ITEP Heavy Ion RFQ – Experimental Facility for Reactor Material Investigation under Irradiation

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Abstract. Development of new materials for future energy facilities with higher operating efficiency is a challenging and crucial task. However, full-scale testing of radiation hardness of reactor materials is quite sophisticated and difficult as it requires long session of reactor irradiation; moreover, induced radioactivity considerably complicates further investigation. Ion beam irradiation does not have such a drawback, on the contrary, it has certain advantages. One of them is high speed of defect formation. Therefore, it provides a useful tool for modeling of different radiation damages. Improved understanding of material behaviour under high dose irradiation will probably allow to simulate reactor irradiation close to real conditions and to make an adequate estimation of material radiation hardness. ITEP heavy ion RFQ HIP-1 provides accelerated beams of Cu^{2+}, Fe^{2+}, Cr^{2+} ions with current up to 4 mA and energy 101 keV/n. The results of beam extraction line adjustment for experiments with reactor materials are presented. The construction of controllable heated target is presented as well. The first experiments will be started at the beginning of 2009.Also, the low energy experiments are carried on at the HIP-1 injector. The construction of target for low energy experiments is presented as well. The main objectives of this work are to study primary damage, cascade formation phenomena, phase stability and self-organization under irradiation. This research is carried out by means of tomographic atom probe and transmission electron microscopy.

1. Introduction

Precipitation hardening (PH) ferritic/martensitic steels are one of the most perspective structural materials for new generation fusion and fission reactors. Their higher heat- and radiation-resistance is the result of high number density nano-sized precipitations that are formed during quenching with subsequent tempering. Development of such steels is based on optimization of macro-properties and micro structure of unpredicted material which requires considerable resources. At the same time, steel with adequate parameters in as-produced state can have miserable performance under irradiation. Thus, at the next step thorough investigation of nano-particles behavior under neutron flux is required. However, the main limiting factor for neutron irradiation is the time which is needed to achieve required displacements per atom (d.p.a.) and to reduce induced radioactivity to the levels where micro structural study is allowed. Normally, it takes from several years for RAFM materials to decades or more for others, which makes such investigations practically impossible. So, the one of the closest way to predict material radiation resistance is to use heavy ion beams as a modeling irradiation. One of its advantages is high dose rates which are changeable in wide range and another is that no material activation occurs.

In previous work the first topographic atom probe data sets of EK-181 (RUSFER EK-181) steel were obtained. This structural material is a 12%-Cr ferritic/ martensitic steel and has better heat-resistance at temperatures above 650 C in comparison with foreign analogues. This increase in mechanical properties (short- and long-term), as considered, is a result of formation of nano-scale structure peculiarities (different types of clusters, precipitates, second-phase nano-inclusions) during heat treatment. TAP investigations revealed presence of nano-sized clusters mainly enriched with V, N, and C. Also the distribution of alloying elements in EK-181 matrix was obtained.

In this work first progress in study of heavy ion irradiation on structure peculiarities and composition of EK-181 at nano-scale will be presented. High potential of ITEP acceleration facility with unique possibilities of atom probe microscopy creates a powerful instrument for detailed study of materials degradation mechanism. This approach will be used in the program devoted to the study of radiation degradation of structural materials. The aim of this research program is to find out the laws, mechanisms and regularities of radiation degradation processes and to analyze nano-scale peculiarities in perspective materials for new generation power plants. This program covers a wide range of materials from pressure vessel steels to the active zone materials. This combination will provide useful information for adjusting and justification for full scale modelling by to investigation of changes at nano-scale in structural materials under modeling irradiation.

To provide radiation resistance investigation of power plant vessel materials under high-dose irradiation, the imitational experiments with accelerated ion beam are developed in ITEP at the 27 MHz heavy ion RFQ HIP-1 (Heavy Ion Prototype). With neutron irradiation required doses (~100 dpa) could be achieved only in a few years even in fast breeding reactors. Heavy ion beams drastically increase defect generation speed preserving nature of cascade formation. As a result the high dpa can be reached in considerably lower time limits. The 27 MHz heavy ion RFQ designed for acceleration of ions with mass to charge ratio up to 60 with energy of 101 keV/u has been put under operation in ITEP (Moscow) in 1999 [2]. The RFQ is the realization of proposed in ITEP new resonant structure [3]. The accelerator assembly consists of the 100 kV terminal with MEVVA ion source [4], low energy beam transport (LEBT) line with two electrostatic einzel lenses and diagnostic chamber A, 12 m long 27 MHz RFQ section and channel with 3 quadruple lenses and diagnostic station B at the output of the accelerator. The ion beam both with low energy (45 ÷ 80 keV/Z where Z – ion charge number at the injector output) and high energy (5.6 MeV for Fe beam) can be used for irradiation experiments. The ion beam delivering to the target with maximum ion beam density was simulated both for low energy and high energy experiments. Results of simulation are presented below. It was found that the ion beam density can be up to 3 -4 mA/cm^2. The ion beam pulse length is 140 μs with repetition rate 1/4 pps, therefore it allows to obtain total flux $\sim 10^{+16}$ cm^{-2} in 10 hours what corresponds with > 10 dpa. To increase the total flux, the mode with ion beam length of 450 μs and repetition rate 1pps was successfully tested. The electrostatic deflector with target assembly for sample acceptable for TAP was developed. Detailed description of new equipment and results of ion beam test are presented. In case of Al ions with energy of 75, 150 and 225 keV used for first experiments, implanted atoms were found in TAP data. Experimental value calculated from TAP data was in agreement with value estimated in SRIM. During experiments the pressure was lower than 2*10^{-6} mbar.

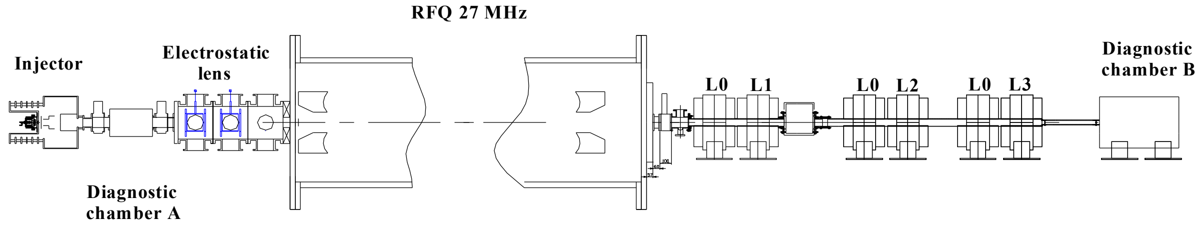


Fig. 1 ITEP RFQ HIP-1. L1, L2, L3 – existing quadruple lenses. , L0- lenses needed for transportation of ions with specific mass of 60 amu (not installed).

2. Low-energy experiment

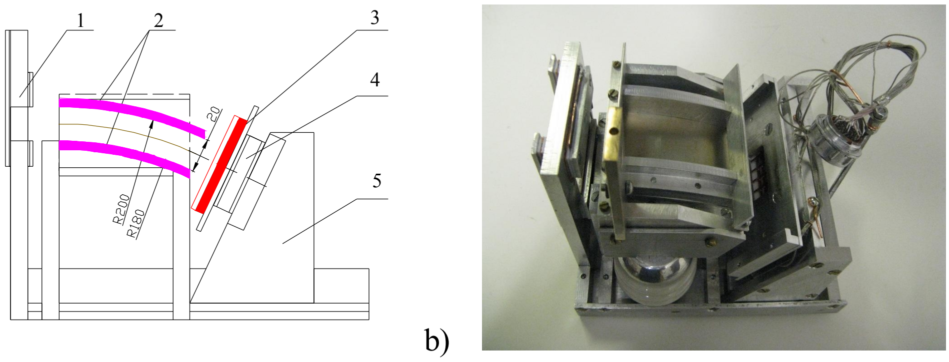
The needle-samples with radii of the needle end up to tens of nanometres are used for TAP technique. According to simulation the ion beam with energy of 150 keV generates maximum defects in the region about 30 – 50 nm which is the center of the needle-sample. Therefore the ion beam from HIP-1 injector with energy of 45 – 80 keV/Z can be used for the irradiation experiments. The sample assembling designed for these experiments was installed in diagnostic chamber A (see Fig. 1). The aluminum ion beam was used for test experiments because they can be easily found by TAP technique in the samples. The iron and chrome ion beams will be used for starting imitation experiments.

2.1. Construction of electrostatic deflector and target assembly

As it is well known the ion beam extracted from MEVVA ion source from time to time has drops of cathode material. To prevent the sample destruction by the drops the electrostatic deflector (ED) was designed and installed in the diagnostic chamber A.

The Kobra3-INP [5] code was used to optimize the ED geometry. The main goal of simulation was an optimization of ED radii and banding angle, to provide the maximum beam current density at the samples. The simulation showed that the 20 mm gap deflector with radii 190 mm and beam bending angle of 25° provides the sample irradiation by ion beam with density up to 4 -6 mA/cm^2. The ion beam with such density, pulse length of 140 μs and repetition rate 1/4 pps provides on the sample the total flux of 10^{16} cm^{-2} after 7 hours of operation.

The construction of target assembly consists of slit diaphragm, electrostatic deflector, sample holder and beam control system (see Fig. 2). To control the ion beam position relatively to the deflector input, the four measuring plates are mounted in front of the diaphragm from each side of slit. The sample assembling is installed at the distance of 20 mm from the deflector output. The photo of the sample assembly with twelve samples is shown in Fig. 3. The cooper grid is installed in front of the samples plane, to shield samples from the deflector potential electrode. As it was found from the first test, the electrostatic field between samples and deflector potential electrode results the sample destruction. The copper grid decreases the electrostatic field at the sample plane more then in 3 orders.



a) b)

Fig. 2 Electrostatic deflector, a)1 – slit diaphragm, 2 – deflector, 3 – sample assembling 4 – beam diagnostic, 5 – beam diagnostic assembly support; b) photo deflector without sample assembling.

Fig. 3 Photo of the sample assembling after irradiation.

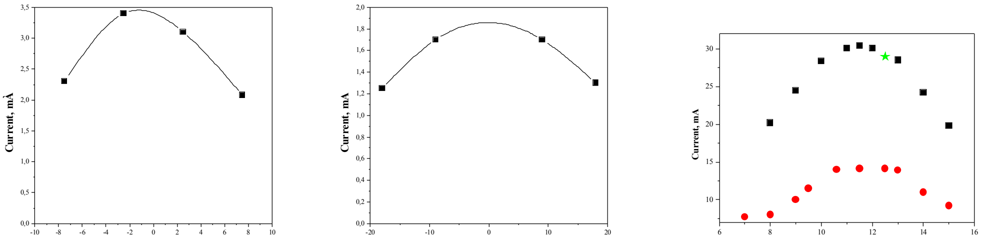
Behind the sample assembling the beam diagnostic is placed. It consists of five vertical and four horizontal measuring wires which are used for beam position tuning at the beginning of the experiment. The measuring plate is used for beam monitoring during the irradiation experiment.

2.2. Commissioning of experimental set-up

The ion beam distributions at the deflector output in both planes were measured by the diagnostic set during the test of experimental setup. The test was done with Fe ion beam. Results of measurements are given in Fig. 4. As one can see the experimental results are in good agreement with results of simulation. The needle-samples placed one over another are irradiated by the beam with the same intensity. In horizontal plane the total flux on the samples placed at the periphery of the sample assembly is ~60 % comparable to the flux on the center ones.

2.3. First experiments with Al beam

The Al ion beam generated by MEVVA ion source and accelerated by the 75 kV electrostatic tube of HIP-1 injector was used for test experiments. The beam consists of Al^{+}, $Al^{2+}$and Al^{3+} ions, therefore the samples were irradiated by aluminium ions with energy of 75, 150 and



a) b) c)

Fig. 4.Results of ED test.
a) and, b) beam profile at the deflector output horizontal and vertical plane
c) beam current at the ED output vs potential at its electrode(black square – simulation, red circles – from measuring plate behind samples,star – the sum of measured currents from all detectors located behind sample assembly at 12.5 kV at the deflector electrode)

225 keV simultaneously. The results of TAP technique are presented in Fig. 5. and TABLE 1. After irradiation the number of aluminum atoms in steel EK-181 bulk composition was increased about in one order, therefore the aluminum atoms showed in Fig. 5 B are mainly the implanted ones.

TABLE 1: BULK COMPOSITION OF STEEL EK-181 BY THE TAP TECHNIQUE BEFORE AND AFTER IRRADIATION BY THE AL BEAM (SEE FIG. 5).

	C	**Cr**	**Si**	**Mn**	**W**	**V**	**N**	**Al**
Composition	0,64	11,9	0,73	0,94	0,3	0,31	0,16	0
Before irr.	0,005	10,0	0,8	0,8	0,2	0,18	0,007	0,02
After irr.	0,029	10,2	0,981	0,757	0,2	0,13	0,009	0,16

3. High-energy experiment

At the output of RFQ the imitation experiments with Fe ion beam accelerated up to 5.6 MeV are under preparation. The target assembly which enables imitation experiments with samples under controlled temperature is under construction. The operation mode of linac output

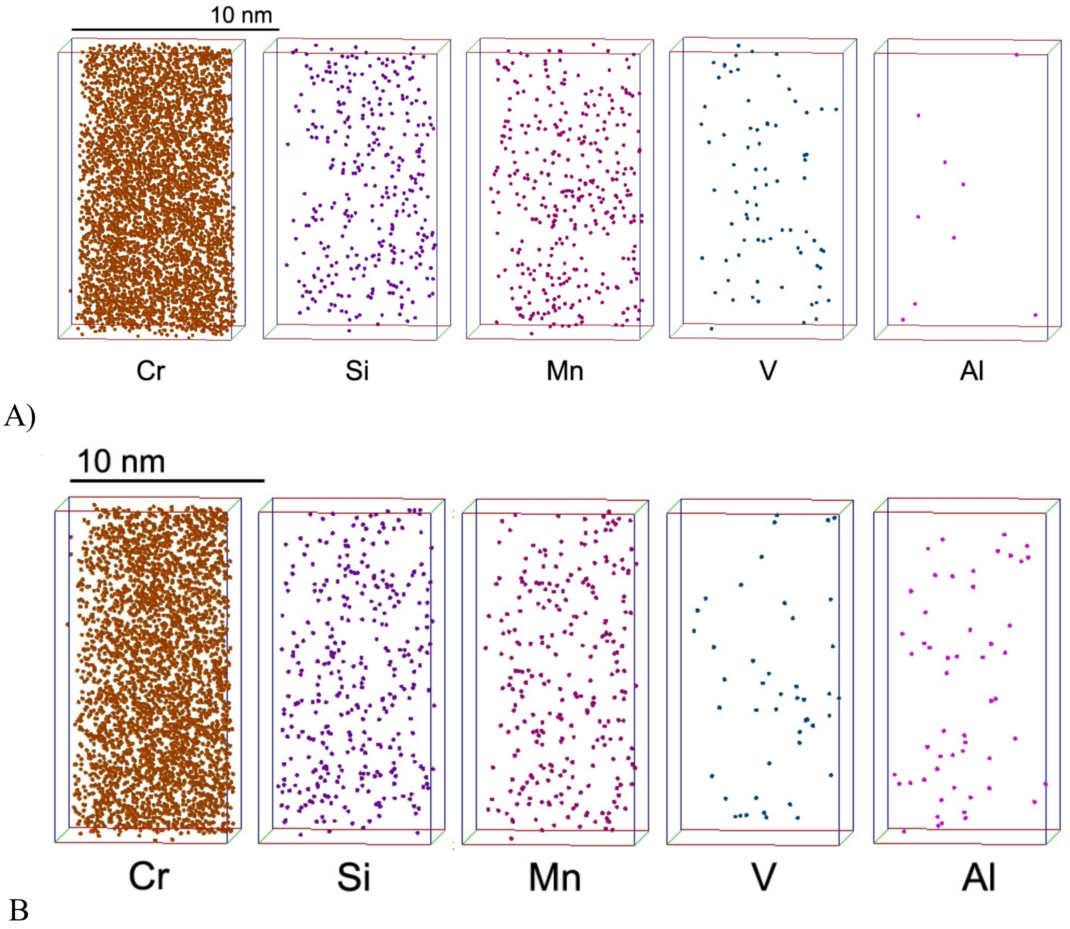


Fig. 5. 3D distribution of different ions in steel EK-181.
A – before irradiation, B – after irradiation by Al beam. Flux: 2•10^{15} cm^{-2}

channel providing the maximum uniform ion beam density at the target were defined by beam dynamic simulation with DYNAMION code developed in ITEP [6].

3.1. Beam simulation at the RFQ output channel for irradiation experiment

To define the 1 cm^2 target position and quadruple lenses parameters corresponding to the maximum ion beam current density, the simulation of the beam dynamics throughout the output channel was carried out. All previous experiments on the HIP-1 were carried out with accelerated Cu^{2+} ion beam of 4 mA. The parameters of this beam at the output of RFQ were used as initial parameters for the simulation. The output channel consists of 3 quadruple lenses (see Fig. 1) with maximum magnetic field of 12 T/m.

The simulation showed that the maximum beam current density of 3.73 mA/cm^2 can be achieved at the target of 1 cm^2 if the target is located 1.5 m behind the last quadruple and gradients on lenses L1, L2, L3 are 3.3, -7.4 и 7.1 T/m correspondingly. Plus sign corresponds to focusing force in horizontal plane and minus one corresponds to defocusing force in the same plane. The ion beam profiles for both planes are shown in Fig. 6. If the ion beam with higher current is accelerated the beam density at the target is higher as well. The results of simulation are given in Table 2. One can see that even if the percentage of ion beam delivered to target decreases with total beam increase the increasing of beam current up to 10 mA provide increasing of density on target in 2 times. The results of beam dynamics simulation are in good agreement with experimental results of Cu^{2+} ion beam transportation throughout the accelerator output channel.

Table 2: ION BEAM DENSITY AT THE TARGET
FOR DIFFERENT ACCELERATED CURRENT.

Accelerated ion beam current, мA	Beam current at the target of 1 cm^2	Percentage of ion beam delivered to target	Ion beam density on target mA/cm^2
4	3.73	93.25	3.73
6	4.96	82.7	4.96
8	6.5	81.3	6.5
10	7.97	79.7	7.97

For Fe^{2+} ions with accelerated beam current of 4 mA the maximum beam current density on the 1 cm^2 target, located at the distance of 1.5 m after last quadruple, is $j=3.62$ mA/cm^2 when gradients at L1, L2, L3 are 4, -6.7, 6.8 T/m correspondently. For Cr^{2+} ions with accelerated beam current of 4 mA the maximum beam current density on the 1 cm^2 target is $j=3.61$ mA/cm^2 under gradients of 4, -6.3, 6.5 T/m. Results of simulation for all ions are

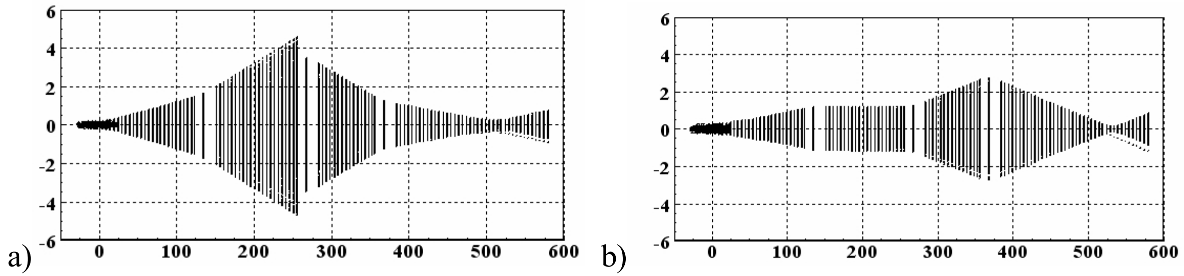


Fig. 6. Result of Fe^{2+} ion beam dynamic simulation in HIP-1 output channel; a) vertical plane, b) horizontal plane

shown in Table 3.

As it was said above the beam pulse length is 140 µs and repetition rate is 1/4 pps. Therefore the total flux of 10^{16} on the target for Fe^{2+} ions can be obtained during 9 hours of accelerator operation. The flux of 10^{17} can be obtained if the pulse length is increased up to 450 µs after 28 hours. To decrease the accelerator operation time needed for given flux, the increase the repetition rate is required. Without any upgrade the repetition rate can be increased up to 1/3 pps. Further increasing of repetition rate requires the RF power system upgrade.

TABLE 3: RESULTS OF ION BEAM SIMULATION FOR DIFFERENT IONS.

Ion	Accelerated current, mA	Gradient at L1, T/m	Gradient at L2, T/m	Gradient at L3, T/m	Beam current density, mA/cm^2
Cu	4	4	-7.4	7.1	3.73
Fe	4	4	-6.7	6.8	3.62
Cr	4	4	-6.3	6.5	3.61

3.2. Heated target chamber construction

The construction of target assembly for high energy imitation experiments with controlled heated target is shown Fig. 7. The cylindrical samples with diameter 3 mm and thickness 0.1 mm are used for investigations. Seven samples are fixed between two copper plates. The plate which looks at the beam has seven holes with diameter 2.9 mm – one at the axis and six at the radii 3.5 mm. Such sandwich is installed at the heated sample support made from copper. To prevent the vacuum vessel surface overheating, the water cooled screen around target assembly is used. According simulation the temperature of heated samples can be regulated in range from 25°C to 700°C with single heater of 250 W. So far all parts of target assembly are under manufacturing. The installation and commissioning of the target is planned for this year.

4. Conclusion

The nano-scale investigations of structure peculiarities and composition of structural materials that are used in power plants are carried on in ITEP. Such investigations are carried out in Russia for the first time with unique technique – tomographic atom probe. The ITEP 27 MHz heavy ion RFQ linac can be used as an effective experimental facility for the investigations. The experimental work can be carried on with Fe, Cr, Cu, Al ion beams with both low energy (45 ÷

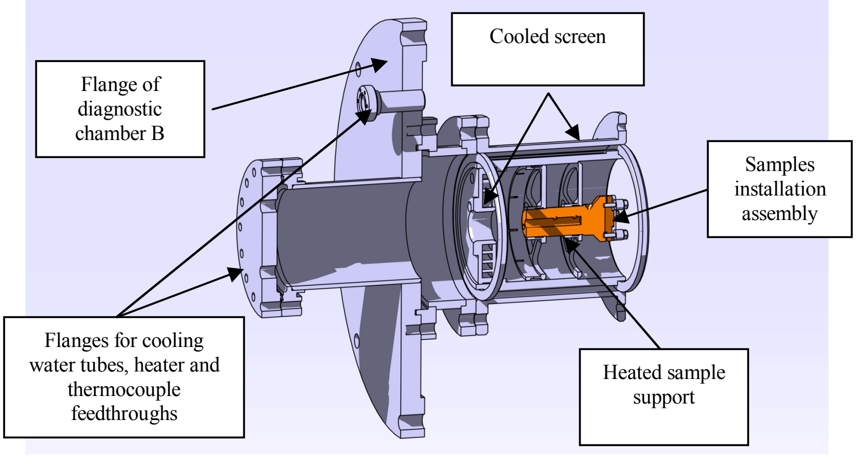


Fig. 7 Design of target assembling for high energy ion beam irradiation experiments with controlled heated target

80 keV/Z) at the output of the linac injector and high energy (101 keV/u) at the output of accelerator. The total flux of $10^{16} – 10^{17}$ cm^{-2} can be provided for both energy levels. For low energy experiments the target assembly was designed and first tests were successfully carried out. The target assembly for high energy experiments is under manufacturing and the first work with accelerated ion beam is planned for nearest future.

5. Acknowledgments

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