KFKI-1980-119

J.S. BAKOS

PLASMA DIAGNOSTICS WITH LASERS

Hungarian Academy of Sciences

CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

KFKI-1980-119

PLASMA DIAGNOSTICS WITH LASERS

J.S. Bakos

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

HU ISSN 0368 5330
ISBN 963 371 762 0

ABSTRACT

Different methods of laser plasma diagnostics is reviewed and the latest results are discussed.

АННОТАЦИЯ

Обсуждаются методы лазерной диагностики плазмы и дискутируются полученные самые новые результаты.

KIVONAT

A lézeres plazmadiagnosztika módszereit ismertetjük és a legujabb eredményeket diszkutáljuk.

1. INTRODUCTION

Laser plasma diagnostics has become the largest branch among the plasma diagnostics methods because of the rapid development of laser techniques during the last twenty years. Both the development of laser physics itself and the associated techniques have initiated new diagnostic methods and the need for new diagnostics has, in turn, started the investigation of new shorts of lasers, detectors, and optical configurations. The research activity in the field of controlled thermonuclear fusion plays a decisive role in this respect.

Almost all laser methods can equally be used for the diagnostics of both low temperature and high temperature plasmas but the needs of thermonuclear plasma diagnostics determines the rate of development. Low temperature plasma diagnostics experiments tend to be only model experiments prior to applying the new method in thermonuclear research. In view of this, emphasis is placed on the high temperature applications in this present report. The boundaries of laser plasma diagnostics have widened very much and from time to time review have summarized the results in widely varying subfields [1-14]. In this paper chiefly the results published after the last review papers /detailed above/ are emphasized besides a brief summary of the essence of the different laser diagnostic methods.

2. WHAT DOES A LASER PLASMA DIAGNOSTICS SET-UP LOOK LIKE?

The general arrangement of a plasma diagnostics measuring set-up can be seen in *Fig. 1* by means of which the plasma created by the plasma device can be diagnosed. The measuring optical configuration depends on the property of the plasma to be measured. For instance, in the case of plasma density measurements, by measuring the index of refraction of the plasma this particular optical configuration acts as a sort of interferometer /see Section 6/. By measuring the electron temperature by Thomson scattering the measuring optical configuration is given by the scattering geometry /see Section 3/. Depending on the plasma to be measured this optical configuration can be realized in many ways. The development of measuring optical configurations results in new plasma diagnostics methods /for instance different interferometers, scattering geometry/. Any given measuring optical configuration is determined, naturally, also by the type of interaction with the plasma /for instance local scattering, phase acceleration during the path of the propagation/.

Lasers are selected according to the plasma properties, the plasma property to be measured, the type of interaction, the type of detection and measuring optical configuration. In accordance with the given requirements the laser wavelength varies from 100 nm to 1 mm. Furthermore the laser can be pulsed or continuous wave and the power requirements are some 100 MW in the pulsed case and from some 100 mW in the CW case. The pulse duration is sometimes required to be some tens of picoseconds; otherwise a longer pulse length in the μsec range is more advantageous.

The type of detector changes according to the wavelength of the laser and many times greater sensitivity and faster response are also required. Recently, special TV cameras and streak-cameras have begun to serve as detectors.

The data acquisition and display system is controlled by computers in modern diagnostics systems of thermonuclear research. Sometimes this data acquisition system is simply an oscilloscope.

Plasma devices do not belong to the diagnostics system but such devices do give control signals to the lasers and the data acquisition system. In more sophisticated measuring optical configurations the data acquisition system controls the optics and the lasers too.

The use of the plasma diagnostics method enables the following plasma parameters to be measured.

1/ Electron density /n_e/
by Thomson scattering /Section 3/, interferometry /Section 6/ and nonlinear scattering /Section 5/;

2/ Spatial and temporal electron density distrubution $n_e/\bar{r},t/$
by Thomson scattering /Section 3/, and interferometry /Section 6/;

3/ Electron temperature /T_e/
by Thomson scattering /Section 3/, and nonlinear scattering /Section 5/;

4/ Spatial and temporal electron temperature distribution /$T_e/\bar{r},t/$/
by Thomson scattering /Section 3/;

5/ Ion temperature /T_i/
by Thomson scattering /Section 3/, nonlinear scattering /Section 5/, and scattering on bound electrons /Section 4/;

6/ Local current density /$\bar{j}_r$/
by Thomson scattering /Section 7/;

7/ Determination of the density of the different species of plasma /impurity atoms, ions in the ground and excited states, background atoms in the ground and excited state/
by scattering on bound electrons /Section 4/.

8/ Local magnetic field /H_φ/
by Thomson scattering /Section 3/ and Faraday rotation /Section 7/.

3. SCATTERING BY FREE ELECTRONS

Laser radiation with propagation vector $\bar{k}_i$ and frequency ω_i is sent through the plasma. The by the plasma scattered light with propagation vector $\bar{k}_s$ and frequency ω_S is observed. The spectrum of the scattered light can be fitted by the theoretical function $S/\omega, \bar{k}; T_e, T_i, n_e/$ given in ref. [14] where $\omega=\omega_i-\omega_S$ and $\bar{k}=\bar{k}_i-k_S \sim 2k_i \sin\theta/2$ where θ is the scattering angle. The parameters are the electron temperature $/T_e/$, the ion temperature $/T_i/$ and the electron density $/n_e/$, all of which can be determined as a result of the fitting procedure.

If $k \gg k_D = \frac{1}{\lambda_D}$ where λ_D is the Debye length, the form of function S is the same as the electron velocity distribution function. In the case of Maxwellian distribution the amplitude of the spectrum gives the density of the electron, the width $/\Delta\omega/$determines the electron temperature $\Delta\omega = k(\frac{3\varkappa T_e}{m_e})^{1/2}$. $\varkappa$ is Boltzmann's constant, and m_e is the electron mass.

The ion temperature does not influence the function S in that case at all.

The measurement is a local one determining n_e and T_e at the point of interaction $\bar{k}_i$ and $\bar{k}_s$.

In the most recent investigations of tokamak plasma [15] the spectrum is measured using a spectrograph with image intensification and video camera detection. The different spatial points among the path of the light through the plasma are simultaneously observed using fibre optics to project the image of the light path to the input slit of the spectrograph. In this spatial distribution of n_e and T_e can be determined simultaneously. In this case, a gaint pulse ruby laser is used as the light source.

In another experiment [16,17] the ruby laser is modulated and so the laser gives a series of light pulses with about 30 µsec separation between the pulses. Using polychromator with simultaneous detection in the channels the temporal evolution $/T_e, n_e/$ of the tokamak discharge is measured in the vicinity of major disruptions.

If $k \ll k_D$ and $\omega \gg \omega_P$ /the plasma frequency/ the function S can be replaced by S' i.e.

$$S(\omega,k;T_e,T_i,n_e) \sim S'(\omega,k;T_i)$$

and the S' function contains only T_i as the parameters, consequently. The ion temperature /T_i/ can be determined from the measured scattered spectrum. The width of the spectrum

$$\Delta\omega_i = \frac{1}{1,15} k\left(\frac{3\varkappa T_i}{m_i}\right)^{1/2} .$$

where m_i is the ion mass.

There are two ways to satisfy the inequality $k \ll k_D$. One way is to decrease the scattering angle, the second is to increase the wavelength of the laser.

In the first case the scattered radiation cannot be separated from the incident beam. The simultaneous detection of the incident and scattered beam causes a beating signal in the detector. Due to the smallness of $\Delta\omega_i$ the spectrum of the beating can be measured electronically instead of using a polychromator. This homodyne detection is used in many experiments [18-25]. The drawback is the poor spatial resolution due to the small scattering angle.

In the second case, long wavelength high peak intensity laser and sensitive detectors are needed. The consequence of this is that extensive research in being carried out to develop pulsed narrow bandwidth submillimeter lasers [26-28] and sensitive detectors.

4. SCATTERING BY BOUND ELECTRONS

Plasma usually consists of different atomic species; this is also true if the original gas was very pure and the ionization grade is nominally 100% /high temperature plasma/. The neutral gas background density is usually many orders of magnitude lower than the electron density in high temperature hydrogen tokamak plasmas, but this low density background plays an important role in particle transport processes to the wall and back [29]. The wall interaction with high energy neutral atoms emits heavy impurity atoms into the plasma thereby changing the content and principally changing the state of the plasma. This means that the diagnostics concerning the densities of the different plasma species is of crucial importance.

The determination of the plasma content is naturally an important task also for the diagnostics of plasmas of low temperature, consequently of low ionization grade.

The laser method for locally determining the density, temperature and drift velocity of the different plasma species is resonance fluorescence induced by tunable laser light. The method has become applicable only since the development of tunable lasers. The resonance light of the laser usually saturates the transition due to the high intensity. In this case the population increase ΔN_3 in the upper level - consequently also the intensity of the resonance fluorescence /G/ - depends only on the population of the lower level $/N_2/$

$$G = t \cdot \alpha \cdot N_2.$$

If the atomic parameters, spontaneous relaxation rates and the relaxation rates induced by electrons are known, α can be calculated [30,31] and the density of the atoms in the lower level can be determined according to the above formula, where t is the duration time of the laser pulse.

In a recent experiment the denstiy of the hydrogen atoms in the first excited state was determined in tokamak plasma [32]. With the knowledge of the density of the excited atom $/N_2/$ the atomic density in the normal state $/N_1/$ can be calculated using an acceptable plasma model. The density distribution are also determined at different discharge times.

The density of different plasma species has been determined in low temperature plasmas in many recent experiments [33-38] using the resonance fluorescence method. Using this method of laser plasma diagnostics it is also possible to measure the diffusion of the impurities in the plasma. In the experiment [39] the diffusion of aluminium atoms was measured in hydrogen plasma. The aluminium atoms are injected into the plasma by a shot from a CO_2 TEA laser to the surface of aluminium in the plasma. The time taken for the diffusion to develop is measured by a timed, tuned laser and by observing the resonance fluorescence. The potential applicability of the method for investigating the plasma-wall interactions in tokamak discharge is of great significance.

5. NONLINEAR SCATTERING BY PLASMA MODES

In the preceding diagnostics methods the absence of perturbation of the plasma by the laser beam is required /no heating/. But sometimes the scattered signal - especially in the case of scattering by free electrons - turns out to be too weak /the Thomson scattering cross-section is too small/. Consequently the laser beam must then be very strong and the plasma is perturbed. The laser beam does not heat the plasma essentially but induces plasma modes by nonlinear interaction and the beam scatters on these induced mode. One of these nonlinear scattering processes is the four wave scattering. Two crossing laser beams induce plasma modes so that the first beam forces the electron to oscillate and the oscillating electron of high velocity interacts with the magnetic field of the second beam of different frequency. The results is a ponderomotive force acting on the electrons with the frequency difference $\Omega = \omega_1 - \omega_2$ of the two pumping beam and with the wave vector $\bar{k} = \bar{k}_1 - \bar{k}_2$. The force acting on the electrons is parallel to the electric field. Consequently, a plasma wave is induced if $\bar{k}$ and Ω satisfy the dispersion relation in the plasma. The use of a third beam it produces scattering on the induced plasma wave giving rise to a fourth scattered wave. The cross-section of the scattering depends on the product of the intensities of the pumping beams and it is of many orders larger than the Thomson scattering cross-section [40-44].

The plasma properties, the density and the temperature can be determined by measuring the spectral properties of the scattered light or by determination of the resonance condition changing the frequency of the pumping beams.

The very first experiments have been performed [45,46] showing the result to be in agreement with theoretical expectations [42]. In these experiments two dye laser beams of different frequency pump the plasma modes in a free burning arc and the ruby laser pulse is scattered on the induced fluctuations. The increase in the intensity of the scattered light relative to the Thomson scattering is between one and two orders of magnitude.

A single laser beam can also excite plasma modes if the intensity is high enough and the beam itself is scattered on the induced fluctuation /for instance Brillouin scattering/. The scattered light can be used to determine plasma parameters such as ion temperature etc. see for instance [47,48].

Many other nonlinear processes are being investigated with a view to using them for plasma diagnostics purposes [49,50].

6. MEASUREMENT OF THE INDEX REFRACTION OF THE PLASMA

The most popular method for determining plasma density is to measure the index of refraction of the plasma using interferometers with laser light source; viz. the phase acceleration of the light beam caused by isotropic plasma without a magnetic field.

$$\Delta\varphi = -4{,}46\cdot 10^{-14}\cdot\lambda\cdot n_e\cdot \ell$$

where λ is the wavelength, l is the length of the plasma. As can be seen the longer the wavelength and the length of the plasma the smaller the density which can be determined. Furthermore, the smaller the phase acceleration which can be measured the smaller the measurable density. This has given rise to research work and papers dealing with the enlargement of l using a multibeam interferometer [51], and the measurement of small phase acceleration [52]. In addition, a great deal of effort has also been made to develop reliable far infrared CW lasers [53-58].

The correct choice of the wavelength depends on two disturbing effects: the mechanical vibration of the parts of the interferometer and the refraction of the beam on the plasma density gradient. To avoid the first effect a longer wavelength, to avoid the second effect a shorter wavelength has to be used. Thus the correct wavelength to be chosen is the result of a trade off between the two effects.

In actual practice a wide variety of interferometers are used to measure phase acceleration taking into account, among the other requirements, the speed of the measurement needed in the case of fast plasma events. These interferometers are the following:

1/ Classical two beam interferometers with reference beam of the same frequency as the scene beam /Michelson, Mach-Zender, Jamin, etc./. The drawback of these interferometers is that the measurement of the phase acceleration is disturbed by the instability of the laser intensity, the in crease of phase acceleration cannot be distinguished from the decrease of the phase acceleration.

2/ Heterodyne interferometers. The plasma is set into the resonator of the laser. The phase change caused by the plasma appears as a frequency change of the laser. The frequency change is measured by heterodying with the beam of the second laser [59,60]. The use of this method anables a high degree of sensitivity to be achieved. Great laser frequency stability is needed. The smallest measured density is about 10^{12} cm^{-3}.

3/ Ashby-Jephscott interferometer. The plasma is set into the Fabry-Perot interferometer which is in series with the laser resonator. The intensity of the laser is modulated according to the resonance caused by the plasma in the compound interferometer. The sign of the plasma density change is ambiguous in such measurements [61].

4/ Modulated interferometer. The pathlength is artificially modulated besides the pathlength change caused by the plasma. The display is on the oscilloscope. The y direction is proportional to the modulation. The interference fringes modulate the brightness of the display. In the x direction the time is displayed /Zebra type display/. The sign of the density change is unambiguous [62,63].

5/ Light beating interferometers [64,58,65]. The frequency of the light in the reference arm differs from the frequency of the scene beam. The phase shift of the beating signal is detected relative to the phase of the beating signal which arises from beating the scene beam with the reference beam before the scene beam enters the plasma. The phase difference is measured as a time difference between the zero crossing of the signals from the two detectors. There is no sign ambiguity in the phase change, good temporal resolution can be achieved. Data acquisition is computer controlled. The interferometer is insensitive to the laser light intensity variations and frequency.

6/ Double interferometer. This is the usual classical type of interferometer but two wavelengths are used simultaneously. Owing to the different dependence of the phase change due to the vibration and the plasma electrons on the wavelength the vibration can be separated [66,52]. This advantage is very useful in big plasma devices such as big tokamaks. If two wavelengths are used the neutral atom contribution can also be separated in partially ionized plasma [67].

7/ Holographic interferometers. The interference is registered in the whole volume of the object plasma. As a rule, the double exprosure [68] method is used. The drawback is the off-line data acquisition, i.e. the holograms are recorded in film or other light sensitive plate. This means that data become available only after development using a laborious data acquisition procedure.

8/ Quadrature interferometer. The interferometric measurement is taken in the two polarization directions simultaneously [69]. This type of interferometer is insensitive to the ray refraction on density gradients.

Nowadays, light beating interferometers seem to be the most reliable for thermonuclear research. Therefore almost all the larger tokamaks are equipped with this type of interferometer for plasma density distribution measurements.

7. FARADAY ROTATION MEASUREMENTS

In current carrying plasma the spatial distribution of the current density is also an important parameter of the discharge. This is especially true in tokamak devices. The current density can be determined by scattering on free electrons too, namely the centre of the scattered spectrum is shifted relative to the line centre of the incident radiation due to the electron drift velocity [70,71]

A further method for current density determination is the Faraday rotation measurement. Namely there is magnetic field around the current and the index of refraction of the plasma depends on the magnetic field. Because of the different index of refraction for left and right circularly polarized light propagating in the direction of the magnetic field the plane of polarization of the linearly polarized light is rotated.

The rotation angle is given by

$$\vartheta = 2,63 \cdot 10^{-14} \cdot \lambda^2 \cdot \int_0^L n_e(\bar{r}) \cdot B(\bar{r}) \cdot d\ell$$

where B is in K Gauss units. After measuring the $n_e(\bar{r})$ density distribution by interferometry and the polarization rotation by polarimetry the longitudinal magnetic field $B(\bar{r})$ consequently the current density can be determined.

The first experiment [72,73] has successfully been performed on the TFR 600 tokamak. On the basis of the result the direction to be taken for further refinement of the measurement is determined. New polarimeter arrangements were recently published [74] designed specially for Faraday rotation measurements in tokamak plasmas.

8. SCHLIEREN METHOD

This method enables plasma inhomogeneity to be measured by detecting only the light refracted by the plasma [1-14].

ACKNOWLEDGEMENTS

Many thanks are due to my co-workers Dr. Zsuzsa Sörlei and Dr. P. Ignácz for their help in collecting the material for this paper, and to Miss Ánges Havas for the editorial work.

REFERENCES

[1] L.N. Pjátnyickij: Lazernaja Diagnostika Plazmi, Moszkva Atomizdat /1976/

[2] H.J. Kunze: The Laser as a Tool for Plasma Diagnostics Plasma Diagnostics /Ed. by W. Lohte-Holtreven/, Nort-Holland, Amsterdam, 1968, p.550

[3] A.W. DeSilva and G.C. Goldenbaum: Plasma Diagnostics by Light Scattering, Methods of Experimental Physics, Vol.9A, /Ed. by Hans R. Griem and R.H. Lovberg/ Academic Press, New York 1970, p.61.

[4] F.C. Jahoda and G.A. Sawyer: Optical Refractivity of Plasmas, Methods of Experimental Physics, Vol.9B, /Ed. by R.H. Lovberg and Hans R. Griem/ Academic Press, New York 1971, p.1

[5] L. Pieroni: Diagnostics of Tokamak Plasmas by Far Infrared Techniques, C.N.E.N. - Edizioni Scientifice, Roma, 1977

[6] D. Veron: Submillimeter Interferometry of High Density Plasmas, Instrumentation and Techniques for Plasma Research /Ed. by K.J. Button/ Academic Press, New York, 1978

[7] G.T. Razdobarin and I.P. Folomkin: Zh. Techn. Fiz., 49, 1353 /1979/

[8] E. Holzhauer: Infrared Physics, 16 135 /1978/

[9] W.B. Johnson: IEEE Transactions on Antennas and Propagation, AP-15, 152 /1967/

[10] A.N. Zajdelj, G.V. Osztrovszkaja and Yu.I. Osztrovszkij: Zh. Techn. Fiz., 36, 1405, /1968/

[11] D.T. Attwood: IEEE Journ. of Quantum Electronics QE-14, 909 /1978/

[12] F.F. Chen: IEEE Trans. on Plasma Science, PS-5, 231 /1977/

[13] D.E. Evans: Physica, 82C, 27 /1976/

[14] D.E. Evans and J. Katzenstein: Rep.Prog.Phys., 32, 207 /1969/

[15] N. Bretz, D. Dimock, V. Foote, D. Johnson, D. Long and E. Tolnas: Appl. Opt., 17, 192 /1978/.

[16] R. Behn: Phys.Lett., 74A, 316 /1979/

[17] R. Behn, H. Röhr, K.H. Steuer and D. Meisel: Appl.Phys.Lett., 36, 363 /1980/.

[18] A. Gondhalekar and F. Keilmann: Report of Max-Planck--Institute für Plasma-Physik, München, IPP IV/26 /1971/

[19] C.M. Surko, R.E. Slusher and D.R. Moler: Phys.Rev.Lett., 29, 81 /1972/

[20] A. Gondhalekar and E. Holzhauer: Phys.Lett., 51A. 178 /1975/

[21] G.M. Surjo and R.E. Slusher: Phys.Rev.Lett., 37, 1747 /1976/

[22] A. Gondhalekar, K. Molving and M.S. Tekula: Phys.Rev.Lett., 38, 354 /1977/

[23] D.R. Baker, N.R. Heckenberg and J. Meyer: IEEE Trans. on Plasma Science, PS-5, 27 /1977/

[24] H. Hailer: Phys.Lett., 62A, 419 /1977/

[25] E. Holzhauer: Phys.Lett., 62A, 495 /1977/

[26] P. Woskoboinikow, H.C. Praddaude, W.J. Mulligan, D.R. Chin and B. Lax: J.Appl.Phys., 50, 1125 /1979/

[27] D.E. Evans and L.E. Sharp: Appl.Phys.Lett., 26, 630 /1975/

[28] D.B. McDermott, T.C. Marshall, S.P. Schlesinger, R.K. Parker and V.L. Granatstein: Phys.Lett., 41, 1368 /1978/

[29] P. Bogen and E. Hintz: Comments Plasma Phys. Cont. Fusion, 4, 111 /1978/

[30] G.T. Razdobarin and I.P. Folomkin: Plasma Diagnostics by the Method of the Resonance Fluorescence, Diagnostics for Fusion Experiments, /Ed. by E. Sindoni and C. Wharton/ Pergamon Press, Oxford and New York, 311, /1979/

[31] G.T. Razdobarin, V.V. Somenov, L.V. Sokolova, I.P. Folomkin, V.S. Burajov, P.Ya. Misakov, P.A. Naumenkov and S.V. Nachaev: Nuclear Fusion, 19, 1439 /1979/

[32] V.C. Burakov, P.Ya. Miszakov, P.A. Haumenko, Sz.B. Hecsaev, G.T. Razdobarin, V.V. Szemenov, L.V. Szokolova and I.P. Folomkin: Pisma v ZsETF, 26, 547 /1977/

[33] H.F. Döbele and K. Hirsch: Phys.Lett., 54A, 267 /1975/

[34] L. Vriene and M. Adriaansz: Journ. of Appl.Phys., 45, 4422 /1974/

[35] A.B. Rodrigo and R.M. Measures: IEEE Journ. of Quantum Electronics, QE-9, 972 /1973/

[36] D.D. Burgess and C.H. Skinner: J.Phys.B., 7, L297 /1974/

[37] R.A. Stern and J.A. Johnson, III: Phys.Rev.Lett., 34, 1548 /1975/

[38] K. Bergstedt, G. Himmel and F. Pinnekamp: Phys.Lett., 53A, 261 /1975/

[39] H.C. Meng and H.J. Kunze: Phys.Fluids, 22, 1082 /1979/

[40] H.C. Praddaude, D.W. Scudder and B. Lax: Appl.Phys.Lett., 35, 766 /1979/

[41] F.V. Bunkin, F.V. Kalinyin, P.P. Pasinyin: Kvantovaja Elektronika, 5, 486 /1978/

[42] J. Meyer: Phys.Rev., 6A, 2291 /1972/

[43] J. Meyer and B. Stansfield: Can.Journ.Phys., 49, 2187 /1971/

[44] N.M. Kroll: Phys.Rev.Lett., 13, 83 /1964/

[45] B.L. Stansfield, R. Nodwell and J. Meyer: Phys.Rev.Lett., 26, 1219 /1971/

[46] L.A. Godfrey, R.A. Nodwell and F.L. Curzon: Phys.Rev., 20A, 567 /1979/

[47] A.A. Offenberger, M.R. Cervenan, A.M. Yam and A.W. Pasternak: Journ. Appl. Phys., 47, 1451 /1976/

[48] Z.A. Pietrzyk and R. Massey: Journ.Appl.Phys., 48, 1876 /1977/

[49] N.G. Baszov, V.Yu. Bychenkov, N.N. Zorev, M.V. Osipov, A.A. Rupasov, V.P. Silin, G.V. Sklizkov, A.N. Starodub and V.T. Tikhonchuk: Pisma v ZsETF, 30, 439 /1979/

[50] N.G. Basov, V.Yu. Bychenkov, M.V. Odipov, A.A. Rupasov, V.P. Silin, A.S. Shikanov, G.V. Sklizkov, A.N. Starodun, V.T. Tikhonchuk and N.N. Zorev: Phys.Lett., 77A, 163 /1980/

[51] V.V. Kotobkin, A.A. Malyutin: Sov.Fiz.Tekn.Fiz., 13, 908 /1969/

[52] Yu.D. Pavlov: IAE-2961 reprint /1978/ Moscow

[53] P. Belland, C. Pigot and D. Veron: Phys.Let., 56A, 21 /1976/

[54] P. Belland, D. Veron and L.B. Whitbourn: J.Phys.D., 8, 2113 /1975/

[55] P. Belland and D. Veron: Opt.Comm., 9, 146 /1973/

[56] P. Belland, A.I. Cinre and L.B. Whitbourn: Opt.Comm., 11, 21 /1974/

[57] D.T. Hodges, F.B. Foote and R.D. Reel: Appl.Phys.Lett., 29, 662 /1976/

[58] S.M. Wolfe, K.J. Button, J. Waldam and D.R. Cohn: Appl.Opt., 15, 2645 /1976/

[59] I.K. Belal and M.H. Dunn: J.Phys.D., 11, 313 /1978/

[60] J. Aiken and G.S. Higginson: J.Phys.D., 18, 1541 /1977/

[61] A.N. Kolerov and G.D. Petrov: Opt. i Spektr., 41, 741 /1976/

[62] A. Gibson and G.W. Reid: Appl.Phys.Lett., 5, 195 /1964/

[63] A. Lesage, J. Richou, P. Charil, M. Combier and J.L. Lebrun: Rev.Sci.Instrum., 5, 1306 /1979/

[64] D. Veron: Opt.Comm., 10, 95 /1974/

[65] C.A.J. Hugenhöltz and B.J. Meddens: Rev.Sci.Instrum., 50, 1123 /1979/

[66] D.R. Baker and Shu-Tso Lee: Rev.Sci.Instrum., 49, 919 /1978/

[67] M.C. Richardson and A.J. Alcock: J. Quantum Electronics, QE-9, 1139 /1973/

[68] W.T. Armstrong and P.R. Forman: Appl.Opt., 16, 229 /1977/

[69] C.J. Buchenauer and A.R. Hacohson: Rev.Sci.Instrum., 48, 769 /1977/

[70] F. Alladio and M. Martone: Phys.Lett., 64A, 199 /1977/

[71] F. Alladio and M. Martone: Phys.Lett., 60A, 39 /1977/

[72] W. Kunz: Nucle.Fusion, 18, 1729 /1978/

[73] G. Dobel and W. Kunz: Infrared Physics, 18, 773 /1978/

[74] C.H. Ma, D.O. Hutchinson and K.L.V. Sluis: Appl.Phys.Lett., 34, 218 /1979/

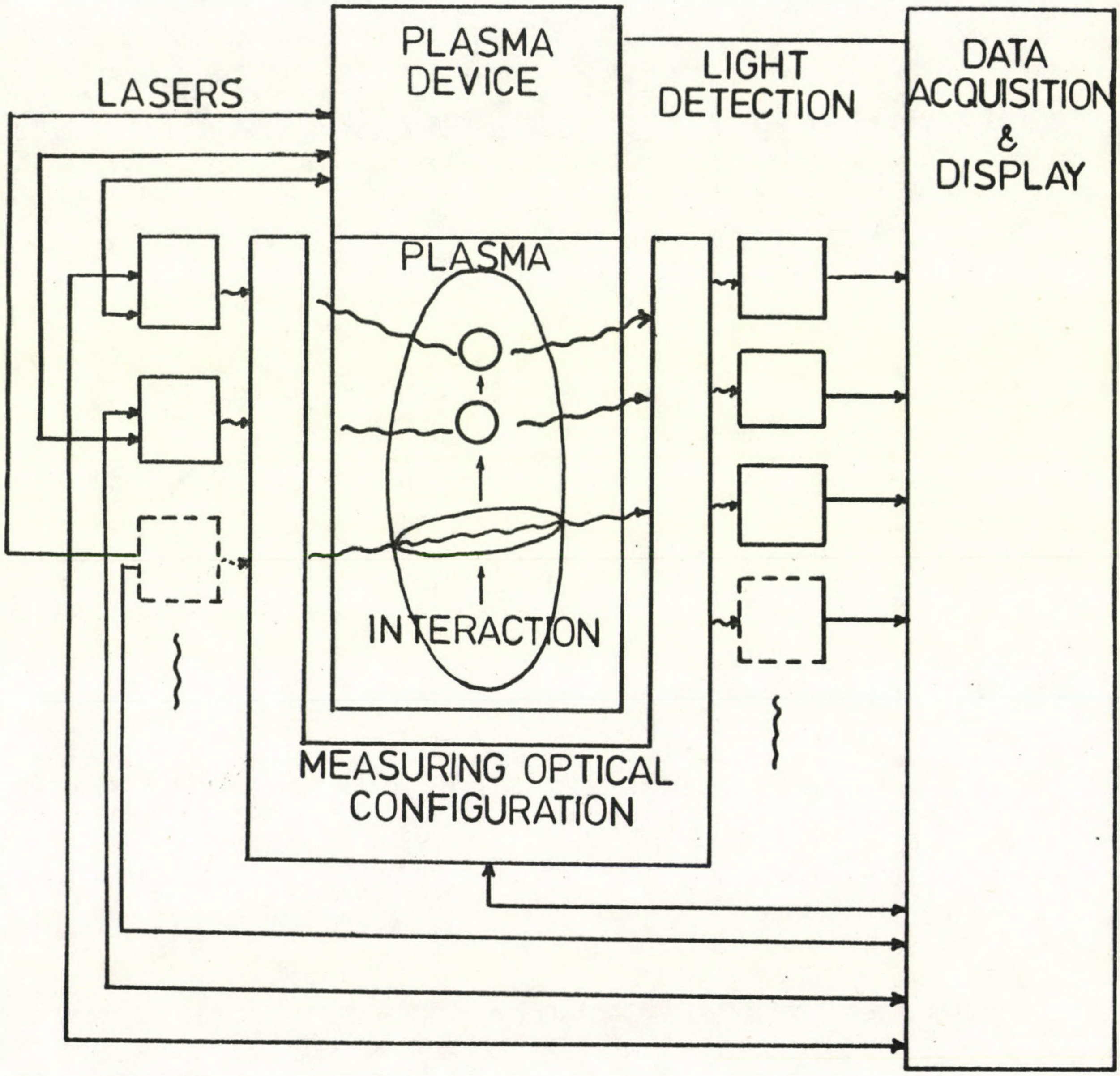
PLASMA
DEVICE
LASERS
LIGHT
DETECTION
DATA
ACQUISITION
&
DISPLAY
PLASMA
INTERACTION
MEASURING OPTICAL
CONFIGURATION

Fig. 1.

63.103

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szegő Károly
Szakmai lektor: Szentpétery Imre
Nyelvi lektor: Harvey Shenker
Gépelte: Beron Péterné
Példányszám: 310 Törzsszám: 80-699
Készült a KFKI sokszorosító üzemében
Felelős vezető: Nagy Károly
Budapest, 1980. november hó