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The Radiation Damage Calculation and Possibility of Irradiation Simulation Experiment of the Beam Window Used for Accelerator-Driven Transmutation System

G. C. Kim, T. Y. Song, W. S. Park

Korea Atomic Energy Research Institute
P.O. BOX 105, Yusong, Taejon, Korea 305-600

Abstract

HYPER (**HY**brid **P**ower **E**xtraction **R**eactor) is the accelerator-driven transmutation reactor developed by KAERI. Pb-Bi is used as the coolant and target material for HYPER. HYPER adopts 1 GeV, 20 mA proton beam and beam window is exposed to that proton beam and neutrons produced by protons. We select low activation martensitic/ferritic steel such as 9Cr-2WVTa as the beam window material. It is essential to know the radiation damage of the beam window for window design and lifetime prediction. We calculate ***dpa*** (displacement per atom) due to protons and neutrons. We also calculate He production. Then Fe and He ion implantation experiment is discussed for irradiation simulation experiment.

I. Introduction

HYPER (**HY**brid **P**ower **E**xtraction **R**eactor) is the accelerator-driven transmutation reactor developed by KAERI [1]. Lead-bismuth liquid is used as the coolant and target material for HYPER. The beam window is irradiated by 1 GeV, 20 mA proton beam. The beam window is also irradiated by neutrons which are produced by both spallation reactions of Pb-Bi and fission reactions of minor actinide fuels. Therefore radiation damage of the beam window is one of the important subjects to be studied.

Several materials were considered as window material. Although stainless steel and conventional martensitic/ferritic steel (CMFS) are widely used in nuclear industry, low activation martensitic/ferritic steel (LAMFS) is the most appropriate material for fusion and spallation sources [2-6]. Stainless steel and

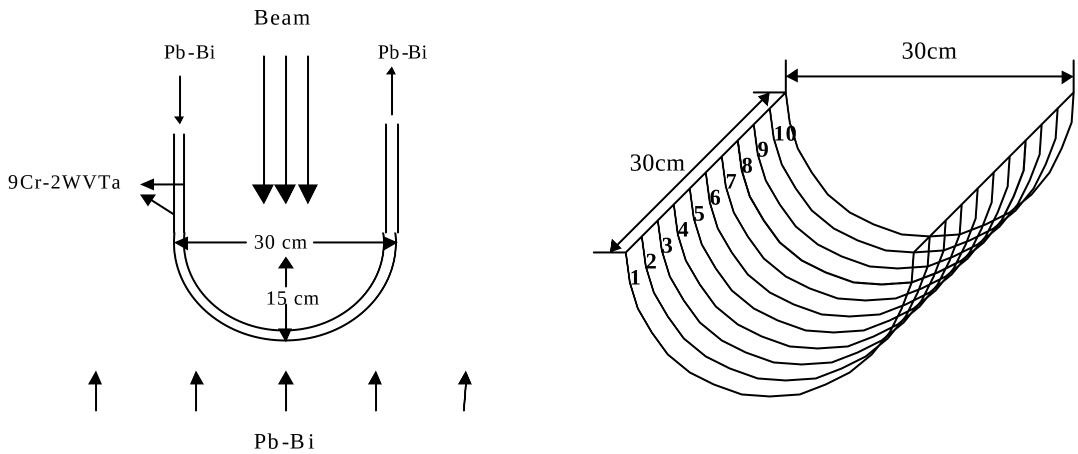
CMFS have undesirable composition elements for spallation sources. For instance, nickel creates helium in the course of two step $^{58}Ni(n,\gamma)^{59}Ni$, $^{59}Ni(n,\alpha)^{56}Fe$ nuclear reactions. Nickel also causes corrosion problem when used with liquid Pb-Bi [7]. Molybdenum and niobium in CMFS form long-lived radioactivity nuclides that will cause additional problems [8]. Therefore we have selected LAMFS such as 9Cr-2WVTa as beam window material [9].

The working temperature of the window is about 300-500 ^{0}C and the window is exposed to thermal and mechanical loads due to the flow of liquid Bi-Pb and non-uniform radiation heating of proton beam. The lifetime of the window is decided based on those factors, corrosion of window material and gas production (helium, hydrogen). The mechanical properties of the window vary according to the radiation damage due to proton and neutron irradiation. The experimental data for materials irradiated under spallation condition is not much available. Therefore experimental data of fission/fusion or other simulation experiments are used for the prediction of the radiation damage under spallation condition although it is not exactly correct.

To predict the efficiency of beam window accurately it is needed to evaluate the level of radiation damages and gas production, and to consider the possibility of ion bombardment experiment. In the working temperature hydrogen diffuses very fast and only small amount remains in window, therefore only helium production is estimated.

II. Target Geometry and the Radiation Damage Calculation of Window

Figure 1 shows target and window geometry. The cross-section of beam tube is 30 cm x 30 cm squre and the window has a cylindrically curved profile. The window is cooled by flowing liquid Pb-Bi.



(a) (b)

Figure 1. Target and window geometry

Although the appropriate width of the coolant channel will be decided after the thermal hydraulic calculations are completed, the thickness of window and channel width are a few mm order.

The window is bombarded by 1 GeV, 20 mA circular proton beam with the diameter of 10 cm which falls in center of the window. Uniform and parabolic forms of proton beam are considered. In case of the uniform proton beam, current density is 255 $\mu A/cm^2$ and maximum current density is 500 $\mu A/cm^2$ in the center of the parabolic proton beam.

Concept of ***dpa*** (displacement per atom) is used for the calculation of radiation damage of window. Value of ***dpa*** due to neutron is calculated by integrating the neutron flux with the displacement cross-section. Because the window material is iron alloy (> 90 % Fe), we use displacement cross-section of iron. Data of Doran [10] is used for neutrons with energy range ($E_n \leq 15$ MeV) and data of Konobeev [11] with energy range ≥ 15 MeV. For evaluation of damage due to proton the displacement cross-section of 3000 barn is adopted based on the results from references 4, 12 and 13 [4,12,13]. Data for helium production cross-section is taken from references 14 and 15[14,15] and from calculation of Filges [16].

Spallation neutron spectrums and flux are calculated by using LCS code [17]. Calculations are performed for different parts of window. Figure 1(b) shows segmentation and surface numbers.

III. Calculation Results and Discussion

Figure 2 shows the neutron spectrums of surfaces 5 (window center), 4 (beam edge) and 1 (window edge) for the case of uniform proton beam. The neutron spectrum is not sensitive to the shape of proton beam, but it becomes softer at window edge. Table 1 shows neutron flux for each surface.

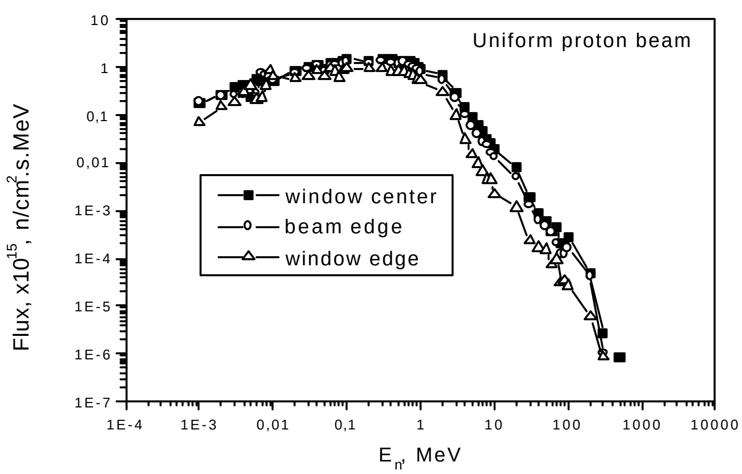


Figure 2. Neuton energy spectrums for uniform proton beam.

Table 1. The distribution of neutron flux for uniform and parabolic proton beam

Surface	Uniform Beam	Parabolic Beam
1	1.2×10^{15} n/cm^2.s	1.2×10^{15} n/cm^2.s
2	1.4×10^{15}	1.4×10^{15}
3	1.7×10^{15}	1.7×10^{15}
4	2.3×10^{15}	2.2×10^{15}
5	2.7×10^{15}	2.8×10^{15}
6	2.7×10^{15}	2.8×10^{15}
7	2.3×10^{15}	2.2×10^{15}
8	1.7×10^{15}	1.7×10^{15}
9	1.4×10^{15}	1.4×10^{15}
10	1.2×10^{15}	1.2×10^{15}

Figure 3 shows the integral displacement rates due to neutrons for different surfaces of window in case of uniform proton beam. Maximum displacement rate is 78 dpa/y at the window center and rate decreases to 25 dpa/y at window edge. In case of parabolic proton beam, displacement rates due to neutrons do not change significantly and rates are 82 and 25 dpa/y at window center and edge respectively.

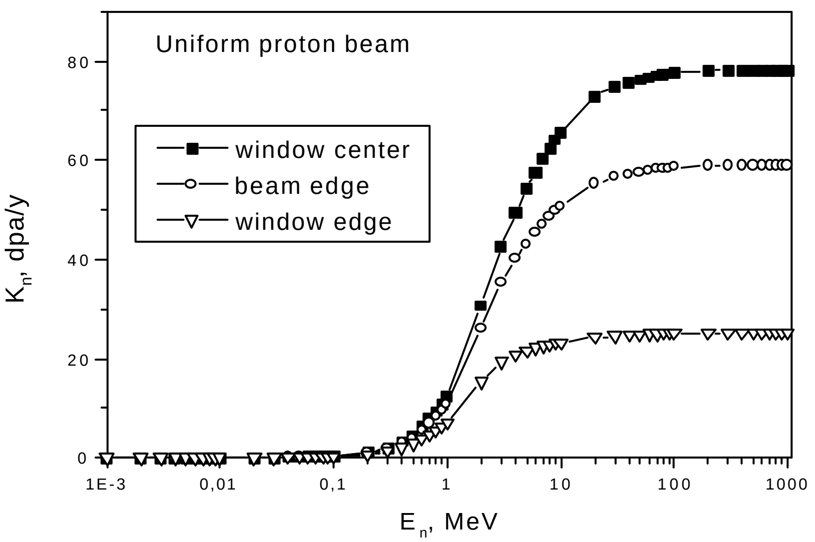


Figure 3. Displacement rates due to neutrons with energies below E_n

For the uniform proton beam displacement rate due to proton is about 150 dpa/y. In case of parabolic beam, displacement rate due to proton reaches 300 dpa/y at window center.

Figure 4 shows the total *dpa.* It is about 380 dpa/y at the center of the window in case of parabolic proton beam. We can see that total radiation damage is determined mainly by distribution of displacements due to protons. Therefore window shape is to be designed to minimize displacement rates.

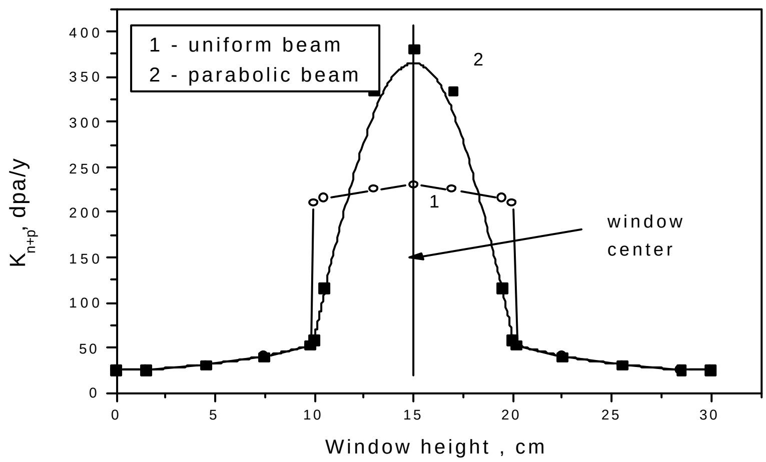


Figure 4. Total displacemnets per atom

The helium production rates K_{He} of HYPER window are shown in Figure 5. Helium is created by neutrons with energy 5-300 MeV and maximum helium production rate is about 410 appm He/y for uniform and parabolic proton beams.

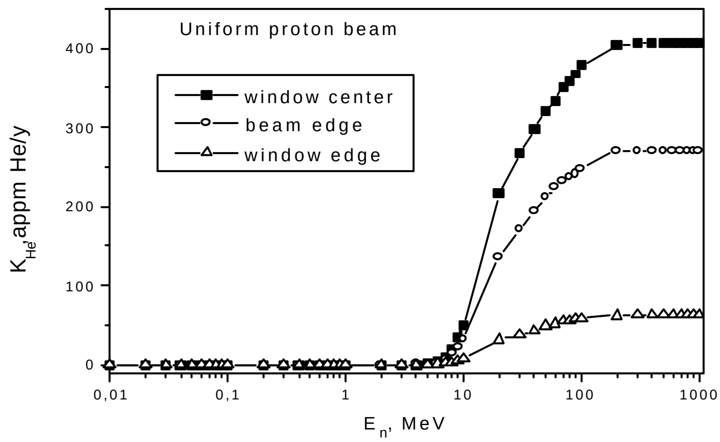


Figure 5. He production rates due to neutrons with energies below E_n

Helium production due to proton bombardment is about 30000 appm He/y in case of uniform proton beam and two times as large as at window center for parabolic proton beam. Therefore total maximum helium production is above 60000 appm He/y and so-called He/dpa ratio varies from 2 appm He/dpa at window edge up to 130-160 appm He/dpa at window center depending on forms of proton beam. High helium production causes problems because helium is accumulated in materials as bubble, especially at grain boundaries and mechanical properties of materials are changed [18].

IV. Simulation Experiment

Once the radiation damage calculation is performed, we need to study how properties of the window material change as the total *dpa* and He production change. The best way is to do irradiation experiments under the real proton beam condition. But since real irradiation experiment takes much efforts, we can study a part of property change due to radiation damage by using ion implantation.

When energetic particles passe through solid, they collide with atoms of the solid, displace atoms from their original sites and often give atoms enough energy for travelling through the solid with sufficient energy to cause further displacements. Such recoiling atoms are known as primary knock-on atoms (PKA). In general, radiation damage is formed by those recoiling atoms and the type of damage is decided by energy spectrum of recoiling atoms.

As mentioned in the above, 0.1-100 MeV is the energy range of neutrons where the radiation damage is mainly created. This energy range is defined as defect forming spectrum (DFS) of neutrons in contrast to the spallation neutron spectrum, which expands up to 1000 MeV. That DFS spectrum includes the range of neutron energy which is typical for fission/fusion neutron spectrums.

Figure 6 shows the differential dpa rate due to neutron which is based on the results of Figure 3.

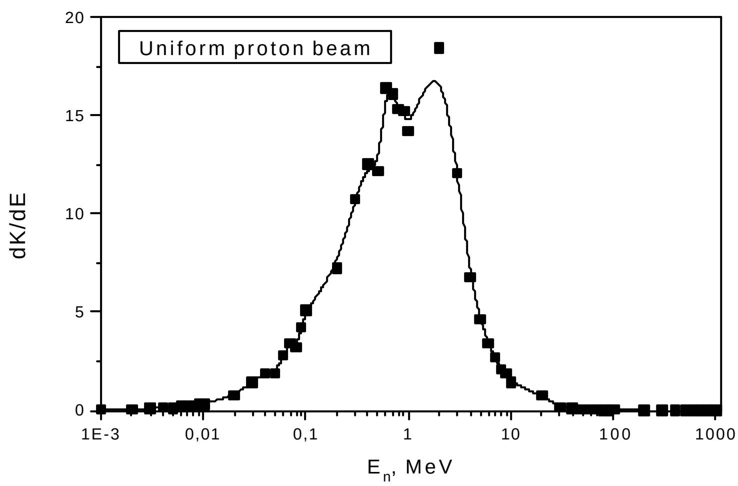


Figure 6. Differential displacement rate due to neutrons for uniform proton beam

PKA energy spectrum in iron is calculated for neutron spectrum of typical fast reactor. The result shows that PKA energy lies in range up to 500-700 keV and 90% PKA has energy below 60 keV [19]. The effective energy of HYPER neutrons which cause most of displacements is about 2 MeV. This means that 90 % of PKA has energy up to 60 keV and 10% of PKA has energy up to about 160 keV [20, 21].

The radiation damage due to proton is caused by 1 GeV proton irradiation and energy of PKA in this case reaches up to 1-2 MeV [22]. This exceeds significantly the effective PKA energy due to spallation neutrons. Nevertheless many investigations show that when energy of recoil atoms are greater than 10 keV, high energy cascades break into sub-cascade and no great differences is expected between the displacement pattern of fission/fusion neutrons (0.1-14 MeV) and spallation particles (up to GeV) [23,24].

Therefore it is useful to produce similar damage by charged-particle bombardment in order to study the radiation damage produced in high energy neutrons or protons. We evaluate some characteristics of ion bombardment based on the parameters of KAERI ion implanter ($E \leq 150\text{-}170$ keV, $I \leq 10\text{-}20$ mA) by using TRIM code [25].

The results of calculations are average projected range $\mathbf{R_p}$, straggling $\Delta\mathbf{R_p}$, maximum concentration of helium $\mathbf{N_{max}}$ and number of displacements $\mathbf{N_{dpa}}$ under iron and helium ions irradiation and they are shown in Tables 2 and 3. The calculation is done for dose of 10^{16} cm^{-2}.

Table 2. The results of TRIM calculation for helium ion implantation.

E, keV	R_p, nm	ΔR_p, nm	$\mathbf{N_{max}}$, appm He	N_{dpa}, dpa
60	248	94	5000	0.41
70	275	101	4600	0.36
100	346	110	4200	0.38

Table 3. The results of TRIM calculation for iron ion implantation

E, keV	R_p, nm	ΔR_p, nm	N_{dpa}, dpa
100	32	15	33
150	47	20	33

We can see that KAERI implanter provides appropriate irradiation conditions for simulation experiments. Because of small range of the bombarding particles, specimens suitable for mechanical tests cannot be produced. Therefore information related to the change of mechanical properties of alloy can only be deduced from microhardness measurements. The post-irradiation examination will be concentrated on the microstructure study by transmission electron microscopy, X-ray diffraction and examination of corrosion.

V. Conclusion

We made evaluation of radiation damage of HYPER beam window due to neutrons and protons. It was established that level of damage of window reaches 230-380 dpa/y and He/dpa ratio up to 130-160 appm He/dpa at window center.

Experimental data for material property change due to radiation and He production is needed to predict the exact lifetime of the beam window. The analysis of PKA energy distribution shows that it is possible to use low energy ion implantation for simulation experiments. We calculated basic parameters related to ion implantation by using TRIM code and will perform simulation experiment by using KAERI ion implanter.

VI. Acknowledgment

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