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

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[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.

5. Material Irradiation

5.1. Introduction

As mentioned above, materials for future fusion reactors will be exposed to a particular hostile environment as a consequence of the intense radiation built during the nuclear reaction. The hot plasma within the reactor will generate a massive flux of high-energy neutrons, gamma photons, and particles. All of which will affect not only the first wall of the reactor, but also other distant equipments such as plasma heating or diagnostic systems. Radiations, via atomic displacement phenomena and ionizing processes will generate a number of defects in the structure of the materials, affecting their physical properties. Moreover, neutron-induced nuclear reactions will generate transmutation products (impurities) that will contaminate the materials, modifying their physical behaviour, and therefore, their reliability as functional materials. The high temperatures and the intense magnetic fields arising during the operation of the reactor will also contribute to the modification of the structural properties.

Considering this scenario, the study of the effect on the confining materials of the neutron radiation generated in fusion reactors is one of the most important research topics to be carried out during the next years.

The effects of neutrons on materials involve, from a fundamental point of view, two physical phenomena: i) the displacement of ions from their equilibrium positions in the lattice creating point defects, and ii) the generation of nuclear transmutating reactions that contribute to the formation of impurities inside the material, with He and H as the most important ones. The ratio between the levels of He and H, and the amount of point defects is one of the main parameters to understand the effect of the radiation on materials.

The straight-forward approach to perform this type of studies is the use of neutron sources as IFMIF. However, these sources have a number of problems and very strict operating conditions, making new approaches for simulating their effects very interesting as well as necessary to decrease the radiological risks.

Computer simulations have concluded that the effect of neutrons can be represented, in a very accurate way, by the simultaneous irradiation with He, H and heavy ions capable of creating point defects (for example, Fe irradiated on steel). This triple irradiation will be a unique and singular tool for the experimental simulation of the effect of the neutron radiation on materials of interest for fusion reactors.

To study the effects of ionizing radiation on the physical characteristics of materials, a source capable of providing a uniform field of gamma radiation is needed. And to obtain reliable results, the dose rate must to be equivalent to the expected one in ITER (radiation levels between 100 and 500 Gy/h[25]). The most suitable *gamma* radiation source for the simulation of this effect is an electron accelerator with a flexible beam line, i.e., able to vary the beam position in a fast way to obtain a uniform radiation field. When the electron beam

[25] Private communication: J. Palmer (Remote Handling Field Coordinator en EFDA-CSU Garching)

collides with a thin film of the right material (usually a heavy metal), a *gamma* radiation field is generated in the surrounding zones.

The use of an electron accelerator has several advantages when compared to conventional *gamma* radiation sources (such as ^{60}Co): The disappearance of the radiation risk when the accelerator is switched off and the regulation of the *gamma* radiation flux by changing the beam current and energy. As a drawback, the emitted *gamma* radiation spectrum (mainly through *bremsstrahlung*) is different to the one expected in ITER[26], [27]. However, this difference is not significant since the relevant parameter in the interaction of ionizing radiation with matter is the level of electronic excitation, measured by the dose rate.

As it was mentioned before, the materials used in the future fusion reactors will work under intense magnetic fields (probably in a steady state or with small variations in time). Up to now, most of the studies of characterization of the effects of radiation on the macroscopic and microscopic properties of materials have not taken the presence of magnetic fields into account. The availability of magnets with a high magnetic fields (between 5 and 10 Tesla), together with the above-mentioned set of ion accelerators will enable a number of experiments to analyze the combined effects of radiation and magnetic fields on materials with interest for fusion reactors.

The **Material Irradiation Facility (MI)** is a key element for the *TechnoFusión* project due to the primary importance of the effects of neutronic and ionizing radiations on a number of materials and processes. Therefore, this Facility must be in close contact with the rest of *TechnoFusión*´s facilities. To name just a few, the Remote Handling and the Metal Liquid facilities involve an extensive use of high energy radiation sources, not to mention the relevance of the radiation in the selection of functional materials.

In conclusion, the MI Facility will be composed by three ion accelerators: one for implanting heavy ions (Fe, Si, C, etc.), and two for light ions (H and He). This combination will enable the study of the effects of neutron radiation on materials similar to those arising in reactors such as ITER and DEMO[28], [29], [30]. The MI Facility will also include an electron accelerator that will be shared by the Remote Handling and Liquid Metals facilities, and a high field magnet to study the combined effects of ionizing radiation and magnetic field in metallic alloys.

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[26] V. Khripunov. "The ITER first wall as a source of photo-neutrons**".** Fusion Engineering and Design 56-57, (2001), p. 899-903.

[27] W. V. Prestwich and R. E. Coté, "Gamma-Ray Spectra of Co^{60} and Mn^{56} Following Resonance-Neutron Capture in Co^{59} and Mn^{55}", Phys. Rev. 155, p. 1223-1229 (1967).

[28] S. Hamada, Y. Miwa, D. Yamaki, Y. Katano, T. Nakazawa and K. Noda "Development of a triple beam irradiation facility". Journal of Nuclear Materials, 258-263 (1), p. 383-387 (1998).

[29] Y. Serruys, P. Trocellier, S. Miro, E. Bordas, M. O. Ruault, O. Kaitasov, O.Leseigneur, Th. Bonnaillie, S. Pellegrino, S. Vaubaillon and D. Uriot, "JANNUS: A multi-irradiation platform for experimental validation at the scale of the atomic modelling", Journal of Nuclear Materials 386-388, p. 967-970 (2009).

[30] D. Jiménez-Rey, R. Vila, A. Ibarra, F. Mota, Christophe J. Ortíz, J. L. Martínez-Albertos, R. Román, M. González, I. García-Cortés, and J. M. Perlado, "The multi-ion-irradiation Laboratory of *TechnoFusión* Facility and its relevance for fusion applications". To be published in Journal of Nuclear Materials.

5.2. Objectives

A primary goal of MI Facility is to understand the mechanisms generating the damage produced on the materials by the combination of heavy and light ions in terms of microstructure and impurities, and to increase in the knowledge of the damage produced by neutrons in a fusion reactor. Therefore, the initial effort will aim to establish the operating conditions of the ion accelerators to best simulate the effects of the neutron radiation without the use of a neutron source; that includes the choice of the most suitable accelerators/implanters.

Other goals of the facility include, as a first step, the demonstration of the capability of the facility to generate damage in a certain volume within the sample, and the production of such damage in a uniform and homogeneous way within the material. Two different approaches will be used for this task:

I. The triple irradiation technique. The irradiation of the target material with ions of the same species (i. e. Fe^+ on Fe) while, simultaneously, implanting light ions (H and He). This triple irradiation will generate the same amount of lattice displacements (via the heavy ions) and the same amount of light ions (via H and He implantation) than the expected in fusion facilities.

II. The irradiation with high energy protons (in a range to be evaluated, but roughly between 20 and 40 MeV. The effects of this beam are two fold: First, according to some generally accepted calculations, this beam will create damage similar to that generated by neutrons from fusion reactors in very thicker areas (in the millimetre range) of the target material. Second, it will generate –at the same time as the damage— H and He via transmutation.

The computer simulations to justify the above-mentioned irradiation methods are described in Appendix IA as the radioprotection studies for the preliminary design of the *TechnoFusión* Facilities are paramount importance, the main obtained results are included in Appendix IB. On them, the following elements were taken into account in order to simulate accurately the effects of a neutron beam: i) the minimum energy of ions necessary to achieve the desired penetration; ii) the homogeneity of the irradiation profile along the whole irradiated volume; iii) the appropriate ratio of light elements to displacements per atom (see Figure 5.1); and iv) *Primary Knock-on Atom* (PKA) energy spectra. The PKA is the recoil atom being displaced by the direct collision --atomic or nuclear— of the incident particle.

The effects of activation and transmutation of the targets elements by means of light element implantation and by irradiation with protons were also studied. These simulations enabled further advances in the design of ion accelerators for both light and heavy ions. Figure 5.1 shows the correlation between generated He and atomic displacements for a Fe target after being irradiated for a week at two different groups of facilities: On the first place, some already existing nuclear fission reactors and particle accelerators. Secondly, the estimation of the results at future facilities as the neutron reactor IFMIF, ITER and DEMO. In the same graphic, the region where *TechnoFusión* facility is expected to operate is highlighted, and shows that the values of generated He vs. damage covered by the new nuclear fusion facilities fit in the operative range of *TechnoFusión*.

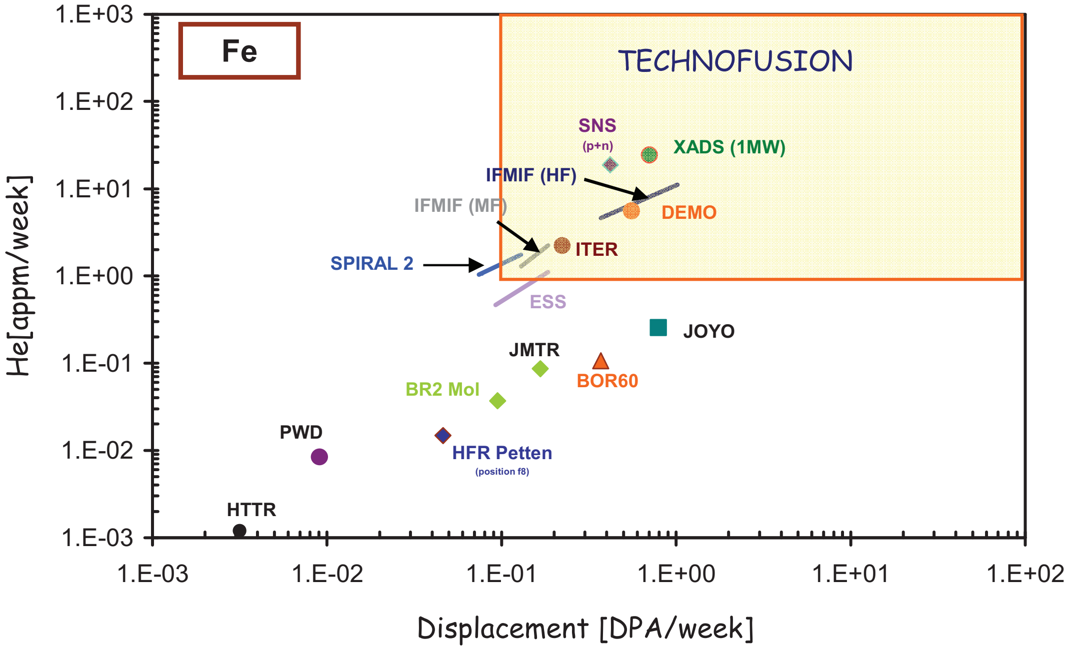

Figure 5.1. Comparison of the levels of damage and of impurities created at different facilities —particle accelerators, fission reactors, some planned fusion experiments, etc. The operative range of *TechnoFusión* covers the operating range of these planned nuclear fusion facilities.

Figure 5.2 shows a comparison between the damage function —*W(T)*— generated by protons (Figure 5.2a) and by Fe ions (Figure 5.2b) in iron, and the *W(T)* function generated by neutrons, as expected for future DEMO reactor. The damage function is the spectrum of kinetic energies of the PKAs —$\sigma_{PKA}(T)$— generated by heavy ions or protons normalized to the damage each PKA creates, as a function of its initial kinetic energy[31]:

$$W(T) = \frac{1}{D/t} \int^{T} \sigma_{PKA}(T) N_d(T)\, dT \,, \qquad \text{eq. 5.1}$$

where *D/t* is the rate of damage created by atomic displacements, and $N_d(T)$ is the number of Frenkel pairs by PKA of energy *T*.

Figure 5.2 shows the calculated damage function irradiating with Fe ions and protons on an iron target. This allows us to compare both irradiation types with DEMO-HCLL (at two positions; first wall [FW] and breeder zone [BZ]). As we can see, both methods could be used to duplicate the neutron damage, but high energy Fe ions give the best approximation. The

[31] D. Leichtle, U. Fischer. "Qualification of irradiation effects on ceramic breeder materials in fusion and fission systems" Fusion Engineering and Design *51-52* (2000) 1-10.

damage curves of Fe ions of energies 300 to 500 MeV being included into the expected damage function covering from FW to BZ regions. The sharper curve observed in protons is related to the fact that they pass all the way through the sample, losing energy mainly by electronic stopping with fewer knock-on processes and in a narrower energy range.

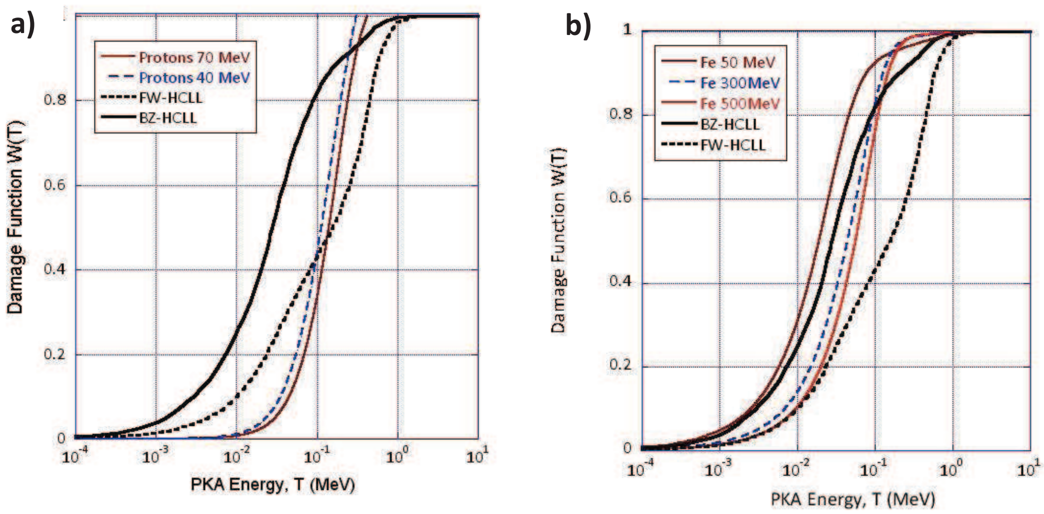

Figure 5.2. Damage functions generated for a Fe material with a) 40 and 70 MeV protons b) 50, 300 and 500 MeV Fe ions, compared with the damage function in DEMO HCLL (first wall [FW] and breeder zone [BZ]). T is the PKA kinetic energy upon which the Damage Function depends.

The disadvantage of this 40 to 70 MeV proton approach (see Appendix I) is that the appmHe/dpa ratio is generally higher than that expected for DEMO-FW-HCLL (in iron is three times higher for 40 MeV H^+). To reduce this rate, irradiations with lower energy protons (around 20 MeV) can be used. At this energy, the damage function does not change considerably whereas the production of He atoms is much lower.The He/dpa ratios calculated for different materials and positions are shown in Table I.A2 of Appendix A1. This allow us to tailor the irradiation conditions to each material and DEMO position.

These procedures to modify materials allow significant studies in a large amount of problems associated to materials, some of them already identified, in the process of developing fusion facilities such as ITER, IFMIF and DEMO. The following are just a sample of these studies:

- Structural properties of materials such as ODS steels, vanadium alloys, tungsten and silicon carbides.

- Physical properties —permeability, corrosion, electric conductivity, etc.— of structural materials.
- Development and characterization of junctions and welding techniques.
- Characterization and modelling of the effect of the radiation on structural materials, coatings, junctions, welding joints, etc.
- Design and implementation of controlled experiments (controlling the level of generated point defects, concentration of impurities such as H and He, electronic excitement, presence of magnetic field, etc.) to model the effects of the radiation on materials.
- Characterization and modelling of the effect of the radiation on insulating materials for diagnostics.

Simultaneously, the set of techniques in the MI Facility at *TechnoFusión* will allow the study of more generic effects, not necessarily related to nuclear fusion phenomena:

- Evaluation of the effect of neutron radiation on materials candidates for use in next generation fision reactors.
- Evaluation of the combined effects of radiation and magnetic field on the above-mentioned materials.
- Study of radiological risks.

5.3. International status of the proposed technologies

5.3.1. Installations of reference in ion and electron irradiation

In Europe, JANNUS (*Joint Accelerators for Nanosciences and NUclear Simulation*) facility is currently been developed in Saclay, France, by the *Centre de Spectrométrie de Masse et de Spectrométrie Nucléaire* (CSNSM[32]). This facility has a similar strategy to that of the Material Irradiation Facility of *TechnoFusión*: both aim at using a triple beam for implantation. JANNUS will have one 3 MV heavy ion implanter, named *Epimèthèe* (a *Pelletron*), and two light ion implanters: a 2.5 MV *Van de Graaff* accelerator (*Yvette*), and a 2 MV *tandem accelerator* (*Japet*). Figure 5.3 shows a layout of the accelerators in JANNUS and their main characteristics. The ion species and the maximum estimated energies for the different accelerators in JANNUS are displayed on Table 5.1.

[32] http://www-csnsm.in2p3.fr

Table 5.1. Values for the maximum energy and the ion species on each of the three accelerators of the JANNUS facility.

Accelerator	Ion	Maximum energy
Epiméthée (Pelletron)	H, D, ^{3}He, C, N, O, Fe, Ni N_2	**3 MeV**
Yvette (Van de Graaff)	H, D, ^{3}He, ^{4}He	**2.5 MeV**
Japet (tandem)	**H, halogen ions, P, S, metallic ions**	**2 MeV**

The main drawback[33] of the accelerators in JANNUS is the low value of the maximum energy they can reach, in the order of 3 MeV, which means a penetration range of just a few hundreds of nanometres. Moreover, JANNUS will only have a Transmission Electronic Microscope (TEM) of 200 keV available for *in situ* analysis of the materials during the irradiation.

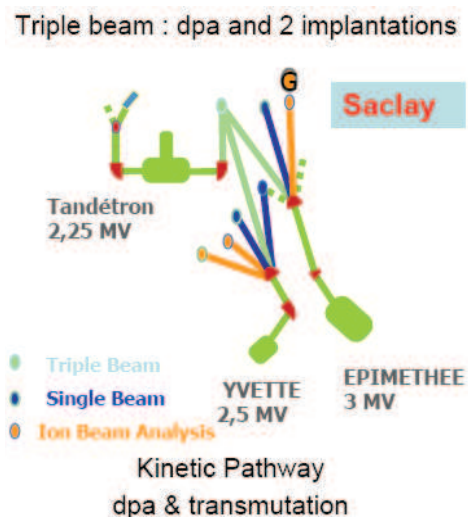

Figure 5.3. Diagram of the different irradiation points for the future JANNUS facility in Saclay. The maximum energies for each accelerator are also shown.

Worldwide there is only one facility similar to *TechnoFusión*'s MI Facility: Japan's *Takasaki Ion Accelerators for Advanced Radiation Application*[34] (TIARA) (Figure 5.4):

[33] Y. Serruys, P. Trocellier, S. Miro, E. Bordas, A. Barbu, L. Boulanger, O. Leseigneur, S. Cabessut, M.-O. Ruault, O. Kaïtasov, S. Henry, Ph. Trouslard, S. Pellegrino, S. Vaubaillon, and D. Uriot, CFRM-13 13th International Conference on Fusion Reactor Materials 2007, December 10 – 14, Nice (France).

[34] S. Hamada, Y. Miwa, D. Yamaki, Y. Katano, T. Nakazawa and K. Noda. "Development of a triple beam irradiation facility". Journal of Nuclear Materials, 258-263 (1998), p. 383-387.

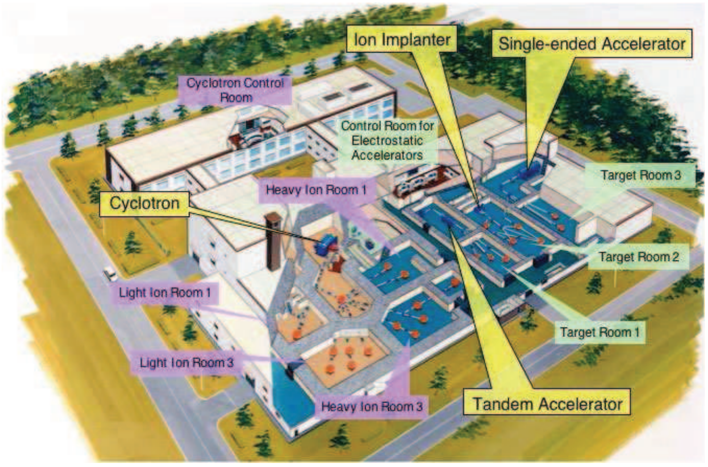

Figure 5.4. TIARA facility, in Takasaki, Gunma (Japan).

This facility has four ion accelerators: A heavy ion AVF cyclotron (*Azimutally Varying Field*) with[35] k =110, a 3 MV *tandem* accelerator, a 3 MV *single-ended* accelerator, and a 400 kV ion implanter. The TIARA complex offers a large variety of ion species, from light ions as H to heavy ions as Au, and covers a large range of energies –from keV to MeV (see Table 5.2 and Figure 5.5). The main studies carried out at TIARA facility are related to irradiation of materials and to biotechnology. However, TIARA accelerators also have their limitations, the main one being the impossibility to combine the cyclotron beam with those from the linear accelerators.

Other than JANNUS and TIARA, there are other facilities and research groups dedicated to the irradiation technologies all over the world. Table 5.3 shows a list of them together with the available accelerators. This list shows that the set of facilities linked to the technology of accelerators is limited due to the maximum energies they can achieve. For a complete analysis of the damage in materials by radiation it is necessary to irradiate at deeper penetration ranges and, therefore, with higher energies. Consequently, a new group of facilities is still required.

In this context, the *TechnoFusión*'s MI Facility has the potential to become an international facility of reference, as it will have ion accelerators with the capacity to achieve up to 400 MeV for heavy ions.

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http://www.taka.jaea.go.jp/tiara/index.html. Checked on August 2009.

[35] K, the proton kinetic energy, is a constant that depends on the magnetic rigidity of the external orbit of the cyclotron (see Appendix II, "Dimensions and cost estimations of the heavy ion cyclotron accelerator", for more information).

Table 5.2. List of available ions and their energies for the different accelerators in TIARA facility

Accelerator	Ion	Energy (MeV)
AVF cyclotron (K110)	H	5~90
	He	10~110
	Ar	94~990
	Kr	200~1030
	Xe	300~930
	Au	440~460
Tandem accelerator (3 MV)	H	0.8~6
	C	0.8~18
	Ni	0.8~18
	Au	0.8~21
Single-ended accelerator (3 MV)	H	0.4~3
	D	0.4~3
	He	0.4~3
	E	0.4~3
Ion implanter (400 kV)	H	0.02~0.4
	Ar	0.02~1.2
	Ag	0.02~1.2

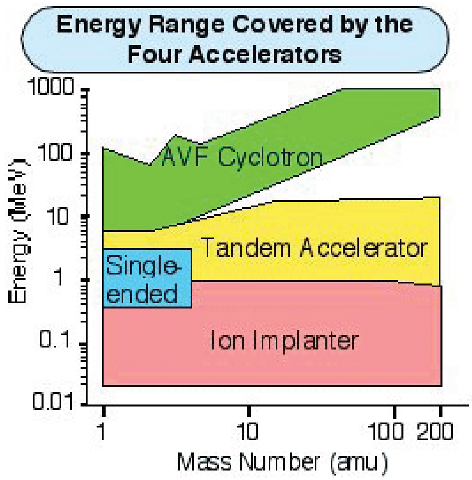

Figure 5.5. Graphic of the different ion energies versus atomic mass for the accelerators in TIARA.

Table 5.3. Research centres in the world dedicated to irradiation technologies.

Research Centre	Accelerators
IAE Kyoto[36] (Japan)	Van de Graaff (1 MV) accelerator Tandetron (1.7 MV) accelerator Singletron (1 MV) accelerator
HIT Tokyo[37] (Japan)	Van de Graaff (3.75 MV) accelerator Tandetron (1 MV) accelerator
CIRSE Nagoya University[38] (Japan)	Ion implanter (200 kV) Van de Graaff (2 MV) accelerator
Hokkaido University[39], Sapporo (Japan)	Ion implanter (300 kV) TEM (1MV)
MSD, IGCAR Kalpakkam[40] (India)	Ion implanter (400 kV) Tandetron (1.7 MV) implanter
FZ Rossendorf [41] (Germany)	Ion implanter (500 kV) Tandetron (3 MV) accelerator
FSU Iena[42] (Germany)	Ion implanter (400 kV) Tandem (3 MV) implanter
Salford University[43] (United Kingdom)	Ion implanter (100 kV) TEM (200 kV)
TIARA facility (Japan), managed by JAERI Takasaki[44]	Cyclotron accelerator AVF K110 Tandem (3 MV) accelerator Single-ended (3MV) accelerator Ion implanter (400 kV)
JANNUS Saclay, (France)[45]	Epimèthèe [Pelletron] (3 MeV) accelerator Van de Graaff [Yvette] (2.5 MeV) accelerator Tandem [Japet] (2MeV) accelerator

5.4. *Projected equipment*

5.4.1. Ion accelerators

The main requirement for *TechnoFusión* MI´s accelerators is the capability to irradiate materials with penetration ranges of, at least, some tens of microns. Other than that, they also need to ensure the possibility of enabling a triple beam irradiation.

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[36] A. Kohyama, Y. Katoh, M. Ando and K. Jimbo, Fusion Engin. Design 51-52 (2000), p. 789-795.
[37] Y. Kohno, K. Asano, A. Kohyama, K. Hasegawa and N. Igata, J. Nucl. Mater. 141-143 (1986), p. 794-798.
[38] M. Iseki, Y. Kikuza, S. Mori, K. Kohmura and M. Kiritani, J. Nucl. Mater. 233-237 (1996), p. 492-496.
[39] H. Tsuchida and H. Takahashi, J. Nucl. Mater. 239 (1996), p. 112-117.
[40] B. K. Panigrahi, The ion beam facilities at MSD, IGCAR Kalpakkam, Acts of the French-Indian Workshop, November 28 – 30, 2005, Saclay (France), http://www.igcar.ernet.in/igc2004/igcanr2006.pdf.
[41] J. R. Kaschny, R. Kögler, H. Tyrrof, W. Bürger, F. Eichhorn, A. Mücklich, C. Serre and W. Skorupa, Nucl. Instrum. Meth. Phys. Res. A551 (2005), p. 200-207.
[42] B. Breeger, E. Wendler, W. Trippensee, Ch. Schubert and W. Wesch, Nucl. Instrum. Meth. Phys; Res. B174 (2001), p. 199-204.
[43] S.E. Donnelly, Comportement des matériaux sous irradiation : un thème de l'Université de Salford, Communication to GDR PAMIR starting meeting, November 25 – 27, 2006, Caen (France), http://www.ganil.fr/ciril/gdr/pleniere.html.
[44] S. Hamada, Y. Miwa, D. Yamaki, Y. Katano, T. Nazakawa and K. Noda, J. Nucl. Mater. 258-263 (1998), p. 383-387.
[45] Y. Serruys, P. Trocellier, S. Miro, E. Bordas, A. Barbu, L. Boulanger, O. Leseigneur, S. Cabessut, M.-O. Ruault, O. Kaïtasov, S. Henry, Ph. Trouslard, S. Pellegrino, S. Vaubaillon, and D. Uriot, CFRM-13 13th International Conference on Fusion Reactor Materials 2007, December 10 – 14, Nice (France).

Electrostatic ion accelerators –Pelletron or Van der Graaf— are the most commonly used for light ions. Spain has already some experience in the operation of this type of accelerators, since there are several of them working at CIEMAT (Madrid), CMAM (Madrid) and CNA (Sevilla). These accelerators can be single-ended, with the ion sources at high voltage terminal, or *tandem*, with the high voltage terminal in the middle of the tank. For *tandem* accelerators, it is possible to obtain higher beam energies as ions are accelerated in two stages. Moreover, *tandem* accelerators allow the ion source not to be at the terminal voltage, as is the case for single-ended, enabling the use of different kinds of sources and increasing its versatility. The use of, at least, two ion sources is considered—one radiofrequency source for ions in a gas state, and one sputtering source for ions in a solid target.

Regarding the heavy ion accelerator, its main goal is the production of defects inside the material similar to those caused by neutron radiation, but without the inclusion of impurities. This means that the irradiation has to be carried out with the same atomic species as those present in the target sample or, in the case of more complex targets, with one its components. Taking into account the materials considered in the European Fusion Project for structural purposes; i. e. steel, W, and SiC; the heavy ion accelerator in MI Facility needs to accelerate Fe, W and Si. In order to ensure a large penetration range (between 5 and 90 µm, see Table 5.4) the ion energy has to be high enough —some hundreds of MeV— and therefore, cyclotron accelerators are more suitable than electrostatic ones.

For light ions, the results from the simulations carried out previously to this report[46] (see Appendix I) have shown that, in principle, no high beam currents are needed. In fact, for normal dose rates, currents in the order of nA are enough to reproduce the formation rate of H and He induced by neutrons, but for accelerated damage aging (up to total dpas expected in DEMO life), currents increase up to a few microamps. In addition, the desired penetration range is achieved with few MeV of energy. Table 5.4 shows the summary of energy values for different ions implanted in different target materials to achieve the same penetration range in the material, according to the above-mentioned simulations[46]. In every case, it is one of the three accelerators that limit the maximum penetration depth. The Table 5.4 shows the energy values assuming a He charge state of +2 at the second stage in a *tandem* accelerator, giving a total energy of 18 MeV. As it can be seen, although the case for He^+ is often the most restrictive, working at 18 MeV makes it possible to take advantage of the cyclotron potential to reach larger depths in the irradiated material. It is also worth to note that the H beam does not exceed the 5 MeV energy in any case, which could reduce the requirements for the terminal voltage in such tandem accelerator[46]. A margin can be added to this energy in order to use deuterium ions (up to 6 MeV) or for some other experiments (like direct irradiation with 10 MeV H^+).

[46] D. Jiménez-Rey, R. Vila, A. Ibarra, F. Mota, Christophe J. Ortiz, J. L. Martínez-Albertos, R. Román, M. González, I. García-Cortés, and J. M. Perlado, "The multi-ion-irradiation Laboratory of *TECHNOFUSIÓN* Facility and its relevance for fusion applications", to be published in Journal of Nuclear Materials.

Table 5.4. Ion energies to be used in the MI Facility assuming a He energy equal to or lower than 18 MeV (*tandem* at 6MV terminal voltage and charge states of -1 and +2). Underlined values on the tables indicate the ion/accelerator combination that limits the penetration range in the material.

		Heavy ion accelerator k =110 cyclotron		4 MV light ion accelerator		6 MV light ion accelerator	
Irradiated material	**Range (μm)**	**Ion**	**Energy (MeV)**	**Ion**	**Energy (MeV)**	**Ion**	**Energy (MeV)**
Fe (7.8 g/cm^3)	26.6	Fe	<u>385</u>	H	2.5	He	10
W (19.3 g/cm^3)	10.1	W	<u>373</u>	H	1.6	He	6
C (2.3 g/cm^3)	148	C	96	H	4.5	He	<u>18</u>
SiO_2 (2.2 g/cm^3)	175	Si	337	H	4.6	He	<u>18</u>
SiC (3.2 g/cm^3)	122.4	Si	337	H	4.6	He	<u>18</u>
SiC (3.2 g/cm^3)	122.4	Si	337	D	6.0	He	<u>18</u>

Results from these previous calculations have been considered to conclude that, for the *TechnoFusión* MI Facility, the following accelerators and characteristics will be required:

- *1 tandem accelerator for light ions with 6 MV terminal voltage to be used with He^+ ions.*
- *1 tandem accelerator for light ions with 4 to 5 MV terminal voltage to be used with protons (H^+).*
- *1 accelerator for heavy ions, cyclotron, with k = 110 to be used with heavy ions or high energy protons (E_{H+} ~20 - 40 MeV; see maximum energies in Table 5.4 for k=110).*

The exact requirements for the set of accelerators (beam energy, beam current, emittances, etc.) are in the process of evaluation. Following, the main requisites of *TechnoFusión*´s MI Facility are presented:

I) <u>Beam energy:</u> table 5.5 shows the expected maximum energies for the different ions to be implanted.

II) <u>Currents:</u> table 5.6 summarizes the minimum desirable beam currents for the different ion species in both types of accelerators together with the equivalent figures in TIARA facility.

Final currents currents depend on the combination of material choice, position in DEMO to reproduce, total dose and time available to irradiate. As an example Table 5.6 shows the He current needed to implant around 1000 appm He in a week.

Table 5.5. Fundamental ions and their maximum energies.

	Tandem accelerators			Cyclotron k=110				
	H	D	He	C	Si	Fe	W	H
A	1	1	1	12	28	56	184	1
Z	1	2		4	9	14	25	1
E (MeV)	8 to 10	2 - 6[47]	10 - 18	96	337	385	373	< 40

Table 5.6. Target currents for different ions in the tandem and in the cyclotron accelerators at MI Facility. Data in ion/s units. Q = charge state. pnA, particle-nanoAmpere, is a current unit: nanoAmpere of single-charged particles

Light ions in a tandem accelerator

Ion	Current (pnA)
H	50-100
D	~10
He	50-100

Heavy ions in a k=110 cyclotron: ion currents in nano Ampere for a single-charged particle.

	MI´s target currents	TIARA
C	500 – 1000	660 (q=3) 80 (q=5)
Si	200	15 (q=10)
O	200	750 (q=4) 250 (q=6)
Fe	25	120 (q=11) 35 (q=15)
W	3	60 (q=9)

III) <u>Emittances:</u> the emittance of a particle beam is the volume they occupied in the phase space (space and momentum) as they move. A beam of low emittance is a beam in which the particles are well confined and all of them have very similar momenta. A transport system allows only particles with a momentum close to the designed momentum. In actual terms, a small emittance favours the control of the beam, and increases the brightness.

For tandem accelerators, literature shows working values of 3.5 π mm mrad for a 1 MeV proton beam.

Companies DREEBIT[48] and Elytt Energy[49] have issued a viability study showing emittance values in the target below 20 π mm mrad, which is considered correct at this first stage of development, until the ion and the charge state were specified.

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[47] Possibly limited by the activation of the material.
[48] DREEBIT GmbH. Zur Wetterwarte 50, Haus 301. 01109, Dresden, Germany. http://www.dreebit.com/
[49] Elytt Energy. Paseo de la Castellana 114, 3º, puerta 7. 28.046 Madrid. Spain. http://www.elytt.com

IV) Beam homogeneity: to achieve homogeneous irradiations in relatively large areas MI's accelerators should contain beam sweeping systems to scan large areas on the samples. At the present moment, several studies are being carried out to select the most suitable beam sweeping systems, and to consider the possibility of using a beam degrader, including its radiological consequences.

V) Angles of incidence on the sample: simultaneous irradiation with three parallel ion beams is not physically possible. Therefore, an important factor to take into account is the maximum angular separation between the ion beams. In TIARA, the irradiation with a triple beam takes place on the same plane, being the angles between beams of 15 degrees. On the contrary, *TechnoFusión*´s plans consider the possibility of locating the beams in a non-coplanar arrangement to reduce the angle between them.

The heavy ion beam, however, will be placed normal to the surface of the sample to avoid any kind of sputtering effect in the material.

VI) Beam lines: the triple irradiation is the key element in the facility and therefore it determines the design of the accelerators, and subsequently, the additional lines to develop. All these systems will establish the characteristics of the MI Facility building.

The study of the different optical elements to steer the beams into the different lines is also necessary. Parameters such as the beam energy and the deflection angles will determine the dimensions of the dipoles, bending magnets, and so on.

VII) Supplies: both the accelerators and the beam lines will need a set of supplies such as cooling systems, liquid nitrogen, compressed air, etc. The evaluation of the vacuum conditions, the dissipated heat or the working temperatures can be done, in a first approximation, taking as a reference other similar accelerators such as those in CMAM[50].

A technical area under the accelerator hall is planned to allow the location of the different lines to drive power, vacuum, gases, cryogenic liquids, etc, to the points where they were needed in the main hall.

VIII) Radiological safety aspects: the computer simulations will determine the radiation doses are being carried out for the different operation steps, and will specify the radiation shields required for the accelerator halls, supply rooms, beam lines, etc.

Considering all the above-mentioned requirements, the acquisition of two 5-6 MV tandem accelerators for light ions, one for H and another one for He, is proposed. It is important to note that the acquisition of these two accelerators is absolutely necessary because the implantation of H and He has to be performed simultaneously. For the third beam, the acquisition of a Cyclotron accelerator for heavy ions (and for high energy protons) with a k constant close to 110 is proposed.

The following sections cover a brief description of the proposed accelerators for the MI Facility:

[50] Internal document of CMAM HVEEA-4-35-174-0049. Installation Requirements and Recommendations. (2002)

5.4.1.1. Light ion accelerator with neutralizer

There are several companies (NEC[51] (USA), TOSHIBA (Japan), HVEE[52] (Netherlands)) able to provide electrostatic tandem accelerators with 5-6 MV in a period of about 1 year. Although not strictly necessary, it is desirable that both accelerators were equals to gain flexibility and to have easier maintenance. Figure 5.6 shows an example of a NEC accelerator.

Figure 5.6. Tandem electrostatic accelerator 4 MV made by NEC.

The neutralization of the ions, necessary for the irradiation of materials under magnetic fields, is obtained by making the beam to pass through a chamber filled with a weakly bonded electrons gas. In there, the charge exchange will take place at low energies.

This type of technology is used frequently in machines for plasma physics, because the heating system of neutral particle injectors must be very efficient. These charge exchange devices are expected to be efficient enough for the purpose of the linear accelerators planned for this facility. Nevertheless, this question remains open and needs further considerations and studies.

These proposed accelerators may also be used in several other applications such as material science (e. g. analysis with Ion Beam Analysis, IBA, techniques), nuclear and atomic physics, biology or even in studies on the historical and cultural heritage. In principle, these other applications have not been considered in the design of the MI Facility or in this report, although evidently, could be included in the moment of making a detailed design.

[51] National Electrostatics Corporation, 7540 Graber Road, P.O. Box 620310 Middleton, Wisconsin 53562. http://www.pelletron.com/

[52] High Voltage Engineering Europa B.V. P.O. Box 99. 3800 AB Amersfoort. The Netherlands. http://www.highvolteng.com/

5.4.1.2. Heavy ion accelerator

According to the computational evaluations performed by the Spanish engineering company Ellyt Energy[53] a k=110 cyclotron should be able to accelerate heavy ions to high energies at low cost. There are several options for the design and construction of this cyclotron:

a) Some contacts with the company IBA[54] have been started. At the present moment, this company produces cyclotrons only up to k=70 (Figure 5.7), but they have shown a great interest on the development of a cyclotron with the required characteristics by *TechnoFusión*.

b) There have been also contacts with the Massachusetts Institute of Technology group led by Prof. Timothy A. Antaya. This group has become specialized in superconductor coils, generating a significant decreasing in the size of the magnet, which allows for important savings in the iron for the magnet core.

c) Finally, the cyclotron design could be carried out by the *Elytt Energy* company.

The MI Facility cyclotron could also be used in other applications, such as radiotherapy (accelerating carbon ions, also of interest for fusion) or for isotope production. These other applications have not been considered in this report, but evidently, could also be included at the moment of making a detailed design.

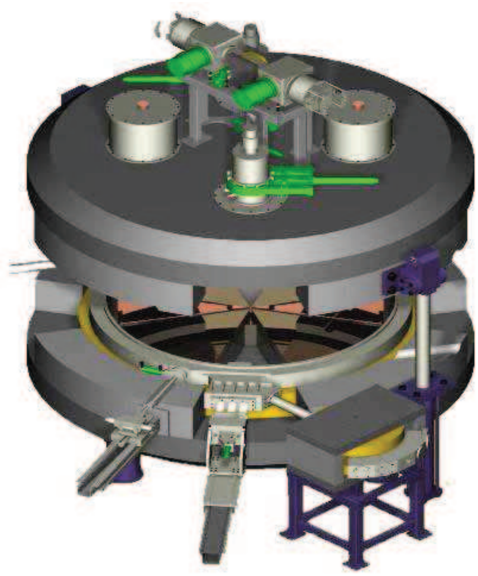

Figure 5.7. Scheme of Cyclone 70 heavy ion accelerator by IBA.

[53] ELYTT ENERGY. Paseo de la Castellana 114. 28046 Madrid. Spain. http://www.elytt.com. September 2009.
[54] IBA. Chemin du Cyclotron, 3 – 1348 Louvain-la-Neuve, Belgium. http://www.iba-worldwide.com. September 2009.

5.4.2. Electron accelerator

According to the calculations described on Section 9.4.2, a 10 MeV electron beam with a current of 1 mA impinging upon a 1 cm thick Al film generates a gamma radiation field of 700 Sv/h at a distance of 3 m. These results were obtained assuming a point source. However, using an extended source (irradiating with the electron beam over a large area, or dividing the beam into several smaller sources) under the mentioned conditions (10 MeV and few mA), a dose rate of 100 - 500 Sv/h could be achieved for a volume of few cubic meters.

A constant-wave electron accelerator *Rhodotron®*[55] (Figure 5.8) is considered for the MI Facility as the most suitable device to generate the right dose of gamma rays in the irradiated samples. Currently, only the Belgian company *Ion Beam Applications* S. A. (IBA) manufactures them after an agreement CEA, home institution to J. Pottier, designer of this type of accelerator.

The main drawback of *Rhodotron®* accelerators is their fixed energies, with a maximum of 10 MeV, and therefore, they are not suitable for scans in energy or to tune this parameter. However, these systems can be built with different beam lines[56] at different energies (3, 5 and 10 MeV, for example), all of them fixed. Its current, though, is tuneable between 3 mA (IBA model TT-100) and 100 mA (IBA model TT-1000), and is extremely stable.

The electron beam from *Rhodotron®* systems can be extracted just at the exit of the magnets. Fractional values of the energy (i. e., 0.5 MeV) are not accessible and only integer values can be employed, starting from 1 MeV because the beam gains 1 MeV per cycle. The beam size at the accelerator exit ranges between 2 and 4 mm. However, using additional collimators these dimensions could be reduced.

IBA´s *Rhodotron®* offers the option of a system to spread the electron beam and turn it into a gamma radiation field. This system, called scanning horn, is combined with a target of water-cooled tantalum-iron. The radiation map obtained with it is shown in Figure 5.9. It can be opened up to distances of 1 m or more. To use the accelerator by the Remote Handling Technologies Facility, the system should be able to extend the beam in perpendicular direction to the previous one to obtain a square profile and, therefore, a more uniform gamma field to test the different devices. Estimations about the maximum irradiation volume for the Remote Handling Technologies Facility are shown in Appendix II.

The *Rhodotron´s®* radiation will also be shared by the Facility of Liquid Metal Technologies in the *TechnoFusión* Centre. The electron beam is an essential element to investigate the effects of an internal heat deposition on a lithium jet. A second application is the generation of tritium by the irradiation of lithium with gamma rays. These processes are more extensively described on the chapter 7 dedicated to the Facility of Liquid Metal Technologies.

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[55] J. POTTIE. Nuclear Instruments and Methods in Physics Research B 40/41, (1989), p. 943.
Marc Van LANCKER et al. Nuclear Instruments and Methods in Physics Research B 151, (1999), p. 242.
http://www.iba-worldwide.com/industrial/products/rhodo.php, Sept 2009

[56] S. KORENEV. The Concept of Beam Lines from Rhodotron for Radiation Technologies. Proceedings of the 2003 Particle Accelerator Conference. IEEE

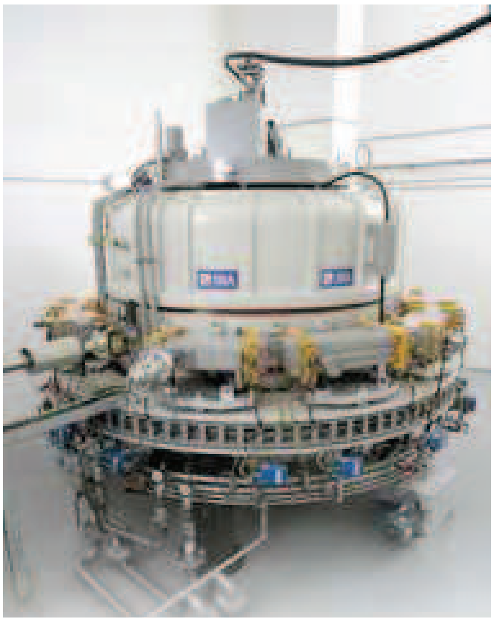


Figure 5.8. An IBA *Rhodotron*® electron accelerator with a maximum energy of 10 MeV.

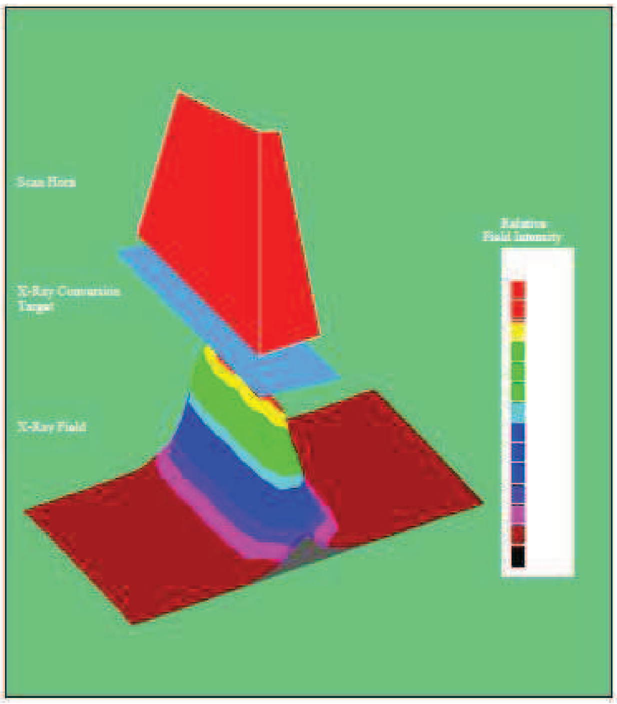


Figure 5.9. Spatial distribution of the intensity of gamma radiation at the exit of the converter with electron scanning system. Image courtesy of IBA.

5.4.3. High field magnet

The goal of having a high magnetic field is to test the performance of materials under similar conditions to those appearing in ITER: between 5 and 10 T of steady magnetic field, and heavy irradiation. The only technical requirement (other than the field intensity) is the necessity of an empty volume to place the sample holder with a temperature control, allowing some characterization measurements during the irradiation. In principle, an inner diameter of 20 - 30 cm should be enough for this purpose. The area where the magnetic field must be constant should be around 10 cm in length, and that implies a coil length of around 30 cm. Such a coil has to be made out of a superconductor material. There are companies –for instance, Oxford Instruments— manufacturing superconductive coils of up to 20 T, satisfying the above mentioned conditions.

5.4.4. Hot Cell

A hot cell is necessary at *TechnoFusión* to provide a secure environment for the processing, repair or refurbishment, and disposal of components that have become activated by exposure to ion irradiation. Special care must be taken to manipulate these activated materials and remote handling systems might become instrumental for this purpose.

5.5. Requirements of space, facilities and safety

(I) Space and facilities

The building for the MI Facility mainly depends on the dimensions and properties of the accelerators and of the characterization techniques. The performance of triple beam irradiation experiments is the figure of merit of the facility and therefore, the building must ensure its operability.

Figure 5.10 shows a proposal for the set of ion accelerators (tandem accelerators for light ions, and cyclotron) and their places in the MI installation, including a doble and a triple beam irradiation experimental areas. The special shielding required by its radioactive character was taken into account in the dimensions of the facility. Figure 5.11 shows a typical example of a cyclotron facility with 3-meter thick walls required to avoid radiation leakages.

Tables 5.7 and 5.8 summarize some of the main characteristics of the cyclotron hall and the additional support rooms for the operation of this accelerator. The proposed cyclotron for *TechnoFusión* Laboratories must have an infrastructure similar to the above-mentioned Cyclone 70 as well as those specified on these tables.

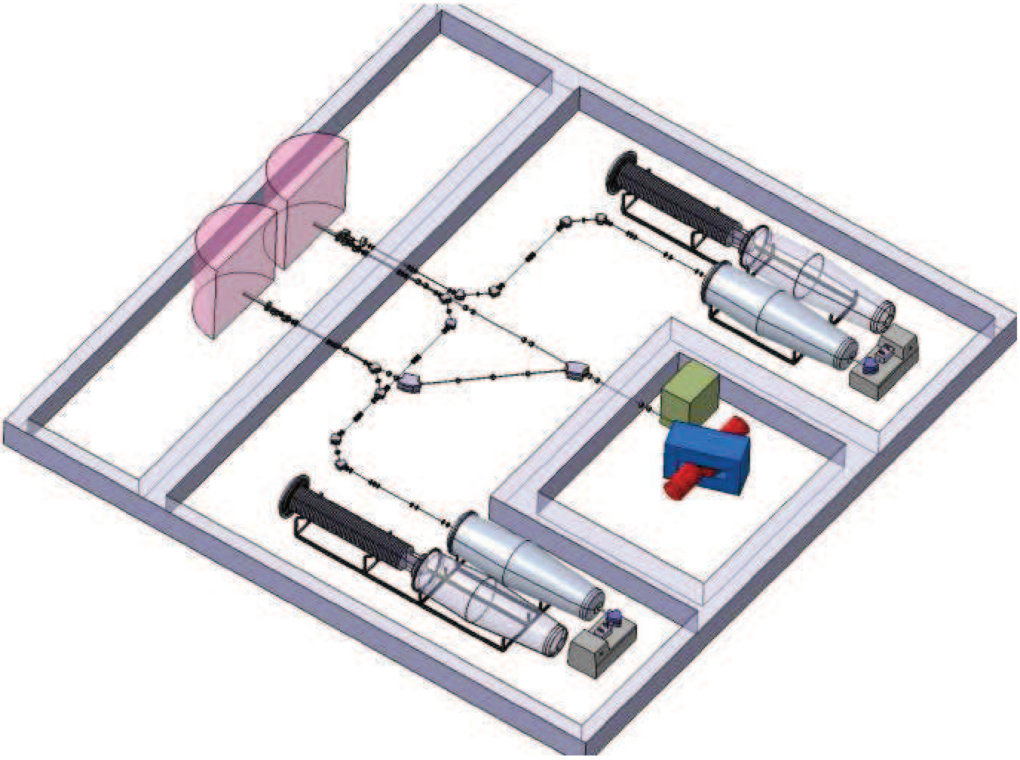


Figure 5.10. Conceptual design of the set of ion accelerators for the MI Facility. The building, include the shielding needed in any radioactive facility.

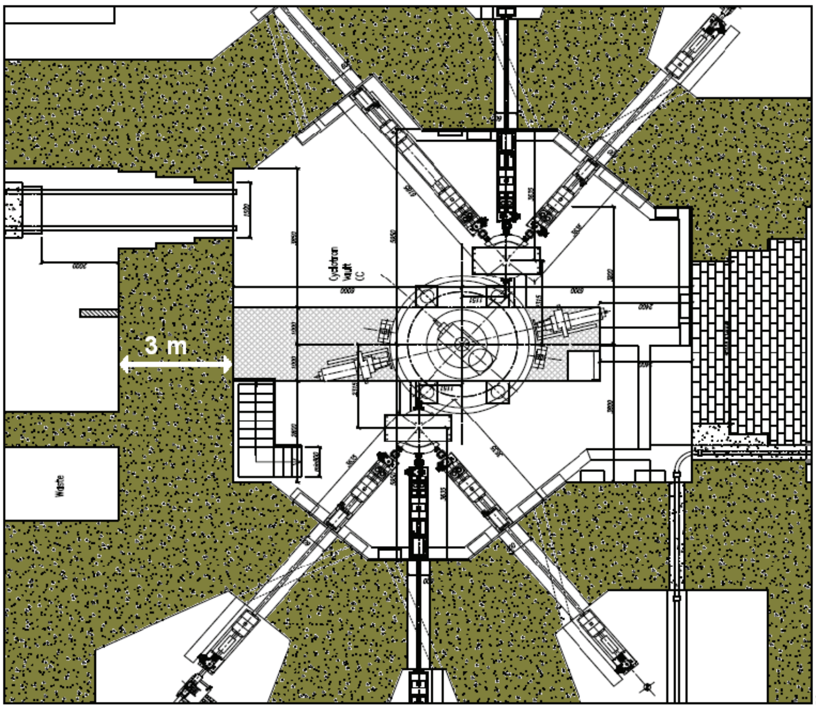


Figure 5.11. Sketch of the cyclotron vault and the irradiation rooms for cyclotron Cyclone 70 by IBA.

Table 5.7. Main characteristics of the cyclotron hall at MI Facility.

Recommended configuration of the cyclotron hall.	
Cyclotron hall	Interior dimensions (minimum): 8 m x 12 m x 5.4 m Main door: 1.5 m (height) x 2 m (width) Dimensions of the cyclotron hall and the irradiation rooms will also depend on the configuration system. Recommended shield for the vault: External walls of the irradiation room 3.7 m thick Walls between irradiation rooms: 3 m thick External walls of the Cyclotron vault: 3 m thick (ordinary concrete, density: 2.35 t/m^3) Load supported on the floor: 140 tons on 4 pillars (cyclotron) 2*10 tons on 4 pillars (magnet) Floor drains: fitted to the local health code and security rules. Pit dimensions: 2.1 m depth x 2 m width x 10 m minimum length. The pit must contain an entrance and be connected by cables to the power supply room. Temperature range: +17 to +25 °C. Humidity range: 35% to 65%, free of condensation. Dissipated power in air: less than 15 kW
Irradiation rooms	Dimensions: (about 60 m^2) * 2.5 m (height) Entrance door: 1.2 m (width) x 2 m (height) Temperature range: +17 to +25 °C Humidity range: 35% to 65%, free of condensation. Dissipated power in air: 2 kW
Power supply room	Interior dimensions: area: 70 m^2, free height: 3 m. Temperature range: +17 to +25 °C Humidity range: 35% to 65%, free of condensation. Dissipated power in air: 23 kW (in operation), 5 kW (stopped) The power supply room, the control rooms and the cyclotron room will be in very close range to avoid the use of long cables. No more than 30 m between them is proposed. Power supply room will be equipped with an elevated floor (40 cm height) with a load capacity of 2T / m.
Room for the cyclotron cooling system.	The cooling system has to be placed as close as possible to the cyclotron room, with access to a water supply. An area of 10m^2 is large enough to include the heat exchanger and the pump (1,6 m x 1,4 m, minimum dimensions). This area must have an easy access for the technical support. The cooling system should be placed at a different level compared to that of the cyclotron: maximum height gap of 7 m from the cyclotron plane. A possibility is to place the cooling system on the vault ceiling.
Cryopump and compressor	The compressor unit, with a weight of 90 kg (width: 445 mm, depth: 630 mm, height: 475 mm), will be placed either in a platform outside the cyclotron room or either inside the room. The length between compressor and cryopumps connections should not exceed 30 m.

Table 5.8. Main support facilities for the cyclotron of the MI Facility.

Specifications for the support facilities	
Power supply	400 V ±5% (between phases), 50-60 ±2 Hz, three AC phases + neuter + ground. Supplied power will depend on the energy expense, and regulated by local laws. For 70 MeV, two beam lines (500 µA): Required power: 500 kVA Required power: 600 kVA Power distributed by: IBA distribution rack [330 kVA], final anode amplifier [74 kVA], power supply source of the main coil, power supply room. The user will supply, install and cut the AC power cables at the entrance of the IBA in agreement with the local electrical rules.
Water for cooling system	Normal water supply in the cooling system room. Drain requirements based on the building regulations. Water pressure: between 2 and 5 bar. Flow: 370 l/min. Temperature: between 7 °C and 20 °C. Cooling power: < 262 kW (double beam, 500µA 70 MeV). Heat exchanger connection: DN 50 stainless steel. Power will be adapted to the cyclotron parameters.
Compressed air for valves	Pressure: between 500 kPa and 700 kPa. Quality: filtered, dry, oil free. Medium flow: < 2 l/min. Maximum flow: < 200 l/min. Dew point: > 10 °C at 25% humidity. Additional tank of compressed air, or compressed nitrogen, with at least 0.5 m^3 capacity, to allow the automatic closing of the valves in case of power failure. Installation of different connection points in the building, in agreement with IBA suggestions.
Dry nitrogen for the cyclotron and ion source ventilation	Pressure: between 50 and 100 kPa. Volume: For cyclotron ventilation: 8 m^3 (STP). For ion source ventilation: 0,3 m^3 (STP). Quality: filtered, dry, room temperature.
Gases for ion sources (hydrogen, deuterium, and helium)	Pressure: between 100 and 200 kPa. Quality: 99.9997%. Oxygen with industrial quality for the electrostatic deflector. Gases will be sent to the cyclotron through an electropolished stainless steel pipeline, in order to avoid gas contamination. The cleaning of the pipelines will be carried out before the installation of IBA systems.

Regarding the *Rhodotron®* electron accelerator, a building with a minimum volume of 6 x 6 x 5 m^3 is necessary. A good cooling system, a ~300 kW electric power, and an adequate suitable shield and control system for radiological risks are required. The building should be large and flexible enough to allow all the proposed procedures. In principle, two working areas are selected in the building: one of 30 x 20 x 10 m^3, where the remote control manipulation tests will be carried out without the presence of radiation, and a second one of 10 x 10 x 5 m^3, where the different qualifying procedures will be performed under radiation. This laboratory (comprising both the accelerator and the testing building) will be considered as a radioactive facility and it will contain the required monitor and control systems.

One of the main added values of the MI Facility is the access, in the same laboratory, to a significant group of characterization techniques and simulation methods for reproducing the working conditions in fusion reactors (high heat fluxes, irradiation, etc.). This facility is unique and singular in Europe and in the world. Therefore, this laboratory has to be organized to allow the performance of different experiments with little changes and simple adaptation processes. These characteristics will require a special attention during the design period of the facility.

(II) Safety

A facility like *TechnoFusión´*s MI Facility precises of a careful evaluation of the radiological risks derived from it regular operation.

A primary set of risks are associated to the operation of the accelerators, which implies photon and high-energy neutron generation).

Other risks are connected to the generation of isotopes, both radioactive and stable. Information of the final activation of the samples (i. e., gamma and neutron radiation after the implantation), and of the time decay of they are of fundamental importance to determine the shielding of the building, and the safety procedures to access the experimental rooms.

Additional hazards in the facility will be I) electrical, II) magnetic, and III) chemical:

I. During operation, the facility will require high voltage supply units. These must be electrically isolated by means of Faraday cages and any other appropriate protection systems.

II. The presence in the facility of high magnetic fields, either from the cyclotron (about 6 or 7 T) or from the high magnetic field electromagnet (between 5 and 10 T) will restrict the access to the experimental room. Although there are no known effects on health caused by exposure to high magnetic fields, the *World Health Organization* (WHO) recommendations[57] are a time-weighted average of 200 mT during the working day for occupational exposure, with a ceiling value of 2 T.

Therefore, there must be signs indicating the presence of strong magnetic fields and the safety warnings for people with special needs—pacemaker users, people with ferromagnetic implants and devices, etc. This information must be located in areas with magnetic fields below 0.5 mT.

[57] World Health Organization. Electromagnetic Fields and Public Health. Retrieved from the Internet on August 2009. http://www.who.int/mediacentre/factsheets/fs299/en/index.html

There will also be clear signs prohibiting the access to areas where the field could exceed 3 mT with any ferromagnetic element. These objects could be projected by the field, damaging equipment and personnel.

III. The use of different hazardous gases –flammable, oxidizing, toxic— will require the separation of the testing area and the area for gas storage. Gases should also be separated according to the specific danger each of them posed.

Proper ventilation, protection from heat, and protection from direct sunlight are also needed. In the storage area for flammable gasses, wiring –if any— should be made according to regulations. The gases should be transported from the storage area to the plant by hermetic pipeline allowing a wide versatility in the use of these gases while maintaining an acceptable level of security. Finally, inside the facility there will be gas detectors for hydrogen, helium, sulphur hexafluoride, etc; gauges to measure oxygen levels; as well as fire prevention measures.

There are also risks associated to the presence of cryogenic liquids at the facility, mainly extreme cold and suffocation.

Finally, as a test facility, the risks may vary during its lifetime. Therefore there will be protective measures for the equipment and people related to the use and status of the facility. In this sense, MI Area must comply with the Law on Prevention of Occupational Risks (BOE n º 269, 10/11/1995, RD 31/1995).

Appendix I: Reports related to simulations of the *TechnoFusión* Material Irradiation Facility

I.A. Report on the TechnoFusión Multi-ion-irradiation Facility and its relevance for fusion applications

Authors: *TechnoFusión Material Irradiation Group*

(I) INTRODUCTION

The effect of neutrons on materials involves two physical phenomena: i) the displacement of ions from their lattice sites creating point defects, and ii) the generation of nuclear transmutation reactions that will contribute to increasing impurities inside the materials, He and H being the most important. Therefore, for many years, the scientific community has being using accelerators to simulate both effects. At present it is well known that neutron effects can be well represented by irradiating simultaneously with He, H (in similar amounts as expected by transmutation) and heavy ions capable of creating point defects [1, 2, 3].

The *TechnoFusión* Centre is envisaged to contribute to such neutron damage studies by means of the multi-irradiation ion facilities that form part of the Material Irradiation Facility (MI) [4]. An in-depth study has been done to demonstrate and optimize the use of ion accelerators to reproduce a damage evolution that mimics that expected in fusion devices (target damage plus helium and hydrogen production). The MI Facility scheme consists of three different ion beams to irradiate samples with medium to high energies.

The aim of the Material Irradiation Facility of *TechnoFusión* is to become a relevant user-facility for the selection of functional materials. MI Facility will incorporate three ion accelerators: two for implantation of light ions (H and He), and one for heavy ions that produce lattice displacements (Fe, Si, C, others). The ion energies chosen for the different ion accelerators are shown on Table I.A1. The effect of neutron radiation on candidate materials for ITER and DEMO will then be simulated by simultaneous triple ion beam irradiation.

(II) OBJETIVES

The main goal of MI Facility is to test and develop materials for fusion reactors [5]. Due to the lack of facilities to study material damage, multi-ion beam facilities are necessary to investigate ion-induced damage mechanisms, the synergistic effects of a dual/triple beam irradiation, and ion-beam modification of materials [1]. One of the requirements of the initial R&D in the material field is to show that a combination of heavy and light ions (in terms of microstructure and impurities) can produce similar damage to that expected in a fusion reactor (damage induced by neutrons). During the design phase this equivalence will be evaluated and the most suitable accelerators will be selected. The next objective of MI Facility will be to irradiate samples homogeneously over a large volume and to produce damage uniformly in the material. To achieve this, two approaches are proposed, depending on the damage-production process and the generation of H and He:

I) Irradiation of a material with ions of the same species (e.g., irradiation of Fe with Fe ions), together with a simultaneous double implantation with light ions (H and He). This triple irradiation solution is expected to produce the same level of defects and the same quantity of light ions (via H and He implantation) that are expected to be reached under neutron irradiation in the fusion facilities. Furthermore, choosing the correct energies for each ion, one can produce the 3 effects in the same region of the material. For example, SRIM and Marlowe codes [6, 10] have been used to calculate the implantation profile of He and H and the damage produced by Fe ions in an iron sample. Results as a function of depth are shown in Figure I.A1. This figure illustrates the methodology used to select energies for each ion in different materials. The triple irradiation procedure must look for a coincidence between the depth for damage produced by heavy ions and the penetration ranges of H, and He implantations.

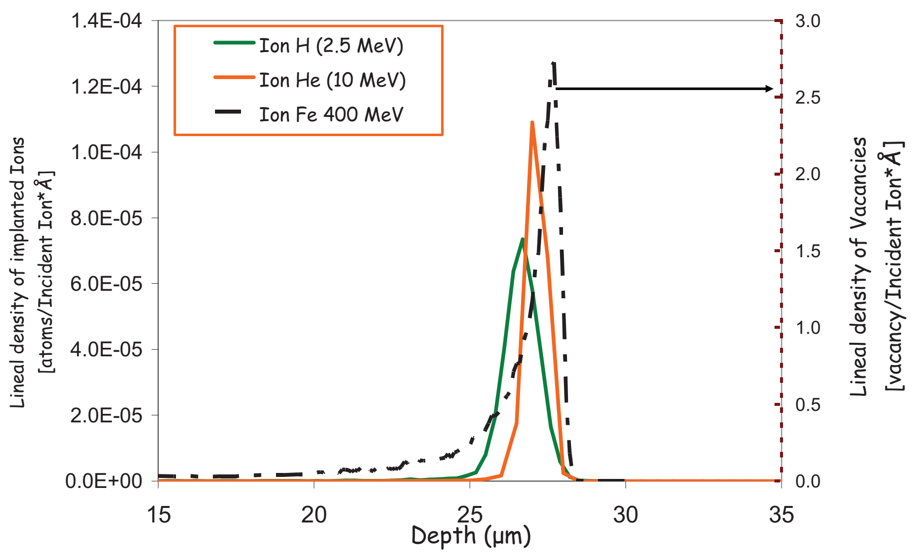


Figure I.A1. Depicts the in-depth coincidence of damage generated by Fe ions and implantation of light ions (H and He) of several energies in an Fe sample.

II) The second method is to irradiate with protons up to 70 MeV in order to produce directly damage and generate light elements in a similar way to that generated by neutrons in fusion reactors. Protons and neutrons have a similar mass and thus could generate a similar amount of displacement. On the other hand, protons can also produce H and He in a material by nuclear transmutations, similarly to neutrons. The displacements produced by different proton energies were estimated by means of SRIM code [6]. In addition, this method presents the important advantage of easily achieving, implantation over large thicknesses (in the millimeter range), much larger than those accessible with ion implantation. A drawback is that during operation radiation and sample activation are produced.

The next section is devoted to calculating the energies and intensities of the ion beams and protons needed to generate the same level of damage in materials as produced by the neutrons expected in nuclear fusion facilities. The main factors taken into account are the following:

i) The minimum beam energy needed for the required penetration in the material.

ii) The homogeneity of beam damage along the whole penetration range.

iii) To maintain an accurate ratio between the concentration of light ions over the damage, as generated in a fusion facility.

iv) The reproduction of an accurate spectrum of the Primary Knock-on Atoms (PKA).

(III) METHODOLOGY AND RESULTS

a) Triple Ion beam

The first technique consists on the irradiation of a target with ions of the same chemical species with the goal of avoiding implantation of other impurities. The typical system is iron ions on an iron target. In order to emulate the damage created by neutron irradiation, the calculations must bear in mind that damage should be homogeneous along the penetration depth. Table I.A1 shows the maximum energies expected for heavy ions in a typical k=110 cyclotron and the penetration ranges of these ions considered for irradiation, as a function of target species. The last four columns show the maximum light ion energies needed to implant these species (hydrogen and helium) along the same penetration ranges established by the penetration of the heavy ions. All these calculations were performed using the SRIM code [6].

One particular condition is that the He energy is limited to a maximum value of 18 MeV. This is due to the fact that, for tandem accelerator, the maximum terminal voltage has been fixed at 6 MV. As the charge states of He can be -1 and +2 in both accelerating sections respectively, this gives the 18 MeV limit. We see that this condition is the limiting one in some cases, but the correction in the respective heavy ion energy is not too high.

After obtaining energy values, and therefore depth profiles, we need to estimate the magnitude of beam currents. For this purpose, the irradiation conditions of fusion materials in an environment as close as possible to the one expected in DEMO have been emulated. The first step has been to calculate the amount of damage as well as H and He generation expected at different positions for the main candidate materials. This combination of materials and positions give rise to a wide range of dpa's and H/He generation amounts that are shown in Table I.A2. These are consequently the values that must be simulated using the *TechnoFusión* accelerators. As can be observed, the range is quite broad. Obviously a selection of conditions must be made, taking into account the main applications of each material. For example, Fe, FeCr alloys and steels will be located in positions going from the first wall to the back, so the most severe conditions must be, in principle, applied. However, at present, SiC is envisaged only for channel insertions in the Breeding Zone and finally many of the insulators included in the table are for diagnostics, therefore located in the Breeding Zone (BZ) Back. Exceptions include some systems located quite close to the first wall (as ICRH antenna) and insulators used as coatings of SiC channels. Therefore a compromise would be to use the BZ Middle conditions as a first study to obtain typical operation conditions. In any case, these values will be defined when specific work-plans will be approved.

Table I.A1. Ion energies that will be used in the MI Facility assuming a He energy inferior or equal to 18 MeV (tandem at 6MV terminal voltage and charge states of -1 and +2).

		Heavy ion accelerator Cyclotron k = 110		Light ion accelerator 4 MV		Light ion accelerator 6 MV	
Irradiated material	**Range (µm)**	**Ion**	**Energy (MeV)**	**Ion**	**Energy (Mev)**	**Ion**	**Energy (MeV)**
Fe (7.8 g/cm^3)	26.6	Fe	385	H	2.5	He	10
W (19.3 g/cm^3)	10.1	W	373	H	1.6	He	6
C (2.3 g/cm^3)	148.0	C	96	H	4.5	He	18
SiO_2 (2.2 g/cm^3)	175.0	Si	337	H	4.6	He	18
SiC (3.2 g/cm^3)	122.4	Si	337	H	4.6	He	18
SiC (3.2 g/cm^3)	122.4	Si	337	D	6.0	He	18

With the energies shown in Table I.A1, plus the vacancy/implantation profiles calculated for each ion, together with the required values of dpa's, He and H in Table I.A2 determine the three different intensities (heavy ions and light ions) needed to generate the damage equivalent to that produced by neutrons. For each combination of material and position, the intensity of heavy ions (see Table I.A2) can be calculated to obtain a damage rate. In Table I.A3, these values have been calculated for the case of 1 dpa per week, which is similar to the damage estimated [7] in a nuclear fusion environment. These are therefore minimum values or "normalized" values. Higher irradiation rates will be required to accelerate the total damage and to obtain convenient irradiation times. For example if it is required to have the total lifetime damage estimated for DEMO (around 300 dpa) in only a week, the current values are directly multiplied by this factor. This very high dose rate would provide the maximum currents needed for each ion at the exit of the cyclotron.

In a similar way, the intensities for each of the light ions (H and He) to obtain the transmutations expected in Table I.A2, are in the range of 50-100 pnA. The defining factor for the light ion intensities is the ratio between implantation (in appm) and damage (in dpa) estimated for fusion facilities [7, 8]. Again, accelerated rates will require proportionally higher currents.

The important fact is that with the values of Table I.A2, while fixing the total irradiation time in *TechnoFusión*, the values of currents needed for each material/position and each accelerator (heavy ions from cyclotron, H and He from tandems) can be directly obtained. Together with the irradiation thickness requirements, that fix the energy, the above quantities define the main accelerator parameters (energies and currents). Another correction must be done to take into account the fact that the beam will pass through a beam degrader and therefore, for strong energy losses, a fraction of the beam will be lost.

Possible future changes in DEMO design can be accommodated thanks to the independent tuning of dpa's, H and He generation available using 3 independent accelerators. Initial accelerators design must be flexible enough to reach the above initial figures plus some margins.

Table I.A2. Calculated values of damage (in terms of dpa) and gas generation (H and He) for several candidate materials in a DEMO scenario. These values are calculated at different typical positions including First Wall (FW)) and Breeding Zone (BZ).

dpa/fpy appm/fpy		*DEMO HCLL (4000MW)*			
		FW (front)	**FW (back)**	**BZ (middle)**	**BZ (back)**
Fe-56	*dpa*	30	29	8	2
	H	982	870	53	4
	He	270	241	16	1
SiC	*dpa*	20	20	8	3
	H	1053	939	62	5
	He	2596	2304	144	11
SiO2	*dpa*	*48*	*49*	*21*	8
	H	929	827	53	4
	He	1477	1319	87	7
Al2O3	*dpa*	19	20	9	3
	H	1114	987	60	4
	He	1290	1150	75	6
Si2N4	*dpa*	*17*	*17*	*7*	*3*
	H	2511	2339	398	117
	He	1287	1207	150	17
CaO	*dpa*	17	17	7	3
	H	2975	2698	215	18
	He	1475	1335	103	8
AlN	*dpa*	*21*	*21*	*9*	*3*
	H	2545	2350	363	104
	He	1076	1011	127	14
W	*dpa*	*12*	*11*	*3*	*1*
	H	12	10	0.5	0.04
	He	3	3	0.2	0.01

Table I.A3. Target intensities for each ion species from the cyclotron planned for the TechnoFusión MI Facility to obtain a **nominal 1 dpa/week** damage level. Intensities data appear as particle nanoAmps for each single charged ion.

	Ion Currents (pnA)
C	500 – 1 µA
Si	200
O	200
Fe	25
W	3

As a special case to illustrate this point, Figure I.A2 shows the ratio of He produced (in appm of He) versus damage (in dpa) in the process of irradiating a Fe target with Fe ions for a week in two different kinds of facilities: a) existing facilities —nuclear fission reactors and particle accelerators—, and b) future facilities under development for nuclear fusion such as IFMIF, ITER and DEMO. In the later case, the figures are computational estimations. The highlighted area on the graph corresponds to the range where the *TechnoFusión* facility is expected to operate (yellow square), and this region covers the values of generated He vs. damage expected from the new nuclear fusion facilities.

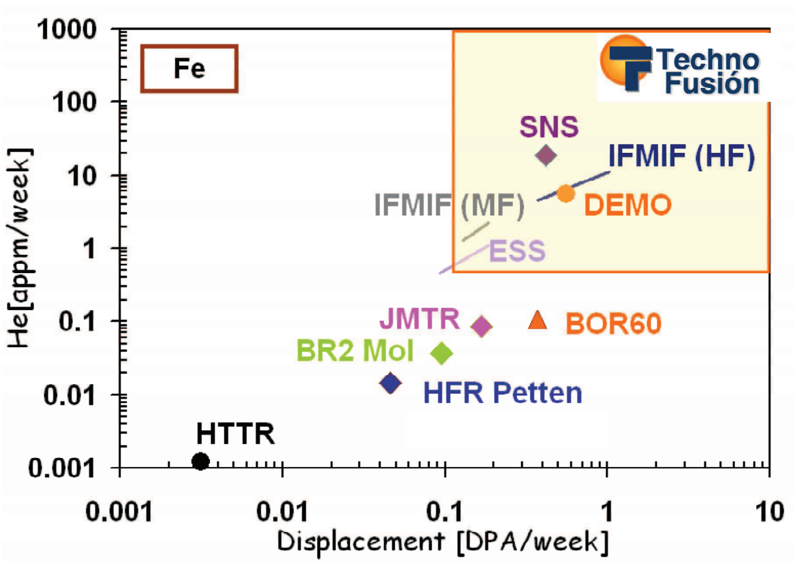


Figure I.A2. Comparison of results from different facilities (particle accelerators, fission facilities and future fusion facilities). He appm/week versus displacement in dpa/week during homogeneous irradiation of Fe and He ions beam with a maximum energy of 300 and 10 MeV respectively, on Fe samples using different intensities.

An additional factor to be taken into consideration to ensure the accuracy of the simulation of neutron damage by other means is the Primary Knock-on Atom (PKA) energy spectrum; up to now, the only parameter considered was the total damage. The PKA spectrum describes how the damage is produced. The damage function W(T) [9] connects the PKA spectrum with the total damage in the material. It is well known that different primary recoil energy spectra can produce completely different damage morphologies, and therefore W(T) indicates the cumulative damage production by all PKAs up to the energy T:

$$W(T) = \frac{1}{D/t}\int^{T}\sigma_{PKA}(T')N_d(T')dT' , \qquad \text{(I.A1)}$$

where $\sigma_{PKA}(T)$ is the PKA spectrum, $N_d(T)$ is the number of Frenkel pairs produced by PKA of energy T, and D/t is the rate of damage created by the atomic displacement.

The PKA spectrum was calculated with the SRIM code. On the contrary, the Marlowe code [10] was used to evaluate the function of Frenkel pairs generated by PKA with energy T because it resolves the cumulative damage better. Therefore, $\sigma_{PKA}(T)N_d(T)$ is integrated to obtain the damage function on eq. I.A1.

The damage functions generated in iron by Fe ions of 500, 300 and 50 MeV are shown on Figure I.A3, and are compared with those expected in DEMO HCLL (first wall and breeder zone). This graph shows that ions with higher energy become closer to the present calculations for DEMO HCLL damage area.

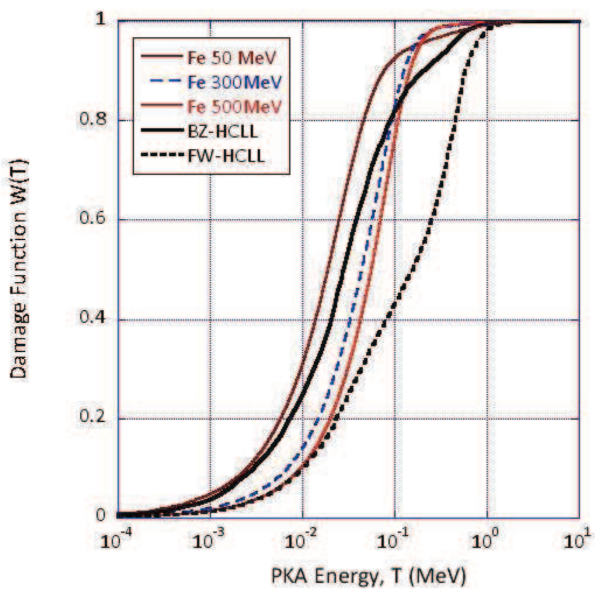


Figure I.A3. Damage function generated in Fe material by Fe ions of 50, 300 and 500 MeV. Comparison with results from DEMO HCLL (first wall [FW] and breeder zone [BZ]), calculated with NJOY code.

b) Proton Irradiation

The second irradiation approach to study the neutron damage is based on the irradiation of high energy protons. SRIM and Marlowe codes were also used to calculate the damage function generated by protons with energies up to 70 MeV. On Figure I.A4 we represent the damage functions obtained for the high energy range (40 and 70 MeV) protons in a 1 mm thick iron sample. It can be seen that the results are also very close to those calculated for DEMO HCLL.

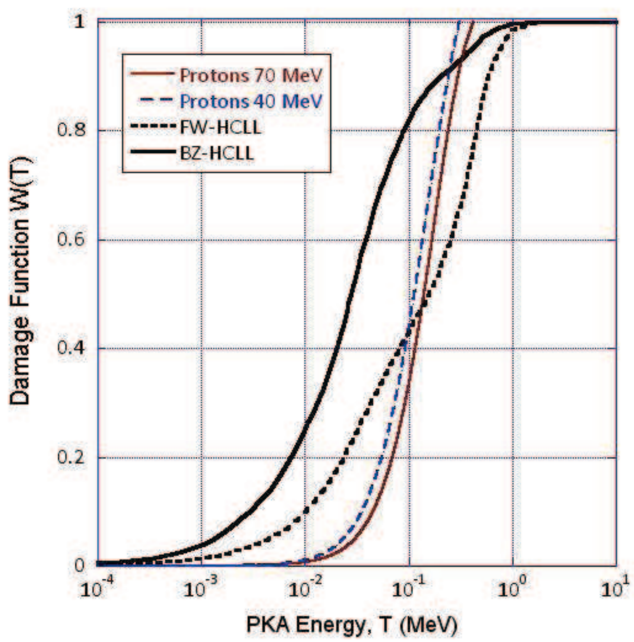


Figure I.A4. Damage function generated in Fe material by protons of 40 y 70 MeV. Comparison with the results from DEMO HCLL (first wall [FW] and breeder zone [BZ]), calculated with NJOY code.

An important factor is the He/dpa ratio. Table I.A4 shows the rough ratios of appm He/dpa calculated for iron targets using cross sections for the generation of He by transmutation [11] and displacements by SRIM code. Sample thickness is chosen in each case in such a way that the protons can pass through the sample and energy deposition is quite constant. This value of thickness is also shown in Table I.A4. In this method, choosing the proton E, we can adjust the He/dpa ratio to values close to the one expected in DEMO. On the other hand, the damage functions are still close to DEMO.

With these initial calculations 40 MeV-protons seems to be a good option for simulating the neutron damage in terms of damage function, while 20 MeV protons can be the best candidate given the good dpa/He ratio and the reduced nuclear activation. Anyway more accurate calculations must involve the use of the MCNPX code to obtain a better PKA distribution and the study must be extended to other materials and positions in DEMO that obviously change the target value of He/dpa.

Other important differences between both methods (triple beam or only protons) are a) the radiation level produced during irradiation with proton beams at these energies and b) the amount of activation present in the irradiated samples. This has strong implications in the radioprotection requirements of the installation. This is the subject of the next section.

Table I.A4. He/dpa relations obtained from simulations in iron irradiated with protons of 10, 20, 40 and 70 MeV compared to the corresponding value near first wall in fusion facilities.

	Sample thickness (mm)	He/dpa
Fusion	---	11
10 MeV	0.2	~1.5
20 MeV	0.5	~11
40 MeV	1	~33
70 MeV	2	~70

(IV) SUMMARY

Triple beam irradiation and proton irradiation are good candidates to simulate the damage on materials by neutrons in a nuclear fusion facility. Each method presenting some advantages and disadvantages.

TechnoFusión´s Material Irradiation Facility aims at exploiting this property by creating a laboratory where materials could be irradiated simultaneously with up to three different ion beams. This facility will test the performance of materials to be used in future fusion reactors, such as ITER, DEMO and IFMIF.

(V) REFERENCES

[1] Y. Serruys, P. Trocellier, S. Miro, E. Bordas, M.O. Ruault, O. Kaïtasov, S. Henry, O. Leseigneur, Th. Bonnaillie, S. Pellegrino, S. Vaubaillon and D. Uriot, "JANNUS: A multi-irradiation platform for experimental validation at the scale of the atomistic modelling", J. Nucl. Mater 386-388 (2009) 967-970

[2] R.S. Averback et al., "Correlations between ion and neutron irradiations; Defect production and stage I recovery", J. Nucl Mater. 75 (1978) 162-166.

[3] H. Ullmaier et al., "The simulation of neutron-induced mechanical property changes by light ion bombardment", Ann. Chim Fr. Sci. Mat. 9 (1984) p.263-274.

[4] J. Sánchez, A. Ibarra, J. M. Perlado, A. Abánades, R. Aracil, N. Casal, J. Ferreira, A. García, I. García-Cortés, M. González, D. Jiménez-Rey, A. Muñoz, F. Mota, R. Pareja, V. Queral, R. Román,

J. Sanz, F. Sordo, F. L. Tabarés, and R. Vila, "*TechnoFusión*: A new centre for the development of fusion technologies and fusion reactor devices", proceeding of the 14th International Conference on Emerging Nuclear Energy Systems (ICENES), Ericeira Portugal.

[5] R&D Needs and Required Facilities for the Development of Fusion as an Energy Source, Report of the Fusion Facilities Review Panel, October 2008.

[6] J.F. Ziegler, J.P. Biersack y M.D. Ziegler, "SRIM: The Stopping and Range of Ions in Matter", http://www.srim.org (2008).

[7] P. Vladimirov, and S. Bouffard "Displament damage and transmutations in metals under neutron and proton irradiation" C.R. Physique 9 (2008) p.303- 322.

[8] P. Vladimirov, A. Möslang, U. Fischer and S. Simakov "Material irradiation conditions for the IFMIF medium flux test module" Journal of Nuclear Materials Volumes 367-370, Part 2, 1 August 2007, Pages 1574-1579.

[9] H.Wiedersich, "Effects of the primary recoils spectrum on microstructural evolution", Journal of Nuclear Material. 179-181 (1991) 70-75.

[10] M. T. Robinson, Phys. Rev. B 40, (1989).10717

[11] C.H.M. Broeders, A. Y. Konobeyev, "Helium Production in Solid target and metallic windows materials irradiated with intermediate and high energy protons" Journal of Nuclear Science and Technology, Vol. 42, No. 10 (2005) p. 897-902.

I.B. First radioprotection studies for the preliminary design of the TechnoFusión facilities

A. Mayoral, J. Sanz, D. López, P. Sauvan, F. Ogando, M. García, J.P Catalán, P. Antón
Departamento de Ingeniería Energética, UNED, Madrid, Spain, jsanz@ind.uned.es
Instituto de Fusión Nuclear, UPM, Madrid, Spain

(I) INTRODUCTION

In the *TechnoFusión* Centre, three particle accelerators are expected to be focused in the simulation of the radiation damage in fusion reactor materials: two linear accelerators for H, D and alpha ions and a cyclotron for heavy ions and high energy protons [*TechnoFusión*, 2009]. These three accelerators will be located in the same building. The beams from these accelerators are inter-connected, that is, two or three beams can be focused on the same target at once and the functions of the accelerator systems are inter-related. In this way, single, double or triple beams can be utilized in the target irradiations.

This report is focused on assessing radioprotection issues associated only to the irradiation of different targets. Issues associated to irradiations with low energy H, D, and alpha as well as with high energy protons are analyzed. The issues associated to irradiation with heavy ions are not considered here.

The results of this task will be used in other radioprotection studies, with regard to the necessary bio-shielding of the vault and the required precautions to handle the irradiated targets to assure that the levels of doses reached are acceptable for workers and public.

Although the methodology to compute the prompt dose due to the neutron production from nuclear interactions of the proton beam with the target is available for many materials, there are not reasonable solutions to compute the prompt dose from alpha and deuteron beams.

This difficulty is due to the fact that the built-in nuclear models included in MCNPX [Pelowitz, 2008] do not allow an accurate assessment of the prompt dose at low energy and there are not available libraries for these particles in the MCNPX code [Sanz, 2008; Joyer, 2009; Mayoral, 2009].

A new methodology has been developed to solve these difficulties in the radioprotection studies for *TechnoFusión* facilities. The details with regard to the computational tools (scenario, the XS libraries and the codes) are described and discussed in the methodology section. The results of the simulations and the main conclusions of this work will be presented in a separate section.

(I) METHODOLOGY: IRRADIATION SCENARIO AND COMPUTATIONAL TOOLS

Regarding the simulation scenario, the target geometry is the same for all the materials analyzed (Fe, SiO_2, SiC, C and W): a solid cylinder of 2 cm diameter and 1 mm of thickness.

All the particle beams have the same shape: circular section of $1cm^2$, uniform current density and axis lined-up with the axis of the target. There is a vacuum cylinder between the beam source and the target. The vault is filled with air. The current intensity for the beams (proton, alpha, deuteron, high energy proton) is the characteristic for each target material. At the moment of writing this report, the data related to the current intensity for SiC, C and W targets as well as the highest energy proton beam value for all the targets are not known. Provisional values of 50 pA for double beams and 1 µA for the highest energy beam will be used for the simulations. True values for the prompt dose can be calculated using the correction factor (the prompt dose is lineal with the current).

The information achieved from the simulations is: i) for the beam on phase, the production rate and dose rate field for emerging neutrons and photons. ii) for beam-off phase, the isotopic inventory and the residual dose rates due to the activation of the target material.

The dose rate due to the radiation is presented through the magnitude named ambient dose equivalent [ICRP-103, 2007]. The values of the conversion factors from fluency to dose rates come from ICRP74 [ICRP-74, 1996].

The ACAB code [Sanz, 2009] with EAF2007 libraries [Forrest, 2007] has been used for activation calculations.

We propose to use a new tool named MCUNED [Sauvan, 2009] for the beam-on phase simulations. The MCUNED code is an extension to the MCNPX code that allows a computational solution much better than the poor accuracy results provided by the MCNPX simulations for alpha and deuteron beam at low energy. This extended MCNPX code is able to handle ACE files format, so MCUNED can use the data from TENDL transport library [Koning, 2008]. This procedure solves the difficulties in those cases where TENDL library is available. This code has been successfully used in our former work to compute the neutron and tritium production rates for EVEDA-IFMIF facility, where low energy deuteron beam interacts with copper material [Mayoral, 2009].

The advantage to apply this procedure to the simulations for *TechnoFusión* facilities is illustrated in Table I.B1. This table shows results of the dose rates and neutron production rate from the simulations made with MCNPX and MCUNED for 10 and for 15 MeV alpha energy beams over iron target.

Table I.B1. MCNPX vs MCUNED code: simulation of alpha beam over Iron target

Fe (α, nx)	MCNPX				MCUNED TENDL08	
	ISABEL		INCL4			
	10 MeV	15 MeV	10 MeV	15 MeV	10 MeV	15 MeV
MAXIMUM DOSE (µSv/h)	0	0	0	0	1.21	14.3
NEUTRON SOURCE	0	0	0	0	8.98E-06	9.84E-05

There is a significant discrepancy between the results obtained with MCUNED and MCNPX simulations. Therefore it was necessary to discuss which one of these results is the more accurate solution. The following figures and comments are the base to recommend the MCUNED option.

- The threshold energy of the reactions are lower than 10 MeV for all the iron isotopes; therefore it is possible the neutron production proposed by MCUNED option. (Table I.B2, National Nuclear Data Center [NNDC]).

Table I.B2. Features of different alpha induced reactions on Iron (From National Nuclear Data Center)

Remote Handling Operation	Q value (keV)	Threshold (keV)
^{54}Fe(4He, n)^{57} Ni	-5816.89 1.87	6248.53 2.010
^{55}Fe(4He, n)^{58}Ni	-2898.08 0.55	3109.22 0.590
^{56}Fe(4He, n)^{59}Ni	-5096.10 0.54	5460.761 0.579
^{57}Fe(4He, n)^{60}Ni	-1354.45 0.54	1449.667 0.578
^{58}Fe(4He, n)^{61}Ni	-3578.93 0.56	3826.191 0.599

- The reasoning will be focus on Fe^{56}, the main contributor to the neutron production (Figure I.B1).

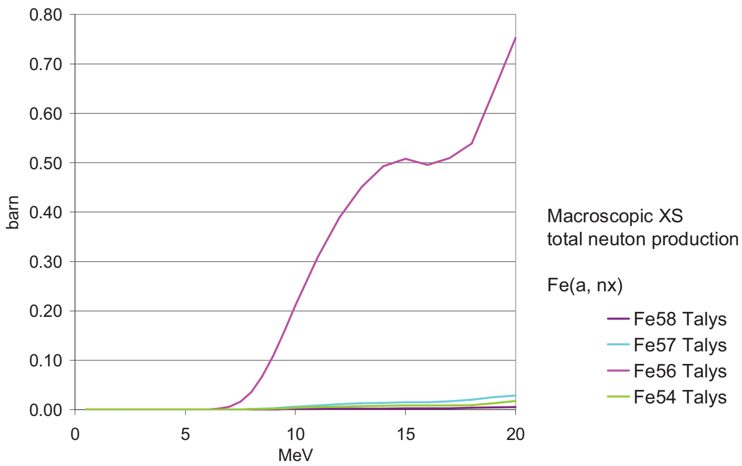


Figure I.B1. Macroscopic XS for Fe(α, nx).

- The Figure I.B2 presents the aim of this discussion: the macroscopic cross section for the total neutron production for Fe^{56} from Talys and from MCNPX Models (Isabel, Bertini and Incl4).

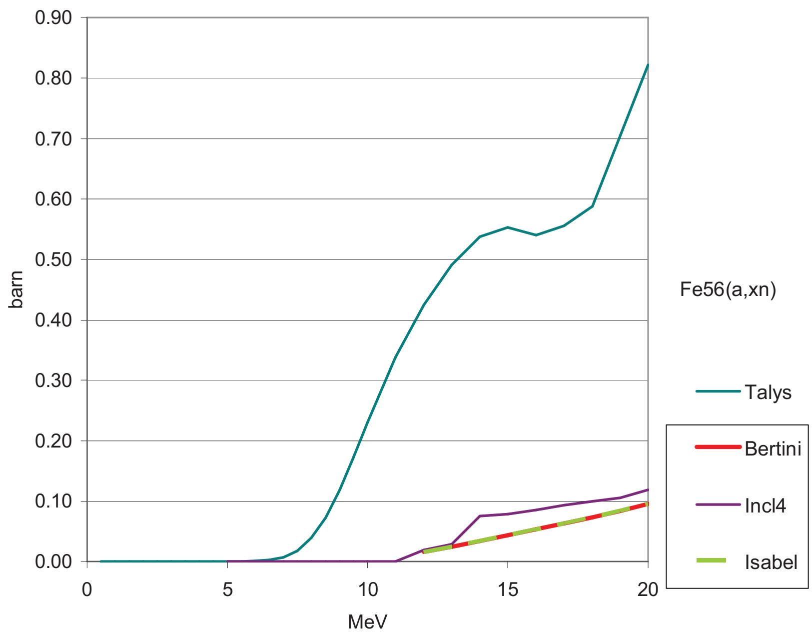


Figure I.B2. XS for total neutron production from Talys & from MCNPX Models

- Only for Fe^{56} (α, np) there are available XS from experimental data (Figure I.B3). The figure includes the XS from Talys for this reaction. The neutron production at 19.6 MeV for Fe^{56} (α, np) from Tanaka experience [EXFOR 2009] is more than twice of the value for total neutron production predicted by MCNPX models. This fact confirms that the MCNPX models are not able to compute the neutron production for alpha nuclear interactions on Fe up 20 MeV. However there is a good agreement between the values predicted by Talys and the experimental data for the XS of Fe^{56} (α, np) reaction.

- With regard to the dose obtained by using the Talys code, the energy spectrum of the emerging neutrons, rules out the error due to high energy tail (Figure I.B4, Table I.B2).

Additionally, MCUNED code is able to reduce the computation time in a factor of 5.000 (depending on the simulation) due to the incorporation of a technique of variance reduction which allows decreases the number of histories necessary to achieve a good statistics for secondary particles [Sauvan, 2009].

The details with regard to the composition of the targets (Fe, C, W, SiO_2 and SiC) and to the availability of XS libraries for the simulation of the nuclear interaction with the particle of the beam (H, D, α) are related in Table I.B3.

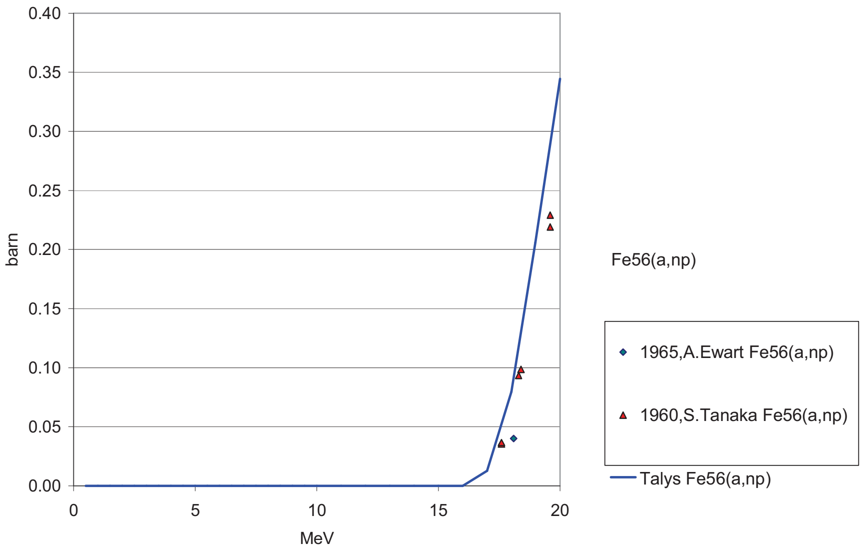


Figure I.B3. Fe^{56}(α,np) experimental & Talys.

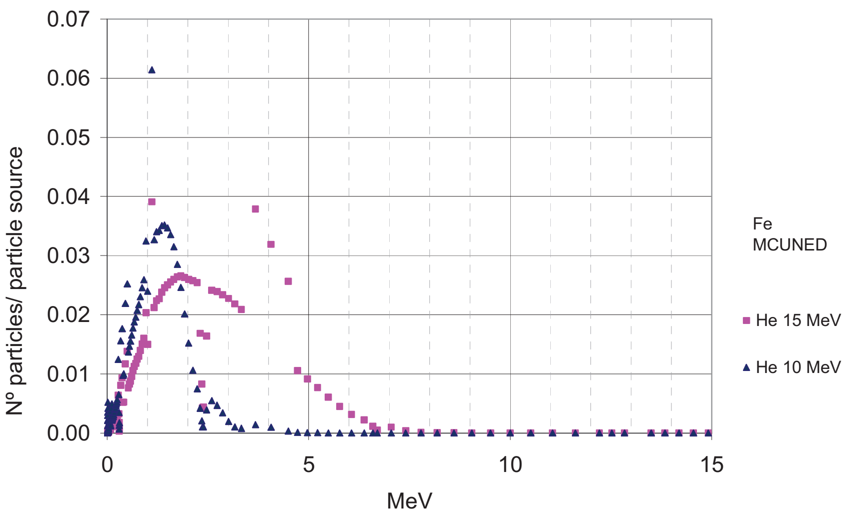


Figure I.B4. Normalize energy spectrum for emerging neutron from Fe (α,nx) 10 and 15 MeV.

Table I.B3. Libraries and built-in MCNPX model used for transport simulations.

The isotopes marked with (*) have not been taken into account since there is no XS library available and its contribution to the prompt dose is negligible.

TARGET			XS LIBRARY / MODEL			
MATERIAL DENSITY (g/cm^3)	Isotope		N	p	PARTICLE: H	PARTICLE: α
Fe 7.8	26054	0.058	ENDF/b vi6	mcplib02	la150	TENDL08
	26056	0.917				
	26057	0.022				
	26058	0.003	* not taken into account			
SiO_2 2.2	14028	0.307	ENDF/b vi6	mcplib02	la150	TENDL08
	14029	0.016				
	14030	0.010				
	8016	0.665				TENDL09
	8018	0.001	* not taken into account			
SiC 3.2	14028	0.461	ENDF/b vi6	mcplib02	la150	TENDL08
	14029	0.023				
	14030	0.016				
	6012	0.494	ENDF	cplib04	la150	Isabel
	6013	0.006	* not taken into account			

			D
14028	0.461		TENDL08
14029	0.023		
14030	0.016		
6012	0.494		TENDL09
6013	0.006	* not taken into account	

C 2.3	6012	0.9889	ENDEF	mcplib04	la150	Isabel
	6013	0.0111	Isabel	cplib04	Incl4 E<5MeV Isabel E<20Mev	Isabel
W 19.3	74180	0.0012	* not taken into account			TENDL08
	74182	0.2650	ENDF/b vi6	cplib02	la150	
	74183	0.1431				
	74184	0.3064				

Those cases in which there are not available libraries for MCUNED code, the different XS options from built-in MCNPX models have been checked. The reference data to evaluate the best estimation are from: i) experimental data [EXFOR, 2009], ii) Talys code [Koning, 2007], iii) JENDL library [JENDL, 2002]. The details related to the problematic cases, alpha and proton interaction over carbon, are presented below.

The dose rates presented in this report for 18 MeV alpha beam over SiC target could be a very poor estimation. The contribution of C^{12} to the total neutron production is very significant (C^{12} and Si^{28} are the main contributors, Figure I.B5a). Only for C^{12} (α,n) reaction experimental data is available. The results by Talys code show that C^{12} (α,n) reaction is the main contributor to the total neutron production, although the values from the simulation have poor fitting with the experimental data. The same conclusion is obtained for simulations using TENDL09 but with a better agreement with the experimental data. We have selected the Isabel model trying to get the more conservative result (Figure I.B5b).

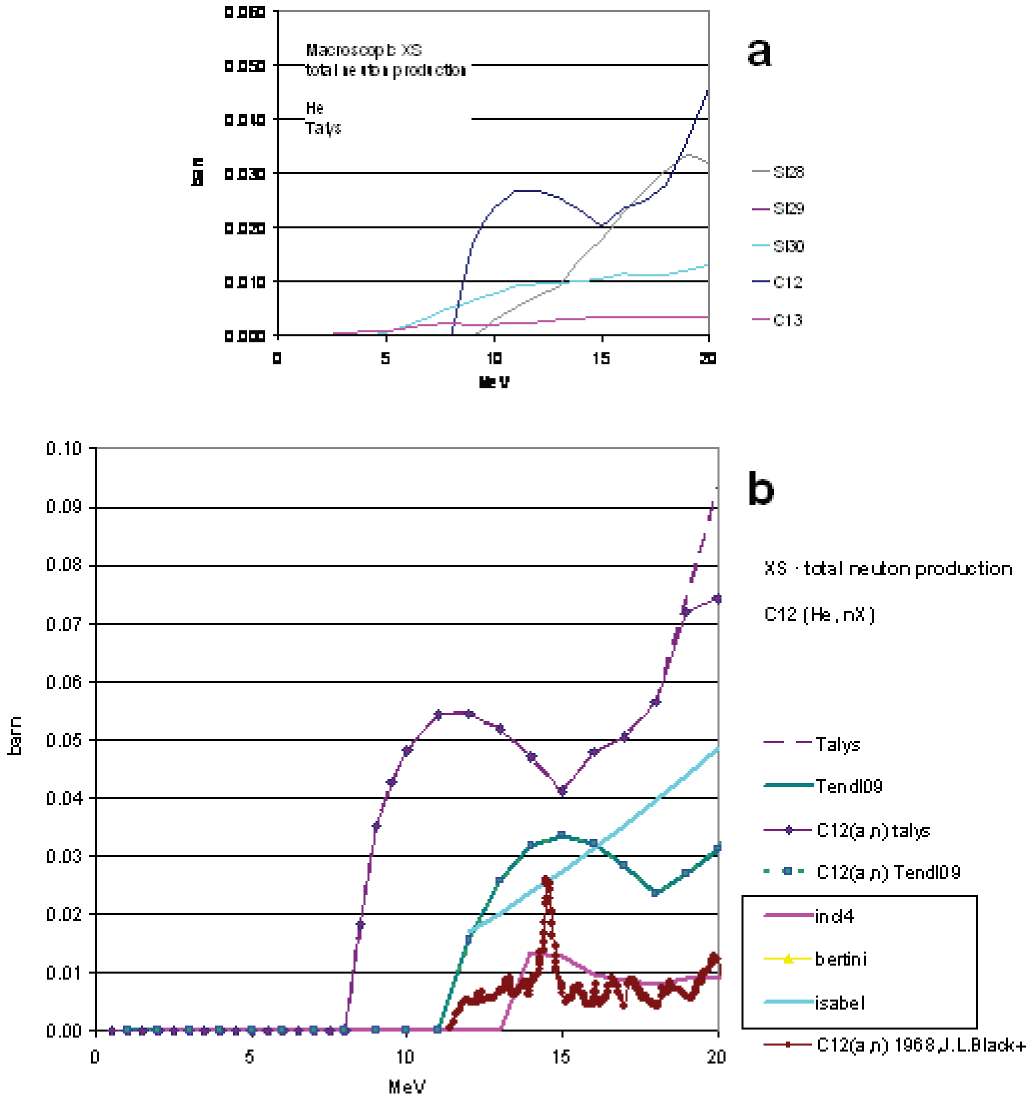


Figure I.B5. SiC (α,nx): (a) Macroscopic XS from ACSLAM. (b) Built-in MCNPX vs Talys & ACSLAM.

The simulation of the neutron production for 18 MeV alpha beam over carbon target could be a very poor estimation. The C^{12} is the main contributor to the total neutron production (Figure I.B6). For the same reason presented above related to the SiC target, the Isabel model was used for C^{12} (Figure I.B5b).

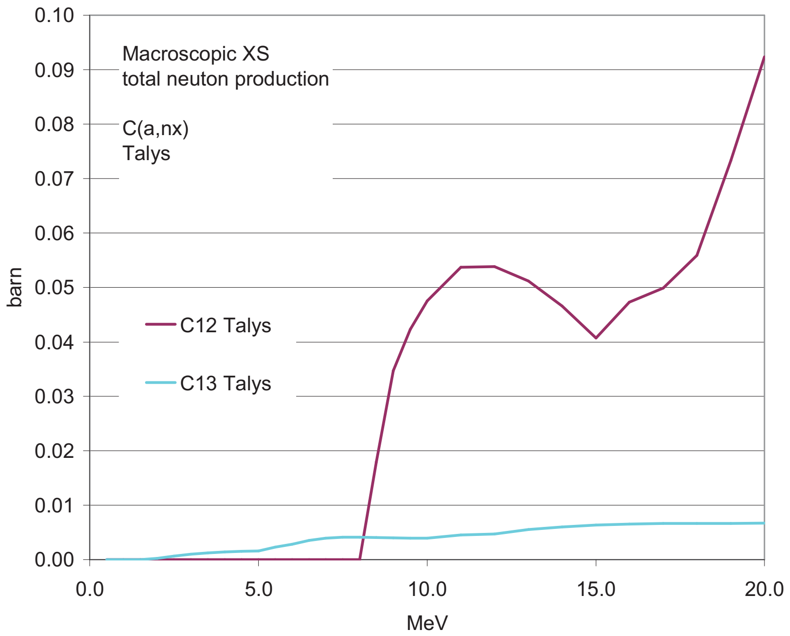
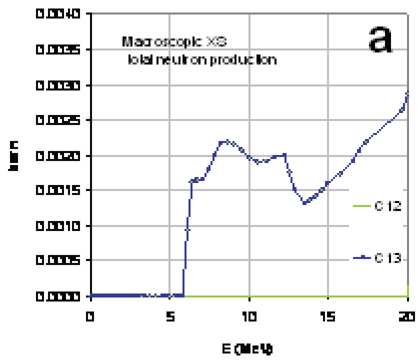


Figure I.B6. Macroscopic XS C(α,nx) from Talys.

The dose value presented in this report for a 4.6 MeV proton beam on Carbon target could be a very poor estimation. The C^{13} is the main contributor to the total neutron production (Figure I.B7). There are not experimental reference data for the test, since we have taken the JENDL library as reference. Therefore we have selected the Incl4 model for proton energy up to 5 MeV and Isabel up to 20 MeV.

With regard to the neutron energy spectrum from the cases simulated with built-in MCNPX models, there are not agreement with the physic of the system but the relevance of the error due to the unphysical high energy tail is expected to be not significant.



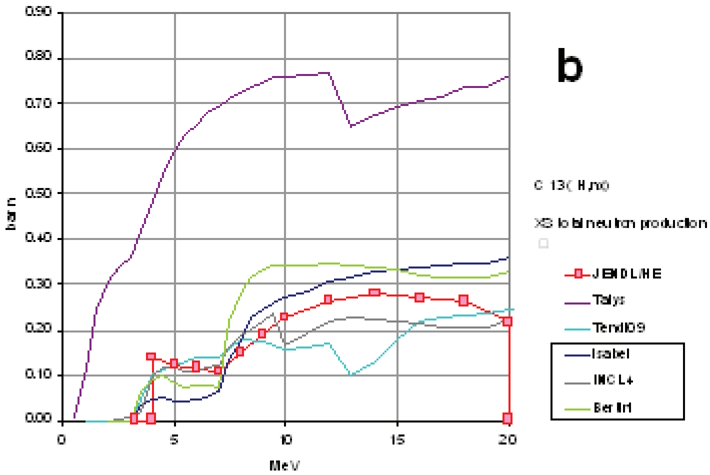


Table I.B2. C^{13} (H,nx): (a) Macroscopic XS from JENDL. (b) Built-in MCNPX vs TENDL & Talys & JENDL..

(III) RESULTS

The results of the simulations presented in this section are provisional. This fact is due to the ignorance of the current beam values for all the cases at the moment of writing this report.

The results for beam-on phase are presented in Table I.B4: neutron and photon production rate and the maximum value of the ambient dose equivalent.

The results on beam-off phase due to the activation for one week irradiation time, are presented only for iron target. The information presented includes the time evolution after shutdown for residual dose, photon production rate and the isotopic inventory.

Table I.B4. Results for double beams and for high energy proton beam (* values for a provisional current of 50 pA) (⊥ the values can be a poor estimation)

Fe	H	α	Total		H
	2.5 Mev 15 nA	10 MeV 4 nA			20 MeV 1μA
MAXIMUM DOSE (μSv/h)	450	97	547		7.66.E+06
NEUTRON SOURCE (n/particle source)	1.59E-08	8.98E-06			2.56E-03
PHOTON SOURCE (p/ particle source)	2.90E-07	6.10E-06			1.34E-02

SiO_2	H	α	Total		H
	4.6 Mev 0.2 nA	18 MeV 0.3 nA			20 MeV 1μA
MAXIMUM DOSE (μSv/h)	0	42	42		0.36E+06
NEUTRON SOURCE (n/particle source)	0.0	3.056E-05			1.20E-04
PHOTON SOURCE (p/ particle source)	3.54E-05	5.79E-05			8.34E-03

SiC	H	$\alpha^{\perp}$	Total		H
	4.6 MeV 3.5 nA	18 MeV 8.5 nA			20 MeV 1μA
MAXIMUM DOSE (μSv/h)	0	826	826		0.56E+06
NEUTRON SOURCE (n/particle source)	0	4.74E-05			1.72E-04
PHOTON SOURCE (p/ particle source)	0	1.94E-04			1.01E-02

W	H	α	Total		H
	1.6 MeV	6 MeV			20 MeV 1μA
MAXIMUM DOSE (μSv/h)	0	0	0		9.0E+06
NEUTRON SOURCE (n/particle source)	0	0			4.13E-03
PHOTON SOURCE (p/ particle source)	0	0			6.89E-03

C	$H^{\perp}$	$\alpha^{\perp}$	Total		$H^{\perp}$
	4.6 MeV	18 MeV			20 MeV 1μA
MAXIMUM DOSE (μSv/h)	0	6.11 *	6.11*		0.21E+06
NEUTRON SOURCE (n/particle source)	0	2.62E-05			9.87E-05
PHOTON SOURCE (p/ particle source)	0	3.82E-05			5.01E-03

SiC	D	α	Total
	6 MeV	18 MeV	
MAXIMUM DOSE (μSv/h)	7.57 *	4.86 *	12.43*
NEUTRON SOURCE (n/particle source)	6.74E-05	4.74E-05	
PHOTON SOURCE (p/ particle		1.94E-04	

III.1. Beam-on phase

The worst condition for radioprotection issues happens during beam-on phase and for the high energy proton beam (the values presented were calculated for a provisional current of 1µA). The contribution of the emerging photons to the total prompt dose was negligible for all the beam and materials (it is more than eight orders of magnitude lower than the dose due to the emerging neutron). With regard to the material target, the tungsten presents the worst behaviour and the dose arising from the iron target is slightly lower.

The dose rate fields arising from the nuclear interaction of 20 MeV proton beam (1µA) over tungsten target and over iron target are showed in Figure I.B8. The maximum value of the dose (located in the target) is higher than 7 Sv/h. These dose levels represent an important risk for health. Therefore it will be necessary to include a shielding to assure that the levels of doses reached are finally acceptable for workers and public.

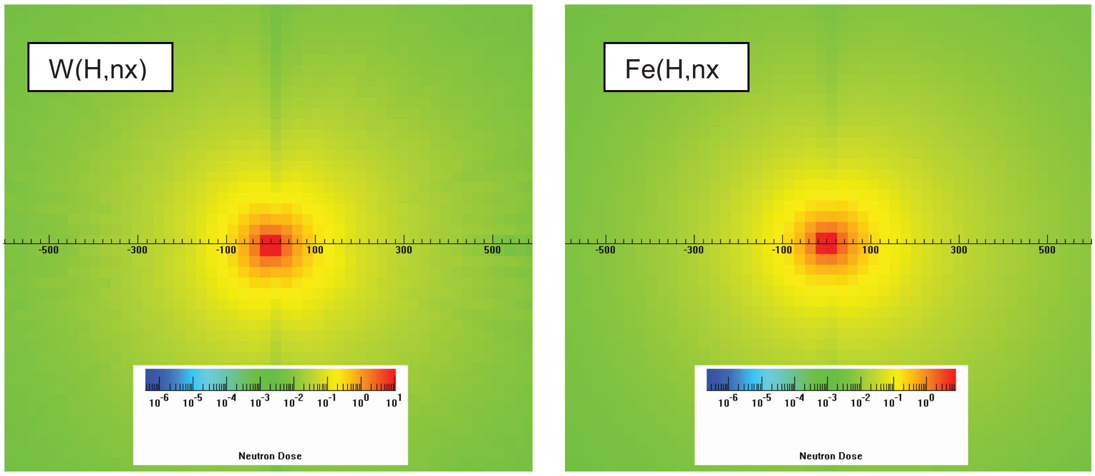


Figure I.B8. Dose field (Sv/h) for a 20 MeV H beam of 50 pA. (left) W(H,nx), (right) Fe(H,nx)

At the date of writing this report, the worst operation conditions for double-beam-on-phase cannot be identified. It is due to the fact that the current beam for some target is not known. The worst material from the point of view of the radioprotection implications is SiC and the safety zone (the distance necessary to reduce the dose to 10 µSv/h) is higher than 3 m from the target in the beam direction (Figure I.B9).

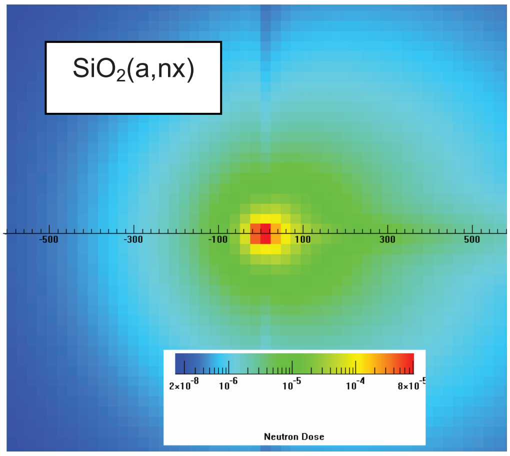


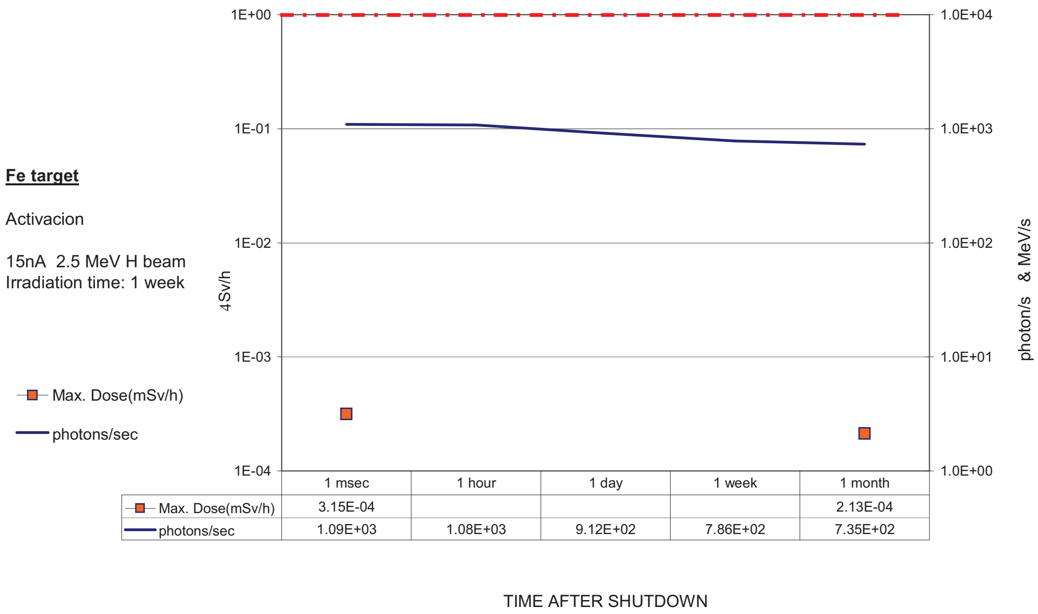
Table I.B9. Dose field (Sv/h): 18MeV - 8.5 nA

III.2 Beam-off phase

The following figures show the results on beam-off phase for the iron target. This preliminary study is a conservative assessment and it was done taking into account the activation due to uniform proton flux of energy equal to the energy beam in the whole volume. The volume of the material activated is 1cm^2 of area and a thickness equal to the maximum penetration of the proton for the energy of the beam. The irradiation time is 1 week.

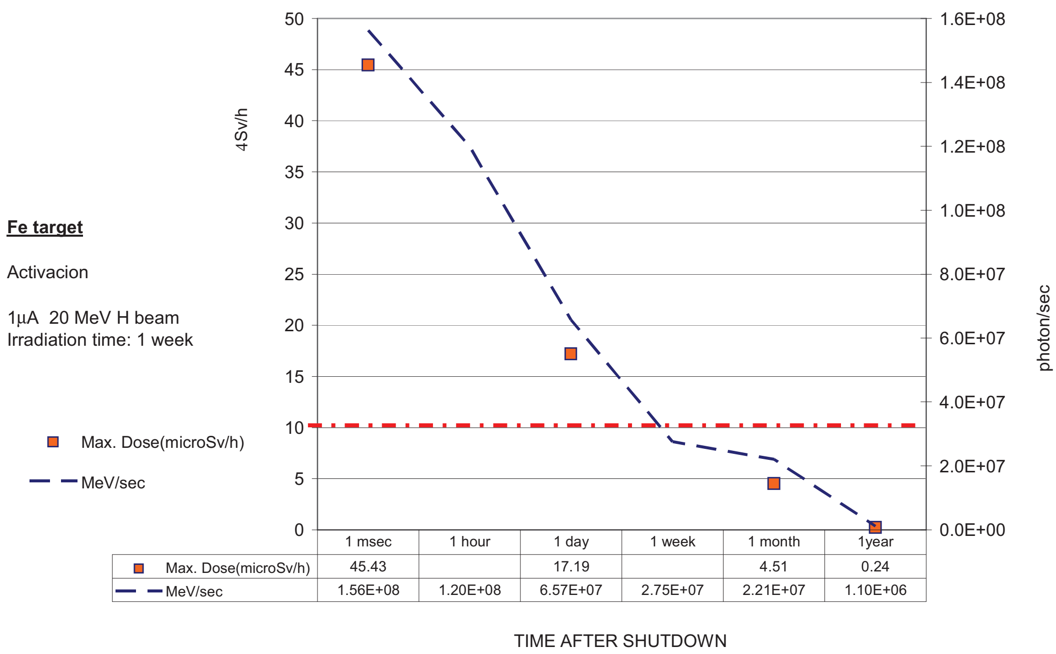
The maximum dose rate value using the MCUNED tool after 1ms and 1 month of cooling time with the proton beam (15 nA of 2.5 MeV) is showed in Figure I.B10. The arising photon source obtained with the ACAB code is included in this figure. The maximum value of the residual dose (located in the target) is lower than 3E-4 µSv/h. One hour after shutdown, the isotopic contributions to the total dose are: 76% Co^{55} (T1/2 = 17 hours), 15% Co^{58} (T1/2 = 79 days), 8% Co^{57} (T1/2 = 270 d). In any case, dose rate is negligible.

The maximum dose value using MCUNED for 1ms, 1day and 1 month of cooling time (10 µA and 20 MeV proton beam) is showed in Figure I.B10. The arising photon source obtained by ACAB are also included. The maximum value of the residual dose (located in the target) at 1 msec after shutdown is higher than 45 µSv/h. For one week of cooling time, the maximum value of the residual dose is lower than 10 µSv/h. The main contributor to the total dose, after 1 week after the shutdown, is Co^{56} (98%, half life 77 days).



	1 msec	1 hour	1 day	1 week	1 month
Max. Dose(mSv/h)	3.15E-04				2.13E-04
photons/sec	1.09E+03	1.08E+03	9.12E+02	7.86E+02	7.35E+02

Figure I.B10. Activation results for 15nA proton beam at 2.5 MeV on iron target.



	1 msec	1 hour	1 day	1 week	1 month	1year
Max. Dose(microSv/h)	45.43		17.19		4.51	0.24
MeV/sec	1.56E+08	1.20E+08	6.57E+07	2.75E+07	2.21E+07	1.10E+06

Figure I.B11. Activation results for 1µA proton beam at 20 MeV on iron target.

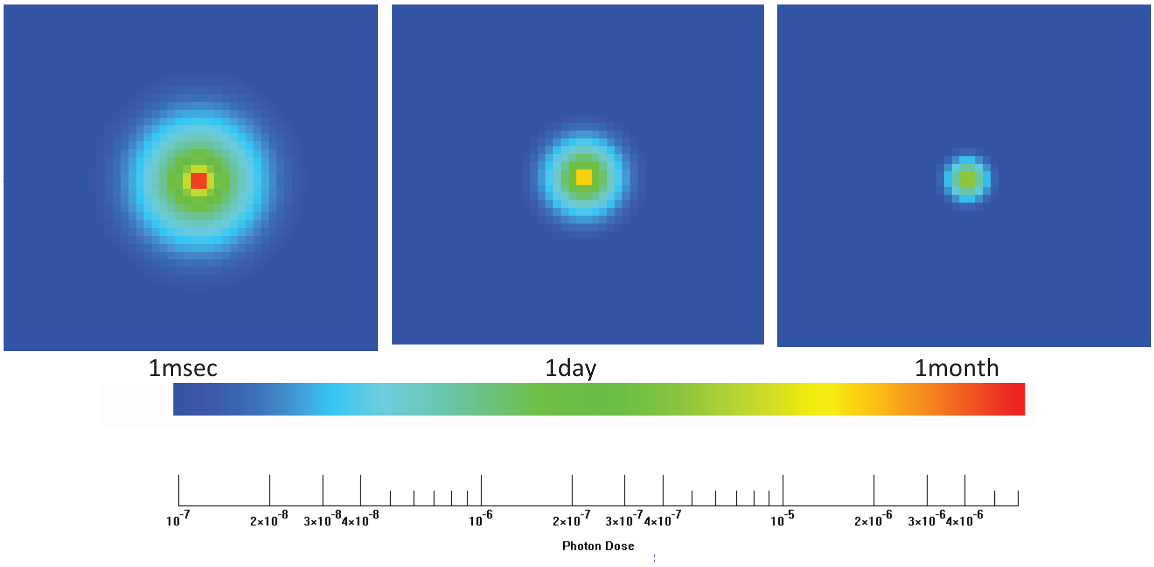


Figure I.B12. Dose field after 1ms, 1day and 1 month after the shutdown. The target is in the center of a vault, full air, of 6 meters of length in all the directions.

(IV) CONCLUSIONS

The MCNPX transport code is not reliable enough tool to predict prompt dose rates in *TechnoFusión* applications based on the use of alpha and deuteron beams.

The use of a new computational tool, an extension of the MCNPX code named MCUNED, allows a more accurate evaluation of the neutron production, and therefore, a more reliable prompt dose rate assessment for those cases where evaluated light-ion cross section libraries are available.

In cases where evaluated libraries are not available, experimental data, and some recent nuclear data compilations from the literature are used to determine the best built-in MCNPX model and to estimate the uncertainties in the calculations. If no evaluated data can be used for the very low energy proton, deuteron and alpha beam irradiations, there is no use in performing any MCNPX calculations.

One the main milestones of this report has been to propose a new methodology, MCUNED plus external evaluated data libraries generated by the Talys code, which is capable to provide better accuracy in the results of the radioprotection simulations for *TechnoFusión* accelerators. The MCUNED code has been recently verified and is now available to make future safety studies.

Regarding to dose rate results from irradiated samples, the values presented in this report are provisional since the values of the beam current are not known for all the cases. Therefore, final conclusions cannot yet be reached about several cases. At the state of this study, the worst condition concerning to radioprotection is obtained during beam-on phase. In the case of the 20 MeV proton irradiations, maximum values are higher than 9 Sv/h when irradiating tungsten and higher than 7 Sv/h for iron using provisional operation conditions of 1µA current. Dose rates during double-beam irradiations are found to be around one order of magnitude lower than those for 20 MeV proton irradiations. Maximum values are 826 µSv/h and 547 µSv/h for SiC and iron samples respectively.

Therefore, due to the significant values of the prompt dose rate around the irradiated targets, the preventive measures during beam-on phase, such as shielding definition, is an issue to be adressed.

Regarding to the dose rates around the irradiated target during beam-off phase, the study has been done only for iron target. The residual dose in the worst case, that is 20 MeV protons at shutdown and inside the target, is around 45 µSv/h. At shutdown and for a distance from the target around 50 cm the value decreases to less than10 µSv/h. For a cooling time of a week the residual dose rate in the target is also something less that 10 µSv/h.

The ongoing work is focused on the recalculation of dose rates for the problematic cases and on the improvement of the methodology limitations.

Current effort to increase the reliability of cross section libraries for *TechnoFusión* applications is based on benchmarking of Tendl libraries against differential and integral experiments and on the fitting of the libraries to the experimental data.

(V) REFERENCES

[EXFOR 2009] EXFOR Systems Manual, IAEA-NDS-207 (BNLNCS-63330-00/04-Rev.)

[ICRP-103, 2007] The 2007 Recommendations of the International Commission on Radiological Protection, Ann. ICRP 37(2-4), 2007.

[ICRP-74, 1996] Conversion Coefficients for Use in Radiological Protection, Ann. ICRP 26(3-4), 1996.

[JENDL, 2002] Japanese Evaluated Nuclear Data Library. http://wwwndc.jaea.go.jp/jendl/jendl.html

[Koning, 2007] A.J. Koning, S. Hilaire and M.C. Duijvestijn, “Talys-1.0”, Proc. of the Int. Conference on Nuclear Data for Science and Technology - ND2007, April 22-27 2007 Nice France editors O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray, EDP Sciences pp 211-214 (2008).

[Koning, 2008] A.J. Koning, D. Rochman. Consistent Talys-based Evaluated Nuclear. Data Library including covariance data (TENDL2008 http://www.Talys.eu/TENDL-2008/).

[Koning, 2009] A.J. Koning, D. Rochman. TENDL-2009beta: "TALYS-based Evaluated Nuclear Data Library http://www.talys.eu/TENDL-2009beta/).

[Mayoral, 2009] A. Mayoral, J. Sanz, P. Sauvan, D. López, M. García, F. Ogando. Relevance of d-D interactions on neutron and tritium productions in IFMIF- EVEDA prototype. ICFRM.14 Sapporo Japan 2009.

[NNDC] National Nuclear Data Center. Brookhaven National Laboratory. http://www.nndc.bnl.gov/

[Pelowitz, 2008] D.B. Pelowitz. Ed. MCNPX User's manual, Version 2.5.0, LA-CP-05-0369 (2005). User's Manual, Version 2.6.0, LA-CP-07-1473. J.S. Hendricks et al.: MCNPX 2.6.0 extensions, LA-UR-08-2216 http://mcnpx.lanl.gov (2008).

[Sanz, 2008] J. Sanz, M. García, F. Ogando, A. Mayoral, D. López, P. Sauvan, B.Brañas. First IFMIF/EVEDA radioprotection studies for the preliminary design of the accelerator beam dump. Fusion Science and Technology In press 2009

[Sanz, 2009] J. Sanz et al., ACAB: Inventory code for nuclear applications, User's manual v2008, NEA-1839 (2009)

[Sauvan, 2009] P. Sauvan, J. Sanz, F. Ogando, M. García, D. López, A. Mayoral, "MCUNED: an improved MCNPX code for deuteron transport. Internal Report, Departamento de Ingeniería Energética, UNED (2009)

[TechnoFusión, 2009] *TechnoFusión*. Informe Científico - Técnico del Centro Nacional de Tecnologías para la Fusión. (*TechnoFusión*). CIEMAT

[Tanaka, 1994] S. Tanaka, N. Yamano K. Hata, K., et al.: (Sumitomo Atomic Energy). ACSELAM library. http://wwwndc.jaea.go.jp/ftpnd/sae/acl.html

[Forrest, 2007] R.A. Forrest, J. Kopecky, J.-CH. Sublet, 'The European Activation File: EAF-2007 deuteron and proton-induced cross section libraries", UKAEA FUS 536 (March 2007)

[Forrest, 2007] R.A. Forrest, J. Kopecky, J.-CH. Sublet, 'The European Activation File: EAF-2007 neutron-induced cross section libraries", UKAEA FUS 535 (March 2007)