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# PHYSICS
# AND
# PLASMA ENGINEERING ACTIVITIES
# IN THE EUROPEAN FUSION ASSOCIATIONS
# 1997/1998

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## MONITORING OF THE ASSOCIATIONS' PROGRAMMES AND ACTIONS

**Report by the Programme Committee**

**February 1999**

# Table of Contents

**EXECUTIVE SUMMARY** ..... **3**

**1 BACKGROUND** ..... **6**

**2 GENERAL DESCRIPTION OF R&D ACTIVITIES** ..... **7**

2.1 OVERVIEW ..... 7
2.2 EUROPEAN AND INTERNATIONAL CO-OPERATION ..... 9
2.3 EDUCATION AND TRAINING ACTIVITIES ..... 10
2.4 NEXT STEP/ITER RELATED ACTIVITIES ..... 11
*2.4.1 Overview ..... 11*
*2.4.2 R&D in Physics and Plasma Engineering for the Next Step - ITER ..... 12*
2.4.2.1 D-T Operation on JET ..... 13
2.4.2.2 Particle and Power Exhaust ..... 14
2.4.2.3 Confinement, Particle and Energy Transport ..... 15
2.4.2.4 Operational Limits and Plasma Control ..... 17
2.4.2.5 Plasma Engineering ..... 18
2.4.2.6 Theory and Modelling ..... 22
2.5 CONCEPT IMPROVEMENTS ..... 22
*2.5.1 Tokamak ..... 22*
*2.5.2 Stellarator ..... 23*
*2.5.3 Reversed Field Pinch ..... 24*
*2.5.4 Keep-in-touch Activities to Other Approaches to Fusion ..... 27*

**3 PHYSICS AND PLASMA ENGINEERING ACTIVITIES IN THE ASSOCIATIONS** ..... **28**

3.1 ASSOCIATION EURATOM - BELGIAN STATE ..... 28
3.2 ASSOCIATION EURATOM – CEA ..... 29
3.3 ASSOCIATION EURATOM - CIEMAT ..... 32
3.4 ASSOCIATION EURATOM - CONFÉDÉRATION SUISSE ..... 33
3.5 ASSOCIATION EURATOM - DCU ..... 35
3.6 ASSOCIATION EURATOM - ENEA ..... 36
3.7 ASSOCIATION EURATOM - FOM ..... 39
3.8 ASSOCIATION EURATOM - FZJ ..... 40
3.9 ASSOCIATION EURATOM - FZK ..... 42
3.10 ASSOCIATION EURATOM - IPP ..... 43
3.11 ASSOCIATION EURATOM - IST ..... 48
3.12 ASSOCIATION EURATOM - NFR ..... 49
3.13 ASSOCIATION EURATOM - ÖAW ..... 51
3.14 ASSOCIATION EURATOM - RISØ ..... 52
3.15 ASSOCIATION EURATOM - TEKES ..... 53
3.16 ASSOCIATION EURATOM - UKAEA ..... 54
3.17 EURATOM - SUPPORTED ACTIVITIES IN GREECE ON FUSION (COST SHARING ACTIONS) ..... 56

**ANNEX I: EU PHYSICS R&D IN RESPONSE TO 'URGENT PHYSICS NEEDS'** ..... **57**

(not included for length reasons)

**ANNEX II: PREFERENTIALLY SUPPORTED ACTIONS** ..... **57**

(not included for length reasons)

## EXECUTIVE SUMMARY

The present report has been established in response to the request of the CCFP "*that the PC and the FTSC shall on a continuous basis organise presentations by the Associations and the JRC on their overall activities in the fields of magnetic confinement fusion physics (including plasma engineering) and technology, respectively, and discuss the programmatic aspects of these activities with respect to*

- *their contribution to the aims of the Community Fusion Programme;*
- *adherence to previously agreed objectives, milestones and time scales.*

*Particular consideration should be given to actions with priority status. Links to other laboratories and industry should be highlighted. ...*"

The presentations and the ensuing discussions at PC meetings were arranged such that the whole Programme could be covered within about two years. JET and the ITER Home Central Team (HCT), though not being part of the monitoring exercise, also provided presentations on their activities and perspectives to assist meaningful discussions of the Association's programmes.

During this exercise the Programme Committee reported on a regular basis to the CCFP.

The activities in the field of Physics and Plasma Engineering were pursued along the two following lines:

Next Step oriented activities: In response to the priorities set by the CCFP and to the physics and plasma engineering tasks defined by ITER, the Programme focused its activities during 1997/8 at further developing the necessary basis for the possible construction of an experimental reactor. This concerned the design proper as well as R&D in support of the design and construction of the Next Step. Work was pursued at JET and in the Associations and closely co-ordinated with the European ITER Home Central Team (NET). This European contribution provided a comprehensive and focused support for the ITER physics basis and plasma engineering developments of the ITER FDR design (see Annex I). The PC points to highlights such as the studies on confinement in the ITER Reference Scenario, the exploration, in deuterium and deuterium-tritium plasmas, of the H-mode threshold and its isotope dependence, the work on operational boundaries, plasma control, steady state scenarios, edge physics, divertor configurations as well as plasma engineering developments for heating, current drive and fuelling systems. Work has also set the basis to address the design of a device with reduced detailed technical objectives but maintaining the overall programmatic objective of ITER namely to

demonstrate the scientific and technical feasibility of fusion energy for peaceful purposes.

The work on Concept Improvements which is mainly DEMO-oriented also assists the preparation of the Next Step operation. For all concepts, milestones were set by the agreed preferential support actions (see below) and by requests emanating from the Programme, in part to corroborate the ITER physics data base, in part to identify new possibilities for further improving integrated concepts of a long-pulse burning plasma. Activities for the Tokamak concerned, inter alia, the study of shear and profile controlled scenarios, the dependence of a broad range of confinement and operational features on shape and aspect ratio and the further development of the beneficial role of edge radiation. The confinement qualities of the Spherical Tokamak concept have been explored in plasmas up to a few keV temperature. For the Stellarator, experimental work has been undertaken to confirm the confinement basis and broaden the data basis and to detail the divertor concept for Wendelstein 7-X. Detailed configurational studies for the flexible Heliac configurations have begun.

For the programme on the Reversed Field Pinch, in response to the request to focus on improving the operational capabilities, detailed investigations of the physics involved have been launched, resulting in a substantial progress in understanding and controlling the intrinsic RFP dynamo action yielding a substantial improvement of operation.

Particularly for the preferentially supported actions (see Annex II) and in the area of Plasma Engineering substantial developments have been conducted in direct interaction with industry. Corresponding information is contained in section 3; particular examples are the superconducting coils and the demo-cryostat for Wendelstein 7-X and gyrotron developments. Some Associations have taken initiative to strengthen the links to industry by specific actions in order to make industry aware of the opportunities which fusion presents and to transfer know-how, which has been developed in fusion, to other fields. Often, such transfer also relates to fundamental plasma physics, the application of computing methods, modelling and the use of databases.

The work within the Programme has been strongly assisted by an increasingly close collaboration among Associations, JET and participating universities. Educational activities have continued with a substantial training effort in the laboratories, participation of a large number of staff in academic teaching, with summer schools and with dissemination actions to universities, schools and the wider interested public.

The PC notes the progress of the priority actions which have been under implementation or exploitation during 1997/8, in particular:

- Wendelstein 7-X (IPP), after delay in the phase of decision making, entered construction:
  The buildings will be completed in 1999;
  The superconducting non-planar coil system has reached the stage of industrial procurement;
  The industrial prototypes of the cryostat and a non-planar coil have been delivered to IPP and FZK, respectively, however, with a delay of 1-2 years, and are currently under preparation for testing;

- The medium-sized flexible Heliac TJ-II (CIEMAT) has been commissioned and started operation;
- The construction of MAST was completed. The device shall carry the study of low aspect ratio tokamaks to Mega-ampere level;
- The Lyra divertor of ASDEX-Upgrade (IPP) was installed according to the foreseen schedule in 1997 providing timely information for the decision on the JET MK IIGB divertor.

Some new priority actions were launched:

- the Dynamic Ergodic Divertor of TEXTOR-94;
- the CIEL project of TORE SUPRA;
- the Neutral Beam Injection System (2MW) of TJ-II;
- the Neutral Beam Injection System (5MW) of MAST;
- the Advanced Diagnostics for TEXTOR-94;
- the modifications of one Neutral Beam Injector and reactive power compensation for ASDEX-Upgrade.

The preferentially supported RTP device, after completing its mission, was phased out. Based on the achieved results, the studies will continue on TEXTOR-94 in the frame of the Trilateral Euregio Cluster. The START spherical tokamak device was phased out, being replaced by MAST.

The PC points to the fact that the physics activities of the Associations, JET and the NET team have been supported and complemented by the integration of the European Fusion Programme in the wider international context, in many cases through collaborations including - besides the wide-ranging ITER-EDA - Implementing Agreements in the frame of IEA and Bilateral Agreements. The Programme has made a leading contribution to the world wide development of fusion and in particular to the ITER collaboration under the auspices of the IAEA.

## BACKGROUND

At its 67th meeting on 29 February / 1 March 1996, the Consultative Committee for the Fusion Programme (CCFP) took note of the 1995 Fusion Programme Monitoring Report and agreed subsequently to discuss ways and means of strengthening its watching brief on the activities within the programme.

At its 69th meeting, the CCFP unanimously endorsed the proposal by the Commission
"*that the PC and the FTSC shall on a continuous basis organise presentations by the Associations and the JRC on their overall activities in the fields of magnetic confinement fusion physics (including plasma engineering) and technology, respectively, and discuss the programmatic aspects of these activities with respect to*

- *their contribution to the aims of the Community Fusion Programme;*
- *adherence to previously agreed objectives, milestones and time scales.*

*Particular consideration should be given to actions with priority status. Links to other laboratories and industry should be highlighted. ...*"

The presentations and the ensuing discussions were arranged such that the whole Programme could be covered within about two years. JET and the ITER Home Central Team (HCT), though not being part of the monitoring exercise, also provided presentations on their activities and perspectives to assist meaningful discussions of the Association's programmes.

A schedule was worked out on the basis of a proposal by the Commission for the oral presentations at the Programme Committee. Written input was provided by all Associations, the Greek groups active in fusion as well as JET and the ITER HCT.

During this exercise the Programme Committee reported on a regular basis to the CCFP.

The present report concerns the Physics Activities. It has been drawn up on the basis of the contributions of the Associations and the ensuing discussion at the Programme Committee. It includes, for consistency, information on the main JET results.

# GENERAL DESCRIPTION OF R&D ACTIVITIES

## OVERVIEW

In line with the Council Decision on the 4th Framework Programme, the physics activities of the Community Fusion Programme continued in 1997/1998 at JET (Joint European Torus) and in the Associations along the mutually interlinked "Next Step activities" and "Concept Improvements" orientations.

The Next Step (ITER) activities have been pursued in the frame of the Engineering Design Activities. The original six-year period expired by July 1998. A three year extension has been agreed by three parties (EU, Japan, Russia) while the US committed itself unilaterally to a 1 year continuation. The work of the (European) ITER HCT continued to be co-ordinated by the NET (Next European Torus) Team. Following the presentation of the ITER Final Design Report in January 1998, the ITER Parties reconfirmed the feasibility of the design, its quality and the fact that it stayed within the original frame of cost estimate. In view of the present financial possibilities they charged the ITER Joint Central Team to consider a version of the device with reduced objectives which could be built at lower cost.

For JET, after the deuterium-tritium campaign during the last months of 1997, the first months of 1998 were used to replace the divertor by a new configuration (Mark II Gas Box). As a consequence of the activation of JET in-vessel components, this exchange had to be performed by using remote handling techniques and turned out to be very successful. JET has subsequently undertaken, together with, and assisted by, the Associations, a campaign for the study of urgent physics issues for ITER which included the characterisation of the new Mark IIGB divertor.

JET and the specialised European devices have conducted the largest part of their R&D in support of the Next Step activities for the data bases and physics design issues of ITER.

Work on Concept Improvements is, for the tokamak, closely linked to work on the Next Step. Its general orientation is to explore options and to prepare, in the longer term, for the definition of DEMO. Work has been undertaken on JET and in the Associations with their specialised devices (the tokamaks ASDEX Upgrade, COMPASS, FTU, ISTTOK, RTP, START, TCV, TEXTOR-94 and TORE SUPRA). The work on stellarators, which offer an intrinsic potential for steady state operation, continued on W-7AS and with the construction of W-7X, and started on TJ-II, driven by the interest in the reactor potential of these confinement concepts and their contributions to the understanding of toroidal confinement systems. Contributions to the toroidal confinement data base were also provided by the reversed field pinch which is akin to the tokamak and which could achieve high density operation at low magnetic fields. Work on RFX and EXTRAP-T2 concentrated on issues of achieving high performance operation and control of modes.

Besides minor upgrades of systems and diagnostics, the following preferentially supported major developments in hardware have occurred on the European fusion physics devices:

- On JET, after the D-T operation a new divertor, Mark IIGB, has been installed fully by remote handling techniques.
- A new divertor configuration (Lyra divertor) and improvements of the heating systems were installed in ASDEX Upgrade during the first half of 1997.
- In September 1998 the Tokamak RTP at the FOM institute in Rijnhuizen has been taken out of operation. The team will henceforth concentrate its activities on TEXTOR-94 at Jülich where the longstanding co-operation between the Associations EURATOM-FZJ and Belgian State (Royal Military Academy) has been extended to the Trilateral Euregio Cluster (TEC) in 1996 with the inclusion of the Association EURATOM-FOM.
- The construction of the spherical Tokamak MAST at UKAEA Fusion in Culham continued through 1997/98; commissioning and first plasma operation took place by end 1998. This device is replacing the START experiment, which was phased out. The procurement of a neutral beam injection system has been approved in 1998.
- For Stellarators, with TJ-II at CIEMAT Madrid a medium sized flexible Heliac has been put into operation around the turn of 1997/98; commissioning and first plasma operation took place in the first half of 1998. (The previous small machines, TJ-IU and TJ-I at CIEMAT, which have helped to prepare for TJ-II had been phased out earlier.) The procurement of a neutral beam injection system has been approved in 1998.
- Additional heating systems are under preparation. In collaboration with the Associations EURATOM- CEA, FZK, Swiss Confederation and European industry, 118 GHz electron cyclotron systems are under development for Tore Supra and TCV. First tests took place in 1997/8. The desired power of the gyrotrons (500 kW) at 5 s was demonstrated. Extension of these tests to the full specification of 210 seconds is underway with European industry. For TCV the same tubes are now being ordered for third harmonic heating. Here, 5s pulse duration is sufficient. Simultaneously, 82.7 GHz tubes are being procured for second harmonic heating on TCV. A 140 GHz ECRH system is also under completion on FTU in collaboration with CNR Milan and industry.
- For Tore Supra the enhancement of power handling capability has been approved in 1997. Aim is the control of 15 MW convected power plus 10 MW radiated power over ultimately 1000s. Development of components is underway in collaboration with European industry.
- Construction of Wendelstein 7-X by IPP in Greifswald continued; commissioning is expected by 2005/6.

The achievements on these medium-sized devices are presented in later sections.

These specialised devices also serve for fundamental fusion physics studies, for the development

of diagnostics, for the preparation of collaboration on larger devices, for innovative studies and for the training of young professionals; also, these devices act as facilities which allow the incorporation of university research into theoretical, numerical, or diagnostic fusion activities.

In 1997/98 the proposals for the 5th Framework Programme (FP 5) and for the specific programmes within FP 5 (including the Fusion key action) were presented and discussed. On December 22, 1998, both Framework Programmes (EC and EURATOM) were formally adopted and a political agreement was reached on the specific programmes. In fusion physics, based on the progress achieved during the 4th Framework Programme, the existing key orientations will be further pursued in the four coming years. In conjunction with FP 5, preparations for a possible exploitation of the JET facilities after the end of the JET Joint Undertaking, on 31.12.1999, took place in 1998. A scientific-technical exploitation by the Associations is considered, the UKAEA being charged with the operation of the facilities. Working groups have developed the legal and administrative aspects as well as the organisational and scientific aspects of such exploitation. A campaign-oriented operation with task forces (staffed by the Associations) is proposed and is currently further refined.

In order to further promote the interaction among the European fusion laboratories (including JET) for the joint exploitation of experiments, policies, protocols and standards for remote access, transfer and exchange of data have to be adapted. A Group was set up to examine practical means to optimise accessibility and exchangeability of data among all participants, in particular in view of the enhanced participation of the Associations in the JET operation during 1999 and the possible campaign-oriented collaborations of Associations beyond 1999 to exploit the facilities.

## EUROPEAN AND INTERNATIONAL CO-OPERATION

The integrated nature of the Programme has led to extensive collaborations, not only between the European fusion laboratories, but also with other laboratories world-wide.

All Associations undertake work for, or in collaboration with, other Associations. The Associations are partners in JET and NET, and carry out work for them through various contracts and notifications. Across Europe there exists a genuine scientific and technical community of large and small laboratories directed towards a common programmatic objective.

JET has executed a very demanding programme during 1997/8 to which Associations participated, partially through Task Agreements, with staff, dedicated work and scientific collaboration. For the exploitation of the JET facilities by the associated laboratories, following the termination of the JET Joint Undertaking at the end of 1999, a new framework (European Fusion Development Agreement, EFDA) between EURATOM and the Associations has begun to be prepared in 1998 with the identification of staff needs, the development of a campaign-oriented structure and a work programme for the period under consideration. Following the

termination of the NET Agreement at the end of 1998, the activities of the European Central Team for ITER are also planned to be included in EFDA.

Collaborations among Associations have been reinforced during the last two years. Incentives for joint work arose from further focussing on the key priorities for the Next Step and the co-ordination of ITER related work by the European Home Central Team (NET Team), the system of Field Co-ordinators and Task Area Leaders, the collaboration in expert groups for ITER and incentives arising from the European Fusion Physics Workshops, the European Transport Task Force, and, in the field of plasma engineering, from the Co-ordinating Commitees for the heating systems and the assessment, carried out by the Programme Committee of the strengths and possible drawbacks of heating and current drive systems. There are many bi- and multi- lateral co-operations between Associations and between Associations and institutions such as universities (see chapter 3 of this report). Assisted by the preferential support scheme (which encourages, by 45% funding, capital investments incurred by an Association for equipment to be specifically used on a machine of a second Association) the Trilateral Euregio Cluster (TEC) started which merges fusion activities of three Associations (EUR-Belgian State, -FOM and -FZJ, together with a "University Club" of the region). Also, following the closure of RTP at FOM in September 1998, the RTP team is starting to work with their equipment on TEXTOR at FZ-Jülich.

Internationally, the most important collaboration is the ITER Engineering Design Activities under the auspices of the International Atomic Energy Agency (IAEA, Vienna) which concluded its original six-years period successfully with the integrated design of an ITER device and was extended by three partners for three more years the US participating for one more year (see below, Next Step Activities). Eight Implementing Agreements in the frame of the International Energy Agency (IEA, Paris) have continued to serve as the frame for collaborations to pool expertise and joint scientific interests. Bilateral or multilateral agreements for collaborations between European and non-European laboratories have assisted the exchange of information, common developments and the definition of complementary scientific investigations.

## EDUCATION AND TRAINING ACTIVITIES

Education and training has been an integral element in the Associations' work. The Associations are linked to many academic institutions, mainly universities, within the EU and beyond. In the recent past, based on a survey of 1995/6 which still is representative, the total number of institutes (in the EU, but outside the Research Units) which are engaged into fusion R&D, has considerably increased and is today in the order of 50-60. A recent survey showed that around 60-75 institutions provide education in fields of relevance for fusion with about 80 professors and an equal number of lecturers and other permanent staff involved in teaching and training. Within the Research Units of the Community Fusion Programme, another 150-165 professionals participate in teaching, mainly at universities but also in summer schools etc.

In the Research Units of the programme, around 350-400 students are trained, thereof 220-250 PhD students. In the academic institutions which are linked to the programme, about 150-180 students are educated. For obvious reasons, specific links to the Fusion Programme (as to other advanced leading edge R&D areas) are established only at a late stage of the studies.

In some countries the number of students in physics, and consequently also in fusion has declined severely in the recent years. Considering also the loss of a larger number of professional staff from JET which started in 1998 and will continue in 1999, the programme will need to undertake increased active measures for maintaining the necessary professional staff potential in the coming years.

## NEXT STEP/ITER RELATED ACTIVITIES

### 1.1.1 OVERVIEW

A strong focus of the programme was on the engineering design of ITER, the overall programmatic objective of which is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

During 1997 the technological choices for ITER systems, such as the magnetic field coils, the first wall and shielding structure, the vacuum vessel, the remote handling devices, and the auxiliaries for heating and current driving, fuelling, pumping and handling of the exhaust have been further qualified through the ongoing R&D programme. For the optimisation and confirmation of the selected solutions and of the attainable performance margins a continuing design effort and a focused R&D activity has been undertaken by the Joint Central Team and the Home Teams. Contributions to the ITER Physics Basis document have been prepared (largely in the frame of ITER Expert Groups) and early in 1998 the ITER Final Design Report, Cost Review and Safety Analysis (FDR) was issued by the ITER Central Team for consideration by the Parties. The European Party undertook an in-depth examination of the report that resulted in a positive recommendation and acceptance of the report.

Recognising that, in case the Parties would eventually be unable to proceed jointly to the construction of the presently foreseen device, the ITER Council charged the Joint Central Team to look into option(s) of a ITER device with reduced detailed technical objectives but maintaining the overall programmatic objective of ITER namely to demonstrate the scientific and technical feasibility of fusion energy for peaceful purposes. For this purpose, a Special Working Group was set up with the charge to propose technical guidelines for possible changes and also provide information on broader concepts. At its meeting of 18 June 1998, the CCFP noted the tasks assigned to the Special Working Group and agreed with the ITER Council that it was prudent to consider reduced cost option(s) of ITER.

The ITER FDR was approved by the ITER Council at its extraordinary meeting on 25 June 1998 and the amendment extending by three years the agreement on co-operation in the ITER EDA

was signed by the Russian Federation on 16 June, by EURATOM on 30 June and by Japan on 14 July 1998. The USA signed on 22 September 1998 a unilateral agreement on continued US participation for a period of one year in view of the completion of ongoing ITER EDA activities and the negotiation of a new arrangement for international collaboration in fusion science. In the meantime, the US DOE took action to suspend participation of US secondees at the Joint Work Sites and instructed them to complete their current activities. The work of the other ITER Partner teams is being pursued.

### 1.1.2 R&D IN PHYSICS AND PLASMA ENGINEERING FOR THE NEXT STEP - ITER

The major part of the work on JET and in the Associations during 1998 continued to be directed towards support of ITER. The key areas were scientifically closely interlinked. Of particular importance were the domains of

- physics of particle and power exhaust;
- confinement, particle and energy transport properties of the fusion plasma (in particular when operating in enhanced confinement regimes);
- operational limits and plasma behaviour at operational limits and related plasma control, pre-emption / mitigation of off-normal events (in particular plasma disruptions and vertical displacement events);
- plasma engineering, i.e. heating and current drive systems, fuelling and exhaust systems, plasma control and diagnostics development.

In this effort, JET provides the data points closest to the ITER working regimes. The medium-sized devices in the Associations complemented JET results for size scaling purposes and explored additional options such as inboard pellet fuelling, detached divertor operation or the radiative enhanced mode. An increasing attention has been paid to optimise (magnetic) shear operation modes of Tokamaks, which could lead to improved performance.

Systems for heating and current drive, fuelling and diagnostics continued to be developed to meet specific requirements of ITER. Concept Improvements along the Tokamak, in particular on the optimised shear operation and the connected issue of internal transport barriers were fed during 1998 into the new considerations for a modified design. Stellarator as well as Reversed Field Pinch groups contributed with studies on specific issues (confinement dependence on current, engineering aspects, disruptions) to the ITER work and the corresponding databases. The NET Team continued to liaise the activities in the European Fusion Programme on the ITER project. The ITER Physics Basis Document was completed with a substantial contribution by NET and the European Field Co-ordinators and Task Area Leaders. In preparation for the EDA Extension Phase a revised list of R&D tasks was established and ITER Reduced Cost Options (defined by the Special Working Group) were assessed. For these, after an exploratory phase, work concentrated on a “low aspect ratio” and a “intermediate aspect ratio” variant. A higher aspect

ratio option, favoured by Japan does not appear to provide an attractive operating range.

#### *1.1.2.1 D-T Operation on JET*

On JET, a full phase of deuterium - tritium experimentation (DTE1) was executed for the first time in 1997. (In 1991, a preliminary exploration of D-T operation with some 10% tritium concentration in the fuelling gas, had been undertaken resulting in 1-2 MW peak fusion power.) Some technical problems delayed the start of the campaign until September. Careful planning had been undertaken to accommodate a programme of high ITER relevance within the budget of 2 - 2.5 $10^{20}$ neutrons available for this campaign. The results obtained were:

- Record fusion power of 16 - 17 MW in the hot-ion ELM-free H-mode with a ratio of fusion to heating power of Q = 0.6 - 0.7;
- Clear evidence of alpha particle heating and, in the investigated range, stability of Toroidal Alfvén Eigenmodes to alpha particle drive;
- Record fusion energy of 21 - 22 MJ in a stationary ELMy H-mode discharge (4 - 5 MW for 4 - 5 seconds) which could have been sustained much longer but was terminated for technical reasons and to economise on the neutron budget;
- Exploration of optimised shear operation demonstrating high performance - high confinement operation with contributions of bootstrap current[1] and current drive;
- Demonstration of a substantial reduction of the power needed to access the H-mode in D-T and pure T operation by about 25% (as compared to pure D operation);
- Demonstration of ICRF heating schemes in ITER relevant conditions:
  - ♦ Minority deuterium heating;
  - ♦ Second harmonic tritium heating.

These results confirm the accessibility of high performance in ITER (the attainable Q should range from Q>8 to infinity) and suggest that the necessary additional heating power may be lower than anticipated. Of particular importance were the ELMy H-mode results, which are the world's first demonstration of stationary D-T fusion power production. In these shots, the temperature and density profiles remained constant and the duration of constant fusion power production was considerably longer than all plasma time scales, with the two exceptions of the current diffusion time and the full plasma-wall equilibration time.

Operation under optimised shear in D-T could not be fully exploited since the limited number of shots planned for this mode did not allow to fully adapt to the favourable H-mode threshold isotope dependence. Thus the potential of this operational mode may be significantly higher than has been demonstrated.

The DTE1 campaign was terminated in November 1997.

[1] see section 1.1.2.5

#### *1.1.2.2 Particle and Power Exhaust*

The so-called "poloidal divertor" is the concept chosen for ITER. It uses a special magnetic configuration to guide particles from the plasma boundary into a separate exhaust volume ("divertor chamber") and eventually towards target plates. Pumps then remove the particles. Limiting the heat load on the target plates by transforming kinetic energy of the plasma particles into electromagnetic radiation and neutral particle fluxes before the plasma hits the target plates, the so-called "detached divertor operation", has continued to be investigated during 1997. Particular attention has been given to a high density in the divertor and to limit neutral particle flux back into the main chamber by baffling the divertor. On ASDEX Upgrade the so-called LYRA divertor was put into operation during summer 1997. A clear improvement of D and He pumping could be demonstrated. These first results were essential for proceeding towards a decision, in fall 1997, to install the Mark IIGB divertor in JET.

In the first part of 1998, scientific operations of JET were stopped to replace the previous JET divertor by the "gas box" configuration (Mark IIGB). The Mark IIGB divertor represents the ultimate, most closed system in the ITER relevant divertor development on JET which started with the open divertor Mark I and then proceeded via two stages of the Mark II (A and AP) divertor. To install Mark IIGB in a radioactive environment, the interior of the JET device has been modified for the first time exclusively with the use of remote handling tools. This has been achieved within the time frame foreseen (and within not much more time than would have been needed by hands-on intervention) by developing a human-machine interface which in effect extends the operators own arms into the interior of JET. The man-in-the-loop remote handling proved to be highly successful, even for performing unplanned interventions. The new configuration is a deep divertor with a well-baffled entrance i.e., which is less open to the plasma main chamber. Operation of JET re-started in June 1998 and preliminary results confirm the expectations for a more closed divertor i.e. the better baffling leading to the enhancement of neutral gas pressure and consequent improved pumping of deuterium and helium. Doubts concerning the possible impact of strong divertor closure on performance could be removed. Although the effect of large ELMs has not yet been tested, the configuration was compatible with the intended operating scenarios. Density limits did not show a significant change to operation with more open divertors. A certain dependence of the H-mode threshold on divertor configuration was found. Positioning the X-point deeper in the divertor reduces the threshold. The septum installed in the Mark IIGB which is separating the inner and outer divertor leg proves useful for dedicated density control of the divertor legs and hence permits to balance the divertor operation.

In 1998 the "LYRA" divertor (divertor II) has been further qualified on ASDEX Upgrade[2]. Quasi-stationary H-mode (CDH) with large radiating fraction and good power and particle

[2] A further modification of the Lyra geometry at ASDEX Upgrade shall be installed in the year 2001.

exhaust has been achieved. Other issues were the demonstration of helium exhaust, quantitative understanding of critical divertor properties and of power fluxes, operation with tungsten-coated divertor target plates and achievement of strongly reduced loads on target and divertor walls in the more closed Divertor II at low radiating power fraction and without reduced density limit. Divertor II operation in ASDEX Upgrade showed an increased exhaust performance and quasi-stationary discharge conditions were achieved. Studies on FTU were undertaken with limiter materials ranging from Silicon to Molybdenum (TZM) and Tungsten showing advantages for high-Z materials coated limiter surfaces in particular with respect to the achievement of lower core impurity content and higher achievable density limit. Combined theoretical and experimental studies of the power scrape-off layers in JET, Alcator C-MOD and COMPASS-D have made possible to discriminate between theoretical models of edge turbulence and to guide divertor designs.

In order to alleviate the observed power limitation in TORE SUPRA, the ergodic divertor was re-designed and its target plates reinforced. With this upgrade, 7 MW of power could be handled at high density, 4 MW could be run for more than 20s. A radiative exhaust fraction of at least 80% was achieved greatly alleviating issues of localised power deposition. In these RF heated plasmas, feedback control of plasma detachment is now the emerging key issue and plasma control for ergodic divertor operation with highly radiating plasmas and low core impurity content is the key focus of the 1998/99 programme.

The study of the various impurity release mechanisms for developing techniques of impurity control and for optimising plasma boundary characteristics with respect to radiation level as well as heat transfer has been carried out in several laboratories, notably at ASDEX Upgrade, JET, TEXTOR-94 and TORE SUPRA. While very high radiated power limits (Pr ~80 - >95%) could be obtained in medium-sized devices, studies on JET have been limited to $P_r$ ~65% and are continuing aiming at the realisation of radiative modes obtained in other devices such as the Completely Detached H-mode or the Radiative Improved mode. In TEXTOR-94 these studies were carried out with a pumped limiter. These studies, linked closely to the ones mentioned above will continue through 1999, thereafter a dynamic ergodic limiter will be installed which is an extension of the ergodic divertor concept used on TORE SUPRA. On this latter device, the ergodic limiter will then be phased out in 1999 until results from TEXTOR-94 give further information on the exhaust properties of this system which provides a new degree of flexibility for modifying the scrape-off layer in a fusion plasma.

#### *1.1.2.3 Confinement, Particle and Energy Transport*

For confinement scaling towards larger devices, such as ITER, dedicated semi-empirical studies are being undertaken, in particular on JET (namely also during the above-mentioned campaign early in 1998) and ASDEX Upgrade as well as COMPASS-D which are of similar, noncircular cross-section but widely different size. Such “wind-tunnel” experiments where dimension-less

plasma quantities can be kept identical enable particularly confident extrapolations to the larger, but geometrically similar, ITER. These studies include work on other devices, also on the non-circular Tokamaks D-IIID (General Atomics, San Diego) and ALCATOR C-mod (MIT, Boston) as well as increasingly on TCV which can study the impact of plasma elongation and shaping in a much wider range than it is possible on other devices.

In reply to the series of "Urgent ITER Physics Tasks" a physics programme was undertaken in the Associations, and on JET following the DTE1 campaign. A major focus of work concerned confinement scaling issues for ITER. Operational modes which show enhanced confinement were further studied, in particular the ITER reference scenario of "ELMy H-mode". The dependence of the H-mode threshold on the atomic mass was confirmed and its origin attributed to the pedestal energy. The core exhibits an inverse scaling with the isotope mass which is consistent with gyro-Bohm scaling. Direct extrapolation with gyro-Bohm scaling of these studies (and the corresponding ones in D-T plasmas) to ITER gives ignition; Q>7 would be attained in case of Bohm scaling. H-mode threshold studies and scaling experiments were performed, besides on JET, on ASDEX Upgrade and COMPASS-D. Scans in dimensionless quantities (gyroradius/plasma radius, q-value, density/Greenwald density, beta) indicated no change in the confinement enhancement factor. A confirmation of the identity principle (i.e. the applicability of dimensionless scaling considerations) was obtained by experiments on JET together with ASDEX-Upgrade, the US tokamaks Alcator C-MOD and DIII-D in L- and H-mode.

The Radiative Improved (RI) Mode, discovered in 1993 on TEXTOR, has been qualified in much detail. This enhanced confinement mode with edge radiation cooling under appropriate heating conditions combines a number of favourable features such as high density and ß, good confinement, and the potential for stationarity without a sophisticated profile control. Similar modes could be reproduced on some other devices, e.g. on TORE SUPRA (though with different density and radiation fraction dependencies) but also on ASDEX-Upgrade and on D III-D, however, its optimisation on the large non-circular devices needs further work. The effects of edge radial electrical fields on confinement (as possible trigger for H-mode behaviour) and exhaust have also been further investigated.

Stationary operation has been demonstrated on several devices, including ASDEX-Upgrade, JET, TEXTOR-94 and TORE SUPRA for periods corresponding to tens or hundreds of energy confinement times. Record 2 min. discharges were obtained on TORE SUPRA by using lower hybrid frequency (LH) current drive albeit at moderate densities. A 70 s discharge was obtained at zero loop voltage in conditions which can be extrapolated to continuous operation. Further work using LH systems, neutral beam injection, ion and electron cyclotron resonance systems aims at extending the parameter space for such operation, in particular to attain the desired higher densities and to apply localized current drive (or heating) for the suppression of modes and instabilities in the plasma.

The study of internal plasma filamentation on transport and confinement has been studied at the RTP Tokamak with dedicated localized ECRH heating experiments, exploiting the extreme high

resolution Thomson scattering diagnostics which had been developed at the Rijnhuizen institute. It appears that very steep temperature gradients can be maintained in the plasma near mode rational surfaces. These studies will continue, in the coming years, on TEXTOR-94 in a larger plasma with stronger electron-ion interactions.

An increasing effort is being devoted to the so-called “advanced” operation scenarios with optimised shear of the magnetic field in the plasma. Internal transport barriers have been experimentally observed which improve confinement and could lead to higher performance in a device of a given size and at lower plasma current. A particular concern is to maintain the necessary radial current profiles in a stationary mode. High bootstrap current fractions should be possible which assist in this task but dedicated current drive appears to be necessary. Intensive work was undertaken both on non-circular (notably also on JET, ASDEX Upgrade and COMPASS-D) and circular Tokamaks (FTU, TORE SUPRA). Following previous studies on several devices and explorations before and during the D-T phase, internal transport barriers were created in JET plasmas for both electrons and ions by combined programmed ICRF and NBI heating and current ramp-up.

Detailed particle and energy transport has been studied in all major devices, in particular in enhanced confinement regimes. For high radiating plasmas with seeded impurities, impurity transport is a key objective of experimental and theoretical / modelling efforts linked to the hydrogen particle transport. Also helium (and alpha particle) transport (and confinement) has been further studied as it will play a particular role as an impurity in ITER as it is continuously generated by the fusion burn in the bulk plasma. In particular the DTE1 phase of JET contributed to this latter subject.

The characterisation of plasma transport for larger devices or different operating conditions using semi-empirical approaches for establishing scaling laws has been continued. The study of fundamental physics models of transport phenomena (including so-called „first principle“ models which however do not yet allow a quantitative extrapolation of similar quality as the semi-empirical scaling approaches), in conjunction with the wide experimental data base, is now becoming a valuable tool for a rapid improvement in the understanding of the underlying physics.

#### *1.1.2.4 Operational Limits and Plasma Control*

Theoretical models and codes for studying the accessible operational space and regimes have been employed and further developed e.g. at the Associations EURATOM-Confédération Suisse (CRPP), -ENEA, -FOM, -NFR, -UKAEA and at JET. Their agreement with measurements could be further improved and they support the physics arguments for the ITER design choices. Limits of the edge density and its scaling with plasma size and heating power has been under investigation, in particular on ASDEX Upgrade, FTU, TEXTOR-94 and TORE SUPRA. Radiation cooling by impurities is investigated as a means of plasma control for possible reactor-

relevant operation scenarios. In TEXTOR-94, various MHD phenomena linked to sawtooth crashes and disruptions have been studied in terms of magnetic flux reconnection. Work in the area of disruptions, operational limits and control has been carried out on JET and ASDEX-Upgrade, but in particular also, to reduce the risk of damage, on the smaller devices (COMPASS-D, RTP, ISTTOK). It was demonstrated that halo currents which are induced, as a result of vertical displacement events, in the conducting structures around the plasma chamber can be large and can have substantial toroidal asymmetries. These results are a further substantiation of the data bases, in particular the ITER disruption data base and have been taken account of in the ITER design. Also, control techniques for mitigating disruptions have been successfully employed (e.g. impurity pellet injection on ASDEX Upgrade and elsewhere).

ITER control schemes for plasma shape and position were successfully tested in a collaboration of several Associations (Conf. Suisse, ENEA /CREATE and UKAEA /Imperial College).

Specific progress was made in the field of on-line (feed-back) control using a variety of diagnostic signals and fast algorithms for plasma state computations. Typical examples are e.g. the control of the fusion neutron yield in JET D-T experiments, control of the radiation level for the CDH-mode, optimised access to the H-mode in ASDEX-Upgrade, LH controlled current profiles in TORE SUPRA or suppression of the neoclassical tearing instabilities by phase-locked ECRH and current drive on ASDEX Upgrade. (Without active control means, these latter modes could be, according to experimental studies on JET, ASDEX-Upgrade, D-IIID and COMPASS-D and theoretical work, a threat to full ITER performance or to lead to disruptions.) These advances provide an enhanced capability to operate devices on prescribed trajectories in parameter space closely along operational limits.

Error field studies on JET, ASDEX-Upgrade and COMPASS-D showed weaker dependence on size than inferred from earlier work alleviating somewhat the very stringent engineering constraints for the ITER magnet. Still, it appears prudent, to foresee correction coils on ITER. Active compensation of the m=2, n=1 error fields allowed unlocking of the corresponding plasma mode and resulted in a clear reduction of disruption probability. Experiments with additional heating confirmed the expected dependence of mode locking and disruptions on plasma rotation. As a basic study, aimed at advantages for exploiting the device, alternating current Tokamak operation has been successfully used on ISTTOK.

#### *1.1.2.5 Plasma Engineering*

The field of plasma engineering covers the auxiliary systems required for plasma heating and current drive, fuelling, and diagnostics. Collaborative efforts by the Associations and JET have continued in these areas.

*Additional Heating and Current Drive*: In addition to the ohmic heating by the plasma current auxiliary plasma heating is needed in present day experiments. Also for a future burning plasma device auxiliary heating systems will be needed for start up and burn control.

For systems like the Tokamak which use a strong toroidal plasma current induced by a transformer, additional means are also necessary for maintaining the current. Recently, experiments on JT60-U, JET, Tore Supra, FTU and other Tokamaks have confirmed earlier theoretical studies which indicated that with proper plasma pressure profiles a significant fraction of the plasma current can be maintained by the plasma itself as a result of the radial plasma pressure differences. Studies have been continued to optimise the exploitation of this self-generated “bootstrap” current and to complement it with "non-inductive” current drive. The efficiencies for current drive have been found to be in fair agreement with models.

The development of auxiliary plasma heating sources has been further pursued. An assessment of the advantages and critical issues of the four different systems, which have the potential to be developed towards the reactor, has been performed[3].

R&D on Heating and Current Drive systems in the Community Fusion Programme is oriented primarily to the needs of the Next Step. Heating and current drive systems on a device like ITER will have to fulfil various needs: start-up assist, access to improved confinement modes, heating to ignition, as well as burn control, MHD control (error field and neo-classical tearing modes) and current drive over a period of 1000s (ultimately steady state). A mix of the major heating and current drive techniques will be required at a delivered power level of 100 - 150 MW, with each system capable of delivering around 50 MW. Presently the decision is still open which heating and current drive methods will be applied on a device such as ITER. The four major methods have been sufficiently well advanced to be confident that they could be further developed to individually meet their part of the ITER requirements. The European activities in this development are oriented towards meeting the key technological aspects of the systems and their interfaces with, and integration into, the Tokamak.

Furthermore, essential work is oriented towards the physics and the operational aspects of heating and current drive. This work is undertaken on, or in conjunction with, the existing devices. Theoretical studies on charged particle beam - resonator interactions and the coupling of electromagnetic waves and power deposition in plasmas have been pursued in the laboratories mentioned below.

- *Electron Cyclotron Heating and Current Drive*

Work progressed for the cylindrical gyrotron (industry with Associations EURATOM-FZK, CEA, -Confédération Suisse) though delays have occurred. A prototype of a 0.5 MW 118 GHz gyrotron for TORE SUPRA and TCV was successfully factory tested. Long-pulse testing has encountered delays and is expected to continue till end of the year. Fundamental aspects of gyrotrons were studied by the above Associations and the Association EURATOM-TEKES as well as the National Technical University Athens. A variant, the coaxial gyrotron has successfully demonstrated short pulse operation above 1 MW. Development work at the Association EURATOM-FZK is ongoing for the co-axial cavity gyrotron to provide the basis for

[3] Heating and Current Drive Systems for ITER and R&D milestones … EUR FU (98) PC 50/7

manufacturing of a 2 MW, 170 GHz, cw gyrotron (1.2 MW output power at 140 and 165 GHz, and 0.5 ms pulse duration, have been reached so far) and on a frequency tuneable 1 MW gyrotron with conventional cavity. Also, FZK has taken over the responsibility for the planning, development, commissioning, installation and test of the complete 10 MW, 140 GHz ECRH system for W 7-X for which the tube is developed with the same partners as above. Step tuneability has been achieved with both cylindrical and co-axial gyrotrons.

The free electron maser is by its principle continuously tuneable. A prototype has been further developed (Association EURATOM-FOM) and has reached its first milestone of demonstrating low loss for the electron beam in the undulator. 700 kW 10 microsecond pulses have been obtained in a system that is tuneable over a range of 130-260 GHz. Currently the initial set-up is re-arranged for further developments.

Work for ECRH systems also addresses the necessary development of components such as transmission lines (Associations EURATOM-FZK and -IPP through collaboration with IPF Stuttgart).

- *Ion Cyclotron Heating and Current Drive*

Ion cyclotron range sources are industrially available. R&D is concentrated on simplified ion cyclotron wave antennae which are less load sensitive. Power densities of up to 18 $MW/m^2$ were reached with a single antenna on TORE SUPRA. Improved actively cooled protections for the antennae of these systems have been operated. Work is undertaken by the Associations EURATOM-Belgian State, -CEA, -IPP and JET; the Association EURATOM-TEKES contributes to the ITER ion cyclotron wave transmission line development.

- *Lower Hybrid (LH) Heating and Current Drive*

Work concentrated on the further development of launchers (quasi-optical and active-passive matrix, Associations EURATOM-CEA, ENEA). Coupling issues (possible causes for fast electron generation have been identified) and the avoidance of generation of fast electrons are in the foreground of modelling and experimental studies.

- *RF and diagnostic windows and components*

The systematic effort under way to characterise the properties of insulator materials (sapphire, alumina, BeO, diamond, silicon) thermo-mechanically, optically and under irradiation, to complete the database necessary for the design of windows and insulators for the ITER heating and diagnostic systems has continued. Contributors are the Associations EURATOM-CIEMAT, -FZK and -UKAEA. The characterisation of materials, to allow transmission of 1 MW, cw at 90-180 GHz for heating and diagnostics purposes, is also undertaken and the suitability of the new large CVD diamond plates for high power ECRH transmission windows has been further assessed. These windows are expected to be able to operate at ambient temperature with edge water-cooling.

- *Neutral Beam Injection*

Large devices such as ITER require higher energy (up to, or even larger than 1 MeV) neutral particle beams in order to achieve deposition of the particles and energy deep inside the plasma. (Correspondingly the particle fuelling is reduced, at the same injected power input, compared to lower energy beams.) For such energies, the primary acceleration must be made with negative ions. A novel accelerator configuration, SINGAP, which has been developed by the Association EURATOM-CEA over the past years, has been further studied. Improved solutions for the large high-voltage insulators, which have shown to be critical elements, have been identified and are under implementation. In collaboration with Japan a negative ion source with the ITER specification of 22 mA/cm$^2$ (for 60s) has been successfully tested. An ion source using a RF excitation has been under continuing development at the Association EURATOM-CEA in collaboration with the Association EURATOM-IPP. Current densities are still in the 3 mA/cm$^2$ range. More fundamental investigations of RF based negative ion sources, linked to these developments, are being undertaken by the Association EURATOM-DCU (Dublin, Ireland).

- *Fuelling*

Regarding the fuelling of the plasma with pellets of frozen deuterium, ongoing development at the Associations EURATOM-IPP and EURATOM-CEA has further proceeded with a view to application to present-day experiments. Previous collaboration with the US (ORNL) has considerably diminished in importance. Pellet injection from the high-field side in ASDEX Upgrade which had been shown to yield significantly higher density increases has been further studied and this technique is planned to be further validated on JET in the coming year.

For ITER, scoping studies have been undertaken in the Associations on shallow fuelling systems (centrifuge, light gas gun) as well as on deep fuelling with compact toroid injection.

- *Diagnostics*

Definition and development of diagnostics for ITER has continued. JET and the Associations with large devices have been developing diagnostics for their own purposes, increasingly in collaboration with other Associations. A number of new diagnostics were developed in Associations without a large Tokamak for application on other devices. Among these were the high-resolution Thomson scattering (Association EURATOM-FOM), a novel laser fluctuation correlation diagnostics (Association EURATOM-RISO), microwave scattering (Association EURATOM-TEKES), neutron diagnostics, in particular a neutron spectrometer (Association EURATOM-NFR), reflectometers (Associations EURATOM-CIEMAT and -IST), heavy ion beam system (Association EURATOM-IST), polarimetry (Association EURATOM-DCU (University Cork) in collaboration with the Associations EURATOM-ENEA (CNR Padova) and EURATOM-Confédération Suisse), motional Stark effect systems (Association Euratom-IPP and –UKAEA (for JET with US collaboration)) and a fast sweeping Langmuir probe (Demokritos, Greece in collaboration with the Association EURATOM-IPP). Most of these diagnostics have been completed and are now employed in experiments. Improved data acquisition and interpretation techniques have been developed in a number of Associations.

#### *1.1.2.6 Theory and Modelling*

Magneto-hydrodynamic studies continued on the further exploration of accessible equilibria, and their stability properties, for Tokamaks (such as the investigation of optimised shear scenarios) and Stellarators. Modelling of the plasma boundary has made a considerable progress. The models predict now phenomena with an acceptable accuracy. Coupling of the confinement and edge regions has been increasingly implemented in several codes in particular with a view to scrape-off layer and divertor (exhaust) studies. Progress towards three-dimensional treatments of a comprehensive physics model is being made but requires demanding computing power even on current super-computers. Studies for specific aspects such as the coupling of fluid and kinetic codes have continued. Turbulent systems have been studied with respect to the creation of vortices, filaments etc. which may be linked to internal transport barriers. These studies approach the stage where more detailed comparison can be made with experiments.

Some “first-principle” codes whose capability for predicting confinement quality in Tokamaks had been put into question because of their poor reproduction of experimental results on existing machines have been improved and now do fit experiments much more closely. That some previous studies performed in the US had been much too pessimistic in their prediction of ITER performances has thereby been confirmed.

Concerning possible instabilities in a hot fusion plasma the main work on (global) Alfvén Eigenmodes and fast particle dynamics continued. These modes had been identified as being potentially unstable in regions of interest for operating large fusion devices with a substantial fraction of fast particles. Present work indicates that, though these modes could in fact be unstable, their impact on heating and transport should be limited and controllable. While theoretical work and modelling continues to focus on micro-instabilities, emphasis has now shifted to some extent to another class of instabilities, the so-called neo-classical tearing modes, which might be unstable at otherwise useful operating parameters. Though growth rates appear to be very small their impact on long-pulse operation might be important and means for their mitigation are being discussed.

Theory of fusion plasmas is connected to other fields in physics such as fluid turbulence or non linear dynamical systems. Therefore, active collaborations with corresponding scientific communities have been developed on some specific topics such as self-organization, coherent structures, intermittency, instability control, etc. These cross-disciplinary collaborations greatly assist the development of understanding in fields such as e.g. cross-field transport.

## CONCEPT IMPROVEMENTS

### 1.1.3 TOKAMAK

A new potential for concept improvements was obtained in ITER-type configurations by

generating internal transport barriers and using bootstrap currents (JET, ASDEX Upgrade). New equipment will be installed on two Tokamaks (Composants Internes Et Limiteurs, CIEL, on TORE SUPRA; Dynamic Ergodic Divertor, DED, on TEXTOR-94), as well as additional heating systems (NBI on MAST, 100 kV tangential injection in ASDEX Upgrade). Work on Concept Improvements concerning the Tokamak principle is tightly linked with investigations carried out for the Next Step. Investigations are oriented especially towards exploring new regimes which allow for enhanced performance and stationary operation through better confinement, higher bootstrap current fractions and lower risk of abrupt termination of the plasma discharges by disruptions. Performance, plasma stability, exhaust and other properties are strongly influenced by the plasma shape. Corresponding studies are undertaken on several devices, in particular on TCV which permits to generate and control a wide variety of plasma shapes. Work concentrates on assessing the impact of elongation and triangularity on confinement. The extreme low limit of the aspect ratio (i.e. the ratio of major to minor radius of the plasma torus) was investigated in a small "Spherical Tokamak" experiment (START, Association EURATOM-UKAEA). Record average beta values of 40% were obtained. Operation with a natural divertor was demonstrated and the excellent configurational stability at elongations well above 2 as well as evidence for H-mode behaviour was shown. Internal relaxations usually do not lead to violent terminations (disruption resilience). The construction of a similar, but larger device, MAST (Mega-ampère Spherical Tokamak), is on completion by end 1998. The spherical tokamak concept has attracted growing international attention.

As mentioned above, an increasing research effort was devoted to the study of the optimised shear operation (in JET and other devices) which would be advantageous for high performance steady state operation under reduced technical requirements (such as plasma current, e.g. in ITER 12 - 14 MA instead of 21 MA) and to the investigation of internal transport barriers which appear to be linked to magnetic field and velocity shear effects on the scale lengths of (turbulent) transport.

### 1.1.4 STELLARATOR

Stellarators rely largely on fields produced by external magnetic field coils to produce its magnetic configuration eliminating the need for a net toroidal plasma current, however, requiring usually a more complex shape of the coils than in Tokamaks. The concept is then intrinsically able to maintain the confinement configuration stationary without the use of major current drive systems, lowering the requirements for recirculating power in future power plants. Disruptions, instabilities and other plasma events associated with the free energy of a large toroidal current do not occur or are strongly mitigated.

The programme is preparing for exploring a wide configurational space in the new TJ-II. The work in preparation for the optimised Helias concept continued with physics studies in the Wendelstein 7-AS device (to be phased out in the coming years) and with the Wendelstein 7-X

project under construction. The programmatic aim of W7-X is to explore the physics and engineering relevant to Stellarator reactor-grade fusion plasmas. Stellarator activities at Garching on WENDELSTEIN 7-AS achieved the following milestones: approaching the beta limit with NBI, expanding the accessible range of plasma density for ECRH, identification of means for implementation of a magnetic island divertor.

The construction of the large advanced (Helias-type) Stellarator, Wendelstein 7-X (W7-X), with superconducting coils has progressed. The preparations at the site and the construction of the buildings started in 1996 and construction work at the new site in Greifswald is underway. The institute buildings including the experimental hall are now being delivered and the main components of the device are beginning to be ordered in industry. The test of the advanced superconductor to be used in the magnet coils has yielded very good results. The large demonstration coil - identical in size and shape to one coil of the real coil system - is being assembled for testing; the demo section of the cryostat has been delivered to IPP.

The construction of the TJ-II flexible HELIAC, which permits the variation of key configurational parameters, has been successfully completed by the end of 1996. The year 1997 was devoted to the commissioning of the device and implementation of diagnostics; the latter is continuing beyond 1998. Plasma operation has started in 1998; full heating power by neutral beams will become available during the year 2000.

Theoretical work on Stellarator configurations and the development of dedicated diagnostics in several Associations (in particular EURATOM-Suisse (CRPP) and EURATOM-RISO) is accompanying the experimental research in the Associations EURATOM-IPP and CIEMAT. Collaborative work has continued in 1998, in the framework of an IAEA Implementing Agreement, with the Stellarator research in Japan (where the large Stellarator LHD has now started its scientific exploitation) and the US.

### 1.1.5 REVERSED FIELD PINCH

The Reversed Field Pinch (RFP) is a configuration much akin to the Tokamak but which relies to a large extent on the internal relaxation (i.e. self-organisation) of the plasma to generate the confinement configuration. The system is studied for its possible low-field, high density confinement capabilities and for its contributions to the toroidal confinement data base and turbulence and transport studies where it allows to provide information on parameter ranges which are inaccessible to the standard tokamak. The large experiment RFX (Association EURATOM-ENEA [Padova]) has progressed in the operation at higher current levels (0.8 - 1.2 MA) and achieved improvements in the control of mode locking to the wall and wall loading. The diagnostic capability of the device has been further upgraded and technical improvements for high current operation and related plasma position control during start-up have been implemented. Particular results were the confirmations of the possibility to achieve an improvement of confinement by assisting the internal dynamo action via inductive poloidal

current drive and of a spontaneous single helicity operating mode which is also linked to a (so far a smaller) enhancement of confinement. Another important observation is that with boronized walls the impurity content could be kept below a level corresponding to Zeff < 1.5 up to the maximum current levels tested. Of high relevance to the concept is the issue of wall stabilisation. Studies on different stabilisation levels (achieved by modifying the resistive time constant of the wall) are being undertaken on the smaller EXTRAP-T2 (Association EURATOM-NFR).

| Table 1 : Fusion Devices in Europe | | | | |
|---|---|---|---|---|
| Device | Association EURATOM - | Main objective | $I_p$ (MA) | Period |
| **Tokamaks** | | | | |
| JET | Joint Undertaking (Abingdon) | integrated high performance operation, DT operation | 5-7 | 83-99 |
| TORE SUPRA | -CEA (Cadarache) | long-pulse operation in Next Step relevant conditions | 1.7 | 88 - |
| ASDEX Upgrade | -IPP (Garching) | relevant divertor topology H-mode, SOL, wall interaction concept improvements | 1.6 | 91 - |
| FTU | -ENEA (Frascati) | Confinement at high density and high current, optimised shear studies | 1.6 | 90 - |
| TCV | -Suisse, CRPP (Lausanne) | physics of strongly shaped plasma cross-section | <1.2 | 92 - |
| TEXTOR-94 | -FZJ (Jülich) | plasma/wall interaction, edge plasma, confinement with additional heating | 0.8 | 81 (94) - |
| COMPASS-D | -UKAEA (Culham) | Beta limits and MHD stability/ control studies, scaling | <0.4 | 89 (92)- |
| START | -UKAEA (Culham) | Study of tight aspect ratio Tokamak physics | <0.31 | 91 - 98 |
| MAST | -UKAEA (Culham) | ADVANCEtight aspect ratio scaling, spherical Tokamak physics at high temperature | >1 | 98 - |
| RTP | -FOM (Nieuwegein) | transport mechanisms studies | 0.2 | 89-98 |
| ISTTOK | -IST (Lisbon) | MHD activity, AC operation | 0.01 | 92- |
| **Reversed Field Pinches** | | | | |
| RFX | -ENEA (Padova) | RFP physics, toroidal confinement and transport, performance prospects | < 2.0 | 91 - |
| EXTRAP-T2 | -NFR (Stockholm) | stabilisation, shell studies, fluctuations, scenarios | 0.26 | 94 - |
| **Stellarators** | | | | |
| Wendel-stein 7-AS | -IPP (Garching) | medium-size device with modular coil system to investigate plasma behaviour in an optimised magnetic field configuration | | 90 - |
| TJ-II | -CIEMAT (Madrid) | highly flexible medium-size device with helical magnetic axis for confinement and high-beta studies | | 97 - |
| Wendel-stein 7-X | -IPP (Greifswald) | Exploration of Stellarator operation at reactor-relevant collisionality (but at lower density) towards steady state operation | | (1997start of con-struction) |

### 1.1.6 KEEP-IN-TOUCH ACTIVITIES TO OTHER APPROACHES TO FUSION

A keep-in-touch activity to the field of civil research in inertial confinement fusion is maintained via competent laboratories in order to monitor the progress in this field. In 1998, efforts continued to further improve the co-ordination of these civil activities. This activity has not been monitored by the Programme Committee. A programmatic document by the ICF Co-ordinating Committee-Technical Group on future activities and their co-ordination in the frame of the Fusion Programme's watching brief is in preparation and is planned to be finalised by the end of 1998.

# 3. PHYSICS AND PLASMA ENGINEERING ACTIVITIES IN THE ASSOCIATIONS

## 3.1 ASSOCIATION EURATOM - BELGIAN STATE

Location of Physics Research Units: Royal Military Academy, Université libre de Bruxelles, Brussels, Belgium

Major Equipment:

- Collaboration on TEXTOR-94 (Association EURATOM-FZJ Jülich) in the frame of the Trilateral Euregio Cluster

Key Areas in Fusion Physics:

- Confinement and transport physics of additionally heated plasmas, RI mode;
- ICRH physics;
- Non-linear plasmas physics, description of magnetic field configurations, statistical approaches of turbulence, plasma kinetic theory and mathematical techniques.

The Association EURATOM-Belgian State ( Brussels), with its Research Unit Royal Military Academy, undertakes work with the Associations EURATOM-FZJ and -FOM on TEXTOR-94 94 in the frame of the Trilateral Euregio Cluster (TEC).

The Radiative Improved (RI) Mode, discovered on TEXTOR-94, has been further investigated, confirming favourable features (high density around the Greenwald value, high ß ($ß_N$ = 2) comparable to maximum values obtained on TEXTOR-94, edge radiation fractions up to 95% of input power, negligible effect of (necessary) seeded medium-Z impurities on fusion reactivity, good confinement, stationarity, > 25% neutral beam co-injection required). Studies have been extended to D-IIID (San Diego). Here, also the transition of the RI mode into an ELMy H-mode and high performance variant (high density `VH mode”) of the mode were observed.

The influence of edge radial electric fields is studied by biasing electrodes, dedicated diagnostics and modelling. Transition to H-mode behaviour was demonstrated. Radial current transport, conductivity and viscosity were studied. High E x B shear flow turbulence suppression with improved particle confinement was demonstrated, helium exhaust is affected. Electric field values for diffusion reduction agree with turbulence theory.

ICRH studies focus on the interaction with fast particles (synergy with NBI injected particles, confinement improvement, control of alpha particle exhaust), high-Z impurity aspects (no accumulation at large RF power level) and RF-plasma production which was reproducibly

achieved for a wide operating range (also ICRH assisted start-up). Coating with ICRH was studied. An antenna is designed for ITER. Wave codes have been developed to study antenna coupling, and (also with a 3D-ray tracing code) wave propagation / absorption in realistic geometry. In quasi-linear Fokker-Planck theory advances have been made which permit, together with a full-wave code, self-consistent modelling of RF-heating. For the dynamic ergodic divertor the low frequency field penetration has been calculated confirming the viability of the concept. Diagnostic developments and spectroscopic work complement the work.

The Research Unit ULB studies the area of non-linear plasmas physics, description of magnetic field configurations, statistical approaches of turbulence, plasma kinetic theory and mathematical techniques. The TOKAMAP 1-D Hamiltonian mapping permits to study bifurcation phenomena in a particular intuitive way. Large eddy simulations which have been developed for strong hydrodynamic turbulence are being transferred to MHD turbulence. For the behaviour of test particles in external non-uniform fields kinetic approaches are being pursued. Mathematical techniques and numerical algorithms are developed for fusion applications.

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: Anomalous transport (ULB) , RI mode, ICRH;
- Associations EURATOM - FZJ, FOM: TEC Collaboration, Anomalous transport (ULB);
- Association EURATOM - IPP: ICRH, comparison RI and other modes;
- Association EURATOM - UKAEA: RI-mode;
- JET: ICRH, modelling, confinement aspects.

### 3.2 ASSOCIATION EURATOM – CEA

Location of Physics Research Unit: CEA Cadarache, France

Major Equipment:

- TORE SUPRA, superconducting large Tokamak with circular plasma cross section;
- Neutral Beam Test Stand for Negative Ion Beam development.

Key Areas in Fusion Physics:

- Physics of long pulse high performance steady state tokamaks;
- Power and particle control;
- cw high frequency wave generators and systems (ECRF, ICRF, LHRF);
- Plasma-wall interaction, exhaust physics.

The Association EURATOM-CEA (Cadarache) is operating the large Tokamak TORE SUPRA. The combination of super-conducting toroidal field coils (providing a permanent magnetic field up to 4.5T), powerful additional heating and current drive systems, and actively cooled in-vessel

components makes it possible to study high performance long-pulse plasma configurations in limiter or ergodic divertor configurations on this device which has a circular plasma cross-section. In parallel to high performance physics, heating and current drive scenarios, dedicated studies are performed to address heat load, turbulence, MHD stability and edge physics. The design aim of TORE SUPRA, 1.7 MA, 30 s, has been by far exceeded: long-pulse steady-state scenarios were performed with record 2mn discharges and fully non inductive 70s discharges at moderate density by coupling 2.4MW of LHRF power to the plasma. Also, record power densities were reached with a single ICRH antenna (up to 18 $MW/m^2$), and so-called advanced Tokamak scenarios are being studied with an emphasis on profile control in steady state modes of operation. The power exhaust (design aim was 15 MW for 30 s) so far has attained 11 MW in short pulses, reducing to 2.4 MW at 2 min. A project for extending high heat load capability to longer duration discharges is under preparation, particularly by introducing a new toroidal pumped limiter and improved actively cooled first wall elements.

Heating and current drive are essential elements for the high performance scenarios on TORE SUPRA. Currently LH (8 MW, 3.7 GHz, 210 s) and IC (upgraded 1996/7 to15 MW, 40-80 MHz, 30 s) systems are in use, ECRH being currently (end 1998) close to installation after first extensive tests of a prototype gyrotron being developed with industry jointly with the Association EURATOM -Conf. Suisse and - FZK (118 GHz, 0.5 MW, 5/210 s). 2.4 MW LH current drive and heating allowed to reach the record of 2 min non-inductively driven discharges at moderate density. Over 8s, 6 MW were coupled in the plasma (37 $MW/m^2$). For ICRH, up to 8.9 MW have been coupled to the plasma over some seconds and 4 MW over 26 s. With fast wave coupling (all power is coupled to the electrons) a database on bootstrap current has been established together with TEXTOR-94 and TFTR (PPPL). The combined use of LH and fast wave IC so far has not produced evidence for synergistic effects as reported from JET and HT6M (China) but plasmas with 4 MW IC heating and 2.2 MW LH current drive could be attained for up to 25 s (limited technically by localized power deposition in the lateral antenna protections).

As a second element of high performance, long pulse operation, methods for controlling heat and particle exhaust at the plasma edge are being developed. High load plasma facing components are being developed with industry, and high radiative power exhaust is studied by means of an ergodic divertor or by operating conditions similar to those of the RI mode which has been explored on TEXTOR-94 with neutral beam heating. Employing on TORE SUPRA IC heating in the H-minority regime, more than one MJ stored plasma energy could be achieved in this mode with a confinement enhancement similar to ELMy H-mode.

The Association has pioneered the use of a ergodic divertor. The original set-up has been reinforced in 1996. In 1997, 6 MW were handled with this divertor at high density. A radiative power fraction >80% was reached. Feedback control of the plasma detachment has been carefully studied in order to maintain wave coupling through the edge plasma and to maintain efficient impurity screening. Regimes similar to the poloidal axisymmetric divertor were attained where the edge density is comparable to the core density. After a further campaign in 1998/9 the ergodic divertor will be removed for the installation of high heat load components. For a possible later upgraded ergodic divertor the Association will maintain its interest in this area through collaboration with the Associations EURATOM-FZJ.

Confinement and stability studies aim at the study of turbulence and transport in TORE SUPRA, in particular with respect to long pulse high performance discharges. Core confinement and understanding of improved confinement as well as edge turbulence and thermal confinement scaling laws and MHD stability of long pulses have been studied. A variety of improved confinement regimes linked to current profile adaptations have been demonstrated and analysed, in particular also with respect to optimised shear regimes. A clear correlation between reduced heat diffusivity and reduced magnetic shear could be established. For RF heated plasmas with dominant loss via the electron channel, gyro-Bohm scaling was found with a strong dependence on density and power. Theoretical and numerical work relates to a number of topics, in particular to transport analysis, ITG induced turbulence (showing fast transport relaxation, ”avalanches”) and neo-classical tearing modes, for the latter stabilisation by resonant RF driven current modulation is examined.

In collaboration with the Associations EURATOM-IPP and EURATOM-DCU, the Association EURATOM - CEA is the European lead laboratory for the development of negative ion-based neutral beam injectors for ITER,. The prototype for the SINGAP[4] acceleration concept, offering a simplified possibility for negative ion beam injectors, has been developed, on the way towards 1 MV acceleration, to 860 kV $H^-$ beams (43 mA, 1s) and 630 kV $D^-$ beams (106 mA, 1s). Further progress is expected after repair of a damaged high-voltage insulator. In collaboration with Japan a negative ion source has been tested delivering 12 mA/cm$^2$ for 500 s and 60 s at the ITER relevant 22 mA/cm$^2$. The Association participates in a RF-source development with IPP and the design of the 1 MV 50 MW negative ion beam system for ITER. Further work concerns the development of radio frequency wave heating and current drive systems for ITER (ICRF, ECRF and LHRF systems). The ITER LHRF system has been designed and a mock-up for a LHRF antenna mouth (built by Japan) is tested at high power. Active-passive antennae are studied in collaboration with ENEA.

[4] SINGAP = Single Aperture-Single Gap

Major Collaborations in Physics within the Programme:

- Association EURATOM - Belgian State: ICRH (RMA /TEC); anomalous transport (ULB);
- Association EURATOM - Conf. Suisse: ECRH, Gyrotrons, modelling;
- Association EURATOM - DCU: Negative ion source development, theory;
- Association EURATOM - ENEA: LHRF antennae; plasma facing components;
- Association EURATOM - FZJ (TEC): Ergodic divertor, RI-mode, plasma facing components;
- Association EURATOM - FZK: Gyrotron development.
- Association EURATOM - IPP: Plasma facing components, negative ions, ECRH physics, edge turbulence;
- Association EURATOM - IST: Turbulence, LH waves;
- Association EURATOM - ÖAW: plasma facing components;
- Association EURATOM – TEKES;
- JET: LHRF and ICRF programmes.

### 3.3 ASSOCIATION EURATOM - CIEMAT

Location of Research Unit: CIEMAT, Madrid, Spain

Major equipment:

- TJ-II flexible Heliac Stellarator.

Key Areas in Fusion Physics:

- Stellarator studies: operational range, parameter dependencies;
- Turbulence and transport studies;
- Diagnostic developments;
- Test of ceramics and insulators for diagnostic and heating applications.

The Association EURATOM-CIEMAT (Madrid) has constructed the TJ-II device, a l=1 and m=4 flexible (Heliac) Stellarator with 1.5 m major radius, 0.1-0.2 m minor radius, 1 T magnetic field and a rotational transform varying from 0.96 to 2.5. The device has been commissioned by the turn of 1996/1997. Electron beam measurements demonstrated the high precision of the magnetic system in producing the desired configuration. During 1998 bean shaped plasmas were produced and studied in a variety of configurations. The commissioning of the essential heating system (Neutral Beam Injection) is planned for the year 2000.

Turbulence, confinement and transport studies as well as the development of a full range of diagnostic systems have been undertaken in parallel with the construction and commissioning of TJ-II. In the area of turbulence the major current research topics were the influence of atomics physics and critical gradients on turbulence and the study of the interdependence between

impurity spectral line widths and electromagnetic fluctuations. In the area of confinement topics are electric fields and plasma rotation, isotope effect and its relation with turbulence, runaway transport and edge physics studies. Comparative studies of Tokamaks and Stellarators concern critical tests of theoretical models. Also, the performance of low-Z coating for first wall conditioning was investigated. These transport and turbulence studies were made on the TJ-IU torsatron and earlier on the TJ-I, a small Tokamak, which had been phased out in 1996. Thereby the operation of the large TJ-II Stellarator was prepared. Initial experiments have explored the flexibility of TJ-II for studying a wide range of plasma configurations.

On diagnostics, particular emphasis has been on the development of reflectometry (in collaboration with the Association EURATOM-IST; application on W7AS, TJI, PBXM [PPPL, USA], ATF [ORNL, USA], and JET), plasma radiation detectors and active He/Li atomic beam diagnostics. Other diagnostics are being developed or exploited in collaboration with universities. Among theoretical activities, linked to experiments, notably transport and turbulence studies are being undertaken.

The Association has a vigorous activity in the characterisation of ceramics for heating and diagnostic purposes and their electromechanical and irradiation properties.

Major Collaborations in Physics within the Programme:

- Association EURATOM - FOM: High resolution Thomson scattering;
- Association EURATOM - IPP: Stellarator physics and development, transport and turbulence studies, reflectometry, NBI studies;
- Association EURATOM - IST: Reflectometry, heavy ion beam probe system, turbulence;
- JET: Divertor physics, diagnostics;
- Association EURATOM – ÖAW: Langmuir probes;
- Association EURATOM – UKAEA: Neutral Beam injection.

## 3.4 ASSOCIATION EURATOM - CONFÉDÉRATION SUISSE

Location of Physics Research Unit: Lausanne, Switzerland

Major equipment:

- Tokamak TCV permitting variable configurations (shape, elongation).

Key Areas in Fusion Physics:

- Physics of strongly shaped plasmas in ohmic and EC heated regimes;
- Gyrotron development in collaboration with other Associations and European industry;
- Theory and numerical simulation with emphasis on equilibrium and stability of toroidal

plasmas, confinement and transport;

- JET and ITER contributions in the field of Tokamak data base, heating and modelling.

A particular focus of the Association EURATOM-Swiss Confederation is, on the Tokamak TCV, the study of strongly shaped plasma cross-sections (in particular, those that are very elongated) in view of their potential for improving confinement and more efficient use of magnetic energy.

In operation since the end of 1992, TCV is a Tokamak with an almost rectangular >3 : 1 elongated vacuum vessel ($B_T$ = 1.5 T, R = 0.88 m, a = 0.28 m). The design value of the plasma current is 1.2 MA at the maximum elongation of k = 3. The largest values of k obtained so far is 2.55 for a limiter plasma, at a toroidal field of 1T. At plasma currents >1 MA, elongations k up to 2.3 have been stably obtained. Systematic studies of configurational confinement aspects have been pursued. Experimental campaigns with 1.5 MW of ECRH at the second harmonic allowed to determine the dependence of the energy confinement time on plasma shape. At $n_{eo} = 2.2\ 10^{19}$ $m^{-3}$ the central electron temperature
$T_{eo}$ has reached 4 keV, an increase of 3 keV above the ohmic value of 1 keV.

Running parallel to this the second substantial effort is on computational plasma physics and code development. Objectives are the exploration of improved magnetic confinement configurations (also mixing Tokamak and Stellarator aspects), prediction of MHD imposed operational limits in Tokamak operation (a long-standing area of competence), studies of confinement, micro instabilities and transport (e.g. non-linear gyrokinetic models of ITG instabilities and turbulence), on RF waves (LH) for the study of current drive and absorption issues and on the stability of Alfvén waves in the presence of fast ions. Recent advances in code developments have been e.g. to improve the speed of spectral calculations by an order of magnitude, to improve discretization methods in a gyrokinetic code for better conservation of energy and particles (in collaboration with JET).

The expertise of the Association in high-frequency systems is joined with that of the Associations EURATOM-CEA and -FZK in a collaborative effort on the development, with European industry, of electron cyclotron heating sources for TORE SUPRA and TCV, as well as for W7-X [140 GHz, 1 MW, cw] also with a view for preparing the expertise for ITER systems. The prototype gyrotron for TORE SUPRA and TCV [118 GHz, 0.5 MW, 210 s] has exceeded the performances required for TCV: 0.5 MW, 5 s (required = 2 s), 30% efficiency. Long-pulse tests (up to 210 s) are being performed at CEA. Some effort is also spent on quasi-optical gyrotron development for high frequency diagnostic applications.

<u>Major Collaborations in Physics within the Programme:</u>

- Association EURATOM - DCU: diagnostics for TCV;
- Association EURATOM - ENEA: IBW coupling,(CREATE):Plasma control;
- Association EURATOM - FZJ: wall coating and conditioning;
- Association EURATOM - FZK, CEA, IPP: Gyrotron development, support of industrial

development;

- Association EURATOM - IPP: Numerical simulations;
- Association EURATOM - IST: Diagnostics;
- Association EURATOM - NFR: Code development;
- Association EURATOM - TEKES: Gyrotron issues
- Association EURATOM - UKAEA: MHD stability calculations;
- JET: Alpha particle driven Alfvénic modes;
- NTUA (Greece): Beam, plasma - microwave interactions in gyrotrons.

### 3.5 ASSOCIATION EURATOM - DCU

Locations of Research Unit: Dublin (Dublin City University and Dublin Institute of Advanced Studies), Cork (University College Cork)

Major Equipment:

- None.

Key Areas in Fusion Physics:

- Optical and laser diagnostics (polarimetry, interferometry, spectroscopy); predictive and statistical modelling of plasma diagnostic data; Modelling of impurity transport in plasmas;
- Physics investigations for negative ion source development;
- Theoretical and computational studies on wave and diffusive processes in plasmas.

In the new Irish Association activities have coalesced which emerged from dedicated collaborations with major fusion laboratories in Europe. Advanced multichannel polarimetry and interferometry systems have been developed for application on RFX, TCV. Spectroscopic work (viz. high z impurity and MARFE spectra) are undertaken on JET, COMPASS-D both for direct interpretation as well as for input to the ADAS database. Rapid and real-time identification of plasmas using function parameterisation is being further developed and applied on ASDEX Upgrade. Contributions such as on pulsed modulation techniques have been provided to the development of high yield negative ion sources for neutral beam injection in conjunction with CEA Cadarache. The modelling of resistive MHD instabilities, ion cyclotron harmonic mode excitation, non-linear Alfvénic structures in MHD and cross-field diffusion are the subjects of theoretical studies which are being undertaken in collaboration with UKAEA Culham and CEA Cadarache.

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: Negative ion source development, theory;
- Association EURATOM - Conf. Suisse: FIR interferometry / polarimetry;
- Association EURATOM - ENEA (CNR Padova): FIR polarimetry;
- Association EURATOM - IPP: Data analysis techniques, statistical methods;
- Association EURATOM - UKAEA: Spectroscopy, theory;
- JET: Spectroscopy.

### 3.6 ASSOCIATION EURATOM - ENEA

Locations of Physics Research Units: Frascati (ENEA Frascati), Consorzio RFX, Padova, CNR Milano, Italy

Major Equipment:

- FTU a high field compact Tokamak;
- RFX a large Reversed Field Pinch.

Key Areas in Fusion Physics:

- High field - high density Tokamak operation;
- ECRH physics, ECRH heated plasmas;
- Optimised shear Tokamak operation;
- High heat flux plasma wall interaction;
- LH physics, LH launcher development;
- Fast particle physics, non-linear dynamics and transport physics;
- Wave physics;
- Reversed Field Pinch physics.

The ENEA-EURATOM Association comprises three Research Groups: The ENEA Fusion Division operating at Frascati, Brasimone and Bologna; the Consorzio RFX at Padua. the Istituto di Fisica del Plasma ”Piero Caldirola” - CNR Milan. The principal experimental and theoretical physics objectives are to improve plasma stability and confinement characteristics in the two toroidal confinement lines, Tokamak and Reversed Field Pinch. This is accomplished in close collaborations with other Associations and JET in a coherent approach by modifying and controlling parameters, and their radial profiles, such as the plasma current or the plasma density and by controlling plasma-wall interaction.

The ENEA Fusion Division explores at Frascati the high field, high density Tokamak line on FTU (R/a 0.93/0.33 m, $I_P$ <1.6 MA, cryogenic (77K) operation, $B_T$ up to 8 Tesla) which has a

circular plasma cross-section and is heated ohmically (FTU has a comparatively very large current density) as well as by LH, IBW and ECRH. In ohmic plasmas, at 7.5 T and 1.2 MA, 2.5 MW heating power can be achieved and 3-4 keV electron temperature have been obtained at low density, around 1 keV at up to 3-4 $10^{20}$ $m^{-3}$. Pellet injection allows to obtain peaked density profiles with the simultaneous achievement of high central density and relatively high temperature for a substantial fraction of the discharge duration. With respect to ITER, studies of confinement and the investigation of radio-wave heating and current drive (together with CNR-Milan) are being the main goals. LHCD efficiency studies were conducted for a wide range of line average density and magnetic field; a good CD efficiency at densities of ITER relevance and a positive trend with the electron temperature were demonstrated. Benefiting of the RF systems for non-inductive current drive or of the skin effect during the current rump-up,, optimized shear (advanced) operation scenarios were investigated. An electron temperature of 14 keV was obtained with 690 kW of ECRH power at to 0.3-0.4 $10^{20}$ $m^{-3}$ In these regimes and also in pellet discharges, a strong decrease of the electron transport was observed over an entire region of small/negative magnetic shear. As another area of research high power fluxes to the target plates have been studied; impurity dynamics and the behavior of different materials, ranging from low-Z to high-Z were investigated (in collaboration with John Hopkins University and Lawrence Livermore Laboratories). While with high-Z walls very low impurity content (Zeff ~ 1) was more rapidly achieved and MARFES occurred only at higher densities, confinement was rather insensitive to low or high-Z.

In fusion theory, activities relate to a range of objectives. Numerical simulations and modelling of transport (in collaboration with JET) have led to the development of an empirically based micro-instability transport model. The stability of ion temperature gradient driven modes was comprehensively studied with lattice Boltzmann parallel simulations. The stability of Alfvén eigenmodes modes and alpha particle confinement in burning plasmas was studied and afterwards calculated for ITER. Also the properties of Energetic Particles modes and low frequency Alfvén modes have been thoroughly assessed. Theoretical analysis and a number of codes were utilised to study propagation and absorption of waves.

The research unit CNR Milan is collaborating on the ECRH experiment on FTU , and develops corresponding millimetre wave components. The system is currently under expansion to the full power of 2 MW (140 GHz, 0.5 s). Furthermore, a collective Thomson scattering experiment for the exploration of thermal density fluctuations is nearing commissioning on FTU. In theory, CNR Milan is also active in areas such as wave-plasma interactions, non-linear wave phenomena, support to the ECRH activities on FTU, as well as transport and MHD.

In collaboration with universities (CREATE consortium) contributions to ITER such as control issues including the electromagnetic response of structures outside the plasma on stability have been addressed. Exploratory work on the properties of spherical tori , in particular on the feasibility of an ULART (ultra-low aspect ratio tokamak) where the role of the central rod is taken by a stabilized screw pinch, is in progress in collaboration with the University of Rome.

On RFX (CNR, Padova), the largest device of its kind, the physics of the reversed field pinch is explored, supported under an international collaboration, in particular by the Association EURATOM - NFR. During 1997/98 the technical work has concentrated on improving the operational conditions in order to avoid limitation on plasma current due to localized plasma - wall interaction caused by locked modes. Implementation of wall conditioning techniques and of pellet injection and enhancement of diagnostic capabilities have been instrumental in conducting a wide scope physics programme. A novel use of the toroidal winding has allowed to shift locked mode location during the pulse and to obtain clean discharges up to 1.2 MA. Particular results were the confirmations of the possibility to achieve an improvement of confinement by assisting the internal dynamo action via inductive poloidal current drive and of a spontaneous single helicity operating mode which is also linked to a (so far a smaller) enhancement of confinement. Another important observation is that with boronized walls the impurity content could be kept below a level corresponding to Zeff < 1.5 up to the maximum current levels tested, evidencing the existence of an impurity screening mechanism. Theoretical activities in 1998 concentrated on three-dimensional MHD plasma simulations including flow. Linear MHD calculations have been applied to the study of resistive kink and tearing mode stability. The Committee acknowledges the success in understanding the nature of different experimental RFP states. A comprehensive survey of single helicity states in RFP devices led to the interpretation of experimental results as bifurcations between single and multiple helicity states. Scientific collaboration on Reverse Field Pinches takes place in the framework of a specific IEA Implementing Agreement, involving EURATOM and the U.S. and Japan governments.

The on-going design and R&D work of a very high field, high plasma density Tokamak, aimed at studying the approach to ignition and ignited plasma regimes during short time periods (a few seconds) is pursued by the Italian partner in the Association. In the future, a revised proposal might be submitted for in-depth examination.

The Association also undertakes a keep in touch activity on inertial confinement fusion.

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: LH launcher development;
- Associations EURATOM - Conf. Suisse and IPP: Coupling and propagation codes;
- Association EURATOM - DCU: Diagnostics;
- Association EURATOM - FOM: Theory;
- Association EURATOM - FZJ: Diagnostics, plasma wall interaction;
- Association EURATOM - IPP/FZK (IPF Stuttgart): mm-wave components;
- Association EURATOM - IST: Theory;
- Association EURATOM - NFR: RFP physics;
- Association EURATOM - RISØ: Pellet injection;
- Association EURATOM – UKAEA: Pellet injection, spherical tokamak, modelling;

- JET: Modelling, heat pulse propagation, error field magnetic island feedback control.

### 3.7 ASSOCIATION EURATOM - FOM

Location of Physics Research Unit: FOM Institute for Plasma Physics, Rijnhuizen, The Netherlands

Major Equipment:

- RTP Tokamak (until September 1998);
- Collaboration on TEXTOR-94 (Association EURATOM-FZJ Jülich) in the frame of the Trilateral Euregio Cluster.

Key Areas in Fusion Physics:

- Experimental and theoretical study of anomalous transport in Tokamaks;
- Experimental and theoretical study of MHD and disruptions;
- Development of advanced and high resolution diagnostics;
- Development of a Free Electron Maser for fusion application;
- Theory of non-linear plasma dynamics, physics of ECH and ECCD.

Within its collaboration in the TEC, the Association EURATOM-FOM (Nieuwegein) is specialised in the study of transport employing advanced diagnostics, in particular a 90° Thomson scattering diagnostic of unprecedented high spatial resolution. Together with ECR Heating and current drive electron temperature profiles and their change under localised heating and electron cyclotron current drive have been examined. The studies have identified fine grain structures “filamentation” which are attributed to internal transport barriers near mode rational surfaces at (half-) integer q-value. Highly hollow temperature profiles could be created which caused hollow current density profiles and negative central shear. Convective heat transport must be invoked for interpreting these results. The activities so far undertaken on the small Tokamak RTP are being transferred by the end of 1998 to TEXTOR-94. This will permit to extend the studies to plasmas with increased collisional electron-ion coupling. In the area of diagnostics development also other diagnostics have been studied, e.g. a pulse-radar reflectometry system.

Theoretically, these experimental studies are accompanied by work in non-linear plasma dynamics for the study of small-scale structures, reconnection and associated anomalous transport with the aim of providing methods for comprehensive modelling of the experimental situations. Work also extends to modelling the non-linear reconnection dynamics in 3D which will be found in the future dynamic ergodic divertor experiments on TEXTOR-94. In the area of MHD, code development has been undertaken on the evolution of systems with flow which occur in fusion e.g. in divertor or NBI heated plasmas. Applications such as an MHD spectroscopy of JET have been undertaken.

The development of a multi-megawatt Free Electron Maser as a tuneable source for plasma heating and current drive is the other important physics area of work for the Association. A high-power tuneable (130-260 GHz) prototype, has delivered 0.7 MW in short pulses (10 μs). Presently, the electrical set-up is inverted to permit operation with a depressed collector allowing much longer pulses in 1999.

Work on specialised topics such as divertor plasma simulation, negative ion formation, cross-section measurements have been undertaken by specialised groups in universities and other institutes.

Major Collaborations in Physics within the Programme:

- Association EURATOM - FZJ, Belgian State as partners in the Trilateral Euregio Cluster: Tokamak physics, filamentation, anomalous transport (ULB), diagnostics;
- Association EURATOM - CEA, -IPP, -UKAEA: Experimental methods of anomalous transport studies;
- Association EURATOM - CIEMAT: Diagnostics;
- Association EURATOM - ENEA : Transport experiments (Milano) and reconnection theory (Pisa);
- Association EURATOM - FZK, Conf. Suisse: mm-wave sources and transmission components;
- Association EURATOM – NFR: Fast phenomena during disruption quench;
- JET: Transport studies, diagnostics.

### 3.8 ASSOCIATION EURATOM - FZJ

Location of Physics Research Unit: Forschungszentrum Jülich, Germany

Major Equipment:

- TEXTOR-94 Tokamak in the frame of the Trilateral Euregio Cluster.

Key Areas in Fusion Physics:

- Plasma wall interaction: wall conditioning, erosion- and deposition mechanisms, recycling, edge particle and energy transport;
- Core physics: MHD and impurity transport;
- Multidimensional modelling of edge plasmas, theoretical study of impurity effects and transport barriers.

Within the Trilateral Euregio Cluster, the Association EURATOM-FZJ, with the Associations EURATOM-Belgian State and –FOM, pursues a joint programme on TEXTOR-94 for a coherent concept for energy and particle exhaust under quasi-stationary conditions.

Wall coating by carbonization, boronisation (used on most devices world-wide) or siliconisation (collaboration with the Association EURATOM - Conf. Suisse), were pioneered by TEXTOR-94 and widen the operational range allowing e.g. operation at higher densities. Siliconized walls appear attractive with respect to density limit and radiation cooling. Feed back controlled injection of selected impurities (e.g. neon) for edge radiation cooling and improved energy exhaust has been leading to the RI-mode. With improving energy confinement at higher densities about 90% of the exhaust power is spread over large areas. For the RI-mode plasma-wall interaction, particle and energy exhaust, confinement (see also Association EURATOM-Belgian State), impurity transport and MHD etc have been studied.

Prolonging the pulse duration and upgrade of heating power on TEXTOR-94 have been instrumental for achieving stationary RI-mode operation with high density (0.96 $n_{Greenwald}$) and high confinement ($f_{H93}$ >0.9) for 7s corresponding to 160 energy confinement times equivalent, in confinement times, to the pulse duration of ITER.

Impurity transport remains a crucial issue. With neon impurity seeding, neon concentrations in the core remain moderate (1% of the electron density). also at high density and radiation fraction. The dependence of high and medium-Z accumulation on operational aspects has been studied.

Wall coating by ion cyclotron generated plasmas is developed for super-conducting devices. Another method is e.g. plasma spraying for thick $B_4C$ coatings as a candidate method for W7-X.

For improving control of erosion and deposition, their mechanisms have been studied in-situ with a comprehensive set of diagnostics (and limiters of different materials). Injection of gases provides control, albeit still at a low efficiency and dependent on local electric fields.Impurity release from graphite and high-Z materials shows a strong decrease of the hydrocarbon contribution to the overall carbon release with electron tempearture (70% at 25 eV, 20 % at 70 eV). For tungsten and molybdenum, physical sputtering by impurities is dominant; the overall effective release rates decrease strongly with plasma density (several percent at low edge density, 0.5% at the highest densities). Prompt re-deposition increases with density. Radiation enhanced sublimation does not enhance noticeably graphite erosion above 1400K. Surface layers have been studied for determining the co-deposition e.g. of carbon on boron.

Energy and particle transport in the edge plasma is studied by a range of diagnostics including probes and spectroscopy, also with helium and lithium beam injection, for validation of edge transport models with emphasis on drifts due to electric fields or pressure gradients and on the role of impurities. The atomic processes of hydrogen recycling have been studied and surprisingly, H atoms (0.1 eV),originating from vibrationally excited molecules were found.

Core MHD studies comprise work on sawteeth, disruptions, m=1 and m/n = 2/1 modes and operational limits. Radiative instabilities (MARFE) and fast radial temperature perturbations are investigated with high time and high spatial resolution of plasma parameters.

Modelling and theory accompany experimental studies of plasma edge / core physics. Several codes have been (co-)developed (e.g. B2-Eirene) which are now widely used for interpreting complex observations such as poloidal asymmetries of electron density and temperature profiles, or the transport of trace impurity ions. Transport including impurity radiation has been studied with a self-consistent transport code RITM (validated on TEXTOR-94 and TORE SUPRA), in particular for understanding the stability of radiative edge plasmas. Analytical models are used, e.g. on the radiation potential, impurities in stochastic magnetic fields and their role for electric fields and hot spot formation on limiters.

The pumped limiter ALT-II plays a key role for the feed-back control of the radiating impurities neon and argon. Efficient helium exhaust could be demonstrated. As a new instrument for influencing edge and exhaust physics, building partly on work on TORE SUPRA, a dynamic ergodic divertor is presently prepared for installation.

Collaboration in the framework of an IEA Implementing Agreement and by a large number of universities through the Euregio University Club provides support to the programme in particular on plasma-wall interactions, transport in magnetized plasmas, and diagnostics.

Major Collaborations in Physics within the Programme:

- Associations EURATOM - Belgian State and – FOM as partners in the Trilateral Euregio Cluster: Tokamak physics, plasma heating, plasma wall interaction filamentation, anomalous transport (ULB), diagnostics;
- Association EURATOM - CEA: Ergodic divertor, RI-mode, Impurity transport, modelling;
- Association EURATOM - Conf. Suisse: Coating techniques, modelling;
- Association EURATOM - IPP: Edge plasma, surface physics, transport, modelling;
- Association EURATOM - NFR: First wall materials and treatment, surface physics;
- JET: Plasma wall interaction, edge plasma studies, diagnostics.

### 3.9 ASSOCIATION EURATOM - FZK

Location of Research Unit(s): Forschungszentrum Karlsruhe, Germany

Major Equipment:

- Test stand for ECRH sources (100 kV, 30 A, CW, 6.5 T SC magnet).

Key Areas in Fusion Physics:

- Advanced gyrotron development and gyrotron development for ECRH systems in collaboration with other Associations and industry;
- High-frequency - high power window development and qualification.

The Association EURATOM-FZK (Karlsruhe) is a key contributor in fusion technology, both for

ITER and the longer term. In plasma engineering, developments are undertaken in collaboration with other Associations (EURATOM-CEA, FOM, Swiss Confederation) on electron cyclotron frequency heating sources for ITER and together with industry for the development and manufacturing of ECRH systems for devices in the Associations (TORE SUPRA and TCV: 118 GHz, 0.5 MW, 5s/210s, W 7-X: 140 GHz, 1 MW, cw).

Prototype developments of advanced coaxial gyrotrons with unit powers well above one megawatt have been successfully achieved in short pulses (140 / 165 GHz, 1.5 MW, 20 ms, 25% / 35% efficiency without / with depressed collector) on the way towards developing the basis for manufacturing a 2 MW, ~170 GHz, cw coaxial gyrotron. A new improved 4.5 MW electron gun has been designed for coaxial gyrotrons. The tube is currently (end 1998) under commissioning in industry.

Related to electron cyclotron heating and diagnostics, the area of developing high-frequency vacuum windows is pursued. A particular result is the confirmation of the feasibility of room-temperature diamond windows.

The Association, together with the Association EURATOM - Conf. Suisse and -CEA is in close connection with industry for the definition, development and manufacturing of high-power high-frequency gyrotrons.

Major Collaborations in Physics within the Programme:

- Association EURATOM - IPP: W7-X ECRH system and mm-wave components (IFP Stuttgart);
- Association EURATOM - Conf. Suisse: General gyrotron development;
- Associations EURATOM - Conf. Suisse, -CEA: 118 GHz gyrotron development;
- Association EURATOM - TEKES: Gyrotron development - cavity aspects;
- NTUA (Greece): gyrotron development - beam stability and interaction aspects.

### 3.10 ASSOCIATION EURATOM - IPP

Location of Research Unit(s): Max-Planck-Institute for Plasma Physics, Garching / Berlin/ Greifswald, Germany

Major equipment:

- ASDEX Upgrade: besides JET the largest divertor Tokamak in Europe;
- Wendelstein VII-AS: a modular Stellarator;
- Under construction: Wendelstein VII-X, a large advanced (Helias) Stellarator.

Key Areas in Fusion Physics:

- General Tokamak physics with main emphasis on confinement, core-edge relation, scrape-

off layer and exhaust physics;

- General Stellarator physics with main emphasis on the optimisation of configurational aspects;
- Numerical modelling of plasmas - configurations, equilibrium, stability, turbulence, transport, collective phenomena ...;
- Surface physics, interaction of hydrogen with surfaces (carbon, tungsten ...);
- Heating systems development (Neutral Beam Injection, ICRH, ECRH).

The Association EURATOM-IPP (Garching, Greifswald, Berlin) has been pioneering the development of the poloidal divertor. It operates, as its main experimental activity, the divertor Tokamak ASDEX Upgrade. Together with the larger JET, and the smaller COMPASS, as well as the US-Tokamaks DIII-D and ALCATOR C-MOD, ASDEX Upgrade is similar to ITER in its plasma shape and has provided essential contributions to establishing a robust database for the scaling towards ITER. A priority task for ASDEX Upgrade has been the ITER-oriented testing of divertor concepts at high power fluxes, including the test of tungsten (instead of graphite based materials) as target plate material. Other tasks have been the demonstration of ITER-sufficient helium pumping and the compatibility of H-mode operation with the radiative exhaust (the latter having been explored in a circular plasma on TEXTOR-94). An increase in the plasma heating power in 1997 (extension of the neutral beam heating system by adding a second injector box giving a total power of 20 MW in D/ [14 MW in H/], addition of an Electron Cyclotron Heating system of 0.8 MW for 2 s and improvement of coupling efficiency of the ICRH system giving 5.7 MW to the plasma) provides a scaling parameter P / R (power divided by major radius) for divertor discharges up to about 12 MW/m which is only a factor 3 below the one for ITER. Presently, values up to 12 MW/m have been achieved.

Simultaneously with the extension of additional heating, a modification of the divertor has permitted investigations with plasma conditions and particle and power exhaust close to those of ITER. The operation with the “Divertor II” started in early summer 1997 with the "closed" LYRE version (including a roof baffle), which is rather similar to the present ITER reference design. The new divertor is combined with a cryopump (100 $m^3$/s pumping speed) for the efficient removal of particles behind the divertor slots. Experiments on power loading, radiation scenarios, impurity production (low and high-Z) and pumping processes proceed in line with a strong modelling effort including advanced 2D codes such as B2-EIRENE (developed with FZJ and NYU, USA). Up to 90% radiative power extraction has been demonstrated in H-mode operation with completely detached divertor resulting in very moderate power load on the divertor target plates (< 0.5 MW/$m^2$; generally the heat flux has been reduced by more than a factor 2 with respect to the previous divertor: at full input power of 20 MW the maximum heat flux remains below 5 MW/$m^2$). At 75% total radiated power exhaust, about 45% of the input power is radiated below the X-point. The enhanced radiation is due to an increased combined radiation efficiency of carbon and hydrogen in the divertor plasma resulting from an interplay of reflection of neutrals, pre-cooling by carbon of the divertor plasma and broadening of the scrape-off layer due

to radial transport. The fractional radiative loss in the divertor is rather independent from the heating power. The Divertor II also provides a much larger compression (neutral density in the divertor compared to ion density at the plasma edge) leading to detachment at lower density and about the same enrichment factor for helium exhaust (yielding $\tau^*_{He} / \tau_E = 4...6$).

Core physics was another major area where comprehensive contributions to the toroidal confinement physics were made: issues were the operation close to regime transitions and operating limits, in particular the exploration of the density limit, characterisation of edge operating conditions and their impact on core behaviour (divertor detachment, L / H mode dynamics, temperature profile resilience, ballooning and edge density limits), disruption studies (thermal and current quench, halo currents, forces, energy deposition during VDEs) disruption avoidance (detection for early warning) and plasma control (currently being extended to profile control). High density H-mode operation has been performed in extensive campaigns using wide parameter ranges ($I_p = 0.4...1.4$ MA, $B_t = 1.3...3$ T, $P_{NBI} = 2.5...20$ MW). At high density considerably more power than the threshold power is needed to stay in the H-mode. Close to the density limit, confinement deterioriation with respect to H-mode scaling is found to be due to an edge - core relation via stiff temperature profiles: since the fuelling increases particularly the edge density, pressure gradient limitation (with a fixed pedestal width) forces the temperature to decrease which in turn leads to a decrease in core temperature. Decoupling of core and edge density becomes therefore an important issue.

A particular interesting result in this context was the demonstration of enhanced (central) fuelling efficiency by inboard pellet fuelling in ASDEX Upgrade.

Heat pulse studies suggest that core transport might be determined by a critical gradient effect; heat conductivities derived from sawteeth propagation are up to twice as high as the value which is found with the more moderate ECRH modulation. Scaling experiments have been undertaken with JET and ALCATOR C-MOD (dimension less) and D-IIID (dimensionally identical). Neo-classical tearing mode studies have been performed demonstrating the possible severe beta limitation but also the possibility of mitigating or eliminating these modes by localised modulated EC heating and current drive which was feed-back controlled by Mirnov signals.

Increasing emphasis has been given to shear control (advanced tokamak operation) which emerges as a major topic in tokamak physics for the near future[5]. In the present situation, stationary discharges with H-mode edge and internal transport barriers (providing improved core confinement) have been produced reproducibly. At 1 MA, 2.5 T, and 5 MW NBI , an $H_{ITER-89P}$ factor of 2.4, $ß_N = 2$, central values $T_i = 11$ keV and $T_e = 6.4$ keV and a line averaged density of $4.1\ 10^{19}$ m $^{-3}$ could be obtained for 6 s, i.e. for more than 40 energy confinement times or several skin times. Despite an initial slight central impurity peaking no further accumulation was observed over 4 s. In the area of shear controlled operation close collaboration with other

[5] Part of the NBI will be oriented to parallel injection for current drive.

partners, in particular with JET and TORE SUPRA, is maintained.

The experimental activities are accompanied by a comprehensive effort in Tokamak theory in the area of modelling and numerical simulation. A great variety of codes is under continuing development and application for equilibrium, stability and transport investigations. In collaboration with the Association EURATOM - FZJ and NYU scrape-off layer and divertor modelling is undertaken which now progresses towards strongly time-dependent situations such as ELMs. The development of first principle based turbulent energy and particle transport simulation codes has received considerable attention in fully toroidal Tokamak geometry, as well as, for checks, kinetic models in simplified geometry. Results highlight in particular the importance of including magnetic fluctuations in the simulation. MHD modelling of neo-classical modes is progressing in collaboration with the Association EURATOM - UKAEA and JET, also with the inclusion of fast particle influenced modes. Wave - plasma interaction in the ion cyclotron range has been studied extensively and a full toroidal wave code is under further development. Together with the Association EURATOM - DCU the statistical analysis of confinement data and regime limits is pursued. Similar approaches are used to complement the experimental work on disruption avoidance.

The Association has supported the design, construction and operation of JET diagnostic systems. Collaborations also include impurity physics and related diagnostics and pellet injection systems as well as plasma wall interaction processes (in collaboration also with the Association EURATOM - FZJ). Other diagnostic developments have also been pursued, e.g. the use of the Cotton - Mouton effect for Stellarator steady state density measurements.

In its other large area of research, the Association operates a modular Stellarator, W7-AS, and is constructing the large superconducting W7-X at Greifswald. The studies on W7-AS on Stellarator physics are also relevant for the Tokamak. The different configuration, in particular the absence of a net toroidal plasma current provides comparative insight in the influence of individual parameters on transport, confinement, instabilities and operational limits. Issues have been studied such as neo-classical MHD , parallel flow damping on the H-mode, non-local transport, magnetic shear effects on confinement, physics of Alfvén Eigen modes, and high density operation without MHD limitations. The increase of the NBI power up to 3 MW (addition of 4 injectors) in W 7-AS has led to <ß> = 1.8% and ß(0)= 4% for B = 0.8 T. The latest results obtained to date are: plasmas with density of $2.10^{19}$ $m^{-3}$ and temperature of 5.5 keV with a neo-classical energy confinement time. Also ICRH heating of Stellarator plasmas is being studied. During the past two years good plasma (second harmonic and minority) heating has been demonstrated and ICRH heated plasmas remained self-sustained for up to 800 ms. The accessible density range in ECRH heated plasmas has been extended in 1997 to more the twice the cut-off density for fundamental (O-mode) launch opening attractive perspectives for high-density divertor operation. The island divertor has been modelled in 1996/7 and in principle feasibility was demonstrated. The machine is presently open for installation of divertor control

coils which should permit the further development of this divertor type in time for W7-X.

The construction of W7-X has progressed to the phase of industrial contracts for the procurement of the major components. The prototype advanced conductor for the W 7-X Stellarator underwent successful testing in the STAR 4 coil at the Association EURATOM - FZK: nominal values were reached and even exceeded. Its margins will allow a reduction of windings in the coils of the magnet. A demonstration coil of the non-planar magnet is currently being prepared at FZK for testing in the background field of the (former) LCT coil. The Demo-section of the cryostat has been delivered by industry and is under mounting at IPP.

A strong modelling and theoretical effort is accompanying the Stellarator line. The conceptual clarification of Stellarator optimisation is further pursued by exploring theoretically the configurational space. Equilibrium and stability are (re-)assessed with improved codes and anomalous transport theory is investigated with respect to Stellarator specific aspects. Work is progressing with the Association EURATOM - Conf. Suisse and Japanese and US partners.

Aspects of a Stellarator power station are examined in systems studies; participation in this work by other Associations is currently envisaged.

The Association undertakes a vigorous effort in surface physics and plasma wall interaction, in particular on sputtering, chemical erosion and hydrogen retention of compound materials. Experimental work on fusion devices concentrates on charge exchange sputtering, determination of ion temperature profiles and impurity aspects. An analytical formula for chemical erosion of carbon was established for use by ITER. The balance between erosion and deposition of hydrogen and carbon on W and Be samples has been determined and W erosion and migration was studied. Results discourage the use of tungsten as first wall material. Specific studies on plasma surface interactions and improvement of corresponding diagnostic methods are being performed at the plasma generator (Berlin branch of IPP) in conjunction with modelling by the B2-EIRENE code (in collaboration with the Association EURATOM - FZJ). Work on dielectronic recombination of ions with open shell configurations (e.g. W) is being performed in an electron-beam - ion-target experiment.

This, the largest Association, is involved in numerous and extensive collaborations with other Associations and universities. Also, at the international level, collaboration with groups in the US and Japan is on-going under IEA Implementing Agreements.

Work on auxiliary systems, in particular on neutral beam injection (radio-frequency ion source for negative ion beam systems), ECRH (in collaboration with FZK and IPF Stuttgart), ICRH, and on fuelling by pellet injection is undertaken, where IPP has a longstanding successful record in the development of centrifuge pellet injectors.

A keep in touch activity in inertial confinement fusion is executed through the Max-Planck Institute for Quantum Optics.

Major Collaborations in Physics within the Programme:

- Association EURATOM-CEA, Cadarache: General Tokamak physics, diagnostics and control, device design;
- Association EURATOM-Conf. Suisse: H-mode physics, ECRH, heat waves;
- Association EURATOM - CIEMAT: Stellarator physics, transport;
- Association EURATOM - DCU, University College, Cork: MHD equilibrium identification, function parametrization of NBI deposition;
- Association EURATOM - ENEA, Milano: Transient energy transport;
- Association EURATOM - FOM, Rijnhuizen: Improvement of ECRH codes;
- Association EURATOM - FZJ: B2-Eirene, radiating scenarios, wall conditioning;
- Inst. Nucl. Techn., Demokritos: Fast sweeping Langmuir probes;
- IESL (FORTH), Heraklion: Erosion and vapour shielding processes;
- Association EURATOM - IST, Lisbon: Reflectometry, data acquisition;
- Association EURATOM - ÖAW , IAP, TU, Vienna: Li beam diagnostics;
- Association EURATOM - NFR: Diagnostics, transport, modelling;
- Association EURATOM - RISØ: Diagnostics;
- Association EURATOM - TEKES: particle orbit calculations in H-mode, fast ion distribution with ICRH, TAE modes and drift turbulence;
- Association EURATOM - UKAEA: Modelling, H-mode, ß-limit and MHD modes, RF heating and CD, mode stabilisation;
- JET: Pellet injection, bolometers, plasma wall interaction, divertor and H-mode physics, scaling experiments, modelling.

### 3.11 ASSOCIATION EURATOM - IST

Location of Research Unit(s): Instituto Superior Técnico, Lisbon, Portugal

Major Equipment:

- Tokamak ISTTOK.

Key Areas in Fusion Physics:

- Experimental Tokamak physics and theory;
- Diagnostics developments: microwave reflectometry, heavy ion beam diagnostics;
- Control and data acquisition techniques and systems.

The Association based at the Instituto Superior Técnico (Lisbon) is operating the small Tokamak ISTTOK for Tokamak physics studies such as biasing experiments, alternating cycle Tokamak

operation (extending the useful shot duration from 30-70 ms up to 240 ms), for diagnostics developments (heavy ion beam diagnostics (HIBD) and correlation reflectometry) and for a vigorous training programme. Localised limiter biasing is studied with respect to its impact on confinement time and central ß. Fluctuation measurements have been undertaken and will be further pursued in collaboration with CIEMAT.

As a second branch, the Association has developed strong on expertise in diagnostics and the related scientific data evaluation techniques with special emphasis on reflectometry and heavy ion-beam diagnostics. An intensive participation on microwave reflectometry was established in the programmes on several larger devices, especially on JET and ASDEX Upgrade. More recently reflectometry is also the subject of collaborations on MAST and in the ITER frame and, in collaboration with the Association EURATOM-CIEMAT, for TJ-II and Wendelstein 7-X. Collaboration on other systems such as HIBD and laser induced fluorescence diagnostics has also been performed on TJ-II. An X-ray spectrometer was developed for TCV.

Data acquisition and control systems have been developed in collaboration with IPP and UKAEA where a novel fast timing system for MAST was established by IST.

Studies of MHD, transport (MHD activity control, tearing modes, MHD activity during hot-ion mode discharges, GAE stability in the presence of energetic ions) and current drive (effects of magnetic ripple, modelling of electron kinetics) are theoretical orientations of the programme which are carried out in collaboration with other Associations and JET.

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: LHCD, reflectometry, control and data acquisition;
- Association EURATOM - CIEMAT: Diagnostics, data acquisition, fluctuations;
- Association EURATOM - Conf. Suisse: X-ray spectrometer;
- Association EURATOM - ENEA (Frascati): control and data acquisition; (CNR Milan): MHD studies;
- Association EURATOM - IPP: Reflectometry, control and data acquisition, X-ray diagnostics;
- Association EURATOM - UKAEA: Edge plasma diagnostics, fast timing and data acquisition, reflectometry;
- JET: MHD studies, reflectometry.

### 3.12 ASSOCIATION EURATOM - NFR

Locations of Physics Research Unit: Royal Institute of Technology, Stockholm, Chalmers University Göteborg, University of Uppsala, University of Lund, Sweden

Major Equipment:

- EXTRAP-T2.

Key Areas in Fusion Physics:

- Reversed field pinch physics;
- Plasma-wall interaction;
- Neutron and optical spectroscopy diagnostics;
- Transport and confinement theory;
- Wave heating and current drive, fast particle theory;
- edge and divertor physics.

The main experimental activity of the Association is centred around the reversed field pinch experiment EXTRAP T2 with a resistive shell ($t_{shell}$ = 1.5. ms, modification to 5 ms foreseen) and a graphite first wall. Plasma currents up to 0.26 MA and pulses up to 15 ms were reached with a wide range of plasma densities (0.1-1 $10^{20}$ $m^{-3}$). Activities are closely connected with the ones of RFX. During 1997/98 temperature and profile effects were studied, also aspect ratio considerations for the intrinsic RFP dynamo effect and effects of rotation on mode dynamics. Diagnostic measurements demonstrated electrostatic turbulence transport in the edge region being dominated by low frequency resonant fluctuations correlated with magnetic fluctuations.

On TEXTOR-94 and EXTRAP T2 plasma wall interaction are studied, in particular collector probes are used for the measurement of composition and energy of hydrogen and impurity ion fluxes in the scrape off layer, of erosion and deposition, and of retention and recycling of hydrogen in graphite (also with, and for JET) including post-mortem analysis of divertor tiles. W and Mo limiters have been studied. Edge plasma conditions in the RFP are explored.

Calibrated and time-dependent spectroscopic techniques are being developed an applied on JET and EXTRAP T2. Contributions to the low-Z element database for JET divertor modelling are made. A large magnetic proton recoil 14 MeV neutron spectrometer (in collaboration with JET and ENEA/CNR Milano) and time-of-flight spectrometers have been built and exploited on JET which serve as on-line diagnostics and provided essential information during additionally heated discharges and in particular in the DTE1 campaign.

In theory and modelling MHD and operational limits are studied for Tokamaks, in particular for ITER and JET including advanced operation scenarios. Rotation in the order of a few percent of the Alfvénic speed is shown to give about 40% increase in the ß limit. Predictive transport simulations with first principle models show good agreement with existing experiments and support the attainment of ignition for the ITER FDR design. Ion transport barrier, LH transitions etc. calculations are in agreement with dimension less scaling experiments. Energetic ion effects are studied for establishing threshold conditions for alpha particle driven instabilities and their effects on confinement. Other studies concern the non-linear alpha particle dynamics in

optimised shear and the channelling of alpha particle energy to thermal ions. Finite orbit effects, RF induced transport and mode conversion are topics in ICRH and FWCD theory and modelling which enabled e.g. to identify RF-induced spatial transport in JET and TORE SUPRA.

Major Collaborations in Physics within the Programme:

- Association EURATOM - ENEA [CNR Padova]: Plasma wall interaction, diagnostics, locked modes); [CNR Milan]: Neutron diagnostics;
- Association EURATOM - FZJ: Plasma wall interaction;
- Associations EURATOM - TEKES, - CEA: RF physics;
- Association EURATOM - UKAEA: Divertor physics;
- Associations EURATOM - UKAEA, Conf. Suisse, -ENEA, -FOM and -IPP: Tokamak theory, fast particle physics;
- JET: Spectroscopy and neutron diagnostics, Tokamak theory and modelling, plasma wall interaction, RF and fast particle physics.

### 3.13 ASSOCIATION EURATOM - ÖAW

Locations of Physics Research Unit: Austrian Academy of Sciences, Vienna, Technical University Vienna, University Vienna, University Innsbruck, University Graz

Major Equipment:

- None.

Key Areas in Fusion Physics:

- Edge plasma physics - processes and diagnostics;
- Edge plasma theory and modelling, transport physics.

The Association EURATOM-ÖAW (Vienna, Innsbruck, Graz) was established in 1996. In its first years of existence, it addresses experimental and diagnostic as well as theoretical and modelling aspects of edge plasma physics. Turbulence, transport and fast particle dynamics are theoretical objects of study.

A long-term goal is to gain, in collaboration with other Associations, a comprehensive, predictive understanding of the entire edge plasma including the physics of fast alpha particles and helium ash. Studies of processes in dedicated experimental set-ups are combined with in-situ measurement on fusion devices. The development of Li-beam edge plasma diagnostics and implementation of Li-CXS on the W7-AS Stellarator and ASDEX Upgrade Tokamak has been completed and measurements are underway. Results assist in improving edge plasma modelling by adapted atomic and molecular excitation and collision process data bases. Probes for the

investigation of fluctuations in the boundary layer in TJ-II (Association EURATOM-CIEMAT) are under development.

In the second strand which concerns theory and modelling the topics of research are particle-simulations and kinetic studies of divertor sheaths and the kinetic modelling of alpha particle behaviour, electron and ion cyclotron heating and current drive. For the latter, computational (mapping) methods have been developed which enhance considerably the efficiency of calculations. As a method for basic transport theory the multiple time scale approach has been developed. Furthermore, numerical studies on burn dynamics of fusion plasmas are undertaken.

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: Spectroscopy, modelling;
- Association EURATOM - FZJ: Edge physics, plasma wall interaction;
- Association EURATOM - CIEMAT: Langmuir probe development;
- Association EURATOM - IPP: Edge physics and diagnostics, theory, modelling;
- Association EURATOM - UKAEA: atomic and molecular data bases;
- JET: Spectroscopy, atomic and molecular data bases.

### 3.14 ASSOCIATION EURATOM - RISØ

Location of Physics Research Unit: Risø National Laboratory, Risø, Danmark

Major equipment:

- None.

Key Areas in Fusion Physics:

- Laser plasma diagnostic;
- Theoretical and numerical studies of non-linear plasma dynamics.

The Association EURATOM-RISØ (Roskilde) is, within its diagnostic activities, concentrating on laser diagnostics for fluctuation studies in fusion plasmas. A novel method of cross-correlation fluctuation measurements by laser scattering has been developed. During 1997/8 a scattering system has been built and installed on Wendelstein VII-AS (IPP Garching). Turbulence at wave numbers from 10 - 140 $cm^{-1}$ have been investigated. The method is also applicable to e.g. air turbulence and speed measurements. A corresponding spin-off is under development with wind-mill industry.

By adapting fluid turbulence mathematical methods to magnetized plasmas the investigation of non-linear phenomena such as vortices, electrostatic turbulence and cross-field transport has become an important domain of the Association. These studies are undertaken in collaboration with the TEC (Jülich/Düsseldorf) and with several universities in Europe and the US.

The Association has developed and constructed light gas multi-barrel pellet injectors which are now in use on several Tokamaks. Though the development has been terminated, competence for maintenance support has been kept in the Association through 1997/8.

Major Collaborations in Physics within the Programme:

- Association EURATOM - ENEA, UKAEA: pellet injectors.
- Association EURATOM - IPP: laser diagnostics;
- Associations EURATOM - FZJ, ÖAW (Univ. Düsseldorf, Innsbruck): non-linear plasma physics.

## 3.15 ASSOCIATION EURATOM - TEKES

Locations of Physics Research Unit: VTT and University of Technology (Espoo), University of Helsinki, Finland

Major Equipment:

- None

Key Areas in Fusion Physics:

- RF-heating and current drive theory;
- Transport theory and plasma wall interaction.

The Association EURATOM-TEKES was established in 1995. In physics, a the main area is theoretical and simulation work on heating and current drive. The main tools are the ASCOT Monte Carlo code and particle-in-cell codes.

Modelling of high performance ICRF heating experiments on JET (together with the Association EURATOM - NFR) and the development of RF modules for transport codes are under JET task agreements. The work of mode conversion and minority current drive for current profile control and the interaction of alpha particles with LH waves (power channelling vs. absorption) is ITER oriented. Together with TORE SUPRA and JET the parasitic absorption of LH power near the grill is studied.

Further work is undertaken in the area of transport and confinement: simulations for the L / H transition on ASDEX Upgrade and density and particle transport studies for Wendelstein VII-AS.

A second area, in collaboration with the Association EURATOM - Conf. Suisse and -FZK, is the participation in gyrotron studies for ECRH and microwave diagnostics.

Fusion technology work in collaboration with industry is devoted to aspects of ITER (vacuum window design, remote handling systems and materials).

Major Collaborations in Physics within the Programme:

- Association EURATOM - CEA: LH physics;
- Associations EURATOM - Conf. Suisse and FZK: Gyrotrons;
- Association EURATOM - IPP: L/H transitions, transport;
- Association EURATOM - NFR: High performance ICRH heating;
- JET: RF heating, current drive, advanced scenarios.

### 3.16 ASSOCIATION EURATOM - UKAEA

Location of Physics Research Unit: UKAEA Culham

Major Equipment:

- COMPASS-D Tokamak (converted from the earlier COMPASS-C);
- until 1998: START Spherical Tokamak;
- under construction: MAST Spherical Tokamak.

Key Areas in Fusion Physics:

- General Tokamak physics, including contributions to JET;
- Physics of low aspect ratio Tokamaks;
- Tokamak confinement, MHD, heating, fast particle studies, off-normal events, edge physics;
- Reactor studies, S&E studies.

At the Association EURATOM-UKAEA, experimental work on the COMPASS-D Tokamak in an ITER-like configuration (similar to JET and ASDEX-Upgrade) is primarily focused on: instability and disruption control studies using localised radio frequency (electron cyclotron and lower hybrid) heating and current drive; participation in physics scaling experiments in collaboration with JET and ASDEX Upgrade, for example on H-mode confinement and thresholds; and long pulse regimes using RF current drive.

Participation in work on, and support of, JET is a main activity of the Association. D-T and neutron physics work includes, inter alia, studies on limits to performance in regimes (notably optimised shear), alpha particle physics and ion cyclotron emission. Main topics of the JET collaboration are: diagnostics and interpretation of plasma instabilities (e.g. ideal MHD limits to edge pressure gradient, outer modes); code work on fast ion stabilising effects, alpha particle driven instabilities and alpha particle distributions; edge physics studies; and H-mode physics.. Plasma stability and discharge optimisation, disruptions (including consequences such as

”runaway” electrons) and vertical displacement events (where a large data base on occurrence conditions and halo currents - including toroidal asymmetry - has been established) are studied experimentally and theoretically with JET and other Associations (and DIII-D in the US). In this context the role of error fields is being studied: their importance was understood by pioneering work on COMPASS-C, and has been extensively studied by UKAEA on COMPASS-D and JET, and by collaboration with DIII-D leading to the design of correction coils considered prudent for ITER. Localised, modulated ECRH has been used on COMPASS-D for demonstrating suppression or reduction of magnetic islands thereby mitigating the disruption risk. These studies shall be continued together with IPP on the larger ASDEX-Upgrade. Theoretical and experimental work has been pivotal in understanding neo-classical instabilities; their impact on plasma pressure limits at low collisionality was studied on COMPASS-D (and other devices). ECRH and LHCD have been used for non-inductive plasma operation at high normalised ß (~2.3) at low collisionality for pulse-lengths approaching the resistive diffusion time (i.e. in relative terms for an appreciable fraction of the pulse length envisaged for ITER). Extensive calculations have been carried out for ITER concerning ECRH, ECCD and start up, as well as RF-wave propagation.

In the area of confinement and edge physics, data from COMPASS-D are used in conjunction with those from ASDEX Upgrade, JET and other devices for scaling studies. Specific experimental and theoretical studies have been devoted to: the H-mode threshold power (in particular the deviation of this threshold at low density from the ITER scaling); the impact of sawteeth; the modelling of turbulence across the plasma; the impact of plasma rotation and profiles on the type of diffusion (Gyro-Bohm vs. Bohm); testing transport models against ITER databases; edge localised modes (impact of perturbations, observation and modelling of precursors, power deposition pattern on divertor target plates, modelling of ELM cycle, MHD stability, and analysis of edge fluctuations); scrape-off layer measurements and theory, and the scaling to ITER; edge modelling and the sensitivity of transport models to the edge temperature pedestal (and $\rho^*$ scaling of the pedestal); and edge pedestal measurements using the novel HELIOS diagnostic.

A very-low-aspect ratio variant of the Tokamak, the Spherical Tokamak, is being successfully investigated. With the START device record <ß> values of ~ 40%, production of H-mode behaviour and resilience to disruptions have been found. A large operational space is accessible, and, with a pellet injector developed by RISØ and on loan from ENEA, densities 50% above the Greenwald value have been achieved. Confinement appears at least as good as the scalings found at normal aspect ratios. Neutral beam heating was added (using equipment loaned from ORNL, US) and fast ion orbits have been modelled to calculate neutral beam heating and current drive. These results provide the basis for a larger successor at the Mega Ampère current level. This new device, called MAST, is currently nearing completion; first plasmas were produced by the end of 1998. In the context of ITER, this work on low-aspect ratio systems provides input to the Tokamak database at otherwise inaccessible parameters, and thereby helps to increase the understanding of Tokamak physics and to test models (e.g. to determine better confinement

scaling with aspect ratio). The other objective of this work is to explore the properties (e.g. strong resilience to disruptions) of variants such as the Spherical Tokamak for conceptual improvements in the longer term.

The Association has been a prime mover in work on fusion safety and environmental studies, and its physics expertise provides input to its systems studies of the economics of conceptual fusion power plants. Other activities include an annual summer school on plasma physics and an initiative to help industry benefit from fusion research. The UKAEA Association has links with many universities, in some cases using its fusion expertise for applications in areas of more basic science such as space physics.

Major Collaborations in Physics within the Programme:

- Association EURATOM – Belgian State (RMA): RI modes
- Association EURATOM - CIEMAT: Neutral beam injection;
- Association EURATOM - Conf. Suisse: Plasma control, MHD modelling;
- Association EURATOM - DCU: spectroscopy;
- Association EURATOM - ENEA: Pellet injection, spherical Tokamak, modelling;
- Association EURATOM - FOM: Pellet injection, Thomson Scattering
- Association EURATOM - FZJ: Edge codes; RI modes
- Association EURATOM - IPP: ß-limits, ECRH for instability control, H-modes, ELMs, modelling and theory; RF heating and current drive
- Association EURATOM - IST: fast timing systems, diagnostics;
- Association EURATOM - NFR: Theory, especially MHD, fast particles and divertors.
- Association EURATOM - Risø: Pellet injection;
- JET: Diagnostics, MHD, fast particles, confinement, edge physics, modelling.

## 3.17 EURATOM - SUPPORTED ACTIVITIES IN GREECE ON FUSION (COST SHARING ACTIONS)

Several research groups in Greece participate in the Fusion Programme. Pending the establishment of an Association, these collaborations so far have been supported by individual cost sharing contracts. All activities are tightly linked to support work in Associations.

At the National Technical University (Athens) plasma / electron beam interactions with electrostatic and/or electromagnetic waves and the connected issues of non-linear relativistic dynamics of charged particles and scattering of e-m waves from complex structures have been studied theoretically and numerically during 1997/98 in support of the gyrotron development at the Associations EURATOM - Conf. Suisse and FZK.

The Plasma Physics Laboratory of the Research Centre Demokritos (Inst. Nucl. Techn. and Rad.

Protect.) has developed a two-dimensionally fast sweeping Langmuir probe system for installation on ASDEX Upgrade. The system has been used during 1997/98 for the investigation of plasma dynamics in the divertor area and in support of scrape-off layer modelling. The intense collaboration with the Association EURATOM - IPP on the exploitation of this instrument and related topics is continuing

The Plasma Physics Group at the University of Ioannina is undertaking theoretical investigations of negative-energy perturbations and their impact on confinement and transport in support of the theoretical exploration of anomalous transport in toroidal confinement. This work is undertaken in collaboration with the Association EURATOM - IPP as is the case for the work at the Theoretical and Computational Physics Group of FORTH (Crete) on the modelling of vapour shield formation and effects on pellet ablation and plasma wall interaction.