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

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

Background and Objectives: A possible application of a sheet beam (whose stability has been studied earlier (see Annex II of 2004 Annual Report) is to have it interact with the propagating Gaussian *rf* beam produced by a conventional gyrotron. A simple preliminary calculation has indicated that the parameters of the *rf* beam from, say, a 2 MW gyrotron are adequate to extract significant amounts of power from the electron beam, with no need for feed-back from the walls of any cavity. Thus, if this work proves promising, a first-stage conventional high-power gyrotron could provide the initial generation of the *rf* beam with mode selectivity and high efficiency and the quasi-optical gyrotron concept can be applied as a second stage to multiply the *rf* power to the levels needed for a fusion reactor. (*This is a multi-annual activity, performed in cooperation with CRPP and FZK.*)

Work performed in year 2005 (*in co-operation with CRPP and FZK*):

For the gyrotron interaction between a propagating Gaussian radiation beam (assumed generated by a conventional gyrotron) and a sheet electron beam, the study on three-dimensional effects and self-consistency advanced, with the following specific results:

1. The electromagnetic field components were recalculated. In particular, they have been obtained analytically using the appropriate derivatives of the electromagnetic potentials. Comparison was performed with the results from the earlier approach (in which the field were obtained by numerical differentiation). From the comparison, the present approach was found to be of superior accuracy. In addition, the radiation fields produced by the perturbed motion of the electrons were calculated, at first in the plane of the electron beam, in order to determine whether the radiation produced has a profile resembling that of the original Gaussian. The results indicate that in many (but not all) cases, this is indeed the case. More details are presented in **Annex I** .

2. The self-consistency approach has been formulated, as a successive iteration scheme consisting of either a short loop (in which electron dynamics need not be recalculated, as is the case when the radiation profile is Gaussian), or of a long loop (with full recalculation of electron dynamics in the total fields, of non-Gaussian profile). The first iterations were performed, in the short loop, using earlier results for the electron dynamics.
3. The study of task (i) was expanded to include the calculation of the fields outside the plane of the electron beam, in order to study of the 3D pattern of the radiation field and to calculate the power radiated to any direction. (*The actual calculation of the radiated power is planned for the next period.*).
4. The use of *Matlab* for the existing code, while useful to obtain the first set of results and to form an opinion on the viability of the interaction, has reached its limits. (A single simulation requires well over one day of execution time.) Therefore, the transition to a code in *C++* with parallelization prospects has been initiated (*and is planned to continue into next period*).

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

Background and Objectives: The available electrostatic codes (*E-GUN and DAPHNE*) for the electron gun and beam tunnel assembly assume azimuthal symmetry and hence they are two-dimensional. As such, they cannot be used to describe situations without azimuthal symmetry, whether they arise out of construction imperfections (e.g., non-uniform emission from cathode, deviations from perfect alignment, etc.) or from inherent necessity for non-symmetric construction (e.g., a sheet beam for the quasi-optical gyrotron). To cover this need, this activity aims to prepare a self-consistent electrostatic code in three dimensions and to use it in gyrotron beam tunnel studies.
(*This is a multi-annual activity, performed in cooperation with CRPP and FZK.*)

Work performed in year 2005: Further improvements have been incorporated to the self-consistent 3-D electrostatic code *ARIADNE*. Specifically, during the period in subject, the following tasks have been addressed:

1. The preconditioning Conjugate-Gradient method has been parallelized and incorporated in the code, as an alternative to the method of successive over-relaxation for the solution of the finite element sparse linear system. The implementation of this method has shown that the convergence is achieved several times faster than before. Details are presented in **Annex II**.

2. The code has been installed in the 64-bit parallel computer system, recently acquired by the Plasmas, Electron Beam and Non-Linear Optics laboratory of NTUA. In addition, the official web page of *ARIADNE* has been developed (hosted in the URL http://147.102.34.16).
3. The object-oriented version of the code *ARIADNE*, called *Ariadne++*, is under development. In this stage the following tasks have been addressed: (i) The introduction of the geometry, which is more simplified for the user than it was in the previous version of the code and allows the introduction of two-dimensional and three-dimensional beam tunnel geometries separately. (ii) The introduction of geometry segments with dielectric material, which is incorporated in the new code facilities. (iii) The new mesh generator, which produces two-dimensional (curvilinear quadrilateral) and three-dimensional (curvilinear tetrahedral) meshes for two-dimensional geometries and three-dimensional meshes for three-dimensional geometries. The mesh can be dynamically adapted to the beam shape (a *body-fitted mesh* is generated) to separate the elements inside the beam from those outside the beam. This will result in a more accurate calculation of the strong variation of the electric field across the beam. All these new features of the new version of the code are presented with more details in **Annex III** .

2a3) Electromagnetic code for beam-tunnel spectrum and slotted coaxial gyrotron cavities

Background and Objectives: The gyrotron beam tunnel, whether cylindrical or coaxial, has a rich electromagnetic spectrum (especially in the presence of corrugated walls), part of which might resonate with the electron beam, as it is in transit to the gyrotron cavity. Such an interaction may have significant consequences, as regards the quality of the electron beam, even if no substantial energy exchange takes place. (Energy spread is typically proportional to the small quantity of the normalized field amplitude, while energy exchanged is proportional to the square of it.) For these reasons, this activity aims at the development of numerical codes, to calculate the frequency spectrum in typical gyrotron beam tunnel assemblies, with the prospect of eventually extending the codes to treat the electron beam self-consistently. In parallel, coaxial gyrotrons employ slotted cavities, to facilitate mode selection. Such structures are typically calculated by employing the model of distributed impedance and therefore the calculations are limited to the domain of applicability of this model. This activity also aims at the development of numerical codes for the calculation of the frequency spectrum of slotted coaxial cavities, to allow performing calculations not constrained by this model. (*This is a multi-annual activity, performed in cooperation with CRPP and HUT/TEKES.*)

Work performed in year 2005: The work of the previous period was continued into the period in subject, on addressing several issues related to the development of electromagnetic modes in geometries representative of typical gyrotron beam tunnels or interaction cavities. In particular:

1. Beam loading and its effects in a gyrotron beam tunnel (*continued from previous period*) : The numerical code for the cases of TM and TE modes for a periodic geometry has been implemented last year. This year, the corresponding subroutines for the case of Hybrid modes for periodic geometries were introduced, while the capability to calculate the power loss or gain on the beam was added in all cases. Extensive optimizations and testing were performed to improve execution time and to assure the faultless execution of the code. Several numerical tests were also performed for the periodic case and the results obtained were investigated for their validity. The code was extended to support non-periodic geometries as well, but it has not been adequately tested yet. In parallel, during our visits to the CRPP, EPFL, Lausanne in January and August 2005, the numerical codes "Fishbone" and "Complex Fishbone" developed in the previous years, were installed to the CRPP computers. Several modifications were made to these codes according to the remarks and suggestions of the CRPP members. Furthermore results from the "Beam Fishbone" code were presented and modifications were made according to their remarks. (This work is done also with the collaboration of colleagues of CRPP, EPFL, Lausanne). Details are given in **Annex IV**.

2. Ohmic losses in a coaxial gyrotron cavity with a slotted inner rod (*continued from previous period*): We made several test runs for special coaxial cavity geometries of great importance such as the 165 GHz - 2.2 MW coaxial gyrotron cavity of FZK, Karlsruhe, Germany and the 170 GHz gyrotron cavity of ITER and compared the results to those in the literature. During this procedure several optimizations where made to the numerical code concerning the high-order Bessel functions calculation algorithm and the spurious solutions refining algorithm. Moreover the numerical formulation presented in Annex V of 2004 Annual Report and the corresponding numerical code have been extended properly in collaboration with Prof. O. Dumbrajs in order to calculate efficiently the ohmic losses on the corrugated insert. The total procedure is described in **Annex V**, where numerical quantitative comparison with other methods (*i.e.* SIM and SIE) is made. This work has been submitted (now is under revision) for publication to the IEEE Transactions on Plasma Science.

3. Coaxial waveguide with circumferential corrugations: For this (new) task, up to now the mathematical formulation of the TM and TE waves and the corresponding numerical code (Coaxial Beam Tunnel, CBT) have been finished. The code has been developed in *C++* and can be used in Windows and Linux environment. Numerical tests for the case of TM waves and comparison with the well-known numerical code *MAFIA*

have been performed. An extensive report on these results can be found in **Annex VI**.

4. Analysis of a circumferentially corrugated circular waveguide with losses, excited at any (real) value of the frequency: In this task, preliminary work has been performed so far, aiming at inverting the code Complex-Fishbone, so that the axial wave number spectrum is obtained as function of a (real) excitation frequency (rather than choosing the wavenumber as a real input quantity to find a, possibly complex, frequency). More specifically, this task has started on July of 2005, but it has been realized that our approach based on the Floquet theorem and spatial harmonics expansion could not be applied due to the non-periodic boundary conditions required. Nevertheless, we will try in the future to solve it by using a different approach.

2a4) Coaxial and harmonic gyrotrons

Background and Objectives: This activity addresses the coaxial gyrotrons, which have been seen as the most promising configurations of high-power, high-frequency RF sources for ECRH heating. In addition, harmonic interactions are also studied in this activity, for the purpose of producing high frequency at reduced magnetic field requirements. The work performed refers both to designing suitable cavities and to studying the fundamentals of the interaction. Furthermore, pertinent numerical codes have been developed, which admit significant improvements. (*This is a multi-annual activity, performed in cooperation with FZK, but also of interest to CRPP.*)

Work performed in year 2005 (*in co-operation with FZK*): In view of the potential of coaxial gyrotron cavities to yield high output power with advanced mode selectivity, as well as of the improvement of the developed interaction code, the following issues have been addressed:

1. The studies on the operation of coaxial gyrotron cavities with corrugated insert at the second cyclotron harmonic have been continued. Further calculations showed that a resistive coaxial insert with conductivity in the extended range of 10 4–106 S/m, is capable of supporting powerful, sub-millimetre-wave, second-harmonic operation. This extended conductivity range broadens the choice of suitable resistive materials, making the potential implementation of a pertinent design easier. An extensive report on these results can be found as **Annex VII**.
2. After a detailed investigation of the physical and technological constraints relevant to ohmic wall loading, voltage depression, mode competition, and electron gun parameters, a general step-by-step procedure for the selection of the operating mode and the operating parameters of a gyrotron has emerged, together with a pertinent mode-selection code. The procedure, which takes into account a set of initial requirements and all the aforementioned constraints, applies to both conventional and coaxial-cavity gyrotrons, as well as to interaction

at the fundamental cyclotron frequency or its harmonics.

3. The background work to extend the developed interaction code to be self-consistent (with respect to the axial field-profile) rather than fixed-field has been continued. However, extensive tests have shown that the way to control the numerical instabilities is by using a significantly large number of initial particle phases (resulting in time-consuming calculations). This has triggered the need for making the code faster. This need was considered as a first priority and a prerequisite for self-consistency, which, in principle, involves calculations that are much more demanding. As a result, work on the parallelization of the code has taken place. (*This work will continue into next period.*)

4. The first results of the study of the behaviour of the spent electron beam (*i.e.* the beam at the cavity output) assuming a Gaussian *rf* field profile, indicate that the operating regimes suitable for the use of a more effective depressed collector are those involving longer cavities and lower values of the *rf* field. Additional calculations with more realistic field profiles are planned for the next period.

2a5) Chaotic electron dynamics in gyrotron resonators

Background and Objectives: The main objective of this activity is to analyse complex electron dynamics in gyrotron resonators in order to provide information about efficient operation of gyrotron devices. The analysis and the methods utilized are within the context of the Hamiltonian formalism, including phase space analysis, Canonical Perturbation Method (CPM) and symplectic integration schemes.

Work performed in the 2005 (*in co-operation with HUT/TEKES*): The Hamiltonian formalism already used for the study of electron dynamics under interaction with a single *rf* mode being at resonance with an arbitrary harmonic of the electron cyclotron frequency (*work performed in year 2004*), has been extended in order to study the following:

1. The general case of electron interaction with multiple modes at different harmonics of the cyclotron frequency has been investigated and it was shown that the phase space of the system, as described by appropriate Poincaré surfaces of section, consists of discrete resonant areas corresponding to each *rf* mode. In the case under consideration, the position of each resonant area depends on the frequency mismatch of the corresponding *rf*

field, while its width depends on the normalized resonator length, the harmonic number and the beam-to-*rf* coupling factor. Depending on the specific parameter choices, the two resonant areas of the phase space are shown to be well separated, neighbouring, weakly or strongly overlapping. The resonant area overlap results in the fact that certain initial transverse momentum values are strongly affected by both resonances. [For more details, see Y. Kominis, O. Dumbrajs, K. A. Avramides, K. Hizanidis and J. L. Vomvoridis, Phys. Plasmas **12**, 113102 (2005).]

2. The hysteresis-like effects occurring in gyrotron resonators have been studied with utilization of the CPM and it was shown that these effects can be successfully recovered in terms of simple analytic expressions, involving the parameters of interest. The extreme transverse momentum values at the output of the gyrotron resonator can be approximated by the solutions of a simple transcendental equation involving local invariants of the motion, calculated through the CPM. Sharp extreme value transitions for varying frequency mismatch, occurring in some cases, are results of the existence of more than one branch of solutions of the equation governing the relation of the extreme transverse momentum values with the parameters of the gyrotron. These cases are related to hysteresis-like effects, which have been experimentally and numerically observed in gyrotron resonators for the case of slowly time-varying parameters. In the case of hysteresis, the behaviour of a gyrotron is very interesting and is related to the existence of the regions of soft and hard self-excitation regions in gyrotrons. This task emerged as a discrete result during the study of task (i). [For more details, see **Annex VIII** and Y. Kominis, O. Dumbrajs, K. A. Avramides, K. Hizanidis and J. L. Vomvoridis, Phys. Plasmas **12**, 113102 (2005).]

3. The Canonical Perturbation Method, used in the previous tasks, was shown to result to a new approach to describing electron dynamics in gyrotron resonators in the context of Hamiltonian maps and symplectic integration schemes. These maps incorporate the dependency of electron dynamics on the parameters of the interacting *rf* field and it can be used for trajectory calculations through successive iteration, resulting in a symplectic integration scheme. The direct relation of the map to the physics of the model, along with its canonical form and the significant reduction of the number of iteration steps required for acceptable accuracy, are the main advantages of this method in comparison with standard methods such as Runge-Kutta. The general form of the Hamiltonian map allows for wide applications as a part of several numerical algorithms, which incorporate CPU-consuming electron trajectories calculations. (For more details, see **Annex IX** and O. Dumbrajs, Y. Kominis, K. A. Avramides, K. Hizanidis and J. L. Vomvoridis to appear in IEEE Trans. Plasma Science, June 2006.).

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

2b1) Diagnostics and modelling of ASDEX-Upgrade SOL and divertor

plasma

Background and Objectives: Divertors remain the main option for handling plasma-wall interaction problems in operating and future magnetic confinement machines like ITER. The rather conflicting requirements to be fulfilled for efficient divertor operation ask for a detailed understanding of the involved physical and chemical processes. Important issues such as transient target plate power loads, pumping efficiency, target plate erosion, impurity migration and re-deposition are still very much under investigation. Langmuir Probes have proved to be a very useful diagnostic technique for divertor plasma studies and are now used extensively in most tokamak experiments. Despite the still existing interpretation problems and the unavoidable interaction with the plasma under investigation, Langmuir Probes can provide information with a spatial and temporal resolution very difficult to be obtained by other methods. The objective is to use and further enhance the fast scanning Langmuir probe system designed, constructed and operated by the Plasma Physics Laboratory at N.C.S.R. “Demokritos” for the ASDEX Upgrade divertor, to describe and eventually predict the detailed evolution of the SOL and divertor plasma, in conjunction with other diagnostic techniques and numerical simulations.
(
This is a multi-annual activity, performed in cooperation with IPP.
)

Work performed in year 2005 (*in co-operation with IPP*): The divertor reciprocating Langmuir probe was used in conjunction with other ASDEX Upgrade diagnostics to study edge-divertor properties. The probe was used in 35 successful discharges in total (10 dedicated and 25 piggy-back) and, despite several interruptions in the operation of ASDEX Upgrade (due to technical problems), most of the divertor reciprocating probe experimental program for 2005 was successfully completed. After the installation of the Mach head at the beginning of the campaign, emphasis was given on divertor flow measurements. For various discharge configurations, plasma flow velocities were measured across both of the Div IIb divertor legs, providing information about impurity migration, divertor recycling and pumping efficiency. In more detail:

1. Measurements of ion saturation current and probe floating potential fluctuations during ELMs were successfully performed. Comparisons between measurements made in the outer scrape-off layer and in the private flux region were made and the observed differences in the edge localized mode (ELM) signatures were attributed to the different flow properties of each region (see next point on the task list). In addition, it was found that the combined $I_{sat} - V_{fl}$ measurements can be used to accurately determine the time when the probe tip crosses the separatrix, providing a very useful tool for the precise determination of the separatrix position.

2. Both stationary and transient flow patterns in the vicinity of the x-point were investigated using the mach head. It was found that at low line-averaged core plasma densities flow

velocities typically reach, but do not exceed, ion-acoustic velocity. In contrast, at high central densities Mach numbers exceeding $M = 1$ were observed, especially at the high field side scrape-off layer where fast flows in the mid-plane caused by asymmetric ballooning transport seem to be further enhanced by the divertor sink action. It was also observed that at low collisionality, flows away from the target plates can occur locally inside the private flux region (for details see **Annex X**). Fast flow fluctuation measurements during type I ELM's were also carried out in a variety of discharge configurations. The fast data acquisition system was used, and 8 successful discharges in total were performed, 5 in lower and 3 in upper single null configurations. Flow reversal near the target plates occurring immediately after each ELM was typically observed in most configurations, but only on the high-field side SOL and private flux. These reversals are thought to be due to a transient pressure increase in the vicinity of the target plates immediately after the ELM. Taking into account the impurity erosion and deposition patterns observed on the divertor strike points of ASDEX Upgrade (erosion on the high-field side, deposition on the low-field side), it was suggested that this flow reversal mechanism (observed only on the high-field side and private flux) can play a role in aiding impurities (created by enhanced sputtering during the ELM) leave the high-field side target plate vicinity.

3. ELM induced arc formation on the probe tips was studied by switching to a larger amplifier to increase the current drawn by the arc. However, it appears that the arcs short-circuit the probe electronics, indicating that rather than being uni-polar (as originally expected) the arcs actually occur between the probe head and the body. It was however observed that in ELMy H-mode discharges arcs tend to form predominantly on the upstream side of the Mach probe, indicating that an increase in the plasma inflow velocity facilitates the arc formation. Some techniques to avoid arc formation when measuring ion saturation current were also tried, including using a square waveform to bias the probe (the positive biasing kills the arc) and slow voltage modulation.

4. The probe influence on the neighbouring plasma was studied mainly in low-density discharges. Several effects were shown to play a contributing role, including the probe electron emission in the *I-sat* part of the voltage sweep (caused by overheating), the ohmic heating of the plasma in the flux tube connecting to the probe (caused by an increase in the current flowing through the flux tube) and plasma cooling in the neighbourhood of the probe caused by fast electron absorption.

2b2) Modification of Langmuir probe hardware and software

Background and Objectives: The current sampling rate of the Demokritos reciprocating Langmuir probe data acquisition system is 500 kHz. However, the optical transmission system from the torus hall to the CAMAC crate (which is positioned in the control room) limits this to 100 kHz. Since such a data acquisition speed is not sufficient to obtain good time-resolved measurements of fast oscillations in the plasma (such as filaments, radially propagating spatiotemporal fluctuation structures and turbulence), the possibility of upgrading the probe electronic system to improve the sampling rate has been proposed.

Work performed in year 2005 (*in co-operation with IPP*): A preliminary analysis of the possibility of upgrading the reciprocating probe data acquisition system to a system with a higher sampling rate was performed. It was found that such an upgrade is feasible but would require a considerable proportion of the laboratory's current personnel resources. For this reason, the continuation of this activity is deferred until it is deemed appropriate.

2b3) Neutron spectral measurements in JET

Background and Objectives (*in co-operation with JET*): This is a new activity, relating to the ongoing development and implementation of a dedicated compact neutron spectrometer in JET, based on a NE213 organic liquid scintillator installed there (diagnostic name KN2M), which can measure neutron spectra in the energy range of 1.5-20 MeV. This energy range, combined with the fact that JET is currently the only fusion facility in the world capable of operating with tritium, makes this diagnostic especially important for the development of fusion relevant neutron diagnostics. The spectra obtained are used to provide information on the fuel ion composition, velocity distribution and temperature of the plasma. Since advanced numerical unfolding algorithms are require to unfold the neutron spectra from the measured pulse-height spectra (a problem similar to tomographic reconstruction), part of the development consists of optimizing and comparing such algorithms (examples of which are the maximum entropy method, MAXED, and the minimum Fisher renormalization method, MFR). The aim is to optimize the spectrometer data acquisition in a variety of JET discharge configurations and to analyse spectrometer data for various plasma scenarios and heating regimes.

Work performed year 2005: The main work for this activity was performed during the first restart stage of the C15-C17 campaigns, in October – November 2005. The NE213 scintillator detector package had already been removed from the KM3/Octant 5 flight path in the roof lab and placed in the KM2 bunker (horizontal port in octant 7), making use of the existing collimator structure, which has a tangential view across the torus, at a 22 degree angle to the normal and 135 mm horizontally above the mid-plane. The detector is now positioned at a distance of 17 m from the port exit. For optimum calibration and measurement, the pulse-shape discriminator was set to make the following measurements during each JET pulse: From 0 to 40 sec, the gamma radiation is measured from the in situ Na 22 small source, for energy calibration purposes. From 40 sec to 72 sec, neutrons produced during the plasma discharge are detected. Finally, from 72s and until the end of the data acquisition cycle, combined γ+n measurements are made, to provide linearity check of the energy calibrations. In addition, the spectrometer was set with a high upper energy threshold (pulse-height spectra acquisition up to 2.2 eMeV corresponding to neutrons of 5.5 MeV energy). This upper threshold was chosen to measure the high-energy neutrons produced during the ICRH high power commissioning. As a result of these activities, the KM2N diagnostic was brought to full operation, ready for campaigns C15-C17.

In addition, work was also performed in the unfolding and analysis of the pulse-height spectra measured by the neutron spectrometer during the DT campaign. Two unfolding algorithms were used for this purpose, the Maximum Entropy (MAXED) and Minimum Fisher Regularization (MFR) methods, and a comparative study of both was performed. For MAXED, the L-curve method for determining the optimal unfolding parameter $\chi 2$ was applied and it was shown that it can be used to significantly increase the unfolding accuracy. Efforts to apply this method to the MFR code were initiated, and this activity will be continued in 2006.

2c) Equilibrium, stability and transport of fusion plasmas

2c1) Transport and chaos in fusion plasmas

Background and Objectives: In this activity, we study the wave-plasma interaction in the electron-cyclotron (EC) frequency regime. Our target is to upgrade the physical schemes used to study ECRH and ECCD, including effects that model the complicated character of the wave propagation and absorption in a more realistic way. We focus on the effect of nonlinear wave-particle interaction on the absorption of EC beams in fusion magnetic configurations. Our modelling is based on the behaviour of the plasma electrons under the influence of the beam. Also, the Hamiltonian formalism, along with a set of accompanying tools such as the phase space analysis, the Canonical Perturbation Method and Lie transforms are being used in order to:

1. formulate the quasi-linear approximation theory in several configurations of wave-particle interactions,
2. extend the investigation of the complex wave-particle dynamics beyond the quasi-linear approximation, and
3. study the self-consistent problem of wave-particle interactions. In all cases the purpose is to extend the theory and provide analytical (if possible) results for realistic configurations where the wave spectrum is of general form, namely the spectrum is no longer discrete, corresponding to the widely studied case of periodic waves, but can also include localized pulses, or aperiodic pulse sequences.

Another part of this activity, performed in collaboration with IPP, considers the application of the beam tracing method in the propagation and absorption of non-Gaussian beams. The beam tracing (paraxial WKB) technique is an asymptotic method for solving the wave equation in the short-wavelength limit, which takes into account the wave properties. Apart from the evolution of complicated wave objects, the study of arbitrary beams is important for the improvement of the modelling of the wave absorption in the plasma, including effects of localization, asymmetry and inhomogeneity.

Work performed in the year 2005 [*in co-operation with IPP (i), (ii) and MIT (iii), (iv)*]: In this activity we study the wave-plasma interaction in the electron-cyclotron (EC) frequency regime, including its role in electron-cyclotron current drive (ECCD), in the stabilization of the Neoclassical Tearing Mode (NTM), and in plasma diagnostics (interferometry, reflectometry). More specifically:

1. We focus on the importance of nonlinear effects in the absorption of EC beams in fusion plasmas. During this period, we continued the self-consistent treatment of nonlinear wave-particle interaction initiated in the last half of the previous year, for more realistic plasma and wave geometries. We studied the absorption of a localized EC beam in a simplified tokamak geometry, for parameters relevant to (a) ECRH experiments in AUG, (b) ITER scenarios. The results of the self-consistent analysis suggest that, within the limits of our model, the absorption of the EC wave is in disagreement with linear theory. The disagreement may in some cases be significant (for more details see **Annex XI**). We believe there is a need to reconsider the importance of nonlinear effects on ECRH, especially when the wave power increases dramatically, as it will be the case for the ITER experiments.

2. The second part of this activity considers the propagation and absorption of non-Gaussian EC beams in tokamak plasmas. During this period, we benchmarked successfully the theory developed during the previous year for the analytic description of non-Gaussian beams in simplified geometry (for more details see **Annex XII**). We also included the description of non-dissipative cases, where the wave is absorbed due to EC resonance. The absorption coefficient depends on the wave-vector of the propagating mode, which means that each higher-order mode is (in general) absorbed with a different rate. We studied the case of a perpendicular non-Gaussian beam, formed by the superposition of a Gaussian and a higher-order mode, for both O- and X-mode polarization. Our results suggest that the EC absorption has a small effect in the evolution of the rms width.

3. Charged particle dynamics have been studied, under interactions with localized waves of continuous spectrum propagating along a uniform magnetic field. A modified canonical perturbation method is employed for analyzing the charged particle dynamics as they interact with a localized wave with continuous spectrum. In contrast with periodic Hamiltonian models, where the method has already been applied in a multitude of respective systems, the system in hand is inherently aperiodic. The localized waves have the form of amplitude modulated fields, ranging from ordinary wavepackets to ultrashort pulses. The analytically obtained approximate invariants of the motion contain rich information for the structure of the phase space and the respective distribution functions. Particle interaction with more than one wave having, in general, different phase/group velocities, is also considered and a resonance overlap feature of the system is demonstrated, in analogy with the periodic cases. The results were obtained for a wide class of perturbations and, thus, can directly be applied to any wavepacket profile and duration, as well as aperiodic and/or finite pulse sequences. [For more details see also **Annex XIII**
and Y. Kominis, K. Hizanidis and A. K. Ram, Phys. Rev. Lett.

96
, 025002 (2006).] This work has been performed in co-operation with MIT.

4. The applicability of the methods of task (iii) for the investigation of particle dynamics under interaction with localized waves of continuous spectrum, propagating at an angle with respect to the magnetic field, has been investigated. The appropriate Hamiltonian system has been defined and analytical results have been obtained, within the context of first order canonical perturbation theory. This work will be continued in the next year, where the possibility of extending the application of the perturbation method to higher order, with utilization of the Lie series method, will be examined.

2c2) MHD turbulent transport in plasmas

Background and Objective: Computational fluid dynamics (CFD) and turbulence modelling have been applied to various MHD flow problems using codes, which have been developed and tested earlier. These codes are based on Navier-Stokes solvers in an Eulerian frame of reference, combined with Lagrangean particle dynamics. It is proposed to extend these CFD codes to solve problems of MHD turbulent transport, including eventually effects due to resistivity, for the purpose of studying numerically the turbulent diffusion of turbulent charged particles, using computational fluid dynamics techniques. A further task is to explore the relevance of the concept of self-organized criticality (SOC) in confined plasmas. In earlier work, we had brought the MHD equations to Cellular Automaton (CA) form, which allows to study SOC and to model extended, macroscopic systems. Scopes of this task are to study the effect of resistive instabilities in specific confinement devices and on global scales, the characterization of the turbulence realized in the SOC state, the implications of SOC on particle transport, the investigation of the self-organizing mechanisms that obviously are active in confined plasmas, and the identification of confinement enhancing mechanisms. L
ow-frequency electrostatic turbulence, driven by spatial gradients, is believed to be the dominant source of anomalous transport in magnetically confined fusion plasma. Furthermore, the excitation of large-scale anisotropic flows by the drift-type turbulence, plays a critical role in the regulation of low-frequency drift instabilities and consequently of the levels of turbulent transport. Special emphasis has been given on the properties and the associated phenomena related to
the development of the toroidal Ion Temperature Gradient mode (ITG) drift-type instability. This is due to the successful interpretations of various experimental results based on the dynamics of the ITG mode which is the best candidate to explain the observed levels of turbulence transport. (
This is a multi-annual activity, performed in cooperation with ULB
,
IKET/FZK and UU.
)

Work performed in year 2005: The following work has been done in the tasks of this activity:

1. *MHD convection and turbulence*: The collaborating work with ULB was continued in year 2005 with the study of MHD convection and turbulence, as follows:

•The magnetic field effects on the liquid metal flow and heat transfer in pipes and annuli are of importance for fusion breeder blanket technology. A suitable CFD model for MHD flow in a 3-D cylindrical geometry is being developed. Two cases were studied: MHD pipe flow, and MHD annular flow, for Re up to 100 and a range of Ha up to 10. In the first case the walls were assumed electrically insulated, while an external uniform and transverse magnetic field was applied. No slip boundary conditions were imposed at the walls, while the first normal derivative of the electrical potential was assumed zero. The second case was similar but the potential was set to zero assuming perfectly conducting walls. A final report will be prepared (see also **Annex XIV**
). (
This work will be continued during the next period.
)

•Direct numerical simulation of the magnetic effects on natural convection cooling in a cylindrical container is performed. The effect of an external magnetic field on the strongly transient and turbulent natural convection cooling of an initially isothermal liquid metal layer is being studied. The electrically conductive low Prandtl number fluid (Pr = 0.02) is placed in a vertical cylindrical container, when the cylindrical wall is suddenly subjected to a uniform low temperature. In this particular cooling process, the flow is characterized by the continuous transition between three almost discrete stages: development of a thermal boundary layer along the vertical cold wall, transfer of heat from the fluid main body, and flow and thermal stratification. The selected high Rayleigh numbers are such that turbulent flow and heat transfer is obtained. The results show that the magnetic field does not affect the initial forming of the vertical boundary layer, but it accelerates significantly the fluid stratification and cooling (see also **Annex XV**). (*This work will be continued during the next period.*)

1. Stability analysis of MHD flows: The stability analysis and dynamic simulation of two-dimensional free convection in a differentially heated cavity in the presence of a magnetic field and volumetric heating was completed. [See **Annex XVI** and N. Pelekasis, *"Bifurcation diagrams, linear stability analysis and dynamic simulations of free convection in a differentially heated cavity in the presence of a magnetic field",*
Phys. of Fluids
(in press)
;I. Sarris, S. Kakarantzas, A. Grecos and N. Vlachos
,
Intl J. of Heat and Mass Transfer
48
,
3443 (2005).] In addition, the formulation of the problem for three-dimensional stability analysis

was established, for flows like the two-dimensional ones studied so far. (*The stability analysis will be continued during the next period.*)

2. CFD Modelling MHD rotating flows in shells: The collaborating work with IKET/FZK continued in 2005, with the study of MHD rotating flows in cylindrical and spherical shells. Analytical and CFD studies of steady laminar flow of a liquid metal driven by a rotating disk in a cylinder and subjected to an axial magnetic field were carried out. In the absence of a magnetic field, the numerical results are in good agreement with experiments. In the presence of a magnetic field, the analytical velocity profiles obtained for a high value of the magnetic interaction parameter N=Ha2/Re are in excellent agreement with the numerical predictions. The effect of the wall conductivity on the flow is found to be important for its control (see **Annex XVII**). In addition, the effect of the electrical conductivities and the wall thickness is being studied, for Re ≥ 100 and 0 ≤ Ha ≤ 100 (0 ≤ N ≤ 100). The magnetic Reynolds number is assumed very small but the induced magnetic field is taken into account. Thin walls are used for simplicity but a moving wall is used for the first time. It is shown that for fixed values of Ha and Re, the velocity field depends strongly on the conductance ratio k, in spite of the fact that the Hartmann and side layer thicknesses do not vary with it. The results will help to analyse the corrosion processes of stainless steels by the Pb-17Li liquid alloy for the fusion reactor. (*This work will be continued during the next period.*)

3. Self-organized criticality models (X-CA model): This activity could not be performed so far during year 2005, since emphasis was given on the development of the Continuous Time Random Walk Model [Task c3(iii)].

4. Large Scale Flows generated by Turbulent Plasma and Transport Phenomena in Tokamaks (*in co-operation with UU*): During year 2005 we focused on the investigation of effects related with the development of the toroidal Ion Temperature Gradient mode (ITG) instability due to the successful interpretations of various experimental trends-related to the observed levels of turbulent transport in tokamak plasmas - which are based on the dynamics of the ITG mode.

•Studies concerning the properties of the large-scale flows associated to toroidal ITG turbulence lead us to novel results concerning the linear properties of the toroidal ITG instability. By taking into account rigorously the finite Larmor radius effects (FLR) we derived explicitly a new marginal stability threshold for the development of the toroidal ITG instability based on a standard two-dimensional reactive fluid model. It was shown that FLR effects may decrease significantly the marginal instability threshold. The results predict that a significant activity of toroidal ITG turbulence may be present at regions of peaked plasma density, such as in the plasma edge, modifying the confinement in the hot ion mode regime of tokamak operation. Furthermore, it was shown that the marginally unstable modes may acquire small finite wavelengths as they deviate from stability. These consequences are crucial regarding the properties of the large-scale flows that are attributed to the development of the toroidal ITG instability near marginal conditions. These results were submitted during 2004 and published in a Letter to Phys. Plasmas **12,** 050701 (2005). (See **Annex XVIII** .)

•A pseudo-spectral numerical code was constructed to implement the two-dimensional two-fluid reactive plasma model and describe the temporal evolution of the toroidal ITG instability which leads to the subsequent formation of two-dimensional large scale coherent structures. The saturated spectrum is characterized by the formation of large scale coherent structures, which are slightly elongated along the radial direction. Several parametric studies on the numerical simulations were performed and the sensitivity of the saturated spectra on the linearly unstable initial spectra was investigated. In addition, the properties of the non-linearities that are responsible for the coupling between the toroidal ITG modes were investigated. It was shown that the polarization drift non-linearity is responsible for the inverse energy cascade, and the ion heat flux non-linearity is responsible for the suppression of the instability. The results of these investigations were submitted during 2005 and published at Phys. Plasmas **13,** 022311 (2006). (See **Annex XIX** .) Furthermore, numerical programs capable of tracing plasma particles in two-dimensional electrostatic turbulence environments have been prepared and tested. However, the findings regarding the dispersion of plasma particles in two-dimensional models of electrostatic turbulence were minor and insignificant.

2c3) Stochastic modelling of transport phenomena

Background and Objectives: This work concerns analytical and numerical investigations of kinetic equations, mainly of Fokker-Planck type, arising from stochastic modelling of the motion of charged particles in magnetized plasma. In particular, it encompasses the questions: (i) Consistent approximation schemes beyond the quasi-linear theory; (ii) Lattice kinetic models in magnetohydrodynamics and plasma turbulence; and (iii) Boundary value problems relevant to fusion devices. The objectives of (i) and (iii), to examine further effects on transport properties due to random components of the magnetic and/or electric field, especially concerning problems of anomalous diffusion. The objectives of (ii) are to develop MHD - Lattice Boltzmann algorithms, to validate their ability to simulate MHD flows and plasma turbulence and finally, to solve in a hybrid manner, three dimensional dissipative MHD flows with particles in toroidal plasma. (*This is a multi-annual activity, performed in cooperation with ULB, IPP-CR and ENEA-Frascati.*) Furthermore, the Continuous Time Random Walk (CTRW) framework for particle transport is developed and applied to confined, turbulent plasmas. The aim in this approach is to model anomalous transport, to be able to understand the mechanism(s) that lead to anomalous transport, and to identify processes and configurations that suppress or increase transport. In particular, the CTRW formalism is developed further to model the combined random walk in position and energy (momentum) space. This allows a more complete modelling of turbulent particle transport that, besides spatial diffusion, also includes the energetic aspects, *e.g.* processes like plasma heating (or cooling).

Work performed in year 2005: The following work has been done in the tasks of this activity:

1. Stochastic modelling: Because of the complexity of transport processes in plasmas, a phenomenological approach is often used where "collisions" are modelled by a random force. In particular, for the motion of a charged test particle in magnetised plasma, the effect of the bulk of the plasma is represented by a Langevin-type force, i.e. a friction term proportional to the velocity of the particle as well as a stochastic component. Assuming non-random (external) fields, exact and/or approximate equations determining the evolution of the probability density for the position and velocity of the particle can be derived and their properties are investigated. During the last three months of this period, work in this area has been resumed. Using methods of non-equilibrium statistical mechanics, assuming a Gaussian process for the stochastic component of the force, Fokker-Planck type equations have been established in case of a homogeneous external magnetic field. In the case of a δ-correlated process ("white noise") the problem reduces to that of Brownian motion and the probability density satisfies the well-known (Markovian) kinetic equation. A similar (exact but non - Markovian) equation, with time-dependant coefficients, has been established when the correlation time of the process is finite (sometimes referred as "coloured noise"). Possible approximations leading to a Markovian equation have been considered and their range of validity is being investigated using analytical as well as numerical methods. (This activity will be continued during the next period.)

2. Lattice Boltzmann methods for MHD flows: A three-dimensional lattice kinetic code (LK3D) has been developed, tested and validated against a pseudo-spectral code kindly provided by D. Carati (Université Libre de Bruxelles, Association EURATOM - Etat Belge) for several 3D isotropic dissipative MHD turbulence configurations. The agreement between the corresponding results is excellent. A hybrid thermal scheme has been developed and as a result non-isothermal MHD flows may be simulated. Efficient scripting of the code has been accomplished in order to facilitate integration of additional modules in the future. Most important the LK3D code has been properly modified to simulate MHD dissipative flows in toroidal geometry. Based on this success we are planning, within our collaboration with ENEA sulla Fussione, C. R. Frascati, to reproduce the results of their MHD solver in toroidal geometry. Certain theoretical advancements on numerical issues related to the convergence speed of the lattice kinetic schemes have been also addressed. A more comprehensive description of this work is presented in **Annex XX** . Finally, some preliminary work on vacuum flows, strongly connected to several subsidiary systems of a fusion reactor, has been performed. More information can be found in
Annex XXI
(This activity will be continued during the next period.)

3. Turbulent transport in Tokamak plasmas: The Continuous Time Random Walk (CTRW) equation for the combined random walk in position and momentum space had been derived during the previous period (2004). The equation describes particles that undergo trapping, are accelerated or heated in localized events, and perform free flights in position space. In year 2005, we were successful in solving the complete CTRW equation numerically. The CTRW equation is a Volterra integral equation, involving at least three convolutions. We first specified it to the one dimensional case along the radial direction. The equation is then solved on a prefixed set of grid-points in position space, momentum space and in the temporal direction. In a first trial, Fourier transform methods were used, in combination with the iterative Nystrom method in the time direction. The numerical precision (conservation of normalization) was

satisfying for integration times only up to some fraction of a second, which turned out to be a too short time for our intended applications. Thus, instead of proceeding to specifying the parameters to self-organized criticality (SOC) conditions, we developed a new numerical method that is reasonable in computing time and allows large integration times without loss of precision. The method used is a variant of the pseudo-spectral methods, which is a quite new approach to integral equations and which, to a large degree, we first had to develop. The basic idea of this method is to expand the unknown function in terms of Chebyshev polynomials, also in time direction, which reduces the integral equation to a set of linear algebraic equations. The solution is in the form of the joint probability distribution function for a particle to have a certain position and a certain momentum as a function of time, which allows to determine the diffusivity in position and in momentum space, and to derive quantities like temperature profiles. Having derived the equations and implemented an efficient method for their numerical solution, we are now able to turn to the application to confined plasmas and SOC conditions in year 2006. First results show how particles can be heated and accelerated, undergoing in parallel sub diffusive behaviour (see also **Annex XXII**).

2c4) Saw-tooth and NTM stabilization by super-thermal particles

Work performed in year 2005: This activity was temporarily suspended from the work programme of year 2005: The principal investigator, Dr. A. Lazaros, was working on this activity at FOM/FZJ, on a Euratom fellowship.

2c5) Stationary MHD modes in magnetically confined plasmas

Background and Objectives: This is a long-term project (*performed in cooperation with IPP*) aiming at constructing equilibria and relaxed states of laboratory (and astrophysical) plasmas of fusion concern (
e.g.
, plasmas of tokamaks and reversed-field-pinches) with flow or/and finite conductivity and investigating their linear and nonlinear stability. Understanding these issues can contribute to improving the current magnetic confinement systems and possibly developing new ones.

Work performed in year 2005:

1. In a recent study we showed that the toroidal flow can change the magnetic topology of tokamak equilibrium eigen-states in producing multi-toroidal configurations [G. Poulipoulis, G. N. Throumoulopoulos, H. Tasso, Phys. Plasmas **12**, 042112 (2005)]. During year 2005 we have extended this study to double toroidal configurations in the following cases: (a) either

toroidal “compressible” flow with isothermal magnetic surfaces and varying density thereon or compressible one of arbitrary direction, *i.e.* having toroidal and poloidal components and (b) the line connecting the magnetic axes located either parallel or perpendicular to the axis of symmetry. These, configurations having reversed magnetic shear profiles and current density ones reversing in the core region are associated with internal transport barriers. It turns out that the flows affect the equilibrium safety factor, current density, pressure and electric field profiles while the equilibrium characteristics are rather insensitive to the orientation of the line connecting the two magnetic axes. (See **Annex XXIII**.)

2. Equilibria with constant magnetic field modulus on magnetic surfaces (isodynamic) are of fusion interest because they are free of neoclassical transport. In a recent study we constructed three classes of axisymmetric equilibria with incompressible flow associated with certain isodynamic-like side conditions [H. Tasso, G. N. Throumoulopoulos, Il Nuovo Cimento **119B**, 959 (2004)]. Extending this study in the current period we have found that there are two alternative transformations under which the above equilibrium problem reduces to a set of five ordinary first-order quasi-linear differential equations (see **Annex XXIV**). The respective initial value problem has unique solution in accord with isodynamicity. Preliminary inspection of these equations indicates that the flow results in a variety of novel configurations including toroidal shells and two island configurations (*to be continued in 2006*).

3. In continuation of previous studies on Lyapunov stability of certain MHD systems [H. Tasso, G. N. Throumoulopoulos, Phys. Plasmas **10**, 4897 (2003); Phys. Plasmas **11**, 334 (2004)] we have pursued to derive a sufficient condition for linear stability of z-independent screw-pinch equilibria with constant axial magnetic field and purely azimuthal sheared incompressible flow under arbitrary three dimensional perturbations. To this end the quadratic functional for the potential perturbation energy which was obtained by Vladimirov and Ilin [Phys. Plasmas **5**, 4199 (1998), Eq. (20) therein] has been employed. The study so far indicates that the identification of Lyapunov functionals for the aforementioned equilibria is difficult and needs further investigation which has been planned for the year 2006. In an alternative study (see **Annex XXV**) a necessary condition for the existence of general dissipative magnetohydrodynamic equilibria has been derived.

2c6) 3-D pellet modelling

Background and Objectives: The 3-D pellet modelling activity is performed in collaboration with IPP Garching/Greifswald. The objectives of this activity are to develop multi-dimensional pellet codes for pellet-plasma interaction studies. The multi-dimensional codes are: the development of a 2-D+1 pellet-plasma code, and the implementation of pellet module in a 3-D MHD code (the *M3D* code developed by Princeton). The 2-D+1 code is 2-D resistive MHD in the poloidal plane plus 1-D Lagrangian in the toroidal direction. The current version of the 2-D+1 has only one magnetic field component, B_z.

Work performed in the year 2005 (*in co-operation with IPP*): This activity refers to the development of multi-dimensional codes for pellet-plasma interaction studies and pellet-fuelling of magnetic fusion reactors. The code development involves the development of a 2-D+1 code (2-D resistive MHD in the poloidal plane plus 1-D Lagrangian in the toroidal direction), and the coupling of pellet modules to the 3-D nonlinear MHD code *M3D* (*developed by PPPL, Princeton University*). This year, work was initiated in modifying the 2-D module of the 2-D+1 code in order to develop a 2-D resistive MHD pellet code for the equatorial plane of a tokamak. The work performed includes:

1. Work continued on further development (improvements) and validating the 2-D+1 code. A number of shock tube tests were performed for a large range of high beta and for very low beta plasmas in order to resolve disturbances generated by Alfvén waves and compare these disturbances with disturbances that are generated in the 2-D+1 code for moving high density neutral particles sources in low density high temperature plasmas.
2. Implementation of non-uniform grids in the 2-D+1 code for moving and stationary neutral particle sources, as it was noticed that grid size around the pellet cloud had to be less than 0.001 m. Unstructured grids were not implemented as this a very large manpower effort, and this may be needed when true tokamak geometries are considered.
3. The development of a 2-D resistive MHD code for the equatorial plane of a tokamak involved the modification of the 2-D module of the 2-D+1 code. Only the temperature diffusion equation was implemented in non-uniform grids. The objective for developing this code is to have a better approximation for the expansion of the pellet cloud along magnetic field lines.

The numerical methods used for the 2-D+1 code were 2nd order Godunov scheme and Flux Corrected Transport for the hyperbolic part of the equations, and the GMRES method for the second order derivatives (the elliptic part) of the equations. A very large number of scenario runs for stationary and moving pellets were performed, and it was noted that in a number of stationary pellet scenarios instability in the velocity field was appearing. It was agreed with colleagues from IPP to change the numerical methods for the hyperbolic system. By applying a high resolution Total Variation Diminishing (TVD) scheme these numerical instabilities in the velocity fields were rectified. Results using the TVD scheme for the hyperbolic part of the equations, for a stationary pellet, are shown in **Annex XXVI** **.** The scheme was also implemented for non-uniform grids, and some progress has been made in implementing a moving refined grid around the pellet cloud.

2c7) Energy transfer due to wave - particle interaction

Background and Objectives: This activity aims at the collection and analysis of experimental data on the behaviour of highly energetic alpha particles in thermonuclear tokamak environment. Issues of fundamental importance are: the collection of data on Alfvén cascades and TAE modes, their theoretical understanding and the study of interaction between fast ion distributions and Alfvénic modes as well as the evaluation of various parameters in such processes.

Work performed in 2005 [*including the work initiated in late 2004 and not reported in the 2004 Annual Report*]:

1. In recent theoretical developments [E. A. Evangelidis and G. J. J. Botha, JGR - Space Physics **110**, A02216 (2005)] for the transfer of energy from waves to particles (and vice versa), analytical expressions have been obtained for the interaction of elliptically polarized waves with hot particles. It has been shown that the currents supported by a magnetized plasma can be classified as 0, □1, □2 modes and further that only the 0 and □2 modes are available for transfer of energy. Thus, the transfer rates have been calculated using certain identities on summation of Bessel function products (derived earlier by EAE) and some integral expressions (appearing in the open literature for the first time) suitable for thermalised plasmas, which simplify the algebra by a considerable amount. Furthermore, transfer rates have been calculated for the interaction of waves with non thermal plasmas, a common occurrence in solar plasma and fast particles in tokamak plasmas, upon using kappa – distribution functions.

2. With the detection of Alfvén Cascades during NBI-heated discharges in JET it has become necessary to extend and develop the theoretical description of wave-particle interactions in the sub-Alfvénic domain of velocities, since the observed interaction take place at $V_{II,NBI} = (1/5)\ V_{Alfvén}$. The wave-particle interactions at sub-Alfvénic velocities and the transfer of energy to particles were

analysed using the formalism developed earlier by Berk, Breizman, Ye, Phys. Let. A, **162**, 475 (1992), and Berk, Van Dam, Guo, Lindberg, Phys. Fluids B **4**, 1806 (1992). An extensive version of these results with the title "*Alfvén cascades in JET discharges with NBI heating*" was presented by Sharapov *et al.* in the 9th IAEA TCM on Energetic Particles, Takayama, 9-11 November 2005. (See **Annex XXVII**.)

3. The analysis of resonances at sub-Alfvénic velocities, as observed in JET in NBI/ECRH heated ions, had been scheduled for November 2005 and would have continued in the year 2006. However, due to technical difficulties the experimental Campaigns C15 -C17 for Autumn 2005 had to be postponed, initially for the end of February 2006 and eventually for after April 2006. Therefore, there are no results to report.

4. In addition, collaboration on the dynamics on equilibrium surfaces has begun and some preliminary results will be presented in the forthcoming European Physical Society Meeting, Rome 2006. Two papers have been accepted by EPS-33 as poster presentations.