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edited by J. Juul Rasmussen and S.G. Hanson

Risø National Laboratory, Roskilde, Denmark
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Abstract Research in the Optics and Fluid Dynamics Department covers plasma physics, fluid dynamics, optics, and neural networks.

Plasma physics is concentrated on basic investigations with relevance to fusion plasmas. Both theoretical and experimental work has been performed. Pellet injection systems have been developed. Within the area of fluid dynamics spectral models for studying the dynamics of coherent structures have been developed. Optical diagnostic methods based on quasi-elastic light scattering have been developed. Beam propagation in random and nonlinear media has been investigated. Spatial and temporal processing schemes, especially for pattern recognition, have been investigated.

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Contents

Introduction

The department performs basic and applied research within fluid dynamics, plasma physics, and optics. The activities do also incorporate the development of methods and equipment for diagnostic purposes, especially in fluids. The activities are often performed in collaboration with other research groups and industry. The training of students at a graduate level is an integral part of the activities and so is the dissemination of the results to research and industry. The results are important for the understanding of (1) the dynamics of fusion plasmas, (2) liquids and gases, and (3) optical diagnostic systems. Several of the results are exploited by industry.

The department was established in connection with the restructuring of the research activities at Risø National Laboratory. Plasma physics was merged with the activities in optics and neural networks of the former Department of Information Technology.

The work described in this report falls within the following categories:

Plasma physics is concentrated on basic physical phenomena with relevance to fusion. Turbulence and coherent structures are being investigated both theoretically and experimentally.

Pellet injection and interaction with fusion plasmas. Pellet injection systems have been developed and are now delivered to other fusion research laboratories. Work has also been performed on the pellet plasma interaction.

Fluid dynamics is currently concentrated on numerical investigations. Spectral models have been developed and used for studying the interaction of coherent structures with boundary layers.

Quasi-elastic light scattering and beam propagation. Diagnostic methods for probing the state of both fluid mechanical systems and systems based on solids have been investigated.

Optical and electronic information processing incorporates work on two-dimensional optical transforms applied to pattern recognition. Schemes for proper data reduction and neural networks have also been investigated.

1 Applied Laser Physics Section

1.1 Introduction to the work in the Applied Laser Physics Section

The work carried out in the Applied Laser Physics Section in 1990 has been dominated by two major projects each of which benefits from the capability of producing smaller quantities of holographic optical elements (HOEs). An EEC funded ESPRIT project named NAOPIA has been progressing throughout the entire year. The partners are equally divided between academic institutions and industrial companies in that the end goal of the project is to establish an optical vision system. A vital part of the project is transformation of filters which are computer-generated and later recorded as HOEs. The second major project aims at introduction of new concepts for industrial sensors, many of which benefit from HOEs as well.

Basic research on photorefractivity, squeezed light, and information processing has been carried along and a synergy between these scientific themes and the work in neural networks has been initialised.

1.1.1 Optical robot vision: the ESPRIT NAOPIA project

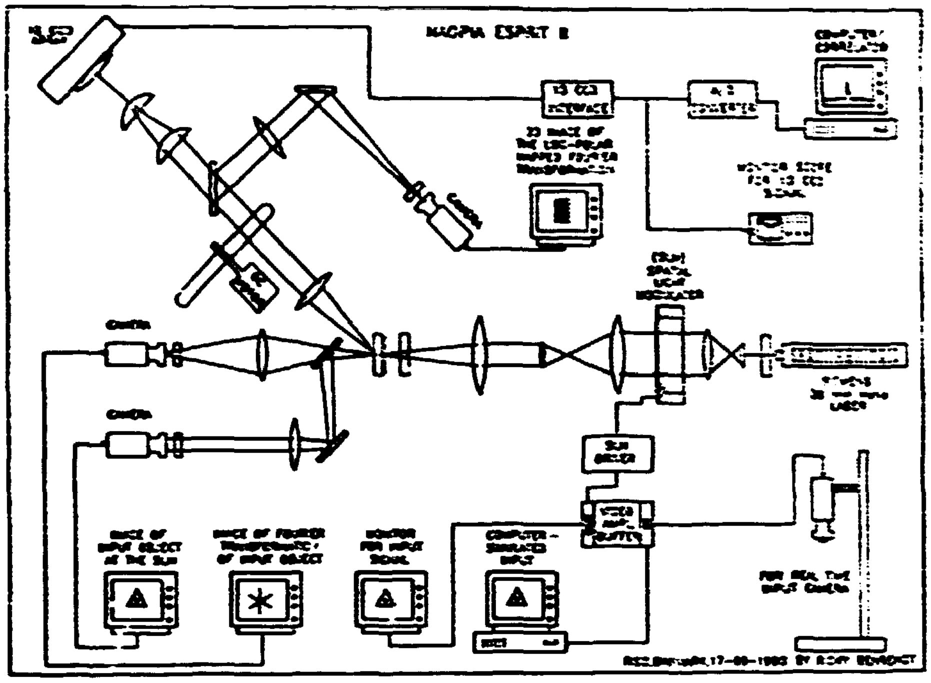
(A. Skov Jensen and E. Rasmussen)

The NAOPIA project is a continuation of earlier ESPRIT projects, formed by a merging of two optically oriented ESPRIT I projects, P534 and P1035. The partners in the project are Krupp Forschungsinstitut (Germany), Thomson-CSF (France), University of Erlangen (Germany), and Risø.

The purpose of the project is to develop an industrial optical vision system capable of sorting objects; recognition and determination of their position and orientation.

In the first year of the project (September 1989 - August 1990) the two concepts developed in P534 and P1035 were supposed to demonstrate their performance with respect to certain objectives of the industrial system. In this competition the Risø system has been chosen to be developed into an industrial prototype.

The work performed in year one in the Risø part of the project has been an intensive documentation of a rebuilt demo system previously developed in ESPRIT I. The main change in the demo system has been the implementation of a spatial light modulator (SLM) which gives real time input images instead of slides of the input objects. A set of four test objects (machine tools) was used: a square, a rhombus, a triangle, and a circularly shaped object. The task of the vision is to be able to recognise and determine the orientation and position of an object presented in an input area. With nine 1D reference filters it was possible to get a recognition rate of 99%, a relative position accuracy of 10%, and an angular accuracy of 5 degrees. The layout of the system is shown in the figure.



Technically the functions of the electro-optics vision system may be described in the following steps:

An image from a CCD camera is fed into an LCD spatial light modulator (SLM). The 2D image on the SLM is Fourier transformed by a lens and this field is mapped into log-polar coordinates by a mapping filter followed by a lens. The mapped image is compressed into two 1D spatial signals which are detected and fed into an electronic correlator where recognition of the object takes place.

1.1.2 Industrial sensors

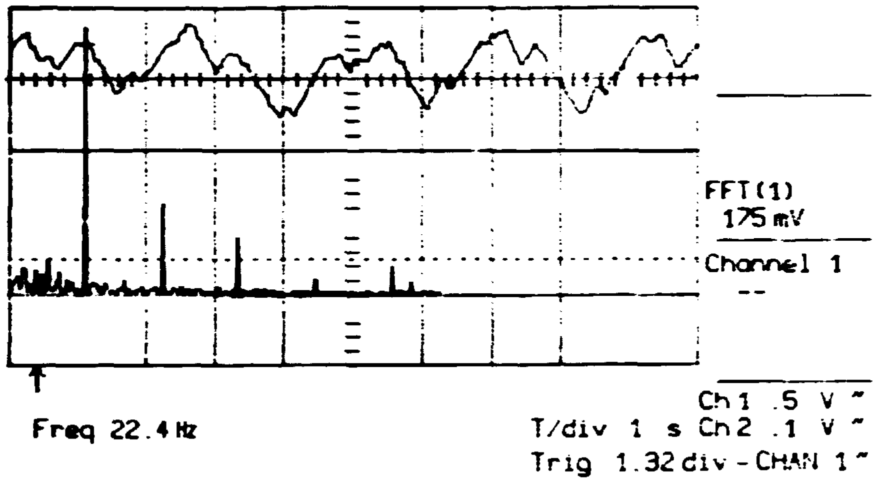
(S. Hanson, L. Lading, and B.H. Hansen)

The Applied Laser Physics Section has been working together with two Danish industrial companies on the development of a series of optical sensors. The three-year programme has now been terminated and various sensor systems are presently either commercially available or in the stage of a prototype development. The economic basis for the introduction of optical methods in industry has been opened by the advent of low-cost optical elements, such as laser diodes, holographic optical elements, and charge coupled diode arrays. Optical sensors were previously considered economically unacceptable for use outside laboratories, but due to the widespread application of laser diodes in connection with optical fibres and CD players, the price has dropped dramatically.

Four sensor systems have been identified which would benefit from the non-contact capability of most optically based systems.

Velocimeters based on the laser Doppler concept and time-of-flight concepts have been dealt with, and a commercially available system has been presented. The system is primarily suited for velocity measurements in connection with paper production and facilitates unprecedented accuracy in velocity and length determination at a production line.

A system for determination of angular speed and fluctuations in angular speed of a rotating shaft has furthermore emerged from the common project. The method is based on optical mixing of backscattered light from two illuminated spots on the shaft. The detected difference in Doppler shift from the two spots will be proportional to the instantaneous rotational speed of the shaft. The conversion factor between detected fr-quency and angular speed is independent of the radius of the shaft and independent of any translational movement. The power spectrum of the fluctuations in the measured rotational speed brings about a means of analysing harmonical oscillations in the driving engine or torsional vibrations in the shaft itself. Figure 1 shows a plot of the power spectrum of the oscillations labelled according to the number of harmonics with respect to the period of one full rotation of the shaft. Measurements on rotating engines could provide a powerful tool for condition monitoring.



Harmonic decomposit.on of the oscillations of the rotational speed of a wind turbine. The fundamental frequency corresponds to the rotational speed 2~5 rpm.

Other types of sensors have also been investigated. However, it has not yet been decided whether commercial exploitation will be pursued.

A continuation of the joint projec' is considered.

1.1.3 Neural networks

(C. Liisberg)

Scientific basis

During the last several years artificial neural networks (NNs), a parallel-type computing system architecture with many independent and densely interconnected processing units, have received widespread attention. Within the last two or three years NNs have been applied to a wide spectrum of practical problems, investigations in applied research, and purely theoretical analyses.

A currently often used NN structure consists of a layer of input units, one layer (or more) of hidden units which have no direct input from outside of the net, and a layer of output units. A vector of input signals is sent into the net, and a vector of output signals is obtained from the net. The outgoing line of an input unit is connected to all hidden units and, similarly, the output line of a hidden unit is connected to all output units. To every unit$_j$ $\rightarrow$ unit$_i$ connection a variable weight factor w_{ij} is assigned which enforces or diminishes the signal. The strength of the weight w_{ij} is determined by a learning algorithm, enabling the NN to learn and reproduce particular output vectors for chosen input vectors. An NN is capable of performing highly nonlinear mappings between input and output vector space. Actually, any continuous mapping can be approximated.

It is important to realise that an NN is not a biological organism capable of "thinking type" activities. Instead, once an input pattern is submitted, the NN reacts in a highly complex but well defined (and optimal) way according to the learned (and frozen-in) weights. Consequently the output of an NN is the result of the appropriately defined ("learned") weights and of an optimisation process.

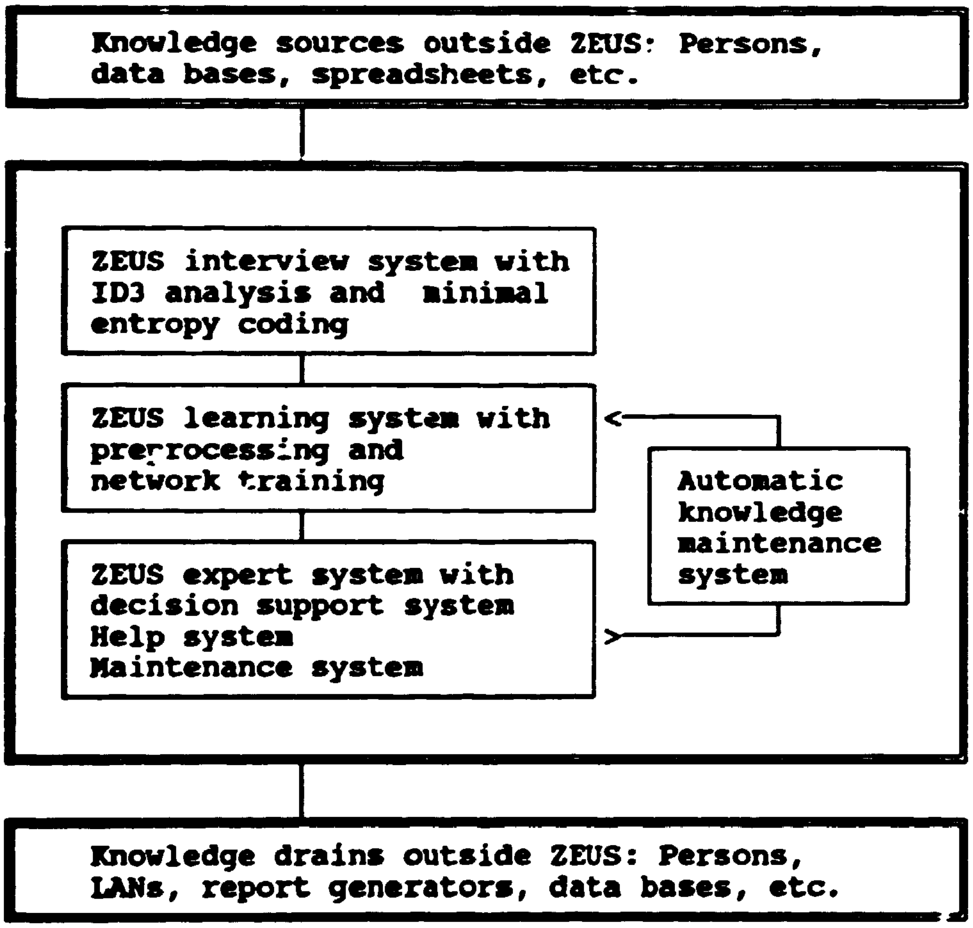
Once the learning phase has been completed, the NN acts like a system with seemingly human qualities, with reasonable guessing and generalisation capabilities. But under the same input conditions the NN always sends the same output; this does not necessarily apply to human beings.

Activities

ZEUS

The neural network expert system shell ZEUS version 1.0 was finished during the fall of 1990 and was turned into the industrialisation phase under the auspices of the Danish firm Rambøll & Hannemann Informatik.

ZEUS is more than just a neural network, as can be seen from the following figure.



ZEUS system overview

In connection with transfer of the ZEUS system a thesis of tractability was formulated. The thesis states, in the notation of vector space to vector space mappings, the maximal complexity of normal human expertise.

1.1.4 The photorefractive effect and possible observation of the influence of external applied magnetic fields

(P.M. Johansen and A.S. Jensen)

The photorefractive effect is a phenomenon in which the local index of refraction is changed by the spatial variation of the light intensity[1]. The generation of space-charge is dependent on the intensity modulation only, whereas the time constant for the photorefractive processes (i.e. the characteristic time scale for build-up of the refractive index) is dependent on the overall intensity (DC intensity)[2].

The most fundamental property of photorefractive materials is, perhaps, their capability of coupling energy between two coherent electromagnetic waves inside the medium. This process is crucially dependent on the spatial nonlocality of the photorefractive effect which manifests itself as a phase shift between the intensity distribution and the refractive index. The maximum energy coupling is obtained when the phase shift is $\pi/2$. Moreover, the actual strength of the refractive index (modulus) determines how efficiently the energy is redistributed between the two incident beams.

Photorefractive materials can roughly be divided into two catagories based on the magnitude of the electro-optic constant.

The first group with large electro-optic coefficients, $r_{eff} \simeq 100$ pm/V, includes materials such as $BaTiO_3$, $KNbO_3$, and SBN. In these materials the gain coefficient may easily exceed 5 cm^{-1} and hence exceed typical attenuation coefficients. Such materials are therefore very suitable for optical gain media. One of the major drawbacks is, however, the relatively slow effective time constant.

The second group of materials which includes materials such as BSO, BGO, and GaAs has a relatively small electro-optic constant, $r_{eff} \simeq 1$ pm/V. These materials are advantageous in optical data processing experiments since they exhibit a fast response (msec) and a large photorefractive sensitivity. The gain in such materials can, however, be enhanced by adding a small frequency shift to one of the optical beams in a two wave mixing configuration[3),4),5)]. In such cases the intensity grating is moving at a definite speed determined by the difference frequency between the optical beams and the corresponding wave vector of the optical interference pattern.

When such a frequency shift is introduced, the corresponding charge density distribution in the conduction band is moving. A moving charge distribution will produce an intrinsic magnetic field (proportional to the velocity) and can therefore interact with an external applied magnetic field. It turns out that applied magnetic fields can be included in the band transport model usually applied to describing the effects found in photorefractive materials. The effect of including an external magnetic field can be shown to be crucially dependent on the free carrier mobility of the actual photorefractive material in question. This indicates that photorefractive semiconductors will be potential candidates for observing the effect experimentally.

In cases where no external electric field is applied the magnetic field has no influence what so ever. Moreover, the external applied magnetic field will influence the space-charge field in cases where it is applied perpendicularly to the grating wave vector, and where the applied electric field and the grating wave vector are non-parallel at the same time. In such cases an external applied magnetic field will influence both magnitude and phase of the refractive index. Even in static cases of no frequency detuning the magnetic field will still influence the magnitude and the phase of the refractive index.

In 1991 the above effects will be further investigated and, hopefully, the effects will be demonstrated experimentally.

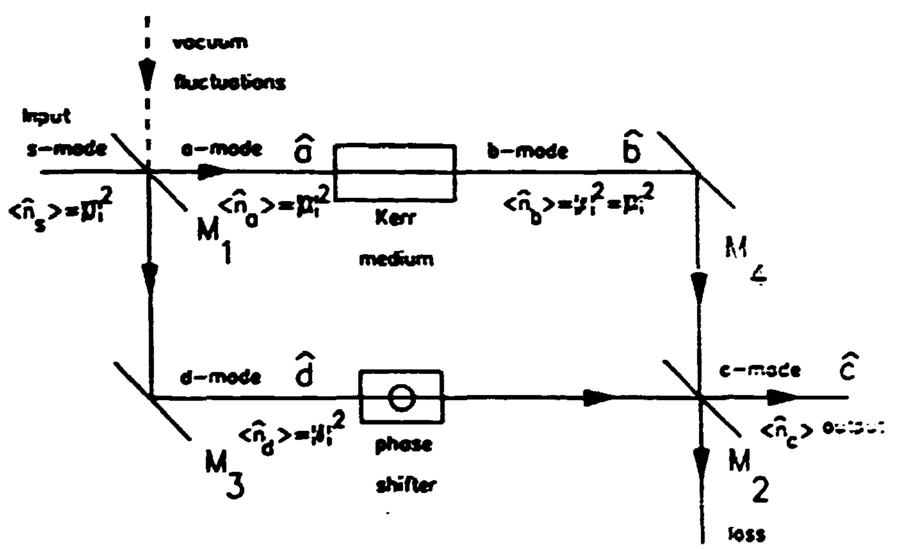
1) Vinetskii, V.L. and Kukhtarev, N.V. (1975). Sov. Phys. Solid State 16, 2414-2415.
2) Kukhtarev, N.V. (1976). Sov. Tech. Phys. Lett. 42, 438-440.
3) Johansen, P.M. (1989). IEEE J. Quant. Electron. 425, 530-539.
4) Johansen, P.M. (1989) J. Phys. D: Appl. Phys. 422, 247-253.
5) Yeh, P. (1989). IEEE J. Quant. Electron. 425, 484-519.

1.1.5 A nonlinear Mach-Zehnder interferometer for generation of sub-Poisson light

(P.S. Ramanujam)

All electromagnetic fields have stochastic fluctuations associated with their amplitudes and phases. Usually, most of these fluctuations are due to environmental influences. However, even after removal of all these perturbations there is a lower limit to the noise in an optical system set by the uncertainty principle. The photon flux from a laser, e.g., obeys a Poisson distribution, i.e. the variance of the flux $<(\delta n)^2> = <n>$, where $<n>$ is the mean number of photons in the given mode. But there are areas where light with a so-called sub-Poisson noise distribution characterised by $<(\delta n)^2> < <n>$ might be required, such as in investigation of biological molecules which cannot survive the large light intensities otherwise necessary to produce a satisfactory signal-to-noise ratio.

A modification of a nonlinear Mach-Zehnder interferometer has been outlined[1] which has been proposed by Kitagawa and Yamamoto[2] to produce a sub-Poissonian output. The interferometer is shown in Fig. 1. A material with a third-order nonlinear optical susceptibility is placed in one arm of the interferometer and a phase shifter in the other. Mirrors M_1 and M_2 are partially transmitting mirrors with



amplitude transmittances τ_1 and τ_2, respectively. The other two mirrors are totally reflecting. The system is otherwise assumed loss-free. By treating the interaction at mirror M_2 as a quantum mechanical process in the Heisbenberg picture, the two independent variables τ_1 and τ_2 are optimised for a given input photon number and nonlinearity of the medium, to achieve minimum variance in the output photon flux. It is shown that it is possible to improve the efficiency of the interferometer to almost 100%.

Funds have recently been received from the Danish Natural Science Research

Council for the construction of such an interferometer. The light source would be an intensity stabilised Ti:Sapphire laser. The Kerr medium would be a polarisation maintaining optical fibre of about 100 m length, single moded at 850 nm. Glass fibres have a typical nonlinear refractive index of about $6 \cdot 10^{-23}$ m^2/v^2, a linear refractive index of about 1.46, interaction cross-section $60 \cdot 10^{-12}$ m^2, and a relaxation time of about 1 ns. Commercially available mirrors have a maximum reflectivity of about 99.6%, and anti-reflection coated mirrors can have a reflectivity of less than 1%. By inserting these parameters in our calculations, $\frac{\delta n}{\sqrt{n}} \approx 0.006$ is obtained. This is much less than that for a coherent state produced by a laser source for which the above factor is 1. The interferometer may be considered as a black box whose input is a coherent laser beam whereas the output from the box has sub-Poisson fluctuations.

1) Grønbech-Jensen, N. and Ramanujam, P.S. (1990). Phys.Rev. A **41**, 2906.
2) Kitagawa, M. and Yamamoto, Y. Phys. Rev. A **34**, 3974.

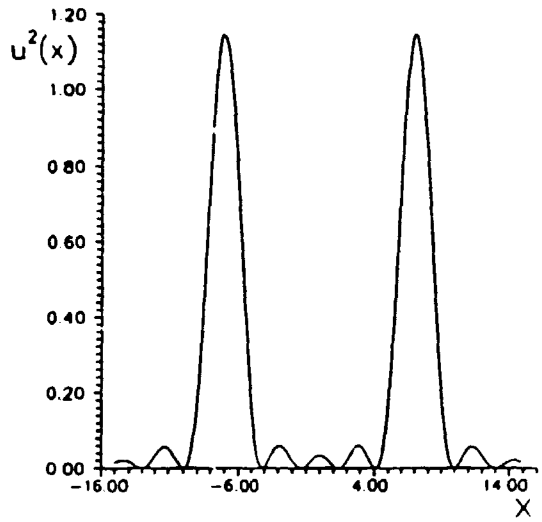
1.1.6 Information measures for comparing and synthesising light scattering systems

(T. Martini Jørgensen and L. Lading)

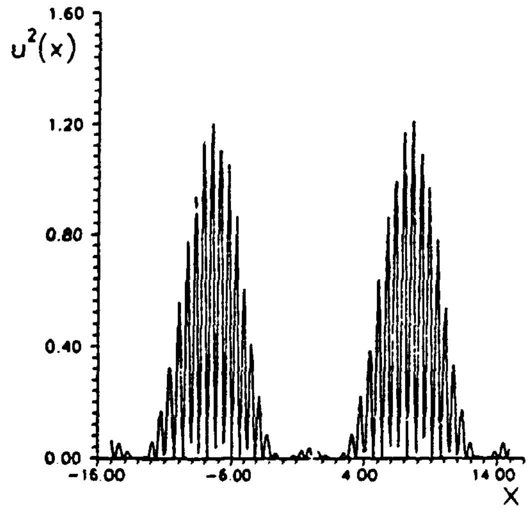
Measuring configurations are often designed in a heuristic way on the basis of knowledge of some general physical relationships. A subsequent analysis then proves the relation between certain parameters of the signal(s) and the quantities to be determined. After design of the measuring system it has to be compared with alternative configurations for measuring the same parameters but such a comparison is frequently hampered by the lack of a relevant figure of merit. Signal-to-noise ratios are often used, but their definitions may often vary for different configurations, and they also depend on system parameters in such a way that in many cases the signal-to-noise ratio is unsuited for optimisation.

To obtain a more rigorous procedure when comparing and optimising measuring configurations possible figures of merit have been investigated. Especially a quantum-limited light scattering system for measuring the velocity of a small particle[1] has been considered. The so-called Fisher number has in many cases proved to be a desirable figure of merit since it describes the information obtained by the measurement, and it is furthermore fairly easy to calculate. The reciprocal value of the Fisher number is a lower limit of the variance of any unbiased estimator - the so-called Cramer-Rao bound. If this limit can be obtained, the estimator will be a maximum likelihood estimator. But even though the limit cannot be achieved, the Fisher number is still a relevant figure of merit.

To synthesise the configuration mentioned above for measuring the velocity of a small particle a computation has been made of the optical system which optimises the Fisher number under some appropriate physical constraints (such as the size of the measuring volume). Our results show that if only one aperture enters into the optical system, then the optimum configuration is the so-called time-of-flight configuration[1]. If the configuration is instead based on two apertures, the optimum configuration will be a mixture of the time-of-flight configuration and the so-called Doppler configuration[2]. If the two apertures are so small that they allow only one spatial mode each, the optimum configuration becomes the Doppler configuration. The results are shown in the figures.



The optimum intensity distribution in the measuring volume if the transmitter aperture is defined by a single area through which several spatial modes can be transmitted



The optimum intensity distribution in the measuring volume if the transmitter aperture is defined by two areas through which several spatial modes can be transmitted

1) Lading, L. and Jørgensen, T. Martini (1990). J. Opt. Sc Am. A 7, 1324-1331.
2) Lading, L. and Jørgensen, T. Martini (1990). In: "Proceedings of the Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurements, Lisbon, Portugal.

1.1.7 Signal processing

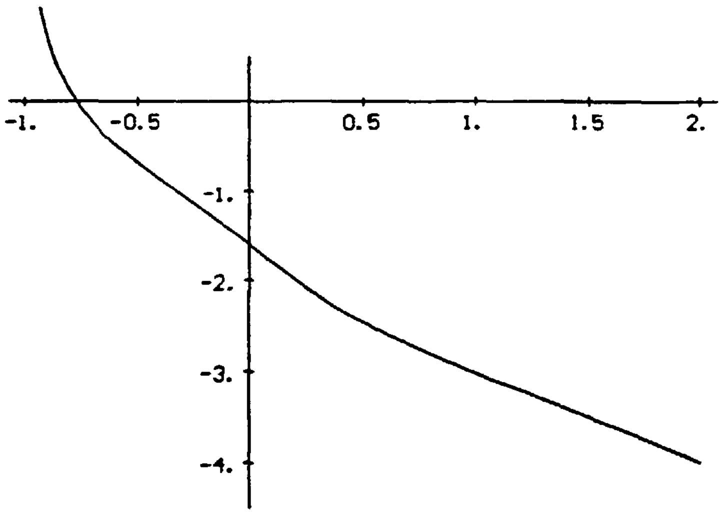
(L. Lading, T.Martini Jørgensen, A. Skov Jensen, and K. Andersen (Dantec A/S, Denmark))

The department has worked with signal processing in connection with the work on optical diagnostic methods. Most of the work has been concentrated on areas relevant to laser anemometry. Several of the results are being exploited in commercial products.

In a laser Doppler anemometer the centre frequency of the detector signal is essentially only given by the particle velocity and the characteristics of the measuring configuration. It is independent of particle size and shape. However, it has been demonstrated that the phase of the detected signal depends on both particle size and the direction of detection. This fact can be applied for the measurement of particle size[1,2].

A new scheme has been devised for estimating frequency and phase at extremely high data rates based on evaluations of the covariance function at a few time lags[3]. An analysis of the performance of such a configuration has been performed and compared with the performance of Maximum Likelihood Estimators (MLE). The basic model for the signals is based on an inhomogeneous Poisson process (or a modulated Poisson photon rate). Both the case of a dominating background and the case where the intrinsic signal noise is dominating have been considered.

The basic result is that three operational regimes can be identified (see the figure).



The logarithm of the variance of the estimated phase difference normalized by $\pi/2$ versus the signal-to-noise ratio ($\times$ 10 in dB).

In the first region the estimates exhibit very little correlation with the true values: the measurements are essentially useless. In the second region the primary uncertainty is caused by terms originating as products of noise signals: the performance is inferior to an MLE. In the third region the uncertainty is primarily caused by terms originating as products of the signal with noise. In this region a matched filtering is obtained. The performance approaches the Cramer-Rao (C-R) lower bound (i.e. optimum performance for an unbiased estimator) for <u>phase</u> estimation. For frequency estimation the performance is still inferior to the C-R bound - depending on the dynamic frequency range[3].

1) Saffman, M. and Buchhave, P. In: "Proceedings of the Second International Symposium on Applications of Laser Anemometry to Fluid Mechanics", Lisbon, Portugal 1984.

2) Bachalo, W.D. and Houser, M.J. NASA Contract Report 174636, 1984.

3) Lading, L. and Andersen, K. In: Laser Anemometry: Advances and Applications, ed. J. Turner, Springer/STI 1990).

1.1.8 European laser anemometry network

(L. Lading and B. Skaarup jointly with acb-CERG, Grenoble, France; EOLAS, Dublin, Ireland; Trinity College, Dublin, Ireland; and BHR Group Limited, Bedford, U.K.)

Laser anemometry allows for non-intrusive measurements of velocities of fluids and solid surfaces. The measurements are often impossible by other methods. This attribute has resulted in a widespread use of the technique for research purposes. However, so far industrial applications are very limited. Consequently, a project has been started under the EC SPRINT programme with the purpose of enhancing the interaction between research and industry.

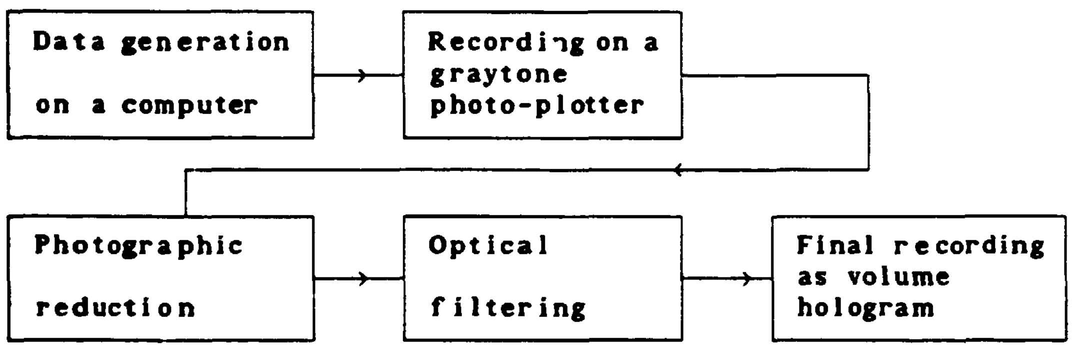
Up to now key researchers and users have been identified and statistics on resources and applications established.

1.1.9 Computer-generated holograms

(E. Rasmussen and A. Skov Jensen)

Computer-generated holograms (CGHs) is a method for producing non-existent holographic objects. Holograms may be considered as spatial filters. If the function of the filter is known, the synthesis of the spatial filter is very simple; a calculation of data and recording as compared with electronics where a filter synthesis can be more elaborated.

Computer-generated holograms may be produced in various ways. The present method is shown in the diagram below. In the NAOPIA project and for research purpose new CGHs have been developed in 1990. Some of the CGHs are shown below. The present method for creating CGHs is very robust and produces high



quality results, but only with very small bandwidth products.

The work on CGHs has mostly been carried out in connection with the NAOPIA project, but other applications have also been considered. The work done on CGHs is both theoretical and practial. A second generation CGH recording device is under development which simplifies the recording process and gives a much higher spatial bandwidth product. The theoretical work is concentrated on new optical filter functions, construction of advanced optical transmitter/receiver configuration with multiple lens functions on the same CGH. A practical realisation of this is highly dependent on the available recording devices.

1.1.10 Electronic speckle interferometry (ESPI)

(S.G. Hanson and B.H. Hansen)

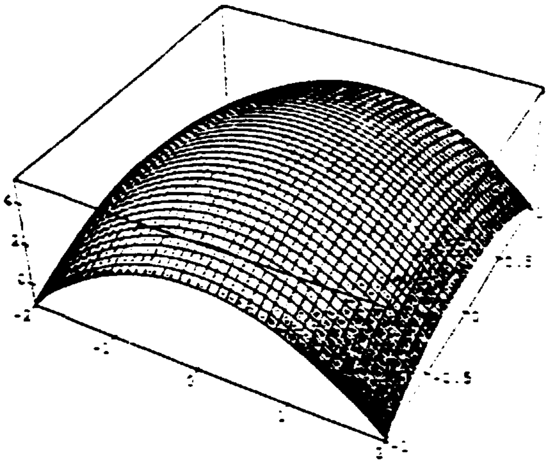
Holographic interferometry provides a very precise method for determination of strain in rigid structures. Unfortunately, the method calls for photographic processing which makes the technique unsuitable for many industrial applications where low-cost and real time processing would prove essential.

To overcome these deficiencies a non-photographic method based on electronic cameras (CCDs or Vidicons) has been developed. The method has opened up for a broader area of applications ranging from scientific use in a laboratory environment to quality inspection in industry. The method is based on recording of the speckled image from a diffuse object illuminated by a laser beam. In the image an object deformation is seen as a cyclic phase change. If the recorded light is backscattered from the object, a translation half a wavelength of the object along the line of sight will cause every bright spot (speckle) to turn black and resume its original intensity. If two recordings are made by the video camera, a subtraction of the two electronically stored pictures will carry information on the imposed strain.

There are basic limitations to the displacement which can be tolerated between exposures before the two images of the speckle fields become uncorrelated which will inevitably destroy the measurement. A general analysis of speckle statistics has been performed[1)] based on a previously developed technique where complex matrices describe optical elements and where analysis of optical beam wave propagation merely consists of matrix multiplication[2)]. A short preliminary note on the use of a PC program for doing computer algebra (Mathematica) to analyse specific optical systems with respect to speckle decorrelation has been prepared[3)].

Unfortunately, in its original version electronic speckle correlation suffers from some shortcomings of which the most important ones are the requirement of interferometrically stable conditions and the sensitivity to optical turbulence in the light path. Furthermore, for many applications the detection sensitivity is too high and inherently fixed by the wavelength. To pave the road for everyday industrial use, these deficiencies have to be overcome. Supported by The Danish Technical Research Council (grant 16-4747.E.) an investigation to identify alternative methods has been established.

An electronic speckle interferometer has been developed which will to some extent overcome some of the deficiencies mentioned above. Instead of measuring the translation in the line of sight which requires interfering one beam from the object with an internal beam, a robust differential system has been constructed which interferes the object beam with a shifted replica of itself. This provides for a controllable resolution, a higher resistance against optical turbulence and, primarily, for a decrease in the demands for mechanical stability. This method called differential electronic speckle interferometry probes the tilt undergone by the object between the two recordings. The probed axis of tilt is determined by the optical set-up, but in the performed experiments it was perpendicular to the line of sight. The figure shows a recording made by subtracting two images taken before and after the indicated deformation of a steel plate. An analysis of the inherent limitations in the two versions of electronic speckle interferometers has been published[4)] together with a description of anisotropy determination in laminated carbon fibre plates.



1) Yura, H.T. and Hanson, S.G. (1990). In: "Proceedings of the 15th Congress of the International Commission for Optics, Optics in Complex Systems", edited by F. Lanzl, H.-J. Preuss and G. Weigelt, Garmisch-Partenkirchen, 5-10 August, p. 67.
2) Yura, H.T. and Hanson, S.G. (1989). Risø Report M-2844.
3) Hanson, S.G., Yura, H.T. and Grum, T. (1990). Risø-I-report 515, pp. 11.
4) Hanson, S.G., Hansen, B.H. and Damgaard, P. (1990). 9th International Conference on Experimental Mechanics, 20-24 August 1990, Lyngby, Denmark.

1.1.11 Dynamic measurements of optical turbulence

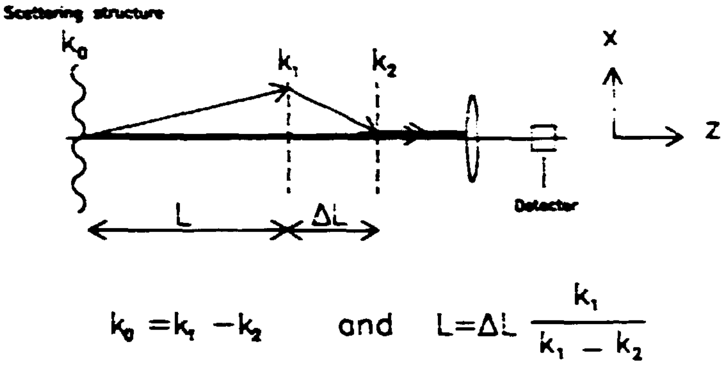
(S. Hanson)

A new measurement scheme has been worked out in collaboration with the Wave Propagation Laboratory, Boulder, USA (J. Churnside, J. Wilson, and S. Clifford).

A system for determination of transversal velocity profiles has previously been proposed by Lee[1] and has later been implemented by J. Churnside et al.[2]. The scheme was based on sending a beam of incoherent light through a grating structure to create the desired spatial coherence properties of the light before it traverses the path in which a spatially resolved determination of transversal velocities is sought. The detector system consisted of another grating structure followed by a lens system which collected the transmitted light. The two gratings determined the turbulent structure probed and its position between the transmitter and the detector. The frequency spectrum of the detector current carried information on the transversal velocities of the convected eddies across the measuring path.

The system was dependent on a cooperative transmitter system emitting light with known and well defined spatially coherent properties. If measurements of the strength of the optical turbulence and horizontal velocity up through the atmosphere are going to be performed, the lack of the desired source is evident. Accordingly, an effort has been made to finding ways to circumvent this restriction and to design a measurement scheme which can work with a natural source of electromagnetic radiation, that being either a planet, the sun, or a star.

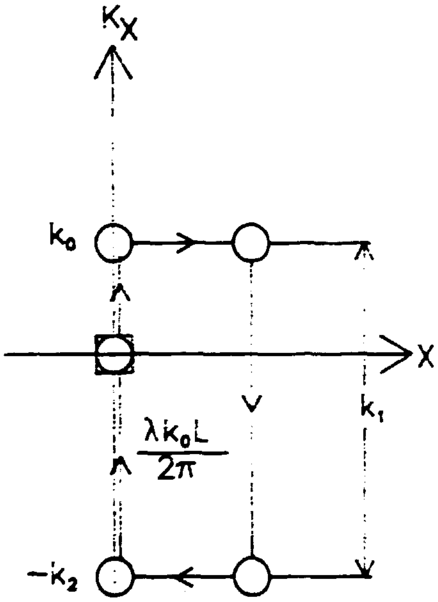
The basic principle is based on mixing light diffracted by the optical turbulence with light traversing the optical turbulence without suffering any phase change[3]. As shown in Fig. 1, the optical turbulence is modelled as a weak phase screen which diffracts the impinging light in three components. A small amount of light is diffracted in the first order and in the minus first order and the major part of the incoming light passes the screen unperturbed. The probed phase screen of wave



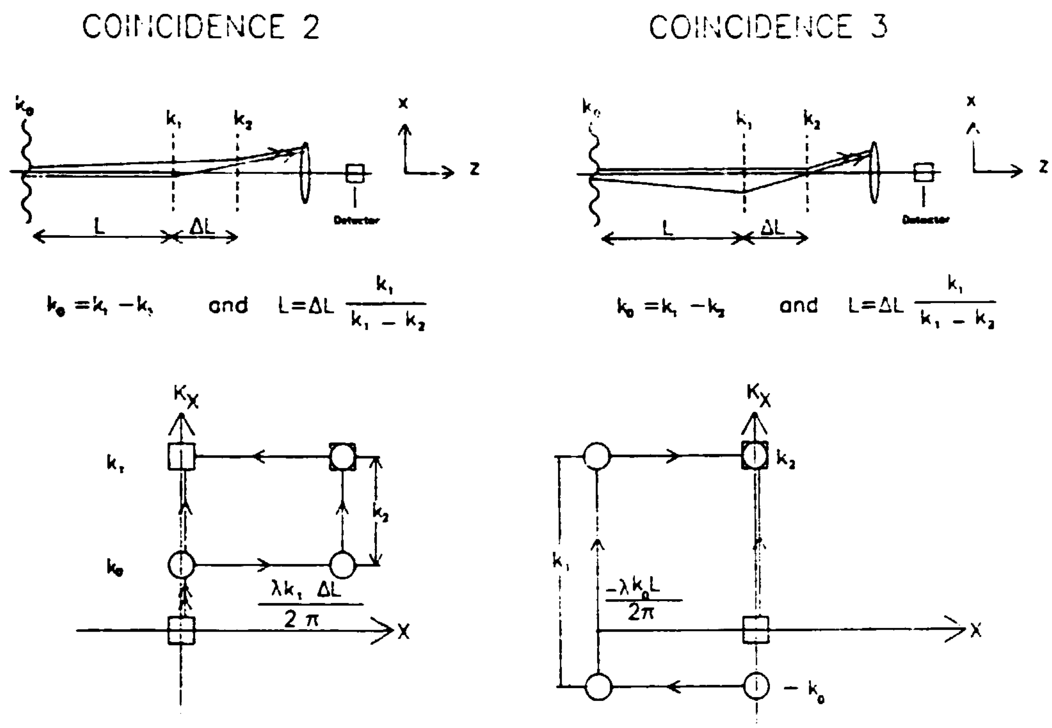
vector K_0 is situated at a distance L from the detector system consisting of two gratings of wave vectors K_1 and K_2 placed a distance ΔL apart. Complete overlap in space and k-space between the first order diffraction and the unperturbed beam can be accomplished in several ways. Fig. 1 shows one "closure" given by bending back the perturbed beam twice by the two detector gratings. It is easy to show that this closure demands the following to be fulfilled:

$$K_o = K_1 - K_2 \text{ and } L = \Delta L \frac{K_1}{K_1 - K_2} .$$

Figure 2 shows the path drawn in phase space by the perturbed beam before it



is recombined with the unperturbed beam which has suffered shift neither in real space nor in k-space. In Fig. 3 two more closures are depicted each of which is satisfied for identical conditions as the first closure. It is noticed that the probed wave vector, K_0, and the distance ΔL is independent of the wavelength of the



source as well as the incoming ray angle of the source. The spectrum of the detector current will thus carry information on the velocity as well as on the strength of the optical turbulence.

1) Lee, R.W. (1974). J. Opt. Soc. Am. 64, 1295.
2) Churnside, J.H., Lataitis, R.J., and Lawrence, R.S. (1988). Appl. Opt. 27, 2199.
3) Churnside, J.H., Hanson, S.G., and Clifford, S.F. (1990). 1990 Technical Digest Series Volume 4, 12-15 February, Nevada, U.S.A.

1.1.12 HERA

(C. Liisberg)

A system of hierarchically organised neural networks (HERA) has been developed especially for fuzzy pattern recognition of black/white images, i.e. images where the single pixels are turned either on or off (no grey tones or colours). The neural networks of the system consist of three layers: (1) an input layer which represents the pixels of the image, (2) a hidden layer which tests for characteristic features of the image, and (3) an output layer which on the basis of the discovered characteristic features classifies the image. The networks are thinly connected between the input layer and the hidden layer where only 3-5% of the possible connections have been established, whereas the networks are fully connected between the hidden layer and the output layer. The hidden neurons do not function by a vector-dot-product which is the normal procedure but use more specific table lookups when testing for characteristic features, and the output layer functions as summation units. The networks are characterised as "hybrid" due to the fact that built into the hidden neurons a kind of rule-based interpretation takes place.

The networks mentioned above are highly flexible as regards adjustment of generalisation capability/specificity and margins of mistakes, and supervised as well as unsupervised training is not time-consuming.

By appropriate adjustment of the generalisation capacity and the internal functionality of the networks the single network can, e.g., classify 50% of the test set correctly whereas 50% is classified as intelligible. By combinations of many networks in ensembles or hierarchies higher recognition rates are obtained, still without (fatal) mistakes.

The system has been preliminarily tested on recognition of handwritten digits with very promising results.

A new entropy-based quality measure called cognitropy has been developed. The cognitropy measure is used for optimisation of the HERA architectures.

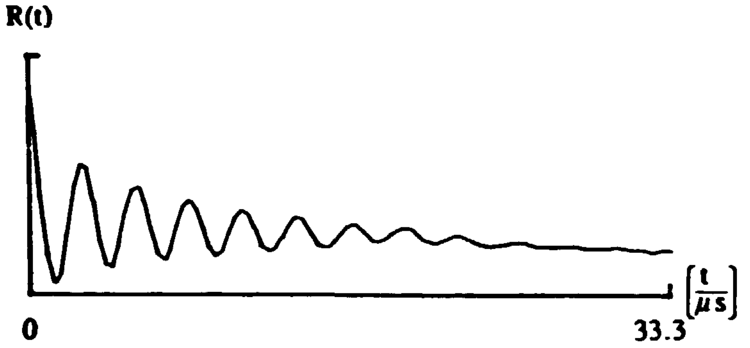
1.1.13 Thermally Excited Surface Waves

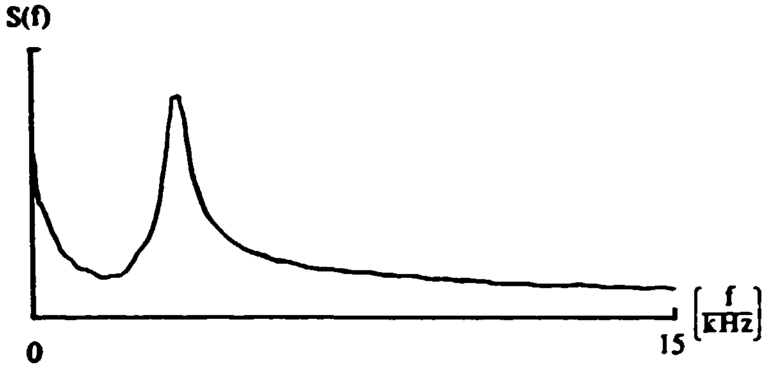
(T. Martini Jørgensen and L. Lading)

A liquid surface is continually disturbed by thermal agitation at the molecular level. The capillary waves on the surface are small decaying waves with amplitudes typically around 10 Å. These disturbances can be described in terms of waves of wavelength so short that their evolution is determined by capillary forces. The frequencies and damping constants of the surface waves are governed by the viscous forces and surface tensions characteristic of the liquids under consideration. The spectrum of light scattered by a liquid interface will therefore reflect the viscoelastic parameters of the system. Therefore, by calculating the spectrum or autocorrelation of the photocurrent obtained by either homodyne or heterodyne spectroscopy the viscoelastic properties can be inferred. Classical techniques for measuring the viscoelastic properties may be more precise but, unfortunately, they perturb the thermodynamic equilibrium. Often these techniques are also slow, inhibiting investigation of dynamic properties.

To obtain a simple relation between the statistics of the surface and the temporal statistics of the scattered electric field it is necessary only to measure the light scattered by a particular wave vector of the surface. Selecting one wave vector from the surface is equivalent to selecting a single scattering angle, since in the far field each wave vector on the surface (which can be considered as a time dependent phase grating) corresponds to a single angle. To detect the phase information on the scattered light the light has to be compared with an unmodulated electric field from the same source. This is done by letting the two fields interfere on the surface of a photodetector - a heterodyne set-up. In many studies based on optical heterodyne spectroscopy the reference field has been generated by scattering from dust particles in the experimental set-up or from rough optical elements. However, a much better way to generate the reference beam is by the use of a grating[1,2]. By using a grating the desired wave vector is selected and at the same time the reference beam is generated. Such a configuration is insensitive to drift in the frequency of the laser source. The influence of finite beam sizes leads to instrumental broadening of the measured spectrum, but by proper computation it is possible to calculate the desired centre frequency and width parameters of the intermediate spectrum[2].

Normally, the measurements are based on the backward diffracted light from the fluid-liquid or liquid-liquid interface[1,2,3]. In the case of transparent liquids this implies a very low signal level and it is consequently necessary to use a photomultiplier tube in the experiment. A set-up based on the forward diffracted light has recently been constructed, and as a consequence only a photodiode was needed in the detection process. With the same set-up it has been possible to use a small semiconductor laser. Below the autocorrelation R(t) and the spectrum S(f) measured for hexane by the use of the semiconductor laser are shown. From the





measured autocorrelation function it can be seen that the shot noise caused by the stochastic nature of light plays no role in the present set-up contrary to the experiments based on the backward diffracted light.

Recently, the possibility of separating scattering caused by the surface waves from that caused by density variations has been investigated. As a result a method[3] has been proposed which in the near future is going to be investigated experimentally.

1) Hård, S. and Neumann, R.D. (1981). J. Colloid Interface Sci. 83, 315-334.

2) Edwards, R.V., Sirohi, R.S., Mann, J.A., Shih, L.B. and Lading, L. (1982). Appl. Opt. 21, 3555-3568.

3) Lading, L., Mann, J.A. and Edwards, R.V. (1989). J. Opt. Soc. Am. A 6, 1692-1701.

1.2 Participants in the work in Applied Laser Physics

Scientific Staff

Hanson, Steen Grüner
Jensen, Arne Skov
Johansen, Per Michael
Lading, Lars
Liisberg, Christian
Ramanujam, P.S. (from 1 June)
Schmidt, Gisela Hanssen (until 22 March)

Ph.D. Students

Damgaard, Preben (working at "Danish Micro Engineering")
Jørgensen, Thomas Martini
Lindvold, Lars (working at "DANTEC Electronics")

Technical Staff

Behrendt, Ricky (from 1 August)
Eilertsen, Erik (from 29 January)
Hansen, Bengt Hurup
Jensen, Rune Holmstykke (until 30 September)
Nielsen, Morten Bøgeholm (until 25 June)
Rasmussen, Erling
Weimar, Bjørn (from 1 October)

Secretaries

Astradsson, Lone
Kjøller, Kæth
Skaarup, Bitten
Toubro, Lene

Guest Scientists

Thuo, Z., Wuxi Institute of Light Industri, P.R. of China

Short time visitors (more than one week)

Kovacs, L.M., Wave Propagation Laboratory, Boulder, U.S.A.

Students working for the batchelor/master degree

Grum, Thomas (1 February - 1 June)
Knudsen, Ulrich (1 February - 1 July)
Petersen, Claus (from 1 September)

2 Publications and educational activities in the Applied Laser Physics Section

2.1 Publications

HANSON, S.G., CHURNSIDE, J.H. and CLIFFORD, S.F. (1990). Optical remote sensing of wind and turbulence using double spatial filtering of scintillations. In: Optical Remote Sensing of the Atmosphere, (Optical Society of America, Washington, DC, 1990) (1990 Technical Digest Series Vol. 4, WD2) pp. 470-473.

HANSON, S.G., HANSEN, B.H. and DAMGAARD, P. (1990). Differential electronic speckle interferometry: Application and limitations in non-destructive testing. In: Proceedings of the 9th International Conference on Experimental Mechanics, Department of Structural Engineering, Technical University of Denmark Lyngby, Denmark, 20-24 August 1990, vol. 5, pp. 1949-1958.

HANSON, S.G. (1990). Optiske sensorer måler uden at røre (Optical sensors measure without touching). Automatik Vol. 15 (No. 5), 30 May 1990.

HANSON, S.G., YURA, H.T. and GRUM, T. (1990). Application of "Mathematica" for algebraic solutions to problems in coherent optics. Risø-I-Report 515.

JENSEN, A. SKOV and RASMUSSEN, E. (1990). Technical report on the performance of a hybrid optical vision system. Risø-M-Report 2895.

JENSEN, A. SKOV (1990). New architectures for optical processing in industrial applications (NAOPIA). Risø-M-Report 2911.

JENSEN, A. SKOV (1990). Error analysis of integer fast Fourier transforms used for 1D signal correlation. Risø-M-Report 2860.

JOHANSEN, P.M. (1989). Frequency analysis of the photorefractive band transport model and its applications in multifrequency wave mixing. In: Optical Information Processing Systems and Architectures (edited by B. Javidi) (International Society for Optical Engineering, Bellingham WA, 1990) (SPIE vol. 1151), pp. 534-543.

LADING, L. (1990). Besøg i Moskva (Visit in Moscow). DOPS-NYT No. 2, 1990, pp. 4-5.

LADING, L. (1990). ICO-15. DOPS-NYT No. 4, 1990, pp. 3-4.

LADING, L. and JØRGENSEN, T. Martini (1990). Maximizing the information transfer in a quantum-limited light-scattering system. J. Opt. Soc. Am. A 7, 1324-1331.

LADING, L. and ANDERSEN, K. (1990). Estimating frequency and phase for velocity and size measurements. In: Laser Anemometry (edited by J.T. Turner, STI/Springer, Oxford 1990).

LADING, L. and JØRGENSEN, T. Martini (1990). Figures of merit and synthesis of optimum laser anemometer configurations. In: Proceedings of the Fifth International Symposium on Appl. of Laser Techniques to Fluid Mechanics, Lisbon 1990 (Universidade Tecnica de Lisboa), paper 29.4.

LIISBERG, C. (1990). Article about Zeus. Aktuel Elektronik No. 34, 5 November 1990.

LIISBERG, C. (1990). Rapid development of high quality, discount-priced expert systems. In: "Workshop on Expert Systems in Agricultural Research", the Ministry of Agriculture, Ebeltoft, Denmark, 4-5 December 1990 (Fællesberetning nr. SF1, 1990), p. 87-93.

LIISBERG, C. (1990). Expert systems at discount price. Risø Nyt No. 3, 1990.

YURA, H.T. and HANSON, S.G. (1990). Speckle statistics for propagation

through complex ABCD systems. In: "Proceedings for the 15th Congress of the International Commission for Optics. Optics in Complex Systems (edited by F. Lanzl, H.-J. Preuss, G. Weigelt). Garmisch-Partenkirchen, (International Society for Optical Engineering, Bellingham, WA, 1990) (SPIE 1319), p.67.

2.2 Conference contributions

CHURNSIDE, J.H., HANSON, S. and CLIFFORD, S.F., Optical remote sensing of wind and turbulence using double spatial filtering of scintillations. Optical Remote Sensing of the Atmosphere, Incline Village, Nevada, U.S.A. (February).

GEISLER, T., RAMANUJAM, P.S., ROSENKILDE, S. and DAHL-PETERSEN, S., Langmuir-Blodgett films in nonlinear optics. Poster presented at the annual meeting of the Danish Optical Society, Risø, Denmark (November).

HANSON, S.G., HANSEN, B.H. and DAMGAARD, P., Differential electronic speckle interferometry: Applications and limitations in non-destructive testing. The 9th International Conference on Experimental Mechanics, Lyngby, Denmark (August).

HANSON, S.G., YURA, H.T. and GRUM, T., Application of "Mathematica" for algebraic solutions to problems in coherent optics. Poster presented at the annual meeting of the Danish Optical Society, Risø, Denmark (November).

JENSEN, A. SKOV and RASMUSSEN, E. 1. Robot vision. 2. Computer-Generated Hologram. Posters presented at the annual meeting of the Danish Optical Society, Risø, Denmark (November).

JØRGENSEN, T. MARTINI, The Fisher number as a figure of merit. Poster presented at the annual meeting of the Danish Optical Society, by (November).

LADING, L., Optical diagnostic methods applied to fluid mechanics (invited). IVTAN/CLMS Conference on Flow Diagnostics, Moscow, U.S.S.R. (February).

LADING, L., Synthesis of optimum configurations (invited). IVTAN/CLMS Conference on Flow Diagnostics, Moscow, U.S.S.R. (February).

LADING, L., Measuring frequency and phase in LDA (invited). FVA Launch. Didcot, U.K. (December).

LADING, L., Validation and burst detection in laser anemometry. Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics, Lisbon, Portugal (July).

LADING, L. and JØRGENSEN, T. MARTINI, Figures of merit and synthesis of optimum laser anemometer configurations. Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurements, Lisbon, Portugal (July).

LIISBERG, C., Conference contributions at the Conference of Dansk Dataforening about expert systems, Holte, Denmark (April).

LIISBERG, C., Fast development of discount-priced, high quality expert systems. Conference of the Ministry of Agriculture Expert Systems in Agricultural Research, Ebeltoft, Denmark (December).

ROSENKILDE, S., STAHL, J., HOLM, A., WINTHER, L., HENRIKSEN, L., RAMANUJAM, P.S. and GEISLER, T., Organic materials for optical second harmonic generation - crystals and Langmuir-Blotgett films. Poster presented at The Chemical Society annual meeting, Nyborg, Denmark (June).

YURA, H.T. and HANSON, S.G., Speckle statistics for propagation through complex ABCD systems. 15th Congress of the International Commission for Optics, Garmisch-Partenkirchen, F.R.G. (August).

2.3 Lectures

HANSON, S.G., What would 250,000 parallel detectors with a frequency response of 60 Hz do for measurement of optical turbulence? Wave Propagation Laboratory, Boulder, U.S.A. (October).

HANSON, S.G., Laseren - dens fysik og anvendelser (The laser - its physics and applications). University Extension, Roskilde, Denmark (March).

HANSON, S.G., Laseren - dens fysik og anvendelser (The laser - its physics and applications). University Extension, Roskilde, Denmark (October).

JOHANSEN, P.M., Den fotorefraktive effect (The photorefractive effect). The Technical University of Denmark, Lyngby, Denmark (May).

JOHANSEN, P.M., Photorefractive media with a constant applied magnetic field. Seminar on "Progress in Nonlinear Optics", The Technical University of Denmark, Lyngby, Denmark (June).

JOHANSEN, P.M., Photorefractive media with a constant magnetic field. University of Oxford, Physical Electronics Group, Oxford, U.K. (October).

LIISBERG, C., Lectures on neural network and ZEUS. Customs and Tax House, Virum, Denmark (January).

LIISBERG, C., Lectures on neural network and ZEUS. Brüel & Kjær, Nærum, Denmark (February).

LIISBERG, C., Lectures on neural network, legal informatic and ZEUS. The Council for Legal Information, Virum, Denmark (March).

LIISBERG, C., Press coverage of ZEUS in Computer World.

LIISBERG, C., ZEUS exhibition. Kontor og Data, Bellacentret, Copenhagen, Denmark. Lectures.

RAMANUJAM, P.S., Squeezed states of light. Talk given at seminar on Nonlinear Optics, The Technical University of Denmark, Lyngby, Denmark (June).

3 Plasma Physics Section

3.1 Introduction to the work in the Plasma Physics Section

The scientific programme includes the following main topics:

(1) A study related to pellet-plasma interaction with the aim of assessing possibilities of refuelling a fusion reactor by shooting deuterium-tritium pellets into the plasma.

The study is divided into the following subsections.
(a) A detailed study of the interaction between charged particles of various energies and solidified gases. This comprises, e.g. investigations of the luminescence from solid hydrogens irradiated by electrons and of the sputtering of solid hydrogens by light ions.
(b) Pellet handling, acceleration and injection. The main activity is concerned with developing and testing multishot pellet injectors for the European fusion programme. The test stand for multishot injectors has been improved and is used for the development and testing of prototype injectors.
(c) Theoretical pellet ablation studies.

(2) Studies of the fundamental physics of plasmas with relation to fusion research. The main activities are investigations of turbulence, turbulent transport and nonlinear effects in general. The study is based on a combination of theoretical, numerical and experimental work. Among other things the following items are included: turbulence in the edge region of magnetically confined plasmas, coherent structures in turbulence, particle dynamics in turbulent plasmas, anomalous cross-field diffusion due to electrostatic turbulence, nonlinear evolution of modulated waves and scattering of microwaves by density fluctuations in tokamaks. In addition the possibility of calculating equilibria for plasmas in magnetic field by means of magnetic stresses is investigated.

(3) Computational and theoretical studies of the dynamics of coherent vortical structures in two-dimensional fluids.

(4) Participation in the scientific work at JET (Joint European Torus). This work comprises studies of the scrape off layer (SOL) and of diagnosing the ion velocity distribution function by means of μ-wave scattering.

3.1.1 Luminescence from pure and impure solid hydrogens during electron bombardment

(J. Schou (Physics Department, Risø National Laboratory), B. Stenum, H. Sørensen, P. Gürtler (Hasylab, DESY, Hamburg, Germany), and R. Brooks (Department of Physics, Guelph University, Guelph, Canada))

The study of luminescence from particle-irradiated solid deuterium does not only yield information about how the electronic excitations relax in the solid, but also provides important data for the pellet-plasma interaction. A material which emits a strong luminescence is expected to have a larger lifetime in a plasma than one without luminescence, since a considerable fraction of the deposited energy is released from the solid. Unfortunately, it turned out that the luminescence per incident electron from solid deuterium and hydrogen is weaker than luminescence from any other known condensed gas.

The previous set-up has been improved so that the photon detection in the VUV-regime has become more efficient. The two LiF-lenses have been replaced by specially coated VUV-mirrors with relatively high reflectivity around 150 nm. The photon detection has been performed with a McPherson VUV-monochromator equipped with a solarblind photomultiplier. Even though the set-up has been optimised to the regime close to Lyman-α, the detection has been fairly good with a suitable photomultiplier up to about 900 nm.

The studies have mainly been concentrated on the possible detection of Lyman-α in electron-irradiated solid deuterium or deuterium-neon mixtures. It is a paradox that one of the most (if not *the most*) common lines in the universe has never been observed in an environment of solid hydrogen. A previous observation of Lyman-α induced by an intensity which is lower than ours was apparently caused by an impurity rather than by an intrinsic deexcitation in pure deuterium or in deuterium-doped neon. No Lyman-α signal, which is expected to lie relatively close to the gas value at 121.6 nm, was observed. The reason for this somewhat surprising result is that the active excited "Lyman-α"-atom is quenched by the large population of D_3^+-ions and D_3^*-neutrals with low-lying electronically excited states in a deuterium matrix. In solid neon doped with a low amount of deuterium D_3-complexes are not generated. Unfortunately, the possible Lyman-α excitations are quenched by metastable neon-deuteride which emits a strong continuum around 230 nm. Emission of Lyman-α light from deuterium may not be expected in other regular condensed gases since they all have (intrinsic) electronically excited states below the Lyman-α level.

As a minor result this neon-deuteride continuum has been observed for the first time in a solid. This metastable molecule has so far only been observed in gas-phase experiments since the ground state of the molecule is not stable.

3.1.2 Sputtering yields and energy distributions from ion-bombarded condensed gases

(J. Schou (Physics Department, Risø National Laboratory), B. Stenum, H. Sørensen, O. Ellegaard (Odense University, Denmark), and R. Pedrys (Institute of Physics, Jagèllonian University, Krakow, Poland))

The studies of sputtering of the solid hydrogens have been continued with the existing set-up. The collection of data for the sputtering rate of solid deuterium by hydrogen ions from 5 to 10 keV has been considerably extended. The data are important for the lifetime of fast fuel pellets of solid deuterium injected into the fusion devices. The fast hydrogen ions generated by the neutral beam heating are very efficient in eroding the deuterium pellets since, in contrast to the thermal plasma particles, these high-energy ions easily penetrate the protecting gas cloud around the pellet. The sputtering yield for a 10 keV H^+ is about 150 D_2/H. This high yield is primarily caused by the low binding energy, 12 meV, of the deuterium molecules in the solid.

The yield of solid deuterium is increasing with the energy of the primary ion, a proton, a diatomic or triatomic hydrogen ion. The key quantity is the electronic stopping power of the projectiles. The total yield is determined by the sum of the stopping powers of the individual atoms in the projectile. The reason is that the atoms in the molecule are so close to each other during the passage of the first layers in the surface that a molecule may be regarded as one primary particle with a stopping power equal to the sum of the stopping power of the atoms. Then the yield turns out to behave like a power of the total stopping power with an exponent between two and three. Actually, this behaviour is similar to the yield of solid nitrogen, which is the most volatile molecule apart from the hydrogenic molecules. This scaling with the total electronic stopping power makes it possible to predict the sputtering yield of protons with energy up to about 50 keV, which is actually close to the energies of the stopping power maximum.

The set-up has been modified by a special soldering point from the cryostat bottom to the electrode of the quartz crystal microbalance. The microbalance then became so cold that it was possible even to erode films of solid hydrogen and deuterium hydride on it. Films of solid hydrogen have not been studied systematically before because of the extreme volatility. It turned out that it was possible to avoid beam-induced evaporation for beam currents below 4.5 nA. The sputtering yield for solid hydrogen and deuterium hydride shows the same energy dependence as that of solid deuterium. The absolute value of the yield from solid hydrogen is about a factor of four larger than for solid deuterium because the binding energy of the molecules is somewhat smaller than that of deuterium.

3.1.3 The test stand for multishot pellet injectors

(H. Sørensen, J.E. Hansen, H. Kossek, P. Michelsen, B. Sass, J. Thorsen, and K.-V. Weisberg)

A number of improvements have been made in connection with the work on an 8-shot unit for RTP.

The differential pumping chamber has been modified to agree with the design suggested for RTP and FTU/RFX.

A number of improvements have been made to the data collection program.

Parts of the electronics equipment have been rebuilt so that silicon diode thermometers and temperature regulation can now be used.

3.1.4 A multishot injector for RTP, Rijnhuizen

(H. Sørensen, J.E. Hansen, H. Kossek, B. Sass, J. Thorsen, and K.-V. Weisberg)

Following a request from Instituut voor Plasmafysica in the Netherlands concerning pellets for the tokamak RTP in Rijnhuizen an agreement has been made between Instituut voor Plasmafysica and Risø National Laboratory.

Two pellet sizes are needed for RTP, $5 \cdot 10^{18}$ and $2 \cdot 10^{19}$ hydrogen atoms per pellet, respectively. For the smaller pellets the velocities should be up to 1200 m/s and for the larger ones they should be up to 600 m/s.

The pellet sizes are much smaller than the ones used in the feasibility study of pellets for FTU and RFX and the low velocities requested are also below the velocities obtained in the feasibility study for FTU and RFX. Another problem foreseen was that the firing accuracy for such small pellets could differ from that of large pellets resulting in a larger angular spread.

Two new pipe guns designed for small pellets have been mounted. After some tests and modifications it was found that pellets of the requested sizes could be obtained in gun barrels with inner diameters of 0.6 and 0.8 mm. Silicon diode thermometers were used in these new pipe guns and temperatures partly regulated. It was further found that for both pipe guns it was possible to vary the pellet size considerably. The reason for this is not fully understood yet. For the smaller pellet it was possible at the same time to vary the velocity between 700 and 1100 m/s while it was possible to vary the velocity for the larger pellet between 360 and 700 m/s. The firing accuracy was still acceptable. All pellets hit within a circle of 23 mm diameter on a target placed 4 m in front of the gun barrels although the points hit depended somewhat on the firing conditions.

Following this four + four new pipe guns for the requested pellet sizes have been made and mounted. A test run with a liquid helium consumption of 2.5 l/h was very satisfactory.

The pellets may be transported to RTP through a first guide tube with a length of 1000 mm and with an inner diameter of 16 mm and a second guide tube with a length of 1000 mm and with an inner diameter of 25 mm while the driver gas will be removed by means of two differential pumping chambers each of 400 l volume with base pressures of 0.001 mbar.

The injector will be operated in a manner similar to the one used in the laboratory and parts of the equipment will be improved versions of the equipment used in the test stand.

3.1.5 The multishot injectors for FTU, Frascati and RFX, Padova

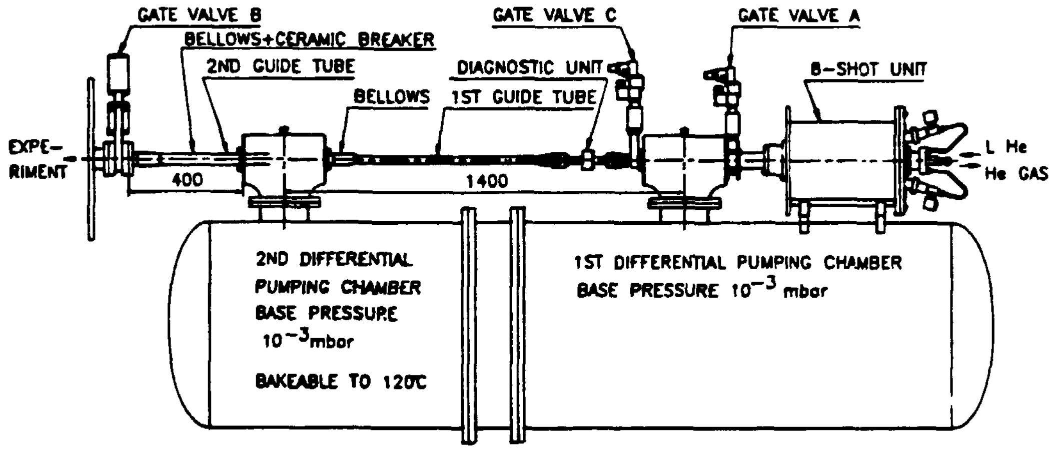
(H. Sørensen, J.E. Hansen, B. Sass, K.-V. Weisberg, J. Bundgaard*, and J. Seir Olsen* (*Engineering and Computer Department, Risø))

The feasibility study concerning design of multishot pellet injectors for FTU and RFX was concluded in January with a report on the feasibility study.

A number of design features have been worked through and a number of improvements have been incorporated into the design.

It is now possible to reduce the velocity range of a pipe gun by inserting a flow resistance before the pellet position. The reservoir for pellet gas is now placed between the two differential pumping chambers as shown in the figure.

Following the tenders sent to Italy in 1989 it was decided that ENEA should apply for priority support from Euratom. The project was approved and recommended by Euratom and an international call for tenders was sent out. A new tender was hereafter worked out at Risø and sent to ENEA in December.



Schematic drawing of the multishot pellet injector

3.1.6 Pellet-plasma interactions in tokamaks

(C.T. Chang)

A review of pellet-plasma interactions in tokamaks was undertaken and a report on the completed work has been submitted for publication. An abstract of the main contents follows:

The ablation of a refuelling pellet of solid hydrogen isotopes is governed by the plasma state, especially the density and energy distribution of the electrons. On the other hand the cryogenic pellet gives rise to perturbations of the plasma temperature and density. Based on extensive experimental data the interaction between the pellet and the plasma is reviewed. Among the subjects discussed are the MHD activities, evolution of temperature and density profiles, and the behaviour of impurities following the injection of a pellet (or pellets). The beneficial effect of density peaking on the energy confinement time, offset by the accumulation of impurities at the plasma core is brought into focus. A possible remedy is suggested to diminish the effect of the impurities. Plausible arguments are presented to explain the apparent controversial observations on the propagation of a fast cooling front ahead of the plasma. The appearance of striations and the curving of the pellet trajectory are discussed in detail. The possibility is given for using these observations to study the plasma current density distribution as well as the existence of suprathermal electrons.

3.1.7 Fast ion distribution in JET

(H. Bindslev)

In a fusion plasma various populations of fast non-thermal ions will exist. These are partly fusion products and partly ions which have been accelerated through various heating schemes. The interaction of the fast ions with the plasma is essential for achieving and sustaining a fusion plasma. The existence of these non-thermal populations is furthermore expected to have a significant impact on the plasma stability. Central to the study of the interaction between fast ions and plasma is a knowledge of the velocity distributions of the fast ions.

At the European fusion research centre JET in Oxfordshire, U.K., a fast ion and alpha particle diagnostic (KE4) is presently under development. It is expected to come into operation in August 1991 for a short campaign before the long shutdown of JET in September 1991 (major upgrading of JET). The diagnostic is based on collective Thomson scattering of 2 mm waves. This is a new regime for plasma Thomson scattering which has necessitated a major review and new development of the theoretical basis.

The main contribution this year has been the development of a new theory for scattering in a dielectric medium where spatial as well as the usual temporal dispersion are taken into account. The inclusion of spatial dispersion manifested itself in a term commonly referred to as the "geometrical factor", G. The resulting expression for G, which is remarkably simple, is a generalisation of earlier expressions. These expressions are recovered in the appropriate limits. The expression exhibits symmetry between incident and scattered field, as expected from the reciprocity relation. One earlier published result[1)] lacks this symmetry. This has been discussed with the authors and it has been found that the symmetry can be restored in their result by the line of argument used in the new derivation. The significance of including spatial dispersion in the theory is that it allows for a hot or relativistic modelling of the plasma. Codes for calculating the new geometrical factor have been written. Codes for calculating the dielectric tensors for hot and for weakly relativistic plasmas have also been written.

The new expressions have been explored with cold, hot, and relativistic models for the plasma. In the parameter range relevant to JET it is found that the cold plasma model is adequate for O to O scattering (O = ordinary mode, X = extraordinary mode). For X to X scattering significant differences of practical importance are found between the results based on the cold plasma model and the ones based on the relativistic model.

1) Hughes, T.P. and Smith, S.R.P. (1989), J. Plasma Phys. **42**, 215.

3.1.8 Investigations of electron density profiles in the JET plasma

(A. Lindholm Andersen)

This year the work has been concentrated on analysis of measured electron density profiles in the edge region of the JET plasma. The typical behaviour of the plasma density has been compared both during the ohmic phase, the L-mode, and the H-mode, in order to understand the L-H transition, to establish whether ELMs could be triggered by the edge plasma density gradient reaching a maximum level, as well as to compare the ELMs and the L-H transitions.

The diagnostic that has been used is the multichannel microwave reflectometer system at JET (KG3).

The contribution to the KG3 system falls in two parts. The first part concerns the swept frequency facility of KG3 which is to calculate the electron temperature profile independently of other diagnostics. The calculation of the profile includes several numerical fits, and the quality of these has been analysed and improved. Calibration data for the period of JET-operations from June to October 1990 have been obtained and processed, the accuracy of the profiles has been reconsidered, and the feasibility of a new statistical method to improve the time resolution has been investigated.

The second part of the work on KG3 consists of the development of a new analysis method for the data obtained with fixed frequency. The principle is that by assuming a linear density profile in the plasma it is possible to find a simple linear relation between the measured phase delays and the critical densities. Thus, the position of the plasma edge and the density gradient in the edge region (constant as the density profile is assumed linear) can be calculated by linear regression from the phase delays measured by KG3.

The results that have been obtained are concentrated on the L-H transition where a large increase in the edge density gradient has been found, followed by a smaller decrease as the plasma enters the H-mode. The same increase of the gradient above the H-mode value has been observed at the end of a large singular ELM, supporting the theory that this type of ELMs is related to fast H-L-H transitions. Furthermore, a change in the plasma edge position has been seen during the formation of the X-point corresponding to the movement measured by other diagnostics.

A tendency for the measured phase delays to "drift", i.e. change an unphysical amount in one direction, during periods where the plasma is less quiescent has been uncovered. This is probably caused by fluctuations in the plasma on a faster timescale than KG3's time resolution. The drift corrupts the KG3 measurements during ELM's periods, but it can be used as a qualitative indicator of the fluctuation level.

3.1.9 Plasma correlation reflectometry

(P. Michelsen and H.L. Pécseli)

A measuring technique denoted reflectometry has been used in tokamak experiments in order to measure density profiles. A microwave beam launched against the plasma surface is reflected where the beam frequency is equal to the plasma cut-off frequency. By monitoring the phase shift of the reflected wave it is possible to follow movements of the plasma surface. The phase change of the wave is usually calculated according to the approximation of geometrical optics, often called the WKB-approximation. In cases where the wavelength of the microwave is short as compared with the typical plasma density gradient length the approximation is rather good.

Recently the principles of a new technique for diagnosing micro-turbulence called correlation reflectometry have been presented[1]. Two microwave beams with a small difference in frequency are launched against the density profile. The phases of the two waves can be measured versus time, and since these phases are equivalent to plasma positions it is possible, by a correlation technique, to follow the motion of plasma perturbations.

In a plasma where the turbulence has characteristic scale lengths smaller than the microwave wavelength it is questionable whether an analysis of the measurements from correlation reflectometry based on the WKB-approximation will lead to the correct conclusions. To investigate this question the wave equation has been solved with a new numerical procedure using the COLSYS differential equation solver. The boundary conditions used assume a constant density plasma outside the region of interest.

1) Costly, A.E. and Cripwell, P. (1989). JET-P(89)82.

3.1.10 The Grad-Shafranov shift calculated on the basis of magnetic compressive and tensile stresses

(V.O. Jensen)

It is well known that a magnetic field can be conceived as a medium where an isotropic compression stress, $B^2/2\mu_o$, is superimposed on a tensile stress, B^2/μ_o, parallel to the lines of force. When an ideal MHD plasma is present in the magnetic field, the particle pressure adds to the magnetic stresses to form a combined pressure tensor. The concept of magnetic stresses has been derived and discussed in many textbooks, but it has been presented more as a matter of curiosity than as a useful tool for understanding and analysis of specific problems. The concept has, however, been used to explain the restoring forces responsible for propagation of Alfvén waves.

An analysis of the magnetic stress concept has been carried out. This analysis is somewhat more detailed than the ones normally given, and it is aimed at using the concept for studies of equilibria for ideal MHD plasmas. The concept is tested by rederiving the equilibrium equations for the θ-, Z-, and screw pinches. The concept is then used to derive the Grad-Shafranov shift of a circular tokamak plasma confined in a flux-conserving vessel with circular cross-section. For the outer Grad-Shafranov shift, i.e. the displacement of the centre of the plasma column with respect to the centre of the vessel, the well known result is rederived. An expression is also found for the inner Grad-Shafranov shift, i.e. for the displacement of the magnetic axis with respect to the centre of the plasma column.

The advantages of using the concept of magnetic stress rather than the Grad-Shafranov equation for calculating tokamak equilibria are:

- the calculations become very simple and straightforward,
- the validity range for the approximations is easy to assess,
- the physical interpretation of the various terms in the expression for the shift becomes very clear.

It is suggested that the concept of magnetic stress should be used also for calculations of problems including dynamics, wave phenomena, and stability.

3.1.11 Spectral solution of a two-dimensional equation with singular behaviour

(J.P. Lynov, A.H. Nielsen, and J. Nycander (University of Uppsala, Sweden))

The Hasegawa-Mima equation is a two-dimensional equation which describes electrostatic drift waves in magnetised plasmas as well as large-scale motion in the atmosphere and the oceans. In the short wavelength limit it reduces to the Euler equation, and in the long wavelength limit the following equation is obtained:

$$\frac{\partial \phi}{\partial t} = \{\phi, \nabla^2\phi\},$$

where ϕ is the electrostatic potential in the plasma case, and $\{\ ,\ \}$ denotes the Poisson bracket. This equation is solved numerically in a two-dimensional domain with periodic boundary conditions. A spectral collocation method has been employed with a fully dealiasing scheme to obtain high accuracy.

In particular the time evolution of the spectrum has been investigated in order to examine a possible blow-up. This is known to occur in, e.g., the nonlinear Schrödinger type equations[1]. The power spectrum then has the form $k^{-\alpha(t)}e^{-\delta(t)k}$, $\alpha, \beta > 0$, where δ measures the width of the "analyticity strip" in the complex plane. At the time when δ has shrunk to zero, a singularity develops in configuration space.

In our simulations of Eq. (1) spectra that decrease exponentially at high wavenumbers have never been obtained; thus, the solution is never analytic. At high wavenumbers the spectrum has the form $k^{-\alpha(t)}$, and it is found empirically that $\alpha(t) \propto \log t/\tau$, where τ is the characteristic time of the development.

Thus, the route to blow-up is quite different from previously studied cases. High order derivatives become singular almost immediately, and the singularities then gradually spread to lower order derivatives. A tentative analytic explanation of this behaviour is given, but no definite proof.

1) Sulem, C., Sulem, P.L., Frisch, H. (1983), J. Comp. Phys. 50, 138.

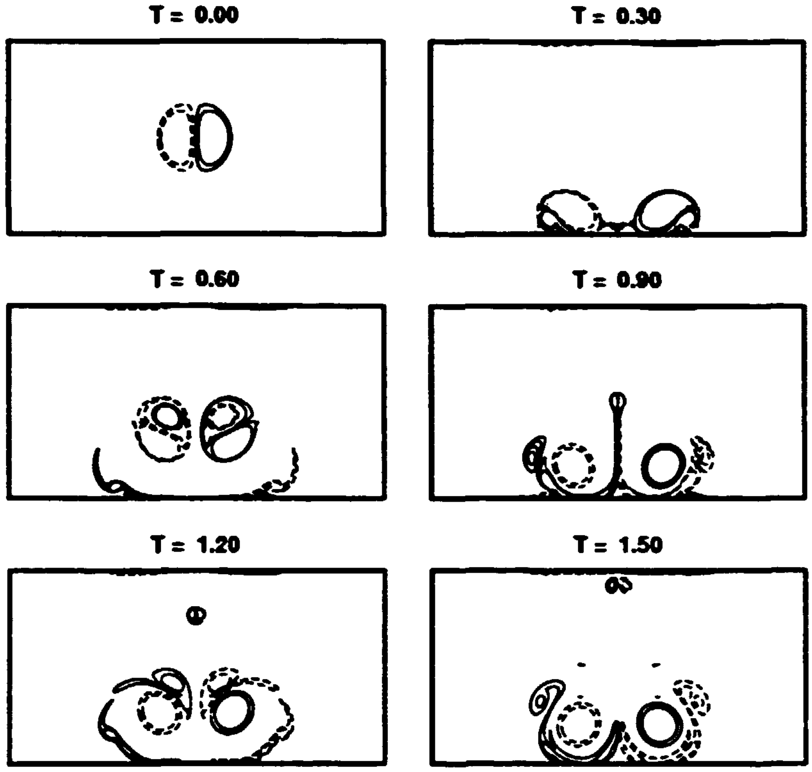
3.1.12 Fundamental interactions of coherent structures with boundary-layers in two-dimensional flows

(E.A. Coutsias (University of New Mexico, U.S.A.) and J.P. Lynov)

Large-scale, long-lived vortical structures emerge naturally in many different types of two-dimensional flows. Such large coherent structures have strong influence on the transport properties of various turbulent systems in ordinary fluids as well as in magnetised plasmas.

The evolution of the flow system is studied by numerical solution of the two-dimensional Navier–Stokes equations in the vorticity-stream function formulation. Though originally derived for ordinary fluids, these equations can also be used to model the dynamical evolution of low frequency, electrostatic perturbations of a plasma in a plane perpendicular to a strong magnetic field. In the plasma case the viscosity is chosen as small as possible determined by numerical accuracy.

For the numerical studies an efficient and accurate spectral scheme developed at Risø was employed. The code has been used for investigations of the generation and interaction of single-vortex (monopole) and double-vortex (dipole) structures in a periodic channel with no-slip walls. The no-slip boundary conditions are expressed by integral constraints on the spectral expansion coefficients of the vorticity and are included as so-called "tau conditions" in the implicit time integration of the viscous term. The figure shows the evolution of the vorticity field when a dipole collides with a no-slip wall. It is seen that strong vorticity fields are generated in the boundary layer near the wall when the dipole approaches. These vorticity distributions detach from the walls, and after a series of complex interactions give rise to a small dipole being ejected back into the main flow.



3.1.13 Three-dimensional stability of drift vortices

(J. Nycander and E.A. Kuznetsov (Inst. Automation and Electrometry, Novosibirsk, USSR))

The coupling between ion-acoustic waves and electrostatic drift waves in a magnetised plasma is described by the equations

$$\frac{\partial}{\partial t}(1-\nabla^2)\phi - \{\phi, \nabla^2\phi\} - v_o\frac{\partial \phi}{\partial y} + \frac{\partial v_z}{\partial z} = 0$$

$$\frac{\partial v_z}{\partial t} + \{\phi, v_z\} + \frac{\partial \phi}{\partial z} = 0$$

where ϕ is the electrostatic potential, and $\{\}$ denotes the Poisson bracket. These equations have z-independent, stationary, and localised solutions $\phi_o(x, y-ut)$ of dipole vortex type. The 3D stability of such dipole vortices to weak sinusoidal modulations along the z-axis is studied.

Setting $\phi = \phi_o(x, y-ut) + \psi(x, y-ut)e^{ik_z z - i\omega t}$ and linearising, a linear eigenvalue problem is obtained. This problem is solved by expansion in k_z. The lowest order solution ψ_o is a neutral mode. This is an eigenfunction with zero eigenvalue of the operator

$$L_o = -u\frac{\partial}{\partial y}(1-\nabla^2) - v_o\frac{\partial}{\partial y} - \{\phi_o, \nabla^2\cdot\} \cdot + \{\nabla^2\phi_o, \cdot\}$$

$\psi_o = \partial\phi_o/\partial y$ is chosen. By standard procedure it is then found that the solution to next order is $\psi_1 = i\omega\partial\phi_o/\partial u$.

A particular problem is that there exists an infinite family of stationary solutions ϕ_o for each value of the propagation velocity u which means that the zero eigenvalue of L_* is infinitely degenerate[1]. Also the adjoint operator $\tilde{L}_*$ has infinitely many eigenfunctions with zero eigenvalue, given by $f(\phi_* - \nabla^2\phi_*)$, where f is arbitrary. Thus, there are infinitely many solvability conditions, and to satisfy them an infinitude of eigenfunctions to L_* must be included.

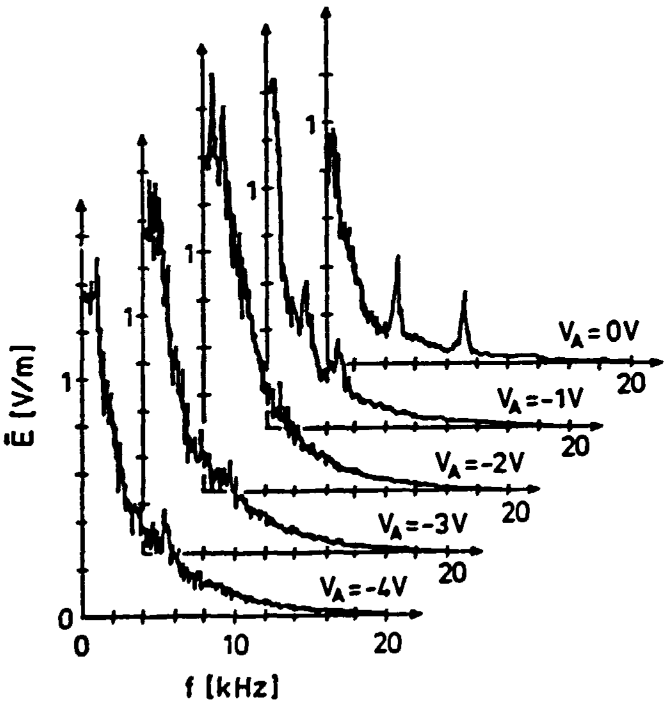
This is impossible. We can, however, obtain an approximation to the exact solution by using only the two most important solvability conditions, i.e. multiplying by ϕ_* and $\nabla^2\phi_*$ and integrating. These two conditions correspond to the energy and entrophy constraints. It is then sufficient to include the eigenfunctions of L_* obtained from the two-parameter family of exact stationary solutions found by Larichev and Reznik[2]. An explicit dispersion relation can then be found.

1) Nycander, J. (1988), J. Plasma Physics 39, 413.
2) Larichev, V.D. and Reznik, G.M. (1976), Dokl. Akad. Nauk SSSR, 231, 1077.

3.1.14 Coherent structures in two-dimensional plasma turbulence

(T. Huld, A.H. Nielsen, H.L. Pécseli, and J. Juul Rasmussen)

The experimental investigations of low frequency, flute-type, electrostatic fluctuations propagating across a strong, homogeneous magnetic field in a plasma have been continued[1,2]. The investigations are performed in the Q-machine plasma. The fluctuations are generated by the Kelvin-Helmholtz instability due to a strongly sheared azimuthal flow of the residual plasma surrounding the main plasma column. The radial potential variation in the residual plasma and thereby the azimuthal flow can be controlled by the bias of a limiting aperture inserted perpendicularly to the plasma column. The characteristics of the fluctuations depend strongly on the radial potential variation as demonstrated in the figure, where the spectral distribution for the fluctuating azimuthal electric field component for



varying aperture bias V_A is shown. The DC-radial electric field, E_0, is very large and localised for $V_A = 0$ and the spectra are characterised by narrow peaks. For decreasing E_0, i.e. when V_A approaches the plasma potential of the main plasma column, the spectra become broader and eventually lose any prominent feature. A detailed statistical study of the turbulence has been performed. Thus, the presence of relatively long-lived vortex-like coherent structures in the background of wide-band turbulent fluctuations has been demonstrated by employing a conditional sampling technique[2)], where the azimuthal electric field fluctuations have been used as the reference signal. Depending on the plasma parameters the dominant structures can appear as monopole or multipole vortices, dipole vortices in particular, with a tendency for the monopoles to dominate in the cases with strong radial electric fields, E_0. In the analysis employed so far only two signals can be recorded simultaneously[2]. It is, therefore, not possible to determine whether the observed dipole vortices, which are averaged, also correspond to dipoles in each realisation, i.e., the averaged dipoles could in principle be built up of monopoles of alternating signs. To remedy this our equipment and data analyses have recently been extended to allow for simultaneous recording and handling of four signals. Preliminary results with this extended analysis indicate that the observed averaged dipole vortices indeed correspond to dipoles in each realisation.

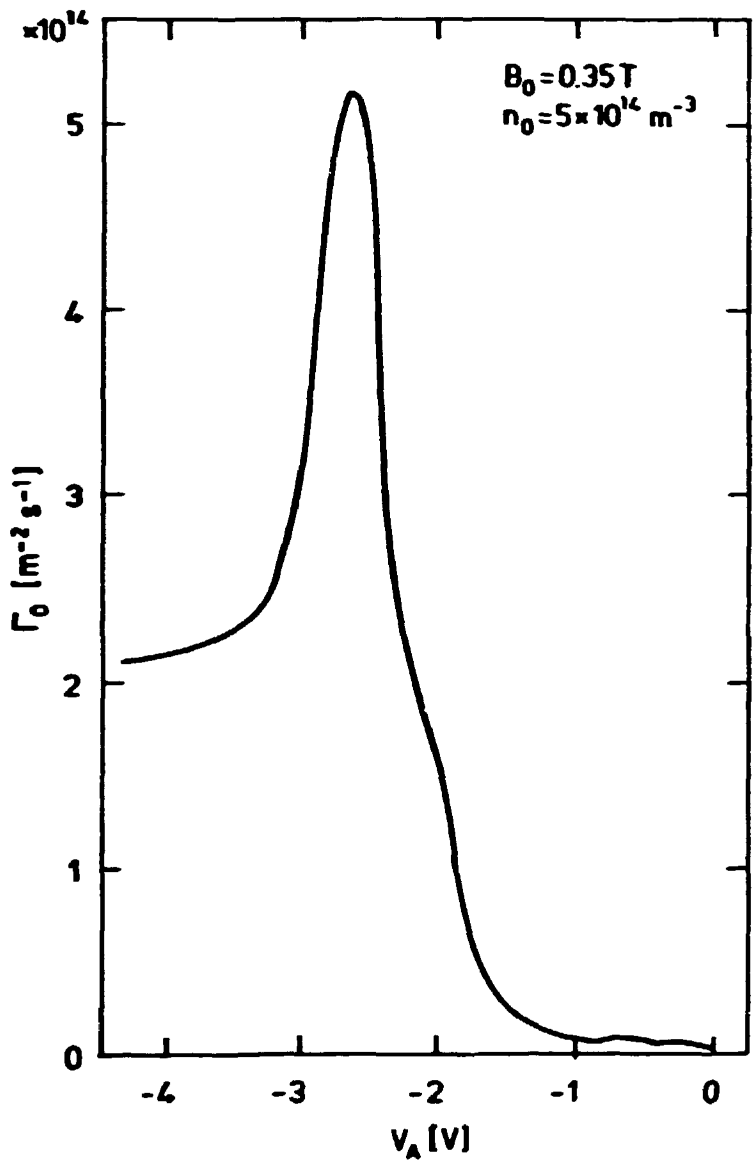
1) Huld, T., Iizuka, S., Pécseli, H.L. and Rasmussen, J.J. (1988). Plasma Physics and Controlled Fusion 30, 1297.

2) Huld, T., Nielsen, A.H., Pécseli, H.L. and Rasmussen, J.J. (1990). Phys. Rev. Lett. 64, 3023.

3.1.15 Cross-field plasma transport caused by two-dimensional turbulence

(T. Huld, A.H. Nielsen, H.L. Pécseli, and J. Juul Rasmussen)

The anomalous plasma transport perpendicular to the magnetic field associated with low frequency, flute-type, electrostatic turbulence (see 3.1.14) is investigated in the Q-machine plasma. This is done by analysing the radial component of the fluctuating flux $\Gamma = nE/B_0$, where n is the density fluctuations and E is the azimuthal component of the fluctuating electric field. The averaged value of Γ, Γ_0, gives the part of the net plasma transport out of the plasma column, which can be attributed to the turbulent fluctuations. This plasma flux depends on the plasma parameters as do the characteristics of the turbulence. Thus, the radial DC-electric field seems to be the most important parameter. As described in 3.1.14 the radial potential profile can be controlled by the bias of the aperture V_A, and in the figure the variation of Γ_0 is shown for varying aperture bias V_A, for the same conditions as in the figure in 3.1.14. For V_A near ground potential, where the DC-radial electric field, E_0, is very large and localised and the spectra are characterised by narrow peaks, the net flux is very small due to a phase locking between the n and E fluctuations. For decreasing E_0, i.e. when V_A approaches the plasma potential of the main plasma column, the spectra become broader and the fluctuations occupy a larger part of the residual plasma measured in the radial direction. The net plasma flux increased, reached a maximum, and then decreased somewhat when V_A was around the floating potential, consistent with a decrease of the overall fluctuation level. The diffusion coefficient deduced from the maximum value of the flux was found to be somewhat smaller than the Bohm diffusion coefficient obtained for the present plasma conditions, but several orders of magnitude larger than the classical diffusion coefficient due to collisional transport. It is thus appropriate to consider these results as evidence of a significant turbulent transport.



The nature of the transport cannot be understood by a simple measurement of Γ_0. The transport can in one extreme be caused by small random displacements, corresponding to a diffusion-like process. In the other extreme it could be due entirely to large sporadic bursts caused by large amplitude coherent structures discussed in 3.1.14. The importance of these structures has been investigated by carrying out a detailed statistical analysis of the fluctuating Γ-signal[1]. It was found that although a significant part of the transport can be attributed to the coherent structures, it is not solely caused by them. A nontrivial part of the transport takes place at time intervals where no large structures are present. However, even if these bursts occur rarely, they may have serious consequences in hot plasma devices as, e.g., tokamaks, where turbulent transport is a dominant transport mechanism in the edge plasma region[2]. A burst of hot plasma hitting the wall can have lasting influence due to, e.g., the resulting sputtered material.

1) Huld, T., Nielsen, A.H., Pécseli, H.L. and Rasmussen, J.J. (1990), Phys. Rev. Lett. 64, 3023.
2) Wootton, A.J. et al. (1988), Plasma Physics and Controlled Fusion 30, 1479.

3.1.16 Fluctuations in a toroidal plasma

(R.J. Armstrong*, H.L. Pécseli, K. Rypdal*, and J. Trulsen* (*University of Tromsø, Norway))

A magnetically confined, steady state toroidal plasma has been produced by discharge ionization of argon in the large new plasma device "Blåmann" at the University of Tromsø. Spontaneously generated fluctuations have been studied for varying magnetic field configurations, with particular attention to the possibility of controlling the plasma properties by varying the bias on a split-limiter.

3.1.17 Analytical expressions for conditional averages: a numerical test

(H.L. Pécseli and J. Trulsen (University of Tromsø, Norway))

Conditionally averaged random potential fluctuations are an important quantity for analysing turbulent electrostatic plasma fluctuations. Experimentally, this averaging can be readily performed by sampling the fluctuations only when a certain condition is fulfilled at a reference position. Alternatively, for time stationary and homogeneous turbulence, analytical expressions involving higher order correlation functions $R_n(\mathbf{r},t) = < \phi^n(\xi,\tau)\phi(\mathbf{r}+\xi,t+\tau) >$ can be derived for the conditional averages. These expressions have the form of series expansions which have to be truncated for practical applications. The convergence properties of the series are not known, except in the limit of Gaussian statistics. By applying the analysis to numerically simulated ion acoustic turbulence, it is demonstrated that by keeping two or three terms in these series an acceptable approximation is obtained even in cases which deviate significantly from Gaussian statistics.

3.1.18 Phase-space diffusion in turbulent plasmas: the random acceleration problem revisited

(H.L. Pécseli and J. Trulsen (University of Tromsø, Norway))

Phase-space diffusion of test particles in turbulent plasmas has been studied by an approach based on a conditional statistical analysis of fluctuating electrostatic fields. Analytical relations between relevant conditional averages and higher order correlations, $< E^n(x_o,t_o)E(x_o+x,t_o+t) >$, and triple correlations, $< E^n(x_o,t_o)E(x_o+x,t_o+t)E(x_o+y,t_o+s) >$, considerably facilitate the practical application of the resulting equations.

3.1.19 A wavenumber-in-cell simulation of weak Langmuir turbulence

(H.L. Pécseli and J. Trulsen (University of Tromsø, Norway))

A wavenumber-in-cell code has been developed[1]) for simulation of a model proposed by Vedenov et al. for study of weak Langmuir turbulence. The model uses a WKB-approach for describing the Langmuir wave field. The high-frequency wave field is described by a superposition of many pseudoparticles or plasmons. Theoretical results for damping of ion acoustic waves caused by resonant interaction with Langmuir waves with group velocity around the sound speed have been confirmed. Simulations where a damping mechanism is included in the ion sound dynamics demonstrate a formation of localised cavities of intense wideband self-trapped Langmuir wave fields. The interaction between two cavities has features in common with the similar process for phase-space vortices. The damping of ion acoustic waves gives rise to a deceleration of the cavitons. Initial conditions with either uniform distribution of the high frequency waves or, alternatively, with localised wave bursts have been considered.

1) Pécseli, H.L. and Trulsen, J. (1990). Phys. Rev. Lett. 64, 285.

3.1.20 Nonlinear modulational instability of whistler waves

(T. Huld, V.I. Karpman (IZMIRAN, Moscow, USSR), J.P. Lynov, H.L. Pécseli, and J. Juul Rasmussen)

The numerical investigations of the nonlinear evolution of the two-dimensional modulational instability of whistler waves in a magnetised plasma have been continued[1]. The emphasis has been on the dependence of the evolution of the details of the initial condition. In general, the instability was found to evolve in a quasi-recurrent manner with the main part of the energy residing in the fundamental mode of the initial modulation, and the energy is spreading slowly to higher mode numbers. As the initial condition the whistler wave is modulated almost perpendicularly to its direction of propagation along the z-axis, i.e. the ratio of the modulation wavenumbers $\alpha = K_z/K_x \ll 1$. The maximum growth rate is obtained at a certain α_c and for low wave amplitudes the evolution shows three clear recurrence periods (corresponding to 4000 whistler wave periods) before a significant spreading of the energy takes place. For this case the evolution is well described by a simplified model based on a generalised Hamiltonian, and truncated to involve only few modes[2]. For increasing wave amplitude the recurrent feature becomes less pronounced and the spreading of the energy to higher mode numbers proceeds faster. For a given amplitude the evolution is found to be very sensitive to the value of α. For $\alpha > \alpha_c$ the recurrence becomes significantly better, i.e. for $\alpha = 1.02\alpha_c$ we observe six clear recurrence periods, and for $\alpha < \alpha_c$ the spreading to the higher modes proceeds considerably faster, i.e. already for $\alpha = 0.99\alpha_c$ only one recurrence period is observed.

In the studies carried out so far an examination of the interaction of the whistlers with the fast magnetosonic waves has been carried out. Also interaction of whistlers with the slow magnetosonic waves gives rise to a modulational instability. The numerical code for investigations of this problem is now being prepared. Here a clear recurrent behaviour is not expected.

1) Karpman, V.I., Hansen, F.R., Huld, T., Lynov, J.P., Pécseli, H.L. and Rasmussen, J.J. (1990), Phys. Rev. Letter 64, 890.
2) Karpman, V.I., Shagalov, A.G., Rasmussen, J.J. (1990), Phys. Lett. A147, 119.

3.1.21 Conditions for wave collapse

(E.A. Kuznetsov*, J. Juul Rasmussen, K. Rypdal (University of Tromsø, Norway), and S.K. Turitsyn* (*Inst. Automation and Electrometry, Novosibirsk, USSR))

In two and three dimensions it is well known that the cubic Schrödinger equation has collapsing solutions, i.e. the solution develops a singularity in a finite time[1]. For the two-dimensional case, the critical case, a sufficient and necessary condition for collapse exists, i.e. the "mass" of the initial wave field, $\int |u(\mathbf{x}, t=0)|^2 d\mathbf{x}$ must be larger than or equal to the "mass" of the lowest order stationary ("soliton") solution. For the three-dimensional case, the supercritical case, only a sufficient condition for collapse has been found, i.e. the "Hamiltonian", H, corresponding to the initial wave field must be smaller than zero. By means of integral relations it has been shown that this sufficient condition can be sharpened, i.e. $H < H_{sol}$

will ensure collapse; here $H_{sol}(> 0)$ is the "Hamiltonian" corresponding to the lowest order stationary ("soliton") solution. It is conjectured that the above condition is also a necessary condition for collapse. This conjecture will be tested by numerically solving the cubic Schrödinger equation in radial symmetry.

1) Rasmussen, J.J. and Rypdal, K. (1986), Physica Scripta **33**, 481.

3.2 Participants in the work in plasma physics

Scientific Staff

Chang, Che Tyan (until 30 June)
Ellegaard, Ole (part time (25%))
Huld, Thomas (until 31 August)
Jensen, Vagn O.
Kofoed Hansen, Otto (deceased 21 July)
Lynov, Jens-Peter
Michelsen, Poul
Pécseli, Hans L.
Rasmussen, Jens Juul
Schou, Jørgen
Sørensen, Hans
Weisberg, Knud. V.

Ph.D. Students

Andersen, Annette (At present working at JET, U.K.)
Bindslev, Henrik (At present working at JET, U.K.)
Nielsen, Anders Henry
Stenum, Bjarne

Technical Staff

Bækmark, Lars
Hansen, John
Kossek, Henryk
Nielsen, Mogens O.
Nordskov, Arne
Reher, Børge
Sass, Bjarne
Thorsen, Jess

Secretaries

Astradsson, Lone
Kjøller, Kæth
Skaarup, Bitten
Toubro, Lene

Guest Scientists

Coutsias, E.A., University of New Mexico, U.S.A.
Nycander, J., University of Uppsala, Sweden

Short time visitors (more than one week)

Brooks, R.L., University of Guelph, Canada
Gürtler, P., Hasylab, Hamburg, Germany
Karpman, V.I., Izmiran, Moscow, U.S.S.R.
Knorr, G., University of Iowa, U.S.A.
Kutznetsov, E.A., USSR Academy of Sciences, Novosibirsk, U.S.S.R.
Turitsyn, S.K., USSR Academy of Sciences, Novosibirsk, U.S.S.R.

Degrees

Huld, T., Ph.D. degree

4 Publications and educational activities in the Plasma Physics Section

4.1 Publications

ANDERSEN, S.A. and BÆKMARK, L. (1990). A fast-acting hydrogen gas source for staged pneumatic high-speed acceleration of fusion plasma fuel pellets. Risø-M-Report 2857, 34 p.

ANDERSEN, S.A. and BÆKMARK, L. (1990). Fast-switching, high-temperature propellant source for multistage pneumatic acceleration of hydrogen fuel pellets. Rev. Sci. Instrum. **61** (7), 1991-1993.

CHANG, C.T. (1990). The ablatant state of a hydrogen pellet during its passage in a tokamak. Physica Scripta **42**, 584-598.

COSTLEY, A.E., BINDSLEV, H., BOYD, D.A., HOEKZENA, J.A., HUGHES, T.P. and O'BRIAN, M. (1989). A high power 140 GHz collective scattering diagnostic to measure fast-ion and alpha particle distributions in JET: Physics aspect. In: Papers presented at joint workshop on ECE and ECRH (EC7), Hefei (CN), May 1989 (edited by Costley, A.E.), JET-P-89-53, p.1-14.

COUTSIAS, E.A., HULD, T. and LYNOV, J.P. (1990). Numerical studies of the evolution of coherent structures in two-dimensional shear flow. In: Proceedings of the 9th Symposium on Turbulence and Diffusion, Roskilde, Denmark, 30 April - 3 May 1990 (American Meteorological Society, Boston, Mass.) 212-215.

ELLEGAARD, O., SCHOU, J. and SØRENSEN, H. (1990). Sputtering of volatile solids from nonoverlapping subspikes. Europh. Lett. **12**, 459-464.

HULD, T. (1990). Experimental and numerical investigations of plasma turbulence. Risø-M-2858, 105 p.

HULD, T. (1990). User's manual for the AIDA data acquisition and display system. Risø-I-470, 24 p.

HULD, T. (1990). Reference manual for the AIDA data acquisition system. Risø-I-471, 43 p.

HULD, T., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Identification of coherent structures in two-dimensional turbulent flows. In: Proceedings of the 9th Symposium on Turbulence and Diffusion, Roskilde, Denmark, 30 April - 3 May 1990 (American Meteorological Society, Boston, Mass.) 266-269.

HULD, T., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Plasma vortices and their relation to cross-field diffusion: a laboratory study. Phys. Rev. Lett. **64**, 3023-3026.

HULD, T., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Ion-acoustic wave propagation in plasmas with ion beams having a finite cross section. IEEE-Trans. Plasma Sci. **PS 18**, 149-158.

JENSEN, V.O. (1990). Kold fusion, varm fusion og pressen (Cold fusion, warm fusion and the press). Tanker i Tiden. Ingeniøren **16**, No. 7, p. 10.

JENSEN, V.O. and SØRENSEN, H. (1990). Piller af kold brint nærer fusionen (Pellets of cold hydrogen for fusion). Ingeniøren **16**, No. 2, p. 15.

JOVANOVIĆ, D., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Interaction of plasma vortices with resonant particles. Phys. Fluids **B2**, 2035-2041.

KARPMAN, V.I., HANSEN, F.R., HULD, T., LYNOV, J.P., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Nonlinear evolution of the modulational instability of whistler waves. Phys. Rev. Lett. **64**, 890-893.

KARPMAN, V.I., HANSEN, F.R., HULD, T., LYNOV, J.P., PÉCSELI, H.L.

and RASMUSSEN, J. JUUL (1990). Nonlinear stage of the modulational instability of whistler waves. In: "Nonlinear World", Proceedings IV International Workshop on Nonlinear and Turbulent Processes in Physics, Kiev, U.S.S.R. (9-22 October 1989) (edited by V.G. Bar'yaktar et al.)(World Scientific Publishing Co., Singapore), **Vol. 2**, pp. 882-897.

KARPMAN, V.I., SHAGALOV, A.G. and RASMUSSEN, J. JUUL (1990). Modulational instability due to nonlinear coupling between high- and low-frequency waves: a study of truncated systems. Phys. Lett. **A147**, 119-124.

KNORR, G., LYNOV, J.P. and PÉCSELI, H.L. (1990). Self-organization in three-dimensional hydrodynamic turbulence. Z. Naturforsch. **45a**, 1059-1073.

KOFOED-HANSEN, O. and PÉCSELI, H.L. (1990). Turbulens, kaos med lovmæssighed (Turbulence, chaos and order). Risø Nyt No. 1, 10-11.

LYNOV, J.P., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL (1990). Autonomous models for two-dimensional turbulence. In: Proceedings of the symposium "Characterizing Complex Systems", Risø, Denmark (June 2, 1989) (edited by H. Bohr)(World Scientific Publishing Co., Singapore) pp 17-21.

PÉCSELI, H.L. (1990). Phase space diffusion in turbulent plasmas. Physica Scripta **T30**, 159-165.

PÉCSELI, H.L. and TRULSEN, J. (1990). Wave-number-in-cell simulation of weak Langmuir turbulence. Phys. Rev. Lett. **64**, 285-288.

STENUM, B., ELLEGAARD, O., SCHOU, J. and SØRENSEN, H. (1990). Thickness dependence of the sputtering yield from solid deuterium by light keV ions. Nucl. Instrum. Method **B 48**, 530-533.

SØRENSEN, H., HANSEN, J.E., MICHELSEN, P., SASS, B., WEISBERG, K.-V., KNUDSEN, O. AND MICHELSEN, E. (1990). A microwave cavity for measurement of the mass of hydrogen pellets. Rev. Sci. Instrum. **61**, 3464-3466.

TANG, F.L. and CHANG, C.T. (1990). Similarity parameters of a steady plane ablated flow under the impact of an electron beam. Risø-M-Report 2837, 49 p.

4.2 Conference contributions

COUTSIAS, E.A., The instability of parabolic solidification fronts (invited). Danish Physical Society, Spring Meeting, Nyborg, Denmark (May).

COUTSIAS, E.A., HULD, T. and LYNOV, J.P., Numerical studies of electrostatic turbulence in two-dimensional bounded geometries. 25. Nordic Plasma and Gas Discharge Symposium, Gausdal, Norway (February).

COUTSIAS, E.A., HULD, T. and LYNOV, J.P., Numerical studies of the evolution of coherent structures in two-dimensional shear flow. The 9th Symposium on Turbulence and Diffusion, Roskilde, Denmark (April-May).

COUTSIAS, E.A. and LYNOV, J.P., Interactions of vortical structures with walls in plane, parallel shear flows. Danish Physical Society, Spring Meeting, Nyborg (May).

COUTSIAS, E.A. and LYNOV, J.P., Interactions of vortical structures with walls in plane, parallel shear flows. The 10th annual CNLS conference "Nonlinear Science - Next Decade", Los Alamos, USA (May).

COUTSIAS, E.A. and LYNOV, J.P., Generation and interaction of vortical structures in bounded, two-dimensional flows. The 4th Nordic symposium on computer simulations in natural science. Sandefjord, Norway (August).

ELLEGAARD, O., SCHOU, J., SØRENSEN, H. and STENUM, B., Sputtering of volatile solids from nonoverlapping subspikes. Danish Physical Society, Spring Meeting, Nyborg, Denmark (May).

ELLEGAARD, O., SCHOU, J., STENUM, B., SØRENSEN, H. and PEDRYS, R., Energy distributions and sputtering yields from subspikes in ion-bombarded

volatile solids. IISC 8, 8th International Workshop on Inelastic Ion Surface Collisions. Wr. Neustadt, Austria (September).

HULD, T., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL, Identification of coherent structures in two-dimensional turbulent flows. Ninth Symposium on Turbulence and Diffusion of the American Meteorological Society, Roskilde, Denmark (April-May).

HULD, T., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL, Coherent structures in two-dimensional turbulent flows. Danish Physical Society, Spring Meeting, Nyborg, Denmark (May).

HULD, T., NIELSEN, A.H., PÉCSELI, H.L. and RASMUSSEN, J. JUUL, Identification of coherent structures in two-dimensional turbulent flows (invited paper). Symposium of the Physics of Ionized Gases, Dubrovnik, Yugoslavia (September).

NIELSEN, A.H., HULD, T., PÉCSELI, H.L. and RASMUSSEN, J. JUUL, Experimental investigations of flute type turbulence. 25. Nordic Plasma and Gas Discharge Symposium, Gausdal, Norway (February).

PÉCSELI, H.L., Phase-space diffusion in turbulent plasmas. Symposium of the Physics of Ionized Gases, Dubrovnik, Yugoslavia (September).

PÉCSELI, H.L., Studies of fluctuations in plasmas. Nordic Society for Space Research, NSSR, 1990-meeting, Bolkesjø, Norway (November).

RASMUSSEN, J. JUUL, KARPMAN, V.I., HANSEN, F.R., HULD, T., LYNOV, J.P. and PÉCSELI, H.L., Non-linear evolution of the modulational instability of whistler waves. 25. Nordic Plasma and Gas Discharge Symposium, Gausdal, Norway (February).

SCHOU, J., SØRENSEN, H., STENUM, B. and ELLEGAARD, O., Sputtering yields and energy distributions from nonoverlapping subspikes in ion-bombarded volatile solids. The Gordon Conference on Particle-Solid Interactions, Plymouth, New Hampshire, U.S.A. (July).

SCHOU, J., STENUM, B., ELLEGAARD, O., SØRENSEN, H. and PEDRYS, R., Sputtering of frozen gases by particle bombardment (invited). IISC 8, 8th International Workshop on Inelastic Ion Surface Collisions. Wr. Neustadt, Austria (September).

STENUM, B., SCHOU, J., SØRENSEN, H. and GÜRTLER, P., Luminescence from pure and impure solid hydrogens (invited). Danish Physical Society, Spring Meeting, Nyborg, Denmark (May).

STENUM, B., SCHOU, J., SØRENSEN, H. and ELLEGAARD, O., Electronic sputtering of thin volatile films on metals. 3rd Topsøe Summer School, Technical University of Denmark, Lyngby, Denmark (August).

SØRENSEN, H., HANSEN, J.E., KOSSEK, H., MICHELSEN, P., SASS, B., THORSEN, J. and WEISBERG, K.-V. (1990). A multishot pellet injector feasibility study. 16th SOFT, London (September).

SØRENSEN, H., BUNDGAARD, J., HANSEN, J.E., KRISTENSEN, E., SASS, B. and WEISBERG, K.-V., A compact multishot pellet injector design for FTU and RFX. 16th SOFT, London (September).

4.3 Lectures

CHANG, C.T., Pellet injection experiments in Tokamaks. Plasma Physics Department, Leningrad Polytechnical Institute, Leningrad, U.S.S.R. (May).

CHANG, C.T., Pellet plasma interactions and their possible relation to some problems in space physics. Department of Electron and Plasma Physics, Royal Institute of Technology, Stockholm, Sweden (December).

JENSEN, V.O., 30 lectures on fusion plasma physics for students at The Technical University of Denmark, Lyngby, Denmark.

JENSEN, V.O., Fusionsforskning og JET (Fusion research and JET). Haderslev Katedralskole, Haderslev, Denmark.

LYNOV, J.P., Self-organization in two-dimensional turbulent flows. (General physics colloquium.) The Technical University of Denmark, Lyngby, Denmark (May).

PÉCSELI, H.L., Turbulence in fluids and plasmas. H.C. Ørsted Institute, University of Copenhagen, Copenhagen, Denmark (May).

PÉCSELI, H.L., Experimental investigations of turbulent diffusion in magnetized plasmas. University of Oslo, Oslo, Norway (November).

PÉCSELI, H.L., Introduction to plasma turbulence. Seven lectures. University of Tromsø, Tromsø, Norway.

RASMUSSEN, J. JUUL, Recent experimental results on turbulence and diffusion of plasma. Royal Institute of Technology, Stockholm, Sweden (January).

RASMUSSEN, J. JUUL, Investigations of flute type electrostatic turbulence and the associated anomalous transport. Institute of Plasma Physics, Garching bei München, Germany (April).

RASMUSSEN, J. JUUL, Nonlinear evolution of the modulational instability of whistlers in two dimensions. University of Tromsø, Norway (July).

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Plasma physics is concentrated on basic investigations with relevance to fusion plasmas. Both theoretical and experimental work has been performed. Pellet injection systems have been developed. Within the area of fluid dynamics spectral models for studying the dynamics of coherent structures have been developed. Optical diagnostic methods based on quasi-elastic light scattering have been developed. Beam propagation in random and nonlinear media has been investigated. Spatial and temporal processing schemes, especially for pattern recognition, have been investigated.

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