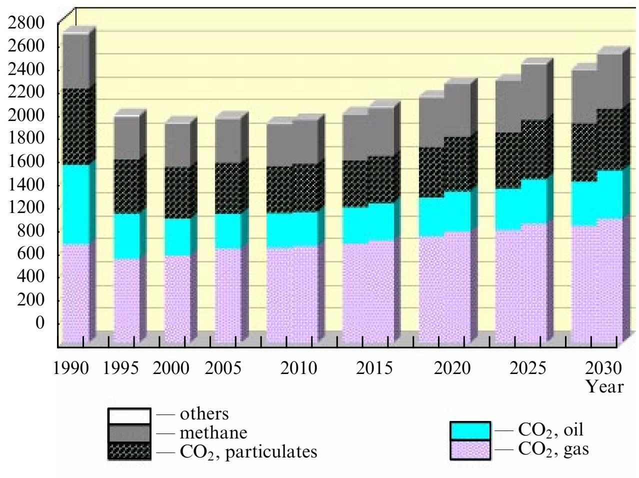

Figure 20. Greenhouse gas emissions by fuel types.

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Lev Andreevich Artsimovich and extremely strong hydrodynamic instabilities

A M Fridman

A brief background account is perhaps in order to explain how it was that Lev Andreevich presented my graduate thesis to *Sov. Phys. Dokl.* journal.

The story starts with the 1962 *Phys. Rev. Lett.* paper [1] by R Geller, a prominent American experimentalist, who demonstrated for weakly ionized plasma in a magnetic field that its diffusion across the field builds up as the field is monotonically increased from a certain value.

This finding seemed to be at odds with well-known earlier experiments indicating that both the classical and the Bohm diffusion coefficients decrease with increasing magnetic field H.

I was then an undergraduate at NGU*, and here is what Roald Sagdeev, my teacher, told me that same year when leaving for summer vacation: "I'll tell you what. I will be back in a month and if I find your paper on my desk explaining the Geller effect, you will be a postgraduate at IYaF upon your graduation. If not, at NGU."

Roald did find the paper on his desk on his return, and he then arranged with Lev Andreevich for the paper to be presented at the T seminar (on thermonuclear fusion) at what was then LIPAN (Russian acronym for Laboratory of Measuring Instruments of the USSR Academy of Sciences, currently the RRC 'Kurchatov Institute'). Two days after my talk there, Sagdeev told me that Lev Andreevich suggested presenting my graduate thesis to *Sov. Phys. Dokl.* (see Ref. [2]), but that he would like to speak to me first.

The conversation with Artsimovich is a memory I will never forget. What I saw and heard struck me. It had never occurred to me that what I did could be looked at in that simple back-of-the-envelope way. With one exception (coefficient $k \ll 1$), all aspects of my work were explained by Lev Andreevich at a totally elementary level.

As an illustration of what our conversation was about, a few pages of my thesis follow below.

The analysis in Ref. [2] leans upon the following equations to describe the dynamics of weakly ionized plasma with electrons magnetized and ions not magnetized:

$$\frac{\mathrm{d}}{\mathrm{d}x}(T\,\delta n) - en_0\,\frac{\mathrm{d}}{\mathrm{d}x}\,\delta\varphi + \frac{e}{c}\,n_0\,\delta v_{\mathrm{e}y}B + \frac{\mathrm{d}\ln n(x)}{\mathrm{d}x}\,T\,\delta n = 0\,, \tag{1}$$

$$\mathrm{i}k_y T\,\delta n - \mathrm{i}k_y e n_0\,\delta\varphi - \frac{e}{c}\,n_0\,\delta v_{\mathrm{e}x}\,B = 0\,, \tag{2}$$

$$\mathrm{i}k_z T\,\delta n - \mathrm{i}k_z e n_0\,\delta\varphi = -n_0 m_{\mathrm{e}}(\nu_{\mathrm{ei}} + \nu_{\mathrm{en}})\,\delta v_{\mathrm{e}_z} - n_0 m_{\mathrm{e}}\nu_{\mathrm{ei}}\,\delta v_{\mathrm{i}z}\,, \tag{3}$$

$$\mathrm{i}\omega\,\delta n + \mathrm{div}\,(\mathbf{v}_{\mathrm{e}0}\,\delta n) + \mathrm{div}\,(\delta\mathbf{v}_{\mathrm{e}} n_0) = 0\,, \tag{4}$$

$$\mathrm{i}\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}x} + e\,\frac{\mathrm{d}}{\mathrm{d}x}\,\delta\varphi = 0\,, \tag{5}$$

$$\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}y} + ek_y\,\delta\varphi = 0\,, \tag{6}$$

$$\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}z} + ek_z\,\delta\varphi = 0\,, \tag{7}$$

$$\mathrm{i}\omega\,\delta n + \mathrm{div}\,(n_0\,\delta\mathbf{v}_{\mathrm{i}}) + \mathrm{div}\,(\mathbf{v}_{\mathrm{i}0}\,\delta n) = 0\,, \tag{8}$$

where T is the electron temperature (it being assumed that $T_{\mathrm{e}} \gg T_{\mathrm{i}}$); e is the electron charge; c is the speed of light in a vacuum; m_{e} and m_{i} are the electron and the ion mass, respectively; ν_{ei} and ν_{en} are the electron–ion and electron–neutral collision frequencies, respectively, and $\mathbf{v}_{\mathrm{e}}$ and $\mathbf{v}_{\mathrm{i}}$ are the directed velocities of the electrons and ions, respectively.

* NGU, Novosibirsk State University; IYaF, Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences.

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

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

for a linear oscillator with the complex energy

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

and the frequency

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

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

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

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

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

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.