Electrostatic accelerators of IPPE for nuclear science and technology

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Abstract. Results of a short review on state of the art in the area of electrostatic accelerators of multiply charged ions at SSC RF-IPPE for diverse applications in nuclear science and technology have been presented with reference to the most interesting results obtained recently.
The possibilities of unique currently operating complex of electrostatic accelerators that provide ion beams of wide mass ranges with energies from 0.1 MeV to 65 MeV and equipped by work stations for the experimental research on emergent problems of nuclear science and technology have been described.

Introduction.

The base for experimental research has been created and developed at SSC RF-IPPE with its complex of high-voltage-accelerators for over half a century. Results obtained have become a major contribution to the solution of problems such as nuclear fission physics, solid state physics, and material irradiation studies; to the establishment of nuclear-physics data bases for the development of fast-neutron reactors, as well as other areas of fundamental and applied research.
Nowadays the applied studies and fundamental research on electrostatic accelerators at IPPE have been underway essentially as a support for creating a new technological basis for nuclear power of Russia, with closed nuclear fuel cycle based on fast-neutron reactors and innovation nuclear technologies. Principal trends of scientific research include the following:

– Nuclear physics of low and intermediate energies. Nuclear data for nuclear power engineering. Closed nuclear fuel cycle. Safe management and disposition of radioactive wastes and spent nuclear fuel.
- Solid-state physics. Physics of radiation damages and radiation material science.
- Nuclear micro-analysis. Analysis of material structure and composition.
- Physics of nuclear-excited dust plasma. Direct conversion of nuclear energy in nuclear-pumped lasers.
- Activation analysis. Wear and corrosion monitoring by surface activation method.
- Beam technologies. Nanotechnologies and nanomaterials.
- Technologies for manufacturing membranes and catalytic systems. Technologies of hydrogen energy.

A complex based on six electrostatic accelerators is operated at the Institute for Physics and Power Engineering (IPPE), including the largest in Russia (in the class terms) tandem electrostatic accelerator EGP-15 developed and constructed at the IPPE.
The accelerator complex provides a wide range of accelerated ions (H, He, Li, C, N, O, F, Al, P, Si, Cl, Fe, Ni, Cu, Zr) with the intensity of few nanoampere to hundreds μA in the continuous and pulsed modes, with energies ranging from several handreds keV to several tens MeV. Table 1 presents the main operation parameters of the accelerator complex.
The accelerators' equipment park includes: electronic system, diagnostic equipment for the monitoring of ion beam parameters. For the half-century period of operation of the accelerator complex by physicists-experimenters, a large scope of nuclear-physical research methods using accelerated ion beams has been developed and practiced.
The following factors determining the interest to electrostatic accelerators as an instrument for applied research and beam technologies can be referred to

- High unification of the accelerated beam energy.
- Wide scope of accelerated ions.
- A possibility of express changing the type of particles accelerated.
- The ion currents obtained at this kind of accelerators are of the order ranging from 10^{-11} to 10^{-3} A.
- Gradual adjustment of accelerated ions energy in the range from several hundreds keV to several tens MeV.
- Compactness, simple maintenance and servicing, reliability, low power consumption (up to 4 thousand operation hours a year, power consumption – several dozens kW).

Table 1.

Type of accelerator	Energy for single charged ions, MeV	Accelerated ions	Continuous/ pulse beams	Beam intensity
EG-2,5	0,2…2,5	H, D	continuous	0,1…50 μA
		He, N, Ar, O		0,01…10 μA
EG-1	0,9…4,5	H, D	continuous	1,0…30 μA
			pulse	2…3 mA $T_{h/2}$ – 1…2 ns frequency – 1…5 MHz
EG-10M	3,5…9,5	H, D	continuous	0,01…10 μA
			pulse	400 μA $T_{h/2}$ – 1 ns frequency – 1…5 MHz
KG-2,5	2,3	H, D	continuous	0,05…2,0 mA
KG-0,3	0,35	H, D	continuous	1,0…2000 μA
			pulse	2…3 mA $T_{h/2}$ – 1…3 ns frequency–0,5…2,5MHz
EGP-15	13	H, D	continuous	5 μA
			pulse	400 μA $T_{h/2}$ – 1 ns frequency – 1…5 MHz
		C, Li, O, Al, Si, Cl, Fe, Ni, Cu, Zr	continuous	0,01…1,0 μA

The above listed operation parameters and features of this type of accelerators explains their active use world-wide as a tool for fundamental, applied research and for beam technologies.
The accelerator complex at IPPE was created for obtaining nuclear data necessary for the designing of atomic reactors. The Institute has been the main and the only supplier of necessary experimental data for the nuclear reactor calculations, and preserves this role.
As the electrostatic accelerators' ion beams have unique properties, they have been widely used in the development of the new high technologies.

2. Nuclear physics of low and intermediate energies

The complex of accelerators has been used at the Institute for Physics and Power Engineering mostly for obtaining the flux of monoenergetic neutrons in the energy range of 0.1 MeV-20 MeV [1,2]. Three time-of-flight spectrometers of neutrons in the nanosecond range were functioning on their base. Unique detectors of neutrons, fission fragments, alpha-particles, and photons were used in the investigations. Spectrometry of nuclear radiation based on the pulse form digitization has been developed.

It was a major task to create the neutron data base to meet the primary requirements of fast neutron nuclear technologies, the development and improvement of model representations of the process of neutron interactions with nuclei which give a possibility to provide the needed level of calculation results' reliability.
The following measurements have been fulfilled on the accelerator complex:
- fission cross-sections in the range of neutron energies of 0 - 7 MeV for the Th-232, Pa-231 nuclei, for all uranium isotopes from 232 to 238, for Np-237, for all isotopes of plutonium, from 238 to 243, all isotopes of curium, from 243 to 248, and for Cf-249,
- the multiplicity of prompt neutrons in nuclear fission by neutrons in the energy range up to the threshold of 6MeV for Th-232 , U-233,-235,-236,-238, Np-237,
- cross-sections and spectra of neutrons in reactions (n,n`), (n,2n), and (n,f) for a wide scope of nuclei from Li-6 to Np-237,
- cross-sections of radiative capture of neutrons for nuclei of structural materials, nuclei-fission products, and several fissionable nuclides,
- yields of delayed neutrons and their dependence on the energy of neutrons which cause fission of Th-232, U-235, U-238, Pu-239, Np-237, Am-243 nuclei.
A wide program in the area of fundamental nuclear physics has been implemented:
A complex program of experimental research on equilibrium and non-equilibrium processes has been fulfilled with reactions covering the (n,n`), (p,n), (n,2n) types for a wide scope of nuclei and range of energies, which opened a possibility for defining the contribution of direct and pre-equilibrium processes into neutron spectra and the excitation functions of collective levels of nuclei and the influence of shell, superfluidity, and collective effects.
The program of research in the area of nuclear fission physics has been implemented. Ample information has been obtained on the form of fission barrier of heavy nuclei, quasi-stationary states in the second well of potential barrier, the range of transient states of nuclei, statistical characteristics of such states at high excitations, dynamic features of the fission process development, the fission fragments distribution by masses and kinetic energies, on the mechanism of prompt fission neutrons emission, etc.
The innovative nuclear technologies stimulate the research aimed at a deeper physical knowledge of the nuclear reaction mechanisms in the low and intermediate energy ranges and a decrease of the error in evaluation of quantitative characteristics of nuclear-physical processes. It is beyond a doubt that the complex of accelerators at SSC RF-IPPE will serve as an optimum instrument to meet these challenges.

3. Physics of radiation damage and radiation materials science

A horizontal ion guide for material science applications equipped with systems for ion beam formation, adjustment, and chamber for sample irradiation has been constructed and commissioned at the tandem electrostatic accelerator EGP-15 (Fig. 1).
After electromagnetic mass-separator the beam is transported by the ion guide equipped with vacuum and ion-optical elements which provide the geometrical parameters specified for the ion beam and its attitude position on the sample irradiated.
The samples are irradiated by doubly charged Ni ions with energy of 7 MeV. The ion beam intensity can be varied in the range from 0.1 to 0.7 μA.
Special attention is given in these experiments to the assurance of uniform distribution of the ion beam on the irradiated sample and control of the distribution and intensity of the ion beam in the process of sample irradiation.
One of the main tasks nowadays is elaboration of radiation-resistant materials for fuel element claddings for fast neutron reactors with fuel burnup up to 15-20 per cent.

Ion irradiation of reactor materials allows one to obtain a high damage dose during several hours, whereas the same damage dose in reactor is obtained for two years or more [3]. The investigations of this kind are fulfilled at the IPPE (under the contract with concern «TVEL») for several years using accelerators ILU-100 and EGP-15 [4 - 6]. The data on microstructure of Cr18Ni9Ti and EK-164 steels are shown in Fig.2 for samples irradiated with 7 MeV Ni^{++} ions to 30 dpa at 625°C.

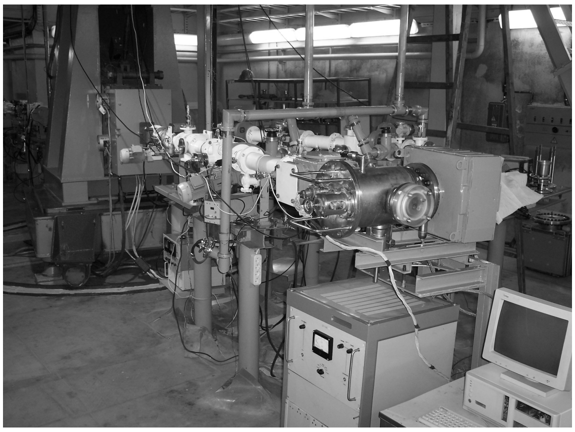
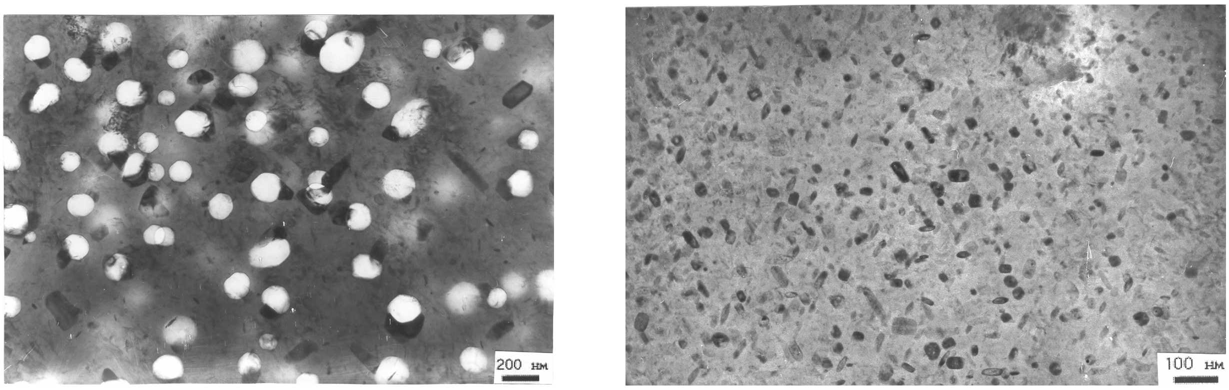


Fig.1. - Horizontal ion guide of EGP-15 accelerator.

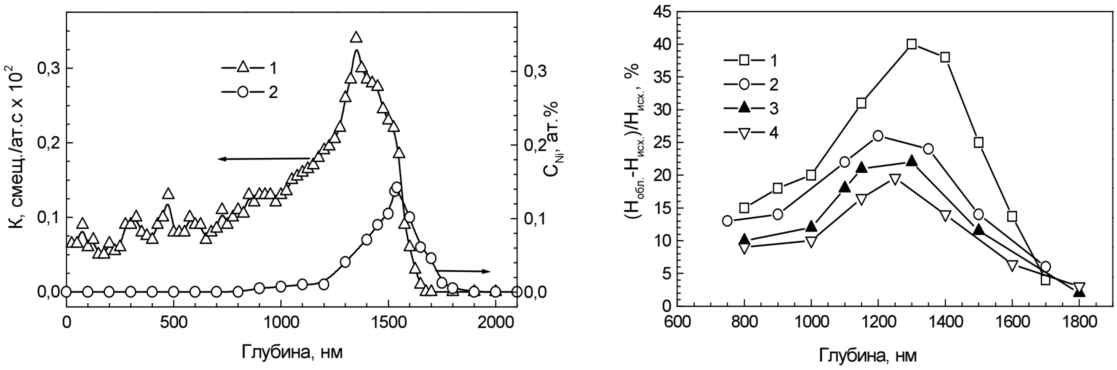


a) b)

Fig. 2. Voids in Cr18Ni9Ti steel (a) and fine-dispersed TiC and G-phase precipitates in EK-164 c. w. steel (b) after irradiation with 7 MeV Ni^{++} ions to 30 dpa at 625°C.

Since there is a correlation between the microhardness values and yield strengths in both ferritic and austenitic steels, the measurements of microhardness allow studying of the radiation-induced hardening in materials after ion irradiation. Fig. 3 presents the depth profiles of radiation damage and implanted ions (a), as well as that of relative changes in microhardness (b) near the sample surface of EP-823 steel after irradiation with 7 MeV Ni^{++} ions in accelerator EGP-15 at different temperatures. The profiles were calculated by TRIM-98 code. The rate of atomic displacements is maximal at the depth of ≈ 1.4 μm, it is equal to 3.4×10^{-3} dpa/s. The maximal fluence of Ni^{++} ions at the profile's peak corresponds to the damage dose of ≈ 114 dpa. The increase in microhardness is observed in entire temperature range. The radiation hardening profile correlates with the radiation damage one. The highest hardening was achieved at 380°C. The radiation hardening decreases with the increase in irradiation temperature.

Radiation-induced segregation (RIS) results in a considerable change in the alloy composition near the main objects of microstructure: the grain boundaries and sample surface, dislocations, precipitates, voids and gas bubbles and strongly affects the phase composition, swelling, corrosion, embrittlement and other radiation phenomena in structural materials (e.g. [7]).



a) b)

Fig.3. - a) Damage rate (1) and Ni ions deposition at 10 dpa (2) profiles near the surface of EP-823 steel irradiated in EGP-15 with 7 MeV Ni^{++} ions; b) depth distribution of relative changes in microhardness under similar irradiation conditions at different temperatures 1 - 380, 2 - 450, 3 - 550, 4 - 600℃.

Accelerators of SSC RF-IPPE also make it possible to fulfill in parallel the studies of RIS near the sample surface in these materials. The investigations have covered V-Fe and Fe-Cr alloys, ferritic-martensitic steel EP-823 irradiated in ILU-100 and EGP-15 accelerators.

The data on RIS in alloys near the sample surface obtained in the ion irradiation can be used in the modeling of RIS in these alloys near other microstructure objects, as well as for other irradiation conditions. Therefore, the heavy ion irradiation of advanced structural materials is an informative express-method for studies of radiation-induced segregation in these materials.

4. In-situ diagnostics of materials during radiation testing at accelerators

In-situ methods allow researchers to overcome the conventional approach, according to which the properties of materials are examined solely before and after irradiation. Utilization of these methods for measurements in intense radiation fields (>10^3 Gy/s) helps to diminish the side effects bearing no relation to responses of examined materials.

Research groups of IPPE developed various in-situ methods for diagnostics of modification of the materials' structure, their mechanical, electrical and optical properties of materials, applicable during ion irradiation [8]. Research is mainly conducted at the EGP-15 accelerator with a wide range of materials, including metal alloys, single crystalline insulators, ceramics and glasses, which are structural materials or materials of diagnostic systems of radiation facilities. In particular, we widely use simultaneous measurements to define correlations between different properties.

In-situ ultrasonic techniques based on the method of composite piezoelectric oscillator allow us to simultaneously measure the Young modulus, decrement of ultrasonic vibrations and strain amplitude of materials during ion irradiation. In experiments, a standing ultrasonic wave is excited in the assembly consisting of a sample glued to the piezoelectric-quartz rod, with the strain amplitude ranging from 10^{-6} to 10^{-3} at a fixed frequency of 102 kHz. The experimental set-up provides means of measurements with the accuracy of 0.002% and 6% for the Young modulus and decrement respectively. Simultaneously with the ultrasonic measurements or separately, radiation-induced optical and electrical properties can be measured. Spectra of radiation-induced photon emission and transient optical absorption are measured in the range of wavelength from 200 to 1100 nm. Applied electric field can be varied up to 10^4 V/cm, and the radiation-induced conductivity as low as 10^{-10} S/cm can be measured. We also use IR laser beams to simulate thermal effects induced by ion beams, which helps us to extract pure radiation-induced effects. The most important results are:

1. The effect of ionizing component of irradiation on the mobility of dislocations has been demonstrated for vanadium, zirconium and chromium-nickel alloys.
2. Experimental results and modeling on the effect of periodic strain on radiation-induced recrystallization of ceramics (BN). It has been shown that increasing strain amplitude accelerates the recrystallization.
3. Effects of macroscopic and microscopic electrical charging on the optical properties of insulators under ion irradiation have been demonstrated.
4. Correlation between mechanical, electrical and optical properties of insulators during irradiation have been found and investigated.

5. Nuclear micro-analysis of the materials composition and structure

The methods of microanalysis on accelerated ion beams have been developed and applied at the IPPE for more than 30 years to date. The main applications of these methods include research in reactor materials irradiation science and semiconductor engineering. A complex of hardware and software has been created for the large-series analysis, which provides the base for nuclear micro-analysis in a computerized mode. The nuclear-physics methods of analysis realized at the institute (RBS, NBS, NRA, ERDA, PIXE) have found applications in the following works:

- Analysis of light impurities (boron, nitrogen, oxygen) in carbon samples;
- Analysis of heavy impurities in semiconductor engineering materials;
- Studies of mass transfer of the main components of structural alloyed steels (Fe,Cr,Ni), nonmetallic interstitial impurities (C, N, O), alloy additions (Mo, Nb), and elements of liquid metal coolants (Li, Na, K, Pb, Bi) in the framework of studies of reactor materials corrosion;
- Analysis of the dynamics of oxide film growth on the structural steel surface in water vapor and the change of the film stoichiometric in the process of oxidation;
- Analysis of laser heterostructures on gallium arsenide;
- Operation-by-operation monitoring of silicon wafers in the integral microcircuit production technologies;
- Analysis of the VTSP film composition and structures;
- Analysis of the distribution of hydrogen implanted into silicon.

6. Fundamental studies in the area of dust plasma physics.

The nuclear-excited dust plasma is a new state of matter formed by the plasma particles, neutral particles, and macroscopic solid particles that have concentration high enough for the potential interaction energy between them could exceed their thermal energy owing to the charge with plasma particles. The world’s first experiments with dust particles in plasma created by proton beams were carried out at SSC RF-IPPE. The results obtained are of considerable interest for plasma physics [9].

The experiments were carried out on electrostatic accelerator EG-2.5. Mono-disperse particles from melamine-formaldehyde with different radiuses from 0.5 μm to 2.75 μm were used in the experiments. Different inert gases were used as the buffer gas in the course of experiments (He, Ne, Ar, Xe, Kr).

The process of dust structure formation with concentration of 5 $10^6 \div 10^7$ particles per cm^3 begins at the near-axis area of the proton beam with pressure of ≈ 25 Torr, there being a weak dependence on the sort of gas.
The structures have cylindrical symmetry with maximum diameter approximately coinciding with the beam diameter in the equilibrium position. In the process of gas pressure decrease to several Torr, crystallization of the dust component takes place on the boundary of the dust structure facing negative electrode at the distance of ~1 cm from the electrode. The crystalline structures have been obtained for all types of gases used in the experiment and for particles with different diameters (Fig. 4).

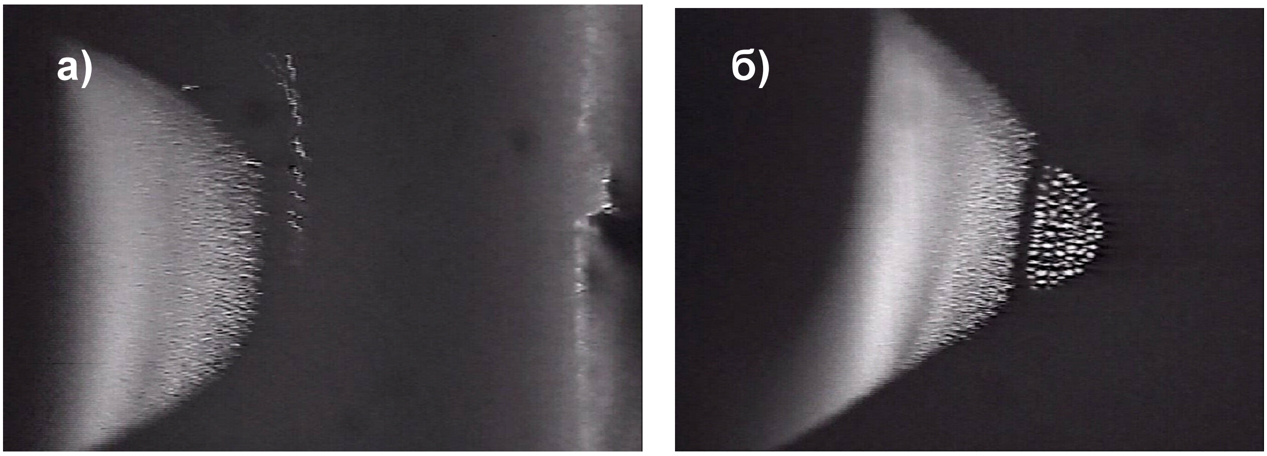


Fig.4 - a) Dust structure formation: gas – crypton, gas pressure – 1 Torr, particle size - 3 μm, voltage on the electrode – 140V, the beam current – 3 μA. b) Dust crystal. Frame size 6×8 mm^2.

In the future perspective the use of multiply charged ion beams from EGP-15 accelerator opens new possibilities, because heavy ions create areas with higher ionization levels compared with protons. Therefore, plasma-dust structures with new properties can be obtained, and new research of fundamental significance can be done with good prospects.

7. Development of membrane technologies

The complex of high-voltage accelerator EGP-15 includes a technological experimental and production section for irradiation of thin polymer films (8 – 12 μm) by accelerated heavy ions (Fig.5).

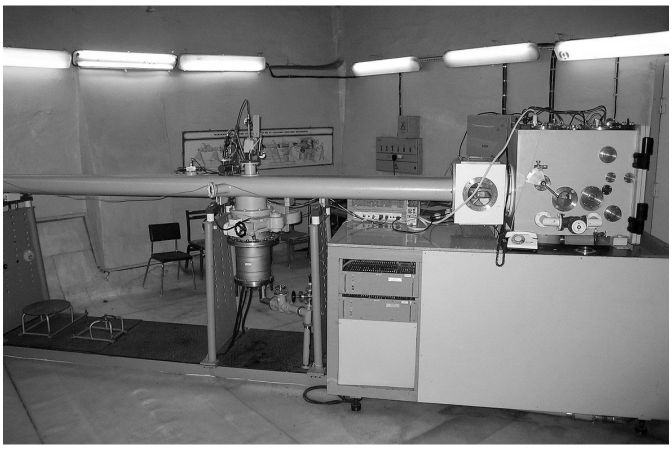


Fig.5. Irradiation complex at EGP-15

After irradiation the film is subjected to treatment in two phases – UV irradiation for the sensitizing and direct etching at a specialized division established and operated at IPPE.
The main characteristics of track membranes obtained are as follows:
- film thickness 8 μm -12 μm;
- pore density $10^5 – 10^9$ cm^{-2};
- pore diameter from 0.03 μm to 5 μm;
- angular distribution of pores: isotropic in one plane;
- the pore form is cylindrical and cone-shaped;

The track membranes obtained can be used in different devices: filters for water purification, analytical track membranes for microbiological monitoring of water and air, analytical track membranes for the parasitological monitoring, primarily that of freshwater, the «breathing» packages of food products, the composite track membranes with sterilizing filtering effect for medicine, bio-technology, pharmaceutical industry.

9. Conclusions

As a result of the development of accelerator-based engineering at the Institute for Physics and Power Engineering is a significant extension of the possibilities of unique currently operating complex of electrostatic accelerators that provide ion beams of wide mass ranges with energies from 0.1 MeV to 65 MeV and equipped by work stations for the experimental research have been significantly extended; its potentials cover a wide scope of applied and fundamental research on emergent problems of nuclear science and technology.

10. References

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