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IAP TRIPLE-BEAM FACILITY FOR SIMULATION STUDIES OF RADIATION DAMAGE OF MATERIALS

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The project of ion irradiation facility for in-situ studies of radiation damage being developed in IAP NAS of Ukraine is presented. The platform comprises 300 kV heavy ion implanter, 50 kV collinear dual-beam light ion implanter and 200 kV electron microscope. The optimal energies of heavy and light ion beams have been estimated. The results of computer simulation of ion transmission in the light ion implanter are presented.

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INTRODUCTION

One of the consequences of the interaction of high-energy particles (photons, neutrons, ions or electrons) with crystalline materials is the formation of lattice defects resulting from the energy transfer from an incident projectile to target atoms and subsequent displacement of target atoms. The result of a radiation damage event is the creation of a collection of point defects (vacancies and interstitials) and clusters of these defects in the crystal lattice [1].

The development of nuclear reactor technology requires new studies of reactor material resistability under neutron bombardment. Radiation - induced microstructural changes significantly degrade materials' properties (increase in electrical resistivity, decrease in thermal conductivity, radiation hardening and embrittlement, irradiation creep, void swelling, reduction in fatigue performance, etc.). The interaction of high-energy neutrons with target atoms also causes the formation of foreign atoms as a result of nuclear transmutation reactions. Transmutation is a process that is very sensitive to the neutron spectrum [2]. The most important products of nuclear transmutation reactions are helium and hydrogen atoms. These atoms modify the process of evolution of the initially formed radiation microstructure, which leads to a change in the macroscopic properties of the irradiated material.

The traditional way to study the irradiation effect is to irradiate candidate nuclear reactor material in nuclear reactor. Radiation damage has been studied using various irradiation sources, such as fission neutrons (fast and mixed - spectrum fission reactors), fusion neutrons in a D - T fusion neutron source, spallation neutron sources, ion irradiation with accelerators, high - energy electron beams, etc [3].

Neutron irradiation experiments are not easy to conduct for a number of reasons. Investigations of damage processes in materials require a wide range of precise and well controlled experimental conditions, which are not possible to tune precisely in neutron irradiation experiments. Due to a low dose rate, typical neutron irradiation experiments in test reactors require 1 to 3 years of exposure to reach appreciable fluence levels. Special precautions are required to handle the radioactive samples during the further analysis which may again take years. Heavy ion irradiation provides an alternate to neutron irradiation which has considerable advantages in contrast to neutron irradiation, such as: higher radiation damage rates (~10^{-2} dpa/s) compared to nuclear reactors (~10^{-7} dpa/s), little or no residual radioactivity, precise control of irradiation conditions, a lower irradiation cost than neutron irradiation.

Thus, heavy ion beam simulation irradiation of structural materials is used worldwide as a valuable technique of studying of their radiation stability under nuclear reactor irradiation. Heavy ion accelerator linked with transmission electron microscope (TEM) allows in-situ observation of micro-structural and micro-chemical evolution of irradiated materials. In recent years more then a dozen ion irradiation facilities have been developed over the world [4]. Most of them are triple-beam facilities not coupled with TEM or dual-beam linked TEM facilities. Recently it was shown that synergistic effects of heavy ion irradiation of iron target along with simultaneous He and H implantation play important role in defect evolution [5]. So in order to conduct more accurate and detailed simulation of neutron irradiation effects it is highly desirable to have a triple ion beam facility with an option of in-situ observation of radiation induced changes on a nanoscale by means of TEM. One of the first facilities of this type was recently put into operation in China [6, 7].

The Institute of Applied Physics of the NAS of Ukraine is developing a project of a triple-beam ion irradiation facility composed of a high voltage heavy ion implanter and a low voltage light ion dual-beam implanter linked with TEM.

1. GENERAL PRINCIPLES AND DESIGN OF IAP TRIPLE BEAM FACILITY

TEM studies of radiation damage are usually carried out in a near-surface layer with a thickness of about 1000 Å. Heavy ion beams are used to produce defects. Since the implanted ions distort the stoichiometric composition of the sample under ion irradiation, it is desirable that the ratio of the concentration of ion induced defects to the concentration of implanted atoms be maximum within a given layer. This can be achieved in the range of heavy ion beam energies from 1 MeV and above (Fig. 1).

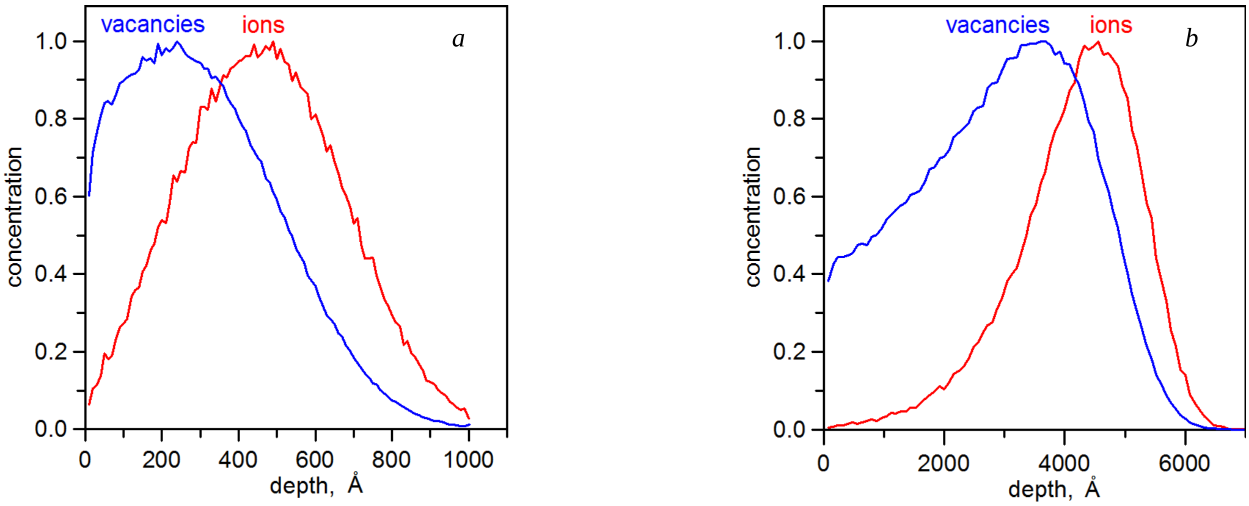

Fig. 1. Normalized depth distribution of implanted ions and ion beam induced vacancies upon irradiation of an iron sample with Ar^{+} ions with energies: 100 keV (a); 1 MeV (b) (simulation using SRIM software [8])

It is possible to obtain high ion energies with relatively small overall dimensions of the heavy ion implanter by using sources of multiply charged ions. The most suitable are ion sources using electron cyclotron resonance (ECR). Ar^{+4} ion beam, for example, generated by ECR ion source has 1.2 MeV energy on 300 kV ion accelerator.

Hydrogen and helium ion beam used for simulation of transmutation processes produce much less defects because of their low atomic mass. The maximum of implanted ions distribution for H^{+} and He^{+} should be within the abovementioned range of 1000 Å. According to SRIM simulation for iron target this condition is fulfilled in the range of H^{+} ions up to 15 keV, and up to 30 keV for He^{+} ions. Thus, the maximum voltage of light ion implanter may be limited to 50 kV.

The proposed design of a triple beam facility is presented on Fig. 2. The facility consists of a 300 kV heavy ion implanter from National Electrostatics Corporation (NEC), a 50 kV hydrogen-helium coaxial ion implanter developed at the Institute of Applied Physics of the National Academy of Sciences of Ukraine and a commercial 200 kV TEM (model FEI Talos F200i). The angle between the ion beam lines and the TEM optical axis is 68^{0}, and the angle between heavy and light ion beam lines is 45^{0}.

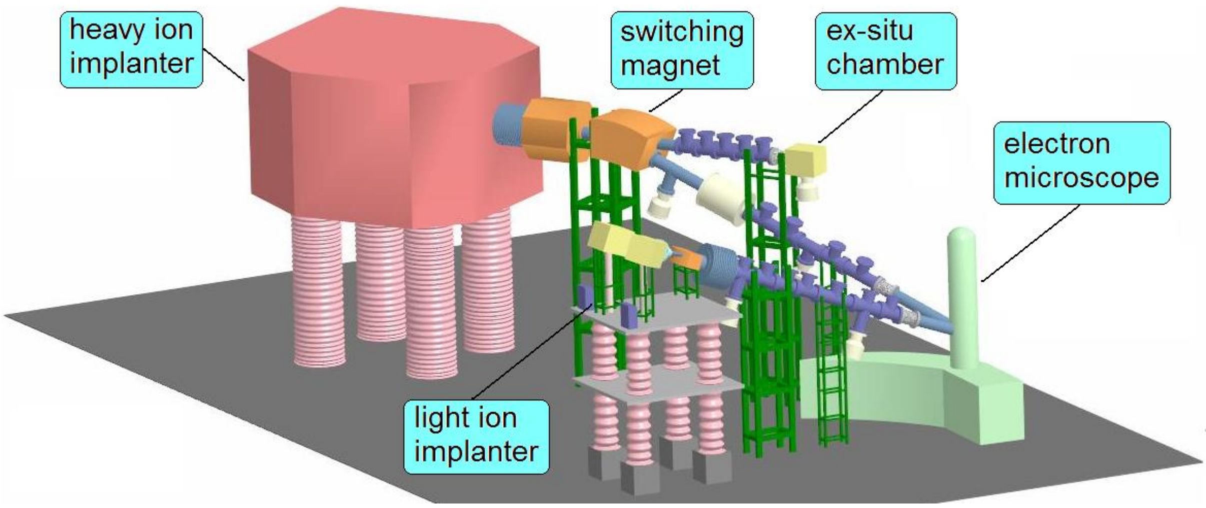

Fig. 2. Layout of IAP triple-beam facility

The Pantechnik's Nanogan 10 GHz 100 W ECR ion source is used as a heavy ion generator in the high-voltage accelerator. This model has good performance and long duty circle and is capable of producing 140 μA of Ar^{+4} ions and 20 μA of Ar^{+8} ions [9]. The source has an oven system for generating metallic ions. The NEC high-voltage deck also contains turbo-molecular pump station backed by an oil-free scroll pump, preacceleration extractor gap lens system, 90^{0} analysis magnet system with a resolution greater than 200, all-metal and ceramic accelerating tube assembly, computer control system with digital light-link telemetry system, post accelerator electrostatic quadrupole triplet lens, and switching magnet with output of 0^{0} and 22^{0}. The 0^{0} output goes to the target chamber for ex-situ irradiation experiments, and the 22^{0} one is linked with TEM via ion beam line containing devices for heavy ion beam manipulating and diagnostics. All deck power is provided by two motor generator sets. The deck is biased by a highly regulated 300 kV power supply. As with the source bias, extractor and lens power supplies, the deck bias supply is a high-frequency voltage multiplier type with low ripple. Ion source, lens, and magnet power supplies are controlled by two separate computer interfaced controllers, one at source potential and on at deck potential. Optical fibers connect these controllers to PC.

Light and heavy ion beamlines are linked to TEM with bellows, which prevent TEM resolution reducing affected by mechanical vibration of implanters. At the end of the ion channels there are collimators with an aperture diameter of 2 mm, which determine the position and size of the ion spot on the sample surface inside the TEM. These apertures also separate the region of relatively high residual gas pressure inside the beamlines (~5·10^{-4} Pa) from that inside TEM (~10^{-4} Pa).

2. HYDROGEN-HELIUM COAXIAL ION IMPLANTER

The main difficulty in designing a light ion implanter is obtaining an ion beam consisting of two types of ions, hydrogen and helium, which simultaneously bombard the target surface. The beam must also be cleaned of impurities of heavy ions. The triple-beam facility at Xiamen University [6] has one light ion source using gas mixture of hydrogen and helium. The hydrogen molecular ion H_2^+ instead of H^+ is selected for this implanter to fulfill the requirement of the same projectile range of helium and hydrogen ions. A symmetrical achromatic system including two identical Wien filters and an Einzel lens was designed for the coaxial transport of H_2^+ and He^+ beams and filtering out of impurities. The initial beam from the ion source is separated to several beams by using the first Wien filter. Then, H_2^+ and He^+ beams are selected by a dual-aperture slit. The two separated ion beams are then focused and recombined to the beamline axis by using the second Wien filter.

A different r approach to the generation and formation of a coaxial beam of helium and hydrogen ions is used in the project of the IAP three-beam setup presented here (Fig. 3). Two separate ion sources are used for generating light ions: one for H^+ ions and one for He^+ ions.

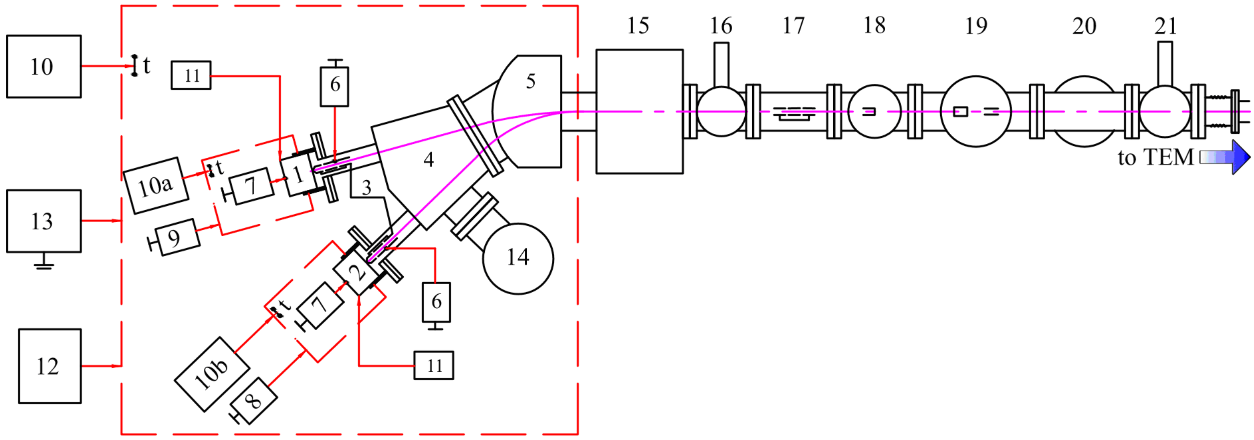

Fig. 3. The layout of IAP hydrogen-helium coaxial ion implanter: 1 – He^+ ion source; 2 – H^+ ion source; 3 – ion optics; 4 – vacuum chamber; 5 – electromagnet; 6 – focusing voltage source; 7 – ion source power supply; 8, 9 – extraction voltage source; 10,a,b – isolation transformers; 11 – gas system; 12 – command and control system; 13 – 50 kV power supply; 14 – vacuum turbo pump; 15 – acceleration tube; 16 – slits; 17 – einzel lens; 18 – Faraday cup; 19 – beam steerer; 20 – ion pump; 21 – profile monitor

Convergence of two beams into one and simultaneous mass separation of the beams is carried out in an electromagnet. The ion sources are mounted to the electromagnet at different angles corresponding to different radii of curvature of ion trajectories. The smaller radius of curvature corresponds to the source of hydrogen ions. Convergence of beams is carried out by adjusting the accelerating voltages for each of the ion sources at a given value of the magnetic field of the electromagnet.

Convergence and transport of two ion beams was simulated using the SIMION code (Fig. 4). The initial beam emittance is set to 20 mm·mrad. The energies of H^+ and He^+ ions at the exit of the ion sources are 7 and 15 keV respectively, and the magnitude of the magnetic field of the electromagnet is 55 mT.

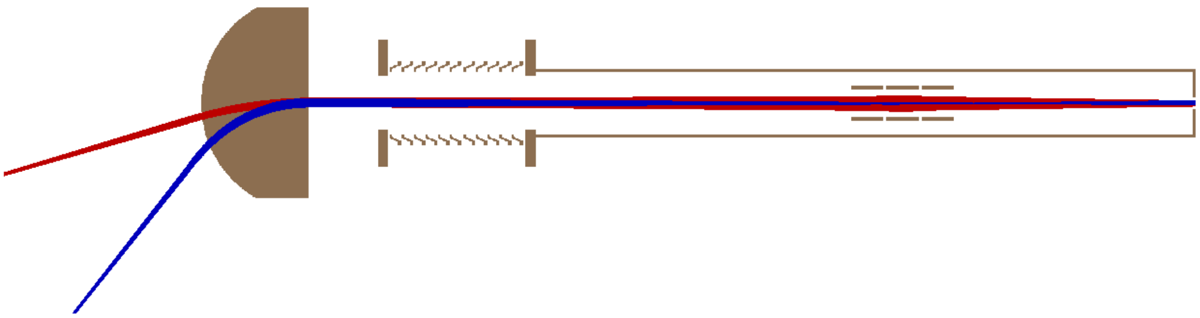

Fig. 4. The simulation of H^+(blue) and He^+(red) ion trajectories in the collinear dual-beam implanter

After post-acceleration in the accelerating tube with a potential drop of 10 kV hydrogen and helium ions gain energies of 17 and 25 keV respectively, which corresponds to an average ion penetration depth in an iron target of about 1000 Å. The magnetic field of the electromagnet has a stronger focusing effect on the ion beam with a smaller radius of curvature of the trajectories. In our case, this leads to a stronger focusing of the hydrogen ion beam. An einzel lens placed after the accelerating tube makes it possible to equalize the profiles of two beams at the TEM entrance. The collinear beam diameter near the TEM entrance is about 8 mm.

The Pantechnik's Monogan-M100 2.45 GHz 30…100 W ECR ion sources capable of producing up to 1mA of H^+ and He^+ ions are used in the implanter. The maximum accelerating voltage of the ion source is 30 kV.

This configuration of H^+ and He^+ ion sources allows to obtain a coaxial ion beam in the receiving chamber of the TEM and change their energy independently.

This design of the hydrogen-helium coaxial ion implanter, in contrast to the setup of Xiamen University, makes it possible to: irradiate the target separately with hydrogen or helium beams; change the currents of H^+ and He^+ ions over a wide range; change the energy of the ions.

3. MAIN PARAMETERS OF IAP TRIPLE BEAM FACILITY

1. The developed installation will allow receive beams of heavy ions of various metals and gases with charge in the range 1…8.

2. In simulation experiments, the energy of heavy.

ions varies within 0.3…2.4 MeV, and helium and hydrogen ions - 0.1…50 keV.

3. Current density of the heavy ion beam $j = 1…50\ \mu A/cm^2$.

4. Current density of ion beams of gases He^+ and H^+ $j = 1…1000\ nA/cm^2$.

5. Defect generation rate range $k = 10^{-5}…10^{-2}$ dpa/s.

6. The temperature of the samples during irradiation can maintained in the range T = 80…600°C.

7. Radiation dose up to 300…500 dpa.

The use of the developed setup for the study of radiation damage on ion beams satisfies the requirements of ASTM E521-83 "Standard Practice for Modeling Neutron Damage Using Charged Particle Irradiation" [10].

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ТРЬОХПУЧКОВА ПЛАТФОРМА ІПФ ДЛЯ ІМІТАЦІЙНИХ ДОСЛІДЖЕНЬ РАДІАЦІЙНОГО ПОШКОДЖЕННЯ МАТЕРІАЛІВ

В.А. Батурін, С.О. Єрьомін, П.О. Літвінов, С.О. Пустовойтов, О.Ю. Роєнко, В.Ю. Сторіжко

Представлено проект іонно-променевої платформи для in-situ досліджень радіаційних пошкоджень, що розробляється в ІПФ НАН України. Платформа містить у собі імплантер важких іонів на 300 кВ, колінеарний двохпучковий імплантер легких іонів на 50 кВ та електронний мікроскоп на 200 кВ. Оцінено оптимальні енергії пучків важких і легких іонів. Наведено результати комп'ютерного моделювання проходження іонів у імплантері легких іонів.

ТРЕХПУЧКОВАЯ ПЛАТФОРМА ИПФ ДЛЯ ИМИТАЦИОННЫХ ИССЛЕДОВАНИЙ РАДИАЦИОННОГО ПОВРЕЖДЕНИЯ МАТЕРИАЛОВ

В.А. Батурин, С.А. Еремин, П.А. Литвинов, С.А. Пустовойтов, О.Ю. Роенко, В.Е. Сторижко

Представлен проект ионно-лучевой платформы для in-situ исследований радиационных повреждений, который разрабатывается в ИПФ НАН Украины. Платформа включает в себя имплантер тяжелых ионов на 300 кВ, коллинеарный двухпучковый имплантер легких ионов на 50 кВ и электронный микроскоп на 200 кВ. Оценены оптимальные энергии пучков тяжелых и легких ионов. Приведены результаты компьютерного моделирования прохождения ионов в имплантере легких ионов.