Techno Fusión

National Centre for Fusion Technologies

Scientific-Technical Report

September 2009

Authors and Contributions

This document has been elaborated with the enthusiastic contribution of a large group of researchers from seven Universities and Research Centres. We are enormously grateful to them for their help and support during these past two years.

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas de Madrid (CIEMAT): J. M. Arroyo, F. Carbajo, N. Casal, P. Fernández, J. Ferreira, A. García, I. García-Cortés, M. González, M. Hernández, M. T. Hernández, A. Ibarra, D. Jiménez, J.A. Jiménez, J.L. Martínez-Albertos, A. Moroño, F. Mota, C. Ortiz, V. M. Queral, L. Ríos, R. Román, F. Tabarés, V. Tribaldos, J. P. de Vicente, R. Vila. *Universidad Politécnica de Madrid (UPM):* A. Abánades, R. Aracil, C. Arévalo, O. Cabellos, D. Díaz, S. Domingo, M. Ferré, L. Gámez, R. González, N. García, Y. Herreras, A. Lafuente, P. Martel, E. Martínez, J. M. Martínez-Val, E. Mínguez, J. Y. Pastor, M. Perlado, E. Río, J. Sanz, F. Sordo, M. Velarde, M. Victoria. *Universidad Nacional de Educación a Distancia (UNED):* M. García, D. López, A. Mayoral, F. Ogando, J. Sanz, P. Sauvan. *Universidad Carlos III de Madrid (UC3M):* D. Blanco, L. Moreno, M. A. Monge, R. Pareja. *Consejo Superior de Investigaciones Científicas (CSIC):* P. González, J. de No. *Universidad Autónoma de Madrid (UAM):* A. Climent, A. Muñoz. *Universidad de Alicante (UA):* M. J. Caturla

General coordination: A. Ibarra (CIEMAT) & M. Perlado (UPM)
Material Production and Processing group coordination: R. Pareja (UC3M)
Material Irradiation group coordination: R. Vila (CIEMAT)
Plasma-Wall Interaction group coordination: F. Tabarés (CIEMAT)
Liquid Metal Technologies group coordination: A. Abánades (UPM)
Characterization Techniques group coordination: M. González (CIEMAT)
Remote Handling Technologies group coordination: R. Aracil (UPM)
Computer Simulation group coordination: J. Sanz (UNED, UPM)
English revision: Kieran McCarthy and B. Ph. van Milligen (CIEMAT)
Project management and edition: D. Jiménez, R. Román & I. García-Cortés (CIEMAT)

Summary

The development of nuclear fusion is rapidly becoming a vital necessity in view of the continuing rise of the world's energy demand. Nuclear fusion offers a virtually endless source of energy that is both environmentally friendly and capable of meeting any foreseeable energy demand.

The progress of fusion constitutes one of the greatest technological challenges for humanity. Indeed, this field is one of the main areas of research of the European Union (EU), as was evident in June 2005, when the final agreement to construct ITER[1] (the *International Thermonuclear Experimental Reactor*) was signed, together with the USA, Russia, China, South Korea, Japan and India. ITER is an experimental reactor intended to demonstrate the scientific viability of fusion.

As the design of ITER is already defined, over the next 20 to 30 years the main focus will be on the development of technological components for future commercial reactors, rather than on basic plasma physics. The most important challenges for fusion research are the selection, development and testing of materials and the various elements for reactors, together with the design of energy extraction systems and tritium production methods.

At present, Spain has a unique opportunity to be at the forefront of this new technological field in Europe. However, there is a need for new facilities to simulate the extreme conditions to which materials and components will be exposed inside a fusion reactor.

The project outlined in this report describes the construction of a singular scientific and technological facility (the National Centre for Fusion Technologies -*TechnoFusión*) in the Madrid region, to create the infrastructure required to develop the technologies needed in future commercial fusion reactors, and to assure the participation of Spanish research groups and companies.

The Spanish scientific community has achieved an international recognition in the science and technology areas needed for the success of this ambitious project, as is evident from the results obtained by Spanish researchers in the fusion field over the past few decades. *TechnoFusión* intends to take advantage of the existing expertise of university research groups, public research institutions (*Organismo Público de Investigación, OPI*) and private companies. The performance of materials and components under the extreme conditions of a fusion reactor is largely unknown, and this is precisely what *TechoFusión* 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

[1] ITER (originally the International Thermonuclear Experimental Reactor) is an international tokamak (magnetic confinement fusion) research/engineering project being built in Cadarache, France.

materials in special environments, to develop remote handling technologies and other areas related to the management of liquid metals.

In summary, *TechnoFusión* focus is the creation of infrastructures for the following research areas: 1) material production and processing, 2) material irradiation, 3) plasma-wall interaction (thermal loads and the mechanism of atomic damage), 4) liquid metal technologies, 5) material characterization techniques, 6) remote handling technologies and 7) computer simulation.

Therefore, *TechnoFusión* Scientific-Technical Facility will thus consist of a complex of seven large research areas, many of which are unique in the world, with the following main technical objectives:

1) *Material production and processing*. There are still some uncertainties about the materials that will be used to construct future fusion reactors, partly because it has not yet been possible to reproduce the extreme conditions to which such materials will be subjected. Therefore, it is of utmost importance to dispose of installations capable of manufacturing new materials on a semi-industrial scale and fabricating prototypes. Top priority materials include metals such as reinforced low activation ODS type steels (*Oxide Dispersion Strengthened steels*) and tungsten alloys. To manufacture such materials, equipment is required that currently is scarce or inexistent in Spain, such as a *Vacuum Induction Melting Furnace* (VIM), a *Hot Isostatic Pressing Furnace* (HIP), a Furnace for Sintering assisted by a Pulsed Plasma Current (*Spark Plasma Sintering*, SPS), or a *Vacuum Plasma Spraying* (VPS).

2) *Material Irradiation*. Even though the exact reactor conditions are only reproduced inside a reactor, it is possible to simulate the effects of neutrons and gamma radiation on materials by irradiating by ion and electron accelerators.

The effect of neutronic radiation will be characterized by combining three ion accelerators: one light ion accelerator of the tandem type for irradiating with He, with an energy of 6 MV, one light ion accelerator of the tandem type for irradiating with H (or D), with an energy of 5-6 MV, and a heavy ion accelerator of the cyclotron type, with k = 110, to implant heavy ions (Fe, W, Si, C) or high energy protons.

Additionally, a high magnetic field, between 5 and 10 T, must be incorporated into this facility in order to study the simultaneous effect of radiation and magnetic fields on materials.

The effects of ionizing *gamma* radiation will be studied using a *Rhodotron®* electron accelerator with a fixed energy of 10 MeV that will be shared with other *TechnoFusión* facilities.

3) *Plasma-wall interaction*. Inside a fusion reactor, some materials will not be subjected only to radiation, but also to enormous heat loads in the case of plasma disruptions. In view of this, both: i) stationary conditions due to the intrinsic reactor properties: high density, low temperature and high power and ii) violent transient events (called ELMs in plasma physics literature) must be reproduced. Therefore, it is essential to dispose of a device (which it will be called "plasma gun") to study plasma-material interactions simultaneously in steady state and transient regimes, thereby allowing an analysis of the modification of the materials and their properties in fusion reactors.

The mentioned plasma gun would consist of two main elements: i) a linear plasma device capable of generating hydrogen plasmas with steady state particle fluxes of up to 10^{24} $m^{-2}s^{-1}$ (i.e., of the order of the expected ITER fluxes) and impact energies in the range of 1-10 eV, and ii) a device of the quasi-stationary plasma accelerators (*QSPA*) type, providing pulses lasting 0.1-1.0 ms and energy fluxes in the 0.1-20 MJm^{-2} range, in a longitudinal magnetic field of the order of 1 T or greater.

These devices are connected by a common vacuum chamber, allowing the exchange of samples, and their simultaneous or consecutive exposure to the steady state and transient plasma flows under controlled conditions. Both devices will operate with hydrogen, deuterium, helium, and argon.

4) *Liquid metal technologies*. A number of, ITER, DEMO (*DEMOstration Fusion Power Reactor*)[2], and IFMIF (*International Fusion Materials Irradiation Facility*)[3] components will use liquid metals as refrigerants, tritium generators, neutron reproducers, moderators, etc., all of them under extreme conditions. Therefore, these applications need further research to be finally implemented in such installations.

The basic working scheme for this Facility in *TechnoFusión* is an arrangement of two liquid lithium loops, one of them coupled to the *Rhodotron®* electron accelerator to investigate the effects of gamma radiation on different conditions of the liquid lithium.

The main goals of this Facility are the studies of i) the free surface of liquid metals under conditions of internal energy deposition, and ii) the compatibility of structural materials and liquid metals in the presence of radiation. In addition, it will be possible to study the influence of magnetic fields on the cited phenomena as well as the development of methods for i) purification of liquid metals, ii) enrichment of lithium, iii) extraction of tritium, and iv) development of safety protocols for liquid metal handling.

5) *Characterization techniques*. Ambitious and well-understood research requires an accurate knowledge of the materials under study. Therefore, a range of techniques to characterize them under different situations is a key element in the global scheme of *TechnoFusión*. These techniques include mechanical testing (creep, nanoindentation, fatigue, etc.), compositional analysis (Secondary Ion Mass Spectrometry and Atomic Probe Tomography), and structural characterization (Energy Filtered Transmission Electron Microscopy, X-Ray Diffraction), as well as a number of material processing techniques (Focused Ion Beam Systems coupled to a Scanning Electron Microscope). Additional systems will be used to characterize physical properties (electrical, dielectric, optical, etc.).

Some of the above-mentioned techniques will be implemented to test the materials either in-beam –while being irradiating— or *in-situ*, inside the lithium loop. Needless to say, these techniques can also be performed before and after irradiation or before and after experiencing any other physical or chemical processes.

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[2] DEMO (DEMOnstration Power Plant) is a proposed nuclear fusion power plant that is intended to build upon the expected success of the ITER experimental nuclear fusion reactor.

[3] IFMIF is a planned high-intensity neutron reactor whose spectrum should be equivalent to that of a fusion reactor. The final design comprises two deuteron accelerators impinging on a liquid lithium target to generate nuclear stripping reactions to provide the desired neutron spectrum

6) ***Remote handling technologies*.** The conditions inside a fusion reactor are incompatible with a manual repair or replacement of parts. Therefore remote handling is indispensable. New robotic techniques, compatible with such hostile conditions, need to be developed; while existing techniques need certification in order to be applied at installations such as ITER or IFMIF.

TechnoFusión Facility will contribute to this knowledge with: i) a large installation for the prototypes manipulation such as: *Diagnostic Port Plug* of ITER, *Test Blanket Modules* of ITER and Modules of irradiation of IFMIF, and ii) an Irradiated Room coupled to the electron accelerator –*Rhodotron®*— in order to carry out validation, certification and characterization of remote handling tools and machines in an uniform ionizing field equivalent to ITER-DEMO trying to simulate the fusion reactor environment.

7) ***Computer simulation***. To study conditions that cannot be reproduced experimentally and to accelerate the development of novel systems for a future commercial fusion power plant, *TechnoFusión* will stimulate an ambitious programme of computer simulations, combining existing experience in the fusion field with resources from the National Supercomputation Network[4]. The goals include the implementation of the global simulation of a commercial fusion reactor, the interpretation of results, the validation of numerical tools, and the development of new tools. Another indispensable goal is the creation of a data acquisition system and the visualisation of results.

Based on the existing experience of research groups at Universities, Public Research Organisations and company research departments, *TechnoFusión* proposes the development of a large scientific infrastructure in order to make a significant contribution to the development of new technologies needed for the construction of commercial fusion reactors. The project described here will permit the generation of highly relevant technological knowledge for all types of fusion reactors, irrespective of the underlying concept (magnetic or inertial confinement).

The goal of TechnoFusión is to bring together sufficient human and material resources to contribute significantly to the development of a safe, clean, and inexhaustible source of energy for future generations.

[4] http://www.bsc.es/index.php. September 2009.

9. Remote Handling Technologies

9.1. Introduction

The consolidation of nuclear fusion as an energy source in the coming years will require an extraordinary development of robotic systems for *Remote Handling* (RH) that can be autonomous or remotely manipulated by an operator. The reasons for considering Remote Handling for performing a wide range of operations in nuclear fusion installations are several for instance the large dimensions and weights of parts to be handled and in particular, the presence of harmful radiation in equipment and materials close to the fusion device. Moreover, envisaged future fusion energy plants (e.g. DEMO) will require an intense and complex maintenance which can only be undertaken by means of Remote Handling. Indeed, the ability to perform such tasks will play a critical role in the proliferation and viability of future fusion reactors. Even in current and near future experimental fusion devices, such as ITER and JET, RH is also present and is/will be continuously improved and adjusted.

The requirement for RH is not just limited to the above scenarios as other related facilities may also depend on the intensive use of Remote Handling, e.g. IFMIF. This facility will allow studies to be carried out on the behaviour of materials under neutron radiation; hence both facility component and test material activation will be considerably high. Thus, the use of RH will be therefore compulsory for both maintenance and operation tasks in this facility.

Table 9.1 provides a comparison of the three fusion devices mentioned above. The different needs for each of them, with regards to Remote Handling, are introduced together with their key features and the foreseen challenges. The most important factors in RH include the degree of activation of components in the toroid and in their areas of influence, the increase in contamination inside the device due mainly to tritium, RH availability, the size and weight of components, and the number and complexity of parts to be maintained. As can be observed in Table 9.1, all these factors, except for complexity, increase in magnitude from the simplest device JET to the reactor DEMO.

In nuclear reactors using deuterium-tritium, the resulting high-energy 14 MeV neutrons can create radioactive isotopes by transmutation of the chemical elements in the internal part of the toroid. Moreover, there are areas (see Figure where the activation could be higher due to the geometrical design of the device, for instance the first level of wall, blankets or shields, divertors, gauge and other port plugs as well as experimental ports. In addition, the vacuum chamber, as the components located outside the toroid, could be activated but at lower degree.

Now, the highest levels of activation are found inside fusion reactors, thus access to operators is strictly prohibited (Figure 9.1). For instance, the doses are estimated to be several hundreds of Sieverts/hour (Sv/h) inside the ITER toroid and such values are several orders of magnitude above permissible levels for exposure (1 mSv/h during a very brief period of less than an hour). Moreover, activated internal impurities and the accumulation of toxic gases and materials make human entry impossible.

Table 9.1. Comparison of three fusion devices in relation to remote handling.

Remote Handling in fusion devices					
Device	**Availability**	**Complexity of facility**	**Weight & Size of components**	**In-torus dose (Gy/h)**	**Status**
JET	Important, medium av.	High	$2x10^3$ Kg <2 m	$\sim10^3$	Presently operating *
ITER	Important, medium av.	Very high	$<50\ x10^3$ Kg <10 m	$\sim10^2$	Near future
DEMO, commercial	Decisive, high av.	Medium-High	$<10\ x10^3$ Kg <10 m	$\sim10^2$	Long term
*JET is equipped with Remote Handling systems that have proven the feasibility of applying robotics to nuclear fusion and has provided valuable knowledge to this field.					

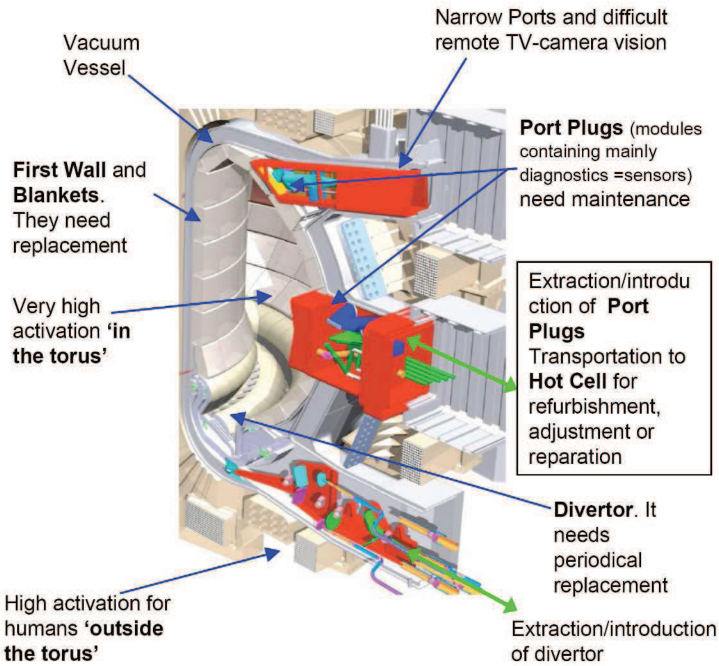

Figure 9.1. Poloidal section view of ITER

Maintenance rooms, where many activated components that require adjustment, refurbishment, or repair after extraction from the toroid are held, are also restricted areas. Thus, a bunker equipped with remote manipulators to perform the above mentioned operations as quickly and efficiently as possible is needed. Such rooms are referred to as *Hot*

Cells and maintenance operations that can be executed in these areas include: movement, extraction, lifting, assembling/disassembling, cutting and re-welding of pipes and containers, bolting or unbolting, connecting or disconnecting flanges and electrical connectors, cleaning, inspection, etc.

As is well known, the performance of the reactor is directly related to the time spent on scheduled or unscheduled maintenance shutdowns. During scheduled maintenance, a series of inspections, adjustments, repairs, and replacements are carried out within the required and planned time. However, unscheduled maintenance can arise during programmed activity and therefore, it requires unplanned shutdowns of the facility, which corresponds to a reduced energy output. The scheme in Figure 9.2 highlights reasons why Remote Handling is essential for future fusion devices.

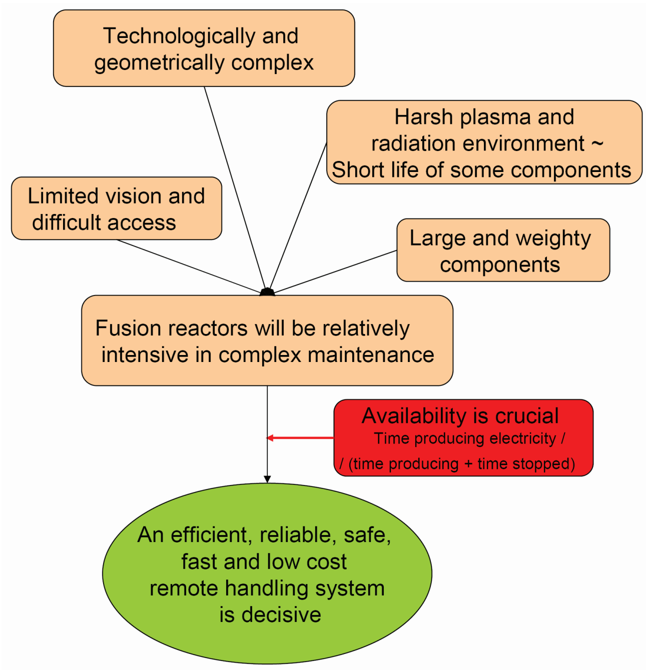

Figure 9.2. Factors that increase the importance of using remote handling in fusion.

In industrial manufacturing, the use of robots and manipulators is widely applied. Robots perform tasks such as the manipulation of components, welding, assembly of parts, as well as numerous other tasks. The design of the components and the operation processes for such systems are undertaken after taking into account available and well tested robotics Technologies. In the case considered here, a remote handling system has to be tested experimentally on every component and part destined for nuclear fusion facility. Thus, such work will not only be used for testing manipulators and possible operation processes, but also for gaining experience in synergies between remote handling and devices by improving their design. Hence, the experience gained from testing remote manipulators with *TechnoFusión* prototypes, models, and equipments will provide valuable and necessary knowledge for application to future fusion devices. Among others, it will enable improvements to maintenance reliability, time cost, and simplicity to be made.

Thus it can be justified that remote handling is essential for nuclear fusion facilities. Moreover, RH systems should be reliable, secure, fast, and economical and they are essential for the technical and economic viability of fusion reactors and related installations. The **Remote Handling Technologies Facility (RHT)** of *TechnoFusión*, should be conceived as a dynamic force to drive science and technology developments in Madrid, Spain, as a long term global strategy.

9.2. Objectives

The main short term objective of RHT Facility is to create an installation where telerobotic tasks for the maintenance and repair of nuclear fusion installations, in particular ITER, DEMO, and IFMIF, can be developed and tested. Furthermore, the installation has to serve as a platform to promote the development of required technologies and as a base to undertake experiments and activities (dissemination, training, and know-how transfer). It means that, in the first instance, the necessary resources must be invested in technical equipment for remote handling and, in the second instance, the distribution of the knowledge acquired on the technologies involved.

In summary, the objectives of the RHT Facility could be summarized as follows:

1) To develop, test, and certify remote handling devices for nuclear fusion installations.

2) To promote the development of knowledge and technology in the field of remote handling in general and for nuclear installations in particular.

In order to fulfill these objectives, the following aspects will have to be achieved:

- To create an installation for the developing, revising, and testing equipment and procedures for remote handling in nuclear fusion.
- To create a remote handling infrastructure that will permit the testing and certifying of equipment destined for nuclear fusion installations.
- To propose and develop research activities on robotics and remote handling by staff and associated researchers.
- To be an active and dynamic centre for the dissemination of scientific and technological results and studies in the areas of advance robotics, service robots, and remote handling in nuclear fusion.

- To contribute to the development of knowledge and distribution of results from research work carried out in the laboratory by having close collaborations with the industrial sector and start-up companies.

Thus, it can be concluded, that given the provisions of suitable resources and infrastructure, together with highly qualified personnel, will allow *TechnoFusión* to be very innovative in the area of remote handling specially focused on fusion. Next, regarding activities to be performed, the following should be highlighted:

- Testing, certification, and homologation: The planned infrastructure, personnel, methods, and procedures will enable the RHT to perform testing, certification, and homologation of equipment and systems that are destined for use in areas with high radiation levels. In addition, this Facility will collaborate with international entities charged with regularization methods and criteria for testing such systems.

- Research and development of technology for remote handling: Having as an objective to contribute with new solutions, tools, and technology for performing remote handling tasks in nuclear fusion, the laboratory will undertake continuous research and development of relevant technologies. Such independent developments, through patents and technological results, will be applied in future in-house research and development projects.

- Provision of infrastructure and installations: It is intended will to provide state-of-the-art installations. In some aspects, these will be unique and will be adequate to evaluate and test procedures and equipment developed by other companies or institutions before their application. Such companies will provide a complementary means of financing *TechnoFusión*. Additional earnings will come from hiring services, since the singular features of the installation will allow it to adapt to the requirements for specific evaluations, tests, and training.

9.3. International status of the proposed technologies

9.3.1. International reference installations for remote handling technologies

The majorities of current remote handling technologies are international and focus mainly on remote handling tasks for ITER due to the urgency involved and the numerous areas that need to be validated and improved. Some of the activities to be developed are related to the handling and the manipulation of different elements, such as divertor cassettes, experimental connecting doors for diagnostics, protection modules, etc. However, new nuclear fusion projects, such as IFMIF, also require laboratories devoted to remote handling. At present three principal Remote Handling laboratories dedicated to Nuclear Fusion currently exist in the world, two of which are in Europe and one in Japan.

(I) Divertor Test Platform 2, Tampere (Finland)

The *Divertor Test Platform 2* (DTP-2) is an installation for testing systems for the extraction, insertion and movement of divertor cassettes in ITER (see Figure 9.3). The installation was commissioned at *Technical Research Centre of Finland* (VTT) premises in May 2007. VTT stands for *Technical Research Centre* of Finland, and an important applied research organization that contributes with valuable technological solutions and innovations. VTT is a non-profit research organization within the *Finnish Innovation System*. The new VTT experimental warehouse is located in the Technological Campus next to the Technical University of Tampere.

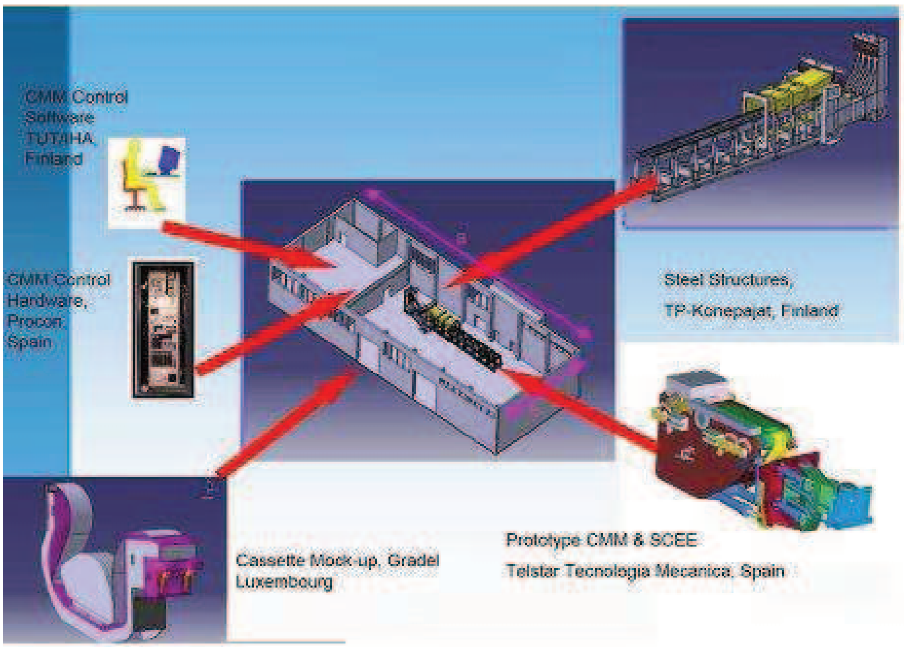

Figure 9.3. Layout and equipment of DTP-2 installation at Tempere,[154]. Dimensions (aprox.): a ≈ 50 m , b ≈ 20m.

A layout of the installations and its main rooms and equipment is shown in Figure 9.3. The contributions of two Spanish companies are noted in the captions. Figure 9.4 shows a picture of the experimental area.

[154] ‘TEKES ITER-projects since1994 = ITER RH interests’ ; Jouni Mattila ; Presentation in Tampere meeting ; Tampere , Finland ; December 2007

Figure 9.4. Experimental area in DTP-2[155] with a divertor cassette in the foreground (black and grey).

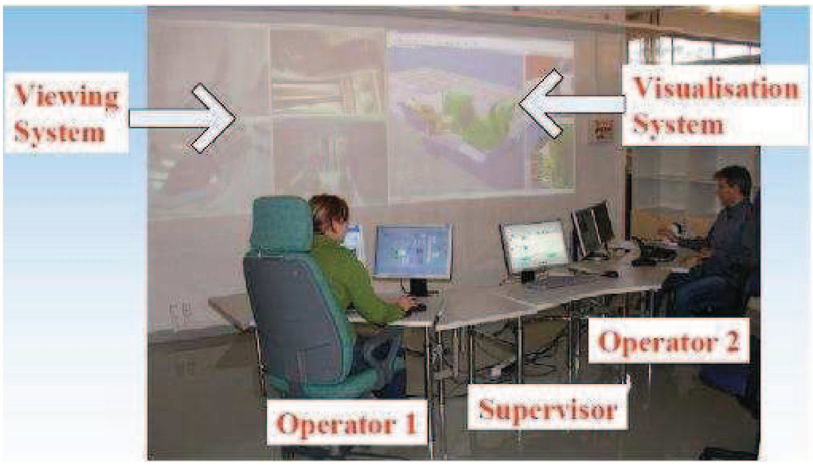

Figure 9.5. DTP-2 control room in 2007. Vision and simulation system.

The test installations at DTP-2 were initially focused on performing radial movements (i.e. from inside the ITER toroid towards the radial exterior) of the divertor cassettes, developed by *Cassette Multi-functional Mover* (CMM) (see Figure 9.3). In a second stage, the installation extended its studies to subjects related to the toroidal movement of the cassettes inside the ITER toroid. Moreover, the installations are equipped with lifting devices, a maintenance robot, a support rail for the divertor, a prolonged metal structure for the

[155] 'RH Activities of the EURATOM/IST Association Portugal' ; Isabel Ribeiro et al. ; Presentation in Tampere meeting ; Tampere , Finland ; December 2007

extraction of divertor cassettes, hardware and software control, plus a control room (see Figures 9.3, 9.4, and 9.5).

(II) Remote Handling Laboratory at the ENEA Brasimone Research Centre (Italy)

This laboratory develops a range of Remote Handling tasks for different fusion devices, thus the project and equipment have been modified since operation began. Three of its installations are descried briefly below.

1) Divertor Refurbishment Platform

The *Divertor Refurbishment Platform* (DRP) is comprised of two stages. In the first stage, refurbishment of the ITER divertor, designed in 1998, was tested, showing correct performance during the test period 1999–2003. Note; a crane was used to perform this test (see Figure 9.6)

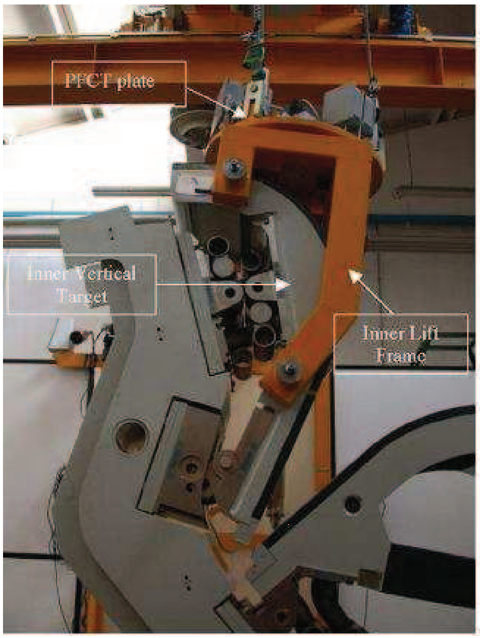

Figure 9.6. Extraction of PFC of ENEA.

However, the current design, called ITER FEAT, is equipped with different divertor cassettes, hence the DRP installation was modified during 2003–2005 in order to adapt it to these new requirements. For this, three lifting devices were designed and installed (Figure 9.7). This experimental machine is called the *Plasma Facing Components Transporter (*PFCT). The principal elements of PFCT are a cart, a set of cables, and a suspended platform (Figure 9.7).

The PFCT is a device capable of elevating, or inclining, loads up to 5 tons. It has six degrees of freedom on a suspended platform, it moves at very low speed when performing remote operations of maximum precision, it can rotate at 1 degree/second and it can perform precise positioning up to 0.25 mm.

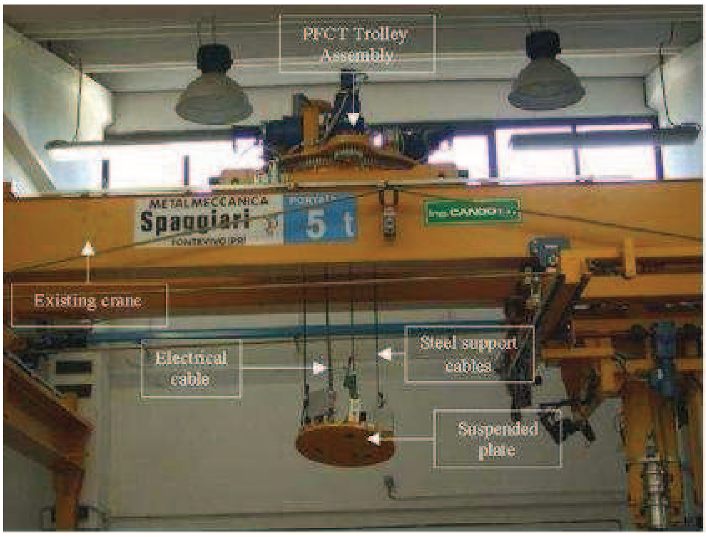

Figure 9.7. General view[156] of the Plasma Facing Components Transporter (PFCT). Assembly cart, cables, and suspended platform.

Furthermore, several tests with PFCT features have been carried out. Some tests of operations and components have also been performed. For instance, some basic features in Remote Handling have been improved, such as elevation, evaluation of position reproducibility, blocking and unblocking of the suspended platform (Figure 9.6), axis testing of the suspended platform (rotation, inclination, elevation of the PFC), as well as tests of hardware and software control execution and other operations.

2) Divertor Test Platform (DTP)

The DTP installation (Figure 9.8), also called DTP1, was the first installation for Remote Handling testing of complete divertors by means of a scale model. The installation was used until 1998 and the initial design of the divertor cassette (ITER 1998) was successfully tested. The current and definitive design of ITER-FEAT will be tested and checked in DTP-2, in Finland.

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[156] 'The plasma-facing components transporter (PFCT): A prototype system for PFC replacement on the new ITER 2001 casete mock-up' ; G. Miccichè et al. , ENEA ; Fusion Engineering and Design ; January 2007.

Figure 9.8. General view of the DTP[157] of ENEA.

The DTP, which can be seen in Figure 9.9, consists of the following elements:

- Sector ‘72" of the lower region of ITER,
- A Cassette Divertor Prototype with blocking system, gripping points, and refrigeration connections,
- A prototype for simulating the inner vessel environment that includes toroidal rails, divertor ports, and other devices,
- A displacement prototype (a device similar to CMM)
- Prototypes of auxiliary Remote Handling equipment, and
- Control and localized data acquisition systems in the control room.

[157] ‘What we do in The Vessel in-Vessel Field’ ; Michael A. Pick ; EFDA activities 2006

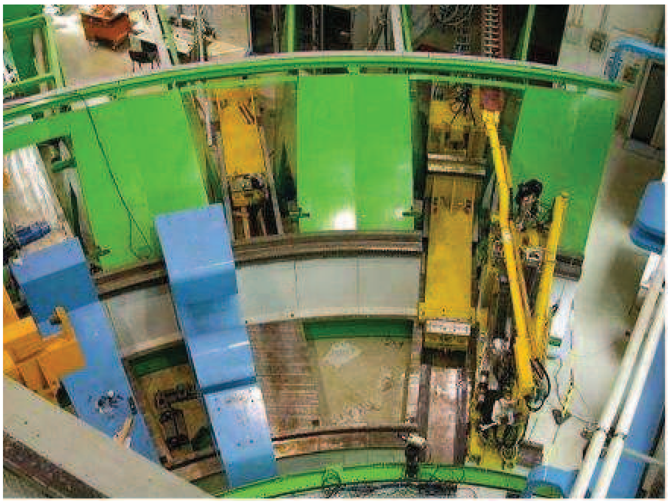

Figure 9.9. Area of the DTP installation showing the cassette Mover inside the vessel (yellow), the divertor model (blue) and Sector '72" of the lower region of ITER and its rails70 (green).

3) IFMIF Test

With the development of IFMIF, new needs have arisen requiring different tests of RH to be carried out. Thus an area is needed to test IFMIF components. The structure and dimensions of such a laboratory can indicated in Figures 9.7 and 9.10.

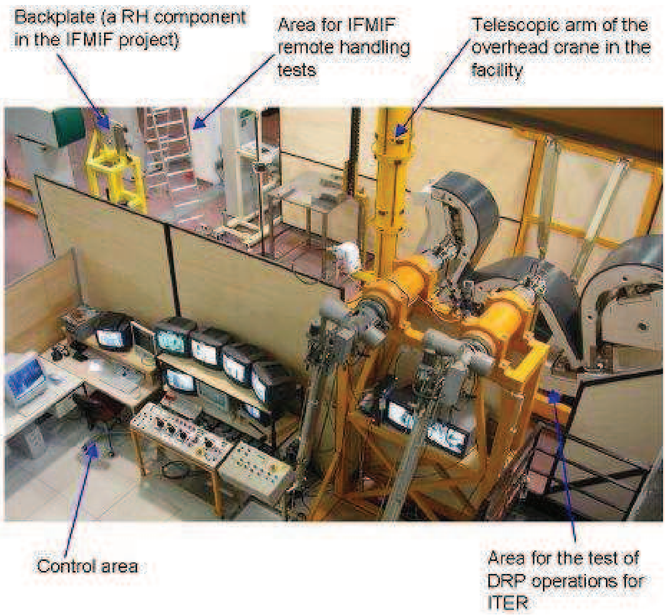

Figure 9.10. A general View of the Remote Handling laboratory at ENEA, Brasimone.

(III) Installations of the Internal Vessel Transporter (Japan)

Figure 9.11 shows a general view of the *Internal Vessel Transporter* (IVT) installations which are a complex for the certification and development of manipulators for interchanging ITER *blanket modules* (a module located on the inside of the ITER toroid to protect the metallic vacuum chamber from plasma induced. It suffers neutron radiation damage and extracts the heat it receives). The *blankets* need to be renewed periodically by substitution because of the damage and deterioration due to being exposed to the plasma and in particular, the neutron irradiation. It may also be necessary to interchange *blankets* in order to make improvements to the device or in case of a failure.

Figures 9.12 and 9.13 show the details of the vacuum chamber transporter inside the IVT. This transporter is the manipulator that permits docking, undocking, and displacing the *blanket* inside the toroid. The three installations were assigned experimental development and certification tasks in accordance to factors such as excellence of the installation, scientific and technical features, experience in past developments, as well as research and development of projects.

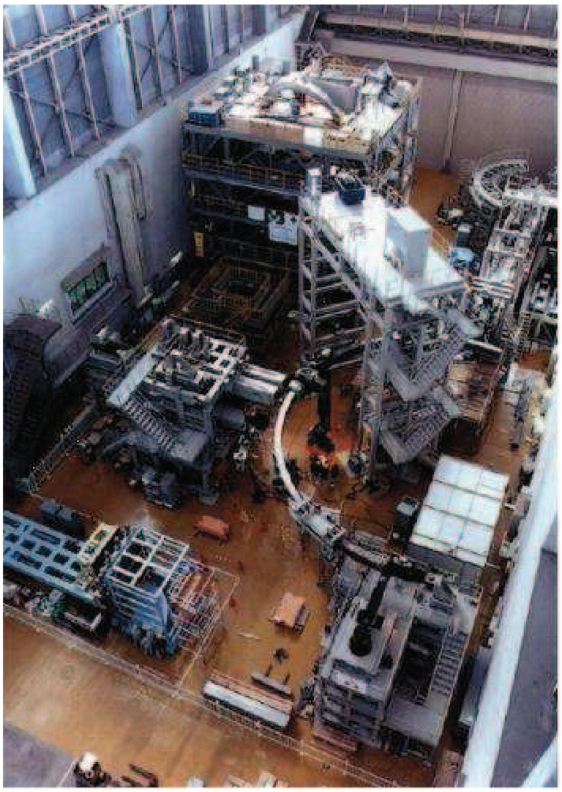

Figure 9.11. A general view of the Japanese IVT installation. The building is 30 m long and 10 m high. The semi-circle in the photograph is the 12 m diameter IVT rail [158].

[158] 'Overview of ITER Remote Handling' ; ESC04-001 / ITA 23-28 Task Motivation , ITER IDM, Remote Handling and Assembly Engineering Support (277VHR_v1_0), Appendix 1-1 - Overview of ITER RH.pdf ; Dr. J. D. Palmer ; 2007

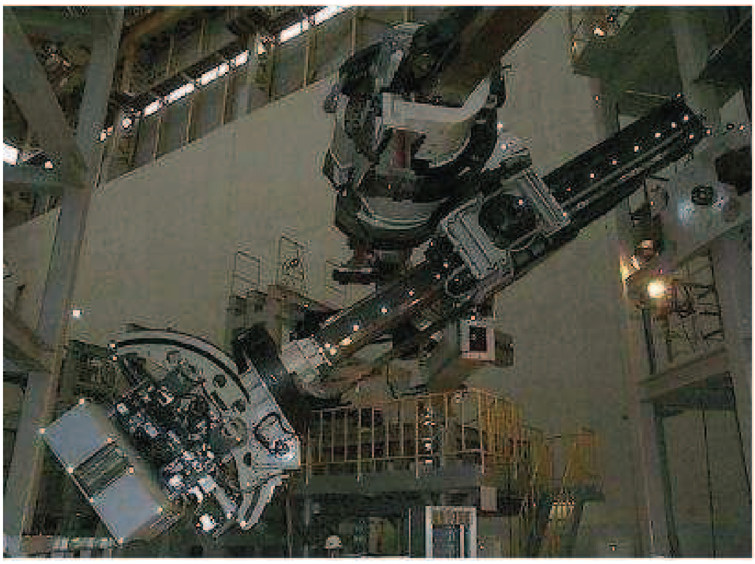

Figure 9.12. The vacuum vessel transporter.[158]

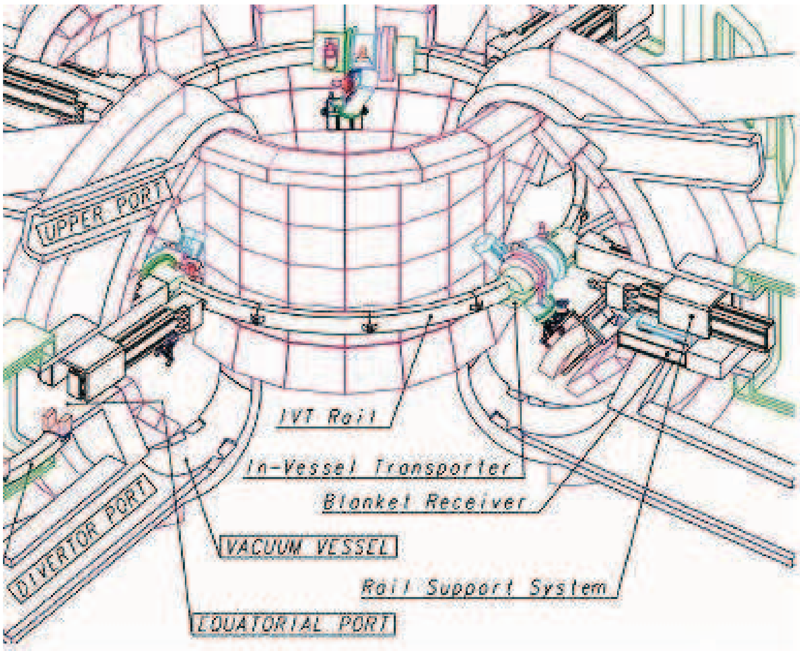

Figure 9.13. A schematic representation of the internal vacuum vessel in the interior of the ITER toroid. [158]

9.4. *Projected facilities*

The equipment requirements for the RHT Facility are defined by the needs of different projects to be developed. In order to determine the basic equipment that will be needed for the laboratory, a variety of relevant activities related to nuclear fusion have been considered. Moreover, in order make it unique the contemplated activities are not currently performed in other installations. The activities are:

(a) Remote Handling operations:

A cold installation is needed to manipulate prototypes for the:

- Diagnostic Port Plugs (DPP) of ITER.
- TBM of ITER.
- IFMIF Irradiation Modules.

Considering the large number of activities related to the above tasks, as well as additional tasks that can arise within a laboratory framework, a bridge crane has been considered in order to control the movement of required elements from the warehouse to the *Laboratory for Experimentation with Large Prototypes (LELP)*:. For this, it is considered that the DPP weights can range from approximately 20 tons (Upper Port Plugs - UPP) up to 45 tons (Equatorial Port Plugs - EPP) (see Figure 9.14).

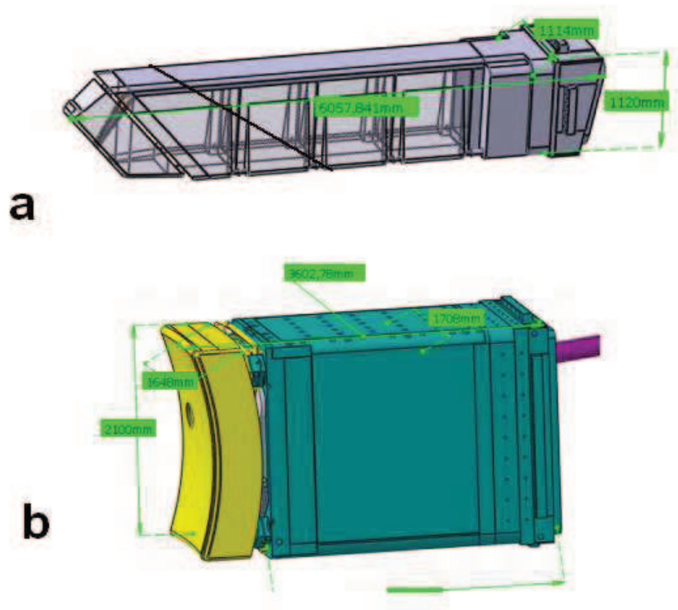

Figure 9.14. Dimensions of UPP (a) and EPP (b) Port Plugs.

In addition, the RHT Facility will need robot manipulators for general use, as well as sensorial and control systems. The warehouse area will also require similar systems. Furthermore, having a crane for transporting large elements (DPP, TBM), the Facility will also require robots and auxiliary systems capable of transporting and storing parts having different sizes and weights.

(b) *Homologation of RH equipment under irradiation*

The RHT Facility will also require an irradiated room in order to carry out validation, certification, and characterization of equipment destined for Remote Handling applications under gamma radiation. Such irradiation procedures will be carried out in an *Irradiation Room* through coupling with an accelerator.

Next, these activities will be explained in detail in the following subsections.

9.4.1. Remote Handling operations

9.4.1.1. Remote Handling of ITER Diagnostic Port Plugs

DPP for ITER contain diagnostic equipment for controlling, optimising, and evaluating ITER plasmas. Among the 18 ITER UPP, 12 have diagnostic equipment, while 10 of the 18 *Equatorial Port Plugs* (EPP)[159] have such equipment.

The most important features of the UPP's are (see details in Figure 9.15):

- Weight: 20 T
- Dimensions: (6.1 x 1.1 x 1.1) m
- In many cases, they have a central tube to locate diagnostic elements. These tubes are installed in the UPP's by rail guides.

In general, the preferred means for extracting a diagnostic module is to open the upper part of the UPP. However, alternative opening possibilities exist such as opening its lower part. According to the most recent conceptual ideas, it should be rotated with respect to its horizontal axis and vertically accedes from the top to the bottom of the UPP.

[159] "Preliminary data for ITER *Hot Room* RH facilities in *TechnoFusión*"; CI-TF-RHSF-002 ; V. Queral ; March 2008.

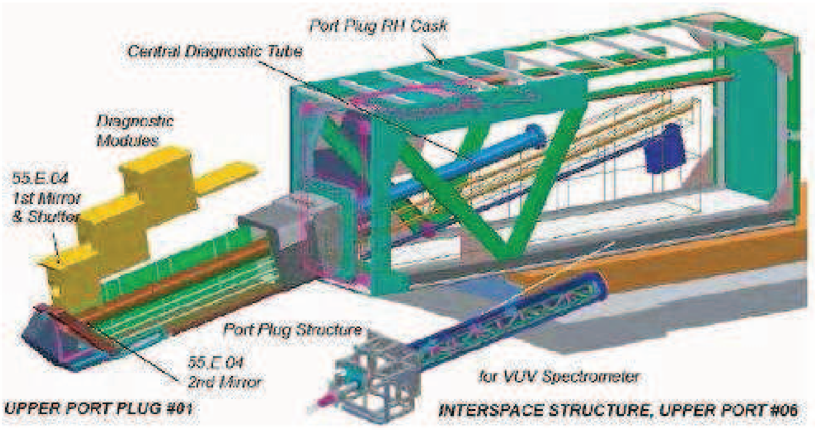

Figure 9.15. Details of an UPP of ITER.

The general characteristics of an EPP are (see details in Figure 7.16):

- Weight: up to 45 T
- Dimensions: (3.6 x 1.7 x 2.1) m
- There exist modules in the EPP that permit replacement of some parts of diagnostic components (mirrors, wave guides, detectors, etc.).
- Diagnostic modules are usually taken out from the top.

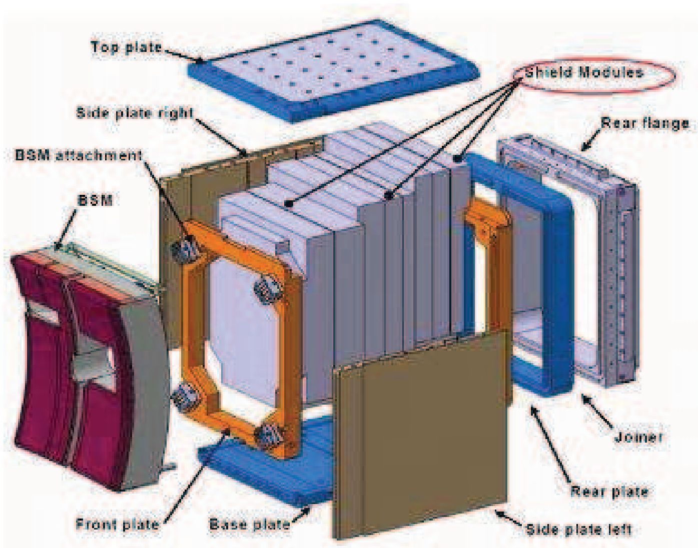

Figure 9.16. EPP details of ITER.

Some diagnostic modules inside an EPP are accessible by removing the BSM (*Blanket Shield Module).* The Blanket Shield Modules are EPP parts situated at the plasma facing end and have perforations to allow the emission or reception of signals. Their approximate weight is 13 tons and their dimensions are 2.1 m x 1.65 m x 0.5 m. Blanket Shield Modules are anchored to the EPP by a system of rivets or by a similar system.

In many cases, the maintenance work on a DPP consists of replacing components or subcomponents. Generally, subcomponents are pre-checked, pre-aligned modular assembled structures which are replaced by extraction and insertion rather than being repaired in-situ. Examples of such subcomponents include telescopes, mirrors, mechanical actuators, etc.

The typical tasks to be carried out for during these procedures are:

- Extraction of *Port Plugs* (PP) from the vacuum vessel (with associated operations).
- Transport of the container to the *Hot Room.*
- Performance of maintenance tasks in the *Hot Room.*
- Transport of the container back to the vacuum vessel.
- Insertion of the PP into the vacuum vessel.

Hence the foreseeable Remote Handling operations for DPP are:

- Elevation and movement of *Port Plugs*, modules, sub-modules, BSMs, and other elements that need replacement.
- Screwing and Unscrewing.
- Cutting of pipes and other elements.
- Soldering of pipes.
- Displacement and adjustment of diagnostic elements.
- Replacement of modules, sub-modules, and other damaged elements.

Taking into account the Remote Handlling of DPP, it is necessary to consider tasks related to the extraction of the DPP from the vacuum vessel, its mounting onto *In-Cask Handling Equipment,* the inverse action of separation from *In-Cask Handling Equipment,* and the reinsertion of the DPP into the vacuum vessel.

In-Cask Handling Equipment is primarily formed by a tractor type system for elevating and placing tasks, or for removing a load from a *Cask* (see Figure 7.16). It also consists of one or two manipulators that perform tasks such as extraction, sealing, removal and cutting of refrigeration pipes, reconnection of pipes by soldering, as well as inspection of soldering work.

The diverse designs of the DPP's that have been presented to date, make it difficult to firmly establish equipment needs. However, it is envisaged that such systems must be equipped with tools for screwing, cutting and soldering. They could also be equipped with pressurized clams and specialized tools adaptable to a particular task.

The DPP Remote Handling tasks to be undertaken in the *Hot Room* require at least a manipulator capable of opening and extracting the *Port Plug* lids. Such a system could be the same as the system used for manipulating TBM's in the *Hot Room*. Considering the dimensions of elements to be manipulated (an Upper DPP is over 6 m in length), it would be convenient to extend the working area of the manipulator by means of a rail. A teleoperated auxiliary system for clamping lids during opening and sealing operations will also be required. In addition, the movement of lids from the storage room while manipulating subcomponents and diagnostic equipment of DPP's will require specific features.

Diagnostic modules inside a DPP can be extracted from the PP at the top. A robotic system with a load capability up to 10 tons (the weight of the EPP[160] screening module) will be required for this. Since the separation distance is 5 mm precise movement capabilities will be necessary even though module position guides are present. Moreover, in order to extract and move a BSM from an EPP, a system capable of transporting approximately 13 tons will be required. Thus, considering both of the above requirements, a robotic system capable of translating 13 tons of load with high precision has to be considered. Finally, a manipulator system will aid in screwing, unscrewing, cutting, or soldering tasks.

In summary, all tasks related to mounting or dismounting of diagnostic equipment located inside a DPP, as well as maintenance tasks to be done in-situ, will require the design, development and construction of specific robotic systems.

Next, RH tasks of complex equipment within a DPP, which require a number of operations with high precision (e.g. alignment of mirrors, cameras, optical devices, etc.), will require systems capable of uploading visual information and haptic devices for the teleoperation of a light manipulator arm that carries out such tasks.

Another foreseen task is the inspection of a PP after RH operations. It will be carried out in a measuring station in order to measure and verify the positioning of some critical PP components. In such a measuring station, a complete visual inspection of all DPP critical areas needs to be performed. Measuring stations and visual inspections will have to done with automated vision equipment and/or a telemetric laser, which is fixed or teleoperated. Some could be placed in pre-set fixed positions. It is also necessary to consider mobile equipment displaced by a robotic arm. In particular, Measuring and Inspection tasks will be designed for performing such operations in ITER. However, some basic equipment for inspection and metrology should be also integrated into the permanent parts of the RH *TechnoFusión* Facility.

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[160] "Technical Specification for the Diagnostic Equatorial Port Plug" ; C.I.Walker ; ITER_D_22FNKA Draft 11 Nov 2005

9.4.1.2. Remote Handling of ITER Test Blanket Modules

TBMs (Figure 9.17) are ITER components for testing Breeding Blankets (these are modules for producing tritium) for DEMO and other fusion reactors. In total, there will be 6 TBMs in ITER to be checked.

The main characteristics of the TBMs are:

- Approximate weight: 2 tons
- Approximate dimensions: 1.7 m x 0.54 m

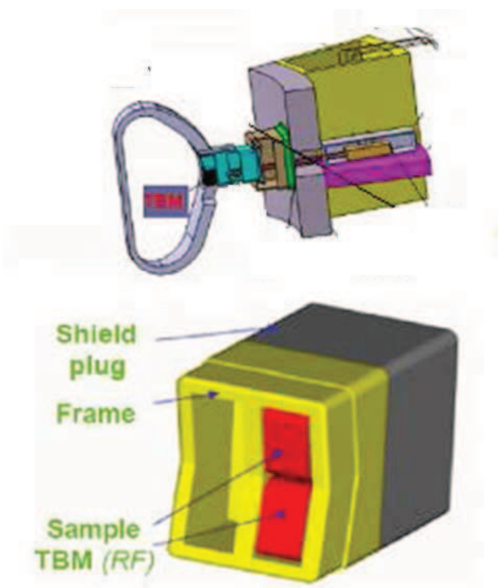

Figure 9.17. TBM structure for ITER.

For the majority of cases, it will be necessary to transfer the TBMs to the *Hot Cell* in order to perform operations related with their replacement.

The tasks to be carried out are:

- For Remote Handling of a TBM in the *Hot Cell*:
    - Arrival of the vessel.
    - Cutting and disconnecting of TBM pipes and electrical connectors.
    - TBM extraction.

- Displacement to the work area.
- Extraction of the TBM from the EPP.
- Displacement to the blanket detritiation area.
- Placement of a new TBM.
- Soldering and connecting of TBM pipes and electrical connectors.
- EPP water-tightness.

- Remote Handling operations to be carried out with the TBM:
  - Elevation and movement of the TBM that is to be replaced.
  - Disassembly, replacement, and mounting of parts that form the component.

The TBM has to be disconnected from the *Port Plug* clamping and to be extracted and replaced by a new TBM.

Regarding the robot for connecting and disconnecting (soldering and cutting), there will be a need for a robotic manipulation system capable of handling 2 tons.

Moreover, the extraction system should be equipped with a manipulator for loading and unloading TBMs. The manipulator can also be used for moving the device from the transport module to the extraction system.

9.4.1.3. Remote Handling IFIMIF irradiation modules

Some tests will be performed at the IFMIF on materials destined for the construction of a nuclear fusion plant. The objective is to study the behaviour of materials under nuclear fusion and generate a materials database for the design of the DEMO reactor. Figure 9.18 shows a scheme of IFMIF irradiated zone.

Due to the radiation, the maintenance or inspection of materials and IFMIF components and the handling of samples for testing irradiation need to be done remotely. Considering all possible Remote Handling tasks in IFMIF to be carried out in the RHT Facility the most demanding one is the handling of irradiated modules, due to the weight and size of the parts. Therefore, it is important to determine tasks to carry out in order to adapt the dimensions of the installations.

Figure 9.18 shows: a) two VTA's (*Vertical Test Assembly*) to locate samples of high irradiation and medium flow, b) a VIT (*Vertical Irradiation Tube*), which is a set of tubes used for inserting test capsules in the region of low flow and test cell covers that support the VTAs and have to be removed in order to accede to the entire cell.

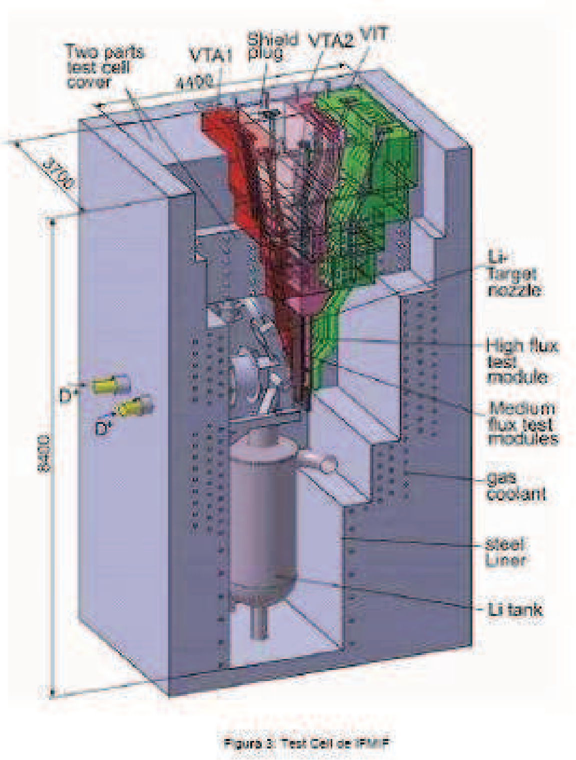

Figure 9.18.. Scheme of IFMIF irradiated zone.

In general, the tasks to be carried out in IFMIF[161] are:

- Extraction of the Test Cell irradiation module,
- Dismounting and treatment of samples therein, and
- Insertion of the Test Cell irradiation module.

The following Remote Handling tasks have been established for remote maintenance of irradiated modules in the IFMIF:

- Disconnection of connectors and bridles in the upper part of the VTAs.
- Hoisting of irradiated modules.

[161] "Preliminary data for IFMIF remote handling facilities in *TechnoFusión*" ; CI-TF-RHSF-001; V. Queral ; November 2007

- Extraction of the Back Plate (the part that supports high neutron radiation) of the Test Cell (if required).
- Insertion of the Back Plate in the Test Cell.
- Insertion of irradiated modules.

In order to carry out these remote handling operations, at least one teleoperated robot manipulator with an interchangeable end-effector will need to be implemented. The robot can perform every operation with the corresponding tool. If the elements to be manipulated have very different properties (weight, size, or shape), different robots could be required for each case. Such robots could be used for elevation, extraction, and posterior insertion of the VTA and VIT. A crane type high-precision robotic system, with the possibility of inclining and rotating parts with respect to three spatial axes, is considered most suitable for this application.

9.4.1.4. Summary of adequate manipulation systems for the majority of remote operations

The RHT Facility must be equipped with a basic system for general manipulation in order to perform validation tasks for research and development, independently from the specific areas previously assigned in the laboratory. Furthermore, it should be recalled that such a basic system has to compete internationally with other laboratories that already possess robotic Installations for testing and validating of fusion components.

The difficulty of predicting and evaluating needs with activities that are still largely unknown is complex. Based on the three examples that have been previously analysed in depth, and also based on budget constraints, an estimate of the minimum installation required to accomplish the basic objectives, while being capable of competing internationally for ITER projects, is defined as follows:

a) A crane bridge referred to as the “Main Crane” with an adequate weight capability (required load between 20 and 40 tons to be decided in future studies) and high precision for part positioning. It must be equipped with a system for the rotation of a part with respect to the vertical axis and with respect to two horizontal axes. Moreover, it has to be equipped with sensors for absolute precise positioning, these being adequate for tasks that require very high precision (to within millimetres or less, obtained by telemetric lasers or similar for absolute reference), a weighing scale, and a weight balance. The type of tow or crane should be the most common and significant of the ITER and IFMIF facilities in order to include the vast part of the experiments without the need of buying specific components.

b) A system for transporting and positioning robotic manipulators about different areas and heights in the *LELP Laboratory:* by means of rails, an articulated arm, crane hoists, and/or vertical or horizontal telescopic systems.

c) Robot Manipulators with two different load capabilities, i.e. 100-500 kg for maximum load capability and 10-50 kg for reduced load capability. Two kinds of robotic manipulators have to be considered: one a commercial type (high reliability and recognition from international groups) and various non-commercial robotic manipulators mainly developed by universities and research centres based around *TechnoFusión* (GIAs[162] and related companies). Non-commercial robots have to be equipped with open and flexible software, have open and modifiable mechanical performance, and moreover, systems that are adequate to research and development around *TechnoFusión*. The minimum number of robots required is: a commercial robot equipped with two arms and minimum load capability of 10 kg (50 kg is the minimum desirable load) and two non-commercial robots equipped with at least one high quality arm.

d) A remote camera vision system, a fixed telemanipulation and control system, and another teleoperated system at the door of the installation for performing minor operations plus a real-time interaction system and a virtual human model.

e) Powerful Graphic Computers for virtual reality and specific software.

9.4.2. Irradiation Room

The RHT Facility of *TechnoFusión* will require an irradiation room to undertake validation, certification, and characterization of equipment designed for performing Remote Handling operations under radiation conditions. The irradiation of such equipment will be carried out in a room called *Irradiation Room*, where such components can be irradiated by gamma radiation via an access port to the electron accelerator (see Chapter 5 on Material Irradiation Facility for more details). Remote handling equipment to be irradiated include servo-manipulators, cranes, stackers, manipulated arms, telescopic posts, articulated arms, in addition to other RH equipment developed for use in ITER, IFMIF, or DEMO, as well as commercial fusion reactors.

The goal of this section is to irradiate manipulator equipment. In the case where irradiation cannot be performed due to space restrictions, the testing will be restricted to the most significant parts of the robot under evaluation. Its capacity to irradiate entire manipulator parts makes this installation unique within its sector.

Gamma rays are generated by the irradiation of a tungsten plate with electrons accelerated by a *Rhodotron®* (see Chapter 5 for more information). Appendix II describes the results of the simulations to evaluate the dimensions of this W plate and the characteristics of the electron beam.

Table 9.2 shows a brief summary of the simulations. The optimized parameters are shown in order to maximize the final volume with doses between 100 and 500 Sv/h.

[162] The GIAs are the *TechnoFusión* Associated Investigation Centres for technological support..

Table 9.2. Simulation summary:

Irradiated material	**W**
Density	**19.25 g/cm^3**
Cosine of the angle of incidence	**0.6**
Beam footprint	**Square area: 1.5 x 1.5 m^2**
Plate thickness	**0.6 cm**
Beam radius	**0.5 cm**
Total volume	**74.80 m^3**
Irradiation Room size	**100 m^3**

9.4.2.1. Estimation of Space and Radiation Dose

In order to estimate the minimum space required for the equipment of *Irradiation Room* as well as a reasonable irradiation dose it is necessary to first necessary to take the following criteria into account. First, it should be recalled that the electron accelerator will be used by different experiments groups within *TechnoFusión*. Remote Handling is just one such area and, as a consequence, the size requirements of the *Irradiation Room* and the irradiation dose will be defined as a function of the performance and limitations imposed by the electron accelerator design specifications.

The size and dose of irradiation in the *Irradiation Room* will depend on:

a) The world market regarding testing and certification of manipulators for fusion and the participation of the *TechnoFusión Irradiation Room* in the world market. In the following sections, some preliminary estimates are made within the limits imposed by the uncertainty of future markets.

b) The size of robots for Remote Handling (including manipulators, cranes, articulated arms, etc.)

c) The irradiation rates for robotic manipulators (in units of robots per unit of time, e.g., four robots irradiated in one year)

d) The dose received by manipulators will depend on the size of the room and accelerator power.

e) Robots in the first line of irradiation will receive higher radiation doses than those located in the second line. For these latter robots, the absorption of radiation depends on the size, shape, and materials of the robots that act as a screen in the first line.

9.4.2.2. Market for the Irradiation of Robotic Manipulators

In ITER, it is estimated that the number of robots working in high-radiation areas of ITER will be between 50 and 100. These estimates include servo-manipulators, the crane bridge, other bridges, stackers, telescopic posts and articulated arms, Plasma Facing Component Transporters (PFCT) in the ITER *Hot Room*, IVT that work inside the vacuum chamber, robots for performing inspections inside the vacuum chamber, as well as CMM and *Second Cassette End Effectors* (SCEE) in ITER ports for replacing divertors.

In IFMIF, the total number of robotic manipulators in the entire installation, including cranes, manipulators, and articulated arms, is estimated to be between 7 and 10 units.

In DEMO and future reactors, it is predicted that the number of robotic manipulators that will have to be validated and certified will be immense. However, due to the large number of existing unknowns, the installations that will be required for such tasks will be considered in future expansions of the *Irradiation Room* as this will need very long term planning.

Other activities that require robotic manipulators as nuclear plants need validated and reliable manipulators. Even though *TechnoFusión* will focus on research and development, some marginal activities related to other fields can be performed. Around 30% of total *TechnoFusión Irradiation Room* activities could be considered in this sector.

Elements not included in the list of robots mentioned above are:

- Components and replacement parts for robots.
- Mechanisms and manipulators found inside the ITER Cask.
- Other robots that work under conditions of reduced radiation (0.1-1 Sv/h) have not been included since validation tests can be performed quickly or can be even avoided.
- Tools for Remote Handling have not been included since their sizes are very small. However, the number of tools will be relatively high, around 200 to 1000 tools.

Estimate and hypothesis of work:

An estimated number of robots has been considered for their use in the *Irradiation Room* under some hypothesis of work:

- There are two types of robots in the installation. Only one type will need certification, this being about 80 robots. The total number of robots is 160 (ITER + IFMIF + other non-fusion units).
- Replacement parts will not need certification or testing.
- The majority of robotic manipulators considered above will be developed and validated during the ITER construction phase, (which means from the present to around 2020), this period being about 10 years.

- A 50% share of the total world market for irradiation services is considered for the *TechnoFusión Irradiation Room*. The number of robots considered for *TechnoFusión* is around 40 robots in 10 years.

In conclusion, it is considered than on average about 4 robotic manipulators per year should be tested and certified in the *Irradiation Room* in order to significantly contribute to near-future world needs.

9.4.2.3. Average robots sizes

The term Robotic Manipulator includes a broad range of Remote Handling equipment such as those as mentioned previously: servo-manipulators, cranes, stackers, telescopic post, articulated arms, etc. The size of such equipment will vary considerably, but here, the largest robotic manipulator is considered to be the most relevant for this study. For this, the robot surroundings, including space to allow partial movement of the robotic manipulator, are considered. The surroundings for some large manipulators (e.g. 4 m x 4 m x 3 m) will be used for stacking machines, partly for ITV as well as for PFCT. The surroundings for large ITER servo-manipulators will be 1.5 m x 1.5 m x 1.5 m, approximately.

9.4.2.4. Estimated gamma radiation dose alter stopping for different areas in ITER and IFMIF

(I) ITER [163]:

- Inside the vacuum chamber: about 7,500 Gy/h, for 2.8 hours after shut off. Manipulators cannot work inside the chamber under such conditions.
- Outside the ITER Cask: 10 Gy/h during 11.6 days after shut off.
- Typically <0.5 mGy/h in the most unfavourable volumes between the bioshield and the vacuum chamber. Manipulators intended for such areas are not considered for radiation testing in this document.
- The radiation dose outside the bioshield is expected to be of the order of several µSv/h except near conductors.
- ITER *Hot Room*: 155 Gy/h per 1 m^2 of a Blanket surface[163]. A value of than 10 Gy/h can be considered for the majority of the areas.

(II) IFMIF:

- The dose inside the most activated volume, which is the Test Cell, will be between 20 and 1000 Gy/h immediately after shut off. The dose will vary

[163] "DESIGN DESCRIPTION DOCUMENT: Remote Handling Equipment (DDD 23) Chapter 1, General", N 23 DDD 66 R0.3 ; ITER IDM ; 2004

significantly with distance from the test modules, since the radiation source is relatively concentrated.

9.4.2.5. Reasonable gamma doses for electron accelerators and robots

Various studies show that a dose rate between 100 and 500 Gy/h could be reasonable attained in a volume of a few cubic meters exposed to radiation from a 10 MeV accelerator with a maximum current of several mA. The objective is to test robotic manipulators at a radiation rate of Gy/h which is 10 times higher than the dose received in a real installation. It is thereby convenient to reduce irradiation periods to practical values. Therefore, a dose rate of 500 Gy/h for the first row of robots in the *Irradiation Room* can be considered as the first step in the design.

Two robot categories are considered due to the different operative conditions both in ITER and IFMIF:

1) Critical robotic manipulators: only manipulators working inside the ITER vacuum chamber will receive doses as high as 500 Gy/h for long periods of time. Inside the vacuum chamber, only an IVT requires long periods of time, about half a year of continuous performance. The integrated dose received by these critical robot manipulators is around 2 MGy so such robots will be placed in the first row inside the *Irradiation Room*.
2) Other robotics manipulators: the majority of the other robots that will occupy a volume of about 10 m^3 in the *Irradiation Room* will receive an integrated dose of 1 to 100 Gy/h. Such robots will require certification for 0.1 MGy to 1 MGy of integrated dose. The client needs are unknown, but 10 years of operation at 10 Gy/h and a 10% workload would be a reasonable starting point. The irradiation dose in the second row of the *Irradiation Room* can be around 100 Gy/h and the total volume occupied by 4 robots will be around 40 m^3. Under such conditions, the average time for 4 such robots to receive 0.1 MGy/h will be about 40 days.

Considering that the electron accelerator will be shared with other laboratories, the *Irradiation Room* availability will become reduced, since various robots with different requirements can be irradiated simultaneously. Therefore, an average of 10 robots could be simultaneously irradiated in the second row for one year to achieve 0.1 MGy of integrated dose. A longer period will be required to irradiate robots in the second line if 1 MGy of integrated dose is required for all robots in the *Irradiation Room*. The values presented here are reasonable with respect to the world market for irradiating entire robots as well as for the electron accelerators considered for *TechnoFusión*.

9.4.2.6. Conclusions: *Irradiation Room* requirements

- The minimum effective volume required is 4 x 4 x 3 m^3. An effective volume of 5 x 5 x 4 m^3 would result in higher performance and greater possibilities for irradiation but it has double the irradiated volume. Note: the effective volume is that volume that can be occupied by robots for testing.
- The gamma dose in the first row will be at least 500 Gy/h. The dose in the second row will at minimum be 100 Gy/h.
- Beam sweeping should be concentrated on a relatively reduced area (about 4m^2 or less) from the wall of the gamma ray generator in order to obtain as high as 2000 or 3000 Gy/h in a small volume inside the *Irradiation Room*. Such characterization may be needed occasionally for special certification cases.

Other requirements that need to be considered include:

- Wall, floor, ceiling, and shelve elements that are used to support the irradiated robotic manipulators.
- Cranes and stacking machines used to position small robots and robotic manipulator tools on structures such as shelves.
- Robot power supply. They must have an adequate power supply as some robot parts will be validated under conditions where these are moving. In other words, the robots are performing the required displacements while being irradiated for their validation and certification. Thus each robot will require an electrical or hydraulic supply as well as conductors for signal cables.
- Standard wireless communication systems will need to be installed. These should be flexible systems in order to have dedicated wireless systems for each client.
- The cell will have to be prepared to permit the future installation of heating systems that could result in room temperatures up to 70 ºC.
- Safety requirements and construction norms related to gamma radiation chambers and rooms will have to be complied.

9.5. *Experimental capacity*

The RHT Facility will develop its tasks around two main work areas: the development of specific robotic systems plus teleoperation and robot control. These areas could be detailed out as:

- Teleoperation of tasks, such as communications, interface, man-machine and bilateral control.
- High performance robots (dimensions and effort) with both parallel and modular structures.

- Perception around semi-structures with 3D vision and force sensors.

- Virtual Reality for the representation of realistic virtual environments and simulation of maintenance operations.

- Mobility and transport (inside and towards the exterior) of robots and mobile manipulators, humanoids, and other locomotion alternatives.

- Radiation hard robot components.

9.5.1. *TechnoFusión* teleoperation tasks

The RHT Facility will have to ensure the efficient performance of teleoperated manipulation tasks, such as component testing for ITER diagnostics or testing of IFMIF module prototypes. A Remote Handling installation consists of two central components, the operator control post and the manipulation remote. Figure 9.19 illustrates the relationships between both posts.

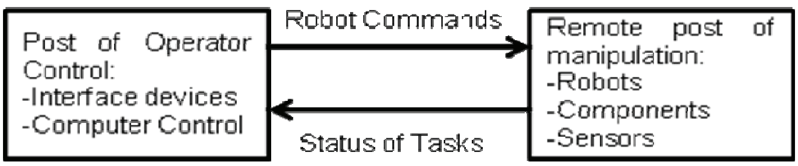

Figure 9.19. Scheme showing how a teleoperated system works.

The operator control post has two objectives: the first, the transmission of orders generated by the operator to remote robots and, the second, to inform the operator about the status of the work in progress. In order to carry out this operation, an advance teleoperation interface is required. The main installations needed for this are:

- <u>Master with force reflection.</u> These devices follow the movement of the operator's hands. This movement is used to generating the corresponding trajectories of movement of the remote robot (also called slave). The forces that are generated when the remote robot interacts with its environment are reflected on the master in a manner that the operator perceives the generated forces. Various types of telemanipulation systems exist on the market, such as those shown in Figure 9.20, which correspond to a master-slave architecture. Moreover, it is important to point out that a haptic interface that complies with the functionality of the master solely would be connected to the remote robot. A clear requirement of tasks relevant to the RHT Facility at *TechnoFusión* is the need to perform bimanual tasks. It will require the use of two masters with force reflection. These are tasks that do not use both masters simultaneously for manipulation. One master usually serves as support for the other. However, using both masters offers a clear advantage and a simplification of the procedure is obtained.

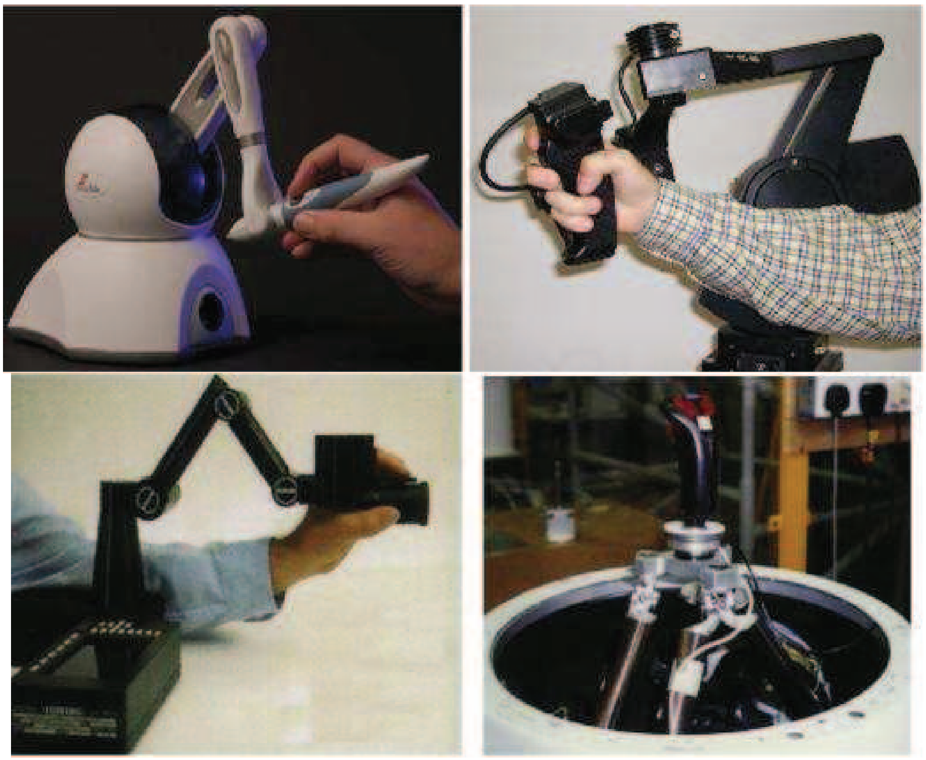

Figure 9.20. Different haptic devices used as masters for controlling remote robots Telemanipulation tasks.

- Visualization of stereoscopic and panoramic images. The visualization of a manipulation procedure being undertaken in a remote environment is done using only two monitors. One monitor shows a panoramic and general images of the environment. The other one is used for visualizing stereoscopic images of the objects to be manipulated. The visualization of panoramic images allows the operator to determine the relative position of objects inside the remote environment and consequently, increases the operator's perception. The stereoscopic images allow the operator to know the size of and distance to the object to be manipulated with precision. Although the use of several monitors is common in Remote Handling laboratories, it is of little use since the operator will have difficulty visualizing several monitors at the same time. Figure 9.21 shows devices of stereoscopic vision.

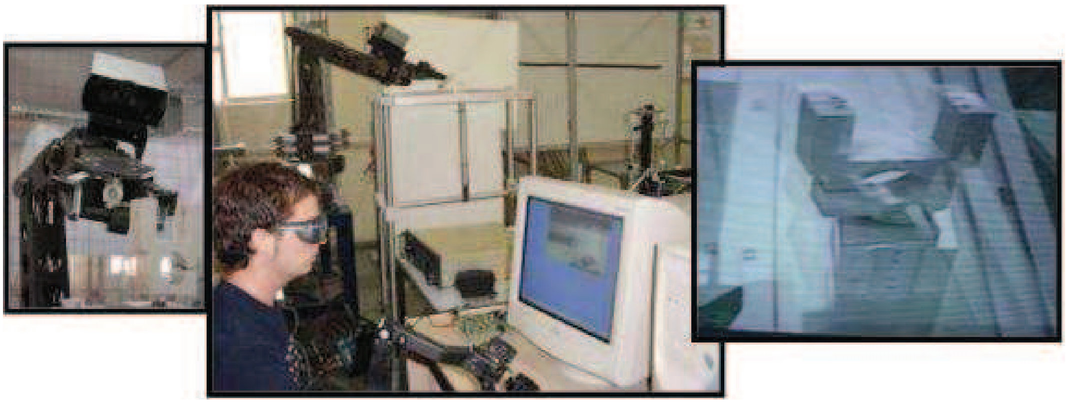

Figure 9.21. Stereoscopic Visualization System. Robot with binocular camera (left), operator with glasses for correct visualization of a stereoscopic image (centre), image of object as seen on the screen (right).

A teleoperation interface also relies on other devices that permit the efficient performance of tasks. These devices, such as switches, handles, etc., will be specific to the task to be carried out. Other devices that are commonly used include voice monitoring systems that allow the operator to generate voice commands or to record technical comments about the work being undertaken or about situations encountered.

9.5.2. High performance robots

Conventional structures are inefficient, since they require actuators with large torque features that are difficult to apply for the manipulation of very large or very heavy objects. As an alternative, parallel structures can be used. Such structures allow actuating on the object to be manipulated at several points in a synchronized manner. Another structure is a modular type formed by simple properly connected elements, which can lead to more complex structures.

Parallel robots are robots whose mechanical structure is formed by a closed-chain mechanism whose end-effector is connected to the base by at least two independent kinematic chains. Figure 9.22 shows three examples of parallel robots in which the advantages of their use in relation to their required performance can be clearly observed.

By careful observation and study of these structures, some of the problems for their development could be figured out: kinematics study, control, and dynamics. All will need some requirements for precision of position and control of force.

Modular structures (Figure 9.23) have demonstrated great flexibility in performing robotic tasks relevant to *TechnoFusión*. These systems have the advantage of adapting to the task by adopting different configurations.

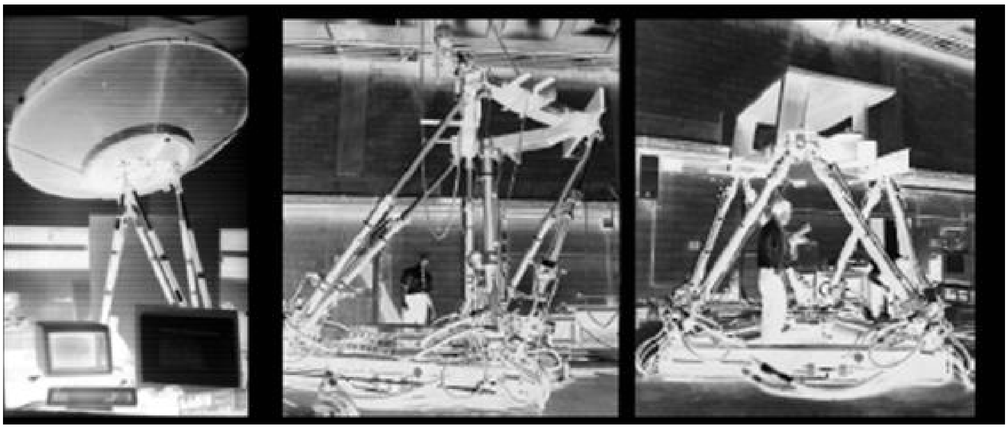

Figure 9.22. Example of parallel robots.

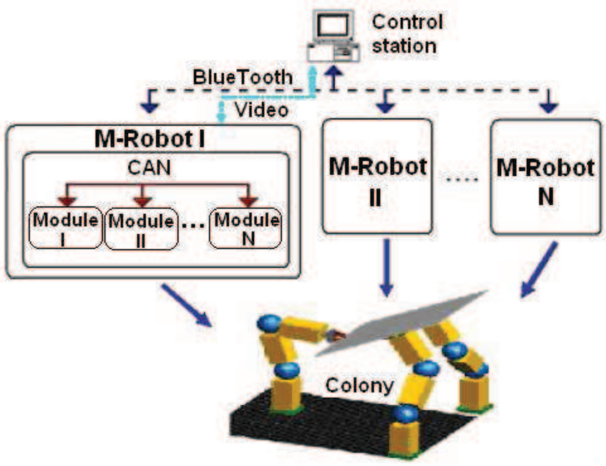

Figure 9.23. Modular system cooperating to perform tasks.

9.5.3. Perception of semi-structured environments

The reconstruction of the work environment is a key point for the semi-automation of teleoperated tasks. It is usually based on using computer visual systems that allow the reconstruction of the work environment from images captured by the cameras. These systems are of great interest, due to the fact that they allow the semi-automation of tasks when the position of certain objects is known. Processing commands of high level relative to the task being carried out can then be performed. Also, 3D laser telemetry can also be considered as a useful tool for environment reconstruction. The direct information of distance to objects that the laser telemetry gives also allows the semi-automation of tasks with great precision.

Figure 9.24 shows a system for environment reconstruction for teleoperation, which allows the monitoring of the work process. Efficient performance of a teleoperated task requires a previous definition of the procedure to perform. It allows a control shared between the operator and the system computers, where computers carry out the task and the operator only intervenes when the operation becomes complex.

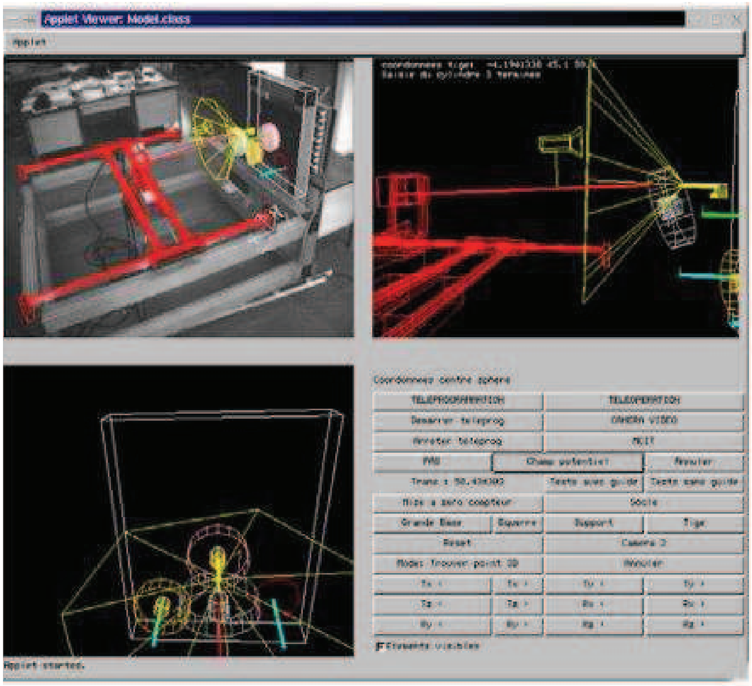

Figure 9.24. System for the reconstruction of the environment for telemanipulation.

9.5.4. Virtual reality

One of the most promising technologies is the incorporation of Remote Handling tasks into Virtual Reality for recreating artificial environments through techniques of realistic virtual representation of objects and properties. These techniques, which are applied to games and also to industrial equipment such as simulators, are considered here for testing manipulator designs and for verifying solution adopted for the operation, especially in situations that require Remote Handling.

Virtual reality is starting to be applied in multiple fields, such as promoting tourism, real estate, and construction projects. The RHT Facility will play an important role in training operators of complex equipments.

Virtual representation is fundamentally important, since the work areas of the manipulators are inaccessible. Regarding operators, the perception is as if they were being governed directly. That is why this area has to be perfectly integrated in the points expressed in 9.5.1 "Teleoperation of tasks for *TechnoFusión*" and 9.5.3 "Perception of semi-structured environments", taking advantage of the sensorial information that these areas give.

9.5.5. Mobility and transport (inside and towards the exterior)

Considering the different operations to be performed, especially in the context of equipment maintenance in fusion installations, the transportation of components of different systems by the same robot is required in order to perform manipulation tasks.

One of the very important transport systems in this type of installation is the Crane Bridge (Figures 9.25, 9.26, and 9.27). In order to define the most suitable type of Crane Bridge to be applied, the specific transport needs of a certain task need to be studied. However, in general terms, cranes with various independent cables can be proposed for the type of installations[164, 165] under consideration.

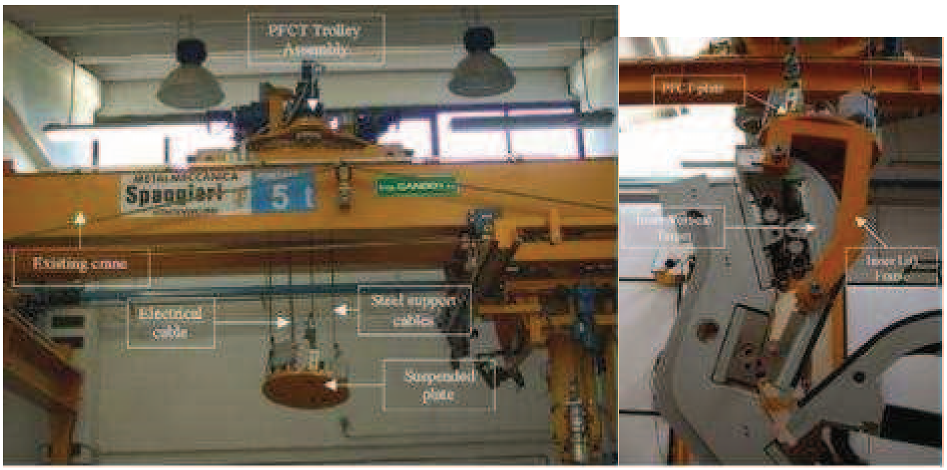

Figure 9.25. A general view of the component transporter from the first wall (PFCT). The principal elements of the PFCT are the trolley assembly, cables, and suspended disc (left). Part of the vertical corner of PFC (right).[164].

[168]'The plasma-facing components transporter (PFCT): A prototype system for PFC replacement on the new ITER 2001 casete mock-up'; G. Miccichè et al., ENEA; Fusion Engineering and Design; January 2007.

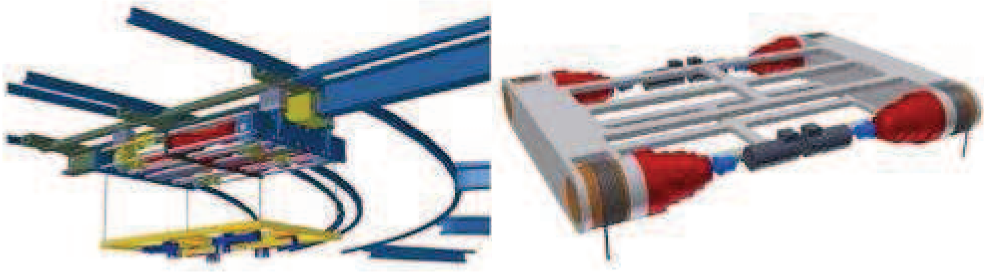

Figure 9.26. Conceptual design of two cranes proposed for IBERTEF for ITER NBI RH [165].

Figure 9.27. Robotic Crane, University Carlos III of Madrid [166].

In this particular case, the crane has to be incorporated with anti-balancing systems and techniques for precise positioning. Such systems have been developed for cranes with heavy loads[167,168] as commercial systems with such characteristics are not available in the markets, so it will require building this type in accordance with *TechnoFusión* specifications. In relation to

[165] "ITER neutral beam remote maintenance system design, crane design report" ; EFDA Task: TW6-TVR-NBRH ; Gonzalo Taubmann (SENER). With permission to reproduce the two figures in this document.
[166] S.Garrido; M.Abderrahim; A.Giménez; R.Díez; C.Balaguer. Anti-swinging Input Shaping Control of an Automatic Construction Crane . IEEE Transactions on Automation Science & Engineering. Vol. 5. No. 3. pp.549-557. 2008.
[166]"A Feedback Control System for Suppressing Crane Oscillations with On-Off Motors". Keith A. Hekman and William E. Singhose. International Journal of Control, Automation, and Systems, vol. 5, no. 3, pp. 223-233, June 2007.
[167]"A controller enabling precise positioning and sway reduction in bridge and gantry cranes"; Khalid L. Sorensen, William Singhose_, Stephen Dickerson; Control Engineering Practice 15 (2007) 825–837.

such needs, it is important to take into account the experience of the research team at the *RobotisLab* of University Carlos III of Madrid in anti-balancing systems for controlling cranes.

9.5.6. Radiation-hard robot components

One area for further study is the Robotic Systems resistance to radiation. Systems developed in *TechnoFusión*, as well as other robotic manipulators, could be studied in detail. The resistance of the main components, such as actuators and sensors, has traditionally been covered, which led to developments of others specific components with guarantees of working under irradiated conditions for a given time. The aspect to be studied by *TechnoFusión* is mainly the effect of radiation on complete manipulator equipment: robots, tools, cranes, etc.

Installations for validation, testing, and certification of robots such as the ROVVER 4 (Figure 9.28), used for nuclear energy generation applications in Palo Verde Nuclear Plant, are practically nonexistent, especially for robots larger than certain dimensions. In this field, the RHT Facility could contribute and work on making large scale robots given its large installation and extensive capabilities.

Figures 9.29 and 9.30 show a preliminary concept and results for the planned installations for testing manipulators, based on calculations done for the *Irradiation Room*, and its gamma irradiation distribution carried out by Y. Herreras[169].

Figure 9.28. Camera and ROVVER 4 robot for PVNGS maintenance and inspection.

[169] Internal Report "Cálculo para la optimización del diseño del Laboratorio de Manipulación Remota". Y. Herreras. Instituto de Fusión Nuclear."

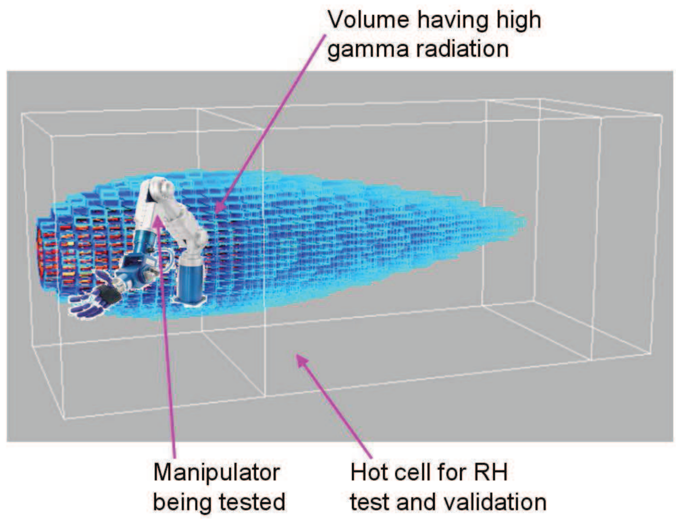

Figure 9.29. Preliminary concept for testing and certifying of manipulators inside the *Irradiation Room* of the RHT Facility.

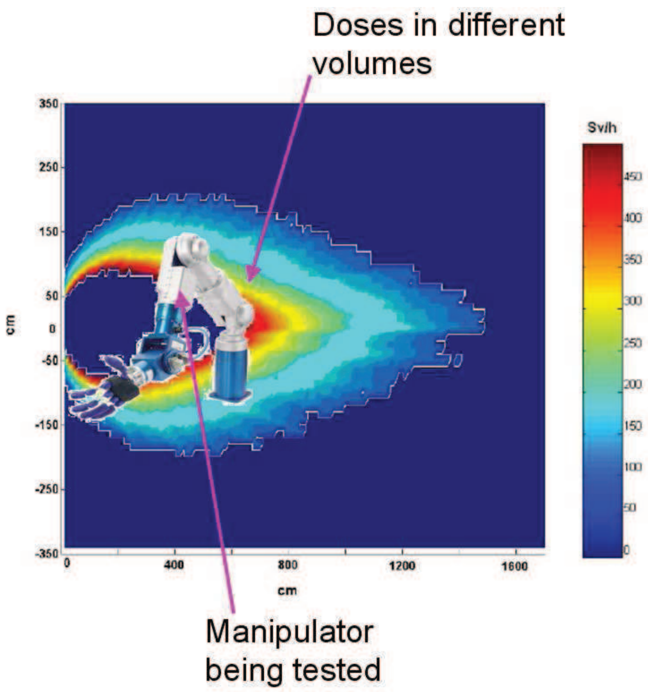

Figure 9.30. Preliminary calculation of the dose for the certification of manipulators and tools for the robotic manipulator.

9.6. Layout, supplies and safety requirements

(I) Required physical space and installations

In order to develop the research activities, the RHT Facility requires the use of the following rooms:

Laboratory for Experimentation with Large Prototypes: a laboratory where part models of fusion reactor installations can be assembled. It will also be used to test the performance of teleoporated robots. This room will accommodate different validation experiments for IFMIF, ITER, and DEMO, although not simultaneously. It is estimated that the minimum space required to carry out such work will be (30 x 13 x 15) m (see Table 9.3).

Irradiation Room: this will be where the performance of entire robotic manipulators as well as robot parts will be validated under low irradiation levels. Manipulators will be placed in this room for irradiation during the required period of time with the possibility to carry out repetitive manipulation tasks while being irradiated.It is estimated that the minimum dimensions (see Table 9.3) is of the order (4 x 4 x 3) m. An area of (5 x 5 x 4) m would be more appropriate in order to achieve more flexibility when certifying large manipulators such as those destined for fusion installations, e.g. DEMO. It should be noted that these estimates may change as they depend on the final engineering and architectural design.

- *Research Laboratory:* 400 m^2
- *Robotic System Design Department:* 100 m^2
- *General storage room:* 500 m^2

The two specific experimental installations must permit both evaluation of the performance of operation tasks of robotic systems and their development and set-up. Taking into account the proximity of the buildings, it would be advisable to consider rails or tunnels that could facilitate the transportation of irradiated equipment as well the sharing of installations such as storage or decontamination rooms. In addition, it there must be a set-up area for teleoperating the robot that should simulate parts of a real teleoperation room in a nuclear fusion plant or any other fusion installation. Moreover, although the occupied space is small, a portable in-situ control panel will be required to facilitate test operations and system performance.

Additionally, a minimum space for general services, such as toilets and washrooms, has to be included. Finally, Table 9.3 shows the space requirements for the *LELP Laboratory*, the warehouse, and *Irradiation Room*.

A detailed description of the two main laboratories of the *TechnoFusión*'s Remote Handling Technologies Facility are explained below:

(a) Laboratory for Experimentation with Large Prototypes

The term "simulation space" implies a minimum space of 30 (l) x 13 (w) x 15 (h) m^3. Some of the criteria to be taken into account for this are:

- The *LELP Laboratory* walls need to support the weight of the main Crane. It would be advisable to consider rails and to have the walls prepared for a second Crane with reduced capabilities that can cover the whole experimental installation or only parts of it. This second crane will emulate the crane of the ITER *Hot Room*. The validation of operations in the testing room cannot be performed correctly "in-service" with the Main Crane so some kind of specific crane may be required.

- An area of the *LELP Laboratory* walls will support the load of a future hoisting crane for manipulating loads in the ITER *Hot Room*.

- Access to the main Crane from the upper part of the *LELP Laboratory* has to be possible. Access times, although quite long, have to be acceptable in order to change the Crane Bridge Cart every 3 to 10 years. Such changes will be necessary in order to adapt the cart to future experimental requirements. Similar changes have already been undertaken, to a certain degree, for example in the ENEA-Brasimone test installation.

- The *Storage Room* has to have easy access through the crane bridge located in the experimental installations. The movement of oversized parts (several metres in length and/or several tons in weight) has to be done in a safe, easy and fast manner. At first, the most convenient manner would be to connect the storage room to the experimental installations in a longitudinal manner so as to use the Crane Bridge both in the storage room and the experimental installations. For small parts, the distribution inside the plant is not needed, as any location could be considered as being adequate.

Table 9.3. Space requirements for the installations of the *TechnoFusión* Remote Handling Technologies Facility.

Remote Handling Operation	Simulation space L x W x H (m^3)	Storage space L x W x H (m^3)	Observations
Extraction and insertion of DPP and TBM	30 x 6.5 x 7	10 x 6.5 x 7 3 units	A module of interchangeable parts is considered
Cask Displacement	20 x 13 x 4.5	8.7 x 2.6 x 3.7 2 units	While one *Cask* is being worked on and the other is in storage
Remote Handling in *Irradiation Room*	5 x 5 x 4*	25 m^2	Small equipment that could have variable shapes for its storage.
Extraction and insertion of irradiated modules	4.4 x 3.7 x 15	4.4 x 3.7 x 2	Determines height of the building. cannot be displaced.

(b) Irradiation Room

An isolated and independent room has to be considered for the *Irradiation Room*. Its exact size is difficult to determine, as this will require some knowledge of the size of the robotic manipulator, the cranes to be validated under irradiation, and the number of robots to be irradiated at the same dose level (TANDRA). However, it is clear that the greater the number of robots to be irradiated simultaneously, the larger the investment needed for the accelerator and the installations. An investment balance based on the following has to be reached:

- For example, the cost of an *Irradiation Room* to validate real sized cranes for ITER. It would be excessive to only consider some parts of the crane to validate and certify. For example, the crane cart equipped with all components and some minimum tracks.

- Robots and structures for the manipulation of large sizes can be relatively big. However, in some exceptional cases, oversized structures can be split into two or three parts (the division into more parts is not possible since it affect the aims a test). The largest envisaged IFMIF robotic manipulator can be placed inside a space of 2 (l) x 2 (w) x 1 (h) m^3. Some manipulators, such as Movers, used for extracting ITER Port Plugs, fit in a space of 3 (l) x 3 (w) x 3 (h) m^3. The main robotic manipulator for maintenance of the UPP ITER Port Plugs could be placed in a volume of approximately 1.5 (l) x 1.5 (w) x 1.5 (h) m^3.

- The potential worldwide market for robot certifications for existing activated environments, which considers more than one hundred different large robots, hundreds of tools over the next 10 years, as well as hundreds of robots.

- The value of gamma radiation ITER, IFMIF and other worksites where more robots perform their tasks and in places of maximum radiation. Values of radiation dose received by robots are very diverse, from 500 Gy/h inside the vacuum chamber during 12 days after shut off the installation to 1 Gy/h or less outside the vacuum chamber. The *Irradiation Room* has to reach a point of equilibrium in order to irradiate the maximum number of robots for the maximum number of potential clients.

- The optimum gamma radiation value in the major irradiation zone inside the *Irradiation Room* and the value for the second row of robots. The minimum value of dose required in the first row of robots (see Appendix II) is of the order of 500 Gy/h, while in the second row it will be of 100 Sv/h. A small area of 1 m^3 exposed to a radiation of around 2000 Gy/s will also be very desirable.

- The number of medium-sized robots that fit in the *Irradiation Room*. The absolute minimum size of this room will be 4 (l) x 4 (w) x 3 (h) m^3 although a larger dimension of 5 (l) x 5 (w) x 4 (h) m^3 would be needed in order to make it relevant in the market for irradiating entire robots for fusion.

- The criteria for determining the required volume of the *Irradiation Room* in the RHT Facility is discussed in section 9.4.2 and in Appendix II specifying the minimum needed volume to cover the demands that may arise for both fusion and industrial devices. A study has been done regarding the average sizes of robots that can be used in ITER, DEMO, and IFMIF and the required gamma radiation doses in order to certify in equivalent and relevant conditions.

(II) Safety

The RHT Facility will be in compliance with the Labour Risk Law published in BOE nº 269, 10/11/1995 (R.D. 31/1995). Some of the specific risks to be taken into account in the Remote Handling Laboratory will be explained further. These specific risks and the required safety measures associated with this laboratory and *TechnoFusión* have to be developed more exhaustively for the external engineering studies.

As specific safety measures for the RHT Facility, norms related to the safety of robots inherent in the industrial installations have to be complied. The mentioned norms are based on ISO 12100, written by the Technical Committee ISO/TC 184 (Industry and Integration of Automated Systems) and the Sub-committee SC2 (Robots for Industrial Purposes), and have to be applied to both the *LEPL Laboratory* and *Irradiation Room*. The main points to consider from these norms are relative to the areas of safety that have to be taken into account in the installation and systems for stopping the robots. The space of safety is understood by all areas of work covered by the robots and the rest of the equipments that intervene in manipulations. This area has to be clearly delimited and access to it prohibited while performing tasks with robots. Shut off can be done as a response to an emergency that normally is activated by a corresponding operator action, or as a protection measure due to an unforeseen entry to the robot safety area. The ISO 10218-1 normative gives a more detailed description about the requirements and recommendations that have to be considered in the design of these installations.

The installations have to be equipped with safety and health signs in the work area as outlined in BOE nº 97 23/1997 (R.D. 485/1997).

Safety measures that have to be taken into account in the *Irradiation Room* of the RHT Facility are subjected to protocols and norms for health protection against ionizing radiation (R.D. 783/2001), since the devices are exposed to the effects of ionizing radiation. The gamma radiation present in the installation, with a dose rate of 100 to 700 Sv/h, obliges the *Irradiation Room* to be equipped with shielding, as mentioned in the norms. It is important note in particular the required shielding for doors from the exterior. The door has to be equipped for easy access while also being large enough to allow manipulators under irradiation to enter. In cases where workers are exposed during operation, there exists the Specific Health Vigilance protocol for workers exposed (category A and B) to ionizing radiation risks, undergoing periodic health examinations by Radiological Prevention Service personnel.

It has to be taken into account that gamma radiation could result in the activation of some of the irradiated components and, in such cases, the undertaking of decontamination and storage of slightly activated material and equipment in the *Irradiation Room*.

Appendix II: Simulations to optimize the plate thickness and the maximum irradiation volume

The main goal is to estimate the maximum volume under irradiation on the remote handling area. This requires the design a sheet of metal (in this case tungsten) emitting gamma radiation under the impact of an electron beam with 10 MeV of energy.

(I) Optimization of the plate thickness

In order to calculate the optimum thickness of the W plate by maximizing the gamma radiation in the *Irradiation Room* (see section 9.4.2), a series of simulations with a beam without divergence of 0.5 cm radius have been carried out. Figure II.1 shows the variation of the irradiation volume as a function of the plate thickness. The maximum value is around the 0.3 cm. However, using this small thickness there is a significant proportion of electrons passing through the plate. To mitigate this effect, a thickness of 0.6 cm will be used. This value is decided upon taking into account the absorption of photons produced by increasing the thickness of the plate.

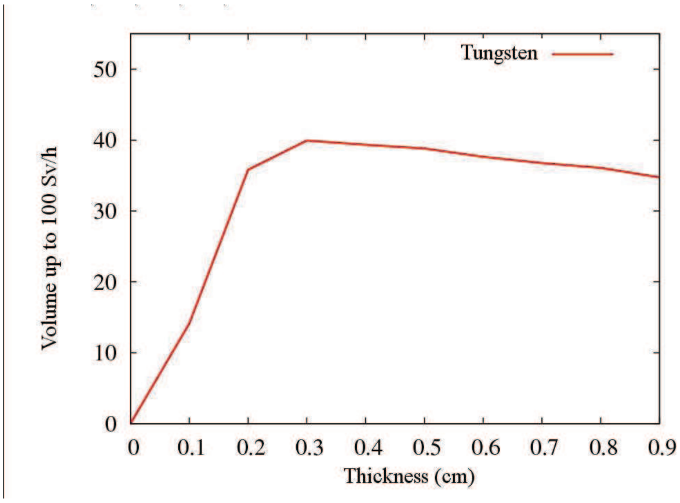

Figure II.1. Evolution of the irradiation volume with the plate thickness.

(III) Beam to generate a square scan

Figure II.2 shows the geometry used in Fluka model (code use for the simulations). The model considers an infinite circular plate with variable thickness on which the electron beam hits. The divergence point is located at 2 m from the plate, and the beam generates a square footprint on it. This shape allows the use of two electronic fields for the sweeping, without increasing the installation complexity. Later sections explore other beam configurations.

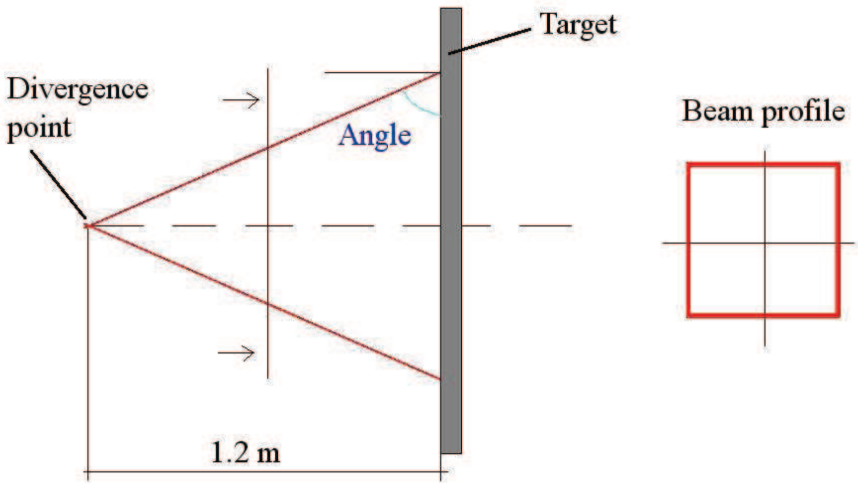

Figure II.2. Simulation model with the geometry introduced for the plate thickness calculation.

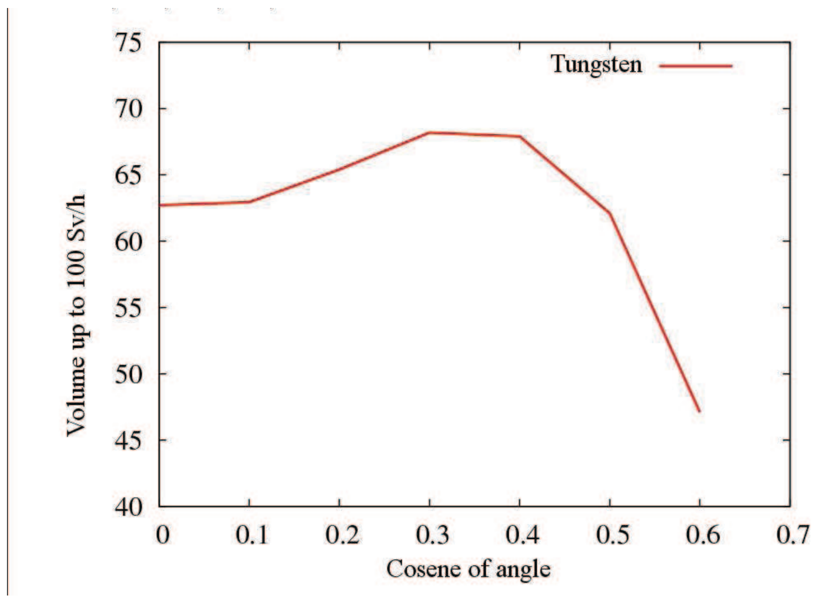

Figure II.3. Irradition volume with dose rates of 100-500 Sv/h for a beam scanning a square area.

Figure II.3 shows the evolution of the room volume with a dose rate between 100 and 500 Sv / h as a function of the cosine of the angle of incidence of the electrons. As shown in the figure, for values between 0 and 0.4, the change in the irradiation volume is very small, reaching its maximum for 0.3. This value will be considered as optimal for a homogeneous radiation.

Figures II.4 and figure II.5 show the distribution of the radiation within the room. The results are obtained by varying the angle of incidence of the neutrons. It can be seen that with a slightly increase of the angle (cos 0.3 and cos 0.4) a substantial homogenization of the dose rate in the room is achieved.

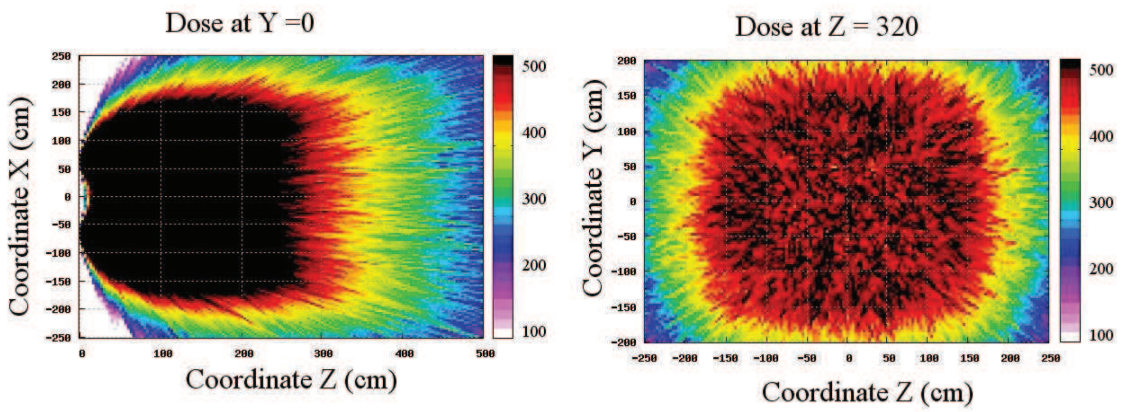

Figure II.4. Dose rate produced by electrons of 10 MeV impacting in a W sheet. The cosine of the incidence angle is 0.3.

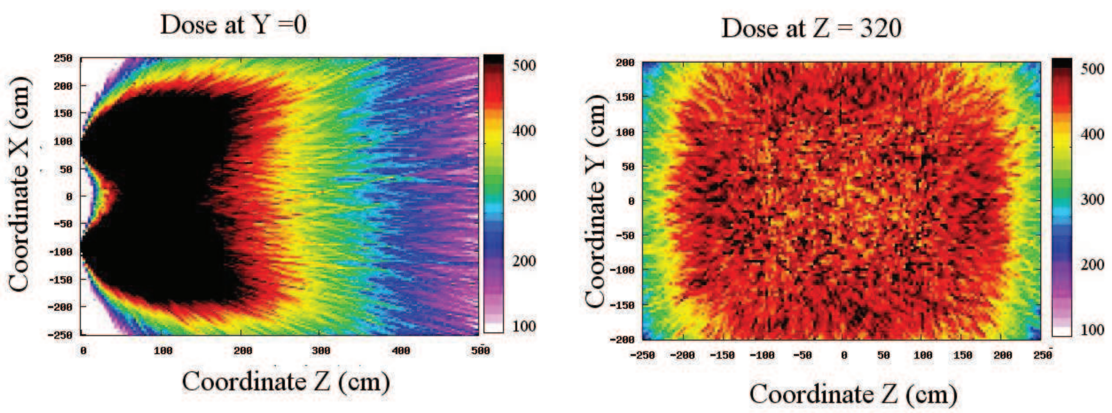

Figure II.5. Dose rate produced by electrons of 10 MeV impacting in a W sheet. The cosine of the incidence angle is 0.4.

(III) Beam scanning a square area

In this section, an evaluation of the irradiation volume obtained by using a beam able to sweep the whole square surface described in figure II.2, is shown.

Figure II.6 shows the evolution of the total irradiation volume as a function of the angle of incidence of electrons. It can be seen as the optimal value is obtained for a cosine value of 0.6.

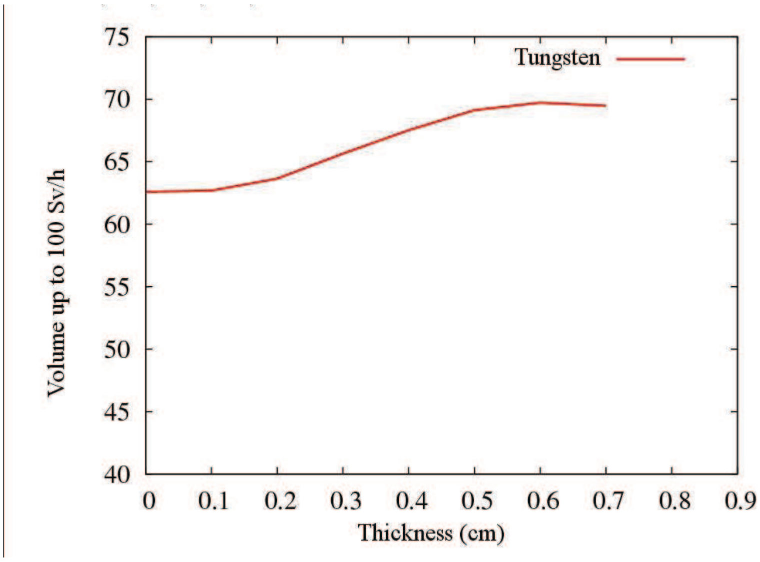

Figure II.6. Irradiated volume with dose rate between 100 and 500 Sv/h for a beam that sweeps the square area.

Figures II.7 and figure II.8 show the dose distribution for an angle of incidence of electrons with a cosine of 0.6. Under these conditions the distribution is very homogeneous. However, the irradiated volumes are lower than those shown in Figure II.5.

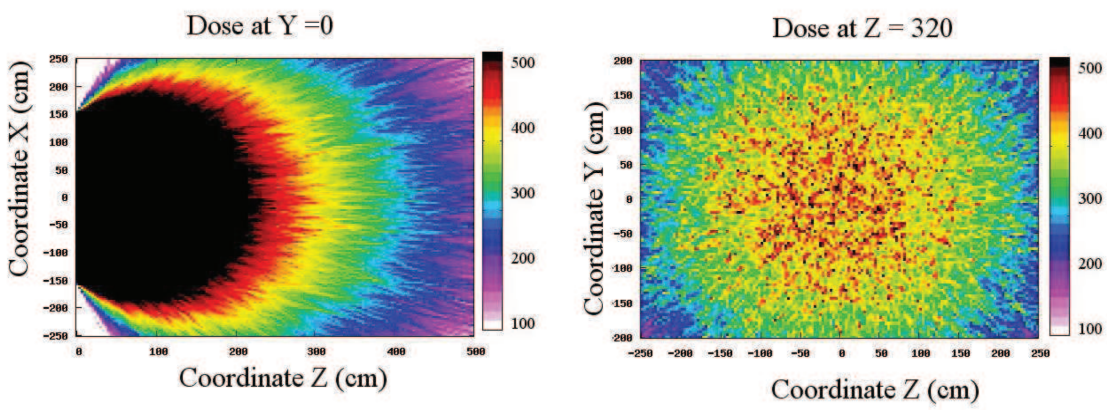

Figure II.7. Dose rate produced by electrons of 10 MeV impacting in a W sheet. The cosine of the angle is 0.6.

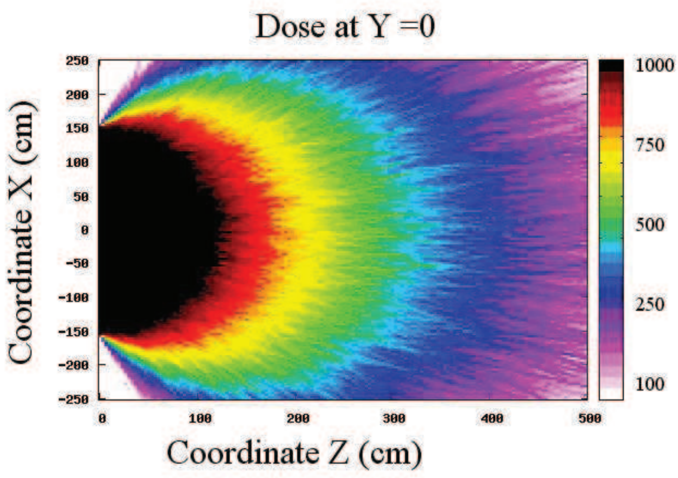

Figure II.8. Dose rate in the range of 100 and 1000 Sv/h produced by electrons of 10 MeV impacting in a W sheet. The cosine of the angle is 0.6.

(IV) Conditions recommended on the basis of simulation results

Table II.1 shows a brief summary of the simulations. The optimized parameters are shown in order to maximize the final volume with doses between 100 and 500 Sv/h.

Table II.1. Simulation summary:

Irradiated material	W
Density	19.25 g/cm^3
Cosine of the angle of incidence	0.6
Beam footprint	Square area: 1.5 x 1.5 m^2
Plate thickness	0.6 cm
Beam radius	0.5 cm
Total volume	74.80 m^3
Irradiation Room size	100 m^3