Annual Report
2003
Alfvén Laboratory

Alfvén Laboratory
Royal Institute of Technology
SE 100 44 Stockholm
# ANNUAL REPORT 2003
Alfvén Laboratory
Royal Institute of Technology

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1 Highlights

- Four doctoral theses were successfully defended in 2003:
  - Marco Cecconello: Experimental studies of confinement in the EXTRAP T2 and T2R reversed field pinches, on January 31
  - Jenny-Ann Malmberg: Experimental studies of tearing mode and resistive wall mode dynamics in the reversed field pinch configuration, on June 6
  - Anita Kullen: Polar auroral Arcs, on June 11
  - Björn Thors: Radiation and Scattering from Conformal Array Antennas, on October 28

- In the fusion division, a demonstration of active feedback stabilisation of resistive wall modes (RWM) has been carried out on the EXTRAP T2R reversed-field pinch. A four (poloidal) by sixteen (toroidal) array of saddle coils, covering 50% of the torus surface, provides the control field. Two types of controllers have been tested, a so-called intelligent shell and a digital controller based on real time mode analysis. Stabilisation of RWMs is required for long-pulse operation in RFPs and can be a method to approach the ideal-wall beta limit in advanced tokamaks. The experiments demonstrating the potential for control of resistive wall modes is an important step in verifying theoretical modes for RWM active feedback stabilisation.

- Scientific staff from the fusion division have been active in campaigns at the JET experiment, which is the large European tokamak located in Abingdon, England. Eight persons from the Alfvén Lab have been on secondment to JET for periods ranging from four to eight weeks. The main areas are RF heating and diagnostics. On a per capita basis Sweden is one of the largest participants in JET via secondment. Jerzy Brzozowski from the Fusion Division is a session leader, which also makes it easier for other persons from the lab to establish contacts at JET and become involved in campaigns.

- The Electromagnetic Theory group participates actively in The Joint Research Centre for Photonics, created by KTH and the Zhejiang University, Hangzhou, P.R.China, where Sailing He is a professor and Director of the Centre for Optical and Electromagnetic Research. The Joint Research Centre for Photonics will serve as a new model for collaboration between Zhejiang Univ. and KTH, and is expected to be followed by other similar Joint Research Centres.

- The Cluster project continues to provide excellent multi-point data of the interaction between the solar wind and the Earth’s magnetosphere. The space group, at the Alfvén Laboratory, manages the Scandinavian Data Centre and takes part in the EFW instrument operations. The Cluster results on the life cycle of the black aurora (Nature & ESAs Cluster page, Dec 2001), was followed by three invited articles by Marklund on the black aurora, published in Investigacion y Ciencia, July 2003, Forskning & Framsteg, January 2004, and in Svenska Dagbladet, November 2003. Two scientific papers were submitted to a special Cluster issue of Annales Geophysicae. The Cluster results were also presented in four invited lectures in 2003.

- The space group participates with hardware on ESAs cometary mission Rosetta and on the SMART-1 mission to the Moon. After its successful launch on 27 September 2003, Europe’s first lunar spacecraft SMART-1 is now on its long journey to the moon, arriving at the end of 2004. The Rosetta launch campaign was resumed on 24 October 2003, with a launch scheduled for 26 February 2004, the primary target being comet 67P/ Churyumov-Gerasimenko.
The space group also participates on an MMS (Magnetospheric Multi-Scale, NASA’s Cluster-like mission) instrument proposal selected for phase-A study. The direct impact of the President’s FY 2005 NASA Budget on MMS is that the launch will be delayed at least until 2012, but the Phase-A study should continue as planned with a probable selection of the science team in late 2004.

Participation on a Japanese-European electric field and wave instrument is being proposed for the Mercury magnetospheric orbiter, MMO, one of the two spacecrafts of the BepiColombo mission to Mercury. The European part consists of a low-frequency electric field instrument using the SCALE wire boom pair developed at the Alfvén Laboratory. A request for proposals will be issued early 2004.

Laboratory experiments have led to a clearer understanding of plasma penetration across magnetic fields. The interplay between macroscopic features and microscopic instabilities in the process has been revealed combining in-house developed plasma simulations and high frequency probe measurements. The probe techniques are also used for laboratory studies of the VASIMR plasma rocket prototype in collaboration with NASA/Houston, USA.

The 2003 Alfvén Lecture was given by Professor Anders Brahme, Karoliska Institutet, on May 22. Från panspermie teori till jonerapi – stråleffekter från kosmos till mikrokosmos.

Astronaut and Professor Franklin Chang-Díaz, director of the advanced space propulsion laboratory at Lyndon B. Johnson Space Center, Houston, Texas, visited KTH in September 2003 to discuss the project and to present the present status in an open lecture which was very well received.

Henrik Holter received the 2003 R.V.P. King Award for the best paper in the 2002 IEEE Transactions on Antennas and Propagation by a person under 36 years of age. The paper by H. Holter and H. Steyskal: On the size requirement for finite phased array models, IEEE trans. Vol AP 50, No 7, July, 2002, was included in Henrik Holter’s PhD thesis. This is the second consecutive year that TET has won this award.

Michael Tendler has been elected member of the Russian Academy of Sciences.
2 The Alfvén Laboratory

The Alfvén Laboratory was established in 1990, following a statutory instruction from the Swedish Government, to provide a national base for Swedish international programmes in space and fusion plasma physics research and accelerator technology.

Today the laboratory is a centre for electrotechnology. There are four divisions;

- Plasma Physics
- Fusion Plasma Physics
- Applied Electrophysics
- Electromagnetic Theory

The foundation for physical electrotechnology is electromagnetic theory. The Division for Electromagnetic Theory therefore has an important role at the Alfvén Laboratory. Research and teaching in electromagnetic theory focus on the basic macroscopic electromagnetic laws as applied to the generation and propagation of electromagnetic fields in various media and how these fields interact with and affect the medium itself or components and devices in the medium. Electromagnetic theory is a basic discipline within the School of Computer Science, Electrical Engineering and Engineering Physics (DEF). The division is responsible for introductory courses in electric circuit theory and electromagnetic theory that are mandatory for students in the electrical engineering programme as well as for introductory courses in the physics and computer science programmes.

Physical electrotechnology in general and plasma technology in particular are incorporated in a wide range of applications used in industry, but at present the research within universities in this area in Sweden is limited. The Division for Industrial Applications was formed to increase research for industrial plasma physics applications drawing upon the expertise, experience and laboratory resources that presently exist at the laboratory.

The activity of the two long-established divisions remains focused on international research programmes. The Plasma Physics Division includes basic laboratory experiments and satellite-borne space experiments. In space physics the laboratory is a centre in the national programme and a home base for international collaborations within the European ESA and USA NASA space programmes. The Alfvén Laboratory also hosts the Scandinavian Data Centre for Cluster science data analysis. The Fusion Plasma Physics Division is integrated in the European Fusion Program and is the home base for the EURATOM priority experiment EXTRAP T2R. The division is also a base for collaborations with the JET experiment in England. Also, there is participation in the planning for the next step experiment in fusion research, the International Thermonuclear Experimental Reactor (ITER).

The Role of the Alfvén Laboratory

The Alfvén Laboratory has an important role at KTH and is in many ways geared to address the goals included in the Development Plan for KTH, for example;

- A university must be involved in international efforts to solve global technology problems and contribute to a sustainable environment and economic welfare.
- Education and research must be coupled.
A clear connection between basic research and applied disciplines must be sustained.

Specialisation and international collaboration are necessary to carry out front-line research. For the programmes of the Alfvén Laboratory, specialisation is coupled to the fact that the experimental facilities require large investments and support from an engineering and technical staff. The development of experiments and their exploitation are a joint effort of the scientific staff and graduate students working together with an experienced and professional engineering and technical staff.

The research is highly specialised, as it must be to maintain a high international standard. There is increased activity in both the graduate and undergraduate programmes. It is natural that the undergraduate courses offered by the laboratory utilise the laboratory's own research expertise. These courses introduce students to current international research areas.

The research programme has a balance between curiosity-driven research and applied research. This also serves to stimulate students. Space plasma physics research investigates Solar-Terrestrial Interaction phenomena that have always fascinated man. However now, in the electronics and satellite communication era, electrical disturbances in the ionosphere are more than just a dramatic northern lights show. Fusion research aims at one of the most pressing problems of our time, the development of a safe and clean energy source. This research focuses on a specific application, and in many ways is conducted as an R&D programme. Yet basic research is still necessary in order to achieve controlled fusion and new ideas developed in a variety of experiments, such as EXTRAP T2, contribute to this highly coordinated international effort. Furthermore, the time scale for reaching the goal is decades so the research must be supported by the public sector. However there are also many areas where the expertise within the laboratory can be applied to critical problems for industry today.

The Board of the Alfvén Laboratory

The Alfvén Laboratory has an external board of directors. This organisation was selected to support the special needs of the research requirements of the laboratory. The programmes require a stable base for projects that have a long-term time perspective, involve large investments in equipment and require a professional engineering and technical staff. When the laboratory was established, funding for academic, research and technical staff was transferred from NFR (now VR) and the Swedish National Space Board (RS) to KTH to establish a base level of support necessary for the specialised activity of the laboratory. Representatives from VR and RS are on the board.

Board members during 2003

Kerstin Fredga Chair Gunnar Larson Electromag. Theory
Nils Brenning Plasma Physics Mats Larsson VR, Vicechair
Bo Cederwall SACO Bengt Lindberg KTH
James Drake Director Lennart Nordh RS
Thomas Elevant Indus. Applications Birgitta Forsberg Chief Administrator
Anders Eriksson KTH Jan Scheffel Director of studies
Håkan Ferm ATF Martin Laxåback Graduate representative
Thomas Hurtig Graduate representative Ingeborg Mau Secretary

VR=Swedish Research Council, RS=Swedish National Space Board, ATF=Union of Administrative Workers, SACO=Swedish Confederation of Professional Associations
2.1 Plasma Physics

The Division of Plasma Physics is devoted to front line research in fundamental plasma physics and to education at both the graduate and the undergraduate levels. The main theme of the research is the electrodynamic properties of matter in the plasma state. The research program is characterized by intense international collaboration. It is also characterized by a unique combination of laboratory experiments, space experiments and theoretical research, including numerical simulation of plasma. The Division consists of two research groups, the Space Group and the Laboratory Plasma Group.

The undergraduate teaching load on both research groups has increased significantly during the last years with various courses such as Electromagnetic Theory, Electrical Circuits, and Electrical Circuit Analysis, requiring a large teaching staff. Successful projects have been contributed to the "Electro project" (5 credit units), an undergraduate course for the first year students of Section E at KTH.

Plasma Physics – Space Group

The projects carried out by the Space Group of the Division of Plasma Physics have as a basic purpose the investigation the electrodynamical properties of various space plasma phenomena by means of in situ experiments on satellites and sounding rockets. These experiments mainly focus on the measurement of electric fields, and in some cases also electron density and temperature, in various space plasma regions, with a view to clarify their role in space plasma electrodynamics. During the last decade the group has also been involved in the development of fluxgate magnetometer electronics used on sounding rockets and a number of small satellite missions.

An essential role in the acceleration processes, that cause auroras, magnetic storms and associated plasma phenomena, is played by the electric field. These acceleration processes are relevant to many important problems in space and astrophysical plasmas. They may also have important technological applications. Marklund and colleagues gave the first conclusive evidence, based on Freja observations, of the existence of positive potential structures in the auroral return current region. Cluster measurements have also revealed the temporal evolution of such structures.

The double probe method is used for the electric field measurements. This method was developed at the Division of Plasma Physics in collaboration with scientists at the University of California, Berkeley, and the European Space Research and Technology Center (ESTEC) in Holland. In different versions it has been used on numerous rockets and on satellite missions, such as Viking, Freja, Astrid-2, and Cluster.

The space group has a heavy involvement in the Cluster project with instrument operations, running of the Scandinavian Data Centre, scientific analysis, active participation in Cluster workshops and Cluster sessions at international conferences.

The German CHAMP and the US-Argentinian SAC-C satellites, launched in 2000, both carried a magnetic field instrument with DPUs designed and constructed at AL. The instruments continue to perform excellently and provide accurate magnetic field measurements which have been used together with Ørsted data to model the magnetic field of Earth with an unprecedented accuracy.
The space group has contributed with hardware on the SPEDE instrument on the SMART-1 spacecraft, successfully launched on 27 September 2003 to the Moon and on the Langmuir probe instrument on the Rosetta spacecraft with a launch scheduled for 26 February 2004. The primary target is now comet 67P/Churyumov-Gerasimenko.

The space group participates on a Japanese-European electric field and wave instrument to be proposed for the Mercury magnetospheric orbiter, MMO. The instrument includes one probe pair for dc and low-frequency measurements, to be provided by a European team, and another probe pair for wave electric field measurements, to be provided by the Japanese team. The European part consists of a low-frequency electric field instrument using the SCALE wire boom system developed at the Alfvén Laboratory. A request for proposals will be issued early 2004.

The space group participates on an MMS (Magnetospheric Multi-Scale) instrument proposal selected for phase-A study. A Concept Study Report, to be completed by the two selected teams, is due by 24 April 2004. The direct impact of the President’s FY 2005 NASA Budget on MMS is that the launch will be delayed at least until 2012, but the Phase-A study should continue as planned with a probable selection of the science team in late 2004.

The scientific activity during 2003 was dominated by scientific analysis of Cluster data. The Cluster results on the life cycle of the black aurora (Nature & ESAs Cluster page, Dec 2001), was followed by three invited articles by Marklund on the black aurora, published in Investigacion y Ciencia, July 2003, Forskning & Framsteg, January 2004, and in Svenska Dagbladet, November 2003. Two scientific papers were submitted to a special Cluster issue of Annales Geophysicae. The Cluster results were also presented in four invited lectures in 2003. One doctoral thesis entitled “Polar Auroral Arcs” by Anita Kullen was successfully defended on June 11, 2003.

Five papers were published in refereed scientific journals during 2003, in addition to 4 popular articles, 4 master theses, one doctoral thesis, 5 non-refereed papers, and 22 forthcoming publications. Five invited and 5 contributed talks and 14 posters were given at international conferences/workshops in addition to 6 seminars at foreign research institutes.

The scientific highlights of the space group in 2003 are summarized in Section 1 above, and described more fully in Appendix A2.

**Plasma Physics - Laboratory plasma group**

The main research theme of the **Laboratory Plasma Group** is plasma research using small-scale laboratory experiments, where low-density plasmas are generated by electric discharges. Several plasma devices are available. The research programme presently focuses on three areas:

- Phenomena associated with high currents in low-density plasmas. Central issues are the ability of a plasma to maintain anomalous potential differences along the magnetic field at high currents, and the coupling between internal high frequency oscillations and the observed external electromagnetic radiation.

- Collisionless heating and anomalous diffusion of electrons. In the experiments a plasma gun is used to study the injection of a plasmoid across a magnetic field exploiting up to
date measurement methods with high time-resolution. Anomalous diffusion is required for the electrons to reach all parts of the beam. A fully three dimensional particle-in-cell (PIC) plasma simulation reproduces many of the experimentally observed features.

- Complex or dusty plasmas. Experiments on the influence of dust grains on a spherical plasma region, “plasma ball”, sustained by ionisation near an anode have lead to interesting results e.g. the modification of the spontaneous oscillations of the “plasma ball”. New theoretical results for the response of a dusty plasma with dynamical grain charging to a moving test charge have been found.

Four papers appeared in refereed publications during 2003. In addition, two papers have been accepted for publication during 2004. Also 3 contributions were made by members of the laboratory group at international scientific conferences. The publications and talks are listed in Appendix A2.

The lab group’s know-how in high frequency probe measurements has led to participation in the NASA development project of a new type of plasma engine, the Variable Specific Impulse Magnetoplasmada Rocket (VASIMR).

Numerical methods, in particular PIC simulations, are used to model the experiments. The development of diagnostic methods is also an integral part of the investigations. Theory provides a link between the simulations and experiments and is essential for planning new investigations.

### 2.2 Fusion Plasma Physics

The European fusion research programme is a co-ordinated effort with contributions from "Fusion Research Units" within each member country. The Fusion Plasma Physics Division at the Alfvén Laboratory is a part of the European Fusion Programme. There is a Contract of Association between VR (Vetenskapsrådet) and EURATOM, which establishes a Swedish Association or Research Unit as it is called. Fusion research is included as a key action in the European research and technology development framework programmes. The recent achievements in fusion research have been very positive and the next step is to build a large facility; the International Thermonuclear Experimental Reactor (ITER). ITER is a prototype for a reactor and is designed to produce 600 MW of fusion power. It is a long-term project. Construction is envisioned to start in 2005 and operation would then start about 8 years later. Funding for the initial stage of this project has been included in the European 6:th framework programme. Another important facility in the European research programme is the JET experiment. JET is a joint European undertaking located in the UK.

At the Alfvén Laboratory, the EXTRAP T2R experiment is the major fusion experiment in Sweden. T2R is one of 16 specialised fusion devices in the European fusion research programme. In addition to the EXTRAP experiment, there are experimental projects aimed at studies of plasma wall interaction. One of the foremost problems facing the fusion programme is the development of the plasma-facing wall. This first wall will be exposed to a high heat flux load as well as a high neutron flux load. There are also theory projects, which address important basic problems in fusion research. One major area of activity is focused on computer modelling of methods to heat plasma using radio frequency (RF) power. RF power is also used to control the plasma and to drive current in the plasma.
Much of the fusion research work at the Alfvén laboratory is done in collaboration with the JET experiment. This experiment is the largest fusion experiment in the world and all of the EU fusion laboratories collaborate in its operation.

**EXTRAP T2R experiment**

The T2R experiment received approval as a priority project in 1990. The experiment was operated with only minor shutdowns through 1999 at which time the experiment was rebuilt and operation resumed in 2001. The goal of the modifications to T2R was to establish an experiment that can be used for the study of long-pulse operation with a resistive wall. The “wall” surrounding the plasma is the electro-magnetic boundary and therefore has a profound effect on the MHD stability of the configuration. The boundary is a “resistive wall” if the magnetic penetration time is shorter than the pulse length so that the stabilising effect of an ideal wall is lost. The operation of the T2R device has shown that the modifications have been successful and since restart of operation many important results have been obtained.

The reversed-field pinch (RFP) configuration, like the Tokamak, is a toroidal configuration characterised by nested flux surfaces defined by a magnetic field with both toroidal \( (B_\phi) \) and poloidal \( (B_\theta) \) components. However the RFP configuration is dependent on a close-fitting conducting wall for MHD stability. For a tokamak the stabilising effects of a conducting wall are not vital, but they can improve stability for pressure driven modes and thereby enhance confinement performance. Resistive wall modes are defined as unstable free-boundary MHD modes that can be stabilised by an ideal conducting wall, but are however unstable when the wall is resistive. The growth rate of a RWM is determined by the rate of diffusion of the magnetic field through the wall. This growth rate is normally much slower than the no-wall growth rate so active feedback can be envisioned as a means of stabilising the RWM.

The EXTRAP T2R device has been used for experimental studies of the stability of resistive wall modes under different equilibrium conditions and measured growth rates have been compared with linear stability theory. The focus has now turned to studies of methods to control the modes and active feedback control of RWMs has been demonstrated. Many relevant features of the physics of the RWM instability and the physics of the active control of the RWM growth are the same for both the RFP and tokamak configurations. The equations for linear stability for both the cylindrical tokamak and the RFP have the same general form when written in terms of the perturbed magnetic flux. Furthermore, for both configurations, the actuators for control of the RWMs are saddle coil arrays that produce control field harmonics with the spatial and time dependence necessary to balance the resistive diffusion in the resistive wall associated with RWM growth.

Two types of controllers have been tested; 1) analogue controllers for so-called intelligent shell control and 2) a digital controller, which is a prototype of the controller under development for the RFX device at Padova in the Italian Association. The RFX real-time digital controller performs a fast Fourier transform on the sensor coil array data and utilises a feedback law to determine the desired control field harmonics. In turn an inverse FFT is used to determine the corresponding distribution of control signals to steer the individual currents to the saddle coils in the array.

An example of feedback control of RWMs is shown in Fig. 1 for the intelligent shell
method of operation. Shown for a single mode, \((m,n) = (1,-6)\) are the current pulse, the mode amplitude and the mode phase angle. A number of shots with and without mode control are superimposed.

![Fig. 1 An example of mode control of the \((m,n) = (1, -6)\) RWM by intelligent shell active feedback. The upper panel is the discharge current, the middle panel is the logarithm of the mode amplitude and the lower panel is the mode phase. The growth of the mode is suppressed by the active feedback.](image)

A three-way collaboration has been established including the Consorzio RFX group, working with the T2R group to develop the feedback system, and theoretical support provided by the Chalmers theory group in the Swedish Association. This theory work is also done in collaboration with the Consorzio RFX group.

In addition to the RWM studies, other primary research areas are detailed studies of tearing mode dynamics, experimental studies of the statistical properties of electrostatic and magnetic turbulence in the plasma edge region based on measurements using electric and magnetic probes and studies of methods to improve confinement.

Turbulence in fusion plasmas refers to the presence of fluctuations in the fluid parameters in time and space that have characteristic statistical averages. An implication of turbulence is that the associated local convective transport is large compared to classical cross-field transport in laminar plasma. The edge region of the RFP is of particular interest because, as is the case in a tokamak, the transport is dominated by electrostatic turbulence. Turbulence and anomalous transport have been studied in the EXTRAP T2R device in a collaborative study with Consorzio RFX, in Padova, Italy. Detailed statistical studies of the electrostatic turbulence in the edge region of the RFX experiment in Padova and the T2R experiment show that the probability distribution function of the events (bursts of fluctuations in potential) do not show self-similarity as expected for the self-organised criticality model but are better characterised by intermittency. A large part of the particle loss (and therefore energy loss) occurs during the intermittent events although the time duration of an event is short compared to the intervening laminar period.
Energy confinement in the advanced RFP

In earlier numerical studies of confinement in the optimized, conventional reversed-field pinch (RFP), the scaling of energy confinement time with plasma current and density was found to be too weak to lead into fusion relevant regimes. In the advanced RFP, however, the detrimental magnetic (dynamo) fluctuations are largely eliminated by the presence of an externally applied electric field. This field is adjusted to generate a tearing mode stable parallel current density profile.

Previous studies used a gaussian shaped electric field with given width and amplitude that was localised at some minor radius of the plasma. A threefold increase in energy confinement was found, but the three associated parameters made further optimisation difficult. In the present work a new, parameter free scheme for current profile control is introduced. An automatic control system continuously replaces the dynamo electric field. Early results indicate strong energy confinement enhancement.

Analytic solution of initial-value problems

An algorithm has been developed that may indicate a path towards ”analytical simulation” in plasma physics. In contrast to purely numerical schemes for solving time-dependent PDEs, the present algorithm employs analytical expansions of variables and parameters. Thus the task of performing scaling studies and investigations of phenomena being sensitive to parameter variations is greatly simplified.

The scheme has applications in e.g. fluid dynamics and magnetohydrodynamics (MHD). An important goal is to solve the resistive MHD confinement and transport equations that govern confinement scaling in the advanced (current profile controlled) RFP.

Plasma – Wall Interactions

Plasma – wall interactions (PWI) comprise all process involved in the exchange of energy and mass between the plasma and the material wall. High particle fluxes cause serious modification of wall materials by various erosion processes: physical sputtering, chemical erosion, melting, evaporation, arcing, etc. As a consequence, species removed from the wall enter the plasma edge where they are ionised. This, in turn, results in the plasma contamination by impurities. Eroded species are transported in the torus and, unless pumped-out, become re-deposited in another location that the place of origin. Re-deposition of impurities is accompanied by co-deposition of fuel atoms. This process causes the accumulation of fuel in wall components and may lead to unacceptably high in-vessel fuel inventory exceeding the safety limits. In summary, the assessment of material lifetime and fuel inventory are the driving forces in PWI studies because they are decisive for economy and safety of a reactor-class device. These issues are on top of the priority list defined by EFDA. Projects of the PWI Group at the Royal Institute of Technology deal with several aspects related to wall erosion, material transport and fuel inventory.

The main topics are:

- Erosion, re-deposition,
- Long term retention of hydrogen isotopes on plasma facing components,
- Laser-assisted fuel removal,
- Assessment of fuel accumulation in castellated structures,
- Dust production mechanism,
- Tracer techniques in studies of material transport and preferential flows in the SOL,
- Modification and damage to plasma facing components,
- Development of diagnostics for studies of material erosion and fuel accumulation,

The work is fully integrated with the EU Fusion Programme and, in particular, with the European Task Force on Plasma – Wall Interactions and the EFDA-JET Work Programme: Task Forces “E”, “FT”, “D” and JET Enhancement Projects. Experiments are carried out at TEXTOR in the Forschungzentrum Jülich and at JET. Close co-operation exists with the PWI groups from IPP Garching, ToreSupra, VTT in Finland and Warsaw University of Technology, Poland.

**RF-heating**

Waves in the ion cyclotron frequency range can be used for heating plasmas to reach ignition. In addition they can be used for driving currents, create plasma rotation, enhance fusion yield and affect the stability of global MHD-modes. The waves can be absorbed by different processes and by different plasma species. Parasitic absorption by rectified RF-sheath potentials can appear near walls and antennas. The latter leads to increased impurity content in the plasma and can for particular scenarios lead to substantial loss of power. High power ion cyclotron damping produce highly anisotropic, non-Maxwellian plasmas with high energy tails on the distribution functions of the resonant species that strongly affect the wave absorption and power partition. In order to analyse experiments and make predictions of this versatile heating method detailed self-consistent calculations of the wave absorption and the distribution function of the heated species are required. The group at KTH has developed a unique tool for making such self-consistent calculations, the SELFO code, which include the effects of finite orbit width of high-energy ions and RF-induced spatial transport of the resonant ions. The inclusion of the effects of finite orbit width of high-energy ions and RF-induced spatial transport were found to be crucial for modelling ICRH with antennas launching waves propagating preferentially parallel or anti-parallel to the plasma current. Analysis with the SELFO and FIDO code have lead to prediction and explanation of a number of new phenomena observed during ICRH.

The group is active in exploring the physics of ICRH in JET, the European tokamak experiment in Great Britain, by proposing, analysing and running experiments.

The control of the electric current profile in magnetically confined plasmas is of importance for stability and confinement, in particular for plasmas with internal transport barrier. A scenario for fast wave current drive based on direct electron absorption has been proposed and studied experimentally in plasmas with internal transport barrier at JET. A large fraction of the wave power was found to be parasitically absorbed by $^{3}$He impurity ions and at rectified RF-sheath potentials formed at the antennas. The modelling showed that the observed driven currents were in agreement with the measured power absorbed by direct electron heating. It was found that it was difficult to affect the plasma current in the transport barrier due to the highly inductive nature of the plasma and the interplay with the bootstrap current.

Experiments on RF-induced plasma rotation, minority current drive and inverted minority scenarios were analysed. Direct evidence of affecting the plasma rotation by absorption of the wave of high-energy ions were found and agreed with SELFO code modelling. Minority current drive was used to prevent excitation of neo-classical tearing modes by destabilising sawtooth instabilities.
The discovery of a large fraction of power absorbed near the antennas during the fast wave current drive experiments triggered an investigation of parasitic absorption for scenarios with weak damping. A model for analysing parasitic absorption by rectified RF-sheath potentials in the presence of eigenmodes was developed. The model was able to explain the difference of the heating efficiency of the JET A1 and A2 antennas in monopole phasing and the parasitic losses in the fast wave current drive experiments with weak single pass damping.

Appearance of global Alfvén wave eigenmodes may degrade the alpha-particle heating of thermonuclear plasmas and has therefore been subjected to intensive studies. In absence of thermonuclear alpha particles fast ions produced by ICRH are used to study the excitation of Alfvén eigenmodes in experiments. By upgrading the SELFO code to include excitation of global Alfvén eigenmodes during ICRH in a self-consistent way differences in the excitation mechanism by cyclotron heated ions and thermonuclear alpha particles are seen. The fast damping of these waves when the ICRH is switched off and the characteristic variation of the amplitude of the global Alfvén eigenmodes have been explained.

Global Alfvén eigenmodes appear also in RFPs. High frequency peaks and the spectra of magnetic field signals have been detected at the edge of Extrap T2R. The fluctuation is polarized with the magnetic field near the toroidal direction and has high toroidal periodicity \( n \) and a frequency scaling proportional to the Alfvén velocity.

### 2.3 Applied Electrophysics

#### 2.3.1 Accelerator Technology

The research focuses on small and medium sized accelerators, which have important applications outside pure physics. Typical areas are medical therapy and technical applications such as research in materials physics, chemistry and biology. Research aimed at technical development of accelerators is scantily covered by other Swedish accelerator laboratories.

A number of different accelerators have been designed, built, tested and further exploited. Several of the accelerator components and sub-systems that have been developed are now incorporated in industry and other research laboratories around the world.

The activities take place in and around the underground accelerator hall (Wallenberg Foundation, 1972), where three of the accelerators are in operation:

- 7-MeV circular microtron.
- 50-MeV racetrack microtron.
- 5-MeV linear accelerator.

The accelerators are used in connection with basic research, development research and in the undergraduate education. The major use is for irradiation service to other research groups, academic as well as industrial. A 2.5 MeV electron linear accelerator will replace the 7 MeV microtron in e-beam treatment.

The most actual areas of study are an accelerator-based low-energy positron source and
nanosecond-pulse acceleration in microtrons.

### 2.3.2 Industrial Applications of Electrophysics

Plasmas are incorporated in a wide range of applications used in industry, but at present the research within universities in this area in Sweden is limited. The aim is to increase research for industrial plasma physics applications drawing upon the expertise, experience and laboratory resources that exist at the Alfvén Laboratory. Our two stages strategy is as follows:

- On a project basis, staff from the Laboratory can work with research institutes and industrial partners in areas where the resources of the Alfvén Laboratory can be used to solve specific problems to advance the project. A number of companies, both large and small, have sought advice to solve problems with their plasma processes. For them it is of vital importance to have experts in Sweden. Consultation with plasma physicists can improve the basis for trying new ideas.

- The aim is also to establish research projects, possibly in collaboration with industrial partners, in areas that tackle potentially important applications of plasma physics but which require further research and development before being sufficiently well developed for specific exploitation. For such projects, during the development period, there is a need for at least partial support from public funding.

Previously received special grant from KTH resulted in a large number of minor projects which have evolved into three major projects. The major part of the budget has covered salary costs both for scientific- and technical/engineering staff. Research and development areas are summarized as follows (for progress reports, see Appendix C):

- Development of diagnostics for applications in rocket and RF-plasmas.
- Development of a negative ion source to be used in commercial accelerators.
- Coating techniques using both magnetron plasma and beam sputter sources.

### 2.4 Electromagnetic Theory

The research and teaching activities of the division of Electromagnetic Theory are centered around the basic macroscopic electromagnetic laws as they apply to the generation and propagation of electromagnetic effects in vacuum, in material media, and in all the various devices that may be constructed to enhance, control, and utilize such effects. Thus the use and further development of all the methods - analytic, numerical, and also experimental - which are relevant for such an endeavour, are of prime interest to us.

Somewhat more specifically, the main thrust of our research effort is in the area of propagation and scattering of electromagnetic waves. Progress in this area is crucial to the development of the various tools which are used so frequently in what is broadly referred to as the information society. This trend in modern society makes us increasingly dependent upon electromagnetic waves as carriers of information.

One of our main areas of research is direct and inverse scattering problems, both in the time and the frequency domain. In a direct scattering or propagation problem one considers
the problem of determining the behaviour of an electromagnetic wave as it encounters an object or medium with known electromagnetic properties. In an inverse problem on the other hand one analyses the way in which an electromagnetic wave has changed after it has passed through an unknown medium, and from this information one tries to infer the electromagnetic properties of the medium.

The proper understanding of electromagnetic information gathering devices (such as sensors) typically requires that one is able to solve, to some degree, a problem of the inverse type. Furthermore, design problems have much in common with inverse problems. Our work in this area is focused on developing the wave-field decomposition approach. The theoretical work ranges from studies of basic mathematical properties to numerical implementation of models relevant for specific applications.

Electromagnetic waves are launched and received by antennas. In response to the needs created by the above-mentioned trends, antenna theory and design has become another main area of research. The focus is on the development of new analytic and numerical methods of importance for the design of advanced antenna configurations, such as broadband antenna arrays and antenna arrays conformal to some prescribed (curved) surface. A new area which is vigorously pursued is antenna applications exploiting the band structure of photonic crystals.

One important trend is that of using higher and higher frequencies, which makes it possible to use smaller and smaller devices. This in turn calls for full electromagnetic field computations for e.g. devices in optical communication systems. The Division is actively involved in these new developments. The Division is actively involved in these new developments, in particular through its participation in the Joint Research Centre for Photonics of KTH and Zhejiang University.

Furthermore, solitons are of obvious interest for such systems and the Division has recently become involved in basic research in that area.

3 Education and research training

Undergraduate education at the Alfvén Laboratory now includes more students than ever before. A main reason for this development is that the TET division, with its considerable participation in undergraduate education, now is part of the Alfvén Laboratory. This has also led to better exposure of and participation in our third and fourth year elective undergraduate courses.

The TET division offers courses which includes first year E programme (Elkretsanalys 5p), first year D programme (Elteknik 6p), second year E programme (Teoretisk elektroteknik 8p) and second year F programme (Teoretisk elektroteknik 6p), as well as a few smaller courses for 3rd and 4th year students. The number of students in the E, D- and F-programmes are well over hundred. As a result, the teaching and scientific staff from the other three divisions of the Alfvén Laboratory have strongly participated in class teaching. Course analysis shows that our staff’s long experience of electrotechnology and electromagnetic field theory has been very fruitful for the teaching and learning processes.

Course development, primarily through course analysis, is emphasized at the Alfvén
Laboratory. The aim of course analysis is primarily to help the teacher reflect on how the quality of each course can be improved from one year to the next. Regular discussions with the director of studies is part of this process. Course analysis is now carried out for all courses given at the Alfvén laboratory. A special form has been developed to support this work. An earlier version of this form was designed by us, and the extended version has now become standard for all course analysis at KTH.

A novelty for 2003 was the course 2A1500 Engineering Science (*Ingenjörsvetenskap*), which is given for the masters programme in Engineering and Education (*Civilingenjör & Lärare, CL*). This course has its core in mathematical modelling, in particular empirical modelling, but also includes history of engineering, basic engineering skills and gender questions for engineers. External experts are invited as guest teachers for some parts of the course. The course aims at providing basic engineering skills for further studies of natural science and engineering at KTH, and may become of interest for other KTH programmes when more matured.

Researchers at the Alfvén Laboratory have collaborated with students and teachers at upper secondary schools (see [www.alfvenlab.kth.se/edu/gymsam.html](http://www.alfvenlab.kth.se/edu/gymsam.html)) during 2003. About ten students from Östra Real and other schools have carried out their last year projects within the fields of electrotechnology and fusion science with co-supervision from our teachers. This is part of the Alfvén laboratory effort to strengthen connections with Stockholm schools in the fields of mathematics and physics with the aim of improving student interest in these subjects. The Alfvén laboratory is one of the leading KTH departments in this work.

### 3.1 Undergraduate education

The Alfvén Laboratory offered 19 undergraduate courses during 2003. An overview of the courses follows:

**Compulsory courses:**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A1700</td>
<td>Project Course in Electrical Engineering 5 p</td>
<td>Course in development of new technological systems. First year students are offered hands-on projects, primarily carried out at the lab. The students are also trained in project management and presentation techniques.</td>
</tr>
</tbody>
</table>
2A1800 Electrical Circuit
Analysis
5 p
Peter Fuks

2A1805 Electrical Circuit
5 p
Gunnar Larson

2A1810 Electromagnetic
Theory EA
4 p
Gunnar Larson

2A1820 Electromagnetic
Theory EB
4 p
Gunnar Larson

2A1840 Electromagnetic
Theory F
6 p
Martin Norgren
Part 1: Static fields

Part 2: Time-dependent fields

2A1850 Electromagnetic
Theory ME
6 p
Lectures: Part 1: Static fields Electrostatics: Coulomb's law. Electric lines of force. Evaluation of electric field and potential in vacuum and with conducting and dielectric
M. Norgren


Optional courses:

2A1001 Master Thesis in Physical Electrotechnology
20 p

This course (Examensarbete) is normally 20 p and is based on a research project which is usually connected to the research activity of the Laboratory. Further information on projects that can be undertaken by students can be found on the Alfvén Laboratory home page.

2A1131 Plasma Physics
4 p
P. Carlqvist

This is a basic course in plasma physics. Plasma physics deals with matter in the ionised state, and is a complicated combination of atomic, electromagnetic and fluid dynamic processes. The course provides an introduction to plasma physics and is the basis for space plasma physics, fusion plasma physics and industrial applications of plasma physics.

2A1133 Plasma Physics (extended)
6 p
P. Carlqvist, M. Raadu

The course treats various aspects of the motion of charged particles in electric and magnetic fields. Also it describes the variational analysis of equilibrium and stability, kinetic plasma theory, and electrostatic structures. Furthermore, it gives an account of the basic theory of plasmas of high, medium and low density. It also contains a description of fusion plasma physics, plasma in the laboratory, and plasma in space.

2A1140 Accelerator and Radiation Technology
4 p
S. Rosander

The course consists of two parts. About 2/3 of the lectures are devoted to a description of the most common types of particle accelerators and their function, the most important accelerator stability problems, and beam transport problems. Invited experts deliver lectures on the use of accelerators in various branches, such as physics, medicine with radiation physics, and chemistry with industrial applications.

2A1141 Accelerator and Radiation Technology
6 p
S. Rosander

Encarged course also containing basic sciences used in Accelerator Technology.
2A1145 Electromagnetic waves in Dispersive Media
The course introduces students to methods of treating electromagnetic waves, which form a basis for a wide spectrum of applications in physics and electromagnetism. The electromagnetic theory is described by Fourier transforms in space and time which is advantageous when treating propagation and emission of waves in dispersive, anisotropic media.
E. Tennfors

2A1151 Energy and Fusion Research
An introduction to fusion oriented plasma physics is given. The central areas of fusion research are emphasised. The progress of fusion research and its present state are discussed in the perspective of future power generation.
J. Scheffel, P. Brunsell

2A1160 Space Physics
The course gives a broad survey of space physics and plasma phenomena from the near-Earth space to the Universe as a whole. The course has, at times, attracted over 100 participants.
Thomas Karlsson

2H1250 Electromagnetic Field Theory
Martin Norgren

2H1255 Electromagnetic Wave Propagation
Staffan Ström

2A1830 Applied Antenna Theory
The course takes a “hands on” approach. Projects and labourations are the principal part. The student will design different types of antennas, build them and measure their properties. The lectures discuss different antenna types such as wire antennas, apertur antennas, broad band antennas, small antennas and array, antenna feeds, antenna synthesis, system aspects on “transmitting – to – receiver” problems, propagation, numerical methods and different aspects of antenna measure-ments.
Gunnar Larson
Master theses projects completed during 2003

Måns Danielsson, *Computational methods for wave propagation in space*. Advisor: Lars Blomberg

Daniel Eriksson, *Criticality and darwinian selection in simplistic games*. Advisor: Michael Tendler

Lars Eriksson, *Development of tool for simulating the effect of radial electric fields on ion-temperature-gradient modes in 3D configurations*. Advisor: Jan Scheffel

Tommy Eriksson, *Wave pulsations in the magnetosphere and their dependence on the solar wind*. Advisor: Lars Blomberg

Eva Frendh, *Design of user manual using network analyzer*. Advisor: Peter Fuks

Christian Hedman, *En positronmaskin*. Advisor: Staffan Rosander

Markus Johansson, *Direct conversion of fusion energy*. Advisor: Jan Scheffel

Petter Larsson, *Positrontransport*. Advisor: Staffan Rosander

Cecilia Nylander, *Passiv repeater för GSM och DECT*. Advisor: Peter Fuks

Magnus Svensson, *Analytic study of resistive instabilities*. Advisor: Jan Scheffel

Ahila Thillainathan, *Numerisk modellering av elektrodynamiken i norrskensovalen under substormförhållanden*. Advisor: Tomas Karlsson

Bengt Ållebrand, *Computer simulation of the extraction slit in an ion source*. Advisor: Nils Brenning

Elman Tabakovic, *Dose regulator*. Advisor: Staffan Rosander

Stefan Kahlson, *One nano second kilovolt pulse generator for electron gun control*. Advisor Staffan Rosander

Mikael Sandzelius, *Fusion potential for spherical and compact tokamaks*. Advisor: Jan Scheffel

3.2 Graduate education

When considering the nature of the research programme at the Alfvén Laboratory in some respects the laboratory has the character of a national research facility. Because of this character, the graduate students working on problems related to electromagnetic theory, the space plasma satellite experiments, the EXTRAP fusion plasma experiment or with the numerical simulation studies have an opportunity to participate in front–line international research. An important part of the research training provided by the division is the opportunity for students to work with professional research and engineering staff on forefront problems in an internationally competitive research environment.
## Graduate courses

<table>
<thead>
<tr>
<th>Code</th>
<th>Course description</th>
<th>Credits</th>
<th>Instructor(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A5021</td>
<td>Accelerator technology, b.c.</td>
<td>3-10 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2A5022</td>
<td>Accelerator technology, a.c.</td>
<td>3-10 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2A5031</td>
<td>General plasma physics (5-10 p) b.c.</td>
<td>5-10 p</td>
<td>N. Brenning</td>
</tr>
<tr>
<td>2A5032</td>
<td>General plasma physics, a.c.</td>
<td>5-10 p</td>
<td>N. Brenning</td>
</tr>
<tr>
<td>2A5035</td>
<td>Motion of charged particles, collision processes and basis of transport theory</td>
<td>3-5 p</td>
<td>T. Hellsten</td>
</tr>
<tr>
<td>2A5041</td>
<td>Magnetohydrodynamics, b.c.</td>
<td>2-4 p</td>
<td>J. Scheffel</td>
</tr>
<tr>
<td>2A5042</td>
<td>Magnetohydrodynamics, a.c.</td>
<td>1-5 p</td>
<td>J. Scheffel</td>
</tr>
<tr>
<td>2A5045</td>
<td>Kinetic theory, b.c.</td>
<td>2-4 p</td>
<td>M. Raadu</td>
</tr>
<tr>
<td>2A5051</td>
<td>Plasma waves</td>
<td>1-3 p</td>
<td>E. Tennfors</td>
</tr>
<tr>
<td>2A5055</td>
<td>Fusion research</td>
<td>1-4 p</td>
<td>J. Scheffel</td>
</tr>
<tr>
<td>2A5087</td>
<td>Research methodology and presentation techniques</td>
<td>2-3 p</td>
<td>J. Scheffel</td>
</tr>
<tr>
<td>2A5089</td>
<td>Computer methods in electrophysics</td>
<td>2 p</td>
<td>J. Scheffel/PhD students</td>
</tr>
<tr>
<td>2A5093</td>
<td>Transport processes</td>
<td>2-4 p</td>
<td>M. Tendler</td>
</tr>
<tr>
<td>2A5095</td>
<td>Accelerator based methods for surface analysis</td>
<td>5 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2A5201</td>
<td>Special problems in accelerator technology</td>
<td>5 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2A5202</td>
<td>Radiation transport technology</td>
<td>5 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2A5203</td>
<td>Vacuum technology</td>
<td>3 p</td>
<td>S. Rosander</td>
</tr>
<tr>
<td>2H5051</td>
<td>Basic Electromagnetic theory</td>
<td>10-15 p</td>
<td>M. Norgren</td>
</tr>
<tr>
<td>2H5052</td>
<td>Analytic methods in electromagnetic field theory</td>
<td>10-25 p</td>
<td>M. Norgren</td>
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<tr>
<td>2H5053</td>
<td>Electromagnetic fields in inhomogeneous media</td>
<td>5-15 p</td>
<td>M. Norgren</td>
</tr>
<tr>
<td>2H5054</td>
<td>Numerical methods in electromagnetic field theory</td>
<td>10-20 p</td>
<td>M. Norgren</td>
</tr>
<tr>
<td>2H5055</td>
<td>Antenna theory and design</td>
<td>10-20 p</td>
<td>M. Norgren</td>
</tr>
</tbody>
</table>

## Graduate students

**Space Plasma Physics:**
- Anita Kullen
- Andrew Collier
- Sonia Figueriedo
- Tommy Johansson
- Tommy Eriksson

**Laboratory Plasma Physics:**
- Tomas Hurtig
- Michael Cyrus
- Muhammad Shafiq

**Theoretical Fusion Plasma Physics:**
- Thomas Johnson
- Martin Laxåback
- Tommy Bergqvist
- Jon-Erik Dahlin

**Experimental Fusion Plasma Physics:**
- Dmitry Yadikin
- Marco Cecconello
- Jenny-Ann Malmberg

**Accelerator Technology and Applications of Electro-Physics:**
- Mats Larsson

**Electromagnetic Theory:**
- Disala Uduwawala
- Jun Lu
- Ola Forslund
- Stig Ekestorm
- Björn Thors
- Jörgen Ramprecht
Graduate theses completed in 2003

Jenny-Ann Malmberg, Experimental studies of tearing mode and resistive wall mode dynamics in the reversed field pinch configuration, PhD Thesis, on June 6. Advisor: Per Brunsell


Marco Cecconello, Experimental studies of confinement in the EXTRAP T2 and T2R reversed field pinches, PhD Thesis, on January 31. Advisor: Henrik Bergsäker

4 Personnel

The Plasma Physics and Fusion Plasma Physics Divisions have large experimental programmes and as a result a professional engineering and technical staff is required. For example in the space plasma physics group there are engineers and technicians responsible for the design, fabrication and testing of satellite equipment and diagnostics. The experimental work in the fusion division is centred on the EU priority project, EXTRAP T2. This experiment incorporates apparatus with demanding specifications. High voltage capacitor banks with energies of several megajoules power the plasma discharge and confining magnetic field. The confinement vessel requires ultrahigh vacuum standard. The experimental work in the accelerator division involves development of new components and operation of three electron accelerators. These experimental systems incorporate advanced technology, which require a professional engineering and technical staff both for the development and the operation of the facilities.

Furthermore the data analysis work requires a sophisticated computer facility. The volume of data from the satellite experiments and the fusion experiments is extremely large. The theoretical work in the laboratory is focused on developing models and numerical codes in the areas of basic plasma physics, space plasma physics, plasma confinement, Magnetohydrodynamics and plasma heating and current drive by radio frequency waves in tokamaks. Advanced numerical techniques are a basic part of the research effort. Computer facilities have been built up in order to provide the necessary computational capacity for the data analysis and the numerical code simulations that are undertaken within the laboratory.

Staff

Division of Plasma Physics

Nils Brenning Director
Göran Marklund Vice-director
Space group:

Göran Marklund  Professor, Group Head  Anita Kullen  Graduate Student
Lars Blomberg  Professor  Per-Arne Lindqvist  Res. Assoc.
Per Carlqvist  Lecturer  Tomas Karlsson  Research staff
Nickolay Ivchenko  Research staff  Tommy Johansson  Graduate Student
Sónia Figueiredo  Graduate Student  Tommy Eriksson  Graduate Student

Laboratory plasma group

Nils Brenning  Professor, Group Head  Mohammad Shafiq  Graduate Student
Ingvar Axnäs  Lecturer  Tomas Hurtig  Graduate Student
Michael A Raadu  Lecturer

Emeriti

Carl-Gunne Fälthammar  Professor
Nicolai Herlofson  Professor

Technical and administrative staff

Lars Bylander  Elec. Engineer, Leader  Bengt Harald Nilsson  Comp. System
Ola Carlström  Elec. Engineer  Stig Rydman  Lab Technician
Sverker Christenson  Elec. Engineer  Göran Olsson  Elec. Engineer
Bengt Johansson  Lab Technician  Jan Wistedt  Lab Technician
Ramesh Mehra  Comp. Engineer  Maud Öberg  Accountant

Division of Fusion Plasma Physics

James R. Drake  Director
Einar Tennfors  Vice-director

Experiment group

James R. Drake  Professor  Jenny-Ann Malmberg  Grad. Student
Henric Bergsåker  Lecturer  Marek Rubel  Lecturer
Per Brunsell  Lecturer  Einar Tennfors  Lecturer
Jerzy Brzozowski  Research Staff  Dmitriy Yadikin  Graduate Student
Marco Cecconello  Graduate Student

Theory group

Torbjörn Hellsten  Professor  Martin Laxåback  Graduate Student
Michael Tendler  Professor  Jan Scheffel  Lecturer
Jon-Erik Dahlin  Graduate Student  Einar Tennfors  Lecturer
Thomas Johnson  Graduate Student  Tommy Bergkvist  Graduate Student
Mats Larsson  Graduate Student

Emeritus

Bo Lehnert  Professor

Technical and administrative staff

Rolf Ekman  Electrical Engineer  Jesper Freiberg  Lab Technician
Håkan Ferm  Lab Technician  Dieter Haslbrunner  Mech. Engineer
Birgitta Forsberg  Chief Administrator  Gunder Hägerström  Lab Engineer
Anita Johansson  Accountant  Ingeborg Mau  Administrator
Ryszard Kalinowski  Lab Technician  Elisabeth Söderhäll  Administrator
Gunnar Kindberg  Lab Engineer  Lars Westerberg  Lab Technician

Division of Applied Electrophysics
Thomas Elevant  Director
Staffan Rosander  Vice director

Accelerator group
Staffan Rosander  Lecturer
Petter Larsson  Lab Engineer

Emeriti
Olle Wernholm  Professor
Miroslav Sedlacek  Professor

Technical and Administrative Staff
Kjäll Olsson  Lab Engineer
Sune Malmgren  Lab Engineer

Industrial Applications of Electrophysics
Thomas Elevant  Director
James Drake  Professor
Ingvar Axnäs  Lecturer
Nils Brenning  Professor

Technical Staff
Kjäll Olsson  Lab Engineer
Gunder Hägerström  Lab Engineer
Gunnar Kindberg  Lab Engineer
Lars Westerberg  Lab Technician
Håkan Ferm  Lab Technician
Jan Wistedt  Lab Technician

Division of Electromagnetic Theory
Gunnar Larson  Director

TET group
Gunnar Larson  Lecturer
Staffan Ström  Professor (Emeritus)
Gunnar Petersson  Lecturer
Peter Fuks  Lecturer
Martin Norgren  Lecturer
Sailing He  Lecturer
Lars Jonsson  Research Staff
Patrik Persson  Research Staff
Gulli Frohmader  Administrator
Ola Forslund  Graduate Student
Lars Josefsson  Adjunct Professor
Hans Steyskal  Adjunct Professor
Björn Thors  Graduate Student
Disala Uduwawala  Graduate Student
Jörgen Ramprecht  Graduate Student

Alfvén Laboratory central services
Juhani Haapasaari  Workshop Tech.
Ove Karlsson  Workshop Tech.
Anders Hurula  Technician
5 Economy

The funding sources for 2003 for the activity of the Alfvén Laboratory included the KTH faculty budget, external grants from funding sources including the Swedish National Space Board (RS), Research Council (VR), and EURATOM (EU), and funding from other external sources such as industrial partners or other research facilities for carrying out of specific tasks.

The KTH faculty funding is divided into three areas; undergraduate education, research and research training and a special Alfvén Laboratory funding to support the special research activity of the laboratory in the international fusion and space plasma physics programmes.

The costs are accounted as personnel, central KTH administration costs, rent, and operations & equipment. The budget for the Alfvén Laboratory is summarised in the table below. The accounts for the year 2003 resulted in a negative result of 0.3 million kronor. The main cause was reduced undergraduate income.

**Budget for the Alfvén Laboratory for 2003.**

<table>
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<tr>
<th></th>
<th>Faculty research and research training</th>
<th>Special Alfvén Laboratory Research Funding</th>
<th>Undergraduate teaching</th>
<th>External (VR, RS, EU)</th>
<th>External (other) &amp; interest</th>
<th>Total</th>
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<tbody>
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<td><strong>Income</strong></td>
<td>12.9</td>
<td>17.6</td>
<td>5.9</td>
<td>13.6</td>
<td>7.6</td>
<td>57.6</td>
</tr>
<tr>
<td><strong>Expenditures</strong></td>
<td>32.5</td>
<td>9.0</td>
<td>8.4</td>
<td>8.0</td>
<td>-0.3</td>
<td>57.6</td>
</tr>
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</table>
6 Professional activity

6.1 Memberships, honours, responsibilities etc.

Lars Blomberg
Co-Project Scientist of the Astrid-2 micro satellite mission
Co-Investigator of the double probe experiment on the Viking, Freja and Cluster satellites and of the Langmuir probe instruments on the Rosetta and SMART-1 spacecraft
Member of the budget planning group in physics, Swedish National Research Council
Member of the Swedish National Committee for EISCAT
Member of SNSBs reference group for Space Physics
Member of ESA Solar System Working Group

Per Brunsell
Principal-investigator for an EXTRAP T2 experimental project funded by VR
Member of European and Swedish Physical Society
Member of FFK, the Swedish Fusion Research Committee – Swedish Research Council

Jerzy Brzozowski
Co-investigator for an Extrap T2 experimental project founded by NFR
Member of Technical Physicist Association
Member of European and Swedish Physical Society

James R. Drake
Member of Royal Swedish Academy of Engineering Sciences (IVA).
Member of Executive Committee, International Energy Agency Trilateral Agreement (EU, Japan, USA) for a Programme of R&D on RFPs.
Member of Scientific and Technical Committee for the Consorzio RFX (Padua, Italy), Association EURATOM/ENEA-CNR.
Member of Standing Committee for Evaluation of Applications for Academic Positions, School of Electrical Engineering, KTH.
Member of the Swedish Fusion Research Committee-Swedish Research Council.
Member of the American, European and Swedish Physical Societies.

Carl-Gunne Fälthammar:
Member of the Royal Swedish Academy of Sciences
Member of the International Academy of Astronautics
Member of Academia Europaea
Member of the European Academy of Arts, Sciences and Humanities
Honorary Doctor’s degree, University of Oulu, Finland
Recipient of the Basic Sciences Award of the International Academy of Aeronautics
Recipient of the 1998 Hannes Alfvén Medal of the European Geophysical Society
Associate Editor of Astrophysics and Space Science
Member of the Editorial Board of Space Science Reviews
Member of the Ørsted International Science Advisory Committee
Member of the International Scientific Reference Group for the Swedish Institute of Space Physics
Member of the Programme Committee for the 2005 Chapman Conference on Corotating Streams and Recurrent Geomagnetic Activity
Guest Co-Editor of a Special issue of IEEE Transactions on Plasma Science
**Torbjörn Hellsten**
Member of FFK, the Swedish Fusion Research Committee for the Swedish Research Council
Swedish Fusion Research Committee Examining Group for Extrap T2
Principal-investigator for the ICR heating and current drive project funded by VR
Responsible for the experimental programme at JET for 2003
Member of (Co-ordination Committee for Fast Wave Current Drive and Heating) CCFW-CD/H

**Lars Josefsson**
Fellow of the IEEE
Member of the Technical Program Committee for the conference Antenn 03, to be held in Sweden 2003.

**Gunnar Larson**
Member of SNRV, Section B: “Fields and Waves”

**Bo Lehnert**
Member of Royal Swedish Academy of Sciences, Physics Class
Member of Royal Swedish Academy of Engineering Sciences, Division of Basic Science
Fellow of the Institute of Mathematics and its Applications, London
Fellow of the Alpha Institute of Advanced Study, Budapest

**Per-Arne Lindqvist:**
Chairman of the Cluster Wave Experiment Consortium
Member of the Cluster Science Data System Steering Committee and Implementation Working Group
Project Scientist / Manager for the Scandinavian Data Centre of the Cluster Science Data System
Member of the Cluster Wave Experiment Consortium Operations Group
Co-investigator of the double probe experiment on Viking, Freja, Astrid-2, and Cluster and of the Langmuir probe instruments on the Rosetta and SMART-1 spacecraft

**Göran Marklund:**
Member of the Royal Swedish Academy of Sciences
Chairman of the Swedish National Committee for Geodesy and Geophysics
Vice-Chairman of Class II of the Royal Swedish Academy of Sciences
Principal Investigator of the electric field experiments on Viking and Freja
Co-Project Scientist of the Astrid-2 micro satellite mission
Co-investigator of the double probe experiment on the Cluster satellites
Co-investigator on the SPEDE instrument on SMART-1.
Member of the Science Committee of the Swedish National Space Board (ended 2001)
Member of SNSBs reference group for Space Physics

**Gunnar Petersson**
Chairman of the Swedish Technical Committee for "Quantities and Units and their Letter Symbols", IEC.
Chairman of the technical committee ISO/TC 12, Quantities, Units, Symbols, Conversion Factors.

**Michael Raadu**  
Member of International Astronomical Union (IAU).  
Member of Australian Astronomical Society (AAS).  
Member of European and Swedish Physical Societies.

**Staffan Rosander**  
Member of European Physical Society.

**Marek Rubel**  
Member of the European Microbeam Analysis Society – EMAS  
Publication Committee member of the Int. Workshop on Hydrogen Isotopes in Fusion Reactor Materials  
Programme Committee member of the 11th Int. Conference on Fusion Reactor Materials  
Programme Committee member of the 10th Int. Workshop on Carbon Materials for Fusion Applications  
Guest Editor of the journal “Physica Scripta”  
Scientific co-ordinator in the EFDA-JET work programme within Task Force “E”  
Responsible officer for the development of collector probe heads, JET Enhancement project  
Responsible officer for the First Mirror Test, JET-EP Enhancement project  
Contact person for EFDA-JET Task Forces “E” and “FT”  
Contact person for the European Task Force on Plasma – Wall Interactions

**Jan Scheffel**  
Director of undergraduate and graduate studies at the Alfvén Laboratory, KTH  
Chairman of undergraduate studies for the Engineering/Teaching programme at KTH  
Chairman of undergraduate studies for the Open Entrance programme at KTH  
Member of the European and Swedish Physical Society.

**Hans Steyskal**  
Fellow of the IEEE

**Staffan Ström**  
Chairman of the Swedish Member Committee of URSI  
Member of the IEEE Heinrich Hertz Medal Committee  
Fellow of the IEEE  
Fellow of the World Innovation Foundation  
Associate Editor, Radio Science  
Programme Director for the SSF Antenna Technology Programme (2000-2003)  
Member of the Technical Programme Committee for the URSI International Electromagnetic Theory Symposium, to be held in Pisa, Italy, in May, 2004

**Michael Tendler**  
Member of the FFK, the Swedish Fusion Research Committee for the Swedish Research Council  
Chairman of the Plasma Physics Section, Swedish Physical Society  
Member of European and Swedish Physical Society  
Member of Plasma Physics Board of the European Physical Society
Member of Programme Committee of Annual Workshops “Role of Electric Fields in Plasma Confinement.”
Chairman of International Board of Advisors, Euratom – CR Association.
Adviser to the Plasma Physics Division of the American Physical Society on the
International Contacts & Grants Policy
Honorary Doctor, Russian Academy of Sciences
Chair, board, University I Studium, Tallin, Estonia

**Einar Tennfors**
Swedish Fusion Research Unit contact person for EFDA-JET Task Force S2S2 *Advanced tokamak Operation*
Swedish Fusion Research Unit contact person for EFDA-JET Task Force H: Heating, current drive and plasma rotation
Member of the EFDA-JET Remote Participation Users Group, representing the Swedish Fusion Research Unit
Member of the EFDA Public Information Group
Member of the Executive Committee for the Fusion Expo consortium
Member of the European and the Swedish Physical Societies

### 6.2 Academic and expert activity

**Doctoral thesis; opponent or examination committee**
James R. Drake, examination committee member at the PhD defence of Fredrik Andersson, *Runaway electrons in tokamak plasmas*, dept of Electromagnetics, Chalmers

James R. Drake, examination committee member at the PhD defence of Eva Mårtensson, *Modelling electrical properties of composite materials*, dept of Electrical Technical Systems, KTH

Jan Scheffel, faculty opponent at the PhD defence of Bob Gravestijn at, dept of Atomic and molecular physics, KTH

Per Brunsell, examination committee member at the PhD defence of Carl-Magnus Fransson, Chalmers

Martin Norgren, external evaluator of PhD thesis of Juha Avelin, Electromagnetics Laboratory, Helsinki University of Technology, Finland.

Martin Norgren, faculty opponent at the PhD defence of Björn Widenberg, dept of Electroscience, Lunds Tekniska Högskola, Sweden.

Lars Blomberg, examination committee member at two PhD defences at IRF-U, Uppsala

Michael A Raadu, examination committee member at a PhD defence at IRF-U, Uppsala

Einar Tennfors, examination committee member at the PhD defence of Hans Henriksson, Uppsala University
**Technical adviser/expert**

Nils Brenning:
- Evaluation of two proposals to the Norwegian Research Council.
- Evaluation for a professorship position.

Jerzy Brzozowski:
- Coordinator for The Swedish Research Council - EFDA-JET Contacts
- Member of the Swedish Fusion Research Committee-Swedish Research Council.
- Member of RUL
- Diagnostic Coordinator in the JET Experiment
- Session Leader in the JET Experiment

James Drake:
- The Swedish Research Council; Fusions Research Committee
- The Swedish Research Council – NT: perparation group N.
- Scientific Technical Council, Consorzio RFX, ENEA, CNR and Univ of Padua
- Ad hoc EURATOM Committee to review the CIEL project

Carl-Gunne Fälthammar:
- Reviewing of an application for collaboration with research groups in the former Soviet Union and East Europe.

Torbjörn Hellsten:
- Evaluation of a senior lecturer position

Bo Lehnert:
- Report on an application to the Natural Sciences and Engineering Research Council of Canada.
- Letter of support for a Leverhulme Emeritus Fellowship, United Kingdom
- Examination of candidates for Research Fellowships in Physics at the Royal Swedish Academy of Sciences.

Göran Marklund:
- Reviewing of five applications for collaboration with research groups in the former Soviet Union and East Europe.
- Evaluation for a professorship position
- Evaluation for a docentur

Jan Scheffel:
- Assigned Public relations officer for Swedish fusion research, a task within EFDA (European Fusion Development Agreement).
- Wrote part of the referral from KTH on the commission of inquiry on sustainable Swedish energy research within the coming seven year period (LångEn-utredningen).
- Represent KTH at Vetenskapens Hus (House of Science) board. (Sw: Vetenskapens Hus, [www.vetenskapenshus.scfab.se](http://www.vetenskapenshus.scfab.se) and [www.kth.se/samverkan/skola/vetenskapens_hus/index.html](http://www.kth.se/samverkan/skola/vetenskapens_hus/index.html))
- Member of Steering Committee for joint educational development, KTH and LHS (Stockholm Institute of Education).
- Member of joint KTH-LHS project group to develop new education for teacher students that wish to chose technology as one of their two major subject fields at LHS.

Michael Tendler:
- Foreign Member of the Russian Academy of Science
- Chairman of the Board for Euratom – CR association
- Board of Council appointed by the Japanese Government of National Institute of Fusion Studies, Toki, Japan
- Advisory Board appointed by the Chinese Academy of Sciences, of the Institute of Plasma Physics, Hefei, P.R. China

Other activities

Marco Cecconello:
Secondee at EFDA-JET during campaigns C10 and C12.
Secondment agreement n. 752

Jan Scheffel:
Student outreach - supervision of students performing upper secondary school project work; see www.alfvenlab.kth.se/edu/gymsam.html.

Member of Alfvén Laboratory board.

Journal referee

Bo Lehnert for Chemical Engineering Communications, USA (1) and for Foundations of Physics, USA (4)

Jan Scheffel for Plasma Physics and Controlled Fusion

Marek Rubel for Nuclear Fusion (1), Physica Scripta (3), Journal of Nuclear Materials (2), Nukleonika (1)

Per Brunsell for Nuclear Fusion (2), Physics of Plasmas (1)


Lars Blomberg, Annales Geophysicae (1)

Judy Cumnock, Journal of Geophysical Research (2)

Carl-Gunne Fälthammar, Annales Geophysicae (1)

Tomas Karlsson, Journal of Geophysical Research (1)

Anita Kullen, Journal of Geophysical Research (3), Annales Geophysicae (1)

Michael A Raadu, New Journal of Physics (2) (original and revision), Physics of Plasmas (3) (one revision), J. Phys. D: Applied Physics (1)

7 Alfvén Laboratory seminars

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<th>Date</th>
<th>Name</th>
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<td>2003-02-07</td>
<td>Cecilia Nylander</td>
<td>Passiv repeater för GSM och DECT</td>
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<td>Master Project in Physical Electrotechnology</td>
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<td>2003-02-11</td>
<td>Mikael Sandzelius</td>
<td>Fusion potential for spherical and compact tokamaks</td>
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<td>2003-03-05</td>
<td>Markus Johansson</td>
<td>Direct conversion of fusion energy</td>
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<td>2003-03-20</td>
<td>Lars Eriksson</td>
<td>Development of tool for simulating the effect of radial electric fields on Ion-Temperature-Gradient modes in 3D configurations</td>
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<td>2003-04-28</td>
<td>Judy Cumnock</td>
<td>Space weather</td>
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<td>Plasma Physics</td>
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<td>2003-05-23</td>
<td>Eva Frendh</td>
<td>Design of user manual using network analyzer</td>
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<td>2003-05-27</td>
<td>Christian Hedman</td>
<td>En positronmaskin</td>
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<td>Applied Electrophysics</td>
<td>Master Project in Physical Electrotechnology</td>
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<td>2003-05-27</td>
<td>Petter Larsson</td>
<td>Positrontransport</td>
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<td>Applied Electrophysics</td>
<td>Master Project in Physical Electrotechnology</td>
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<td>2003-05-28</td>
<td>Magnus Svensson</td>
<td>Analytic study of resistive instabilities</td>
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<td>2003-05-28</td>
<td>Bengt Ållebrand</td>
<td>Computer simulation of an ion source</td>
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<td>2003-06-06</td>
<td>Jenny-Ann Malmberg, PhD defence</td>
<td>Experimental studies of tearing mode and resistive wall mode dynamics in the reversed-field pinch</td>
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<td>Polar auroral arcs</td>
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<td>2003-06-24</td>
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<td>Criticality and darwinian selection in simplistic games</td>
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<td>2003-08-12</td>
<td>Daniel Oberti</td>
<td>Forming materials of the Earth into works of art</td>
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<td>2003-09-08</td>
<td>Franklin Chang-Diaz</td>
<td>Future Technologies for Space Travel</td>
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<td>2003-09-18</td>
<td>Prabhakar Pathak</td>
<td>General research on hybrid methods for large arrays – present and future</td>
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<td>2003-09-19</td>
<td>Prabhakar Pathak</td>
<td>Introduction to hybrid APE-MoM for large body radiation/scattering</td>
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<td>2003-10-06</td>
<td>Johan Hedin</td>
<td>Feedback – quality assurance for diagnosis in radiology</td>
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<td>Fusion Plasma Physics</td>
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<tr>
<td>2003-10-28</td>
<td>Björn Thors, PhD defence</td>
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<td>2003-10-29</td>
<td>Werner Wiesbeck</td>
<td>Radiation from ultra-wide-band antennas</td>
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<td></td>
<td>Electromagnetic Theory</td>
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Appendix A

Detailed Report from the Division of Plasma Physics

The Division of Plasma Physics is a centre for front line research, research training and education in fundamental plasma physics. The main theme of the research is the study of the electrodynamic properties of matter in the plasma state. The research programs are carried out with intense international collaboration. The research program is also characterized by a unique combination of space experiments, theoretical research including numerical simulations of plasma phenomena, and laboratory experiments. Problems investigated by the laboratory group are often relevant to both space and basic plasma physics.

A.1 Space physics group research

The Space Group is one of two research groups of the Division of Plasma Physics, which is one of four divisions at the Alfvén Laboratory (the other divisions are: Applied Electrophysics, Electromagnetic Theory and Fusion Plasma Physics).

The space group is devoted to front line research in space plasma physics and to education at both the graduate and the undergraduate levels. The space group staff is now heavily involved in undergraduate teaching, with courses in Plasma Physics, Space Physics, Electromagnetic Theory, Electrical Circuits, Electrical Circuit Analysis, and the "Electro project", the last course being for first-year E-students.

The research aims at a better understanding of plasma phenomena associated with the solar wind interaction with the magnetosphere and ionosphere of the Earth and of other planets. Space experiments are carried out in various space plasma regions by means of satellites and space probes. The analysis and interpretation of the experimental data are often done in parallel with numerical simulations to reveal the physics of the explored phenomena. The speciality of the group is double-probe instruments for measurements of electric fields and of electron density and temperature. The group has also developed fluxgate magnetometers for several sounding rocket and small satellites, such as Ørsted and Astrid-2, and recently also developed the DC/DC converters for instruments on Rosetta and SMART-1.

The electric field plays an essential role in various space plasma processes and phenomena, such as the energy transfer by reconnection between the solar wind and the Earth’s magnetic field, acceleration processes that produce auroras, and magnetospheric convection. The processes associated with auroral particle acceleration are relevant to many important problems in both space and astrophysical plasmas and also have important technological applications. The temporal evolution of the positive potential structures that accelerate ionospheric electrons away from Earth above black aurora, as first discovered by Freja, was recently revealed by Cluster measurements and found to be closely tied to the formation of ionospheric density holes (Marklund et al, Letter to Nature, 2001a).

The technique for double probe electric field measurements is subject to a continuous development and refinement, to which the space group contributes. In different versions it has been used on more than 25 sounding rockets and on many satellites, such as Viking, Freja, Astrid-2, Polar, and Cluster.
A brief outline of the project activity during 2003 is given below.

A.1.1 Overview and Summary

The German CHAMP and US-Argentinian SAC-C satellites, launched in 2000, carried magnetic field instruments with DPUs designed and built at AL. The instruments continue to perform excellently and provide accurate magnetic field measurements which together with Ørsted data produce a unique dataset for detailed modeling the magnetic field of Earth.

The space group developed the DC/DC converter for the SPEDE instrument on the SMART-1 spacecraft, launched in September 2003 to the Moon, and for the Langmuir probe instrument on the Rosetta spacecraft to be launched in 2004, the primary target being comet 67P/Churyumov-Gerasimenko.

The space group participates with a significant hardware share on an electric field and wave instrument for the magnetospheric orbiter of BepiColombo, to be proposed by Professor Matsumoto, Kyoto, after the AO release in spring 2004. The instrument includes one European probe pair for dc and low-frequency electric field measurements and another Japanese probe pair for wave electric field measurements. The SCALE wire boom system developed at KTH is to be used for deployment of the European probe pair.

The space group participates on a MMS instrument suite proposal that was selected for phase-A study in 2003 together with a Berkeley proposal. The budget levels given in the President's FY 2005 NASA Budget implies that the MMS launch will be delayed to or beyond 2012. However, MMS is given the highest priority of NASAs new Solar Terrestrial Probe (STP) missions and the Phase-A study should continue as planned with a final selection of the instrument team in late 2004.

The space group has a heavy involvement in the Cluster project with operations of the Scandinavian Data Centre and of the EFW instrument. The scientific activity during 2003 was dominated by analysis and publications of Cluster data. Following the Cluster results in Nature, three invited popular publications on the black aurora phenomenon by Marklund appeared in print in 2003 (in Investigacion y Ciencia, Forskning & Framsteg, and Svenska Dagbladet) and three scientific reports on this theme were submitted to Annales Geophysicae in 2003. One doctoral thesis, entitled "Polar Auroral Arcs” by Anita Kullen, was successfully defended on 11 June 2003.

A.1.2 Detailed Space Project Activities 2003

Our involvement in satellite experiments started gradually with participation in GEOS-1, GEOS-2 and ISEE and came to full fruition with Viking, launched in 1986, and carrying an electric field experiment entirely built at KTH. Freja, launched in 1992, also carried an electric field instrument built at KTH and which operated for four years, the entire life time of Freja. Astrid-2, launched in Dec 1998, carried a combined electric and magnetic field instrument built at KTH, which operated perfectly during the entire life time of Astrid-2 and produced data which will continue to be analysed for several years to come. In Summer 2000 the Cluster II satellites were launched, delivering data of extraordinary good quality.
A.1.2.1 Projects in data analysis phase

Freja

The scientific outcome from Freja is outstanding with more than 150 scientific publications and some pioneering results such as of the positive potential structures that accelerate ionospheric electrons away from the auroral ionosphere associated with the optical phenomenon black aurora. The characteristics of such acceleration structures and their role as an important element of the auroral current circuit have been presented in eleven publications and numerous invited lectures since the first discovery was made in 1994. Freja results still contribute to several invited lectures and publications per year.

Astrid 2

The Astrid-2 microsatellite mission was a great success. The EMMA instrument, built at KTH, provided excellent data from over 3000 polar orbits. In addition to the articles included in the special Astrid-2 issue of Annales Geophysicae, Astrid-2 data analysis result in several publications yearly, such as a statistical SAID study by Figueiredo et al. (2004), a transpolar arc study by Blomberg and Cumnock (2004a), and an instrument summary by Blomberg et al. (2004a), and will continue for several years to come.

A.1.2.2 Spacecraft in operation

Polar

Analysis of Polar UVI images, made in collaboration with University of Washington, Seattle, formed an important part of the doctoral thesis by Anita Kullen, defended on 11 June 2003. Kullen identified characteristics of transpolar and polar arcs and how these are influenced by various solar wind conditions (Kullen and Karlsson, 2004). Another study involved the development and use of a theoretical model of the tail response to the solar wind and of MHD simulations of the tail dynamics (Kullen and Janhunen, 2004).

Ørsted, SAC-C, CHAMP

The space group designed and built the electronics for the Ørsted fluxgate magnetometer and data processing units for the CHAMP and SAC-C fluxgate magnetometers, instruments that continue to operate well and provide excellent data. The presence of three magnetic field satellites simultaneously in orbit at different altitudes and inclinations offers an unheralded opportunity to resolve not only the core and crustal magnetic fields, but at the same time the contributions from ionospheric, magnetospheric and electromagnetically induced sources, enabling a true field separation, and mapping of the geomagnetic field at an unprecedented resolution and accuracy, as reported on by Merayo et al. (2002).

Cluster

The space group is co-investigator on the electric field and wave experiment (EFW) on the Cluster satellites, launched in summer 2000. The space group built a total of 16 flight circuit boards for the bias current, guard and puck potentials for the EFW instruments. These perform excellently (with an exception for a probe1 failure on satellites 1 and 3) and provide data of unprecedented quality even in very low density regions. The Alfvén Laboratory runs the Scandinavian Data Centre for analysis of the Cluster electric field data and distributes these to
other data centres. Lindqvist is the chairman of the Cluster Wave Experiment Consortium and Project Scientist / Manager of the Scandinavian Data Centre.

The science effort has so far been dominated by the search for large-amplitude electric fields from low-altitude crossings of auroral field lines. These fields could either be the high-altitude signatures of quasi-static converging or diverging electric field structures in the auroral and auroral return current region, respectively, or Alfvén waves, or a combination of both. Analysis of some diverging electric field events led to the discovery of a characteristic time of growth of these, being closely tied to the formation of ionospheric density holes. The results, presented in Nature (Marklund et al, 2001a) and on ESAs Cluster home page in December 2001, were followed up by three invited, popular articles by Marklund on black aurora where the Cluster results revealing its life cycle were put in a larger context (Marklund, 2003; Marklund, 2004; Smeds, 2003).

Since the Cluster separation distance has changed several times during the mission, we possess today a unique data set of intense electric field events and how these evolve on the different time scales defined by the separation distances. Three new publications on this theme were submitted in 2003 for publication in a special Cluster issue of Annales Geophysicae, and formed the topic of several invited and contributed lectures during 2003. The Nature results were included in the Cluster mission extension report which contributed to the positive decision taken by ESA to extend the Cluster mission to Dec 2005.

The SPEDE instrument on SMART-1

After its successful launch on 27 September 2003, Europe’s first lunar spacecraft SMART-1 is now on its long journey to the moon, arriving at the end of 2004. The space group built the DC/DC converter for the SPEDE plasma instrument, for which A. Mälkki, Finnish Meteorological Institute, is the Principal Investigator. The instrument is to monitor plasma disturbances induced by the electric propulsion and electron density variations and wave electric fields during Earth orbit and then Moon orbit. One of the two probes has been found not to function properly in the Langmuir mode of operation. This has, however, only minor effects on the science to be conducted.

A.1.2.3 Spacraft ready for launch

ESA corner-stone mission Rosetta

The space group participates as co-investigators on the Langmuir probe instrument (for which IRF-U has the PI responsibility) for which we built a flight and a spare model of a DC/DC converter and also fabricated other circuit boards, all delivered in 2001. The Rosetta launch campaign was resumed on 24 October 2003, scheduled for a launch on 26 February 2004, to comet 67P/Churyumov-Gerasimenko with fly-by’s of some Asteroids, to be finally selected shortly after launch.

A.1.2.4 Planned projects

BepiColombo

The space group participates on an instrument proposal for the magnetospheric orbiter (MMO) of the BepiColombo mission to Mercury, to be submitted in response to the request for proposals to be issued in spring 2004. Our participation, with a significant hardware share
in a Japanese-European electric field and wave instrument, led by Professor Matsumoto, Kyoto, is today well established. The instrument includes one probe pair for dc and low-frequency measurements, to be provided by a European team, and another probe pair for wave electric field measurements, to be provided by the Japanese team. The SCALE wire boom system developed at the Alfvén Laboratory will be used for the European part of the instrument. Following the SPC decisions and strong support for the BepiColombo mission, the Independent Peer Review of the Model Payload for the MPO is being implemented and in parallel JAXA is implementing the MMO.

**MMS**

The space group participates on an electric field instrument on an instrument suite proposal for the Magnetospheric Multi-Scale mission (MMS), to perform multi-point and high-resolution measurements of reconnection in the magnetosphere of Earth. The proposal was selected in 2003 for phase-A study together with another proposal from U. of California, Berkeley. For cost reasons, the three initial mission objectives, reconnection, turbulence, and particle acceleration, were cut down to reconnection only, and the two teams have been asked to re-design the proposals accordingly and submit these no later than 24 April 2004. Three-D electric field measurements at high-resolution are crucial and require axial electric field booms and a re-design of the spacecraft to accommodate them. The President's FY 2005 NASA Budget implies a delay of the MMS launch to or beyond 2012, but despite this delay the Phase-A study should continue as planned. A final selection of the science team will probably take place in late 2004.

**A.1.2.5 Development of SCALE**

A new boom system (entitled SCALE) has been invented, funded by SNSB, to enable deployment of long wire booms needed for measurements at high altitudes (> 1000 km). A brief summary of the SCALE system is given here. The wire, stored in between two cylinders, is fed by a motor using a technique similar to the spinning rod. The system is scalable; boom length and probe diameter determine volume and mass of the unit. Two prototypes in aluminum exist today. Vibration tests were performed in 2001 with excellent result. A finite element model of the design, developed in 2001, allowed calculation of stress forces and the system response to vibrations. Further work is needed, such as choice of motor and material with suitable thermal properties. SCALE is a candidate for electric field instruments on BepiColombo and MMS. Negotiations with SSC and DLR have been made in 2003 to find an opportunity to test SCALE on a sounding rocket. Such a flight test may be requested by NASA if it is to be used on MMS.
Figure 1. SCALE wire boom deployment system developed at the Alfvén Laboratory

A summary of current and planned space projects with KTH-participation is shown in Table 1

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<th>Current and planned space projects</th>
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<td>Legend:</td>
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<td>Red = Pre-Launch Planning, Design, Manufacturing, Testing</td>
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<td>Green = Operations</td>
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<td>Blue = Post-Mission Data Analysis</td>
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Table 1. Current and planned space projects

A.1.3 Summary of Scientific Results

Characteristic of the research is the combined use of space experiments, theory and numerical simulation to clarify various plasma physical phenomena. The results described below derive from the fruitful cross-fertilization among these complementary lines of approach.

A.1.3.1 The Swedish small satellite program for space plasma investigations

A comprehensive review has been made of the accomplishments of the Swedish small satellite program, which comprises a total of six research satellites, five of which were auroral or space plasma missions. Viking and Freja, the most well-known of these missions, have made substantial and sometimes
Figure 2. Occurrence rate of electric fields with magnitudes > 100 mV/m based on four years’ worth of Freja electric field data, presented in a magnetic local time-corrected geomagnetic latitude coordinate system for winter (left), equinox (middle), and summer (right) conditions. Note that the occurrence rate is higher for winter than for summer conditions and that the winter events peak around magnetic midnight whereas the summer events peak around dusk (from Marklund et al., 2004a, figure provided by Karlsson)

pioneering contributions to the understanding of the aurora, in particular on the topic of acceleration and energization of auroral particles. More than 400 papers on Viking and Freja results have appeared in print, including the papers contained in two Viking special issues (GRL, 14, No 4, April 1987; and JGR, 95, No A5, May 1, 1990) and three Freja special issues (Space Sci. Revs, 70, Nos. 3-4, 1994; GRL, 21, No 17, August 15, 1994; and JGR, 103, No A3, March 1, 1998). Astrid, Astrid-2 and the Munin satellites proved powerful both for performing tests of new space technologies and instruments and for providing high-quality scientific data. Astrid-2 results have been presented in more than 20 papers, many of which were included in a special Astrid-2 issue of Annales Geophysicae (19, No 6, 2001). The Swedish small satellite missions have been recognized internationally as cost-efficient and scientifically very successful and the results have had a great impact on the progress in auroral research. An extensive review on this topic has been accepted for publication in Space Science Reviews (Marklund et al, 2004a), and a brief review has been submitted to EOS (Marklund et al, 2004b).

A.1.3.2. Freja studies of the aurora and related phenomena

Freja results on the auroral return current

Results from event, statistical and numerical studies of the narrow-scale diverging electric field structures that develop in the auroral return current in connection with black aurora and ionospheric density holes have been much reported on in earlier reports. This research has produced eleven refereed publications and numerous invited lectures since 1994, when the pioneering discovery was made by Freja. Freja results continue to contribute to new publications and presentations and are used as a basis for Cluster studies of how such structures evolve in time and contribute to the particle acceleration and energy flow between the magnetosphere and the auroral ionosphere as described in Section 3.3 below.
**Freja results and numerical simulation results on the auroral bulge electrodynamics**

As reported on earlier, Freja results, supported by results from numerical modelling studies of the surge electrodynamics, point at a modified scenario for the electrodynamics of the auroral bulge. The results suggest that the upward surge current may, at times, essentially be closed locally rather than remotely, as in the classical picture. This was the case also for an intense auroral bulge, intersected by a gap, observed during a steady magnetospheric convection event (Marklund et al, 2001b). This problem was further addressed in a Master thesis by Thillainathan, completed 2003, based on numerical model results of the bulge electrodynamics and comparisons with Astrid-2 data (Thillainathan, 2003).

**A.1.3.3 Cluster studies of the aurora and related phenomena**

To understand the cause and origin of the auroral acceleration processes and the associated energy flow between the magnetosphere and the auroral ionosphere, all parts of the auroral current circuit need to be considered and, ideally, subject to simultaneous measurements. Viking explored the primary auroral acceleration region (5000-13000 km), whereas Freja and FAST traversed the bottom and the upper part of the return current acceleration region, respectively (800-4500 km). Above these regions, data are presently available from Polar and Cluster, but only Cluster has the unique capability to handle the spatial-temporal ambiguity problem. Examples of some unsolved key problems, serving as motivation for the Cluster auroral studies are:

1) How do quasi-static electric field structures evolve in time and contribute, together with Alfvén waves, to the acceleration of auroral particles and to the energy transport between the magnetosphere and the auroral ionosphere? What is the altitude dependence of these relative contributions?

2) What is the nature of the generator(s) driving the auroral current circuit, and how does one part of the current circuit impact on another. For example, how do the dynamics of the return current impact upon the auroral current dynamics?

**Cluster results on the life cycle of the black aurora**

In early 2001, the large separation between the Cluster spacecraft was such that close to perigee, the spacecraft were oriented nearly as pearls-on-a-string, separated in time by about 100 s. This geometry allowed to study the temporal evolution of quasi-static acceleration structures associated with aurora and black aurora provided these extend up to the Cluster-altitudes at about 5 Earth radii geocentric distance. Suitable events were required to be fairly stable and to roughly maintain their identity and location between consecutive crossings, which excludes many substorm events. Two diverging electric field structures were selected, encountered at the PSBL-CPS boundary, and being associated with a downward FAC and a distinct plasma density gradient. For both events, the structures increased in amplitude and width whereas the FAC magnitude remained roughly constant throughout the four crossings. For the 14 January 2001 event, the acceleration (or parallel) potential given by the upward electron beam energy, increased, in perfect agreement with the perpendicular potential, from the first to the third crossing on a time scale of ≈ 200 s, after which the structure faded away. Closely tied to this evolution is the formation of an ionospheric plasma density hole, caused by the upward escape of the electrons and the perpendicular transport of ions, on a similar time scale. The sudden disappearance of the acceleration structure after 200 s coincides with a sudden widening of the return current sheet, making return current carriers accessible from
remote regions where the hole formation had just begun.

These results were published in Nature and on ESAs Cluster page in December 2001, and subject to an intense media response and numerous invited lectures from December 2001 to summer 2002, as reported on in the Progress report 2002. Furthermore, Marklund received invitations from Investigacion y Ciencia (the Spanish edition of Scientific American) and Forskning & Framsteg to write popular articles on the black aurora phenomenon and its role as an element of the auroral current circuit, thereby putting the Cluster results into a larger context. These two articles were completed and published in 2003 and early 2004 (Marklund, 2003; and Marklund 2004a), and formed the basis for two invited lectures by Marklund given as an open lecture at the Royal Swedish Academy of Sciences in November 2003, and at the LEIF-EU network conference in Stockholm, December 2003. Furthermore, the discoveries by Freja and Cluster revealing the nature of the black aurora, formed a full-page invited contribution to a KTH-section of Svenska Dagbladet, 16 November 2003.

**Figure 3.** Spatial variations in the perpendicular magnetic field components caused by the four Cluster spacecraft crossings of a quasi-static FAC sheet. The geometry of the four spacecraft with respect to the orientation and velocity of the sheet is given to the right. Note that s/c 1 and 2 crossings of the sheet occur almost simultaneously, as is the case for the s/c 3 and 4 crossings ≈ 20 s later (after Karlsson et al, 2004).

*Cluster results on the temporal and spatial characteristics of intense high-altitude electric fields*

The search for large-amplitude electric fields on auroral field lines and their origin has continued and today we have a large dataset of events, obtained for different Cluster separations, which is subject of detailed analysis conducted by our new graduate students, Tommy Johansson and Sónia Figueiredo, and supervised by Marklund and Karlsson. Two such studies, addressing the problems listed above, were initiated and completed in 2003 and submitted for publication in a Cluster issue of Annales Geophysicae.

In the first study, electric and magnetic field data from one Cluster auroral crossing are used to show that
it is possible to resolve the ambiguity of temporal versus spatial variations. The largest electric fields, of the order of 300-400 mV/m mapped to the ionosphere, are of a quasi-static nature, unipolar, associated with upward electron beams, stable on a time scale of at least half a minute, and located in two regions of downward FACs (see Figure 3). They are the high-altitude analogues of the intense return current electric field structures, observed at lower altitudes by Freja and FAST. In between these structures there are temporal variations, likely due to downward travelling Alfvén waves with periods of 20–40 s, thus inconsistent with periods of either the Alfvénic ionospheric resonator, typical field line resonances or substorm onset related Pi2 pulsations. The multipoint measurements enable an estimate of a minimum, perpendicular to B, wavelength of the Alfvén waves to be \( \approx 120 \) km, similar to the dimension of the region between the two quasi-static structures. This might indicate that the Alfvén waves are ducted within a wave guide, where the quasi-static structures are associated with the gradients constituting this waveguide. These results were presented by Karlsson et al in an invited lecture at the IUGG General Assembly, Sapporo, Japan, June 2003, and in a contributed lecture at the AGU Fall Meeting, San Francisco, December 2003. A paper on these results was submitted for publication in a special Cluster-issue of Annales Geophysicae (Karlsson et al, 2004).

In the other study Cluster electric field, magnetic field, and energetic electron data, are analysed for two events of intense auroral electric field variations, both encountered in the PSBL, in the evening local time sector, and at \( \approx 5 \) Earth radii geocentric distance. The most intense electric fields were found to be quasi-static, unipolar, (peaking at 450 and 1600 mV/m, respectively), relatively stable on a time scale of at least half a minute, and associated with moving downward FAC sheets (peaking at \( \approx 10 \) mA/m2), downward Poynting flux (peaking at \( \approx 35 \) mW/m2), and upward electron beams having characteristic energies consistent with the perpendicular potentials. For these two return current events, quasistatic electric field structures and associated FACs (see Figure 4) were found to dominate the upward acceleration of electrons as well as the energy transport between the ionosphere and the magnetosphere, although Alfvén waves clearly also contribute to these processes. Results of this study conducted by Johansson / Figueiredo, in collaboration with Karlsson and Marklund, were presented as a poster at the EGS-AGU-EUG Joint Assembly, Nice, France, April 2003, at Rymdforum 03, Kiruna, Sweden, May 2003, at the 40th Culham Plasma Physics Summer School, Oxford, United Kingdom, July 2003, and by Marklund in an invited lecture at the Cluster EFW meeting, Uppsala, October 2003. A paper on these results was submitted for publication in a special Cluster-issue of Annales Geophysicae (Johansson et al, 2004).

A.1.3.4 Alfvén waves and the fine structure of the aurora

Alfvén waves and their relation to the auroral fine structure is a topic that has been studied intensively and resulted in many publications, as reported on earlier, and many of which were included in Ivchenko's doctoral thesis "Alfvén waves and spatio-temporal structuring in the auroral ionosphere" June 2002. During 2003 Ivchenko worked part time at KTH (10%) and most of his time (90%) at University of Southampton, UK. In collaboration with staff at University of Tromsõ Ivchenko studies small scale structures in the aurora by combining optical data and EISCAT incoherent scatter radar data. A paper was submitted to Annales Geophysicae (Blixt et al, 2004), on the relation of rayed aurora to enhanced radar echoes. Furthermore, Marklund and Ivchenko were invited to participate in the NASA Cascades sounding rocket mission, aimed for studying the structuring in the aurora by means of multi-probe measurements, and planned to be launched in early 2005. The Principal Investigator of this project is Kristina Lynch, Dartmouth College, USA, with whom the space group has a
productive collaboration.

Figure 4. Cluster data illustrating three intense electric field peaks, of which the first and the third were found to be of quasistatic nature, unipolar, and associated with upward energetic electron beams, downward FACs, and downward Poynting fluxes, and the second peak to be of a temporal nature, presumably associated with Alfvén waves (Johansson et al, 2004).
A.1.3.5 Satellite and numerical simulation studies of polar auroral arcs

Field-aligned currents associated with transpolar aurorae

A multitude of fundamentally different configurations of field-aligned currents were found during the course of a long transpolar arc event. The FAC's include pairs of current sheets which lead to localised sunward plasma flow as well as isolated current sheets which result in larger-scale regions of sunward flow. A publication is forthcoming in Adv.Space Res. (Blomberg and Cumnock, 2004a).

Figure 5. The Polar UVI image at the top shows the global auroral distribution when Astrid-2 was close to its maximum northern latitude. A faint transpolar arc is just about to detach from the polewardly expanded dawn side oval. At the bottom are shown the duskward electric field (E2msp) and the sunward residual magnetic field (B3msp). Note the correlated negative peaks in the electric and magnetic field components associated with the polar arc poleward of the dawnside Region 1/2 system (after Blomberg & Cumnock, 2004a; Cumnock & Blomberg, 2004)
Event studies of transpolar arc convection patterns using satellite and numerical modeling results

The convection patterns associated with transpolar aurorae moving across the high-latitude region were studied using optical Polar UV data in combination with numerical modelling. The modelled convection patterns agreed excellently with measurements from two DMSP satellite traversals. The results are in press in Ann. Geophys. (Cumnock and Blomberg, 2003a). An extension of this study to simultaneous transpolar aurorae in both hemispheres is underway. Initial results were presented by Judy Cumnock at the AGU Fall Meeting 2003. Another extension of this study is to compare the model convection patterns with those predicted by the Paraboloid Model of the Magnetosphere developed at the Moscow State University. Initial results were presented by Lars Blomberg at the AGU Fall Meeting 2003.

Characteristics of polar arcs from analysis of Polar UVI-images and ACE solar wind data

A large statistical study of transpolar arcs and their connection to solar wind parameters was made by Kullen using Polar UVI images and ACE solar wind data (Kullen et al., 2002). The paper identifies a number of different polar arc types and the solar wind conditions during which these types occur. Polar arcs were found to have a high occurrence probability after one to three hours of predominately northward IMF and high solar wind energy flux. The IMF clock angle also seem to play a major role for which type of polar arc that appears. The ”anti-epsilon parameter,” introduced by Kullen by replacing the sinus by a cosinus in Akasofu’s epsilon parameter to make it applicable for northward IMF, is found to correlate remarkably well with the polar arc activity level. This paper was one of four papers included in the doctoral thesis by Kullen, defended on 11 June 2003.

Numerical simulation of the structure of the magnetotail and its relation to polar arcs

An MHD code by Pekka Janhunen was used to study the topological changes in the magnetotail and ionosphere for various IMF clock angles and how these relate to the occurrence and dynamics of polar arcs. The results confirm the semi-analytical transpolar arc model by Kullen that relates the polar arc location and dynamics to a twisting of the magnetotail. The results further demonstrate that a long and highly twisted tail occurs only for small IMF clock angles. This tail topology causes closed field lines to map to very high latitudes, which is where polar arcs occur. This paper has been accepted for publication in Annales Geophysicae (Kullen and Janhunen, 2004)

A.1.3.6 Other studies on Solar wind-magnetosphere-ionosphere coupling

Magnetospheric wave pulsations and their dependence on the solar wind

Data from the SHARE HF radar in Antarctica are used to compare ionospheric Pc5 oscillations with low frequency oscillations in the solar wind pressure, measured by the ACE spacecraft. Ten different days in 2000 and 2001 are analysed for different frequencies and geomagnetic latitudes. Both data sets are bandpass filtered and a complex demodulation technique is used to calculate the correlation in each band. On a number of occasions the Pc-5 wave packet structure is in good or excellent agreement with that of the solar wind pressure oscillations, strongly suggesting that the oscillations were directly driven by the solar wind. Particularly good correlation is found in the frequency band 0.8-1.2 mHz. Pulsations in this frequency range are hard to reconcile with the magnetospheric cavity mode model. We conclude that Pc5 pulsations may be directly driven on some occasions, for which the
magnetosphere cavity / waveguide assumes a more passive role. This work which forms Tommy Eriksson’s Master Thesis was completed in January 2003 and presented by Eriksson in a seminar at Natal University, Durban, South Africa, in August 2003. A paper is under preparation for publication in Advances for Space Research.

**Freja results on the sources of the cross-polar potential drop**

The relative contributions from the high-latitude and the low-latitude dynamos at the magnetopause to the cross-polar potential drop was studied using Freja data. Somewhat surprisingly, the low-latitude dynamos make a significant contribution even at times of persistent southward IMF. A paper has been accepted for publication in J. Atmos. Solar-Terrest. Phys. (Blomberg et al., 2004b).

**Astrid-2 results on Sub-Auroral Ion Drifts (SAID)**

Based on Astrid-2 satellite data a statistical study on subauroral ion drifts (SAID) was performed by Sónia Figueiredo. SAID is a subauroral phenomenon characterized by westward ionospheric ion drifts with velocities greater than 1000 m/s. The results show that SAID events occur predominantly in the premidnight sector with a maximum probability located within the 2000 to 2300 MLT sector. Data from one SAID event are given in Figure 6 below. The SAID events are substorm related and show the following changes with substorm evolution: a decrease in the peak drift velocity and in the cross-potential drop; an increase in the latitudinal width of the SAID. By using a new method to calculate the height-integrated Pedersen conductivity, the conductivity minimum as well as the associated SAID are shown to move equatorwards with increasing magnetic activity. However, both these features show a faster response to magnetospheric disturbances than that of the ionospheric trough. Combining these results with the results of the FAC analysis gives a scenario where a current system closing through a preexisting trough region will create an intense poleward-directed electric field to maintain current continuity. The depletion of the ionospheric electron concentration by downward field-aligned currents located equatorward of the SAID peak, will create an even lower conductivity region within the preexisting trough. A paper on these results will appear in Annales Geophysicae (Figueiredo et al, 2004).
Figure 6 SAID event observed by Astrid-2 on 22 January 1999. The top panel shows upward FACs in blue and downward FACs in red and the equatorward electric field (solid line.) The SAID is seen between the two green lines; panel 2 shows the E-field perpendicular to the current sheet; panel 3 shows the east-west B-field (solid line) and the B-field parallel to the current sheet (green line), panel 4 shows the local variation of the E-field (green line) and of the B-field (red line) which correlate well. Panel 5 shows the height-integrated Pedersen conductivity (Figueiredo et al, 2004)

When do pseudobreakups occur in the substorm cycle and why?

More than 400 substorms and 330 pseudobreakups, identified from Polar UV images, have been examined using simultaneous ACE solar wind data to determine the influence of solar wind parameters on the occurrence of different types of substorms and pseudobreakups. The statistical results confirm that the IMF clock angle and the amount of solar wind energy flux control the strength of a substorm. Pseudobreakups occur mainly for weakly positive or zero IMF Bz and for lower solar wind energy flux than observed during substorms. These results support the hypothesis that pseudobreakups represent the weakest type of substorm activity. An analysis of different pseudobreakup events reveals that these may develop during quiet times, during a substorm growth phase or at the end of a substorm recovery phase. (see Figure 7 below). Pseudobreakups are not appearing randomly within a substorm cycle. They typically develop before the first of several substorms, about an hour after an IMF southward turning, or appear after the last substorm in a cycle, when the IMF has returned to a northward
direction. A paper on these results have been submitted to Journal of Geophysical Research (Kullen & Karlsson, 2004).

**Figure 7.** All pseudobreakups identified from Polar UVI data (red bars) overlaid on the AE index for the time period Dec 8-12, 1998. The pseudobreak events are shown to occur for low AE index values during quiet times, and at the beginning or after the end of larger substorm cycles. The fasciated bars mark the times when no UV images were available (Kullen and Karlsson, 2004).

**Electrodynamics of the Mercury environment**

Mercury has an intrinsic magnetic field strong enough for a magnetosphere to be formed. Because of the planet’s proximity to the Sun, photo-emitted electrons from the surface may be significant as a means of conducting current. Blomberg is responsible for the European part of a Japanese-European electric field and wave instrument, to be proposed by Professor Matsumoto at the Kyoto group, for the magnetospheric orbiter of BepiColombo, the first mission to Mercury after Mariner 10’s few encounters in 1974-75 and the NASA Messenger mission to be launched 2004. Presentations of the scientific case for electric field measurements around Mercury and how to accomplish this on the MMO, were given by Blomberg at EGU, Nice, April 2003, and at the IUGG General Assembly, Sapporo, July 2003. A paper on electromagnetic phenomena in Mercury’s environment has been accepted for publication in Adv. Space Res. (Blomberg & Cumnock, 2004b). An extensive literature survey on planet Mercury and its environment was conducted by Cumnock and Blomberg (2003b).

**Plasma diagnostics in Mars’ environment**

Inspired by the upcoming Rosetta fly-by of Mars, a review of the capabilities of Langmuir probes for electric field and plasma density measurements in the Martian plasma environment was published (Blomberg et al., 2003a). This review will be used as input to the operations planning for the fly-by. The results may also be useful for the planning of future missions to the Red Planet.

**A.1.3.7 Disturbances of the plasma environment around a satellite**

The presence of a satellite disturbs the ambient plasma. Charging of the spacecraft creates a sheath around it, and the motion of the satellite through the plasma creates a wake disturbance. Such disturbances complicate the measurement of electric fields and plasma densities using the double-probe technique. This problem was addressed in an Astrid-2 study, as described in earlier progress reports. The Cluster satellites have also experienced problems to measure the electric field, in particular in the polar cap regions characterized by cold outflowing ions and a very low-density plasma, creating wakes around the spacecraft. Studies of these effects are made both by comparing data from several different instruments and by numerical simulations, in collaboration with groups at IRF Uppsala, University of Oslo, Space Sciences Laboratory, University of California, Berkeley, University of New Hampshire, Institut für Weltraumforschung, Graz, and Max-Planck-Institut für Extraterrestrische Physik,
Garching (Eriksson et al, 2004).

A.1.3.8. Astrophysics

Elephant trunks and dark filaments in H II regions

Using images of the Rosette Nebula captured in the H-alpha line with the 2.6 m Nordic Optical Telescope on La Palma, Spain, in 1999 and 2000, Carlqvist has, in collaboration with G. F. Gahm, Stockholm Observatory, and H. Kristen, Lund Observatory, studied dark filaments and elephant trunks in some H II regions. The elephant trunks have turned out to have a very interesting morphology. To a large extent they are built up by dark filaments and knots (Carlqvist et al, 1998). The filaments often seem to be twisted that the trunks appear to have a helical geometry. A new model has been proposed for the formation of such twisted elephant trunks (Carlqvist et al, 2002). The model assumes that an expanding shell around young and luminous O-stars near the centre of an H II region hits a magnetic filament which exists in the molecular cloud out of which the hot stars have been formed. If the filament contains a local mass condensation, and if further the internal magnetic field is not too much twisted, it will assume a V-shape with the apex tending towards the hot stars. Dark, filamentary clouds of such a shape have been observed in several H II regions. If, however, the magnetic field of the mass loaded filament is twisted beyond a certain critical limit, the whole filament next to the apex will be twisted into a double helix. This process may be considered an example of self-organization. The filamentary structure now resembles a Y. The double helix is identified with the twisted elephant trunks.

Figure 8. Picture taken by the Nordic Optical Telescope on La Palma in November 2000. The picture shows one of the larger elephant trunks in the nebula IC 1805 (after Carlqvist et al. 2002, 2003)
The model of the twisted elephant trunks has been further studied both theoretically and by means of a simple, mechanical analogy model (Carlqvist et al, 2003). The analogy model is based on the similarity of magnetic field lines and elastic strings pointed out by Faraday and Alfvén. In the model a mass loaded bunch of elastic strings hangs down from two fixed points of attachment. If, on the one hand, the bunch is only moderately twisted it hangs down in V-shape. If, on the other hand, the bunch is twisted beyond a certain critical limit it forms a double helix next to the mass load so that the overall shape resembles a Y. This is in good agreement with the shape of many elephant trunks. A number of experiments have been performed with the analogy model using various values of the relevant parameters.

A theoretical model of the trunks, based on energy considerations and the conservation of helicity of the magnetic field, has also been worked out. In essence the results of the theoretical model are in good agreement with the experimental results obtained with the mechanical analogy model.

The fingers of the Crab Nebula

The Crab Nebula is the expanding remnant of a supernova observed by Chinese astronomers in A.D. 1054. It consists of a very hot, synchrotron emitting plasma surrounded by a filamentary network of cooler plasma. Images taken by the Hubble Space Telescope (HST) have revealed wonderful details in the filaments. It turns out that in most of the filaments there are outgrowths which point like fingers towards the centre of the nebula. The fingers are not without structure but generally consist of two or more subfilaments. In some of the fingers the subfilaments seem to be twisted around each other. The general view has been that the fingers are the result of the Rayleigh-Taylor instability occurring in the shell of the expanding nebula. However, with this scheme it is not easy to understand the presence of the subfilaments and in particular their twisting. Hence, a new mechanism for the Crab Fingers has been advanced which is capable of explaining both the substructure and its twisting (Carlqvist, 2004). The theory relies on the double helix mechanism that is suggested to be active in the twisted elephant trunks. Although the two kinds of object represent two different environments, the conditions in them are, in principle, rather similar with a hot, expanding inner region surrounded by a shell containing filaments. Double helices are therefore likely to develop in the filaments of the Crab Nebula thus forming the fingers. The double helix mechanism is probably not limited only to the Crab Nebula out of all supernova remnants. HST images of the supernova remnant Cassiopeia A have revealed that twisted fingers seem to be present also in this nebula.

A.1.3.9 References not contained in the list for the year report.


### A.2 Laboratory plasma physics group research

The Laboratory Plasma Group focuses on small-scale experiments aimed at isolating and studying problems in basic plasma physics (often of relevance to space physics). This represents the main research effort, although the group is increasingly engaged in applications of plasma physics (reported in Appendix C2). An essential feature of the research, which has proved scientifically fruitful, is the application of state of the art technology, in order, for example, to achieve high time resolution in data acquisition and storage. This has proved to be of great value in revealing new aspects of plasma dynamics on time scales down to the inverse plasma frequency. Numerical simulations, designed to model as closely as possible actual experimental conditions, are used. These are often indispensable for interpreting the experimental results and in formulating theoretical explanations. An important consequence of this approach is that the group’s PhD students acquire a unique combined competence in both numerical and experimental research. Theory also provides a natural interface to space and astrophysical research. On the other hand, earlier experimental work has often been inspired by questions concerning cosmic plasmas. At present the Laboratory Plasma Group runs three major projects, which are in different stages of development. These are concerned with:

1. **Phenomena associated with high currents in low-density plasma.** This is a well established group of projects, which has produced three Ph. D’s: Herbert Gunell 1997, Torbjörn Löfgren 1999, and Martin Wendt 2001. A central plasma physics issue is the ability of a plasma to maintain anomalous potential differences along the magnetic field, at high currents. Experiments in this area have been made both in stationary and in time-varying situations. Another area concerns the non-linear electric field driven by the electron beams which naturally arise in these situations. These investigations are made using purpose built plasma devices, well developed diagnostic techniques, and computer simulations developed to match the experiments. A major key issue that remains to be resolved concerns the nature of the mechanism coupling the measured high frequency oscillations to the electromagnetic radiation observed outside the plasma. Funding (from the Science Research Council) has been obtained for a concerted experimental and theoretical effort to reveal the basic mechanisms.

2. **Collisionless heating and anomalous diffusion of electrons.** This project has now been running since 1998, when we found that this new and interesting phenomenon could be reproduced in one of our existing plasma devices, a plasma gun where a fast plasma stream penetrates into a region with transverse magnetic field. Such collective motion of plasma across magnetic fields has long been of interest both in the fusion community and in space
physics. We have now, for the first time, experimentally demonstrated anomalous diffusion on an extremely short time scale. New diagnostics and computer simulations have been developed. Fully three dimensional particle-in-cell simulations reproduce many experimental features, and a consistent physical picture is now emerging.

3. Dusty Plasma. This is a relatively recently started project, where future growth will depend to some extent on the interest of the plasma physics community and in particular the availability of funding for external collaboration. Our most recently appointed Ph D student, Muhammad Shafiq, is working on test charge theory and has found new results including the effects of dynamical grain charging and size distribution. We have built up experiments, with suitable diagnostics and a supply of monodispersive dust. The Laboratory Group is also part of the project team for experiments on dusty plasma in microgravity in the International Microgravity Plasma Facility (IMPF) on the Space Station.

In addition to these projects of “basic plasma physics” nature, the lab group members are often engaged in projects within other disciplines of plasma physic. During 2003:

• Axnäs, Brenning, and technician Wistedt have been involved in Applications of microwave plasma, and in A new discharge type for atmospheric plasma processing (Applied Electrophysics, Appendix C).
• Axnäs and Brenning have been involved in Development of a negative ion source (Applied Electrophysics, Appendix C).
• Brenning, together with Tennfors from the fusion group and Marklund from the space group are also engaged in the NASA development of a new type of plasma engine, the Variable Specific Impulse Magnetoplasma Rocket, VASIMR (Appendix A.2.5).
• Raadu together with Rosander and Sedlacek is involved in Electron Beam Sterilization, a project funded by the European Community under the “Competitive and Sustainable Growth” Programme.

A.2.1 Plasma devices and diagnostic methods

The experiments are performed in small-scale devices where low-density plasma is generated by electrical discharges. The devices can easily be adapted for different types of experiments and may be run at reasonable costs. Five experimental devices are currently available:

• A triple plasma machine generating a magnetized plasma column
• A plasma gun giving a streaming plasma,
• A high frequency discharge
• A large tank (“The Green Tank”) where different types of discharges can be run.
• A dusty plasma device with a dust dispenser and plasma source.

Diagnostic tools include motor-driven hot and cold Langmuir probes for time-resolved measurements. Microwave interferometers (8 and 4 mm wavelength) and helium spectroscopy are available for time resolved measurements of electron densities and electron energies. Among available instruments are spectrographs for time resolved measurements and an image intensifier camera. There are three spectrum analysers and three systems with waveform recorders and digital oscilloscopes (sampling frequencies up to 5 Gsamples/s) for data acquisition and data processing. Programs for computer controlled movement of probes, data acquisition and data processing are continuously being developed. Methods for plasma diagnostics are continuously developed to meet the demands from the different projects.
A.2.2 Electromagnetic radiation from high current plasmas

The response of a collisionfree plasma to an electric field parallel to the magnetic field is important in many space and astrophysical situations. Even if particle collisions are negligible the plasma can exhibit an *inertial resistivity*. This has been the subject of both experimental and theoretical studies. A case which has received much attention is that where the electric field becomes localised within *double layers (DLs)*. The concept can be applied in more general situations where DLs appear transiently or may not even reach a fully equilibrium state e.g. for life times shorter than the ion transit time over the structure. An example of the latter case has been used for models of potential drops in the magnetosphere, assuming a given non-equilibrium ion density distribution. This project is intimately connected with turbulent resistivity. Interaction between electron beams and thermal electrons has been studied in our laboratory for some time. An important new finding (Gunell, Verboncoeur, Brenning, and Torvén, Phys. Rev. Lett. 77, 25, p. 5059, 1996) was that the high frequency waves can become concentrate into sharply localised spikes when the beam moves towards increasing density. A theoretical model has also been worked out for this new type of localisation of wave energy. It gives an alternative to the, previously known, mechanism of localisation by strong Langmuir turbulence.

These experiments have been continued in a plasma column with a uniform axial magnetic field. A sudden voltage drop is periodically applied to the plasma along the magnetic field. The initial increase of the current to a maximum value corresponds to an inertial resistance, and can be derived theoretically as for a plasma diode. The subsequent current drop leads to a saturation value nearly independent of the applied voltage. During this development the potential profile steepens and the ion density is redistributed. The current decrease is mainly due to a density decrease caused by radial ion losses. These losses are the consequence of the strong radial electric field that appears when the potential drop is applied along the magnetic field. The results throw light on earlier experimental work on turbulent (anomalous) resistivity. Particle-in-cell simulations show that when a step voltage is applied to a plasma with a density minimum high potential drops can form over the region where electrons move towards decreasing density. There is good agreement with the experimental results. An equivalent circuit analysis leading to a modified van der Pol equation agrees well with the experiments and explains the observed hysteresis and jumps in oscillation amplitude. This work was an important part of Martin Wendt’s doctoral thesis (2001).

In a separate series of experiments a sharp density maximum can be observed at the position of a high frequency spike, when the field is sufficiently strong (typically 40 kV/m) and when the background density of neutral gas is not too low. The electrons may get a kinetic energy in their oscillatory motion that exceeds the ionization potential of the background gas. There are possible connections with the narrow density spikes observed on the topside of the E-layer in the ionosphere (e.g. Schlesier et al., Geophys. Res. Lett. 24, 1407, 1997).

A key question that needs further research is the mechanism for producing the observed electromagnetic radiation observed outside the plasma. An experimental series has been made with magnetic pickup coils to measure the radiation from the high frequency spike. The radiation contains the same frequencies as the spike itself, but also other frequencies which might be apparatus-dependent. In order to investigate whether there is any correlation between the observed electromagnetic radiation and the oscillations in the hf spike, a probe was inserted in the hf spike in order to measure the local electric field. This resulted in an increase in the measured electromagnetic field signal by a factor of typically four, without any
indication that the hf spike amplitude changed. One interpretation is that the electric field probe acted as an antenna which was fed by the field in the hf spike. The conclusion from this experiment (apart from the obvious fact that such measurements must be made with care) is that the radiation indeed originates in the hf spike, and not in the charged particles which are accelerated in the double layer itself. Further experiments and theoretical investigations are planned financed by funding from the Science research council.

A.2.3 Collisionless heating and anomalous diffusion of electrons

The injection of plasma across a magnetic field has received attention both in connection with fusion plasma experiments and in space physics. Relevant situations in the interstellar space are many. Magnetized plasmas in relative motion are driven by the stellar winds from young stars, by the shock fronts from supernovas, and by the rotation of neutron stars. Where magnetized plasmas in relative motion meet, processes of the type we study become relevant. The involved mechanisms are of interest to a general understanding of plasma dynamics. Theoretical, numerical, and experimental studies have been made for a long time, but still fundamental aspects of the physics remain to be understood. Also more practical applications are of interest. Some specific examples are the refuelling of magnetically confined fusion plasmas, the dynamics of high energy industrial plasmas for surface treatment, and the coupling between plasma jet and magnetic nozzle in next generation’s plasma rockets for interplanetary space propulsion, see for example http://spaceflight.nasa.gov/mars/technology/propulsion/aspl/vasimr.html.

The project is part of the PhD thesis work by Tomas Hurtig, supervised by Brenning and Raadu. There is current interest in these processes in magnetospheric physics. The plasma gun experiments are used to study the injection of plasma across a magnetic field exploiting up to date measurement methods with high time-resolution. In these experiments a conical theta pinch shoots a beam of fully ionized plasma into an interaction region with a transverse magnetic field component. The beam is deflected in a direction opposite to the curvature of the field in the interaction region, and this reverse deflection occurs already in the upstream region. The beam crosses the magnetic field by setting up a polarisation electric field such that particle drift motion is comparable to the beam velocity. The dynamics of the strongly magnetised electrons is difficult to understand. An anomalous diffusion is required for the electrons to reach all parts of the beam. Energetic tails in the electron distribution function are formed when the plasma enters the transverse magnetic field. We believe that this process is intimately coupled to the anomalous diffusion of electrons across both the magnetic field and the electric equipotential surfaces. Extensive laboratory measurements are being made to be clarify the mechanisms. The above results were presented by Hurtig at the Sixth International Workshop on Interrelationship between Plasma Experiments in the Laboratory and Space, 2001 at Niseko, Japan, and published as a TRITA-ALP report (Hurtig, Brenning, and Raadu, 2001).

The experiments reveal that there is high level of electrostatic waves in the transverse field region. Different types of probes are being developed to find the phase velocities, polarisation, and amplitudes, in order to determine the nature of the waves and to assess the consequences for electron transport. A direct measurement of density and electric field fluctuations (500kHz to 20MHz) gives on averaging an estimate of this transport. Multiple probes are used to measure phase velocities and electric field direction. Reliable and tailor-made diagnostics is a key to the advanced analysis techniques we use. Hf measurements of density, electric fields, and magnetic fluctuations can be combined to yield quantities such as the anomalous...
resistivity, and the magnetic Reynolds number. In such an approach, the reliability of the measurements is essential. A publication is in print (Hurtig and Wistedt, 2003).

The reverse deflection and electron diffusion mechanisms are also studied by modelling the experiments by XOOPIC simulations. The XOOPIC code uses the particle in cell (PIC) method with two space and three velocity dimensions. The simulations show many points of agreement with the plasma gun experiments: The heating of electrons as they enter the region of curved magnetic field is reproduced; There is clear evidence of anomalous transport; There is an upstream reverse deflection of the plasma beam.

Fully three-dimensional particle-in-cell simulations, using the code written by Hurtig, have also been run and analyzed in detail. The simulation reproduces a large number of experimental features which have earlier been incompletely understood, and gives the first comprehensive and self consistent physical picture of the penetration of a plasmoid under the conditions of the simulation (Figure A.9). The detailed studies of the diamagnetic current systems and the magnetic-field-aligned electric fields are of particular interest to understanding the penetration of plasmoids in the magnetosphere.

Work has been initiated to parallelize the 3-D computer code for more powerful computers, with the intent to better approximate the parameter range of the experiments. Computer time, 150 CPU-hours per month, has been approved by the National Supercomputer Centre in Linköping. A detailed study of the instabilities is not within reach of our 3-D simulations. Therefore a separate 2 1/2-D (periodic boundary) simulation of the instabilities has been initiated, and preliminary runs show promising parallels to the experimental data.

A.2.4 Complex Plasmas

Recent years have seen a rapid development of research on complex (dusty) plasma. This is partly a consequence of the natural progress of plasma physics towards the study of more complex systems, such as the present case where the presence of dust grains adds significant new physics. There are many applications to astrophysical regions such as planetary rings, comet tails, and interstellar nebulae. Dust can cause practical problems in plasma applications, such as industrial plasma processing where it is a troublesome contaminant. Improved diagnostics and a better understanding of the interrelated physics of the dust and plasma can hopefully lead to more effective dust removal methods. Even though fusion plasmas are designed to have high temperatures, dust can play a significant role in the cooler outer layers of fusion devices. Specially designed, relatively inexpensive, small scale experiments can contribute to a greater understanding of dusty plasmas that can have wide application both to technical applications and other pure research areas.

The Laboratory Group at the Alfvén Laboratory has aimed at identifying research areas within the rapidly growing field of dusty plasmas that are ripe for development and are suited the group's particular combination of research interests and expertise. In this way it is possible to be in a position to make a contribution to front line research. One such area concerns the collective effects of the time dependent charging of dust grains in a dusty plasma. The general purpose of the research is to obtain a clearer general insight into how the dynamical charging effects can be theoretically modelled and to test this knowledge experimentally.

Conventional plasmas exhibit a complicated behaviour due to the collective interaction of the constituent charged particles, neutral gas, ions and electrons. The relevant physics of the
individual particles is in principle simple: they have charge and mass and their motion is
determined by collisions and by the electromagnetic field. To understand the complexities that
arise due to the mutual interaction of large numbers of particles requires extensive theoretical
analysis and numerous experiments. In a dusty plasma the dust grains, normally negatively
charged by the plasma random currents, provide an extra component. The complexity of the
resulting collective properties is enhanced by the introduction of new physical processes, in
particular the dynamics of the charging of the dust grains.

The time dependent charging of grains adds a completely new factor to be taken into account
in studies of the dynamic behaviour of dusty plasmas. The grain size influences the response
to all perturbations which vary in time. The dust component can in such situations be grouped
in three classes. Small grains with a long time constant for charging will have close to constant
charge during the perturbation. Large grains with short charging times will at all times be in
equilibrium with the changing plasma conditions. The group with intermediate size can be
called Critical-Charge-Time (CCT) grains. Those will show hysteresis effects: the charge will
be changing but delayed in time with respect to the perturbations. The finite charge relaxation
time leads to a new type of wave damping due to the resulting time delay (phase shift)
between the plasma perturbations and the resulting changes in grain charge (F. Melandsø, T.
K. Aslaksen, O. Havnes, Planet. Space Sci. 41, 321 (1993)). For a dust component with a grain
size distribution the most efficient damping should be provided by CCT-grains i.e. those with
charging time comparable to the wave period.

A.2.4.1 Dusty Plasma Research Activity

Laboratory experiments on dusty plasmas have been made exploiting preexisting laboratory
resources and using purposely built equipment for the present studies. An array of plasma
sources, measuring and recording devices has already built up over many years. Dust
dispensers have now been specially developed, in order to give a controlled steady delivery of
dust grains within a vacuum chamber

The main experimental work (Figure I) concerns the influence of dust on the oscillation modes
of an extended anode plasma region ("plasma ball") bounded by a spherical double layer
(initiated as diploma work by Tommy Johansson led by Ingvar Axnäs). The double layer was
formed close to an extra anode in an unmagnetized plasma created by a discharge between
emitting tungsten filaments and a main anode. Dust could be released through a hole in the
extra anode, situated in the upper part of the discharge tank, and then fall down into the
plasma. The grain flow was controlled by a motor-driven dust dispenser. The double layer
electric field was strong enough to in principal support the negatively charged grains against
gravity.

It was found that the dust can inhibit the oscillations of the "plasma ball". For the chosen
experimental parameters the oscillations took the form of a pulse train with pulse widths about
20% of the oscillation time. The double layer disappeared totally between the pulses. When
dust grains were introduced into the spherical double layer it was found that the oscillation
time increased by a factor of five whereas the pulse width remained about the same as without
dust. The free fall time of a dust grain in the double layer region is much larger than any of the
oscillation times so that the dust grain will repeatedly be in two different plasma
environments. For the experimental parameters the dust charging time is of the order of the
observed oscillation times. Grain charging effects may therefore be responsible for increasing
the "recovery" time to form a new pulse.
Most recently a detailed parameter study has been made, varying the density of the background plasma (Ingvar Axnäs). This was found to have a direct influence on the period and form of the pulses in the oscillating mode. However the nature of the “plasma ball”, in particular the sharpness of the boundaries, could only be controlled by varying the secondary discharge current. This indicates the relevance of both the external circuit and the internal plasma properties to the physics of the “plasma ball”.

![Image of plasma ball with and without dust](image)

*Figure A.2.1. Oscillations of the plasma ball with (lower right panel) and without (upper right panel) dust. The ball forms at an anode and is maintained by ionising electrons accelerated by a double layer at the surface. Excitation of the neutral gas makes the ball visible (left panel).*

The project financed by RS is within a broader program on dusty plasmas. Within this program a series of scientifically interesting experiments are planned and can be performed depending on the funding obtained:

- Collisions between dust clouds trapped in striations. This is a first experiment of its kind.
- Elevation and strong coupling of non-spherical dust.
- Extraction of unwanted dust from plasma.
- Dust in strong magnetic fields. In sufficiently strong magnetic fields, $B > 1 \, \text{T}$, dust becomes magnetized (the gyro radius becomes smaller than the apparatus dimensions).

The theoretical work on dusty plasmas relates to the experiments as well as to basic plasma physics and space research, and includes work on the kinetics of dusty plasmas (Raadu, Shafiq) and the theory for the spoke structure in Saturn's rings (Brenning). Specific theory projects include:

- Effective distribution functions for the electrostatic response of a dusty plasma with grain size distribution have been found. For a class of size distributions there is an equivalence to a Lorentzian distribution of mono-sized particles [Raadu (2001) IEEE Trans. Plasma Sci., **29**, 182]. This work is of general interest since a naturally occurring dust component should normally have a size distribution. A size distribution of dust grains changes the plasma response to a moving test charge [Shafiq & Raadu (2002) Phys. Lett. A, **305**, 79]. Also the resulting effective distributions can provide a test bed for studying the response for non-
Maxwellian distributions. A related new type of collisionless damping in magnetised dusty plasmas is also being studied.

• Consequences of dynamical grain charging for the dielectric properties of a dusty plasma [Raadu TRITA-ALP-2002-04; Raadu, 2003; Raadu & Shafiq, 2003; Shafiq & Raadu, 2004]. Since the charging time depends on the grain size rather than the mass, typical rates can approach the frequencies for the conventional plasma components, e.g. the ion plasma frequency. (This is of relevance to the “plasma ball” oscillation experiments.) Results including the combined effects of dynamical charging and a size distribution have also been obtained [Raadu TRITA-ALP-2002-04].

• Non-linear electrostatic structures such as double layers and solitary waves are modified by the presence of a charged dust component. The effects of charge fluctuations have been considered. In the special case where the grain charge is in equilibrium with the local plasma there is a constant of motion which may be used to find a generalisation of the Sagdeev potential [Raadu, 2003].

• The electrostatic response of a dusty plasma with a grain size distribution to a slowly moving test charge has been investigated [Shafiq & Raadu (2002) Phys. Lett. A, 305, 79]. Fully analytical results have been found up to second order in the charge velocity. The form of the grain size distribution strongly influences the linear dielectric response of a dusty plasma, and consequently the structure of the electrostatic response potential. The effects of collisions were included.

• The response of a dusty plasma to a moving test charge in the case of dynamical grain charging has been studied. Earlier results were only found using an asymptotic approximation, whereas a fully analytical expression for a slowly moving test charge to second order in the velocity has now been found [Raadu & Shafiq, 2003]. Comparisons with a model using a delay operator for the charging clearly demonstrate that the main modification to the response is due to a delayed shielding [Shafiq & Raadu, 2004].

• Numerical results have been found for a test particle in a dusty plasma moving with high velocity (large Mach number) for the case of a dust component with a distribution of grain sizes and dynamical grain charging. The dusty plasma response has a complex pattern due to the dispersive properties of the wave modes as in Figure A.2.2 for the case of a monosized Maxwellian dust distribution. (This work will be continued by a diploma student)
A.2.5 The VASIMR plasma Rocket Engine

The Laboratory group continues to be involved in a new project, the NASA development of a new type of plasma engine, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR). This involves a cooperation across ordinary disciplinary borders, making good use of the broad plasma and space science competence within the Alfvén Laboratory.

The key to the VASIMR rocket operation is its capability to vary or “modulate” the plasma exhaust velocity while maintaining maximum power. This new type of technology could dramatically shorten transit times for missions to other bodies in the solar system compared to conventional rockets. The present VASIMR research programme is based on a history of laboratory prototypes of increasing power. The first space flight experiment using this new technology is presently being designed, is proposed for use in keeping the Space Station in orbit, neutralizing the drag against the upper ionosphere. From the scientific aspect, plasma production and heating are key problems. Production of plasma is made with a Helicon plasma source at 25 MHz, while the final heating of ions to exhaust energies is made by Ion Cyclotron Resonance Heating (ICRH). Computer simulations are used to guide and understand the experimental effort. Specialized plasma diagnostics are critical for determining the behaviour of the system. High frequency (HF) probe measurements and modelling of the ICRH heating region are subprojects where the KTH group are involved. Tailor-made probes and matching circuits have been developed (Brenning, Cyrus, Tennfors, and Chang-Diaz, 2003, High-Frequency Probing Diagnostics for the VASIMR Rocket Engine).

During 2003 two students did their Master theses within the project: Anna Forsell studied the ICRF heating and developed a graphical Matlab interface for data access. Christian Valenzuela studied the plasma source, in particular the lower hybrid wave (Trivelpiece-Gould mode), which is in fact responsible for the ionization in the “helicon source”. (The helicon wave is evanescent in the VASIMR plasma, as well as in many other “helicon sources” due to the small radial extension.)
Measurements are made on the VX10 experiment in Houston with an electrostatic probe, offering good spatial resolution, and a combined electrostatic-magnetic probe for Poynting flux measurements. The measurement programme is aimed at:

- The azimuthal electric field strength as a function of the radius and the axial distance z from the antenna, employing double probes, each measuring the azimuthal field.

- The radial electric field component as a function of radius. This field is zero at the antenna, and should indicate where the plane polarised vacuum wave field is modified by the plasma.

- Vector electric field measurement, i.e. simultaneous radial and azimuthal field components, (the axial z field is expected to be weak). This should give information about which of the two polarization directions that is surviving in the plasma, a very important measurement since only one of them heats ions.

The magnetic field at the ICRH antenna is adjusted for the fundamental cyclotron resonance for the used ion species, singly ionised helium, and frequency, 1.85 MHz, using the left-handed elliptic polarisation. This wave cannot propagate in the probe region, where the magnetic field is lower and the ion cyclotron frequency is below the generator frequency. The wave observed by the probes appears to be right-handed elliptically polarized but still evanescent. The “helicon antenna” is also changed and the combined changes in wave number spectra turns out to modify the observed non-linear interaction.

A.2.6 Computer simulations and theory

Numerical methods, in particular particle in cell (PIC) simulations, are used to model the experiments. Theory provides a link between the simulations and experiments and is essential for planning new investigations. Recent results concerning the simulation of plasma penetration across a transverse magnetic field are referred to above using a three-dimensional electrostatic code developed in-house for the purpose by Tomas Hurtig. In order to benefit from future developments of new PIC codes (or hybrid codes for long time simulations) as well as using existing codes and numerical methods, the computing capability is continually updated.

A.3 Publications by the Division of Plasma Physics

A.3.1 Refereed publications


Hurtig, T., Brenning, N., and Raadu, M., Three dimensional particle-in-cell simulations with
open boundaries applied to a plasma beam entering a curved magnetic field, Phys. Plasmas. Vol 10, 4291 – 4305, 2003


A.3.2 Other publications


A.3.3 Forthcoming publications 2004 ---


Marklund, G. T., Unveiling the Secrets of the Black Aurora, to be published as Royal Institute of Technology Report, 2004b.


A.4 Conferences and workshops

A.4.1 Invited talks and articles

2003-06-30
T. Karlsson, G. Marklund, S. Figueiredo, and T. Johansson, Cluster electric field
measurements from the plasma sheet boundary layer at IUGG General Assembly, Sapporo, Japan

2003-10-07
**G. Marklund**, Cluster Science Studies at Alfvénlab, KTH at Cluster EFW meeting, Uppsala, Sweden

2003-11-26
**G. Marklund**, Cluster-satellite kastar nytt ljus över norrskenet, KVA open lecture, Stockholm, Sweden

2003-12-08

2003-12-09
**G. Marklund**, Rythms of the Auroral Dance at LEIF-EU network conference, Stockholm, Sweden

### A.4.2 Contributed papers – oral presentations

2003-06-30
**L. G. Blomberg** and J. A. Cumnock, Electrodynamics of transpolar aurorae at IUGG General Assembly, Sapporo, Japan

2003-07-07
**L. G. Blomberg** and J. A. Cumnock, Electric fields at Mercury at IUGG General Assembly, Sapporo, Japan

2003-10-27
**G. Marklund**, Cluster Science at Alfvénlab, KTH at IRF-U/IRF-Um/KTH meeting, Uppsala, Sweden

2003-10-27
**T. Hurtig**, N. Brenning, and M. A. Raadu, Experiments on the penetration of plasma clouds across magnetic boundaries: the role of high frequency oscillations at 45th Annual Meeting of the Division of Plasma Physics, Albuquerque, NM, USA

2003-12-09
**T. Karlsson**, G. T. Marklund, S. Figueiredo, T. Johansson, S. Buchert, Separating spatial and temporal variations in auroral electric and magnetic fields by Cluster multipoint measurements at AGU Fall Meeting, San Francisco, CA, USA
A.4.3 Contributed papers – written contributions and poster presentations

2003-04-07
L. G. Blomberg and J. A. Cumnock, Electric Fields in Mercury's Magnetosphere at EGS-AGU-EUG Joint Assembly, Nice, France

2003-04-08
N. Ivchenko, B. Lanchester, M. Rees, A. Stockton-Chalk, and K. Throp, The occurrence of OII lines in electron and proton aurora over Svalbard at EGS-AGU-EUG Joint Assembly, Nice, France

2003-04-08
A. Kullen, T. Karlsson, and Y.-K. Tung, Pseudobreakups and their relation to solar wind parameters: a statistical study at EGS-AGU-EUG Joint Assembly, Nice, France

2003-04-10
T. Johansson, S. Figueiredo, T. Karlsson, G. T. Marklund, P.-A. Lindqvist, A. Fazakerley, and S. Buchert, Analysis of high-altitude auroral electric fields based on CLUSTER data at EGS-AGU-EUG Joint Assembly, Nice, France

2003-04-10
J. A. Cumnock, L. G. Blomberg, S. B. Mende, and J. F. Spann, Transpolar Arcs and Hemispheric Asymmetry at EGS-AGU-EUG Joint Assembly, Nice, France

2003-05-06

2003-05-06
L. Bylander, P.-A. Lindqvist, Research, education and technical developement performed by the Space group at Rymdforum 03, Kiruna, Sweden

2003-07-08
J. A. Cumnock, L. G. Blomberg, S. B. Mende, and J. F. Spann, Simultaneous high-latitude aurorae in both hemispheres at IUGG General Assembly, Sapporo, Japan

2003-07-15

2003-09-09
M. Shafiq, and M. A. Raadu, Delayed shielding of a test charge in a dusty plasma with grain charging dynamics at International Topical Conference on Plasma Physics, Complex Plasmas in the New Millenium, Santorini, Greece

2003-10-22
G. Olsson, L. Bylander, and G. Marklund, Varför finns Alfvénlaboratoriet i rymden? at Rymdforum i Riksdagen, Stockholm, Sweden
2003-10-31
T. Hurtig, N. Brenning, and M. A. Raadu, Two dimensional electrostatic simulations of fast anomalous electron transport due to the modified two stream instability at 45th Annual Meeting of the Division of Plasma Physics, Albuquerque, NM, USA

2003-12-08
J. A. Cumnock and L. G. Blomberg, Simultaneous Polar Aurorae and Convection Patterns in both Hemispheres at AGU Fall Meeting, San Francisco, CA, USA

2003-12-08
L. G. Blomberg, J. A. Cumnock, I. I. Alexeev, E. S. Belenkaya, S. Yu. Bobrovnikov, V. V. Kalegaev, Transpolar Aurora: Time Evolution, Associated Convection Patterns, and a Possible Cause at AGU Fall Meeting, San Francisco, CA, USA

2003-12-09

A.4.4 Seminars at foreign research institutes and other lectures

2003-03-12
N. Ivchenko, Time resolved imaging of metastable ions in the aurora at University of Leicester, Leicester, United Kingdom

2003-04-28
J. A. Cumnock, Space Weather, at KTH, Stockholm, Sweden (docent lecture)

2003-08-15
T. Eriksson, Wave Pulsations in the Magnetosphere and Their Dependence on the Solar Wind at Natal University, Durban, South Africa

2003-08-15
L. G. Blomberg, The Space Research Programme at AL, KTH at Natal University, Durban, South Africa

2003-10-06
N. Ivchenko, Deriving plasma drifts from the [OII] auroral emission - an instrument concept at Atmospheric Physics Laboratory seminar, University College London, United Kingdom

2003-10-13
A. Kullen, The dependence of global auroral morphology on solar wind conditions: A statistical study based on Polar UVI images and ACE solar wind data at University of Southampton, United Kingdom
A.5 Collaboration and contacts

Most of the projects are carried out in international collaboration, the main partners being:

Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts, USA
Centre d’Etude des Environnements Terrestre et Planétaires, Vélizy, France
Cornell University, Ithaca, NY, USA
Danish Space Research Institute, Copenhagen, Denmark
Danish Technical University, Lyngby, Denmark
European Space Research and Technology Center, Noordwijk, Holland
Finnish Meteorological Institute, Helsinki, Finland
Imperial College, London, UK
Institute for Nuclear Research, Kiev, Ukraine
Institut für Weltraumforschung, Graz, Austria
Izmiran, Troitsk, Russia
Johns Hopkins University, Laurel, MD, USA
Laboratoire de Physique et Chimie de l’Environnement, Orléans, France
Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
Max-Planck-Institut für Aeronomi, Lindau, Germany
Northeastern University, Center for Electromagnetics Research, Boston, MA, USA
Southwest Research Institute, San Antonio, TX, USA
Swedish Institute of Space Physics, Kiruna and Uppsala, Sweden
Technische Universität, Braunschweig, Germany
University of California, Berkeley, CA, USA
University of Calgary, Calgary, Canada
University of Iowa, Iowa City, USA
University of Natal, Durban, South Africa
University of New Hampshire, Durham, NH
University of Oulu, Oulu, Finland
University of Sheffield, Sheffield, UK
University of Texas, Dallas, TX, USA
Appendix B
Detailed Report from the Division of Fusion Plasma Physics

B.1 EXTRAP T2R experiment

EXTRAP T2R is a medium sized reversed-field pinch (RFP) experiment (aspect ratio R/a = 1.24 m / 0.18 m). The RFP configuration is dependent on an ideal wall for MHD stability. A special feature of the T2R device is that the wall is resistive with a magnetic penetration time (6 ms) that is shorter than the pulse length (typically 20 ms).

The scientific programme for the EXTRAP T2R device during 2003 has focused on the following areas:

- The study of MHD stability with a resistive wall boundary.
- The development of active feedback control methods to stabilise resistive wall modes.
- The study of turbulence in the plasma edge region and the effects of turbulence on transport.
- The study of confinement improvement based on pulsed poloidal current drive (PPCD) and quasi single helicity (QSH).
- The use of resistive 3-D MHD numerical simulation codes to model and predict the confinement properties of the RFP with profile control effects included.

The T2R device is an excellent experimental platform for these studies, many of which are generic for toroidal confinement experiments. In particular the studies of resistive wall mode (RWM) stability and active feedback control of RWMs are providing information that is important for the RFP (in order to operate with pulse lengths longer than the wall magnetic penetration time) and for advanced operation in the tokamak (in order to operate above the no-wall beta limit).

T2R is unique among resistive wall RFPs because during normal operation the internally resonant tearing modes (also called the dynamo modes) are rotating with a sufficiently high velocity so that the radial component of the modes at the wall is suppressed. This has several beneficial effects:

- The growth of the non-resonant resistive wall modes can be easily diagnosed and active feedback control can be studied at low current levels.
- A wealth of nonlinear MHD mode dynamics such as 3-wave mode coupling, phase alignment and wall locking can be studied.
- The edge region is axisymmetric so local studies of turbulence and transport in the edge region, using probes, can be generalised.

Furthermore, the experiment has been equipped with a comprehensive set of magnetic diagnostics that enable detailed measurement of mode dynamics.
**Scientific studies**

The major part of the experimental programme has focused on studies dealing with resistive wall mode stability and the first results of active mode control have been achieved. The RWM work has been done in collaboration with the staff of Consorzio RFX, Padova and the fall of 2003 has been devoted to commissioning and operation of the feedback systems. A smaller effort has focused on the dynamics of the resonant tearing modes and has largely involved analysis and interpretation of data. The edge plasma turbulence studies are also done in collaboration with a group from Consorzio RFX. Extensive campaigns were carried out on T2R in the Spring of 2003 and these have been followed by analysis and interpretation. Confinement improvement studies have focused on PPCD and QSH.

**Resistive wall mode stability**

Resistive wall modes are unstable free-boundary MHD modes that can be stabilised by an ideal conducting wall placed in the proximity of the plasma boundary but modes are unstable when the wall is resistive. The magnetic field produced by the perturbation can diffuse through the wall, hence the name resistive wall mode. The growth rate, which is determined by the rate of diffusion of the magnetic field through the wall, is normally much slower than the no-wall growth rate so active feedback can be envisioned as a means of stabilising the RWM.

Many relevant features of the physics of the RWM instability and the physics of the active control of the RWM growth are the same for both the reversed-field pinch (RFP) and tokamak configurations. The Eigenmode equations for linear stability in cylindrical geometry for both the cylindrical tokamak and the zero beta RFP have the same general form when written in terms of the perturbed magnetic flux. The modes are helical with poloidal and toroidal mode numbers \((m,n)\) and the basic physics can be described by considering a single mode. In the RFP the most important RWM modes are the \(m = 1\) non-resonant, current-driven ideal kink modes, and active feedback is necessary for long pulse operation. In the high beta tokamak configuration, the unstable modes of interest that can be stabilised by an ideal wall are \(n \neq 0\), pressure-driven, external kinks. These modes limit beta in advanced tokamaks and there is a “no-wall” beta limit and a larger “ideal-wall” beta limit. With a resistive wall, the mode limits beta to the no-wall limit, but the growth rate of the mode is determined by the wall penetration time. Active control of RWMs can therefore give access to high-beta operation approaching the ideal wall limit in advanced tokamaks.

The no-wall unstable mode is stabilised by the presence of an ideal wall at \(r = r_w\) outside the plasma of radius \(a\) with \(a < r_w\). The region between plasma edge and the wall and the region outside the wall are vacuum regions. The basic function of active feedback is to provide a control magnetic field outside the wall with the appropriate spatial structure to compensate for the decay of the perturbation-produced eddy current pattern. An array of saddle coils provides the control field. In effect the field in the magnetic region inside the wall is sustained as if the wall were ideal and the growth of the mode is suppressed. Thus the actuator in the feedback loop is the saddle coil array placed outside the resistive wall. The sensors are toroidal arrays of magnetic diagnostics placed inside the wall on the surface of the toroidal vacuum vessel.
Here it is appropriate to comment on the role that field errors can play in affecting the growth of RWMs. In general two types of field errors can be discussed. First there can be non axisymmetric features external to the wall that produce magnetic field errors. Coil misalignment, current feeds to coils and transformer core leakage flux are classic examples of this type field error. These externally produced field errors diffuse through the wall penetrating the region inside the wall. The second type of field error is produced by imperfections in the wall itself such as gaps and access port cut-outs. When there are changes in the equilibrium current, (i.e. current rise), such defects in the wall produce field errors that promptly appear inside the wall and perturb the force balance. During a sustained flattop current, these field errors decay with a characteristic circuit-like L/R time.

Both the externally-produced field errors and the wall-produced field errors can have a broad spectrum of harmonics including harmonics resonant with the potential RWMs. Resonant field error amplification occurs when the eddy current produced by the growth of the plasma perturbation harmonic itself is coherent with the wall current pattern associated with a field error. The coupling between the perturbation and the eddy current (field error) circuit can drive growth of the field error and reinforce growth of the plasma perturbation.

The starting point for RWM studies is the capability to measure the growth of the modes. An example of the time dependent growth of three different RWMs during a discharge is shown in Fig. 2.1. Note that the perturbations are shown on a logarithmic scale. The growth rates are quite constant for the flat-top phase of the discharge. An example of the effect of field errors can be seen in the growth of the \( n = -8 \) mode, which shows an initial fast growth for the first 1-ms of the discharge during the plasma current ramp up phase, when the prompt field error is large. This initial fast rise is therefore attributed to field errors caused by non axisymmetry features in the resistive wall.

The RWMs are current driven non-resonant kinks and therefore the growth rates are dependent on the equilibrium current density profile. The current profile equilibrium is modelled using three traditional RFP parameters, the pinch parameter, \( \Theta \), the reversal parameter, \( F \), and the plasma beta. The amplitudes of RWMs without feedback are in agreement with what is expected from the RWM stability analysis except for the low \( |n| \) modes.
The active feedback system for stabilisation of RWMs on T2R

Active feedback control requires a sensor (an array of magnetic coils), an actuator (an array of saddle coils) and a controller which implements a feedback law for real-time control of the RWMs. An array of 64 saddle coils has been installed on EXTRAP T2R with the following parameters:

- The array has four coil positions in the poloidal direction (width of $360^\circ/4$) and is $m = 1$ connected (i.e. top-bottom coils series connected and inboard-outboard coils series connected).
- There are sixteen positions in the toroidal direction (width of $360^\circ/32$) so that the coverage is 50%. Control harmonics can be produced for targeted modes in the range $-8 < n < +7$ with sidebands at $\Delta n = 16$ intervals. For example targeting $n = +2$ also produces an $n = -14$ and an $n = +18$ control field harmonic.

There are 256 coils in the sensor coil array, which measures the radial component of the perturbation inside the wall (shell). The array has the following parameters:

- Four coil positions in the poloidal direction (width of $360^\circ/4$ and $m = 1$ connected).
- Sixty-four positions in the toroidal direction (width of $360^\circ/64$) so that the coverage is 100% and the sensor coil width is 1/2 the saddle coil width. Mode harmonics can be resolved for modes in the range $-32 \leq n \leq +31$.

Two types of controllers have been developed tested:

- A digital controller, which is a prototype of the controller under development for the RFX device at Padova. (reference G Marchiori, Fus Eng and Design 66-68 (2003) 691.).

The intelligent shell utilises multiple analogue PID controllers. There is one controller for each sensor-coil/saddle-coil feedback loop. The feedback nulls the net radial field at each saddle coil position. An overview of the analogue intelligent shell controller is presented in Fig. 2.

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Fig. B.1.2 A schematic of the analogue intelligent shell active feedback control system. The controller freezes the average radial field at the sensor coil to zero thus simulating an ideal wall locally.
The RFX real-time digital controller performs a fast Fourier transform (FFT) on the sensor coil array data and utilises a feedback law to determine the desired control field harmonics. An inverse FFT is used to determine the corresponding distribution of control signals to steer the individual currents to the saddle coils in the array. The digital controller has been operated both as 1) a pseudo-intelligent shell controller where the feedback law implemented simulates the analogue intelligent shell controller and 2) as a multiple mode controller where the feedback gain for each RWM Fourier harmonic is individually selected in order to generate an output distribution of currents to the saddle coils appropriate to optimise feedback stabilisation of as many modes as possible.

Results from active feedback studies

The saddle coil array is used to produce control field harmonics. The potential of the system for effective feedback is dependent on the quality of the control harmonic spectrum. A perfect helical harmonic cannot be produced by an array of saddle coils (with finite coil width) that cover only 50% of the surface. The spectrum of the control field can be calculated, but in order to include the effects of non axisymmetry in the vacuum vessel and wall, an accurate 3-D representation of the device must be used. However the spectrum of the control field harmonics can be measured with the same sensor coils that are used to measure the plasma mode spectra. This is a straightforward test and can be used to determine the transfer function without plasma, which relates the saddle coil-produced field to the field measured by the sensor coil array. The transfer function is necessary to implement a feedback law in the controller function. In the tests, the RFX controller is used to produce a specific control harmonic with a specified time dependent amplitude and time-dependent phase. A database for transfer functions has been established for T2R.

The example spectrum of the control harmonics is shown in Fig. 2.3 for a case where the targeted mode is $n = -8$ and a side band at $n = +8$ is seen as expected since saddle coils are located at 16 toroidal positions (i.e. side bands at $\Delta n = 16$).

![Figure B.1.3](image-url)  

Fig. B.1.3 Spectrum of control harmonics produced when the $n = -8$ mode is targeted. The spectrum is measured using the sensor coil array data. Note the sideband at $n = +8$.  

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The next step in developing the active feedback system was to verify that the control field harmonic can alter the growth of the unstable mode in accordance with linear stability theory. In the absence of feedback, the radial perturbation, $b_r$, is derived from the solution of the stability equation for the single mode. The growth rate $\gamma_{mn}$ of the RWM is then defined by the jump of the radial derivative at the wall [ref C G Gimblett, Nuc Fus 26 (1986) p 617.],

$$2\gamma \tau_w = r_w \left( \frac{b_r'}{b_r} \right)_{\tau w+} - \left( \frac{b_r'}{b_r} \right)_{\tau w-} = r_w (\Delta_{\tau w} - \Delta_{\tau w}) = r_w \Delta' .$$

Here $\Delta$ is the logarithmic derivative of $b_r$, $\Delta_{\tau w}$ and $\Delta_{\tau w+}$ are values at the inside surface (plasma-facing) and outside surface of the wall respectively and $\Delta'$ is the discontinuity in the logarithmic derivative at $r_w$. When introducing feedback, the main assumption is that the external feedback currents do not modify the equilibrium. Therefore the role of the plasma is specified by a single parameter, the growth rate, $\gamma$, of the RWM without feedback currents.

With feedback the outer solution is changed and Eq. 1) becomes

$$2s \tau_w = r_w \Delta' ,$$

where $s$ is the growth rate with the effects of feedback included and $\Delta'\gamma$ is the discontinuity in the logarithmic derivative with the control magnetic field outside the wall (saddle-coil produced) included in the solution for the perturbation. Clearly the aim of feedback is to achieve $\Delta'\gamma \leq 0$ so that $s \leq 0$ and the perturbation does not grow.

The salient features of open loop mode control are demonstrated in Fig. 2.4, which shows the effect of a preprogrammed control field harmonic on a targeted plasma mode, $n = -8$. The time evolution of the amplitude and phase of the $n = -8$ harmonic of the radial field perturbation is shown for different cases. For a given set of discharge parameters, the $n = -8$ mode is shot-to-shot reproducible. Therefore the mode growth with a preprogrammed control field can be compared with the growth without the control field. Without control, as seen in Fig. 2.4, the mode grows throughout the discharge. The preprogrammed control harmonic field induces a field at the sensor coil as shown in the middle panel. The amplitude, time dependence and phase of the control field have been selected to suppress the $n = -8$ mode during the first part of the pulse. In a feedback system, the controller would adjust the feedback to achieve and sustain $b_r = 0$. However with the preprogrammed control field, the mode amplitude does not go to zero but it is clearly controlled. The time development of the perturbation shown in Fig. 2.4 has the following characteristic features:

$t < 2\text{ms}$ This is the initial start-up, current-rise phase and the prompt field error causes a perturbation to grow to an initial amplitude during the first 2 ms.

$2 < t < 7 \text{ ms}$ The control field is preprogrammed to have negative feedback on the observed mode (a phase shift of $\pi$ relative to the plasma produced perturbation). The amplitude of the control harmonic is sufficiently large so that the perturbation decreases under the influence of the control harmonic.
Fig. B.1.4 The mode amplitude (left-hand side figures) and phases (right-hand side figures) are shown for: Upper) discharge without a control field applied. Middle) the preprogrammed control field harmonic in vacuum. Lower) the plasma mode harmonic affected by the preprogrammed control field harmonic.

\( t \approx 12 \text{ ms} \) The amplitude is low. The phase of the mode changes from its original phase angle and the mode starts to align with the control field harmonic. Therefore the control field gives positive feedback.

\( t > 12 \text{ ms} \) The mode amplitude increases. The control field is now equivalent to an error field and the mode amplitude grows but with the phase approaching that of the control harmonic.

The data in Fig. 2.4 demonstrate that the modes can potentially be controlled, both with negative and positive feedback. Control theory is being developed and different feedback models are being tested on T2R.

The first tests of active feedback control have also been carried out. The intelligent shell concept applies feedback on all harmonics and the basis of the intelligent shell is that the average radial field in each sensor coil is frozen to zero. An example of feedback control of RWMs is shown in Fig. 2.5 for the case of the RFX digital controller operating as an intelligent shell. In the upper panel of Fig. 5, the spectra of \( m = 1 \) modes without feedback is shown for toroidal mode numbers in the range \(-20 < n < +20\). There are two types of RWMs. The modes in the range \(-11 < n < -5\) are internally non resonant (i.e. have the same helicity as the field inside the reversal surface). The modes in the range \(+3 < n < +8\) are externally non resonant (i.e. have the same helicity as the field outside the reversal surface). There is a general correlation between the amplitudes of the RWMs and the theoretical growth rates.
Note that the $n = -8$ mode has a larger amplitude believed to be due to prompt field error effects. The modes in the range $-2 < n < +2$ have large amplitudes although they are marginally stable according to theory. There is good evidence that these modes are perturbations stimulated by field errors associated with asymmetries in the external magnetic systems and these large amplitudes are therefore attributed to field error amplification.

Fig. B.1.5 In panel (a) the $m = 1$ mode amplitudes are shown for $n$ in the range $-20 \leq n \leq +20$ for a discharge without feedback at a time equal to 1.5 shell penetration times. The $n$-range includes internally resonant tearing modes (IRM), RWMs and field error (FE) stimulated modes. The solid curve shows theoretically calculated normalised growth rates for the RWMs. In panel (b) the mode amplitudes are shown with active feedback in operation.

The spectral region $n < -12$ corresponds to internally resonant tearing modes (IRM). These are the dynamo modes that are always present in an RFP and are responsible for the dynamo and Taylor relaxation. As seen in Fig. 2.5 the tearing modes have radial field amplitudes smaller than the resistive wall modes because the modes are rotating and therefore the radial component of the perturbation is suppressed at the wall.

The lower panel shows that the feedback system reduces the amplitudes of the dominant unstable RWMs (note $n = -10, -9, -8, +6, +2$) and also reduces the FE stimulated RWMs (note the dominant $n = +2$ mode). The side-band effect due to the fact that the saddle coil array consists of 16 toroidal positions is also evident. Among the control harmonics being produced by the intelligent shell feedback controller is a strong $n = +2$ control harmonic to reduce the $n = +2$ mode. There is a sideband at $n = -14$, which is resonant with a ubiquitous RFP tearing mode that is normally rotating and therefore normally has very low radial field amplitude. The $n = -14$ control harmonic is then in effect a stationary field error which locks the $n = -14$ resonant tearing mode so that the radial component of the perturbation starts to grow, as seen. This case has been selected because it demonstrates RWM control, suppression of FE amplification and the effect of a control harmonic sideband on resonant tearing modes.
In summary, during 2003 the feedback systems for RWM active control on T2R have been developed installed and tested. The first experiments have demonstrated that feedback can suppress RWM instabilities. Furthermore, the development and testing of the RFX prototype has been very beneficial for preparation for the upcoming operation of the rebuilt RFX device. Finally, collaboration between the RWM active control work done on T2R and the programme for RWM control in tokamaks is now well established.

**Turbulence studies in the plasma edge**

Turbulence in fusion plasma refers to the presence of fluctuations in the characteristic fluid parameters in time and space, which have characteristic statistical averages. An implication of turbulence is that local convective transport of particles, momentum and energy is dominant over classical diffusive transport. Turbulence of course plays a fundamental role in plasma confinement in magnetically confined plasmas. The edge region of the RFP is of particular interest because, as is the case in a tokamak, the transport is very much affected by electrostatic turbulence. Turbulence and anomalous transport have been studied in the EXTRAP T2R device in a collaborative study with Consorzio RFX.

Statistical studies performed by the RFX group on the T2R database of electrostatic turbulence in the edge region of T2R show intermittent bursts of fluctuation in plasma potential. The observed intermittent events are correlated in time with tearing mode reconnection events, which are present in the RFP core region and are associated with the relaxation phenomena. It is not known how the reconnection events produce the electrostatic structures, and this will be one of the aims of future work. However the structural features of the turbulence can be derived from arrays of probes that monitor an edge layer region. The intermittent coherent structures appear as tubes of local positive or negative potential relative to the ambient potential aligned with the magnetic field, which is predominantly poloidal in the edge region. In cross-section the structures appear vortex-like with a characteristic rotation direction. Data for the distribution of the vortex structures are depicted in Fig. 2.6.

The toroidal ExB velocity in the edge region is shown and the fractions of positive (potential hill) and negative (potential well) vortices are shown for the same region. It would be expected that the natural occurrence would be an even distribution of positive and negative structures. However the edge region has strong shear in the ambient toroidal E×B velocity due to a radial dependence of the radial electric field. The spatial distribution of the population of the vortices with positive respective negative rotation is correlated to the sign of the E×B drift velocity shear. Estimates of the velocity shear give values large enough to potentially suppress turbulence, but the rate of suppression apparently depends on the direction of the shear for a given vortex polarity. The implication is that shear in velocity is suppressing turbulence, however the suppression process is faster for adverse vortices. Such conditions determining the rate suppression may be a factor in the development of transport barriers. Although the bursts events are intermittent, about 50% of the cross-field transport is associated with the bursts due to the relatively large-scale convection associated with a vortex. This fact together with the evidence that shear suppresses the vortex turbulence gives insight into the details of the transport barriers associated with shear in rotation velocity.
Fig. B.1.6 In the upper figures, the radial $E \times B$ velocity and fractions of positive and negative vortices are shown as a function of minor radius. The schematic depicts how vortices are transported with the ambient $E \times B$ velocity so that the shear in the $E \times B$ velocity in effect gives rise to a co- or counter-differential flow (prograde respectively adverse). The fraction of prograde vortices is significantly higher.

**Confinement improvement studies**

Confinement studies are of importance to develop methods to improve confinement and to provide insight into the processes responsible for transport. Comparison studies between the RFP and tokamak are valuable in order to identify the fundamental physics issues behind anomalous transport.

One method to improve confinement that has been demonstrated in a number of RFP experiments is based on the fact that magnetic turbulence can be reduced by modifying the current profile using a technique called pulsed poloidal current drive (PPCD). The method was first developed at the MST RFP at the University of Wisconsin. Recently PPCD has been implemented on T2R. The basis for the concept is that the self-organisation process inherent in Taylor relaxation, which requires magnetic turbulence, is replaced by external profile control. Improved confinement is seen in T2R. Theoretical code simulation, which simulates PPCD, is being undertaken as a part of this project [see RFP theory section].

Another phenomenon is the emergence of a dominant mode so that a single helicity state is approached (in experiments called quasi-single helicity or QSH). The phenomenon is interesting because there is a theoretical prediction that the RFP can spontaneously access, through self-organisation, a SH state where the dynamo needed to sustain the configuration is driven by a single $m = 1$ saturated mode. QSH was first studied in the RFX experiment and now also studied in T2R. The QSH state has the potential for improving confinement because the level of magnetic chaos is reduced.
Special features of the QSH regime that have been studied in the T2R device include the following:

- EXTRAP T2R has a large aspect ratio and a resistive shell. The fact that QSH is observed in T2R shows that a large aspect ratio and resistive wall do not seem a severe problem for the onset of QSH and, hopefully, for the path towards pure SH.
- As is typical, the QSH phase is associated with a rather quiescent phase in the plasma and the soft x-ray emission increases over the whole plasma core, which implies a core plasma heating and better confinement.
- The QSH spectra are obtained also as a result of Pulsed Poloidal Current Drive (PPCD) experiments.

In conclusion, the EXTRAP T2R results are promising and the T2R results complete the worldwide database on QSH and prove that this kind of spectrum is found in all existing RFP devices, characterized by very different magnetic boundary conditions and operating regimes.

Collaborations

Collaborations with RFX

During 2003 there has been collaboration between the Consorzio RFX group and the T2R group in the development of diagnostics for the T2R experiment:

- Edge probes have been developed for use with the manipulator on loan from RFX for studies of edge plasma equilibrium, flow, turbulence spectra and transport.
- The interferometer is being rebuilt in order to improve the resolution for long pulse discharges.

A major effort has been the development of feedback controllers that have been installed and tested on T2R during 2003. The digital controller is a prototype of the controller that will be used on the rebuilt RFX device. The controller is characterised as follows:

- 32 x 2 channels of sensor coil data acquisition.
- Onboard CPU for real time FFT analysis and control calculations.
- 2 x 16 channels of output to saddle coil amplifiers.
- 32 channels of amplifier/saddle coil (1.5 kW power).

Staff from the RFX experiment have been very involved in development work and experimental campaigns at T2R:

- Four persons from the RFX edge physics group have visited for a total period of 6 man-months primarily involved with experimental campaigns and data analysis.
- Eight persons working with the development of the feedback controllers have visited for a total period of about 5 months. The work has involved installation and testing of hardware as well as preliminary experimental campaigns.
- Collaboration in feedback theory has been carried out as a three-way collaboration between RFX Chalmers and the Alfvén Laboratory.

European Fusion Development Agreement JET activity

Scientific activity is carried out in the following areas:

- Task Force work in the area of VUV spectroscopy.
- Task Force work in the area Tritium retention and material transport in the scrape-off layer.
- Task force work in the area of neutral particle spectrometer development.
• Task force work in the area of resistive wall mode studies (planning started 2003 and first campaign in 2004).
• JET enhancement activity in the area of First Mirror Tests.
• JET session leader.

B.2 RFP Theory

Resistive wall mode studies

J. Scheffel, J E Dahlin (student), D. Yadikin (student)

In order to compare the experimental growth rates with theory, it is important to achieve the best possible model for the equilibrium profiles. The experimental equilibrium profiles are estimated using external magnetic diagnostics and a measurement of the central plasma pressure obtained from different plasma diagnostics. The RFP equilibrium magnetic field and pressure profiles are modelled by specifying two profiles $\mu(r)$ and $\chi(r)$ which characterize the parallel current density profile and the plasma pressure profile respectively. The linear MHD equations used are the full equations including equilibrium plasma pressure. The main effect of plasma pressure on the RWM calculation for a given fixed $\mu(r)$ profile is to widen the spectrum of unstable modes existing at zero beta and increase the growth rates of the modes. In addition, a new group of high $n$ external pressure driven RWMs just nonresonant at the plasma boundary are in some equilibria destabilized when plasma pressure is introduced. However, during normal experimental conditions these modes have high toroidal mode numbers and are not further considered in this study.

Fig. B.2.1. Stability boundaries for the a) $m=1$, $n=-10$ internal and the b) $m=1$, $n=5$ external modes. Boundaries with pressure (+) and without pressure (○) are shown. Experimental equilibrium points are shown modelled with pressure (*) and without pressure.

Generally, the effect of plasma pressure on the RWM calculation for a given $\mu(r)$ profile is to increase the growth rate of the mode, as compared to the zero pressure case. On the other hand, including plasma pressure by including the parameter $\chi(r)$ in the modelling of the experimental equilibrium profiles results typically in broader $\mu(r)$ profiles with reduced growth rates for the internal modes (Fig. 3.1). These effects; 1) the modification of the $\mu(r)$ profile and 2) the increase of linear MHD growth rates with pressure, will then combined give the resulting effect of pressure on the RWM growth rate.
DEBS code simulations

Alfvén Laboratory; J. Scheffel, J.-E. Dahlin (student) and Dr. D. Schnack at SAIC, CA, USA

In this work, optimised scenarios for confinement in the reversed-field pinch are modelled numerically using a time-dependent, 3-D resistive MHD code. The conventional RFP develops naturally and features high levels of magnetic fluctuations as well as limited confinement at high plasma currents. The advanced RFP, where the dynamo fluctuations are externally controlled through e.g. radio frequency current profile control, is found to have better confinement properties. The 3-D numerical simulations, where the current drive is adjusted to result in a minimum of dynamo fluctuations, show that energy confinement can be substantially enhanced, at least by a factor three.

In the initial study, an ad hoc electric field was applied, being modelled as a Gaussian radial profile, characterized by its radial position, width and amplitude. Although successful, we have embarked on an alternative study where these three parameters are eliminated. The approach is to externally supply exactly the dynamo $v \times B$ field that is inherently generated in the plasma. This scheme would generate a more quiescent plasma state with optimised confinement, being governed by the pressure gradient and associated perpendicular ion heat conduction at the edge. Recent advances show that this scheme is feasible and does indeed considerably modify fluctuations (removes sawteeth, eg) and confinement. The work is now focused on determining a suitable model, including stabilising regulation models, for obtaining confinement scaling data in the advanced regime. As tearing modes are now removed, it is of considerable interest to determine the effects of resistive interchange modes.

Analytic approach for solving initial-value problems in fusion plasma physics

In plasma physics, initial value problems of stability and transport relevance usually need be solved by fully numerical schemes. When scaling relations are sought, the obvious drawback is that, in lack of analytical parameters, a number of code runs must be carried out, whereafter intelligent use of methods such as multiple linear regression is called for.

Using symbolic computer math, we have developed an algorithm that produces analytical, parametrical solutions to systems of time-dependent, nonlinear partial differential equations. The PDEs are solved as if they were ordinary differential equations in time. Thus no spatial grid is used. Physical variables are expanded in suitable basis functions like Chebyshev polynomials. The core of the scheme is the "imprint" that formally represents the coefficients of the expansion functions for the general time advance by a single time step. Addition or removal of terms in the basic equations are easily handled. Several ways of treating boundary conditions have been determined. For illustration, the algorithm has been successfully applied to the nonlinear 1-D viscous Burger equation, where exact solutions exist.

From a technical point of view, the imprint algorithm has features in common with numerical, weighted residual methods (WRM), in particular the pseudo-spectral method; an approximate, analytical solution is assumed, Chebyshev polynomials are used (spectral expansion) and a global residual is minimized by Chebyshev approximation. The method differs from WRM, apart from that both space and parameter dependence is analytical, in that the expansion coefficients are constants (facilitates efficient numerical computation of...
next time step coefficients) and that aliasing errors due to nonlinear terms are handled by Chebyshev approximation.

This scheme may indicate a path towards analytical solution of a large class of partial differential equations. The spectral solutions used so far are polynomials. These may, in turn, be further approximated by lower order polynomials or power laws, if more compact analytical expressions are desired as problem solutions.

We have applied the algorithm to the two-dimensional Rayleigh-Taylor instability in a compressional medium. Results from this study will be published in 2004. During 2004, the evolution of nonlinear, resistive MHD modes in the RFP will be studied.

**B.3 Fluctuation control in biasing experiments on small tokamaks**

*Michael Tendler*

The concept of ExB flow velocity shear suppression is utterly fundamental in modern fusion research. It is asserted that there are models enabling to understand the physics involved in LH transitions. To improve the understanding of the mechanisms leading to formation of Transport Barriers, especially the relation between Internal and Edge barriers it is necessary to invoke the issue of electric fields. Edge transport barriers are the feature of the H-mode, the baseline regime of ITER, whereas Internal Transport Barriers are used to develop regimes that might be employed for steady state operation of ITER, definitely beneficial for design and operation of fusion power plants in the future. Their synergy will be addressed.

Plasma flows are closely connected to electric fields. Therefore, their role is crucial for understanding of tokamaks aimed at the achievement of fusion energy. This appears in the well known neoclassical theory as the most accomplished and selfconsistent basis for understanding of fusion plasmas. It pertains to the novel concept of “zonal flows” emerging from the recent development of gyro-kinetic transport codes. The equilibrium poloidal and toroidal flows are also crucial for the concept of the electric field shear suppression of plasma turbulence in tokamaks. Yet, this timely and topical issue has remained largely unaddressed experimentally because of great difficulties of measuring flows in plasmas.

The impact of sheared radial electric fields on turbulent structures and flows at the plasma edge is investigated. A non-intrusive biasing scheme called “separatrix biasing” whereby the electrode is located in the scrape-off layer (SOL) with its tip just touching the LCFS was found to be efficient, as predicted by our theory. There is evidence of a strongly sheared radial electric field and ExB flow, resulting in the formation of a transport barrier at the separatrix. Advanced probe diagnosis of the edge region has shown that the ExB shear rate that arises during separatrix biasing is larger than for standard edge plasma biasing (with the electrode inserted inside the LCFS). The plasma flows, especially the poloidal ExB drift velocity, are strongly modified in the sheared region, reaching Mach numbers as high as half the sound speed. The corresponding shear rates ($\sim 5 \times 10^6 \text{s}^{-1}$) derived from both the flow and electric field profiles are in excellent agreement and are at least an order of magnitude higher than the growth rate of unstable turbulent modes as estimated from fluctuation measurements.
The optimized Gundestrup probe is used to compare ion flows with the phase velocity of fluctuations moving poloidally across the Gundestrup collectors. The ion mass flow is measured by the standard arrangement, i.e. signals of all the segments are digitized at a standard sampling rate. From these data, the perpendicular Mach number of the ion flow is derived. Then, the cross-correlation function is calculated and the transit time of a poloidally localized structure across the corresponding segments is deduced from the shift of its maximum.

Measurements of the parallel Mach numbers have also been performed at biasing. In contrast to Alcator C-Mod results at L-H transition, we do not observe a dramatic increase of the toroidal rotation. This may be due to the much higher q values employed on CASTOR.

### B.4 Theory and code simulation

*T. Hellsten, E. Tennfors, T. Bergkvist, T. Johnson and M. Laxåback*

The group carries out theoretical and experimental research focused on RF-heating and current drive, studies of global Alfvén eigenmodes and excitation of them by fast ions.

**RF-heating theory and modelling**

Waves in the ion cyclotron frequency range can be used for heating of electrons and ions, drive currents, give rise to plasma rotation, enhance fusion yield, affect the stability of global MHD-modes. To make accurate predictions for such a versatile heating method detailed calculations of the wave absorption and the effects on the distribution function of the heated species are required. The group has specialised in developing advanced codes for self-consistent modelling of the power deposition and the distribution functions during ion cyclotron resonance heating, ICRH. The PION code, initiated by T. Hellsten during his stay at JET, had been developed into the standard code for ICRH heating on JET together with L.-G. Eriksson. It has become the main tool for analysing RF-heating and calculating power depositions. It gives in general good agreement between experiments and modelling. A more advanced code SELFO has been developed at Alfvén Laboratory to include the effects of finite orbit width of high-energy ions and RF-induced spatial transport of the resonant ions. This code is the only in its kind and has been found to be instrumental for calculating the velocity distribution when detailed information on the distribution function and power deposition is required. The inclusion of the effects of finite orbit width of high-energy ions and RF-induced spatial transport was found to be crucial for modelling ICRH with antennas launching waves propagating preferentially parallel or anti-parallel to the plasma current. These effects could explain a number of new phenomena observed during ICRH. Often good agreements with experimental results and modelling with the SELFO code were found.

The SELFO code has been used to model minority ion current drive based on cyclotron absorption on ions, calculate the RF-induced torque in RF-heating scenarios, analyse heating with polychromatic spectra, model fast wave current drive by direct damping of the wave on electrons and analyse parasitic absorption by impurity ions during fast wave current drive scenarios. In the latter significant parasitic absorption appear in the presence of low impurity concentrations of $^3$He, which because of the weak single pass damping by
the direct electron absorption by transit time magnetic pumping and electron Landau damping becomes important.

The SELFO code uses the Monte Carlo code FIDO for calculating the distribution function in 3D-geometry. In order to extend the modelling capability of the SELFO-code to allow computations of the RF-induced torque, model scenarios with several resonant ion-species including beams and for polychromatic heating (heating with several frequencies) substantial upgrades of the FIDO and SELFO codes have been done. The accuracy and speed of the Monte Carlo code FIDO used in SELFO have been improved for calculating the distribution function in generalised coordinates by developing a dynamic weighting scheme and improving the accuracy near boundaries of the region where RF-interactions in the phase space take place. The improvement of accuracy was necessary for calculating the net RF-induced torque, which is obtained as a small difference between the torque caused by ion-ion collisions and by radial transport of resonant ions and for modelling of heating with high RF-power density in high temperature plasmas.

Magnetosonic modes localised at the edge has been proposed to explain non-thermal emission of waves in the ion cyclotron frequency range. Excitation of such modes during ion cyclotron heating was thought of as a potential mechanism for degrading the heating profile in particular for scenarios with weak single pass damping. When studying these modes it was found that these modes propagate poloidally around the torus and are in generally not localised to the low field side of the plasma as has previously been proposed by other research groups.

Parasitic absorption of RF-power during ICRH scenarios has been seen under various conditions in JET. We have analysed the coupling of RF-power for scenarios with weak single pass damping for coupling to a wide spectrum of toroidal eigenmodes. Such coupling results on averaged in a lower coupling and higher antenna voltage, which increase the losses due to rectified RF-sheaths potentials at the antennas and the walls. This becomes in particular severe for phasings coupling to low toroidal modes and when the coupling spectrum is narrow. This model can explain the difference of the heating efficiency of the JET A1 and A2 antennas in monopole phasing and parasitic losses in the fast wave current drive experiments with –90° for weak single pass damping.

**Experiments at JET**

Control of the central plasma current is important for obtaining plasmas with good energy confinement. Current drive by direct electron absorption of the fast magnetosonic wave, by transit time magnetic pumping and electron Landau damping, is a potential tool to control the central current in tokamak plasmas because of the strong localisation of the current to the centre. There is a tendency to develop so called current holes for internal transport barriers in strong magnetic shear reversed plasmas. The presence of such a hole leads to a reduction of the central confinement. Fast wave current drive is suitable a tool for controlling the central current in plasmas with internal transport barrier requiring a hollow current profile for good confinement. Scenarios for fast wave current drive and direct electron heating in ITB plasmas have been developed based on preheating the plasma with lower hybrid waves to produce high temperature plasma with hollow current profile suitable for fast wave current drive. Only a small fraction of the RF-power was absorbed directly on the electrons in the centre by transit time magnetic pumping and electron Landau damping. A large fraction of the power was absorbed by other “parasitic” mechanisms. The losses of heating for certain scenarios and antennas have been one of the
outstanding unsolved problems in ICRH. Experiments to find the cause of the parasitic absorption were conducted by the group. Parasitic mechanisms had been identified. A significant factor of the power is absorbed by residual $^3$He ions, which even at concentrations of the order of 0.1% can absorb a considerable when they reach high energy. Experimental evidences of such high-energy $^3$He ions were found. We also found that when the single pass damping is weak a large fraction of the power is parasitically absorbed outside the plasma, in some experiments only a third of the power was absorbed in the plasma. Thus the loss of power can not be found by parasitic damping mechanism inside the plasma and at the wall. Evidences of parasitic absorption caused by the presence of rectified RF- sheath effects at the wall and antennas have been obtained consisting of the imbalance of energy delivered to the plasma and energy radiated and conducted from the plasma measured with bolometer camera and thermo couplers, and from the strong Be and C radiation during FWCD experiments. The losses depend not only on the single pass damping but also on the antenna phasing. Fast wave heating with the dipole heating for plasmas with similar single pass damping demonstrated good heating and the Be radiation in the divertor region was much less consistent with less interaction by rectified RF-sheath effects at the beryllium screen of the antenna.

Because of the large fraction of parasitic absorption, due to weak single pass damping, the inductive nature of the plasma current and the interplay between the RF-driven current and the bootstrap current only small changes are seen in the central current profiles, which are in qualitatively agreement with modelling. But demonstrating the difficulties in controlling the central current in plasmas with internal transport barriers with strongly reversed magnetic shear.

**Analysis of JET results**

Minority ion current drive, which gives a localised change in the current profile, is of interest for destabilisation of sawteeth in order to prevent large sawteeth crashes triggering neo-classical tearing modes. The neo-classical tearing modes, which are meta-stable, limit the achievable plasma pressure. The method of destabilsing sawteeth with minority current drive has been successfully demonstrated at JET. Accurate modelling of the destabilsation of the sawteeth is of importance for extrapolation of the method to ITER.

Strong velocity shear has been proved to be important for achieving good confinement through the development of internal transport barriers. Heating with ICRH has shown to produce toroidal plasma rotation. Modelling of the RF-induced torque has been done for JET experiments. The difference in the torque calculated for different heating is consistent with the observed differences in the rotation profiles.

**Global MHD Eigenmodes**

For intense heating of plasmas with high energy ions arising from thermonuclear reactions, beams or ion cyclotron heating global Alfvén waves can be excited and through out resonant ions or redistribute them giving rise to a degradation of fast particle heating in thermonuclear reactors and is regarded to be a serious issue. Excitation of various Alfvén eigenmodes is often seen during ICRH. In order to study the effects of excitation of global Alfvén modes on the power deposition during ICRH the SELFO code has been upgraded. The SELFO code is the only code allowing for self-consistent computations of the velocity distribution for ion cyclotron heating in the presence of Alfvén eigenmodes. The modelling with the SELFO code demonstrates the importance of de-correlation of the interactions.
with the Alfvén eigenmodes by ion cyclotron resonance heating. These results are important for extrapolating experimental results from Alfvén eigenmodes excited during ion cyclotron resonance heating to reactor regimes where the modes can be excited by thermonuclear alpha particles for which the interactions are not decorrelated by ion cyclotron heating.

Studies of TAE-modes in RFP plasma

High frequency peaks in magnetic signals in Extrap T2R have been interpreted as Toroidicity-induced Alfvén Eigenmodes (TAE). The mode shows the right scaling under different experimental conditions. A confirmation of the radial localization of the mode is still missing, but it is expected to be edge resonant. Gas puffing experiments show that local density variations are responsible for rapid changes of the mode frequency. The electron diamagnetic drift gradient appears to be a good candidate as a drive mechanism.

B.5 Plasma – surface interactions and plasma facing materials

M. Rubel

Work programme related to JET Task Forces “E”, “FT” and “D”

The work was carried out under the Science and Technology Orders during campaigns C-8 to C12. The main goal was to determine material transport in the scrape-off layer (SOL) plasma and its impact on the morphology of plasma facing components (PFCs). The emphasis was on the distribution and amount of retained fuel and co-deposited beryllium and carbon on PFC following the operation with various JET divertors. Two subjects were of particular interest:

- Material transport in the presence of the Gas Box divertor
- Deposition and fuel inventory in castellated structures: grooves and gaps between tiles.

Material transport in the presence of the Gas Box divertor

The Mark-II Gas Box divertor was in operation in the period of 1998-2001. Afterwards, a number of tiles from the divertor (a whole poloidal set) and limiter (inner guard and outer poloidal) were removed for ex-situ analysis by means of various techniques. In 2003 the investigation with accelerator-based ion beam analysis methods was continued. It was carried out at the University of Sussex, Brighton in a very close co-operation with Dr. J.P. Coad of UKAEA- Culham Fusion Division. The surface analysis station is equipped with an isolator for handling beryllium and tritium contaminated materials. Three topics gathered particular attention:

- Quantification of C-13 tracer ($^{13}$CH$_4$) introduced to JET on the last operation day with the Mk-II GB;
- Detailed analyses of the Gas Box components;
- Erosion of Rhenium (600 nm) and Boron (2500 nm layer of C-B10%) marker layers from the limiters.

The results are summarized as follows. 45% of the injected C-13 tracer has been found on the inner divertor tiles 1 and 3 (vertical target). The co-deposition of deuterium inside the Gas Box structure (made fully of carbon fibre composites) is mostly in the range 5 – 10 x 10$^{17}$ D at cm$^{-2}$. Greater deposition (10$^{19}$ D at cm$^{-2}$) is found only in a narrow region on the
Bas Box support structure from the inner divertor side. No flake formation was observed. This shows that the GB can not be considered as the major area for the fuel retention and material re-deposition. Rhenium and boron-containing films were eroded from most of the limiters. While the erosion of B was complete, the erosion of Re was reaching 97% in the central part of the limiters. The result gives strong indication on the erosion of Re by mainly impurity fluxes (C and Be).

In the fall 2003 preparation began for tracer experiments to be carried out at the end of the C-14 campaign. The selection of tracers \( ^{13}\text{CH}_4 \), \( \text{B(CH}_3)_3 \) and laser-ablated Hf) and injection ports were decided.

**Deposition and fuel inventory in castellated structures: grooves and gaps between the tiles**

**Background:** Castellated structure of tiles in the ITER divertor is deemed as the best solution to ensure thermo-mechanical durability and integrity of materials under high heat flux loads, especially when the use of tungsten is considered. It is known, however, that in the environment containing also low-Z elements (e.g. carbon) eroded material is transported and co-deposited together with fuel species to areas shadowed from the direct plasma line-of-sight. In consequence, re-deposition occurs in grooves and on side surfaces of plasma facing components (PFCs), i.e. in gaps separating the tiles. Therefore, the study was initiated to investigate in detail side syerfaces of tiles and various probes from the TEXTOR and JET tokamaks (results for TEXTOR are reported in the next section). The emphasis is on the fuel inventory and material mixing occurring on side surfaces of limiter and divertor components.

**Summary of results:** The water-cooled Mk-I divertor composed of small carbon and beryllium tiles was so far the largest structure resembling castellated components for ITER. Co-deposition associated with significant fuel inventory was observed deep in the gaps, at least several cm from the plasma facing surface. As a result, the inventory on side surfaces located in the gaps of the Mk-I structure with carbon tiles was twice greater than that determined on plasma facing surfaces: \( 15.9 \times 10^{23} \) D atoms and \( 8.9 \times 10^{23} \) D atoms, respectively. Fig. 1 shows the appearance of side surfaces covered by thick flaking co-deposits. In subsequent divertors (Mk-II type) composed of large tiles, the inventory was strongly confined to the corner in the inner divertor: in shadowed areas of the tiles and on water-cooled louvers, but the magnitude of deposition in gaps was distinctly smaller than in the Mk-I case.

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**Figure B.5.1:** Deposition on side surfaces of the water-cooled Mk-I divertor tiles: (a) carbon fibre composite; (b) castellated beryllium.
**JET Enhancements. First Mirror Test for ITER at JET**

First Mirror Test (FMT) project was initiated at JET in year 2002 within the Project on Tritium Retention Studies (TRS). The origin of this dedicated experimental programme is related to the fact that first mirrors will be plasma facing components of optical diagnostic systems in ITER. Mirror surfaces will undergo modification caused by erosion and redeposition processes influencing reflectivity of mirrors and thus affecting the spectroscopy signals. The limited access to in-vessel components of ITER calls for testing the mirror materials in present day devices in order to gather information on the material damage and degradation of the mirror performance, i.e. reflectivity. Therefore, the ITER Team requested the FMT experiment to be carried out.

The Swedish Association (Responsible officer: Marek Rubel) in co-operation with UKAEA carries out the project aiming at the manufacturing, delivery and installation of mirror samples and their carriers in several locations inside the JET vacuum vessel. In the beginning of 2003 the conceptual design was completed. It included the selection of mirror materials (polycrystalline molybdenum and stainless steel), selection of relevant locations in the JET torus and the design of pan-pipe like cassettes as mirror carriers. Compatibility of the assembly with remote handling was taken into account. Following discussions with the ITER Team, five locations in the divertor and the main chamber wall were selected. The design allows for exposures of the two mirror materials under the same plasma conditions and, therefore, for a direct comparison of the material behaviour. The inclusion of the FMT project in the framework of Tritium Retention Studies ensures that specimen exposures will be accompanied by exposure of other deposition diagnostic tools located in vicinity of mirrors: quartz micro-balance devices and indexable collector. Figures 2 and 3 show the location of cassettes with mirrors in various locations inside JET.

![Image of cassettes with mirrors and indexable deposition monitor]

Fig. B.5.2. *Mirror and other deposition monitors in the main chamber wall mounted a clip (wall bracket) compatible with remote handling.*

**TEXTOR**

*Marek Rubel, Birger Emmoth and Kristina Stenström*

The co-operation between the Swedish Association and the TEXTOR Team at the Institute of Plasma Physics of the Forschungszentrum Jülich is established within the framework of the EURATOM Programme. In the recent period the activity has been focused on:
• Assessment of fuel inventory in gaps between the limiter tiles
• Morphology of the erosion zones on the limiters
• Assessment on the carbon-14 content in PFC

Summary of results
Fuel co-deposition in gaps between tiles of various limiters was examined: (i) toroidal belt pump limiter (ALT II); (ii) tungsten-coated main poloidal limiter, (iii) test limiters. The study of ALT II has revealed that the inventory in gaps accounts for about 4% of the total long-term fuel retention: $0.1 \times 10^{23}$ D atoms in gaps in comparison to the total inventory of $2.2 \times 10^{23}$ D atoms in the ALT II tiles. Fig. 4 shows a side surface of a plate from that limiter. Also the inventory in gaps between tiles of other limiters was not exceeding moderate values of $10^{18}$ D at cm$^{-2}$.

Comparison of results (JET and TEXTOR) and recommendations
The results give strong indication that the deposition in gaps separating tiles of PFCs is an issue that deserves further detailed studies. In case of water-cooled castellated structures with sharp edges pronounced accumulation of mixed material could be expected. It is not our intention to give here a quantitative prediction for ITER because the data base is still too small. Secondly, the distribution of plasma facing materials (Be, W and CFC) and plasma density in the ITER divertor will be different than in any present-day device. The results also lead to a conclusion that it is not just the existence of gaps, slots or grooves on PFC that is decisive for the deposition but the arrangement and shaping of tiles with respect to the field lines. Mk-I is a good example supporting this tentative statement. However, it becomes obvious that currently developed or proposed methods of tritium removal should be tested on castellated structures in order to ensure effective fuel removal on a reasonable time scale. In turn, this calls for testing and exposures of castellated components in existing tokamaks. A test of the macro-brush tungsten and castellated TZM limiters in TEXTOR is the first step, but similar experiments should be done for CFC tiles with the ITER-like structure. Tracer techniques developed at TEXTOR and JET, e.g. injection of rare isotopes ($^{13}$C labelled methane) and marker tiles, would help the determination of transport mechanism to the gaps.

Fig B.5.3. Deposition on side surfaces (i.e in gaps) of the ALT II tiles in TEXTOR
**Morphology of erosion zones on limiter tiles**

**Background information:** The study has been carried out in the framework of EFDA Technology Task TW4-TPP-ERCAR. The aim is to characterize the morphology of erosion zone. The task was initiated in relation to the fact that erosion experiments performed in PISCES (EFDA-DoE Cooperation) resulted in a very significant topography evolution on carbon fibre composites exposed to doses over $10^{21}$ ions cm$^{-2}$. Erosion lead to significant roughness due to the formation of a grass-like structure in CFC. The aim of the EFDA TW4-TPP-ERCAR task was to study the erosion zones on plasma facing components exposed to fluences of the order of $1 \times 10^{22}$ cm$^{-2}$ in tokamaks. ALT-II limiter tiles were examined with ion beam analysis and microscopy methods.

**Summary of results:** Ion beam analysis revealed the deuterium content in the erosion zone is in the range of $2 - 5 \times 10^{17}$ cm$^{-2}$. This is related predominantly to the implantation of deuterium in graphite. Images in Fig. 5 show surface topography of graphite and carbon fibre in the initial state (a and b), after exposure to the fluence exceeding $1 \times 10^{22}$ cm$^{-2}$ (c) and after cleaning the tile by sand blasting (d). The comparison clearly proves that the smoothest surface is observed after exposure to the plasma. No pits and erosion craters are detected. The study was carried out for a number of tiles.

**Assessment on the carbon-14 content in PFC**

In a search for new and ultra-high sensitivity tracer techniques in studies of carbon migration in fusion experiments the use of $^{14}$C-labeled compounds has been considered. Therefore, we have initiated studies of the C-14 isotope background in PFC. The work has been done in co-operation with Lund University. The investigation has carried out by means of accelerator mass spectrometry (AMS), an ultra sensitive technique capable of detecting some $10^{17}$ g (5x$10^5$ $^{14}$C atoms). A number of samples of co-deposits and dust from TEXTOR have been studied. The content is on the level of 10-20 mBq g$^{-1}$ in comparison to approximately 2 mBq g$^{-1}$ in non-exposed graphite. This comparison indicates that the presence of C-14 in TEXTOR is related to the neutron activation during the D-D operation.
Fig B.5.4. Surface topography of graphite and CFC tiles from TEXTOR: non-exposed graphite (a), non-exposed CFC - CX2002 (b), after exposure to fluences exceeding $1 \times 10^{22}$ cm$^{-2}$ (c), after cleaning by sand blasting (d).

B.6 Publications by the Division of Fusion Plasma Physics

Paper published in international journals


V. S. Tsypin, ...., ...., M. Tendler, A. S. De Assis, *Particle's flows and ambipolar electric field in dusty partially ionized plasmas with temperature gradients*, Physics letters A **31**(2003)2123


T Hellsten and M Laxåback, *Edge localized magnetosonic eigenmodes in the ion cyclotron frequency range*, Physics of Plasmas **10** (2003) 4371


Other publications


M. Johansson, *Direct conversion of fusion energy*, Royal Institute of Technology Report, TRITA-ALF-2003-02

L. Eriksson, *Development of tool for simulating the effect of radia electric fields on Ion-temperature-Gradient modes in 3D configurations*, Royal Institute of Technology Report, TRITA-ALF-2003-03


**Forthcoming publications as of January 2004**


M. Rubel et al, *Overview of tracer techniques in studies of material erosion, re-deposition and fuel inventory in tokamaks*, J. Nucl. Mater., in press


J R Drake, J A Malmberg and the EXTRAP T2R team, *Experimental studies of MHD dynamics in a RFP magnetically confined plasma*, Accepted for publication in Contributions to Plasma Physics.
B.7 Conferences and workshops

Invited talks and articles


M. Tendler, *Plasmabased waste treatment – a source of a renewable energy within the framework of sustainable development*, Symposium on Energy within the Nobel Laureats meeting on Sciences and Mankind Progress, St. Petersburg 12 – 23 June 2003


M.F. Stamp, ...., ...., ...., M. Rubel et al, *Carbon and beryllium migration in JET*, 10th Int. Workshop on Carbon Materials for Fusion Applications, Jülich, Germany, September 2003

B. Lehnert, *Keynote Address at VIGIER IV Symposium* in Paris on Applications of an Extended Electromagnetic Theory

J R Drake, *EXTRAP T2R Programme*, 9th IEA International reversed-field pinch workshop, Tsukuba, Japan, 5-7 March 2003

**XXVI International Conference on Phenomena in Ionized Gases, Greifswald Germany July 15-20, 2003**

M Spolaore, N Vianello, V Antonni, R Cavazzana, E Martines, G Regnoli, G Serianni, E Spada, H. Bergsåker, J Drake, V Carbone, *Turbulence and coherent structures in reversed-field pinches*


J R Drake, *Intelligent shell experiments on EXTRAP T2R*, 8th Workshop on Active Control of MHB Stability, Univ of Texas-Austin organized jointly by Columbia University, General Atomics, Princeton Plasma Physics Laboratory, University of Texas, and
University of Wisconsin, Nov 3-5, 2003, presentations published on internet
http://fusion.gat.com/mhd/activemhd03/

**Contributed papers – oral presentations**


L.-G. Ericsson et al. incl. J. Brzozowski, *Plasma rotation induced by directed waves in the ion cyclotron range of frequencies*, submitted to PPCF.


M. Rubel, P. Coad, D. Hole, J. Likonen, *Distribution of fuel, carbon and beryllium on in-vessel components following the operation of JET with MK-IIA and Gas Box divertors*, Int. Workshop on In-Vessel Tritium Inventory, Culham, United Kingdom, March 2003

J.P. Coad ...., ...., ...., M. Rube et al, *Tritium retention diagnostics to be installed at JET*, Int. Workshop on In-Vessel Tritium Inventory, Culham, United Kingdom, March 2003

M. Stamp, ...., ...., ...., M. Rubel et al, *Material migration in JET*, Int. Workshop on In-Vessel Tritium Inventory, Culham, United Kingdom, March 2003

M. Rubel et al, *Overview of tracer techniques in studies of material erosion, re-deposition and fuel inventory*, 11th Int. Conf. on Fusion Reactor Materials (ICFRM-11), Kyoto, Japan, December 2003


**Contributed papers – written contributions and poster presentations**

30th EPS Conf. on Plasma Physics and Controlled Fusion, , St. Petersburg, Russia, July 7-11, 2003

M. Rubel et al, *Erosion and re-deposition on diagnostic mirrors for ITER: First Mirror Test at JET and TEXTOR*, Book of Abstracts P-4.59


R M Gravestijn, M P Kuldkepp, M Ceconello and E Rachlew, *A spectroscopic method to determine changes in the electron temperature profile*, ECA Vol. 27A, P-2.71
D Yadikin, P R Brunsell, J-A Malmberg, and M Ceconello, *Comparison of experimental resistive wall mode growth rates in the EXTRAP T2R reversed-field pinch with linear MHD theory*, ECA Vol. 27A, P-3.219

P R Brunsell, M Ceconello, J R Drake, J-A Malmberg, P Franz, P Martin, L Marrelli, P Piovesan and G Spizzo, *Quasi single helicity in EXTRAP T2R*, ECA Vol. 27A, P-1.211


M. Rubel et al, *Fuel inventory and co-deposition in grooves and gaps of limiter and divertor structures*, 10th Int. Workshop on Carbon Materials for Fusion Applications, Jülich, Germany, September 2003

K. Sugiyama, …, …, …, M. Rubel et al, *Tritium retention in plasma facing components following D-D operation*, 11th Int. Conf. on Fusion Reactor Materials (ICFRM-11), Kyoto, Japan, December 2003

K. Ohya, …, …, …, M. Rubel and N. Noda, *Modeling of erosion and deposition patterns on C-W and W-Ta twin limiters exposed to TEXTOR edge plasmas*, 11th Int. Conf. on Fusion Reactor Materials (ICFRM-11), Kyoto, Japan, December 2003


E. Tsitrone, ...., ...., M. Rubel et al, *Carbon migration and deposition in limiter machines*, 11th European Fusion Physics Workshop (EFPW-11), Heraklion, Crete, Greece, December 2003

**9th IEA-RFP Workshop, March 5-7, 2003, Tsukuba, Japan**


M. Laxåback, T. Johnson, T. Hellsten, and M.J. Mantsinen, *Self-consistent modelling of polychromatic ICRH*

M.J. Mantsinen, M. Laxåback, ...., .....,..., T.Hellsten, L.C. Ingesson, T. Johnson et al, *Comparison of monochromatic and polychromatic ICRH on JET*

T. Hellsten and M. Laxåback, *The effect of weak single pass damping on the coupled ICRH power spectrum*, p 126


**Organization of conferences and workshops**

B. Lehnert, Co-chairman of the International Organizing committee of the VIGIER IV Symposium held at Université Pierre et Marie Curie, Paris, France

M. Rubel, *10th International Workshop on Carbon Materials for Fusion Applications*, Jülich, Germany, September 2003, Programme and Publication Committee member, editor of the proceedings
M. Rubel, 11th International Conference on Fusion Reactor Materials, Kyoto, Japan, December 2003: Programme Committee member

B.8 Main collaborations and contacts

**International collaboration**

*Visiting researchers from RFX, Padova, Italy*
- Dr Alessandra Canton (2 w)
- Lionello Marelli (10 Feb - 14 Feb, 8 Nov - 14 Nov)
- Nicola Vianello (March)
- Francesco Milani (16 Jun - 18 Jun)
- Rita Lorenzini (August, 2 w)
- Tommaso Bolzonella (4 Nov - 14 Nov)
- Gabriele Manduchi (16 Okt - 17 Okt, 3 Dec - 9 Dec)
- Giuseppe Marchiori (8 Dec - 13 Dec)

*Visiting graduate students from RFX, Padova, Italy:*
- Giorgio Regnoli (Jan, Jun-Aug)
- Paolo Piovesan, (10 Feb - 14 Feb)

**JET task assignments**

- Torbjörn Hellsten: work at JET, March, May, August, Oct. 7 weeks al together.
- Martin Laxåback, secondee, JET-EFDA corporation, 7 weeks
- Tommy Bergkvist, secondee, JET-EFDA corporation, 6 weeks

Jerzy Brzozowski:
Work at JET under EFDA agreement:
Orders:
- Experimental Campaign 7b, 27 January – 21 February
- Experimental Campaigns 8 and 9, 24 February – 16 May
- Experimental Campaigns 10, 11 and 12, 18 August – 19 December
Notifications:
- Work with the experimental data from C5-C7 at JET, under Umbrella Mobility, 19 May –27 June
- Diagnostics preparation and Session Leader duties during Restart before C10 at JET, under Umbrella Mobility, 21 July – 15 August
Appendix C

Detailed Report from the Division of Applied Electrophysics

C.1 Accelerator Technology research

C.1.1 Accelerator technology development

Irradiation service to other research groups

A most important part of the activities, is to provide high energy electron beams - soon also slow positrons - to several external research groups and industries. The Nuclear Chemistry division, KTH is the most frequent customer doing pulse radiolysis experiments since 1969.

Positron beam being set up in the accelerator hall

A positron beam source is being set up based on pair production in the bremsstrahlung beam from 50 MeV electrons accelerated in the AL racetrack microtron. The positrons will, above all, be used in surface analysis utilising annihilation radiation.

- Internal elements of the central chamber are being built. Part of the beam transport has been tested with electrons. A computer control system is being developed.

Nanosecond pulse acceleration in racetrack microtrons

Nanosecond pulses of accelerated electrons are of great interest in a number of applications like injection into storage rings, potentially improved cancer radiation therapy, and time-of-flight experiments with positrons. This is of interest for improved performance of commercial microtrons. Applied to the AL microtron, it also has a strong connection to the positron project. To achieve the short pulses, injection from a triode electron gun is a requisite. Due to the very limited available space in present microtrons, the gun construction is delicate.

- The nanosecond pulse generator has been tested in the microtron. An improved trigger unit and a control system for the pulse generator has been designed and construction is under way.

EB-station

An electron irradiation facility for research, mainly in polymer chemistry. The existing accelerator (circular microtron, 37 years of service) will be replaced by a more modern solution in order to increase the beam intensity, to improve reliability and to ease of maintenance. A linear accelerator (linac) has been the choice.

- All equipment has been assembled, vacuum system and electron gun have been tested. An improved dose regulation system has been tested.
- The linar project is presently idle due to lack of manpower.
- The existing facility already has its customers. Hopefully, the number of experimenters will increase due to the foreseen improved quality.
Production of accelerator components

Another important activity, going on during the last three decades, is manufacture of electron guns and microwave parts of own construction for industries and research laboratories all over the world. During the year a waveguide window and 25 microtron cathodes have been delivered to various customers.

External injection in racetrack microtrons

Presently commercial racetrack microtrons, like those at the Laboratory, utilise injection from a small electron gun placed inside the central vacuum tank. This project concerns construction of a beam duct for the electrons injected from an external gun, which should result in strongly increased flexibility. This should pave the way for new properties of the accelerated electron beam.

C.2 Industrial Applications of Electrophysics

Several applied plasma projects were initiated during the years 2000-2002 with special support from KTH to develop research in the area of applications of electro-physics. Two projects have been discontinued during the year 2003 due to resource limitations: the projects applications of microwave plasmas, and a new discharge type for atmospheric plasma processing which involved key personnel (Axnäss and Wistedt) who since the summer 2002 are reduced to 30% employment. The project development of a negative ion source is also ended. It was a time-limited investigation, commissioned by private industry.

C.2.1 Diagnostics development for the VASIMR rocket engine

A spin-off from the laboratory experiments, as is described in appendix A2, is the development of skill in diagnostics of high frequency (10's of MHz and higher) waves in plasmas. We have been invited to further develop these methods for use in the VASIMR prototype rocket engine, which is being developed in Houston, Texas, USA. Probes have now been run in two campaigns in the machine, with great success. In 2003, we applied for and obtained funding for three years (2004-2006) from SNSB, the Swedish National Space Board. Main persons involved in this project have been Nils Brenning, Einar Tennfors, Göran Marklund, and technician Jan Wistedt.

Achieved scientific and technical goals

During 2003, the major parts of two diploma thesis works were made by Anna Forsell and Christian Walenzuela, with Einar Tennfors as supervisor. The thesis works primarily concerned the theory for the waves which are used to create and heat the plasma in the VASIMR rocket engine. During the first week in November 2003 measurements of electric and magnetic wave fields were performed with probes developed at the Alfvén laboratory. These were made in laboratory experiments in the rebuild device VX10, at ASPL. in Houston, USA. The measurements, a continuation of Brenning’s and Tennfor’s work of April 2002, have primarily been focused on testing the probes in the experiment. In spite of the limited experimental time these also have given significant new information regarding the waves.
plasma source is called a “helicon source”, but it is now clear that the involved wave is better described as a lower-hybrid wave, also called a Trivelpiece-Gould wave, which is active in the ionisation. The helicon wave does not propagate in the device, which has too small a radius. The two frequencies used for ionisation and heating become mixed, with sum and difference frequencies as a result. Our measurements show that this depends on the antenna construction, which has been changed between our two visits (see the figure below). The VASIMR project as a whole is progressing at a very good pace, with plans for the first space prototype before 2010. The main new aspects regarding our involvement are:

- Theory for the waves is further developed by Tennfors and put in quantitative relation to the probe measurements.
- There is a proposal concerning development of a version of our hf probes to be used as a standard diagnostic method on further, upscaled, versions of VASIMR.
- We have now made the first magnetic wave measurements, and have the indications that they, together with the electric field measurements, can be used to directly obtain the Poynting flux which shows where the wave energy is travelling.
- We aim to include a Swedish PhD student within the project and have as additional theory adviser recruited Prof. Torbjörn Hellsten to the project.
Fig C.2.1. Christian Valenzuela, Anna Forsell and Alfonso Tarditi
In Houston, during a VX10-shot (Foto: Einar Tennfors)

Fig C.2.2. April 2002: Right hand polarized 3 MHz +25 MHz give 28 and 31 MHz, but much less 22 MHz.

Fig C.2.3. Nov 2003: Left hand polarized 1.85 MHz +25 MHz give 23.15 MHz but nothing over 25 MHz.


\textbf{C.2.2 High power pulsed magnetron sputters}

With the aim to intensify the cooperation with industrial partners in the area of applied plasmas an agreement has been achieved with a small Swedish company Chemfilt AB. The company is specialized in coating of industrial products using high power pulsed metal plasmas. The purpose of our collaboration is to expand the technique developed by Chemfilt into a industrial scale method using the experience at AL. With the agreement follows financial commitments by Chemfilt contributing financially to AL both in terms of using and paying for skilled labor and for the rent of laboratory and office space.

Another line of research regarding high power pulsed magnetrons is cooperation with the Institute of Technology at Linköping University, the thin film physics division. This cooperation was initiated during 2003, and has so far resulted in analysis of magnetic field perturbations in the discharge, with a manuscript to be published in 2004. We have also during 2003 outlined future cooperation both on the practical side (hf probe construction and implementation) and on the theory side, and regarding an application within an European Union Integrated Project (submitted 2004).

\textbf{C.2.3 The wire boom system SCALE}

SCALE (Sverker Christenson Advanced Light wEight) is a wire boom system to be used on spin-stabilized scientific spacecraft. To be accepted by the space community it is necessary to be qualified, i.e. to show that the wire boom system will work in orbit. Participation in three different projects is under consideration:

- BepiColombo (ESA), a probe and orbiter to Mercury
- MMS (NASA), a four-satellite mission
- MagCAT (NASA) a 16-satellite mission

Presently work is focused on the BepiColombo mission, where the high temperatures require special attention. A Swedish patent was granted on November 5th 2001.

\textbf{C.2.4 Positron-annihilation photon detector}

A new type of radiation detector (a spin-off from fusion diagnostics) has been explored. The detector, based on scintillating optical fibres, provides improved spatial resolution in millimetre range of the source of the two photons resulting from positron annihilation. Positron beam probes are used in solid material analysis to examine defects. A prototype detector has been designed and partially fabricated. During the development work it has become clear that the procedure for fabrication is far more complicated than anticipated in spite of several trials of many suggested ideas. Calculations have shown promising features for a version with relatively thick fibres. However, earlier resulting tests of this version have shown significant reduction in signal amplitude and the conclusion is that the making procedure will be very time consuming and therefore very expensive. The project has come to an end with the conclusion that the method is useful for small area detectors but lacks practical fabrication methods for making large units.
C.3 Publications by the Division of Applied Electrophysics


Einar Tennfors, *Waves in the Ion Cyclotron and Helicon regime of frequencies*, working paper on the analysis of the probe measurements


Commissioned education

**Basic course in medical radiation physics (KTH)**
15.10 Mikrovågsteknik, SR
17.10 Elektronacceleratorer, SR
19.10 Elektronacceleratorer, SR

**Therapeutic radiation physics and biology (KTH)**
22.3 Acceleratorer för strålterapi, SR

**Radiation sources in radiation therapy (KI)**
22.3 Acceleratorer för strålterapi, SR
Appendix D

Detailed Report from the Division of Electromagnetic Theory

D.1 Research at the Division of Electromagnetic Theory

Our research focuses on the development of new theoretical methods and approaches in electromagnetic field theory. Extensive numerical implementations of the methods form an integral part of our work. Important technical applications are found in inverse and design problems. Both these areas require comprehensive use of optimization methods. Below our research is described under five different headings.

D.1.1 Inverse problems

Martin Norgren has continued the investigations on the unshielded cable used in the EU-funded project Snowpower: Diagnosing the properties of snow by means of submerged transmission line. The cable is a flat three-conductor transmission line, submerged into snow, and thereby detecting the properties of the snow from inversion of measurement data for the reflection coefficient. An improved frequency-domain optimization based reconstruction algorithm has been developed, using Chebyshev collocation in the direct solver and quasi-Newton methods in the inversion algorithm. Together with Peter Fuks several series of measurements have been done on the cable, when it is exposed to different surrounding media. The goal is to find out how multi-mode dispersion affects the attainable resolution in the parameter reconstruction. If the surrounding medium is asymmetric over the cross-section of the cable (which may happen when the cable is submerged into snow) the mode situation becomes complicated, with hybrid-modes instead of the conventional even and odd modes. Preliminary results indicate that for the particular cable the multi-mode dispersion is a limiting factor that must be considered seriously, if one aims at a fine resolution in the reconstruction.

D.1.2 Antenna theory and design

Conformal Antennas:
The research on Conformal Antennas involves Lars Josefsson, (now retired from Ericsson Microwave Systems AB in Mölndal, Sweden (EMW), but back as a part-time guest scientist), and Patrik Persson and Björn Thors. Björn Thors graduated in October, and continues in the field. The research has mostly been about writing and preparing results for the book “Conformal Array Antenna Theory and Design” to be published by IEEE Press/Wiley in 2005 (preliminary). In addition, the work with circular cylindrical waveguide aperture arrays coated with a dielectric layer has continued by modifying the numerical approach. Part of this work is done in collaboration with The Ohio State University/Roberto Rojas.

For doubly curved (parabolic) arrays radiation patterns have been investigated and compared (for a single element) with measured data.
The research is coordinated with work at Ericsson Microwave Systems AB in Mölndal, Sweden (EMW). In particular experiments and measurements performed at EMW have been used for verification of theoretical results.

During the year the research concerning the radiation and scattering properties of conformal antenna arrays has continued. Our method of moments (MoM) code to analyse radiation and scattering properties of a cylindrically conformal array antenna with waveguide elements has been further developed to include the effect of a protective dielectric coating surrounding the antenna.

The radiation characteristics and the matching properties for a cylindrical conformal finite array antenna coated with a dielectric layer were investigated within the BFA-project, sponsored by the Swedish Defence Material Administration (FMV). The results from the investigation was documented in the technical report TRITA-TET 03-05, *Radiation characteristics and matching properties for a cylindrical conformal finite array antenna coated with a dielectric layer*.

**Wideband Array Antennas:**
Dr. Hans Steyskal from AF Research Laboratory, USA, is also back as a part time (15%) guest researcher. He is working primarily with PhD student Stig Ekestorm in the area of wideband phased array antennas. Their research is supported by two external sources, the SSF Antenna Technology programme and the FOI contract Wideband Thin Array Structures.

**Development of a Subsurface Radar Imaging System:**
The research by Peter Fuks, Martin Norgren and Disala Uduwawala has been based on the use of resistor-loaded bow-tie antennas for GPR applications. A deep parametric study was done on the antenna using FDTD. In this study, the length, flare angle, lump resistors, position of the antennas (transmitting and receiving) with respect to each other and ground were varied to find what effect these parameters have on the GPR response. Next, the performance of this antenna when it operates above real ground conditions was assessed after selecting the antenna parameters to get a better target discrimination based on the parametric study. Losses and dispersion in soil, ground surface roughness and soil inhomogeneities were considered to simulate real ground conditions.

**Laterally periodic structures:**
Ola Forslund has during 2003 worked on developing methods on scattering from periodic structures with inhomogeneous constitutive parameters including thin metallic elements. He has also studied waveguide array antennas consisting of circular apertures and coaxial chokes.

**D.1.3 Electromagnetic fields in meta-materials**

Author(s): Simovski, CR; Belov, PA; He, SL
Title: Backward wave region and negative material parameters of a structure formed by lattices of wires and split-ring resonators Source: IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, 51 (10): 2582-2591 Part 1 OCT 2003

C. Simovski, P. Belov, and S. He, has studied a structure formed by combined lattices of infinitely long wires and split-ring resonators. A dispersion equation is derived and then used to calculate the effective permittivity and permeability in the frequency band where the lattice
can be homogenized. The backward wave region in which both the effective permittivity and permeability are negative is analyzed. Some open and controversial questions are discussed. It is shown that previous experimental results confirming the existence of backward waves in such a structure can be indeed explained in terms of negative material parameters. However, these parameters are not quasi-static and thus the known analytical formulas for the effective material parameters of this structure, which have been widely used and discussed in the literature, were not correct, and it was the reason of some objections to the authors of that experiment.

Author(s): Simovski, CR; He, SL
Title: Frequency range and explicit expressions for negative permittivity and permeability for an isotropic medium formed by a lattice of perfectly conducting Omega particles
Document Type: Article
Abstract: An analytical model is presented for a rectangular lattice of isotropic scatterers with electric and magnetic resonances. Each isotropic scatterer is formed by putting appropriately 6 Omega-shaped perfectly conducting particles on the faces of a cubic unit cell. A self-consistent dispersion equation is derived and then used to calculate correctly the effective permittivity and permeability in the frequency band where the lattice can be homogenized. The frequency range in which both the effective permittivity and permeability are negative corresponds to the mini-band of backward waves within the resonant band of the individual isotropic scatterer. (C) 2003 Elsevier Science B.V. All rights reserved.

Author(s): Lu, J; He, S
Title: Numerical study of a Gaussian beam propagating in media with negative permittivity and permeability by using a bidirectional beam propagation method
Abstract: Gaussian beam propagation in structures containing meta-materials with negative permittivity and negative permeability is numerically studied by using a bidirectional wide-angle finite-difference beam propagation method. Illustrative and quantitative views are given for various anomalous behaviors, such as the negative angle of refraction, beam refocusing, arbitrarily thin distributed Bragg reflector, and negative lateral shift of the reflected beam from a grounded slab, by a Gaussian beam propagating in some meta-material structures. (C) 2003 Wiley Periodicals, Inc.

D.1.4 Design of optronic devices

Author(s): He, SL; Ao, XY; Romanov, V
Title: General properties of N x M self-images in a strongly confined rectangular waveguide
Source: APPLIED OPTICS, 42 (24): 4855-4859 AUG 20 2003
Abstract: General properties of N x M self-images in a strongly confined rectangular waveguide are given. Analytical formulas are derived for the positions, amplitudes, and phases of the N x M images at the end of multimode interference section. The formulas are verified with numerical simulation of a three-dimensional semivectorial beam propagation method. (C) 2003 Optical Society of America.

Author(s): Dai, DX; He, SL
Title: Analysis of multimode effects in the free-propagation region of a silicon-on-insulator-based arrayed-waveguide grating demultiplexer
Source: APPLIED OPTICS, 42 (24): 4860-4866 AUG 20 2003
Abstract: Multimode effects in the free-propagation regions (FPRs) of an arrayed-waveguide grating (AWG) demultiplexer based on silicon-on-insulator are considered. Some undesired multimode effects, such as the increase of the insertion loss and the cross talk, are studied by use of a method of three-dimensional guided-mode propagation analysis. It is found that the multimode effects for the edge channels are more serious than those for the central channel. For an AWG demultiplexer with a small channel number, the multimode effects can be minimized by choosing appropriate FPR parameters such as the length and the thickness of the FPR. The coupling coefficient between the FPR and an arrayed waveguide is sensitive to the thickness of the FPR. (C) 2003 Optical Society of America.

Author(s): Dai, DX; Mei, WQ; He, SL
Title: Using a tapered MMI to flatten the passband of an AWG Source: OPTICS COMMUNICATIONS, 219 (1-6): 233-239 APR 15 2003
Abstract: A tapered multimode interferometer (MMI) is used to flatten the passband of an arrayed-waveguide grating (AWG). The tapered MMI is connected at the end of the input waveguide of the AWG. The influences of the tapering angle to the performances (such as the 3 dB passband width, the ripple, the crosstalk and the insertion loss) of the flat-top AWG are studied. An AWG which has simultaneously a good flat spectral response and a good dispersion characteristic is designed by choosing appropriately the tapering angle and the length of the tapered MMI. (C) 2003 Elsevier Science B.V. All rights reserved.

Author(s): Dai, DX; Liu, SZ; He, SL
Title: A flattened AWG demultiplexer with low chromatic dispersion Source: FIBER AND INTEGRATED OPTICS, 22 (3): 141-149 MAY-JUN 2003
Abstract: A design method is introduced to obtain a flat-top arrayed-waveguide grating (AWG) demultiplexer with low chromatic dispersion. A multimode interference (MMI) section is connected at the end of the input waveguide, and a tapered waveguide is connected at the entrance of each output waveguide of the AWG demultiplexer. The design procedure is presented. A design example is given and shown to have a much better performance than the conventional flat-top design using only an MMI section. The insertion loss of the designed AWG demultiplexer is also reduced.

D.1.5 Optimal control for direct scattering

In a collaboration with M. Gustavsson (LTH, Sweden), M.V. de Hoop (Colorado School of Mines, USA), and V.H. Weston (Purdue univ. USA), Lars Jonsson has studied optimal control of direct scattering. Using the symmetry properties of the hyperbolic equations (in particular the equations of linear acoustics and electromagnetics equations, an algorithm has been constructed that gives the optimal boundary data for reconstruction of any field in the domain at a given time. The result is optimal in the sense that it minimizes a weighted L2 norm between the obtained field and the field distribution searched for. It has been shown that the result reconstructions the field up to controllability.
Applications include non-destructive testing, inverse problems (construction of optimal probing data). A medical application is lithotripsy, where one tries to avoid damaging the spine, while requiring maximal pressure field amplitude into the gall stone(s). The above result enables the physicians to find the optimal to apply and evaluate how much the uncontrallability of the set-up degenerates the interior field distribution.
D.1.6 Soliton dynamics

Lars Jonsson has continued his research concerning a generic model for non-linear effects like solitary waves. Together with I. Segal (Univ. of Toronto, Canada), J. Frölich (ETH, Switzerland), and S. Gustafson (Univ. of British Columbia, Canada), he has systematically investigated how perturbations of a background medium affects the dynamics of a solitary wave.

They have studied the behaviour of solitary wave-solutions of a class of generalized nonlinear Schrödinger equations with an external potential. A solitary wave is a solution to a Hamiltonian PDE, and to obtain the dynamics of the wave, it has been required to solve this nonlinear Hamiltonian PDE, while preserving its conservation laws. This simulation is exceedingly difficult, and the time span for which it can be obtained is fairly short. Their new results enable one to describe the solution to the nonlinear Hamiltonian PDE for a very long time, by solving certain ODEs. Thus the dynamics can now be calculated in detail for that time interval.

D.2. Publications by the Division of Electromagnetic Theory

D.2.1 Papers published in international journals


### D.2.2 Other publications

Disala Uduwawala, Martin Norgren, Peter Fuks, and Aruna Gunawardena, A Complete FDTD Simulation of a Real GPR Antenna System Operating above Lossy and Dispersive Grounds, Submitted to IEEE transactions on Geoscience and Remote Sensing. TRITA-TET…


### D.2.3 Forthcoming publications as of January, 2004


**D 2.4 The TRITA-TET series of reports**

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<td>L. Jonsson, M. Gustafsson, V. Weston and M. de Hoop. Retrofocusing of Acoustic Wave Fields by Iterated Time Reversal</td>
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<td>5</td>
<td>B. Thors, L. Josefsson and M. Norgren. Radiation characteristics and matching properties for a cylindrical conformal finite array antenna coated with a dielectric layer.</td>
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<td>6</td>
<td>D. Uduwawala, M. Norgren, P. Fuks and A. Gunawardena. A Complete FDTD Simulation of a Real GPR Antenna System Operating above a Lossy and Dispersive Ground Medium</td>
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<td>J. Fröhlich, S. Gustafson, B. L. G. Jonsson, I. M. Sigal. Solitary wave dynamics in an external potential</td>
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**D.3 Conferences and workshops**

**D.3.1 Contributed papers – oral presentations**


**D.3.2 Organisation of conferences and workshops**

As a Plenary Speaker of APOC 2004 (the 4th Asia-Pacific Optical Communications Conference, Beijing, China, Nov. 7-11, 2004), Sailing He has been invited to give a talk “Research and Applications of Photonic Crystals” in the plenary session.

Sailing He organized a session (and will chair this session and give an invited talk) entitled "Meta-materials and structures with negative refraction" in the PIERS (Progress in Electromagnetics Research Symposium) 2004, Nanjing, China, August 28 - 31, 2004.

P. Persson organised and attended meeting on antennas (“triangelmöte”) in Stockholm, KTH/TET 30 September 2003, with participants from FOI, KTH, LiTH and EMW.

S.Ström organised the SSF Antenna Technology Program Workshop, 26-27 November, 2003. At this Workshop,Lars Josefsson, Patrik Persson, and Björn Thors gave an overview of Project 5A: Conformal Antennas on Curved Surfaces, and Hans Steyskal and Jörgen Ramprecht did the same for projects 3 and 4, ‘Inherently Wideband Antennas’, and ‘Active Impedance Matching for Wideband and Wide Angle Scanning Arrays’, respectively.

Martin Norgren was Local organizer of SNOWPOWER 4th Partner Meeting, September, 24th –26th 2003 at KTH, Alfvén Laboratory, Stockholm

**D.4 Other activities**

Patrik Persson acted as co-chairman at the session ”Analytical and Computational Scattering Analysis”, *IEEE AP-S Int. Symp.*, June 22-27, 2003, Columbus, Ohio, USA.

Prof. Prabhakar Pathak, ESL, Ohio State Univ. visited KTH/TET September 18-19, 2003. He also gave two seminars with the following titles:

• General Research on Hybrid Methods for Large Arrays - Present and Future.
• Introduction to Hybrid APE-MoM for Large Body Radiation/Scattering.
KTH/TET has been selected as one of the participating partners in the EU Sixth Framework Programme, ACE (Antenna Center of Excellence). The program plans to start with a kick-off meeting at ESA in January 2004.

**D.4.1 External seminars and visits**

P. Persson is visiting the Dept. of Physics and Measurement Technology (IFM) at Linköping University regularly.

**D.4.2 Miscellaneous**

Martin Norgren participated in the SNOWPOWER 3rd Partner Meeting, March, 16\(^{th}\) –19\(^{th}\) 2003, Weissfluhjoch-Davos, Switzerland. Gave an informal seminar about limitations of the sensor cable, due to multi-mode propagation and radiation.