenon confirm this assumption.

6. Other experiments

Recently, the automated image capturing and processing system has been applied in experiments with laser-produced plasma confined in external magnetic field. The plasma was created by the Nd-glass laser pulse with 1 ns duration, incident on the target positioned in a magnetic coil. The part of the main laser beam was cut out, converted into the second harmonic (visible) and used in the three-frame interferometer. Due to such division of the laser beam the synchronization was achieved automatically.

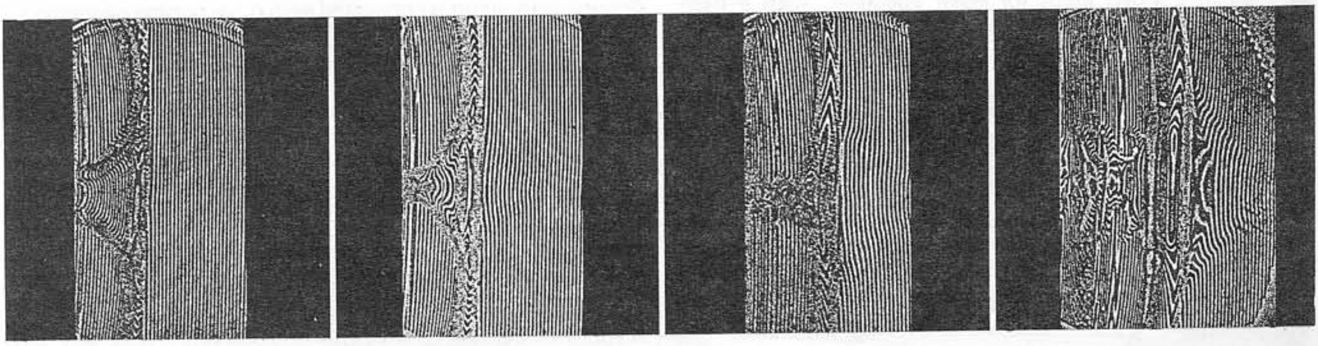

Fig. 6. Sequence of interferograms of collapsing plasma column in the PF-150 device: a) before the maximum compression near the electrode face, b) after the maximum compression, c) phase with MHD instabilities, d) plasma column disintegration

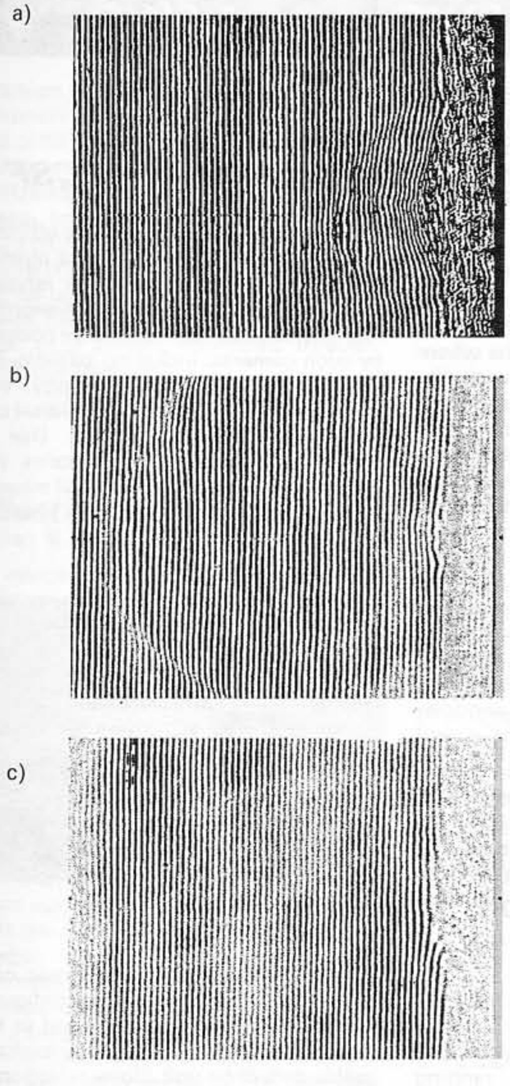

Fig. 7. Sequence of three interferograms of plasma created by a single laser pulse. The shock wavefront in the remaining gas is also clearly visible. The time interval between each image is 10 ns, gas pressure is 20 Tr

The examples of interferograms obtained in this experiment are shown in Fig. 7. The interferometric images of the plasma created in the remaining gas are done with 1 ns exposure time. The images are preliminary processed by the software.

7. Conclusions

The optical, non-perturbing methods are commonly used in studying of high-speed phenomena in laboratory plasma, but many authors concentrate on a single diagnostics only. We have developed simultaneously operating and automated diagnostic equipment which provides the possibility of detailed investigation of the plasma sheath structure and dynamics. Complexity of many technical problems is well-known in the investigation of high-speed electric discharges, which are the base of operation of the PF devices. The problems relate to the shortening of the exposure time, screening and separating of diagnostic equipment from over-voltages, synchronizing of the diagnostic system with the device under test, etc.

All these problems were solved in our system and the obtained results are quite satisfactory. Automatization of the image capturing in each diagnostics will ensure the system to be more flexible and versatile in other experiments on the PF device, laser-target experiments and so on.

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References

1. *S. Czekaj, S. Denus, A. Kasperczuk, R. Miklaszewski, M. Paduch, T. Pisarczyk, Z. Wereszczyński*: MHD stability of the plasma in the PF-150 and PF-360 devices. Proc. 4th Int. Workshop on Plasma Focus and Z-Pinch Research, p. 124, Institute of Plasma Physics and Laser Microfusion, Warsaw 1985.
2. *A. Kasperczuk, M. Paduch, K. Tomaszewski, Z. Wereszczyński*: Electro-optical frame cameras applied in plasma-focus investigations. Proc. Symposium on Image Processing Techniques, p. 147, Warsaw Technical University, Warsaw 1988 (in Polish).
3. *M. Paduch, R. Socha, K. Tomaszewski, Z. Wereszczyński*: Optical diagnostics of a plasma-focus device. Opt. Eng., **31** (1992) p. 453.
4. *W. Lochte-Holdgreven*, ed.: Plasma Diagnostics. North-Holland, Amsterdam 1968.
5. *Ya. B. Zeldovich, Ya. R. Raizer*: Physics of Shock Waves and High-Temperature Phenomena. Academic Press, London 1966.
6. *A. Kasperczuk, R. Miklaszewski, M. Paduch, K. Tomaszewski, Z. Wereszczyński*: Plasma sheath structure in the PF-150 plasma-focus device. Proc. 14th European Conf. on Controlled Fusion and Plasma Physics, p. 138, Dubrovnik-Cavtat 1988.
7. *A. Kasperczuk, M. Paduch, L. Pokora, Z. Wereszczyński*: Numerical solution to Abel integral equation in optical diagnostics of axisymmetrical objects. J. Tech. Phys., **19** (1978) p. 137.
8. *M. Takeda, H. Ina, S. Kobayashi*: Fourier-transform method of fringe-pattern analysis for computer- based topography and inteferometry. J. Opt. Soc. Am., **72** (1982) p. 156.
9. *K. A. Nugent*: Interferogram analysis using an accurate fully automatic algorithm. Appl. Opt., **24** (1985) p. 3101.
10. *M. Kalal, K. A. Nugent, B. Luther-Davies*: Phase-amplitude imaging: its application to fully automated analysis of magnetic field measurements in laser-produced plasmas. Appl. Opt., **26** (1987) p. 1674.