KFKI-1983-50

J.S. BAKOS
I.B. FÖLDES

SELF-FOCUSING IN LASER PRODUCED SPARK

Hungarian Academy of Sciences

CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

KFKI-1983-50

SELF-FOCUSING IN LASER PRODUCED SPARK

J.S. Bakos, I.B. Földes

Central Research Institute for Physics
H-1525 Budapest 114, P.O.B.49, Hungary

"Lasers and Applications" International Conference and School (LAICS) Bucharest 30 August - 11 September 1982.

HU ISSN 0368 5330
ISBN 963 372 084 2

ABSTRACT

The self-focusing effect appearing in different phases of development of laser produced breakdown plasma in air is investigated. Self-focusing during the ionization process is demonstrated. Thermal self-focusing was observed in the later stage of the plasma development at moderate light intensities. Plasma development was investigated by forward and side scattering of the laser light in the plasma. A crossed beam experiment gave evidence of the thermal mechanism of self-focusing.

АННОТАЦИЯ

Изучается самофокусировка в разных фазах времени жизни лазерного пробоя в воздухе. Самофокусировка наблюдается уже в ходе процесса ионизации. В более поздней фазе развития плазмы наблюдается термическая самофокусировка даже при сравнительно малой интенсизности света. Развитие плазмы изучается с помощью рассеяния лазерного излучения вперед и в стороны. Результаты эксперимента с пересекающимися пучками показывают, что причиной самофокусировки являеься неравномерный нагрев плазмы лазером.

KIVONAT

A levegőben létrehozott lézer plazma időbeli fejlődése során az önfókuszálás több izben is megfigyelhető. Önfókuszálás lép fel már az ionizációs folyamat alatt is. A plazma fejlődésének későbbi időszakában termikus önfókuszálás volt megfigyelhető már viszonylag kis fényintenzitás alkalmazásakor is. A plazma időbeli változását a lézerfény előre és oldalra történő szórásával vizsgáltuk. A keresztező nyalábokkal végzett kisérlet bebizonyitotta, hogy az önfókuszálást a nem egyenletes fütés mechanizmusa okozza.

INTRODUCTION

Self-focusing can be observed under different physical conditions in solids, liquids and gases if high intensity electromagnetic radiation propagates in the media. The material properties - including those that determine the propagation of the wave, i.e. the index of refraction - change under the influence of the radiation thereby causing the self-action of the wave on itself, the self-focusing or defocusing effect. The physical situation is usually complex because not only the index of refraction is changed but characteristics of the material such as local pressure, temperature and density, too. Other nonlinear effects such as induced scattering and parametric processes are strongly influenced by the simultaneously appearing self-focusing effect. Thus the effect has a general character.

Self-focusing has become important in laser thermonuclear research, where the plasma created by the laser beam on the surface of a ball-shaped pellet compresses the material thereby producing the thermonuclear condition. The self-focusing or the filamentation effect may appear due to nonuniformities in the illumination causing leakage consequently the compression is smaller and the thermonuclear burn is less effective [1,2].

When radiation is focused in gas, the well-known interaction between the high intensity pulsed laser beam and the material takes place resulting in a phase transition around the focal point, i.e. the breakdown of the gas, the appearance of the laser spark. The material properties, among them the index of refraction, continually change during the formation and the blowing off of the plasma leading to transient self-focusing in different phases of the process.

We review here the investigations on the self-focusing effect appearing in different phases of development of the laser spark and discuss the results of our recent investigations.

EXPERIMENTAL ARRANGEMENT

The block scheme of a typical experimental set-up is very simple /Fig.1/. The laser is usually pulsed solid state or TEA laser. The interaction of the gas and radiation is highly complex in the case of multimode operation so it is advantageous to use a single mode single frequency /bandwidth limited/ laser. We shall deal only with these cases henceforward and the earlier results on self-focusing in laser spark [3,4], where the observations were performed by using the annular beam of a TEA CO_2 laser, will not be considered. Similarly, we omit all investigations where other than nanosecond pulse duration was used because the physical phenomena are likely to differ to a very great extent because of the different experimental conditions.

The focusing lens is usually corrected for spherical aberration and is antireflection-coated to reduce stray backscattered light. The focused beam quality is tested by measuring the intensity distribution around the focus using the attenuated beam of the laser.

The plasma is formed in the gas chamber filled by different gases of pressure ranging from some hundredths of a torr to tens of atmospheres. In some measurements - including ours - no chamber is used and atmospheric air is used as the target. Special care needs to be taken to get rid of dust particles.

The measuring apparatuses MA1-MA3 measure the different properties of the plasma. MA1 can be a monochromator with film, photomultiplier or streak camera as a detector. When using a photomultiplier, not only the spectrum but also the pulse shape of the backscattered radiation can be measured using a storage oscilloscope.

The measuring apparatus MA2 can be a simple camera photographing the time averaged light of the plasma, or the 90° scattered light on the plasma. Sometimes MA2 is a streak camera whose slit is parallel to the direction of the propagation of the focused light. Thus the time development of the plasma can be measured in one shot. Plasma development is studied more simply by using a slit movable in the beam direction shot by shot together with a photomultiplier. This last method also gives the pulse shape of the scattered light at different points x /see Fig. 1/. If the filter in front of the detector is changed, the time development of the plasma's own light or the 90^{o} scattered light is measured.

In refined investigations MA2 is an interferometer, Schlieren system or holographic interferometer giving the time history of the charge density distribution.

The measuring apparatus MA3 can simply be a camera photographing the distribution of the light transmitted by the plasma, generally screening the original beam by an opaque disk. In other cases MA3 is a photodiode or photomultiplier with different size of aperture and different filter giving the transmitted pulse shape or the shape of the light pulse emitted by the plasma. Using a second lens in telescopic configuration with the first one and a detector with a movable aperture in the second focal plane of the second lens, the pulse shape and the angular distribution of the scattered light are measured. Transposing the neutral filter from the position before the measuring apparatus MA3 to the position before the focusing lens, the difference in the pulse shape caused by the plasma can be displayed on the screen of the storage oscilloscope.

If the measuring apparatuses are synchronized the complete temporal behaviour is obtained.

EARLY STAGE OF PLASMA DEVELOPMENT

At small light intensity, i.e. at the beginning of the laser pulse, the gas is transparent, the radiation propagates without attenuation. Later, at higher intensities the laser pulse creates free electrons by multiphoton ionization of the atoms and molecules of the gas in the focal volume. These seeding electrons are accelerated by the high intensity beam in the inverse bremsstrahlung process. The energetic electrons excite and ionize further atoms in the fast cascade process of ionization. /However, the multiphoton process may play a dominant role in creating plasma when using short, picosecond laser pulses./

The excited atoms have much higher polarizability than the neutral ones [5], thus the growing number of excited atoms may cause a nonlinear change of the refractive index leading to the appearance of the self-focusing effect in the early stage of plasma development. The high light intensity in the self-focused filament ionizes the gas more effectively, consequently a high density plasma filament is formed. This narrow plasma filament scatters the incoming light at a wide angle. Furthermore when this fully ionized plasma appears at the focal point, the transmitted pulse shows a sharp decrease in intensity due to the absorption and scattering in the plasma [6]. We shall call the time of the absorption the time of the breakdown /see Fig. 2/.

Figure 3a shows the pulse shape of the transmitted pulse which is measured by a fast photodiode with diaphragm and filter in the second focal plane of the second lens of the telescopic system in place of the measuring apparatus MA3 of Fig. 1. The focal length of the focusing lens was 32 mm. The measurement was made at the edge of the original light beam, i.e. the distance of the aperture is 7 mm from the axis of the optical system. Curve (1) is the laser pulse measured without spark using the method of the transposed filter; curve (2) is the transmitted pulse, (3-4) are monitor pulses after electronic delay. The transmitted pulse is smaller than the laser pulse before the time of the breakdown showing the self-focusing effect before the plasma formation. Namely the light intensity is increased, at the same time, near the optical axis because of this self-focusing effect, as can be seen in Fig. 3b /curve (5) before time t_o/. The curves of Fig. 3b are measured closer to the optical axis, i.e. with the diaphragm at 1.7 mm from the optical axis. The plasma is formed at time t_o, when the sharp decrease of the transmitted pulse can be seen. At the same time a sharp spike appears on the pulse at larger scattering angle, i.e. when the diaphragm is 7 mm from the optical axis /see Fig. 3b curve (5) at time $t_1=t_o$/.

This sharp scattered peak outside the original light cone was observed first by Korobkin and Alcock [7] and Alcock et al. [8]. The consequence of this scattering is that on collecting the radiation emerging at angles up to 30°, 80% of the incident pulse was found to reach the photodiode, and thus the true absorption is, in fact, quite small.

Side scattering of the laser light on the plasma revealed that the scattered light originated in regions running parallel to the beam and had a diameter that was no more than the 5 μm resolution of the optical system, whereas the diameter of the focal spot was varied between 15 and 80 μm. It was found also that, in general, molecular gases were characterized by almost continuous filaments, whereas in the noble gases a number of widely separated scattering points were observed. This scattering is known to be due to reflection on the fronts of the plasma [9,10].

The large proportion of incident light scattered in the forward direction on the thin plasma filament cannot be explained otherwise than by the appearance of self-focusing during the ionization process. This is also confirmed by the laser pulse distortion before the breakdown of the gas /see Fig. 3/.

Subnanosecond interferograms of the spark also show the formation of the filament and how it develops. As it moves opposite to the laser beam, additional, high density blobs of plasma are generated at intervals of 200-400 μm, and following their formation, the filament between them gradually decays. The width of the filament was no more than 13 μm [11].

It is to be emphasized that the plasma filament is probably the result of the self-focusing before the plasma formation, during the ionization process. The plasma itself causes the appearance of the scattered pulse /see Fig. 3a/.

LATER STAGE OF PLASMA DEVELOPMENT

Once plasma appears at the focal point, it begins to propagate toward the focusing lens, and also in the direction of the beam. As the backward propagating shock front screens the forward going one, later only the backward going front can be observed.

Alcock et al. [8] investigated the development of the pearl--necklace-like plasma, measuring 90° scattered light on the plasma boundary, and also the plasma's own light using a streak camera and interferometer as the measuring apparatus MA2 of Fig.1.

Using a moving slit and photomultiplier we also investigated plasma propagation, displaying the result on a storage oscilloscope. We were able to measure the shape of the 90° scattered pulse on plasma density gradients, the time of the appearance and the amplitude of this pulse depending on the position of observation along the line of propagation of the light, i.e. along the line of propagation of the plasma. The scattered pulse was a narrow 5 ns one in each position compared with the 40 ns laser pulse.

The result of the measurement is given in Fig. 4. Curve ⓒ is the appearance time versus the observing position curve of the reflected light on the forward propagating plasma front. This forward going front can be followed only for a short distance because of the limited intensity of the scattered light. The intensity of the scattered light is given by curve ⓑ. The cause of this faintness of light scattering is the smaller density of the front compared with the density of the main body of the plasma and the light screening effect caused by the front propagating opposite to the propagation of the light, which is from the left to the right in Fig. 4. The time versus position curve of the backward going front is given by curve ⓐ. The solid curve is the theoretical fit using the theory of laser supported detonation wave [12,13]. Because of the good fit we can calculate the internal energy of the plasma behind the front and can thus obtain the plasma temperature [14]. A typical valocity was $5.5\cdot10^6$ cms^{-1} and the temperature $T\simeq1.5\cdot10^5K$.

The absorption from the laser beam at the moment of breakdown was shown in Fig. 2. During the above described process of plasma development the energy of the incoming light beam is absorbed and scattered. The time of breakdown is indicated by the upright line /A/ at the right side of Fig. 4. However, not only absorption can be observed with the apertures of MA3 on the optical axis. After a while /20 ns/ the transmitted pulse starts to increase and it forms a narrow spike whose amplitude is about ten times higher than the original pulse at the same time /Fig.5/. This type of transmitted pulse can be observed only on the optical axis. For comparison, the pulse of the laser without spark is also displayed on the same screen. If the opening of the measuring apparatus is far from the optical axis, only the absorption can be registered, which is well-known from the measurements without diaphragm [6].

The above mentioned narrow spike is explainable in two different ways.

It was explained recently by the defocusing effect of the plasma [15]. The main body of the plasma is in front of the focus of the focusing lens therefore the plasma, as a negative lens, forms a Galilean telescopic system with the focusing lens. The result is a narrow cone light beam with higher divergence angle than the incoming beam.

The cond explanation is the self-focusing effect taking place in the plasma [16,17]. Two mechanisms can cause the appearance of self-focusing in the plasma. The first of them is that the plasma is heated nonuniformly by the laser beam because of the nonuniform /Gaussian/ intensity distribution. The hotter electrons at the optical axis diffuse out, and rarification of the plasma is the result. A tube is dug into the plasma, and the wall of this tube corresponds to a smaller index of refraction than the index of refraction on the axis of the tube. The incoming radiation is trapped in the tube and a narrow light cone is formed at the exit of the tube. The second mechanism, leading to tube formation and consequently to self-focusing in the plasma, may be the acceleration of charges by the ponderomotive force taking place also because of the Gaussian distribution of the light intensity.

Of the two explanations for the appearance of the spike the self-focusing seems to be the most probable. Namely the spike appears when the plasma front is wholly developed and slowed down. This can be seen in Fig. 4, where the time of the appearance of the spike is indicated by the upright line /R/. According to ref.[15] the spike should appear earlier, when the main body of the plasma is developed. Saturation of the focused amplitude at increasing intensities, and the result that the position of the plasma front at the time of the spike is different at different intensities also confirm the self-focusing hypothesis.

To obtain a convincing argument about the origin of the spike on the transmitted pulse we performed a crossed beam experiment /Fig. 6/. The incoming light is split into two beams by the beam splitter /BS/. The intensity of the first beam can be changed by the attenuator and it does not create plasma; the second beam is intensive enough to create target plasma for the first beam. L1-2, M1-2, PD, OSC are lenses, mirrors, photodiode and storage oscilloscope, respectively. The position of the target plasma on the first beam can be changed by shifting L2 and M2.

The results of the experiment are:

1. The first beam is attenuated by the target plasma at low light intensities /up to 50 kW/.

2. At elevated intensities self-focusing of the first beam can be observed at definite positions of the target plasma, nearly symmetrically to the focus of the first beam /Fig. 7/. In this figure the calculated beam radius of the first beam is plotted depending on the coordinate along the beam propagation disregarding the spherical aberration. The observed transmitted pulse of the first beam is given for the target plasma positions as indicated in the figure.

These observations indicate:

/a/ The spike appears at a definite threshold intensity. This is characteristic of self-focusing.

/b/ The spike can be observed equally using a converging or diverging beam. The latter excludes negative lensing.

/c/ The self-focused spike can be observed at almost symmetric plasma positions to the focus of the first beam. This fact refers to the thermal self-focusing effect, where the threshold depends on the radius of the beam:

$$P_{cr}^{th} \sim \frac{1}{r^2}$$

CONCLUSIONS

Summarizing the results, the distortion of the laser beam before the breakdown is direct evidence of self-focusing during the ionization process - supposed earlier according to indirect evidence. Thermal self-focusing was observed during the second stage of the plasma development in atmopheric air at moderate light intensities. The observed self-focusing can be disturbing in some thermonuclear and nonlinear optical investigations but it can be used to form short high intensity pulses. Further investigations are necessary to assess the practical applications of the effect.

REFERENCES

[1] Haas, R.A., Boyle, M.J., Manes, K.R. and Swain, J.E.: J. Appl. Phys. 47, 1318 /1976/

[2] Willi, O. and Rumsby, P.T.: Opt. Comm. 37, 45 /1981/

[3] Johnson, L.C. and Chu, T.K.: Phys. Rev. Lett. 32, 517 /1974/

[4] Cohn, D.R., Raff, G.J., Brooks, R.L., Loter, N.G. and Halverson, W.: Phys. Lett. A 49, 95 /1974/

[5] Askarian, G.A.: Pisma v Zh. Eksp. i Teor. Fiz. 4, 400 /1966/

[6] Tomlinson, R.G.: Phys. Rev. Lett. 14, 489 /1965/

[7] Korobkin, V.V. and Alcock, A.J Phys. Rev. Lett. 21, 1433 /1968/

[8] Alcock, A.J., DeMichelis, C. and Richardson, M.C.: IEEE J. Quant. Electron. QE-6, 620 /1970/

[9] Ahmad, N., Gale, B.C. and Key, M.H.: J. Phys. /Atom. Mol. Phys./, ser. 2, vol. 2, p. 403 /1969/

[10] Tomlinson, R.G.: IEEE J. Quant. Electron. QE-5, 591 /1969/

[11] Richardson, M.C. and Alcock, A.J.: Appl. Phys. Lett. 18, 357 /1971/

[12] Raizer, Yu. P.: Zh. Eksp. i Teor, Fiz. 48, 1508 /1965/

[13] Daiber, J.W. and Thompson, H.M.: Phys. Fluids 10, 1162 /1967/

[14] Mandelstam, S.L., Pashinin, P.P., Prokhorov, A.M., Raizer, Yu.P. and Sukhodrev, N.K.: Zh. Eksp. i Teor. Fiz. 49, 127 /1965/

[15] Askarian, G.A. and Mukhamadzhanov, M.A.: Pisma v Zh. Eksp. i Teor. Fiz. 33, 48 /1981/

[16] Bakos, J.S., Földes, I.B. and Sörlei, Zs.: Phys. Lett. 75A, 206 /1980/

[17] Bakos, J.S., Földes, I.B. and Sörlei, Zs.: J. Appl. Phys. 52, 627 /1981/

FIGURE CAPTIONS

1. General scheme of experiments on laser gas breakdown. BS - beam splitter, L - focusing lens, MA1, MA2 and MA3 - measuring apparatuses.

2. Shape of laser pulse transmitted by the plasma (2) compared with pulse (1), when no plasma appears. (3) and (4) are monitor pulses.

3. a/ Pulses (1), (2), (3) and (4) are, respectively, the pulse distorted by the self-focusing taking place before the discharge, and the monitor pulses; y=7 mm.
   b/ Pulses (1), (5), (3) and (4) are, respectively, the reference pulse, the pulse distorted by the self-focusing taking place before the discharge, and the monitor pulses; y=1.7 mm.
   Focal length of focusing optics = 33 mm.

4. Side-scattered intensity /curve (b)/ and time of the peak of the side scattered pulses /curves (a) and (c)/ vs distance on the optical axis. The propagation towards the focusing lens /curve (a)/ is fitted by the detonation wave model and is represented by the solid line. Curve (c) shows the propagation in the direction of the beam. The dotted line is for guidance only. Focal length of lens=50 mm.

5. Focused pulse on the optical axis (2) compared with the reference pulse (1). (3) and (4) are monitor pulses.

6. Crossed beam experiment. BS - beam splitter, A - attenuator, M1 and M2 - mirrors, L1 and L2 - lenses, PD - photodiode, OSC - oscilloscope.

7. Oscilloscope traces show self-focusing when the target plasma is at definite positions nearly symmetrical to the focus. The solid curve is the calculated beam radius vs. coordinate. The laser intensity is 400 kW.

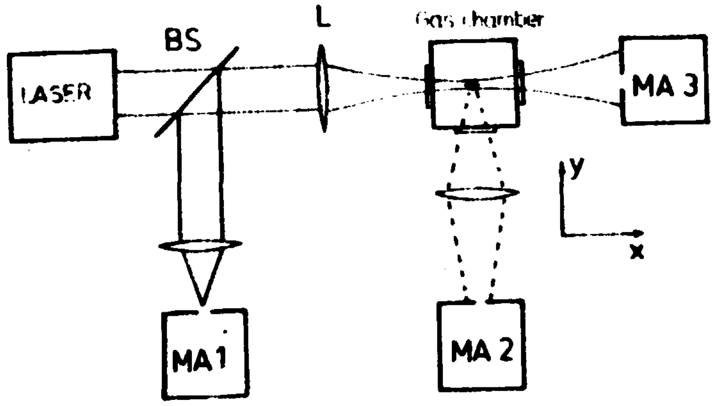


Fig. 1.

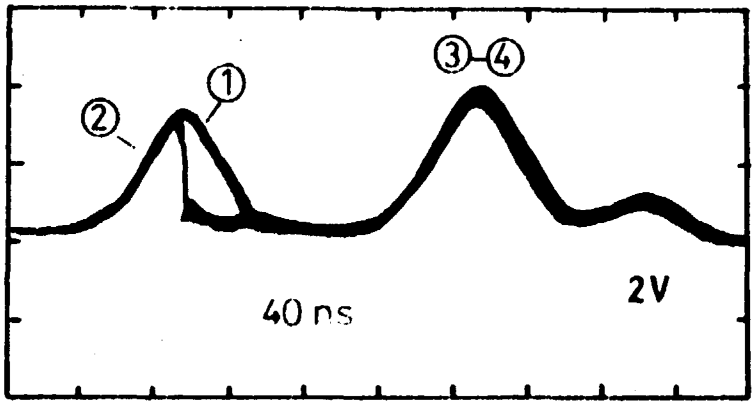


Fig. 2.

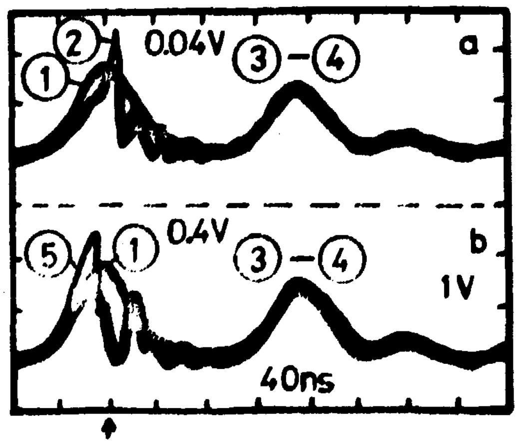


Fig. 3.

Fig. 4.

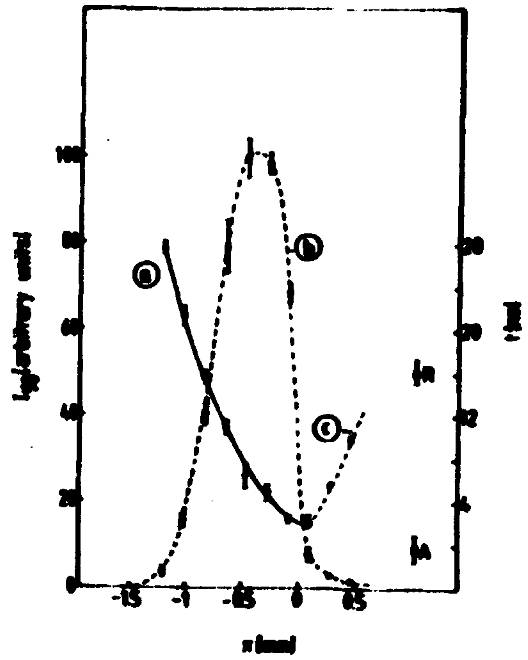
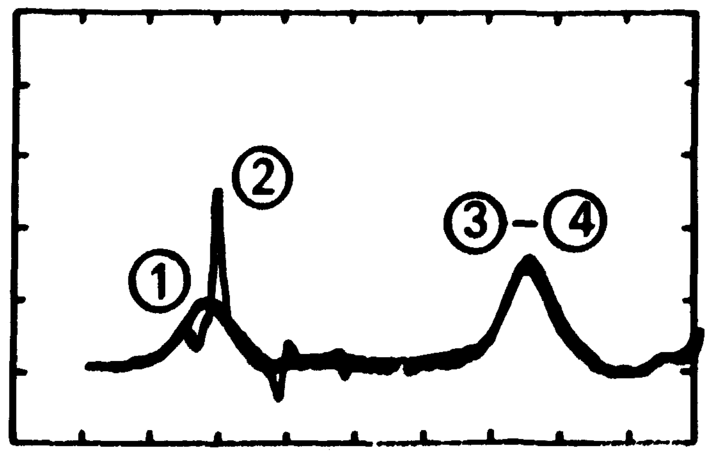


Fig. 5.



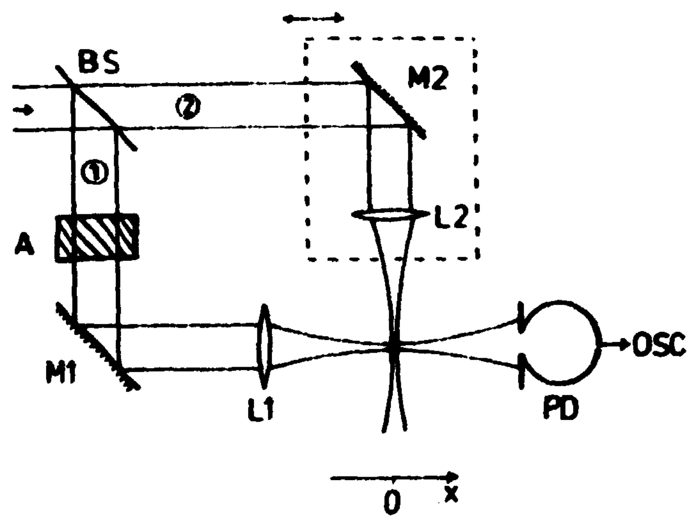


Fig. 6.

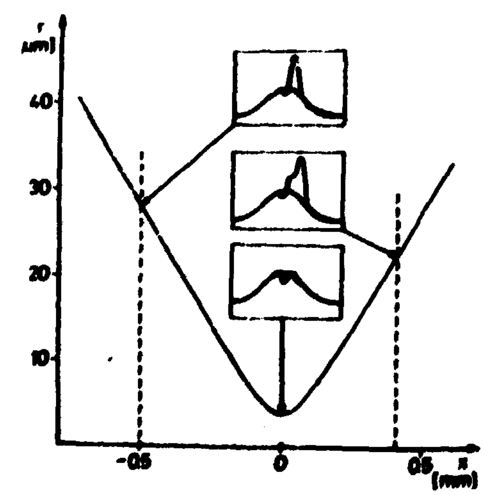


Fig. 7.

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szegő Károly
Szakmai lektor: Párizs Gyula
Nyelvi lektor: Harvey Shenker
Gépelte: Simándi Józsefné
Példányszám: 320 Törzsszám: 83-290
Készült a KFKI sokszorosító üzemében
Felelős vezető: Nagy Károly
Budapest, 1982. május hó