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Leningrad Fiztekh Fellows in the tokamak team of Lev Andreevich Artsimovich (1962 – 1973)

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Fate decreed that a small group of Leningrad Fiztekh Fellows in the early 60s found themselves involved in the tokamak research supervised by L A Artsimovich at the I V Kurchatov Institute of Atomic Energy in Moscow. This happened owing to the following circumstance. At that time, a new method of considerable promise, intended for the diagnostics of hot plasmas, had been developed in our Leningrad Fiztekh. The method involved the analysis of atoms escaping from a plasma. It made use of the fact that in any, even very hot hydrogen plasma, which might seemingly be fully ionized, there exists a small fraction of neutral hydrogen atoms being in thermal equilibrium with the ions. The possibility of the occurrence of this phenomenon was first pointed out by A D Sakharov in the calculations of a toroidal fusion reactor with magnetic confinement [1]. "These atoms", Sakharov wrote, "should originate in a plasma due to the successive charge exchange of neutral hydrogen coming to the plasma interior from the chamber walls". Sakharov also noted that the fraction of atoms will be very small and will have no tangible effect on the energy balance of the plasma; nevertheless, a noticeable atomic flux will be emanating from the plasma and bombarding the wall. After publication of Sakharov's calculations, this phenomenon came to the attention of another outstanding physicist — B P Konstantinov, at that time Director of the Fiztekh [or in full, A F Ioffe Physical-Technical Institute (PTI), RAS]. He proposed using the atoms emerging freely from the plasma to diagnose ions and measure the ion plasma temperature, because the energy distributions of atoms are very close to that of ions. It is pertinent to note that the problem of measuring the ion plasma temperature was a pressing one at that time. No practical solutions of the problem were in sight. Starting from B P Konstantinov's proposal, in the PTI Laboratory directed by Prof. N V Fedorenko, under the supervision of V V Afrosimov during 1958 – 1960 the instrumentation was developed for detecting atoms emanating from the plasma (the so-called atom analyzers) and a technique was devised for determining the ion distributions from the measured atomic flux [2]. By the early 60s, this technique had successfully passed the tests at the legendary Leningrad fusion 'Alpha' facility, and the results were presented at the IAEA Conference in Salzburg in 1961 [3]. This report [3] attracted considerable attention in Salzburg. The result was that we at the PTI conceived the idea of testing the new technique in tokamaks, the tokamak research expanding vigorously at that time under the aegis of L A Artsimovich in Moscow. The PTI proposal was readily accepted, and a group of Fellows from Leningrad, including the author of this report, found themselves in the Department supervised by Artsimovich.

Lev Andreevich's attitude to us was determined primarily by the following two factors. First, he was deeply interested in the new method of plasma diagnostics. Second, Lev Andreevich himself had been a PTI staff member in the past (1930 – 1944). It had been at the PTI where he had turned into a prominent physicist. Therefore he was keenly interested in everything related to the Leningrad PTI. Moreover, this was an opportunity to establish with the PTI direct scientific cooperation, which Lev Andreevich appreciated highly, in addition to administrative and managerial relations (Artsimovich had already become the Academician-Secretary of the Division of General Physics and Astronomy of the USSR Academy of Sciences).

I saw Lev Andreevich for the first time at the tokamak sectorial (sector 44) seminar. At that time, after the tragic death of N A Yavlinskiĭ, V S Strelkov, a very young scientist, stepped in as the supervisor of the seminar. The seminar proceeded in Strelkov's office. I saw an athletic-looking, elegant man of medium height entering the office quickly and sitting down in the shabby oak armchair allotted to him. By the way, legend had it that the armchair, which had been brought from the Kaiser Wilhelm Institute in Berlin after the World War II, had belonged to W Heisenberg. It was striking how acutely and vividly Artsimovich reacted to everything discussed at the seminar. It was evident that he grasped the heart of the matter immediately, recognized the weak points quickly, and asked the speaker challenging questions. After the seminar, its participants crowded by the blackboard and continued to discuss what had just been heard. The young V Strelkov, A Razumova, D Ivanov and others crowded

round Artsimovich. I was struck by the ease and the unconstraint of what was going on. They argued with Artsimovich vigorously, objected to him, and in doing this nearly pulled him by the sleeve, i.e. behaved themselves in a family style neglecting courtesy. For me, a newcomer, Artsimovich was a legendary personality, one of the originators of nucleonics, a Hero of Socialist Labor, Academician-Secretary, etc. All this did not tally with the unceremonious behavior of the young 'tokamak' Fellows. To my good fortune, shortly after I also became a member of this wonderful family and gained access to discussions with him, which were lively and at times vigorous.

Before long, I could communicate with Artsimovich directly. The point was that he began to take an active interest in our experiments on measuring the atomic fluxes from tokamak plasmas. Artsimovich's attitude to experimental data merits special consideration. It should be admitted that I regarded him at that time as a theorist rather than an experimenter. He had an intimate knowledge of all the existing theoretical models related to plasma physics, a knack for combining them and applying to specific circumstances. But he was also capable of performing a remarkably thorough analysis of experimental data, apprehending their physical origin, and estimating the measure of reliability and the range of applicability. This rarely occurring capacity allowed him to compare experimental results with theoretical predictions in the course of discussions, on the spot.

One more feature of Artsimovich, which revealed itself in direct communication with him, produced a strong impression on me. It was his phenomenal ability to quickly bring theoretical results to numerical estimates. Before my very eyes, he would pick up some exceptionally cumbersome equation or formula, simplify something, neglect something, expand it in a series, drop small terms, and obtain a numerical result, like a magician conjuring a dove or a rabbit out of his sleeve. Subsequently, you would solve this equation numerically on a computer to obtain a similar result to within 10–15%.

He liked to busy himself with raw experimental data. I recollect an event of the mid 60s which made a strong impression on me. At that time I spent much time in Moscow due to the tokamak research and stayed with my friends. One Saturday or Sunday we strolled the Moscow streets through the day, and in the evening a big company gathered at home. Suddenly, when the mirth was in full swing, I was called to the telephone. I was surprised at that, for I believed that there was nobody to phone me there. I was still more surprised to hear the voice of Lev Andreevich in the receiver. "Misha", he said, "I am sorry to trouble you on a day off. I am rearranging your data... Please tell me, do you divide the readings by the square root of the energy to obtain the dimensionality of density, or not?" I was dumbfounded by the fact that Academician-Secretary himself was calling me, a junior research scientist, at home. I murmured: "Yes, I do..." "Well", he said, "we will compare our plots on Monday..." I could not come to myself for a long time. The huge dynamic range of this man stunned me. On the one hand, he was involved in the process of science management and fostered new branches of it, and on the other plotted my experimental points on a millimeter paper with a pencil. In addition, I was ashamed by the fact that I was having fun on my day off while he was making plots and writing formulas for me in his suburban house.

The use of Leningrad atom analyzers on tokamaks proved to be very fruitful. We succeeded in pursuing reliable measurements of the ion plasma temperature on the tokamaks operated in Moscow at that time. In particular, starting from these measurements, we managed to confirm the fusion origin of the neutrons which were first recorded in fusion research on Tokamak-3 in 1969 [4]. I should say that the most important outcome of our activities under Lev Andreevich's supervision was the origination of the famous Artsimovich formula for the ion temperature in tokamak plasmas in 1970 [5]. Artsimovich noted that, assuming a classical ohmic nature for ion heating, the energy flux from electrons to ions is independent of the electron temperature. As for the ion energy losses, he assumed them to be primarily due to classical thermal conduction. Artsimovich borrowed the expression for thermal conductivity from the Galeev–Sagdeev theory of classical thermal conduction by trapped particles, which had just been developed. Eventually, Lev Andreevich obtained the expression describing the ion temperature versus combination of plasma parameters:

$$T_i \sim (IH_z n_e R^2)^{1/3} A^{-1/2} . \quad (1)$$

Here, I is the plasma current, H_z the strength of longitudinal magnetic field, n_e the electron plasma density, R the major plasma radius, and A the isotopic number (hydrogen or deuterium).

It was a great honor for me to become Artsimovich's co-author in this paper. I honestly admit that my contribution was purely technical. Lev Andreevich had asked me to collect the magnitudes of ion temperature which we had measured employing the atom analyzers and the corresponding plasma parameters. The magnitudes of ion temperature measured in the ohmic tokamak regime proved to be in good agreement with formula (1). This allowed a vitally important conclusion that the ion energy balance in tokamak plasmas is classical in nature. Clearly this conclusion reinforced the international position of the Moscow tokamaks supervised by Artsimovich.

Formula (1) was derived for a stationary plasma. Next Artsimovich suggested that I should consider the dynamics of the ion energy balance proceeding from the dynamics of ion temperature and density. The objective of this consideration was to determine the ion energy lifetime and its changes during discharge. "If you succeed, professor", Lev Andreevich spoke ironically, which was his way, "write an article for *JETP Letters*". He could have done this consideration much faster and written the article by himself. But by nature he was not only an outstanding scientist, but a remarkable teacher as well. He brought me to this consideration by the hand for obviously pedagogical purposes, willing to promote his young disciple and let me do it by myself. I left for Leningrad and shortly after returned to bring him the manuscript. Well aware of the responsibility, I had tried to write the manuscript to the best of my abilities and believed to have done it well. Artsimovich did not find any errors in the paper but covered the whole text with stylistic corrections. When returning the fair copy, he spoke some words that stuck in my memory: "Misha, appropriate writing is manful and elegant..." Later we published the paper corrected by him [6].

In this connection it is pertinent to note that he himself possessed a remarkable literary style. It will suffice to read his book *Controlled Thermonuclear Reactions* (Moscow: Fizmatlit, 1961) to leave no doubt of it. For instance, this is how he writes about a plasma cloud (p. 195): "*However, the shape of this cloud boundary is by no means a pleasure to the eye. ...it resembles an ink blot rather than an even circle*". And like

examples of metaphoric and in a way ironic description of phenomena are many in this book.

By the way, the literary style of Artsimovich would make a book by itself, which is beyond the scope of this short communication. Be it as it may, we certainly know that only an author with a perfect command of the material can afford pleasure to himself and the reader by presenting scientific information in a refined literary style. This is precisely the way Artsimovich would write his scientific and popular works.

Artsimovich derived formula (1) for the so-called 'collisional' mode, in which all the contemporary tokamaks operated. In his famous review entitled 'Tokamak facilities' [7], Lev Andreevich showed that the tokamak plasma should transit to a 'collisionless' mode with increase in ion temperature. In this case, the dependence of the temperature on the plasma current and the isotopic number will be stronger and take on the form $T_i \sim I^2 A^{-3/2}$ in lieu of $T_i \sim I^{1/3} A^{-1/2}$ for the collisional mode. Artsimovich also showed that in Tokamak-4, which was put into service in early 1970 (the last tokamak in Artsimovich's lifetime), a transition to the collisionless mode was possible. This signified that a gain in the ion temperature far exceeding that predicted by formula (1) could be expected in passing to the maximum current in T-4 when operating with a hydrogen plasma. Had we then succeeded in accomplishing this effect, it would have been a regular tremendous advance of tokamaks and one more unassailable proof of the classical character of ion thermal conduction. Artsimovich posed this problem before us in 1972. Experiments in T-4 on the build-up of current and simultaneous measurements of the ion temperature became a real passion for Lev Andreevich, this being his last scientific passion, for the experiments were underway only two-three months before his decease. That wintertime of 1972 – 1973 was engraved on my memory forever. For the first time in our ion temperature measurements we were using a new five-channel model of the atom analyzer, which was capable of measuring the ion temperature and its time dependence in every tokamak discharge. It was a marked time saver for experimenters but the progress in raising the current was arduous. Malfunctions of different sorts would appear one after another. Lev Andreevich was already unwell but would call us at the control desk room from home several times a day. As is often the case with large experimental facilities, after numerous adjustments work would commence by the evening and continue until late at night. Alas, several weeks of intensive work on Tokamak-4 did not yield the expected results.

Despite the fact that the plasma current was successfully raised by nearly a factor of two in comparison with the previous experiments, the ion temperature did not go beyond the limits defined by formula (1). This indicated that the plasma transition to the collisionless mode did not occur. Lev Andreevich could not conceal his disappointment. His last scientific passion ended in a negative result. True, his disappointment was assuaged, because Lev Andreevich recognized the reason for the negative result. During one of the last telephone connections with the T-4 control desk room, he was informed that the plasma temperature did not rise properly even for maximum currents. He hypothesized that a lot of impurities supposedly come into the plasma in heavy-duty operating modes to prevent the plasma from attaining the collisionless mode. This was the last I ever heard from him. Only a few days later he died, remaining a devotee of science until the very end.

It is significant that his last scientific prediction was borne out. Our subsequent comprehensive analysis showed that there exists a wealth of data indicative of the intensive ingress of impurities to the T-4 tokamak plasma at high discharge currents. We published these results [8] four months after the decease of Artsimovich. Since then, the impurity problem in tokamaks has been in the foreground. In the tokamak generations to come, no longer with Artsimovich, it was solved successfully using divertors (devices for removing impurities from the plasma exterior) and resorting to special technologies to process the walls of the plasma chamber.

This year, we commemorated the 90th anniversary of Lev Andreevich's birth. He has not been with us for twenty six years. But the tokamak type facilities, which were the concern of a considerable part of his life, now are operated in the world's leading laboratories and demonstrate the practicability of controlled fusion reactions with a high useful energy output.

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