In Eqns (5)–(7), we neglected dissipative terms because of the condition $\omega \gg \nu_{in}$.

In the region of maximum plasma density, the system of equations (1)–(8) reduces to the Schrödinger type equation

$$\frac{d^2\delta\varphi}{dx^2} + 2\left(E - \frac{\tilde{\omega}^2 x^2}{2}\right)\delta\varphi = 0 \qquad (9)$$

for a linear oscillator with the complex energy

$$E = \frac{ik_z^2 \dfrac{\omega^2}{\nu_{en}}\dfrac{m_i}{m_e} + \dfrac{\nu_{en}}{\nu_{en}+\nu_{ei}}\omega k_z^2}{2\left(i\dfrac{k_z^2}{\nu_{en}}\dfrac{T}{m_e} - \omega + \dfrac{\omega^2}{\omega_{Hi}}\dfrac{1}{k_y}\dfrac{d\ln n_0}{dx}\right)} - \frac{k_y^2}{2} \qquad (10)$$

and the frequency

$$\tilde{\omega}^2 = -\frac{\dfrac{\omega^2}{\omega_{Hi}}\dfrac{\ln' n_0}{k_y}\dfrac{1}{R^2}\left(ik_z^2\dfrac{\omega^2}{\nu_{en}}\dfrac{m_i}{m_e} + \dfrac{\nu_{en}}{\nu_{en}+\nu_{ei}}\omega k_z^2\right)}{\left(i\dfrac{k_z^2}{\nu_{en}}\dfrac{T}{m_e} - \omega + \dfrac{\omega^2}{\omega_{Hi}}\dfrac{1}{k_y}\dfrac{d\ln n_0}{dx}\right)^2}. \qquad (11)$$

As is known, the solution of this equation is given by

$$\delta\varphi_{\tilde{n}} = \left(\frac{\tilde{\omega}}{\pi}\right)^{1/4}\frac{1}{\sqrt{2^{\tilde{n}}\tilde{n}!}}\exp\left(-\frac{\tilde{\omega}}{2}x^2\right)H_{\tilde{n}}\left(x\sqrt{\tilde{\omega}}\right), \qquad (12)$$

where $H_{\tilde{n}}\left(x\sqrt{\tilde{\omega}}\right)$ is the Hermite function, $\tilde{n} = 0, 1, 2, \ldots$.

The critical magnetic field induction is then

$$B_c \sim \frac{c}{e}\sqrt[4]{T\frac{m_e m_i^2}{R^2}\nu_{en}\nu_{in}}, \qquad (13)$$

which is exactly what was found by Geller [1] (the theoretical curve fitted the experimental points very closely).

What was found in Ref. [2] was a new instability whose increment has the magnetic field dependence opposite to that of the drift instability increment (hence my term 'antidrift instability').

So much for how L A Artsimovich 'blessed' the publication of my first paper on hydrodynamic instabilities. Owing to Lev Andreevich, the beautiful physics of these instabilities became my lifelong love. It is therefore only natural that my talk at the scientific session of the RAS Physical Sciences Division commemorating the centenary of the birth of Academician L A Artsimovich is titled as it is: "Prediction and discovery of ultrastrong hydrodynamic instabilities caused by a velocity jump: theory and experiment" (review [3] in *Physics–Uspekhi* published last year under the same title reflects the content of my talk today).

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Electromagnetic isotope separation method and its heritage

Yu V Martynenko

This talk briefly reviews the history of development of the electromagnetic isotope separation method in the USSR and discusses the new scientific and technological possibilities it left as its heritage.

Today, the name Lev Andreevich Artsimovich is primarily associated with thermonuclear fusion and thermonuclear energy. It was L A Artsimovich who became the scientific leader in this field in the USSR and who was instrumental in making the tokamak the focus of world fusion research. But there is also another major twentieth century scientific effort where Artsimovich proved his caliber as a scientist — the creation of nuclear weapons. More specifically, it was the Soviet Atomic Project [1], and, speaking chronologically, his involvement in this project started even earlier.

The most serious challenge the atomic bomb project faced from the very beginning was how to obtain fissionable material, the 'explosive'. The two available alternatives were plutonium and uranium-235. Plutonium could be extracted from an atomic reactor, and such a reactor, the first of its kind on the continent, was indeed launched on 25 December 1946 at the Kurchatov Institute, but it took more than two years before the required amount of plutonium was produced. Uranium-235 had to be separated from natural uranium, where its content is as low as 0.72%. The production of plutonium-239 and the extraction of uranium-235 from natural ore were carried out in parallel, and one of technologies used to extract uranium-235, the so-called electromagnetic isotope separation, was developed by L A Artsimovich; the two others were the gaseous-diffusion separation (I K Kikoin) and the centrifugal separation (F F Lange and I K Kikoin). What really triggered the serious work on the electromagnetic separation of uranium isotopes was apparently the 24 November 1944 memo by I V Kurchatov to Lavrentiy Beria as to who should do the job. Here is the reference I V Kurchatov gave L A Artsimovich in that memo [1]:

"*Prof. L A Artsimovich*

L A Artsimovich, Professor, Dr. Phys.-Math. Sci., is currently a laboratory head at the Physical-Technical Institute of the USSR Academy of Sciences and a consultant to Laboratory No 2 of the USSR Academy of Sciences [*now the Russian Research Centre 'Kurchatov Institute' (KI)* — YuVM]. L A Artsimovich is a very able physicist and the USSR's top expert in electron optics. His primary current interest is vision in darkness, and the magnetic extraction of uranium-235 is only his part-time work. I consider it necessary to make it full-time."

The decision was immediate, resulting in two research bodies being set up by the end of 1944 under the leadership of L A Artsimovich: Sector No. 5 (uranium ion isotope separation) at Laboratory No. 2, and Sector 1 at the Leningrad Physical-Technical Institute (LFTI) [now the A F Ioffe Physical-Technical Institute, RAS (FTI)]. Intensive work on the electromagnetic separation of isotopes began.

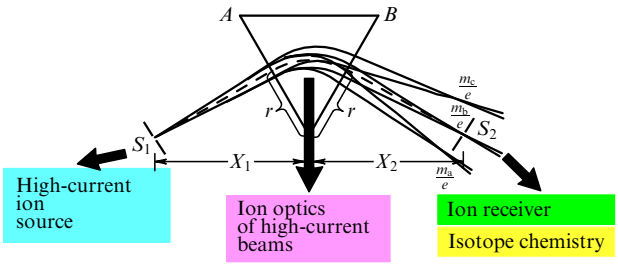

Figure 1. Schematic of electromagnetic isotope separation and major problem areas.

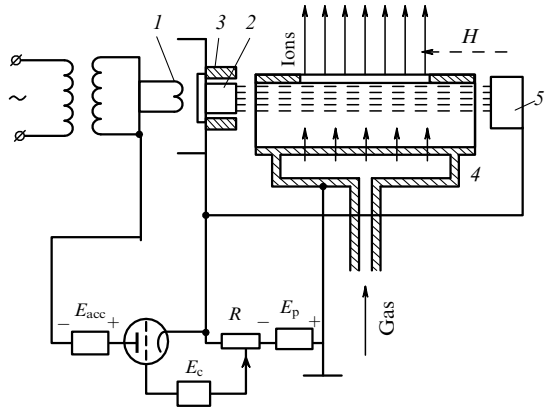

Figure 2. Schematic of the ion source: *1*, tungsten filament; *2*, heated cathode; *3*, screen; *4*, anode chamber, and *5*, reflector.

In parallel, after 1945, a research center working in this area operated in Sukhumi, Georgia, staffed by German and Soviet specialists and led by Manfred von Ardenne, a German physicist who agreed to work in the Soviet Union.

The problem was how to employ the mass spectrometer principle — the phenomenon that a transverse magnetic field separates accelerated ions by mass — to produce uranium isotopes in large quantities. Until then, the mass spectrometer developed by A J Dempster back in 1918 [2] had been applied only to the analysis of small amounts of material.

To accomplish this task, three major issues needed to be addressed: (1) a high-current ion source, (2) the ion optics of high-current beams, and (3) the ion receiver and the extraction of the uranium-235 isotopes from it (Fig. 1). A 1957 paper [3], one of the first open publications on the subject, describes the principles and basic parameters of the electromagnetic isotope separation facility that was developed and built.

While ***ion sources*** had already existed and been used in mass spectrometers, the source current did not exceed a few nanoamperes — a value which now had to be raised by 7 to 8 orders of magnitude to achieve at least one tenth of an ampere, a *sine qua non* minimum for separation. There was also a requirement that the source have a high output — hence the additional requirement for dozens of hours of uninterrupted operation.

As to the question of the method of substance ionization, the obvious choice was electron impact, clearly advantageous in being material nonspecific (provided a material could be obtained in gaseous form). Of the several types of ion sources that were tried (some, independently, at the Sukhumi Physical-Technical Institute under Ardenne), it was the Kurchatov Institute's design which was found to be best and was 'put into service'.

The source, named I-22 [4], was a hot cathode arc discharge in a longitudinal magnetic field; the ions were extracted by an accelerating voltage across a magnetic field through a slot (Fig. 2). Initially, the working material used was uranium tetrafluoride (UF_4). However, its advantage — the fact that fluorine is a single-isotope element — was compromised in that the vapor pressure required, $P = 10^{-2}$ Torr, was achieved at 800 °C, a temperature at which the vaporizer crucibles rapidly burned out. The result was that in September 1946, following necessary experiments, a switch to UCl_4 was made — a material which, although bi-isotopic [^{35}Cl (75.4%) and ^{37}Cl (24.6%)], has a vaporization temperature of as low as 400 °C. With this material, a U^+ current of up to 80% of the total current was obtained by selecting operating conditions.

Considerable work was done on optimizing the operating variables, including the working chamber pressure and the discharge current and voltage. For example, a low discharge voltage provides insufficient ionization efficiency, whereas too high a voltage gives rise to strong cathode sputtering and, besides, produces a large proportion of multiply charged U^{+2} and U^{+3} ions, thus reducing the current of singly charged U^+ ions. The parameters for optimization were naturally the maximum current of singly charged U^+ ions and the uninterrupted service life of the source.

The distribution of vapor supply to the ion source was also a factor affecting the parameters of a beam extracting from the source. It was found that a rectangular shape — the optimum — was obtained when the vapor supply rate increased in the cathode to the anode direction.

Discharge oscillations in the source and their associated beam oscillations in the separating chamber were yet another area of concern. Studies showed that they were due to the oscillations of the volume charge near the cathode. The influence of this factor on the extracted beam was reduced by moving the extracting slot farther away from the cathode.

A review paper [5] by M K Romanovskii, L A Artsimovich's deputy at the Kurchatov Institute, provides more details on the work concerning the physics of electromagnetic isotope separation. Although written only from memory — there were no publications on the subject at the time, nor did any technical report survive — this paper is a dramatic account of the problems encountered and solutions attempted and found.

The development of ion sources was the task of P M Morozov's laboratory at L A Artsimovich-led Section No. 5. Comprising the team were M S Ioffe, A V Zharinov, B N Makov, Yu D Pigarov, V I Agafonov, V V Zhukov, B G Brezhnev, N I Chizhov, S M Naftulin, L I Staroverov, and E N Braverman.

Ion optics of high-current beams. What was needed here were well-focused beams of isotopes with a dispersion of at least 1 cm at a relative mass difference $\Delta M/M = 1\%$ in order that each $^{235}U^+$ and $^{238}U^+$ ion could get into its own receiver cell.

In an ion source, although the region where the primary electrons move and produce ionization is highly localized due to electron magnetization, ions and electrons diffusing transversely to the magnetic field form a secondary plasma near the chamber wall, with the result that the former can lose ions to the latter. This loss of ions is reduced by applying the anode potential to the wall. With a slot in the wall, it is possible for ions to be extracted from the chamber using an

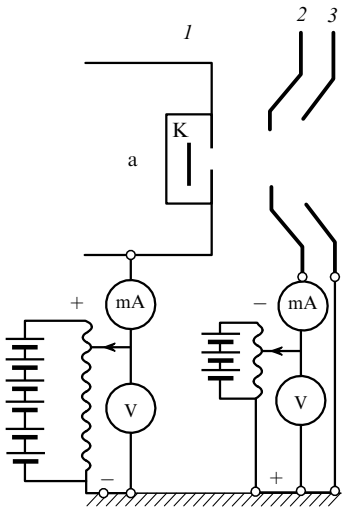

Figure 3. Schematics of three-electrode optics.

array of electrodes (Fig. 3). Importantly, the accelerating voltage should be sufficiently large (more than 2.5 kV; actual figures were 30–50 kV) — otherwise the boundary of the secondary plasma penetrates the slot and the beam being extracted becomes divergent.

An increase in the accelerating voltage increases the velocity of ions and decreases their density in the beam, resulting in the plasma boundary coming closer to the primary plasma column. The approach used first was a system of two electrodes, one the chamber wall and the other the accelerating electrode. With this setup, however, tests showed that the ion beam volume charge is not compensated for because of the exit to the second electrode of all the electrons produced by the beam ionization of the residual gas in the separating chamber. As a result, the beam diverges due to Coulomb repulsion, and isotope separation becomes impossible except for negligible currents. In addition, there is the melting effect of the electron current on the accelerating electrode. Introducing a third electrode, less negative than the second, slows ions to some extent but leads to the formation of an electron cloud between the second and the third electrodes which — at currents of less than ~ 100 mA cm^{-2} — automatically ensures the compensation for the beam volume charge owing to the ionization for the residual gas. For stronger currents, the so-called 'plasma curtain' was proposed as a compensation scheme, which consisted in mounting a hot cathode above — and at 250–300 V relative to — the third electrode. As a result, a discharge occurred at the plane of the slot, which was fully transparent for ions from the source. Electrons, on the other hand, could not enter the source and served to perform volume charge compensation.

Another important problem, the oscillations of the high-current ion beam, turned out to be related both to the operation of the ion source and to the compensation for the beam volume charge.

It was found, in particular, that fluctuations in the ion current density j due to ion source oscillations should be less than the ionization rate of the residual gas:

$$\frac{\mathrm{d}j}{\mathrm{d}t} < jnv\sigma\,,$$

where n is the residual gas concentration, v is the ion velocity, and σ is the ionization cross section. Otherwise, oscillations in the beam build up due to the decompensation for the volume charge.

Oscillations may also arise in ion optics itself. The field of the second electrode can penetrate through the slot behind the third electrode, and the slow secondary electrons drifting in the crossed $\mathbf{E} \times \mathbf{H}$ field accumulate near the third electrode to form there a volume charge which grows until slow ions are ejected toward the second electrode and the field E is restored. After that, the process repeats. To suppress these oscillations it is necessary that the electric potential of the second electrode relative to the third electrode be not less than a certain source-specific value.

Beam oscillations also occur due to the fact that the beam cross section is nonuniform (because the ionization rate and the volume charges are so). As mentioned earlier, this problem was solved by properly distributing gas supply to the ion source.

The above list of problems that were encountered, while brief and far from complete, still gives an idea of how complex was the goal achievement, both overall and in terms of how its constituent parts interrelated. In solving these problems, both calculations and empirical selection were employed. In particular, the shape of and spacing between the electrodes were chosen either using an electrolytic bath or directly during experimentation.

The researchers involved in work on ion optics were V S Zolotarev, A F Malov, A M Andrianov, G Ya Shchepkin, S Yu Luk'yanov, V A Suzdal'tsev, V M Kel'man, and E P Fedoseev [6], plus some members of N V Fedorenko's laboratory at the Leningrad Physical-Technical Institute. Extensive theoretical work on atomic collisions was conducted by O B Firsov.

L A Artsimovich was very active in all aspects of work, but his main activities were in ion optics and in making calculations. His major proposal — not to be realized until later, though — was to enhance mass dispersion by using a magnetic field weakening with radius.

To give an idea of the scale of the work done, about 1,500 experiments of many hours' duration were conducted at only one facility [7], of which there were several and which operated simultaneously and in parallel.

The ***ion receiver*** depended for its realization on understanding some totally new phenomena related to the interaction of ions with solids. It was not clear at the time what occurs when a fast ion collides with a solid surface: is it reflected by or does it penetrate the surface? What is the role of sputtering? One possibility was, for example, that all the ions penetrating the surface layer are sputtered together with the layer. It is from studies of these problems — studies that were intertwined with the development of the ion receiver — that the major research discipline, the interaction of ions with a surface, emerged.

The primary requirements regarding the ion receiver are the maximum catching of separated isotopes and small damage from ion bombardment. In order for reflected ions not to leave the receiver, the ion beam should be incident at an angle to the surface. This causes the reflected ions to be directed into the receiver, but simultaneously increases sputtering coefficient and accelerates the destruction of the receiver. With these difficulties overcome, the receiver developed, with a capacity of 10,000 Ampere-hours, ensured the simultaneous reception and satisfactory separation of all the isotopes involved.

Also under development was energy recuperation technology for by-product ions (such as Cl^+). Acceleration receivers developed for the purpose about halved the load on the high-voltage rectifier because the current of U^+ ions was $\sim 50\%$. However, energy recuperation is not possible for main beams (due to the loss of collected ions), so that the recuperation idea was later abandoned as being of no use for the electromagnetic separation of stable isotopes — a method where all isotopes are needed.

Ion receiver researchers included, at the Kurchatov Institute, I N Golovin, B V Panin, and V G Tel'kovskii, and, in Sukhumi, M Ardenne, V M Gusev, M I Guseva, R A Demirkhanov, and D V Chkuaseli.

The work was conducted overall very intensely. Below is the step-by-step chronology of what was done [1].

5 November 1945. L A Artsimovich (Laboratory No. 2) produced 70 micrograms of 12–15% enriched uranium-235 in one day.

Late 1946. The following developments took place at Sector No. 5 of Laboratory No. 2, and Sector No. 1 of LFTI:

(1) theoretical and experimental studies were made of various types of systems for forming and accelerating ion fluxes;

(2) a number of types of ion sources were developed experimentally;

(3) ion composition analysis was made for an ion source using uranium tetrafluoride as a working material;

(4) separation chambers were designed and manufactured for conducting initial isotope separation experiments.

Uranium enrichment exceeded 90%. The ion current amounted to 20 mA. Source lifetime ranged from 1 to 2 hours.

With the experience acquired, the design and manufacture of an industrial prototype of a separation unit started at Plant No. 814 (Sverdlovsk-45).

Late 1947. The ion current was increased to 50 mA, uninterrupted service time was 8–10 hours.

Fourth quarter 1950. The first batch of highly enriched uranium-235 was produced at the SU-20 facility (20 separation chambers) at Plant No. 814 (Sverdlovsk-45). Ion current ranged up to 100 mA; source lifetime, up to 48 hours. Thus, the industrial-scale separation of atomic bomb uranium-235 became a reality. In parallel with electromagnetic separation work, studies on molecular methods for separating isotopes were conducted at Plant No. 813 (Chelyabinsk-40) under the leadership of I K Kikoin. Molecular methods, while much superior in efficiency, did not provide more than 75% enrichment of uranium-235 — compared to 94% needed for the atomic bomb. The first Soviet atomic bomb successfully tested in August 1949 used plutonium made in a nuclear reactor. The second atomic bomb, tested in October 1951, used uranium-235, specifically that produced at Plant No. 813 at an enrichment of 75% and subsequently improved to the required level by using the electromagnetic method.

However, as a result of advances in developing molecular separation techniques for enriching uranium-235, a resolution was issued by the USSR Council of Ministers in October 1951 whereby Plant No. 814 was terminated as an autonomous enterprise. Electromagnetic separation equipment was then made part of Plant No. 418 targeted at producing ^{6}Li isotopes for the hydrogen bomb using the reaction $^6\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + {}^4\mathrm{He} + 4.785$ MeV — an idea proposed by V L Ginzburg and first described by him in classified reports dated 2 December 1948, and 3 March and 23 August 1949 (see Ref. [8] for more details). The task was successfully accomplished and on March 1953 the first Soviet hydrogen bomb was tested, which used ^{6}Li produced by the electromagnetic method alone. This event contributed hugely to the prestige and authority of the Soviet Union.

Following this success, more than 3,500 people were awarded the Stalin Prize, the following precisely for the electromagnetic isotope separation method: at the Kurchatov Institute, L A Artsimovich, I N Golovin, P M Morozov, A M Andrianov, G Ya Shchepkin, B A Alekseev, V S Zolotarev, B N Makov, S Yu Luk'yanov, M S Ioffe, and V N Zhukov; and at the Sukhumi Physical-Technical Institute, M Ardenne, V M Gusev, R A Demirkhanov, and D V Chkuaseli.

The first two hydrogen bombs used ^{6}Li produced by electromagnetic separation, but after that only molecular methods were employed. The high-power electromagnetic facilities were in the meantime given the task of separating stable isotopes. By the early 1970s, new separation technologies were developed for important stable isotopes of more than forty elements. The SU-20 facility in the USSR produced stable isotopes of a large number of elements in amounts ranging from fractions of a gram to many kilograms (depending on the natural abundance), leading to isotope applications in medicine, nuclear physics research, biological tracer method, neutron activation analysis in geology, and so forth.

The construction of new electromagnetic facilities for stable isotope separation led to a considerable improvement in the quality of isotopes and, most importantly, in that of isotope enrichment. The facilities currently in use are S-2 and S-5M. The development of isotope separation technologies using nonuniform magnetic fields resulted in a 2–5-time increase in dispersion. Instrumental in the development of such facilities were L A Artsimovich, A F Malov, E P Fedoseev, and others.

Also of great importance for further advancement of the method are ongoing improvements in ion sources for electromagnetic isotope separation, including high efficiency with respect to the material being separated and high working temperatures (up to 1500 °C), the latter allowing the industrial-scale, fluorine-free, environment-friendly production of isotopes (of the platinum–palladium group, as well as the isotopes of other elements with high vaporization temperature).

Although the electromagnetic method cannot be as highly efficient as its molecular counterparts, it still continues to play a major role in the production of stable isotopes. This is currently the only method for producing isotopes of 25 – 30 elements which include all rare-earth, alkaline-earth and alkaline elements, thallium, etc.

Today, the Laboratory of Electromagnetic Isotope Separation at the Nuclear Fusion Institute (NFI) of RRC 'Kurchatov Institute' produces stable isotopes of Ca, Cd, Gd, Eu, Hg, Pd, Sm, Tl, Yb, and Zn, which are distributed both domestically and internationally (Germany, Iran, Canada, China, South Korea, USA, Taiwan, Uzbekistan, France, Sweden, and Japan). Table 1 above lists the species and enrichment factors of the isotopes produced at the Laboratory [9].

However, the benefit gained from the electromagnetic separation method is not so much the production of stable isotopes as the vast scientific and engineering experience accumulated in the process of its development.

The ***ion sources*** developed for this technology formed the basis of most ion sources currently used in experimental and commercial ion-beam facilities.

The first 'spin-off' application of the high-current ion source developed for the electromagnetic separation method was apparently the neutron source developed for research

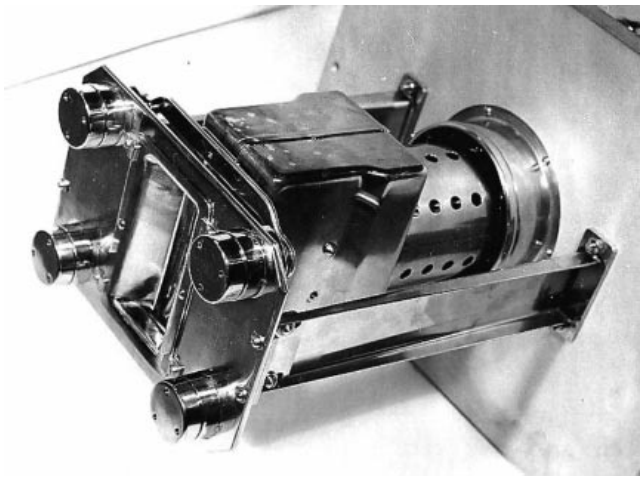

Figure 4. High-current ion source I-22 designed at P M Morozov's laboratory in KI.

Table 1 (compiled by R N Kuz'min, 1998).

Element, isotope	Facility	Natural abundance, %	Enrichment level	Enrichment factor
^{176}Yb	S-2	12.7	99.43	1030
^{168}Yb	S-2	0.13	86.9	5096
^{168}Yb	S-2	0.13	82.4	3597
^{160}Gd	S-5M	21.9	99.87	2740
^{157}Gd	S-5M	15.7	99.5	1070
^{151}Eu	S-2	47.77	99.91	1213
^{153}Eu	S-2	52.23	99.97	3047
^{104}Pd	S-2	11.1	99.1	882
^{102}Pd	S-2	1.0	95.5	2100
^{67}Zn	S-5M	4.1	97.0	750

purposes in the late 1950s. The underlying technology of the device was ion implantation where 200-keV deuterium ions were implanted into titanium until reaching the concentration ratio of 1:1, after which the same deuterium ion beam, now bombarding deuterium-enriched titanium, produced neutrons by the reaction $D + D \rightarrow n + {}^3He$. V M Gusev and M I Guseva used the identical reaction at the same time to study the depth distribution of deuterium implanted into metals.

In the 1960s, a space ion engine was built around an ion source (Fig. 4) developed by P M Morozov's sector researchers in cooperation with a design team from the Institute of Engines (aka Zarya Special Design Bureau). The Kurchatov Institute motor design team included N F Balaev, A G Zimelev, A Ya Kozlov, R N Kuz'min, L I Staroverov, Yu D Pigarov, L N Pil'gunov, N I Chizhov and some others, and their principal Zarya collaborators were Khan Girun, V A Vetrov, M T Dedyukhin, G M Antropov, V A Shchepetilov and some others. In 1968, a bismuth-based, 10-g-thrust multislot model of an ion engine demonstrated a continuous service lifetime of 3016 hours. The research conducted in that period revealed a number of advantages of ion engines over other types of electrical rocket engines. These include:

— higher energy efficiency;

— the possibility of a higher specific momentum (the ratio of the thrust to the propellant weight flow rate);

— long service lifetime;

— larger assortment of propellants.

These features were instrumental in realizing already in the period we are discussing that the best application for ionic

Figure 5. Ion engine Zefir.

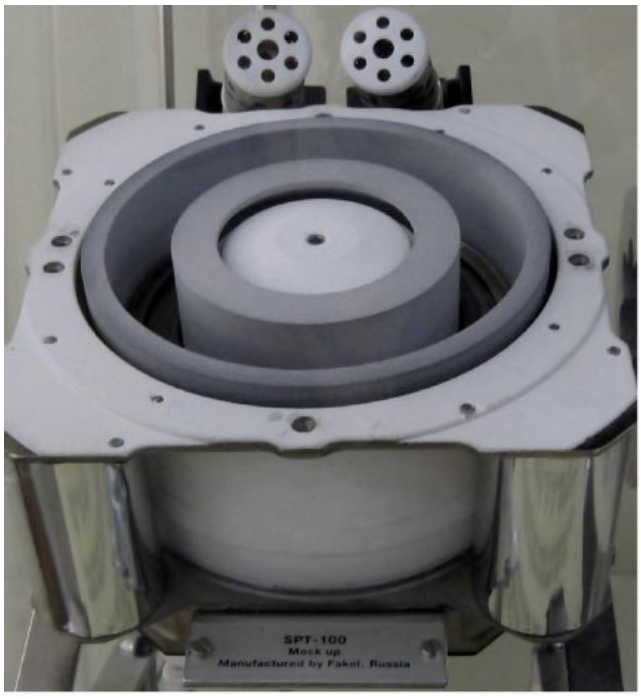

Figure 6. Stationary plasma engine Eol.

engines is in long-term space missions. Plasma engines, by contrast, seemed more suitable for near space — as maneuvering engines capable of rapidly moving satellites from orbit to orbit.

In December 1971, an artificial Earth satellite, Meteor, was launched into orbit on the initiative of A G Zimelev, being equipped with the liquid-metal (mercury) propelled ion engine Zefir (Fig. 5), and in the same month the stationary plasma engine Eol (Fig. 6) designed by A I Morozov, also of L A Artsimovich's Plasma Research Department, was tested. Both space engines stood up well to testing, showing a good

correlation of prediction to measurement for all performance parameters, including the thrust.

Today, admittedly, ion engines find no application because the long-term space missions for which they are mainly intended cannot currently be provided with enough electrical energy on board. A multiyear flight on a spacecraft with marching ion engines is only a dream at this point. By contrast, stationary plasma engines are currently in demand in the space industry for their well-established ability to rather rapidly perform orbital transfer operations with space objects.

Based on ion sources developed in P M Morozov's laboratory, sources of multiply charged ions were developed for the Dubna cyclotron, which were also used in the G N Flerov laboratory to produce artificial transuranium elements. For this achievement, the team led by G N Flerov (including the Kurchatov Institute's B M Makov, who developed the source of multiply charged ion) was awarded the USSR State Prize in 1975.

Ion optics has also left a good legacy. Solutions found for electromagnetic isotope separation find direct applications in ion implanters and ion injectors.

The problem of ion beam neutralization — a phenomenon that occurs for high-current beams in the electromagnetic method of isotope separation — also had to be addressed in relation to space engines. R N Kuz'min and N F Balaev developed a high-efficiency plasma neutralizer for the space ion engine Zefir. Even earlier, in 1966–1970, a neutralizer was utilized on the ionospheric laboratory Yantar'.

Problems with high-current ion beams stimulated in-depth research on the physics of atomic collisions, bringing world recognition to N V Fedorenko's laboratory at FTI and to O B Firsov and V A Belyaev at the Kurchatov Institute. In 1972, a series of studies titled "Elementary processes and inelastic scattering in atomic collisions" brought the Lenin Prize to a group of researchers including V V Afrosimov, V A Belyaev, V M Dukel'skii, N V Fedorenko, and O B Firsov.

But perhaps the greatest impact was made by research on ion–surface interaction, which was initiated for developing an ***ion receiver*** and which was given much impetus when work on the production of uranium-235 and lithium-6 was completed. The principal researchers in this field were V M Gusev and M I Guseva (initially of the Sukhumi Physical-Technical Institute and later, from the early 1960s, of the Kurchatov Institute); B V Panin, V G Tel'kovskii, and V M Chicherov (of L A Artsimovich's department at the Kurchatov Institute), and V A Molchanov and E S Mashkova of the Chair of Atomic Physics and Electronic Phenomena at the Physics Department of Moscow State University. Led by L A Artsimovich, the Chair conducted significant research on ion–surface interaction. In a major development, the Kurchatov Institute produced a mass monochromator (mass separator) which was transferred to the MSU Research Institute of Nuclear Physics (staffed in part by researchers from L A Artsimovich's Chair). Two other research centers on ion–surface interaction — and ones with leading positions globally — were the Chair of Electronics at the MSU Physics Department (V E Yurasova), and the Institute of Electronics of the UzbekSSR Academy of Sciences, Tashkent (U A Arifov, an alumnus of Leningrad State University and a close collaborator with FTI and the Kurchatov Institute).

The ion sputtering of solids was studied primarily in the late 1950s and in the 1960s. It is these studies that led to the possibility today of controlling erosion processes in a variety of ion–beam and plasma facilities, including thermonuclear ones (among them ITER, the International Thermonuclear Experimental Reactor). Sputtering is also widely used in coating technologies of various purposes.

The in-depth studies that were done of ion reflection from a surface and of ion–ion emission (the latter with the use of secondary-ion mass spectroscopy, or SIMS) formed the basis of modern surface diagnostics techniques.

The discovery titled "The phenomenon of anisotropy in the ion–electron emission of single crystals" (E S Mashkova, V A Molchanov, D D Odintsov, V G Tel'kovskii, and V M Chicherov, discovery diploma No. 126, priority date 13 October 1960) was made and filed by the members of L A Artsimovich's Chair and those of his Department at the Kurchatov Institute.

A remarkable legacy of the electromagnetic isotope separation method is ion implantation. V M Gusev and M I Guseva were the first to realize that electromagnetic separation facilities, allowing as they do the control of ion implantation into surface layers, are best suited for doping semiconductors to obtain a near-surface p–n junction. The reverse of the conductivity type in p-Ge was achieved for the first time by M M Bredov, who in 1961 bombarded germanium with Li^+ ions. In the same year, V M Gusev and M I Guseva obtained electron–hole transitions in silicon by bombarding it with group III and group V ions. The year 1963 witnessed the creation of the Ion Bombardment Laboratory (IBL) in L A Artsimovich's Department at the Kurchatov Institute, with V M Gusev as its head. The fundamental studies conducted at IBL in the 1960s and early 1970s provided the basis for ion implantation in semiconductors. As a result, in 1979 the team led by M I Guseva was awarded the USSR State Prize for Science and Technology for the "Development and implementation of the series production of special-purpose industrial ion–beam facilities, and the basic development of industrial ion implantation technology for the series production and development of new types of semiconductor devices and integrated circuits for the national economy and defense."

In the mid-1970s, having laid a good basis for and thus ensuring the further development of ion implantation in semiconductors, IBL changed its focus to other topical questions, including plasma–surface interaction in relation to nuclear fusion and the ion implantation in nonsemiconducting materials.

The ion–beam accelerator currently in operation at IBL is the ILU (Russian abbreviation for Ion Beam Installation Accelerator) [11], which separates ions by mass (analogous in fact to the mass separator S-5M) and is used both for scientific research and in ion implantation technology (Fig. 7). Ion implantation can increase the hardness, corrosion resistance, and wear resistance of a metal and can reduce its friction coefficient. It is successfully applied to drawing, cutting, and stamping tools. Implanting ions also improves the wear resistance and reduces the friction coefficient of elastomers. A good illustration is the deadwood bearings on the icebreaker *Arktika*, whose elastomer bushings survived the North Pole expedition unreplaced — in contrast to their best foreign counterparts, which need re-bushing bearings after each major trip. Ion-implanted elastomers were also used for the same purpose on the icebreaker *Leonid Brezhnev* and in pump bushings at the Kalinin atomic-power plant in the town of Udomlya.

A later development, the implantation-plasma accelerator Vita [12] features both high-energy (up to 40 keV) and low-energy (250–300 eV) ion beams (Fig. 8).

Using the Vita apparatus as a compressor blade finishing tool at the Ufa Engine Plant increases the blades' useful life

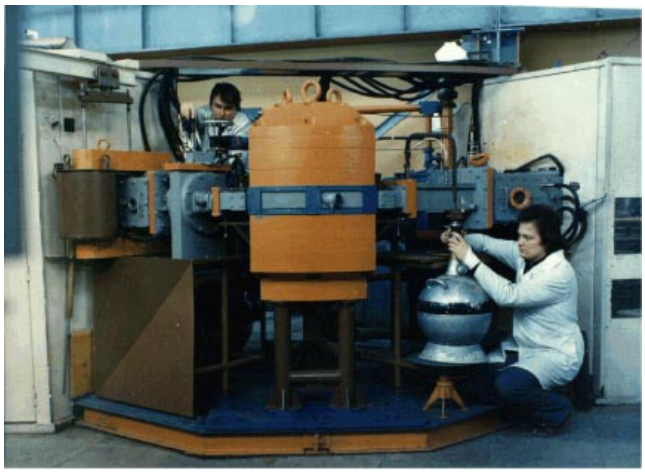

Figure 7. Ion–beam accelerator ILU. Ion energy: up to 40 keV; total current: up to 30 mA; magnetic field: up to 5500 Oe; processed area: 15×20 cm^2; ion species: throughout the Periodic Table.

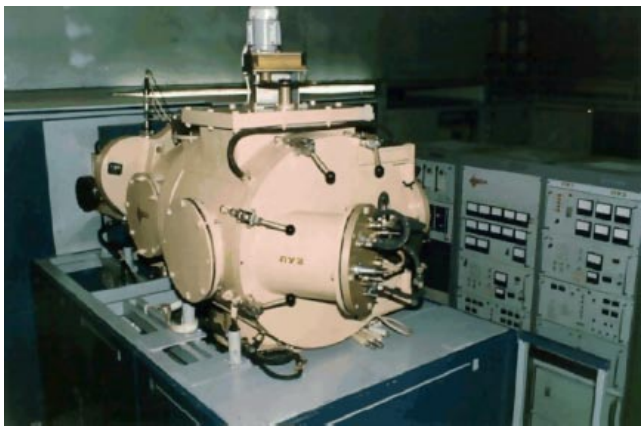

Figure 8. Implantation-plasma accelerator Vita. High-energy ions: energy — 4.0×10^4 eV, current density — 2.0×10^{-4} A cm^{-2}; low-energy ions: energy — 250–300 eV, current density — 2.5×10^{-2} A cm^{-2}; processed area: 110×250 mm^2.

time by a factor of 2.5 to 3 compared to traditional technologies.

In a recently developed technology, vacuum plasma coating deposition (including reactive deposition) is conducted simultaneously with ion implantation using high-energy (up to 50 keV) metal ion beams (Fig. 9). This hybrid technology increases the adhesion of coatings, including multilayered ones, and improves their performance characteristics (hardness, wear resistance, etc.).

The hybrid technology will be utilized in the joint project in which the Saturn Research and Production Association cooperates with Rosnano and Gazprombank to construct a tool plant in the town of Rybinsk using RRC 'Kurchatov Institute's technologies and equipment.

In conclusion, it can be said that the electromagnetic isotope separation method played a crucial role in the implementation of the Soviet Atomic Project and paved the way for numerous research avenues that led both to remarkable scientific achievements and to major modern technologies. The electromagnetic isotope separation method left a great legacy to build on.

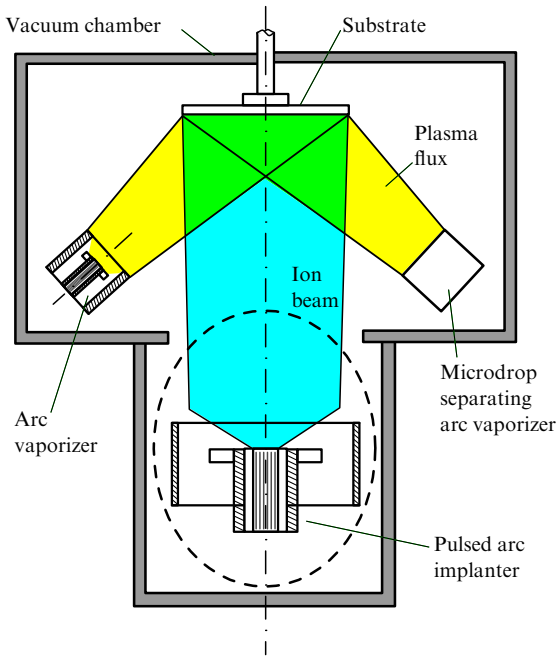

Figure 9. Hybrid technology facility (vacuum plasma coating combined with ion beam bombardment).

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