ITEP HEAVY ION RFQ OUTPUT LINE UPGRADE FOR EXPERIMENTS OF 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 behavior 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.

Since 2008 in ITEP the ion beam irradiation experiments are under development at the ITEP heavy ion RFQ HIP-1. 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. This linac provides accelerated beams of Cu^{2+}, Fe^{2+}, Cr^{2+} ions with current up to 10 mA and energy 101 keV/u. The first experiments with ion beam at the linac injector demonstrated promising results. The linac output beam line is now under upgrade. The results of beam extraction line adjustment for experiments with reactor materials are presented. The construction of controllable heated target is presented as well.

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 (dpa) 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.

High potential of ITEP acceleration facility with unique possibilities of atom probe microscopy creates a powerful instrument for detailed study of materials degradation mechanism. As a demonstration of this potential, the first set of topographic atom probe data for EK-181 (RUSFER EK-181) steel were obtained [1]. 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. It will provide useful information for adjusting and justification for full scale modeling by investigation of nano-scale changes in structural materials under modeling irradiation.
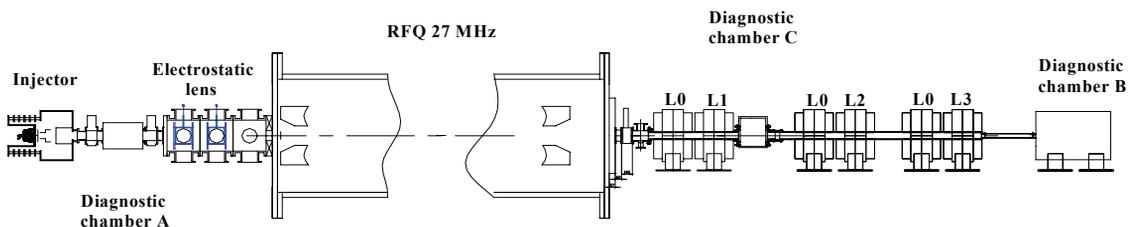
Figure 1: ITEP RFQ HIP-1. L1, L2, L3 − existing quadruple lenses, L0- lenses needed for transportation of ions with specific mass of 60 amu (not installed).

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 provides acceleration of ions with mass to charge ratio up to 60 with energy of 101 keV/u [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, diagnostic chamber A, 12 m long 27 MHz RFQ section and channel with 3 quadruple lenses and two diagnostic station B and C at the output of the accelerator (see Fig. 1). 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 maximum of the radiation degradation dose is achieved at the end of ion track into the sample, so the beam ions are accumulated into the sample. The implanted particles must not change dramatically the chemical structure of the sample. Therefore the Fe and Cr ions are preferable for irradiation modeling experiments with reactor steels. Nevertheless, to enable the direct detection of ions implanted into the samples. the Al ion beam can be used for first test with the steels.

The status of the activity was presented at the IAEA meeting in May [5]. In this report the detailed results of the ion beam delivering to the target with maximum ion beam density in high energy experiments are presented. It was found that for routine linac operation the ion beam density at the target 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 ~ 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.

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. The previous experimental program on the HIP-1 were carried out with accelerated Cu^{2+} ion beam [6]. This beam was taken for the initial work for beam line optimization for irradiation experiments. The following parameter limitations were used for output line optimization were used:

- Cu^{2+} ion beam with energy 101 keV/n.
- Beam current – 4, 6 ,8, 10 mA.
- The initial Twiss beam parameters are defined at the RFQ output (from beam dynamics simulation with DYNAMION code) [7].
- Quadruple lenses L1, L2, L3 can be used in any combination. The lenses magnetic field gradient can be up to 8 T/m, effective length is 23.5 cm, distance between poles is 7 cm. The maximum gradient can reach even 12 T/m, but for stable routine operation it is better not to exceed 8 T/m.
- The distance from the last lens and the target should be less than 2 m.

Number of particles for simulation is 10^3 for tuning procedure and 10^5 for final simulations

The transverse dynamics of Cu^{2+} ion beam in the HIP-1 and its cross section are shown in Fig. 2 Twiss parameters for the beam at the linac output are shown as well.

a)   b)
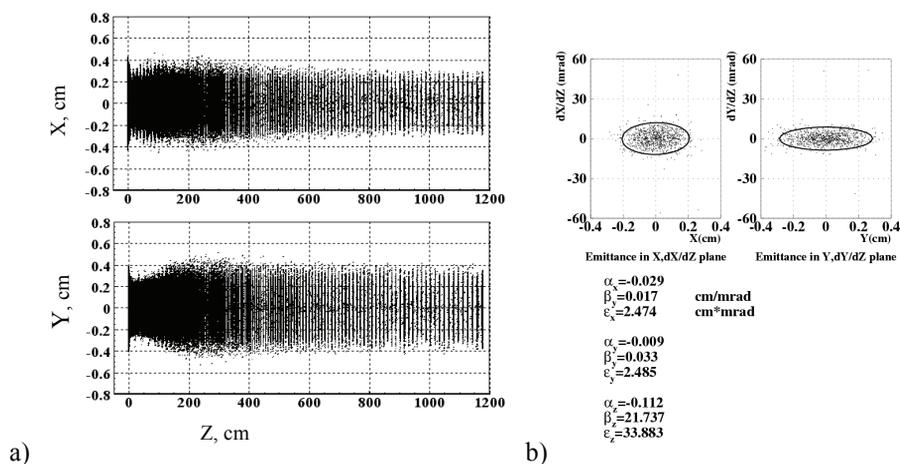
Figure 2: Result of Cu^{2+} ion beam simulation in the HIP-1 RFQ by DYNAMION code. a) Transverse plane of beam along linac; b) beam Twiss parameters at the output of linac.
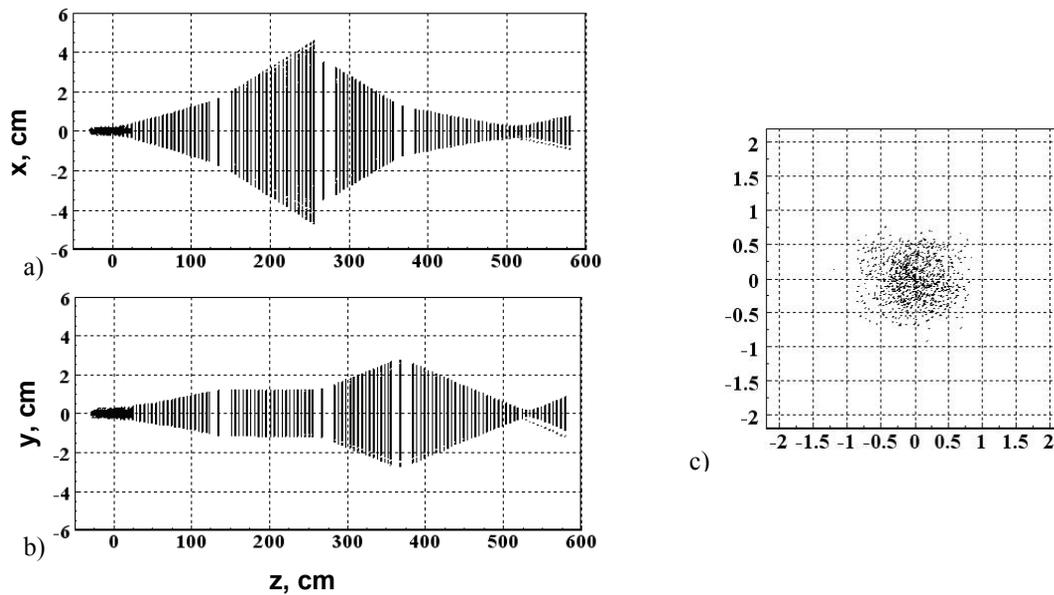
Figure 3: Result of Cu^{2+} ion beam dynamic simulation in HIP-1 output channel; a) vertical plane, b) horizontal plane c) beam cross section at the target plane.

It was very interesting to install the target in the diagnostics chamber one. In this case only lens L1 could be used. It is obvious that the beam profile is not axially symmetric from target point of view it can be even better because the set of samples can be installed in line. The simulation showed that the maximum beam density at the target installed into this chamber would not exceed 0.6 mA/cm^2.

At the next step the different combination of two lenses were investigated and finally the mode when all three lenses operated together was investigated. Let's consider optimization problem to get maximal beam density at the target with cross-section of 1 cm^2. Therefore our optimization criteria is beam density. The optimization procedure was following:

1. define the step of variation for distance after last lens;
2. fix the distance after last lens;
3. define the step of magnetic field variation for all lenses;
4. vary the magnetic field gradient at the one lens meanwhile all other are fixed;
5. make procedure 4 till the variation will not increase the beam density at the target;
6. change distance from last lens at carry out procedure 3, 4, 5.

The simulation showed that for two lenses the maximum beam density would not exceed the 0.77 mA/cm^2. For three lenses operated mode it was found that the beam density at the target with cross section of 1 cm^2 can reach j = 3.73 mA/cm^2 when the total beam current is 4 mA. The target should be located at the distance of 150 cm after the last lens and gradients at the lenses L1, L2, L3 should be 4, -7.5 and 7.9 T/m consequently. The transverse beam dynamics into the channel is given in Fig. 3. It is necessary to note that at the target plane the beam current density is about

uniform. Also it was found that this beam density can be obtained at the distance range of $130 - 170$ cm from the last lens with small correction of lenses magnetic field gradients inside the above mentioned limits. The tolerance of magnetic field gradients for lenses L1 and L3 should be better than 5 % and for lens L2 it should be better than 2 %.

At the next step the Cu^{2+} ion beam with current of 6, 8 and 10 mA was transported throughout the channel. To define the input Twiss parameters for every beam current, the beam dynamics simulation into HIP-1 was carried out. Result of the simulation is given in Figure 4. One can see that for beam current 10 mA the density at the target can reach 7.97 mA/cm^2.

As one can see from the Table 1 the beam density increases with total beam current. The increase of beam current can be obtained by upgrading of accelerator initial part (LEBT). Nevertheless, the simulation of ion beam dynamic into HIP-1 showed that the increase of input beam current in 3 times results just 30 % increase of accelerated beam current (see Table 1).
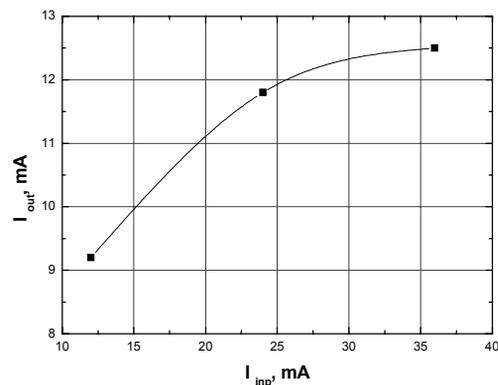
Figure 4: Beam current transmission throughout HIP-1 linac.

Table 1: Ion Beam Density at the Target for Different Accelerated Currents

beam current, mA	Beam current at the target of 1 cm^2, mA	% ion beam delivered to target
4	3.73	93.25
6	4.96	82.7
8	6.5	81.3
10	7.97	79.7

Table 2: 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

The results of simulation correlates with experimental results obtained at the linac during previous experiments. For stable linac operation the ion beam with current of 4 mA is preferable. Therefore the following simulation of Fe^{2+} and Cr^{2+} ion beam needed for irradiation experiments was carried out for this beam current. For these ion beams the same optimization procedure was carried out. With one exception – the position of target was fixed at 150 cm from the last lens. For both ion beams the Twiss parameters at the RFQ output were defined from beam dynamics simulation into HIP-1 RFQ. The magnetic field gradients and maximum beam density for all beams are shown in Table 2.

At the RFQ output the accelerated beam has pulse length of 140 µs. The repetition rate is 1/4 pps. Therefore the total flux of 10^{16} on the target for Fe^{2+} ions can be obtained during 10 hours of accelerator operation. The flux of 10^{17} can be obtained if the pulse length is increased up to 450 µs after 30 hours. To decrease the accelerator operation time needed for given flux, it is necessary to increase the repetition rate. 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.

HEATED TARGET CHAMBER CONSTRUCTION

The construction of target assembly for high energy imitation experiments with controlled heated target is shown in Figure. 5. 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. Copper is used to provide the temperature uniformity and stability for all samples. To prevent the vacuum vessel surface overheating, the water cooled screen around target assembly is used. The screen is manufactured from stainless steel. Two sets of 5 pillars with cross section 5x5 mm from stainless steel are used to keep the heated sample support inside the cooled screen. Stainless steel is chosen for both screen and pillars to provide the higher thermal gradient between screen and heated support.
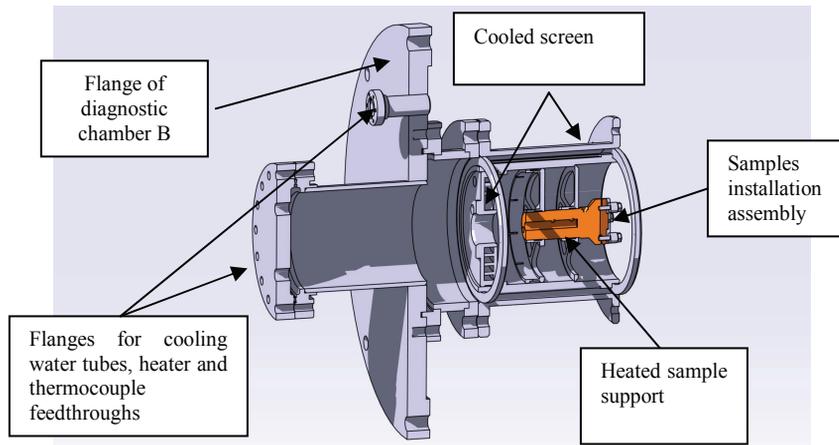
Figure 5: Design of target assembling for high energy ion beam irradiation experiments with controlled heated target.
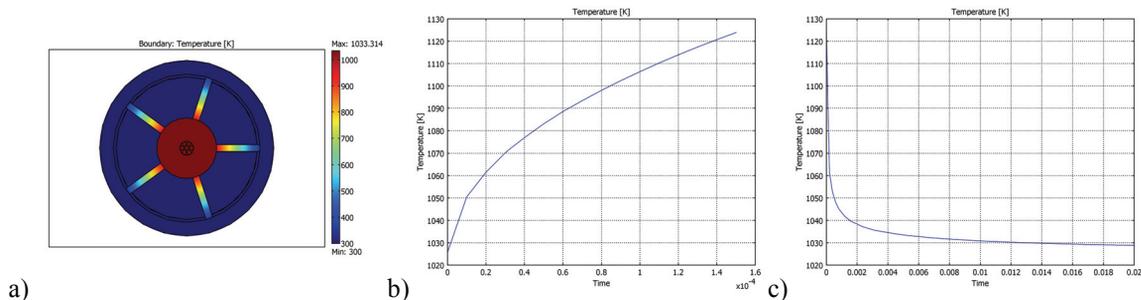
Figure 6: Temperature distribution at the target assembly. a) stationary solution before beam irradiation b) temperature of sample outside surface during the 4 mA beam irradiation, c) temperature of sample outside surface after beam.

The construction was investigated with COMSOL multiphysics code. Results of preliminary simulation are shown in Figure 6. The surface-to-surface radiative heat transfer was not yet taken into account for practical reasons. According to the simulation the temperature of heated samples without beam can be regulated in range from 25°C to 700°C with single heater of 250 W. During the irradiation by 4 mA beam with pulse length 0.14 ms the temperature of sample front side increases by 100º. The beam heating was added to the heat flow boundary condition. The temperature of sample inside surface connected to support surface increases by 30º. After irradiation the temperature of the sample reaches the initial stationary level in about 10 ms. The parts of target assembly are manufactured and now are under installation at the HIP-1. At next step the sample and its support surface radiation will be investigated with well known surface-to-ambient approximation. Moreover as a refinement, we plan to insert the actual beam energy loss distribution taken from SRIM simulation as a volume heat source (instead of the heat flux boundary condition term).

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 and Al ion beams with energy of 101 keV/u. As it was demonstrated in routine operation mode of the linac with 4 mA accelerated ion beam the beam current density at the target can reach 3.6 mA/cm^2. To reach this level, the target should be installed at 150 cm from the last quadruple lens of output linac channel and the gradients at the lenses less than 8 T/m. The precision of magnetic field gradients should be better than 5 % for first and last lens and better than 2 % for central one what can be easily provided. The total flux of $10^{16} – 10^{17}$ cm^{-2} can be provided. The target assembly with heated samples for the experiments is under manufacturing. The simulation showed that without irradiation the sample temperature can reach 700ºC. The irradiation of ion beam with current density of 3.6 mA and pulse length of 0.14 ms provides the increase of target surface temperature of 100 ºK. The temperature comes back to stationary level in 10 ms after beam irradiation.

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