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Radiation damage parameters for modelling of FRM irradiation conditions at the RADEX facility of INR RAS

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Abstract

Results of MC calculations of primary radiation damage generated by the intense proton beam at the RADiation EXperiment (RADEX) facility of the Institute for Nuclear Research, Russian Academy of Sciences (INR RAS) are presented. RADEX is the irradiation channel located inside a proton target at the beam stop of the INR RAS linear proton accelerator having energy up to 600 MeV. The position of the irradiation channel at the facility can be changed by rotation of the proton target relative to the vertical axis, thus varying the relative influence of the primary protons and spallation neutrons on the primary damage kinetics. By shifting the proton target position outside the horizontal beam axis, one may reduce the predominant input of high-energy protons to the irradiation field. As a result, the spectrum of primary knock-on atoms in the irradiated sample may be significantly softened. This gives the possibility of changing irradiation parameters to simulate irradiation conditions at other installations (ITER and DEMO fusion devices and the IFMIF project).

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1. Introduction

The primary radiation damage (PRD) depends on the energy spectra of primary knock-on atoms (PKA) and integral characteristics: the radiation damage rate of a target material and the rates of accumulation of helium and hydrogen atoms. The less investigated characteristics, with respect to the degree of their influence on the properties of structural materials, are the mass distribution and the charge states of nuclides – the products of nuclear reactions initiated by irradiation.

Because of the absence of intense sources of neutrons with the energy of 14 MeV, there is a special problem of predicting the behaviour of materials in radiation fields of fusion devices. The need to extrapolate the accessible data to the doses and conditions of irradiation which have not been realised so far experimentally creates a problem for comparative analysis of the results for irradiation at various nuclear power installations.

In view of the importance of PRD parameters, the difficulty to reproduce all combination of conditions that are characteristic for one installation in experiments on the installation of other type is obvious. The most acute problem is a forecasting of behaviour of materials for the first wall and blanket layers of the fusion reactor. The selection of fusion device materials will be greatly aided by the international project IFMIF [1].

Neutron targets of high intensity proton accelerators may give intensities of spallation neutrons that are much higher than the neutron fluxes at presently operating nuclear power devices, and they have characteristics

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more nearly like those of fusion energy reactors [2]. Radiation tests of fusion reactor first wall candidate materials, under conditions near those expected in reality, can be obtained in the neutron target (trap) of a proton beam – the RADiation EXperiment (RADEX) installation. This facility is the part of the neutron complex at the experimental area of the Moscow Meson Factory (MMF) of the Institute for Nuclear Research, Russian Academy of Sciences (INR RAS) [3].

2. Description of the installation RADEX

The characteristics of the MMF linear accelerator of protons and H^- ions are presented in [4]. The design of the MMF proton beam stop for protons of energy 600 MeV and current up to 500 μA [5] was developed by the Research and Design Institute of Power Engineering as an installation for research on the radiation behaviour of materials RADEX. The physical start-up of RADEX took place in 1998. A picture of the installation is presented in Fig. 1. The proton beam from the ion guide passes through an aluminium first wall and falls onto an active zone of the beam stop assembled from tungsten plates with titanium coatings, cooled by water. The cylindrical irradiation channel, with a diameter of 52 mm an height of 100 mm, is located inside the active zone at a depth of ~4 m from the top of the beam stop and a distance of ~40 mm from the first wall. In the irradiation channel the radiation tests of standard samples of prospective alloys can be performed in either a purely neutron spectrum, or in a mixed spectrum of protons and spallation neutrons. The active zone of the beam stop is mounted in a cylindrical body that can be rotated around a central axis to vary the position of the irradiation channel relative to the axis of the proton beam and the first wall. Six positions are available, and details of the spectra, rates and temperatures are given in [6]. The fluxes of neutrons and protons in the irradiation channel are maximum in a position located most closely to the first wall. The intensity of the proton component in the beam decreases with distance from the first wall and from the axis of the proton beam, while at the same time the neutron component varies little. Thus, the irradiation spectrum is softened, giving rise to considerable decreases of helium and hydrogen formation.

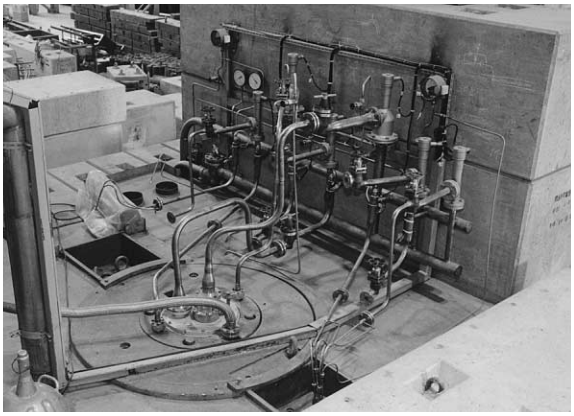

Fig. 1. The top view of the RADEX. The output of the irradiation channel at the level of ~4 m above the proton beam with tubes of the cooling system is seen.

Data from detailed calculations of PRD in steel samples by primary protons and secondary (spallation) neutron beams of RADEX are presented below.

3. The method of calculation of hadron cascade in condensed matter

For calculation of neutron fluxes and PRD, statistical modelling of interactions (the Monte-Carlo method) was developed. The tool for such modelling is the Russian hadron transport code SHIELD. The transport code SHIELD is intended for computer modelling of the interaction of high-energy particles with complex macroscopic targets. It was developed as a universal tool for a wide range of research. The modern version of the code SHIELD [7] is applied in the same areas of research as the known transport codes HETC and FLUKA, which have their own singularities and advantages. The code SHIELD includes the known Russian models of nuclear reactions ensuring the modelling of inelastic hadron-nuclear interactions in the field of energies up to 1 TeV.

A simple computer code RADDAM [8] for evaluation of the accumulation of point defects in targets due to the passage of nucleons, as well as light and heavy ions, was used. The RADDAM code is connected with the hadron transport code SHIELD, which gives all the necessary input information for the RADDAM code. The information includes the individual characteristics of the nuclear reactions, i.e., all primary and residual nuclei and particles formed in the nuclear reactions, including their masses, charges and kinetic energies. All products formed by nuclear reactions and primary particles are considered by the program RADDAM as the sources of PKA. Thus, the result of a joint operation of SHIELD and RADDAM is the distribution of PRD in a volume of the target. The LOENT code for transfer of slow neutrons is included in the structure of the SHIELD code, therefore the evaluation of energy of PRD both from cascade and evaporative processes, as well as from the slow neutrons occurs at the RADDAM stage. Detailed information about the calculation procedure and the results presented below may be found in [6].

4. Results of calculation for the RADEX facility

Four positions of the irradiation channel were considered. They correspond to rotation angles of the installation of 0°, 60°, 120° and 180°. The rotation angle of 0° corresponds to the greatest intensity of irradiation in the channel. The test samples are represented by natural iron (${}^{\mathrm{Nat}}{}_{26}\mathrm{Fe}$) spheres with a radius of 1 or 2.5 cm. The sample is placed in the irradiation channel at the axis of the proton beam, i.e., the centre of the sphere and the axis of the proton beam were in one horizontal plane. At the location of the irradiation channel of the installation at angles of 60°and 120°, the sample is removed from irradiation of the primary protons and is irradiated only by secondary (mainly neutron) irradiation. The mean free path of 600 MeV protons in the beam stop is equal and approximately to the diameter. Therefore at the rotation angle of 180° the test sample again falls under influence of the primary proton beam (but now with lower energy of protons). The proton beam in the calculations had 'zero' cross-sectional size (narrow, or point beam). With such a beam, four versions of calculations corresponding to the rotation angles of the installation were made. In addition, at the rotation angle of 0° two calculations for a proton beam with both the energies of 600 and 300 MeV were carried out for the actual cross-sectional sizes of the proton beam. It was assumed that the density of protons in the cross section of the beam has a normal distribution with a spatial dispersion $\sigma_x = \sigma_y = 1$ cm. Experimental verification of some values presented above for a beam current of 1–50 μA are now in progress. Results will be available in the future.

5. Comparison of experimental capabilities of the installation RADEX and the fusion and fission facilities

The calculations for various positions of the irradiation channel in RADEX confirm the capability to vary the PRD parameters inside the sample due to changing the ratio between proton and neutron radiation. The calculation results are summarised in Tables 1 and 2 and Fig. 2.

In Table 1 the PRD parameters of RADEX are compared with those of ITER and DEMO and the existing fission research reactor IVV-2M, the high flux research reactor SM-3, fast research reactor BOR-60 [9], and IFMIF. In Table 2 the RADEX results are given for different sizes of the irradiated sphere and different beam dispersion in comparison with the same fission and fusion facilities as in Table 1.

In Table 1 for the irradiation channel oriented at 0° relative to the proton beam, the results are given for both 600 and 300 MeV protons and are separated by a horizontal line. For the other channels, oriented differently, the values are given for 600 MeV protons only. At an energy of 300 MeV, protons practically stop before entering the irradiation channel for the case of zero position. The remaining positions of the irradiation channel correspond to irradiation by secondary neutrons.

The comparison of the data for nuclear reactors and the RADEX facility indicates the increase of generation rates of helium and hydrogen relative to the rate of PRD formation. This is as expected given the mechanisms of both protons at intermediate energies and secondary (spallation) neutron interactions with the targets. The decrease of primary proton energy results in greater heat release in the target, a decrease in defect formation rate

Table 1
The comparison of installation RADEX at different location of irradiation channel and proton energies with the nuclear power facilities of fusion and fission in terms of their PRD parameters

PRD parameters	The location of RADEX irradiation channel relatively the proton beam[a]				Nuclear power facilities					
	$0° \frac{600\ \mathrm{MeV}}{300\ \mathrm{MeV}}$	60°	120°	180°	Fusion			Fission		
					ITER	DEMO	IFMIF	SM-2	BOR-60	IVV-2
Point defects										
generation rate in dpa/year	$\frac{7.7}{3.9}$	$\frac{0.77}{-}$	$\frac{0.44}{-}$	$\frac{1.5}{-}$	8.7	19	20–55	9.6	4.4	4.6
dpa/s	$\frac{2.6 \times 10^{-7}}{1.3 \times 10^{-7}}$									
Helium accumulation rate (appm He/dpa)	$\frac{26}{16}$	$\frac{4.8}{-}$	$\frac{5.9}{-}$	$\frac{11}{-}$	12	8.2	9.5–13	0.31	0.088	0.12
Hydrogen accumulation rate (appm H/dpa)	$\frac{340}{1200}$	$\frac{60}{-}$	$\frac{65}{-}$	$\frac{1200}{-}$	45	32	35–60	4.9	3.7	4.7

[a] Radius of irradiated sphere of iron is 2.5 cm, proton current is 200 μA (1.2×10^{15} proton/s), beam dispersion is $\sigma_x = \sigma_y = 1$ cm.

Table 2
The comparison of installation RADEX at different beam dispersions and the sizes of irradiated sphere with the nuclear power facilities of fusion and fission in terms of their PRD parameters

PRD parameters	Installation RADEX[a,b]			Nuclear power facilities					
	$R = 2.5$ cm, $\sigma_x = \sigma_y$ $= 0$ cm	$R = 1.0$ cm, $\sigma_x = \sigma_y$ $= 0$ cm	$R = 1.0$ cm, $\sigma_x = \sigma_y$ $= 1.0$ cm	Fusion			Fission		
				ITER	DEMO	IFMIF	SM-2	BOR-60	IVV-2
Point defects generation rate									
in dpa/year	19	95	30	8.7	19	20–55	9.6	44	4.6
dpa/s	0.61×10^{-6}	3.0×10^{-6}	0.94×10^{-6}						
Helium accumulation rate (appm He/dpa)	34	39	12	12	8.2	9.5–13	0.31	0.088	0.12
Hydrogen accumulation rate (appm H/dpa)	450	470	150	45	32	35–60	4.9	3.7	4.7

[a] Proton current is 500 μA (3×10^{15} proton/s), proton energy is 600 MeV.

[b] Channel location relatively proton beam 0°. Radius of irradiated sphere and beam dispersion.

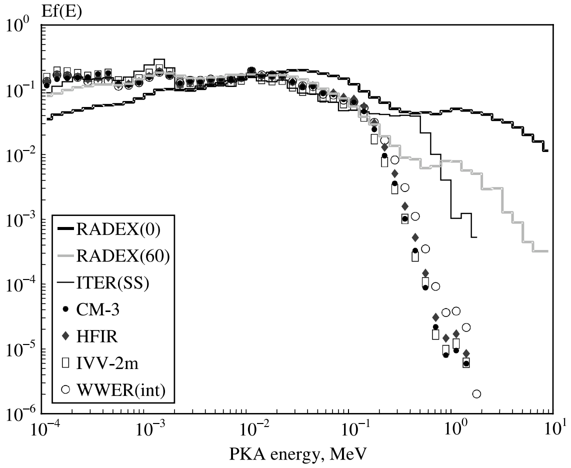

Fig. 2. Spectral distribution of PKA, Ef(E), with energies above 10^{-4} MeV for different installations.

and an increase in hydrogen generation rate. In terms of the integral characteristics, the irradiation parameters in RADEX may be similar to the characteristics of PRD in fusion reactors. Comparing the data presented in Tables 1 and 2 and in Fig. 2, it is easy to see that the capabilities of RADEX may allow us to approximate the conditions of irradiation in ITER and DEMO in terms of such parameters as the dpa/s, appm He/dpa, and appm H/dpa. As can be seen from Fig. 2, significant differences in the distribution of PKA energy for various neutron spectra are observed at $E > 100$ keV. This fact should have an effect on the mean volume of a cascade, and also on the fraction of defects surviving in a cascade, and types and concentration of clusters. The influence of PKA with energies above 100 keV on the structure of cascades and sub-cascades, which are typical to the recoil nuclei formed at interaction of neutrons with energies of the order 14 MeV and higher, has not been well investigated [10].

The PRD characteristics from cascades serve as the initial conditions to modern kinetic rate theory models of long-term evolution of microstructure and properties of irradiated metals and alloys. However their role in various stages of evolution of microstructural evolution remains to be explored. It is believed that the use of experimental capabilities of the installation RADEX for a variation of the characteristics of PRD provides an opportunity to advance knowledge in this area.

6. Conclusions

1. The RADEX facility provides an opportunity to conduct irradiation experiments in mixed radiation fields of primary protons of intermediate energies and secondary (spallation) neutrons. The experimental capabilities of RADEX make it possible to vary the PKA spectra and yields of gaseous elements.
2. The integral PRD parameters of RADEX may approach the appropriate characteristics of fusion devices, and may make possible simulation studies of structural materials in conditions that approximate those expected in fusion reactors.
3. By increasing the intensity and focussing of the proton beam, it may be possible to perform experiments at an accelerated rate of displacements, if the corresponding physical basis can be formulated.
4. Temporal modulation of the irradiation is possible in order to study the effects of temporally modulated fusion installations.
5. The general effects of the differences in radiation damage due to differences in PKA spectra can be

studied using a combination of RADEX and other existing nuclear materials research facilities.

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