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Radiation effects in IFMIF Li target diagnostic systems

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A B S T R A C T

Diagnostics for the lithium target will be crucial for the operation of IFMIF. Several parameters as the lithium temperature, target thickness or wave pattern must be monitored during operation. Radiation effects may produce malfunctioning in any of these diagnostics due to the exposure to high radiation fields. The main diagnostic systems proposed for the operation of IFMIF are reviewed in this paper from the point of view of radiation damage. The main tools for the assessment of the performance of these diagnostics are the neutronics calculations by using specialised codes and the information accumulated during the last decades on the radiation effects in functional materials, components and diagnostics for ITER. This analysis allows to conclude that the design of some of the diagnostic systems must be revised to assure the high availability required for the target system.

1. Introduction

A liquid lithium target will be used in IFMIF to produce the neutronic irradiation as a result of the deuterium–lithium stripping reaction. The lithium target will be at the intersection of the three main systems: the accelerators, the lithium loop and the test facilities. The target assembly will consist of a liquid lithium curtain flowing at 10–20 m/s and 250 °C from a nozzle and on a curved back plate [1,2]. The curvature of the back plate (25 cm) will produce acceleration in the lithium of 160 g which will increase the boiling temperature to 1090 °C. An average heat load of 1 GW/m^2 will be deposited on a lithium volume of 20 cm width, 5 cm height and 25 mm thick. Several parameters will be critical during the operation for the good functioning of the whole installation: the Li temperature, its thickness, its velocity, the wave pattern and wave amplitude or the state of the back plate and the nozzle. Additionally, the availability of the system should be higher that 95%, a challenging requirement as far as the erosion and corrosion induced by the lithium flow in the nozzle and on the backplate are concerned.

The required diagnostic systems for such in-beam measurements will be exposed to high radiation fields, both gamma and neutrons. Malfunctioning of any of these diagnostics may arise due to radiation effects in materials and components. The objective of this paper is to assess on the radiation effects on the presently proposed diagnostic systems. Assessment will be based on data calculated by specialised neutronics codes and the radiation effects in materials and components reported the last 10–15 years during the research performed for ITER functional materials.

2. Calculation of radiation fields in the target assembly volume

The d–Li neutron source and neutron transport was simulated by the Monte Carlo code McDeLicious [3]. This code is an extension to MCNP-4C with the capability of simulating the generation of neutrons, γ-rays and other d–Li reaction products on the basis of evaluated Li(d,xn) data [4]. Neutron cross sections from general purpose high energy libraries [5,6] were used for the transport and nuclear response calculations.

A comprehensive three dimensional model has been recently developed to represent the IFMIF Test Cell for the Monte Carlo calculations [7]. It includes the latest IFMIF design modifications and describes in detail the geometry and material specifications of the IFMIF Test Cell: the deuteron beam pipe, the lithium loop, the Vertical Test Assemblies accommodating the High, Medium and Low Flux Test Modules, as well as the cover, walls and floor of the Test Cell.

Fig. 1 represents the energy deposited in SiO_2 in the horizontal plane containing the deuteron beams. These calculated data represent the main input information for the assessment on the radiation effects in the diagnostic systems. *Z*-axis is the deuteron downstream direction. The origin of this reference system is in the centre of the lithium target. Silica was chosen because most of the diagnostics will be based in optical measurements using this

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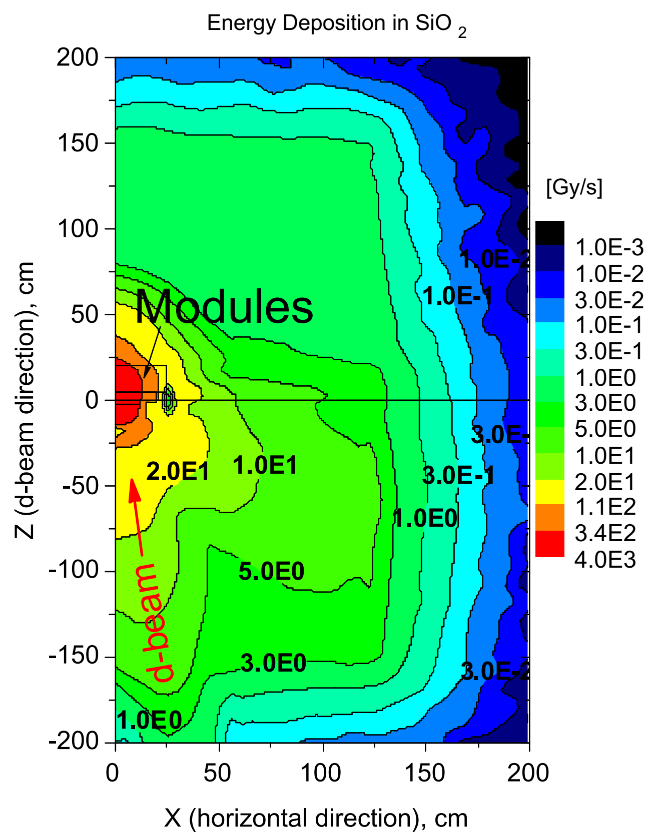

Fig. 1. Horizontal cut of Li target, test modules and test cell along *Z*-axis (deuteron beam downstream direction) and half of *X*-axis direction (horizontal direction). Numbers express the radiation energy deposition in glass in Gy/s.

kind of material for windows, lenses and optical fibres. Calculation in different insulating materials as MgO or Al_2O_3 would not produce very different results. A large volume around the target was considered in the calculations to include most of the points where the critical diagnostic components will be located. The energy deposited in the material, indicated by numbers and colours in the figure include the neutrons and gammas.

3. Assessment of the radiation effects in proposed diagnostics

The most serious problems reported for ITER functional materials and components are radiation induced conductivity (RIC), radiation induced electrical degradation (RIED), radiation induced optical absorption, photoluminescence (PL), changes in the refraction index (and as a result in lens characteristics) and radiation induced electromotive force (RIEMF) [8–10]. These problems gave rise often to ITER design modifications, such as labyrinths to reduce the dose rate in the optical components down to 10^{-2} Gy/s, or to a revision of materials to be used [11].

Radiation field close to the target may be as high as several hundred Gy/s (see Fig. 1). This dose rate is much higher than that expected for ITER diagnostics and close to the dose rate in ITER first wall. Many of the radiation effects studied along the last decade in functional materials for ITER may also appear in the Li target diagnostics since they will be mainly based on electrical and optical measurements.

3.1. Infrared camera system for lithium temperature measurement

The infrared camera (IR) is at present the reference system for the measurement of target temperature [12]. This system will require several optical components that may suffer several radiation effects.

Depending on the design, a *focusing lens* will be required to form an image of the target on the transmission line. It would be located quite close to the target being exposed to a relatively high radiation field. The distance between this lens and the lithium target may be between 30 and 50 cm. From the neutronics calculations, see Fig. 1, one may estimate the dose rate in the lens between 20 and 50 Gy/s. Experiments with silica lenses to be used in ITER diagnostic systems were performed to assess on the radiation-induced changes in the refraction index or in visible transmission. No changes was observed neither in refraction index nor in visible transmission following the irradiation experiment; but the irradiation was performed with gamma rays and only up to 100 MGy [13]. No experiments with neutron irradiation were performed. Under the expected radiation flux in IFMIF, the 100 MGy dose may be overcome in one or two months. Changes beyond this dose, under gamma irradiation, or potential changes under neutron irradiation are unknown. Specific experiments would be required to assess these potential changes focusing on the specific IR wavelengths.

The radio-luminescence produced in the *optical fibres* may be a serious problem in this diagnostic system. If the radio-luminescence is too intense it may result in the impossibility to transmit a reasonable image of the target. These optical fibres will be located at 1–2 m from the target and will transmit the image to the IR camera placed at 20 m. Experimental data obtained in silica indicate that for the expected dose rate for this component (5 Gy/s in the target end and 5×10^{-4} Gy/s in the IR camera end) will not be excessively high but a careful selection of material must be done to reduce this effect taking into account the experience obtained for ITER R&D [14]. Experimental or theoretical validation of the signal to radio-luminescence ratio may be required.

The plasma facing components in ITER will be mirrors instead of lenses due to their minor sensitivity to radiations. As a consequence radiation effects in *mirrors* have been also one of the concerning problems that required dedicated studies during the R&D on functional materials for ITER diagnostics. Mirrors may be required in the IR camera system located at around 10 m from the target. The neutron flux at the mirrors may be around 4×10^8 n/cm^2/s. It is known that up to 10 MGy no major effects are expected provided that no humidity is present [15], but high doses of neutron irradiation can cause surface degradation and reflection loss. Even a worse effect can be expected in the case of IFMIF where some Li corrosion will be present and radiation will enhance it. This is an important issue since probably a large number of diagnostics will end with a mirror near the beam target as in most of the ITER diagnostics.

3.2. Wave pattern

The wave pattern measurement is extremely important. The deuteron deposition profile will have a sharp peak of about 0.4 mm at around 2.1 cm from the lithium surface, the thickness of the lithium flow being about 2.5 cm. This means that around 50% of the total input power will be deposited in a layer located at a few mm from the backplate. Any change in the lithium level due to surface waves could lead to a backplate overheating (and even destruction) and to a non complete deuteron absorption by the lithium. Level changes over ±1 mm should trigger an interlock system aimed to shut down the accelerator in a very affordable way. Two different systems have been proposed, a mechanical diagnostic, less precise but more affordable and an optical diagnostic.

The mechanical diagnostic consists of a simple array of metallic contact probes strictly connected to a level transducer positioned just downstream with respect to the beam footprint to avoid the effect of the Li flow perturbation in the beam footprint area [12]. The main components of such a device would be just a 4-pins probe and a stepping electrical motor. In spite of its simplicity this electrical conductivity probe may give rise to several problems due its proximity to the target. Metals may suffer a serious swelling when exposed to neutrons [16]. This swelling may give rise to a change of size as high as 10%, i.e. 7 mm in the 7 cm probe pins, what may be really important when the required space resolution is 0.01 mm. Ceramic MgO material is proposed for insulation between the probe pins. Radiation effects on its electrical properties probably will not be important [17,18] but lithium ions coming from the hot target will be impacting against the insulators that following some time may be short circuited. The stepping motors need a number of coils to produced magnetic fields. The insulator covering the thin cables used to construct the coils is usually a thin film made of some polymeric material which is very sensitive to radiation. The swelling, due to radiation, in the central metal gear of the motor may be also a source of problems.

The optical diagnostic system is based on the measurement of the wave pattern by a stereoscopic system. Two CCD cameras symmetrically positioned with respect to the beam axis would image the beam footprint area [19]. The CCD cameras with two optically transparent windows will have to be placed in such a way that the angle between the two sight lines is close to 90°. The design of this system is not yet available but according to the conceptual designs of the target assembly the probable position would be at a distance of around 1 m and under an angle near 45° with respect the main axes. The radiation field would be quite intense at this distance, around 7–8 Gy/s. Optical diagnostic windows in ITER have been protected by labyrinths to reduce the radiation flux down to 10^{-2} Gy/s [10,11]. Otherwise transparency could be rapidly reduced. As an example of the tolerable level in this kind of materials, measurements in KU1 and KS4V showed that, up to 10^{22} n/m^2, windows are still transparent enough in the visible range but experiments with higher doses would be needed to set operation limits [20].

3.3. Back-plate and nozzle erosion

Surface roughness of the back plate and of the nozzle is a parameter to keep under control since it has been proven by different experiments that there is an influence of surface roughness on fluid stability [21]. Erosion during the IFMIF operation may be even worse than in the experiments since vapour bubbles, created by the strong Lithium temperature, could generate intense shock waves responsible of the so-called pitting erosion patterns.

The accuracy of roughness measurement should be in the Micron range since changes in this scale may already affect the lithium fluid-dynamics. The optical interferometer technique has been proposed as diagnostic system to provide a measurement of the roughness. A laser beam and a CCD camera are the main components of this system [21,22]. In order to achieve a satisfactory resolution, the CCD camera cannot be placed very far away from the nozzle. Both the camera and its windows should be at a maximum distance of 5–10 m. The measurement accuracy decreases linearly with the camera-target distance. A compromise has to be found between the maximum radiation level allowed and the measurement accuracy. A radiation field of about 10^8–10^9 n/cm^2/s is expected at this distance. Radioluminescence may be expected in the window under this radiation flux. The window material should be carefully selected. Experiments to validate the diagnostic system under irradiation should be performed. Experience for ITER indicates that amorphous silica can be a good starting candidate. The gravity of this effect will depend on the wavelength. Specific experiments for the used wavelength and phase should also be evaluated. By using mirrors, the laser can be positioned far away from the high radiation area. In that case, the last mirror facing the lithium target may be a source of concern.

4. Conclusions

Following the analysis of the proposed diagnostics, the radiation field at which they would be exposed and the information available in the literature on radiation effects in relevant materials and components we can summarize the following most concerning points:

- Changes in refraction index for the IR camera system: there are no data beyond an accumulated dose of 100 MGy. This limit may be overcome in IFMIF in two months operation.
- Swelling in the metallic contact probes for wave pattern: radiation will give rise to an elongation of several per cent depending on the material and the exposition time. It may be a serious problem since it will give rise a false wave measurements.
- Radioluminescence and Radiation induced optical absorption in windows for optical systems were protected in ITER to reduce the dose rate down to 10^{-2} Gy/s. The dose rate in IFMIF will be several Gy/s depending on its location. This may be a serious problem depending on the wavelength. As the accuracy of these systems will depend on its distance to the object, a compromise must be found between the lost of accuracy and its exposition to radiation.

Radiation effect on these critical components should be revised in detail in order to assure the high performance required for the target system. During the ongoing Engineering Validation and Engineering Design Activities (EVEDA) of IFMIF, which aims at producing the complete design of IFMIF by summer 2013 [23], diagnostics for the lithium target will be proposed and designed. The construction and the tests of a Li loop target prototype will offer a unique opportunity to check the good performance of the diagnostic systems but additional validation of their good performance under irradiation should be addressed.

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