Dose rates evaluation of HiPER facility

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ARTICLE INFO
Article history:
Available online xxx
Keywords:
Prompt dose
Residual dose
Neutrón activation
Radiation shielding
HiPER project

ABSTRACT
During the operation of the HiPER first engineering facility, up to $1.2 \times 10^5$ MJ/yr of fusión neutrons yields are foreseen. This irradiation level could be distributed in 100 MJ detonations, accounting up to 100 detonations in a single burst, with 10 Hz repetition rate. A burst would take place every month. The dose rates are computed and different concrete shields are evaluated within the target bay. During the operation of the facility the entrance is forbidden inside the bioshield. Between bursts, manual maintenance might be performed inside the bioshield but outside the final optics assembly (FOA) shield. Inside the FOA shield the residual dose rates are so high that only remote maintenance is allowed. The FOA shield reduces the delivered dose rate to optics in a factor of 30.3.

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1. Introduction

The HiPER phase 4 engineering facility irradiation scenario is not still decided. The most demanding one, up to the moment, has been thought to consist of $1.2 \times 10^5$ MJ of neutrons yield per year. The D-T detonations could achieve 100MJ of fusión (14.1 MeV peaked distribution) neutrons yield. Distributed in bursts, up to 100 detonations could take place in an only sequence, with a repetition rate of 10 Hz. A burst could be performed every month or less.

This high neutrons yield makes necessary the study of the radiological implications of the operation of the facility. The workers are exposed to neutrons and gamma yields. The dose rates are compared to the recommendations given in ICRP74 [1], 20mSv/yr for workers (10 μSv/h distributed in 8 h of work during 50 weeks).

The final optics assembly (FOA) is one of the most sensitive parts of the facility to the radiation. Even when the shields are designed to protect the workers, it is mandatory to compute their effect on the dose rate delivered to the FOA for further considerations.

The design studied in this paper consists of a reaction chamber, 48 beam tubes, 48 renewable lenses and 48 FOA assemblies of 6 optical elements each one [2]. To accomplish a correct operation of facility, four concrete shields have been added and evaluated in different parts of the design.

During the operation, we have computed the absorbed dose rate in the FOA and the ambient dose equivalent (ADE) to workers inside the facility. Then, considering the resulting activation of the components, we have calculated the ADE delivered to the workers between bursts. Dose rates during operation and between bursts are computed as independent and they are summed because the working plan is not defined and total exposures cannot be computed.

With this information we have evaluated the different shields and made recommendations on the maintenance procedures. If necessary, further studies would be carried out on FOA specifically.

2. Design proposal

This study is focused on the target bay. It has to be understood as that part of the reactor building where the radiation level demands special attention. It is considered to be the rooms inside the bioshield.

2.1. Basic components

The reaction chamber is the closest component to the detonations. A 10cm thick, 10 m of inner diameter spherical shell, it is assumed to be built of stainless steel SS304L [3] because its good equilibrium between neutrons activation, thermomechanical properties and economics. There would be 48 beam penetrations in the reaction chamber, distributed into six rings, with the angular distribution specified in Table 1. There are only three rings described since the lower part of the chamber is a specular reflection on the plane $z = 0$, and rotated 23.36°. The penetrations are 40 cm radius rings. Diagnostics penetrations are not considered in this study.

In order to accomplish the inertial laser-driven fusión D-T reactions, the láser should be entered into the chamber from the láser bay. The láser beams are transported inside the beam tubes, where
### Table 1

<table>
<thead>
<tr>
<th>( N_r )</th>
<th>( \theta_r(\degree) )</th>
<th>( \rho_r(\degree) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>21.23</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>47.03</td>
<td>23.36</td>
</tr>
<tr>
<td>12</td>
<td>74.95</td>
<td>29.83</td>
</tr>
</tbody>
</table>

The reaction chamber shield is a 40 cm thick of borated gunite concrete spherical shell, adopted from NIF design [6]. This shield is pursued to reduce the dose rate between bursts due to the activation of the chamber as well as reducing the total amount of neutrons, which activate the whole facility.

From 15 to 17 m from the center of the reaction chamber, there is a spherical shell shield, called the FOA shield. Despite its name, it has consequences in many aspects: it protects the FOA against high doses in operation, helps to reduce the total dose rates delivered outside the target bay and reduces the dose rates between bursts after it. This shield creates two different areas inside the target bay and allows certain manual maintenance in the external one.

It has been modeled as a spherical shell because this geometry improves the efficiency of the Monte Carlo modeling and simulation. In order to explore different thicknesses, it was thought to be the best approach. Once the shield thickness is decided according to dose limit criteria, this shield will adopt another form, with better constructive and structural properties.

The rims, the beam tubes and the penetrations in FOA shield represent a free way for the neutrons to spread out, and in order to protect the FOA, there is a cylindrical shield placed inside the beam tubes. As the beam travels, it adopts a variable focusing profile. Where the beam is focused (minimum spot size), at 16 m from the center of the chamber, the center of this shield is placed, presenting a 5 mm radius pinhole to allow the beam to pass through. It is a 2 m long, 1 m diameter cylinder, which lies in the final optic shield, in the transition between one tube and its prolongation after the final optic shield. Other materials for the pinhole shield different to concrete will be tested in further studies.

Finally, as high neutron yields are expected, it has been added a 2 m thick bioshield at 25 m from the center of the reaction chamber. Its aim is to definitely separate the target bay from the rest of the facility.

Inside the target bay there are two different rooms, called area 1 and area 2; (see Fig. 1) the two first meters of air outside the bioshield, i.e., the exterior of the target bay, are referred as the area 3.

The composition of no-borated concrete assumed in this study for the FOA shield, pinhole shield and bioshield is taken from [7].

### 3. Methodology and assumptions

**3.1. Methodology**

To perform this study we have used the following methodology. The first step has been to design the geometry of the facility using MCAM [8] code. This is a tool conceived to draw and translate complex geometries into Monte Carlo transport codes.

Once the geometry was decided [2], with MCAM it was generated an input file valid for MCNPX [9] transport code. The resulting neutrons transport from the detonations was performed with MCNPX and cross-section libraries lal 50n, endf60 and endf92, depending on the availability for every isotope. The absorbed dose rate in the FOA was calculated directly with MCNPX. With the flux-to-dose conversion coefficients [10] for ambient dose equivalent, the dose rates to workers were calculated. Extended vitamin-J

![Fig. 1. HiPER design to study neutronics and activation, performed with MCAM.](image1)

![Fig. 2. Scheme of computational methodology.](image2)
Residual dose rate between burst

- zone 239U1 — zone 223Mi — zone 3 239th — zone 1st — zone 21st — zone 3 1st

Fig. 3. Residual dose rate in the three different areas after the 1st and the 239th burst. The red line stands for the hands-on maintenance, 10 μSv/h. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The source neutrons have been assumed to be born according to a direct drive inertial fusion detonation spectrum [13].

With ACAB code [11] and the EAF activation libraries [12], it was then computed the activation derived from the exact pulsed regime of the reactor for every component of the facility. With MCNPX the resulting decay gammas were transported through the target bay and the residual dose rates were computed, again with the ICRP coefficients.

3.2. Assumptions

The source neutrons have been assumed to be born according to a direct drive inertial fusion detonation spectrum [13].

Concerning with the dose rates between bursts, as there is no specific procedure for the maintenance up to now, the general idea of what happens in every area is given by the average ADE in that area.

Outside the target bay, the ADE is averaged in the first 2 m of air, representing the closest position of a person to the bioshield.

It has to be kept in mind that the average dose rates represent no more than estimates. In order to compute the accurate dose rate received by the workers it is necessary to know the whole activity, the place where it is carried out and its duration.

The absorbed dose rate to the FOA has been averaged in the whole group of lenses in order to increase the efficiency of the simulations. So, the results are average dose in all the lenses. When further decisions were made on the design, a more precise calculation will be carried out in every single component (Fig. 2).

With regards to the composition of the different materials, reasonable concentrations of impurities have been assumed for SS304L [3] and concretes [6,7]. The SiO2 has been considered to be puré.

Fig. 4. Contribution of different components to the residual dose rate in area 1.
4. Results and analyses

The presence of the FOA shield affects dramatically to the absorbed dose rate in this group of lenses during operation. We have computed the absorbed dose rate in the FOA every year considering the absence and presence of the FOA shield, being present in both cases the pinhole shield.

The results, in Table 2 show that this shield reduces in a factor of 30.3 the total dose delivered to these components. If those levels of irradiation result to be unacceptable in the FOA, further protection will be added.

The ADEs to workers (Table 3) indicate that entrance is not allowed area 1 and area 2 during the operation of the reactor. The exterior of the target bay fulfills the conditioning of representing a dose rate below the limit to workers.

The high radiation level present inside area 1, and even in area 2, makes necessary to carefully design and protect the electronics which could be present in these areas during the operation of the reactor.

The time evolution between bursts of the ADE to workers is depicted in Fig. 3. The cumulative effect of long-live radioisotopes makes the residual dose rate to increase in up to a factor of 4 between the first and the last burst.

The contributions between bursts of every activated component to the total ADE to workers in areas 1 and 2 are depicted in Figs. 4 and 5. The residual dose rate in area 3 is exclusively due to the activation of the bioshield.

The entrance in area 1 is forbidden also between bursts. There are several activated components, which represent an ADE much higher than 10 μSv/h during the whole month. Thus, in case that maintenance was necessary, robotics would be essential. From 1 h after the shutdown to the next burst, the main contributors to the dose rate are the beam tubes, the optical shield and the rims. However, due to the high dose rate, it is not worthwhile to try to reduce it.

It is not the case for the area 2. Around 36 h after the first burst, the ADE falls below the 10 μSv/h limit, and workers could enter 8h per day. However, two facts must be kept in mind. The first one is that the average dose is an estimate, and in order to make decisions on the maintenance, it is necessary to know the activity to be carried out, the position, and the exposure time. The second fact is that even when workers could not stand inside the area 2 for 8h per day, as bursts happen, collective dose planning could allow manual maintenance.

Another alternative is to act on the second beam tubes, as they are the main responsible for this dose rate after some minutes. Different strategies are: to shield the tubes against neutrons, to shield the workers against the gamma that they emit or choosing another material with lower activation at these timescales.

The area 3 is below the recommend limit for the public and the workers, so, it stands for the exterior of the target bay.

Table 2
Prompt dose rate delivered to the FOA considering the absence and presence of the final optic shield.

<table>
<thead>
<tr>
<th></th>
<th>No-shield (Gy/yr)</th>
<th>Shielded (Gy/yr)</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>571</td>
<td>34.1</td>
<td>16.7</td>
</tr>
<tr>
<td>Gamma</td>
<td>891</td>
<td>14.2</td>
<td>62.7</td>
</tr>
<tr>
<td>Total</td>
<td>1460</td>
<td>48.2</td>
<td>30.3</td>
</tr>
</tbody>
</table>

Table 3
Prompt dose rates to workers averaged in areas 1, 2 and 3.

<table>
<thead>
<tr>
<th></th>
<th>Area 1 (Sv/yr)</th>
<th>Area 2 (Sv/yr)</th>
<th>Area 3 (Sv/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>3.46 x 10^5</td>
<td>32.9</td>
<td>1.69 x 10^5</td>
</tr>
<tr>
<td>Gamma</td>
<td>8.70 x 10^3</td>
<td>0.63</td>
<td>1.88 x 10^3</td>
</tr>
<tr>
<td>Total</td>
<td>3.55 x 10^5</td>
<td>32.6</td>
<td>2.05 x 10</td>
</tr>
</tbody>
</table>

5. Conclusions

The shielding requirements for a preliminary HiPER design have been analyzed.

The absorbed dose rate during operation in the FOA reaches values of 1460 Sv/yr in the absence of FOA shield. The FOA shield reduces this quantity to 48.2 Sv/yr, a reduction of a factor 30.3.

During the operation, workers are not allowed to enter in areas 1 and 2, while the area 3 fulfills the recommendations to workers regarding with dose rates.

Maintenance inside area 1 must be strictly remote. Inside the area 2, it is expected manual maintenance after some considerations, planning and likely modifications of the design. In area 3, manual maintenance is recommended.
Acknowledgements

This work has been performed for HiPER: European High Power Laser Energy Research Facility (Preparatory Phase Study). The authors gratefully acknowledge the support of the funding agencies in undertaking this work (EC FP7 project number 211737): EC, European Commission, MSMT, Ministry of Education, Youth and Sports of the Czech Republic and STFC, Science and Technology Facilities Council of the United Kingdom.

The authors thank to Bruno Le Garree from CEA for providing the information of the preliminary design of the HiPER reactor and helpful and fluid communication during the development of this study.

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