2a) Beam-Wave Interactions and High-Power *rf* Generation

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

Background and Objectives: The development of the gyrotrons as a major high power microwave source makes now possible to provide an *rf* beam with output power of approximately 2 MW at the frequency of 170 GHz that is needed for ECRH in ITER. This output power may be increased by introducing a sheet electron beam that travels along a magnetostatic field, and intersects perpendicularly the *rf* beam produced by a gyrotron. This configuration is similar to the initial concept of the quasi-optical gyrotron (QOG) and inherits most of its common advantages but also has significant beneficial differences. Thus, a conventional gyrotron would provide the generation of the initial beam, and the QOG will be introduced as a second stage device, in order to amplify the *rf* power to the levels needed for the fusion reactor.

Work performed in year 2006 (*in co-operation with CRPP and FZK*):

1. Self-consistency was introduced in our calculations in an iterative scheme, where in each step the properties of the electrons are governed by the field of the previous iteration and vice-versa. The equations of motion were recalculated adopting a more general expression, which is an essential prerequisite in order to handle adequately not only the Gaussian field form of the first iteration, but also the field that will be produced during the interaction, and furthermore, gives the opportunity to apply an *rf* beam of any convenient form in the input line (i.e. with rectangular rather than Gaussian cross section).

2. The radiation field induced by the nonlinear electron motion was first calculated at the plane of the e-beam. After convergence had eventually occurred and a steady state condition was established, the off-plane radiation was calculated in order to finally have the 3D field pattern. Additionally, the total power produced by the interaction (and integrated over all directions) is determined (see **Annex I**).

3. The existing Matlab code was concluded by also introducing the self-consistency process, and it is now fully operational for possible future use. However, the relatively long time of execution that is required for the corresponding calculation suggested that a new code should be developed, this time in C++. While this code is now operational and in use, it is still under development and evaluation, and our efforts are focused on the improvement of the numerical efficiency and on speeding-up the calculations, first by implementing a code

parallelisation. (*Task to be continued in 2007*.)

4. Our initiated plan to compare our code results with a prescribed analytical excitation is postponed, because of our concentrated efforts to design and implement a new C++ code. This task will be rescheduled for the following year.

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 2006 (*in co-operation with CRPP and FZK*): The object-oriented version of *ARIADNE* code has been brought to an operational state. The following specific tasks have been addressed:

1. The implementation of the solver for the object-oriented version of the *ARIADNE* code has been completed. It is capable of solving the Laplace/Poisson equation in two-dimensional as well as three-dimensional geometries. A curvilinear quadrilateral mesh (eight degrees of freedom per element) is used for the two-dimensional simulations (see **Annex II**) and a curvilinear tetrahedral mesh (ten degrees of freedom per element) is used for the three-dimensional simulations. Sample simulations indicate, that, as expected, for such a mesh to give comparable accuracy, a much smaller number of nodes is needed and substantial savings on computing time are achieved.

2. The SML library, which is used for the storage and the parallel solution of the huge sparse linear system generated by the finite element method, has been rewritten in the object-oriented language C++. Many improvements have been incorporated such as the replacement of the two independent lists for the storage of the sparse matrices with one complex list, the definition of several operations between sparse matrices and arrays, etc.

3. The subroutine searching for the mesh element containing a particular point in the beam tunnel region has been implemented. Its function is based on the numerical inversion of the transformation of the Cartesian space to the local coordinates system of each mesh element (see **Annex II**).

4. A new object-oriented subroutine for the management of the external magnetic field has

been developed (see also **Annex II** for more details).

5. The new version of the code has been designed to be a PIC code for the dynamical simulation of beam tunnel. The calculation of the potential on the mesh nodes takes place for each time step (which is defined by the user) instead of the calculation of the overall beam electron trajectories. This function is achieved by the storage of all beam-electron trajectory steps in the computer memory of parallel computer system for each time step.

6. The gun and the collector (with sweeping coils) of the European 170 GHz, 2 MW gyrotron have been simulated using the new code. The results show good agreement between the new and the older version of the code.

[As of September 2006, the main effort on this activity has moved to *CRPP*, Lausanne, where the principal investigator, Mr. J. Pagonakis, has moved temporarily, under a Euratom fellowship.]

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 normalised field amplitude, whereas energy exchange 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 for cases which are beyond domain of validity of the aforementioned model. (*This is a multi-annual activity, initiated in 1999 as a continuation of work performed earlier under cost-sharing contracts with Euratom, performed in cooperation with CRPP, FZK and HUT/TEKES.*
)

Work performed in year 2006 (*in co-operation with CRPP and HUT/TEKES, but also of interest to FZK*): This activity addresses the development of numerical tools, for the quick and accurate determination of the frequency spectrum of electromagnetic structures with discontinuities (corrugated beam tunnels and slotted coaxial cavities) of relevance to gyrotrons.

1. Beam loading and its effects in a gyrotron beam tunnel (*continued from previous period*) : The numerical code for the cases of TM, TE and hybrid modes for both periodic and non-periodic geometries was implemented last year (2005). This year, several numerical tests were performed for the TM and TE cases and appropriate modifications were made to improve the stability and accuracy of the numerical algorithms of the code, especially on the algorithms used to find complex roots, which were significantly improved (details are given in **Annex III**). The numerical code, which was also ported to the Linux and Unix environments and tested in part, was used to determine the dependence of the dispersion relation and the beam-wave interaction intensity on the geometrical and beam parameters (details are given in **Annex IV**).

2. Ohmic losses in a coaxial gyrotron cavity with a slotted inner rod (*continued from previous period*): A new implementation of the numerical code for the solution of the second order ordinary differential equation describing the high frequency longitudinal field profile [eq. (3) of Annex V of the 2005 Annual Report], has been developed. The new algorithm has been introduced to the numerical code developed in 2005 for the calculation of the ohmic losses and has been examined for stability and accuracy. Moreover, extensive comparisons of the numerical results with results available from FZK have been performed (details are given in **Annex V**).

3. Coaxial waveguide with circumferential corrugations: The numerical codes for the TM and TE waves for the cold coaxial waveguide have been improved and comparison of the numerical results with those of MAFIA has been done. Moreover, the mathematical formulation and the corresponding numerical code for the calculation of the beam loading effects in such a waveguide have been implemented for the case of TE waves, but it is not adequately tested, yet.

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, initiated in 2002 as a continuation of work performed earlier under a cost-sharing contract with Euratom, performed in cooperation with FZK, but also of interest to CRPP.*

)

Work performed in year 2006 (*in co-operation with FZK*): Regarding the studies on the design and performance of high-power coaxial gyrotrons and in view of the improvement of the developed interaction code, the following issues have been addressed:

1. The code has been parallelised and the degree of parallelisation is close to ideal. The work on the improvement of the code, regarding self-consistency with respect to the axial field-profile, has continued. In particular, the subroutine for the calculation of the cold-cavity field profile, which will be used as initial condition in the self-consistent version of the code, has already been developed. (*This work will continue into next period.*)
2. The parallelised code has been extended in order to take into account an electron beam with azimuthally inhomogeneous current density. Simulations of the operation of the European 170 GHz, 2 MW coaxial gyrotron for ITER, considering a sinusoidal azimuthal inhomogeneity of up to 50 % in the beam current density, have been performed. According to the simulations, the operating $TE_{34,19}$ mode is always excited and oscillates at the operating voltage (90 kV). However, the beam inhomogeneity results in a 6-7 % reduction of the output power and a 2-3 kV shortening of the voltage range of oscillations of the operating mode ($TE_{34,19}$ is detuned at 91 kV). In addition, some degree of multimoding takes place, since the azimuthal satellites of the operating mode are simultaneously excited at power levels ~ 2 % of the output power. More detailed and realistic simulations, taking also into account the spreads in the electron guiding centre, energy and velocity, which are caused by the inhomogeneity of the beam current density, will be performed into next period. (*This work will be done in co-operation with FZK and also with CRPP.*)
3. The systematic procedure for the selection of the gyrotron operating mode and operating parameters, developed during the previous period, has been extended to incorporate the results from the study of the behaviour of the spent electron beam. It has thus become possible to take into account, when choosing the gyrotron operating regime, the optimisation of the efficiency of a depressed collector. The mode-selection procedure has also been used to investigate the interaction efficiency limitations in 170 GHz-3 MW CW coaxial gyrotron designs (relevant to the ITER ECRH system) and to provide a list of candidate operating modes for such a design. The results, together with an overview of the procedure (not extensively reported in the previous period) are given in **Annex VI** .
4. An intensive investigation has been initiated, in order to explain the discrepancy between simulations and experiment regarding the pre-prototype 170 GHz coaxial gyrotron at FZK. Due to the direct connection of this gyrotron with the European coaxial gyrotron for ITER, this investigation has been considered a top priority and will continue into next period. This urgency, combined with the fact that the experimental facilities of both FZK and CRPP will not be available for a second-harmonic gyrotron experiment in the near future, resulted in the postponement of pertinent studies 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 utilised are within the context of the Hamiltonian formalism, including phase space analysis, Canonical Perturbation Method (CPM) and symplectic integration schemes. (*This is a multi-annual activity, initiated in 2004, performed in cooperation with TEKES/HUT* .)

Work performed in year 2006 (*in co-operation with HUT/TEKES*): The studies of complex electron dynamics under resonant wave-particle interactions in gyrotron cavities have been continued and the following tasks have been performed:

1. The Canonical Perturbation Method has been extended to higher order with the utilisation of Lie transform techniques, in order to provide analytically a higher order approximate invariant of the motion describing the electron phase space under interaction with *rf* modes.

2. The results of task (i) have been used in order to obtain approximate electron distribution functions, as solutions of the corresponding Vlasov (or Liouville) equation. The distribution functions have been used further for the calculation of quantities describing collective characteristics of an electron beam, which are relevant for effective gyrotron design and operation. As a result an analytic formula for the calculation of the perpendicular efficiency has been obtained, which is accurate up to fourth order with respect to the effective strength of the beam to *rf* coupling factor. Moreover, the results are shown to be a higher order extension of the Madey's theorem for the calculation of gain in microwave sources or other quantities related to collective particle behaviour for general cases where wave-particle interactions occur (see **Annex VII**).
3. A specific self-consistent model for electron interactions with *rf* modes has been defined as being preferable for the application of the Hamiltonian formalism and the corresponding methods. The study of this model will be continued in the next year.

2b) Diagnostics and Theoretical Support

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 fusion 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, initiated in 1999 as a continuation of work performed earlier under cost-sharing contracts with Euratom, performed in cooperation with IPP.
)

Work performed in year 2006 (*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 following tasks were addressed:

1. The Mach head was used to investigate in-out divertor transient flow asymmetries during ELM’s in low power H-mode discharges with up to 2.5 MW of NBI. The inter-ELM toroidal flow was measured, and the deviation from this during ELMs investigated. During the inter-ELM phase, the main observation was that the flow profile exhibits features very similar to what is observed in ohmic discharges, although the Mach number was found not to exceed M = 1, except possibly in the vicinity of the high-field side separatrix, where peak values of M ~ 1.2 were measured. However, when taking into account the uncertainties in the Mach probe interpretation, it is not possible to determine if the flow is supersonic or not. Near the high-field side vertical target plates, the Mach number was observed to drop to about ~ 0.3, lower than what was measured in similar ohmic shots. In the private flux, the flow was observed to reverse slightly inwards of the poloidal field minimum. During ELMs, flow measurements performed using a fast data acquisition system (sampling frequency ~ 100 kHz, analog bandwidth ~ 500 kHz) suggested that the divertor flow is significantly perturbed. In the high-field side scrape-off layer, it was found that the flow is accelerated to velocities much larger than the ion acoustic velocity, typically exceeding M = 2, while in the low-field side scrape-off layer possible flow reversal was observed. In the private flux, the ELMs were found to induce a bulk movement first in the counter-current and then in the co-current direction. These results are discussed in more detail in **Annex VIII**.

2. Plasma properties in the vicinity of the 2nd x-point were investigated with the reciprocating probe in upper single null (USN) discharges. In this configuration the probe trajectory crosses only the 2nd x-point, where the heat load is much lower, allowing its use in discharges with very large auxiliary heating power. A number of plasma configurations and heating scenarios were investigated; both in NBI and ICRF heated L and H-modes with up to 5 MW of additional heating power and normal and reversed toroidal field direction. Good measurements were made in all cases and the 2nd x-point region was fully characterised in terms of electron density, temperature, pressure and parallel flow velocity. Preliminary analysis from these measurements suggests the following: a) significant plasma density (of the order of ~10^{19} m^{-3}) is measured even at very large distances from the main plasma, especially in the low-field side scrape-off layer, b) relatively flat electron temperature profiles with magnitude of the order of 3-8 eV are measured, c) the flow magnitude and direction near the 2nd x-point depends strongly on the ion B´ÑB direction and d) the toroidal flow direction reverses very near the 2nd x-point.

3. The information obtained by the probe was used for the validation of edge-divertor simulations for low, medium and high collisionality ohmic discharges. Modelling and model validation was performed using the SOLPS multi-fluid code. For the moment, only medium-high density ohmic discharges were modelled, with some encouraging results. Best agreement of electron temperature and density profiles between measurements and simulation was obtained in the private flux and high-field side scrape-off layer. The discrepancy in the low-field side is currently being investigated, mainly by incorporating scrape-off layer drifts in the simulations. Concerning simulations of flow velocities, in most cases the simulations determine accurately the flow direction, in both the high-field side and low-field side scrape-off layer. The flow magnitude is however underestimated, typically by factor of 2. In the private flux, the calculated flow profile is symmetric, and does not reflect the uni-directionality observed experimentally at high and low densities.

2b2) Neutron spectral measurements at JET using an NE213 organic scintillator

Background and Objectives: This activity relates 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 has neutron/gamma discrimination capability and 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 required to unfold the neutron spectra from the measured pulse-height spectra (a problem similar to tomographic reconstruction), part of the development consists of optimising and comparing such algorithms (examples of which are the maximum entropy method, MAXED, and the minimum Fisher regularisation method, MFR).

Work performed in year 2006 (*in co-operation with JET*): The aim for 2006 was to further optimise the MAXED and MFR codes, which use the Maximum Entropy and Minimum Fisher Regularisation methods respectively to perform spectral unfolding. The following tasks were performed:

1. The MAXED L-curve method, which finds the optimal χ^2 value with which to perform the unfolding, was modified to improve convergence for a wide variety of pulse-height spectra. Then, the MFR code was translated into C and modified to read JPF data. It was also made compatible with the HEPRO format for reading response functions and light spectra, which is widely used at JET.
2. A new interface program was written to run both MAXED and MFR codes in parallel and compare the calculated (unfolded) neutron spectra from both methods. An operations manual was also produced, describing the installation and use of this interface.
3. Using this tool, selected discharges from campaigns C15-C17 were then analysed. It was found that in most cases the agreement between MAXED and MFR is good and that the ion temperature derived independently from the neutron spectrum (from the full width at half maximum) is in good agreement with the ion measurements made by the core CX.

In addition, in July 2006 a new detector was installed, which required the implementation of a new response function. Analysis of the neutron spectra measured with this new detector is still ongoing.

2b3) Calculation of electromagnetic field distribution on TORPEX

Background and Objectives: TORPEX is a toroidal device, in operation (at CRPP, Lausanne) since March 2003, which aims at addressing, inter alia, (a) the relative contribution to the cross-field flux from correlated density and potential fluctuations, associated with unstable modes, or with isolated intermittent events and (b) the modes most relevant for transport and their relation to the specific configuration and plasma parameters of different devices. Microwaves are injected into the (toroidal) vacuum chamber from the side by an appropriate rectangular waveguide, with the waves being in the ordinary mode (O-mode) polarisation at the

output of the waveguide. In addition, a transition from rectangular to circular cross-section is used to match the waveguide to the vacuum chamber. Since no focusing elements are present, microwaves are actually injected into the chamber with a mixed polarisation, which can be represented as a superposition of O- and X-mode. The objectives of this activity are the modelling and the numerical simulation of the corresponding electromagnetic problem, i.e., the calculation of the spectrum of electromagnetic waves, which excite in the toroidal vacuum chamber, as well as the influence of the transition to the field properties. Furthermore, optimal transition configurations, which minimise the reflection coefficient at the excitation port, will be searched. For all these calculations the commercial code MAFIA will be used. (
This is a new activity established in 2006, which extends the co-operation of the Research Team of the University of Athens with CRPP
).

Work performed in year 2006 (*in co-operation with CRPP*): The problem of simulating a toroidal waveguide with a rectangular excitation port and an appropriate transition (TORPEX project) has been addressed and several approximations of the real geometry have been considered. The electromagnetic field distribution and the eigenmodes of several simplified geometries of cylindrical waveguides with and without surface losses have been obtained. Moreover, the field distributions in several simplified geometries, like cylindrical waveguides with surface losses excited by a rectangular excitation port, have also been obtained.

2c) Equilibrium, Stability and Transport in Fusion Plasmas
2c1) 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 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 2006 (*in co-operation with IPP*): The work performed includes:

1. Axisymmetric equilibria with incompressible flows of arbitrary direction have been studied in the framework of magnetohydrodynamics under a variety of physically relevant side conditions. To this end a set of pertinent non-linear ordinary differential equations are transformed to quasilinear ones and the respective initial value problem is solved numerically with appropriately determined initial values near the magnetic axis. Several equilibria are then constructed surface by surface. The non field-aligned flow results in novel configurations with a single magnetic axis, toroidal shell configurations in which the plasma is confined within a

couple of magnetic surfaces and double shell-like configurations. In addition, the flow affects the elongation and triangularity of the magnetic surfaces. An extensive summary is presented in **Annex IX** .

2. We have shown that the non-existence of ideal MHD tokamak equilibria with purely poloidal incompressible flow can be extended to the cases of (i) compressible MHD flows (ii) Hall-MHD incompressible and compressible flows and (iii) one fluid equilibria with pressure anisotropy and incompressible flows. The non-existence is related to the toroidicity. Specifically, for incompressible flows an inconsistency appears in terms of relations, which, in addition to surface quantities, have an explicit dependence on the radial distance from the axis of symmetry, otherwise only isodynamic-like equilibria are possible. For compressible flows the density gradient does not have unique definition on the magnetic axis. Also, for MHD compressible flows the proof can be extended near the magnetic axis. Details on this study are provided in [Throumoulopoulos, Weitzner and Tasso, "On non existence of tokamak equilibria with purely poloidal flow" *,* Phys. Plasmas 13, 102501 (2006)].

3. We have derived a sufficient condition for the linear stability of cylindrical steady states in connection with plasmas of constant density and flow of arbitrary direction. For vanishing flow this condition reduces to a known one pertinent to static equilibria of a hard-core pinch. A summary of this study is given in **Annex X** .

2c2) Alfvén wave-particle interactions at sub-Alfvénic velocities

Background and Objectives: Low frequency Alfvén Cascades (ACs) are observed in many experiments with NBI and NBI-driven ACs in Tritium experiments. The project aims at calculating the power transfer between particles to waves using the Toroidal Alfvén Eigenmode theory and in particular in the sub-Alfvénic range of frequencies. (*This activity is performed in collaboration with JET.*)

Work performed in 2006: Work continued throughout the year and the general expression was derived for the transfer of power. Various distribution functions for the hot particles can be used to assess their effectiveness. One key observation is the excitation of Alfvén Cascades by low power NBI at sub Alfvénic velocity $V_{||} = 0.2\ V_A$. NBI-driven ACs are seen on JET tritium NBI-blip experiments with very low NBI power. The energy of the D-beam is E = 128 keV while that of the T-beam E = 101 keV (Pulse #61488). There were 20 discharges with NBI- driven ACs with power about 1 MW (JET Pulse #1216). Some of the questions arising are (a) why these modes do not experience strong Landau-damping, (b) what is the resonance condition for driving these modes by beam ions. By using the drift kinetic equation for fast ions in the presence of an Alfvén wave given by Berk, Breizman, Ye (Phys. Lett. A, 1992) and the coordinate transformation by Breizman, Sharapov (Plasma Phys. Controlled Fusion

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, 1057 1995) we were able to find the general expression. One of the envisaged developments is the comparison of the analytical results for the power transfer with the CASTOR-K.

2c3) TM avoidance in ASDEX-Upgrade and TEXTOR by early application of EC waves

Background and Objectives: The suppression of tearing modes, which degrade the energy confinement in fusion plasmas, has been one of the highest priorities in present tokamaks and a key issue for ITER. More specifically, it has been shown in ASDEX Upgrade that neoclassical tearing modes (NTMs) could be suppressed by localised electron cyclotron current drive (ECCD) inside the magnetic island, and it was also demonstrated in TEXTOR that classical tearing modes could be suppressed by localised electron cyclotron resonant heating (ECRH). A unique result, however, obtained in JT-60U during “early” and “late” application of ECCD (i.e. before and after the growth of the magnetic island) was that the saturation width of the magnetic island in the former case (i.e. during early ECCD) was significantly smaller than in the latter case (i.e. during late ECCD). In the present work we investigate this effect, and evaluate the operational regime of TEXTOR and ASDEX Upgrade for the avoidance of tearing modes by early application of EC waves.

Work performed in year 2006 (*in cooperation with FOM and FZJ*): A theoretical model was developed for the advantage of the early application of electron cyclotron current drive (ECCD) for the suppression of neoclassical tearing modes which are destabilised in ASDEX Upgrade by high beta. The model was subsequently extended to address the advantage of the early application of electron cyclotron resonance heating (ECRH) for the suppression of classical tearing modes, which are destabilised in TEXTOR by perturbation fields (generated by the dynamic ergodic divertor). It is shown analytically that the advantage of early ECCD (for the suppression of NTMs) in ASDEX Upgrade is favoured by the broad deposition profiles compared to the critical island width (at which perpendicular transport across the island becomes comparable to the parallel transport). The model is consistent with the preliminary experimental results. In TEXTOR it was previously established that the suppression of tearing modes by ECRH is dominated by heating, but the advantage of the early application is a consequence of the non-inductive current drive, which is found to be more important for small islands (details can be found in **Annex XI**).

2c4) Transport and chaos in fusion plasmas during ECRH

Background and Objectives: In this activity, we study wave propagation and absorption as well as wave-particle interactions in the ECRH frequency regime. The activity has three parts. In the first part, we focus on the importance of nonlinear effects in the absorption of electron-cyclotron wave beams in tokamak plasmas. Our purpose is to upgrade the physical schemes used to study the wave absorption in the tokamak plasma, including effects that model the complicated character of the absorption in a more realistic way. The main tool used in this task is a full wave code based on the Finite Difference - Time Domain method (FDTD). In the second part (*performed in collaboration with IPP*) we consider the propagation and absorption of non-Gaussian EC beams in tokamak plasmas. Our aim is to provide a more realistic model for the description of EC propagation and absorption, including effects of localisation, asymmetry and inhomogeneity in the beam. The propagation and absorption of non-Gaussian beams is formulated in terms of the beam tracing asymptotic technique. Finally, in the third part (*performed in collaboration with MIT*) nonlinear dynamics of wave-particle interactions in fusion plasmas are considered from the point of view of applications to Electron Cyclotron Resonant Heating (ECRH) and its role in the stabilisation of the Neoclassical Tearing Modes (NTM), Electron Cyclotron Current Drive (ECCD) and plasma diagnostics through interactions with *rf* pulses. The Hamiltonian formalism along with a set of accompanying tools such as the phase space analysis, the Canonical Perturbation Method and Lie transforms are used in order to extend the theory beyond the quasilinear approximation for realistic plasma configurations and general form of the wave spectra.

Work performed in year 2006 (*in collaboration with the Institutes indicated*):

1. In the period in subject, we initiated the development of a full-wave code for the description of the perpendicular propagation and absorption of localised EC beams in simplified tokamak geometry, based on the Finite Difference - Time Domain method (FDTD), and using different physics models for the dielectric response of the plasma. We have developed versions of the code in all dimensionalities of the method (1-D, 2-D and 3-D), each version being useful in treating different cases with the least computational burden (processor and memory) for each case. At this stage, the code is benchmarked by treating simple cases, like the propagation in a lossy medium and in cold plasma. (For details see **Annex XII**)

2. The second part of this activity considers the propagation and absorption of non-Gaussian electron-cyclotron beams in tokamak plasmas. During the period in subject, we completed the numerical implementation of the sequence for tracing non-Gaussian beams, which is based on the analysis of the (arbitrary in general) initial beam profile into Gaussian-Hermite modes, the computation of the generalised beam width and the damping of the higher-order modes. The coupling of our method for the propagation and absorption of non-Gaussian beams with the TORBEAM code, including also the realistic case where the tensor describing the beam width in the lab frame is not diagonal, was also completed. (*This task is performed in collaboration with IPP.*)

1. Finally, on the third part of this activity (the nonlinear dynamics of wave-particle interactions in fusion plasmas), the following work has been performed (*in collaboration with MIT*):

2. The investigation of electron dynamics under interaction with localised waves, propagating at an angle with respect to the magnetic field, has been continued. Higher order canonical perturbation theory has been applied for the case where the variation of the electron velocity parallel to the magnetic field is negligible. It has been shown that the canonical perturbation theory along with the utilisation of Lie transform techniques, is the appropriate context for the derivation of velocity diffusion equation to higher-order (see **Annex XIII**). The latter is of particular importance for several cases occurring in ECRH/ECCD scenarios where the effective nonlinearity of the wave-particle interaction cannot be considered as very small, and the quasilinear theory and the corresponding Fokker-Planck diffusion equation fail.

3. A simplified Hamiltonian model describing the case, where the variation of electron velocity parallel to the magnetic field is not negligible, has been defined [R. Kamendje et al., Phys. Plasmas 10, 75 (2003); ibid 12, 012502 (2005)]. This is a two-degree of freedom, nonautonomous system, which can be considered as near-integrable, for small wave field amplitudes, so that perturbation theory can be applied. The investigation of this case will be continued in the next period, along the lines of task (a).

4. Preliminary considerations for the application of the Hamiltonian formalism and the corresponding methods to the self-consistent model of wave-particle interactions have been performed. It has been estimated that the application of perturbation theory to higher than first order would be quite complicated for this case. In order to treat the self-consistent problem more efficiently, we need to have more solid results from the simpler non-self-consistent models of the tasks (a)-(b), which can be used for building our physical intuition on the full problem. So, the study of this problem has been postponed for a next period.

2c5) 3-D pellet modelling

Background and Objectives: 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)(*in collaboration with IPP*), a 2-D resistive MHD pellet code for the equatorial plane, and the coupling of pellet modules to the 3-D nonlinear *MHD* code *M3D*

(
developed by PPPL, Princeton University
).

Work performed in year 2006 (*in co-operation with IPP*): Work continued on further development (improvements) and testing of the 2-D+1 code. A number of scenario runs were performed with the 2-D+1 code using a single moving neutral source for various injection velocities, these velocities were in the range of 500-2000 m/s. Scenario runs were also performed for various limits (in the range 0.0 to 2 Mach) on the velocity in the 3rd direction.

1. To the 2-D+1 code, two moving (or stationery) neutral particles sources (representing two pellets) were implemented numerically. These two neutral particles sources are allowed to have different trajectories and different parameters (i.e. size, velocities, prescribed ablation rates). Calculations were performed for the scenario where two identical moving neutral particle sources are injected in the poloidal plane at some distance apart (in both R and Z directions) and with constant and opposite velocities, in order to have parallel but opposite trajectories (see **Annex XIV**). These two-dimensional computations with opposite moving neutral particle sources show the versatility of the possible code applications (shock-heating, density ramp-up etc.).
2. Work continued on the 2-D resistive MHD code (which represents the equatorial plane): Flux limiters were implemented to the Spitzer thermal conductivity, for the temperature diffusion parallel to the magnetic field.

1. Modifications were made to the 2D+1 code so that more than one pellet is allowed to be injected in different trajectories, with different pellet parameters and different time delays. These modifications allow the 2D+1 code to accommodate up to 3 pellets being injected at different times, no large scenario runs have been made yet.

2c6) MHD flows and turbulence

Background and Objectives: 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. The aim of this activity is, to develop extensions of 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 CFD techniques. (*This is a multi-annual activity, performed in cooperation with ULB and I*

KET/FZK.
)

Work performed in year 2006 (*in co-operation with the Institutes indicated*):

1. MHD convection and turbulence (*in co-operation with ULB*):

- *MHD flow and heat transfer in liquid metals*: Results of the MHD flow of an electrically conducting liquid metal in a pipe and an annulus for Reynolds number up to 100 and a range of Hartmann number up to 10 were obtained. While an external uniform and transverse magnetic field was applied, the walls were assumed electrically conducting in contrast to our study in 2005 where they were assumed insulated. The MHD fully convective CFD model in a 3D cylindrical geometry has been developed, to include a variety of boundary conditions and external magnetic fields (see also **Annex XV**).

- *Direct numerical simulation of MHD turbulence*: A direct numerical simulation was performed to study the natural convection flow in a concentric cylinder, at several Rayleigh and Hartmann numbers for an aspect ratio H = 3. The buoyant convection is driven by a temperature difference between the inner and outer walls, with the inner wall at lower temperature, while an external transverse magnetic field is imposed (see also **Annex XVI**).

1. Stability analysis of MHD flows: The three dimensional formulation for the stability analysis of steady state solutions obtained for free convection in a square cross section of a long duct, subject to a magnetic field, has been finalised. The base flow solution is characterised by two recirculation cells that extend along the longitudinal direction of the duct. The emergence of three-dimensional structures with the vortices aligned with the magnetic field, developing periodically in the longitudinal direction, has been investigated. For completeness sidewall conductivity was also accounted for. The numerical methodology for eigenvalue, $\sigma = \sigma_r + i\sigma_i$, calculations via the Arnoldi method has been optimised and different options have been tested. The wave-number k has been sought for, to achieve neutral stability (σ_r

= 0) with respect to the above disturbances (see also **Annex XVII**). During the last part of 2006, code development for three-dimensional stability analysis of 2D recirculating flows, including the effect of conducting walls, was initiated. The Arnoldi method was implemented for the evaluation of eigenvalues for given wavenumber. The complex version of the method was employed in order to accommodate modes corresponding to travelling waves. The numerical convergence tests will be completed in 2007.

2. CFD modelling of MHD rotating flows in shells: The collaborating work with IKET/FZK was continued in year 2006 with the study of MHD steady laminar flow of a liquid metal driven by a rotating disk in a cylinder, subjected to an axial magnetic field. The magnetic Reynolds number is assumed very small but the induced magnetic field is taken into account. The effect of the fluid and wall electrical conductivities and the wall thickness has been studied, in order to assess their importance for the control of these flows. In particular, the following subtasks were performed:

- Study of the mechanism of formation of parallel jets in MHD flows resulting from the counter-rotation conducting metal bodies (disks or spheres) in cylindrical or spherical shells with conducting walls and comparison with analytical solutions which are valid for region of high and low Hartmann numbers. (See also **Annexes XVIII** and **XIX**.)
- Investigation of the flow of conducting fluids and of the electric behaviour of finite wall conductance in cylindrical enclosures with rotating or not parts. (See also **Annex XVIII.)**
- Application of wall function methods for the prediction of the flow of conducting fluids in the Hartmann and side layers. Development and incorporation of high-order accuracy numerical schemes in a CFD code for three-dimensional simulations of MHD flows. (See also **Annex XX.)**

2c7) Discrete kinetic and stochastic models for transport

Background and Objectives: Lattice Kinetic (LK) simulations provide a mesoscale description of the transport properties of physical systems implementing kinetic equations. The benefit of this description arises from avoiding expensive computations present in classical micro and macroscopic approaches. The benefits of LK simulation are compounded by the inherent local and thus highly parallelised nature of kinetic descriptions. This activity aims to develop computer codes based on suitable kinetic equations capable to simulate, in a computationally efficient manner, dissipative MHD flows and plasma turbulence in complex geometries. In addition, another objective is the simulation of fusion related vacuum flows and systems using discrete kinetic modelling. Then, the system can be simulated in a unified manner for any type of vacuum conditions (high, medium, low). Finally, with regard to stochastic modelling, this work concerns the study of anomalous transport, an important issue in fusion plasmas, and it is aimed to develop consistent schemes beyond the quasi-linear approximation. (

This is a multi-annual activity, to be continued in the following periods, performed in cooperation with ENEA-Frascati, FZK and ULB.
)

Work performed in year 2006 (*in co-operation with the Institutes indicated*):

2. Lattice Boltzmann methods for MHD and vacuum flows: (*This task is performed in cooperation with ENEA and FZK.*
)

- We have developed a toroidal geometry version of the, in-house, LK3D code. Initial conditions can be set at will, due to its generalised formulation. In addition, an ITER field reconstruction has been successfully incorporated through an interface with the ITM mdsplus data server. The evolution of continuous shear Alfvén waves in cylindrically symmetrical plasma has been investigated as a benchmark case comparing to ENEA's results. Initial results suggest that the proper behaviour is qualitatively reproduced but more exhaustive analysis is needed for a quantitative agreement. (See **Annex XXI** . *This work is part of the Integrated Tokamak Modelling Task force, IT5-11.*
)

- Our work is related to the implementation of a kinetic-type approach to fusion vacuum systems in the whole range of the Kn number is well under way. We have developed and applied kinetic algorithms for solving flows of gases in circular and rectangular channels under low, medium and high vacuum conditions. The flow is modelled with the BGK kinetic equation, which is solved based, depending upon the configuration and conditions, on the integro-moment method (IMM), the discrete velocity method (DVM) and the direct simulation Monte Carlo method (DSMC). (See **Annex XXII** .) A comparison with the corresponding experimental results obtained by the Vacuum Pumping Task Force of FZK has been performed. Work on channels with triangular and trapezoidal cross sections, including the development of a corresponding computer code has started and is still under development.

1. Stochastic modelling of transport phenomena: (*This task is performed in cooperation with ULB.*) An exact Fokker-Planck type equation, with time-dependant coefficients, had been established for a particle in homogeneous magnetic field, subject to a Gaussian stochastic force with finite correlation time. Properties of approximate Markovian equations have been investigated analytically.

2c8) Turbulence and transport phenomena

Background and Objectives: In this activity we study turbulence and transport phenomena in fusion plasmas. The activity consists of three parts. In the first part, we study diffusion in turbulent plasmas with the use of the Continuous Time Random Walk (CTRW) model, which we extended to comprise the combined diffusion in position and velocity space. The plasma is assumed to be a complex system, with sporadic localised electric fields appearing, with which the particles interact, as well as with regions where the particles may be trapped. The aim is to identify conditions for enhanced or suppressed diffusion. The main benefit of the CTRW approach is that it allows us to model the complex dynamics of particle transport on a global scale, by using statistical laws for the uncountable interactions on small scales. The second part concerns the exploration of a particular turbulence model that is based on the concept of Self-Organised Criticality (SOC). The turbulent plasma is considered as a complex system, in which localised instabilities relax small-scale field inhomogeneities. It is claimed that confined plasmas are in the state of SOC, and our aim is to investigate this claim and to identify the consequences of the SOC state on particle transport with the use of the X-CA model, a fully MHD compatible SOC model that allows detailed and physically interpretable studies of SOC in turbulent plasmas. Finally, in the third part we study phenomena related to the development of low-frequency electrostatic turbulence, driven by spatial gradients, which is believed to be the dominant source of anomalous transport in magnetically confined fusion plasma. Special emphasis is given on the properties and the associated phenomena related to the toroidal Ion Temperature Gradient mode (ITG) instability. This is due to the successful interpretations of various experimental results based on the dynamics of the ITG mode. Hence, the properties of zonal flows which are excited by the toroidal Ion Temperature Gradient turbulence and determine the levels of observed transport are investigated using a wave-kinetic equation. Furthermore, by taking into account the presence of trapped electrons (TE) in toroidal magnetic configurations, we study how the finite Larmor radius effects determine the dispersive and the stability properties of the coupled toroidal ITG and TE modes.

Work performed in year 2006:

1. Turbulent transport in Tokamak plasmas: We modified the CTRW equation in order that it contains the free flight times instead of the waiting times, which we had implemented in the previous year and which had turned out to allow to model only sub-diffusive phenomena. This modification implied a substantial reformulation and restructuring of the CTRW equation, and a corresponding effort had to be made to modify the method for the numerical solution (pseudo-spectral method based on Chebyshev polynomial expansions), as well as the Monte-Carlo simulation code had to be modified. We then implemented a set-up that models off-axis fuelling. First results showed that there can be a fast inward transport of particles in the case of power-law distributed spatial increments. The parametric study was extended to include also the distribution of the momentum increments, which so far were kept distributed according to a Gaussian. This and the trial to reproduce the observed phenomenon of profile

stiffness revealed two unforeseen problems. The first one was of technical nature, related to the fact the simulation box in momentum direction should be large enough to comprise also the highest energy particles that appear, and to the fact that the momentum distributions are either very fast decaying (Gaussians) or may contain extended power-law tails. The problem was solved by finding an adequate variable transformation in the related integrals, which weights the different regions of momentum space according to their population with particles. The second problem was of conceptual nature, it turned out that power-law increments alone could not account for profile stiffness. In order to solve this problem, we introduced spatially dependent position increments, in such a way that towards the central region of the simulation box the position increments are small scale and distributed according to a Gaussian, whereas towards the edge a certain fraction of the increments is allowed to be of a large scale (power-law distribution). This modification made necessary the adjustment of the numerical method used to solve the CTRW equation. Furthermore, we also developed an algorithmic method that allows to determine the spatial temperature profile from Monte-Carlo simulations, in order to be able to verify the results. The results show that, under certain conditions, a reasonable stiffness is achieved for the density profile, the temperature profile exhibits though only a moderate degree of stiffness. (For details see
Annex XXIII
.)

2. Self-organised criticality models (X-CA model): This activity was planed to resume at the beginning of autumn 2006, it was though delayed and could not be performed during year 2006 due to two unforeseen problems that appeared in the development of the Continuous Time Random Walk Model [Task c8(i)], namely numerical problems related to integration in momentum space, and the need to improve the model's capability to reproduce observed phenomena.

3. Drift-type turbulence, Large Scale Flows and Transport Phenomena in Tokamaks (*performed in collaboration with UU*):

- A self-consistent analytic description of non-linearly self-generated zonal flows (ZF) in toroidal ITG turbulence was developed. By constructing the adiabatic invariant of the TITG fluctuations - including finite Larmor radius effects - and applying the appropriate wave kinetic equation for the description of TITG turbulence in the presence of a ZF, we determined the stability criteria of a ZF in terms of the TITG turbulent spectra. Furthermore, we showed that the coupled system of the ZF with turbulence may lead to the formation of long - lived coherent structures, which can be characterised as regions with reduced level of anomalous transport. This work is completed and details can be found in Annex XXIV .
- We have proceeded with the construction of a 3D parallel spectral code to implement the evolution of drift type electrostatic instabilities and the associated development of electrostatic turbulence in tokamak plasmas. Furthermore, analytical and numerical investigations focused on the Finite Larmor Radius (FLR) effects on the properties of the coupled Ion Temperature Gradient and the Trapped electron modes were initiated and completed. It is shown that in the peak density plasma regions where the coupling between the

ITG and the TE modes is strong, the FLR effects determine the dispersion and the stability properties of the coupled modes. This work is completed and details can be found in Annex XXV
.

- The investigation of the dispersion of plasma particles for the used two-dimensional models of electrostatic turbulence have been continued from previous year but the findings, regarding the dispersion of plasma particles in two-dimensional models of electrostatic turbulence, were minor and insignificant.