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Para Fusión
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INTRODUCTION

The present document reports on the Association activities during 2009 following the outline of the approved 2009 Work Programme.

• Chapter I describes the contributions from the Association to the enhancement of the physics basis for ITER.

As regards experimental activity, our participation in the 2009 JET campaigns has been instrumental in relevant MHD, confinement, transport and control studies, ELM dynamics (ECE, fast visible imaging) and ELM mitigation techniques, high temperature pedestal scenarios, hot-ion H mode and ICRH wall conditioning (also in Tore Supra).

TI-II has also contributed in this field with momentum transport and shear flow physics studies that provide critical test conditions for the L-H transition models. Plasma wall experiments (edge transport, detritiation methods) have been performed in TI-II, other stellarators (LHD), tokamaks (Tore Supra) and linear devices (PILOT-PSI). It is worth mentioning also the joint ITPA X2 breakdown experiments performed in TI-II.

As regards modelling, the development of the EFIT code (equilibrium reconstruction) for JET has continued and substantial work has been produced at CIEMAT in two areas: development of 3D geometry routines for the EIRENE code (applied also to TEXTOR tokamak) and studies for the ITER NBI system in the EFDA tasks of current drive and rotation characterization (FAFNER2 code) and simulation of an electrostatic residual ion dump.

• Chapter II is devoted to the development of auxiliary systems: heating & CD, plasma fuelling, diagnostics, plasma control and pattern recognition methods.

As regards new developments in heating and current drive systems, the Association’s activity has been focused in the first real tests of Electron Bernstein Wave heating, not successful so far.

Plasma fuelling (H and He) and recycling studies in TI-II, after lithium coating of the vacuum vessel have been also addressed in 2009.

As for diagnostics development, the larger effort in new developments has been focused on TI-II. New diagnostics have been successfully installed and commissioned (Doppler reflectometer, second fast camera, diagnostic neutral beam injector, 2D-imaging for electron temperature and density measurement) or are being designed and further developed (second HIBP, pellet injector, soft X-ray based electron temperature diagnostic, edge ion temperature passive diagnostic). Upgrades have been also implemented in existing TI-II diagnostics (new fast power supply for dynamic plasma biasing, infrared interferometer...
extended to a multi-channel expanded beam system, new power supply for the high resolution Thomson Scattering system).

Nevertheless, an intense effort has been also devoted to collaborative diagnostic development for the main European and international projects: JET (fast imaging for plasma wall interaction, ELMs and disruption studies), W7X (two-colour interferometer) and ITER. The latter activity, still mainly in the engineering phase has been concentrated in the following diagnostics: plasma position reflectometer, equatorial visible/infrared wide angle viewing system, Lidar Thomson Scattering and magnetic sensors.

Simulation studies have been done in the framework of EU 3D full-wave reflectometer simulation code for ITER edge modelling (European Reflectometer Code Consortium) under the auspices of the EFDA Integrated Tokamak Modelling task force.

Aiming at efficient ITER-class data treatment procedures, significant resources have been also invested in developing data handling techniques for JET, based on the remote experimentation concept oriented to long pulse shots and data mining tools for very large data series and video movies.

Real time measurement and plasma control is another vital subject in which the Association has put effort and resources, namely in the areas of pattern recognition techniques, full inductive plasma control (Ip, li) and a real time simulator specifically developed for studying disruption in JET.

• **Chapter III** covers an important section for our Association: stellarator physics, including experimental as well as plasma theory and modelling activities. Here we report on the TJ-II status as regards engineering and operation, and summarize the TJ-II operation highlights (lithium coating, heating systems). The collaborative activities under the auspices of the IEA Stellarator-Heliotron implementing agreement are also described.

A number of TJ-II experimental physics results on: electric fields, magnetic topology, density limit, fast particles and momentum and impurity transport are reported.

Theory and modelling activities in TJ-II constitute a major part of the results included in this chapter. They include heating and current drive and wave-particle interaction studies (Electron Bernstein emission and current drive) and divertor physics. More general modelling studies include statistical description of transport, turbulence studies (fractional diffusion equations, EUTERPE 3-D global gyrokinetic code), ITER modelling using the ISDEP particle code and Grid computing applied to extremely heavy calculations.

A pioneering modelling activity has been the stellarator concept development using a combinatorial optimization process (metaheuristics) in a distributed computing environment.
• **Chapters IV** describes the Association's activities in development of material science (characterization of functional and structural materials, including modelling), advanced materials for DEMO (tungsten and SiC) and engineering and design work on remote handling (definition of a test facility for diagnostic port plugs and conceptual design of a EU TBM demonstration facility).

As regards functional materials, intense research activity has been conducted in three types of materials: silica glasses (used in windows and optical components), different candidate insulator materials for ITER and Li-based materials (Li silicate spheres). For the first two types of materials, irradiation and thermal treatments have been performed. As for the silicate spheres, efforts have focused on production and characterization (X-ray diffraction).

A conceptual design of a LiPb loop for breeder blanket studies has been also been started.

The work on structural materials has focused on the microstructure optimisation of ODs steels.

Regarding advanced DEMO-relevant materials, tungsten and tungsten alloys (W-V and W-Ti) have been developed and the electrical properties of SiC materials have been measured.

Radiation effects modelling and experimental validation constitute a major research area of the Association. The main topics studied have been He and defects accumulation and validation experiments on He desorption in Fe and resistivity measurements.

• **Chapters V** covers training and educational activities, outreach actions and socioeconomic studies.

The training actions (under EFDA) are materialised in two programs, with one person each: Microwave diagnostic engineering for ITER (CIEMAT and short stay at IPP-Greifswald) and Tritium transport modelling for breeding blankets (CIEMAT).

Two important outreach actions promoted by the Association have taken place in 2009: preparatory activities for the creation of a Plasma Physics Group within the Royal Spanish Physical Society and reinforcement of the volunteer computing desktop grid called Ibercivis, which is helping to disseminate Fusion interest nation-wide.

Regarding socioeconomic studies, research has been done in two main areas: external cost evaluation of the energy sources using the EFDA-TIMES model and the issue of social perception of the risks associated with Fusion energy.

• **Chapter VI** describes the work on Inertial Fusion keep in touch activities.
• Chapter VII covers other activities to which the Association is also devoting very substantial resources, like the research and development related to TechnoFusión, and to the Broader Approach (IFMIF/EVEDA, JT-60 SA cryostat and DEMO R&D). It also describes the yearly operation of our Fusion Technology facilities (van de Graaf accelerator, Nayade irradiation facility)
I. PROVISION OF SUPPORT TO THE ADVANCEMENT OF THE ITER PHYSICS BASIS

I.1 Development of candidate operating scenarios

I.1.1 Comparison of ELM mitigation techniques (EFCC, vertical kicks and pellets)

In JET several techniques have successfully demonstrated their capability for ELM amelioration (reduction of ELM losses and increase of ELM frequency), including resonant perturbations of the edge magnetic field by using the error field correction coils (EFCCs) and ELM magnetic triggering by fast vertical movements of the plasma column (‘vertical kicks’). A series of dedicated experiments was carried out in JET focused on integrating kicks and EFCCs into similar plasma scenario and scans. The impact of each control method on the plasma confinement and the effect of the reduction in ELM size on the divertor heat loads have been studied. In addition, the potential of using EFCCs for ELM mitigation in He4 plasmas has also been explored in JET. In He4 plasmas the effect on ELMs caused by the EFCCs is weaker and no density pump-out is observed. A summary of these results was presented as an invited talk in the 51st American Physical Society Conference (Georgia, Atlanta) [APS09_delaLuna].

The plasma response to the application of these two ELM control method shares common features: the reduction in ELM size is accompanied by a reduction in pedestal pressure (mainly due to a loss in density), resulting in a 10% reduction of the thermal stored energy. A key ingredient in the ELM mitigation experiments in JET is the diagnosis of the ELM-resolved heat load profiles on the outer divertor target by a fast high resolution infrared camera. In general it was found that the averaged ELM peak-power decreases almost linearly with the ELM size but a smaller reduction is observed on the peak heat flux (40% for EFCCs when the reduction in peak power is ~50%). This difference is related to a reduction in the width of the ELM heat flux profile. This observation is common to any small ELM regime, independently of the method employed to reduce the ELMs size (gas fuelling, kicks or EFCCs and also enhanced toroidal ripple). Interestingly, all observations described above have been obtained in H-mode plasmas where the reduction in ELM losses is accompanied by some pedestal density loss. In contrast, a stronger reduction in the peak heat flux is observed in gas fuelled plasmas, where the reduction in ELM losses is correlated with an increase in collisionality. A detailed analysis of the divertor heat loads (time scales, target profiles and energy arriving to the target) for both mitigated and spontaneous ELMs will continue during 2010. This analysis will allows us to better understand the implications of these new data for ITER.
1.1.2 High temperature pedestal studies:

Specific experiments were made at JET, led by ER Solano, to study high temperature pedestals, in the range $T_{e,\text{ped}} \sim 2.5-5$ keV. The idea was to see if the ELMs are qualitatively different when resistivity and collisionality are low. Experiments were carried out at low density, in the so-called hot-ion H-mode, where pedestal electron and ion temperatures observed are similar to those expected in ITER, therefore the study is also highly relevant for ITER. With very little experimental time, only $T_{e,\text{ped}} \sim 3$ keV was reached transiently with $I_p=2.5$ MA and 17 MW of NBI (as high as any in recent high current experiments at JET). On the other hand, a surprising result of the experiment was a new insight on pedestal stability: with low gas fuelling and low recycling conditions (required to achieve high temperature pedestals) an outer mode often appears, delaying ELMs. The outer mode had been assumed previously to be an ideal kink, unstable in the steep gradient region of the pedestal, which would eventually grow into an ELM. We have now found that the outer mode is in fact a fairly stable field-aligned current ribbon, lasting as much as 1.5 s, located at the top of the pedestal. There are tantalising similarities with the EHO observed in DIII-D. This could provide a new route to ELM-free operation.

The work was presented at the pedestal ITPA 2009 [ITPA_Solano], it was chosen as a post-deadline oral at EPS 2009 [EPS_Solano], was presented at the EFTSOMP 2009 workshop [nf_solano_2009] and published in Physical Review Letters [PRL_Solano].

1.1.3 Observation of a current ribbon in JET and ELM pacing:

Beyond the work with EFIT, An interesting H-mode related work was done on observation of a confined current ribbon in the hot-ion H-mode of JET. The motivation of her recent measurements was to study strongly heated discharges with a low gas puff rate where the edge collisionality is low. This reduces resistivity and the higher edge current is expected to stabilize the ballooning modes. The difference in ELM behaviour might give information on ELM physics. In the JET hot-ion H-mode high pedestal electron and ion temperatures are observed as expected for ITER, therefore the study is also highly relevant for ITER. After the H-mode transition and before the first ELMs the confinement of these discharges is transiently very good ($H_{98} \sim 1.4$). It is observed that a perturbation called an outer mode (OM) appears, delaying ELMs. This stops the rise in the pedestal temperature and causes a reduction in confinement to $H_{98} \sim 1$. [nf_solano_2009]

1.1.4 Inboard and outboard Type I ELM dynamics in JET measured by ECE

Fast electron cyclotron emission (ECE) radiometry allows a space resolved study of the dynamic behaviour of the ELMs. During the reporting time, we have extended previous studies of the ELM dynamics carried out in JET by including simultaneous ECE measurements in the outboard (low-field side or LFS) and the inboard (high-field side or HFS) midplane.
This is possible in JET because the existing ECE heterodyne radiometer can be set up to measure simultaneously 1st harmonic/O-mode and 2nd harmonic/X-mode radiation. Access to the plasma HFS is obtained by using O-mode polarization, which is not affected by harmonic overlap, while the X-mode polarization is used to measure the LFS temperature profile ($T_e$). This allows comparing, for the first time, the $T_e$ crash caused by type I ELMs in both the inboard and outboard midplanes in JET at different plasma scenario. Type-I ELM precursor modes in both poloidal regions are also shown together with the MHD activity linked to the outer-mode observed in two ECE channels located in the LFS and the HFS pedestal midplane. [Barrera]

I.1.5 Equilibrium reconstruction studies for tokamaks

The development of EFIT code has continued, to facilitate detailed equilibrium reconstruction. This code is a basic tool for JET scientific exploitation since it provides the actual equilibrium of JET plasmas.

Beyond this work, a new model of the iron core was developed for EFIT and is presently being tested. In this way, a better description of the magnetic equilibrium at JET is provided. The simulation of the iron core is basic to better interpret the magnetic measurements at JET and, hence, to get a better reconstruction of the equilibrium.

I.2 Energy and particle confinement / transport

I.2.1 Momentum transport and shear flow physics

I.2.1.1 Multi-scale physics mechanisms during plasma transitions

Multi-scale physics (i.e. coexistence of short and long-range spatial scales) can be considered a new fingerprint of plasma behaviour during edge transport bifurcations. Multi-scale measurements were made possible in TJ-II by the use of a unique detection system: two Langmuir probe arrays located at two different toroidal locations, approximately 180º apart. This set-up permitted the simultaneous investigation of short-range and long-range fluctuation scales (a few millimetres and about ten meters, respectively) in the plasma boundary region.

Long-range correlations measurements in ECRH plasmas

In the TJ-II stellarator sheared flows can be easily driven and damped at the plasma edge by changing the plasma density or the density gradient. Above a threshold density value the perpendicular phase velocity reverses sign at the plasma edge from positive to negative values due to the development of the natural shear layer.
The long-distance correlation between potential signals increases in the proximity of the threshold density value for sheared flows development, mainly due to the rise in the correlation at low frequencies (below 20 kHz). Simultaneously there is a decrease in the local (measured in one of the probes systems) density-potential correlation, directly related to the local radial particle flux, is observed.

**Long-range correlations during biasing induced transitions**

Edge sheared flows development can be also induced in TJ-II using an electrode that externally imposes a radial electric field at the plasma edge. We used dynamic edge biasing that produces modulation in the edge electric field providing a new strategy for studying edge momentum transport and transition physics. Previous experiments have shown that long-range correlations are present during the development of the edge shear flows and how these correlations are amplified by externally imposed radial electric fields. Strongly long-range correlated transient events have been observed during the transitions to improved confinement regimes in the dynamical biasing experiments. These results can be interpreted as an indication of long-range correlated structures arising as sheared flows are developed [Pedrosa2010].

**Long-range correlations during confinement transition in NBI plasmas**

Measurements of the long-range cross-correlation between potential fluctuations signals toroidally apart have been obtained at the plasma edge \((r/a\approx0.9)\) as plasma changes from ECRH to NBI phase. Near the plasma conditions where the transport bifurcation occurs, the correlation rises.

The local \(S(k, f)\) spectrum of the potential fluctuations, computed in the improved confinement regime, shows that the dispersion relation is dominated by frequencies below 300 kHz and a local phase velocity of about \((1 - 5) \times 10^3\) m/s can be deduced, in agreement with the expected \(E \times B\) drift velocity. The short-range wave number is close to zero at the lowest frequencies \((f < 40\) kHz\), where long-range correlations are observed. The long-range \(S(k, f)\) spectrum, computed during the improved confinement phase is dominated by frequencies below 40 kHz; the long-range \(S(k, f)\) spectrum indicates propagation. Cross-correlation functions of floating potential signals show small time delays that depend on the relative radial probe positions; this finding suggest a radial propagation of structures with a significant toroidal extent.

The dynamic interplay between the different frequency ranges of the potential spectra shows that the integrated power in the low (below 25 kHz) and high (above 60 kHz) frequency ranges are approximately anti-correlated; thus, as the low frequency fluctuations power increases, the power in the high frequency range decreases. This result is consistent with the idea of an inverted energy transfer between broadband turbulence and low frequencies (i.e. between different plasma scales), providing a mechanism for the development of long-range correlations.
The discovery of the amplification of multi-scale physics mechanisms and the dominant role of long-range correlations when approaching plasma conditions in which the edge transport bifurcation develops spontaneously in the TJ-II stellarator, provide a critical test for L-H transition models [Hidalgo2009].

I.2.1.2 Momentum re-distributions (parallel, perpendicular and radial dynamics) during transport bifurcations in the TJ-II stellarator

The effect of externally applied electric field on the turbulence anisotropy was studied with electric probes. The radial-parallel velocities' cross-correlation coefficient reveals an increased anisotropy in the presence of a strong radial electric field. The observed increase in the correlation of velocity fluctuations is high enough to sustain absolute values of Reynolds stress in the reduced turbulence level conditions associated with the improved confinement regimes induced by external biasing. While the expected increase in the Pfirsch-Schlüter parallel flow caused by the bias-induced increase in the E-cross-B velocity roughly agrees with the observed changes in the parallel rotation profile, the observed pre-bias parallel Mach number profile does not lend itself to a simple interpretation in terms of equilibrium first-order neoclassical flows [RSwB]. Similar investigation in the poloidal direction are in progress in TJ-II.

I.2.2 L-H transition physics

Tokamaks and stellarators develop edge plasma bifurcations with similar properties. In the TJ-II stellarator, spontaneous L-H transitions are achieved under NBI heating conditions when operating with lithium coated walls. H-mode transitions reproduce common features found in other devices: i.e. an increase in plasma density and plasma energy content, a reduction in Hα signal, the development of steep density gradients, an increase in the radial electric field and radial electric field shear, and a significant reduction in the density fluctuations level. Besides the observation of a significant radial electric field, the main result obtained using Doppler reflectometry is the observation of remarkable fluctuating radial electric fields during the development of edge bifurcations. The dynamics of the radial electric field and density fluctuations reveal an increase in the fluctuations of the radial electric field and radial electric field shear within the frequency range 1-10 kHz. Both, the increase in the low frequency oscillating radial electric field and the reduction in the broadband density fluctuations happen simultaneously at the transition and are detected a few milliseconds before the radial electric field shear development. Those observations may be interpreted in terms of turbulence suppression by oscillating sheared flows (zonal flows). These results have motivated an invited talk in the 36th EPS Conference on Plasma Physics [EP509_Estrada_talk] and the publication [PPCF09_Estrada].

A collaboration with the Max-Planck-Institut für Plasmaphysik, Garching (Germany) was started with the objective of comparison of wavenumber spectra of density fluctuations...
measured using Doppler reflectometry in ASDEX Upgrade and in TJ-II. First results show that, at the L-H transition, the main turbulence reduction in TJ-II takes place at the radial position of maximum radial electric field shear. Spectral indices in TJ-II change from about -3 in L-mode to -6 in H-mode. The H-mode value is comparable to the ASDEX Upgrade measurement. In both machines, a knee in the spectra can be identified at structure scales of about 1 cm. The results will be published in 2010.

**Zonal flows and long-distance correlations during the formation of the edge shear layer in the TJ-II stellarator.**

Recent experimental results in TJ-II plasmas have shown the existence of long-range potential correlations in the toroidal direction during the development of the edge shear layer. This long range correlation appears when the plasma confinement is enhanced spontaneously or by inducing a radial biasing. We have given a theoretical interpretation in the framework of the paradigm of shear generation by Reynolds stress and turbulence suppression by shearing. Within this interpretation poloidally asymmetric zonal flows are essential to reproduce the experimental observations

[Calvo_TorCorr_PPCF2009].

I.3 MHD stability and plasma control

I.3.1 ELM Physics

Comparison of Te profiles, ELM dynamics and MHD activity in low / high field plasma sides using ECE diagnostics:

Fast electron cyclotron emission (ECE) radiometry allows a space resolved study of the dynamic behaviour of the ELMs. During 2009, we extend previous studies of the ELM dynamics carried out in JET by including simultaneous ECE measurements in the outboard (low-field side or LFS) and the inboard (high-field side or HFS) midplane. This is possible in JET because the existing ECE heterodyne radiometer can be set up to measure simultaneously 1st harmonic/O-mode and 2nd harmonic/X-mode radiation. Access to the plasma HFS is obtained by using O-mode polarization, which is not affected by harmonic overlap, while the X-mode polarization is used to measure the LFS temperature profile (Te). This allows comparing, for the first time, the Te crash caused by type I ELMs in both the inboard and outboard midplanes in JET at different plasma scenario. Type-I ELM precursor modes in both poloidal regions are also shown together with the MHD activity linked to the outer-mode observed in two ECE channels located in the LFS and the HFS pedestal midplane [EPS09_Barrera].

I.3.2 Fast visible imaging of ELM Wall interactions on JET
The experience of CIEMAT-TJII team in fast imaging allows us to coordinate a project, in JET, for the installation of a fast camera in collaboration with HAS, IST and CODAS. The generation of ELM instabilities in the low field side and proximity of the X-point has been investigated. The FC7 project provides information of plasma wall interaction, ELM’s and disruption physics. Fast visible camera installed at JET has monitored pellet ablation experiments during type-I ELM. The filter wheel and interference filters make possible to image the deuterium emission, the carbon and the beryllium emission coming from the divertor and the first wall and the helium emission. One of the conclusions was that to speed up the images (>10,000 kfps) with an impurity filter we need to increase the SNR. Now, the final report and operation manual is in hands of the operator to finish the hand-over. At the later part of the C27 campaign (ending October 23rd, 2009) a CIEMAT image intensifier was installed in fast camera system. The installation and operation of the system was successful and the intensifier showed a robust behaviour against magnetic fields and neutrons. The results were very promising and push us to propose a new project that includes the image intensifier. Now we are proposing to JET this second step of FC7 project with an exhaustive test of the image intensifier, for different impurity sources that requires increases in the signal level.

I.4 Power and particle exhaust, plasma-wall interaction

I.4.1 Edge transport and particle and impurity sources

LHD boundary region transport studies The analysis of joint LHD-CIEMAT fast camera experiments back in 2008 has continued. A detailed description of filament ejection events during high beta discharges has been provided [LHDcam1], [LHDcam2]. Relation with peripheral MHD activity characteristic to this regime has been determined by comparison with magnetic probe data. Parallel and velocities of the structures propagating through the SOL has been calculated and compared. Finally, statistical analysis of the ejection pattern has revealed long term persistence.

A second joint experimental campaign has been conducted in LHD during November-December 2009. Its main objectives were the systematic search of filament ejection parametric dependences (mostly on beta) in the previously studied high beta regime and the evaluation of future fast camera observation of TESPEL experiments.

I.4.2 Studies of de-tritiation methods for ITER

Very intense activity has been developed in the field of tritium removal and control by chemical techniques for ITER. Scavenger experiments in PILOT-PSI (FOM) and in a RF reactor in Liubliana were undertaken. It was found that injection of ammonia in the afterglow region of a divertor provides a simple, non-perturbative technique for the inhibition of carbon co-
deposit formation in hidden areas [Scav_1]. Moreover, the mechanism responsible for the inhibition was identified [Scav_2], [Scav_3]. Ammonia plasmas, which were found to remove carbon films very efficiently, were unable to clean deposits in gaps, thus suggesting the need of ion impact for the removal effect [Scav_2]. Finally, NO2 at high pressure (50 mbar) was able to fully oxidize carbon co-deposits in narrow gaps at temperatures fully compatible with the design of ITER Divertor (540 K), with very much improved performance respect to Oxygen thermo-oxidation.

I.4.3 Experimental validation of carbon transport models

Molecular beams of methane, deuterated methane, hydrogen and deuterium were injected in TJ-II under well-characterized plasma conditions. The spatial distribution of the cracking fragments (CH and H) was followed for the different plasma edge parameters produced in the experiments. Analysis of the data to extract information about the cracking rates by electron impact and kinetic energy of the fragments is underway.

I.4.4 Eirene developments

Eirene 3D geometry options have been included in the current version of EIRENE. For this, a set of routines developed at CIEMAT, which worked for an old version of EIRENE (prior to 2005) have been implemented in the general trunk of EIRENE code. The system for describing the geometry is based on a system of Tri Linear Hexaedron, called TriLinHex. These routines have been included in the new version of EIRENE, some as user-supplied routines and some as external programs. In its present version, the code EIRENE can use several geometry modules that can work in different magnetic configuration geometries.

Additional applications developed at CIEMAT which perform different actions over the input / output of EIRENE were also included.

Also the routines that create magnetic inputs for EIRENE TriLinHex for an arbitrary device (not only TJ-II) have been studied and applied to TEXTOR.

I.4.5 ICRH wall conditioning (ICWC) studies in JET and Tore Supra

ICRF wall conditioning (ICWC) was recently confirmed as a functional requirement on the ITER ICRF heating and current drive system and thanks to encouraging results will be most probably applied routinely to ITER. Most important results in 2009:

i) Confirmation of ICWC for wall isotope exchange and thus as a tritium recovery technique. In Tore Supra 15 minutes of deuterium ICWC changed the hydrogen isotope ratio H / (H+ D) from 5% to 50%.
ii) In Tore Supra wall recovery after disruptions was studied and He pulsed ICWC was identified as very promising: 5 minutes ICWC was sufficient to recover ohmic plasma start-up.

iii) In JET ICWC scenarios for ITER were simulated, using IC resonance positions for the same M/Z ions at the same normalized radius.

1.5 Physics of plasma heating and current drive

1.5.1 Electron Bernstein Waves heating calculations with Astra using the ray tracing code TRUBA on distributed GRID computing resources.

Dynamic simulations of the EBW power deposition profile in TJ-II NBI plasmas have been performed using the Astra system and the TRUBA ray tracing code [015]. TRUBA has been included as an external Astra module that calculates the properties of plasma heating by O-X-B means for a given density and temperature profiles, which in turn are obtained from Astra.

Due to the specific properties of the electron Bernstein waves, a large number of rays are needed to reproduce the behaviour of the propagating electrostatic field inside the plasma. To obtain an accurate description of the plasma evolution during an EBW+NBI heated discharge, a large number of TRUBA runs, each of them with a large number of rays, must be considered. The final calculation (50 milliseconds of plasma evolution with 193 rays each millisecond) were performed using GRID computing techniques in order to shorten the computing time. Radiation losses were also considered in the simulation [Cappa].

1.5.2 Characterization of (off-axis) current drive and rotation capability of NBI

Upgrade of the FAFNER2 Monte Carlo code.

The FAFNER2 code is a numerical tool designed to simulate the injection of fast neutral particles into magnetically confined plasmas of fusion devices, and their further effects. The essential part of the code is devoted to description of both the energy and the momentum transfer from the captured fast ionized particles to the background plasma. The fast ion slowing-down model realized in the existent version of FAFNER2 has a serious shortcoming of an assumption of isotropic plasma species distribution in velocity space. As a result, such effects as strong plasma currents and plasma rotation, which are usually driven by NBI, cannot be adequately simulated. The undertaken upgrade of FAFNER2 is intended for bringing this ability. In this way, the following model of axially symmetric velocity distribution for the background plasma was introduced. The distributions of particular species are represented by the Legendre polynomial expansions, thus uncoupling the pitch-angle and the energy dependencies. A finite number of terms in these expansions are retained. As compared to the preceding formulation, the collisional part of the Fokker-Planck equation, which describes the modification of the fast ion distribution function, is notably revised. The main change in the whole computational scheme comes from the presence of a mixed energy–
pitch-angle partial derivative in the new collision terms. So the Monte-Carlo technique of FAFNER2, which is a stochastic equivalent of the Fokker-Planck approach, must be modified so as to replace the independent increments in the energy and the pitch-angle by the increments in two certain linear combinations of these variables. The eigenvectors of the velocity-diffusion matrices must be found numerically in order to define these combinations. In the view of these tasks, several modules of the FAFNER2 code are under significant modernization. The details of the ongoing activities are presented in the EFDA report [FAFNER report]. The coding and benchmarking parts of this work are in progress. Along with the upgrade of FAFNER2, the adaptation of this code to the ITER geometry is under development. This adaptation consists in replacement of the G3D numerical library by the new one representing the ITER configuration.

1.5.3 Electrostatic Residual Ion Dump (ERID) studies

During the year 2009, the activity concerning the EFDA H&CD Task HCD-04-02 consisted in the development of a particle-in-cell/Monte Carlo (PIC/MC) code [016], [017] for the simulation of the neutralizer and electrostatic residual ion dump (ERID) devices for neutral beam injectors. At the present time, we have implemented the routines for the integration of the equations of motion, based on the Boris algorithm [018] and symplectic methods [019], while for the time-advancing of the electric and magnetic field, compact finite difference schemes with spectral-like resolution [020] have employed to approximate the spatial derivatives of the fields. Moreover, the development of an efficient parallel solver for tridiagonal systems of linear equations [021], which will be used to produce a parallel implementation of the compact finite difference methods. In order to simulate the interaction of the beam particles with the background gas, particularly ionization and heating processes, I will introduce the effects of particle collisions by means of Monte Carlo techniques. Once completed, this code is expected to provide a reliable tool for studying the potential critical issues that may affect the proper functioning of the neutralizer and ERID, like, for instance, the influence of the neutralizer plasma on the ERID deflecting properties or the role of the stripped electrons created during the neutralization process [ccnb_feb2010-talks].

1.5.4 Second harmonic X mode breakdown experiments

Assist of plasma breakdown by ECRF is a key issue for ITER. Although previous results indicate that 170GHz ECRF system will be enough for plasma breakdown in ITER with the low electric field, effect of oblique injection remained to be an issue, since breakdown efficiency was found to be dependent on toroidal injection angle and decreased with oblique injection. A joint experiment has been carried out in the framework of the ITPA Integrated Operation Scenario Task Force. Dependence of breakdown efficiency on the toroidal injection angle has been investigated in several devices (Tore Supra, AUG, DIII-D, FTU, JT-60U (old existing data) and TJ-II). The dependence of the plasma breakdown time on the launching
direction of the ECRH beam was investigated for different values of the parallel refraction index \((N_{||})\) on-axis in TJ-II. The experiments were performed with one gyrotron (G1) at constant power (300 kW) and constant prefill pressure \((10^{-5} \text{ mbar})\). The last mirror of the quasi-optical transmission line, which is a steerable mirror located inside the vacuum vessel, allows variations in the launching direction from \(N_{||} = -0.3\) to \(N_{||} = +0.55\), corresponding to \(-15\) and \(35\) degrees in respect to the perpendicular injection. A reliable breakdown was demonstrated for all the directions. Prompt breakdown (4 ms) was observed for \(N_{||} = 0\) whereas maximum delay was found for \(N_{||} = +0.55\) [001].
II. DEVELOPMENT OF PLASMA AUXILIARY SYSTEMS

II.1 Heating and current drive systems

II.1.1 EBW Heating studies (TJ-II)

II.1.1.1 28 GHz ECRH system

a) 28 GHz Gyrotron.

The factory tests of the new 28 GHz GYCOM gyrotron (GLGT 28/500/0.3 sn1) were conducted in Nizhny Novgorod (June 15th-17th) and its commissioning at CIEMAT was carried out at the end of the summer (September 17th - 23rd). All the tests were successful. The main parameters achieved during the tests were:

- A maximum power of 510 kW at beam voltage \( V_b = 70.0 \) kV and beam current \( I_b = 21.2 \) A was obtained in 300 ms pulses.
- An operational reliability around 90% was also demonstrated.
- Modulation capabilities up to 10 kHz with 30% modulation depth and 50% duty cycle were achieved.

A LabVIEW® interface was developed at CIEMAT to remotely control the power supply of the cryomagnet and the ionic pump of the gyrotron.

b) High power transmission line.

The power delivered by the gyrotron is transmitted to the plasma using a hybrid quasi-optical / waveguide transmission line. The first quasi-optical part of the line includes a couple of polarisers that are used to achieve the needed O mode polarization for O-X-B heating. Both remotely controlled polarisers were recalibrated in order to have a precise determination of its rotation angles. The other two focusing mirrors of the matching optics unit (MOU) had to be redesigned to match the characteristics of the output beam of the new gyrotron. The design of the mirrors was made in collaboration with GYCOM, where they were also manufactured. The high power corrugated waveguide (100 ms, 300 kW) was carefully aligned with a laser beam in order to prevent arcing and power losses when used in high power conditions.

c) High Voltage Modulator.

The commissioning at CIEMAT of the high voltage modulator, based on an Eimac-Y676A vacuum electron tube previously used in IPP Garching was conducted at the beginning of 2009. The first tests were performed without connection to the gyrotron, using instead a high power dummy load. The final tests previous to the installation of the gyrotron
and with the gyrotron itself were performed in September 2008 showing an excellent behaviour and reproducibility in all the shots. With this system, modulation capabilities of the gyrotron could be demonstrated (up to 10 kHz for 65/68 kV). This work has been carried out in the frame of the collaboration with IPP-Garching and IPF-Stuttgart (Ref.: 08/324).

d) High power alignment.

The final high power alignment of the MOU and the corrugated waveguide was performed using thermal graphic paper and IR camera measurements. A well delimited spot was obtained at the entrance of the waveguide and the proper alignment was later demonstrated when high power full length shots without arcing were achieved. However, the IR camera measurements were not conclusive due to the high reflectivity of the graphite target in the microwaves range. The pulse length needed to have an admissible signal to noise ratio in the IR images was much higher than the pulse length for which an arcing in the gyrotron was produced. Other targets are being considered in order to obtain a reliable Gaussian beam pattern reconstruction.

II.1.1.2 Electron Bernstein Waves Heating experiments

EBW heating experiments in the TJ-II stellarator began at the end of October. Approximately 250 kW of 28 GHz power has been launched in different operation scenarios, with and without NBI, for different lengths of the second harmonic X mode heating pulse (53.2 GHz) and with different modulation frequencies of the 28 GHz power. Only the first 53.2 gyrotron (G1) was used in these experiments. Density control above the O mode cut off density \( n_e = 1.0 \times 10^{19} \text{ cm}^{-3} \) is easily achieved in NBI conditions while it is hard in TJ-II to obtain a second harmonic X mode sustained steady plasma for line densities above \( <n_e> = 0.8 - 0.9 \times 10^{19} \text{ cm}^{-3} \).

In order to obtain a non polarization dependent diagnostic of the stray radiation, a sniffer probe was installed in a bottom port of the B8 TJ-II sector. The probe is originally designed for 140 GHz and the validity of the results provided for 28 GHz is not clear yet. Moreover, the probe is located far from the EBW injection port (D6) and thus it detects a very low level signal. Finally, four detection diodes (ECA’s) in the WR28 band are distributed around the torus. The diodes are sensitive to 53.2 as well as to 28 GHz stray radiation and this must be consider in the interpretation of the measurements.

So far, no clear proof of EBW heating has been obtained. A few preliminary experimental sessions have been devoted to a launching direction scan and a wave polarization optimization in the different scenarios. However, the level of 28 GHz stray radiation in the TJ-II vessel has not shown any noticeable decrease above the O mode density cut off, and therefore, no O-X conversion have been demonstrated yet. Moreover, neither plasma energy content nor plasma radiation shows any evidence of plasma heating by electron Bernstein waves. Further experiments including a detailed scan in all the relevant
parameters, i.e. polarization, launching direction, magnetic field, and density, will be accomplished during 2010.

II.1.1.3 Electron Bernstein waves emission diagnostic (EBE)

A 28 GHz electron Bernstein waves emission diagnostic (heterodyne detection) was installed in September 2007. During 2008 and 2009, EBE system has been measuring in NBI plasma discharges. 28 GHz radiation is clearly obtained for line averaged densities well above the cut off density of the corresponding X and O mode at these frequencies. However, due to the complicated geometry of the TJ-II plasma, there is still a possibility for the collected radiation to be produced in the plasma edge where the density is below cut off. The experiments that scan the O-X conversion window have shown a clear dependence in the poloidal direction while the toroidal dependence remains unclear [002]. More experiments and analysis are underway. This work has been carried out in the frame of the collaboration with the Oak Ridge National Laboratory, Oak Ridge (USA).

II.2 Plasma diagnostics

II.2.1 Development of plasma diagnostics in TJ-II stellarator

II.2.1.1 Reflectometry

Installation and first results with a new reflectometer antenna system for Doppler reflectometry measurements:

The new Doppler antenna system consists of a choked-corrugated antenna and a steerable ellipsoidal mirror that controls the launching angle and focuses the beam with a defined beam waist to the cut-off layer. The system was taken into operation in TJ-II in February 2009. With this new system, it is possible to measure the perpendicular velocity of density fluctuations, their wavenumber spectra and radial electric fields. The details of the system along with first measured spectra were presented in the 9th International Reflectometry Workshop [IRWO9_Happel] and afterward published in [RSI09_Happel]. A wide range of plasmas scenarios was characterized. It was studied in detail that the reversal of the perpendicular velocity in ECRH plasmas is related to the radial position of the maximum of the density profile gradient, previously seen in [EPL08_Happel]. Besides, radial electric field profiles were compared with HIBP measurements in different plasma scenarios [EPS09_Happel]. Furthermore, L- and H-modes and the L-H transition were characterized in detail (see section 1.2.2).

Initial feasibility studies for the installation of a new Doppler reflectometer have been performed. The new reflectometer, working in the frequency band 50-75 GHz, will allow to
covering higher densities. Preliminary studies show that the initial design location in TJ-II, though suitable for a conventional reflectometer, is inappropriate for a Doppler one. Presently, alternative geometry schemes and locations are under study.

Studies on Doppler and correlation reflectometry have been carried out during 2009 using the two-dimensional full-wave code. Numerical simulations show that the measurement of radial correlation lengths larger than the probing wavelength can be obtained accurately from the amplitude signal in the linear regime. The transition from linear to non-linear regime shows a marked decrease in the correlation length estimated from all reflectometry signals. In non-linear regime, radial correlation lengths are underestimated. Finally, numerical simulations show that the measurement of correlation lengths smaller than the probing wavelength is not possible [IRW09_Blanco].

II.2.1.2 Operation of new power supply for dynamic biasing experiments

A power supply that permits modulations of electrode biasing voltage amplitude (±300V) and frequency (≤1kHz) during a single shot has been successfully operated during the last operational campaign (see Sec. I.2.1.1).

II.2.1.3 Design of a second HIBP system in the sector A4 for fluctuation and transport measurements

A second HIBP system was planned to be installed along 2010 to address, amongst others, the issues of large scale zonal-flow-like structures in the electric potential that are believed to be generated by Reynolds stress momentum transfer and to participate in the confinement transitions.

II.2.1.4 Installation and operation of a second fast camera for fluctuation studies

A second fast camera equipped with a special 2-stage image intensifier capable of plasma imaging at 600 000 frames per second has been installed in TJ-II. The system is unique for its ultra-fast recording speed and for its very high sensitivity. It is used for turbulence studies, spectroscopic plasma imaging or dust observations.

II.2.1.5 Installation of pellet system

The construction of and the preparation for the TJ-II pellet injector (PI) continued during 2009 at both the Laboratorio Nacional de Fusión and at Oak Ridge National Laboratory (where the main hardware PI is being built). In the first instance, the electronic instrumentation for temperature control of the cold head, where up to 4 hydrogen pellets are
formed, and for propulsion control of the pellets was completed at ORNL. Work continued on mechanical elements for the PI, e.g. the pellet guide tubes, the cold head components plus the mechanical/precursor propulsion systems. Also, Ciemat sent a cryorefrigerator and compressor unit to ORNL, as a temporary export, for their installation on the PI. In parallel, at Ciemat two gas manifolds, one to provide predetermined quantities of gas for forming pellets and the other to provide short gas pulses at high pressure to the pellet propulsion mechanism, were designed and built. In addition, the vacuum pumping and measurement system designs were both completed and the required vacuum pump and transducer components were procured. Finally, a 16-way fibre optic bundle was designed, procured and installed on TJ-II. It will be to transfer light from pellet ablation to light detectors. It is expected that the PI build at ORNL can be completed during 2010 for testing before being transferred to TJ-II. At Ciemat, the PI support structure, vacuum coupling to TJ-II, electrical installation, control systems and data loggers will be completed in 2010.

II.2.1.6  Diagnostics for edge Ti measurements

Passive diagnostic: The edge ion temperature was measured in TJ-II plasmas, heated by electron cyclotron waves and neutral beam injection, using passive spectroscopy of impurity ions in low ionization stages. The measurements, which provide both temporal and some spatial resolution, offer some advantages over more intrusive or more sophisticated methods. It was found that Lithium emission line was more appropriate to measure edge temperature than Carbon and Helium ones in this kind of TJ-II plasmas [SPEC_3].

II.2.1.7 Design of a multi-channel filter method for electron temperature measurements

The TJ-II plasma soft X-ray emission was studied in order to establish an adequate setup for an electron temperature diagnostic suitable for high density, with spatial and temporal resolutions, based on the two-filters method.

Preliminary experimental results were obtained with other two TJ-II diagnostics systems (an X-ray PHA based on a Ge detector and a tomography system). Results lead to the conclusion that the two-filters method (M2F) was a suitable option for an electron temperature diagnostic for high-density plasmas. An M2F prototype was designed and installed in TJ-II. It consists in two AXUV20A detectors that measure the soft X-ray plasma emissivity through beryllium filters of different thickness. First data were analysed with the help of IONEQ code to estimate the electron temperature, once plasma composition was assessed [Baiao].

II.2.1.8 Interferometry
The works required to extend the interferometer to a multichannel, expanded beam, high spatial resolution system have been carried out in 2009 [EPS09_Pedreira] and its final installation is scheduled for 2010.

II.2.1.9 Thomson scattering

The diagnostic has provided during 2009 in a regular way electron temperature and density profiles for TJ-II discharge documentation.

During 2009 the characteristics of a new Power Supply Unit (PSU) for the ruby laser have been defined, in collaboration with the supplier of the laser, INNOLAS of Rugby, UK. The new PSU will make the system more robust, since some parts of the old PSU don't have replacement parts and/or maintenance any longer. The call for tender procedure will take place most probably along 2010. Together with the PSU, a new Pockels cell will be ordered, so that the laser would be able to provide two shots during the discharge (separated in time ≤ 800 ms) in NBI regime; that could be interesting for studies on fast or transient phenomena.

The collaboration with the FOM Institute for Plasma Physics in the Netherlands has allowed modifying the data acquisition programme, so that now it re-starts automatically when an error in the raw data acquisition is detected. Hence, The operation of the diagnostic is, to a large extent, fully automatic with respect to data acquisition and error management.

Software/Hardware (SUN workstation) and Hardware (ruby laser) maintenance policies, which have been shown to be operative in the past, have been continued during 2009.

II.2.1.10 Diagnostic Neutral Beam Injector (DNBI) progress

During 2009 new light collection optics were installed in the top and bottom ports of sector A7 where the diagnostic neutral beam injector (DNBI) is located. This was done in order to increase the radial plasma coverage of the plasma poloidal cross section (r = 0.1 to 0.8). The lenses selected were commercial f#1.4 50 mm camera lenses. A third such lens was also installed outside a nearby vacuum viewport located in the tangential port of sector B1. In addition, a mobile 50 mm diameter mirror was installed in the same sector in order to collect light from charge exchange recombination interaction between the plasma and beam in the toroidal direction. This mirror is mobile as it shares the port is with a neutral article analyser system. Finally, considerable effort was made to align the mirror, lens and fibre array with the neutral beam located 1.5 m away.

In a study to evaluate the sensitivity of the impurity ion temperature to the best-fit parameters for the fitting profile used to obtain the instrumentation function of the short focal length spectrograph associated with the DNBI it was found that a correction factor is needed to determine the true ion temperature. It was determined, that for ion temperatures below about 200 eV, as is the case for TJ-II, this effect is associated with the relatively large
input slit width, 100 mm, that was chosen to achieve high detected photon count rates [Arevalo].

II.2.1.1 Experimental 2-D imaging of electron temperature and density in TJ-II stellarator

The helium line ratio technique as applied usually with beams for 1D $T_e$ and $n_e$ profile measurements is being applied in TJ-II to 2D imaging with a camera that obtains the emission of two filtered images through a double brunch coherent fibre bundle looking on to a recycling limiter. During 2009 the absolute Thomson Scattering) and the limits and errors of the proposed method were analysed. The EIRENE code was used to simulate the emission along the camera lines of view.

II.2.2 Diagnostic exploitation and development in JET

The experience of CIEMAT-TJII team in fast imaging allows us to coordinate a project, in JET, for the installation of a fast camera in collaboration with HAS, IST and CODAS. The FC7 project provides information of plasma wall interaction, ELMs and disruption physics. Fast visible camera installed at JET has monitored pellet ablation experiments during type-I ELM. The filter wheel and interference filters make possible to image the deuterium emission, the carbon and the beryllium emission coming from the divertor and the first wall and the helium emission. One of the conclusions was that for speed-up the images (>10,000 kfps) with an impurity filter we need to increase the SNR. Now, the final report and operation manual is in hands of the operator to finish the hand-over. At the later part of the C27 campaign (ending October 23rd, 2009) a CIEMAT image intensifier was installed in fast camera system. The installation and operation of the system was successful and the intensifier showed a robust behaviour against magnetic fields and neutrons. The results were very promising and push us to propose a new project that includes the image intensifier. Now we are proposing to JET this second step of FC7 project with an exhaustive test of the image intensifier, for different impurity sources that requires increases in the signal level.

II.2.3 Development of plasma diagnostics in W7X

II.2.3.1 Interferometry

Participation in the definition of the two-colour interferometer for W7-X: studies relatives to the adaptation of the TJ-II phase measurement system to the stationary pulses in W7-X. Development of diplexing strategies. Cooperation in the optical design.

During 2009, the behaviour of diagnostic dispersive elements, ZnSe windows and air, has been evaluated for several wavelengths, mainly the corresponding to CO2-CO
The results obtained in TJ-II as consequence of the accomplished modifications were presented in the Infrared Interferometer Workshop in Greifswald [IIW09_Sanchez].

The new phase measurement system based in FPGA that is being developed for TJ-II was proposed for W7-X. It includes the new diplexing strategy based in the simultaneous detection of the CO2 and CO signals over different carriers (40 MHz for 10 microns CO2 laser and 25 MHz for 5.3 microns CO laser). Then the signal is digitalized at 105 MHz and separated using two band pass filters. The system is more reliable, avoid several noise sources and reduce considerably the number of optical and detectors components. The system was presented in 7th IAEA technical meeting on Control, Data Acquisition and Remote Participation for Fusion Research in Aix en Provence [IAEA_TM09_Esteban] and in the Infrared Interferometer Workshop in Greifswald [IIW09_Esteban].

Several trials were carried out using the TJ-II phase measurement system over the W7-X prototype using CO2 CO lasers and one detector. The results will be published during 2010. The system is not only simplest but it is much more accurate.

During the Infrared Interferometer Workshop, we manifested greater confidence on Two Colour Interferometer technology than on the alternative one, Dispersive Technology. Also we manifested the necessity to avoid water vapour in air, short sights for laser beams, radiofrequency prevention and temperature stability. As consequence a modular, small and robust modular system was proposed. The Ciemat group will study this possibility.

II.2.4 Reflectometry simulations

Participation in the reflectometry code benchmarking cross-validation and optimization.

First results on the reflectometry code benchmarking were discussed during 2009. Benchmark on the one-dimensional (1D) single sinusoid perturbation and two-dimensional (2D) broadband turbulence simulations with normal incidence were completed. The comparison between existing codes shows good general agreement. However, it was found that the speed of the perturbation is crucial in obtaining consistent results. The perturbation/turbulence must be frozen between simulation steps to get similar results.

Concerning the optimization two topics have been investigated during 2009: accuracy and performance. The numerical accuracy can be improved if the spatial discretization of the computational domain is properly chosen. Different spatial discretizations have been studied in two-dimensions. However, the implementation of free space boundaries (perfect absorbers without significant reflection) has been found to be difficult in geometries other than the standard rectangular grid. The reflection coefficient is significantly higher than the one that can be easily obtained in a rectangular grid. The reduction of the reflection coefficient is mandatory before
these discretizations can be extended to 3D. The performance of the code with the number of processors has been studied with a 2D code (rectangular grid). Parallelization in 2D has shown that the speed up of the code is approximately proportional to the number of processors only up to 4 processors for small/medium fusion devices (1500 x 1500 computational grid points). Increasing the number of processors increases the communications and synchronization time between them and no further reduction in the computational time has been achieved.

II.2.4.1 3D full wave reflectometer code development.

A simplified 3D code has been developed during 2009 to test the performance with the number of processors in 3D and to estimate the speed up that can be achieved. These tests are scheduled for the 2010 period.

II.2.5 Diagnostic development in ITER: Participation in association diagnostic clusters

II.2.5.1 Plasma Position Reflectometer

Thermal and mechanical analysis of the ITER plasma-position reflectometry antennas carried out using ANSYS simulations indicates that the proposed antenna arrangement is properly designed against thermal and mechanical loads [FED09_Perez].

II.2.5.2 Development of Equatorial Visible/InfraRed Wide Angle Viewing System

Ciemat in co-operation with CEA has continued different aspects concerning the study of the Wide Angle Infrared/Visible Viewing System for ITER, Procurement Package 11 [see e.g. 1]. The principal handled items have been:

i) IR materials suppliers list and contact with them in order to get a quotation for the samples to be tested;

ii) Update the zemax file for the separated-lines design concept in a second position in the port-plug. Check distances and available sizes with CAD;

iii) Study and revision the ITER specifications list for this diagnostic. Meeting with ITER to discuss their starting specifications;

iv) State-of-the-art on visible/fast cameras and IR detectors meeting ITER spatial/temporal resolutions. Prevision of developments for the next five years.
v) Documentation on optical fiber bundles with visible transmission for fusion environments. Techniques to recover irradiated elements.

vi) Study of micro-scanning technique as a solution to solve the restrictions on spatial resolution for IR sensors.

vii) Attendance to the introduction course of LightTools in ITER offices. Invitation to ORA to give a presentation on CodeV and LightTools in CIEMAT and acquisition of two demo licenses to become familiar with the softwares.

In summer 2009 a Consortium Agreement was signed between the laboratories of five European Countries (France, Hungary, Italy, Portugal and Spain) to efficiently manage the project and to be prepared for next Grants and Call for Tenders. The first formal meeting of the Consortium will be held in CEA-Cadarache by the 4th July 2010 [vis-ir viewer1], [vis-ir viewer2].

II.2.5.3 Lidar Thomson Scattering

ITER activities. Some in-kind activities for the LIDAR Thomson Scattering System in ITER (mainly in theoretical/numerical aspects) have been maintained during 2009. The contributions to LIDAR consist on an analysis of the solution of the movement of the electron in the field of an arbitrary intensity EM wave, which can later on be used as a basis for the computation of radiated EM fields (Scattered Fields). The analysis carried can be applied to fast, relativistic electrons (preliminary tests of the numerical codes are satisfactory up to kinetic energies of 1 MeV) and to high-intensity lasers as well.

II.2.5.4 Magnetic sensors. Cluster CEA /CRPP /Ciemat /IPP-CR / TEKES

ITER requires an extensive and reliable set of magnetic diagnostics; measurements of fields, fluxes, plasma current, and diamagnetic flux made inside and outside the vacuum vessel. CIEMAT joined last year the ITERMAG consortium, created to offer a single response to grant calls from Fusion for Energy (the European Domestic Agency for ITER). Within this context, a review of the multiple set of requirements for the ITER magnetic diagnostic systems and the current status of the various R&D activities performed by the EU partners has been performed [mag1]. There are also specific challenges related to developing such diagnostic systems for ITER in which CIEMAT experience with radiation testing of materials is useful, such as gamma radiation and thermal effects on the in-vessel sensors and cabling [mag2]. Also, additional non-inductive steady-state diagnostics are also being studied to meet the challenges associated with the long-pulse operation for inductive sensors.

II.2.6 Remote experimentation test-bed at JET
Based on the remote experimentation concept oriented to long pulse shots, a test-bed system has been implemented in JET [REXP_1]. Its main functionality is the real-time monitoring, on remote, of a reflectometer diagnostic, to visualize different data outputs and status information. The architecture of the system is formed by: the data generator components, the data distribution system, an access control service, and the client applications. In the test-bed there is one data generator, which is the acquisition equipment associated with the reflectometer diagnostic that generates data and status information. The data distribution system has been implemented using a publishing-subscribing technology that receives data from data generators and redistributes them to client applications. And finally, for monitoring, a client application based on JAVA Web Start technology has been used.

There are three interesting results from this project. The first one is the analysis of different aspects (data formats, data frame rate, data resolution, etc) related with remote real-time diagnostic monitoring oriented to long pulse experiments. The second one is the definition and implementation of an architecture flexible enough to be applied to different types of data generated from other diagnostics, and that fits with remote access requirements. Finally, the third result is a secure system, taking into account internal networks and firewalls aspects of JET, and securing the access from remote users. For this last issue, PAPI technology has been used, enabling access control based on user attributes, enabling mobile users to monitor diagnostics in real-time, and enabling the integration of this service into the EFDA-Federation.

II.2.7 Data mining tools for off-line data analysis

Big physics experiments can collect Tbytes (even Pbytes) of data under continuous or long pulse basis. The measurement systems that follow the temporal evolution of physical quantities translate their observations into very large time-series data and video-movies. A universal and automatic technique has been developed [DM_1] to recognize and locate inside waveforms and video-films both signal segments with data of potential interest for specific investigations and singular events. The method is based on regression estimations of the signals using Support Vector Machines. In the regression process, a reduced number of the samples are shown as outliers and these samples allow the identification of both special signatures and singular points. Examples with the JET database are: location of sawteeth in soft x-ray signals to automate the plasma incremental diffusivity computation, identification of plasma disruptive behaviours with its automatic time instant determination and, finally, recognition of potential interesting plasma events from infrared video-movies. Results have been shown in the 7th IAEA Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research. 15-19 June 2009. Aix-en-Provence (France)[DM_2]. The temporal locations of ELMs in JET were presented in the 6th Workshop on Fusion Data Processing, Validation and Analysis. January 25th-27th, 2010. Madrid (Spain) [DM_3]. Also in this Workshop, a contribution about machine learning methods for image processing has
been presented [DM.4]. Techniques for automatic event location, automatic recognition of regions of interest and their temporal evolution were discussed.

In addition to this, an automated system to estimate the L/H transition times in JET has been developed [DM.5]. This system is based on a pattern recognition method for off-line estimation of both L/H and H/L transition times. The technique is based on a combined classifier to identify the confinement regime (L or H) at any time instant during a discharge. The classifier is the combination of two different classification systems: a Bayesian classifier whose likelihood is computed by means of a non-parametric statistical classifier (Parzen window) and a Support Vector Machine (SVM) classifier. They are combined through a fuzzy aggregation operator, in particular the Einstein sum. The success rate achieved exceeds 99% for the L to H transition and 96% for the H to L transition. The estimation of transition times is accomplished by following the temporal evolution of the confinement regimes.

II.3 Plasma fuelling

II.3.1 Fuelling studies in TJ-II

Fueling and recycling of the plasma by H and He were investigated [Li.1]. Also, the desorption yield by plasma particles of the gas trapped in the lithium coating was addressed [Li.2], [Li.3]. Comparative studies of fuelling efficiency at different poloidal locations are still underway.

II.4 Real Time Measurement and Control

II.4.1 Calibration techniques and pattern recognition methods

Data access in huge databases can no longer be efficiently based on shot number or temporal interval. Taking into account that diagnostics generate reproducible signal patterns (structural shapes) for similar physical behaviour, high level data access systems can be developed. In these systems, the input parameter is a pattern and the outputs are the shot numbers and the temporal locations where similar patterns appear inside the database. These pattern oriented techniques can be used for first data screening of any type of morphological aspect of waveforms and images. Techniques to look for similar images in huge databases in a fast an efficient way have been developed [PR.1]. Also, previous techniques to search for similar waveforms and to retrieve time-series data or images containing any kind of patterns have been reviewed.

In order to standardize the use of pattern recognition methods for data retrieval, a distributed open environment has been designed [PR.2]. It is based on a client/server architecture that supports distribution, interoperability and portability between
heterogeneous platforms. The server part is a single desktop application based on J2EE (Java 2 Enterprise Edition), which provides a mature standard framework and a modular architecture. It can handle transactions and concurrency of components that are deployed on JETTY, an embedded web container within the Java server application for providing HTTP services. The data management is based on Apache DERBY, a relational database engine also embedded on the same Java based solution. This encapsulation allows hiding of unnecessary details about the installation, distribution, and configuration of all these components but with the flexibility to create and allocate many databases on different servers. The DERBY network module increases the scope of the installed database engine by providing traditional Java database network connections (JDBC-TCP/IP). This avoids scattering several database engines (a unique embedded engine defines the rules for accessing the distributed data). Java thin clients (Java 5 or above is the unique requirement) can be executed in the same computer than the server program (for example a desktop computer) but also server and client software can be distributed in a remote participation environment (wide area networks). The thin client provides graphic user interface to look for patterns (entire waveforms or specific structural forms) and display the most similar ones. This is obtained with HTTP requests and by generating dynamic content (servlets) in response to these client requests. This work has been presented in the 7th IAEA Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research. 15-19 June 2009. Aix-en-Provence (France).

II.4.2 Advanced control systems and application to magnetic control in tokamak

This activity is partially performed in the framework of the Task WP08-DIAG-02-01 (WP III-2-c) (0.3 ppy): Assessment of the status and control needs in current and future fusion devices and identify weak areas and the present status in the field of integrated control, and on control techniques used in different fields of science and industry.

The study of control strategies for the ramp-up and ramp-down phases of tokamaks was identified as one control needs for current and future fusion devices by the EFDA feedback control group in 2009 (romt). The aim of this new control concept is the demonstration of full inductive control (I_p, L_i) using the main transformer as the sole actuator, independently of the availability of additional heating / current drive. This is a work very relevant for ITER, useful to save valuable volt seconds [004], [005] to reduce vertical instability growth rate[006], [007]and to provide accessibility to advanced tokamak scenarios [008]

Within this context, CIEMAT has established collaborations with TCV and EHU (Basque Country University) to develop an inductive control system for TCV. This collaboration has already produced results, namely a real time architecture to host the control algorithms and a first version of a real time inductance and plasma beta sensor developed by EHU, which is valid only for TCV circular plasmas. Some beta control tests have been performed already to
test this new real time sensor. There is work underway to develop a real time internal inductance sensor valid for elongated plasmas.

Regarding the plant modelling tasks, a first order, lumped parameter models for tokamak inductive control developed originally for JET\cite{Rom2}, \cite{Rom3} is currently being adapted to TCV. To support this task, open loop testing of TCV plant to identify flux diffusion high order dynamics has been recently performed. This will serve to build an lumped parameter model for tokamak inductive control at TCV. Once the dynamic model is completed, it will serve as the basis for the design of a controller and experimental testing at TCV will follow after that, hopefully within 2010.

II.4.3 RT simulators

Disruptions are sudden and unavoidable losses of confinement that may put at risk the integrity of a tokamak. However, the physical phenomena leading to disruptions are very complex and non-linear and therefore no satisfactory model has been devised so far either for their avoidance or their prediction. For this reason, machine learning techniques have been extensively pursued in the last years. A real-time predictor specifically developed for JET and based on support vector machines has been developed \cite{RT_1}. The main aim of this investigation is to obtain high recognition rates in a real-time simulated environment. To this end the predictor has been tested on the time slices of entire discharges exactly as in real world operation.

Since the year 2000, the experiments at JET have been organized in campaigns named sequentially beginning with campaign C1. In this paper results from campaign C1 (year 2000) and up to C19 (year 2007) are reported. The predictor has been trained with data from JET's campaigns up to C7 with particular attention to reducing the number of missed alarms, which are less than 1%, for a test set of discharges from the same campaigns used for the training. The false alarms plus premature alarms are of the order of 6.4%, for a total success rate of more than 92%. The robustness of the predictor has been proven by testing it with a wide subset of shots of more recent campaigns (from C8 to C19) without any retraining. The success rate over the period between C8 and C14 is on average 88% and never falls below 82%, confirming the good generalization capabilities of the developed technique. After C14, significant modifications were implemented on JET and its diagnostics and consequently the success rates of the predictor between C15 and C19 decays to an average of 79%. Finally, the performance of the developed detection system has been compared with the predictions of the JET protection system (JPS). The new predictor clearly outperforms JPS up to about 180 ms before the disruptions.

RT simulators for L/H transitions and disruptions have been developed for JET. With regard to L/H transitions, results were presented in the 7th IAEA Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research. 15-19 June 2009. Aix-en-Provence (France)\cite{RT_2}. Concerning disruptions, the simulator has been presented in the
III. DEVELOPMENT OF CONCEPT IMPROVEMENTS AND ADVANCES IN FUNDAMENTAL UNDERSTANDING OF FUSION PLASMAS

III.1 Optimization of operational regimes for improved concepts

III.1.1 Participation in the on-going activities of the International Stellarator Confinement and Profile Data Bases and Neoclassical transport

The Ciemat team has participated actively in the above-mentioned activities through the participation in the 5th and 6th Coordinated Working Group Meetings (CWGM) organized by IPF (Institüt Plasmaforschung) Stuttgart and PPPL (Princeton Plasma Physics Laboratory) and held in Stuttgart and Princeton in July and October, respectively.

Seven contributions were presented in CWGM5 by Ciemat members:

- "Major activities and international collaboration in TJ-II" [CWGM5_1] and "Global confinement in TJ-II NBI plasmas" [CWGM5_2] by E. Ascasibar
- "Grid computing for Fusion research" [CWGM5_3] and "Island healing in TJ-II" [CWGM5_4] by P. Castejón
- Dynamic configuration scans in TJ-II by [CWGM5_5] by D. López-Bruna
- "Reflectometry measurements: low order rationals and electric field in TJ-II" [CWGM5_6] and "Sheared flows and transitions to improved confinement regimes in TJ-II" [CWGM5_7] by T. Estrada.

The contribution of TJ-II plasmas to the stellarator database requires a characterization in terms of transport and confinement properties. The studies of the source and transport terms has been continued with special emphasis on the larger database of low density ECRH plasmas. The approach followed for these studies consists of developing an integrated environment for transport calculations: the Astra transport system is coupled to several other large codes that solve consistently several source and flux terms in the transport equations [Lopez-Bruno-D]. As an example, the density dependence of particle transport in ECRH plasmas was characterized using the Eirene code coupled to Astra. Two confinement regimes can be clearly established: low confinement, with particle confinement on the order of the electron energy confinement time, \( \tau_p \sim \tau_E \), related with ECRH-driven kinetic effects at low densities and corresponding positive plasma potential in most of the plasma; and a “regular” confinement regime with strongly reduced fast particle losses [CIEMAT1129] and confinement times \( \tau_p \sim 4 \tau_E \). Further studies have been devoted to analyze the electric fields from ambipolar neoclassical models [eps09-sofia], an ongoing task that is aimed at establishing the dominant mechanisms for the radial electric field inversion in ECRH plasmas as a first step to model collisional transport in general TJ-II plasmas.
Transport calculations have also been pursued from the viewpoint of kinetic theory in the full three-dimensional geometry of the TJ-II Heliac. The work on a new transport code – presented last year– has continued with the documentation of the theoretical aspects [CIEMAT1165], the numerical procedures [CIEMAT1172], [jmrbLisboa2009] and the first checkings on convergence and agreement with theoretical results.

### III.1.2 Influence of magnetic configuration on confinement and transitions

One singular contribution of the TJ-II Heliac to the development of stellarator concepts is the possibility of using resonances of the confining magnetic field (e.g. magnetic islands) for confinement control. The ability to perform dynamic configuration studies at low magnetic shear [dlbNF2009] has allowed for a better characterization of the effect of magnetic resonances within the plasma: there is a modification of the electron temperature gradients linked to the position of the magnetic resonances with no flattening of the emissivity profiles. The effects of the resonances seems to be beneficial for confinement in agreement with previous works, although this aspect must be further investigated. The radial electric field is modified by the presence of the resonances, which is posed as the explanation for the modification of gradients. Preliminary three-dimensional calculations of collisional transport indicate that the manetic resonances are able to “heal” their expected deleterious effects on transport through neoclassical current densities inside the resonant zones [C03_Lopezbruna_d].

### III.1.3 Full lithium coating in TJ-II

The characterization of the peculiarities arising from the operation of TJ-II under full lithium walls was performed by different diagnostics. Global energy and particle balance in ECRH plasmas indicate little difference with the boronized walls [Li_4]. Special effort was devoted to the understanding of the physics responsible for the transition from peaked to broad plasma profiles. Perturbative experiments by external gas seeding were carried out [Li_4], [Li_5]. A possible mechanism for the transition of the profiles has been identified.

### III.1.4 Liquid lithium limiter in TJ-II

Preliminary design activities have been carried out in 2009 in order to develop two liquid lithium limiters to be installed in TJ-II, taking advantage of the mobile support structure the existent poloidal limiters. These activities have proceeded in collaboration with the Russian company Fluorit and have resulted in the signature of a contract between both institutions in April 2010. The contract foresees an execution period of one year.

### III.2 Understanding of plasma characteristics for improved concepts
III.2.1 Momentum transport

**Activities in Fast Ion Simulations in Stellarators**

A key point to understand the momentum transport both in tokamaks and stellarators is to know the non-intrinsic momentum source in the plasma. The main momentum driving in fusion plasmas is the Neutral Beam Injection (NBI) heating. It is mandatory to study the momentum transfer from fast ions coming from NBI. As a first step, fast ions trajectories coming from NBI are simulated in the LHD and TJ-II Stellarators. The initial fast ion distribution function is given by two Monte Carlo codes that give us the ionization of fast neutrals in the plasma and, hence, the birth points of fast ions in phase space. This codes are FAFNER for TJ-II and HFREYA for LHD. The ions evolve in these two devices following guiding centre trajectories corrected by finite Larmor radius in the background magnetic, and colliding with the thermal plasma. Cartesian coordinates are used in the two devices. We have calculated the steady state fast ion distribution function, assuming a constant source, using the Green's function method. This distribution function can be used to investigate couplings with Alfvén Eigenmodes. In addition, energy slowing down time and escape point maps have been calculated. Comparison with Neutral Particle Analyser experimental measurements will be performed soon. Once the fast ion distribution function is known, it will be possible to solve the Fokker-Planck equation between the background plasma and the fast ion distribution functions. [bustos_proceedings_ITC]

III.2.2 Impurity transport

Confinement of impurities injected by laser blow-off. Impurity injection experiments using the laser blow-off technique have been performed in ECRH and NBI plasma regimes of the TJ-II stellarator to probe the impurity confinement. The measurements indicate that core impurity confinement in TJ-II does not have a strong mass dependence, suggesting that impurity confinement is limited by ExB-type transport. Also, a trend in increasing confinement is observed with increasing electron density, possibly due to the concomitant change in radial electric field [SPEC_2].

**Differential diffusion of impurities and bulk ions**

The present strategy for studying impurity transport is to explore the different characteristics of impurity and bulk ion transport. There are several possible radial scales that could play a role in this transport and one of them is the imposed by zonal flows that can appear spontaneously when the non-linear evolution of the turbulence happens. The code EUTERPE (see Section 3.3.9) has been used to perform non-linear simulations of ITGs were also carried out in a screw pinch with W7-X parameters and the development of a zonal flow was observed, in good agreement with previous results from TORB [Nuhremberg05]. While a finite beta only reduces very slightly he growth rates of ITG modes, its influence in the non-
linear regimes was observed to be much more remarkable. The amplitude and the radial scale of the zonal flow structures appearing in the non-linear simulations were clearly reduced in the finite beta cases. Although the growth rate of instabilities is reduced with beta, the heat flux showed a higher level and a slower decay as beta increases. These results are in agreement with those obtained with TORB in a theta pinch [Sorge04]. Future work will concentrate on the influence of zonal flows on bulk and impurity ion transport. [ICNPS09_EUTERPE_Sanchez], [022], [023].

III.2.3 Operational limits

Perturbative experiments by external gas seeding (pure H2 and hydrogen-diluted neon) were performed in plasmas with bell profiles to force the transition to dome-shaped [Ref Li 5]. A possible mechanism for the transition of the profiles has been identified. The larger ratio of edge to core emissivities found in the dome profile makes them prone to radiative collapse and therefore they are thought to be responsible for the density limit achieved under pure NBI heating, at central densities of \( \sim 0.8 \times 10^{20} \text{ m}^{-3} \).

III.2.4 Fast particles

High frequency modes (150-300 kHz) are found in several magnetic configurations of TJ-II plasmas heated by Neutral Beam Injection (NBI). The clear dependence of mode frequency on plasma density and mass species suggests them to be Alfvén Eigenmodes. The appearance of these modes is linked to the presence of low order rational surfaces close to the rotational transform profile. They can exhibit steady or chirping behaviour depending on the plasma profiles. NBI plasmas with broader temperature profiles show frequency chirping meanwhile it is not or rarely observed for relatively peaked ones. The Alfvénic activity has been characterized in detail with magnetic coils for the standard configuration. Cross analyses with HIBP and reflectometer signals have yielded spatial resolution and radial profiles of the perturbation. Correlation of magnetic coil signals with the ones from diagnostics sensitive to edge ion losses, as Langmuir probes and a Fast Ion Loss Detector, has been observed in some cases and characterized taking advantage of the chirping nature of the observed Alfvénic activity. A paper compiling the results is in the last phase of preparation and will be submitted for publication in May 2010. A preprint can be seen in [F_PART].

III.3 Theory and modelling

III.3.1 Heating and CD

Power-flow formulation of a ray approach to the modelling of inhomogeneous waves.
We have developed the axiomatic power-flow formulation of ray tracing methods, which provides a clear substantiation of the real valued ray technique as applied to modelling of wave propagation in inhomogeneous dissipative systems. All the analyses and results are notably independent of the physical origin of waves, which make that our results are valid for any wave. In the framework of the adopted formalism the ray method is not intended for the accurate description of the wave field structure, but instead allows one to conceive individual ray trajectories as the particular waveguides for the eigenmodes of locally plane waves. This virtue is especially advantageous in studying the patterns of wave propagation and absorption in complicated 3D-inhomogeneous systems, e.g. in various magnetically confined plasma configurations. In such systems, massive ray tracing is usually the most efficient modelling strategy due to both a visual picture of how the wave perturbations propagate and a relatively simple organization of parallel or distributed calculations. Therefore the power-flow substance of ray trajectories defined in real space lets one to directly locate areas of the wave energy deposition and also to use the computed set of trajectories as a reference base for reflectometry and some other methods of wave diagnostics, without a detailed description of the wave field. This work is unpublished yet [PhysRevE].

**Electron Bernstein Current Drive.**

One of the advantages of driving current by means of electron Bernstein waves (EBW) is the absence of cut-off density for the propagation of this mode, the high value of the parallel refractive index that this it achieves, and the subsequent higher current drive efficiency than that induced by electromagnetic waves. Furthermore, due to the recent installation of an electron Bernstein wave heating (EBWH) system, which is performing its first experimental tests, the numerical characterization of the Electron Bernstein Current Drive (EBCD) has been carried out, by performing multi-ray tracing simulations using the ray tracing code TRUBA, and coupling to it the numerical subroutines for the current drive estimation. The several models that have been considered for the calculation of the EBCD, have allowed a wide comparison between them, and the evaluation of how important the trapping of relativistic effects can be, as well as the validity of the models considered checked. From this work it has been concluded that a non-negligible current value will be present in the EBW heating experiments of around 1-2 kA, and that the total current drive efficiency is indeed larger than for the electromagnetic case. The work was partially presented [1mgr_ebcd_eps09] to the 36th International European Physics Conference on Plasma Physics held in Sofia (Bulgaria), and accepted for publication in Plasma Physics and Controlled Fusion [1mgr_ebcd_ppcf_proof].

### III.3.2 Wave-particle interaction

**Electron Bernstein Emission.**
Due to the installation of the EBW heating system in the TJ-II Stellarator (O-X-B mode conversion at 1st harmonic and 300 kW), an Electron Bernstein Emission (EBE) diagnostic was installed, as diagnostic tool for measuring the 28 GHz radiation outflowing the plasma column and reaching the steerable mirror that the EBWH system uses for defining the launching direction of the beam. The aim of the EBE diagnostic is locating the mirror position that receives the maximum B-X-O-converted radiation front the plasma. Since the value of the radiation collected by the mirror is strongly dependent on the O-X conversion efficiency, the EBE diagnostic would provide experimentally information about the best launching direction for heating purposes (maximum O-X conversion efficiency). Thus, previously to the experimental analysis a numerical estimation was carried out by using the TRUBA code as multi-ray tracer. Along the rays the radiative transfer equation is solved and the outflowing radiation estimated. This provided the numerical characterization of the EBE in TJ-II scanning the plasma parameters and mirror position space [jmgr_ebe_Sherwood_poster]. In a second stage, the experimental analysis, focused on the scan of the mirror positioning angles, was performed. From the comparison of the numerical and experimental work, it is concluded that the O-X-B conversion process is taking place in over-dense plasmas in TJ-II [jmgr_ebe_ishw09_proc.pdf], and that the experimental emission window is displaced approximately two degrees respected to the theoretical one.

III.3.3 Divertor stellarator physics

**Improvement of the EIRENE code to be used in Divertor studies.**

The code ISDEP (Integrator of Stochastic Differential Equations in Plasmas), developed by Dr. Velasco during its PhD, is being employed for benchmarking of a module of ion orbit tracing in a magnetic confinement devices within its EIRENE kinetic Monte Carlo solver. This module has been developed at FZ-Juelich, in collaboration with the University of Innsbruck. TEXTOR magnetic 2D geometry (toroidally symmetric) was included in ISDEP. ISDEP was also upgraded in order to track not only H+ ions but also any type of impurity. A large number of simulations were made in order to find the optimum set of numerical parameters of the Monte Carlo calculation (time-step, spatial discretization ...).

III.3.4 Statistical Description of Transport

In recent years, we have focused part of our research efforts to the problem of test particle transport, as this technique can provide additional information on transport not revealed by more common profile analyses.

We have used this technique to study transport in the numerical turbulence simulation code CUTIE, a full-tokamak fluid code in which the turbulence feeds back nonlinearly on the profiles. Long-range spatial and temporal correlations were detected,
indicating that effective global radial transport in CUTIE does not satisfy the traditional paradigm of diffusive transport. Part of this result could be explained from the existence of propagating ballistic events, and another part from a dependence of local transport properties on the safety factor: local transport was found to depend sensitively on the position relative to specific rational surfaces \[ \text{POP2009_Burillo} \].

The same analysis techniques were also applied to study the difference between an L-mode and an H-mode in CUTIE. This is the first such comparison ever performed in any simulation. The analysis of self-similarity parameters of the motion reveals that these differences, if any, are slight. Nevertheless, the study of the mean step size indicates that transport is more local and the anomalous diffusion contribution less dominant in the H mode \[ \text{Popsubmitted_Burillo} \].

### III.3.5 Eirene code Studies

Eirene 3D geometry options have been included in the current version of Eirene. For this, a set of routines developed at CIEMAT, which worked for an old version of Eirene (prior to 2005) have been implemented in the general trunk of Eirene code. The system for describing the geometry is based on a system of Tri Linear Hexaedron, called TriLinHex. These routines have been included in the new version of Eirene, some as user-supplied routines and some as external programs. In its present version, the code Eirene can use several geometry modules that can work in different magnetic configuration geometries.

Additional applications developed at CIEMAT which perform different actions over the input / output of Eirene were also included.

Also the routines that create magnetic inputs for Eirene TriLinHex for an arbitrary device (not only TJ-II) have been studied and applied to TEXTOR.

### III.3.6 GRID computing

Grid computing techniques have been used successfully to perform heavy calculations for fusion research. There are about ten applications running on grid and it is now possible to establish complex workflows among those applications. From the beginning of fusion computation in the grid up to now, the range of plasma physics topics that are being investigated by means of grid technologies has been widened, and so have the techniques that have been developed to work on fusion in the grid \[ \text{[024]} \]. The strategy that has been used to extend the use of grid among the fusion community is to start porting those applications that can be easily gridified because of their distributed nature, and still can give physically relevant results. With this objective, we have identified embarrassingly parallel applications that are composed of a huge amount of identical processes. The codes that are based on Monte Carlo techniques or on input parameter scans are clearly of this type: Both are serial and do not need any communication between the CPUs, so they are perfectly
suited to run on the grid. After these two types of applications have been ported, others with more complexity have been identified. In these cases, more complicated workflows appear. Remarkably, a PIC code that requires more communication among CPUs has been ported. And, as another important example, an application to optimise the stellarator configuration based upon genetic algorithms has been also ported. Beyond considering the extension of the grid use to different types of applications, it is necessary to consider the extension of these techniques to different research topics relevant for fusion reactors. This is why it could be necessary to make an especial effort in porting applications to the grid, although they could not be fully appropriated for this distributed architecture. From the core of the reactor to the edge, very different research fields can be identified. The plasma dynamics can be studied both by fluid and kinetic theories. The first ones consists of solving continuity-like and conservation equations in the presence of the three-dimensional background magnetic field, while the second consists of studying the properties of the individual plasma particles. The fluid equations must be solved using finite differences or even finite element techniques, so they are not, in principle, the most appropriated for the grid, while the kinetic approach problems can be easily ported to the grid, as has been done with the application ISDEP [025]. Another kinetic code that estimates collisional transport from a totally different point of view is DKES (Drift Kinetic Equation Solver) code, which solves the drift kinetic equation for the distribution function under several approximations [026].

Plasma heating can be performed experimentally by several methods, but there are two of them that can be modelled by means of grid technologies: Electron heating by a microwave beam, which can be modelled by the estimate of a large number of rays as it is done with the TRUBA code [027], and neutral beam injection (NBI) that can be simulated by means of the Monte Carlo code FAFNER [028]. The plasma wall interaction and the edge transport can be simulated by means of the use of a Monte Carlo code like EIRENE [029], a widely distributed code for plasma-wall interaction studies, or by a PIC code like BITi [030].

The Magneto-hydromatic (MHD) equilibrium and stability are also important disciplines since they study the dynamics of the geometry of the magnetic trap. The main application that estimates the equilibrium is VMEC (Variational Moment Equilibrium Code), which has been also ported to the grid in the frame of the stellarator optimization. Finally, some material research codes should be considered in order to include the simulation of the reactor structure behaviour in the grid simulations. [castejon_ibergrid09], [Uppsala10]

III.3.7 Stellarator Development

Stellarator optimization using metaheuristics:

There are several good stellarators configurations optimized following several criteria like diminishing the neoclassical transport or improving the stability. The search for an optimised configuration that fulfils multiple optimization criteria is a key topic to propose a stellarator-based configuration for a reactor. We have developed an algorithm based on
metaheuristics to look for such an optimised configuration. A metaheuristic is a combinatorial optimization process that tries to maximize or minimize a function defined by the user, which is called objective function. There are several different metaheuristics concepts, but all of them have some commonalities like the exploration of the phase space - that is, the exploration of solutions using a widely range of values for different parameters - or the use of a predefined number of candidate solutions. As a first step to test the algorithm, we have introduced the minimization of the neoclassical transport by reducing the average sum of the $B \times \text{grad}(B)$ drift. Hence, the objective function is in our case defined by $\sum_i (B \times \text{grad}(B))$. In this equation, $i$ represents the different magnetic surfaces, whereas $B$ is the intensity of the magnetic field in each point of the magnetic surface. To get the values of the magnetic field, the 3D equilibrium code VMEC is used. The last version of VMEC includes the calculation of the Mercier stability criterion, which allows us to introduce this criterion in our optimization process, thus having two target functions presently. Mercier criterion has been introduced in a way that if a given configuration does not satisfy the condition established by the user, the configuration is rejected. In the same way, the user can specify a desired value for the plasma pressure profile or for any other parameter given by VMEC; all these considerations have to be satisfied so the configuration can be considered as a candidate solution. Moreover, the ballooning stability code COBRA has also been introduced to include this criterion in the optimization process.

As introduced, these processes explore the solution space so a large number of executions of the fitness function are required. The best approach to perform all these computations is to use a distributed computing environment to carry out several evaluations in parallel, being every evaluation independent from the others. A centralized master process controls the exploration of the solution space and also leads the process to optimized solutions by using improvement methods over the candidate solutions.

To our knowledge, this is the first time that metaheuristics processes have been used to solve this problem in a distributed computing environment. The algorithm is described in [information-sciences].

### III.3.8 Theory and modelling for ITER

ITER tokamak will have a non-negligible toroidal ripple due to the separation of the coils and, remarkably, to the insertion of the test blanket modules (TBM). We have solved the neoclassical transport in ITER considering a background magnetic field with ripple using the particle code ISDEP. The ripple is introduced as a small perturbation to the magnetic field and the transport is solved for different ripple intensities form 1 to 10%. This is relevant because the ripple is influenced by the Blanket Modules and most of the simulations performed assume axisymmetry. We have obtained particle and heat fluxes, from which the global particle confinement time is calculated. The transport quantities are studied as functions of the ripple intensity, concluding that the ripple influences the transport in an appreciable way and should be taken into account.[bustos_proceedings_EPS]
III.3.9 Turbulence studies

Topological characterization of the transition to fully developed plasma turbulence in reduced MHD.

For the resistive pressure-gradient-driven turbulence model, the transition from laminar regime to fully developed turbulence is not simple and goes through several phases. For low values of the plasma $b$ parameter, a single quasicoherent structure forms. As $b$ increases, several of these structures may emerge and in turn take the dominant role. Finally, at high $b$, fully developed turbulence with a broad spectrum is established. A suitable characterization of this transition can be given in terms of topological properties of the flow. We describe the computational topology tools, analyze the topological invariants that provide an understanding of the turbulence-induced transport and give a measure of the breaking of the homogeneity of the turbulence. [Garcia_PhysRevE_09].

Path integral formulation of fractional Lévy motion.

It is already a well-known fact that fractional diffusion equations and Lévy statistics can be relevant in the description of particle transport in certain regimes of turbulent fusion plasmas and we would like to make progress in the theoretical understanding of the phenomenon and its rigorous mathematical description. In this paper we have advanced the comprehension of the link between Langevin equations with Lévy statistics and fractional diffusion equations. Fractional Lévy motion (fLm) is the natural generalization of fractionalBrownian motion in the context of self-similar stochastic processes and stable probability distributions. In this paper we give an explicit derivation of the propagator of fLm by using path integral methods. [Calvo_JPhysA2009].

Development of Euterpe a 3D global Gyrokinetic code.

During 2009, the activities in gyrokinetic simulations have been centred in the comparison of EUTERPE and TORB codes.

The comparison of both codes was done both in linear and non-linear simulations of ion temperature gradient (ITG) turbulence in cylinder geometry. The influence of finite beta in the linear and also in the non-linear regimes was studied. Firstly, linear simulations in a theta pinch were carried out and the results were in good agreement with those obtained previously with TORB by Sorge et al. [Sorge04]. Linear simulations of in a screw pinch with W7-X physical parameters were also carried out and the influence of finite beta on the growth rate of ITG instabilities was found to resemble previous results for W7-X obtained by Kornilov et al. for W7-X geometry [Kornilov05]. The growth rates was observed to reduce as beta increases. [ICNSP09_EUTERPE Sanchez], [031].

III.4 TJ-II Engineering and Operation
III.4.1 Basic Machine Engineering

III.4.1.1 Introduction.

The engineering group of TJ-II has developed the following tasks in the TJ-II experiment:

- Technical operation of TJ-II device during the experimental campaigns that basically is to check the status of all the systems necessary to produce the pulses.

- Maintenance of the components of the device and its auxiliary systems to guarantee the availability of them.

- To implement the modifications to improve the performance of the experiments.

III.4.1.2 Technical operation of the TJ-II.

The technical operation of the experimental device TJ-II involves the participation of two engineers:

- The engineer in charge of the experiment itself and the auxiliaries except the power supply. He is responsible for: correct operation of the coil cooling system, the access control to the torus hall between the experiments, the grounding loop surveillance system, the starting of the pulse sequence and the supervision of the pulse results (coil currents, coil displacements due to the magnetic forces, etc.) and for the whole safety of the TJ-II.

- The engineer in charge of the power supply. He is responsible for: implementation of the currents in the coils within a precision around 0.1%, the correct operation of the pulse generator and its pony motor, the operation of the power rectifiers and the safety of the whole power supply and its auxiliary systems.

The operation of the machine in “Mode C” has started this year. The modification respect to normal pulses is that the current profiles in the coils are provided by the central control system (engineer in charge of the experiment) instead of being pre-programmed by the control of the power supply (engineer in charge of the power supply). The coil currents can be varied during the plasma pulses, i.e. they are not anymore a flat-top, and it allows the change of the rotational transform of the magnetic field structure during the plasma evolution.

The incidences occurred during the operations are documented in the operation books of the TJ-II. Two of them are filled each year. [on]

III.4.1.3 Maintenance tasks

The maintenance and inspection tasks during 2008 have been the following:
**Power supply.** The following annual maintenance works have been done:

- Control of the mechanical conditions of the motor-generator set (inspection of collector surface and brushes state of the motor and generator, check of the generator pole position, etc.)

- Rotor and the stator insulation measurements of the main machines (generator and pony motor).

- Check of the right functionality of the auxiliary systems (cooling, lubrication, etc.)

- Adjustment and test of the protection systems parameters of the motor-generator and power rectifiers.

- Insulation test and inspection of: power cables, 15 kV breakers, transformers and no-load DC switches.

- Cleaning of the all equipment.

**Cooling System.** The maintenance of the cooling plant has been done as planned. Different actions have been performed:

- Substitution of the sprinklers inside the cooling tower.

- Substitution of the mechanical seal of the pump installed in the hard HC coil system.

- Substitution of the deionized water system.

**Crane bridges.** The annual maintenance of the crane bridges installed in the different fusion buildings, e.g. TJ-II torus hall, cooling plant, and power supply system, has been performed.

**Control System:** The maintenance of the different Control Systems of the TJ-II has been performed. Periodic checks were made and some preventive maintenance tasks were conducted through, as e.g. calibration and test of the whole system channels, and repairing damage channels. The Control System instrumentation is splitted in four VME racks inside of the experimental room: to avoid aging problems, they have more than ten years old, all of them have been changed by new models.

**III.4.1.4 Power supply.**

**Reparation of the water cooling tower fan motor**

The two main machines of TJ-II power supply (the 132 MVA pulse generator and the 1.5 MW pony motor) are cooled by a water-cooling system. This system contains a 1.5 MW cooling tower located on the power supply building roof. At the end of the year, a malfunctioning of
the water cooling tower fan motor was detected. The isolation of the motor to ground was detected to be very low and the bearings were worn out. These damages have been provoked by the operation during more than ten years under very aggressive conditions. To avoid major damages to the system it was decided to rewind it and to change the bearings. Afterwards, the fan motor was properly tested and installed.

**Adjusting and preparation of the Radial Field Power Rectifier for TJ-II**

TJ-II Power supply contains seven power rectifiers for supplying the DC required currents to the seven TJ-II coils (TF, CC, HX1, HX2, VF, OH and R). All the coils are usually in operation during the plasma experiments except the Radial Field (R). This system was designed to be used to compensate possible error fields due to the lack of precision either in the manufacturing or the positioning in the rest of the coils. Since those mistakes never occurred, the Radial Field coils were never used for TJ-II experiments. Recently it was thought over the possibility to use the R coils to produce any additional effect in the magnetic field structure and it has been renewed and put in operation.

The Radial Field system produces a horizontal field up to 100 Gauss. It is supplied by a controlled rectifier with a maximum DC voltage of 200 V and maximum DC output current of 5.2 kA

During the first half of the year, the following tasks were carried out:

- Electronic control boards: all the rectifier control boards were checked; some of them were repaired and later on, all together were tested separately from the power rectifier.

- Power components of the rectifier: it was checked the proper operation of the following main components: 15kV circuit breaker, rectifier transformer, thyristor rectifier, HV&LV cables and DC no-load switch. Also, insulation tests were carried out to all of them.

- Control systems: fast current regulator and main PLC were checked.

- Load tests of the power rectifier with a dummy load up to the nominal current (5.2 kA).

- Load tests with Radial Field TJ-II Coil at full current.

The tests were successfully finished in June 2009. All these tasks were done with the help of an Erasmus Mundus programme student and resulted in his Master Thesis. [ENG_2]

**III.4.1.5 Cooling system**

A fail occurred in the circuit dedicated to the cooling of the central coils of TJ-II. When these coils operate with high current and long pulses, in order to avoid high thermal stresses inside the coils, it is necessary to start the cooling cycle after the TJ-II pulse with higher than normal temperature in the water. For this purpose the circuit has a reservoir with hot water (36 °C) and a mixing valve. The water available normally in the circuit (around 20 °C) is
mixed with the one in the reservoir and, in a 5 minutes ramp, is gradually reduced at the entrance of the coils from 32 °C at the beginning of the cooling cycle until 20 °C. Because of a fault in the electrical switch that connect the heating resistances of the reservoir, the resistances remained connected for too long time and very hot water reached some parts of the circuit. The following components were damaged and replaced:

- Electrical switch (initiator of the event).
- Instrumentation installed in the tank.
- Thermal isolation around the tank.
- Teflon sealing of different valves

Some actions have been initiated regarding the control system of the cooling plant,

- The control programme will be modified in order to implement an additional safety layer for the performance of the heating system of the tank.
- In the near future it is planned to change the PLC (SIEMENS) of the control system and move from Simatic S5 to S7 taking into account the S5 model is becoming obsolete.

### III.4.1.6 Control system

The tasks carried out during 2009 are mainly related to the wholemeal renovation and updating of the TJ-II control system. The main works during the year 2009 are described hereafter.

#### III.4.1.6.1 Software development

As the update process is gradual, both current and future real-time control systems must work simultaneously until this upgrade is completed. A new communication middleware architecture that implements X-MDS, XML-based Messages Distribution Service, has been developed and applied for this. It has been created in response to the need to standardize the message publish-subscribe programming model for the TJ-II distributed control systems. It permits data, events and commands to be sent and received between distributed control applications that run on different real-time operating systems (OS9 and VxWorks) as well as Java-based applications running on any Windows or Linux platform. It has been fully tested and found to be both reliable and safe. Specific software tools have been developed to create, manage and monitor any distributed control variables involved in TJ-II experiments.

Three embedded systems (fast control, gas inlet and diagnostic timers) have been update to use the new middleware software.
III.4.1.6.2 Fast Control system

Following the renewal strategy of the control system, which consists in gradually replacing each subsystem, the Fast Control system is now fully functional under the operating system vxWorks.

The most significant changes, according to foreseen plans, are the following ones:
- The system works under the new real time operating system vxWorks instead of OS9.
- The processor MVME147, 68040 @ 33 MHz, has been changed by the new one MVME5500, MPC7455 @ 1 GHz.
- The hard disk and the graphics card have been removed.

For graphical user interfaces we have developed a Java application which will act as main console of the TJ-II Control System. This interface has been developed using the communication middleware architecture (X-MDS). [ENG_3].

The system software has been completely redesigned. Protection functions, such as, checking of parameters, pulse dependencies, etc, are now running in the Java application. The embedded system takes care only of the real-time processes.

The tasks to be done during the sequence before the pulse: ECH system preparation, charging capacitor banks, loading of timers, preparing data acquisition, etc, are now performed from the Java application.

The system is presently in operation since about half a year and has proved to work properly. An accurate commissioning work has been necessary in order to interface it with all sub-systems.

A technical procedure has been published with a detailed description regarding the installation and configuration of the operating system vxWorks on the MVME5500 single-board computer. [ENG_4].

A display has been installed over the main entry door of the experimental room so as to inform about the state of the installation.

III.4.1.6.3 Installation and assessment of EPICS.

EPICS (Experimental Physics and Industrial Control System) has been chosen as baseline software for the ITER control system.

EPICS software has been installed and tested in order to prepare collaborations with IFMIF and the ITER projects. We have used Scientific Linux as operation system to accommodate EPICS.
Plasma operation activity in TJ-II during 2009 was organized in two experimental campaigns. The spring campaign proceeded between 4 February and 25 June, with 53 days of operation and 2068 shots. The autumn campaign took place between 28 October and 17 December with 22 days of operation and 868 shots. The main remarks that must be mentioned as regards TJ-II operation in 2009 are:

- The ECRH system has been operating routinely during 2009 with a high degree of reliability.
- From the campaign start in January through to the end of June, both injectors have been available, injecting Hydrogen beams of 32 kV energy, and average power of 450 kW. After the summer break, only Injector #1 was available, due to a water leak in the Plasma Grid of Injector #2.
- The EBW heating system was finally completed and commissioned during the summer shutdown. EBW heating experiments began at the end of October. So far, no clear proof of EBW heating has been obtained.
- Li coating by vacuum evaporation has been routinely used as plasma wall conditioning technique. The lithiumization process was done at the campaign start, on 4 February, and it was repeated five times along the spring campaign (16 March, 30 March, 20 April, 27 May and 8 June). At the end of this campaign the vacuum vessel was boronized to study the degree of “reversibility” of the wall conditioning. Similarly, lithiumization was performed four times during the autumn campaign.

A summary of the experimental sessions performed, along with the number of shots allocated to each experiment/activity, is listed below:

- Start-up, commissioning of control and data acquisition systems and diagnostics: two sessions, 47 shots
- Test of diagnostics: two sessions, 57 shots
- ECRH studies: calibration, power deposition profile (modulation) and ECCD experiments: one session, 52 shots
- NBI plasmas in H and He (experiments devoted to optimize the coupling of the neutral beam to the ECH target plasma: working gas, ECH providing on/off axis heating, electrode biasing, characterization after lithium coating): fourteen sessions, 537 shots
- Rotational transform and plasma volume scan in NBI plasmas: one session, 44 shots
- Impurity transport in NBI plasmas. Evolution of radiation profiles driven by external puff: six sessions, 257 shots
- Alfven activity in NBI plasmas: two sessions, 99 shots
- Studies of plasma rotation and shear flow in ECH and NBI plasmas: Doppler reflectometry: five sessions, 207 shots
- Dynamic configuration scan in ECH plasmas: four sessions, 133 shots
- 2D visualization of turbulence with fast cameras: one session, 27 shots
- Edge characterization and electric fields: Langmuir probes, fast cameras, electrode biasing: six sessions, 250 shots
- Impurity transport in ECH and NBI plasmas. Blow-off impurity injection: eight sessions, 336 shots
- Studies of causality between potential, flux and temperature: 1 session, 34 shots
- Magnetic well scan: four sessions, 102 shots
- L-H transition and magnetic configuration scan: six sessions, 278 shots
- Plasma wall studies: Impurity injection: five sessions, 210 shots
- Tests of EBW heating: seven sessions, 268 shots

III.4.2.1 ECRH in TJ-II

a) 53.2 GHz ECRH system

The ECRH system has been operating routinely during 2009 with a high degree of reliability. None of its main systems, i.e. internal mirrors for changing power deposition, high power modulators, cryomagnets or the high power supply \[013\], \[014\] that feeds both gyrotrons has suffer any mishap. The only drawback is the still unsolved problem that prevents the second gyrotron from reaching its full power regime, due to an arcing in the gyrotron window when the power exceeds 250 kW in long pulses (larger than 100 ms).

General maintenance and improvements tasks.

The main tasks concerning the improvement and the maintenance of the ECRH system that were carried out during 2009 are:

- The installation of the power measurement system components inside the TJ-II hall which are now remotely controlled from the ECRH control room. The calorimetric measurements of the 53.2 GHz gyrotrons and the 28 GHz gyrotron can be made simultaneously. This work has been carried out in the frame of the collaboration with PLASMA IOFAN Science and Technology Center, Moscow, Russia (Ref. 07/302).

- Improvement of the liquid nitrogen leakage system for the two gyrotrons of the 53.2 GHz system. This system helps to prevent the freezing of the surrounding components during the cryomagnets tank refilling. This work has been carried out in collaboration with the Institute of Applied Physics (Russian Academy of Science), Moscow and Nizhny Novgorod (Russia).
- Connection to the general TJ-II cameras system in order to increase human safety and operation reliability during ECRH tests.

- Other general tasks regarding the ECRH control system which are not detailed here.

\textbf{b) Changes in the gyrotron radiation properties induced by a small amount of reflected modulated power}

The basis for these experiments is the hypothesis that a low fraction of the gyrotron emitted power which is reflected back to its source with a thin metallic foil can strongly modify the gyrotron behaviour and produce a reaction on the output radiation. In the experiments, a small part of the gyrotron power is diverted towards the reflecting foil using two different mica foils with 6\% and 15\% reflection coefficients. Moreover, the reflecting foil can be modulated. The results obtained during 2009 considered the following situations:

- Scan of the phase of the reflected radiation (without modulation) by changing the position of the reflecting foil by fractions of a wavelength (\( \lambda = 5.64\) mm). A 12\% maximum variation of the gyrotron power is found.

- Scan of the delay between the start of the gyrotron emission and the reception of its own reflected power in order to investigate the reaction time of the generator (the gyrotron).

- Gyrotron power modulation for different positions and modulation frequencies of the reflecting foil.

The analysis of the different results is still underway and will be finally completed with future experiments. All experiments have been carried out with a 53.2 GHz gyrotron. This work has been carried out in collaboration with the Institute of Applied Physics (Russian Academy of Science), Moscow and Nizhny Novgorod (Russia).

\textbf{III.4.2.2 NBI Heating in TJ-II}

\textbf{III.4.2.2.1 NBI Operation}

From the campaign start in January through to the end of June, both injectors have been available, injecting Hydrogen beams of 32 kV energy, and average power of 450 kW. After the summer break, only Injector #1 was available, due to a water leak in the Plasma Grid of Injector #2.

\textit{Injector #1: Beam Injection}

The number of pulses per day ranged between 20 and 43. The injection parameters were 32 kV energy, 450 kW power, 100 ms pulse duration. The main problem affecting beam
reliability was the plasma instability that appears as a Anode 1 overcurrent (Anode 1 “Flip”). This plasma instability forbids the upgrade of beam parameters such as beam current and beam pulse length. [Flips]

Injector #2: Beam Injection

Injection parameters were 32 kV beam energy, 550 kW Port-Through Power, 100 ms pulse duration. Beam reliability was good, with only a small percentage of breaks. But energy coupling to the plasma was poorer than that of Injector #1.

During the summer break the duct pieces were dismounted in order to examine the graphite protections and the alignment of the Target Calorimeter. It was found a beam misalignment of 0.35 ° to the left and 0.4° downwards, due to a malfunctioning of the gimbal remote control system. This misalignment may be at the origin of the poor beam-plasma energy coupling. [Alin] [Teod]. After the summer pause, a water leak appeared in the Plasma Grid. The Ion Source was dismounted in order to clean the electrodes and replace the faulty grid. Operation of the Ion Source did not resume until January 2010.

III.4.2.2.2 NBI Maintenance

Injector #1: Maintenance

a) Ion Source

The main difficulty in trying to upgrade beam parameters is the instabilities that appear in Anode 1 current when trying to increase the pulse length beyond 100 ms or the extracted current beyond 45 A. In order to improve the stability of the Arc current three different problems have been addressed: the reliability of the piezoelectric valves, the cleanliness of the plasma and the design of the intermediate electrode called Copper Button.

The two piezoelectric valves (Ion Source and Neutralizer) were replaced in May. The vacuum tightness had been lost after many years of intensive operation, and valve operation was not reliable. As a result of the increase in gas load the Titanium gettering pumps were soon saturated after evaporation, and pressure in the tank and duct raised faster through the day of operation. Higher base pressure means higher beam reionization losses and higher cold gas fueling into TJ-II. As a result, density control in TJ-II was more difficult. After the valves were replaced in May, the titanium pumps started recovering its normal operation, and the pressure was in better control. Nevertheless, the plasma instabilities in the ion source were still present.

Plasma cleanliness: after the piezoelectric valves replacement showed no significant improvement of the Anode 1 Flip problem, it was decided to dismount and clean the plasma chambers (Cathode and Anode chambers). The filaments are made of tantalum wires with a
barium oxide coating. After some time of operation, the oxide flakes off, and ashes are found sticking on the liner walls. The electrodes were disassembled and cleaned. When beam operation resumed, the Anode 1 Flips showed only a moderate improvement.

The copper button is part of the intermediate electrode, its role being to stop the central current of electrons travelling to the Anode chamber. By design this electrode sits close to the Anode 1, and is thought to have a role in the Anode 1 instabilities. During the summer break a new copper button was fabricated at the Fusion Laboratory workshops with some improved features affecting geometry and water cooling efficiency. [CopButt]

Beam conditioning proceeded smoothly after the summer pause and in the operation weeks from October to December, reliability of the Ion Source #1 was excellent. Anode 1 flips do still occur but only at higher pulse lengths and current values, and with less deleterious effects.

Ion Source filaments were replaced in October. They are the first to be fabricated at home, and their behaviour is satisfactory.

b) Titanium pumps

After the piezoelectric valve problem was fixed the pumping speed of the Titanium gettering pumps did not fully recover its former values. Extensive maintenance of the pumps had not been undertaken since the summer of 2004 so wire replacement was needed.

During August, the four pumps were taken out of the beam box and fixed to supporting frames in the TJ-II hall. The wires were dismounted, the panels and mounting pieces cleaned. New wires were mounted on the four cells of each pump and some improvements were introduced in the wire supporting pieces aiming to avoid electric contact between neighbouring pairs.

The subsequent wire conditioning proceeded smoothly and pumping speed has reached the design values again.

Injector #2: Maintenance

a) Ion Source

a1) Copper Button: during the summer maintenance the Copper Button electrode was found to have a clogged cooling tube, therefore it was replaced with a new piece made at the Laboratory workshops.

a2) Iron Sleeve: similarly, the electrode called Iron Sleeve was found to have a deteriorated surface, and was replaced with a spare piece home repaired. [Iron]

a3) Plasma Grid: after the Ion Source cathode was complete it was mounted on the injector. During the subsequent conditioning a water leak appeared in the Plasma Grid, the
Ion Source had to be dismounted and fully disassembled. The Decel and Ground grids were thoroughly cleaned of the copper oxide layers, their curvature was checked. A spare Plasma Grid was cleaned and re-curved for a focal length of 4 m. The grids were later mounted and carefully aligned, accurate measurements of the Accel and Decel gaps were taken. The Ion Source was mounted again on the injector in December. [Rej]

III.4.2.2.3 NBI Upgrades

**Control & Instrumentation System**

- Reliability was improved by making the Timing System independent from the TJ-II Control System and replacing old fibre optic links with new ones.
- Security was increased by adding direct signals to the Interlock System (Variac Current Trip, Independent Crowbar Trip and Bias PS Trip) using faster fault detection mechanism and fibre optic links.
- Faster current sensors were introduced in the Crowbar System.
- Instrumentation in the HV Power Supply System was improved by replacing old Hall Effect current sensors with new ones and recalibrating the data channels voltage to frequency conversion stages.
- In the HV Power Supply System a PID controller was installed to monitor and regulate the power supply of the tetrodes' filaments. Additionally, new overcurrent protection sensors have been included at the exit of the Variac Transformers, that feed the HV Tetrode filaments.
- The Gas Injection System of injector #1 was improved by fitting a regulator into the piezo valve Power Supply.
- Two software analysis tools were developed using Labview. The first one integrates the signals from the Calorimeter Diagnostic and calculates the power of the neutral beam. The second one is capable of measuring from an ion gauge signal the pumping speed of our Primary Vacuum System.
- VESDA System: a ultra-sensitive particle-in-air detection system has been installed in the High Voltage areas, for the early detection of faults in electrical systems.

**Diagnostics**

- A Fast Ion Gauge prototype power supply was developed and tested on site.
- Target calorimeter of injector 2 was commissioned and used for the first time.
**Power Supplies**

- **Decel Power Supply:** A prototype of the regulator has been fabricated that is free from the noise problem that plagued NBI operation at Injector #2 commissioning.

  RS485 communication bus was installed in each local cubicle to allow remote control of the Vacuum System Instrumentation.

- **Core Snubber of Injector #2:** Four additional elements have been installed.

- **Grounding System:** A new distribution of the ground connections has been implemented.

- **High Voltage Power Supplies:** After last year's careful tuning of the switching tetrodes, the voltage drop during beam pulses at the tetrodes has been reduced to a satisfactory level. Nevertheless, a significant amount of “voltage sag” does still occur, that prevents beam voltage upgrades. In order to identify the origin of that “voltage sag” that occurs during beam pulses, a careful set of synchronised voltage measurements from the Power supplies building down to the High Voltage decks has been undertaken. These measurements show that most of the voltage drop takes place at the transformers and rectifiers at the Power Supply building. Further measurements are envisaged in order to help determine a future course of action.
IV. DEVELOPMENT OF MATERIAL SCIENCE AND ADVANCED MATERIALS FOR DEMO

IV.1 Functional materials

IV.1.1 Radiation evaluation of silica glasses

The results for isochronal thermal treatment up to 850 °C on seven silica samples of different origin and different OH content, previously gamma irradiated under identical conditions up to 11.6MGy, indicate that the OH and impurity contents play an important role in the thermal stability of E’ defects. In samples with high OH concentration the E’ defects are completely removed at a lower temperature than for silica with low OH content. In particular high purity KU1 showed the simplest annealing, and lowest annealing temperature (~ 400 °C). For the other silica grades, the existence of two different processes for E’ centre annihilation with different activation energies, detected by the change in the slope of the annealing curves about 400 °C, suggests the presence of different E’ centre variants. In terms of fusion applications, these results allow one to predict the optical transmission behaviour for possible candidate silicas over a wide temperature range, and in particular assess the possibility of in-situ annealing. [SILICA_1].

Also Electron Paramagnetic Resonance (EPR) studies have been carried out on gamma and neutron irradiated KU1 and KS-4V high purity quartz glasses and commercial silica Infrasil 301. Oxygen-related centres (POR and NBOHC) have been well characterized by means of electron paramagnetic resonance. [SILICA_2].

The evolution with gamma dose (from 6 kGy up to 20 MGy) of the E’ defects was studied in a batch of different types of silica irradiated at 100°C in the Nayade 60Co gamma pool installation at CIEMAT. Comparing with the evolution of this defect with dose in samples irradiated at 30°C, the initial rate of growth of these defects increases more rapidly than in the irradiation at 30°C. The main difference was observed for KU1 silica, the absorption reaches a maximum at about 2 MGy and then decreases at higher dose, the saturated absorption is lower than at 30°C for KU1, the transmission in the ultraviolet is improved in irradiations at 100°C. For other types of silica no improving was observed at 100°C.

IV.1.2 Radiation induced electrical currents on insulator surfaces

Insulator materials required for ITER and beyond must operate in a significant radiation field, extending well beyond the first wall. As a result, these materials will be subjected not only to neutron and gamma irradiation, but also to particle bombardment, due mainly to ionization of the residual gas and acceleration of the resulting ions by local electric fields. A systematic study was carried out on the main insulating candidate materials for ITER (Al2O3, SiO2, BeO, and AlN), in order to assess this potential surface degradation issue,
and clarify possible mechanisms. Severe surface optical and electrical degradation has previously been reported for these materials bombarded with H\(^+\), D\(^+\), and He\(^+\) ions, at different energies, temperatures, and dose rates, as well as for electron irradiation. In all cases, dramatic degradation has been found and related to loss of oxygen (nitrogen) from the implanted/irradiated zone due to preferential radiolytic anion sputtering.

A theoretical model has been developed [Morono1] to explain the surface electrical degradation of insulators under ion bombardment. Experimental data for silica bombarded with H\(^+\), D\(^+\), and He\(^+\) ions have been fitted to an expression for the surface conductivity. The model is based on the fact that the material band gap energy (E\(_g\)) is determined by the stoichiometry (ion concentration), i.e. the bonds present in the material. Therefore, if the stoichiometry changes, the bonds will be affected, and modify the band gap energy. It has been shown experimentally that the most electronegative ion (anion) is preferentially removed from the material surface during both ion and electron irradiation. So in this case, band gap energy of the material surface volume (E\(_g\)SZ) affected by the radiation will mainly depend on the most electronegative ion concentration in this region (C\(_S\) anion). Very good agreement between the experimental data and the theoretical model has been obtained, and a clear dependence of the sputtering cross-section on the bombarding ion mass has been identified.

IV.1.3 Production and characterization of Li silicates spheres

During 2009 the efforts over the production and characterization of the Li silicates spheres were addressed to check different synthesis processes. Depending of method is possible to introduce more or less lithium in a silicate and so, some procedures as mechanical milling, sol-gel, and Spray Dryer have been used. An exhaustive characterization has been carried out to identify the most appropriate method that combines rich lithium compounds and spherical sharpes.

The crystalline phases obtained by the different processes were analyzed by X-Ray Diffraction (XRD). And the IR spectra were also collected in the range of 400-4000 cm\(^{-1}\). Thermogravimetry (TG) and Differential Thermal Analysis (DTA) tests were performed from room temperature to 1200 ºC at 10 C/min to observe the evolution with the temperature.

The “as prepared” and the calcined powders were observed by SEM. Spray Dryer followed by heating have been demonstrate that it is possible to obtain sphere-like particles of lithium Ortho-silicate as unique phase, as can be seen in the fowolling figure.
IV.1.4 Conceptual design of LiPb loop for breeder blanket technology validations

A conceptual design of a loop has been generated in order to anticipate the detailed engineering of a new experimental facility in Spain. The lay-out fits dual-coolant blanket loops specifications through coupling LiPb and He loop in a 2 th-MW heated exchange module under 5 T magnetic field. A secondary SC-CO2 loop for He and LiPb primaries is included. Experimental goal of the new facility are: (1) to support with experimental data the design of dual-cooled breeding blanket modules in diverse aspects (fabrication, TM testing, MHD testing, EM control and tritium (as hydrogen) control), (2) to test and experimental qualify key effluents control instrumentation (e.g.: H partial pressure sensor) and processing technologies (e.g.: permeators against vacuum, cryotrap technology,...), (3) to test and experimental qualify key components under development (e.g. LiPb/SC-CO2 components) or supposed range adaptable (e.g.: EM pumps). The figure presents a conceptual lay-out for the proposed loop.
The proposal fits Spanish Programme goals for the development of underlying technologies for dual coolant breeding blankets and has an added major strategic value of supporting a EU support to US for the involvement of EU in a third ITER Test Blanket Module.

The proposed facility is considered as one of the major installation in the proposal of Barcelona Fusion Centre, b_Fus included in the map of fusion technology infrastructures to be built in Spain.

Based on the conceptual design in Figure X provided by CIEMAT, the loop engineering detailed design is at present being developed by a engineering company.

IV.2 Insulator materials for components development

IV.2.1 Characterization of new cable types (silica coatings)

During 2009 there was no specific task concerning TIEMF effects in cables, but activity was maintained through the participation of CIEMAT in the ITERMAG consortium agreement, with the final agreements and consolidation. Unfortunately during this year there was still no grant or contract approved by F4E concerning this R&D in irradiation effects in cables and prototype coils for magnetic diagnostics.

IV.2.2 Mirrors radiation resistance

To examine the stability of reflectivity and coatings following neutron irradiation it is necessary to overcome the problem of activation of the Pyrex glass substrate due to the boron content. Boron has a large low energy neutron capture cross-section and causes severe limitations for post irradiation examination. To surmount this difficulty prototype mirrors have been prepared with the standard Pyrex substrate support being replaced by high purity silica (KU1 and KS-4V from the Russian Federation). To avoid the SiO to SiO₂ conversion problem, in collaboration with ENEA the Al layer has been overcoated with SiO₂. X-ray Photoelectron Spectra (XPS) analysis of the surface was performed and showed the overcoating to be ≈ 100% SiO₂. The reflectivity of these prototypes mirrors from the ultraviolet to infrared was examined, showing high reflectivity.

The mirrors were then gamma irradiated in the CIEMAT ⁶⁰Co pool facility (Nayade) at 4 Gy/s and 170 °C in a dry nitrogen atmosphere up to 5 and 10 MGy. Following irradiation, no degradation in reflectivity was observed for the range 200 to 2500 nm. The mirrors have now been delivered to SCK/CEN Mol for irradiation in BR2.

IV.2.3 Window assemblies and seals, radiation enhanced T diffusion
Windows will be required for H&CD and many diagnostics in ITER. These form not only a vacuum, but also an important tritium barrier. Recent work has shown that radiation enhanced H isotope diffusion in candidate materials (alumina, sapphire, silica, diamond, BeO, AlN) will not be a serious problem. However, the question remained as to the bonding region between the different window materials and flanges, not only the mechanical integrity but also the possibility of diffusion through the modified interface. Prototype diagnostic window assemblies have already been manufactured and mechanically tested. The simplified window assemblies using the same bonding were tested, for radiation enhanced H isotope diffusion. Diffusion has been determined for 3 simplified windows consisting of crystal quartz with Al diffusion bond on 316 stainless steel, fused silica with Al diffusion bond on tantalum, and silicon nitride with Al diffusion bond on titanium. The different windows were mounted in a special chamber at the end of the beam line of a Van de Graaff accelerator with one window face in vacuum irradiated with 1.8 MeV electrons and the other subjected to deuterium or helium at 2000 mbar. Gas leakage through the window assembly was measured with a helium/hydrogen leak detector during irradiation at 200 Gy/s, ≤ 35 ºC. After irradiation the gas pressure was increased to 4000 mbar to check for possible mechanical failure of the assemblies. Optical absorption was also measured before and after irradiation. The results indicate extremely low enhanced diffusion for all 3 bondings.

IV.3 Nanostructured ODS ferritic steels development (ODSFS Task Agreement)

IV.3.1 Grain size and microstructure optimisation of nanostructured ODS steels

Reduced activation the ferritic/martensitic Fe-12 wt%Cr and Fe-12 wt%-0.4wt% Y₂O₃ alloys and the ferritic Fe-14 wt% Cr and Fe-14wt%Cr-0.3wt%Y₂O₃ alloys were characterized both in the as-HIPed state and after tempering by Transmission Electron Microscopy (TEM) and Atom-Probe Tomography (APT) [ODS1], [ODS2], [ODS3], [ODS4]. These alloys were produced by mechanical alloying and hot isostatic consolidation followed by either normalization and tempering or forging and tempering [ODS2], [ODS5], [ODS6].

The ferritic/martensitic Fe-12Cr alloys exhibited the characteristic microstructure of lath martensite and contained a high density of dislocations. Small voids with sizes <10 nm were also observed. Both alloys also contained M₆C and M₂₃C₆ carbides (M = Cr, Fe) probably as a result of C ingress during milling. After tempering at 1023 K for 4 h the microstructures had partially recovered. In the recovered regions, martensite laths were replaced by equiaxed grains in which M₂₃C₆ carbides decorated the grain boundaries. In the ODS alloy nanoparticles containing Y were commonly observed within grains, although they were also present at grain boundaries and adjacent to large carbides [ODS1]. In the case of the ferritic Fe-14Cr alloys, the effect of the milling atmosphere on the characteristics of the consolidated alloys was investigated [ODS4]. These alloys exhibited a submicron-grained structure and a homogeneous dispersion of oxide nanoparticles that enhanced the tensile properties in
comparison to the $Y_2O_3$ free alloy [ODS2], [ODS3]. The strengthening induced by the $Y_2O_3$ dispersion appears to be effective up to 873 K, at least [ODS2]. A uniform distribution of Cr-rich nanoparticles, stable upon a heat treatment at 1123 K for 2 h was also found in both alloys [ODS3], [ODS4].

The formation voids in ODS EUROFER processed by powder metallurgy, and their thermal stability, was also investigated using positron annihilation techniques [ODS5]. Non-ODS EUROFER 97 fabricated by Plansee was processed by Equal Channel Angular Pressing (ECAP) at 823 K for a total of 4 or 8 passes, using a die angle of 105°, and its microstructure and tensile behavior in temperature range 568-873 K investigated. A single ECAP pass induced a deformation texture {1 1 0};{0 1 1} that was practically stable during subsequent ECAP passes. The materials processed using 4 or 8 passes exhibited nearly equiaxial submicron grained structures with a high density of high-angle grain boundaries. These materials became softer than the as-received material at a testing temperature of ∼ 823 K. EUROFER ECAP processed under the present conditions exhibited hardening ratio somewhat higher than that of the as-received material, i.e tempered after normalizing [ODS6], [ODS7].

**IV.4 Tungsten and Tungsten Alloys Development (WWALLOY Task Agreement)**

**Brazing development**

The first part of the study consisted on the selection of a commercial high temperature brazing alloy to be applied for joining pure tungsten to pure tungsten (W-W) in the range a brazing temperature of 900 – 1200 °C. Among several candidates, a Ni alloy (Ni23Mn7Si5Cu) was selected. Although this alloy has high contents of high activation elements, such as Ni, the study of its brazeability in W-W joints was carried out to have a reference for the development of alternative brazing alloys. The second phase of the research was planned to design and manufacture these alternative brazing alloys constituted by low activation elements, with the objective to reach brazing temperatures up to 1200 °C. Two binary systems were tested: Ti-Cu and Ti-Fe. In the first case, Ti50Cu foils were manufactured by a powder metallurgy route working with two different processing states: green and sintered foils. In the second case, powders of Ti25Fe alloys were applied into the joints, as cold pressed foils, for brazing tests. The study consisted on the thermal characterization of commercial and developed alloys determining their melting temperature ranges. Studies of brazeability have been carried out by HPD laser systems and in a vacuum furnace. For the second method, two brazing temperatures were tested for each filler (25 and 50 °C higher than the liquidus temperature determined from the thermal analysis). The following table shows the tested temperatures:

<table>
<thead>
<tr>
<th>Material</th>
<th>Brazing temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

65 | Asociacion EURATOM-CIEMAT para Fusión. - *Annual Report 2009*
Obtained results showed that laser method have problems associated to the large temperature gradients originated in the welds which favour cracking during cooling. Better results were obtained with vacuum furnace tests. All the tested alloys were able to fill the joints for the tested conditions, producing continuous brazed welds in W-W sheets. Filler and filler-parent material microstructures have been characterized in all cases and a micromechanical evaluation of the hardening effects across the joints was also carried out by means of Vickers microhardness. The conclusions of these studies suggest that alloys of the Ti-Fe binary system with Fe compositions close to the eutectic point could be proper candidates for producing a low activation joint by vacuum brazing in W-W.

**IV.4.1 W-V and W-Ti ODS alloys development**

Laboratory batches of W-0.5%Y₂O₃, W-1%La₂O₃, ODS W-xTi-0.5%Y₂O₃ and ODS W-xV-1%La₂O₃ (wt %, and x=2 or 4) have been produced by mechanical alloying and subsequent consolidation by hot isostatic pressing. The description of the method applied to prepare these alloys has been reported in [WALL1], [WALL2], [WALL3], [WALL4]. The powders at each stage of the alloying processing, and the microstructure of the consolidated alloys, were analyzed. In order to optimize the properties of the alloys, the milling conditions were changed and the effect on the density, microhardness and microstructure of the consolidated alloys investigated. The microstructural characteristics and mechanical properties of these alloys can find in [WALL4], [WALL5], [WALL6]. The alloys have been delivered for their mechanical assessment by the ESTRUMAT group at the Polytechnic University of Madrid.

**IV.4.2 Oxidation resistant W-alloys development**

Tungsten is presently the main candidate material for the plasma exposed areas of DEMO. However, the use of tungsten as Plasma Face Materials (PFM) implies an important safety concern in case of an accident with loss of coolant and air ingress into the reactor vessel due to tungsten oxidation at high temperature with release of volatile radioactive tungsten oxides. A possible way for avoiding this would be the addition to tungsten of alloying elements forming a self-passivating oxide layer in the presence of oxygen at high temperatures.
temperatures. Powder metallurgy is a suitable route for the production of alloys of complex composition with the desired microstructure, while being a route of relatively low cost. The objectives of this task during 2009 were to explore the manufacturing of W-Cr-Si alloys by two routes: 1) mechanical alloying (MA) and sintering in hydrogen, 2) MA + HIP, and to produce first samples for oxidation measurements at IPP Garching. The results during 2009 can be summarized as follows: the first route was discarded because of lack of densification. First samples with different Cr and Si amount were produced by MA + HIPing obtaining a densification > 90%. MA was performed in a SPEX mill using vials of hardened steel and different MA parameters were studied to reduce contamination during milling. The microstructure and the existing phases were observed by FEG-SEM/FIB and XRD. Some of these samples were sent to IPP for further characterization (oxidation tests up to 1000°C, measurement of thermal conductivity).

IV.5 SiC materials

IV.5.1 Measurement of electrical properties

Studies of silicon carbide based ceramic composites for applications in fusion have been carried out for more than ten years, and although understanding of the basic radiation damage processes as well as microstructural evolution has shown significant advances, considerable further work is required to fully understand the physical mechanisms and varied irradiation effects for the different forms of SiC and SiCf/SiC. Clearly in order to improve the radiation behaviour of SiCf/SiC, one must fully understand the basic radiation response of the SiC matrix material.

Recent in-situ measurements for hot pressed (HP) SiC irradiated with 1.8 MeV electrons at 450 °C, have shown a significant reduction (order of magnitude) in the volume electrical conductivity, together with material amorphization for a relatively low ionizing dose (420 MGy), with essentially no displacement damage (6x10^{-5} dpa) [Moroño2]. For the HP SiC, the
role played by irradiation temperature and electric field has now been addressed during year 2009, with samples being irradiated at 290, 450, and 650 °C. Almost identical reduction in volume electrical conductivity is observed with no temperature dependence. In the case of irradiation without an electric field applied, conductivity reduction is larger. In addition to HP SiC, preliminary results for reaction bonded (RB) and CVD SiC have been obtained, which in contrast show initial rapid increases in electrical conductivity. The results not only highlight the important role of ionization and material type, but also suggest that some of the material modifications observed for neutron irradiation in experimental reactors may be due to the ionizing radiation.

IV.6 Materials modelling

IV.6.1 Radiation Effects Modelling and Experimental Validation (REMEV Task Agreement)

IV.6.1.1 Ab-initio based kinetic MC modelling of He and displacement accumulation

At the University of Alicante, a work was carried out on extending the object kinetic Monte Carlo (OKMC) model to include the effect of grain boundaries (GB) on defect accumulation and evolution. This work is part of the MAT-REMEV Task Agreement of 2008-2009 within the Radiation Effects and Experimental Validation.

The OKMC code was modified to include a single grain boundary in the simulation box as a first step. The GB is considered as a flat surface and does not include atomic details on the structure of the GB. The reason for such an approach is to maximize the efficiency of the calculations, such that the time scales on the order of the experimental one can still be modelled, and the validity of the models be tested. However, the interaction of defects with this surface and between defects close to the surface is different than those interactions in the bulk. The different energetics come from ab initio calculations performed by C. C. Fu and coworkers at CEA in Saclay. Therefore, the character of the grain boundary will be included in the model through the different energetics used. The details on the implementation and approached selected were described in the EFDA MAT-REMEV Meeting that took place in Massy in July 2009 [MCM_1].

Currently defects at GB move two-dimensionally in the grain boundary plane or can be detached from the GB to migrate again in the bulk. The species included at this moment in the simulations are vacancies and helium as well as their clusters. The migration mechanisms and values vary significantly between the bulk and at GB. The interactions of self-interstitials with GB will be added at a later stage, when enough information from ab initio calculations is available.
With this initial model, the concentration of defects in the bulk as compared to defects at GB was studied for a Σ3{112}(110) grain boundary and a homogeneous distribution of vacancies and helium. Different temperatures regimes are studied: 300K, 600K and 800K, as well as different He to vacancy ratios. The results of these calculations were presented in the second monitoring meeting of 2009 [MCM_2]. This second monitoring meeting of EFDA MATREMEV took place in November 2009 in Alicante and was attended by 21 researchers from the different associations. The agenda for the monitoring meeting can be found in [MCM_3].

Besides the work described above, the current model for pure Fe to Fe-Cr alloys have been extended. Two different approaches are taken. On one hand details of the interaction between self-interstitials and Cr atoms are explicitly included in the model to study the effect of Cr in the case of dilute Cr alloys under electron irradiation. On the other hand a more phenomenological approach is being followed to study the effect of Cr in Fe-Cr alloys of up to 12% Cr that have been irradiated by ions, in order to compare with the experimental work of M. Hernández-Mayoral from CIEMAT and D. Diaz from UPM.

IV.6.1.2 Rate theory modelling of He and displacement accumulation

(a) Simulation of Desorption of He

The Morishita experiment, which consists in a 8 keV implantation of He in Fe followed by a temperature ramp, was simulated with our Rate Theory model. In order to simulate the initial He profile due to a 8 keV implantation, and the corresponding damage, MARLOWE code which is based on the binary collision approximation, was used. The implanted He profile simulated for an energy of 8 keV in a polycrystalline structure indicates that a significant fraction of He atoms is channelled in polycrystalline Fe. Using the initial profiles of He, vacancies and interstitials obtained with MARLOWE, the desorption of He from Fe was simulated for different implantation doses, monitoring the He desorption rate as a function of temperature, as in the experiment. In agreement with experiment, our model predicts a clear structure of the desorption spectrum, evidencing thermally-activated mechanisms. In particular, our model successfully predicts the presence of a peak at T~400 K, as observed in the experimental data, and which is due to the dissociation of He\textsubscript{n} clusters [RT HE_1]. Our model also predicts that the desorption peaks appearing at higher temperature are due to the dissociation of various types of He\textsubscript{n}V\textsubscript{p} clusters.

(b) Influence of carbon on He kinetics

Using the rate theory approach, the interaction of carbon with He and point defects in Fe was implemented. Using input parameters from ab initio calculations, it was shown that the presence of carbon could significantly influence the kinetics of He in Fe. In particular, our model predicts that at low V/C ratio, most vacancies are trapped by carbon impurities at room temperature, which inhibits the growth of He\textsubscript{n}V\textsubscript{p} clusters at later stages, favouring the
(c) Simulation of He permeation in Fe

In order to reproduce permeation experiment of He in Fe and/or FeC, the different processes that take place at the surface were implemented in our Rate Theory model. Namely, these are adsorption, desorption, absorption and recombination. Using an estimate of the different energy barriers that characterize the surface properties, the He permeation was simulated for different conditions of pressure and temperature. A detailed analysis of the simulation results indicates that most complexes that form in the bulk during permeation are Heₙ clusters. This is not surprising since in this experiment there is no damage due to implantation, and thus, there is a very low vacancy concentration. This highly inhibits the trapping of He atoms by vacancies and favours the formation of pure He clusters.

IV.6.1.3 Experiments for modeling validation: He desorption in Fe and other model materials

In strong collaboration with University of the Basque Country (UPV-EHU) permeation experiments have been performed in pure and carbon doped iron. These samples were specially developed by EFDA to test simulation codes and were prepared at Ciemat and measured at UPV.

Results indicate that helium permeation is extremely low and, in fact, helium has not been detected, even with very long times under vacuum and at the maximum temperature (550 °C) available.

By the contrary, hydrogen was perfectly detected and values of permeation and diffusion could be obtained and are summarized in the following table:

<table>
<thead>
<tr>
<th>Transport parameters for H in pure Fe according to a non linear fitting taking (D) and (KS) as parameters ((T = 500 \text{[°C]}) and (p = 1012 \text{[mbar]}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Permeability</strong></td>
</tr>
<tr>
<td>(P = 1,43 \cdot 10^{-10} \text{[mol}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-0.5}])</td>
</tr>
<tr>
<td><strong>Permeated flux</strong></td>
</tr>
<tr>
<td>(J = 7,912 \cdot 10^{-5} \text{[mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1]})</td>
</tr>
<tr>
<td><strong>Diffusivity</strong></td>
</tr>
<tr>
<td>(D = 2,894 \cdot 10^{-9} \text{[m}^2\cdot\text{s}^{-1}])</td>
</tr>
<tr>
<td><strong>Sieverts’ constant</strong></td>
</tr>
<tr>
<td>(KS = 0,049 \text{[mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-0.5}])</td>
</tr>
</tbody>
</table>
These values are also important to evaluate and compare tritium permeation.

Future work includes ab-initio calculations to evaluate the energy barrier that exists for the adsorption process (from He(gas) to He into solid Fe) that would limit the incorporation of He in solid solution, because out-diffusion can be measured if He is pre-implanted in Fe. It is also planned to repeat this experiment using the same samples at an IPP facility (Germany) to be sure of these experimental results.

IV.6.1.4 Experiments for modelling validation: Resistivity measurements

Using the samples specially developed by EFDA it is intended to also test simulation codes in this case concerning the creation, transport and recombination of vacancies, interstitials and their clusters. In order to do this, samples must be first irradiated at low temperature, where mobility is very low. Measuring electrical resistivity recovery (RR) one can estimate the initial number of defects. Increasing the annealing temperature defect dynamics create new types of defects and annihilate others which is reflected in the resistivity change. As no experimental equipment was present, this year has been devoted to the construction of this set-up. A Janis continuous flow cryostat was purchased and prepared the coupling to the accelerator. Other experimental work include several tests of micro-welding of the four electrode wires (several laser micro-welding procedures were tested), sample preparation and manipulation (thickness of only some microns). A specific varnish with optimum thermal conductivity and high vacuum compatibility was also tested. With all these tests, a pre-sample holder has been designed. In the near future a better procedure must be found for the laser spot welding.

In parallel hardware and software for RR measurements are been developing.

As a second step, a conceptual design of another RR chamber has been done. In this case for very thin samples (of only a few microns). This work was presented at the EFDA materials MAT-REMEV monitoring meeting held at Alicante (19-20th November 2009).

IV.7 Remote handling

IV.7.1 Definition of needs for a general purpose RH test facility for Diagnostic port plugs

Completion of the 50% of the definition of a Test Facility for the test and validation of the Transfer Cask System (TCS) of ITER has been carried out as a parallel activity for the definition of RH Test Facility for Diagnostic Port Plugs. The specification of the crane(s),
viewing and illumination system, fixed structures, monitoring and sensor devices, and control system has been developed. A meeting and presentation ‘Remote Handling activities in CIEMAT and collaboration with ITER-NL’ for the ITER Organization RH leaders was given in FOM, The Netherlands, May 2009.

**IV.7.2 Conceptual design of EU TBM integral RH demonstration facility**

Test Blanket Modules (TBM) are safety components class-1. Thus, before installing in ITER, ITER IO will require experimental demonstration of an integral capability, to install, repair, manipulate, de-install and refurbish them. Together with some specific fabrication technique needed facility, a TBM integral RH demonstration installation is the only lacking facility in the EU to accomplish the scheduled TBM testing programme before installing in ITER.

In the context of TBM-Consortium of Associates agreement meeting, Ciemat expressed programmatic interest to host in the future an integral TBM RH demonstration facility. Under this prospective, CIEMAT launched with national resources (CDTI founding) an initial study during 2006 to review main design features of TBM systems and main TBM integration aspects together with Industry. Through yearly step-by-step studies, a conceptual design of the EU TBM RH demonstration facility and a building cost assessment for the facility has been generated. A scheme of the proposed facility can be found in Figure XX. The proposed facility is considered as one of the major installation in the proposal of Barcelona Fusion Centre, b_Fus included in the map of fusion technology infrastructures to be built in Spain.

During 2009 the last year this activity has been carried out in parallel with the involvement of CIEMAT in F4E specific grants on RH and integration tasks.
V. TRAINING, OUTREACH AND TECHNOLOGY TRANSFER ACTIONS. SOCIOECONOMICS STUDIES

V.1 V.1 Training activities under EFDA

V.1.1 Microwave Diagnostics Engineering in preparation for ITER (MDEI)

Part of the training has been devoted to operate the reflectometers at TJ-II stellarator, AM and Doppler reflectometer systems, and to learn about the required data processing techniques.

Besides, the trainee has performed feasibility studies for the installation of a new Doppler reflectometer working in the frequency band 50-75 GHz, which will allow to covering higher densities. It includes the study and design of the Gaussian antenna-mirror system. Preliminary studies show that the initial design location in TJ-II, though suitable for a conventional reflectometer, is inappropriate for a Doppler one. Presently, alternative geometry schemes and locations are under study.

V.1.2 GOT-EUROBREED programme

The programme, inserted in the Goal Oriented Training scheme, is focused on the preparation of experts in breeding blanket technologies. In particular, CIEMAT hired a trainee for developing WP7: “Training on tritium transport predictive modelling tool for Breeding Blanket design analyses and system modelling”.

Work started in the second half of 2009 and has developed around the following lines:

- Determination of H/D Solubility and Diffusivity in LiPb eutectic
- LIBRETTO-4 modelling Analyses
- Anti-Permeation Barriers Produced by Ionic Implantation

V.2 Outreach activities

Preparatory activities for the creation of a Plasma Physics Group in the RSEF

During last year, some activities devoted the cration of a Plasma Physics Group belonging to the Real Sociedad Española de Física (Spanish Physical Royal Society) were carried out. In particular, a large number of contacts with Spanish plasma physicist were...
established in order to include them in this working group. The contacts were so successful that about 100 scientist demonstrated interest to belong to the group, including fusion plasma and technological plasma physicists, computer scientists, chemists and engineers.

A general meeting with more than 50 attendees was hold at CIEMAT in order to establish the concrete actions to take for creating the group.

**Volunteer computing**

A stable desktop grid called Ibercivis ([http://www.ibercivis.es](http://www.ibercivis.es)) has been created in order to run fusion applications together with other codes belonging to different scientific disciplines. Ibercivis is based on BOINC (Berkeley Open Infrastructure for Network Computing) and uses the idle time of the home computers of people registered in Ibercivis. Presently, about 25,000 people are registered and one can access about 10,000 CPUs every day, which is a quite high computer power, provided that the codes that are running on Ibercivis are suitable for such an infrastructure: the task to solve must be composed of a large number of independent jobs, which cannot be longer than 40 or 45 minutes.

Ibercivis has been demonstrated as a fantastic tool to disseminate fusion (as well as other discipline applications) since people who are lending some CPU to some research activity become really interested by such an activity. Volunteer computing has played an important role in the support that Spanish society devotes to Fusion research.[paper_ibercivis]

### V.3 Socioeconomic studies

#### V.3.1 External cost of Energy Sources: EFDA-TIMES model

**Activity 1: Integration**

Update of the resources (fossil and renewable) and test of the model, assessment of results and contribution to the identification of sectors requiring adjustments.

**Activity 2: Validation**

Definition of validation scenarios, assessment of results.

This task is the continuation of the work started the previous year whose objective was to review, validate, improve and document the fossil and renewable resource potentials for the different regions of the EFDA-TIMES based on literature and databases.

Other objective consisted of performing model testings and assessing the results. Some sectors requiring adjustments were identified.
This kind of work involves the constant updated of VEDA templates and scenario files.

**Activity 3: Supporting tasks**

Model documentation.

A final report has been prepared gathering both, a synthesis introducing the model and identifying all the documents produced in the previous tasks, and a technical report with techno-economic data for all the technologies [EFDA].

The report is divided into two parts. The first part contains the introduction to the model and the identification of the different documents part of this model documentation. The second part deals with the technical part of the model describing the techno-economic data included in it.

A series of excel sheets have also been prepared and are also enclosed with the information of all the power generation technologies.

**Activity 4: Joint Reference Publication**

Draft publication

CIEMAT has coordinated the preparation of a joint reference publication on EFDA-TIMES. The first draft is finished waiting for the authors' review.

Besides, CIEMAT has prepared and sent a long abstract to the International Energy Workshop that will be held in June 2010 with the title “The possible role of fusion power in a future sustainable global energy system using the EFDA Times global energy model”.

CIEMAT has also collaborated in other presentation to the International Atomic Energy Agency Conference on Fusion Energy to be held in October 2010, with the title “The Potential Role for Fusion Power in Future Energy Markets”

Finally, CIEMAT continued collaborating with the other teams of EFDA and attending the working sessions in Garching.

**V.3.2 Social perception of Fusion research**

Towards a participative dialogue with society about the risks associated with fusion energy (WP08-SER-AWF) The EFDA (2008) Ad-Hoc Group on Socio-Economics identified a need to move towards creating a dialogue with society about the risks associated with fusion energy. Ciemat and Cardiff University proposed work that will make a significant contribution towards this overall objective by: Understanding and assessing stakeholders’ perception of fusion technology and fusion energy; and Identifying appropriate communication channels and participative methodologies. To do so, the team relied on both
the previous Ciemat-Cardiff University EFDA work, and on additional research on which we are collaborating, which is being funded by the UK Economic & Social Research Council (ESRC). This latter project, which will run until February 2010, has been using the same hybrid methodology to collect data in the UK.

In this way, a comparative corpus of data was generated, making possible a (limited) cross-cultural Spanish-UK analysis. We then implemented a thorough comparative analysis of the two corpora of data. Finally, we used the resulting cross-cultural understanding of lay reasoning about fusion in order to identify practical communication and participation options for the implementation of a societal dialogue about fusion. This latter activity entailed a detailed examination of existing best international practice for citizen engagement. The Final Report of this Task was sent to EFDA in December 2009.

The main findings of the comparative work were presented in the Annual Meeting of the Society for Risk Analysis Europe, held in Sweden [WP09-SER-AWF_1], were published as a Ciemat Technical Report [WP09-SER-AWF_2], and have just been approved for publication in Public Understanding of Science [WP09-SER-AWF_3].

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VI. INERTIAL CONFINEMENT FUSION KEEP IN TOUCH ACTIVITIES

VI.1 Scientific development in target design

VI.1.1 Radiation hydrodynamics and jet impact fast ignition

We have continued the work already done in code developing and physics simulation. Advances in the parallelization of ARWEN have been obtained. The HIPS library (HIPS (Hierarchical Iterative Parallel Solver, Jeremie Gaidamour and Pascal Henon, http://hips.gforge.inria.fr/) has been used to solve the thermal diffusion equation. This library uses advanced methods to solve linear systems in parallel computers. With this improvement, another step towards the fully parallelization of the ARWEN code has been done. In addition to this, the study of plasma amplifiers of coherent soft x-ray radiation has continued, finishing the research started in 2008 about the influence of the plasma width in the performance of the amplifiers. Briefly, the improvement of computational tools (i.e. the ARWEN code) has continued, with the parallelization of the thermal conduction part of the code using libraries thoroughly benchmarked. The code has been used to study the evolution of plasma amplifiers of coherent X-ray radiation, resulting in several peer-reviewed papers and presentation in congresses, [REF_RAD_HYD_1], [REF_RAD_HYD_2], [REF_RAD_HYD_3], [REF_RAD_HYD_4].

A study has been performed of equation of state and transport properties for hot dense matter and warm dense matter in which a fitting of a global equation of state to the available experimental shockwave data and ab initio molecular dynamics simulations to improve the accuracy has been performed. The applications are focused in fast ignition (HiPER project), x-ray secondary sources (ELI project) and laboratory astrophysics simulations, an article and paper has been submitted for presentation at HEDLA2010 en Pasadena titled “Equation of State for laboratory astrophysics applications”. Collaboration with French, Polish and Czech Republic are under way and work will be published for HiPER related target design.

VI.1.2 Atomic Physics

We obtain analytical expressions for the radiative opacity of several low Z plasmas (He, Li, Be, and B) in a wide range of temperature and densities. These formulas are obtained fitting the proposed formula to mean opacities data computed by using the code ABAKO/RAPCAL. This code has been successfully validated in the range of interest in previous works [REF_ATOMIC_1]. An analysis of the influence of the atomic description and the configuration interaction effects in the calculation of plasma average ionization and relevant plasma radiative properties such as the spectrally resolved emissivities and opacities, radiative power...
losses and mean opacities has been performed. A wide range of plasma densities is considered, covering these way different plasma thermodynamic regimes [REF_ATOMIC_2].

We discuss the modeling of population kinetics of nonequilibrium steady-state plasmas using a collisionalradiativemodel and code based on analytical rates, ABAKO. ABAKO can be applied to low-to-high Z ions for a wide range of laboratory plasma conditions: coronal, local thermodynamic equilibrium or nonlocal thermodynamic equilibrium, and optically thin or thick plasmas. ABAKO combines a set of analytical approximations to atomic rates, which yield substantial savings in computer running time, still comparing well with more elaborate codes and experimental data. A simple approximation to calculate the electron capture cross section in terms of the collisional excitation cross section has been adapted to work in a detailed-configuration accounting approach, thus allowing autoionizing states to be explicitly included in the kinetics in a fast and efficient way. Radiation transport effects in the atomic kinetics due to line trapping in the plasma are taken into account via geometry-dependent escape factors. Since the kinetics problem often involves very large sparse matrices, an iterative method is used to perform the matrix inversion. In order to illustrate the capabilities of the model, we present a number of results which show that the ABAKO compares well with customized models and simulations of ion population distribution. The utility of ABAKO for plasma spectroscopic application is also outlined [REF_ATOMIC_3].

A flexible computation package for calculating radiative properties for low and high Z optically thin and thick plasmas has been presented, both under local thermodynamic equilibrium and non-local thermodynamic equilibrium conditions, named RAPCAL. This code has been developed with the aim of providing accurate radiative properties for low and medium Z plasmas within the context of detailed level accounting approach and for heavy elements under the detailed configuration accounting approach. In order to show the capabilities of the code, there are presented calculations of some radiative properties for carbon, aluminium, krypton and xenon plasmas under local thermodynamic and non-local thermodynamic equilibrium conditions [REF_ATOMIC_4].

International collaboration was kept during this time mainly with European laboratories as: Laboratoire de l’Utilisation des Lasers Intense (LULI), Ecole Polytechnique (France), Imperial College, University of Czech Republic; also with laboratories and universities in USA, as: University of Reno, University of Michigan (Paul Drake’s laboratory), Lawrence Livermore National Laboratory and University of Rochester. Special relationship has been started with Osaka University, in the area of photoionized plasmas, determining opacities for gold and xenon. In parallel, comparison of atomic data for experiments in photoionized plasmas were done during a visit to the University of Michigan (Paul Drake’s laboratory), and multigroup opacities for hydrocodes were obtained.

VI.2 Materials for IFE (and (MFE) under irradiation
VI.2.1 Radiation Damage and Chamber Dynamics for IFE

We have developed an Object kinetic Monte Carlo (OKMC) model of nucleation of He-vacancy complexes under irradiation of Nickel. The model has been constructed using the existing atomistic information on migration energies and binding energies of vacancies, self-interstitials and He-vacancy interactions, as well as He migration from embedded atom interatomic potentials. We focused our work on He effects in fcc materials, known to be more prone to swelling, and in particular in Nickel, used as a surrogate material for austenitic steel. Firstly, we study defect production in Ni under electron irradiation and compare to existing experimental data as a validation model. The isochronal annealing of electron irradiated Ni has been studied in order to obtain different annealing stages and compared with experimental observations. With these calculations we have validated the values of migration and binding energies of defects used in the model. Secondly, this model described for vacancies and self-interstitials in Ni has been extended to include He and the formation of He-vacancies clusters in the conditions of the experiments. We study the desorption of He from Ni to understand the nucleation and stability of He-vacancies complexes. For the case of Nickel, the defects that are include in the model are vacancies and self-interstitials, including clusters of these effects, He at an interstitial position and He,V$_n$ clusters, where is $n$ the number of He in the cluster and $m$ is the number of vacancies. The results of the model are compared with experimental data for low and high dose of implanted He in Ni. The influence of self-interstitial mobility on He desorption has been study and the conclusions of these simulations are that the assumptions made in the model for the mobility of self-interstitials affect significantly the He desorption spectra in Ni, and could be used as an indirect validation of the mobility of self-interstitials in fcc Ni [REF_MAT_1], [REF_MAT_2].

We have just developed also an Object kinetic Monte Carlo (OKMC) model for dilute (less than 1%Cr) FeCr alloys. The already existing model is capable of reproducing defect recovery stages during isochronal annealing in high purity Fe in accordance with resistivity measurements after electron irradiation. Keeping original parameterization for Fe, this model is modified to include effects of Cr on the mobility of radiation defects, using information obtained either from density functional theory or molecular dynamics calculations. The main goal of this work is to identify the most relevant parameters determining the role of Cr in microstructure evolution during irradiation and subsequent annealing, so that an efficient OKMC model to study damage accumulation up to doses and times measured experimentally can be built. The simulations follow the experimental trend in terms of temperature shift but a difference between height of the peaks for pure iron and Fe-Cr alloy is now under study. Further work is underway to study both Cr concentration dependence and dose dependence [REF_MAT_3].

In fusion environments Vitreous silica will be exposed to high radiation fields, both neutrons (with energy up to 14 MeV) and gamma rays and radiation induces changes in optical properties (final optics). At the present time there is abundant experimental information on different defects and their optical properties. In spite of this, we have
to increase their knowledge and evolution under irradiation; and, in particular, the number of MD studies in oxides and amorphous systems, is reduced. The objective of our work was to study by MD the lattice structure modification and the defects variation that occur in fused silica produced by radiation. To analyze the defects in presence of H atoms we generated the simulation box with a 1% of H atoms. These H atoms were implanted randomly into the materials, in those positions that do not coincide with other atoms of the lattice; the annealing process lets H atoms to move to their more stable positions in the bulk of the simulation box. It is possible the production of defects as a function of the PKA energy, and they have been identified. The defects in presence of H atoms are basically of two types. It is absolutely clear that in both kinds of defects, the number of defects, both without H atoms and with H atoms, increases with increasing PKA energy [REF_MAT_4].

The Institute has contributed in the review of results of a recent substantial effort focused on understanding the fundamentals of radiation damage infusion materials, and on the development of quantitative mathematical models for the observed effects. The EU fusion materials modelling programme has succeeded in bringing together a diverse group of experts in materials modelling whose work already addressed many issues of practical significance, and has developed close links with experimental work. We expect that the commissioning of new materials testing facilities, especially accelerator facilities for multiple ion beam irradiation, and further extensive interaction with experimental groups will enhance the future role played by mathematical modelling in the fusion materials and technology programmes [REF_MAT_5].

Work has been performed [REF_MAT_6] to test whether a new version of the concentration dependent model (CDM) potential (at LLNL/USA) could be used in radiation damage studies. We have implemented the 2BM and the new version of the CDM potential in our simulation programs and performed a comparative study between them. Vacancy and interstitial formation energies in pure bcc Cr and in pure bcc Fe are calculated. Differences between these two potentials can be observed mainly in Fe-Cr and Cr-Cr interstitials in pure bcc Fe. We have also calculated formation and binding energies for some Cr clusters. The main conclusion we can obtain of all these calculations point to the fact that the CDM potential can be used in radiation damage studies for ferritic alloys. Next, we have studied the vacancy formation energy dependence on Cr concentration using the CDM potential. We have performed calculations of vacancy formation energies for concentrations from 1 up to 17% and for each concentration we have performed calculations for four different and random Cr distributions.

Atomistic simulations, using advanced Molecular Dynamics and computational methods, will play a crucial role in the task of defining new advance materials under high pressure in target design for IFE. We did calculations [REF_MAT_7] and sent article; there were also presentations of work inside the Preparatory Phase of ESFRI HiPER project) of nonequilibrium Molecular Dynamics simulations, by means of empirical potentials, able to cover similar times and length scales as laser-shock experiments. Our results try to fill the present
gap providing detailed information at the atomic scale for the mechanisms of lattice deformation, plasticity, dislocations and relaxation in the response to wave propagation. First benchmarks involve materials ranging from single crystal structures to more complex nanostructures (nanocrystals) or nano-porous materials.

A wise selection of wall material and radius of the chamber for IFE system in next phase post ignition after NIF in repetitive regime (such as HiPER in Europe, LIFE in ISA and LIFT in Japan) has been started in order to minimize the received damage so that the facility can be fully functional during its planned lifetime. The effect of protection (LIFE) or not protected wall depending of operation conditions (in HiPER) is being assessed in Final Optics and Wall Materials calculation. The figure of merit for both x-ray and charged particle threats is the maximum fluence, J/cm² that the chamber components can resist without risk of failure. It is of paramount importance to understand that this upper limit comes determined by how these particles deposit their energy spatially and temporally on the materials. Results in this consideration have started to be presented [REF MAT 8] (IFSA, and HiPER meetings and expected articles in new year 2010) related to different materials and operation modes. Two other key threats need to be considered, i.e. laser fluence on walls and the impact of debris and Shrapnel. The former will depend very much on the conversion efficiency of the doubling and tripling crystals used in the path of the fundamental laser wavelength. Fluences on walls of more that 1 J/cm² of unconverted laser wavelength should not be allowed. The latter, directly related to the target design (geometry and composition), will probably be the principal menace to the final optics. At the moment, it is the most unexplored thread to be tackled. In these areas large collaboration is established with LLNL (USA), ILE Osaka (Japan), RAL STFC (UK), CEA France, SCK Mol Belgium, Academy of Science Check Republic, PSI Switzerland.

VI.2.2 Safety and RadioProtection

Technologies of high repetition rate (up to 10 Hz), which are critical in the path to Power Systems in IFE, such as those proposed in HiPER in Europe, LIFT in Japan or LIFE in USA, are critical for realistic implementation. The aspect related to safety and radioprotection under study are: material definition for the chamber reaction, definition of the shielding of the chamber, shielding of the final optics assembly and shielding of the target bay; damage to reaction chamber, electronics, disposable lenses and final optic assembly. The computational methodology to address these issues has been already implemented and some results have been obtained. With regards to materials for the chamber, the aluminum alloy 5083 used in NIF could not be appropriate under the HiPER irradiation scenario. Commercial and reduced activation steels are under study, and preliminary results indicate that commercial steels could offer an attractive response in terms of maintenance during operation and waste management. As for impurities, it seems that they will not represent a restrictive problem for the activation of the chamber. As for shielding, the neutron and gamma yields produced during operation make necessary a system of different shielding to protect the different parts.
of the facility. Starting with the model of the NIF chamber shielding, calculations will be done to shield the chamber, the final optic assembly and the target bay, including special shielded areas for electronics. Reports for HiPER Project have been produced and several presentations in Meetings of such Project to be published along 2010.
VII. OTHER ACTIVITIES

VII.1 Activities related to the Broader Approach

VII.1.1 IFMIF/EVEDA Project

VII.1.1.1 Accelerator Facilities: RF Power system

The radiofrequency (RF) Power System contains all the equipment necessary to generate the required conditioned RF power for input to the IFMIF-EVEDA accelerator cavities. These cavities demand 18 RF Chains working at 175 MHz distributed as follows: eight 200kW chains for RFQ cavity, two 105kW chains for the MEBT cavities and another eight 105kW chains for the SRF Linac.

An additional 200kW chain will be manufactured, it will be the first manufactured chain and it will be installed and extensively tested in CIEMAT/Spain in order to demonstrate its full capabilities. This RF Chain will be used also for the testing and conditioning of the SRF Linac couplers and will be permanently available during the complete duration of the project.

Description of the work performed in 2009:

HV Anode Power supplies: the Anode HVPS Technical Specification was finished on February 2009 and sent to Accelerator System Group. Later on, it was presented during RF System Preliminary Design Review (PDR).

RF tubes (Driver and Final): the RF Tubes Technical Specification was also presented during RF System PDR. The procurement proceedings began on December 2009.

RF Power System Procurement Arrangement (PA): many different modifications have been done to this document along the year. Finally, the PA has been approved on January 2010.

RF Power System Preliminary Design Review (PDR): the RF System PDR was held on April 2009. So, the preliminary design of the different components was finished during the first months of 2009. That includes the preliminary design of:

All the main components of each RF chain including their technical specifications: power supplies, RF amplifiers, LLRF, circulators, circulators loads, RF coaxial lines at all the stages, directional couplers...

RF module
RF Cooling system
RF Local Control system
The experts recommended a list of minor issues and made clear that no major show-stoppers had been identified.

**Low Level RF (LLRF):** the integration process of the prototype LLRF main components began at the beginning of 2009 and the tests at low power were successfully passed in May.

**Low Power Commercial Power Supplies:** during the last trimester of 2009, a new configuration of commercial power supplies (PS for filament, screen & control grids...) has been studied, taking into account more different manufacturer.

**VII.1.1.2 Accelerator Facilities: Beam Dump & High Energy Beam Transport (HEBT) Line**

The work on beam dynamics simulations of the HEBT line continued during 2009 [BD1]. The effect of errors in the different line elements has been studied. The results of these simulations served to define the tolerances on magnet alignment, the power supply requirements and the minimum beam tube radius necessary to avoid particle losses.

A preliminary design of the magnets (8 quadrupoles, dipole and steerers) has been performed based on both 2D and 3D calculations. To simplify the manufacturing, only three types of quadrupoles (for the first triplet, the doublet and the last triplet) have been considered. A detailed study of the different options for the 30 G.m orbit correctors has also been performed.

With regard to the auxiliary systems, a preliminary proposal for the vacuum system has been made.

Concerning the beam dump design [BD2], the main activities developed have been the following:

- Sensitivity studies of the thermomechanical behavior of the beam dump to variations on the input beam parameters, to define the acceptable working range of the beam dump.
- Extensive simulations of the water flow through the cooling channel, with special emphasis on the possible critical points.
- Study of the possible inner cone manufacturing technologies and market survey of different companies and workshops. Two techniques have been found to be feasible: 1) several pieces welded by electron beam and 2) manufacture it in a single piece by electrodeposition.

A preliminary local shielding design based on a water tank has been found to strongly reduce the neutron doses but it has been shown to be insufficient to fulfill the dose limits at some locations outside the accelerator vault.

All these aspects were shown in a Preliminary Design Review which was held on 27th-28th April 2009. During the second half of 2009 an optimization of the local shielding has been...
performed. Also, first studies of mechanical properties, composition and microstructure of electrodeposited copper have been made. Several aspects of the detailed design of the cartridge have been addressed such as the support of the inner cone tip and the flange connecting the beam dump to the beam line.

VII.1.1.3 Accelerator Facilities: Diagnostic

Two different FPM prototypes have been designed and procurement of prototype components has been completed during 2009. One prototype is based on a customized radiation hard camera coupled to an intensifier (ICID) and other based on a PMT linear array mounted on a hardware driver. Mechanical design of support structures for the beam profilers prototypes has been finished and is expected to be manufactured beginning 2010. [Diag 1].

A program developed in Matlab environment has been written to acquire images from the camera-based prototype and to treat the signal including background/noise reduction algorithms and profile generation. A modelling code has been written also to estimate the number of photons, image size and resolution expected in front of the detector as a function of the main parameters involved (beam-detector distance, lens parameters, beam parameters...) to help in the design of the monitors.

A detailed mechanical design and post-manufacturing of a prototype vacuum chamber has been built in the first half of 2009 and will be used during the monitor tests (first half of 2010). The support structure of all diagnostics (called Diagnostic Plate) and the interface between diagnostics and the vacuum chamber are being designed at present.

Preliminary design of the cryogenic beam position monitors. Fabrication of buttons for the prototype was launched and it is expected to receive them for tests at the beginning of 2010 (after several months of delay from the manufacturer). In parallel, the integration of the BPM in the solenoid package went on, and a 3D model is designed.

Work was done also on the mechanical design of the MEBT BPMs. A similar design to the SPIRAL2 BPMs was chosen, with the feedthroughs inserted between the gaps of the iron yoke for the quadrupole coils. A capacitive type pickup is chosen to maximize the signal strength. The result of the comparison of the pickup response with theoretical or simulated models was presented during DIPAC 2009. [Diag 2].

Two test benches are also in development at CIEMAT. One especially devoted to the determination of the capacitance of the cryogenic BPMs has been already fabricated, and another one based on a wire setup to measure the linearity and resolution of all the BPMs has been already designed.

VII.1.1.4 Accelerator Facilities: DTL & MS
Solenoid package

A preliminary design of the sc solenoid with passive shielding was presented during the SRF PDR held in Saclay in July. After the feedback from the reviewers, a second solution based on superconducting solenoid with a nominal current of 220 A and an active shielding is finally chosen. On-axis field profile is compatible with beam optics requirements. The solenoid and the correction coils are spaced of some millimeters gap, in order to facilitate cooling with liquid helium and assembly. Resistive copper current leads are also proposed (3 pairs per magnet). The maximum on-axis field integral for the solenoid is 1 T.m. The fringe field at the cavity flange location was optimized in order to stay lower than 20 mT. The overall length of the helium vessel from flange to flange is 400 mm. The horizontal and vertical correction coils (also called steerers) are cos-θ type, with a maximum integrated field of 2.5 mT.m. They will be integrated in same helium vessel than the solenoid coils, sitting on the outer surface of the main solenoid. Conduction-cooled copper current leads seem the simplest solution, which means a low nominal current (~ 50 A). Simulations showed the signal level for the proposed type of BPM's is good enough for beam position and phase detection even for low-energy beam.

RF test bench

A preliminary definition of the RF couplers testbench has been done after discussing with specialists from various european laboratories and with CEA colleagues. It has been decided to test the couplers in pairs both in travelling and standing wave modes.

Matching section

The first half of the year was devoted to the design of the components of the beamline: quadrupoles (with steerers), bunchers and BPMs. Several types of quadrupoles were studied, but problems were found to keep the beam dynamics specifications of the steerers. In the case of the bunchers, the study was focused on the optimization of the electromagnetic design of the pillbox buncher proposed by CEA-Saclay, and the thermomechanical design studies. A Design Orientation Review was held in May in which a complete conceptual design of the MEBT was presented. During this design several critical points were detected, like the magnetic quadrupoles and steerers, or the power consumption of the buncher. Following the recommendations of the review, a new layout was presented later. The specifications for the quadrupoles and steerers were relaxed whilst the specifications for the buncher remained unchanged. The second half of the year was devoted then to design and optimize the components for this new version. Finally, the steerers were inserted inside the quads to fulfill the length specifications of the MEBT. In the case of the bunchers, several types of resonant cavities were studied in order to reduce the power consumption of the pillbox type. QWR structures were first simulated electromagnetically and coupled to thermomechanical simulations. Cooling issues were detected in the stem due to the power density. The beamline vacuum was studied, placing one pump at each buncher cavity. Pressure profile curves have been issued analyzing the vacuum quality along the beamline. The integration of the BPMs in the middle of the magnet was also solved, using same principle of the SPIRAL2 BPMs, with
the feedthroughs placed in the gaps at the iron yoke for the coils. A preliminary design of the MEBT was presented in the beginning of January 2010, in a PDR held together with the HEBT in CIEMAT. As the bunchers studies did not finish in time for the review, it was decided to hold a separate review for that system in the forthcoming months.

VII.1.1.5 Accelerator Facilities: Radioprotection

The activities related to radioprotection of the EVEDA/IFMIF facility have addressed several issues associated to deuteron losses effect on the accelerating component of the EVEDA/IFMIF accelerator [EVEDA_1] and radioprotection analysis for EVEDA/IFMIF beam dump design [EVEDA_2]. Those activities dealt with the following issues:

Evaluation of nuclear data: nuclear data from appropriate models have been compared among themselves and with available experimental results. The examined data consisted of neutron production and activation cross sections by deuterons of materials relevant to EVEDA facility. The results allowed defining scaling factors to fit experimental data using best available transport codes.

Implementation of deuterium into copper: new and more detailed implantation and steady state deuterium profiles have been developed by making a coupled use of the SRIM and TMAP7 with semiempirical diffusion coefficients. These profiles are essential in order to accurately evaluate the neutron source from implanted deuterium under deuteron irradiation.

Shield design for beam stop: a preliminary radiological shield for the beam stop has been designed and reported considering operation and maintenance phases. Taking into account the strong neutron source from the beam stop during operation, the design has been based on low-Z low-cost materials (water). The preliminary design proved to strongly reduce dose rates outside the accelerator vault, but insufficiently to comply with local (Japanese) regulations. With the basis of this preliminary data, a new shield design (not yet published) has been created with successful results.

VII.1.1.6 Test and Target activities: Modelling Li behaviour in the target

No activities related to this issue have been performed during 2009.

VII.1.1.7 Test and Target Activities: Radiation effects on IFMIF Target diagnostics

Diagnostics for the lithium target will be crucial for the operation of IFMIF. Several parameters as the lithium temperature, target thickness or wave pattern must be monitored during operation. Radiation effects may produce malfunctioning in any of these diagnostics due to the exposure to high radiation fields. The main diagnostic systems proposed for the
operation of IFMIF are periodically reviewed from the point of view of radiation damage. The main tools for the assessment of the performance of these diagnostics are the neutronics calculations by using specialised codes and the information accumulated during the last decades on the radiation effects in functional materials, components and diagnostics for ITER. This analysis allows us to conclude that the design of some of the diagnostic systems must be revised to assure the high availability required for the target system. The main conclusions regarding radiation spectra and flux expected at different locations and assessment of radiation effects have been published during this year (J.Molla et al, J. Nucl Mat, 386-388, (2009), pp 983–986. Proceedings of the Thirteenth International Conference on Fusion Reactor Materials)

VII.1.1.8 Test and Target activities: RH Engineering

Two Notes, have been produced so as to comment the possible issues of the Referential Table, the Merged TTC Concept and the April 09 TTC Concept. Such concepts have been presented by the Test Cell design team for the definition of a new Test Cell. The notes try to contribute to a better integration of the new Test Cell design with the RH procedures and operations. The issue of the high number of pipes at the top of the Test Cell, the weight and proper shape of the shielding plugs, the necessary division of the Removable Intermediate Ring and the extraction of the Target Assembly without disconnecting the Test Modules are some of the assessed aspects.

A Preliminary database of the main operations of the ‘RH Procedures and Operations in the Test Facilities of IFMIF’ has been developed. The aim of the report is to start the development of an appropriate structure of database so as to manage the RH maintenance operations in the Test Facilities, compile the list of remote handling procedures and operations of the present reference design, and define tentatively new operations. DELMIA software (simulation package from Dassault Systems) has been purchased and installed aiming to study the logistics of maintenance operations in the Test Facilities. A training course on it was satisfactorily organized.

A review of the relevant tools for the maintenance in the Test Facilities of IFMIF, compiling a list of commercial tools that may be capable for the general RH operations in the Test Facilities, has been created. The study gives key information of the tools, like dimensions, behaviour in hazardous environment, working range, weight, etc. The study will be useful for the design of RH tools for the Test Facility of IFMIF and as input for the design of the remotely maintained components. Besides the review of the relevant RH equipment has been started.

A second draft of the ‘Basic guidelines for the design of remotely maintained components in the Test Facilities of IFMIF’ has been published, after improving the report with the revision and advice from international RH experts. The guidelines are structured in two main chapters: general guidelines and specific guidelines. The general guidelines establish general rules and guidelines for the design of the components remotely maintained.
(modularity, accessibility, simplicity, standardization, decontamination, radiation hardness, adequacy for the RH equipment, labelling, viewing and illumination) while the specific guidelines deal with positioning aids, gripping devices, lifting devices, electrical connectors and cables, pipes and flanges and fasteners for enhanced and reliable remote handling.

The 60% completion of the ‘Preliminary Definition Report’ has been carried out during 2009. This report has the major importance since it will be the starting point for the Definition Report. The ‘Preliminary Definition Report’ defines a first concept of the main and critical elements in the maintenance and RH System for the Test Facilities focussed on the maintenance of the new concept of Test Cell, will allow anybody to criticize the concepts and contribute with improvements, and supply early inputs about the RH System to other interrelated IFMIF teams. The key chapter of the report is the ‘Technical Documents’ where the generation and selection of alternatives of design is carried out and the definition of the Maintenance and RH System is defined.

**VII.1.1.9 Test and Target activities: Medium Flux modules engineering**

During 2009 the definition of the Liquid Breeder Validation Module experiments has continued. Irradiation experiments related to liquid breeders R&D and to functional materials for fusion reactors diagnostics have been studied and their technical specifications have been defined. The conceptual design for the overall container of the LBVM has been started, by considering the Tritium Release Module present design (included in the CDR of IFMIF) as a starting point, from the point of view of the allowable space for the experimental rigs. However, the experimental capability of the LBVM has been extended with respect to the TRM, by adding some lateral rigs, as it has been done in the present design of the HFTM, in order to use the IFMIF neutron irradiation capabilities as maximum. This way, a container with 16 rigs is being considered.

Also the conceptual design of the rigs and capsules has been started. Draft thermal hydraulic calculations have been performed to demonstrate that the design fulfill the technical specifications (range of temperatures, etc.) required.

By other hand, the assessment of the suitability of IFMIF irradiation conditions for testing functional materials related to liquid breeders and diagnostics for fusion reactors has been continued [MFTM 1]. For that, some neutronic calculations have been performed to obtain, basically, the displacement damage (dpa) and gas to dpa ratios as initial indicators of behaviour under irradiation of Fe, SiC, CaO, Al₂O₃, AlN, SiO₂ and Si₃N₄ in different areas of IFMIF (in high flux and medium flux irradiation zones), in DEMO HCLL (first wall and breeder zone) and in a typical high flux fission reactor (HFR). It is well known that different primary recoil energy spectra can produce completely different damage morphologies; therefore these spectra should be taken into account for each material in a future extensive assessment. In the case of DEMO HCLL, four locations of an inboard blanket have been selected: the front of the first wall, the back of the first wall (FW), a middle point of the breeder zone (BZ) and the
back of the breeder zone. For comparison also with a fission reactor, typical spectrum for a high flux fission reactor (HFR) has been considered.

The results indicate that the medium flux region of IFMIF is a suitable position to perform irradiation experiments obtaining DEMO relevant dpa and gas production ratio concerning the studied functional materials.

VII.1.1.10 Test and Target activities: Microfission chamber validation activities

During 2009 the work concerning the fission chamber (FC) as neutron diagnostic for the HFTM has been mainly focused on experimental tests under conditions as close as possible to the IFMIF ones. For that, two prototypes were acquired during 2008 (IC + FC, technical characteristics showed in [FC-1]. The experimental activities can be divided into three different phases: phase-1 (PH-1) for studying the FC behavior under an environment free of neutrons; phase-2 (PH-2) for monitoring fast neutron fluxes; and phase-3 (PH-3) for testing the robustness of the detectors. In 2009 PH-1 and PH-2 have been finished [FC-2]. The PH-3 will be performed during 2011.

Since fission chambers are sensitive to high energy photons, the prototypes were tested early during 2009 in an X-rays and in a $^{60}$Co irradiation facilities. These experiments constituted the PH-1 and they have been completed satisfactorily:

- Saturation behavior (I/V curves): normal behavior.
- Nominal voltage: within the saturation domain.
- Linearity of response: checked during exposure to 120 kV X-rays. OK.
- Comparison between FC and IC: expected behavior for irradiation with gamma rays.
- Gamma sensitivity: coherent with basic theoretical calculations.
- Signal-to-noise level: insulation resistances measured.

After the preliminary tests at CIEMAT the detectors were sent to the BR2 reactor (SCK-CEN, Belgium) to study the detectors response under a combined neutron-gamma field (PH-2). The test of the detectors proved their reliability and adequate functioning:

- Saturation behavior (I/V curves): normal behavior.
- Linearity of response: very satisfactory.
- Long term behavior (for 50 BR2 full power days): stable signals, evolution of the neutron sensitivity due to transmutation of $^{238}$U into $^{239}$Pu.
- Signal-to-noise level: observed noise far below the 1% level.
- Gamma sensitivity: coherent with theoretical calculations.
As a final result, the figure at left shows the comparison between calculated values and experimental data for three different channels during the BR2 irradiation. Fission rates were calculated with ACAB code, while the final FC current was calculated through a numerical code developed at CIEMAT.

The trends of the experimental data and the calculated curve are very similar, considering the uncertainties in the evolution of the irradiation conditions as well as in the flux gradients. Absolute values of the saturation current are in reasonable agreement (discrepancies less than 30% on average).

**VII.1.1.11 Neutron-induced damage evolution under Beam Raster Scanner conditions for IFMIF**

The formation and evolution of defects in materials irradiated with the reference continuous neutron source of IFMIF and the one produced from the Beam Raster Scanner (BRS) solution have been compared. The intensity neutron source fluctuations inherent to the BRS system were determined using the neutron transport McDeLicious code. Defects generated during irradiation were calculated using the binary collision approximation MARLOWE code, using the primary knock-on atom (PKA) energy spectrum resulting from neutron interactions with the material. In order to predict the evolution of defects during irradiation, a Rate Theory model based on \textit{ab initio} parameters was developed. Our model accounts for the migration of mobile defects, the formation of clusters and their recombination. As an example, it was investigated defect evolution in Fe irradiated at room temperature in both beam configurations. Simulation results clearly indicate that the defect evolution expected in the BRS configuration is nearly the same as the one expected in a
homogeneous irradiation system, at least in these conditions of temperature and for this material. This work strongly suggests that a Beam Raster Scanner system, which is technologically easiest to implement, would generate the same damage as a homogeneous irradiation system [BeamRasterS].

VII.1.1.12 Design Integration: Safety

Definition of critical accidental conditions

A revision of the IFMIF PSAR reference accident sequences and identification of needs of assessment was performed. Review of information about the source term, chemical reactions, mobilized components... in accident sequences was made, and modified MELCOR code for fusion applications was selected as the appropriate tool. Review of capabilities of this code, including the thermodynamic and transport properties of lithium, and physical models for predicting the rate of reaction of and energy production from the lithium-air reaction, was started.

VII.1.1.13 Design Integration: RAM evaluation

RAM Design Guidelines

A proposal of technical guidelines aimed at including RAM methodology in the design of IFMIF has been made. The main objectives of these guidelines are: providing main ways of improving RAM of a system, providing guidelines linked with the operating experience of similar facilities, pointing out reliability and maintenance problems at existing facilities and how they have been solved, and providing premises to be taken into account by designers.

RAM Database

A database structure and data management proposals have been performed for IFMIF. Besides, a data capture methodology for IFMIF prototypes has been proposed. [RAM_Database]. Reliability databases in Accelerator Driven Systems and Liquid MethalTechnologies have been explored together with other facilities with similar components or systems [RAM_Data].

Modelling of IFMIF Accelerator Facilities

A first RAM analysis of the Accelerator Facility has been performed. [RAM_Accelerator]. The main issues approached are the following: elaboration of a brief but consistent database of failure rate and repairing time, elaboration of FMEA (Failure Mode and Effect Analysis), modelling of fault tree, and reliability and availability analysis and comparison with previous analysis.

Modelling of IFMIF Target Facility
A model of the Target Facility (not updated design) has been elaborated in order to perform a sensitivity analysis focused in the back plate: the two MTTR (Mean Time to Repair) proposals have been compared, and the impact of the back plate lifetime has been evaluated [RAM_Target].

VII.1.2 JT-60 SA Cryostat

VII.1.2.1 Introduction.

Spain has to manufacture the Cryostat for the tokamak experiment to be installed in Naka. The component will be supplied in two different contracts, one for the lower part, the Cryostat Base (CB) and another one for the upper part, the Cryostat Vessel Body (CVB).

The first approach to carry out the supply of the CVB was to provide this part without the access ports for the services (diagnostics, heating plasma systems, cooling and cryogenic lines, etc.). The ports would be opened in Japan after the manufacturing in Spain. During several meetings the risk of this approach has been evaluated and it has been found not acceptable: the possibility of permanent deformations after the machining of the holes and welding of the ports was too high.

During 2009 a new share for CVB has been agreed to overcome the problem. The new distribution of the manufacturing taking into account the different pieces of this upper part of the Cryostat will be:

- Spain will provide the lateral walls of the component with all the holes and required ports (no additional machining or other manipulation will be necessary in Japan).
- Japan will manufacture the top lid of the component and will also deliver the material (Stainless Steel) for the part to be manufactured in Spain.

The works in the CB have not been affected by this new work distribution.

The presentation of the work has been carried out in the Technical Coordination Meetings (TCM) held during the year in January, April, September and December.

VII.1.2.2 Cryostat Base

During the 2009 the design has been concluded. Only minor and not relevant modifications are expected. The call for tender is expected to be launch at the beginning of 2010.

The work carried out has been organized in the following areas:
• FE calculations: several calculations have been carried out with different models just to have a cross-check of the results. Within the calculations the validation according to ASME Code Sect VIII Div. 2 has been carried out.
• Configuration model: the Catia model have been finalized.
• 2D drawings for call for tender have been prepared.
• The call for tender specification has been concluded.

VII.1.2.3 Cryostat Vessel Body.

This part of the Cryostat is still under possible design modifications. During the year a few tasks have been carried out:
• Definition of the rupture disks that will be necessary for overpressure protection of the Cryostat.
• Preliminary CATIA model.
• Approach definition for the FE calculation that will be necessary to be done.
• First studies for the leak detection procedure after assembly of the component, and the sealing method to be used for vacuum tight.

VII.1.3 DEMO R&D

VII.1.3.1 SiC/SiC characterization

During 2009 this task has been carried out to study the microstructural change observed in hot pressed SiC at relatively low doses and establish its origin. The irradiation conditions were: 1.8MeV electrons irradiations in a high vacuum chamber mounted in the beam line of a Van de Graaff electron accelerator at 450 °C, 7kGy/s, up to 420 MGy and different techniques were used for its characterization as XRD, SEM and ADX Link INCA), TEM.

From observations in high resolution TEM it was possible to conclude that the “as received” material presents highly crystalline structure with a mainly hexagonal symmetry, and abundant rombohedral politypes coexist on it.

After irradiation, a sub-nucleation and amorphization phenomenon in the original grains occurs [XXXX]. The size of the new domains is about 20 nm that become amorphous or very low crystalline. On the other hand the amorphous Si material that surrounded the original grains is lost. Microstructure of hot pressed SiC is seriously affected by electron irradiation at 450 °C by 420 MGy. So, the main consequence of irradiation in Hot Press SiC is the lost of cristallinity. Such a result may possibly explain the marked decrease in electrical volume conductivity observed for this material.
VII.1.3.2 Insulators ceramics

Although a potentially powerful tool capable of monitoring material modification during irradiation, radioluminescence (RL) has been largely neglected within the fusion materials activities. This in part is due to the difficulty in interpreting the resulting emission spectra. However in recent years this technique has been successfully employed to study insulating materials such as alumina and silicas, as well as breeding ceramics for fusion applications. Within the Broader Approach activities work is now underway to further develop radioluminescence for the characterization of ceramics.

The ion beam RL facility at IMR Sendai, and the electron beam RL facility at CIEMAT Madrid are being developed as complementary systems to enable radiation induced material modification and degradation to be observed during irradiation (in-situ). The two systems can jointly measure RL from 200 to 1500 nm, and will enable one to separate purely ionizing from displacement plus ionization processes. Preliminary results have been obtained during 2009.

VII.2 Dual Coolant Breeder Blankets Programme

Spanish FT Programme focus breeding blanket developments on He/LiPb dual-coolant concepts. TECNO_FUS -National founding through obtained through competitive Spanish government grant (CONSOLIDING-INGENIO 2010) - represents a new Programme of Fusion Technology for Spain articulated around the conception and development of a set of components and systems key for future plants of production of energy with origin in Thermonuclear Fusion: a Breeding Blanket concept and its Plant Auxiliary Systems. By “Programme” it is understood a technologically oriented integration of competencies and singular areas of knowledge actively participating in TECNO_FUS proposal:

1. on advanced neutronics for design of fusion technology components,
(2) on development of production and characterisation capabilities of fusion reactors materials,
(3) on computational fluid-dynamics for magneto-hydrodynamics for Fusion Technology,
(4) on the component structural thermo-mechanics and electromagnetic design analysis,
(5) on conception and design of singular plants auxiliary systems as power or tritium systems,
(6) on safety and environmental impact Studies of fusion technology,
(7) on development of specific instrumentation for the basic set of design responses,
(8) on components and systems engineering integration,
(9) on confined plasma for fusion reactor design and specifications.
These knowledge areas participate interactively with clearly identified active interfaces in the attainment of the technical objectives of the TECNO_FUS Programme proposal.

The proposed designs of components and systems will be developed from Conceptual Design up to a certain degree of Engineering Detail (to be defined for the period (2008-2011) but anticipating future studies of components and systems manufacture under the perspective and hypothesis of continuity in later National Programmes.

An important goal of TECNO_FUS Programme relies on the achievement of new engineering and underlying technology capabilities on design and on material (EUROFER, SiC as Flow Channel Inserts, Lead-lithium eutectic) production and characterization capabilities.
The most remarkable results during 2009 are outlined hereafter.
Departing from general 3D DEMO plasma specifications:
A starting geometric design detail in fully parametric Catia.v5R17 for:
(1) breeding blankets modules,
(2) an optimized reactor segmentation,
(3) a structural design for an actively cooled double-walled vacuum camera,
(4) an adapted cryostat,
(5) dual systems auxiliaries lay-out and key components designs as double
connectors with gap, optimized Permeator Against Vacuum or LiPb/ ^{3}{\text{C}}{{\text{O}}_{2}})
exchangers among others,
(6) Bio-shield and reactor building structures.
As main progress on underlying technologies and achievements during 2009 being consolidating:
Capability of production of hundred kgs.EUROFER-like ferritic-martensitic batches (ASTURFER®) with optimized composition in terms of impurities has been demonstrated at ITMA/Asturias. Impurity limits and metallography are confirmed. Mechanical material testing of rolled (in Gent, Belgium) to certify specifications is on-going.

Fully characterization capability for lead-lithium with high quality (small amounts) produced in CIEMAT and UCM/Madrid as progress to establish standards for Pb15.7(2)Li,

First samples of porous SiC with dense-SiC coating geometric channel forms have been produced (CEIT) and being improved (according to ideal Flow Channel Insert thermal, mechanical, specs.). Permeation, electrical and thermo-mechanical testing on-going.

A selection of technique for ⁶Li enrichment has been done. Electrophoresis has been selected as reference scalable technique for experimental qualification and development. Cells have been designed and are, at present, under construction (CIEMAT).

An experimental demostration facility to qualify a Permeator Against Vacuum (PAV) CIEMAT-patented design Fuskite® efficiency is under construction in collaboration with Industry (SENER) under CDTI founding.

New engineering capabilities (key for breeding blanket technologies) are under development with some partial achievements during 2009.

One major engineering goal of TECNO_FUS (within a transversal programme INTEGRA*) focuses on the development of a complete platform (a VBA multidirectional interface) managing bi-directional input/output compatibility of coupled BB design analyses.
Progresses in solving interface and compatibility problems have been done during 2009:

- Solving 3D general distributed neutron source plasma from reactor specifications and coupling Catiav5/MCNP interfaces (UNED CIEMAT) for full neutronic design is a recently demonstrated engineering capability.

- A fully coupling of liquid metal MHD fluid-dynamics simulation in banana-shaped channels and coupling with two-phase solute transport has been demonstrated at UPC/Ciemat. Needed validation pending, this new engineering capability is key to assess He-bubble nucleation phenomena and refined tritium transport assessments at BB channels and recovery technology qualification.

- Progress on development of Process Flow Diagram (PFD) using TMAP7 (as the unique tools today having ITER QA pedigree) for tritium transfers between BB/auxiliary systems have been accomplished during 2009 at CIEMAT/IQS.

- Progress on modelling capabilities of HFR/Petten irradiation tests LIBRETTO-4 (Liquid Breeder Experiment with Tritium Transport Option) at CIEMAT/UPM has produced transport models showing capabilities to fit tritium permeation and desorption release from LiPb/EUROFER capsules. This data is being then assumed for tritium analyses for design.

- New irradiation tests (corrosion, permeation) are been defined to be performed at LRV-15 Check reactor (HFR with a LiPb in-pile section).

VII.3 Fusion Technology Facilities

VII.3.1 Operation of presently available facilities

VII.3.1.1 Operation of the van de Graaf accelerator

During the year 2009 the 2 MeV Van de Graaff electron accelerator has been operating for 34 days corresponding to 200 hours. Optical, electrical and diffusion measurements have been performed during irradiation for SiC, LiNbO₃, SiO₂, Si₃N₄ and Er₂O₃. The experimental set up to measure radiation enhanced desorption of He and H isotopes during 1.8 MeV electron irradiation was upgraded. Concerning the radioluminescence experimental set up preliminar near infrared radioluminescence measurements were carried out.

VII.3.1.2 Operation of the “Nayade” irradiation facility
Irradiation of different types of silicas at 3.2 Gy/s and irradiation temperatures of 100 and 200 °C in nitrogen atmosphere have been performed during the year 2009 in the $^{60}$Co NAYADE irradiation facility at CIEMAT.

**VII.3.1.3 Irradiation line at the CMAM ion accelerator**

Work is in progress in this line. Problems found concerning a high ion current loss have been solved. At present, two beam lines of CMAM facility are being developed in parallel. The first, the original one, with beam scanning possibility and a second beam line normally used for ERDA-TOF experiments that could be used for some specific experiments as Recovery Resistivity. Although several hardware components must still be built, it is expected that during 2010 first irradiations could be done in both beam lines. Work in the irradiation room is not straightforward due to the fact that CMAM facility is continuously operating and available beam time for testing is quite reduced.

**VII.3.2 TECHNOFUSIÓN**

**VII.3.2.1 Introduction**

Throughout the year 2009 a scientific and technical proposal was initiated and concluded in an attempt to complete a previous draft document on TechnoFusión facilities by the definition of the different structuring technologies and their needing facilities. The document compilation was achieved through meetings of the technical working groups where the original objectives were improved, new ideas were discussed and technical parameters were defined towards the definition of the required equipment for the best experimentation. A 379-page document in its English version reviews the Fusion technological demands for the following years, the objective and administrative structure of such a Centre of technological development and a further description of the seven proposed technological areas. The performance of materials and components under the extreme conditions of a fusion reactor is largely unknown, and this is precisely what TechnoFusión intends to explore. For this purpose, facilities are required for the manufacture, testing and analysis of critical materials. Additional resources are planned to develop and exploit numerical codes for the simulation of materials in special environments, to develop remote handling technologies and other areas related to the management of liquid metals.

The TechnoFusión facilities and the required equipment was proposed to be implemented in several complexes located in three different sites, as follows:

* **TF Leganés**, will be located at the place of the Parque Tecnológico de Leganés, which will have the adequate facilities to carry out the activities of the Area of Production and Processing of Materials and supported by a number of related characterization techniques.
* **TF Getafe I and II**, will be located on two parcels of the Parque Equipado Getafe-Sur, whose buildings will house both the headquarters of TechnoFusión and the experimental facilities of the Area of Liquid Metal Technologies, Remote Handling Technologies, Characterization Techniques and Computational Simulation most of them related with the electron radiation source facility.

* **TF Madrid I and II**, will be located in the Campus of the Universidad Complutense de Madrid (at the CIEMAT research centre) and will include the facilities required for the technology development of the Area of Material Irradiation by using a triple ion sources and the Area of Plasma-Wall Interaction.

In the context of the ICTS TechnoFusión and within the technical activities that have been done during the past year, the pre-basic design concerning the **TF Getafe I and II** buildings was completed. The aim was the technical and architecture definition of the buildings, spaces and experimental facilities outlined above, defining the criteria for implementation, construction, structural and building facilities from previous data and future needs of TechnoFusión. It allowed also estimating the total amount of investment to be made, and propose a schedule of performances to launch the facility. From the pre-basic design document, the development of the basic and executive designs of architecture, engineering facilities and individual laboratories may begin, as well as initiating the first contacts with the regional administration before the construction and operating license. The documentation consists of a memory and maps, establishing the requirements for the licensing as a radioactivity building of category 2.

At the same time, the construction sketch designs of the **TF Leganés and TF Madrid II** complexes were finished, which lead to the precise definition of the general characteristics of the building facilities through the adoption and justification of specific solutions. It would apply for the municipal licenses and other administrative authorizations prior to address its construction. The sketch document contains the main specification of the adopted solutions, the projections of different horizontal and vertical sections together with the different elevations, the estimated budget of investment for each chapter, and other appendix.

Most of the effort of the scientific groups related to the different TechnoFusión areas was put on the appliance to national and international proposals in an attempt to finance from public organisms the development of general and specific identified issues. Additionally, some areas are participants of international networks related with subjects of TechnoFusión interest.

Several oral and poster contributions [032], [033], [034],[035], [036] were presented at international conferences with the aim of reviewing the different TechnoFusión areas of technological development and their associated facilities and equipment. The presented contributions reported to the specific solutions taken to implement most of the different technological areas. It must be emphasized that the corresponding written papers were already send to publication on high impact journals.
Special emphasis was also paid on stressing the divulgative aspect by structuring the TechnoFusión technical information into invited communications to national and international conferences, as well as invited lectures to universities and technological centres.

**VII.3.2.2 Characterization Techniques**

To solve a number of technological aspects, the engineering development of some characterization and testing techniques associated to other TechnoFusión facilities was started in 2009. Through the collaboration with students and their university departments, it was possible to establish the first approach to the conceptual design of both the chamber and machine to test the thermomechanical properties of small specimens during triple ion irradiation, and the experimental loop for in-situ fatigue and creep tests of material immersed on a lithium liquid loop.

The state-of-the-art on testing techniques and the international facilities where in-beam mechanical tests were implemented were reviewed and the inputs to enhance TechnoFusión facility were established. Fatigue and creep tests on fusion related materials were defined to be performed up to 800-1000ºC. A possible electrodynamic machine to apply medium loads has been considered among the commercial ones. The systems to measure and control both temperature and displacement were decided while the fixing method of non-conventional testing specimens should require detailed studies.

Similarly, a conceptual design of an experimental system to test structural materials under dynamic loads while immersed in a flux of lithium liquid was also technically studied. To increase the experiment complexity, the mechanical test module was considered to work also under gamma radiation coming from an electron accelerator coupled to a metal screen part of the metal liquid loop.

The interest for implement an in-beam Transmission Electron Microscope (TEM) in the double or triple line of TechnoFusión accelerators was reviewed. Several inconvenients were found among which are the existence of few other TEMs coupled to accelerators distributed in Asia, American and Europe that are sufficient to attend the actual scientific demand, and the technical difficulties which will decrease the microscope resolution. The edited internal report leads to conclude that when having just one microscope it should be used in an open regime.

**VII.3.2.3 Irradiation methods**

*Computation of the irradiation conditions required to simulate fusion neutron effects*

Previous works confirmed the possibility of using a triple ion beam to reproduce the evolution of displacement damage (dpa's) and the increases of H and He into materials in a similar way to the one that will occur in Fusion reactors like DEMO.
Following the task of 2008, pka’s energies and damage functions using several simulation codes have been calculated. The comparison of the damage function obtained using DEMO and IFMIF spectra with the above mentioned accelerator sources give us the best working conditions and also the expected differences to a real fusion irradiation. Results for iron target are shown in the following picture.

MARLOWE and SRIM codes combined to Molecular Dynamics have been used. It is worth mentioning that the stopping power function included in MARLOWE had to be expanded to higher energies (up to hundreds of MeV’s).

Among the necessary ion beams the calculations started with a first group [Fe, He and H]. Their needed energy values were previously calculated.

Next year the damage function comparison will be extended to other fusion candidate materials like Al$_2$O$_3$, W, SiO$_2$...

**Conceptual design of a beam degrader and beam dump for volumetric uniform irradiation using ion sources.**

The work has been concentrated in the beam degrader concept, calculations and first engineering design. As energy of each beam is fixed at each operation condition, a device is
needed to modulate this energy on order to obtain damage and implantation profiles as uniform as possible. After extensive revision of concepts, a rotating target with several thin metals sheets has been chosen. The detailed calculations of damage and concentration profile have been done for a model with 27 different iron foils (from 1 to 27 microns). The results for vacancies and He profile are shown in the following figure. As some diffusion exists for both species, the profile is expected to be even more uniform.

Future work includes:

More detailed design on the sheets preparation. We need a lot of different thicknesses are necessary and with quite good accuracy. One method used elsewhere was by cold rolling (in the case of aluminium foils)

Fixation system to the wheel

Foils temperature distribution at maximum currents (we just have some rough estimations but without radiation loss terms).

Profile calculations have to be also extended to other interesting materials/incident ions combinations.

Contacts have been done with facilities using this concept of beam degrader (JANNUS and FZJülich) to exchange information.

VII.3.2.4 Plasma-Wall Interaction
In 2009 Plasma Wall Interaction section has divided its efforts in three main topics:

Plasma wall interaction facility design: Several advances were done in the design of the facility, mainly involving the magnet system. One internal report was generated [PWI_1]. The QSPA design was also improved as a consequence of the collaboration with the Kharkov Institute of Physics and Technology (KIPT) [PWI_2].

Training and collaboration with FOM Institute: There is an open collaboration with FOM with the aim of improving the cascaded arch source design. One CIEMAT scientist was in Utrecht from 1st September 2009 to 28th February 2010. During this stay she has helped to improve the source radius in hydrogen plasmas using three channel sources and an annular electrode in order to improve the mixing by ExB drift. In March 2009 some experiments about nitrogen scavenging was carried out using PILOT-PSI facility in conditions similar to those that could be obtained in the PWI facility of TechnoFusión.

Popularization of the TechnoFusión facility: The preliminary design of PWI facility was presented in several meetings. An oral presentation given by Francisco Tabarés was presented on the “Workshop on Plasma-Wall Interactions in Nuclear Environment” in Jülich. A poster titled “TechnoFusión: A new facility for Material and Technologic Studies” was presented in the “12th International Workshop on Plasma Facing Materials and Components for Fusion Applications” by J.A. Ferreira [PWI_3].

VII.3.2.5 Liquid Metals

Liquid metal technology is one of the key aspects to be carried out for Fusion. There is a shortage of experimental facilities devoted to the development of this technology either focused on studies for eutectic lithium lead breeder foreseen in some concepts of fusion reactors blankets, or, even less, conceived for the research on lithium, base material for some other components of fusion reactors and the IFMIF facility. Therefore, in the framework of TechnoFusión, a liquid metal laboratory is being proposed to meet the experimental deficit that has been detected in this field. Moreover, such laboratory has the commitment to be integrated in national and international programs towards the understanding and mastering of corrosion, magneto- hydrodynamics, free surface heating, material compatibility or any other technological issue concerning liquid metals, and lithium in particular [Tech-LiqMet_1].

Conceptual design of a Li loop with the capability to simulate heat deposition in the liquid metal: the activities carried out during 2009 have been focused in the development of a conceptual proposal for the liquid metal laboratory, in which the design requirements have been set as starting point for a basic engineering project, including sizing of the loops for building design. The development strategy for the facility suggests the building of two basic loops with common auxiliary systems for purification, liquid metal filling and storage, and control. On the other hand, scientific and technological show-stoppers have been identified for their proposal to R&D programs.
The work carried out has been done by a joint group UPM-CIEMAT, with the support of IDOM and Empresarios Agrupados.

VII.3.2.6 Materials Production Techniques

A facility for Materials Production and Processing (MPP) is planned to be operative at TechnoFusión. In order to have in operation this facility just at the beginning of TechnoFusión, a research team has taken in charge of its planning, and at the same time, of the development of structural alloys within the framework of the EFDA fusion materials program. A detailed report with the corresponding description of the installations, equipments, techniques to be implanted and general requirements was submitted by the team in 2009 [TF REPORT] report was used for carrying out the draft of the building to house the MPP facility with the specifications of its installations.

With regard to the specific activities devoted to production and processing of fusion materials in 2009, the team fabricated and processed different alloys of interest for the EFDA materials program in the LMNM laboratory at the UC3M. This laboratory presently operates as an associate laboratory of TechnoFusión. The produced and processed alloys were: 1) Fe-Cr and ODS Fe-Cr model alloys, 2) ODS W-V alloys and 3) ODS and non-ODS EUROFER steel.

Fe-Cr model alloys with composition Fe-14%Cr and ODS Fe-14%Cr-0.3%Y2O3 (wt%) were produced by a powder metallurgy route and subsequent consolidation by hot isostatic pressing. Several batches of these alloys, mechanically alloyed under different atmospheres, were produced to check the effect of the milling atmosphere on the microstructure and mechanical properties of the alloys [ODS4]. Also, Fe-12Cr and Fe-12Cr-0.3%Y2O3 were supplied to Dr. P. Trocellier at CEA-JANUS for irradiation experiments with 10MeV 56Fe4+ in JANUS.

Several batches ODS and non-ODS W alloys were fabricated and delivered for being characterized by the research groups ESTRUMAT-UPM and ESTRUMAT-MNM/UC3M [WALL2], [WALL3], [WALL6]. In addition, within the activities of the FP7 Coordination ActionFEMaS(Fusion Energy Materials Science), the team in the LMNM laboratory collaborated with the Prof. Faulkner's group (University of Loughborough) in the fabrication and processing of ODS and non-ODS EUROFER batches, which are being characterized at the Materials Department of the University of Loughborough.

Also, in 2009 the MMP team carried out experiments of the ECAP processing of EUROFER and ODS EUROFER fabricated by Plansee, as well as of ODS Fe-Cr alloys and ODS EUROFER produced in the LMNM Laboratory [ODS4].

VII.3.2.7 Remote Handling

Several activities have been and are being developed in the area of Remote Handling in TechnoFusión.
Ciemat is participating in the project “Remote Manipulation Techniques for Nuclear Fusion Research Centers” coordinated by the UPM, in the framework of the ‘Plan Nacional de I + D + I (2008-2011)’.

Ciemat is participating in the ‘Red de Robótica y Manipulación Remota para Tecnofusión (R-RMRT)’ in the framework of the ‘Investigación Fundamental del Plan Nacional de I + D + I (2008-2011)’, coordinated by the CSIC. The objective is to create a training program, integrate the robotic companies with the research centres and researchers, and create a net for enhanced collaboration between the participating centres.

In the framework of the project “Remote assembling of a virtual HFTM Rig”, partial validation of the operations of introduction of the Rigs in the HFTM Container of IFMIF has been performed by real-master/virtual model simulation, activity coordinated by CIEMAT and carried out by UPM.

Ciemat has participated in the multinational proposal for the ‘EFDA Goal Oriented Training Programme’-Remote Handling, coordinated by TEKES (Finland). This Programme aims for the practical formation of several engineers for ITER RH in a collaborative international environment.

### VII.3.2.8 Simulation Techniques

In structuring the activities within the computer simulation laboratory, the different fusion technology areas of interest for Technofusión have been classified in those associated to the Technofusión facilities themselves (short-term) and those related to the installations of ITER-DEMO-Commercial Fusion Reactor, and the supporting IFMIF irradiation facility (medium and long term). A relevant progress has been performed for the identification and selection of the computational tools required for design analysis of Technofusión facilities and the development of the associated scientific programs. With regards to the radioprotection and safety multi-facility area, several efforts have been addressed to the Material Irradiation Facility. The radioprotection issues associated to the irradiation of different targets have been studied. The most limiting case has been identified, which was that of irradiating iron with accelerated protons. Different candidate materials have been explored in order to choose the best material for the sample holder. Nickel has been found it as an attractive option. The proton intensities necessary to meet the helium production specifications have been also determined. As for shielding, it was found that the neutrons produced during beam-on by proton interactions with the irradiated sample make necessary to design a biological shielding to protect the public. Preliminary results show that 1-m concrete shielding is not enough for radioprotection purposes. With the basis of this preliminary data, a new shield design is being designed.
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