# *Раздел пятый*
# ДИАГНОСТИКА И МЕТОДЫ ИССЛЕДОВАНИЙ

# FACILITY FOR MODELING THE INTERACTIONS EFFECTS OF NEUTRONS FLUXES WITH MATERIALS OF NUCLEAR REACTORS: MAIN CHARACTERISTICS AND CAPABILITIES

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A triple beam ion irradiation facility has been developed to study the synergistic effects of displacement damage, helium and hydrogen on microstructure changes on structural materials under environments representative for future generation reactors. The system consists of vacuum chamber and one beam line, which allows providing simultaneously dual and triple ion irradiations. Samples can be irradiated in the wide temperature range from 350…800 $^0$C and doses up to 1200 dpa. The ferritic-martensitic steel EP-450 was simultaneously irradiated with dual and triple beam of chromium, helium and hydrogen ions at temperature of swelling maximum 480 $^0$C, doses 50 and 200 dpa and different levels of gases. It was shown that levels of helium and hydrogen effect on swelling parameters.

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## INTRODUCTION

Materials for future reactors include structural materials, ceramics solid tritium breeder materials will be exposure to sever irradiation environment of displacement damage and large amounts of helium and hydrogen. In order to develop materials for fusion reactors, it is important to study the effect of both displacement damage and transmutation reaction gas products as helium and hydrogen on properties of fusion reactor materials [1]. Therefore, to simulate the irradiation environment of fusion reactor, a triple beam facility, which can simultaneously irradiate samples on target, has been developed and completed.

The problem of material development for operation in unique conditions of irradiation and evaluation of their radiation resistance consists in the use of existing irradiation facilities for determination of mechanisms of radiation damage and selection of materials with high radiation resistance.

Radiation damage in structural materials is of major concern and a limiting factor for a wide range of engineering and scientific applications, including nuclear power production, medical applications, or components for scientific radiation sources. The usefulness of these applications is largely limited by the damage a material can sustain in the extreme environments of radiation, temperature, stress, and fatigue, over long periods of time. Although a wide range of materials has been extensively studied in nuclear reactors and neutron spallation sources since the beginning of the nuclear age, ion beam irradiations using particle accelerators are a more cost-effective alternative to study radiation damage in materials in a rather short period of time, allowing researchers to gain fundamental insights into the damage processes and to estimate the property changes due to irradiation. However, the comparison of results gained from ion beam irradiation, large-scale neutron irradiation, and a variety of experimental setups is not straightforward, and several effects have to be taken into account. Recently, possibility of irradiation programs mainly reduced due to the shutdown of the series of nuclear reactors. It is the intention of this article to introduce the reader to the basic phenomena taking place and to point out the differences between classic reactor irradiations and ion irradiations. It will also provide an assessment of how accelerator-based ion beam irradiation is used today to gain insight into the damage in structural materials for large-scale engineering applications [2, 3].

As a result of nuclear reactions in materials are formed transmutation gases (helium and hydrogen), which contribute to helium embrittlement, hydrogen brittleness and swelling. The generation of helium and hydrogen is significant process of transmutation reactions.

Helium and hydrogen production in nuclear facilities

| Parameters Reactor type | Rate dose, dpa/year | Helium, appm/year | Hydrogen, appm/year | Materials |
|---|---|---|---|---|
| Fast reactors | 100…200 | 20…30 | | Austenitic stainless steels, ferritic/martensitic steels |
| Fusion reactors | 20 | 300 | 800 | Ferritic/martensitic steels, vanadium alloys |
| Gen IV, ADS | 5…40 | 950…3500 | 3000…4000 | Austenitic stainless steels, ferritic/martensitic steelss |

Table gives the production rates of dpa, helium and hydrogen at different reactors. It can be seen that the damage rate for fast reactor can achieves 200 dpa/year with accumulation of helium up to 30 appm/year. For fusion reactor the damage rate is about 20dpa/year and helium and hydrogen levels are 300 appm/year and

800 appm/year, respectively. For GenIV and spallation ADS levels of helium and hydrogen accumulation are increase in almost 10 times. On the basis of this data it is required to use the facility which allows providing the simulation experiments for studying the effects of damage rates with high levels of helium and/ or hydrogen and given simulation results could be compared with data obtained from reactor experiments.

The character of radiation damage in metals depends on rate dose (dpa/s) of radiation damage of displacement that determines the direction of evolution processes of primary-produced radiation microstructure; the rate of He atoms generation influences on density and geometric dimensions of gaseous bubbles produced by He; ratio of rates (that is, ratio at. He/dpa) and temperature of environment determine "critical" values of these parameters, increasing sharply the process of hardening of irradiated materials (increase of yield strength, δ).

In majority of science centers that carried out simultaneous experiments, the requirements for simultaneous beam irradiations meet by trivial design: creates accelerator that is equal to quantity of ions sort, and ion beams are concentrated to the irradiated object [4]. In comparison with conventional accelerators, which is use three accelerators for three ion beam irradiation, at NSC KIPT was created an unique facility that provides irradiation with one accelerating tube. The whole irradiation system is shown in Fig. 1.

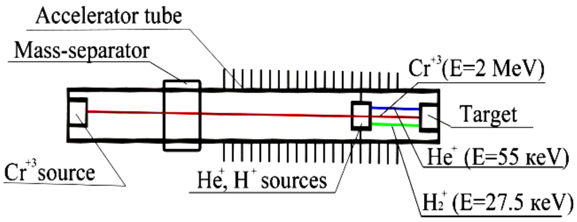

*Fig. 1. Design of facility for simultaneous ion irradiation*

Use of accelerators in radiation material science and in physics of radiation phenomena was deployed in Kharkov Institute of Physics and Technology (KIPT) at 1974. Over the past four decades has accumulated experience of the use charge particle accelerators in simulation technologies, developed and service a variety of accelerators. Electrostatic accelerator with external injector "ESUVI", developed and used at Kharkov Institute of Physics and Technology NSC KIPT, because its design require for a correct simulation neutron irradiation [4].

Facility for modeling the effects of neutron flux interaction with the nuclear reactor materials "Prime Idea" ("PI") was designed, manufactured and put in to operation on the base of "ESUVI".

## 1. THE FACILITY "PRIME IDEA"

The facility "PI" was created for modeling effects of neutron flux interaction with materials of nuclear reactors. The Fig. 2 shows the basic units of new facility.

In previously paper was described main components of the facility "PI" [5]. It consists of:

- the multiply charge ion source (MCMIS) such as arc–plasma with sputtering of the substance. The source allows getting five- and six-digit ions of nickel, chromium and others ions with current 20…40 mA, sputtering of the working substance in to the chamber by electron beam. The source provides the simultaneous gas and metal ion irradiations;
- the hollow gas ion source "GiV-3M", which transmits a beam from source "MCMIS", was developed by authors. It is placed in the accelerator tube;
- the electromagnetic mass separator with turning angle 60˚;
- the ion beam forming and focusing systems;
- Van der Graf elerostatic accelerator;
- the target complex;
- the vacuum system;
- the telemetry control and operation system (TCOS).

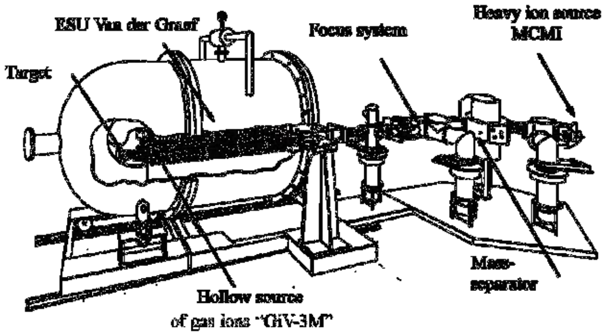

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*Fig. 2. The facility "PI"*

## 2. MAIN PARAMETERS AND ADVANTAGES OF FACILITY "PI"

Facility "Pi" allows simulating irradiation of 3 mm in diameter target. Beam current measurement in the target area is performed using Faraday cup. Data received from Faraday cup arrival on the integrator which sums dose and turn off the beam after set the dose. The facility "PI" takes into account the required rate of radiation damage produced by heavy ion irradiations from the MCMIS source, and the influence of gases (He and H) using beams generated from hollow gas source "GIV-3M". The main parameters of our facility are:

1. Metals ion beams in the range charge of z = 1…6, and gas beams from $H_2{}^{+1}$ to $Xe^{3+}$.

2. In simulation experiments the ion metals energy range E = 0.3…1.8 MeV, and the helium and hydrogen ions energy range E = 0.1 to 60 keV. The ion energy used in other experiments may vary within much wider limits.

3. Metal ion beam current density j = 1…40 μA/cm$^2$.

4. Gas ion beam current density (helium and hydrogen) j = 1…500 nA/cm$^2$.

5. Dose rate range $k = 7\cdot10^{-5}…10^{-2}$ dpa/s.

6. Pressure (vacuum) of the source chamber $P_s = 2\cdot10^{-6}$ mm Hg, of the accelerator tube $P_t = 2\cdot10^{-7}$ mm Hg.

7. The temperature range $T_{irr} = 35…800\ {}^0C$. Variation of heating temperature is set on the control panel during irradiation.

8. The ion beam current density incident on the target and temperature of the sample is measured directly. Measurement precision of the ion beam current density and temperature – 1.0%.

9. Irradiation dose is more than 1000 dpa.

The main advantage of facility "PI" is that it has one accelerator and, therefore, it become possible to: lower the cost of irradiation and of the device; to easier and cheaply the process of irradiation; steady the probability of unplanned downtime, since there is no need to maintain three separate accelerator that significantly increases the number of exposures per year; to simplify beam focusing, since the optical axis of the same sources.

## 3. RESULTS OF EXPERIMENT

To simulate radiation damages under the different doses and high levels of gases (helium and hydrogen) , irradiation experiments was conducted on the typical ferritic – martensitic steel EP-450 used as standard structural material for hexahedral cladding fuel assembly in BN-600 and future fast reactors. Standard 3 mm diameter microscopy disks of 0.2 mm thickness were produced from EP-450 ferritic-martensitic steel.

In the present work we discuss swelling changes of EP-450 steel after irradiation under 1.8 MeV Cr$^{3+}$ ions at temperature of swelling maximum 480 $^{0}$C, doses 50 and 200 dpa and different levels of helium 200…1000 appm and hydrogen 2000…10000 appm. Samples after heat treatment were irradiated with single ion beam (Cr$^{+3}$) and triple ion beam (Cr+ He+ H), E = 1.8 MeV, He = 40 keV, H = 20 keV, respectively, at damage rate k = $2\cdot10^{-2}$ dpa/s.

To minimize the influence of the injected interstitial the irradiated specimens were thinned from both sides, choosing a layer at a depth of 100…200 nm from the ion-incident surface for microscopy analysis. This depth also minimizes the effect of the surface on the examined region, especially at the very high dpa rate of $1\cdot10^{-2}$ dpa/s in this region. Fig. 3 shows the gas injection profiles and accompanying damage profiles for 40 keV He$^{+}$ and 20 keV H$^{+}$, showing that very high but well-defined levels of gas can be deposited in the examined region without inducing significant amounts of additional damage dose.

Fig. 4,a shows the swelling behavior of EP-450 steel irradiated at 50 dpa and 480$^{0}$C under dual and triple beam irradiation. Under dual irradiation (Cr+H) at 50 dpa, 1000 appm H leads to reduce of voids size and to increase of number density. The swelling increases from 0.02 to 0.37%. The triple beam irradiation with 1000 appm He and 10 000 appm H strongly rises the voids size from 7 to 20 nm and decrease the number density from $7\cdot10^{16}$ to $1.7\cdot10^{15}$cm$^{-3}$ and swelling decrease to 0.17%. The results suggest that changes in swelling may be slightly influenced by the presence of helium.

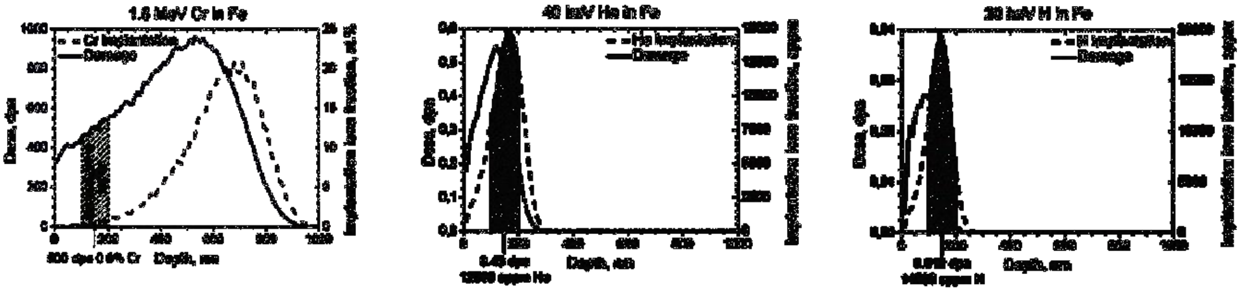
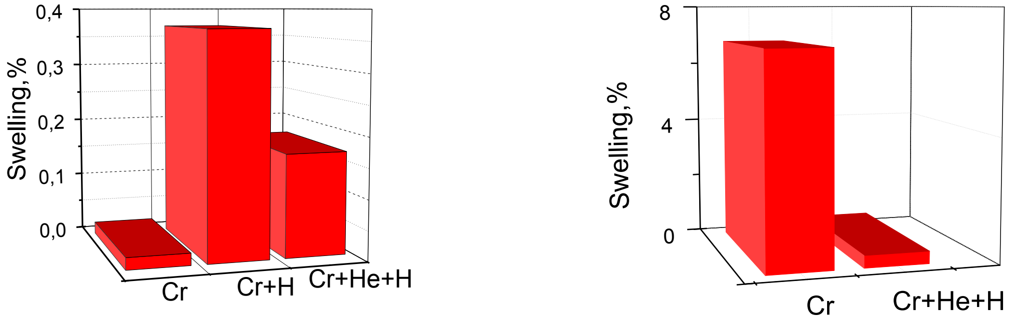


*Fig. 3. Profiles of damage (——) and of deposition (⋯⋯) 1,8 MeV Cr$^{3+}$, profiles of deposition 20 keV H (----) and 40 keV He (----). Shaded area is investigated layer*



a b

*Fig. 4. Gistogramms of simultanious effect of dual (Cr+H) and triple(Cr+He+H) ion beam irradiation on swelling in EP-450 steel at $T_{irr}$=480$^{0}$C and doses: 50 (a) and 200 dpa (b)*

Fig. 4,b shows the swelling changes in EP-450 steel irradiated under single irradiation D = 200 dpa and $T_{irr}$ = 480 $^{0}$C and triple beam irradiation (Cr + 200 appm He + 2000 appm H). Under triple beam irradiation the voids size are reduced from 32 nm to 7 nm and number density increased from $5\cdot10^{15}$ to $1.5\cdot10^{16}$ cm$^{-3}$. The swelling of in EP-450 steel decreased from 6.8 to 0.3%.

## SUMMARY

A triple ion irradiation facility has been developed to study the effects of displacement damage, helium and hydrogen atoms on microstructure changes in materials. It should be noted, that throughout the world there is no analogue as of the system as the hollow source of gas ions. Fundamentally new system for simultaneous triple beam ion irradiation, involving the use of the one accelerator instead of three is proposed and starts to operate.

The design and implementation of simulation experiments serves two purposes: first, to accelerate the process of the radiation swelling, the second-to put into practice the results of simulations to predict the behavior of a material under the influence of reactor irradiation on the basis of simulation experiments.

The ferritic-martensitic steel EP-450 was simultaneously irradiated with triple beam of chromium, helium and hydrogen ions using unique facility “PI”. Firstly was obtained results on the swelling behavior in structural materials at very high doses of radiation and ultra-high levels gases – hydrogen and helium. The most important of these is that the swelling behavior of the typically ferritic-martensitic steel EP-450 depends on the levels of hydrogen and helium, which have different effects on the kinetics and magnitude of swelling in different stages (on the incubation and the steady state period). Triple beam ion irradiation leads to voids number density reducing and decreasing of swelling at 50 dpa due to voids number density reducing. At dose 200 dpa swelling in EP-450 steel decrease due to void size reducing.

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## ОБОРУДОВАНИЕ ДЛЯ МОДЕЛИРОВАНИЯ ВЛИЯНИЯ ВЗАИМОДЕЙСТВИЯ ПОТОКОВ НЕЙТРОНОВ С МАТЕРИАЛАМИ ЯДЕРНЫХ РЕАКТОРОВ: ОСНОВНЫЕ ХАРАКТЕРИСТИКИ И ВОЗМОЖНОСТИ

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Оборудование для одновременного облучения тройным пучком ионов было разработано для изучения совместного влияния смещающих повреждений, гелия и водорода на микроструктурные изменения конструкционных материалов в условиях, характерных для реакторов будущих поколений. Система состоит из вакуумной камеры и одного ионного трубопровода, который позволяет проводить одновременно двойное и тройное ионные облучения. Температурный диапазон облучения составляет 350…800 $^0$C, а дозы облучения может достигать порядка 1200 сна. Для изучения совместного влияния повреждений и газов ферритомартенситная сталь ЭП-450 одновременно облучалась двойным и тройным ионными пучками, состоящими из ионов хрома, гелия и/или водорода при температуре максимума распухания 480 $^0$C, дозах 50 и 200 сна, а также при различных концентрациях газов. Показано, что концентрация гелия и водорода влияет на поведение распухания.

## ОБЛАДНАННЯ ДЛЯ МОДЕЛЮВАННЯ ВПЛИВУ ВЗАЄМОДІЇ ПОТОКУ НЕЙТРОНІВ ІЗ МАТЕРІАЛАМИ ЯДЕРНИХ РЕАКТОРІВ: ОСНОВНІ ХАРАКТЕРИСТИКИ ТА МОЖЛИВОСТІ

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Обладнання для одночасного опромінення потрійним пучком іонів було розроблено для вивчення спільного впливу зміщень, гелію та водню на мікроструктурні зміни конструкційних матеріалів в умовах, характерних для реакторів майбутніх поколінь. Система складається з вакуумної камери і одного іонного трубопроводу, який дозволяє проводити одночасно подвійне і потрійне іонне опромінення. Температурний діапазон опромінення складає 350…800 $^0$C, а дози опромінення може досягати близько 1200 зна. Для вивчення спільного впливу пошкоджень і газів одночасно опромінювалася феритомартенситна сталь ЕП-450 подвійним та потрійним іонними пучками, що складаються з іонів хрому, гелію і/або водню при температурі максимуму розпухання 480 $^0$C, дозах 50 і 200 зна, а також при різних концентраціях газів. Показано, що концентрація гелію і водню впливає на поведінку розпухання.