JP0150629

JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000-10-23 Tsukuba, Japan

23.8 The RADEX facility as a tool for studies of radiation damage under proton and spallation neutron irradiation

E.A. Koptelov[1*], S.G. Lebedev[1], V.A. Matveev[1], N.M. Sobolevsky[1], Yu.S. Strebkov[2], and A.V. Subbotin[2]

[1]Institute for Nuclear Research of Russian Academy of Sciences, Prospekt 60-letiya Oktyabrya, 7a, Moscow, 117312, Russian Federation.
[2]Research & Development Institute of Power Engineering, Moscow, Russian Federation
*E-mail: koptelov@inr.troitsk.ru

Abstract

We present results of numerical modeling for processes of primary protons and spallation neutrons interactions with structural materials at the RADiation EXperiment facility of the Neutron Complex. The installation has a vertical irradiation channel inside the beam stop for horizontally incident protons with energies up to 600 MeV of the Moscow Meson Factory of the INR RAS. The calculations are based on a set of computer codes SHIELD and RADDAM, which were developed in the INR RAS and give data on point defect generation by irradiation, rate of accumulation of H and He atoms produced in nuclear reactions, energetic spectra of primary knocked-off atoms in collision displacements, temperature of samples under irradiation. Different positions of the channel, which are available by rotation of a target relatively the vertical axis for angles 0, 60, 120 and 180 degrees to the proton beam direction, are considered. Changes of irradiation damage parameters due to various inputs of primary protons and spallation neutrons at different target orientations are demonstrated. It is shown also that the spallation neutron facility RADEX may provide with perspective experimental possibilities for modeling of irradiation conditions for fusion reactors ITER and DEMO.

1. Introduction

Neutron targets of high intensity proton accelerators may give intensities of spallation neutrons much higher than neutron fluxes at operating nuclear power devices and expected characteristics of fusion energy reactors [1]. This circumstance gives unique opportunities for nuclear materials testing under irradiation. The existing experience of radiation damage investigations at high current proton accelerators of Los Alamos Meson Physics Facility (LAMPF, USA) and Paul Scherrer Institute (PSI, Switzerland) shows, however, the necessity of more advanced understanding of fine details in radiation damage kinetics. This is in the course of the total situation in the radiation damage physics where different neutron spectra of various neutron sources must be compared. Simultaneously, a growing interest to spallation neutron sources as tools for irradiation experiments becomes evident [2].

According to tentative estimations [3], the Moscow Meson Factory (MMF) of the theInstitute for Nuclear Research (INR) of RAS allows to perform a broad circle of irradiation experiments in studies of a radiation behaviour of nuclear materials. This work may be based on the primary beams of protons (with the initial energy 160 -- 600 MeV) and secondary (spallation) neutrons. The MMF gives a capability of a fast accumulation of dozes in terms of atomic displacement numbers and hydrogen and helium concentrations produced in nuclear reactions.

The certain possibilities for radiation tests of fusion reactor candidate materials for first wall, in conditions close to the expected in reality, can be obtained in the neutron target (trap) of a proton beam -- the RADEX installation. This facility enters into the structure of a neutron complex at the experimental area of the MMF [4].

A reliable operation of nuclear power installations is limited by the degradation of physical and mechanical properties under prolonged irradiation. The physical background of such transformations is attributed to production of atomic displacement cascades by energetic irradiating particles.

The primary violations of a crystalline structure are determined by a nature of bombarding particles, dynamics of atom-atomic collisions in a lattice and nucleation of small initial complexes of point defects with the sizes of the order of nanometer. The long-term kinetics has a quasi-chemical nature: the diffusion-controlled processes of growth of vacancy, interstitial and impurity substructures are displayed on macroscopic scales about the crystallite size.

The primary radiation damage (PRD) depends on the energy spectra of primary knocked-off atoms (PKA) and integral characteristics: the radiation damage rate of a target material, the rate of accumulation of helium and hydrogen atoms. The less investigated characteristics, on a 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. A special interest of researchers, in a more precise consideration of PRD by molecular dynamics modelling, attracts probable contribution of the spatial distribution, sizes and mobility of small point defects clusters, which are forming immediately during several picoseconds of a collision cascade relaxation [5].

The available experimental data about influence of irradiation on metals and alloys are obtained at the nuclear power reactors,with different energy spectra and fluxes of neutrons, and other irradiation facilities. Due to absence of intense sources of neutrons with the energy of 14 MeV the special problem of prediction of behaviour of materials in radiation fields of fusion devices exists. The need to extrapolate the accessible data toward the dozes and conditions of the irradiation, which have not been realised so far experimentally, puts a problem of the comparative analysis of the results for irradiations at various nuclear power installations. The purpose of such analysis is the consideration of a capability to reproduce expected radiation effects at one installation by means of the other. As it follows from the said above, the starting point for such analysis is the comparison of the characteristics of PRD for considered irradiation sources.

In view of distinction of parameters of PRD, the impossibility to reproduce all combination of conditions, that are characteristic for one installation, in experiments on the installation of other type is obvious.

Experimental data are necessary for materials used in reactors with fast neutrons, at dozes up to 10^{23} 1/cm^2. The smaller dozes (up to 10^{21} 1/cm^2), but at much more hard spectra of neutrons, are of interest for researches of materials intended for the first wall of fusion installations. The intense beams of protons with the energy about 1 GeV and the fluxes of spallation neutrons are the working conditions for the materials of electronuclear breeding systems.

The actual duration of irradiation experiments is essentially less than operation terms of nuclear power plants or fusion reactors. Researches at high fluxes of irradiation for property estimations may be desirable for a preliminary selection of structural materials.
According to contemporary point of view at PRD, the accelerated experiments with materials intended for fission and fusion reactors are imitative. Any extension of the data of imitative experiments to real working conditions of particular materials requires theoretical interpretations of differences in spectra of primary knocked-off atoms. Such a translation is essentially dependent on the used physical models and perfection of the theory. Therefore the special attention is attracted to the possibilities of material testing in conditions approaching those in the projected installations of interest.
The most acute is a problem of materials for the first wall and blanket layers of the fusion reactor. To make a selection of fusion device materials the international project of the installation IFMIF [6] is intended.
Below, in Section 2, a design sketch of the installation for realisation of irradiation experiments in mixed fields of primary protons and secondary (spallation) neutrons is presented. In Section 3 the calculation a code of hadron cascade SHIELD is described. In Section 4 the procedure of calculation of PRD by means of the code RADDAM is adduced. In section 5 the new computational data on the parameters of PRD inside the installation RADEX are presented. In Section 6 results of calculations of cooling modes of samples in the RADEX irradiation channel are concerned. Section 7 contains the discussion of the results and comparison of experimental capabilities of the RADEX installation and nuclear power facilities of fission and fusion. Section 8 contains conclusions.

2. Description of the installation RADEX

The characteristics of MMF linear accelerator of protons and H^- ions are presented at this Conference in [7]. The proton current density can be varied over a wide range by means of a focussing of the proton beam.
Design of MMF proton beam stop [8] was developed by Research and Design Institute of Power Engineering (RDIPE) and represents the installation for research of a radiation behavior of materials RADEX (RADiation EXperiment). The proton beam from ion guide passes through an aluminum first wall and falls to an active zone of the beam stop assembled from tungsten plates with titanium coatings, cooled by a light water. Inside the active zone, on the depth of ~ 4 m from a top of the beam stop and at a distance ~ of 40 mm from the first wall, the cylindrical irradiation channel with the diameter of 52 mm and altitude of 100 mm is located. The channel is completely autonomous. It can be vacuumed and arranged with its own system of cryogenic [9], water, liquid metal or gas cooling. In the irradiation channel the radiation tests of standard samples of perspective alloys can be performed both in purely neutron spectra, and in a mixed spectra of protons and spallation neutrons. The installation RADEX is arranged with the beam monitoring system representing a combination of a few induction and ionization sensors, arranged along the ion guide length with the purpose to determine precisely the proton beam propagation direction and its shape. For on-line monitoring of neutron flux in RADEX irradiation channel the special radiochemical detectors having small sizes are developed, that allows to receive the cartogram of neutron fluxes inside the irradiation channel. The active zone of a beam stop is mounted in a cylindrical body, which can be rotated round a central axis to cause the variation of the position of irradiation channel concerning an axis of a proton beam and first wall. Six various positions are available (Fig. 1). In a position located most closely to the first wall, the fluxes of neutrons and protons in the irradiation channel are maximum. In accordance with distance from the first wall and from an axis of a proton beam, the intensity of proton component in a spectrum of irradiation

drops, at the same time the neutron component varies a little. Thus, the spectrum of irradiation is softened, giving rise to considerable decreases of helium and hydrogen formation .
Complementary to horizontal variation of the irradiation channel position concerning the axis of a proton beam, vertical movement of irradiating samples along the irradiation channel is possible. The given circumstances also allow changing a spectrum of irradiation and both the ratio of accumulation rate of helium and hydrogen in a sample to the generation rate of displaced atoms.
In the MMF experimental hall the horizontal distribution of beams of protons is adopted. In this connection, the input of a proton beam in the target implements sideways at altitude 1.5 m from a zero mark.
According to tentative estimations [3], the fast neutron flux density, which is considerd as the mean over time and average over volume of the irradiation channel of 250 cm^3 value, can reach 2×10^{14} $1/cm^2s$ at a full current of protons 0.5 mA (i.e. 3.10^{15} protons/s). Such estimation allows considering a possibility of irradiation tests for structural materials at the RADEX facility in conditions close to the radiation loading in the nuclear-power installations of fission and fusion.
Below the new data of detailed calculations of PRD in steel samples by primary protons and secondary (spallation) neutron beams of the installation RADEX are presented. These calculations were made to determine modeling possibilities of the RADEX facility for radiation effects in nuclear materials.

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

The PRD of a material of the macroscopic target under an operation of a proton beam of intermediate energy (about 1 GeV) grows out of complex, multistage process. The primary proton, passing through the target, interacts with the atomic nuclei of a substance of the target, initiating nuclear reactions (inelastic hadron-nuclear interaction). Yields of this reactions are the secondary particles – the fast cascade protons, neutrons, pions, mesons, slow "evaporated" particles, and also – the residual nucleus. The latter has certain recoil energy and represents a PKA, which initiates a cascade of atomic displacements in a crystalline lattice of a target material, that results in PRD of a material.
The secondary particles, in turn, initiate similarly the nuclear reactions, generating particles of the next generation and the new PKAs. At elastic hadron-nuclear scattering, the recoil nuclei - PKAs also will be formed which, despite of a smaller kinetic energy as compared with the case of inelastic interaction, also give the certain contribution to PRD of the target material. The contribution to PRD of a material of the target is introduced also by the secondary neutrons of low energies (about several MeV), formed on final, equilibrium (or "evaporation") stage of a nuclear reaction. Though the PKA, formed due to transfer of "evaporative" neutrons have, on the average, much lower energy, their contribution to PRD can be significant, due to a large plurality of evaporative neutrons and their much more short mean free path before an interaction as compared with the fast hadrons.
Under irradiation, beside the PRD, the generation of gas (isotopes of hydrogen and helium) in the target has a large influence on the properties of a material. The main part of gas generation corresponds to the "evaporation" stage of a nuclear reaction due to emitting of slow protons, deuterons, nucleus of ${}^3{}_1H$, ${}^3{}_2He$, ${}^4{}_2He$. Such process also happens at the expense of the fast protons, which have stopped in the target. Some of gas atoms will be formed during the transfer of a slow neutrons in reactions of (n, p), (n, α), etc.
Thus, the processes of PRD and gas generation in a material of the target are rather complicated under nuclear physics point of view. These processes require for their theoretical description the knowledge of many nuclear constants in a broad interval of energies, and also

adequate procedure of the description of the hadron cascade in the medium. The additional difficulty is that the design of the macroscopic target can be rather complicated in a sense of a geometric configuration and chemical composition. This situation practically excludes the application of analytical methods for calculation of neutron fluxes and PRD.
Therefore the unique method of the solution of a posed problem is the statistical modeling of process of interactions (the Monte-Carlo method). The tool of such modeling is a so-called hadron transport code. Only a little bit transport codes exist which are adequate to the given problem and one of them is the Russian code SHIELD used in the present activity.
The transport code SHIELD is intended for computer modeling of the interaction of high-energy particles with complex macroscopic targets. It was developed as the universal tool for a wide range of researches. The initial version of a code SHIELD was developed in JINR (Dubna) in the beginning of 1970-th [10,11]. During more than 25-years of its successive progress the code SHIELD was fruitfully applied to the solution of various problems.
The modern version of the code SHIELD [12] is applied in the same areas of research, as the known foreign transport codes HETC (High Energy Transport Code) and FLUKA and has their own singularities and advantages. The code SHIELD includes the known Russian models of nuclear reactions ensuring the modeling of inelastic hadron-nuclear interactions in the exclusive approach in the field of energies up to 1 TeV
At the end of 1998 the code SHIELD was included to the program library of an information center RSICC (Radiation Safety Information Computational Center) of the Oak-Ridge National Laboratory (USA). The code SHIELD successfully participates in an international comparison of transport codes (benchmarking) in 1995 [13].
The modern version of code SHIELD allows to simulate the transfer of nucleons, pions, kaons, antinucleons and muons at the energy up to 1 TeV, and also heavy ions. The ionization losses of charged particles and ions, straggling (for particles) are taken into account. For transfers of pions and kaons, the two-particle and three-particle modes of decay are taken into account.
The geometric configuration of the target can represent arbitrary combination of bodies bounded by the surfaces of the second order [14]. The chemical and isotope composition of medium in geometric zones of the target is arbitrary. Any chemical elements can be included, beginning from hydrogen and up to transuranium elements.
The tree of the hadron cascade in the target is stored completely during its generation. So all individual parameters of all secondary particles, ions and nucleus -- products of all generations are recorded in special files, as well as all cases of a lost in the target, decay, absorption and interaction. Such organization of calculations allows uniformly organize a procedure of filing and output of results for any particular problem without any interference in a simulating part of a code. Such additional possibilities like as visualization of a tree of the hadron cascade remain opened.
Under the modeling of hadron cascade in the target, the sources of γ-quantum, electrons, positrons and neutrino (as a products of the meson decays), and also source of low energy ("evaporated") neutrons with the energies $E_n < 14.5$ MeV are formed. After the modeling of the hadron cascade is completed, the calculation of transfer of particles from sources begins. The transfer of neutrons with the energies lower than 14.5 MeV is simulated by a Monte-Carlo method with the help of the original neutron transport code LOENT based on a 28-group system of neutron constants BNAB [15].
Under development of a code SHIELD the opened architecture of a code was stipulated, which facilitates its modification and development. In particular, the inclusion of new particles in the process of transfer, replacement of the current version of the generator of nuclear interactions with newer, increase of dimensionality of the internal arrays due to

increase of the energy of particles and complexity of the target, use of the statistical weights etc. were stipulated. All these items have justified themselves in practical activity with a code. The capabilities of hadron transport code essentially depend on the used generator of inelastic nuclear interactions. In a code SHIELD the generator MSDM (Multy Stage Dynamical Model) [16] is used. It includes the known Russian models of nuclear reactions. The generator MSDM allows to simulate in the exclusive approach hadron-nuclear and nucleus - nucleus inelastic interactions in the field of energies up to 1 TeV (up to 1 TeV/A for the nuclei). The fast, cascade stage of a nuclear reaction at energies lower than 1 GeV is simulated on the base of Dubna's model of intranuclear cascades (DCM).
The evolution of the excited residual nucleus to an equilibrium condition is described in terms of preexcitation model based on the solution of appropriate master-equation by means of the Monte-Carlo method.
Further equilibrium deexcitation of the residual nuclei includes a few mechanisms. For the light nuclei (A < 16) the modified model of the Fermi break-up is used. The mean and heavy nuclei at moderate excitations (E^* < 2 MeV/nucleon) break up by means of evaporation of particles, including a competition of evaporation and fission for the heavy nuclei. Highly excited nuclei (E^* > 2 MeV/nucleon) can break up to some excited fragments according to Statistical Model of Multifragmentation (SMM) with consequent emission of particles from the fragments. The equilibrium stage of deexcitation finishes the activity of the generator MSDM.
It should be outlined that in the given problem of PRD the interaction of protons of rather low energy (below 1 GeV) with substance of mean nuclear mass (structural materials) is considered. Therefore the many of capabilities of a code SHIELD in the given problem are not involved. Actually only the nucleon cascade in the target, and also the transfer of low energy neutrons are simulated. The contribution of π-meson components to the hadron cascade is not essential.

4. The description of RADDAM code.

The passage of nuclear particles in substance of the target is accompanied by the energy loss of particles in this media. The mechanisms of energy transfer in the medium can conditionally be divided into three parts: process of electron excitation and ionization, processes of elastic and inelastic interaction of projectile particle with the nuclei of atoms. The dominance of one or other mechanism in each particular case depends on many factors, in particular on a kind of particles, their energy, and physical properties of the media. From a point of view of the creation of radiation defects, the processes of elastic and inelastic scattering of particles are interesting, which result in the transfer to atoms of the target of some kinetic energy E_o. This energy can turn out to be above the threshold energy E_d, which is necessary to displace the atom from its steady state position in a lattice and to transfer it in the interstitial position or even to initiate the whole cascade of atomic displacements. The intersitial atoms and formed on the places of displaced atoms vacancies are the point radiation defects. Thus, the radiation defects will be formed as a pair of defects of Frenkel. The PRD of media under irradiation of proton with intermediate (600-800 MeV) energies occurs as a result of elastic (electromagnetic and nuclear) and inelastic interactions of primary protons with atoms of the target. The inelastic interactions introduce the main contribution in defect production at energy of protons E_o > 100 MeV. At inelastic interactions, apart the displacement of atoms of the target due to the nuclear reactions, the nuclei-fragments (nuclides) will be formed, and the light particles such as nucleons, hydrogen, helium are emitted. Thus the residual nucleus gains a kinetic energy about several MeV. Under the moderation in a material of the target such residual nuclei creates the primary knocked-off atoms (PKA), which in turn transfer their energy to another atoms of medium by means of the cascade of atom - atomic collisions. The energy of PKA, T, is distributed into two parts: η (T), which is spent for electron excitation and part of energy, $\nu(T)$, going to the creation of radiation defects. Further $\nu(T)$ will refer as a cascade function.

The maximum energy transferred by an external nonrelativistic particle to an atom of matter in the event of elastic interaction, T_m, is determined by the expression:

$$T_m = \frac{4E_0Mm}{(M+m)^2}, \qquad (1)$$

where E_0 and m -are the energy and mass of projectile particle, and M -is the mass of the nucleus- target.

Unlike the T_m does not depend on a nature of interaction between a particle and atom, the distribution of transferred energy T is determined by a kind of particles and their energy. It is convenient to express the energy distribution of PKA with the help of the differential cross section $d\sigma(E_0, T)$ of transfer the energy in an interval from T up to $T + dT$ from a particle with the energy of E_0 to the displaced atom. The energy transferred by the recoil nuclei in the result of the cascade of atom - atomic collisions, is determined by the expression:

$$E = \frac{1}{S(E)}\int_{Ed}^{Tm}\nu(T)\frac{d\sigma(E,T)}{dT}dT, \qquad (2)$$

$$S(E) = \frac{1}{N_A}\frac{dE}{dx} + S_n(E), \qquad (3)$$

where N_A - is the concentration of atoms in the unit volume of substance of the target, dE/dx - the ionization losses of a charged particle at passage in the media, S_n (E) – the energy loss of a particle due to nuclear interactions at their motion in the medium. The expressions for $S_n(E)$ and $d\sigma/dT$ were obtained by Lindhard e.a. [17] within the framework of Thomas-Fermi model. As ionization losses the tabulated values from the ref. [18] were used. Thus, the full energy, which is spent by one primary particle on the PRD at passage in medium of the target, can be related as follows:

$$\hat{E}(E_0) = \int_{Ed}^{E_0}\frac{dE}{S(E)}\int_{Ed}^{Tm}\nu(T)\frac{d\sigma(E,T)}{dT}dT. \qquad (4)$$

The cascade function $\nu(T)$ is determined by means of well known expressions of the NRT - standard [19]:

$$\begin{aligned} &\nu(T) = T/(1+kg(\varepsilon)), \\ &k = 0.134Z_2^{2/3}/A_2^{1/2}, \\ &g(\varepsilon) = \varepsilon + 0.402\varepsilon^{3/4} + 3.4\varepsilon^{1/6}, \\ &\varepsilon = T/Z_2^{7/3}/0.0869keV, \end{aligned} \qquad (5)$$

where Z_2, A_2 – are the charge and mass of the nuclei of a material of the target.

The above mentioned relations were putted in the basis of a simple computer code RADDAM for an evaluation of accumulation of point defects in targets at passage of nucleons, and also light and heavy ions. RADDAM code is connected with the hadron transport code SHIELD, which after playing of the events by means of a method of Monte Carlo gives all necessary input information for RADDAM code. They are the individual characteristics of nuclear reactions, all primary and residual nuclei and particles formed in the nuclear reactions, including their masses, charges and kinetic energies. All formed products of nuclear reactions and primary particles are considered by the program RADDAM as the sources of PKA and pass a procedure of (4-5) for the evaluations of energy, spent by them on the creation of point radiation defects. Apart from the energy of PRD (4) in thin (in comparison with free path of primary particles in a material of the target) samples, sometimes it is expedient to enter the so-called cross-section of radiation damage σ_d:

$$\sigma_d = \sigma_{in} \hat{E}, \qquad (6)$$

where σ_{in} - is the cross-section of inelastic interaction of a primary particle with the nuclei of the target. However in the general case of extended targets the approach (6) ceases to be fair and the basic computational value is the energy, spent by primary particle on the creation of point radiation defects (4). The energy of PRD created by each primary and all secondary particles are summarized over geometric zones, into which the geometric module of the program SHIELD breaks the real macroscopic body. Thus, the result of a joint operation of SHIELD and RADDAM is the distribution of PRD in a volume of a macroscopic body of the target. The LOENT code for transfer of a slow neutrons is included in a structure of SHIELD code, therefore at the RADDAM stage the evaluation of energy of PRD both from cascade and evaporative, and from a slow neutrons happens.
In summary, we compare the PRD of the thin target made of the various substances from Be up to W under irradiation of protons with the energy of 600 MeV, calculated with the help of codes SHIELD+RADDAM and HETC (High Energy Transport Code) [20]. This comparison is illustrated in Fig. 2. As it may be seen, the results are in a good agreement.

5. The results of calculation for the RADEX facility.

The sketch of the installation is presented in Fig. 1. This geometric configuration was used in the calculation. In the Figure all necessary sizes and the direction of a proton beam are specified. In the calculation a number of the simplifying suppositions was made. In particular the tungsten target with the water-cooling was assumed to be a homogeneous mixture of tungsten and water (see Fig. 1), the metal walls of a target container are not taken into account. However all essential moments are taken into account and the adopted simplifications cannot noticeably affect the results of calculation. The installation can be rotated round a vertical axis. Thus the irradiation channel displaces from an axis of a proton beam. This possibility provides a variation of a radiation field in the irradiation channel. The four positions of the irradiation channel were considered. They are shown on Figure 1 and correspond to rotation angles of the installation of 0, 60 120 and 180 degrees. The rotation angle of 0 degrees corresponds to the greatest intensity of irradiation in the channel. The test sample is represented by natural iron (Nat^{26}Fe) sphere with a radius of 1 and 2.5 cm. The sample is placed in the irradiation channel at the axis of the proton beam, i.e. the center 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 on the angles of 60 and 120 degrees, the sample goes out from the irradiation of the primary protons and is irradiated only by secondary (mainly neutron) irradiation. The mean free path of 600-MeV protons up to a stop in the target of the installation RADEX is equal approximately to its diameter. Therefore at the rotation angle of 180 degrees the test sample again falls under influence of the primary proton beam (but already with smaller energy of protons). The proton beam, in the calculations, had the zero cross-sectional sizes (narrow, or point beam). With such beam four versions of calculation corresponding to the rotation angles of the installation of 0, 60 120 and 180 degrees were made. In addition, at the rotation angle of 0 degrees 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 supposed, that the density of protons in cross section of a beam has normal distribution with a spatial dispersion $\sigma_x = \sigma_y = 1$ cm. The results of the calculations of PKA energy spectra are shown in a Fig. 3 and in Table 1. The PKA spectra, formed as the result of: (1) the inelastic interactions of the cascade hadrons; (2) the elastic interactions of the cascade hadrons; (3) the interactions of neutrons with the energy lower than 14.5 MeV, are shown separately. The PKA spectra, formed in inelastic interactions are summarized over all types of PKA (A_i, Z_i); that mostly concerns to the PKA formed by a slow neutrons. The PKA spectra are given in absolute units PKA/MeV/proton/g.

6.The thermal regimes inside the irradiation channel of RADEX facility.

The feature of operation of design elements in a MMF proton beam is connected to non-uniformity of density of the proton beam, which can be approximated by the normal Gaussian distribution. The advantage of experiments at accelerators, as compared, for example, with in reactor experiments, consists in a capability of focusing of a proton beam. Under this circumstances its intensity grows in inverse proportion to the square of a dispersion of the Gaussian distribution σ. However the capabilities of the increase of the proton beam intensity in irradiation channel of the installation RADEX are largely limited by necessity of picking up heat allocated in the samples under irradiation. Some estimations for the colling problems for the first wall of neutron targets were done in [21,22,23]
The problem of heat pick up for samples having the form of cylindrical is considered in [24]. Such a form is the acceptable approximation for the standard samples, which mechanical properties are studied in nuclear reactor tests. The solution of a problem of determination of a temperature field inside the sample is presented in [24]. The calculation of temperature fields in the samples of various length and diameter was considered for the cooling by gas flows of an air or helium.
The calculations of temperature fields in the rods of the different sizes made of nuclear steel cooled by various gas heat-carriers were carried out. The temperature distributions along the length of a sample depending on speed of helium flow, which is cooling a sample, for the regular proton beam (σ=1 cm, I=0.2 mA) and for the case of extreme narrow and intensive proton beam (σ= 0.4 cm, I = 1mA) were estimated. For the first case, it seems to be quite probable to cool the sample rods (with length 1.5 cm and diameter 0.075 cm) at rather small speeds of helium flow (20-50 m/s). However, the difference of temperature along the length of a sample in the case of extreme intensive and narrow beam is much higher, than in ordinary case. Beside helium the air-cooling has been considered. As it follows from the carried out calculations, gas cooling can easily allow to remove the heat allocated inside the samples and to hold the temperature of samples in the required temperature range between 300 – 500^{0}C.

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

As it has been described in the Introduction due to impossibility of nowadays realizations of irradiation experiments up to dozes ~ 10^{23} n/cm^2 in fusion devices the study of radiation stability of structural materials intended for the designing of installations ITER and DEMO requires the imitative experiments. It is believed that such experiments can be performed on the existing nuclear reactors and irradiation devices such as the projected neutron generator IFMIF and existing installation RADEX of MMF of INR RAS.
The reliability of the results obtained in imitative experiments, requires the development of a few items, namely: (i) the criterions of a comparison of parameters of PRD realizable in various conditions of irradiation; (ii) the criterions of a similarity of radiation - induced changes of a microstructure at distinguishing parameters of PRD; (iii) the criterions of a similarity of the evolution (degradation) of the mechanical properties and dimensional stability of the structural materials on the macroscopic level, having in mind the differences in evolution of a microstructure.

It is necessary to note, that the rather full criterions of a similarity are not yet formulated even for the more simple case -- the transfer of the experimental data obtained in the research nuclear reactors to the conditions of irradiation in power nuclear reactors.
It is known, that properties of structural materials, with other things being equal, are, in a great extend, some function of its internal structural-phase state. Hence, rather full understanding and description of degradation of macroscopic properties requires the establishments of interrelations between the items: the macroscopic properties -- the morphology -- the microstructure at a level of a grain. Moreover the description of evolution of the grain microstructure can be considered as the first link in the causal network of radiation-induced mechanisms governed by the internal parameters of substance, the fields of temperatures, the stresses and PRD.
The calculations for various positions of the irradiation channel of the installation RADEX relatively an axis of a primary proton beam confirm a capability to vary the PRD parameters inside the sample due to change of a ratio between nuclear processes. The calculation results are summarized in the Tables 2 and 3 and Fig. 4. The data of Tables 2 and 3 are normalized to one primary proton and a unit weight of a sample. The presented data can permit the comparison of PRD characteristics of different facilities.
In Table 3 the parameters of the installation RADEX and fusion (thermonuclear reactors ITER and DEMO) and fission (research reactor on thermal neutrons IVV-2M, the high flux research reactor SM-3 and research reactor on fast neutrons BOR-60) facilities [25], and also the data on the international project of the neutron generator IFMIF are adduced.
For a zero degree position of a irradiation channel relatively the proton beam, the results of evaluations appropriating to the energy of protons 600 MeV(in a numerator) and the energy of 300 MeV (in a denominator) are presented. For the other positions of a channel the computational values correspond to the proton energy of 600 MeV on the input of the target. At the energy of 300 MeV, protons practically stop before entering the irradiation channel in the case of its zero position. The remaining positions of the irradiation channel correspond to the case of irradiation by the field of secondary neutrons. As can be seen from the Table 3 the data on relative rate of hydrogen accumulation inside the target for the proton energy of 600 MeV at the rotation angle of 180 degrees and for energy of 300 MeV in the position of 0 degrees are coincided. In both cases the high rate of hydrogen generation is stipulated largely by stop of primary protons at the end of their run.
The comparison of the data at the zero position of the irradiation channel for the energy of 600 MeV shows (see Tabs. 2 and 3), that the defect generation rate normalized to the unit of proton current does not depend on the dispersion under its variation from $\sigma_x = \sigma_y = 0$ up to $\sigma_x = \sigma_y = 1$ cm at the radius of irradiated area $R = 2.5$ cm. These data reflect the fact, that the radiation defects will be formed inhomogeneously within the irradiated volume, being grouped near to an axis of a proton beam.
The calculation results for irradiated volume with a radius of 1 cm show, that the rate of PRD in such volume is approximately 5 times higher at a zero dispersion, or 1.5 times higher at the dispersion $\sigma_x = \sigma_y = 1$ cm as compared with the case of R=2.5 cm. The difference between the cases of zero and 1 cm dispersions is explaned by the Gaussian distribution of the beam intensity when the part of protons fly outside of considered volume. The values of PRD parameters adduced for $R = 1$ cm and $\sigma_x = \sigma_y = 0$, give the upper evaluation of the PRD rate. The spreading of a proton beam reduces the value of PRD rate. The data for the greatest radius of irradiated area ($R = 2.5$ cm) give the lower evaluation of possible PRD rate in a material of the target.
The comparison of the data for nuclear reactors and RADEX facility indicates the increase of generation rates of helium and hydrogen relatively to the rate of PRD formation. This is pursuant to general imaginations about the mechanisms of both protons at intermediate

energies and secondary (spallation) neutrons interactions with the substance of targets. The decrease of primary proton energy results in the greater heat release in the target, decrease of defect formation rate and increase of hydrogen generation rate. In terms of the integral characteristics, the parameters of irradiation in the installation RADEX can be close to the characteristics of PRD in thermonuclear reactors. According to evaluations of [24], the irradiation of rather large number of samples is possible under the appropriate temperature regime. Comparing the data presented in Tabs. 2, 3 and in Fig. 4, it is easy to notice, that the capabilities of the installation RADEX allow to approximate the conditions of irradiation in ITER and DEMO in terms of such parameters as the dpa/sec, appm He/dpa, and appm H/dpa. As can be seen from Fig.4, the significant difference in the distribution of PKA energy is observed at E> 100 keV. This fact should have an effect on the mean volume of a cascade zone, and also on the fraction of defects surviving in a cascade, and types and concentration of clusters.

Such characteristics of PRD, as mean volume of a cascade zone, mean quantities of the vacancies, interstitials and their primary small clusters formed after the recombination stage during a relaxation of cascades of atom - atomic collisions, are essentially the phenomenological parameters estimated with the help of data obtained by the molecular dynamics simulation. So, for example, from the data of [5] it is possible to estimate the number of point defects pairs N_F, which are finally created by the cascade of atom - atomic collisions (after its relaxation) in iron initiated by PKA with the energy E_p, following the relation:

$$N_F = 5{,}57\ (E_p,\ keV)^{0.83}. \qquad (7)$$

According to this expression and conventional imaginations, the number of the survived point defects is less than the NRT-standard computational values. The difference grows with the increase of PKA energy. The area of applicability of the relation (7) is limited to PKA energies about 100 keV. The influence of PKA with higher energy 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, is essentially less investigated [2]. The characteristics of PRD at a level of cascade events enter as the initial parameters in the modern kinetic models of a long-term evolution of irradiated metals and alloys properties (see, for example, ref. [26]). However the problem of their role at various stages of evolution of a microstructure remaines opened till now. It is believed that the use of experimental capabilities of the installation RADEX for a variation of the characteristics of PRD allows achieving the progress in the given direction of researches.

8. Conclusions

1. The installation RADEX of MMF of INR RAS allows conducting the irradiation experiments in the mixed radiation fields of primary protons of intermediate energies and secondary (spallation) neutrons. The experimental capabilities of the installation suppose a variation of PKA spectra and gaseous yields of nuclear reactions.
2. The integral parameters of PRD of the installation RADEX are closest to the appropriate characteristics of fusion devices, that submits capabilities to realize the imitative studies of structural materials in conditions approximate to expected in fusion reactors.
3. There is a capability to realize the experiments at an accelerated rate of displacements, for the express analysis of radiation stability of samples at the search researches, by means of increase in intensity and additional focussing of proton beam.
4. The temporary modulation of a irradiation regime is possible with the purpose to produce the temporary structure of thermonuclear installations.

5. From the carried out evaluations it is visible, that it is possible to maintenance temperature in samples within the range of 300-500^{0}C.
6. The coordinated experimental researches of the standard samples of nuclear materials within the framework of the unified approach on the installation RADEX and other nuclear facilities would allow to reveal the regularities in degradation properties of structural materials connected with the difference of PKA spectra and generation of gaseous yields.

References

[1] M.S. Wechsler, J.F. Stubbins, W.F. Sommer, P.D. Ferguson, and E.H. Farnum, Selection and qualification of materials for the Accelerator Transmutation of Waste project, LA-UR-92-1211, June 1992, LANL, Los Alamos, USA.
[2] 20th Symposium on the Effects of Radiation on Matetrials, ASTM, Program and Abstracts, June 6-8, 2000, Williamsburg, Virginia, USA.
[3] E.A. Koptelov and Y.Y. Stavissky, Proceedings of the 4th All-Union Workshop on the Using of New Nuclear Physics Methods for Solving of Scientific and Economic Problems, October 20-23, 1981, Dubna, JINR, p. 104 (in Russian). E.A. Koptelov, V.V. Korolev, and Y.Y. Stavissky, Preprint of INR RAS, P-0288, Moscow, 1983 (in Russian). S.E. Boriskin, N.V. Kolmychkov, E.A. Koptelov, and Y.Y. Stavissky, Preprint of INR RAS, P-0431, Moscow, 1985 (in Russian).
[4] E.A. Koptelov, S.G. Lebedev, N.M. Sobolevsky, Y.Y. Stavissky, I.V. Al'tovsky, and V.V. Orlov, J. Nucl. Mater., **233-237**(1996)1552.
[5] D.J. Bacon, F.Gao, Yu.N. Osetsky, J. Nucl. Mater., **276**(2000)1.
[6] J.R. Hains e.a., Proc. of the ICFRM-8, October 26-31, 1997, Sendai, Japan.
[7] M.I.Grachev, E.A.Koptelov, L.V.Kravchuk, V.A.Matveev, A.D.Perecrestenko, S.F.Sidorkin, and Y.Y.Stavissky, Status of Neutron Complex of INR RAS, ICANS-XV.
[8] S.F.Sidorkin, A.D.Perekrestenko, Y.Y.Stavissky, V.I.Trushkin, and N.M.Sobolevsky. Neutron targets of Moscow Meson Facility. Status, problems, prospects, ICANS-XV.
[9] S.Y. Grachev, D.V. Kon'kov, E.A. Koptelov, S.G. Lebedev, A.V. Rakseev, N.M. Sobolevsky, and Y.Y. Stavissky, Preprint of INR RAS, 0946/97, Moscow, 1997 (in Russian).
[10] N.M. Sobolevsky, JINR Report, B1-2-5458, Dubna, 1970 (in Russian).
[11] V.S. Barashenkov, N.M. Sobolevsky, and V.D. Toneev, Atomnaya Energiya, **33** (1972) 123 (in Russian).
[12] A.V. Dementyev, and N. M. Sobolevsky, Proc. of Specialists' Meeting "Intermediate Energy Nuclear Data: Models and Codes", Paris, May 30- June 1, 1994.
[13] N. Sobolevsky, Report of NEA OECD, NSC/DOC (96)-15.
[14] A.V. Dementyev, Preprint of INR RAS 872/94, Moscow, 1994 (in Russian).
[15] L.P. Abagyan, N.O. Bazazyants, and M.N. Nikolaev, The Group Constants for Calculation of Nuclear Reactors and Shieldings., Energoatomizdat, Moscow, 1981 (in Russian).
[16] A.S. Botvina, A.V. Dementyev, N.M. Sobolevsky, and V.D. Toneev, Report of NSC/DOC (97)-1, NEA/P&T, N14, OECD, Paris, 1997, p. 307.
[17] J. Lindhard, V. Nielson, M. Scharff, and P.V. Thomsen, Klg. Danske, Videnskab, Selskab, Mat. Fys. Medd., **33**(1963)N10.
[18] L. S. Northcliffe, and R. F. Schilling, Nuclear Data Tables, **A7** (1970) 233.
[19] M.J. Norgett, M.T. Robinson, and L.M. Torrens, Nucl. Eng. and Des., **33**(1975)50.
[20] S.L. Green, W.F. Green, F.H. Hegedus, e.a., J. Nucl. Mater., **155-157**(1998)1350.
[21] S.G.Lebedev, Nucl. Instr. and Meth., **A397**(1997)172.
[22] S. G. Lebedev, Preprint of INR RAS, P-0356, Moscow, 1984 (in Russian).
[23] V.V. Orlov, and I.V. Al'tovsky, Preprint of IAE –3380/8, Moscow, 1981 (in Russian).

[24] E.A. Koptelov, S.G. Lebedev, V.A. Matveev, N.M. Sobolevsky, Y.S. Strebkov, and A.V. Subbotin, Proceedings of the 20-th World Conference on the INTDS. Targets for Particle Beams: Preparation and Use, October 2-6, 2000, Antverp, Belgium.
[25] A.V. Subbotin, B.S. Rodchenkov, N.A. Demin, and A.V. Tselischev, Report of RDIPE, N 070-248-5357, Moscow, 1998 (in Russian).
[26] A.A. Semenov, and C.H. Woo, J. Nucl. Mater., **205**(1993)74.

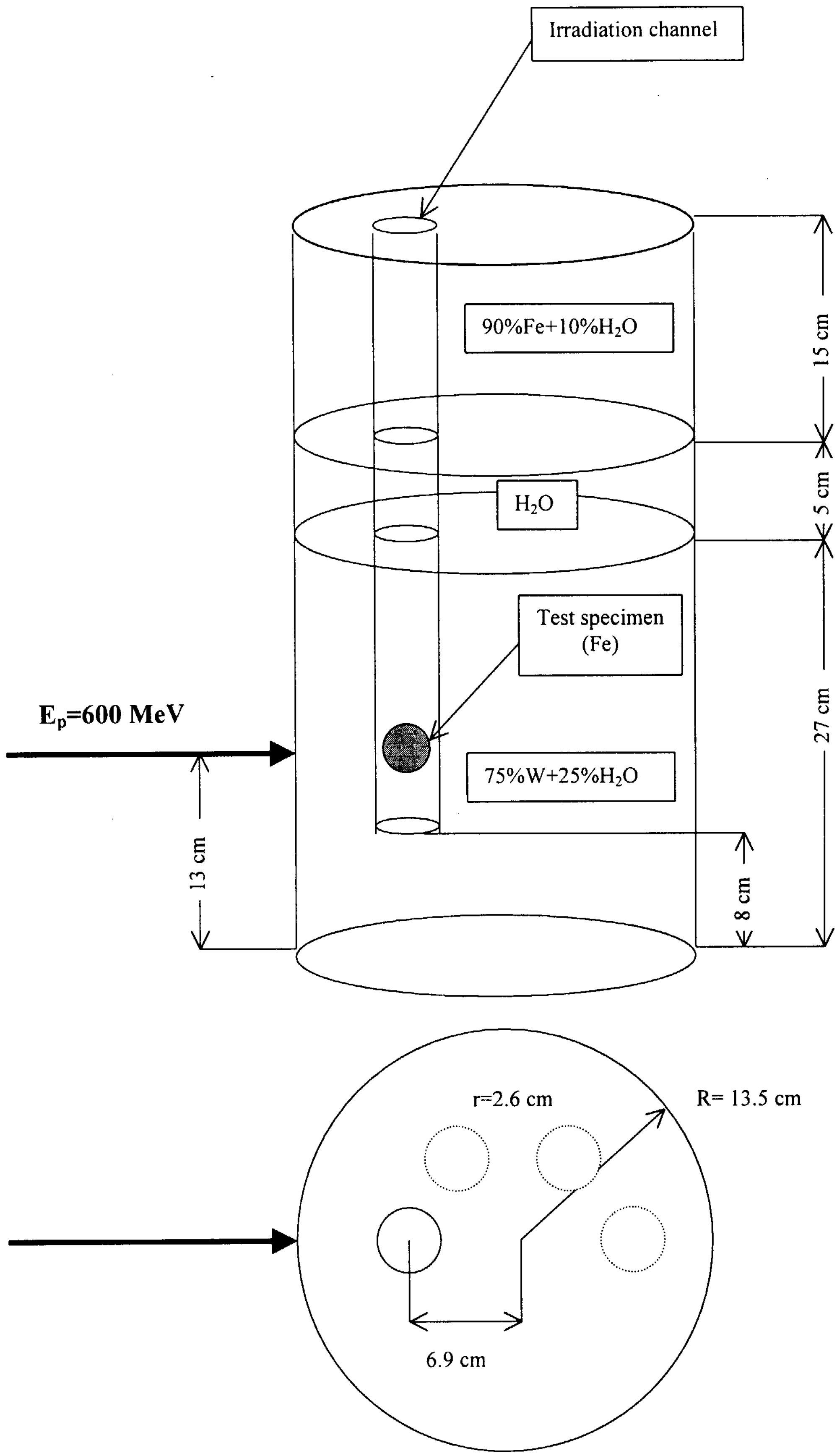

Fig. 1. The sketch of the RADEX facility. The cylinder can be rotated by 0, 60, 120, and 180° around the vertical axis.

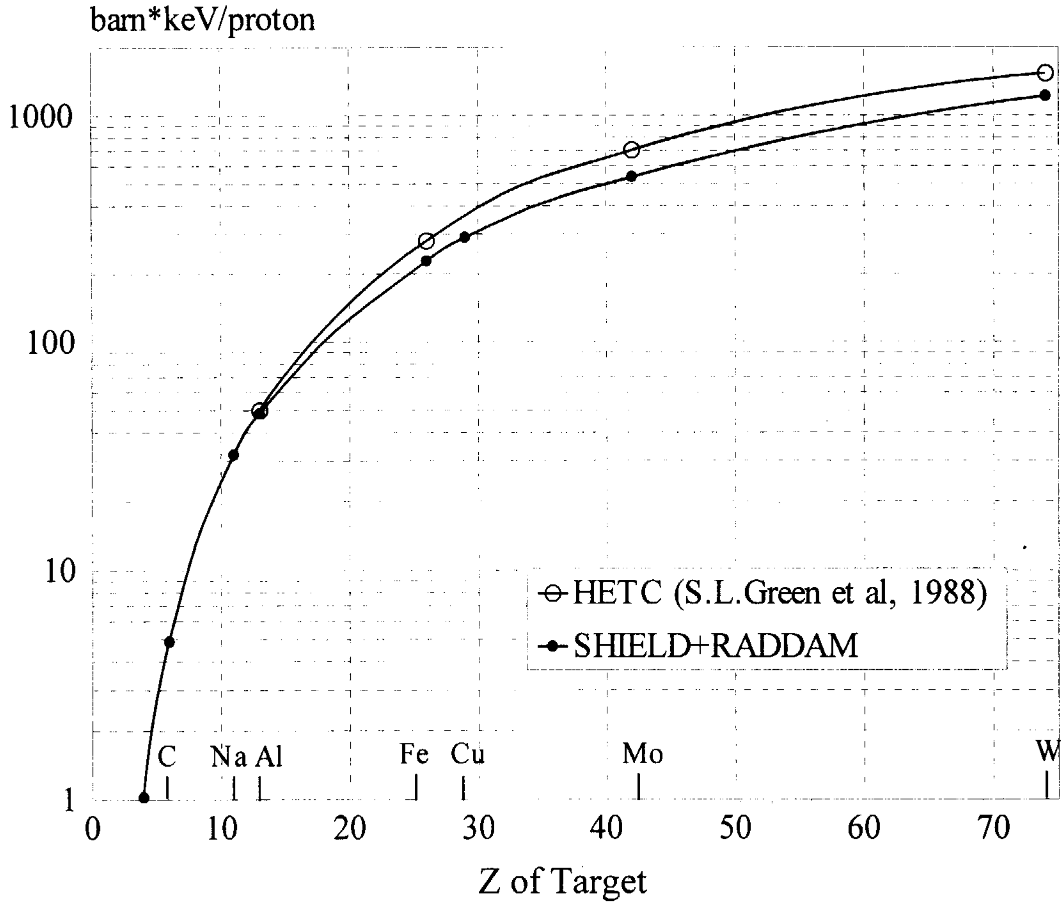

Fig. 2. The comparison of calculation results of SHIELD+RADDAM and HETC codes on primary radiation damage in thin layers of Be, C, Na, Al, Fe, Cu, Mo and W under irradiation of proton beam with the energy of 600 MeV.

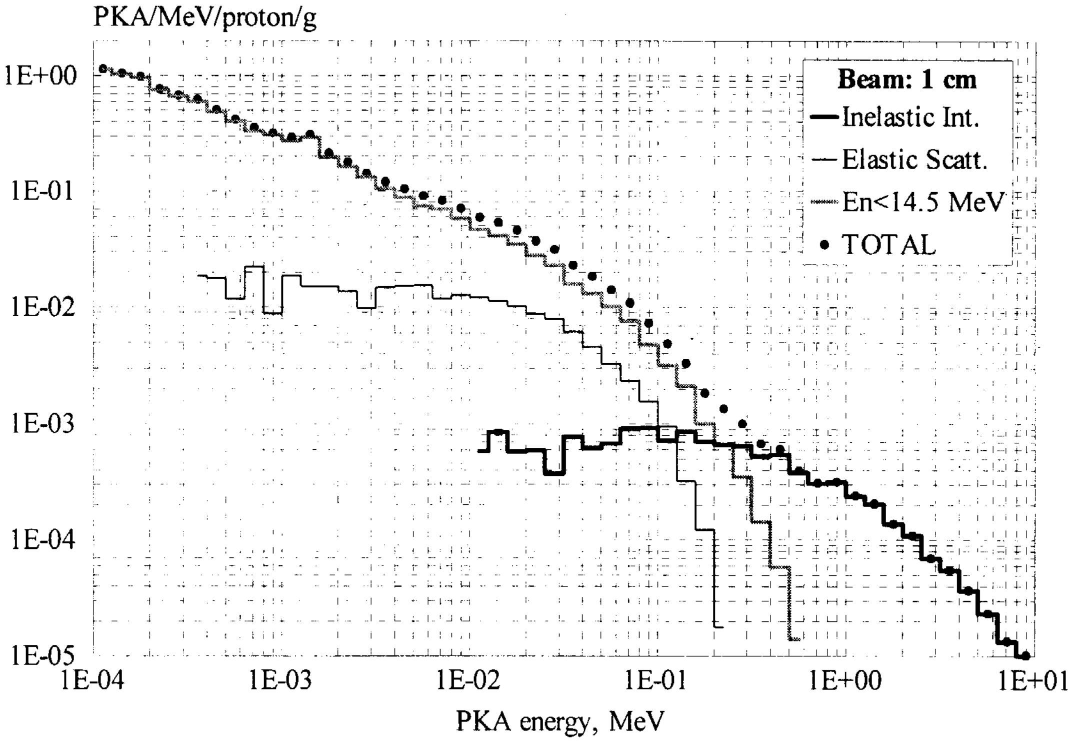

Fig. 3. The energy spectra of PKA, formed in iron sphere of radius R=1cm under irradiation of proton beam with the energy of 600 MeV and $\sigma_x=\sigma_y=1$ cm. The rotation angle of irradiation channel is- 0°.

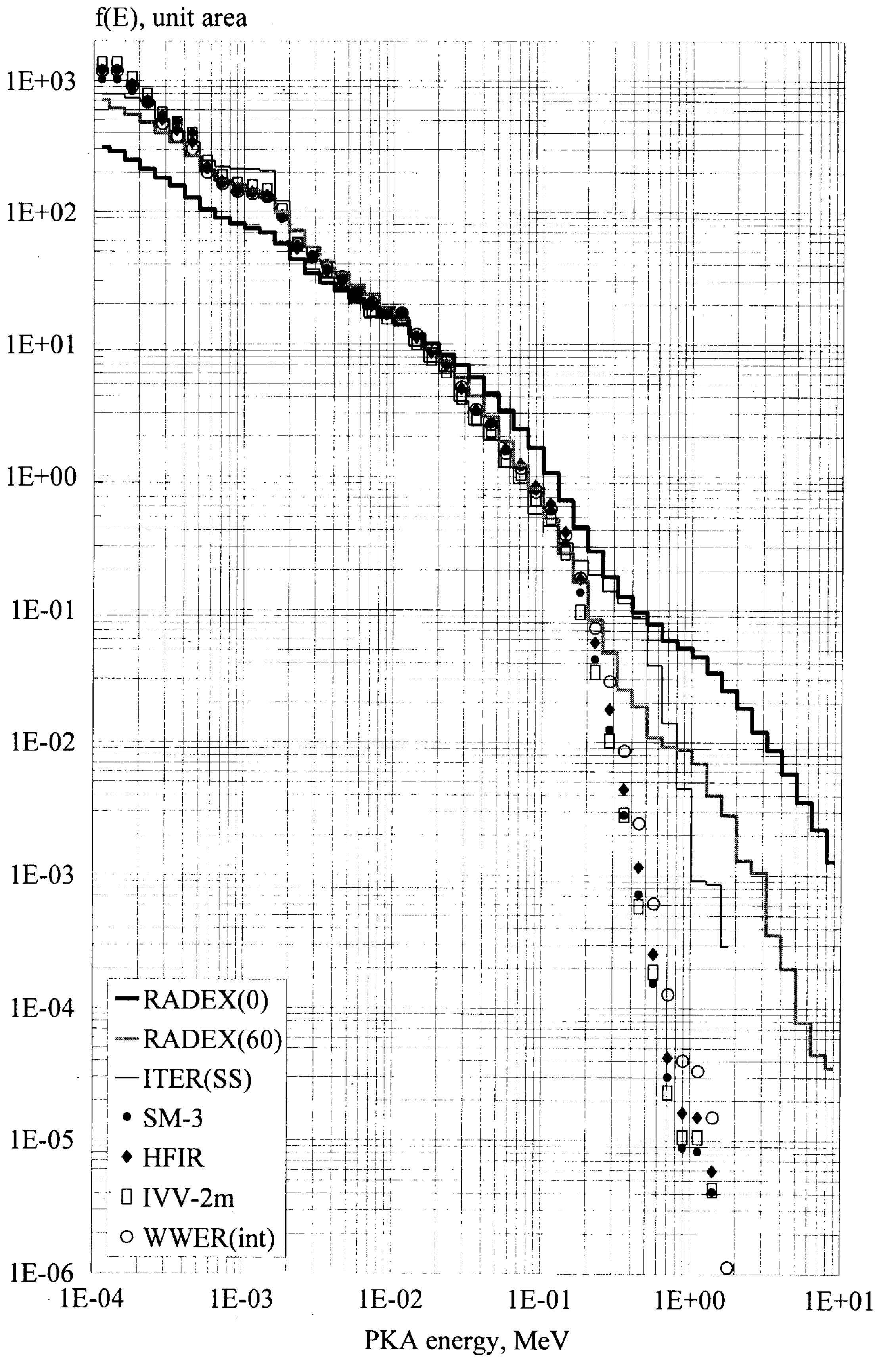

Fig. 4. The comparison of PKA energy spectra of RADEX and fusion and fission facilities.

Table 1. The parameters of radiation effect of proton beam with the energy of 600 MeV on the iron test sample of different sizes located in the 0° position of irradiation channel of installation RADEX at different beam dispersion.The influence of cascade hadrons and neutrons with the energies lower than 14.5 MeV are shown separately. All quantities are normalized to one primary proton and one gram of specimen weight.

Specimen radius Beam dispersion	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
Hadron cascade			
Number of inelastic interactions	6.18E-04	2.97E-03	9.48E-04
Mean PKA, (A,Z)	(51.5,24.5)	(50.7,24.2)	(51.2,24.3))
Mean PKA energy (keV)	1830	2160	1920
Number of elastic interactions	4.17E-04	1.74E-03	5.96E-04
Mean PKA energy (keV)	38.3	38.4	37.0
Total number of interaction	1.04E-03	4.71E-03	1.54E-03
Mean PKA energy (keV)	1110	1380	1190
Total radiation damage RD (keV)	0.210	1.04	0.324
Inelastic interaction part	0.199	0.995	0.308
Elastic interaction part	0.0106	0.0441	0.0146
Heat release(MeV)	0.155	0.830	0.249
Gas production: ^1H	8.24E-04	4.15E-03	1.32E-03
^2H	8.7E-05	5.10E-04	1.49E-04
^3H	2.7E-05	1.63E-04	4.7E-05
^3He	2.2E-05	1.14E-04	3.5E-05
^4He	4.8E-05	2.93E-04	8.2E-05
Under transfer of neutrons with $E_n < 14.5$ MeV			
Number of capture (n,c)	1.6E-05	2.5E-05	1.6E-05
Number of inelastic interactions. (n,n')	3.50E-04	6.09E-04	3.75E-04
Number of (n,2n) reaction	2.7E-06	5.8E-06	2.7E-06
Number of elastic inter.	2.71E-03	3.52E-03	2.84E-03
Total	3.08E-03	4.16E-03	3.24E-03
Mean PKA energy (keV)	30.5	39.0	31.4
Total radiation damage RD (keV)	0.0593	0.101	0.0642
Elastic interaction part	0.0345	0.0553	0.0378
Gas production: ^1H	4.5E-06	7.9E-06	6.0E-06
^2H	1.9E-07	2.5E-07	2.2E-07
^4He	1.3E-06	2.2E-06	1.7E-06

Table 2. 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*)				Nuclear Power Facilities					
					fusion			fission		
	0° **600 MeV** / **300 MeV**	60°	120°	180°	ITER	DEMO	IFMIF	SM-2	BOR-60	IVV-2
Point defects generation rate, *dpa/year*,	7,7 / 3,9	0,77 / --	0,44 / --	1,5 / --	8,7	19	20-55	9,6	44	4,6
dpa/sec	$2{,}6\times10^{-7}$ / $1{,}3\times10^{-7}$									
Helium accumulation rate, *appm He/dpa*	26 / 16	4,8 / --	5,9 / --	11 / --	12	8,2	9,5-13	0,31	0,088	0,12
Hydrogen accumulation rate *appm H/dpa*	340 / 1200	60 / --	65 / --	1200 / --	45	32	35-60	4,9	3,7	4,7

*) Radius of irradiated sphere of iron is 2,5 cm, proton current is 200 μA ($1{,}2\text{x}10^{15}$ proton/sec), beam dispersion is $\sigma_x=\sigma_y=1$ cm.

Table 3. 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*). Channel location relatively proton beam 0°. **Radius of irradiated sphere and beam dispersion**			Nuclear power facilities					
				fusion			fission		
	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	ITER	DEMO	IFMIF	SM-2	BOR-60	IVV-2
Point defects generation rate, *dpa/year*, *dpa/sec*	19 $0,61\times10^{-6}$	95 $3,0\times10^{-6}$	30 $0,94\times10^{-6}$	8,7	19	20-55	9,6	44	4,6
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

*) Proton current is 500 μA (3 x10^{15} proton/sec), proton energy is 600 MeV.