Simulation of irradiation effects with ions on the RFQ linac HIPr

P A Fedin\textsuperscript{1,2,3}, M S Saratovskikh\textsuperscript{1,3}, R P Kuibeda\textsuperscript{1,3}, A L Sitnikov\textsuperscript{1,3}, T V Kulevoy\textsuperscript{1,2,3}, A A Nikitin\textsuperscript{1,2} and S V Rogozhkin\textsuperscript{1,2}

\textsuperscript{1}NRC “Kurchatov institute” – ITEP, 25 Bolshaya Cheremushkinskaya Str., Moscow, 117218, Russia
\textsuperscript{2}NRNU MEPhI, 31 Kashirskoe Highway, Moscow, 115409, Russia
\textsuperscript{3}NRC “Kurchatov institute”, 1 Akademika Kurchatova Sq., Moscow, 123182, Russia

E-mail: Fedin@itep.ru

Abstract. Radiation damage is the limiting factor in the choice of structural materials for advanced fission and fusion reactors. Neutron irradiation of materials is a slow and cost intensive process often extending over several years. Heavy ion irradiation is the only viable means to conduct accelerated testing to assess irradiated microstructures at high dpa levels. In the NRC "Kurchatov Institute” – ITEP the specimens of perspective steels and alloys are irradiated at the RFQ Heavy Ion Prototype (HIPr) by a beam of accelerated heavy ions (Fe, Ti, V, ...) up to dose $10^{17}$ ions/cm$^2$. During irradiation the investigated specimens can be heated up to 700°C. We have studied the heavy ion distribution on the target. The results of beam profiles measurements for different irradiation modes are presented. To improve the beam control a device was developed and produced. This device is based on the Arduino platform and software for analysing the data received in the streaming mode. The device allows to control all BPM signals together and takes account of these signals for the fluence calculation. Heavy ion irradiated specimens can be analyse with transmission electron microscopy, atom probe tomography and nanoindentation to measure mechanical properties of irradiated surface layers. Results of TEM analysis of Eurofer97 steel irradiated at 300°C to $10^{16}$ ions/cm$^2$ are demonstrated.

1. Introduction

Development of radiation resistance steels and alloys for the new generation of the modern fission and fusion reactors requires the understanding of the material properties and microstructure alteration due to the exposure to the radiation [1]. It was well established [2, 3] that ion beams can be used to simulate the irradiation effects of neutrons on relevant nuclear materials. Ion irradiation can produce essentially all of the standard microstructural features observed in neutron-irradiated materials (dislocation loops, cavities, radiation-induced solute segregation, radiation-induced precipitation, etc.). Therefore ion beams can be utilized to understand fundamental radiation effects with the benefits of low material activation and ease in changing irradiation conditions such as projected range, temperature, dose rate, fluence, etc. Several multi-beam facilities around the world are involved into material science experiments on simulation of the irradiation effects of neutrons on relevant nuclear materials. They include TIARA [4], DuET [5], HIT [6], FZ Rossendorf [7], FSU Iena [8], LANL [9], JANNUS [10, 11], the facility at Oak Ridge National Laboratory [12], the facility at Michigan Ion Beam Laboratory [13] and the facility at Kharkov Institute of Physics and Technology [14].
Since 2009 RFQ Heavy Ion Prototype (HIPr) facility located at NRC "Kurchatov Institute" – ITEP is used for providing material science experiments on irradiation of promising steels and alloys with accelerated heavy ions (Fe, Ti, V, …) [15]. In this paper we report about facility capabilities, recent improvements and acquired results obtained in heavy ion irradiation experiments for simulation of radiation damages in structural materials.

2. HIPr facility
The HIPr operates in a pulsed mode with a pulse duration of 450 µs and a repetition rate one pulse per two seconds. HIPr layout is shown in figure 1. Metal ion beam is generated using the metal vapor vacuum arc ion source (MEVVA). To generate the gas ion beam the duoplasmatron ion source is used [16]. In RFQ structure, the beam is accelerated up to total energy of 101 keV per nucleon (5.6 MeV for iron). RFQ structure was produced for accelerating of heavy ions with the mass to charge ratio ~60 [17]. The output channel includes three magnetic quadruple lenses responsible for the focus and transverse beam profile formation at target. The specimen holder is mounted in the target chamber and connected to the heating stage with the temperature range up to 700°C. The target chamber is equipped with the beam profile monitor (BPM) that provides beam measurement and control [18, 19].

Figure 1. HIPr layout. 1 – ion source (MEVVA or duoplasmatron); 2 – electrostatic lenses; 3 – RFQ structure; 4 – output channel, 5 – target chamber.

Material science specimens used in irradiation experiments are prepared in the shape of the disk with 3 mm in diameter and 0.1 mm thickness. Specimens are mounted on the holder (figure 2a). Specimen holder is set on a copper stage with a heater and 2 thermocouples. BPM is located in front of the holder. BPM is composed of 4 horizontal wires, 4 vertical wires and a shutter-collector with a suppressing electrode. The BPM wires are located in front of the shutter-collector. The suppressing electrode is used to suppress the secondary electrons and provide accurate measurement of a beam current by the shutter-collector. In figure 2b layout of the BPM measuring wires is shown.

Figure 2. a – photo of the specimen holder; b – Layout of BPM measuring wires in front of the specimens.
3. **Fe²⁺ ion beam parameters**

High and low intensity modes can be used for the irradiation experiments with the $3 \times 10^{12}$ and $0.7 \times 10^{12}$ ions/cm² per pulse fluence rate accordingly. For these modes the Fe²⁺ ion beam dynamics was both simulated and beam profiles were measured [20]. In figure 3 the beam transverse distribution is shown for the low intensity mode. For this mode the total beam current is 125 µA on the shutter-collector, beam distribution non-uniformity is about ±10% on three specimens. A nonsymmetrical horizontal profile is explained by beam touching the channel wall during the profile measuring. In figure 4 the transverse distribution is shown for the high intensity irradiation. For this mode the total beam current is 300 µA on the shutter-collector, beam distribution non-uniformity is about ±10% on one specimen. The measured beam distribution can be described with Gaussian distribution. The mean square deviations of Gaussian distribution equal $\sigma_x = 2.9$ mm, $\sigma_y = 2.25$ mm for horizontal and vertical profiles respectively.

![Figure 3. Transverse distribution for the low intensity mode.](image1)

![Figure 4. Transverse distribution for the high intensity mode.](image2)

4. **Fluence measurements**

At first the irradiation experiment current is measured by the shutter-collector that shields the specimens. The beam is centered on the central specimen using the BPM wires. Calibration and measurement of the beam current are provided with BPM before the irradiation because during the irradiation, the shutter-collector stays opened.

---

3
During calibration, the current on the shutter-collector $I_{\text{colletor calibr}}$ and the current on one wire $I_{\text{wire calibr}}$ are measured and their ratio calculated as follows:

$$k_{\text{calibr}} = \frac{I_{\text{colletor calibr}}}{I_{\text{wire calibr}}}.$$

During irradiation the current on the collector $I_{\text{colletor irr}}$ can be recalculated from the current measured with wires $I_{\text{wire irr}}$ as:

$$I_{\text{colletor irr}} = k_{\text{calibr}} \cdot I_{\text{wire irr}}.$$

To increase the accuracy, the measuring procedure is divided into steps (each step contains from 1 to 5 thousand pulses) to avoid errors when the beam shape is shifted or changed. The coefficient $k_{\text{calibr}}$ is calculated before and after each step and the average value is taken for the final calculation. The fluence acquired on each step in low intensity mode can be calculated as:

$$\text{Fluence} = N k_{\text{calibr}} \int \frac{I_{\text{wire irr}} \, dt}{Z e S_{\text{collector}}},$$

where $N$ is amount of pulses, $z$ – ion charge, $e$ – electron charge [C], $S_{\text{collector}}$ – shutter-collector area [cm$^2$], $\int I_{\text{wire irr}} \, dt$ – total charge per pulse [C].

For the fluence calculation in high intensity mode this approach cannot be used, due to the beam non-uniformity on the shutter-collector area. In this case the beam current on specimen, $I_{\text{specimen}}$ should be calculated using the measured beam profiles (figure 4):

$$I_{\text{specimen}} = k_{\text{fraction}} \cdot I_{\text{colletor}},$$

where $k_{\text{fraction}}$ is the coefficient calculated from the measured beam profiles as described in [21]. It is equal to 0.304 for the 3 mm disk specimen. Finally, the fluence acquired on each step in high intensity mode can be calculated as:

$$\text{Fluence} = N k_{\text{calibr}} k_{\text{fraction}} \int \frac{I_{\text{wire irr}} \, dt}{Z e S_{\text{specimen}}},$$

where $S_{\text{specimen}} = 0.07 \text{ cm}^2$ is the specimen area [cm$^2$].

5. Fluence control device
A measuring device and software was designed and produced to analyze data from the BPM and for fluence control. The device based on the Arduino platform has 12 channels connected to the BPM wires and the shutter-collector. During the pulse, charges accumulate in the gage capacitors. Voltages on gage capacitors are measured with ADC. The designed software allows calculating measured results and visualizing them. The control device enables to use all BPM wires to increase the accuracy of measuring data and to observe beam drift during irradiation. It provides a fast automatic calibration and monitoring of irradiation fluence for each ion beam pulse.

6. Results
Heavy Ion Prototype facility was used for the series of irradiation experiments on ferritic/martensitic (f/m) steels Eurofer97 (Fe9Cr1WVTa) [22], Ek-181 [23], Chs-139 [24]. Experiments were carried out in the framework of the project aimed towards understanding of the origins of the low temperature radiation embrittlement of f/m steels. Ions stopping range profile and damage dose calculations were done according to guidelines provided by Stoller et al in [25]. Figure 5 shows transmission electron microscopy (TEM) image of the cross section specimen prepared from Eurofer97 steel irradiated with Fe$^{2+}$ ions at 300 °C. Analysis of the cross section specimens showed formation of the interstitial dislocation loops. Loops number density correlates with damage dose profile (which varies with depth). Detected radiation effects in heavy ion irradiated samples allow to understand microscopic origin of low temperature radiation embrittlement of f/m steels.
Figure 5. (a) Calculated with SRIM2008 profiles of displacement damage dose and implanted ion concentration for the irradiation of pure iron by 5.6 MeV Fe$^+$ ions. (b) Compared with TEM image of cross-section of Eurofer97 specimen irradiated up to $10^{16}$ ions/cm$^2$ at 300°C. (c) High-resolution TEM image of dislocation loops formed in the vicinity of the radiation damage peak.

7. Summary
Irradiation experiment details for simulation of radiation effects in structural materials with heavy ion RFQ linacHIPr are presented. Specimens can be irradiated by various ions (Fe, Ti, V, …) with an energy 101 keV/nucleon up to dose of $10^{17}$ ions/cm$^2$ in the temperature range from RT to 700°C. Transverse distribution for the low and intensity mode was measured and used for irradiations. The control device for acquisition and visualization was produced. Influence of ion irradiation on steel microstructure is demonstrated on Eurofer97 specimens irradiated up to $10^{16}$ ions/cm$^2$ at 300°C.

Acknowledgments
This work was supported by the Russian Science Foundation (17-19-01696).

References
[1] Nelson R, Mazey D and Hudson J 1970 J. Nucl. Mater. 37 1
[2] Voevodin V and Nekludov I 2006 Evolution of structural phase state and radiation resistance of structural materials (Kiev: Naukova dumka) 376 p
[3] Was G and Averback R 2012 Radiation Damage Using Ion Beams (Oxford: Elsevier) 195 p
[4] Hamada S, Miwa Y, Yamaki D, Katano Y, Nakazawa T and Noda K 1998 J. Nucl. Mater. 258–263 383
[5] Kohyama A, Katoh Y, Ando M and Jimbo K 2000 Fusion Eng. Des. 51–52 789
[6] Kohn Y, Asano K, Kohyama A, Hasegawa K and Igata N 1986 J. Nucl. Mater. 141–143 794
[7] Kaschny J, Kögler R, Tyrrof H, Bürger W, Eichhorn F, Mücklich A, Serre C and Skorupa W 2005 Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 551 200–207
[8] Breeger B, Wendler E, Trippensee W, Schubert C and Wesch W 2001 Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 174 199
[9] Yu N, Nastasi M, Levine T, Tesmer J, Hollander M, Evans C and Maggiore C 1995 Nucl. Instrum.
Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 99 566

[10] Serruys Y, Trocellier P, Miro S, Bordas E, Ruault M, Kaitasov O, Henry S, Leseigneur O, Bonnallie T, Pellegrino S, Vaubailon S and Uriot D 2009 J. Nucl. Mater. 386-388 967

[11] Trocellier P, Serruys Y, Miro S, Bordas E, Pellegrino S, Vaubailon S, Ruault M, Henry S and Kaitasov O 2008 Nucl. Instrum. Meth. Phys. Res. Sect. B-Beam Interact. Mater. Atoms 266 3178

[12] Lewis M, Allen W, Buhl R, Packan N, Cook S and Mansur L 1989 Nucl. Instrum. Meth. Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 43 243

[13] Taller S, Woodley D, Getto E, Monterrosa A, Jiao Z, Toader O, Naab F, Kubley T, Dwaraknath S and Was G 2017 Nucl. Instr. Meth. Phys. Res. B 412 1

[14] Permyakov A, Mel’nichenko V, Bryk V, Voyevodin V and Kupriyanova Yu 2014 PAST 90 180

[15] Kulevoy T, Aleev A, Ivanov S, Kozlov A, Kropachev G, Kuibeda R, Nikitin A, Rogozhkin S, Semennikov A, Sharkov B and Zaluzhny A 2009 Proceedings of International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, AP/P5-07 1

[16] Kulevoy T, Chalykh B, Fedin P, Sitnikov A, Kozlov A, Kuibeda R, Andrianov S,1 Orlov N, Kravchuk K, Rogozhkin S, Useinov A, Oks E, Bogachev A, Nikitin A, Iskandarov N and Golubev A 2016 Review of scientific instruments 87 02C102

[17] D. Kashinsky, A. Kolomiets, T. Kulevoy, R. Kuybida, V. Kuzminov, S. Minaev, V. Pershin, B. Sharkov, R. Vengrov and S. Yaramishe 2000 Proceedings of EPAC 854

[18] Kuybida R, Kulevoy T, Chalykh B, Semennikov A, Kropachev G, Stoyakin I, Cheritsa A, Fertman A, Aleev A, Nikitin A, Orlov N and Rogozhkin S 2012 Problems of atomic science and technology, ser. Nuclear physics iinvestigations 80 68

[19] Chalykh B, Kozlov A, Kuibeda R, Andrianov S, Aparin D, Fedin P, Orlov N, Nikitin A, Bogachev A, Aleev A, Andreev A, Kropachev G, Iskandarov N, Golubev A, Rogozhkin R and Kulevoy sT 2014 Proceedings of RuPAC2014 269

[20] Fedin P, Kuibeda R, Saratovskikh M, Chalykh B, Sitnikov A and Kulevoy T 2016 Russian Physics Journal 59 293

[21] Fedin P, Kuibeda R, Saratovskikh M, Chalykh B, Sitnikov A and Kulevoy T 2017 Nuclear physics and engineering 8-3 221

[22] Rogozhkin S, Nikitin A, Orlov N, Bogachev A, Korchuganova O, Aleev A, Zaluzhnyi A, Kulevoy T, Lindau R, Möslang A and Vladimirov P 2017 MRS Advances 21-22 1143

[23] Rogozhkin S, Iskandarov N, Aleev A, Zaluzhnyi A, Kuibida R, Kulevoi T, Chalykh B, Leont’eva-Smirnova M and Mozhanov E 2013 Inorganic Materials: Applied Research 5 426

[24] Rogozhkin S, Iskandarov N, Lukyanchuk A, Shutov A., Raznitsyn O, Nikitin A, Zaluzhnyi A, Kulevo T, Kuibida R, Anfrionov S, Leontyeva-Smirnova M, Mozhanov E and Nikitina A 2018 Inorganic materials: Applied research 2 231

[25] Stoller R, Toloczko M, Was G, Certain A, Dwaraknath S and Garner F 2013 Nuclear Instruments and Methods in Physics Research Section B Beam Interactions with Materials and Atoms 310 75