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

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

A possible application of a sheet beam (whose stability has been studied earlier) is to have it interact with the propagating Gaussian RF beam produced by a conventional gyrotron. A simple preliminary calculation indicates that the parameters of the RF beam from, say, a 2 MW gyrotron are adequate to extract significant amounts of power from the e-beam, with no need for feed-back from the walls of any cavity. Thus, if this work proves promising, a first-stage conventional 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.*
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Work performed in year 2003: The work of the previous period was continued, on assessing the feasibility of using a sheet electron beam on the output radiation beam from a conventional gyrotron directly (that is, without employing a resonator), with the aim of amplifying the propagating RF power (from the gyrotron) to values well in excess of 2 MW. The work performed has included the following:

(i) A simple numerical code has been prepared to solve for the equations of electron motion in prescribed radiation fields (with Gaussian cross-section). The electrons are treated as test particles. The code allows for the electron beam crossing the radiation beam at any angle. The code has been bench-marked, both by comparing with earlier results and by checking the conservation of the invariants of motion.

(ii) The code has been applied to the case of normal incidence of the electron beam to the radiation beam (which conceptually addresses the gyrotron, rather than the CARM interaction). Exhaustive search (see Annex I) of the values for the parameters, with realistic distribution for the beam electrons, has indicated, that a convenient arrangement (i.e., such, for which the highest possible efficiency is reached at a radiation field power of, say, 2.5 MW) would be at a normalized frequency mismatch of 3% and for a radiation field with rms. spread r_0

= 3λ. For such an arrangement the electronic efficiency (fraction of electron beam power lost to the interaction) has been found to be 16%.

(iii) On the assumption, that all lost electron beam power is simply added to the power of the propagating RF beam, the amplification of the radiation was found to follow a simple scaling law, with average conversion efficiency of 20%. For example, a beam power of 8.8 MW would amplify a 2.5 MW radiation beam to 4.2 MW, while a 17.6 MW beam would produce an output of 6.2 MW.

(iv) Since it is by no means certain, that all generated radiation power will add coherently to the initial RF power, work has been initiated, on the spatial distribution of the RF radiation generated. In a preliminary analytic study, the far field has been computed, due to only the axial component of the perturbed current density. The results indicate, that most of the power produced (with a logarithmic dependence on the electron beam width) is in the direction of the initial Gaussian beam, however a fixed (independent of the electron beam width) amount of power is radiated backwards. (These results need to be independently confirmed. The continuation of this task is scheduled for year 2004.)

The initial planning for year 2003 foresaw that the calculations in item (ii) would refer to an arbitrary angle between the electron and radiation beam axes, while items (iii) and (iv) were to be addressed in year 2004. In view of the significance of the results for normal incidence under item (iii), it was chosen to initiate work on items (iii) and (iv) in year 2003, ahead of the initial planning (and to postpone the study of oblique incidence to year 2004 or later).

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

Background and Objectives: 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 2003: During this period, the 3D electrostatic code ARIADNE was further improved (see also Annex II) and has been used to study the effects of azimuthal density nonuniformity in the beam tunnel of a gyrotron. In order to decouple these effects from those associated with either the emission process, or with the axial uniformity, the first application has addressed a cylindrical tunnel (with $\partial/\partial z = 0$), in which the electron beam is introduced from one end and its self-consistent propagation is followed numerically. The deformation of both the beam cross-section and the electron distribution was studied, as they depend on the beam current and the intensity and harmonic content of the nonuniformity. It was found, that the numerical results follow very closely the predictions of a simple analytical theory, in which it is assumed, that the behaviour is dominated by the E×B drift, where it suffices to consider the electric field related to the initial beam distribution (i.e., at the entry into the system and not the one modified by the electrostatic fields along the length of the system). The most important results (see Annex III for more details) include the following:

- All deformations are proportional to the beam current and the axial distance (as expected from the effects of the E×B drift).
- The local spreads in radial position, beam energy and momentum (at any given azimuthal position φ) are very small, even at very large beam currents (400 A) and azimuthal nonuniformities (50%).
- The total (over all values of φ) spreads in radial position, beam energy and beam momentum are significant, but only at too high values of beam current and of azimuthal nonuniformity. If these quantities are confined to values relevant to present-day gyrotrons, these spreads are well within acceptable limits.

In addition, the numerical code ARIADNE has been used (with the azimuthal nonuniformity suppressed) to simulate the beam tunnel of the industrial coaxial gyrotron, to compare with the results of the code DAPHNE at CRPP. Furthermore, the work has advanced in modifying the input requirements, in order to make the code user-friendlier. (Task to continue into year 2004.)

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, part of it 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. (*This is a multi-annual activity performed in cooperation with CRPP and FZK.*)

Work performed in year 2003: 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:

(i) Final corrections and test runs of the numerical code Complex-Fishbone: The numerical code Complex-Fishbone, which was developed during previous years, has been finalized by optimizing all versions of the code, i.e., Windows, Linux and different Unix environments, replacing Bessel function algorithms with new faster ones, improving the procedure, which is employed to find complex roots in order to reduce the CPU time, and making the necessary test runs for specific geometries.

(ii) Beam loading and study its effects in a gyrotron beam tunnel: We have finished the analysis for the case, where the beam tunnel is assumed to be a periodic corrugated waveguide with losses. The interaction between the beam electrons and the electromagnetic fields results in the development on the electron beam of electric current and charge volume densities **J** and ρ. In the small-signal regime, which describes the behavior when the wave is about to grow from noise due to the interaction, these quantities are linear functions of the local values of the fields **E** and **H**, as well as of their transverse variation. Since **E** is related to **H** by Faraday's law, while electric charge conservation relates ρ to **J**, it suffices to consider the linear relation **J**(**H**), which for a thin beam, as a first approximation, degenerates to an expression for the surface current density **K**(**H**). For this purpose, we calculate the fields in the three beam-free regions (from the center until the beam position ρ_b, from ρ_b up to the metallic walls and inside the corrugations) as summations of eigenfunctions, and then we relate the expansion coefficients in adjacent regions by employing the appropriate boundary conditions at $\rho = \rho_b$, at the position of the beam, using the linear expression **K**(**H**, and at the metallic walls. Then, we solve the appropriate kinetic equation for the electron beam in the wave fields, integrating in momentum space to obtain the current density, and finally integrating across the beam width to obtain the surface current density. Note that no transverse variation of the wave fields in the beam position has been assumed. In this limit, the Larmor radius of the electrons, while it is still finite, is small compared to the transverse wavelength of the wave and therefore the analysis does not include any interactions at harmonics of the gyrofrequency.

(iii) Analysis and the numerical results for a circumferentially corrugated circular waveguide with variable (e.g., sinusoidal) metallic radius as well as for a rectangular waveguide grating: For the first part of this subtask, we have studied the problem of a waveguide with variable metallic surface (e.g., sinusoidal, triangular, and step-wise). We have made the analytical work and we have also written the corresponding numerical code. At this moment, we perform the final test runs. For the second part, we have studied the dispersion characteristics of a rectangular waveguide grating. More details are given in Annex IV .

(iv) Azimuthal Bloch modes in a coaxial gyrotron cavity with a slotted inner rod: This task is currently under development and up to now only the introductory mathematical formulation has been carried out. We expect that the work (numerical code and results) will be completed during year 2004.

2a4) Coaxial and harmonic gyrotrons

Background and Objectives: Coaxial gyrotrons have the important advantage, that they provide more flexibility in suppressing the unwanted competing modes, in spite of the large-size cavities they employ, allowing for record-high power output. In addition, coaxial gyrotrons can produce extremely high frequency output, albeit at much lower power levels. For these reasons, coaxial and harmonic gyrotrons have been designed and studied. The numerical codes that have been used for this activity can be used for additonal designs, while thy also admit significant improvements. (*This is a multi-annual activity performed in cooperation with FZK.*)

Work performed in year 2003: The time-depended, multimode, multiharmonic, fixed-field numerical code for the beam-field interaction in a coaxial gyrotron cavity, developed during previous periods, has been used to simulate some realistic second-harmonic, coaxial gyrotron designs. More specifically, the code verified the performance of a 340 GHz – 100 kW CW, second-harmonic, coaxial gyrotron, which had been designed earlier in order to illustrate the suitability of coaxial cavities with corrugated insert as regards powerful and efficient, second-harmonic operation. Moreover, a realistic design of a second-harmonic, coaxial-cavity gyrotron of the same frequency and output power employing a resistive inner rod instead of a highly conductive one, was also realised. The code verified the performance of this gyrotron too and indicated in this way that cavities with a resistive corrugated insert also appear to be suitable for CW powerful second-harmonic operation. Additional simulations for both designs, taking into account a realistic spread of about 6% in the perpendicular electron velocity, showed only a minor decrease of the interaction efficiency η_{el}, which was reduced to about 27% (whereas η_{el} 29% without spreads). More details about the results of the simulations and the design parameters of the two second-harmonic gyrotrons can be found in K. A. Avramides et al., “Design considerations for powerful continuous-wave second-cyclotron-harmonic for coaxial-cavity gyrotrons”, IEEE Trans. Plasma Science June 2004 (in press), together with a brief review of the conclusions of the former research at NTUA concerning general design considerations for powerful, CW, second-harmonic coaxial gyrotrons.

For reasons of testing, the code was also used (see Annex V) to simulate the start-up of the 170 GHz – 2 MW coaxial-cavity gyrotron for ITER. This gyrotron is currently being designed at FZK and the simulation included only modes interacting at the fundamental cyclotron frequency. The results of the code were compared to those obtained by existing codes at FZK and at the Helsinki University of Technology. Some instabilities occurred at the results of the code (not previously observed in the simulation of the aforementioned second-harmonic gyrotrons) probably because of the dense spectrum of the competing modes in the ITER gyrotron cavity. This fact motivated the development of diagnostic tools for the code such as phase-space diagrams of the electrons in order to decide, whether the instability is purely numerical or derives from physical reasons. This matter is still under investigation. In parallel to that, a comprehensive research culminated in the identification of the most dangerous competing modes both at the fundamental and at the second cyclotron harmonic in the ITER gyrotron cavity (Annex VI). In order to study the effect of energy spread and finite beam thickness on the start-up sequence of the modes $TE_{35,19} \rightarrow TE_{34,19}$

→ TE

33,19

and on the efficiency of the ITER gyrotron, some indicative simulations have taken place. It seems that even for a guiding center spread of four Larmor radii, the decrease of the electron efficiency is less than 1% whereas the transition from the TE

35,19

mode to the operating TE

34,19

mode always takes place albeit at somewhat different values of the beam voltage. The plans for the immediate future include further testing of the code in order for the existing problems to be resolved. Further simulations of the ITER gyrotron cavity will probably take place, taking also into account spreads in the electron velocity ratio α. If necessary, the code will be modified in order to accept a magnetic field which varies along the cavity-axis. At the same time, additional investigation of the second-harmonic operation of coaxial cavities with corrugated insert will take place in order to determine the values of the parameters for a proof-of-principle experiment utilising the FZK facilities related to the ITER gyrotron project.

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

Background and Objectives: Divertors remain the main option for handling plasma-wall interaction problems in current and future magnetic confinement experiments like ITER. The requirements for successful divertor operation ask for a detailed understanding of the physical and chemical processes involved. Reciprocating Langmuir probes have proved to be a very useful diagnostic technique for such divertor plasma investigations and are now used extensively in most tokamaks. 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 unmatched by other methods. The objective is to use and further upgrade the fast scanning Langmuir probe system operating in the ASDEX Upgrade divertor, in order to describe and, eventually, predict the detailed evolution of the SOL and divertor plasma, in conjunction with other diagnostic techniques. (
This is a multi-annual activity, performed in cooperation with IPP.
)

Work performed in year 2003: The main activity was the refurbishment of the ASDEX Upgrade divertor manipulator, which has not been in operation since 1999. The following hardware upgrades where made in collaboration with the IPP technical staff:

(i) A new front support structure was constructed, and used to test the manipulator outside the tokamak vessel.

(ii) The control computer was upgraded with a newer SUN ULTRA I machine.

(iii) A new locking mechanism was designed, constructed and mounted on the manipulator, to prevent a repeat of the 1999 malfunction.

(iv) The operation of the positioning switches was reviewed, to provide better feedback and control of the manipulators' position.

(v) The driving software was revised, taking into account the new limit switch positions and making the motion routines safer.

(vi) A new probe head was designed and constructed. The new tip is made of graphite, and the head has been designed specifically for flow and fluctuation measurements. It can be biased in the following configurations: single, double, mach and floating.

(vii) The manipulator was repositioned in the divertor of ASDEX Upgrade. Its position was calibrated with respect to the tokamak vessel and extensive tests of the fast motion and of the data acquisition system where performed. As a result of this refurbishment, the "Demokritos" manipulator is now fully operational. However, ASDEX Upgrade is currently vented for upgrades and maintenance, and is not due to resume operation until January 2004. For this reason, first results are not expected until February 2004.

In parallel to the refurbishment, several other tasks where performed, providing the basis for the 2004 research program. In preparation for the use of the divertor manipulator, measurements where made with the mid-plane manipulator, already in operation at ASDEX Upgrade. During 86 AUG shots, measurements where made of the plasma density and temperature in the divertor shadow, and in the scrape off layer, just before the first separatrix. For shots 17170 to

17235, a single floating tip, combined with a double swept tip configuration was used, measuring temperature and density profiles. The tip configuration was subsequently modified for shots 17235 to 17253 and 17280 to 17329 to a triple Langmuir probe, for plasma fluctuation measurements. The obtained results compare favourably with the Thomson scattering data, and have been entered in the ASDEX Upgrade diagnostic database.

In addition to this activity, previous data collected with the Demokritos manipulator in the time period 1996 – 1999 was reviewed. The following observations where made (see also Annex VII for more details):

(i) In discharges near the L - H power threshold, an ELM mitigation effect is observed when the probe tip crosses the separatrix. This appears to be caused by the probe tip current influencing the plasma, as it is not observed when the body of the probe crosses the region. Further experiments to study this effect are planned for 2004.

(ii) In H-mode discharges with type I ELM's, a localized perturbation is occasionally observed before the ELM onset. These precursors are not well understood and will be further studied during the next campaign.

2c) Equilibrium, stability and transport of fusion plasmas

2c1) Transport and chaos in fusion plasmas

Background and Objectives: One of the most complicated behaviours in dynamical systems is the motion of the turbulent fluid. In general, for a non-turbulent state, there exists some simple, usually linear, relation between the fluxes and the thermodynamic forces. The linearity leads, at least at macroscopic level, to predictability. On the contrary, the evolution of turbulent systems is unstable and two almost identical systems are very likely to evolve rapidly towards very different states. Turbulent systems are unpredictable. The sensitive dependence on initial conditions is a mark of «chaos». Our aim is to study chaotic dynamics and transport during critical situations in toroidal plasmas, such as sawteeth crashes, by utilizing the Lagrangian formulation of the guiding centre motion, which incorporates finite and neo-classical effects, as well as effects due to turbulence and fluctuating field components. The investigation is analytical as well as numerical. *(This is a multi-annual activity, performed in cooperation with ULB.)*

Work performed in year 2003: During this period, the following issues have been addressed:

(i) This activity is the result of our collaboration with ULB (B. Knaepen and D. Carati are involved). B. Knaepen visited Thessaloniki for two weeks (mobility) where part of this work was done. Our work is devoted to the numerical study of trajectories of test particles in MHD turbulence. Indeed, the complex structure of magnetic field lines and electric fields present in a turbulent plasma may have some important quantitative influence on the efficiency of particle acceleration in that medium. Our study is thus relevant for many different applications ranging from astrophysics to laboratory experiments. For example, the presence of turbulence close to walls in tokamaks may influence the confinement properties of the device. In order to study this problem, two numerical schemes have to be used. The first concerns the construction of a turbulent MHD field. This is obtained through a full 3D simulation code of incompressible MHD. This numerical code enables one to compute a turbulent velocity field and magnetic field. From these quantities, one can obtain the electric current and through Ohm's law the electric field contained in the plasma. The second numerical scheme computes particle trajectories in an arbitrary static electromagnetic field. Since the particles can become highly energetic, they obey relativistic equations of motion. At present, both numerical codes are operational but still need to be interfaced together. When this is done, statistics on particle trajectories will be obtained and acceleration mechanism will be studied. In particular, the influence of an external mean magnetic field will be examined. In the figures presented in Annex VIII , the location in space of strong electric field and the location in space of strong electric current are presented. It is believed that these regions contribute significantly to particle acceleration because particles remain trapped in them for long times.

(ii) In this activity, we study the wave-particle interaction in the ECRH frequency regime. During 2003, we focused on the effect of single- and multi-frequency waves on particle dynamics in simple plasma cases. An article is already completed and submitted to Plasma Physics. We have also worked in collaboration with IPP (mobility of C. Tsironis) on an existing code, which models the propagation and absorption of Gaussian EC wave beams in weakly inhomogeneous plasmas (TORBEAM), using the beam tracing technique. An effort is made on the extension of the formalism used to describe the absorption of the EC wave in the plasma. Also, a method is needed to describe the change in the beam shape due to localised absorption. In particular, during the present period we have (a) considered more complicated beams by superimposing many Gaussian modes and follow their evolution during their propagation and absorption in the plasma, and (b) described the change in the beam shape due to localised absorption in terms of generation of higher-order Gaussian modes. (See also Annex IX .)

2c2) MHD turbulent transport in plasmas

Background and Objectives: Computational Fluid Dynamics (CFD) and turbulence modelling have been applied to various 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. In addition, as regards task (iii), earlier work to cast the MHD equations in Cellular Automata form, a formalism seen very efficient for 3D global simulations in confining magnetic topologies, is extended, in order for Cellular Automata to be used to study resistive instabilities on specific confinement devices. (*This is a multi-annual activity, performed in cooperation with ULB.*)

Work performed in year 2003: The following work has been done in the tasks of this activity:

(i) MHD natural convection of liquid metals in the presence of a magnetic field were studied as follows:

- Transient MHD natural convection in a square cavity with the two vertical sidewalls at different temperatures under the effect of a uniform magnetic field has been studied. A steady flow field is established by maintaining different temperatures at the two vertical sidewalls, represented by an external Grashof number Gre. A uniform internal heat generation, measured by a properly defined internal Grashof number Gri, is switched on impulsively at t = 0. The study was conducted for Hartmann numbers from 0 to 100, Gre from 105 to 106, the Gri number from 106 to 107, and Prandtl number 0.0321 (characteristic of Pb-17Li at 573 K) (see Annex X).
- The effect of a non-uniform magnetic field on MHD natural convection flow of an electrically conducting fluid (liquid metal) in a square enclosure was studied numerically. The study was conducted for a range of N number, which expresses the intensity of the magnetic field, from 0 to 300, while the Rayleigh number was kept to zero. Streamlines and magnetic induction distributions are presented for flow without gravity forces (see Annex XI).
- MHD flow stability analyses were focused on 2D natural convection flow in a rectangular enclosure with internal heat generation and in the presence of a magnetic field, using finite elements, analytical methods and bifurcation theory. A simplified mathematical model was employed for the problem, equilibrium states were computed through a parametric study, the corresponding bifurcation diagram was constructed and, finally, stability analysis was performed in order to establish the connectivity between different solution branches. The methodology was first tested successfully on the classical Rayleigh-Benard problem and subsequently applied on the above problem. It was found that application of an external horizontal magnetic field,

expressed by a progressive increase in Hartmann number, stabilizes the flow resulting in an increase of the critical external Grashof number, that marks the appearance of a Hopf bifurcation characterizing the onset of periodicity in the flow. In fact, application of the magnetic field works in favor of symmetry, leading to relatively smaller Nusselt numbers along the hotter left side of the cavity (see Annex XII).

(ii) MHD Turbulent Transport in Fusion Plasmas: The established collaboration with ULB was continued in year 2003, with the study of MHD turbulence, using direct numerical simulations, in flows subjected to spatially periodic external magnetic fields. More specifically, the results from the Kolmogorov flows (studied also during 2002) were extended for higher Reynolds numbers as well as for more intensive magnetic fields. The magnetic Prandtl number effects were also studied (see Annex XIII).

(iii) Particle tracing and dynamics in a Cellular Automaton turbulence model: In the past years, the so-called X-CA (extended cellular automaton) model for MHD turbulence had been developed. It represents a cellular automaton model for the magnetic field structure and evolution, which is fully compatible with the MHD equations. The scope of this activity is to adjust the X-CA to Tokamak topologies, and to study the role of Self-Organized-Criticality (SOC), as well as the behaviour of particles in the system. In the period in subject, first trials with particle tracing were made, neglecting though the sporadically appearing localized electric fields. Diffusion so far is found to be ballistic for small times, entering though a subdiffusive regime for larger times, due to trapping and loss-effects. Moreover, the numerical problem of making the currents everywhere available in the simulation box was solved, which is a prerequisite to include energization of particles when they are traced in the simulated volume (the model assumes resistive electric fields). The currents are derived as J = ^ × B, with B = ^ × A, ^ x denotes the curl opeator and A is the vector-potential. The derivatives are done numerically, whereto the vector-potential is interpolated with 3D cubic splines.

(iv) Modelling MHD flows in rotating cylindrical shells (in collaboration with IKET/FZK): The CFD code CAFFA was adapted to rotating cylindrical shell geometries and the electric potential equation was implemented in order to simulate 2D axisymmetric flows of interest in MHD. The flow inside a cylindrical shell with a rotating inner disk at low Reynolds numbers and slowly increasing Hartmann numbers was investigated. A magnetic field was imposed parallel to the axis of the rotation. Linear and angular velocity fields, and distributions of the electric potential were obtained. The results were compared with known test cases for the hydrodynamic part and the coupled electric potential equation (see Annex XIV).

2c3) Stochastic modeling 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) Relation of stochastic models to theories based on statistical mechanics; and (iii) Boundary value problems relevant to fusion devices. The objectives are to examine further effects on transport properties due to random components of the magnetic and/or electric field, especially concerning problems of anomalous diffusion. In addition, lattice gas methods are applied to MHD, with objective to formulate appropriate discrete kinetic equations simulating problems with boundary conditions studied under item (c2) and compare the results from this scheme with those from conventional CFD. (*This is a multi-annual activity, performed in cooperation with ULB.*)

Work performed in year 2003: The following work has been done in the tasks of this activity: (i) Lattice Boltzmann Methods for MHD Flow (see Annex XV): The work on lattice Boltzmann methodologies related to fusion applications has been continued during 2003, demonstrating the potential of this novel method to simulate complex systems. Specifically, a 3-D Lattice Boltzmann code for MHD and plasma simulation has been developed and implemented. A multigrid numerical procedure has been added to deal efficiently with the thin Ha layers in the case of high Ha MHD flows. The computational efficiency of the 3D LB code has been significantly increased by its parallelization on a cluster consisting of six non-uniform Seleron PCs with 128MB Ram memory each. The effort of thermal MHD flows simulation has been continued, supplemented by a theoretical advancement of lattice kinetic schemes.

(ii) Particle transport through turbulent plasmas with fractally distributed electric fields: In this activity, diffusion and acceleration of particles in turbulent plasmas is modeled with the stochastic approach of Continuous Time Random Walk. Magnetic field inhomogeneities in the turbulent plasma give rise to localized electric fields, which are expected to be distributed on a fractal support, and which influence strongly the diffusion and energization of particles. Particles thus perform a random walk, both in position and in velocity space, whose nature determines the particle dynamics. In the previous two years, we had completed the analysis of the corresponding constant-velocity random walk, and we had started the implementation of a new random walk simulation code of the Monte Carlo type, which incorporates the energy gains in interactions with the electric fields. During the period in subjected, the simulation code was completed (see Annex XVI), including also trapping effects near magnetic inhomogeneities. The increments in position space are assumed to be power-law distributed, as it corresponds to the case of fractally distributed electric fields. The velocity increments and the trapping times are also assumed to be power-law distributed, with the respective indices free parameters. Numerical results show that the modelled turbulent environment can give rise to an accelerated subpopulation of particles, as well as to heating. It also turns out that there is strong parameter dependence of the results on the assumed plasma-conditions. Diffusion in position space is of the sub-diffusive type, $\langle r^2(t)\rangle \sim t^\gamma$, with $\gamma<1$, as long as there is sufficient trapping, else diffusion may become normal or even of the super-diffusive type. Diffusion in velocity-space can be sub- as well as super-diffusive, depending on the assumed parameters. In a second step, the analytical random walk equations, which describe the problem, were developed. They are basically a set of two coupled, linear integral equations.

(iii) Stochastic modelling: Most of the work performed during this period concerned the completion of our studies on the microscopic theory of a charged test-particle weakly coupled to plasma subject to a homogeneous magnetic field. The drift and diffusion coefficients are expressed in terms of the autocorrelation matrix of the interaction potential and they are being evaluated numerically. These investigations show that there is a region where the drift may be taken proportional to the velocity while the diffusion may be approximated by a constant, with an appropriate dependence on the magnetic field. This approximation leads to a multivariate Fokker-Planck equation, analytically solvable, obtaining expressions for the evolution of the particle distribution function and its moments for various initial conditions. Some results have been presented in recent conferences and a comprehensive expository article on the problem is in preparation (see: I. Kourakis and A. Grecos, "Plasma diffusion and relaxation in a magnetic field", Commun. Nonlinear Sci. Numer. Simul. 8, 547-551 (2003), I. Kourakis and A. Grecos, "Microscopic theory for random processes in weakly-coupled open systems", Intl. Conf. on Noise and Fluctuations, Prague, 2003 [ICFN0118], and I. Kourakis and A. Grecos, "Random particle motion in magnetized plasma", Intl. Conf. on Noise and Fluctuations, Prague, 2003 [ICFN0212])

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

Background and Objectives: Sawteeth stabilization during ICRH (observed basically in JET and TFTR) has been a major result in the 80's. This was attributed to the resonant precession of the superthermal trapped-ion "banana"-orbits. Although this interpretation is accepted, there are several unresolved issues, indicating additional stabilising mechanisms. In particular, the toroidal precession of the banana orbits is not the only superthermal ion flux. Superthermal ions experience also radial diffusion in the background plasma, out from the IC resonance where they are produced. The objective is to investigate any additional stabilizing effect on sawteeth due to the radial diffusion of the superthermal ions, in the framework of the recent theory of the non-resonant diffusive interaction of superthermal electrons with the MHD modes during ECRH, including the potential confirming of the proposed scaling law of the superthermal density

growth time, τ_{se}~$(r_{EC}/P_{EC})^3 n_e^5$. (*This is a multi-annual activity, performed in cooperation with FOM at FZJ and CEA.*
)

Work performed in year 2003: The work performed for this task was done primarily during the mission of A. Lazaros to FOM/FZ-Juelich (January-July 2003). It was at first found out that significant work was required for the preparation of the pulse height analysis (PHA) system, which in fact was available at TEXTOR with five channels, but had been inactive/abandoned since 1994 in the absence of scientific personnel and interest. The preparation of the system (after such a long time of negligence) had been an enormously time- consuming procedure, which was not originally foreseen, neither included in the proposed work-plan. The following work was done:

- The electronics were tested and any defective pieces of equipment were replaced.
- The X-ray sources (for the calibration of the silicon-lithium detectors of the PHA) were also removed and tested. Three out of five X-ray sources were found in good condition.
- The silicon-lithium detectors were cooled-down and calibrated using the X-ray sources. Two out of the five silicon-lithium detectors were found in good condition.
- The original five-channel PHA system was reassembled as a two-channel system using the functioning components and detectors of the original system. The system was designed to be sensitive in the thermal part of the spectrum with one channel, and the superthermal part with the other one, as required for our project.
- The software was developed for the evaluation of the measurements. The PHA system was finally commissioned on time for the first plasma of TEXTOR (May 2003).

In addition to the above preparations a new X-ray camera was designed for a direct observation of the superthermal density variation (in microsec scale), for future deployment. With the PHA system operational, and TEXTOR producing steady-state plasmas of 4-6 sec long by May 2003, the experimental program regarding the investigation of superthermal electron generation during on-axis ECRH was largely accomplished. The investigation was conducted during 0.5 sec pulses of the new gyrotron at the power range of 0.4-0.8 MW and the electron density range of $1\text{-}3\times10^{19}$ m^3. The first estimate of the electron temperate (of 0.6 keV) was also obtained from the thermal spectrum of the PHA, at the time that no other diagnostic for the electron temperature was available. The only problem at this stage of the project, however, was not related with the performance of the hardware (i.e. operation of TEXTOR, the new gyrotron and the PHA) but with the reliability of the results in a systematic investigation. At the present range of plasma parameters it was realised that the photon flux (through the entry slit of the PHA) was too low, and the integration time of the superthermal radiation should have been much longer (than the 0.5 sec of the ECRH pulse) to provide a reliable measurement. The new gyrotron, of course, is designed to operate with 10 sec pulses, but this will be feasible after the summer brake, when the glass window is replaced by a diamond one (with a much lower absorption of RF heating). This was the reason why (at this stage of the project) we did not decide or attempt any formal presentation of the results in a publication, neither did we commit ourselves to perform the initially envisaged "shot-to-shot" radial scans of the EC resonance, and the subsequent investigation of MHD stabilization (which was proposed as a future objective).

2c5) Stationary MHD modes in magnetically confined plasmas

Background and Objectives: This is a long term project 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. The understanding thus obtained can contribute to improving the current magnetic confinement systems and to possibly developing novel ones. (
This is a multi-annual activity performed in cooperation with IPP.
)

Work performed in year 2003: During this period, the following work has been performed:

(i) We made an estimate of a numerical study on our proposed method of stabilization of the resistive wall mode (RWM) [H. Tasso and G. N. Throumoulopoulos, Phys. Lett. A 307, 304-312 (2003) and references therein] for tokamak equilibria. It turned out that on account of the contemporary speed limitation a very long CPU time is required. Furthermore, we proved that the RWM theorem can be extended in a "weak sense" to the case of time-dependent wall resistivity. Instability growth behaviour remains, however, an open problem (Annex XVII).

(ii) In addition, we extended a Lyapunov functional containing the cross-helicity and introduced recently for conservative magnetized Beltrami flows [Yoshida et al. J. Math. Phys. 44, 2168-2178 (2003)] to dissipative magnetized Trkal flows. In particular, nonlinear stability is proven under limitations on maximal velocity and current without introducing an upper bound on the Reynolds number (Annex XVIII).

(iii) Finally, we investigated tokamak equilibria with reversed magnetic shear, and sheared flow, which may play a role in the formation of Internal Transport Barriers (ITBs), in cylindrical geometry within the framework of two-fluid theory. The study includes construction of exact self-consistent equilibrium solutions and evaluation of the impact of $s < 0$ and the sheared flow on the radial electric field, its radial variation and the variation of the $E\times B$ velocity. The results clearly indicate that $s < 0$ and the sheared poloidal and toroidal velocities act synergetically on the formation of ITBs (Annex XIX).

2c6) 3-D pellet modelling

Background and Objectives: To study the evolution of pellet clouds, we have been developing multidimensional pellet codes, a two-dimensional plus one code, 2-D resistive MHD in the poloidal plane plus 1-D Lagrangian in the toroidal direction. Results have been obtained with specifying the ablation rate. These preliminary results start to yield information on the structure of the pellet cloud in the poloidal plane. In addition, the interfacing of pellet ablation modules to the 3-D nonlinear MHD code M3D continues. (*This is a multi-annual activity, performed in cooperation with IPP and also with Princeton and Courant.*)

Work performed in year 2003: The work was continued on the "2D+1" pellet code in collaboration with IPP-Garching. Variable ablation rate, as a function of the local temperature and density, was implemented. Scenario calculations were performed with this variable ablation rate, small oscillations in the ablation rate were noticed, these oscillations are due to grid size. A routine for stopping length calculations, for a single Lagrangian cell over a two dimensional grid, was developed. This stopping length routine will be modified for multi-cells. A large number of scenario calculations with constant ablation rate were performed in order to understand striations that have been observed in experiments. (See also Annex XX.) With respect to the work done on the M3D code (developed by Princeton) a new version of the M3D, for compressible fluids and with the unstructured grid aligned to the magnetic flux surfaces, was obtained. Work started in implementing finite rate ionisation, and heavy particles in the M3D. Some of the problems that are foreseen are the grid size and upwinding. The present version of M3D has no upwinding; Princeton and Courant are planning to implement upwinding to M3D soon. The implementation of spectral elements to M3D by Princeton is also planned.