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Potential irradiation of Cu alloys and tungsten samples in DONES

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Tungsten and Cu alloys are currently proposed as reference candidate material for ITER and DEMO first wall and divertor. Tungsten is proposed for its high fusion temperature and CuCrZr alloys for their high thermal conductivity together good mechanical properties. However its behaviour under the extreme irradiation conditions as expected in ITER or DEMO fusion reactors is still unknown. Due to the determinant role of H and He played in the material behaviour any irradiation experiment must take into account the important amount of these gases produced during the irradiation in Fusion reactors with high-energy neutrons.

DONES (DEMO Oriented Neutron Source) has been conceived as a simplified IFMIF (International Fusion Material Irradiation Facility) like plant to provide in a reduced time scale and with a reduced budget – both compared to IFMIF - the basic information on materials damage. The objective of DONES-IFMIF in its first stage will be to test structural materials under similar neutron irradiation nuclear fusion conditions as expected in fusion reactors. These tests will be carried out in specimens irradiated in the so called High Flux Test Module (HFTM).

The objective of this paper is to assess on the potential use of DONES to irradiate Copper (Cu) alloys and Tungsten (W) in the HFTM together with other stainless steel based materials. The presence of Cu alloys or W specimens may have an effect in the irradiation parameters of the stainless steel samples placed also in the HFTM and in the samples of the Creep Fatigue Test Module (CFTM).

McDeLicious code is used for neutron transport calculations. Damage dose rate and H and He production are analysed in the different locations and compared with the actual irradiation conditions in first wall and divertors in fusion machines.

Keywords: IFMIF, DONES, Early Neutron Source (ENS), Nuclear Fusion, divertor

1. Introduction

The divertor of the future DEMOnstration Power Plant (DEMO) must be designed to withstand the high heat and particle fluxes from the plasma. Suitable concepts are available and will be tested on ITER and, if successful, extrapolated to DEMO. The fast neutrons from the fusion reaction activate and damage divertor and blanket, so that these components must be periodically replaced. To avoid too frequent replacements, the divertor and blanket materials must be resistant to neutron bombardment. The strike point area of the divertor will be exposed during normal operation conditions to heat fluxes up to 20 MW/m^2 and up to several GW/m^2 during transient events such as disruptions and Edge Localised Modes (ELMs) [
1, 2].

Therefore, with the aim to withstand the high heat and particles from plasma fluxes, Cu-alloys and tungsten are candidate materials foreseen for the first wall and divertor of ITER and DEMO, Tungsten for its ability to withstand erosion and high temperature and the Cu-alloys for its ability to remove a large quantity of heat. In fact tungsten has been selected as one of potential Plasma Facing Materials (PFMs) for its high melting point, excellent stability at elevated temperature, good thermal conductivity, excellent anti-plasma sputtering and low Tritium retention [3]. On the other hand, due to their high strength up to ∼400 °C, good ductility, high thermal and electrical conductivity along with their commercial availability, precipitation hardened CuCrZr alloys have been chosen as heat-sink materials for International Thermonuclear Experimental Reactor (ITER) high heat flux (HHF) components such as the divertor, limiter and first wall of the reactor vacuum vessel [4, 2, 5, 6]. Moreover, they exhibit higher fracture toughness and high resistance to radiation damage, allowing them to be good candidates for heat sinks in HHF applications in the baseline design of the prototype power plant DEMO [7, 8, 9].

Besides, the power necessary to maintain plasmas at high temperatures is ultimately exhausted in a narrow region of the reaction chamber called divertor. The need to withstand large heat loads led the development of plasma facing materials and exhaust systems that should be adequate for ITER. However, the development of an adequate solution for the much larger **heat exhaust** of DEMO is still a challenge.

It is well known that the displacement damage induced by neutrons depend strongly on the neutron spectrum, the neutron flux and the material irradiated. Thus, under different neutron irradiation conditions the materials suffer different displacement damage. Furthermore, the displacement damage represented by the damage dose rates does not take into account other process related with the diffusion process on the bulk of materials such as recombination, migration, agglomeration, etc. The nuclear fusion roadmap requirements for the early neutron source regarding the damage dose rate are: 10 dpa/fpy for iron, 5 dpa/fpy for Cu-alloys, and 1 dpa/fpy for tungsten [2]. However, the ratio between the levels of He and H, and the amount of point defects is also essential to understand the effect of the radiation on materials [10].The damage dose rate has a direct impact on the amount of primary displacement damage induced by neutrons and the helium and hydrogen production by transmutation have a direct impact on the diffusion of defects and the damage evolution tracks. Therefore, in order to be able to design equivalent irradiation experiments, it is essential that the gas production to damage dose ratios would be similar to the nuclear fusion reactors ones. For stainless steels in the first wall of a future DEMO, the He and H ratios expected are about 10 He appm/dpa and 40 H appm/dpa [11, 12, 13]. Furthermore, He and H ratios suffered by CuZrCr-alloy and Tungsten material in the divertor area of a DEMO are calculated in this work in a neutronic model of DEMO-DCLL (Dual Cooland Lithium Lead) concept.

On the one hand, fission neutron sources, which show an average energy around 1 -2 MeV, cannot adequately reproduce the nuclear fusion irradiation conditions since the transmuted He production rates are far from nuclear fusion reactor (currently about 0.3 appm He/dpa) [14, 15]. On the other hand, the spallation sources produce a neutron spectrum with long tails achieving hundreds MeV range generating light ions as transmutation products which induce measurable changes of the material properties above 10 dpa and about one order of magnitude higher appm He/dpa than the produced by the nuclear fusion neutrons. This situation, besides the fact that the pulsed nature of the spallation sources and that the known difficult control temperature in the irradiation specimens [16] suggest that spallation neutron sources are not adequate to emulate the materials degradation process occurring in nuclear fusion power plants. The uncertainties associated with the impact of these high gaseous concentrations and those solid transmutation rates give the greatest drawback in the utilization of spallation source for fusion materials studies [14].

In this framework is where IFMIF-DONES (DEMO Oriented Neutron Source) [17, 18] plays an important role in order to test materials under similar neutron nuclear fusion irradiation condition. But, as the irradiation requirements of High Flux Test Module (HFTM) [19] of IFMIF-DONES were designed to reproduce the nuclear fusion irradiation condition for stainless steel samples, in this work the potential use of the HFTM to test Cu-alloys and tungsten under similar nuclear fusion irradiation conditions is addressed, i.e. to verify whether design equivalent nuclear fusion irradiation condition is possible.

Neutron transport calculations have been performed to assess the radiation effects in the irradiation area of IFMIF-DONES. First, the irradiation effect requirements of the Fusion Roadmap [2] have been crosschecked with neutron transport calculation in the divertor area of a DEMO-DCLL concept. Then, in order to evaluate the potential use of HFTM of IFMIF-DONES to test materials involved in the divertor technology several response functions have been evaluated and compared with the values obtained in the divertor area of a DEMO-DCLL. The irradiation parameters evaluated are the following:

- Damage dose rate [dpa/fpy];
- He and H production [appm/fpy]; and,
- He and H production to damage dose ratio [appm/dpa].

In the section 2 IFMIF-DONES vessel and the irradiation area characteristics are briefly shown. In Section 3, the methodology used to develop the neutron transport calculations in the divertor area of a DCLL DEMO model [20, 21] and in the Test Cell of the IFMIF-DONES is explained. Next, in Section 4, with the objective to crosscheck the damage dose rate nuclear fusion roadmap requirements, nuclear transport calculation have been performed to analyse the irradiation effects in iron, tungsten and Cu-Alloys in the divertor area of a DEMO-DCLL. In Section 5, neutron transport calculations to assess the radiation effects in the HFTM-DONES area are shown. Finally, in section 6 the conclusions are exposed.

2. IFMIF-DONES (DEMO Oriented Neutron Source)

IFMIF-DONES is been designed to test materials under similar neutron irradiation condition than nuclear fusion reactors. It has been conceived as a simplified IFMIF-like plant [22] to provide in a reduced timescale and with a reduced budget the basic information on materials damage. Then, the Conceptual Design of IFMIF-DONES will consist on a number of changes oriented to reduce the time required for construction and for producing the required damage. It will consist of only one accelerator with the same performances as IFMIF (40 MeV and 125 mA). The deuteron beam will impinge on lithium jet with a scale 1:1 of IFMIF in order to produce the neutron source with the appropriate energy spectrum to test materials for DEMO

[7]. A CAD model of the test cell of the future Early Neutron Source (ENS) DONES is show in **Figure 1**.

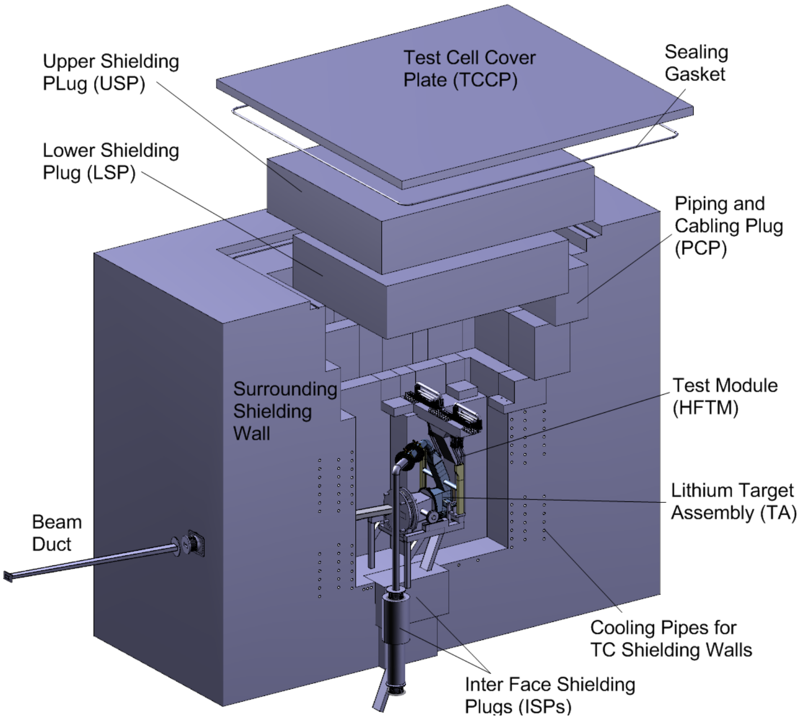

Figure 1.- Vessel of the IFMIF-DONES, in which is observed the Test Cell

As it has been previously mentioned, only the volume with the higher dose rate will be used in IFMIF-DONES to irradiate structural materials: a high flux area of about 0.5 litre and a neutron fluence of typically 10^{17} n/m^2/s, inducing up to 20 dpa/full power year (iron equivalent) in the materials are foreseen. In Figure 2 the current CAD design of the HFTM [19, 23, 24] assembly and the irradiation rigs with specimen is shown. In the beam footprint region, the HFTM is built from a thin walled container divided into 8 compartments, and 3 rigs can be placed on each of them (a total of 24 rigs, 720 cm^3 volume available for specimens). The beam footprint (20 x 5 cm) where neutron flux gradients and flux levels are optimum for high quality irradiation experiments cover the central four compartments (12 central rigs, 360 cm³ volume available for specimens). [25].

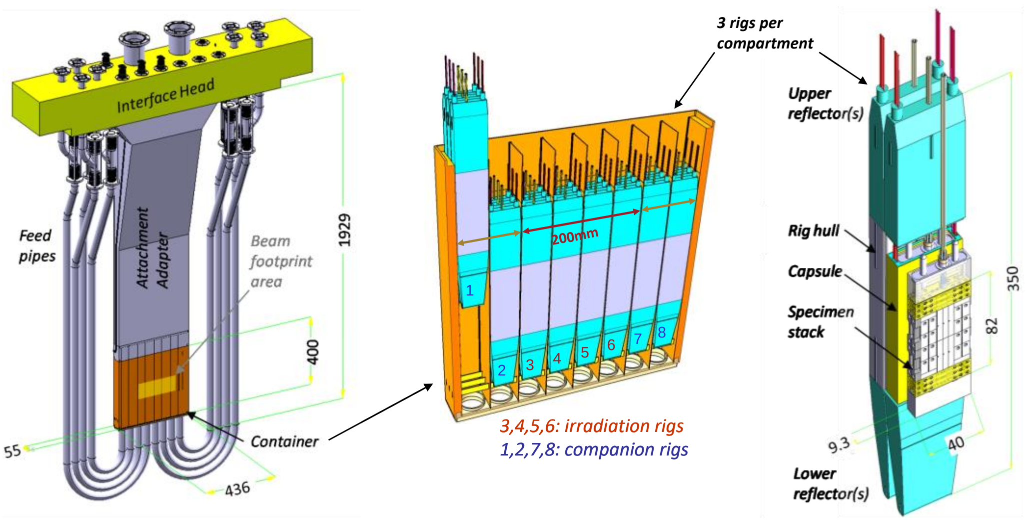

Figure 2.- Structure of HFTM, Left: High Flux Test Module assembly. Center: HFTM container with 8x3 rigs. Right: three irradiation rigs, consecutively stripped of layers to show the rig hull, the capsule and the specimen stack inside (the dimensions are expressed in "mm") [19,25]

3. Methodology for neutron transport

Neutron transport calculations have been performed in both IFMIF-DONES irradiation area and the divertor area of a DEMO-DCLL concept with the aim to compare the results. For both facilities, in order to make coherent the comparison the calculations have been performed using the same MCNP5 Monte Carlo code and the same nuclear data libraries FENDL3.1b for neutrons and mcplib84 for photon transport simulation.

As commented above, the irradiation parameter calculated to evaluated the radiation effects are the damage dose rate, the He and H production and the He and H ratios. The response functions considered for this study (damage dose rate, H and He production) are obtained by multiplying the neutron flux averaged in each cubic bin by response functions, i.e. the energy-dependent gas production cross sections and displacement production cross section. Once the response function per emitted particle is obtained, it is integrated for a full-power year. The definition of full-power year (fpy) is continuous operation for 24 h a day and 365 d with a beam current of 125 mA.

The methodology used to calculate it is the Norget, Robinson, Torrens (NRT) model [26]. The effective threshold displacement energies used for the different material assessed are: E_{Fe} = 40 eV [27], E_{Cu}= 30 eV [28] and E_{w}= 128 eV [29, 30].

Regarding gas production calculation by transmutation reaction, the He and H production has been calculated integrating the neutron spectrum with the specific cross sections MT=203 for H production and MT=207 for He production.

The isotopic composition for CuZrCr-alloy and Tungsten are shown in table 1 and 2, respectively.

Table 1.- CuZrCr-Alloy-IG isotopic composition. [31]

Isotopes	Weight[%]	Density[gr/cm3]	Density atoms/cm3
Cr 50	0.033	2.876E-03	3.47E+19
Cr 52	0.628	5.539E-02	6.42E+20
Cr 53	0.071	6.280E-03	7.14E+19
Cr 54	0.018	1.567E-03	1.75E+19
Zr	0.110	9.695E-03	6.40E+19
O 16	0.030	2.644E-03	9.96E+19
Co 59	0.060	5.288E-03	5.40E+19
Si 28	0.010	8.941E-04	1.92E+19
Si 29	0.001	4.547E-05	9.45E+17
Si 30	0.000	2.996E-05	6.02E+17
Cu 63	68.505	6.038E+00	5.78E+22
Cu 65	30.534	2.691E+00	2.50E+22
Total	100.000	8.814	8.376E+22

Table 2.- Tungsten isotopic composition [32]

Isotopes	Weight %	Density [gr/cm3]	Density [atoms/cm3]
C 12	9.89E-05	1.91E-03	9.58334E+19
C 13	1.07E-06	2.07E-05	9.56777E+17
W 80	1.20E-03	2.31E-02	7.74494E+19
W 83	2.65E-01	5.11E+00	1.69155E+22
W 84	1.43E-01	2.76E+00	9.08444E+21
W 86	3.06E-01	5.91E+00	1.93455E+22
O 16	2.84E-01	5.48E+00	1.77572E+22
O 17	9.98E-05	1.93E-03	7.24759E+19
O 18	3.80E-08	7.33E-07	2.59839E+16
N 14	2.05E-07	3.96E-06	1.32389E+17
N 15	9.96E-05	1.92E-03	8.27258E+19
Ni 58	3.68E-07	7.10E-06	2.85185E+17
Ni 60	6.81E-05	1.31E-03	1.3644E+19
Ni 61	2.62E-05	5.06E-04	5.08046E+18
Ni 62	1.14E-06	2.20E-05	2.17224E+17
Ni 64	3.63E-06	7.01E-05	6.81433E+17
Si 28	9.26E-07	1.79E-05	1.68118E+17
Si 29	9.22E-05	1.78E-03	3.82898E+19
Si 30	4.68E-06	9.04E-05	1.87722E+18
Si 54	3.09E-06	5.96E-05	1.19619E+18
Fe 54	5.85E-06	1.13E-04	1.25823E+18
Fe 56	9.18E-05	1.77E-03	1.90461E+19
Fe 57	2.12E-06	4.09E-05	4.32142E+17
Fe 58	2.82E-07	5.44E-06	5.65186E+16
	100	1.93E+01	6.35144E+22

4. Neutronic Analysis of the DCLL DEMO divertor

In this section the neutron transport calculations performed in a DEMO-DCLL concept are shown. The analysis of the radiation levels in a representative DEMO divertor has been performed over the DEMO baseline 2014 design [20, 21] which is made by16 sectors of 22.5º (given by the number of Toroidal Field Coils), each one equipped with 3 ports (Equatorial, Lower and Upper Port), 3 divertor cassettes, 3 Outboard and 2 Inboard Blanket segments. The plasma, power of 1572 MW corresponding to a 5.581×10^{20} n/s source. An ITER-like single-null divertor configuration with the divertor cassette at the bottom of the VV was initially considered **Figure 3**[20]. For the neutronic studies, an MCNP 11.5º half sector of the 360º torus tokamak has been used with reflective boundary conditions on the lateral sides to take into account full 3D transport. The MCNP model was developed with support of Spaceclaim software [33] for the handling of the 3D CAD model and SuperMC code [34, 35] for the conversion into MCNP format.

The responses under study are gas production (helium and hydrogen production in atomic part per million) calculated in a full power year (appm/FPY); displacement per atom in a full power year (dpa/FPY) and their ratios: He/dpa and H/dpa.

The results are provided as 3D maps obtained through the "mesh tally" capability of MCNP5 in the divertor area. The mesh area has been subdivided in 84x60x70=352800 voxel (elements of volumes) of 5 cm^3 each.

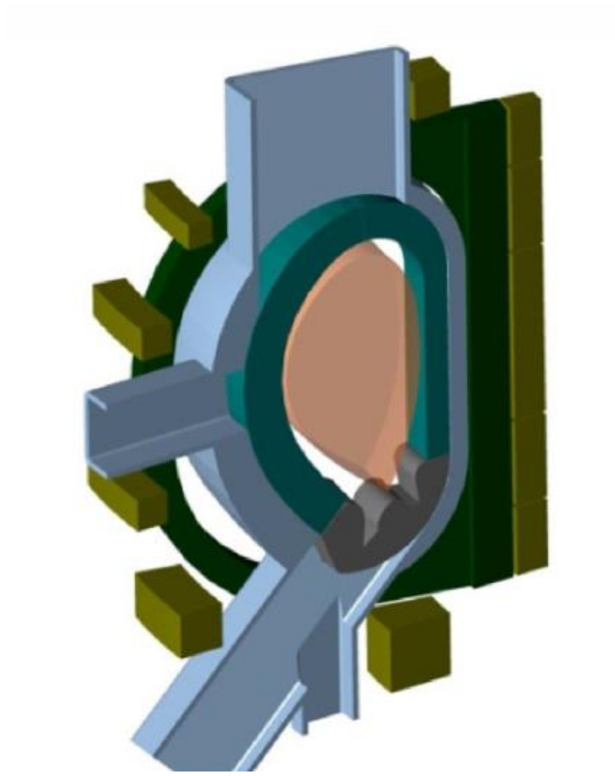

Figure 3.- DCLL DEMO model development sequence using SuperMC sofware (a) generic DEMO model

Results

The results obtained in the divertor area for the CuZrCr-alloy and for Tungsten are shown from **Figure 4** to **Figure 8**. The values for Tungsten chosen correspond to the zone nearest to the plasma surface, and the ones for CuZrCr-alloys correspond is located right behind of the Tungsten layer. The average values obtained from the figures are shown in **Table 3**.

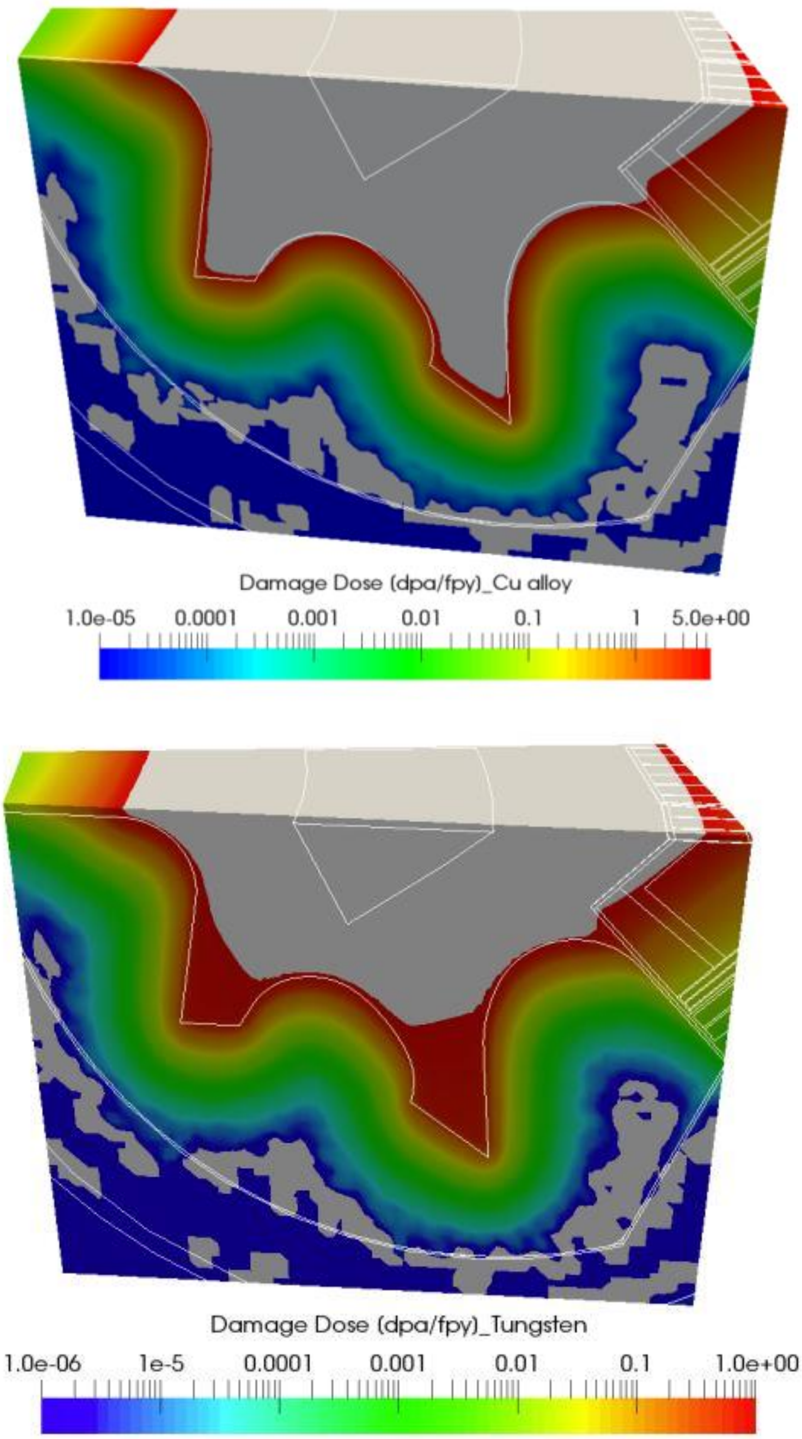

Figure 4.- Damage as displacement per atom (dpa/fpy) for a) Copper alloy and b) Tungsten

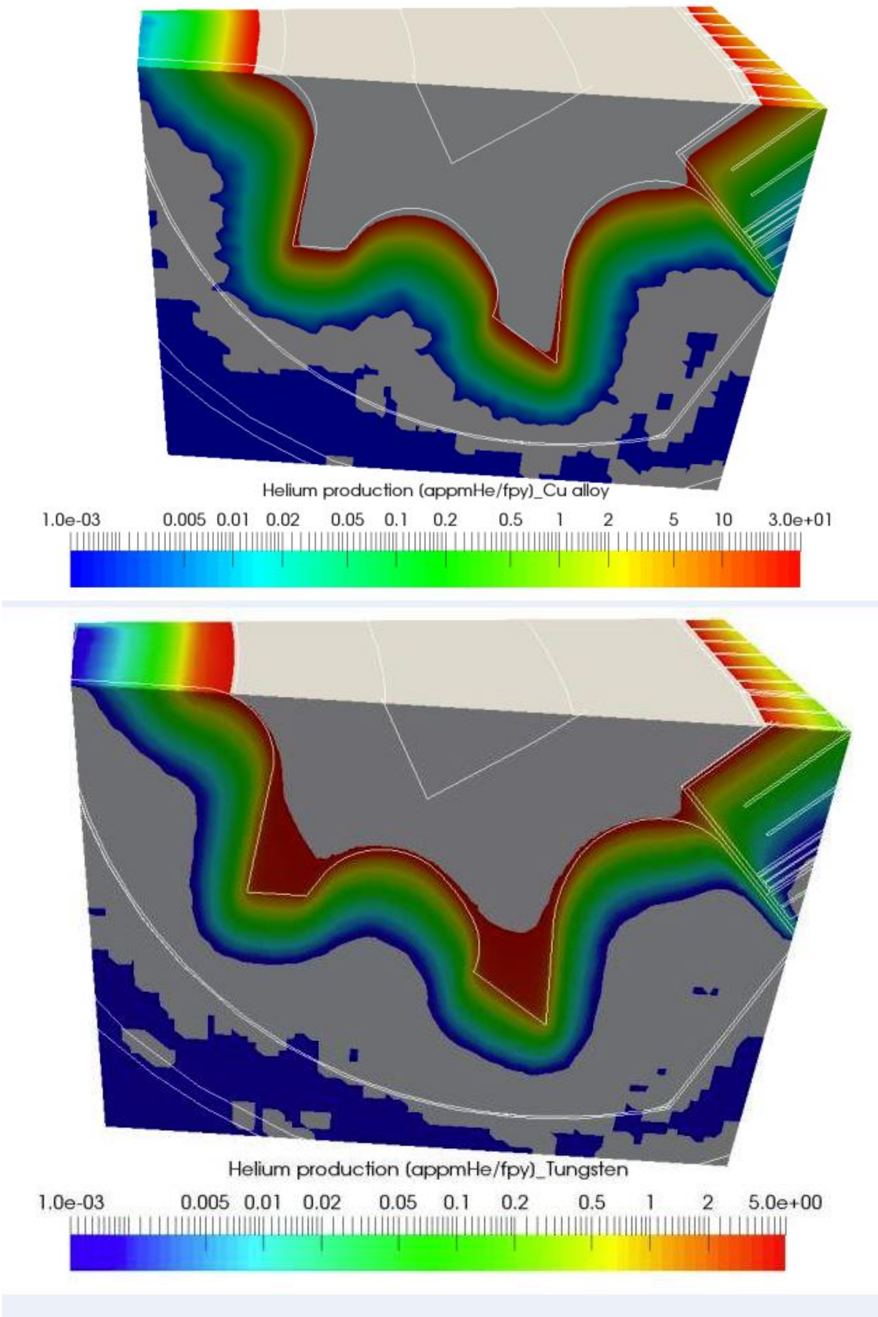

Figure 5.- Helium production in appm/fpy for a) Copper alloy and b) tungten

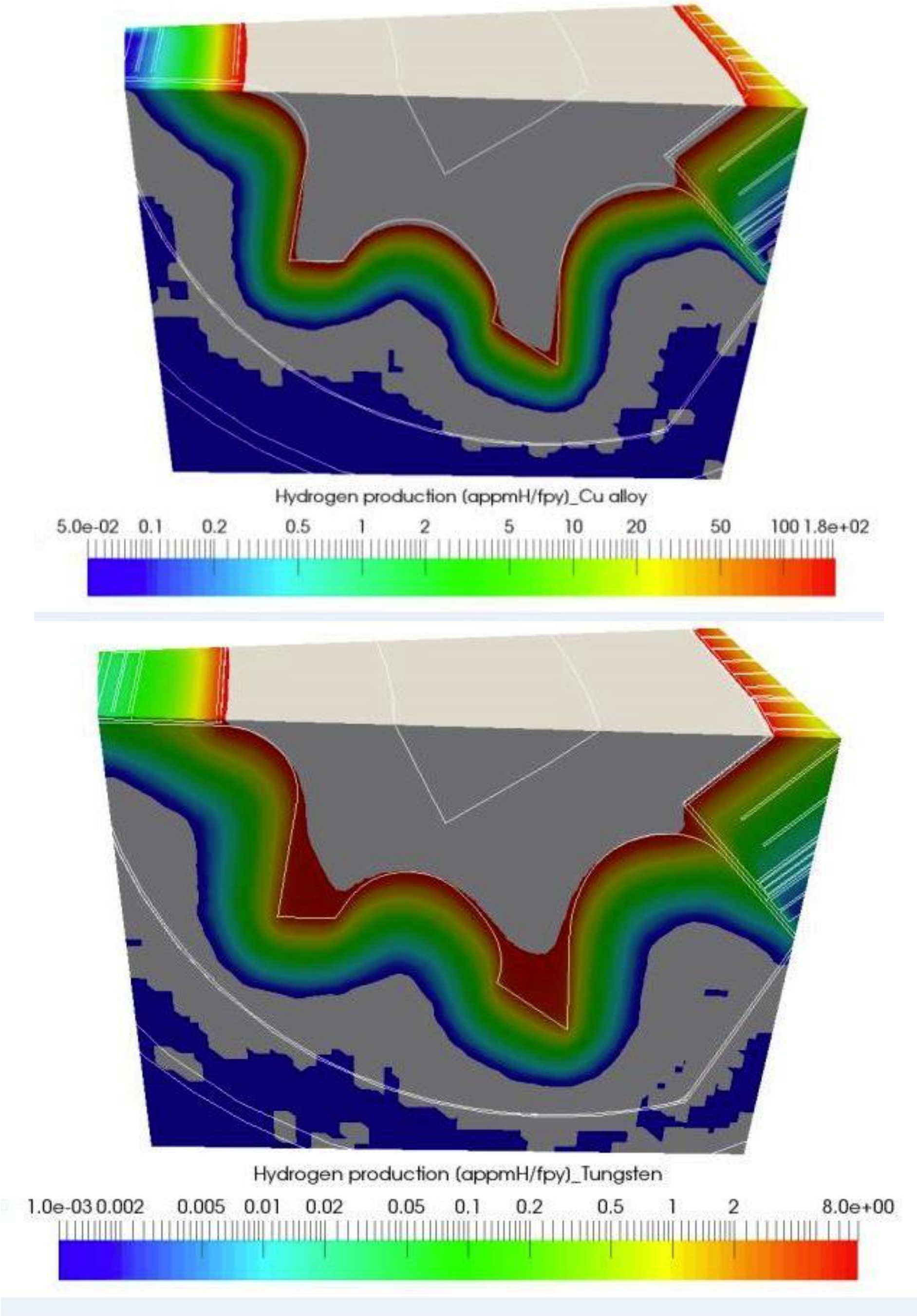

Figure 6.- Hydrogen production in appm/fpy for a) Copper alloy and b) Tungsten

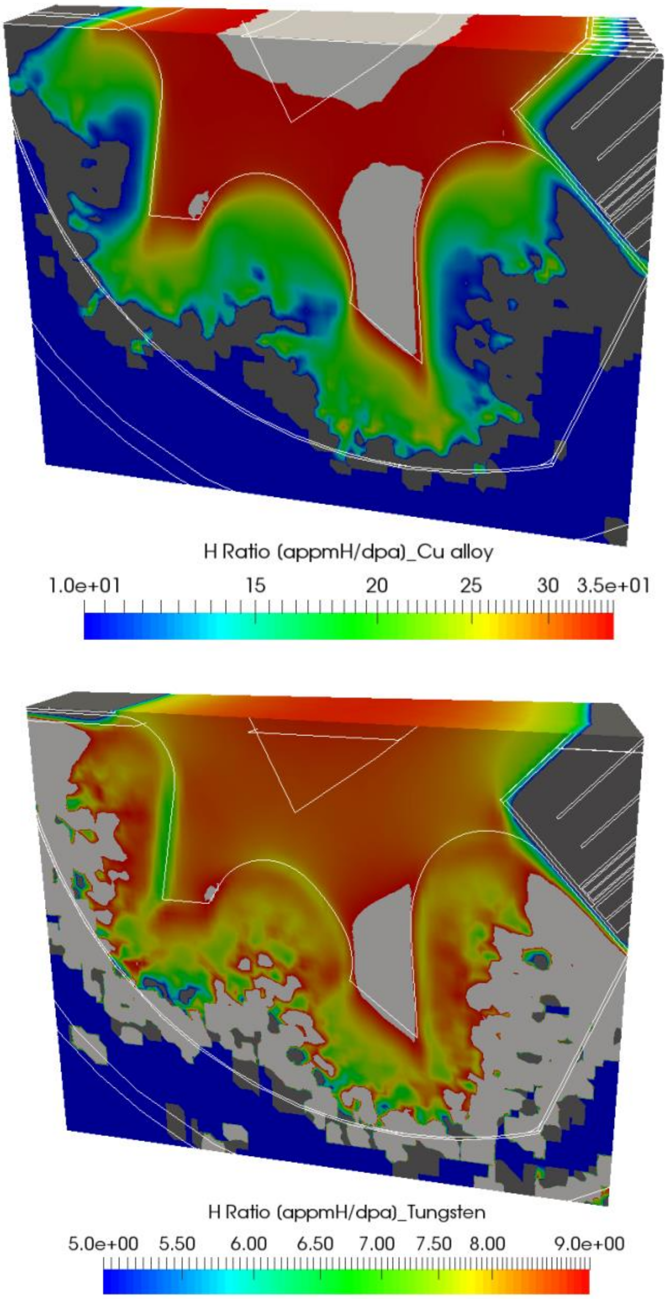

Figure 7.- Hydrogen per dpa ratio (H/dpa) for a) Copper alloy and b) Tungsten

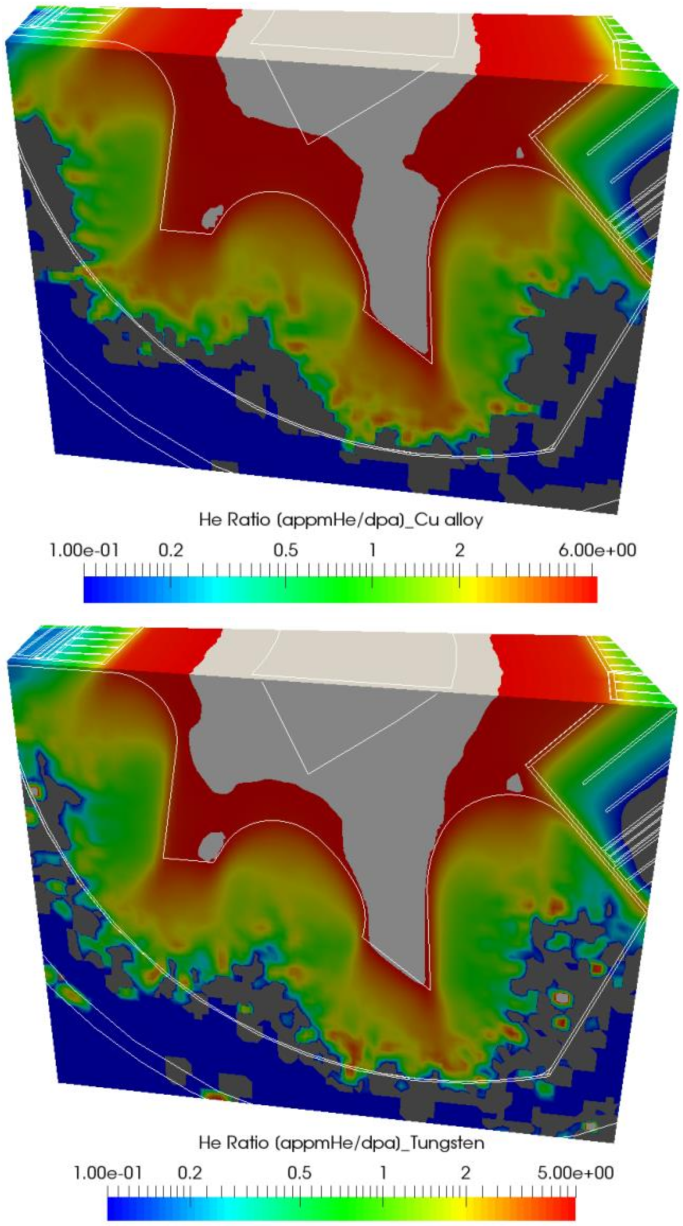

Figure 8.- Helium per dpa ratio (He/dpa) for a) Copper alloy and b) Tungsten

Table 3.- Damage dose rate, He and H production and He and H ratios calculated in the surface of the divertor.

	Damage Dose Rate [dpa/fpy]	H production [H appm/fpy]	He production [He appm/fpy]	H Ratio [H appm/dpa]	He Ratio [He appm/dpa]
CuZrCr Alloy	5	180	30	36	6
Tungsten	1	8	5	8	5

Therefore, the damage dose rate requirements demanded in the fusion roadmap for Cu-alloys and tungsten to future early neutron source DONES meet with the maximum values calculated in the divertor area of a DEMO-DCLL.

5. IFMIF-DONES neutron transport calculations

In this section, neutron transport calculations in the HFTM-DONES area are present and compared with the ones obtained in the divertor area of DEMO-DCLL. The neutron transport calculations have been performed using the McDeLicious-2011 Code [36], an upgrade of the MCNP5 v1.6 [37] in order to simulate the IFMIF neutron source, based on the evaluated D + ^{6,7}Li cross sections [38].The nuclear data library FENDL-3.1b [39] has been used for the neutron transport calculations, although the INPE-FZK [38] nuclear data evaluated libraries have been used in the present analysis for ^{6}Li and ^{7}Li isotopes [40].

The MCNP geometrical model of the IFMIF-DONES test cell was based on the model mdl69, reference MCNP model of the IFMIF Test Cell [32], but removing all the irradiation modules (Medium Flux Test Module and Low Flux Test Module) except the HFTM. In Figure 9, horizontal sections of both MCNP geometries are shown: being **Figure 9** a) the horizontal section of the complete mdl69 geometrical model and **Figure 9** b) the mdl69 geometrical model adapted to the IFMIF-DONES Test Cell concept. The blue block surrounding the irradiation area is the concrete shielding of the vessel. In addition, as in a previous work [41], the option to expand the irradiation area of the HFTM has been studied. With this aim, a replica of the HFTM has been placed right behind of the original HFTM. The horizontal view of the HFTM1 and HFTM2 of the irradiation area of Test Cell IFMIF-DONES is shown in Figure 10. In addition, the CFTM is installed right behind of the HFTM2.

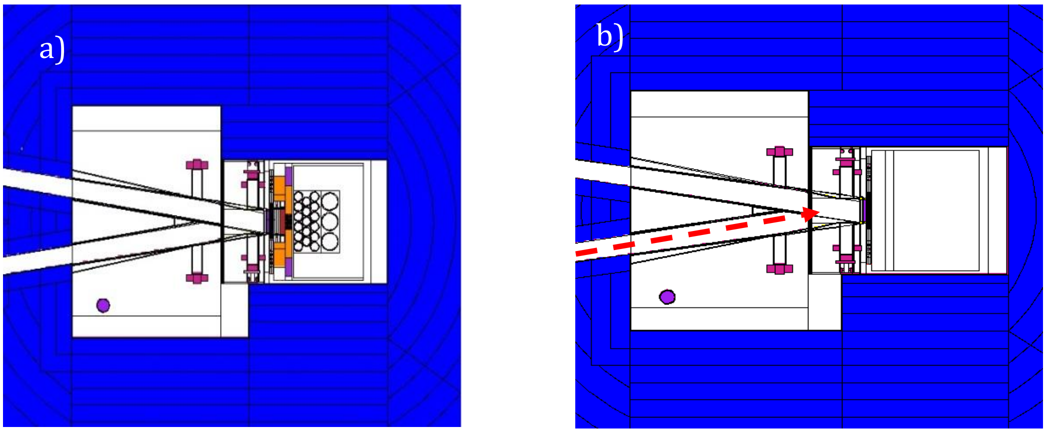

Figure 9.- a) Horizontal section of the Test Cell MCNP model mdl69, b) Horizontal section of the MCNP model mdl69 modified to be adapt to the IFMIF-DONES Test Cell. The dotted line indicates the Deuteron beam incident direction.

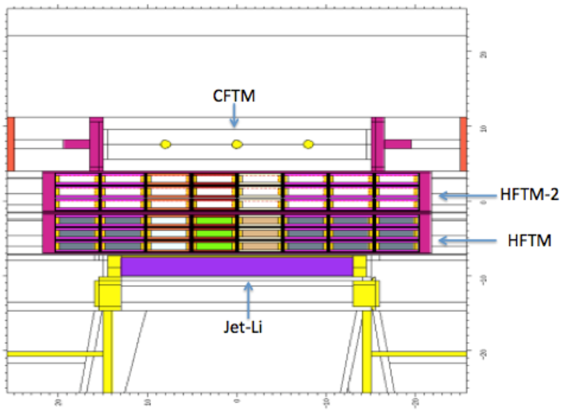

Figure 10.- Horizontal cross section of the Test cell of IFMIF-DONES, where the Lithium jet, back plate, the HFTM1, its replica HFTM2 and the CFTM are shown.

Although, the configuration and shape of the specimen containers, named rigs in the IFMIF-literature, could suffer changes in IFMIF-DONES to optimize the irradiation area, in this work the same than IFMIF-HFTM [42], have been used.

The 3D mesh-tally used for the neutron transport calculations to determine the radiation effects covers the whole volume of the rig containers of the HFTM1 and HFTM2. The total dimension of each mesh-tally considered is 40.6 × 8 × 5 cm^3, and the minimum cubic bin size is 0.25 × 0.25 × 0.25 cm^3. In **Figure 11**, the 3D mesh-tallies used for a) HFTM1 and b) HFTM2 is shown.

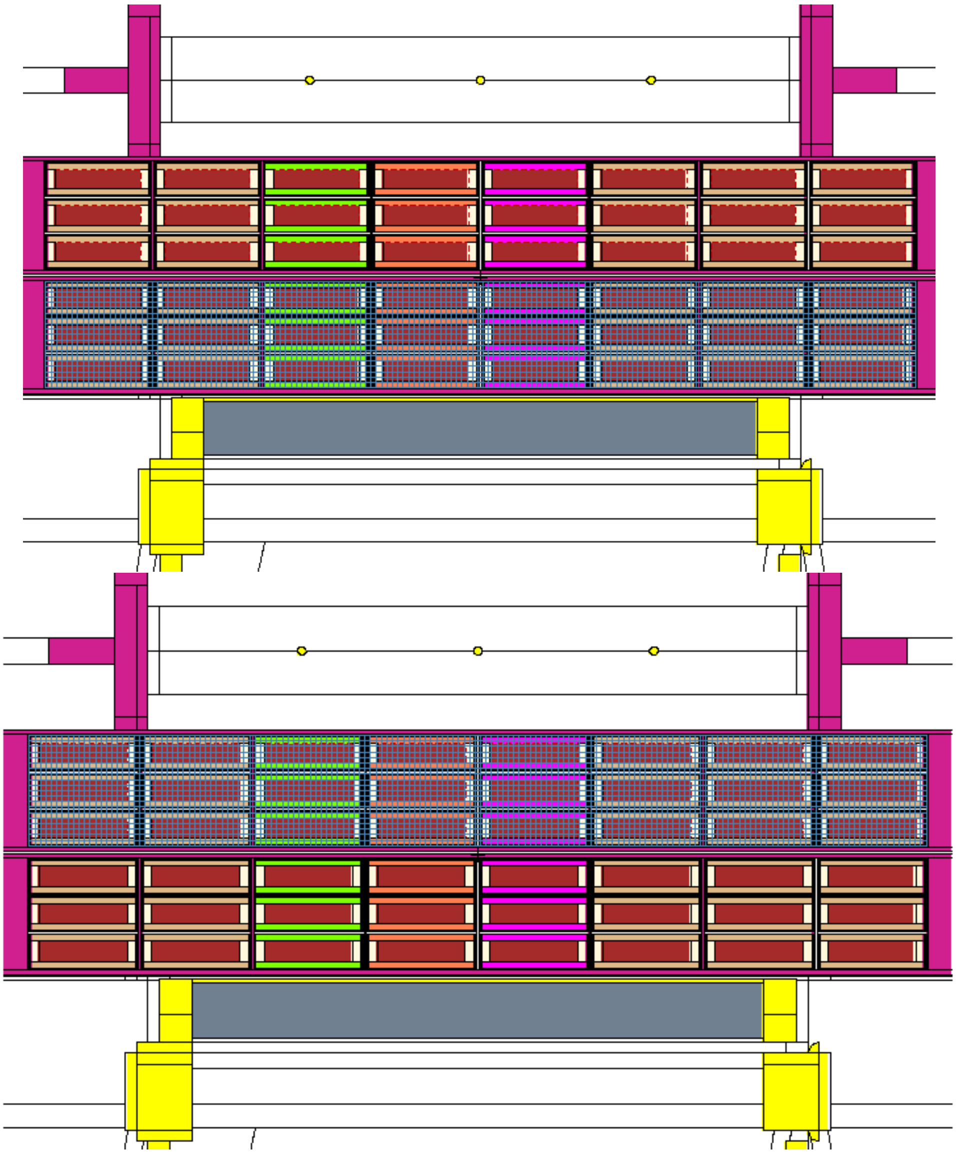

Figure 11.- The mesh-tally used to tally the radiation effect in the whole volume of the a) HFTM1 and b)HFTM2.

Cases evaluated in a function of the kind of filled up.

Several configurations of filled up of samples of EUROFER, Cu-Zr-Cr-Alloy and Tungsten have been studied trying to find the optimized configuration for each kind of samples for designing nuclear fusion equivalent irradiation experiments. The volume fraction considered for experimental specimen packaging is the same for all the materials evaluated. The packaging used is 74.19% of the material under study and 25.81% of NaK, as specified in the HFTM DDD report [43].The criterium chosen to evaluate whether the filled up configuration of the samples is optimal regards how close are the damage dose rate or gas production to damage dose ratio from the nuclear fusion reactor ones. They can be divided in three studies, cases in which a dedicated irradiation campaign is designed, cases in which a joint irradiation campaign is tested and the cases in which a optimization of the irradiation area have been tried. The different cases evaluated are shown divided in the three different studies commented. They are following:

1.- Dedicated irradiated campaign

- **Case 1:** HFTM1 and HFTM2 filled with samples of EUROFER; Figure 12.
- **Case 2:** the whole HFTM and HFTM2 filled up of samples of Cu-Zr-Cr alloys. **Figure 12**
- **Case 3:** The whole HFTM and HFTM2 filled up of samples of Tungsten. **Figure** 12

2.- Joint irradiation campaign

- **Case 4:** The central part of the HFTM1, i.e. the 12 central rigs, is filled with samples of EUROFER, and the lateral rigs of the HFTM1 and the whole HFTM2 are filled up of samples of Cu-Cr-Zr alloys, Figure 13.
- **Case 5:** The central part of the HFTM1, filled with samples of EUROFER, and the lateral rigs of the HFTM1 and the whole HFTM2 filled with tungsten, Figure 13.

3.- Joint irradiation campaign to optimize the irradiation parameters

- **Case 6:** The central part of the HFTM1, filled up with samples of EUROFER, the lateral rigs of both HFTMs with Cu-Zr-Cr alloys and the central part of the HFTM2 with samples of tungsten. **Figure 14**
- **Case 7:** The central part of the HFTM1, filled up with samples of EUROFER, the lateral rigs of both HFTMs with Tungsten and the central part of the HFTM2 with samples of CuZrCr-Alloys.

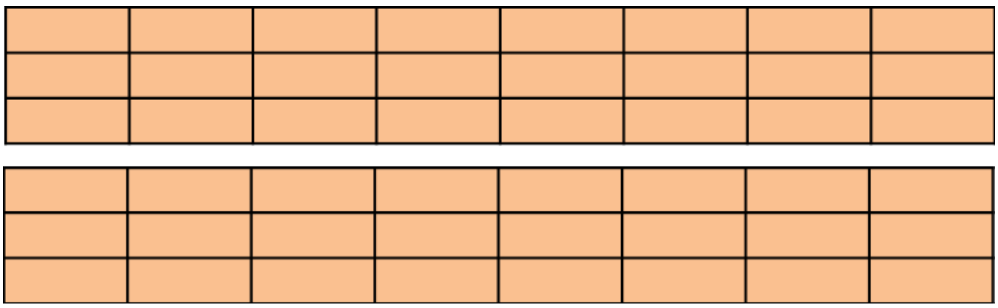

Figure 12.- Schedule of the kind of filled up of the case 1, 2, and 3. All rigs are filled up of samples of EUROFER, CuZrCr alloys and Tungsten respectively.

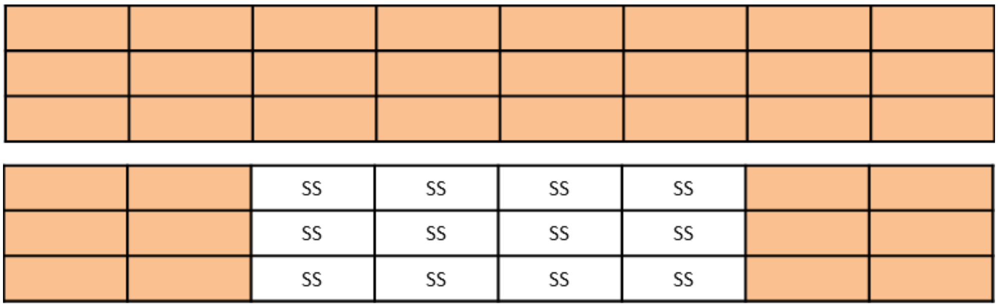

Figure 13.- Schedule of the kind of filled up of the case 4 and case 5. The brown rigs correspond to rigs with samples Cu-Zr-Cr alloys for the case 4 and with tungsten for the case 5. The White central area corresponds to the 12 rigs filled up with samples of EUROFER.

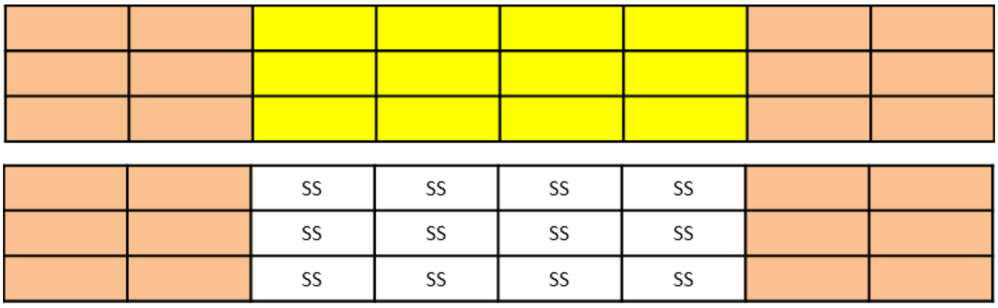

Figure 14.- Schedule of the kind of filled up of the case 6. The central part of the HFTM, i.e. the 12 central rigs, is filled of samples of EUROFER, the lateral rigs of both HFTMs, in brown colour, filled up of samples of Cu-Zr-Cr alloys and the central of the HFTM2, in yellow colour, are filled up of samples of tungsten

Regarding the possibility of reassigning the creep fatigue test module (CFTM) for the irradiation campaigns to evaluate the radiation effect in Stainless steel under mechanical fatigue, the radiation effect have been evaluated in all the cases mentioned above. The CFTM is placed right behind of the HFTM configurations show above.

Results

The damage dose rates have been evaluated in the HFTM area with the aim to assess whether they agree with the ones calculated in the divertor area of a DEMO-DCLL concept (section 4), in agreement with the damage requirements established in the EUROfusion Roadmap. With the aim to evaluate the amount of irradiated volume submitted to a certain damage dose rate a very descriptive function which compares the available integrated irradiation volume (24 rigs) versus damage dose rate [dpa/fpy] is used. This function provides a quick vision of the available volume with a minimum damage dose rate values, therefore it has been obtained for all the cases studied to verify whether there is enough volume to irradiate Cu-alloys or tungsten with damage dose rates higher than the ones found in the divertor area of a future DEMO.

The results are shown following the criteria shown on previous subsection 5.1. First the irradiation parameters in a dedicated irradiation campaign for CuZrCr-Alloys or Tungsten are evaluated in order to obtain the limit values of radiation damage achievable and to identify the location most favourable to irradiate each material regarding He and H ration consideration. Once studied the broadness of the irradiation parameters calculated in the whole irradiation test area, the possibility to irradiate both materials evaluated in a joint irradiation campaign with EUROFER is evaluated. Finally, the optimization of the irradiation test volume is assessed taking into account damage dose requirement and He and H ratios considerations.

Dedicated irradiation campaign

First, the 3 cases in which the whole volume has been completely filled with only one of the 3 materials under assessment are analysed, with the aim to identify the maximum values of the achievable damage dose rate in each case. Therefore, in **Figure 15**, the available integrated volume versus damage dose rate for the cases 1, 2 and 3 is shown. The main conclusions obtained from the figure are the following: firstly, the volume in the HFTM with damage dose rates (dpa/fpy) higher than a given value obviously decreases with an higher damage dose rate; secondly, the maximum damage dose rate reached is 5, 27 and 38 dpa/fpy for Tungsten, EUROFER and Cu-alloys respectively; and lastly but by no means least, the volumes fulfilling the damage requirements for the three materials is sufficiently high for the needed of such a kind of experiments.

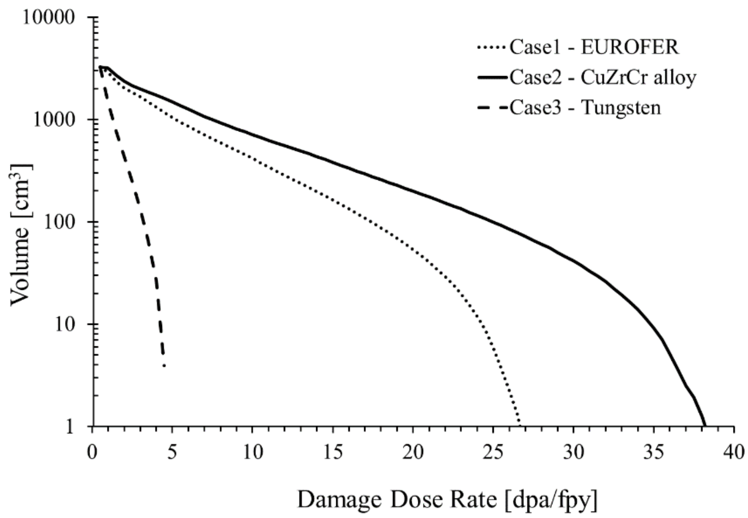

Figure 15.- The available integrated irradiation volume (24 rigs) versus damage dose rate [dpa/fpy] for the cases 1, 2 and 3, i.e. the whole specimen volume of the HFTM are filled up of EUROFER, CuZrCr-alloy and Tungsten, respectively.

In order to evaluate the available volume with more detail, the volume for the cases 1, 2 and 3 with damage dose rates for Cu-alloy, tungsten and EUROFER higher than the fusion roadmap requirements have been evaluated and shown in **Table 4**. The main result of this table is that, the volume with damage dose rate higher than requirements are big in a dedicated irradiation campaign for the three materials assessed CuZrCr-Alloys, Tungsten and EUROFER. In addition, it is noted that the volume for tungsten is smaller than the one obtained for CuZrCr-Alloy. The reason of this effect is better understood whether is observed **Figure 16** in which a damage dose rate map of the horizontal cup in the middle of the HFTM is shown for case 2 a) and for case 3 b). On the one hand, for CuZrCr-alloy the damage dose rate target of 5 dpa/fpy is overcome in the central part of both HFTMs achieving the final row of the HFTM2, **Figure 16** a) therefore, almost the whole volume of the central part of both HFTMs can be used to hold CuZrCr-alloys samples which is agree with the volume show in **Table 4**. On the other hand, for Tungsten only reach up to first row of the HFTM2 (1 dpa/fpy), **Figure 16** b), then the volume shows in **Table 4** is smaller than the one obtained for CuZrCr-Alloy samples.

Table 4.- Volume with dpa values higher than the Fusion Roadmap requirements for Cu-Alloy, Tungsten and Stainless Steels for the cases evaluated.

Cases assessed	Cu -Alloy	W	Eurofer	
	Volumes with Damage dose > 5 dpa/fpy [cm^3]	Volumes with Damage dose > 1 dpa/fpy [cm^3]	Volumes with Damage dose > 10 dpa/fpy [cm^3]	Volumes with Damage dose > 20 dpa/fpy [cm^3]
Case 1. EUROFER	X	X	377	46
Case 2. CuZrCr	1364	X	X	X
Case 3. Tungsten	X	763	X	X

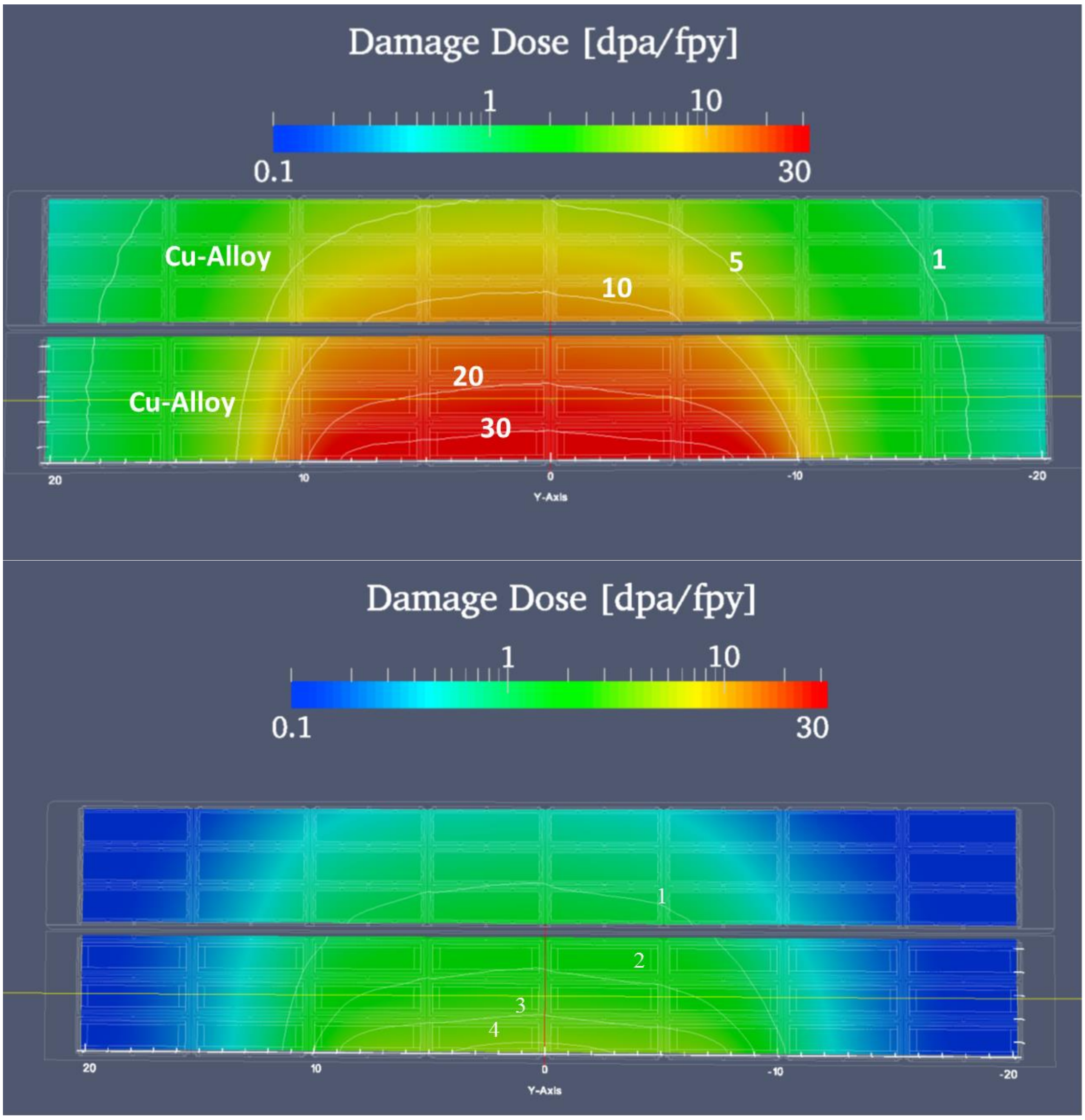

Figure 16.- Damage dose rate [dpa/fpy] horizontal section in the central part of the HFTM1 and HFTM2 for a) Case 2 and b) case 3.

Regarding the gas production to damage dose ratios, in **Figure 17 Figure 18** s the He ratio and H ratio are shown for case 2 and 3 respectively. Both figures show a horizontal cup in the middle of the HFTMs for the He and H ratios 3D mesh results.

Respect to the case 2, in which both HFTMs are filled up of CuZrCr-Alloy samples, the He ratio similar to the fusion ones are found in the volume in which the damage dose rate fulfil the damage requirement, being those 6 appmHe/dpa, **Table 3**. Furthermore, the H ratio, **Figure 17** b) is only a slightly higher, approximately a 25% higher, than the one expected in the divertor area of a future DEMO, (36 appmH/dpa, **Table 3**). Therefore the central part of the HFTM is ideal to design equivalent nuclear fusion irradiation experiments for CuZrCr-alloys samples

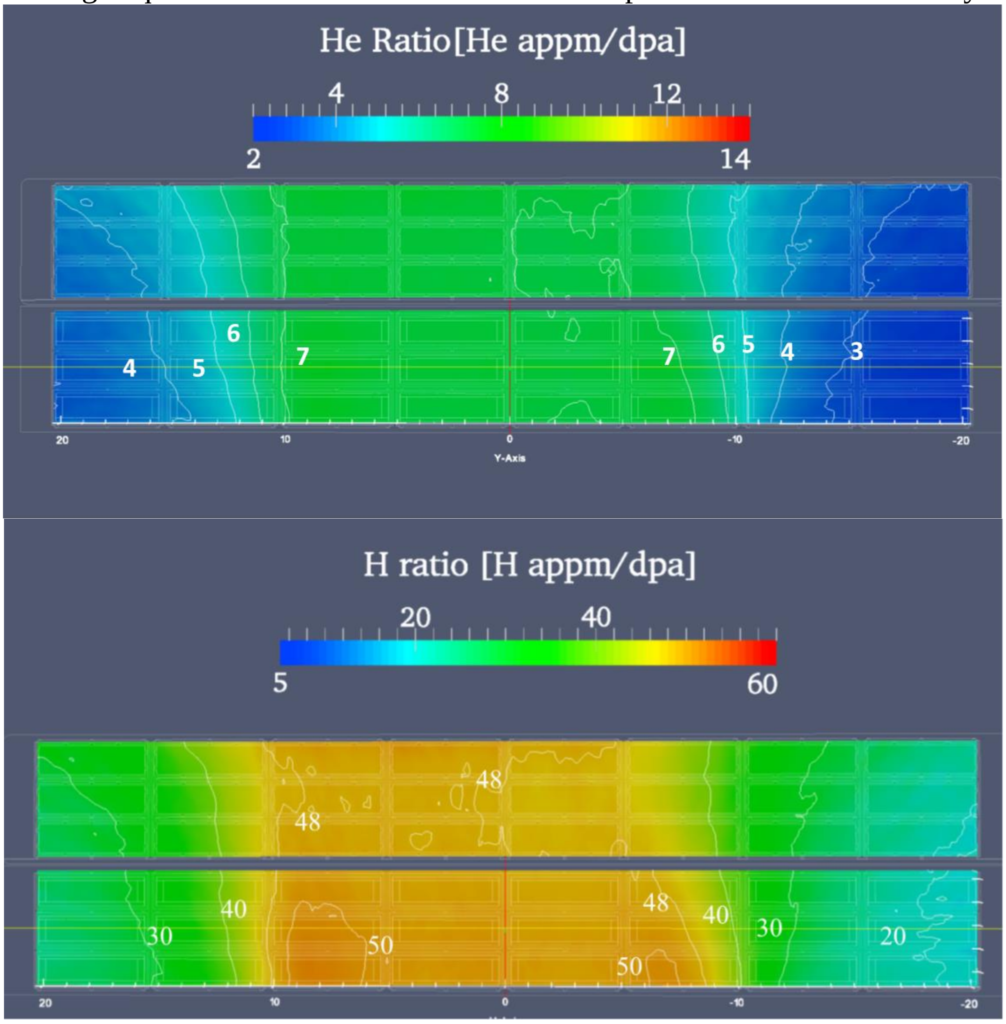

Figure 17.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally in CuZrCr-Alloy for the case 2; a) He ratio, b) H ratio

Regarding the case 3 in which the whole HFTMs are filled up of samples of Tungsten, the He ratio, **Figure 18** a) the situation is not as favourable as for the CuCrZr-Alloys cases, because in the area in which the damage requirements are reached the He ratio is approximately the double than the one expected in the divertor area (5 He appm/dpa, **Table 3**). On the other hand, although, the representative volume of those values is found in the lateral areas of the HFTM the damage dose requirements are not reached. In addition, although, the He ratio of divertor area is achieved in the lateral rigs is also noted, in these areas the damage dose rates are too low. Therefore, the best area to design irradiation experiments for tungsten samples to emulate the nuclear fusion irradiation conditions of the divertor area is again the central part of the HFTM. Furthermore, respect to the H ratio, **Figure 18** b), where the damage dose rate requirement is reached, i.e. the central part of the HFTM, H ratio is approximately three or four times higher than the expected in the divertor area (8 H appm/dpa, **Table 3**). However, taking into account that the He and H ratios of the others kinds of neutron sources, fission or spallation are further, the double for He ratios and between three to four times for H ratios are the best results achievable so far.

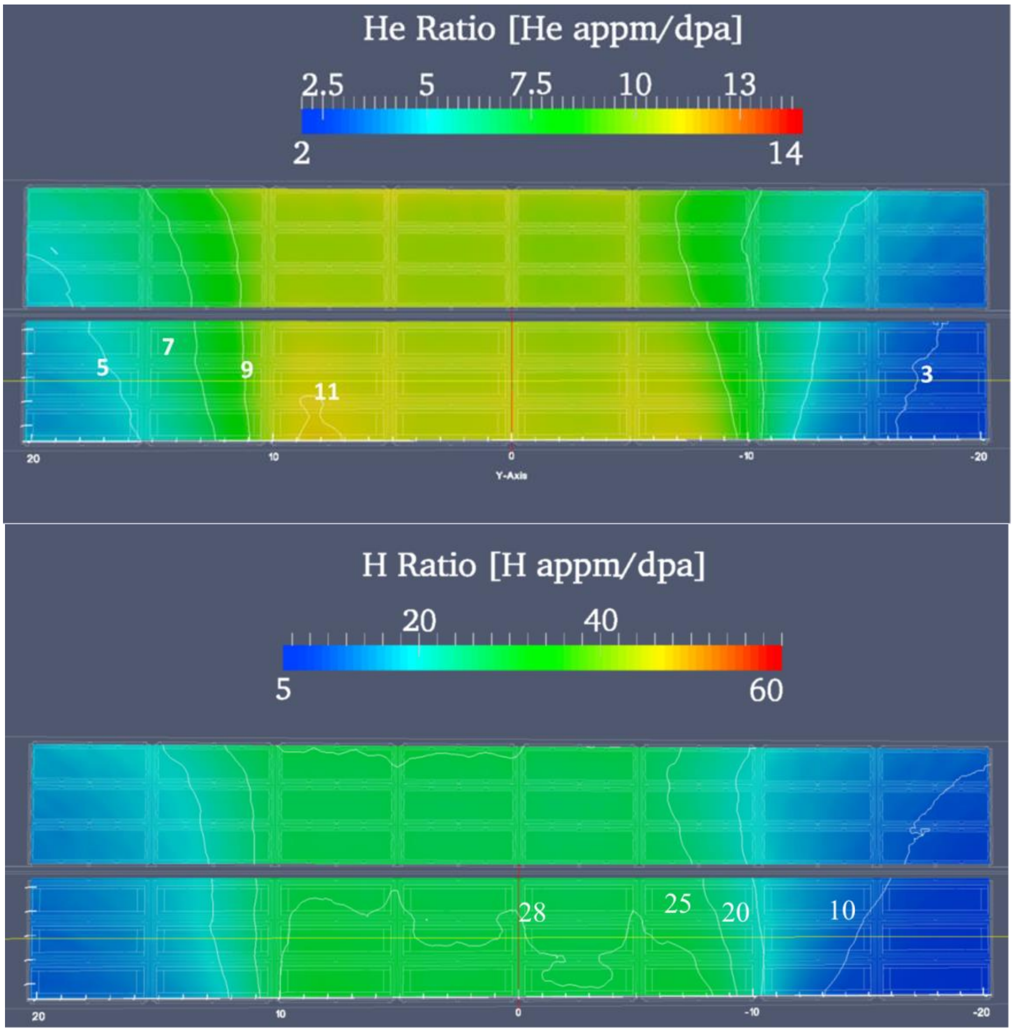

Figure 18.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally in Tungsten for the case 2; a) He ratio, b) H ratio

Joint Irradiation campaign

Besides, the possibility to irradiate samples of Cu-alloy and Tungsten in joint irradiation campaigns with EUROFER is evaluated in this subsection. The configuration of samples evaluated are the cases 4 and 5, in which the 12 central rigs are filled in of EURFER samples while the rest of specimens volume is filled up of Cu-Alloy in case 4, **Figure 13**, and tungsten in Case 5, **Figure 13**, as it was explained in section 5.1. The integrated volume with a minimum damage dose rate for the cases 4 and 5 are shown in Figure 19. In both cases the damage requirement are achieved is noted in this figure. However, the volume with damage dose rate higher than requirement is too small in case 5 for the tungsten sample, as it is shown in **Table 5**, contrary to the case 4 in which the available volume is high. These results can be understood better crosschecking Table 5 with **Figure 20** and **Figure 21** a) in which damage dose rate [dpa/fpy] map in a horizontal section in the middle of the HFTM is shown for case 4 and 5, respectively. On the one hand, For CuZrCr-alloy, case4, the achieved maximum damage dose rate fulfilled the damage requirements and they are reached mainly in the central part of the HFTM2 almost up to the rear part, what can be observed in **Figure 20**. On the other hand, in case 5, the damage dose rate suffered by the tungsten samples reaches the requirements only up to the first row of the HFTM2 and in the lateral rigs right closer to the central part, **Figure 21** a), therefore, the available volume to hold tungsten samples with damage dose rate higher than the damage requirements is too low, as it was shown in **Table 5**. Therefore, it means that considering an irradiation campaign of one full power year for CuZrCr-Alloy samples the available volume is 587 cm^3, however for tungsten samples are only 101 cm^3. Furthermore, in order to increase the useful volume to design equivalent irradiation experiment for tungsten is necessary to achieved the two year of full power irradiation what is it shown in **Table 5** and **Figure 21** b). With an irradiation of 2 fpy the damage requirements are achieved up to the rear part of the HFTM2, what means that whether the tungsten samples do not take the central part of the HFTM1 it is necessary to extend irradiation time.

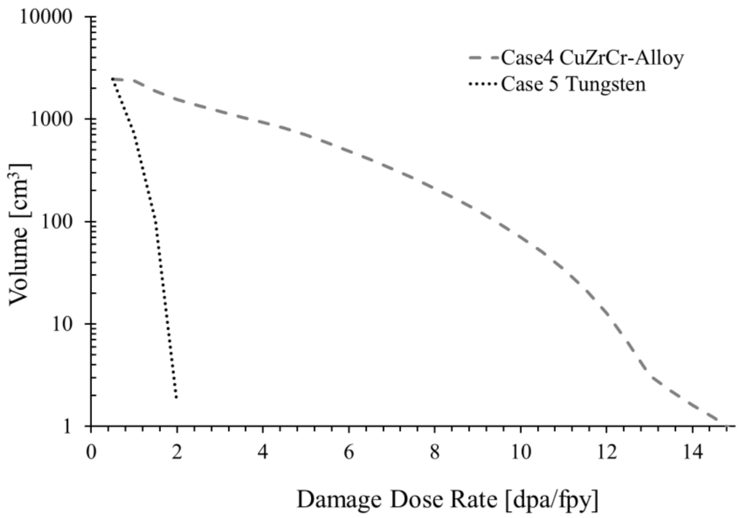

Figure 19.- The available integrated irradiation volume (24 rigs) versus damage dose rate [dpa/fpy] for the cases 4 and 5.

Table 5.- Volume with dpa values higher than the Fusion Roadmap requirements for Cu-Alloy, Tungsten and Stainless Steels for the cases evaluated.

	Cu -Alloy	**W**	**Eurofer**	
Cases assessed	Volumes with Damage dose > 5 dpa/fpy [cm^3]	Volumes with Damage dose > 1 dpa/fpy [cm^3]	Volumes with Damage dose > 10 dpa/fpy [cm^3]	Volumes with Damage dose > 20 dpa/fpy [cm^3]
Case 4 (1fpy)	587	X	380	47
Case 5 (1fpy)	X	101	382	47
Case 5 (2fpy)	X	728	737	378

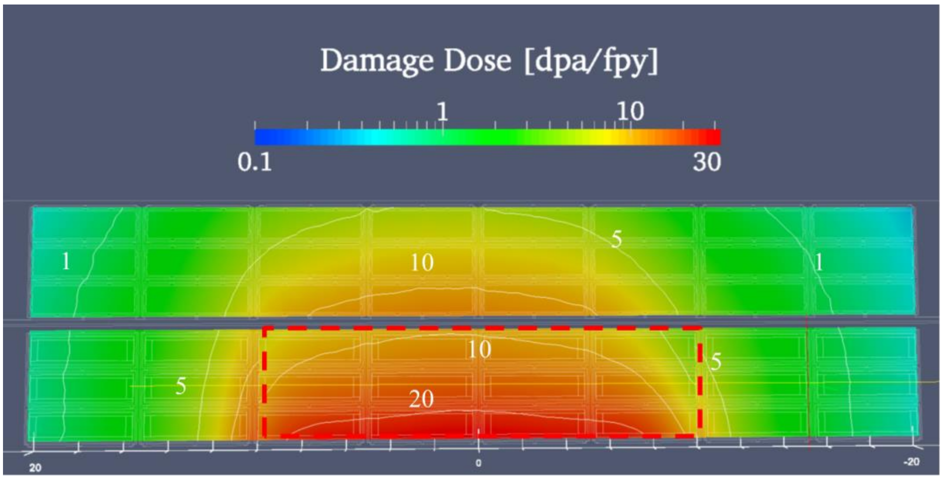

Figure 20.- Damage dose rate [dpa/fpy] horizontal section in the central part of the HFTM1 and HFTM2 for case 4. The red dotted lined surround the SS samples area.

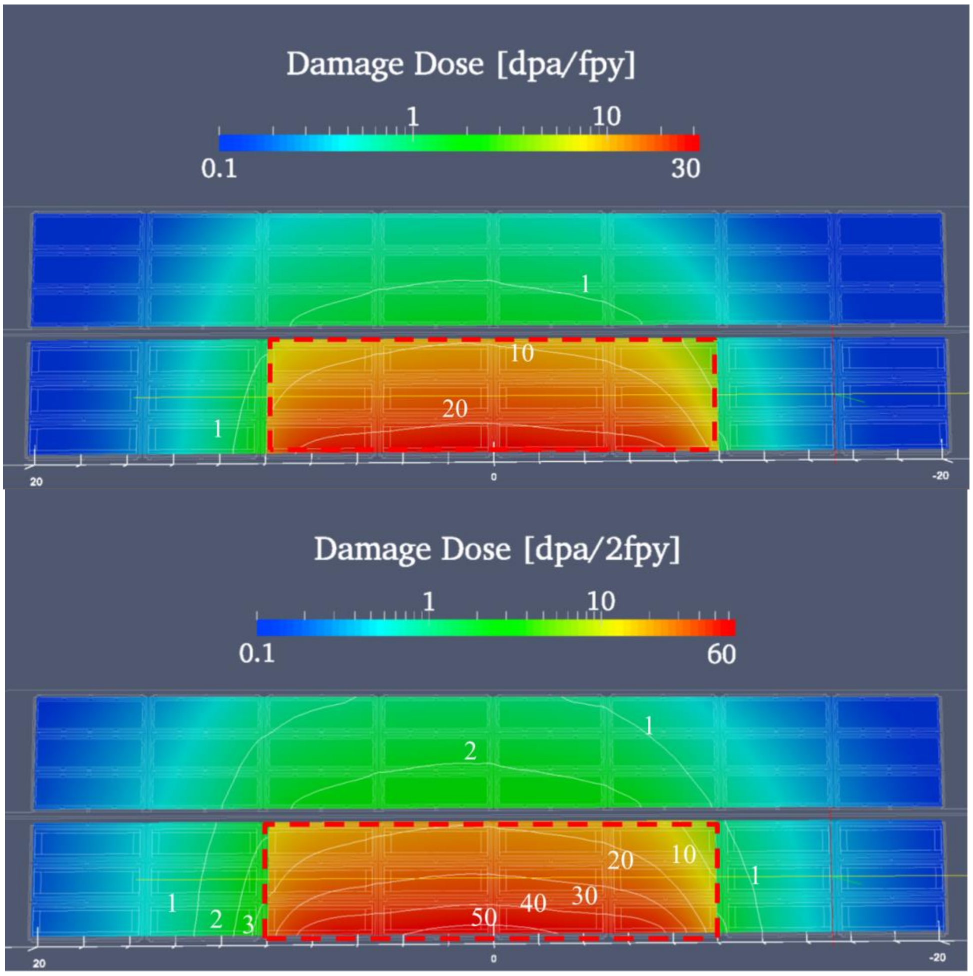

Figure 21.- Damage dose rate [dpa/fpy] horizontal section in the central part of the HFTM1 and HFTM2 for case 5; a) 1fpy of irradiation; b) 2 fpy of irradiation

Respect to gas production to damage dose ratio, in **Figure 22**, the H and He ratios map are shown for CuZrCr alloy samples, case 5. It is clearly noted that He ratio is similar to the expected in divertor area of DEMO in the central part of the HFTM2, overlapping with the area in which the damage requirements are met. Furthermore, the H ratio is slight higher than the one expected in divertor area, identically equal what is happen in case 2. Hence, taking into account the He and H ratios good results and that damage dose rate requirements are met in great part of the irradiation area used is conclude that the case 4 is an optimum configuration to irradiate CuZrCr-Alloys samples for nuclear fusion irradiation tests.

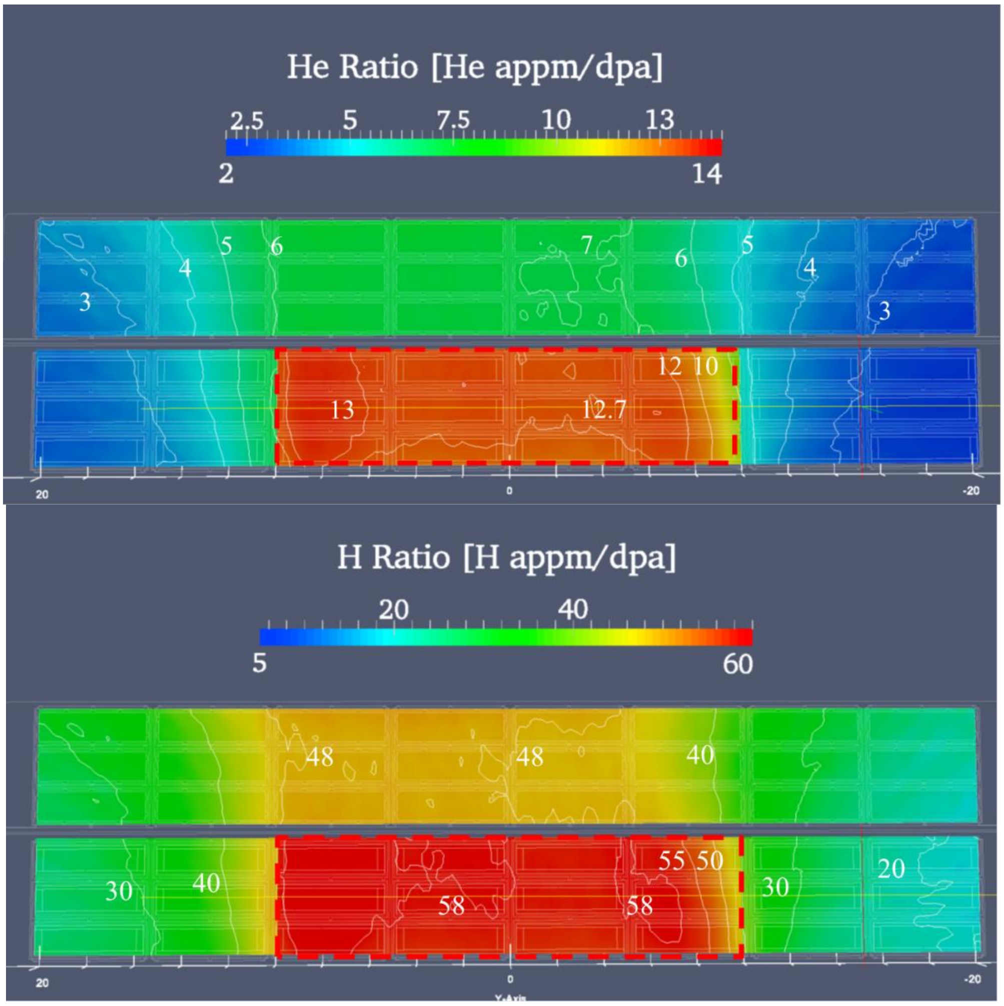

Figure 22.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally for the case 4, in which EUROFER is located in the central part of the HFTM1 and CuZrCr-Alloy samples around the EURFER samples; a) He ratio, b) H ratio

In case 6 the gas production to damage dose ratios are not so favourable like for the CuZrCr-alloy samples, as it was shown above in case 3. Because, in the area in which the damage requirements is fulfilled, the He ration is approximately the double and the H ratios are three or four times higher than the ones expected in divertor area of a DEMO-DCLL, **Figure 23**. However, as it was commented above, taking into account that the He or H ratios of the others kinds of neutron sources, fission or spallation are further, they are the best results achievable so far

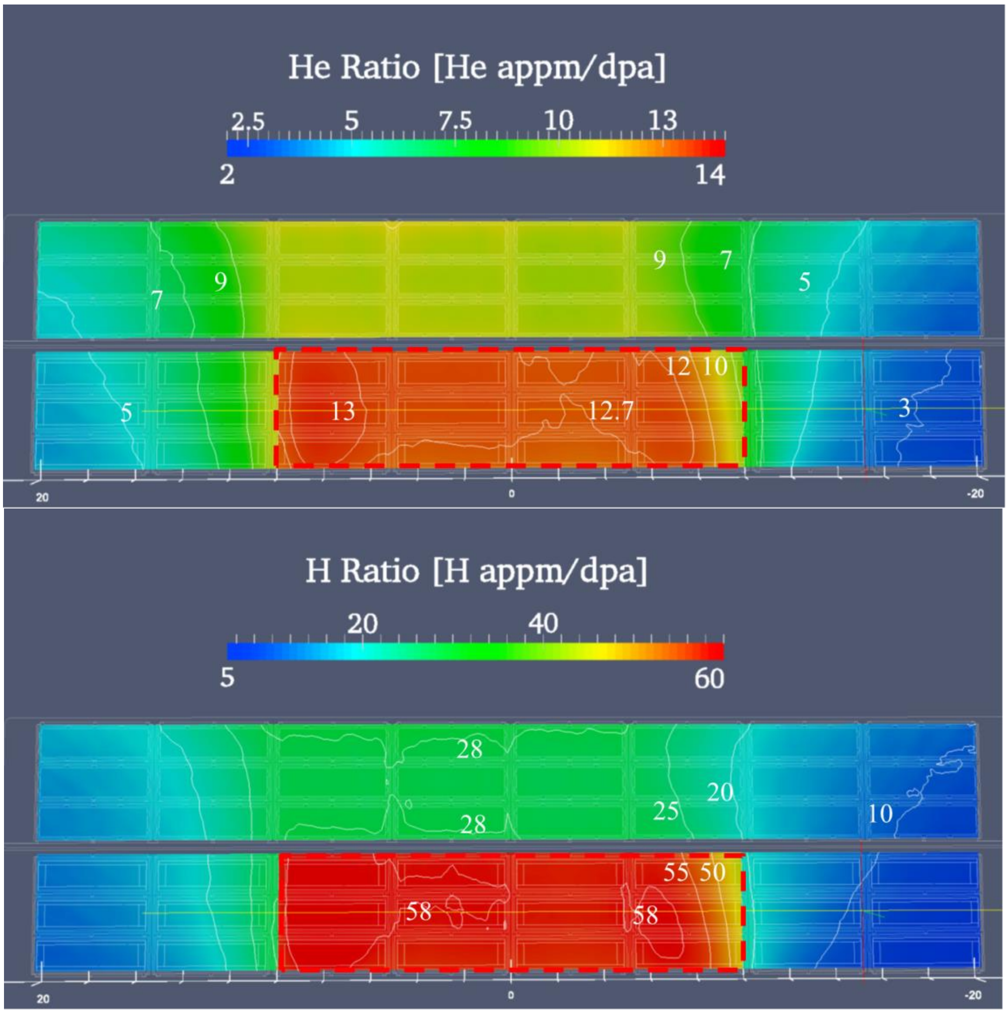

Figure 23.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally for the case 4, in which EUROFER is located in the central part of the HFTM1 and Tungsten samples around the EURFER samples; a) He ratio, b) H ratio

The irradiation parameters in EUROFER samples are not affected significantly for placing samples of both materials evaluated around them. In fact, the volume which fulfils with the damage dose rate requirements are practically equal for the cases 4, 5 (Table 5) or case 3 (Table 4). In addition, from the comparison between cases 4 and 5 with case 1 is deduced EUROFER samples have to be located in the central volume of the HFTM1 because in the lateral rigs of behind of the HFTM1 the volume does not met with the damage requirements.

Joint irradiation campaign to optimize the irradiation parameters

Then, the possibility to optimize the irradiation parameter was explored using the behaviour of each material under neutron irradiation, in order to design a joint irradiation campaign together with EURFER, CuZrCr-alloy and tungsten. Although, the irradiation parameters in EUROFER samples are not affected by the location of the different sample around him have been already proved in previous section, in this subsection whether there would be some configuration of samples which could shift the irradiation parameters with the aim to closer them to nuclear fusion ones will be analysed. Two different configurations of samples have been tested, case 6 and 7, in which, the configuration of samples is opposite, although the EUROFER samples are always located in the central part of the HFTM1 the best location for them. In **Figure 24** in which the integrated available volume versus damage dose rate for case 6 and 7 is shown, is observed that the damage requirement is achieved for Tungsten samples and for CuZrCr-alloy samples. However, for tungsten samples the volume which achieves the damage requirements is small in both cases evaluated, **Table 6**, since the lateral parts and the HFTM2 are not favourable places to hold these samples, but naturally considering only a irradiation of 1 fpy. If the irradiation is prolonged until 2 fpy, **Table 7**, the volume achieved in case 6 fulfilling the damage requirement increase up to 578 cm3 while for case 7 increases only slightly.

For CuZrCr-Alloy samples the most suitable configuration correspond to the case 7 in which the CuZrCr-Alloy are placed in the central part of the HFTM2, because in only 1 fpy of irradiation campaign the volume fulfilling the damage requirements is equivalent to the one obtained for EUROFER samples in the HFTM1, **Table 6**. In addition, it is no necessary to reach 2 fpy to obtain a great volume of sample with damage requirements. Although, the best configuration to irradiate the three kind of samples at the same time would be the case 6 but irradiating during 2 fpy, because the volume available is acceptable for them.

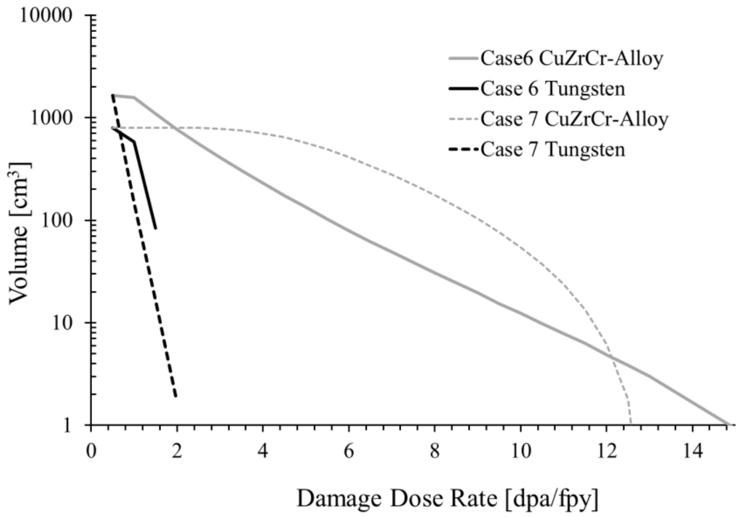

Figure 24.- The available integrated irradiation volume (24 rigs) versus damage dose rate [dpa/fpy] for CuZrCr-Alloy and tungsten samples holded the cases 6 and 7.

Table 6.- Volume with dpa values higher than the Fusion Roadmap requirements for Cu-Alloy, Tungsten and Stainless Steels for the cases 6 and 7 and after 1 fpy of irradiation.

Cases assessed	Cu -Alloy	W	Eurofer	
	Volumes with Damage dose > 5 dpa/fpy [cm^3]	Volumes with Damage dose > 1 dpa/fpy [cm^3]	Volumes with Damage dose > 10 dpa/fpy [cm^3]	Volumes with Damage dose > 20 dpa/fpy [cm^3]
Case 6	102	84	381	47
Case 7	490	17	381	47

Table 7.- Volume with dpa values higher than the Fusion Roadmap requirements for Cu-Alloy, Tungsten and Stainless Steels for the cases 6 and 7 and after 2 fpy of irradiation.

Cases assessed	Cu -Alloy	W	Eurofer

	Volumes with Damage dose > 5 dpa/**2 fpy** [cm^3]	Volumes with Damage dose > 1 dpa/ **2fpy** [cm^3]	Volumes with Damage dose > 10 dpa/**2fpy** [cm^3]	Volumes with Damage dose > 20 dpa/**2fpy** [cm^3]
Case 6	407	578	737	378
Case 7	776	146	737	377

In **Figure 25** and **Figure 26** horizontal sections of 3D mesh results of the damage dose rate are shown for the case 6 and 7, respectively, and for 1 or 2 fpy of irradiation campaign. In which, the lateral rigs are filled in with CuZrCr-alloys samples and the Tungsten samples are placed in the central part of the second HFTM for case 6 or to contrary for case 7, while the EURFER samples keep the central part of the first HFTM, the best location to irradiate stainless steel samples. Observing, **Figure 25** a) is clearly observed why the suitable volume for both tungsten and CuZrCr-Alloy samples is small considering 1 fpy irradiation conditions, and besides, how it increases, for both kind of samples, **Table 7**, when the irradiation campaign is prolonged until 2 fpy **Figure 25** b).With 2 fpy of irradiation campaign respected to the Tungsten samples the 1 dpa contour line achieves the rear part of the HFTM2 and, for CuZrCr-Alloy samples, the 5 dpa contour line is moved up to almost covers the first lateral rigs on both sides.

Furthermore, using the configuration of samples of the case7 is also observed how neither increasing the irradiation time the suitable volume for tungsten samples increases up to 146 cm^3, **Table 7** and **Figure 26**, i.e. the lateral rigs are not the best place to hold tungsten samples. On the other hand, neither it acts like reflector since the tungsten samples do not made significant effects upon the CuZrCr-Alloy or EUROFER samples. However, the case 7 is suitable configuration to irradiate CuZrCr-alloy samples.

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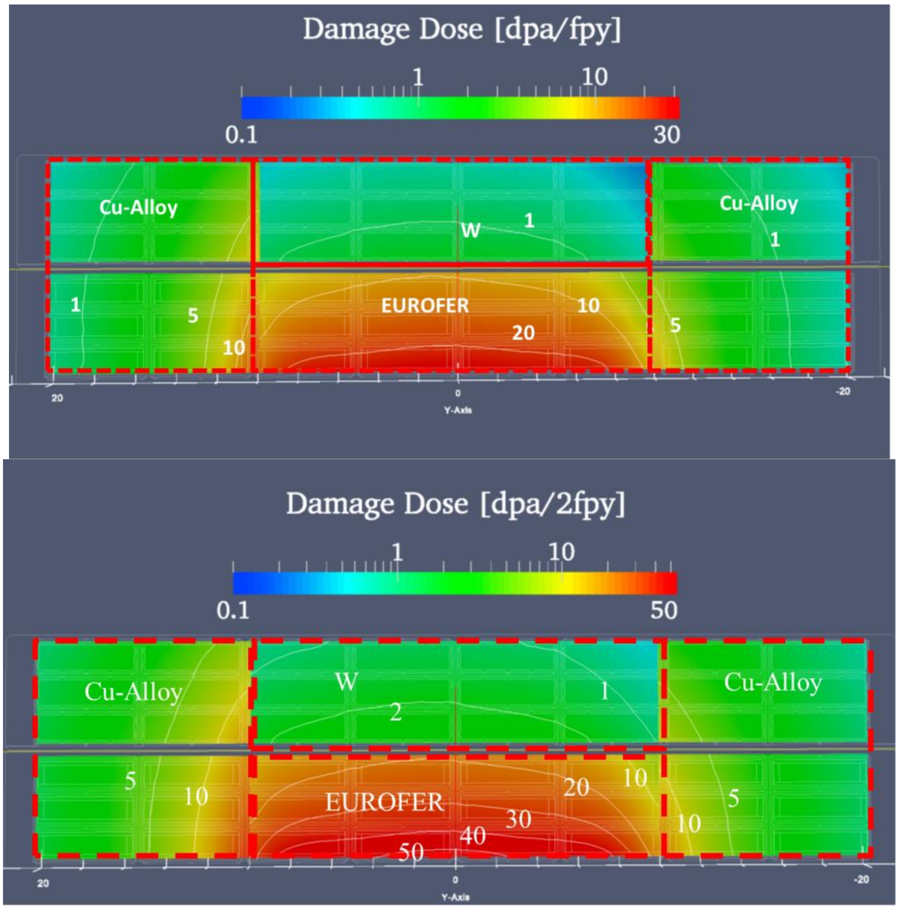


Figure 25.- Damage dose rate [dpa/fpy] horizontal section in the central part of the HFTM1 and HFTM2 for case 6; a) 1fpy of irradiation, b) 2fpy of irradiation

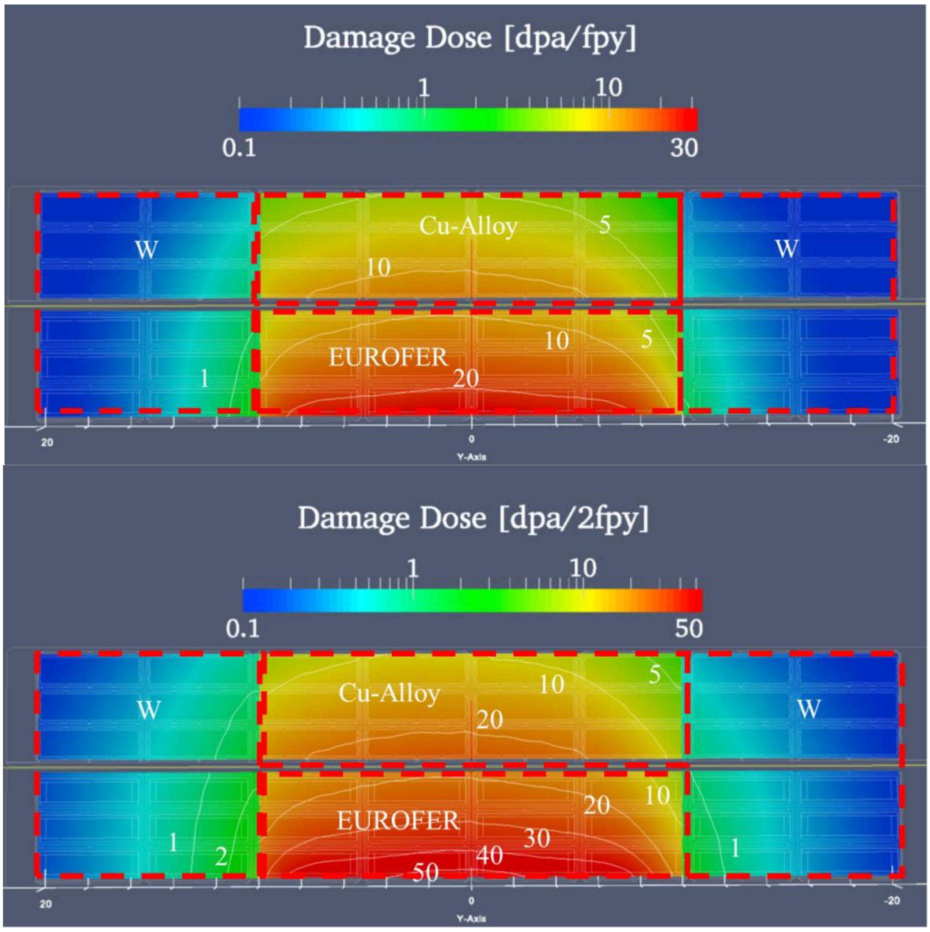


Figure 26.- Damage dose rate [dpa/fpy] horizontal section in the central part of the HFTM1 and HFTM2 for case 7; a) 1 fpy of irradiation; b) 2 fpy of irradiation

Respect to the gas production to damage dose ratio, in **Figure 27** and **Figure 28**, the He and H ration horizontal cup maps area shown for cases 6 and 7, respectively. In both cases, the He and H ratios are similar to cases 1, 2 and 3 in equivalent locations, i.e. the He rations do not suffer changes due to the presence of the rest of samples.

Therefore, in case 6 the He ration is the double of the nuclear fusion ones for tungsten samples and the H ratios is between three of four times higher than fusion ones. While for CuZrCr-Alloy the He and H ratios are lower and have a higher variation since they are located in the lateral rigs of both HFTMs. And contrary, in case 7 the He and H ratios for tungsten samples are still higher than the fusion ones and suffer a great variation from edge to the other because they are located in the lateral rigs. While the He and H ratios are optimum for CuZrCr-Alloy, since they are located in the central part of the HFTM2.

Therefore, designing irradiation experiments for Cu-alloys, Tungsten and EUROFER in a joint irradiation campaign following case 6 or case 7 configurations appears to be not suitable. Furthermore, respect to damage dose rate requirement and in irradiation campaign of 2 fpy the case 6 is appropriated to irradiated samples of the three materials evaluated, nevertheless, the He and H ratios are the less favourable than previous cases 2, 3, 4 and 6.

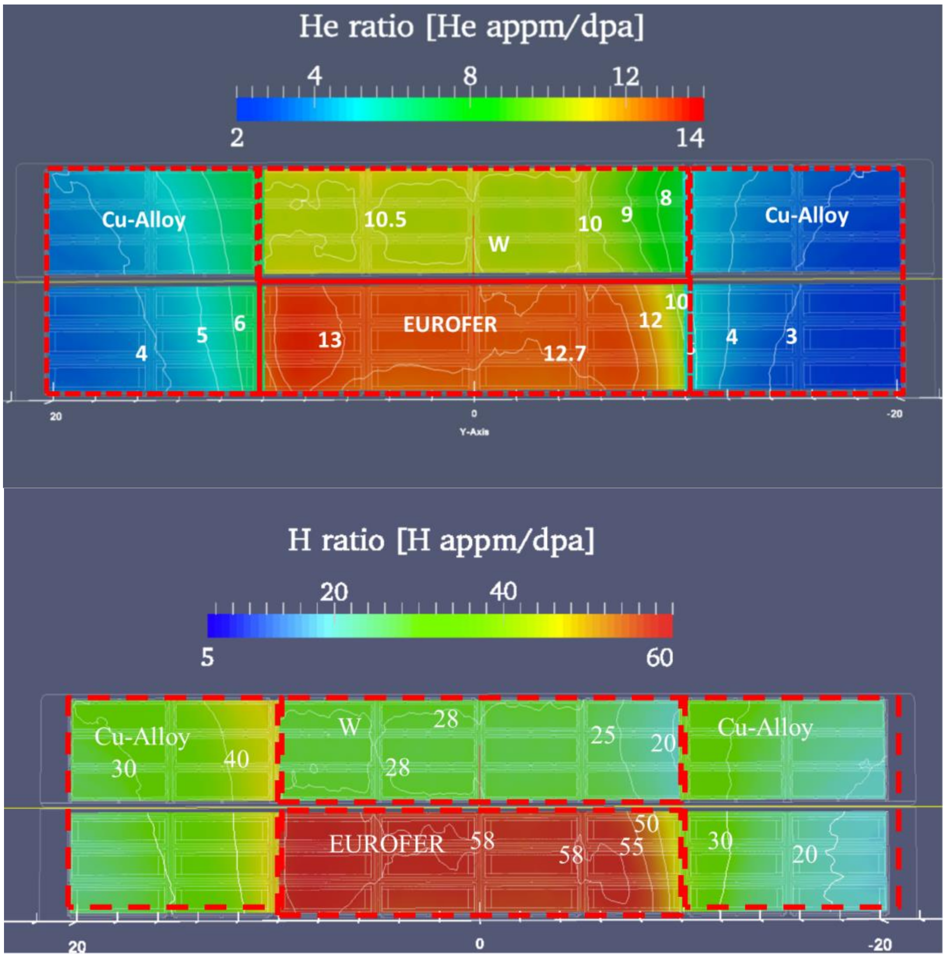
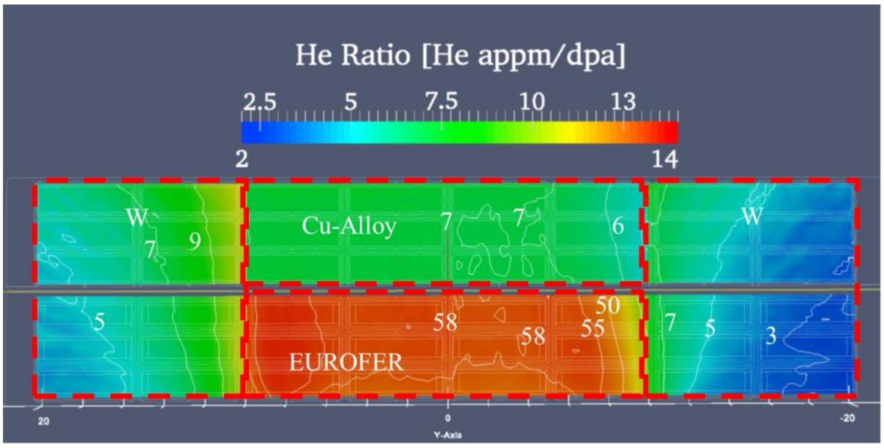


Figure 27.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally for the case 6; a) He ratio, b) H ratio



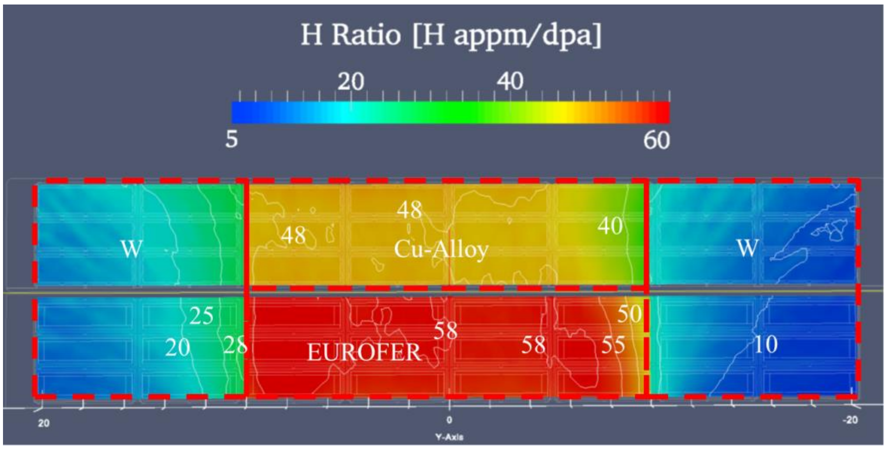


Figure 28.- Gas production to damage dose ratios [appm/dpa] horizontal section of the 3D mesh-tally for the case 7; a) He ratio, b) H ratio

Therefore, taking into account only damage dose rate requirements it is possible to design joint irradiation campaigns unless it is recommended that the campaigns combine only two kind of materials, i.e. EURFER-Tungsten (case 2) or EUROFER-CuZrCr-alloys (case 1), because the minimum required volumes are higher.

6. Conclusion

Neutron transport calculations have been performed to assess the potential use of the DONES-HFTM to irradiate tungsten and CuCrZr Alloys, which are foreseen to be employed in the first and second layer of a DEMO divertor, respectively, in equivalent nuclear fusion irradiation conditions. In this framework, an extended version of the HFTM with 6 rows of samples containers has been evaluated respect to the reference version with 3 rows. This has implied on the one hand to preform neutron transport calculations in the irradiation area of IFMIF-DONES to cross-check with the damage dose rate requirement stablished in the nuclear fusion roadmap document, and on the other hand to develop neutron transport calculation in a DEMO-DCLL in the divertor area with the aim to crosscheck both, the roadmap requirements and the gas production results obtained in IFMIF-DONES.

The main conclusion is that, for both, Tungsten and Cu-Alloys samples, the damage dose rate nuclear fusion damage requirements established (5dpa for CuZrCr-Alloy and 1 dpa for tungsten) in the frame of the EUROfusion roadmap are reached in the most of the irradiation area.

For CuZrCr-alloy samples the damage requirement is achieved in the central part of both HFTMs almost up to the rear part of the HFTM2, then, a great part of the volume of both HFTMs can be used to hold CuZrCr-alloy samples. In addition, the lateral parts of both HFTMs are not useful to the irradiation tests. Regarding to the gas production to damage dose ratios, for CuZrCr samples, on the one hand, the He ratio in the central part of both HFTMs is similar to the one calculated in the divertor area of a DEMO-DCLL and on the other hand, the H ration is a little bit higher, approximately a 25% higher, than the one calculated in the divertor area. Therefore, both HFTMs are a suitable area to design nuclear fusion equivalent irradiation experiments for CuZrCr-Alloy samples, taking into account damage dose rate and gas ratios results.

While, for Tungsten samples the damage requirement is fulfil in the central part of the HFTM, but only in the first row of the HFTM2, considering 1fpy irradiation campaign. Therefore, the available volume to irradiate samples is lower in this case or it is necessary to prolong the irradiation campaign up to 2 fpy in cases to share the space with EUROFER samples like in case 5. Respect to the gas production to damage dose ratio, on the one hand, the He ratio similar to the divertor area is obtained in the lateral part of the HFTM, but the damage dose rate is too low in this area. Furthermore, in the central part, in which is satisfy the damage requirement the He ratio is the double. On the other hand, the H ratio is three or four times higher than the ones calculated for the divertor area of a DEMO-DCLL. However, taking into account that the He and H ratios obtained in others kinds of neutron sources, fission or spallation are further, is the best result obtained together with the high damage dose rate. Therefore, the status is not so favourable than for the case of CuZrCr-Alloy but it is the best irradiation conditions achievable.

Comparing the cases 1, 4, 5, 6 and 7, in which EUROFER samples is involved, is observed that the useful volume to irradiate EUROFER samples with damage dose rates higher than 10 dpa/fpy or 20 dpa/fpy is the same in all the cases considered. Therefore, it means that on the one hand, the suitable volume to irradiate EUROFER samples corresponds to the central part of the HFTM, i.e. the volume occupied by the central 12 rings and on the other hand the tungsten and CuZrCr-alloys surrounding the EUROFER samples do not affect to the irradiation parameter experimented by the EUROFER samples.

Finally the best situation to design equivalent nuclear fusion irradiation experiments to test CuZrCr-Alloy and Tungsten samples is the dedicated irradiated campaigns i.e. the whole volume of the HFTM1 and HFTM2 filled up of samples of each material evaluated. However, the joint irradiation campaigns shown in case 4 and 5 are also suitable to design equivalent irradiation experiments, although for tungsten samples, case5, is better to reach 2 fpy of irradiation in order to increase the volume fulfilling the damage requirements.

Another important conclusion obtained from the results shown is that, whether 1fpy of irradiation is considered, extending the HFTM in strain forward direction is only useful for Cu-alloys and tungsten samples. Although for tungsten sample is only useful up to the fourth row. However, the nuclear fusion damage requirements is not achieved in the whole volume of HFTM2 for EUROFER samples, therefore the HFTM2 is not useful in a dedicated irradiation campaign for EUROFER samples. However, if the irradiation time is extending up to 2 fpy the HFTM2 is useful in anycase.

7. Acknowledgment

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