2a) Beam-wave interactions and high-power rf generation

2a1) Application of sheet e-beam to quasi-optical gyrotron

During the period in subject, work has been initiated, to assess the feasibility of using a sheet electron beam on the output radiation beam from a conventional gyrotron directly (that is, without employing a resonator), with the aim of amplifying the propagating rf power to values possibly in excess of 2 MW. The work performed has been necessarily of preparatory nature, so no detailed results can be reported yet. The particular activities performed have been: viagra wirkung
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The equations for the rf field profile and for the electron dynamics have been obtained, taking into consideration an arbitrary angle of impact for the electron beam and arbitrary polarization for the rf fields.

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A simple numerical code has been prepared, to solve for the equations of electron motion. (*The code is expected to be fully debugged soon, so that the first results, concerning the evolution of constituent beamlets, hopefully will be available early in year 2003.*
)

2a2) Self-consistent 3-D electrostatic code for gyrotron beam tunnel

During the period in subject, the 3D electrostatic code *ARIADNE* (**Annex I**) has been brought to a fully operational state. (Although further improvements are envisaged for the future.) The following specific tasks have been addressed:

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The user manual of the programme has been developed. All available possibilities to the user, such as, the installation of the programme, the syntax of the commands, the manipulation of the output data, are presented in the text. Furthermore, an extensive and detailed description of the structure and the procedures of the programme is included.

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Second order interpolation is incorporated in the programme for the calculation of the potential. The potential in any tetrahedrical element are expressed by the value of potential on the vertices and the middle-edges points. This approximation improves dramatically the calculation of the electric field in the region of the electron beam.

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The parallelization of the code has been done successfully. The domain decomposition method is applied for the manipulation of meshes with large number of nodes through the usage of parallel computer systems. The solution of the sparse linear system is obtained by the parallel implementation of the successive over relaxation method.

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In addition, the code has been used to obtain the first set of results, on the effects of cathode emission with no azimuthal symmetry (*This activity is expected to be completed by the end of January 2003.*).

2a3) Electromagnetic code for beam-tunnel spectrum

The following work has been done in the tasks of this activity:

(i) *Development of the numerical code Complex Fishbone in C under Unix environment, for the non-periodic corrugated waveguide, which include all types of waves (continued from previous period).* We have finished the numerical code Complex Fishbone for the non-periodic corrugated waveguide with dielectric material with losses, for all types of waves. The code has been written in C language and now there are available versions of this code for different operational systems, i.e., Windows, Linux, HP-UX and Sun OS unix. Our difficulty is that many systems with Unix environment do not support all the libraries included in the code and therefore special attention has to be given in the transformation and the compilation of these codes. We have also finished the interface for Linux, Windows NT and Windows 2000, WindowsXP. Special effort has been given to check the validity of our code in several different OS. For this purpose, Dr. Micha Dehler, from PSI, Switzerland, has visited Athens for a week last November in order to check the results of our code with those obtained by the commercial code MAFIA. From the numerical results it has been found excellent agreement between the two codes. Most of the effort of the team during this year has been given to finalise this numerical code in order to be ready for any user. To this end, we have made several changes in order to make the code as fast and user friendly as possible. A part of this work has been presented in the 2nd European Symposium on Numerical Methods in Electromagnetics, JEE-'02, Toulouse, France, 6-8 March 2002 (see Annex II).

(ii) *Development of the beam-loading code with azimuthal dependence of eigenmodes of the beam tunnel (to continue into next period).* For this subtask, we have written the flow chart of the code as well as the main subroutines of the numerical code. This part will be continued next year.

(iii) *Development of the numerical code for a non-periodic corrugated waveguide for which the inner radius of the metallic wall and the inner radius of the dielectric material are not equal (continued from previous period).* Using the analysis developed during 2001, we have written a code to calculate the dispersion relation and the electromagnetic field components of a periodic corrugated waveguide, in which the inner radius of the metallic walls do not coincide with the inner radius of the dielectric material. The code includes both TE and TM modes. We have made the necessary test runs and we have compared the results obtained by this code with those obtained by MAFIA and we have found that they are in an excellent agreement. Note also that our results are in a good agreement with results found in the literature. In the same subtask, we have made the analysis of a rectangular cross-section waveguide with an inner periodic corrugation (grating) along the propagation axis. Based on this analysis we have made a numerical code and we have found that our initial results are in a very good agreement with those obtained by MAFIA as well as with those appeared in the literature.

(iv) *Preliminary studies for the co-axial azimuthally corrugated waveguide.*Analysis of the eigenwaves that can propagate in a co-axial waveguide with azimuthally corrugated internal walls. For this subtask we have found some relevant papers from the literature and we have written the first part of the analytical work. The main part of this work will be done next year.

2a4) Coaxial and harmonic gyrotrons

The gyrotron-interaction of an annular electron beam with the RF electromagnetic fields in a coaxial cavity whose inner conductor is longitudinally corrugated has been studied analytically, for the purpose of improving the internal consistency of the available numerical code, primarily as regards the exact transverse structure of the modes. The RF-field representation in the cavity has assumed a superposition of TE modes and has been based on the surface impedance model as far as the corrugated inner rod is concerned. Simultaneous interactions with different modes and at different harmonics of the electron cyclotron frequency have been taken into account. Special attention has been paid to the important issue of ohmic losses.

Apart from the careful calculation of the ohmic losses in the cavity, a theoretical manipulation has been proposed in order to incorporate the ohmic quality factor of a mode in its field equations in addition to its diffractive quality factor.

The comprehensive non-linear theoretical analysis has culminated in the derivation of the equations of motion of the particles and in two equations for the time dependence of the electromagnetic field of each mode (equations for amplitude and phase). These equations assume a fixed-field approximation, i.e. the field profile of each mode is obtained by the solution of the relevant electromagnetic problem in the cold cavity.

Following the theoretical model, a time-dependent, multi-mode, multi-harmonic, fixed-field numerical code has been developed for the simulation of the beam-field interaction in a coaxial gyrotron cavity with corrugated inner conductor. This code is being used at the moment to verify the results obtained by a similar older code for a 340GHz-100kW CW second-cyclotron-harmonic, coaxial-cavity gyrotron design. (The design was initially realised with the help of this older code, which was previously developed for a hollow gyrotron cavity. This was done after a well-justified estimation that the code could produce acceptable approximate results for the aforementioned coaxial-cavity design).

The new code has been extended to take into account the influence of the axial RF magnetic field on the electron motion. This influence, usually neglected, becomes more significant as the transverse velocity of the electrons increases. A further extension has also taken place and it involves the optional consideration of a normal spread in the energy of the electrons, in the radius of their guiding-centers and in the beam alpha. More details about the beam-field interaction equations and the way they are solved numerically by the code can be found in **Annex III**.

The plans for the immediate future include further testing of the code and efforts to make it faster. The developed code will provide a means to the study of the beam-field interaction in coaxial cavities with a resistive corrugated inner rod and to the consequent design of a powerful second-harmonic gyrotron that utilises such a cavity. The already predicted capability of such cavities to favour powerful second-cyclotron-harmonic operation will thus be illustrated.

2b) Diagnostics and modelling of boundary layer plasmas and wall effects

The main activity of the Plasma Physics Laboratory (PPL) is the maintenance and operation of a Langmuir probe manipulator, operating in the divertor region of the ASDEX Upgrade tokamak. This manipulator was designed and constructed at Demokritos, *in collaboration with IPP*, and in implementation of the Contract ERB 5000 CT 91 0007 001 between the European Atomic Energy Community and the NCSR "Demokritos" (see e.g. Fixed Contribution Contract Final Report, 439/90-12-FUA GR). The probe has been used in the past to take density, temperature and flow measurements of the plasma in the ASDEX Upgrade divertor region [see e.g. Tsois et. al., J. Nuclear Mater. 266, 1230-1233 (1999)].

After a three year suspension of the PPL activities due to the illness of Dr. Tsois, the program restarted with the appointment of a post-doctoral fellow, Dr. M. Tsalas, in September 2002. Dr. Tsalas carried out his first visit to IPP, Garching, in December 2002 (for 3 weeks) for a preliminary inspection of the probe state (after 3 years of inactivity). It was found that, although in apparently poor condition, it was technically possible to put the diagnostic back in operation at no major cost. More specifically, it was found that:

- The electrical subsystem of the probe was in good condition and operational.
- The two driving motors where in good condition, and operating properly.
- The probe software required some modifications to bring it up to date.
- A new probe head was required and had to be constructed.
- Some broken limit switches had to be replaced.
- A safety loop to prevent the manipulator from remaining stuck inside the tokamak had to be introduced.
- In addition, the state of the port equipment (at that point inaccessible due to the tokamak operation) had to be inspected.

After consultations with ASDEX Upgrade staff, it was decided that there was extensive interest to put the manipulator back into operation, as it could provide valuable information on the new divertor of ASDEX Upgrade (Div IIb.). In addition to this, the manipulator could also be used to investigate the observed changes in the ELM characteristics when the probe tip approaches the separatrix (observed only close to Type I to II threshold), and arcing during ELM's. There is also the prospect of using various types of probe heads to investigate, for example, fast particles (collection probes), fluctuations (emissive probes) and ELM control by current pulse. It was therefore jointly decided that efforts should be made to put the manipulator back into operation by September 2003.

2c) Equilibrium, stability and transport of fusion plasmas
2c1) Transport and chaos in fusion plasmas

The period in subject was devoted to the study of the diffusion of particles, non-linearly interacting with obliquely propagating electromagnetic waves. We study mainly the diffusion in velocity space close to the threshold for stochasticity. We study in particular the role of the organized regions (islands) on the diffusion process and compare our results with the quasi-linear diffusion equation. We continue our study on the evolution of the same system when a narrow wave packet replaces the coherent wave. Our work will expand to include radiation losses from our system and toroidal magnetic topologies. (*This activity will be continued into the following period and is performed in collaboration with ULB and IPP.*
)

During this period, we have studied the nonlinear interaction of relativistic electrons with a constant magnetic field and an oblique (a) monochromatic electromagnetic wave (b) electromagnetic wavepacket of narrow bandwidth, consisting of a central frequency mode and two sidebands. The dynamical behaviour of each system was visualized using Poincare surfaces of sections (for (a) only) and energy distributions, over and under the estimated threshold to chaos. Issues related to the energetic, spatial and velocity diffusion across the ambient magnetic field lines were examined by following the evolution of the ensemble mean square displacements $<(\gamma-\gamma_0)^2>$, $<(\mathbf{r}-\mathbf{r}_0)^2>$ and $<(\mathbf{p}-\mathbf{p}_0)^2>$ for various values of the wave power. We focused our attention in strong as well as moderate amplitudes, in the area near the threshold to chaos where the phase space is complex and a mixture of periodic and stochastic orbits co-exist. The type of diffusion in each space was determined and found to obey simple power law with scaling exponents indicant of sub-diffusion, a behavior connected with the existing regions of regular evolution in the phase space. Details can be found in
Annex IV
.

In addition, we have studied the dynamics of charged particles inside a turbulent flow. Our first step, reported in Annex V , was the development of a cascade model for turbulence. It is well known that at high Reylonds, numbers R, the degrees of freedom which are necessary to describe the flow increase as a power of R. Therefore, the direct numerical simulation of the Navier- Stokes equation becomes quite difficult. So, in order to study our system one has to introduce simplified models with the same phenomenological properties as the Navier-Stokes equations. In particular, a shell model, the so-called GOY model, has been used, which has been initially introduced by Gledzer, Ohkitani and Yamada in order to simulate the turbulent flow of a fluid. In the aforementioned Annex the dynamical properties of this model are analyzed.

2c2) MHD turbulent transport in plasmas

Computational Fluid Dynamics (CFD) and turbulence modelling have been applied (prior to the conclusion of the Contract of Association) to various flow problems using codes developed and tested in the Laboratory of Fluid Mechanics of the University of Thessaly. The general objective is to extend these CFD codes to solve fusion-relevant problems of MHD laminar and turbulent transport, including eventually effects due to electrical resistivity, and to compare the results with those using LES (Large Eddy Simulation) techniques, as well as using Direct Numerical Simulation (DNS). The specific objective is to study numerically the turbulent diffusion of charged particle, using computational fluid dynamics techniques, and to examine also the possibility of using laser flow diagnostics. (*This is a multi-annual activity, continued into the following periods and performed in cooperation with ULB.*
)

During the period in subject, the work in this field was mainly focused in extending and using the CFD codes (FUSION3D, FUSION2D and CORE2D) developed in the Laboratory for MHD flows. These source codes are basically Navier-Stokes solvers, using the finite volume approach. The FUSION3D code (based on the DIAN3D code) can simulate steady or time-dependant laminar and eventually turbulent MHD flows in Cartesian or General coordinates. The FUSION2D code (based on the TEACH code) can simulate time-dependent MHD flows, in particular natural convection. The CORE2D code (based on the CAFFA code) can simulate time-dependent MHD flows, in general body-fitted coordinates. The following MHD flows have been investigated:

- Transient MHD natural convection with internal heat sources: The MHD flow in square enclosures with isothermal walls and volumetric internal heat sources subject to homogeneous magnetic fields has been studied (see Annex VI).
- Natural convection in shallow tanks with uniform magnetic field: A natural convection flow in a shallow rectangular tank under the effect of a magnetic field has been studied numerically. In addition, a method of matched asymptotic expansions was used to predict the fluid flow and heat transfer in a shallow rectangular tank (see Annex VII).
- MHD natural convection between horizontal concentric cylinders with external temperature differences and internal heat sources : The two-dimensional code CAFFA with body-fitted coordinates has been extended to include MHD flows in the annulus between horizontal concentric cylinders. The transient flow is subjected to temperature differences between the hot inner wall and the cold outer one and to volumetric internal heat sources in addition to the homogeneous (for this time period) magnetic field (see Annex VIII).

In the framework of the collaboration between the Fluid Mechanics Lab of the U. of Thessaly and the Statistical and Plasma Physics Unit of the ULB, Dr. I. Sarris visited ULB and worked on MHD turbulence using direct numerical simulations (DNS) in a flow subject to an inhomogeneous magnetic field. Periodic boundary conditions have been used and a time-independent spatially periodic external magnetic field has been imposed. Thus, both velocity and magnetic fields are sheared and anisotropic. The effects from the magnetic forcing have been analysed. The numerical simulations show that for relatively small values of the Reynolds number, the turbulent fluctuations are damped by the magnetic field and the flow becomes laminar and two-dimensional after a short time. For higher Reynolds numbers, the flow remains turbulent and exchange of energy between velocity and magnetic fields takes place.

In addition, in the past years, we had constructed the X-CA (extended Cellular Automaton model), an MHD compatible Cellular Automaton model for plasma turbulence. Our general aim in this project is to adjust its magnetic topology as close as possible to a Tokamak, and to study the behaviour of particles in this system. (This activity will be continued into the following period.) During the period in subject, we implemented the possibility to trace particle orbits in the frame of the X-CA model. We expect soon to have first results on the diffusive behaviour of particles in the system.

2c3) Stochastic Modelling of Transport Phenomena

During the period in subject our efforts have focused on the development of a source algorithm based on the scalar-vector LB-MHD model. The code has been developed and successfully tested solving the typical Hartmann flow problem. The results of our simulations with bounce-back boundary conditions have been compared to the analytical solutions. It has been found that a Mach number proportional to Δx must be taken to establish second order convergence. Also in the viscous stresses there is an error of order $O(Ma^2/Re)$. Comparison with the corresponding results obtained by the single distribution function code developed last year (2001) clearly indicates that the scalar-vector model is a numerically more stable scheme, yielding results of higher accuracy. A more thorough and systematic investigation of the detailed features and characteristics of the two methodologies is still under way.

In addition the more advanced Orsang-Tang vortex problem, containing most of the features of MHD turbulence, has been solved. The Orsang-Tang vortex is a two-dimensional flow evolving from simple deterministic initial conditions. This flow nevertheless contains most of the features of MHD turbulence, notably selective decay, magnetic reconnection, formation of jets and dynamic alignment. The deterministic initial conditions allow a direct comparison with previously published results. In addition features in the lattice kinetic simulations, which are due to the inherent compressibility of the scheme can be identified. Magnetic current and vorticity profiles indicate that after 4000 time-steps turbulence has set in the form of localized filaments (see An

nex IX
for more details).

A parallel activity refers to particle transport through turbulent plasmas with fractally distributed electric fields. Continuing this activity from year 2001, during the period in subject, we derived analytically the rate of direct escape from the system, i.e. the probability to leave the plasma without meeting an electric field inhomogeneity again. We generalized the Continuous Time Random Walk formalism to include the case of finite direct escape rate. The results show that diffusion is practically ballistic when the dimension of the fractal support is below two, and for dimension above two diffusion becomes normal for long enough times. We also derived the expected number of interactions with localized electric fields per particle. It is shown that fractal supports with dimensions below two are practically not seen by the particles, with a sharp transition at the dimension of two, above which the interactions with the electric fields become dominant. All results were confirmed with extended Monte-Carlo simulations. We proceeded to implement a new code for random walk through a fractal environment in position space, extended to include the changes in velocity (acceleration) at the encounters with the electric fields. Some first results seem to allow explaining the appearance of power-law tails as the result of a general, statistical law. (The results on constant velocity random walk are in press at Phys. Rev. E, an extensive summary is presented in Annex X .)

2c4) Experimental demonstratin of sawtooth and NTM stabilization by superthermal particles (ions and electrons) during ICRH and ECRH

The theory of the non-resonant suppression of MHD modes (such as the sawtooth instability and the neoclassical tearing modes) by superthermal particles (i.e. ions and electrons) during r.f. heating (i.e. ICRH and ECRH) was recently developed and published by A.Lazaros (see Progress Reports of previous periods). The objective of the collaboration of A.Lazaros with the CHS Group and the Tore-Supra Group was the experimental demonstration of the stabilising effect of the superthermal particles during r.f. heating, and the two experimental facilities were the most suitable devices for this type of experiments.

The stabilizing effect of the superthermal electrons, which are produced through the avalanche effect during ECRH was demonstrated in CHS (during the mobility of A.Lazaros at NIFS-Japan) by the suppression of the “fishbone” mode with ECRH, in an experimental arrangement which favours the development of a superthermal electron avalanche and excludes any other stabilizing effect. The concept, technique, and results of the experiment are analysed in a published paper (**Annex XI**).

The stabilizing effect of the superthermal ions, which are produced during ICRH, was investigated in Tore-Supra (during the mobility of A.Lazaros at CEA-France) by the analysis of the (3,2) magnetic islands following the monster sawtooth crash. Despite some problems in the restart of Tore Supra, the required data have been obtained for the above study. The results of this study are included in paper and poster (**Annex XII** ; *a formal publication to the appropriate international journal is now also being prepared*).

2c5) Stationary MHD modes in magnetically confined plasmas

During the period in subject, a possible stabilization method of the "resistive wall mode", which consists in modulating in time the resistivity of the wall [H. Tasso and G. N. Throumoulopoulos, Phys. Plasmas 9, 2662 (2002)], was further studied by means of the monodromy matrix for a two-step modulation. In this case the monodromy matrix is the product of two matrix exponentials and can be evaluated either by reducing the matrix exponentials to polynomials on the eigenvalues of the corresponding matrices or, without knowledge of the eigenvalues, by using the Baker-Campell-Hausdorff formula. In addition to the dissipative Mathieu-Hill equations the method was applied successfully to a 3×3 matrix model, a mock up of the actual wall-mode equations. The latter, however, is too crude to give all qualitative features of the resistive wall mode, in particular because of its connection with a wall of zero thickness. This means that we have to go to much larger systems approaching more realistically the plasma and a resistive wall having a thickness larger or comparable to the "skin" thickness (Annex XIII).

In addition, the equilibrium states of a toroidal axisymmetric plasma were studied in the framework of the Hall-MHD model (Annex XIV). The main conclusion is that that the Hall term makes the ion-flow surfaces to depart from the magnetic surfaces and restricts the possible equilibrium states.

Finally, we have constructed several exact solutions of the axisymetric MHD equilibrium equations with peaked toroidal-current-density profiles and incompressible sheared flows for plasmas of laboratory and astrophysical concern. In particular, from a tokamak solution with flows non-parallel to the magnetic field it turns out that appropriate electric field and density profiles and their variation perpendicular to the magnetic surfaces result in a drastic reduction of the Shafranov shift without requiring large velocity magnitudes (Annex XV).

2c6) 3-D Pellet modelling

To the 2-D vapour shield code, which was modified for hydrogen plasma, Lagrangian modules were implemented (see Annex XVI). Thus this "2D+1" code consists of the 2-D resistive MHD model, which describes the evolution of the pellet cloud in the poloidal plane, and 1-D Lagrangian model which describes the expansion of the ablatant along the magnetic field lines. A Eulerian mesh system is used for the poloidal plane, and a Lagrangian "flux tube" is ascribed to each Eulerian coordinate point in the poloidal plane. For the time being, single Lagrangian cells are used, and also prescribed ablation rates are used.

Results stemming from this "2D+1" code are expected to yield information on the structure of the pellet cloud in the poloidal plane, the modulation of the ablation rate along its path, and, if in the presence of magnetic field gradient, on the magnitude of the grad(**B**)-induced drift. It should be noted, however, for a consistent treatment of the problem a three-dimensional resistive MHD code is required. Such a model, coupling of pellet ablation modules to the M3D code, is also under development.

Preliminary calculations, using the "2D+1" code with prescribed ablation rates, were presented in ICPP, Sydney, July 2002.