1. INTRODUCTION

1.1. PREFACE

Fusion is a potential clean, safe, economically attractive and practically inexhaustive energy source. This nuclear process provides the energy to power the stars. Fusion occurs when two light atoms (hydrogen or its isotopes) collide with each other and fuse, forming a heavier atom and releasing neutrons and large amounts of energy. The typical fusion reactions are:

$$D + T \rightarrow He^4 + n + 17.6\ MeV$$
$$D + D \rightarrow He^3 + n + 3.27\ MeV$$
$$D + D \rightarrow T^3 + H + 4.03\ MeV$$
$$D + He^3 \rightarrow He^4 + H + 18.3\ MeV$$

Research and development programmes on nuclear fusion are being carried out in many places in the world, with particular importance in the European Union, United States of America, Japan and Russian Federation.

The European Fusion Programme is being performed in multi-annual research and training programmes, in agreement with Article 7 of the Treaty that has established the European Atomic Energy Community (EURATOM). This Programme integrates all the R&D activities in magnetic confinement fusion within all the Member States plus Switzerland and most of the countries which are candidates for membership of the European Union, aiming at the joint construction of prototype fusion reactors.

Portugal has participated in the European Fusion Programme since 1987. A Contract of Association between EURATOM and "Instituto Superior Técnico" (IST) was signed on January 1st 1990. "Junta Nacional de Investigação Científica e Tecnológico" was a member of the JET[1] Joint Undertaking. IST belonged to the NET Agreement until its end on 31 December 1998 and afterwards became a member of the European Fusion Development Agreement (EFDA) and the JET Implementing Agreement (JIA). IST has also signed the Agreement on the Promotion of Staff Mobility in the field of Controlled Thermonuclear Fusion.

The Portuguese participation in the European Fusion Programme has the following main objectives:

- Operation of a fusion plasma device at IST, for the development of a scientific programme on tokamak plasma physics, testing of new diagnostics as well as control and

[1] JET (Joint European Torus) is located in Culham (United Kingdom)

data acquisition techniques and education and training of engineers and physicists on plasma physics and engineering;

- Participation in the R&D programmes of other fusion experiments;
- Participation in the Fusion Technology Programme;
- Development of keep-in-touch activities on inertial fusion energy;
- Contribution to the improvement of the public understanding of nuclear fusion.

To fulfil these objectives the Association EURATOM/IST carried out in 2001 activities in the frame of the following projects:

- Tokamak ISTTOK;
- Participation in the collective use of the JET Facilities by the EFDA Associates;
- Participation in the ASDEX Upgrade[2] programme;
- Participation in the TJ-II[3] programme;
- Participation in the MAST[4] programme;
- Participation in the TCV[5] programme;
- Collaboration with the ITER[6] Project;
- Other studies on theory and modelling;
- Other activities in control, data acquisition and signal processing;
- Keep-in-touch activities on inertial fusion energy;
- Participation in the Fusion Technology Programme

which are briefly summarized in the next section and described in detail in chapters 2 to 12 of this document, where some technical notes concerning the main results obtained in these projects are also presented. Chapter 13 reports other fusion related activities and chapter 14 contains information about the scientific publications of the Association.

Table 1.1 presents information about the responsible person(s) for each project as well as the collaborating Institutions. Section 1.3 contains information about the human and budgetary resources of the Contract of Association EURATOM/IST.

1.2. SUMMARY OF THE ACTIVITIES

The *Tokamak ISTTOK* was in operation for about 35 weeks in 2001. Activities related with discharges production systems, diagnostics and tokamak plasma physics were carried out. Concerning

[2] ASDEX-Upgrade is a tokamak located in Garching (Germany).
[3] TJ-II is a stellarator located in Madrid (Spain).
[4] MAST is a tokamak located in Culham (United Kingdom).
[5] TCV is a tokamak located in Lausanne (Switzerland).
[6] ITER is the International Thermonuclear Experimental Reactor, of the configuration tokamak, which is proposed to be built in the frame of an International Agreement between EURATOM, Russian Federation, Japan and Canada.

Project	Responsible Person(s)	Collaborating Institutions	
		Portuguese	Other
Tokamak ISTTOK	José Cabral Carlos Varandas	CFN[7], UBI[8], GEI[9], CFA[10]	CIEMAT[11], IPP-Kharkov[12], UI[13], IFUR[14], IFUSP[15]
Participation in the collective use of the JET Facilities by the EFDA Associates	Fernando Serra	CFN, GEI, UBI	EFDA[16] CSU[17] Culham UKAEA[18]
Participation in the ASDEX Upgrade programme	Maria Emília Manso Fernando Serra	CFN	IPP-Garching[19]
Participation in the TJ-II programme	Carlos Varandas Maria Emília Manso	CFN, GEI	CIEMAT
Participation in the MAST programme	Carlos Varandas Maria Emília Manso	CFN	UKAEA
Participation in the TCV programme	Carlos Varandas	CFN	CRPP[20]
Collaboration with the ITER Project	Carlos Varandas Maria Emília Manso	CFN	EFDA CSU Garching
Other studies on theory and modelling	Fernando Serra J. Pedro Bizarro	CFN	IFP[21], PT[22], DFRC[23]
Other activities on control and data acquisition	Carlos Varandas	CFN, GEI	IFUSP
Keep-in-touch activities on inertial fusion energy	J.T. Mendonça	CFP[24]	
Participation in the Fusion Technology Programme	Carlos Varandas J.C. Soares	ITN[25], CFN, GEI	ENEA[26]

Table 1.1 – Responsible person(s) and Institutions involved in each project

the discharge production systems, and besides the normal maintenance, a new slow control system has been developed and a proposal for the testing of the liquid metal limiter concept was elaborated in collaboration with University of Latvia (Riga, Latvia). Regarding diagnostics the new injector of the heavy ion beam diagnostic was installed, a real-time MHD diagnostic has begun to be developed, several electronic units for the visible spectrometer, the triple emissive probe and the heavy ion beam diagnostic were designed, commissioned and tested and a movable electrode for limiter biasing was developed. Studies of the influence of

[7] CFN means "Centro de Fusão Nuclear"
[8] UBI means "Universidade da Beira Interior"
[9] GEI means "Grupo de Electrónica e Instrumentação da Faculdade de Ciências e Tecnologia da Universidade de Coimbra"
[10] CFA means "Centro de Física Atómica da Universidade de Lisboa"
[11] CIEMAT means "Centro de Investigaciones Energeticas Medioambientales y Tecnologicas"
[12] IPP- Kharkov means "Institute of Plasma Physics of the National Science Center" "Kharkov Institute of Physics & Technology".
[13] UI means "University of Innsbruck".
[14] IFUR means "Institute of Physics of the University of Riga"
[15] IFUSP means "Instituto de Física da Universidade de São Paulo"
[16] EFDA means "European Fusion Development Agreement"
[17] CSU means "Close Support Unit"
[18] UKAEA means "United Kingdon Atomic Energy Authority"
[19] IPP-Garching means "Max-Planck-Institut für PlasmaPhysik"
[20] CRPP means "Centre de Recherches en Physique des Plasmas de École Polytechnique Federal de Lausanne"
[21] IFP means "Istituto di Física del Plasma"
[22] PT means "Politécnico di Turim"
[23] DFRC means "Department de Recherches sur la Fusion Controlée".
[24] CFP means "Centro de Física dos Plasmas"
[25] ITN means "Instituto Tecnológico e Nuclear"
[26] ENEA means " Ente per le Nuove Tecnologie, l'Energie e l'Ambiente"

electrode and limiter biasing on the plasma confinement and stability, of the plasma potential fluctuations in the edge plasma and of the transport modelling and numerical reconstruction of the runaways process were made.

The Association EURATOM/IST participated in 2001 in *the collective use of the JET facilities by the Associates in the frame of the "European Fusion Development Agreement" (EFDA)* through the "JET Operation Contract" and the "JET Implementing Agreement". Activities concerning operation, scientific exploitation, performance enhancements and management were carried out. Two engineers were seconded to the JET Operation Team, working on the reflectometry and Motional Stark Effect diagnostics. Concerning the scientific exploitation, eleven Portuguese physicists participated in the JET campaigns as well as in the evaluation of the experimental data. Work was focused on transport, MHD activity, edge plasma physics and diagnostics. Regarding the JET Enhanced Performance Project (JET-EP), IST has been the leading Associate in two Projects and has participated in four Projects on microwave reflectometry, including in one the development of the dedicated control and data acquisition system. Concerning management, IST/CFN staff participated in meetings of the EFDA JET Sub-Committee and of Ad-Hoc Groups for the evaluation of the JET-EP Project, diagnostics and remote participation. One physicist was a member of the EFDA Culham Close Support Unit.

The *Portuguese participation in the ASDEX Upgrade programme* has been focused on microwave reflectometry and MHD and turbulence. IST/CFN was responsible for the routine operation and maintenance of both the fixed frequency channels and the ultra fast sweeping system as well as for the development of upgrades and new channels of the reflectometry diagnostic, upgrades of the dedicated control and data acquisition system, studies for diagnostic exploitation, new applications for ITER and studies on plasma physics. Concerning the upgrades and new channels of the reflectometry diagnostics the following main activities were performed: development of in-phase and quadrature heterodyne detection for the V-band fixed frequency channel, development of a numerical code to calculate the calibrated amplitude and phase signals, improvements in the heterodyne detections of the V and W channels, development of switches to commute the diagnostic operation mode, installation of a new harmonic mixer and active frequency duplicator in the Q channel and assessment of possible locations for the W-band antenna (X mode) at the lower field side. Upgrades of the dedicated control and data acquisition system included the increase of the memory of the 250 MHz VME transient recorder modules, integration of a new timing/acquisition clock generation board, modification of the device drivers for the upgrade graphical user interface, development of hardware and software to split the reflectometry system into two separate

diagnostics, implementation of software to control the new fixed frequency V-band heterodyne channel and development of a Web supported database. The studies for diagnostic exploitation included the comparison of two data processing tools developed for automatic profile evaluation, development of software tools to generate automatically level 2 shot files in the ASDEX Upgrade shot-file system, development of novel algorithms for classifying the density profiles with a parameter that weights the degree of distortion due to the plasma turbulence, development of software tools to detect automatically the edge pedestal parameters with high spatial and temporal resolutions, absolute calibration of density profiles using both O and X mode reflectometry and development of algorithms to extract information about plasma fluctuations from broadband signals. The new applications relevant for ITER are described in another paragraph. The plasma physics studies were focused on profiles and fluctuations studies in advanced scenarios, density profile evolution in improved core confinement with H-mode edge, turbulence reduction during ITB with L-mode type edge and HFS/LFS measurements of a quasi-coherent mode at the edge. The activities on MHD and turbulence were focused on studies of disruptive events and turbulence studies in the edge/Sol region.

The *participation of the Association EURATOM/IST in the TJ-II programme* has been focused on microwave reflectometry, heavy ion beam diagnostic, laser induced fluorescence system and edge plasma physics. The following main activities were performed on microwave reflectometry: development and installation of switches enabling consecutive fast broadband sweeping of the two microwave bands, operation of the AM section allowing the determination of the first density profiles and tests without plasma of the FM section. Concerning the heavy ion beam diagnostic the following main tasks were made: improvements on the software of the dedicated control and data acquisition system, design and construction of new transimpedance amplifiers aiming at matching the diagnostic operation requirements, installation on the diagnostic of the first multiple cell array detector (MCAD), development and installation on the diagnostic of a new MCAD based on deep Faraday cups and beginning of the development of a third MCAD based on improved concept cells. The work in the laser induced fluorescence system included the maintenance of the dye laser and alignment of the beam steering optics, alignment of the detection optics and set-up of the observation system, analysis of a RF noise picked-up by the detection electronics and attempt to achieve its suppression and estimations of Rayleigh scattering for LIF diagnostic calibration in the TJ-II experiment. Regarding edge plasma physics, studies were carried out on the dynamical interplay between gradients and transport in TJ-II magnetic well experiments.

The *Portuguese participation in the MAST programme* has been focused on microwave reflectometry and control and data acquisition. Reflectometry activities included the: installation of the waveguide and antenna on the MAST port, test in vacuum and calibration of the reflectometry system as well as adjustment of the reference pin, first evaluation of the diagnostic performance, design and construction of the detection amplifiers, construction of the drivers for fast sweeping of the HTO oscillators, calibration of the HTO oscillators and installation of the rack with the electronics and the microwave equipment on the cubicle, final test of the system and first measurements with plasma. Concerning control and data acquisition the CAMAC version of the fast timing and event management system was finalized and IST/CFN staff collaborated on the integration of the system in the MAST control and data acquisition system.

The *participation of the Association EURATOM/IST in the TCV programme* has been focused on the development of three X-ray diagnostics: an horizontal pulse height analysis (PHA) spectrometer, a vertical PHA spectrometer and a rotating crystal spectroscopic diagnostic. The following main activities were carried out in 2001: improvements on the operation of the horizontal PHA spectrometer, design of the vertical PHA spectrometer as well as ordering of the detector and a CAMAC module for signal conditioning and data acquisition, finalization of the design of the X-ray rotating crystal spectroscopic diagnostic, continuation of the tests of the hardware lent by the Princeton Plasma Physics Laboratory, purchase of a high-voltage power supply and a step motor and design of some new electronic units.

The *Portuguese collaboration with the ITER Project* included studies on microwave reflectometry, participation in the Joint Central Team (JCT) and International Team (one physicist work all the year in Garching on diagnostic integration) and participation in the ITER Explorations and Negotiations as well as in meetings of the Diagnostic Expert Group. The following main activities were performed in the area of reflectometry: participation in a Design Task to re-evaluate the conceptual design of reflectometry for ITER presented on the Final Design Report and to assist the JCT in the updating of documentation and cost of the system, development of two new ITER-relevant applications related with the localization of resonance surfaces and measurements of $B_t(r)$ from simultaneous ordinary and extraordinary probing at the low B-field side and demonstration of these two new applications on ASDEX-Upgrade.

The Project "*Other theory and modelling studies"* included work on transport and MHD, non-inductive current drive and modeling of microwave reflectometry measurements. The transport and MHD activities were focused on triggering of neo-classical tearing modes by

mode coupling, sawtooth and impurity accumulation control in JET radiative mantle discharges, sawtooth precursors at the onset of neoclassical tearing modes, numerical simulations of sawtooth stabilization by ICRH driven fast particles for different JET scenarios, influence of the position of the ICRH resonant layer over the internal kink mode stability, nonlinear dynamics of magnetic islands and physics of disruptions. Concerning non-inductive current drive the following main activities were carried out: continuation of the writing of a fully 3-D (toroidal plus ripple effects) ray-tracing code, application of beam-tracing techniques for lower hybrid wave propagation in tokamak plasmas and improvement of kinetic codes, with interesting developments obtained with path-sum codes. Finally, the following main tasks were performed regarding the modeling of reflectometry experiments: development of 2D wave propagation models to characterize the wave scattering at micro and macro turbulence, development of a 2D code for broadband reflectometry which replicates the main characteristics of the ASDEX-Upgrade diagnostic, simulations of profile changes occurring during type I ELMs and when a rotating magnetic island is present and identification of mode signatures on the broadband reflectometry signals.

The Project *"Other activities on control, data acquisition and signal processing"* had four research lines: low-cost fully integrated real-time control and data acquisition system, a DSP-based real-time control system, PCI instrumentation for control and data acquisition and signal processing techniques. The development of the low-cost fully-integrated real-time control and data acquisition system included the beginning of the conceptual study, analysis of new emerging buses for digital instrumentation and analysis of commercially available DSP and FPGA based systems. The development of a DSP-based real-time control system included the finalization of the assembly and test of the hardware of the VME version of this system and the development of the operation software. The development of PCI instrumentation for control and data acquisition included the purchase of development tools for PCI and Compact PCI, the study of the PCI rules and of the requirements of dynamic memory and the beginning of the design of a PCI transient recorder module with 8 channels, 12 bit resolution, 3 MSPS maximum sampling rate and 64 Mbytes memory per channel. Regarding the signal processing techniques the variational approach was applied to the extraction of quadrature from broadband reflectometry signals.

The Project *"Keep-in-touch-activities on inertial fusion energy"* included activities related with the laser system, target area, experiments, technology and theory simulation. Concerning the laser system the following main activities were carried out: high-dynamic characterization of the pulse energy distribution in time, acquisition of a new ultra-short pulse main oscillator, design of a new broadband grating pulse stretcher, design and assembly of a

vacuum spatial filter and optimization of the overall shot-to-shot energy stability of the entire system. Regarding the target area two new and important diagnostics were added in 2001: a single-short second-order auto-correlator and a scanning third-order auto-correlator. First experiments were made on laser channeling inside pre-formed plasmas, which required the development of a shielded high voltage power supply, a capacitor bank and a discharge vacuum chamber. Concerning theory & simulation an infrastructure for intensive numerical particle-in-cell simulation was installed. Propagation of intense electron beams with current in excess of the Alfvén current generated from the interaction of intense laser pulses with solid targets was examined in detail.

The *participation of the Association EURATOM/IST in the Fusion Technology Programme* included underlying technology activities on fusion material characterization and surface ion beam modifications and R&D activities carried out in the frame of four Technology Tasks concerning the design, construction and test of the VME monitoring system of the ITER-FEAT in-vessel vision system, the development of Be pebble beds, the characterization of SiC/SiC composites and the development of ceramic breeders.

Finally, and among the *other fusion related activities,* the collaboration with the Portuguese Universities in post-graduation programmes, the participation in science divulgation events and the organization of the "28th EPS Conference on Controlled Fusion and Plasma Physics" must be underlined. This conference, held in Funchal, was attended by about 620 participants from more than 30 countries.

1.3. HUMAN AND FINANCIAL RESOURCES

Table 1.2 and 1.3 contain information about the human and financial resources of the Association EURATOM/IST.

Area		Type of Activity	Type of Staff	Professionals			Non Professionals	Total
				Ph.D	Master	Graduation		
Physics	Magnetic Confinement	Research	Physicists	17.7	12.0	4.0	0	33.7
			Engineers	1.85	4.0	10.0	0	15.85
		Support	Administration	0	0	1.0	1.0	2.0
			Technicians	0	0	0	3.0	3.0
			Secretaries	0	0	0	4.0	4.0
	Inertial Fusion Energy	Research	Physicists	5.0	0	6.7	0	11.7
			Engineers	0	0	0	0	0
		Support	Administration	0	0	0	0	0
			Technicians	0	0	0	0	0
			Secretaries	0	0	0	0.3	0.3
Technology		Research	Physicists	3.05	0	0	0	3.05
			Engineers	0	0	0	0	0
		Support		0	0	0	0	0
Total				27.6	16.0	21.7	8.0	73.6

Table 1.2 – Personnel of the Association EURATOM/IST in person year

Category	Expenditure	
	Escudos	Euros
General Support		
Physics		
Magnetic Confinement	717.670.985	3.579.727,78
Inertial Fusion Energy	105.253.050	525.000,00
Underlying Technology	6.392.262	31.884,47
JET Notifications	18.397.052	91.764,11
European Fusion Development Agreement		
Technology Tasks	85.263.138	425.290,74
Article 5 Contracts	27.721.337	138.273,45
Article 6 Contracts	41.379.399	206.399,57
Article 9 secondments	11.621.750	57.969,04
Mobility	65.924.325	328.829,15
Total	1.079.623.298	5.385.138,31

Table 1.3 – Expenditure (in Escudos[27]) in 2001 of the Association EURATOM/IST

[27] 1 Euro=200.482 Escudos (the portuguese currency until December 31st 2001.