National Programme of
Controlled Thermonuclear Fusion

ASSOCIATION EURATOM - HELLENIC REPUBLIC
ΕΝΩΣΗ EURATOM - ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ

Εθνικό Πρόγραμμα
Ελεγχόμενης Θερμοπυρηνικής Σύντηξης

9TH SCHOOL OF FUSION PHYSICS & TECHNOLOGY

ABSTRACTS - ΠΕΡΙΛΗΨΕΙΣ

9Ο ΣΧΟΛΕΙΟ ΦΥΣΙΚΗΣ & ΤΕΧΝΟΛΟΓΙΑΣ ΣΥΝΤΗΞΗΣ

Volos 19 - 23 April 2010

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EURATOM - Hellenic Republic
National Programme of
Controlled Thermonuclear Fusion

Website: http://www.hellasfusion.gr

We look forward to your active participation
in the 9th School of Fusion Physics & Technology

The Programme & Organizing Committees

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FOREWORD

The 9th School of Fusion Physics & Technology brings together students who have heard little about plasma and fusion, doctoral candidates who are working on problems related to fusion, researchers working on fusion topics for some years and academics staff from universities who are coordinating MHD and fusion research. Also, distinguished researchers from Europe and the USA will give invited talks. The joint attendance of such a school by all these scientists and engineers creates additional needs and is going beyond traditional schools. Thus, the programme committee developed a multi-level series of lectures with the aim to satisfy as many of the audience needs as possible. The programme is divided in three categories: *School Classes, Invited Lectures, and Workshops or Advanced Seminars*.

The School will start Monday morning with the invited lectures on topics of common interest to all, such as plasma physics and the current status of fusion research in Europe. In the afternoon the School classes will start with introductory classes on electrodynamics, plasma and charged particle dynamics. The afternoon will end with the first «*Teacher-Student Interaction*» session with general and specific questions posed by students to be answered by their teachers.

The School will continue on Tuesday morning with kinetic theory and waves while the first «*Workshop on Stochastic Modeling & Transport*» will be held in the afternoon with advanced seminars presented by invited speakers and expert researchers. The afternoon will end with the second *Teacher-Student Interaction* session.

Wednesday morning will be devoted to School classes on MHD theory, CFD, plasma transport, and MHD and plasma instability. In the afternoon, the second «*Workshop on MHD & Plasma Stability*» will be held. At the end of the afternoon session, there will be a third «*Teacher-Students Interaction*» on open problems in plasmas. The third day of the day will close with the «School Dinner», where all participants are welcome.

The School will continue on Thursday morning with lectures on Gyrotrons followed in the afternoon by the third «*Workshop on Gyrotrons & ECRH*». Again, the afternoon will end with the fourth and final «*Teacher-Student Interaction*» with general and specific questions posed by students to be answered by their teachers.

Friday morning will be the last session of School classes on plasma turbulence, vacuum flows and computational MHD. In the afternoon, the fourth and final «*Workshop on MHD, Vacuum Flows, Turbulence & Heat Transfer» will be held*.

The 9th School of Fusion Science & Technology will come to a close on Friday afternoon and the «*Certificates of Attendance*» will be distributed to all «good standing» participants.

In this manner the School of Fusion Physics & Technology serves as a multi-disciplinary forum covering the interests of all. We hope that you will find the programme structure rewarding, and we look forward to your active participation, which will warranty its success.

In concluding, the organizers of the *Fusion Schools in Volos* would like to express their sincere thanks to the European Commission, the Hellenic General Secretariat of R&T, and the University of Thessaly for their continuous support, which make possible these productive meetings on Fusion science and technology.

Volos 19 April 2010 - The Scientific Programme and Organizing Committees

ΠΡΟΛΟΓΟΣ

Το *9ο Σχολείο Φυσικής & Τεχνολογίας Σύντηξης* φέρνει μαζί φοιτητές που έχουν ακούσει ελάχιστα για πλάσμα και σύντηξη, υποψήφιους διδάκτορες που εργάζονται σε προβλήματα σχετικά με σύντηξη, ερευνητές που ασχολούνται με θέματα σύντηξης αρκετά χρόνια, και μέλη ΔΕΠ πανεπιστημίων που κατευθύνουν έρευνα σε ΜΥΔ και σύντηξη. Επίσης, διακεκριμένοι ερευνητές από την Ευρώπη και ΗΠΑ θα κάνουν προσκεκλημένες ομιλίες. Η κοινή παρακολούθηση ενός τέτοιου *σχολείου* από όλους τους παραπάνω είναι φυσικό να δημιουργεί πρόσθετες ανάγκες και να ξεφεύγει από τα παραδοσιακά *σχολεία*. Έτσι, η επιτροπή προγράμματος ανέπτυξε μία πολυ-επίπεδη σειρά διαλέξεων με στόχο να ικανοποιήσει όσο το δυνατόν περισσότερες από τις ανάγκες του ακροατηρίου. Το πρόγραμμα χωρίζεται σε τρεις ενότητες: Μαθήματα *Σχολείου*, *Προσκεκλημένες Ομιλίες* και *Σεμινάρια Εμβάθυνσης*.

Το *Σχολείο* ξεκινά την Δευτέρα το πρωί με τις προσκεκλημένες ομιλίες σε θέματα κοινού ενδιαφέροντος για όλους, όπως φυσική πλάσματος και παρούσα κατάσταση της έρευνας σύντηξης στην Ευρώπη. Το απόγευμα αρχίζουν τα μαθήματα του Σχολείου πάνω σε ηλεκτροδυναμική, πλάσμα και δυναμική φορτισμένων σωματιδίων. Το απόγευμα θα τελειώσει με την πρώτη συνεδρία «*Αλληλεπίδρασης Διδασκόντων–Φοιτητών*» με γενικές και ειδικές ερωτήσεις από του φοιτητές για να απαντηθούν από τους καθηγητές τους.

Το Σχολείο θα συνεχιστεί την Τρίτη το πρωί με μαθήματα πάνω σε κινητική θεωρία και κύματα ενώ το απόγευμα θα διεξαχθεί η πρώτη σειρά «*Σεμιναρίων Εμβάθυνσης* σε *Στοχαστικά Μοντέλα & Μεταφορά» με παρουσιάσεις από προσκεκλημένους ομιλητές και έμπειρους ερευνητές. Το απόγευμα θα κλείσει* με την δεύτερη συνεδρία «*Αλληλεπίδρασης Διδασκόντων–Φοιτητών*».

Το πρωί της Τετάρτης θα αφιερωθεί σε μαθήματα Σχολείου πάνω σε ΜΥΔ θεωρία, CFD, μεταφορά σε πλάσμα, και ΜΥΔ και αστάθεια πλάσματος. Το απόγευμα, θα διεξαχθεί η δεύτερη σειρά «*Σεμιναρίων Εμβάθυνσης* σε *ΜΥΔ & Αστάθεια Πλάσματος*». Στο τέλος του απογεύματος θα γίνει η τρίτη συνεδρία «*Αλληλεπίδρασης Διδασκόντων–Φοιτητών*» πάνω σε ανοικτά προβλήματα πλάσματος. Η τρίτη μέρα θα κλείσει με το «*Δείπνο του Σχολείου*», όπου όλοι οι συμμετέχοντες είναι ευπρόσδεκτοι.

Το Σχολείο θα συνεχιστεί την Πέμπτη το πρωί με διαλέξεις πάνω σε γυροτρόνια και το απόγευμα με την τρίτη σειρά «*Σεμιναρίων Εμβάθυνσης σε Γυροτρόνια & ECRH*». Πάλιν το απόγευμα θα τελειώσει με την τέταρτη και τελευταία συνεδρία «*Αλληλεπίδρασης Διδασκόντων–Φοιτητών*» με γενικές και ειδικές ερωτήσεις από φοιτητές που θα απαντηθούν από τους καθηγητές τους.

Την Παρασκευή το πρωί θα γίνουν τα τελευταία μαθήματα του Σχολείου πάνω σε τύρβη πλάσματος, ροές κενού, και υπολογιστική ΜΥΔ, και το απόγευμα θα διεξαχθεί η τέταρτη και τελευταία σειρά «*Σεμιναρίων Εμβάθυνσης σε ΜΥΔ, Ροές Κενού, Τύρβη & Μεταφορά Θερμότητας*».

Το 9ο Σχολείο Σύντηξης θα κλείσει την Παρασκευή το απόγευμα και θα διανεμηθούν τα *Πιστοποιητικά Παρακολούθησης στους «καλώς έχοντες» συμμετέχοντες*.

Με τον τρόπο αυτό το Σχολείο Φυσικής & Τεχνολογίας Σύντηξης λειτουργεί ως ένας πολύ-επιστημονικός χώρος που καλύπτει τα ενδιαφέροντα όλων. Ελπίζουμε ότι θα βρείτε αυτή την δομή του προγράμματος ενδιαφέρουσα και προσδοκούμε στην ενεργή συμμετοχή σας που θα εξασφαλίσει την επιτυχία του.

Κλείνοντας, οι οργανωτές των *Σχολείων Σύντηξης στο Βόλο* επιθυμούν να εκφράσουν τις θερμές ευχαριστίες τους στην Ευρωπαϊκή Επιτροπή, την Γενική Γραμματεία Έρευνας & Τεχνολογίας, και το Πανεπιστήμιο Θεσσαλίας για την συνεχή υποστήριξη, η καθιστά δυνατή αυτή την παραγωγική συνάντηση για την φυσική και τεχνολογία Σύντηξης.

Βόλος 19 Απριλίου 2010 - Η Επιτροπή Προγράμματος και η Οργανωτική Επιτροπή

CONTENTS

Proceedings: All Participants are kindly requested to submit their presentations in PDF for the School Web

PLENARY SESSION: INVITED LECTURES

P01 - Abhay Ram: Energy, environment and thermonuclear fusion

Massachusetts Institute of Technology, USA

The global demands for energy are increasing at a rapid pace. The resources being used to satisfy the energy needs are leading to concerns about the environment and the climate. This talk will compare and contrast per capita energy consumption, means of energy production, and the human development index of a few chosen countries. A large fraction of the energy is produced from fossil fuels, which in turn, impacts the environment. The role that thermonuclear fusion can play in nourishing our energy needs without adversely affecting the environment will be discussed.

P02 Stamos Papastergiou: The role of F4E in the European Fusion Program and its "in-kind contribution" of the Cryogenic Vacuum Pumping Systems to ITER

Fusion for Energy (F4E), European Commission, Barcelona, Spain

F4E was established in 2007, under the Euratom Treaty, by a decision of the Council of the European Union in order to: a) Provide Europe's contribution to ITER b) Implement the Broader Approach agreement between Euratom and Japan, and c) Prepare for the construction of demonstration fusion reactors (DEMO). F4E will work with Fusion associates and European Industry to develop and manufacture almost half of the ITER components, defined in 2001 Procurement Packages. The official F4E role starts with the Procurement Arrangements (PA), which are the responsibility of IO (in 2013, for the main Vacuum Pumping activities). F4E, IO, KIT and CEA Grenoble in close collaboration, have identified technological issues to be solved before the PAs. This is done via ITER Task Agreements (ITAs) issued by ITER, and Grants (R&D @40% eligible cost) or Procurement Contracts (100%) managed by F4E. Integrated Product Teams (IPTs) coordinate the work between the IO and Domestic Agencies.

The progress to date is significant and as follows: 1) Torus pumps: Model pump (1998-2006) addressed pumping speed, performance of activated (highly porous) charcoal coated cryopanels and confirmed analytical Monte-Carlo predictions. Detail design advanced, 2) NB Pumps: successful analytical predictions of speed and performance, detail design advanced and no need for specific mock-up (use of MITICA pump), 2) Cold Valve Boxes (CVBs): EFDA VP76 contract, in collaboration with IO, gave acceptable performance/ regeneration predictions of the pump. The still open key issues are: for the Torus cryopumps: 1) Valve vacuum and cycle performance, limited temperature difference, max. 4.7K for He pumping, fast regeneration, 2) No LN, large He flow rates resulting to high pressures/velocities and large pressure drops, 3) Determination of flow resistance of quilted panels outstanding, 4) Protection against accidents 5) Design completion (safety, instrumentation, RH etc). All issues to be addressed by the Pre-Production Cryopumps. For the NB Cryopumps:1) Experimental determination of pumping speed, 2) Design completion (safety, instrumentation, regeneration etc), To be addressed by NB ITA and MITICA cryopumps. And for the CVBs: 1) Update flow resistance influence on performance, incorporate Pellet Injection Systems, safety issues (LOVA, water ingress). To be addressed by the CVB ITA/contract.

The official role of F4E in Vacuum Pumping starts with the related PAs (defined by IO) and ends with the in-kind delivery of the ITER Cryopumps (+MITICA) and CVBs/Cryojumpers. F4E in close collaboration with the IO, KIT and CEA Grenoble, has defined the necessary pre-PA activities to address open issues, minimize risks and has sufficiently planned them for the timely delivery of all these components. The progress in these activities is such that none of them appears in the critical path for 1st plasma (Nov. 2019).

P03 - Boris Weyssow: The European Fusion Development Agreement (EFDA)

European Fusion Development Agreement, EU

Plasma Physique et Statistique, Université Libre de Bruxelles, Belgium

Magnetic confinement fusion research in Europe is aimed at demonstrating that nuclear fusion is a viable future energy option. Achieving this aim requires a sustained, long-term and large scale research effort, which would be impossible to sustain for any single European country. Fusion research organisations in the Member states have so-called "Contracts of Association" with the European Commission (which represents Euratom), in which the long-term commitments and work plans are laid down. In 1999, the European Fusion Development Agreement (EFDA) was created to provide a framework between European fusion research institutions and the European Commission to strengthen their coordination and collaboration, and to participate in collective activities. Between 1999 and 2007 EFDA was responsible for the exploitation of the Joint European Torus, the coordination and support of fusion-related research & development activities carried out by the Associations and by European Industry and coordination of the European contribution to large scale international collaborations, such as the ITER-project. With the appearance of Fusion for Energy (in short F4E), the european domestic agency for ITER, EFDA´s role has changed and it has been reorganised. A revised European Fusion Development Agreement entered into force on 1 January 2008 focusing on research coordination with two main objectives: to prepare for the operation and exploitation of ITER and to further develop and consolidate the knowledge base needed for overall fusion development and in particular for DEMO, the first electricity producing experimental fusion power plant being built after ITER.

Further information: www.efda.org <http://www.efda.org/>

PLENARY SESSION: SCHOOL LECTURES – 1

S1.1 - Anastasios Anastasiadis: Basic Concepts of Plasmas

Institute for Space Applications & Remote Sensing, National Observatory of Athens - Greece

1. Τι είναι το Πλάσμα: Πλάσμα στην φύση και στο εργαστήριο, Παράμετροι του πλάσματος (πυκνότητες, θερμοκρασίες), Η εξίσωση Saha, Μέθοδοι περιγραφής του πλάσματος (μικρο–μακροσκοπική περιγραφή), Κίνηση σωματιδίων, Εξισώσεις Maxwell.
2. Βασικές παράμετροι πλάσματος: Μήκος και σφαίρα Debye, Ηλεκτροστατικό δυναμικό-θωράκιση, Οιονεί ουδετερότητα, Συχνότητα πλάσματος, Μαγνητισμένο πλάσμα.
3. Συγκρούσεις Coulomb: Συχνότητα συγκρούσεων, Συγκρούσεις με ουδέτερα σωματίδια, Ηλεκτρική αντίσταση πλάσματος.

S1.2 - Yannis Kominis: Charged particle dynamics - I & II

National Technical University of Athens, Greece

1. Τροχιές φορτισμένων σωματιδίων σε στατικά πεδία: Κίνηση σε στατικό ομογενές ηλεκτρικό πεδίο, Κίνηση σε στατικό ομογενές μαγνητικό πεδίο, Ολίσθηση E×B, Κίνηση σε μη ομογενές στατικό ηλεκτρικό πεδίο, Κίνηση σε μη ομογενές στατικό μαγνητικό πεδίο (διαμήκης ανομοιογένεια, εγκάρσια ανομοιογένεια, καμπυλότητα πεδιακών γραμμών), Αδιαβατικές σταθερές

2. Αλληλεπίδραση φορτισμένων σωματιδίων με κύματα: Ομαλή και χαοτική κίνηση φορτισμένου σωματιδίου σε ομογενές στατικό μαγνητικό πεδίο υπό την επίδραση ηλεκτροστατικών κυμάτων (Χαμιλτονιανή περιγραφή της κίνησης φορτισμένου σωματιδίου, Κανονική θεωρία διαταραχών και υπολογισμός προσεγγιστικών σταθερών της κίνησης, Ο ρόλος των συντονισμών και το πρόβλημα των μικρών παρονομαστών, Επικάλυψη των συντονισμών και μετάβαση στο χάος), Περιπτώσεις (Διάδοση κύματος υπό διαφορετικές γωνίες ως προς το μαγνητικό πεδίο, Κυμάτων διακριτού και συνεχούς φάσματος)

S1.3 A. Ram: Dancing with the stars: Quest for fusion energy
Massachusetts Institute of Technology, USA

How do our earthly efforts to generate fusion energy compare with nature's working fusion reactors? This highly illustrative talk will compare and contrast the approach to fusion from a laboratory perspective with that taken by nature in forming and operating the Sun. The progress towards energy's holy grail will be part of the presentation.

PLENARY SESSION: SCHOOL LECTURES – 2

01

S2.1 - J.L. Vomvoridis: Kinetic theory – I & II
(Κινητική Θεωρία – I & II)
National Technical University of Athens, Greece

1. Η συνάρτηση κατανομής: Ροπές της συνάρτησης κατανομής, Βασικές συναρτήσεις
2. Οι κινητικές εξισώσεις
3. Εφαρμογές κινητικής θεωρίας (Στατικές καταστάσεις ισορροπίας, Διάδοση κυμάτων (μικρού πλάτους) σε πλάσμα
4. Κύματα Langmuir σε μη μαγνητισμένο πλάσμα
5. Απόσβεση Landau

S2.2 A. Ram: Waves and applications
Massachusetts Institute of Technology, USA

(Abstract not available at time of print)

PLENARY SESSION: SCHOOL LECTURES – 3

S3.1 Leo Buehler: Asymptotic methods for modeling of liquid-metal flows in strong magnetic fields
Karlsruhe Institute of Technology, Karlsruhe, Germany

A key issue for the design of reliable liquid-metal blankets for fusion reactors is the accurate prediction of magnetohydrodynamic flows. The latter ones occur when the electrically conducting liquid breeder or coolant is circulated through the blanket in the region where the plasma-confining magnetic field is present. The strong magneto-hydrodynamic interaction has a decisive impact on the thermo-mechanical layout of liquid metal blankets. Despite the fast development of numerical techniques and increasing computational power, nowadays it is still not possible to simulate complex 3D MHD flows in blanket components at fusion relevant parameters.
Asymptotic methods are efficient tools for predicting magnetohydrodynamic flows in intense magnetic fields, i.e. when electromagnetic forces dominate in the problem. They have been applied since several decades for investigations of engineering applications like liquid metal flows in fusion blankets or in crystal growth technology. The basic assumptions used to derive asymptotic solutions are introduced and the strategy for obtaining efficient solution procedures is outlined. The impact of strong magnetic fields and resulting consequences for 3D MHD flows are discussed.

S3.2 Karl-Heinz Spatschek: Plasma transport: Basic Aspects
Institut für Theoretische Physik I - Heinrich-Heine-Universität Düsseldorf

The statistical description of a hot, magnetized, and classical plasma is reviewed. The latter represents the appropriate model for a fusion plasma in magnetic confinement. The presentation starts with a summary of the various approaches for (reduced) kinetic descriptions, such as the Landau-Fokker-Planck equation, the Balescu-Lenard equation, as well as the drift-kinetic and gyro-kinetic approaches. The famous Boltzmann equation for dilute gases is used (without a systematic derivation) to demonstrate on a classical model the differences between the kinetic and the hydrodynamic regimes.The Chapman-Enskog method is presented as the matter of choice for neutral systems. Then the consequences of long-range Coulomb interactions are discussed. Plasmadynamical variables are introduced, and the moment equations of the Landau-Fokker-Planck equation are shown. The hierarchy of moment equations is truncated by a Hermite polynomial expansion. Transport coefficients are discussed. Neoclassical theory is briefly mentioned. The problems of linear response theory are elucidated and heuristic approaches for nonlinear and nonlocal transport are discussed.

WORKSHOPS-1: STOCHASTIC MODELING AND PLASMA TRANSPORT

W1.1 Karl-Heinz Spatschek: Transport in stochastic magnetic fields

Institut für Theoretische Physik I - Heinrich-Heine-Universität Düsseldorf

Transport in stochastic magnetic fields is investigated. In the first part, the topic is motivated by commenting on the problems of known (nonlinear) transport theories. Non-integrable magnetic field line systems, their generation and Hamiltonian description are discussed. It is shown that they have very important consequences and applications, such as ELM mitigation, distribution of heat loads, and so on. The symplectic mapping is introduced as the adequate tool for the analysis of the statistics of magnetic field lines. Transport along the unstable and stable manifolds of hyperbolic fixed points is an effective mechanism for heat transfer from the hot core to the plasma boundary. The second part deals with anomalous test particle transport theories starting from stochastic descriptions, e.g. Liouville-type models. First, within simple models stochastic transport in the presence of collisions is investigated. It is shown that the so-called Kadomtsev-Pogutse diffusion coefficient is the strong collisional limit of the Rechester Rosenbluth formula. The theoretical estimates are supplemented by numerical simulations. For the latter the standard map is used after it is generalized to account for strong collisions. Finally, for large Kubo numbers, new transport regimes are identified. New results are presented for the pitch angle diffusion coefficient and its relation to the longitudinal mean free path. Astrophysical consequences for fast particle transport are briefly discussed.

W1.2 Boris Weyssow, Sara Moradi: Fractional transport in plasma

European Fusion Development Agreement - Université Libre de Bruxelles, Belgium

Anomalous diffusion combined or not with plasma heating leads to particle acceleration and macroscopic transfer processes whose description may require one to go beyond the "traditional" plasma kinetic theory. Kinetic equations with fractional derivatives allowing for alpha-stable equilibrium have been developed previously as a possible tool for the description of anomalous diffusion. In the first part of the presentation fractional derivatives are defined and used to describe particle motion in a formalism mimicking the classical Hamiltonian one. We will show how this procedure can be used to retrieve the mapping technique. Then, as another approach to fractional transport in plasma, we use the solution of the Fokker-Planck equation with fractional velocity derivatives in a constant external magnetic field and shear less slab geometry to solve the plasma dispersion equation for plasma with adiabatic electrons and singly charged ions. In the Fourier representation, the fractional derivatives appear as a fractional exponent, which we expand around the Gaussian value where the derivatives are of second order. The impact of such deviation on the solutions of the plasma dispersion equation, have been studied. It is observed that the imaginary part of the mode frequency, i.e. the growth-rate of the mode, increases significantly when the deviation from Maxwellian grows. This effect can lead to a significant increase of the anomalous diffusion.

W1.3 H. Isliker: Particle and heat transport in turbulent environment

Department of Physics, Aristotle University of Thessaloniki, Greece

We introduce a simple, but general conservation law in state space that is formulated in terms of probabilities and that actually expresses a mathematical identity in probability theory. In particular, the conservation law allows for non-local effects in space, velocity and time, and it can naturally be interpreted as describing a general random walk process. It is then shown how from the conservation law the classical diffusion equation, as well as the standard Fokker-Planck equation, can be derived, basically by excluding non-local effects. These equations are models of classical, stochastic transport. In a second step, it will be shown how from the state-space conservation law also deterministic transport equations can be derived, namely the Boltzmann equation and, more specific for the case of plasma, the Vlasov equation. In a third step, non-localities will explicitly be allowed by making use of Levy distributions in the state-space conservation law, which, in the random walk picture, corresponds to Levy walks in state space. The fluid limit will then be applied to the conservation law, which leads to the fractional Fokker-Planck equation. Finally, it will be discussed how the deterministic, stochastic, and fractional transport equations, due to their common derivation from the same conservation law, can be combined into a realistic transport model for turbulence that includes static background magnetic fields, turbulent magnetic and electric fields, and collisions.

W1.4 I. Kominis, A. Ram, K. Hizanidis: Kinetic formulation of transport of charged particles interacting with coherent EM waves in plasmas

National Technical University of Athens

We have developed a general kinetic theory for momentum and spatial transport of charged particles by radio frequency (RF) waves in the presence of magnetic field perturbations, e.g. due to neoclassical tearing modes (NTM), in a tokamak plasma [1]. The kinetic formalism is valid is particularly useful for modeling RF induced currents in tokamaks. It applies to present-day machines as well as to ITER where electron cyclotron waves will be used for controlling the NTMs. Our theory, in contrast to the usual

quasilinear (QL) theories takes into account the long time correlations that persist in the dynamical phase space of the particles interacting with coherent RF waves. In QL theory it is assumed that the RF waves continuously act on particles randomizing their motion with respect to the phase of the wave in a short interaction time. This is akin to the Markovian assumption and is characterized by phase mixing and ergodicity. However, for coherent RF waves, the particle phase space is a mix of chaotic and coherent motion with islands of coherent motion embedded within chaotic regions. Also, the phase space is bounded as particles do not continuously interact with the same spectrum of waves - either the waves evolve in time or are spatially confined. In the vicinity of phase space boundaries and islands, the particle motion is correlated over long times - much longer than an interaction time. By taking the actual phase space structure into account, our kinetic theory for evolution of the distribution function during wave-particle interactions does not possess the singular structure of QL theories. The master equation is time reversible and the operator evolving the distribution function is time-dependent and non-singular. From this equation we can construct a hierarchy of equations by sequential averaging over various phases (e.g., phases related to the Larmor, bounce and drift motion in a tokamak). The final one, obtained by averaging over all phases, leads to a well-behaved time dependent diffusion operator which is amenable to implementation in numerical codes. It also describes wave-particle interactions which are outside the scope of QL theories. Results and comparisons with the QL theory will be presented.

[1] Y. Kominis, A. K. Ram, and K. Hizanidis Phys. Plasmas 15, 122501 (2008).

PLENARY SESSION: SCHOOL LECTURES – 4

S4.1 George Throumoulopoulos: Introduction to Magnetohydrodynamics

Department of Physics, University of Ioannina, Greece

Basic components of plasma confinement in fusion devices as the tokamak are equilibrium and stability. In equilibrium the pressure-gradient force acting on a plasma element is balanced by the magnetic force. Good confinement additionally requires stability for perturbations around an equilibrium state. The simplest model to study plasma confinement is magnetohydrodynamics (MHD). In the framework of MHD the plasma is described as a single fluid the physics of which is governed by electromagnetic interactions. In this talk the basic elements of the MHD model is first reviewed, then certain MHD equilibrium and linear stability issues of magnetically confined plasmas are presented. In addition, some current research problems in connection with the ITER project are briefly outlined.

S4.2 Paraskevas Lalousis: Compressible MHD (ideal/resistive)

Συμπιεστή Μαγνητοϋδροδυναμική χωρίς/με ηλεκτρική αντίσταση

Ινστιτούτο Ηλεκτρονικής Δομής και Λέιζερ
Ίδρυμα Τεχνολογίας και Έρευνας - Ηράκλειο, Κρήτη

Η εξίσωση Boltzmann, για κάθε στοιχείο του πλάσματος, σε συνδυασμό με τις εξισώσεις του Maxwell περιγράφουν πλήρως τη δυναμική του πλάσματος. Η επίλυση αυτών των εξισώσεων (αναλυτικά ή υπολογιστικά) δεν είναι εφικτή. Μια καλή προσέγγιση είναι η Μαγνητοϋδροδυναμική (ΜΥΔ), θα περιγράψουμε πώς παίρνοντας ροπές της εξίσωσης Boltzmann παράγουμε τις εξισώσεις διατήρησης μάζας, διατήρησης ορμή, και διατήρησης ενέργειάς της ΜΥΔ. Θα παράγουμε την γενική εξίσωση του Ohm's, και από αυτήν την εξίσωση θα περιγράψουμε τι είναι Ιδανική ΜΥΔ, ΜΥΔ με αντίσταση, ΜΥΔ Hall, και ΜΥΔ δυο-ρευστών.

Η εξίσωση Grad-Shafranov, η οποία παράγεται από την εξίσωση ορμής της ΜΥΔ σε σταθερή κατάστασή, περιγράφει το πλάσμα και τα μαγνητικά πεδία σε ένα tokamak. Θα καταδείξουμε την αριθμητική επίλυσης της Grad-Shafranov, με πεπερασμένες διαφορές και πεπερασμένα στοιχεία Επίσης θα παρουσιάσουμε τί είναι ΜΥΔ κρουστικά κύματα, και την αριθμητική επίλυσή των εξισώσεων της ΜΥΔ με ηλεκτρική αντίστασή σε πολλές διαστάσεις και χρονική εξέλιξη.

PLENARY SESSION: SCHOOL LECTURES – 5

S5.1 Nikos Pelekasis: Introduction to hydrodynamic and MHD stability

(Εισαγωγή στην υδροδυναμική και Μαγνητοϋδροδυναμική ευστάθεια)

University of Thessaly, Volos, Greece

1. Στοιχειώδης θεωρία ευστάθειας και θεωρία διακλαδώσεων: Γραμμική και ελαφρώς μη γραμμική ανάλυση, Παραδείγματα από κλασσική υδροδυναμική ευστάθεια, Υπολογιστική κατασκευή διαγραμμάτων διακλάδωσης
2. Δυναμική σε χαμηλούς μαγνητικούς αριθμούς Reynolds: Μαγνητική απόσβεση – Δημιουργία κίνησης, Οριακά στρώματα (Στρώματα Hartmann και πλαϊνά)
3. Ευστάθεια μαγνητοϋδροδυναμικών ροών: Ευστάθεια στρωμάτων Hartmann και πλαϊνών στρωμάτων, Ροή υγρών μετάλλων σε σωλήνες – Εξαναγκασμένη και ελεύθερη αγωγή, Εφαρμογές στο σχεδιασμό αντιδραστήρων πλάσματος

S5.2 Valentin Igochine: Introduction to plasma stability

Max-Planck Institute of Plasma Physics, Garching, Germany

This introductory talk is aimed to give an overview of the stability problems in modern tokamaks. Starting from the construction of the toroidal equilibrium we continue with energy principle. This allows understanding sources of instabilities, which limits operational space in modern tokamaks and in International Thermonuclear Experimental Reactor (ITER). The main part of the talk is dedicated to simple explanation of main MHD instabilities: Sawteeth - Neoclassical Tearing Mode (NTM) - Edge Localized Mode (ELM) - Resistive Wall Mode (RWM) - Fast particle instabilities. All these instabilities are subjects for intensive research in most fusion labs all over the world. They have also shown to be particularly important for ITER. The presentation does not require special knowledge in MHD and does not contain heavy mathematics.

WORKSHOPS-2: MAGNETOHYDRODYNAMIC & PLASMA STABILITY

W2.1 Valentin Igochine: Operation limits and MHD instabilities in modern tokamaks and ITER

Max-Planck Institute of Plasma Physics, Garching, Germany

This is an overview talk about main performance limiting instabilities in modern tokamaks and in ITER. Starting from the basic discussion of the operating space of fusion devices we continue with discussing main MHD stability problems, which have to be solved for ITER needs. Assuming the basic knowledge about plasma instabilities we will focus on recent results and problems. We will discuss the proposed ways to solve the problems with main instabilities in present tokamaks (Sawteeth, NTMs, ELMs, RWMs, fast particle instabilities, etc.).

W2.2 - Avrilios Lazaros: Magnetic islands - The “cancer” of magnetically confined plasmas

School of Electrical & Computer Engineering, National Technical University of Athens, Greece

Here we present an outline of the very serious problem of magnetic islands in magnetically confined plasmas. More specifically, the following issues are addressed: 1) Definition of the magnetic island in magnetically confined plasmas, 2) Disruptions of magnetically confined plasmas, due to the formation of magnetic islands, 3) The classical theory of magnetic islands and the Rutherford equation, 4) The neoclassical theory of magnetic islands, 5) Control of Neoclassical Tearing Modes (NTMs) by electron cyclotron current drive (ECCD), 6) The design of “Upper Launcher” for NTM control by ECCD in ITER, 7) Control of magnetic islands by in-vessel coils, and 8) Introduction to the concept of the “island-free” magnetic topology of stellarators.

W2.3 Leo Buehler, Chiara Mistrangelo: Magnetohydrodynamic flows in fusion blankets: experiments and simulations

Karlsruhe Institute of Technology, Karlsruhe, Germany

Liquid-metal magnetohydrodynamic flows in a scaled mock-up of a helium cooled lead lithium (HCLL) test blanket module for the fusion reactor ITER have been investigated experimentally and numerically. The geometry is scaled down by a factor 2 compared to the original dimensions to fit into the gap of the large dipole magnet available in the MEKKA laboratory of the Karlsruhe Institute of Technology (formerly Forschungszentrum Karlsruhe), where sodium-potassium (NaK) is used as model fluid. Pressure and electric potential on the surface of the mock-up have been recorded for various magnetic field strengths and flow rates. The experiments confirm theoretical predictions according to which the major contributions to the total pressure drop arise in access pipes and manifolds. The experiments show that additional but smaller contributions are also present when the flow passes through the narrow gaps in the back plate or at the first wall. A pressure drop correlation has been derived that allows extrapolating the recorded data to ITER operating conditions for which the pressure drop in the blanket module is most likely inertialess. Results of electric potential measurements on the surface of the test section yield information about flow distribution in the mock-up. A strong electrical coupling of the various flow domains results in sufficiently uniform flow distribution in the breeder units in accordance with numerical simulations.

W2.4 C. Dritselis, N. Vlachos: Near-wall coherent structures in MHD turbulent flows

Department of Mechanical Engineering, University of Thessaly, Volos, Greece

A detailed investigation of the modifications induced by the magnetic field on the coherent structures in the near-wall region of a turbulent channel flow is presented. A conditional sampling scheme is used to extract the entire extent of the quasistremwise vortices and to educe ensemble-averaged coherent structures for the flow cases with and without the external uniform magnetic fields at the same Reynolds number. The vortical events are identified by using the $\lambda 2$-criterion of Jeong & Hussain [JFM, 285, 69, (1995)]. The size of the educed quasistreamwise vortices is significantly increased in the magnetohydrodynamic cases. However, the level of increase is smaller than that of the turbulent structures in the outer flow region. This is attributed to the mean shear which is dominant in the near-wall region and also controls the evolutionary dynamics of coherent structures. The underlying organized turbulent motions are substantially damped by the direct action of the Lorentz force. The educed results show that the magnetic field creates torques of opposite signs to that of coherent vorticity produced by the advection of the quasistreamwise vortices by the mean flow. Consequently, the magnitude of the pressure is decreased and the intercomponent energy exchange is influenced by the magnetic field. The latter leads to indirect changes in the coherent velocity and vorticity fluctuations around the conditionally averaged vortices. The present study suggests that the near-wall coherent structures are more efficiently modified by a wall-normal magnetic field. The main characteristics of near-wall turbulence are generally maintained, but a substantial reduction of the Reynolds stresses and the production of turbulent kinetic energy is observed.

W2.5 Apostolos Kuiroukidis: ECCD and island saturation in realistic magnetic fields

Department of Physics, Aristotle University of Thessaloniki, Greece

We consider a toroidal magnetic field described by a generic Shafranov shift, elongation and safety factor and expand the poloidal magnetic field in terms of the poloidal angle ($\cos\theta$). Demanding that the poloidal field does not depend on ($\cos\theta$), to first order, determines the Shafranov shift. We then consider the problem of NTM stabilization through ECCD. This is a toy model presented for educational purposes. Our aim is to generalize this and determine general criteria in terms of Shafranov shft, elongation and other magnetic equilibrium quantities such as the safety factor, if possible, for optimum ECCD and power deposition.

PLENARY SESSION: SCHOOL LECTURES – 6

S6.1 Daniele Carati: Introduction to MHD Turbulence

Physique Statistique et Plasmas, Université Libre de Bruxelles

(Abstract not available at time of print)

S6.2 Abhay Ram: Heating and current drive by radio frequency waves in fusion plasmas

Massachusetts Institute of Technology, USA

Electromagnetic radio frequency waves occur naturally in terrestrial, space, and astrophysical plasmas. The waves are a consequence of collective motion of the plasma constituents. There is a rich diversity of electromagnetic waves in plasmas - much more so than for waves in vacuum. The generation of waves in a laboratory plasmas can be controlled by appropriately designed sources of electromagnetic radiation. Controlled thermonuclear magnetic fusion reactors have to operate in steady state at temperatures exceeding 200,000,000 degrees. Electromagnetic radio frequency waves, generated by external sources, can be used for heating the confined plasmas to the required temperatures, controlling instabilities, and for maintaining steady state operation. The variety of plasma waves allows for mixing and matching of different waves with the desired goals.

PLENARY SESSION: SCHOOL LECTURES – 7

S7.1 Bernhard Piosczyk: Gyrotrons: basic operating principles and application

Karlsruhe Institute of Technology (FZK), Karlsruhe - Germany

Gyro-devices are based on the cyclotron resonance instability, a relativistic phenomenon which provides an energy transfer mechanism between the rotating electrons in the beam and the excitation field. In difference to conventional vacuum tubes as travelling wave tubes (TWT), klystrons or magnetrons which are categorized as slow wave devices, gyrotrons are classified as fast wave devices. With gyrotrons microwave radiation in the frequency range between ~ 10 GHz and 1000 GHz has been generated. Due to the fact that strongly overmoded cavities can be used, the generation of microwave power in the MW at CW has been demonstrated at frequencies around 100 GHz. In the talk, first the basic gyrotron operating principles will be explained. The application of gyrotrons as microwave sources is growing. In the second part of the talk some applications and possible applications are presented.

S7.2 Guenter Dammertz: Technical design of high power gyrotrons and its components

Karlsruhe Institute of Technology (FZK), Karlsruhe - Germany

The development of high power gyrotrons in continouos wave (cw) operation for heating nuclear fusion plasmas as for example the stellarator W7-X in Greifswald or ITER has been in progress for several years. These gyrotrons and its components differ in many respects from medium and low power gyrotrons. A very careful physical and technical design, special materials and good performance are necessary to handle the internal radiation and losses, to guarantee long life-time. Special physical methods are necessary to reduce the power density of absorbing surfaces, to eliminate overheating and to produce an output beam suitable for transmission. Special physical methods are necessary to reduce the power density on the surfaces. The important components as gun, beam tunnel, resonator, mode converter and so on will be described with special consideration of high power tubes.

WORKSHOPS-3: GYROTRONS – ELECTROCYCLOTRON RADIO HEATING (ECRH)

W3.1 Bernhard Piosczyk: European gyrotron development for ITER

Karlsruhe Institute of Technology (FZK), Karlsruhe - Germany

In the first stage of ITER, which is presently under construction at Cadarache, France, 24 MW of microwave power at 170 GHz are foreseen for heating, current drive and stabilization of NTM instabilities. In a further stage a doubling of the microwave power is under discussion. The European countries are committed to deliver 1/3 of the microwave sources. In contrast to hollow-cavity Gyrotrons, which are under development for ITER in Japan and Russia, the EU gyrotron consortium is investigating a coaxial-cavity gyrotron with the potential to produce an RF output power of 2 MW per tube. The coaxial arrangement reduces the problem of mode competition and limitations due to beam space charge. Coordinated by F4E a development of a 170 GHz, 2 MW, cw coaxial gyrotron is in progress in cooperation between different European research centers. Within this development activities a short pulse (up to ~ 5ms) experimental gyrotron at KIT Karlsruhe is used for verifying the basic operating behavior and to prove the design under relevant conditions. A first industrial prototype tube has already been fabricated and tested at CRPP Lausanne in 2008. In these tests several problems occurred. At present the prototype tube is under refurbishment in order to improve the performance. In the talk the status of the development work will be presented.

W3.2 K. Avramides, I. Pagonakis*: Gyrotron interaction simulations (On the effect of the employed assumptions)

SECE, National Technical University of Athens, Athens, Greece
*CRPP, École Polytechnique Fédéral de Lausanne, Lausanne, Switzerland

High-power gyrotrons are the leading microwave sources for plasma heating and current drive in magnetic confinement fusion experiments. In a gyrotron, a helical electron beam, formed by a MIG-type electron gun and guided by an external magnetostatic field, delivers energy to a RF electromagnetic wave (i. e. a TE mode supported by the interaction cavity) through electron cyclotron resonance. Numerical simulations of the beam-wave interaction in high-power gyrotrons are the basic tool for the design of the interaction cavity in these devices. In order for the interaction codes to be used efficiently as designing tools undertaking detailed parameter studies, fast simulations are necessary. Several simplifying assumptions are thus employed in the interaction codes, to make them capable of fast calculations. However, as the resonators get larger to meet the increasing needs in output power and their mode spectrum becomes denser, the validity of some of the aforementioned assumptions needs to be revisited. We discuss the modelling of the beam-wave interaction, focusing on the adopted assumptions. In addition, we present results from investigations on the influence of these simplifying assumptions on the electron trajectories, using two pertinent numerical codes: (1) EURIDICE, which is based on the slow-time-scale approximation for the electron motion and also on further assumptions, widely used in similar fast interaction codes, and (2) Ariadne++, which, contrary to EURIDICE, uses no approximations when calculating the electron motion in a given electromagnetic field.

W3.3 Zisis Ioannidis, Ioannis Tigelis: Recent numerical results for eigenvalues and ohmic losses in coaxial corrugated cavities

Department of Physics, National University of Athens, Athens, Greece

In high-power high-frequency gyrotrons, coaxial cavities have been proposed to provide additional means in mode selection. The inner conductor brings on deformation in the eigenvalue spectrum that may rarefy the spectrum of the competing modes, by selecting the geometrical characteristics of the insert properly. The selective properties of the resonator can be further enhanced by the introduction of longitudinal corrugations on the inner conductor. Such structures have been studied mainly using the simplified Surface Impedance Model (SIM), provided that the corrugations are dense enough, so we can treat them as a smooth surface of proper impedance, ignoring the coupling of azimuthal modes that the corrugation evokes. The previous assumption is usually expressed in the form $N > 2m$, where N is the number of the corrugations and m the azimuthal index of the mode. More complex full-wave approaches based on the Singular Integral Equations (SIE) method and Spatial Harmonics Method (SHM) have no such limitations. In this work, we employ a full-wave numerical code based on SHM to study the eigenvalue spectrum, the field distribution and the ohmic losses in coaxial cavities. Numerical results are presented to clarify the influence of the higher – order spatial harmonics on these calculations and comparison with the standard design method based on SIM is made.

W3.4 Guenter Dammertz: ECRH system for the W7-X stellarator

Karlsruhe Institute of Technology (FZK), Karlsruhe - Germany

Electron Cyclotron resonance heating (ECRH) plays a key role in fusion plasma devices esp. in stellarator research, as it provides net current free plasma start up and heating. For the stellarator W7-X presently in construction at Greifswald, Germany, a 10 MW ECRH system is foreseen as the main heating system. Some years ago, a development started together with an industrial partner to built ten gyrotrons with an output power of 1 MW each. The development phase was successful and the series production is in progress. Unfortunately some of the gyrotrons failed the acceptance tests. The measurements of the gyrotrons, the results and the problems of the gyrotrons will be described and the present status will be given.

W3.5 George Latsas, Ioannis Tigelis: Parasitic oscillations in the gyrotron beam tunnel

Department of Physics, National University of Athens, Athens, Greece

The development of parasitic oscillations in a gyrotron beam tunnel may result in the degradation of the electron beam quality, leading to the reduction of the overall gyrotron efficiency. Appropriate design of the gyrotron beam tunnel is therefore required in order to ensure the prevention or the adequate damping of such parasitic modes that might develop there. In this work, the possible beam-wave interaction mechanisms, which may appear in a gyrotron beam tunnel are studied using a semi-analytical method, which is based on a full wave analysis along with the linear Vlasov equation. Numerical results are presented for parasitic oscillations observed in several modern gyrotron beam tunnels. In particular, the dispersion characteristics, field profile and growth rate of the observed parasitic modes are given, for both conventional and coaxial beam tunnel geometries. The effect of the losses of the ceramic material on these modes is studied and discussed.

W3.6 Christos Tsironis[1,2,3], Iordanis Giannopoulos[3]: Automatic control systems and applications to Tokamak fusion

[1]School of Electrical & Computer Engineering, National Technical University of Athens, Greece
[2]Department of Physics, Aristotle University of Thessaloniki, Greece
[3]Department of Automation, Technological Educational Institute of Piraeus, Greece

The development of fusion power plants requires the resolution of several physics and engineering problems in tokamak experiments. An important element for the optimal operation of tokamaks is the development of automatic control systems that implement the entire loop from sensors, a combination of different plasma diagnostics, to proper actuators like gas puffs and microwave heating systems. Integrated tokamak control targets to the simultaneous control of multiple plasma parameters, among which are the plasma vertical position, magnetic equilibrium and MHD stability, with a limited number of actuators and a constrained set of diagnostics. There are a lot of activities on-going in the field of real-time tokamak control, leading to significant progress in theory and applications, however it is only recently that there is significant effort in developing integrated control systems. Most of the control algorithms that are presently used have been developed by researchers within the fusion community, and only a few by scientists or engineers working in the field of automatic control of scientific or industrial processes. Especially in this field, many advanced techniques have been developed that may be suitable for application to fusion devices, giving the prospect for novel improvements. In this talk, we review the current status in the field of automatic control systems theory and applications to tokamaks, as well as on the specific needs for more advanced techniques, especially for ITER. We also make an introduction to the knowhow already available in the control community of science and industry, in terms of an initial exploration in how far tokamak research can benefit, and certain directions in theoretical modeling and design are depicted.

W3.7 Stavros Moustaizis: Compact magnetic fusion devices: initiative for a neutron test facility

Technical University of Crete, Greece

(Abstract not available at time of print)

PLENARY SESSION: SCHOOL LECTURES – 8

S8.1 Grigoris Haidemenopoulos: Materials at high temperatures

Department of Mechanical Engineering, University of Thessaly, Volos, Greece

In many engineering applications, materials are facing high temperatures, usually above half the melting point, for extended periods of time. The mechanical behavior under these conditions determines the structural integrity of engineering components while in several cases the development of certain new technologies is limited by the development of materials. In the present lecture the basic principles of the mechanical behavior of materials at high temperatures are presented with emphasis on time-dependent deformation, i.e. creep. The mechanisms for creep deformation and creep fracture are analyzed and the criteria for high-temperature resistance, such as the melting point, the maximum service temperature and thermal distortion are discussed. Finally the basic characteristics of heat-resistant materials are presented such as ferritic, martensitic and austenitic stainless steels, refractory metals and alloys, intermetallics, ceramic matrix composites as well as carbon-carbon composites.

Γ.Ν. Χαϊδεμενόπουλος: Τα Υλικά σε Υψηλές Θερμοκρασίες

Τμήμα Μηχανολόγων Μηχανικών - Πανεπιστήμιο Θεσσαλίας

Σε πολλές μηχανολογικές εφαρμογές τα υλικά καλούνται να αντιμετωπίσουν υψηλές θερμοκρασίες, συνήθως πάνω από το ½ του σημείου τήξεως, για μεγάλα χρονικά διαστήματα. Η μηχανική συμπεριφορά των υλικών στις συνθήκες αυτές καθορίζει την δομική ακεραιότητα και λειτουργικότητα των μηχανολογικών διατάξεων και σε πολλές περιπτώσεις η ανάπτυξη συγκεκριμένων τεχνολογιών περιορίζεται από την αντίστοιχη ανάπτυξη των υλικών. Στην παρούσα διάλεξη παρουσιάζονται οι βασικές πτυχές της μηχανικής συμπεριφοράς σε υψηλές θερμοκρασίες, με έμφαση στη χρονικά εξαρτημένη παραμόρφωση, δηλαδή στον ερπυσμό. Αναλύονται οι μηχανισμοί του ερπυσμού και προσδιορίζεται η επίδραση της μικροδομής του υλικού. Επίσης παρουσιάζεται το πρόβλημα της θραύσεως σε υψηλές θερμοκρασίες. Στη συνέχεια αναλύονται τα κριτήρια τα οποία πρέπει να ικανοποιεί ένα υλικό για να αντέχει σε υψηλές θερμοκρασίες, όπως το σημείο τήξεως, η μέγιστη θερμοκρασία λειτουργίας και η θερμική παραμόρφωση. Στο τέλος παρουσιάζονται τα βασικά χαρακτηριστικά των υλικών με αντοχή σε υψηλές θερμοκρασίες, όπως: φερριτικοί/μαρτενσιτικοί/ωστενιτικοί ανοξείδωτοι χάλυβες (stainless steels), υπερκράματα νικελίου (superalloys), πυρίμαχα μέταλλα και κράματα (refractory metals), ενδομεταλλικές ενώσεις (intermetallics), κεραμικά υλικά και σύνθετα υλικά με κεραμική μήτρα (ceramic-matrix composites), σύνθετα υλικά με βάση τον άνθρακα (carbon-carbon composites).

S8.2 George Apostolopoulos: The grand challenge for Fusion energy: developing materials for DEMO

National Centre for Scientific Research “Demokritos”, Athens, Greece

ITER, the new fusion research device under construction in France, has been possible after twenty years of Fusion Physics research and development of advanced materials and Fusion related technologies in Europe and elsewhere in the world. The challenge for researchers around the world is in the next twenty years to develop the tools for the next step for Energy production from Fusion. New Fusion Physics will be carried out in ITER and at the same time new Physics and Technological innovations are required for the development of new materials. In order to develop these materials, which will make true the Human dream for cheap and clean energy we need to understand basic Physics of material science and the behaviour of materials in extreme environments.
In the future fusion power reactors, the plasma facing (first wall, divertor) and breeding blanket components will be exposed to plasma particles and electromagnetic radiation and will suffer from irradiation by an intense flux of 14MeV neutrons. In combination with the high operating temperatures, this harsh radiation environment may result in a degradation of the physical properties of materials, such as a decrease of the thermal and electrical conductivity, as well as degradation of the mechanical properties, leading to strong hardening and embrittlement. Gas formation by nuclear transmutation reactions may induce macroscopic swelling, leading to a loss of dimensional stability. These effects are the main factors limiting the choice of candidate materials for fusion power reactors. The residual radioactivity of the large amount of material exposed to neutron radiation is another important concern.
Current research activities on materials for fusion power reactors are focused on plasma facing, functional and structural materials. Research is carried out world wide and some of the most actively investigated topics include the development of new high temperature, radiation resistant materials, the characterization of candidate materials in terms of mechanical and physical properties and the assessment of irradiation effects. The aim of this talk is to give an overview of the challenges faced today in the field of materials for future fusion power reactors, i.e. DEMO and beyond. The main achievements obtained in the different investigation areas will be summarized. Furthermore, the materials research activities carried out currently at “Demokritos” within the Hellenic Fusion Association program will be presented.

S8.3 Dimitris Valougeorgis: Kinetic modeling for vacuum flows in DT fusion reactors

Department of Mechanical, University of Thessaly, Volos, Greece

All large fusion devices and in particular DT fusion machines, such as ITER and DEMO, require the existence and smooth operation of advanced and demanding vacuum pumping systems, which are needed for the generation, evacuation and maintenance of the specified pressure levels in the torus, the NBI and the cryostat. The flow conditions in the pumping systems cover the whole range of the Knudsen number. The accurate design of such systems (pumps and piping) is still a challenge. The main approach capable of handling such flows is kinetic theory. Here a brief overview of the vacuum systems and conditions of DT fusion machines is presented. Then, based on kinetic theory some specific flow configurations are examined. Suitable kinetic model equations coupled with appropriate boundary conditions are formulated and solved numerically both in a deterministic and probabilistic manner. The deterministic scheme is based on the discretization of the applied kinetic equations in the physical and molecular velocity spaces, while the probabilistic scheme on the direct simulation of a sample of model molecules, which statistically mimics the behavior of real molecules. Results for the flow rates and the pressure drop are presented for flows through basic elements of vacuum systems such as channels of infinite and finite length and various cross sections. Simulation of unsteady flows is also discussed. Comparisons with available experimental work are included.

S8.4 Nicholas Vlachos: Examples of CMHD codes for viscous MHD flow and heat transfer

Department of Mechanical, University of Thessaly, Volos, Greece

Navier-Stokes equations for boundary layers and recirculating flows – Integration of Navier-Stokes equations using finite volumes – Decoupling of the velocity field from the pressure filed – Derivation of numerical counterparts for boundary layers: Calculation of velocities and scalar quantities, Application to MHD flows – Derivation of numerical counterparts for recirculating flows: Calculation flowchart, Applications to MHD separating flows - Modeling of turbulence, buoyancy and particle dynamics.

Νικόλαος Βλάχος: Παραδείγματα κωδίκων υπολογιστικής ΜΥΔ για μελέτες Μαγνητοϋδροδυναμικών ροών και μεταφοράς θερμότητας

Τμήμα Μηχανολόγων Μηχανικών - Πανεπιστήμιο Θεσσαλίας

Εξισώσεις Navier-Stokes σε οριακά στρώματα και ροές με ανακυκλοφορία - Ολοκλήρωση εξισώσεων Navier-Stokes με πεπερασμένους όγκους - Αποσύζευξη του πεδίου ταχυτήτων από το πεδίο πίεσης - Παραγωγή των αριθμητικών εξισώσεων για ροές σε οριακό στρώμα: Υπολογισμός ταχυτήτων και βαθμωτών μεγεθών, Εφαρμογές σε απλές ΜΥΔ ροές - Παραγωγή των αριθμητικών εξισώσεων για ροές με ανακυκλοφορία: Διαγράμμα ροής υπολογισμού, Εφαρμογές σε απλές ΜΥΔ ροές - Μοντελοποίηση τύρβης, άνωσης και δυναμικής σωματιδίων.

WORKSHOPS-4: MODELING VISCOUS MHD, VACUUM FLOWS, TURBULENCE & HEAT TRANSFER

W4.1 Daniele Carati: Large Eddy Simulation (LES) ideas for gyrokinetic equations

Physique Statistique et Plasmas, Université Libre de Bruxelles

In fluid turbulence, large-eddy simulations are based on a scale separation in which the variables describing the largest structures of turbulence are computed directly while the influence of the smallest structures is accounted for through a model. This technique has been widely used in simulations of Navier-Stokes and magnetohydrodynamic turbulence. We will report on the extension of the same approach to gyrokinetic simulations. In particular, the physical role of the small unresolved scales in under-resolved gyrokinetic simulations will be discussed. Diagnostics for improving the modelling of these unresolved scales will be proposed and simple models will be considered.

W4.2 Sarantis Pantazis, Serafim Misdanitis, Dimitris Valougeorgis: Modelling of fusion related nonlinear vacuum gas flows

Department of Mechanical Engineering, University of Thessaly, Greece

Transport phenomena in fusion vacuum systems are largely influenced by non-equilibrium effects. As we depart from the hydrodynamic regime, physics on a microscopic scale need to be considered on the basis of kinetic theory. Both deterministic and stochastic mesoscale methods are commonly used. The former ones are based on the direct descretization of the governing kinetic equations and the later ones on the implementation of the Direct Simulation Monte Carlo (DSMC). These methods are valid in the whole range of the Knudsen number. In the present work the formulation of both approaches is presented and then ‘in house” developed codes are applied to solve flows through channels of finite length, which are very common in fusion vacuum networks. Results are presented for the macroscopic quantities of practical interest in terms of the flow and geometry parameters. A comparison between the two approaches is presented pointing out the strong and weak points of each of them.

W4.3 Dimitris Dimopoulos, Nikos Pelekasis: Magnetic field effects on 3D stability of natural convection in differentially heated cavities

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The parametric study of two dimensional free convection flow in a square cavity is extended in order to cover three dimensional disturbances. Identification of the mechanism for generation of quasi two-dimensional structures is also attempted in ducts where Rayleigh-Bernard convection takes place. The parametric study of two dimensional free convection flow in a square cavity is extended in order to cover three dimensional disturbances. The magnetic field is taken to be perpendicular to gravity, in the cavity cross section. Mass continuity and the momentum, energy and electric charge conservation equations are solved for. The Galerkin finite element method is used for calculating the two-dimensional steady state and discretizing the linear stability problem, in the param¬eter space defined by the dimensionless numbers, Gr, Ha, Pr, volumetric heat production S, and aspect ratio A of the cross section. The Arnoldi method is used for the calculation of eigenvalues with the highest absolute value. Parametric continuation is performed via the GMRES method in order to obtain the evolution of specific critical modes as k, Gr. First, a temperature gradient parallel to the Hartmann walls is assumed. In all cases examined three dimensional disturbances are less stable than two dimensional ones, while increasing the Ha number increases critical Gr as well. A travelling and a standing wave arise as dominant eigenmodes as a result of centrifugal instability due to the curvature[1] of the stream lines in the base flow[2]. A parametric study is performed in order to identify the effect of the magnetic field, increasing Ha, on the direction and strength of the emerging recirculation vortices as the aspect ratio of the cavity A varies.

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W4.4 Demokratis Grigoriadis, Stavros Kassinos: Computational modelling of liquid metal flows

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(Abstract not available at time of print)

W4.5 - Ioannis Sarris, Daniele Carati*: Plasma stability and turbulent simulations in tokamaks based on the openFOAM

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The recent software developments of the University of Thessaly MHD group for the simulation of plasma stability and turbulence in tokamaks are presented. These developments concern mainly the adaptation and modulation of the open source library called openFOAM, which is a general took for solution of partial differential equations, for the ITER plasma geometry and flow conditions. In particular, the basic features of the object oriented library openFOAM and the use of them for the solution of the compressible non-linear magnetohydrodynamic equations are reviewed. Results of the MHD model presented for basic flows and successive comparisons with analytic solutions are presented. Numerical issues like, the success of divergence-free magnetic fields, the construction of the three-dimensional mesh in the tokamak torus, the global mesh refinement, but also, possible adaptive local refinement techniques based on strong local current gradients are discussed. Computational details from the benchmark solution of the 3D sawtooth cycle in the CDX-U tokamak with the present MHD model and the comparison with existing non-linear results from the M3D and NIMROD codes are presented. Finally, we focus on the future work of the group and the possible data and object input/output and connection of our model with the KEPLER interface within the IMP12 activities of the ITM.

POSTERS OF RESEARCH ACTIVITIES

RP01 Ioanna Chatziantonaki[1], Christos Tsironis[1,2], E. Poli[3], Loukas Vlahos[1]: Electron-cyclotron wave propagation, absorption and current drive in the presence of neoclassical tearing modes

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We analyze the propagation of electron-cyclotron (EC) waves, their absorption and the current drive (ECCD) when Neoclassical Tearing Modes (NTMs) are present in a tokamak, forming magnetic islands, as well as the resulting effect on the dynamics of the NTMs. The most promising method for the stabilization of NTMs is to deposit ECCD in the vicinity of the island's O-point. So far, the analysis of the EC propagation and deposition has been done mainly in terms of an axisymmetric magnetic topology, ignoring any effects from the islands. Our analysis starts with a stable magnetic equilibrium, which is perturbed and forms magnetic islands [1]. In this geometry we study the EC propagation and absorption, with a ray-tracing code (CODERAY) as well as the beam-tracing code TORBEAM [2], focusing on the effect of the island topology on the efficiency of the EC absorption and ECCD [3,4]. The EC propagation up to the O-point is found to be little affected by the island topology, whereas the power absorbed and the driven current are crucially affected due to the strong dependence of the new geometry, which appears because the resonant particles are trapped in the small volumes between the flux surfaces of the island chain. The consequences of these effects on the NTM evolution are investigated in terms of the modified Rutherford equation.

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RP02 Chris Dritselis, Ioannis Sarris, Dimitris Fidaros, Nicholas Vlachos: Neutral particle transport and deposition in turbulent MHD flows with lateral and volumetric heating

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(Abstract not available at time of print)

RP03 Heinz Isliker, Theophilos Pisokas, Dafni Strintzi*, Loukas Vlahos: A 1D self-organized criticality model for turbulence driven by micro-instabilities in tokamak plasmas

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We introduce a new Self-Organized Criticality (SOC) model in the form of a Cellular Automaton (CA) for ion temperature gradient (ITG) mode driven turbulence in fusion plasmas. Main characteristics of the model are that it is constructed in terms of the actual physical variable, the ion temperature, and that the temporal evolution of the CA, which necessarily is in the form of rules, mimics actual physical processes as they are considered to be active in the system, i.e. a heating process and a local diffusive process that sets on if a threshold in the normalized ion temperature gradient R/L_T is exceeded. The model reaches the SOC state and yields ion temperature profiles of exponential shape, which exhibit very high stiffness, in that they basically are independent of the loading pattern applied. This implies that there is anomalous heat

transport present in the system, despite the fact that diffusion at the local level is imposed to be of a normal kind. The distributions of the heat fluxes in the system and of the heat out-fluxes are of power-law shape. The basic properties of the model are in good qualitative agreement with experimental results.

RP04 Sotiris Kakarantzas*, Ioannis Sarris, Nicholas Vlachos: Magnetic field effect on MHD natural convection in vertical annuli with lateral and volumetric heating

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MHD liquid metal free convection is studied in a closed vertical annulus in which the upper and bottom surfaces are adiabatic while the cylindrical walls are kept isothermal at different temperatures. The flow is driven by two different mechanisms, the temperature difference between the inner and the outer cylindrical walls and the volumetric heating. An external horizontal magnetic field is also imposed resisting the buoyant fluid motion. The dimensionless parameters characterizing the present flow are: the external Rayleigh number Rae corresponding to the magnitude of the temperature difference between the external and internal cylinders, the internal Rayleigh number Rai representing the intensity of the volumetric heat generation, and the Hartmann number Ha expressing the magnitude of the magnetic field. The laminar and turbulent regimes of the flow are assessed by performing three-dimensional direct numerical simulations. The results show that the flow in the hydrodynamic case is turbulent for Rae ≥ 104. As the magnetic field increases the flow becomes less turbulent and, for large enough Hartmann numbers (Ha ≥ 75), it becomes laminar. The magnetic field causes loss of axisymmetry due to the development of Hartmann and Roberts layers near the walls normal and parallel to it, respectively. The volumetric heating increases the temperature of the fluid resulting in significant changes of the flow pattern, depending on the ratio of the internal to external Rayleigh numbers, S = Rai/Rae. More specifically, for the case of S = 1, a second region (very close to the external wall) develops where the temperature becomes almost equal to the maximum value at the external wall. For higher values of S, this region moves towards the middle of the annular gap, the fluid temperature increases further and its value exceeds that at the external wall. This leads to the creation of two convection currents because the fluid ascends near the regions of higher temperature and descends close to the colder walls.

RP05 Athina Kappatou, Kyriakos Hizanidis: Study of the discrepancy in temperature measurements in high temperature plasmas

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Systematic discrepancies between the temperature profiles measured by the Electron Cyclotron Emission and Thomson Scattering diagnostics have been observed in various JET experiments with high temperature plasmas with strong auxiliary heating. The discrepancy appears in the ECE spectra as a difference between the temperature deduced from the 2nd ECE harmonic X-mode and the temperature deduced from the 3rd ECE harmonic X-mode (which is optically thick in such high temperatures).
Measured ECE spectra are compared with simulations from SPECE, a simulation code which assumes a maxwellian electron distribution function. The measured spectra can be very well simulated, enhancing our confidence in the ECE calibration, however in cases where the discrepancy appears, the spectrum cannot be simulated, supporting the assumption that the maxwellian distribution function is distorted under strong auxiliary heating. In addition, through simulations it is shown that the discrepancy exceeds the known errors of the Thomson Scattering diagnostic.
In order to select suitable shots to be studied, simulated and compared, a program was created in IDL so as to create a database. The program is based on the fact that the discrepancy can be identified as a difference between the temperatures deduced from the

2nd and 3rd ECE harmonics X-mode and the assumption that this is an indication that the velocity distribution function is not maxwellian. Since the 3rd ECE harmonic X-mode always agrees with the Thomson Scattering temperature measurements, the program reads the difference between the two harmonics rather than doing a direct comparison of the two diagnostics. The selected database of JET shots, although limited, gives an overview of the conditions (auxiliary heating, density, temperature, magnetic field etc) under which the discrepancy in temperature measurements appears.

RP06 Avrilios Lazaros: Evaluation of current drive efficiency for the suppression of NTMs

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An analytic and numerical evaluation of the current drive efficiency for the suppression of NTMs is presented, in which the precise topology of the driven current in the magnetic island is included. It is found that the correction of the equilibrium term is no longer constant (i.e. independent of the island width), as previously assumed, but it is much stronger for small islands. This implies that early application of ECCD at the resonant surface provides a much stronger stabilizing effect, leading subsequently to a more efficient prevention of the NTMs.

RP07 Serafim Misdanitis, Sarantis Pantazis, John Lihnaropoulos, Dimitris Valougeorgis, Stellios Varoutis*, V. Hauer*, Christian Day*: Experimental and numerical investigation of vacuum gas flows in fusion vacuum systems

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Fusion vacuum pumping systems are responsible for the evacuation and maintenance of the required pressure levels in the torus (during burn and dwell, conditioning and leak detection), the neutral beam injector (NBI) and the cryostat vessel. The achievable pumping speed in all the above systems is of major importance for the performance and burn time of a fusion reactor and therefore a thorough and complete study of the flow conditions is mandatory, in order the optimum values to be achieved. Each of the vacuum systems consists of a network of various channels and piping elements with different lengths and cross sections. The flow in these networks varies from the free molecular through the transition and slip regimes all the way up to the hydrodynamic limit.

Through a close collaboration between the University of Thessaly (UTH-Hellenic Association) and the Vacuum Pumping Task Force at the Karlsruhe Institute of Technology, a thorough investigation involving both computational and experimental approaches for channel flow prediction has been performed. The work focuses on gas flows through ducts of various lengths and cross sections. The experimental work is conducted in the TRANSFLOW (Transitional Flow Range Experiments) test facility at KIT, while the computational work is performed both at KIT and UTH, based on the direct simulation of kinetic model equations and the Direct Simulation Monte Carlo method (DSMC) method.

In the present paper a review of recent results obtained through this collaboration is presented. Most of the presented work is related to low and high speed flows through channels of infinite and finite length respectively. In the former case the flow is considered as fully developed and modeling is based on linear kinetic theory. In the latter case channel end effects can not be ignored and modeling is based on nonlinear kinetic theory and the DSMC method. Glows through orifices and slits are also considered. Even more some very recent results related to unsteady vacuum flows are provided. Whenever available, comparison with corresponding experimental results is performed.

RP08 Stavros Moustaizis: Negative Ions: Production and applications to magnetic fusion (ITER and DEMO)

(Abstract not available at time of print)

RP09 Theodore Panis[1], P. Blanchard[1,2], C. Bower[3], H Carfantan[4], A. Fasoli[1], A. Goodyear[3], N. Mellet[1,5], S.E. Sharapov[3], D. Testa[1] & JET-EFDA contributors: Recent damping rate measurements of antenna-driven toroidal Alfvén eigenmodes of intermediate n on JET and comparison with plasma models

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In tokamak burning plasma experiments such as ITER, it is expected that Alfven eigenmode (AE) instabilities of, typically, intermediate and high toroidal mode number n will be triggered by populations of energetic ions, such as _-particles [1, 2]. The stability of this speci_c class of AEs is studied experimentally in the Joint European Torus by observing the plasma response to antenna-driven frequency-sweeping perturbations at the plasma edge. During the 2008/9 experimental campaigns, the complete set of the new antennas was operated and intermediate-n AEs were excited
under various plasma conditions. A big collection of damping rate measurements of moderate-n toroidal AEs (TAEs) has been obtained following the technical optimization of the diagnostic[3]. We focus here on measurements of n = 3 TAEs, as well as n = □□5, -1 TAEs. These measurements are compared to different plasma models, as implemented in the codes LEMan[4] and CASTOR[5], allowing the identification of the damping mechanisms that come into play.

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RP10 S. Pantazis, C. Lalescu*, D. Carati*, D. Valougeorgis, A. Grecos: Simulation of trajectories for a particle in a helicoidal magnetic field, subject to a random electric field

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Numerical simulations of trajectories were carried out for charged particles placed inside a magnetic field with helicoidal lines. This field is derived by the superposition of a homogeneous component and a poloidal component caused by a current flowing in an infinite wire. Furthermore, the influence of a spatially random electric field, generated by a Fourier series with random phases when the field correlation is known, has been considered. Results on particle trajectories as well as on the mean square discplacement transverse to the magnetic field are presented.

RP11 I. Sarris, A. Iatrides, C. Dritselis, N. Vlachos: Magnetic field effect on the cooling of low-Pr fluids in a vertical cylinder

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Results of direct numerical simulations are presented for the transient and turbulent natural convection cooling of an initially isothermal quiescent liquid metal placed in a vertical cylinder in the presence of a vertical magnetic field. The electrically conductive low-Prandtl number fluid is put to motion when the cylindrical wall is suddenly cooled to a uniform lower temperature. For this particular cooling process, the flow is characterized by three sequential almost discrete stages: (a) development of momentum and thermal boundary layers along the cylindrical cold wall, (b) intrusion of the cooled fluid into the main fluid body, and (c) flow and thermal stratification. The selected Rayleigh numbers in the present study are high enough so that turbulent convection is established. The numerical results show that the magnetic field has no observable effect at the initial stage of the vertical boundary layer development and conduction heat transfer is favored during the intrusion stage. An interesting effect of the magnetic field during the stratification stage is the deceleration of the cooling process for low Rayleigh numbers and its acceleration for high ones. This dependence of the magnetic field effect on the Rayleigh number was found to be related to the cold vortices emanating from the vertical boundary layer. In contrast with the hydrodynamic cooling, the magnetic field was also found to accelerate the cooling near the bottom of the cylinder.

RP12 G. Throumoulopoulos, H. Tasso*, G. Poulipoulis: Equilibrium nonlinearity and combined stabilizing effects of magnetic field and plasma flow

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The nonlinear “cat-eyes" and counter-rotating-vortices hydrodynamic solutions are extended to the magnetohydrodynamic equilibrium equation with incompressible flow of arbitrary direction [1,2]. The extended solutions cover a variety of equilibria because four surface quantities remain free. Unlike to linear equilibria, the flow has a strong impact on isobaric surfaces by forming pressure islands located within the equilibrium vortices even for values of ¯ (de¯ned as the ratio of the thermal pressure over the external magnetic-¯eld pressure) on the order of 0.01. Also, the axial (\toroidal") current density is appreciably modified by the °ow. Furthermore, a magnetic-field-aligned flow of ITER relevance, i.e for Alfven Mach numbers of the order of 0.01, and the °ow shear in combination with the variation of the magnetic field perpendicular to the magnetic surfaces have significant stabilizing effects potentially related to the equilibrium nonlinearity. The stable region is enhanced by an external axial magnetic field.

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RP13 A. Vogiannou, M. Negrea[1], I. Petrisor[1], G. Fuhr[2], B. Weyssow[3], H. Isliker, L. Vlahos: Ion transport coefficients in turbulent tokamak plasma
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The magnetic field of a tokamak is known to be in a turbulent state, with stochastic magnetic and electric fields. These perturbations can influence transport properties of the impurities that reside inside the tokamak. We examine two different types of turbulence models, (i) stochastic magnetic fields, constructed with prescribed statistical properties, and (ii) electric and magnetic fields from MHD simulations in the edge region. The perturbations are superposed onto realistic unperturbed background fields, either in slab or in toroidal geometry, respectively, to form an environment for test-particle simulations. From a large number of simulated orbits, the running diffusion coefficients are determined for different impurity species and for varying degree of anisotropy in the field perturbations. The two different models for turbulence and geometry (slab and toroidal) give substantially different results for the transport coefficients, those obtained in toroidal geometry being in quantitative agreement with observed ones. The obtained results are also compared to the ones from the semi-analytical Decorrelation Trajectory (DCT) method, and reasonable qualitative agreement was found.

RP14 Kyriakos Hizanidis, Panagiotis Zestanakis, Abhay Ram[+], Yannis Kominis: Nonlinear heating of ions by electron cyclotron frequency waves
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In a variety of naturally occurring plasmas the observed wave frequency spectrum is usually broadband. The waves are usually coherent with a reasonably well defined frequency and wave vector spectrum. The motion of charged plasma particles with these coherent waves can exhibit interesting nonlinear behavior. In previous studies it has been shown that high frequency electrostatic lower hybrid waves can interact with ions and nonlinearly energize them [1]. Since the lower hybrid frequency is much higher than the ion cyclotron frequency there would be no such interaction for a single coherent plane wave. It has been demonstrated that the nonlinear interaction could explain the transverse acceleration of ions observed in the lower magnetosphere by various rocket observations [2]. We are presently studying the nonlinear interaction of ions with coherent electromagnetic electron cyclotron waves. The electron cyclotron waves can be either the extraordinary X mode or the ordinary O mode. We assume that the waves are propagating as a beam and consider the interaction with ions in the spatial region where the beams overlap. The wave frequency of each beam is modulated with the modulation frequency near the ion cyclotron frequency. The kinematics of the ions in the overlap region is studied by applying canonical perturbation theory to the Hamiltonian describing the ion motion in the presence of coherent electromagnetic waves. A description of the theoretical approach and the results from our analytical analysis will be presented. The aim of this study is to determine parameters pertaining to the two waves that ensure energization of the ions in the interaction region.

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9TH SCHOOL OF FUSION PHYSICS & TECHNOLOGY

University of Thessaly, Volos-Greece, 19-23 April 2010

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