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The multi-ion-irradiation Laboratory of TECHNOFUSIÓN Facility and its relevance for fusion applications

D. Jiménez-Rey[1], R. Vila[2], A. Ibarra[3], F. Mota[4], Christophe J. Ortiz[5], J. L. Martínez-Albertos[6], R. Román[7], M. González[8], I. García-Cortes[9], and J. M. Perlado[10]

[1] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, d.jimenez@ciemat.es.

[2] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, rafael.vila@ciemat.es.

[3] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, angel.ibarra@ciemat.es.

[4] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, fernando.mota@ciemat.es.

[5] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, christophe.ortiz@ciemat.es.

[6] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, albertos@ciemat.es.

[7] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, raquel.roman@ciemat.es.

[8] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, maria.gonzalez@ciemat.es.

[9] Laboratorio Nacional de Fusión-CIEMAT, Av. Complutense 22, 29040, Madrid, Spain, isabel.garciacortes@ciemat.es.

[10] IFN, ETSII, Universidad Politécnica de Madrid, P. de la Castellana, 28006, Madrid, Spain, mperlado@din.upm.es

Correspopnding Author:
Name : David Jiménez-Rey
Postal address : CIEMAT, E2.P0.28k,
Avenida Complutense, 22, 28040 Madrid.
Telephone number : +34 91 3466578
Fax number : +34 91 3466068
E-mail address : d.jimenez@ciemat.es

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[1] Laboratorio Nacional de Fusión, CIEMAT, Av. Complutense 22, 29040, Madrid, Spain
[2] IFN, ETSII, Universidad Politécnica de Madrid, P. de la Castellana, 28006, Madrid, Spain

Abstract

Thermonuclear fusion requires the development of several research projects, in addition to ITER, related to the advancement of technologies needed for future fusion reactors. Among the priority areas identified in the framework of international fusion programmes, TechnoFusión will focus on the following fields: i) the evaluation of radiation effects on structural and functional materials, ii) the development of robotics and automated systems for remote handling, iii) advanced manufacturing technologies, iv) liquid metal technologies, v) plasma-wall interaction, and vi) computer simulations.

In particular, the TechnoFusión Area of Irradiation of Materials aims at simulating the effects of neutron irradiation on materials by a combination of ion beams. This article justifies this approach using some computer simulations.

Therefore, this irradiation facility will investigate the effects of high energetic radiations on reactor-relevant materials. On a second stage, it will also be used to analyze the performance of such materials and to design new ones.

Keywords: (Fusion, Irradiation Facilities, Ion Irradiation Damage, Test Fusion Technologies)

1. Introduction

Structural materials of future fusion reactors will be exposed to a particular hostile environment as a consequence of the intense radiation created during the nuclear reaction. The hot plasma inside the reactor will generate an important flux of high-energy neutrons, gamma radiation and particles, which will affect especially not only the materials on the first wall of the reactor, but also to other distant equipments such as plasma heating or diagnostic systems. Ionizing radiation, via atomic displacement phenomena and ionizing processes, will be able to produce a number of defects in the structure of the materials, affecting their physical properties at different scale. In addition, the nuclear reactions induced by the neutrons will generate transmutation products (impurities) that will contaminate the material, modifying its physical properties, and therefore, endangering 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 those properties.

The effect of neutrons on the 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 the rising of impurities inside the materials, being He and H the most important ones. It is well known that the effect of neutrons can be represented by irradiating simultaneously with He, H and heavy ions capable of creating point defects [1, 2, 3].

The new TechnoFusión facility will contribute to the neutron damage study by means of the Area of Irradiation of Materials (AIM), using multi-irradiation ion facilities. An in-depth study has been done in this area to demonstrate and optimize the use of ion accelerators to reproduce a damage evolution that mimics the expected one in fusion devices (target damage plus helium and hydrogen production). The AIM scheme consists of three different ion beams to irradiate samples with high energies.

2. TechnoFusión

The Scientific-Technical Facility of the National Centre for Fusion Technologies, TechnoFusión, will bring together the required infrastructures to develop the technologies needed for future commercial fusion reactors [4]. TechnoFusión aims at exploring the extreme conditions that reactor components will experience, and their expected properties, enabling the following research areas: i) *Material Production and Processing* with advanced manufacturing technologies, ii) *Area of Irradiation of Materials* to analyse the radiation effects on structural and functional materials using ion and electron accelerators, iii) *Plasma-Wall Interaction* to study the thermal loads and atomic damage mechanisms by using a plasma linear device in consonance with a quasi-stationary plasma accelerator (QSPA), iv) *Liquid Metal Technologies*, proposed as important technology in some fusion concepts, v) *Material Characterization* with a set of advanced characterization techniques for the material damage evaluation vi) *Demonstration Facilities for Remote Handling* for equipment in fusion environments, and vii) *Computer Simulation* with predictive analysis codes for the experiments carried out in TechnoFusión Facility.

3. Area of Irradiation of Materials (AIM)

Area of Irradiation of Materials (AIM) of TechnoFusión will be a relevant user-facility for the selection of functional materials. AIM will incorporate three ion accelerators: two for light ions (H and He), and one for heavy ions (Fe, Si, C, others) for implantation. The ion energies for the different ion accelerators are shown on Table 1. The effect of neutron radiation on candidate materials for ITER and DEMO will be simulated by a simultaneous triple ion beam irradiation. In addition, this facility will include a high magnetic field (up to 10 T) to evaluate the combined effects of radiation and magnetic fields.

3.1. Objetives

The main goal of AIM is to test and to 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 R&D in the material field is to demonstrate that a combination of heavy and light ions (in terms of microstructure and impurities) can produce similar damage to those expected to be produced by neutrons in a fusion reactor. Once evaluated and selected the most suitable implanters, the next objective of AIM will be to irradiate samples homogeneously over a large area and 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 the material with ions of the same species (e. g., irradiation of Fe with Fe ions), alongside with a simultaneous double implantation with light ions (H and He). This triple irradiation solution is expected to produce the same amount of defects and the same amount of light ions (via H and He implantation) that are expected to be reached under neutron irradiation in the fusion facilities.

II. Irradiation with 40 and 70 MeV protons to produce 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 displacements. On the other hand, protons are able to produce H and He in the material by nuclear transmutations, similarly to neutrons. The energy required to achieve this was estimated by means of SRIM code [6]. In addition, this method presents the important advantage of achieving, in an easy way, the implantation over large thicknesses (in the millimeter range), much larger than those accessible with ion implantation.

This article describes the analysis of the intensities of the ion beams and of the protons needed to generate the same damage on materials as neutron beams, as expected in nuclear fusion facilities. The main factors taken into account are the following: i) the minimum beam energy needed for the required penetration into the material; ii) the homogeneity of the beam damage along the whole penetration range; iii) maintaining an accurate ratio between the concentration of light ions over the damage, as generated in a fusion facility; and iv) the reproduction of an accurate spectrum of the Primary Knock-on Atoms (PKA).

3.2. Methodology and Results

The primary technique was the irradiation of a target with ions of the same chemical species with the goal of avoiding the implantation of any impurity. The typical system was iron ions on an iron target. To emulate the damage created by neutron irradiation, the calculations must bear in mind that the damage is homogeneous along the penetration depth. Table 1 shows the maximum energies, and the penetration ranges of the ions considered for irradiation, as a function of the target species. The last four columns show the maximum light ion energies needed to implant those 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].

The energies shown on Table 1 and the vacancy profiles for each ion determine the three different intensities (heavy ions and light ions) needed to generate the damage equivalent to that caused by neutrons. The intensity of the heavy ions (see Table 2) was calculated to obtain a damage of 1 dpa per week, which is similar to the damage estimated [7] in a nuclear fusion environment.

Table 3 displays these two intensities for each of the light ions (H and He). 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].

Figure 1 shows the ratio of produced He (in appm of He) over the damage (in dpa) in the process of irradiating a Fe target with Fe ion 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.

An additional factor to be taken into consideration to ensure the accuracy of the simulation of neutron damage by other means is the PKA spectrum: up to now, the only parameter considered was the total damage. The PKA spectrum describes how the damage is actually 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*:

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

where $\sigma_{PKA}(T)$ is the PKA spectrum, $N_d(T)$ is the number of Frenkel pairs 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. 1.

The damage functions generated in iron by Fe ions of 500, 300 and 50 MeV are shown on Figure 2, and are compared with those expected in IFMIF test cell facility [7]. This graph shows that ions with higher energy become closer to the actual calculations for IFMIF damage area.

The second irradiation approach to study the neutron damage is based on the irradiation of protons. SRIM and Marlow codes were also used to calculate the damage function generated by protons with energies of 40 and 70 MeV. And it can also be seen on Fig. 3 that these damage functions are very close to those calculated for IFMIF.

Table 4 shows the ratios appm He/dpa calculated for iron targets using cross sections for the generation of He by transmutation [11]. In this method, these ratios are higher than those expected for fusion experiments, while the damage functions are closer to IFMIF expected results than those obtained by the triple irradiation method.

This table shows that 70 MeV protons generate too many He atoms, creating a lot more nuclear activation on the sample. Therefore, 40 MeV-protons seem a much better option for simulating the neutron damage. 20 MeV protons seem to be a suitable candidate given the very reduced nuclear activation and the limited generation of He atoms, much closer to that of a fusion facility.

4. Conclusions (or Summary)

Triple beam irradiation and proton irradiation are good candidates to simulate the damage on materials by neutrons in a nuclear fusion facility.

TechnoFusión´s Area of Irradiation of Materials 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.

Acknowledgements

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Table 1. Ion energies that will be used in the AIM assuming a He energy inferior or equal to 12 MeV (tandem at 6MV terminal voltage and charge states of -1 and +2).

		Heavy ion accelerator Cyclotron k=110		**Light ion accelerator 4MV**		**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	C	96	H	4.5	He	18
SiO_2 (2.2 g/cm^3)	175	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	4.6	He	18

D. Jiménez-Rey, one column

Table 2. Target intensities for each ion species in the cyclotron planned for the TechnoFusión AIM facility. Particle intensities data in nanoAmps/sec for each single charged ion.

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

D. Jiménez-Rey, one column

Table 3. Target intensities for each ion species in the tandem linear accelerators planned for the TechnoFusión AIM facility. Particle intensities data in nanoAmps for each single charged ion.

	Ion Currents (pnA)
H	50 – 100
D	~ 10
He	50 – 100

D. Jiménez-Rey, one column

Table 4. He/dpa relations obtained by computer simulations with protons at 40 and 70 MeV in fusion facilities.

	He/dpa
Fusion	11
40 MeV	33
70 MeV	70

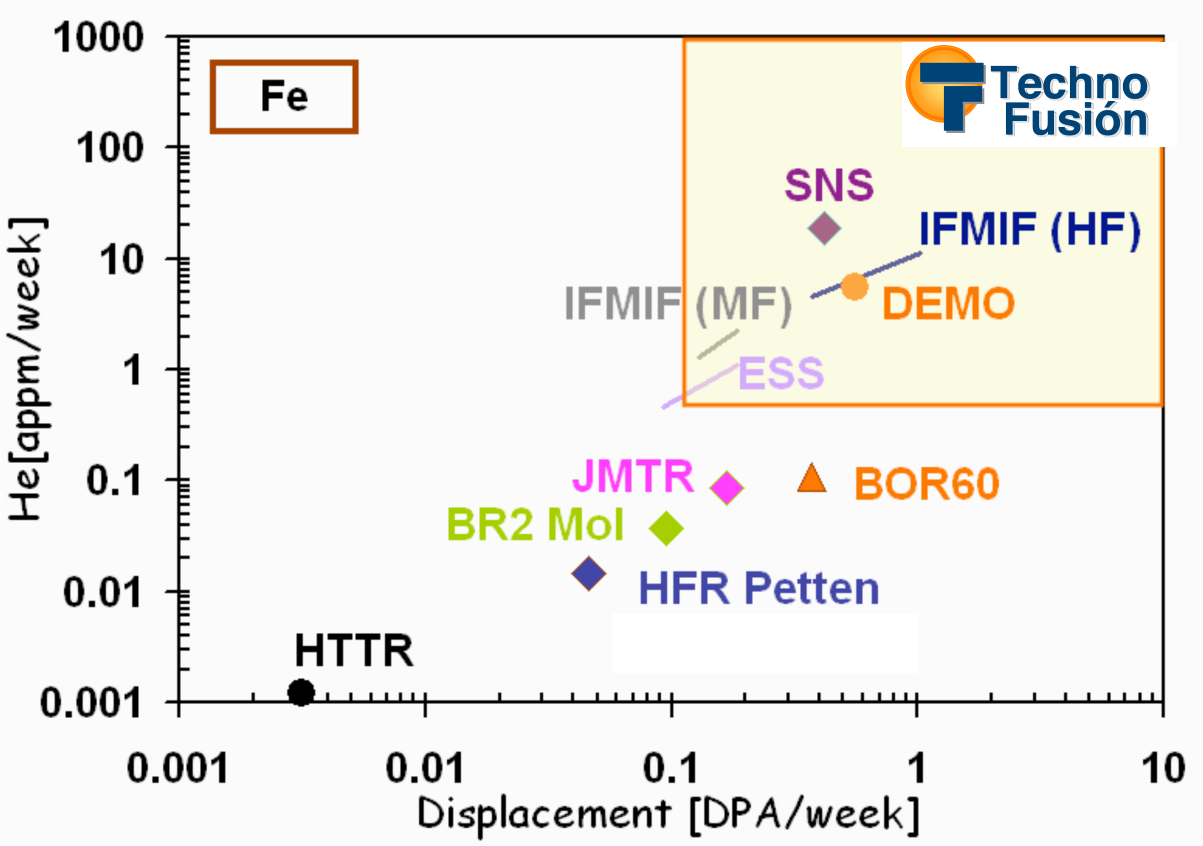
D. Jiménez-Rey, one column

Figure captions

Fig. 1: 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.

Fig. 2: Damage function generated in Fe material by Fe ions of 50, 300 and 500 MeV. Comparison with the results from IFMIF. The acronyms HFTM and LFTM are related to two different neutron spectra at the planned IFMIF facility.

Fig. 3: Damage function generated in Fe material by protons of 40 y 70 MeV. Comparison with the results from IFMIF.



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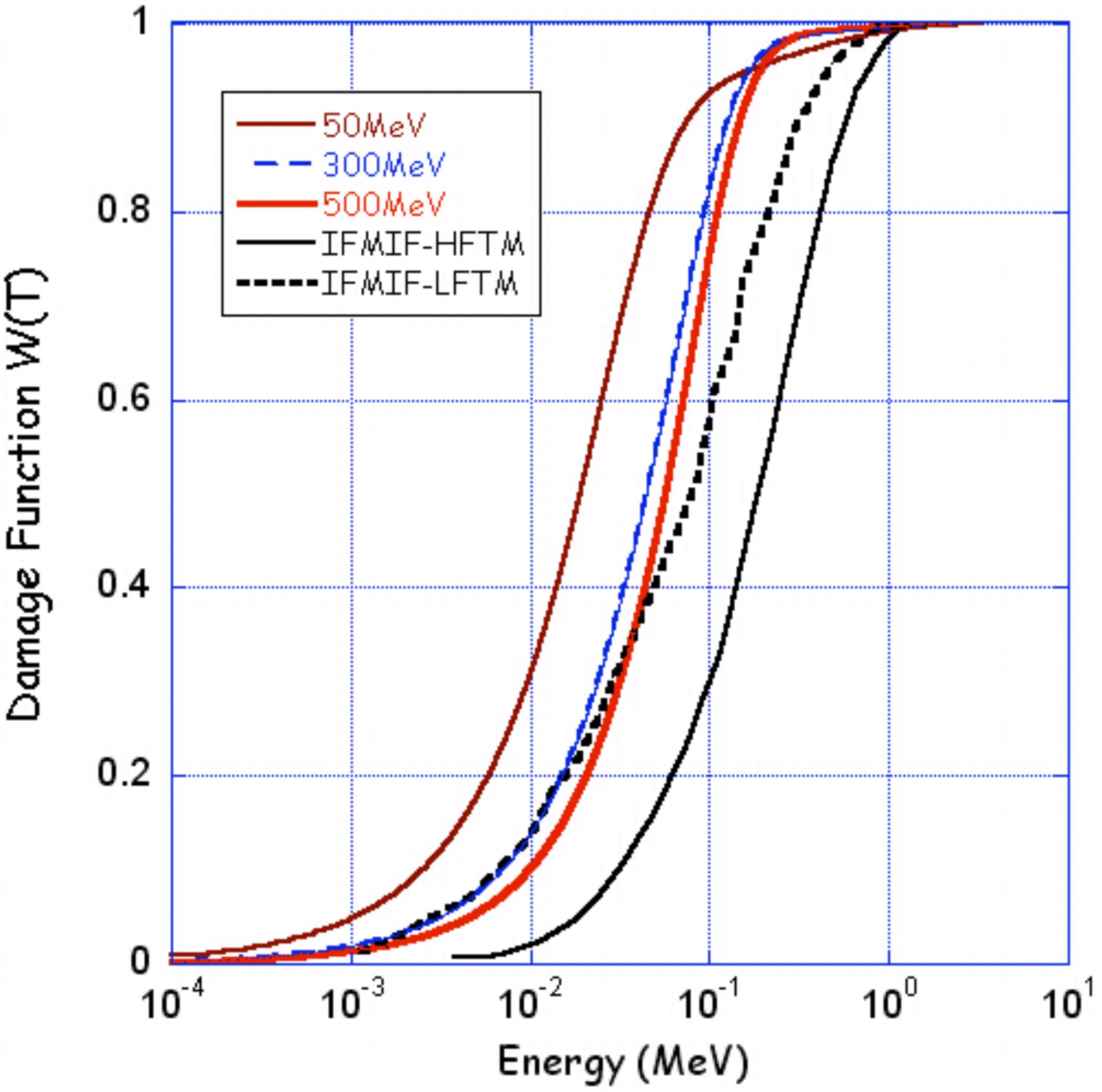

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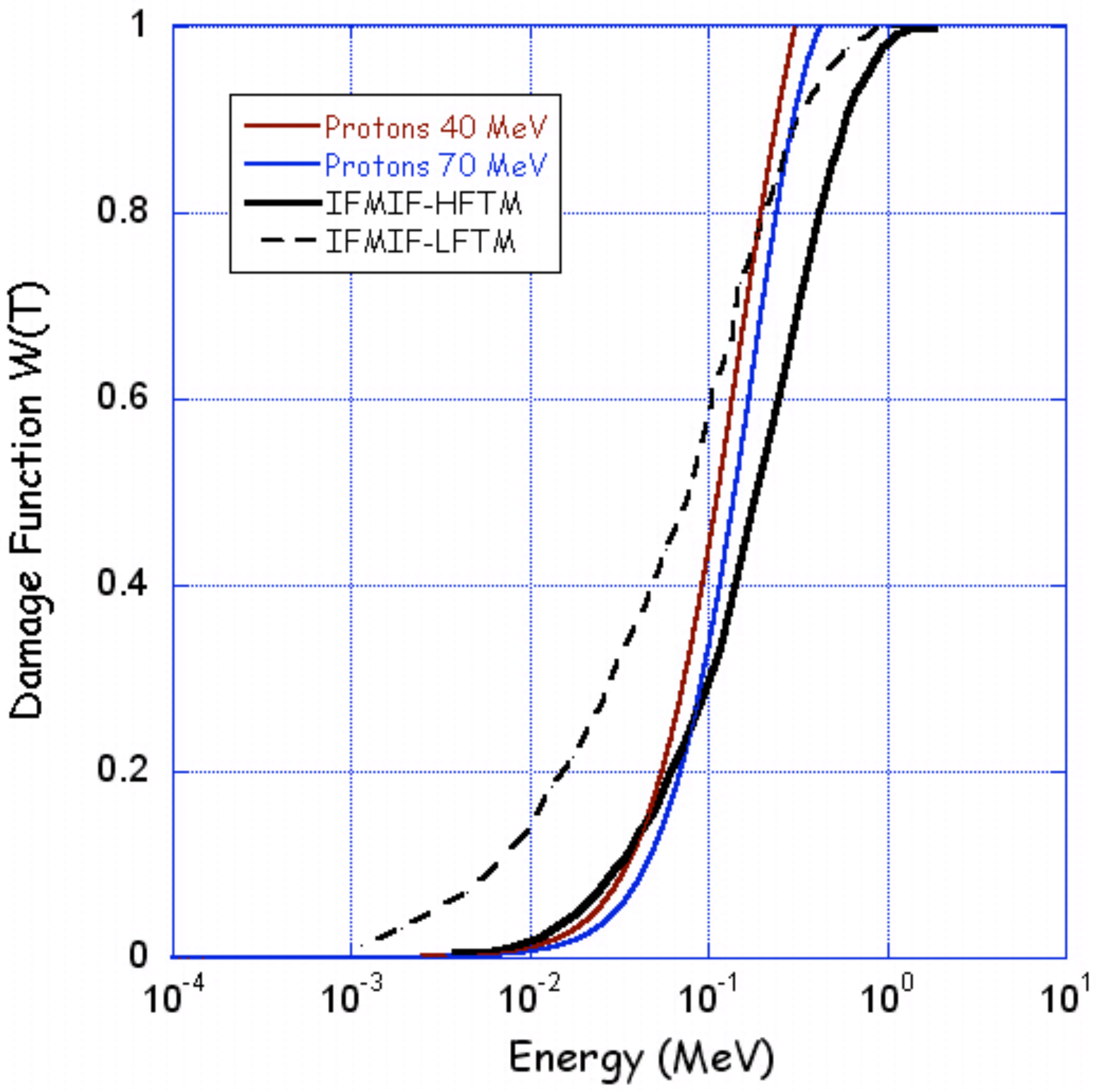

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