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Association Euratom - Risø National Laboratory Annual Progress Report 1998

Edited by J.P. Lynov and B.N. Singh

Risø National Laboratory, Roskilde, Denmark
August 1999

Abstract The programme of the Research Unit of the Fusion Association Euratom - Risø National Laboratory covers work in fusion plasma physics and in fusion technology. The fusion plasma physics group has activities within development of laser diagnostics for fusion plasmas and studies of nonlinear dynamical processes related to electrostatic turbulence and turbulent transport in magnetised plasmas. The activities in technology cover investigations of radiation damage of fusion reactor materials. These activities contribute to the Next Step, the Long-term and the Underlying Fusion Technology programme. The technology activities also include contibutions to macrotasks, which are carried out under the programme for Socio-Economic Research on Fusion (SERF). A summary is presented of the results obtained in the Research Unit during 1998.

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Contents

1. Research Unit

The activities in the Research Unit cover two main areas:

Fusion Plasma Physics which includes:

- *Laser plasma diagnostics.* Development of laser diagnostics for spatially localised turbulence measurements. In collaboration with IPP Garching measurements are being performed on the W7-AS stellarator with a collective scattering diagnostic.
- *Nonlinear dynamics of fusion plasmas*. For the interpretation of the results from the laser diagnostic, extensive computer simulations are carried out of the plasma density fluctuations under various types of electrostatic turbulence. These simulations are also used for studies of nonlinear plasma processes of relevance to turbulent transport.

Fusion Technology which includes:

- Experimental and theoretical investigations of the effects of irradiation on the microstructural evolution and on the physical and mechanical properties of metals and alloys relevant to the Next Step, the Long Term and Underlying Fusion Technology Programme.
- Contributions to macro-tasks carried out under to programme of Socio-Economic Research on Fusion (SERF).

The **global indicators** for the Research Unit in 1998 are:

• Professional staff	11.5	man-years
• Support staff	8.4	man-years
• Total net costs	2.97	MioEuro
• Total Euratom support – incl. mobility	0.85	MioEuro

2. Fusion Plasma Physics

2.1 Introduction

The activities in this area have been carried out under the Plasma Physics and Fluid Dynamics Programme in the Optics and Fluid Dynamics Department. The main objective of the research is to contribute to the understanding of turbulent transport in fusion plasmas. In the work towards this objective, the programme interacts with other activities in the department in the fields of optics and fluid dynamics to the mutual scientific benefit of the projects involved.

The main results obtained during 1998 can be summarised as follows:

In collaboration with the Max-Planck-Institute for Plasma Physics in Garching, Germany, a number of successful measurements have been carried out with Risø's laser diagnostic on the Wendelstein 7-AS stellarator. These measurements include determination of the turbulent two-point cross-correlation functions, which are found to be highly anisotropic, and of the relationship between confinement and core plasma fluctuations. These experimental studies were supported by a number of theoretical and numerical studies. Fully three-dimensional simulations of plasma turbulence have been carried out, and effects of magnetic field geometry and of plasma boundary conditions have been investigated. Numerical simulations were used with good results to test predictions from the Turbulent Equipartion Model and these simulations demonstrated the formation of transport barriers in the plasma.

In this report, a brief description is included of two external projects, which are derived from the main scientific programme. These projects are: 1) Pellet injectors and 2) Industrial spin-off of laser anemometers for wind turbines.

2.2 Laser Plasma Diagnostics

2.2.1 Theoretical analysis of two-point collective scattering correlation functions using a drift wave model

N. Heinemeier and M. Saffman

Drift waves are believed to be responsible for a large part of the loss of particles and energy in fusion experiments. Because of this, the measurement of these waves is important. Collective light scattering is one of the methods used, and a two-point collective light scattering configuration is currently being used at the W7-AS experiment at IPP-Garching for this purpose. The basic idea in the two-point scheme is this: a small-scale structure is registered at one point using a collective light scattering system. The structure then moves with the flow to the measurement point of another similar system. Using the crosscorrelation of the photocurrents from the two systems to recognise the structure, the time-of-flight can be found. This is then used to estimate the group velocity of the large-scale structures in the flow.

We have calculated[1,2] the expected crosscorrelation function, using a drift wave dispersion model. This must be regarded as only a crude model, since many types of wave phenomena may contribute to experimentally observed signals. The calculations result in a closed expression for the correlation functions. The results, such as those shown in Figure 1, confirm the possibility of observing correlations due to drift waves. Furthermore, they provide quantitative estimates of the reduction in the correlation due to viscous dissipation and shear.

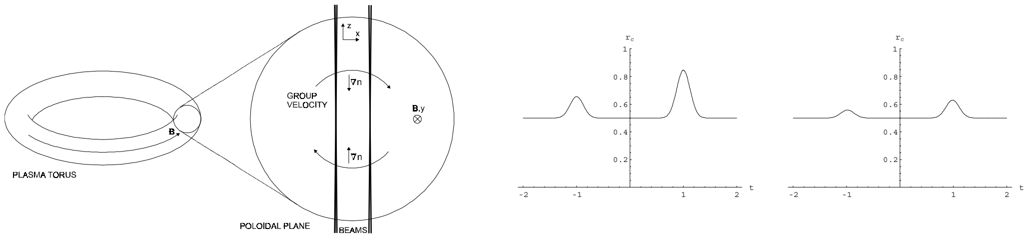

Figure 1. The geometry of drift wave measurements in the W7-AS stellarator (left). The beams all lie in the poloidal plane and are aligned along the z-direction. The main magnetic field is along y. This set-up is sensitive to drift waves propagating in the x-direction. The measurement volume is so elongated in the beam direction that group velocities in both the positive and the negative x-directions contribute to the signal. The crosscorrelation coefficients for a typical measurement system and plasma parameters are shown in the next two frames. The time is normalised to the time-of-flight. The centre picture shows the result assuming no viscous dissipation, and the right-hand picture shows the result for finite dissipation.

1. N. P. Heinemeier, “Flow speed measurement using two-point collective light scattering”, M.Sc. Thesis, Risø report Risø-R-1064 (1998).
2. N. Heinemeier and M. Saffman, “Theoretical analysis of two-point collective scattering correlation functions using a drift wave model”, International Conference on Plasma Physics, paper F071 (Prague, June, 1998).

2.2.2 Relationship between confinement and core plasma fluctuations in the W7-AS stellarator

S. Zoletnik, M. Saffman, W. Svendsen, M. Endler (Institut für Plasmaphysik, Garching, Germany), N. P. Basse and G. Kocsis* (*CAT_SCIENCE, Budapest, Hungary)*

Core plasma electron density fluctuations have been measured with a two-channel CO_2 laser scattering diagnostic at the W7-AS stellarator experiment. The analysing wave number was equal for the two channels and can be varied in the range 10-130 cm^{-1}. Both channels integrate the fluctuations along vertical paths which can be offset relative to each other by a few centimeters either poloidally or toroidally.

The typical frequency spectra of the scattered signals show a turbulent character and extend to a few hundred kHz in ECRH and to 1 MHz in NBI heated discharges as shown in Figure 2. The presence of global modes in the plasma (e.g. Global Alfven Eigenmodes - GAE) causes the appearance of sharp lines in the frequency spectrum although these modes have a much longer poloidal wavelength than is directly detected by the CO_2 laser scattering diagnostic. Their appearance is possibly caused by modulation of the microturbulence level by the rotating mode and makes it possible for us to gain some information on the dependency of the local fluctuation amplitude on the plasma parameters.

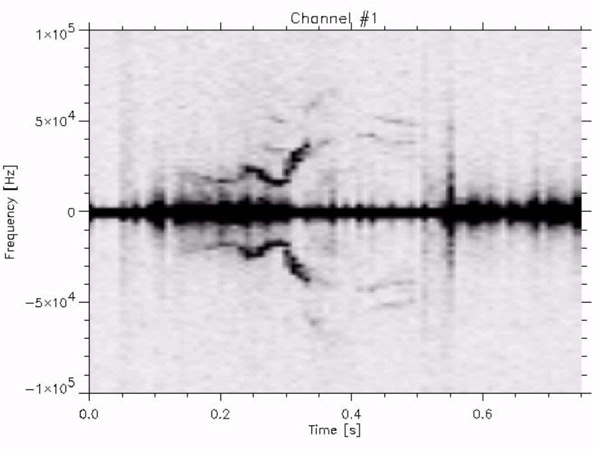

Figure 2. Time evolution of the power spectrum of the scattering signal in the presence of GAE activity. The GAE modes are the sharp lines at 20-40 kHz.

Changes in frequency spectra, crosscorrelation and scattering power were analysed at different types of confinement transitions: changes in response to magnetic configuration alterations, enhancement of confinement in high-density NBI discharges (H-NBI) and degradation of the confinement at the upper density limit of W7-AS. To gain additional information on the phenomena involved, the CO_2 laser scattering data are compared with fluctuation data obtained from other diagnostics: microwave scattering, Mirnov coils, Li-beam BES electron density fluctuation diagnostic, X-ray tomography and others. The results show pronounced changes both in frequency spectra and scattered power at confinement changes. Confinement degradations are usually accompanied by an increase in the scattered power.

Ongoing work is aimed at further characterising the distribution of turbulence in the core and edge regions of W7-AS under different heating scenarios.

2.2.3 Two-point correlations of collective scattering signals in the W7-AS stellerator

S. Zoletnik, M. Saffman, N. P. Basse, W. Svendsen, and G. Kocsis* (*CAT_SCIENCE, Budapest, Hungary)*

Electron density fluctuations have been measured with a two-channel CO_2 laser scattering diagnostic at the W7-AS stellarator experiment. Measurements were made with the two-channels displaced either perpendicular or parallel to the toroidal magnetic field. Measurements were made over a wavenumber range of about 25-60 cm^{-1}, with the measurement volumes separated by 14 mm.

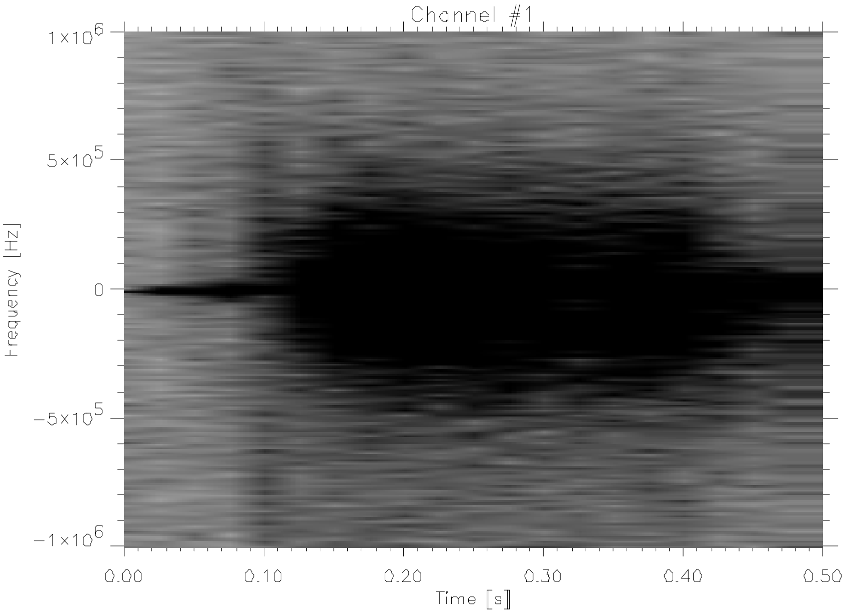

Figure 3. Time evolution of the turbulence power spectrum measured at 46 cm-1.

The time evolution of the measured power spectrum in a single channel for ECRH discharges with nearly constant plasma parameters is shown in Figure 3. The turbulence appears at about T=0.1 sec. and persists until about T=0.5 sec. Cross power spectra for two different time windows and toroidally displaced measurement volumes are shown in Figure 4. In the first time window, before the appearance of the plasma microturbulence, the cross power spectrum shows a peak in the amplitude centered at zero frequency, and a widely oscillating phase. The zero frequency peak is due to correlated technical noise in the two channels. In the second time window the strong plasma turbulence results in a broad feature in the cross power spectrum that extends to about +/- 1 MHz. In this frequency region the phase depends linearly on frequency. This can be interpreted as a turbulent structure propagating along the magnetic field with a constant velocity. Examination of the cross-correlation shown in Figure 5 confirms the presence of a peak at non-zero delay times.

When the measurement volumes are displaced perpendicular to the magnetic field the results are rather different as shown in Figure 6. In this case the cross power spectrum only contains a peak centered at zero frequency, and there is no evidence of a propagating turbulent structure. This measurement is qualitatively consistent with the analysis described in Section 2.2.1 that highlighted the rapid decay of the two-point correlation under the influence of shear and viscous dissipation.

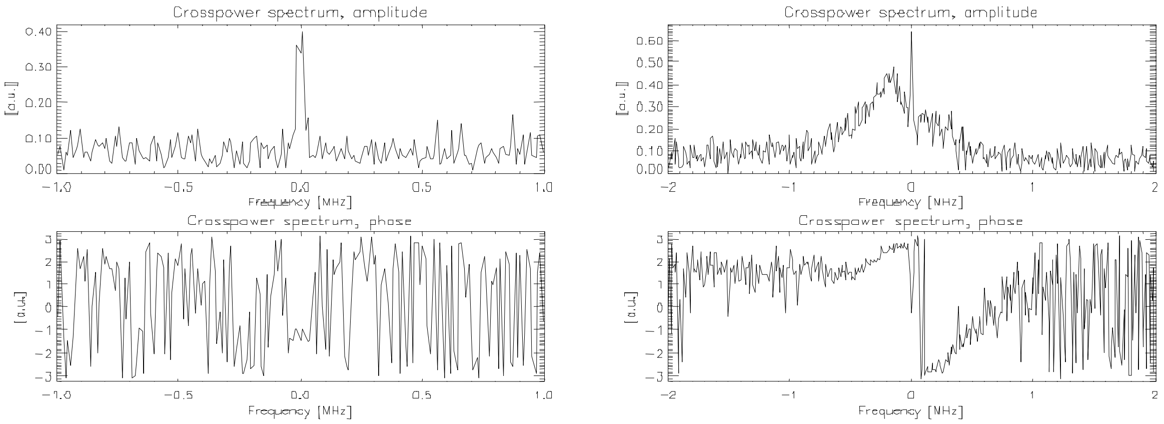

Figure 4 Cross power spectra for toroidally displaced points: T=0.-0.05 sec. (left) and T=0.3 – 0.35 sec. (right)

Interpretation of the correlation results for points separated perpendicular or parallel to the magnetic field lines is not unambiguous. Naively one might assume that the correlation should be ideal along the field lines. The observed reduction in the correlation from a normalized peak value of unity can be attributed in part to technical noise sources, and in part to curvature of the field lines combined with the large spatial extent of the measurement volumes along the optical beams (see Figure 1 in Section 2.2.1) which gives a small effective poloidal/radial separation. Although the time delay in Figure 5 indicates a toroidal velocity of order 30 km/sec it should be recalled that a small effective poloidal/radial displacement of the measurement regions can alter the observed time delay. Indeed the normal assumption of equilibration along the field lines implies that the time delay should vanish for toroidal separation.

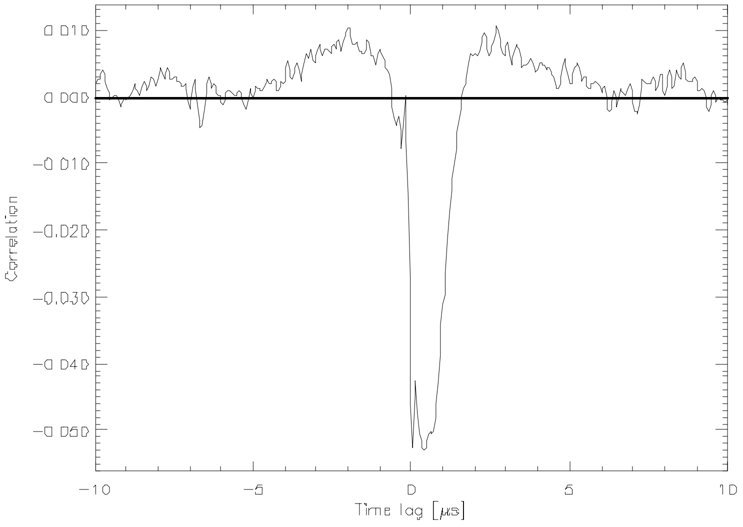

Figure 5 Crosscorrelation of toroidally displaced points in the time window T=0.3-0.35 sec.

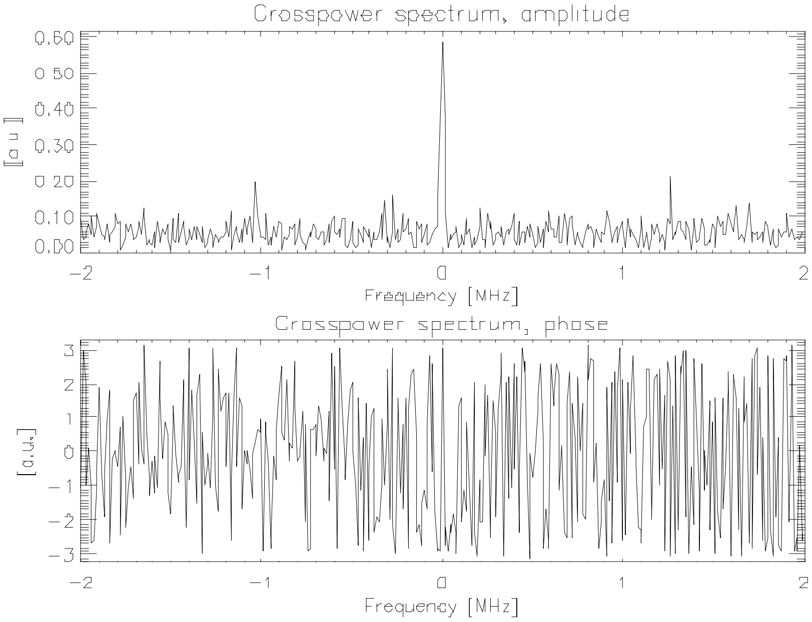

Figure 6 Cross power spectra of poloidally/radially displaced points.

In order to clarify these and other questions ongoing measurements are being performed in which the measurement volumes are continuously rotatable about their center. In this way it is possible to access variable toroidal and radial/poloidal separations and to look for the true peak in the toroidal correlation and the corresponding value of the correlation time delay. Likewise it is hoped to measure the spatial correlation length of the turbulent fluctuations in the plane perpendicular to the toroidal field.

2.2.4 Spectral time series analysis of plasma turbulence

T. Jessen and P. K. Michelsen

A hybrid Doppler/time-of-flight laser anemometer has been developed at Risø and is now in operation at the Wendelstein 7-AS stellarator.[1] The apparatus yields time series of the fluctuating plasma density in neighbouring measurement volumes, from which a subsequent correlation analysis allows extraction of density fluctuation velocities.

The associated data analysis and interpretation has resulted in the development and implementation of a suite of new spectral data analysis techniques.

We have solved the Hasegawa-Mima plasma drift wave equation using a high resolution Fourier-Galerkin method to obtain realistic model data for the analysis techniques. In particular, the effect of various experimental configurations can be isolated and investigated, and data interpretation can profitably be compared with the full field information provided by the simulations.

The Hasegawa-Mima model was solved for various scenarios, ranging from nearly linear conditions dominated by uncorrelated linear drift waves to strong turbulence dominated by spectral cascades, vortex merging and emergence of large coherent structures. The profound change in dynamics was found to imprint important signatures in sampled two-point time series. Spectral time series analysis is found to be a powerful and reliable tool to extract these signatures and, hence, illuminate key features of the underlying dynamics.

From the model simulation two time series of the plasma density at two probe positions are obtained. A preanalysis step involves decomposing each series into an ensemble of elementary series, filtered by a window weight function that minimises amplitude leakage. The data are subsequently fast Fourier transformed to frequency space, where the actual analysis is performed.

Autocorrelations are computed to estimate decorrelation times, while the crosscorrelation yields the time-of-flight of density fluctuations between the two probes and, as a result, estimates their typical propagation speed. A subtle correlation analysis is based on the crossseries coherence. Retaining only coherent frequencies, the phase velocity of individual frequency components can be computed and the dispersion relation recreated. From power spectra, the wave number spectrum can subsequently be resolved. Thus, two-probe measurements allow us to resolve fluctuations both temporally and spatially and to determine their relation.

Nonlinear wave dynamics is identified in the bispectrum that measures the wave triplet interactions. The bispectrum is found to be a useful indicator of nonlinear effects, capable of identifying important features such as three-wave interactions and spectral cascading.

The outlined data treatment techniques are currently being employed in the analysis of W7-AS fluctuation data. Ongoing research aims at enlarging the range of data analysis tools and enhancing their applicability by studying yet more realistic plasma models.

1. W. Svendsen *et al.*, "Collective scattering turbulence measurements at the W7-AS stellarator," Association Euratom – Risø National Laboratory Annual Progress Report for 1997, Risø-R-1070.

2.2.5 Phase contrast methods applied to plasma diagnostics

J. Glückstad, L. Lading and P. C. Mogensen

Interaction between electromagnetic radiation and plasma provides one of the few methods by which direct information about the state of plasma can be obtained. Radiation from a CO_2 laser has the advantage of being readily available with high power and very good coherence properties. The frequency is far above the plasma frequency implying a relatively simple interaction, and the wavelength is so long that probing of collective phenomena is possible. Since the optical wavelength is shorter than the Debye length, forwardscattering is necessary.

From an optical point of view the plasma behaves as a weak dynamic phase object. Visualising spatial phase structures can in principle be performed with a Zernike phase-contrast method. However, for dynamic measurements it turns out that the modelling usually applied is inadequate: the dynamic information may not be present in the detector outputs. Let the impact of the plasma be described by a *transmission function*, $t(x,y)$, which is a pure phase object (no absorption); thus $t(x,y) = e^{i\varphi(x,y)}$, which is often approximated by

$$t(x,y) = e^{i\varphi(x,y)} \cong 1 + i\varphi(x,y) .$$

The detector responds to the intensity, i.e. the absolute square of the electric field. If φ is small, then φ^2 is negligible. The Zernike principle implies that the reference (the directly transmitted beam indicated with a "1") is phase shifted with a small retardation filter with little effect on the diffracted light (φ) so that an interference term between signal and reference appears. However, a complete analysis based on a system indicated in Figure 7 shows that the interference term will vanish. We have developed a new and improved model[1,2] and have investigated schemes where a spatial coding of the transmitted light in conjunction with a generalised phase contrast filter will make it possible to detect the dynamics of spatial structures.[3]

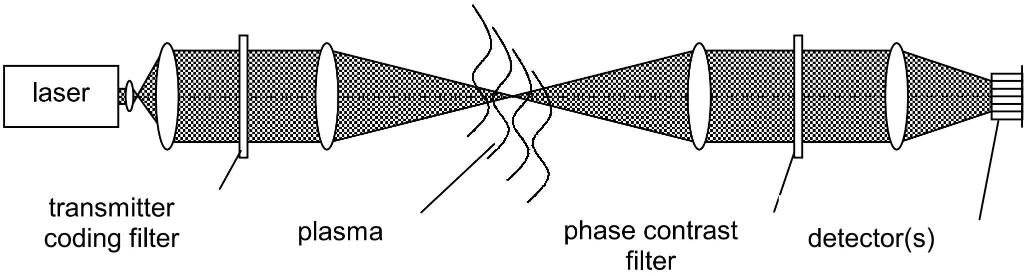

Figure 7. A general configuration with a spatial transmitter filter and a phase contrast filter in the receiver.

1. J. Glückstad, L. Lading, H. Toyoda and T. Hara, Lossless light projection. Opt. Lett. (1997) **22**, pp. 1373-1375.
2. J. Glückstad, Graphic method for analyzing common path interferometers. Appl. Opt. (1998) **37**, pp. 8151-8152.
3. J. Glückstad, L. Lading, Optimising visibility and irradiance in common path interferometers. In: Proceedings of international conference on optical technology and image processing in fluid, thermal, and combustion flow. VSJ-SPIE '98, Yokohama (JP), 6-10 Dec 1998. (Visualization Society of Japan, Yokohama, 1998) AB 010.

2.3 Nonlinear Dynamics of Fusion Plasmas

2.3.1 Plasma simulations in cylindrical and toroidal geometry

V. Naulin, P. K. Michelsen and S. B. Korsholm

The increase in available computational power over the last years sets the stage for more elaborate and complex plasma simulations in 3D. A goal of this project is to make the transition from two- and three-dimensional flat geometries to the complex curved geometry of real magnetic confinement systems. This step is necessary as the major phases of plasma discharges are possibly only explainable by the plasma interaction with the topology of the magnetic field. A parallel, finite-difference code is under development for that purpose. It honours the magnetic field configuration by using Glasser co-ordinates that have one co-ordinate aligned with the magnetic field. This allows the use of a rather rough resolution in that direction as the correlation length along the magnetic field lines is very long. The curvature as well as the magnetic shear is taken into account in the way that they result from the MHD equilibrium. Numerical simulations up to now show the buildup of large structures on the weak magnetic field side and the long correlations along the magnetic field lines. Figure 8 shows a toroidal set-up, where these correlations can be seen. The properties of flux driven transport in this geometry are currently under investigation.

It is planned to extend the code to include non-axisymmetric geometries as in stellarator type devices. Output from standard MHD equilibrium codes will be used to calculate the metric elements required for the simulations.

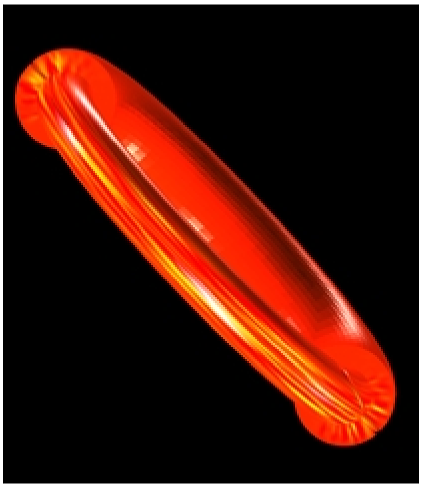

Figure 8. Colour plot of the density calculated with the full toroidal code. The structures visible tend to align to the magnetic field, winding around the torus with a winding number of q = 2.34.

2.3.2 Relation between coherent structures and transport induced by higher order particle drifts

V. Naulin and J. J. Rasmussen

In plasma physics usually only the ExB-drift is considered when fluxes are determined, as the ExB-drift is the dominating particle velocity. However, when the phase shift between particle density fluctuations and fluctuations of the potential is small, the flux due to this drift approaches zero. In a system showing zero ExB-flux there is finite transport due to higher order drifts such as the non-linear polarisation drift. It was shown[1] that the flux connected to this drift is directly linked to the motion of non-linear coherent vortex structures and reflects the Reynolds stress. Moreover, these structures not only transport particles or heat, they also carry charge and are thus capable of organising large charge separations in the plasma leading to large-scale potential structures and, most often, to flows perpendicular to the background density gradient. These zonal flows play an important role in the formation of transport barriers and an understanding of their formation is consequently crucial for the progress in fusion research.

It could further be shown[1] that there is a difference in behaviour between isolated structures and structures moving in the turbulent velocity field generated by neighbouring structures. In the first case the structures arrange for an up-gradient transport of density, thus steepening the gradient. In the turbulence, however, the structures move opposite to the first case, thereby decreasing the density gradient.

1. V. Naulin, Europhysics Letters, **43,** September, 533 (1998).

2.3.3 Turbulent equipartition and the formation of transport barriers

V. Naulin, J. Nycander (FOA, Stockholm, Sweden) and J. J. Rasmussen

Turbulent equipartition (TEP) is a powerful tool for predicting background profiles and gradients. It is, however, dependent on the presence of some kind of turbulence. We investigate a model system of 2D electrostatic pressure driven flute modes. A pinch flux is observed and for boxes of large aspect ratios the TEP profiles are approached. The turbulence is supplied via a Rayleigh-Taylor instability setting in when the pressure gradient exceeds the magnetic field strength gradient. Several different configurations were examined and the results were in good agreement with the theoretical predictions. Up-gradient flows of heat and density were demonstrated[1].

For small aspect ratios, however, the numerical simulations show the evolution of a poloidal shear flow. The curvature of the poloidal velocity leads to stabilisation of the instability and, thus, to a local reduction of the turbulence. In that region the transport then changes from being anomalous, i.e. fluctuation driven, to being diffusive. Therefore, a much steeper gradient evolves in the first region. Subsequently, short burst-like destabilisation occurs which flattens out the profiles locally. The transport associated with these burst-like events propagates down the background gradient and has the properties of an avalanche-like event. A typical event of that type is shown in Figure 9.

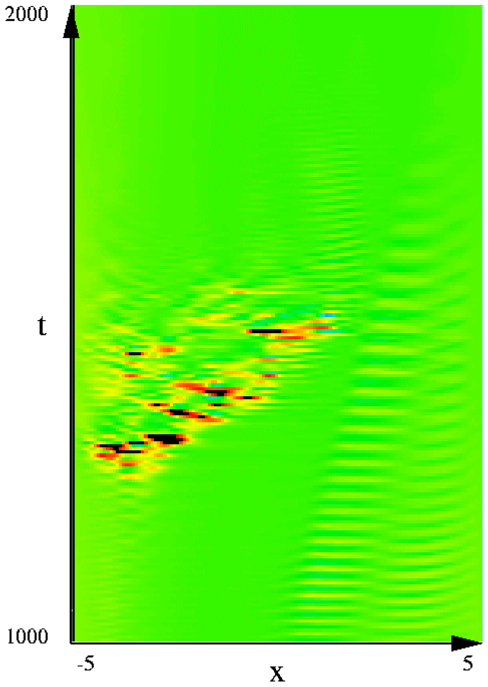

Figure 9. Poloidally averaged heat flow in the radial direction over time. The system is heated from the left and is in a state stabilised by a background shear flow. At t = 1250 local destabilisation causes a large heat flux. The disturbance moves from x = -4.5 to x = 0 in an avalanche-like fashion.

A systematic study of the conditions for the build-up of zonal flows is currently being performed. A central point is determination of the locations and widths of these flows.

1. V. Naulin, J. Nycander, and J. Juul Rasmussen, Phys. Rev. Lett, **81**, 4148 (1998).

2.3.4 Three-dimensional drift wave simulations in a periodic geometry

S. B. Korsholm, P. K. Michelsen, V. Naulin Naulin, and H. L. Pécseli (University of Oslo, Norway)

Control of the transport of energy and particles out of fusion plasmas is a major concern in the development of a fusion reactor. This calls for investigations of the nature of turbulent transport. Resistive drift waves are believed to be important for the turbulent or *anomalous transport*. In the present work, drift waves have been investigated numerically in a periodic geometry in the scope of the Hasegawa-Wakatani model[1] and modifications thereof.

The Hasegawa-Wakatani model describes linearly unstable drift waves driven by the density gradient at the edge of the plasma. The model consists of two coupled non-linear partial differential equations in the perturbations of the density, n, and the electrostatic potential, ϕ. The model was investigated in a triply periodic geometry using Fourier spectral methods. After an initial exponential growth of the energy of the turbulence, the turbulent flow self-focuses into large magnetic field aligned coherent structures[2], so-called *convective cells*. To determine the effect of more physical boundary conditions, simulations were performed with damping applied at the boundaries of the simulation domain. A condensation of energy into convective cells is still present with damping applied, but it is much less profound. In Figure 10 the temporal evolution of the energy is presented in the cases with and without damping. Currently simulations using Dirichlet boundary conditions in the radial direction are performed in order to approach more realistic situations compared to the finite Larmor radius effects.

In the Hasegawa-Wakatani model the ion temperature is assumed to be negligible as compared with to the electron temperature which is assumed constant. The result of assuming a finite but small ion temperature is that finite Larmor radius effects are retained. This modification to the Hasegawa-Wakatani model was investigated numerically but the results were not significantly different because non-linear effects soon become dominant.

In order to make a model with a wider range of validity the Hasegawa-Wakatani model was extended to include electron temperature perturbations as well as an electron temperature gradient. This was done by extending the set of equations by Braginskii's[3] equation for electron temperature. Now both the turbulent particle flux and the heat flux out of the plasma are calculated. The results of the numerical simulations of this model are very preliminary and it is still too early to draw any conclusions.

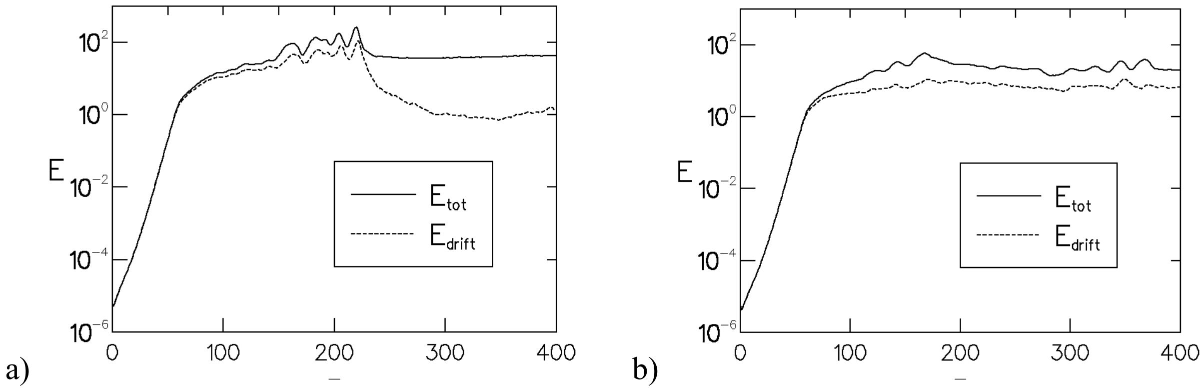

Figure 10. Plot of the evolution of the total and the drift wave energies of a) a non-damped and b) a damped simulation. The initial state is low-level noise and the resolution is 96^2*48.

1. A. Hasegawa and M. Wakatani, *Plasma Edge Turbulence*, Phys. Rev. Lett. **50**, 682 (1983).
2. See also animations at the homepage http://www.risoe.dk/euratom/plasmatheo.html.
3. S. I. Braginskii, *Transport Processes in a Plasma*, Rev. Plasma Phys. **1,** 205 (1965).

2.3.5 Vortex merging as a spectral cascade mechanism in 2D turbulence

T. Jessen and P. K. Michelsen

A hallmark of two-dimensional turbulence is the inverse cascade of energy to large scales of motion, facilitated by the merging of like-signed vortices.

This process has been investigated by studying the vortex dynamics of various dipole and monopole collision events and by numerically solving the two-dimensional plasma fluid equations in the guiding center approximation. A spectral Fourier-Galerkin method with cyclic boundary conditions was employed at high resolution (a minimum of 512^2 modes).

In the absence of viscosity, vortex merging is prohibited, but a similar phenomenon can be observed. Like-signed vortices can spiral into one another effectively forming a single vortex.

An example of a dipole collision is shown in Figure 11. Two stable Lamb dipoles were released on a collision course. Depending on the dipole alignment - ranging from head-on collision to near misses - the dipoles can undergo exchange scattering or pure scattering, i.e., the dipoles persist but may change partners by pairing up with the oppositely signed vortex of the other dipole. This is an indication of the robustness of dipole structures.

For the particular initial alignment shown in Figure 11, a point vortex model predicts a bound, but unstable, state. Our simulation indicates the merging of two like-signed vortices, surrounded by two satellite vortices in an unstable tripole formation. Careful inspection reveals that the vortices do not actually merge, but rather form interlocking spirals with extremely delicate vortex filaments.

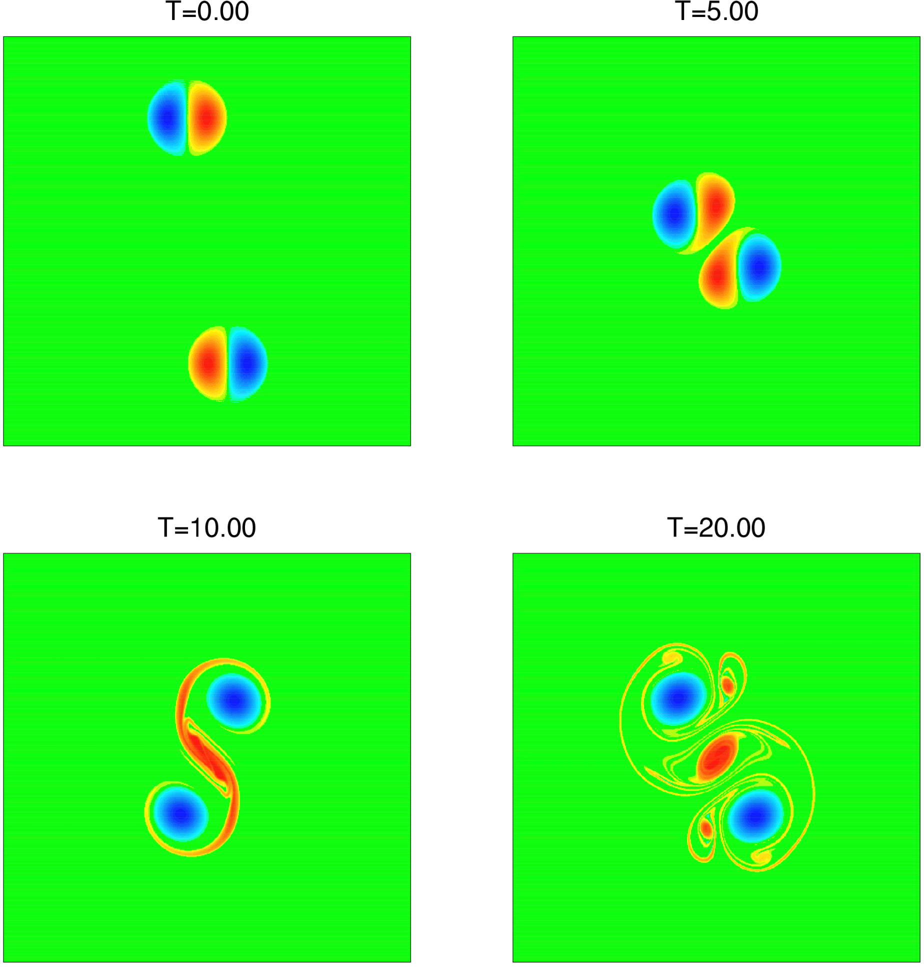

Figure 11. High-resolution numerical simulation of a dipole collision in an inviscid fluid.

2.3.6 Particle tracking in two-dimensional flow field

A. H. Nielsen and J. J. Rasmussen

Particle tracking is an important tool to determine the transport and mixing properties of a flow field. Generally we solve the plasma fluid equations in the guiding centre approximation (equivalent to the Navier-Stokes equations) in the Eulerian framework where the flow field is known at all times in a (fixed) spatial grid. The plasma inside a small element located at a grid point will consist of different particles at different times. The information about how these particles is transported or convected by the flow field is not directly present in this framework.

We have investigated the particle dynamics in a circular shear flow. We have solved the plasma fluid equations using a pseudo-spectral method. As expanding functions we use Chebyshev polynomials and Fourier modes. To follow the trajectories of the particles we evaluate the full spectral expansion of the velocity field. Hereby we use all the information stored in the flow field. Such evaluations are quite expensive in terms of computer time and 200-300 particles take as much CPU time as solving the plasma fluid equations alone. An example of our particle tracking is shown in Figure 12 that displays the time evolution of an unstable axisymmetric annular shear flow developing seven vortices. In the initial flow field 16,000 particles are inserted and traced. The particles are divided into four groups labelled with different colours. Red and green particles are located inside the shear whereas blue and turquoise colours are located just outside the shear. During the creation of the vortices we observe no radial mixing but close examinations of single-particle trajectories reveal strong azimuthal mixing.

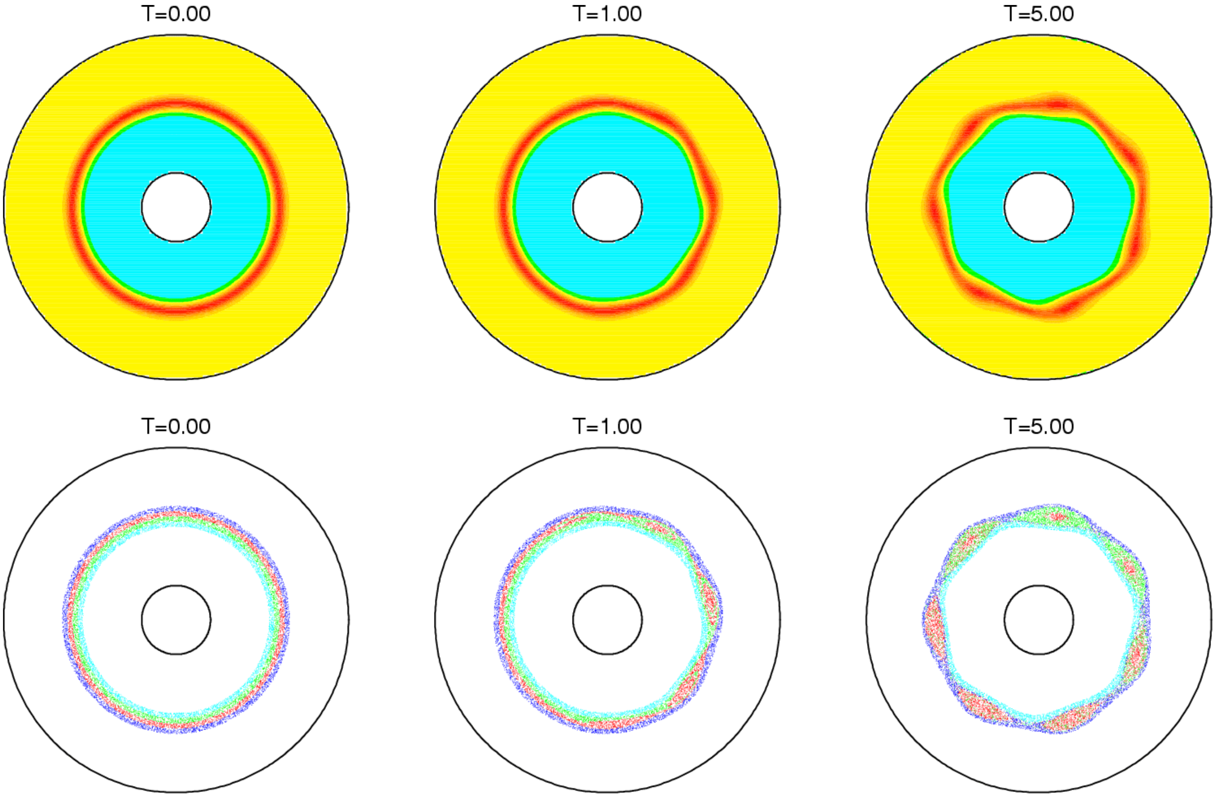

Figure 12. Time evolution of an unstable shear annular flow for a Reynolds number of Re = 101.2. The top figure displays the charge density distribution, and the bottom figure displays 16,000 particles divided into four groups.

2.3.7 Two-dimensional turbulence in bounded flows

A. H. Nielsen, J. J. Rasmussen, D. J. Torres (Physics Dept. and Geophysical Research Center, New Mexico Tech, USA), H. J. H. Clercx (University of Technology, Eindhoven, The Netherlands) and E. A. Coutsias (University of New Mexico, Albuquerque, USA)

Two-dimensional turbulence in unbounded or double periodic domains in neutral fluids as well as in plasmas has been investigated intensively during the last decades by means of numerical simulations. These flows exhibit an inverse cascade of energy, and for decaying turbulence coherent structures comparable with the size of the domain will eventually emerge. Thus, the presence of boundaries and the conditions imposed on them will play a significant role in the evolution of the turbulence and the coherent structures.

In this study we numerically investigate decaying turbulence on circular and square bounded domains and compare with results obtained from double periodic geometries. The model equations are the plasma fluid equations in the guiding centre approximation (equivalent to the Navier-Stokes equations) that are solved using a pseudospectral method. For bounded flows we investigate two different kinds of boundary conditions, no-slip and free-slip. From random (turbulent) initial conditions we observe that the flow organises into large coherent structure(s), see Figure 13, regardless of the boundary conditions. Furthermore, we observe a relative spin-up of the flow as the normalised angular momentum increases with time. For the no-slip boundary condition strong boundary layers are observed; these layers are not present using the free-slip boundary condition.

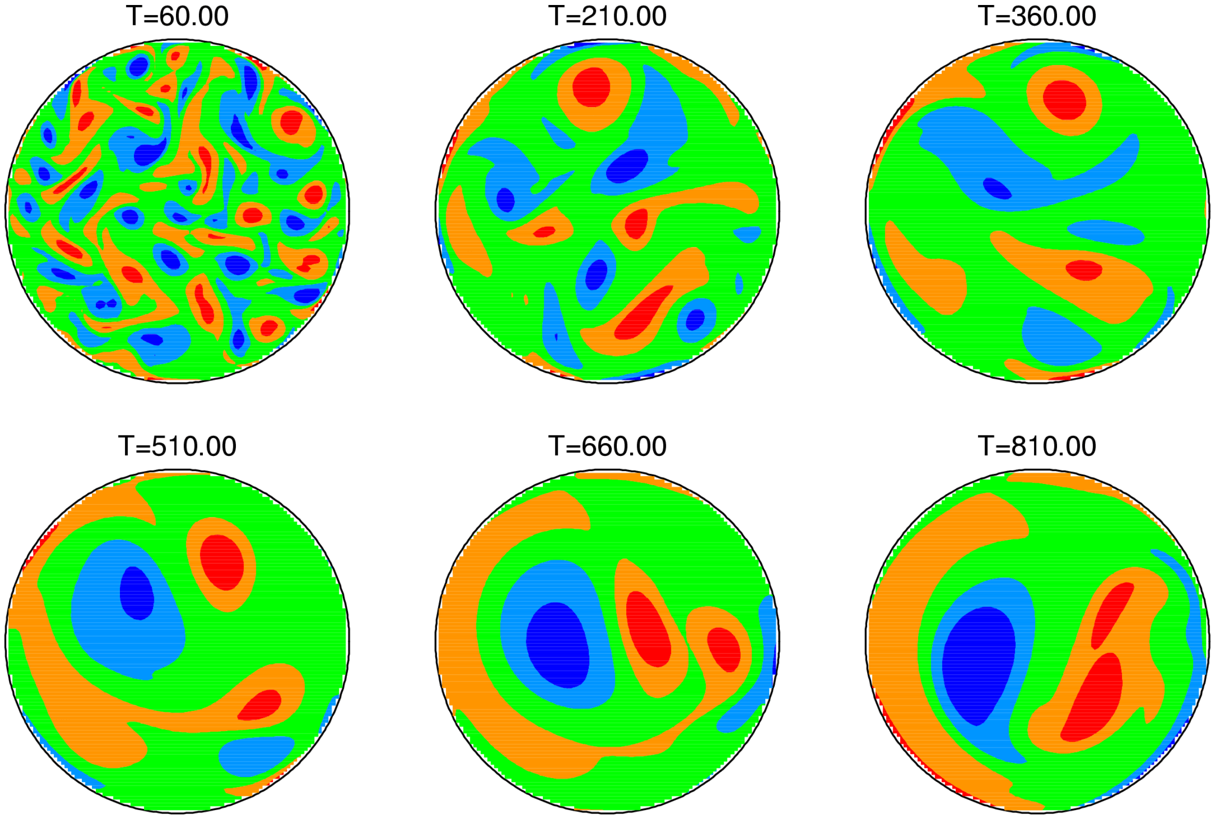

Figure 13. Time evolution of the charge density in a plasma flow initialised with random initial conditions and for no-slip boundary conditions. Red colours correspond to positive values, whereas blue colours correspond to negative values. Limits are adjusted to the individual pictures. Spectral evolution M = 1024, N = 512 and Reynolds number Re = 4950.

2.3.8 Formation of monopolar and tripolar vortices in two dimensional flows

A. H. Nielsen, J. J. Rasmussen and M. R. Schmidt

The formation of vortices from localised perturbation in a two-dimensional flow is investigated theoretically and by direct numerical solutions of the two-dimensional plasma fluid equations in the guiding centre approximation (equivalent to the Navier-Stokes equations). We consider the evolution of a turbulent patch characterised by its energy and enstrophy. In previous studies[1], we have investigated the formation of dipolar vortices evolving from a turbulent patch with a finite linear momentum, but with no angular momentum. Here we consider the opposite case: the patch has a net angular momentum, but no linear momentum. It is constructed from fluctuations with random phases and an isotropic energy spectrum. Depending on the initial condition the patch is found to organise into a non-shielded monopolar vortex for patches with a finite circulation, or into a tripolar vortex for patches with zero circulation. In both cases the functional relationship between the charge density and the electrostatic potential is in general non-linear with a cubic form. The development is qualitatively described as self-organisation in a viscid flow following the approach employed by Leith,[2] where the self-organised structure is characterised by minimising of the enstrophy for a fixed energy. Figure 14 shows the formation of a tripolar vortex for the case where the initial patch has zero circulation.

1. A.H. Nielsen, J. Juul Rasmussen and M.R. Schmidt, Physica Scripta **T63,** 49-58 (1996); A.H. Nielsen and J. Juul Rasmussen, Phys. Fluids, **9,** 982-991 (1997).
2. C.E. Leith, Phys. Fluids, **27,** 1388-1395(1984).

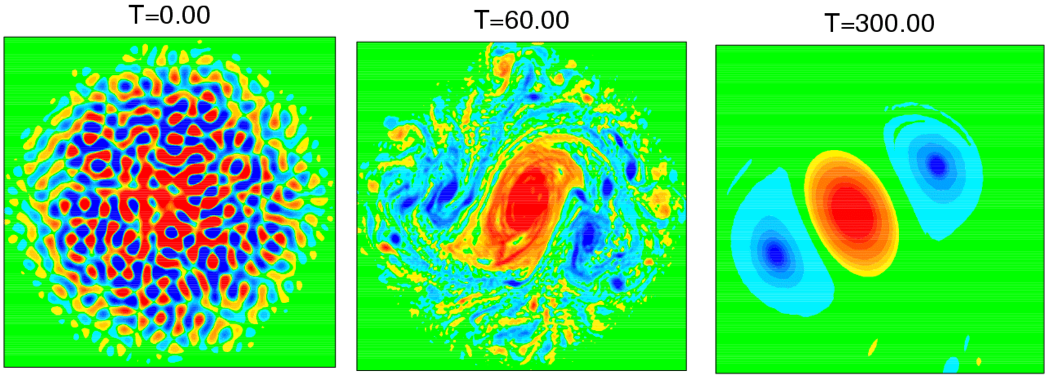

Figure 14. Time evolution of the charge density in a turbulent patch with finite angular momentum, but with zero net circulation.

2.3.9 Full-wave solution of Maxwells equations

P. G. Dinesen, J. S. Hesthaven (Brown University, Rhode Island, USA) and J. P. Lynov

A multidomain pseudospectral code for full-wave solution of Maxwells equation in two-dimensional plasmas with complex geometries has been developed. Full-wave solutions are needed whenever the usual WKB assumption breaks down, which is the case in many applications of plasma heating or plasma diagnostics. The code includes an efficient scheme for absorbing outgoing waves from the computational domain. The Maxwells equations are solved in the time domain (rather than in the frequency domain) so that transient field effects are fully resolved. If a stationary solution is wanted, an efficient acceleration algorithm has been included which greatly reduces the computational time. The code has been tested on problems of electromagnetic wave propagation in inhomogeneous dielectrics with characteristic scale lengths similar to, or even smaller than, the free-space wavelength. In all cases very good accuracy has been obtained. The code is presently being extended into a full three-dimensional version.

2.4 External Projects

2.4.1 Pellet Injectors

P.K. Michelsen and B. Sass

Technical advice of pellet injectors has been given through 1998. A few technical problems of the Frascati 8-shot pellet injector have been solved in collaboration with the Engineering and Computer Department at Risø and the Frascati Pellet Group. Furthermore, the discussion on how to insert a two-stage pellet driver on the Risø injector has continued. A visit of Mr. Sass to Frascati in the beginning of 1999 has been planned in order to perform this operation. In connection to the transfer and installation of the 8-shot pellet injector from RTP to MAST, advise has been given with respect to which modifications of the injector would be possible in order to increase pellet velocities and to change pellet masses.

2.4.2 Laser anemometry for wind turbines

L. Lading, R. Skov Hansen, and S. Frandsen (Wind Energy and Atmospheric Physics Department)

The work on plasma diagnostics based on collective scattering of laser light has given the Association a competence within light scattering, CO_2 laser technology, and light beating. This knowledge is being applied in a very different context, namely long range wind velocity measurements for power curve measurements and control of wind turbines. The aim is a very compact and robust system that is mounted on the nacelle of a turbine and measures the instantaneous wind velocity several hundred meters upstream.

In 1998, the system requirements and definitions were established. A waveguide laser in a so-called autodyne configuration is investigated. In this system, the laser serves both as the generator of transmitted light and as the detector of the back-scattered light. The collected light is fed into the laser and modulates the power output of the laser at the Doppler shift frequency. Such a system is much simpler and more robust than traditional systems based on external mixing. A model for this type of detection is being developed. It appears that the signal-to-shot noise ratio may be almost as good as that obtainable with external mixing. However, the optimum laser design is different from the design giving the largest output power.

The project is not supported by Euratom, but is partly funded through the EU Joule programme. The partners in the project incorporate the world largest manufacturer of wind turbines, *NEG-Micom* (Denmark), a major manufacturer of CO_2 lasers, *Howden Lasers* (United Kingdom), and a small-and-medium-size-enterprise WEA-Engineering (Denmark).

2.5 Participants in Fusion Plasma Physics

Scientific Staff

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Kristensen, Jesper Glückstad (part time)
Lading, Lars (part time)
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Michelsen, Poul K.
Nielsen, Anders H.
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Saffman, Mark

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Naulin, Volker
Svendsen, Winnie (until 31 August)

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Korsholm, Søren Bang (from 1 May)
Schmidt, Michel R. (until 28 February)

Technical Staff

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Bækmark, Lars (until 31 August)
Jessen, Martin (from 15 September)
Sass, Bjarne
Thorsen, Jess

Guest Scientists

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Hesthaven, Jan, Brown University, Rhode Island, USA
Karpman, Vladimir I., Racah Institute of Physics, Hebrew University, Jerusalem, Israel
Mezentsev, V.K., Novosibirsk, Russia

Short-term Visitors

Coutsias, E.A., University of New Mexico, Albuquerque, USA
Garcia, Odd Erik, University of Tromsø, Norway
Klinger, Thomas, University of Kiel, Germany
Kuznetsov, E.A., Landau Institute for Theoretical Physics, Moscow, Russia
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Paulsen, Jim Viktor, University of Tromsø, Norway
Pécseli, Hans, University of Oslo, Norway
Rypdal, Kristoffer, University of Tromsø, Norway

Students Working for the Master's Degree

Heinemeyer, Nicholas (until 31 May)
Korsholm, Søren Bang (until 28 February)

Student Assistants

Basse, Nils Plesner

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3. Fusion Technology

3.1 Introduction

The work reported in this section has been carried out in the Materials Research Department. The overall objective of the research activities in this area is to determine the impact of neutron irradiation on physical and mechanical properties of metals and alloys, so that appropriate materials can be chosen for their application in an irradiation environment (e.g. in a fusion reactor). Various experimental techniques are employed to study different aspects of the microstructural evolution during irradiation and the resulting consequences on the post-irradiation physical and mechanical properties of metals and alloys. Computer simulations are carried out to understand the evolution of surviving defects and their clusters in collision cascades. The kinetics of defect accumulation during irradiation and the influence of irradiation-induced defects and their clusters on the deformation behaviour of irradiated metals and alloys are studied theoretically. In the following, the main results of these activities are highlighted

3.2 Next Step Technology

3.2.1 Effects of Neutron Irradiation on Low Cycle Fatigue Behaviour of Copper Alloys

B.N. Singh, J.F. Stubbins (University of Illinois at Urbana-Champaign, USA), and P. Toft

The ITER design conditions require the use of high thermal conductivity materials for heat sink applications in the first wall, limiter and divertor components and copper alloys provide the best potential for meeting these requirements. Fatigue behaviour is central to materials selection since the vacuum vessel components will be subjected to thermal cycling, and thus thermal-mechanical cycling, as a result of the cyclic plasma burn operation of the system. Design requirements set the limits of useful fatigue testing in the range between ~10 to ~10^6 cycles to failure. Currently, two copper alloys are under consideration including one dispersion strengthened (DS) alloy, Glid Cop CuAl-25 and one precipitation hardened (PH) alloy, CuCrZr. The dispersion strengthened CuAl-25 alloy is, at least at present, the primary candidate alloy. The current work, which is part of a much larger experimental effort on evaluating a number of copper alloys, examines the low cycle fatigue performance of the DS and PH copper alloys both in the unirradiated and neutron irradiated states.

A number of fatigue specimens of these alloys were irradiated in the DR-3 reactor at Risø at 250 and 350°C (in temperature controlled rigs) to a dose level of ~0.3 dpa (NRT). Both unirradiated and irradiated specimens were tested in an Instron machine with a specially constructed vacuum chamber at 250 and 350°C. Fatigue tests were conducted in a strain-controlled mode in a servo-electrical mechanical test stand. The loading cycles were always fully reversed (i.e. R = -1) so that the maximum tension strain was the same as the maximum compressive strain. The loading frequency was 0.5 Hz. The specimens tested in fatigue were cycled to failure. The specimens were heated by electrical resistance furnaces such that the heat was conducted through the specimen grips.

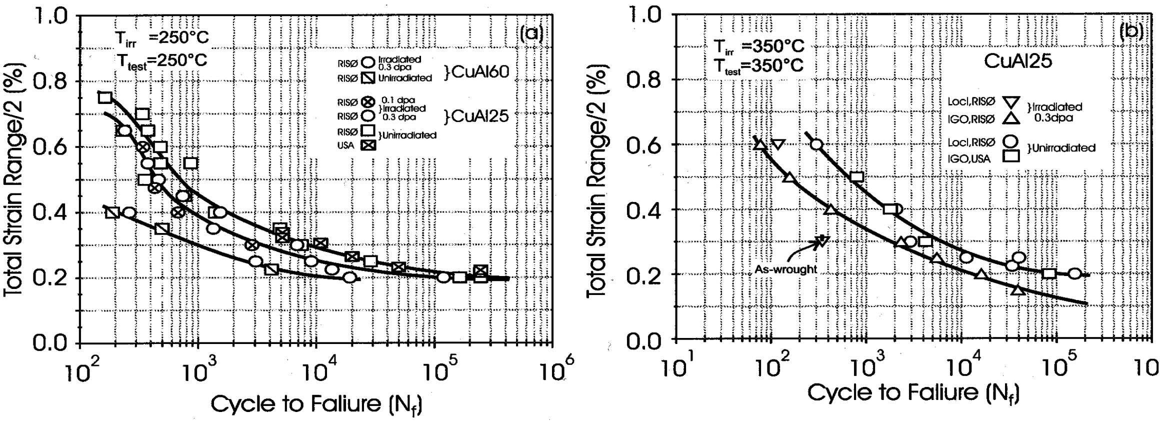

Figure 1. Fatigue life (N_f) as a function of total strain range for unirradiated and irradiated dispersion strengthened copper alloys (a) CuAl-25 and CuAl-60 irradiated and tested at 250°C and (b) CuAl-25 irradiated and tested at 350°C. All fatigue tests were carried out in vacuum (~10^{-5} torr) and in strain-controlled mode with a loading frequency of 0.5 Hz.

The fatigue performance of DS copper alloys (CuAl-25 and CuAl-60) determined at 250°C in the unirradiated and irradiated (250°C, 0.3 dpa) conditions is shown in Figure 1(a). Figure 1(b) shows the fatigue behaviour of DS copper alloy CuAl-25 tested at 350°C in the unirradiated and irradiated (350°C, 0.3 dpa) conditions. Figure 1(a) also includes the results on CuAl-25 irradiated at 250°C but only to a dose level of ~0.1 dpa. The results shown in Figure 1(a) indicate that the neutron irradiation at 250°C (even to a dose level of only ~0.1 dpa) does lead to some degradation in the fatigue lifetime, particularly at higher strain amplitude levels. Another significant aspect of these results is that the fatigue life of the CuAl-60 alloy (containing twice the volume fraction of Al_2O_3 particles than that in the CuAl-25 alloy) is substantially shorter than that of the CuAl-25 alloy both in unirradiated and irradiated states. The effect of neutron irradiation on the reduction in fatigue lifetime of the CuAl-25 alloy is clearly more pronounced at 350°C (Figure 1(b)) than that at 250°C (Figure 1(a)). Furthermore, at 350°C the decrease in lifetime due to irradiation is not limited only to the low strain amplitude regime, but seems to occur at all strain amplitude levels.

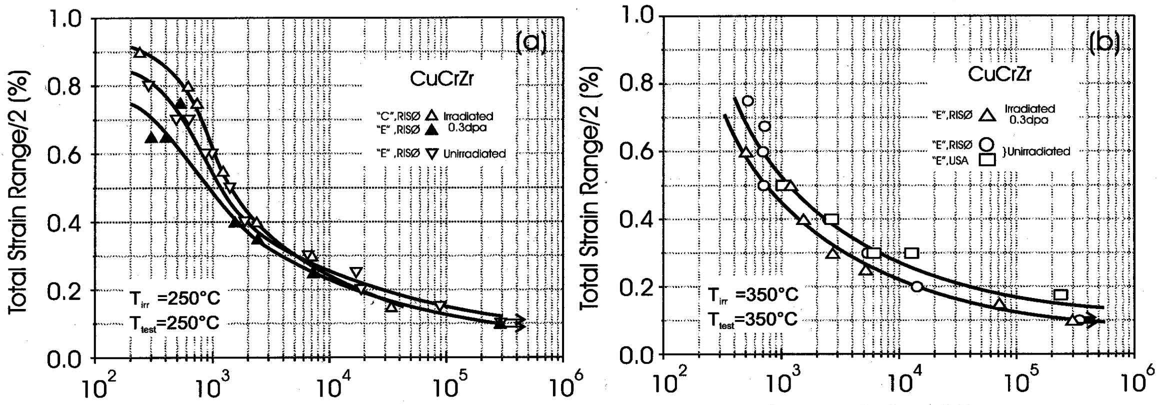

Figure 2. Fatigue life (N_f) as a function of total strain range for unirradiated and irradiated precipitation hardened CuCrZr alloy (a) irradiated and tested at 250°C and (b) irradiated and tested at 350°C. All tests were performed in vacuum (~10^{-5} torr) and in strain-controlled mode with loading frequency of 0.5 Hz.

Figure 2 shows the fatigue behaviour of the PH copper alloy, CuCrZr, irradiated and tested in the prime-aged condition at 250°C (Figure 2a) and 350°C (Figure 2b). The effect of neutron irradiation on the fatigue lifetime is very similar to that observed in the case of DS CuAl-25 at 250 and 350°C.

In general, the fatigue life of CuAl-25, both in the unirradiated and irradiated conditions, is found to be longer than that of CuCrZr alloy at strain amplitudes lower than ~0.3%. At higher strain amplitudes, however, this behaviour reverses.

3.2.2 Effects of HIP Thermal Cycles and Neutron Irradiation on Fracture Toughness of Copper/Stainless Steel Joints

*M. Pyykkönen**, *S. Tähtinen** *(*VTT Manufacturing Technology, Finland), B.N. Singh and P. Toft*

The present design of the ITER Plasma Facing Components consists of a copper alloy heat sink layer between plasma facing materials and stainless steel structure. The main option for manufacturing these components is the Hot Isostatic Pressing (HIP) method and several HIP thermal cycles would be needed for manufacturing, for example, the complete blanket module. Naturally, all the joints must be able to withstand the thermal, mechanical and neutron loads. Since only a limited amount of information is available on the effects of successive HIP thermal cycles on the properties of the base materials and the joints, experimental investigations were initiated to determine fracture toughness of HIP joints between CuAl-25 and CuCrZr alloys and 316 (LN) stainless steel in unirradiated and neutron irradiated conditions.

The appropriate joints were produced by HIP at 960°C for 3 hours at a pressure of 120 MPa. Multiple HIP thermal cycles were simulated by giving two additional heat treatments at 960°C for 3 hours followed by subsequent heat treatment at 460°C for 2 hours for CuCrZr HIP joint specimens. Three point bend specimens for fracture toughness testing were machined such that the crack propagated along the joint interface. All specimens were pre-cracked to the initial crack length to specimen width ratio of about 0.5 and 20% side grooved. The fracture resistance curves were determined at temperatures in the range of 22 – 350°C in a silicon oil bath following the ASTM E1737-96 standard procedure. A number of fracture toughness specimens were irradiated with fission neutrons in the DR-3 reactor at Risø at temperatures in the range of 50 – 350°C to a dose level of 0.3 dpa (NRT).

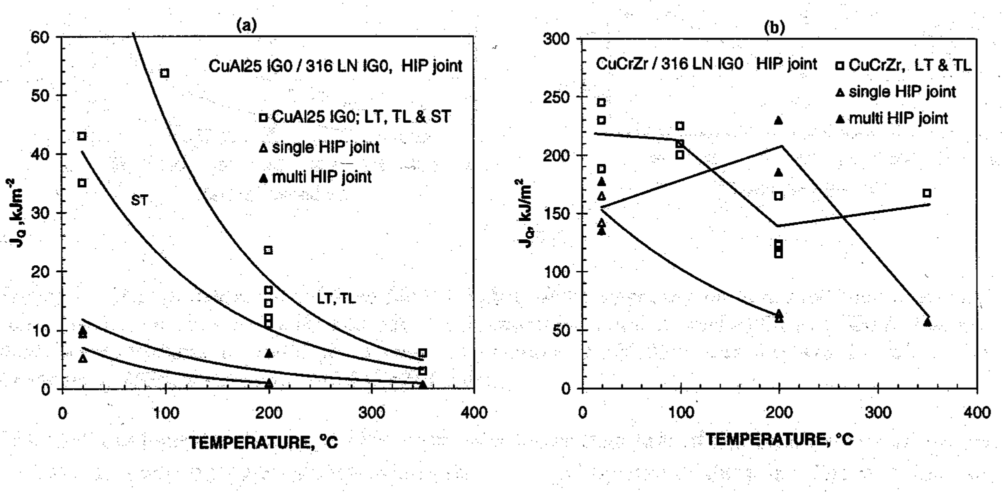

Figure 3. Effect of HIP thermal cycles and temperature on the initiation fracture toughness of HIP joints of (a) CuAl-25 (IGO) and (b) CuCrZr alloy with 316 (LN) stainless steel.

The effect of HIP thermal cycles on the initiation fracture toughness of HIP joints of copper alloys to stainless steel in unirradiated condition is illustrated in Figure 3 for test temperatures in the range of 22 – 350°C. It should be noted that the fracture toughness of multiple (i.e. triple) HIP joints was found to be higher than that of the single HIP joints. However, the fracture toughness of CuAl-25 HIP joints was very low both after single and multiple HIP thermal cycles in the whole temperature range. It should be also mentioned that the crack propagation did not occur exactly at the joint interface but within the copper alloy side of the HIP joints. In the case of CuAl-25 specimens, the crack propagated parallel and close to the joint interface, whereas in CuCrZr specimens the crack deviated away from the interface into the copper alloy. The tendency for the crack to propagate closer to the joint interface increased at elevated temperatures in both copper alloy joints.

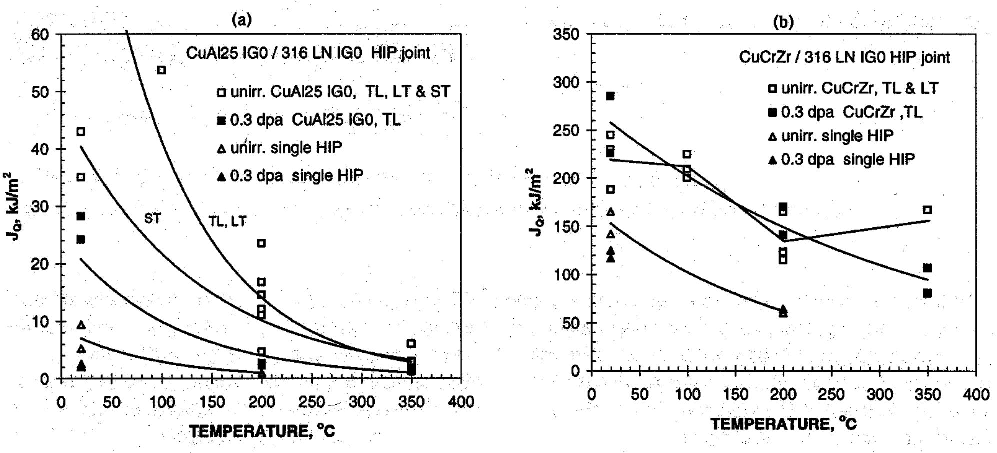

Figure 4. Effect of neutron irradiation (dose 0.3 dpa) and temperature on initiation fracture toughness of copper alloys and their HIP joints with 316 (LN) stainless steel: (a) CuAl-25 (IGO) and (b) CuCrZr.

Neutron irradiation further decreased the fracture toughness of single HIP joints of copper alloys to stainless steel (Figure 4) compared to the fracture toughness of the unirradiated single HIP joints at 22°C. Once again, fracture toughness of the CuAl-25 joints is very much lower than that of CuCrZr joints.

3.2.3 Microstructure and Tensile Properties of Titanium Alloys in the Unirradiated Condition. (Post-EDA Task No. BL 14),

B.N. Singh and P. Toft

The (α + β) Ti-alloy (Ti-6Al-4V) has been selected as the candidate material for the flexible connectors between the blanket modules and the backplate of ITER. At present, not much is known about the effect of neutron irradiations on the mechanical propeties of Ti-alloys. However, the limited amount of the available data on the (α + β) alloy suggests that at elevated irradiation temperatures β-phase may become unstable under neutron irradiation. This may have adverse consequences on high temperature mechanical properties of the alloy. It was, therefore, decided to initiate investigations to examine the effects of neutron irradiation on microstructural evolution and mechanical properties of α (Ti-5Al-2.5 Sn) and (α + β) alloys. It is worth pointing out that the programme did not start until the end of July 1998.

A number of tensile and fatigue specimens were manufactured from the as-supplied materials. Most of the tensile specimens have already been irradiated. The irradiation of fatigue and fracture toughness specimens are in progress.

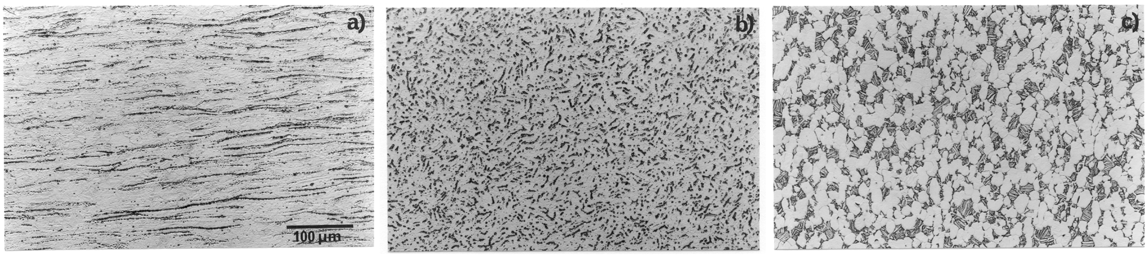

Figure 5. Microstructure of the as-supplied titanium alloys: (a) transverse direction, α-Ti alloy, (b) longitudinal direction, α-Ti alloy and (c) transverse direction, (α + β)-Ti alloy.

The microstructure of the as-supplied α and (α + β) alloys has been examined and examples are shown in Figure 5. As can be seen in Figure 5(a), the α Ti-alloy shows the presence of a reasonably homogeneous distribution of some kind of precipitates in the transverse direction, whereas the precipitates are seen to be aligned along the extrusion direction in the longitudinal section of the α-Ti alloy (Figure 5(b)). In the case of the (α + β) alloy, on the other hand, the microstructure is found to be homogeneous and equiaxed both in the longitudinal and in the transverse direction (Figure 5(c)).

A number of unirradiated specimens of α and (α + β) alloys were tensile tested at 22 and 350°C and the results are shown in Figure 6. As it can be seen in Figure 6, the (α + β) alloy is only slightly stronger than the α-alloy both at 22 and 350°C. It should be noticed, however, that the α-alloy tested at 350°C shows an indication of yielding which is not present in the case of the (α + β) alloy.

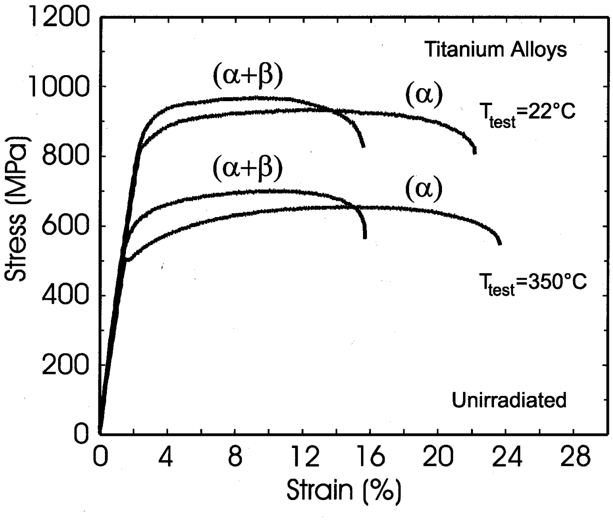

Figure 6. Stress-strain curves for α and (α + β) titanium alloys tensile tested at 22 and 350°C in vacuum in the as-supplied condition.

3.3 Long Term Technology

3.3.1 Effect of Irradiation on Microstructure and Mechanical Properties of Pure Iron and Low Activation Steels

B.N. Singh, A. Horsewell and P. Toft

Effects of neutron irradiation on physical and mechanical properties of low activation ferritic-martensitic steels are being extensively studied internationally since these alloys are considered to be candidate materials for the blanket and first wall of fusion reactors (e.g. DEMO). The present work is a part of the European activities devoted to mechanistic studies of damage accumulation, irradiation hardening and loss of ductility under neutron irradiation conditions.

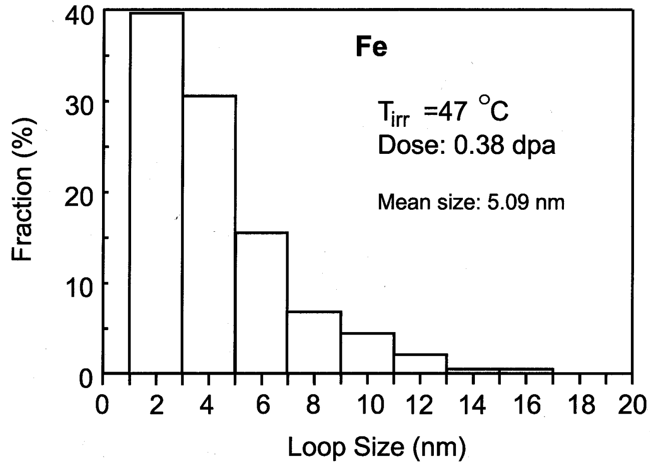

Figure 7. Size distribution of defect clusters/loops in pure iron irradiated at 47°C to a dose level of 0.38 dpa.

Transmission Electron Microscopy investigations were carried out on irradiated specimens of pure iron, F82H and MANET-2 low activation steels. The size distribution of defect clusters/loops for pure iron irradiated at ~47°C to a dose level of 0.38 dpa is shown in Figure 7. In F82H and MANET-2 steels the pre-irradiation microstructure is very complicated. Because of this, it was not possible to quantify the evolution of the irradiation-induced defect clusters and loops. No evidence of visible voids could be found. In the case of F82H steel irradiated at 350°C the dislocation microstructure indicated that the microstructure had partially recovered during irradiation.

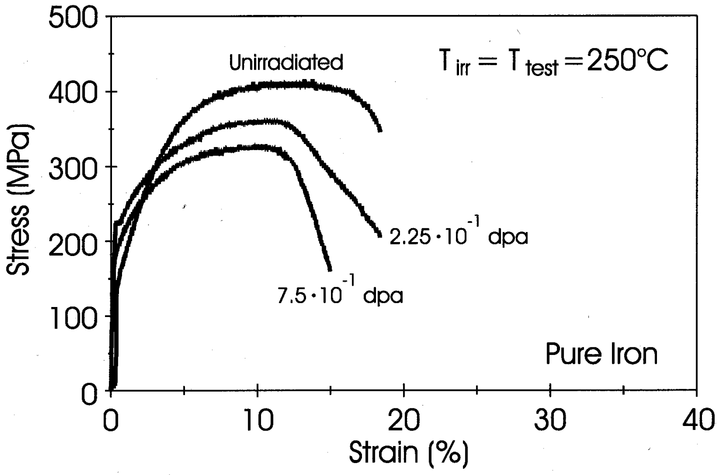

Figure 8. Stress-strain curves for pure iron irradiated and tensile tested at 250°C in vacuum (~10^{-5} torr). Note the appearance of yield-drop phenomenon in the specimen irradiated to 0.23 dpa.

Figure 8 shows stress-strain curves for pure iron irradiated at 250°C. It is interesting to note that the tensile strength first decreases significantly and then increases again, but even at 0.23 dpa the strength remains lower than that of the unirradiated specimens. Furthermore, at 0.23 dpa, the phenomenon of yield drop can be seen again. It should be pointed out that the phenomenon of the yield drop and plastic instability is not observed in F82H and MANET-2 steels irradiated at temperatures in the range of 50 to 350°C.

The temperature dependence of the yield stress of F82H and MANET-2 steels is shown in Figure 9 for the unirradiated and irradiated conditions. It can be seen that the irradiation-induced increase in the yield stress decreases rather strongly with increasing temperature for F82H as well as MANET-2 steels. In the case of F82H steel, the irradiation at 350°C causes softening, i.e. the irradiated F82H is softer than the unirradiated F82H. The reason for this irradiation induced softening in F82H and the strong effect of temperature on the reduction in the level of radiation hardening is not clearly understood at the present moment.

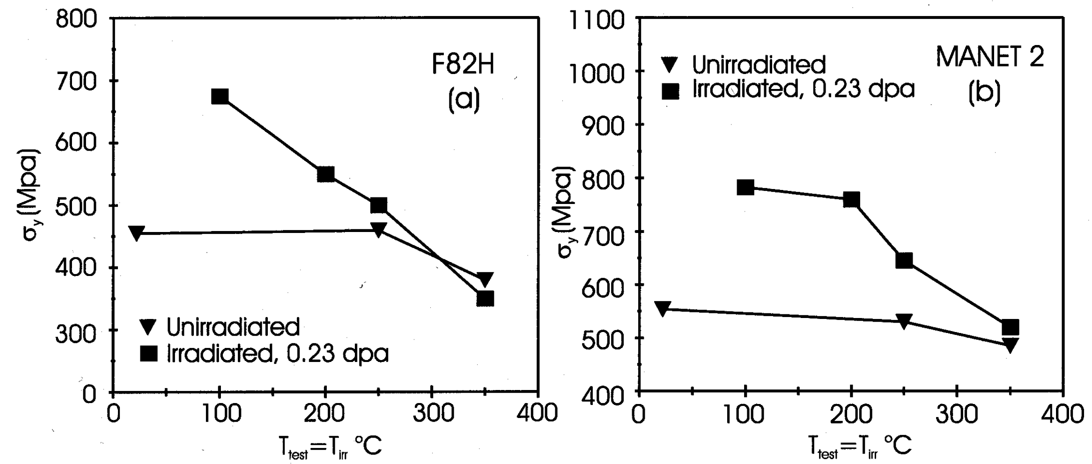

Figure 9. Temperature dependence of the yield stress in the unirradited and irradiated (0.23 dpa) condition for (a) F82H and (b) MANET-2 steels.

3.3.2 Annealing Behaviour of Irradiation-Induced Defects in Pure Iron

M. Eldrup and B.N. Singh

The problem of void swelling in the F82H steel is being studied in several laboratories. Only a limited amount of experimental results are available at present. Some of the results show evidence of void formation, but there are also experimental results showing the absence of voids. This uncertainty needs to be resolved since these steels will have to survive very high doses in a DEMO reactor. In addition to high displacement doses, these steels will also have to remain swelling resistant in the presence of large amounts of hydrogen and helium produced by 14 MeV neutrons. Gases, particularly inert gases such as helium, are well known to assist cavity nucleation.

In order to clarify some of the basic aspects of void formation in bcc metals and alloys, it was decided to study the problem of void formation in pure iron using the positron annihilation spectroscopy (PAS) and electrical resistivity measurements. The PAS technique was chosen because it is sensitive to defects such as single vacancies, two-dimensional vacancy clusters (i.e. loops) and three-dimensional vacancy clusters such as voids and gas bubbles. The lifetime of positrons that are trapped in three-dimensional vacancy clusters (i.e. voids) increases with cluster size in the size range of ~1 to 50 vacancies. Thus, with the PAS technique it is possible to detect sub-microscopic voids. Furthermore, the technique provides information about both cavity density as well as the cavity size.

Specimens of pure iron were neutron irradiated at 100°C in the DR-3 reactor at Risø to a displacement dose level of 0.23 dpa. The irradiation temperature of 100°C was chosen because this is above recovery stage III where vacancies become mobile and is below stage V so that vacancies cannot evaporate from vacancy clusters. This means that vacancy clusters formed during irradiation at 100°C in the form of single vacancies, two-dimensional loops or three-dimensional cavities can be identified by the PAS technique in the as-irradiated specimens.

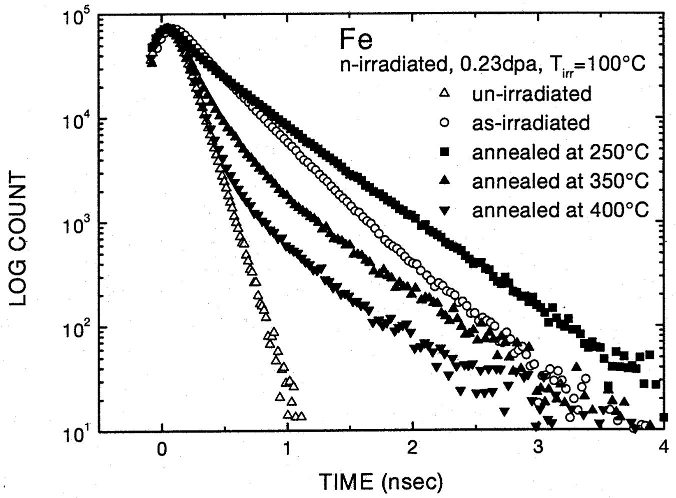

Figure 10. Positron lifetime spectra for irradited and annealed pure iron. The spectrum for the unirradiated iron is also shown for comparison. The spectra for pure iron contain components with much longer lifetime indicating the presence of micro-voids and voids.

The PAS measurements were made on the as-irradiated specimens. Further evolution of the defect microstructures in the same specimens was followed by isochronal annealing in steps of 50°C with a hold time of 50 min. at each annealing step. Electrical resistivity measurements and PAS measurements were carried out after each step. This procedure was continued until a temperature at which practically all defects were found to have annealed out. Positron lifetime spectra for irradiated and annealed specimens are shown in Figure 10 and the three positron lifetimes and the intensities of the two long-lived components extracted from the measured lifetime spectra are shown in Figure 11 as functions of annealing temperature.

The results clearly demonstrate the presence of micro-voids containing 10 – 15 vacancies (0.6 nm in diameter) in the as-irradiated specimens. The concentration of these micro-voids is estimated to be ~1 x 10^{24} m^{-3}. On annealing the micro-voids grow into voids of ~1 nm in diameter (i.e. containing about 50 vacancies) with a concentration of ~1 x 10^{23} m^{-3}. These results directly imply that the low activation steel such as F82H may have potential of void swelling particularly in the environment of 14 MeV neutrons, where considerable amounts of hydrogen and helium will be generated via mutational reactions.

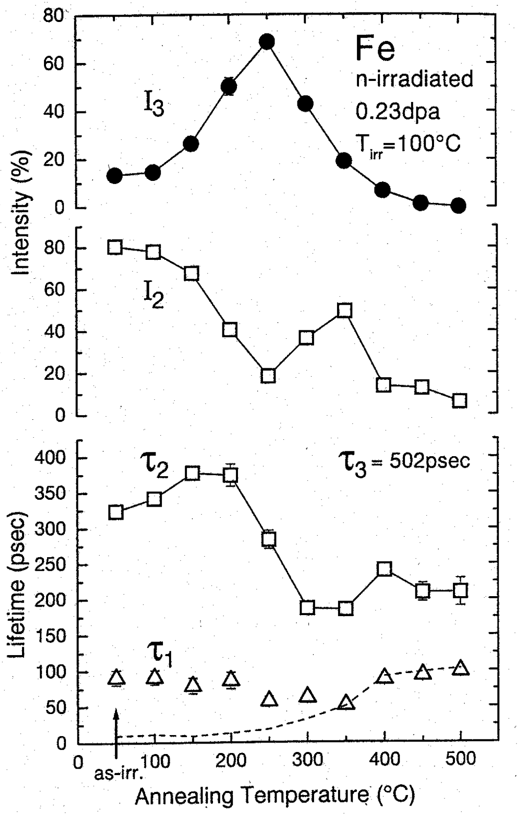

Figure 11. The three position lifetimes and the intensities of the long-lived components extracted from the spectra for the irradiated iron as functions of annealing temperatures.

3.4 Underlying Technology

3.4.1 Simulation of the Kinetics of Defect Accumulation in Copper under Neutron Irradiation

H.L. Heinisch) (*)Pacific Northwest National Laboratory, Richland, USA) and B.N. Singh.*

Experimentally it is well documented that neutron irradiation of metals and alloys at temperatures below the recovery stage V (i.e. <0.3 T_m where T_m is the melting temperature) causes a substantial amount of radiation hardening, a drastic decrease in ductility (commonly known as “low temperature embrittlement”) and induces plastic instability. The problem of irradiation-induced loss of ductility and plastic instability has been a mater of serious concern from the point of view of materials performance and lifetime in radiation environment of energetic neutrons. Recently, this problem has been reanalysed and a new model called Cascade Induced Source Hardening (CISH) has been proposed[1] in order to understand the initiation of plastic deformation in materials irradiated with cascade producing neutrons. In order to establish the validity of certain assumptions made in the CISH model, it was deemed necessary to investigate the process of damage accumulation under cascade damage conditions, using kinetic Monte Carlo simulations.

This kind of simulations was used earlier to study defect evolution within individual displacement cascades[2]. Using sufficiently large volume with periodic boundaries, similar Monte Carlo simulations have been carried out to study evolution and accumulation of defects and their clusters during continuous irradiation. The irradiation is simulated by successive introduction of collections of defects representing the primary damage state of individual cascades placed in the simulation volume randomly in time and space. Cascade energies and the rate of their occurrence are chosen to approximate the damage due to the neutron flux of the 14 MeV neutrons in the RTNS-II. The cascades are chosen from a library of cascades generated in molecular dynamics simulations for recoil energies from 5 to 25 KeV. The numbers of each type of defect, defect cluster size distributions, as well as the positions of the defects within the crystal, are monitored as a function of time (i.e. dose). Simulated defect cluster densities at room temperature as a function of displacement dose up to 0.1 dpa are compared with experimental results in Figure 12. The simulated cluster densities are within about a factor of two of the experimental results for copper irradiated with 14 MeV neutrons at room temperature over several orders of magnitude of displacement dose.

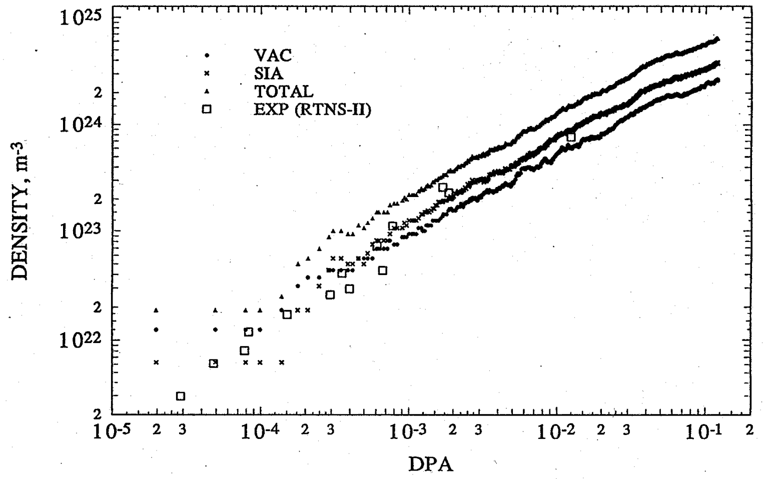

Figure 12. Simulated densities of single vacancies, self-interstitial atoms, and vacancy and interstitial clusters as a function of accumulated dose for copper irradiated at 300K under cascade-producing irradiation (as by 14 MeV neutrons) at a damage rate of 10^{-10} dpa/s. Simulation results are compared with experimental results for copper irradiated in RTNS-II.

1. B.N. Singh, A.J.E. Foreman and H. Trinkaus, J. Nucl. Mater. 249 (1997) 103.
2. H.L. Heinisch and B.N. Singh, J. Nucl. Mater. 251 (1997) 77.

3.4.2 Analysis of Damage Accumulation in fcc and bcc Metals and Alloys in Terms of Production Bias Model

S.I. Golubov, B.N. Singh and H. Trinkaus⁾. (*⁾Forschungszentrum Jülich, Germany)*

In recent years, it has been shown that the problem of defect accumulation (e.g. void swelling) under cascade damage conditions (e.g. during irradiation with fission and fusion neutrons) can be properly addressed within the framework of production bias model (PBM)[1, 2]. Furthermore, it has also been demonstrated that various aspects of experimentally observed behaviour of void swelling in fcc metals can be described quantitatively in terms of the PBM.

While analysing the problem of very large differences in the defect accumulation behaviour between fcc and bcc metals[3] in terms of the PBM, it was recognised, however, that the reaction kinetics of the one-dimensionally diffusing interstitial clusters in fcc and bcc crystals may be different. We consider that this difference in the reaction kinetics may be due to changes in the direction of the 1-D diffusional transport (e.g. due to Burgers vector changes) of interstitial clusters before they are absorbed at sinks in the crystal. The impact of such changes in the direction on the reaction kinetics of interstitial clusters with other sinks in the crystals (e.g. dislocations, voids) has been treated.

The analysis suggests that at present the PBM is able to rationalize the whole variety of experimental observations when the effects of Burgers vector changes of 1-D diffusing interstitial clusters are properly taken into account. In the case of random distributions of sinks (dislocations and voids), for which a rigorous treatment of the mixed 1-D and 3-D kinetics are in preparation, the treatment of defect accumulation by the recent version of the PBM does not require any substantial revision as long as the cluster reaction kinetics do not become effectively of 3-D type. In order to treat the formation and evolution of void lattices, on the other hand, details of the reaction kinetics used in the present version of the PBM would have to be modified.

1. B.N. Singh, S.I. Golubov, H. Trinkaus, A. Serra, Yu.N. Osetsky and A.V. Barashev, J. Nucl. Mater. 251 (1997) 107.
2. B.N. Singh, J. Nucl. Mater. 258 – 263 (1998) 18.
3. B.N. Singh and J.H. Evans, J. Nucl. Mater. 226 (1995) 277.

3.4.3 Effect of Neutron Irradiation on Physical and Mechanical Properties of Copper and Cu-Ni Binary Alloys

B.N. Singh, M. Eldrup and P. Toft

In studies of defect generation and accumulation during irradiation, electrical resistivity measurements have been carried out on high purity copper neutrons irradiated at different temperatures in the range of 100 – 350°C to a dose level of ~0.3 dpa. The effect of irradiation on electrical conductivity was found to be almost independent of irradiation temperature and at a level of 90.5 ± 1.5% of the conductivity of pure unirradiated copper. On annealing the recovery of the defect microstructure and the conductivity are observed in the temperature range of 250 – 550°C but the conductivity does not recover fully to 100% even at the highest annealing temperature. This is thought to be due to the impurities produced during irradiation via nuclear reactions.

The sensitivity of the electrical conductivity to impurities or alloying elements is clearly demonstrated by results for copper-nickel alloys. For an alloy with 2% Ni, the conductivity is reduced to about 38% of that of pure copper, while 5% Ni reduces the conductivity down to 20% of the copper value. Neither neutron irradiation (to 0.3 dpa) nor the post-irradiation annealing at 300°C for 50 hours led to any changes in these conductivity values. This suggests that the conductivity of copper would decrease during irradiation since nickel will be produced continuously during irradiation with fusion neutrons via nuclear reactions.

Figure 13(a) shows the stress-strain curves for Cu-2% Ni and Cu-5% Ni irradiated at 200°C to a dose level of 0.3 dpa and tested at 200°C. For comparison the curves for the unirradiated specimens tested at 200°C are also shown in Figure 13(a). It can be clearly seen that irradiation causes an increase in the yield stress, a decrease in the ductility and a decrease in the rate of work hardening. It is interesting to note, however, that the irradiated Cu-Ni alloys deform homogeneously and do not show any sign of plastic instability as can be seen in the case of CuCrZr alloy also neutron irradiated and tested at 200°C (Figure 13(b)).

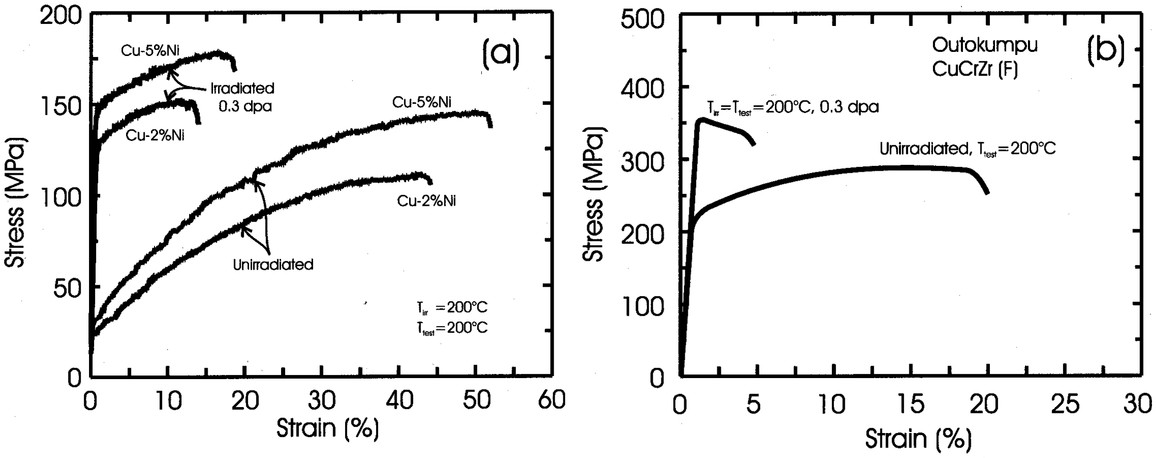

Figure 13. Stress-strain curves for (a) Cu-2% Ni and Cu-5% Ni and (b) CuCrZr alloy irradiated and tensile-tested at 200°C. Note that Cu-Ni alloys do not exhibit occurrence of yield drop and plastic instability.

3.5 Participants in Fusion Technology

Scientific Staff

Eldrup, Morten	(part time ~70%)
Horsewell, Andy	(part time ~20%)
Singh, Bachu N.	
Toft, Palle	(part time ~60%)

Technical Staff

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Nilsson, Helmer	(part time ~10%)
Olsen, Benny F.	
Pedersen, N.J.	(part time ~40%)

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Heinisch, H.L.
Pacific Northwest National Laboratory, Richland, USA

3.6 Publications and Conference Contributions

3.6.1 International Publications

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Lynov, J.P.; Singh, B.N (eds.), Association Euratom - Risø National Laboratory annual progress report for 1997. Risø-R-1070(EN) (1998) 60 p.

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Singh, B.N.; Toft, P., Effect of post-irradiation heat treatment on mechanical properties of OFHC-copper and copper alloys. Risø-R-1009(EN) (1998) (ITER R&D Task No. T213) 19 p.

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3.7 Socio-Economic Research on Fusion (SERF)

3.7.1 Macrotasks

Risø National Laboratory has contributed to three macro-tasks in the Programme for Socio-economic research on Fusion:

- Macro task SE0: Development of long term scenarios.
  In this task Risø has mainly contributed with analysis of existing long term studies.

- Macro task E1: Production costs of energy technologies.
  The Risø contribution in this macro task was mainly related to the long-term cost assessment of renewables, especially wind energy and photovoltaics.

- Macro task E2: External costs and benefits of energy technologies.
  Using the ExternE methodology Risø has been responsible for the evaluation of external costs for wind energy and photovoltaics.

All three tasks are finished by now and the following final reports published:

Lemming, J. and Morthorst, P.E.: Analysis of long-term energy scenarios, Risø National Laboratory, September 1998. (SE0)

Morthorst, P.E.: Wind power development – Status and perspectives, Risø National Laboratory, September 1998. (E1)

Fenhann, J.: Solar photovoltaics development – Status and perspectives, Risø National Laboratory, September 1998. (E1)

Schleisner, L. and Korhonen, R.: Socio-economic Research on Fusion, SERF 1997-98. Macro task E2: External costs and benefits. Task 2: Comparison of External costs, Risø National Laboratory, Denmark, VTT, Finland, December 1998. (E2)

3.7.2 Scientific staff

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Abstract (max. 2000 char.)

The programme of the Research Unit of the Fusion Association Euratom - Risø National Laboratory covers work in fusion plasma physics and in fusion technology. The fusion plasma physics group has activities within development of laser diagnostics for fusion plasmas and studies of nonlinear dynamical processes related to electrostatic turbulence and turbulent transport in magnetised plasmas. The activities in technology cover investigations of radiation damage of fusion reactor materials. These activities contribute to the Next Step, the Long Term and the Underlying Fusion Technology programme. The technology activities also include contibutions to macrotasks carried out under the programme for Socio-Economic Research on Fusion (SERF). A summary is presented of the results obtained in the Research Unit during 1998.

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