In memory of Vitaly Dmitrievich Shafranov

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The 1st of December 2014 would have been the 85th birthday of Academician Vitaly Dmitrievich Shafranov—the outstanding physicist and one of the founders of the contemporary theory of high-temperature plasma and controlled thermonuclear fusion. Shafranov's work laid the foundation of the theory of plasma confinement, equilibrium, and stability in toroidal magnetic systems (now called tokamaks).

V D Shafranov was born in 1929 in the village of Mordvinovo in the Ukholovskii district of the Ryazan region. His father, Dmitry Matveevich Shafranov, worked as an engineer building roads, and his mother, Faina Dmitrievna Shafranova, was a teacher. V D Shafranov went to primary school in the village of Chashnikovo, and then Kryukovo in the Moscow region. In 1941, his family fell into German occupation for several days, but then miraculously managed to get out. In the difficult war years, Vitaly Shafranov learned at school and worked together with his father on road building. For this labor he received his first government award at the age of 14-it was Certificate 442 of the USSR NKVD Main administrative directorate of roads "for the pre-term accomplishment of planned works in 1943." In 1946, V D Shafranov finished school with a Gold medal in Smolensk. In 1951, he graduated successfully from the Faculty of Physics of Moscow State University (the Chair of Structure of Matter) and was offered a job in the Theoretical Sector headed by Academician Mikhail Aleksandrovich Leontovich at LIPAN (Laboratory of Measuring Instruments of the USSR Academy of Sciences), as today's Russian Research Centre 'Kurchatov Institute' was known at the time.

V D Shafranov's first scientific study — "On the stability of flexible wire in a longitudinal magnetic field," was accomplished together with M A Leontovich in 1952. This work became fundamental for further studies on the stability of plasma with current in a magnetic field. In several years, at the 4th International Conference on Ionization Phenomena in Gases held in Venice in 1957, V D Shafranov gave a talk on "Equilibrium of magnetohydrodynamic configurations" and, having derived the general equation of plasma equilibrium in an axisymmetric magnetic field, he immediately found himself in the cohort of leading world-renowned thermonuclear physicists.

Among V D Shafranov's numerous scientific advances, we should particularly mention three pioneering results rightfully named after him, without which the plasma theory and experimental practice in all countries dealing with controlled nuclear fusion can hardly be imagined.

We should first of all point out the above-mentioned equation of plasma equilibrium in an axisymmetric magnetic field (derived by V D Shafranov in 1956 and published in 1957), which was later called in the scientific literature the

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Vitaly Dmitrievich Shafranov (01.12.1929-10.07.2014)

Shafranov–Grad equation¹. This second-order differential equation relates the shape of a magnetic surface cross section to the shape of the plasma pressure profile and the current running in the plasma.

This equation laid the basis for the calculation and construction of all tokamaks in the world, including the largest experimental tokamak-reactor, ITER (International Thermonuclear Experimental Reactor), now being built in France. It is successfully applied in astrophysics, hydrodynamics, meteorology, radio physics, etc.

Another relatively simple equation known to many plasma physicists relates the displacement of magnetic surfaces with respect to the magnetic axis to the plasma pressure and the internal inductance of plasma pinch. This 'Shafranov displacement' is perhaps the first concept with which students who begin studying plasma physics in tokamaks get acquainted.

And, finally, the third pioneering result (obtained in 1953) is the Shafranov–Kruscal criterion, which determines the

¹ It should be emphasized that the work of G Grad, in which an analogous equation was obtained, appeared in 1958.

stability boundary of plasma with current under helical perturbations. It is remarkable that already in 1958, on defending his thesis for Candidate of Science, Vitaly Dmitrievich Shafranov was awarded with a Doctor of Science degree.

V D Shafranov's professional activity was inseparable from the Kurchatov Institute [I V Kurchatov Institute of Atomic Energy (IAE) in Moscow], where he had graduated from a senior laboratory assistant to a Chief Researcher and founded the world renowned school of plasma physicists, which worked very fruitfully (V V Arsenin, L E Zakharov, V I Ilgisonis, M Yu Isaev, A B Mikhailovskii, M I Mikhailov, D Kh Morozov, V P Pastukhov, V D Pustovitov, A A Skovoroda, A A Subbotin, E I Yurchenko, and others). As a successor of M A Leontovich, V D Shafranov headed the Plasma Theory Department at the Institute of Nuclear Fusion (INF) affiliated with IAE, for over twenty years (1981–2007). The director of the institute was in those years Boris Borisovich Kadomtsev, who was an intimate friend of Vitaly Dmitrievich. This team initiated one of the leading scientific schools of our country, the world renowned Leontovich-Kadomtsev-Shafranov school.

In 1981, V D Shafranov was elected a Corresponding Member of the USSR Academy of Sciences, and in 1997 a Full Member of the Russian Academy of Sciences (RAS).

On the honorable list of V D Shafranov's awards are the USSR State Prize 1971 (together with L A Artsimovich, E P Gorbunov, D P Ivanov, S V Mirnov, N A Monoszon, V S Mukhovatov, M P Petrov, K A Razumova, A K Spiridonov, V S Strelkov, and A M Ushu), the Lenin Prize 1984 (together with A A Galeev, B B Kadomtsev, L M Kovrizhnykh, O P Pogutse, R Z Sagdeev), the Alfven Prize, the Gold Medal of the European Physical Society (2001), and a Honorary Award (2001) from the Japan Society for the Promotion of Science.

The area of Vitaly Dmitrievich's predilections in plasma physics is not limited to the theory of equilibrium and stability. He also engaged in comprehensive research on electromagnetic wave propagation in plasma, one of the fundamental studies on the shock wave structure in plasma, and others.

Among V D Shafranov's more than two hundred scientific publications, we should mention a number of fundamental reviews in the remarkable series *Reviews of Plasma Physics*, whose issues became handbooks for several generations of Russian and foreign physicists. V D Shafranov was always painstaking in his work on the texts of scientific publications. His own papers are written in a simple and clear language.

Vitaly Dmitrievich Shafranov did hard inestimable work as an outstanding editor of scientific literature. Over about thirty years (1981–2011), he was Editor-in-Chief of the journal Fizika Plazmy [Plasma Physics Reports], and after 1980 the Scientific Editor of the series *Fizika Plazmy*. *Itogi* Nauki i Tekhniki [Plasma Physics. Advances in Science and Technology]. From the 21st volume issued in 2000, the English-language series Reviews of Plasma Physics was edited by V D Shafranov (after the death of B B Kadomtsev, who had been the Editor-in-Chief of this series from 1987 to 1998). This remarkable series of books, founded by M A Leontovich in 1963, became handbooks for several generations of physicists engaged in plasma physics. Till 1989, it had been an English translation of many volumes of Russian-language issues of Voprosy Teorii Plazmy, which unfortunately stopped being published in Russian in the early 1990s. When V D Shafranov became the Editor-in-Chief of the series, he published as the first review the English translation of the book by B B Kadomtsev, Collective Phenomena in Plasma, in the 22nd volume because he believed it necessary to acquaint the English-speaking reader with this remarkable book and considered it his duty to carry out the translation and editing work on this book which, due to the untimely demise, his friend B B Kadomtsev could not do himself. The textbook Plasma Physics and Controlled Nuclear Fusion by K Miyamoto was translated into Russian and then edited by V D Shafranov in 2007. From January 1999 to March 2005, Vitaly Dmitrievich was a member of the Editorial Board of Uspekhi Fizicheskikh Nauk [Physics-Uspekhi] journal and took an active part in the life of the journal. For example, Shafranov initiated and edited a very interesting selection of papers celebrating the fifty years of research on controlled nuclear fusion, which appeared in Usp. Fiz. Nauk 171 (8) 877 (2001) [Phys. Usp. 44 835 (2001)]. It should also be emphasized that all the papers on plasma physics submitted to Usp. Fiz. Nauk in those years were looked through by V D Shafranov. When in 2005 Vitaly Dmitrievich felt himself unable to continue working on Usp. Fiz. Nauk as intensively as before, because of the state of his health, and the responsibilities and heavy workload he had elsewhere, he addressed the Editor-in-Chief of Usp. Fiz. Nauk [Physics-Uspekhi] journal (then VL Ginzburg) with a request to let him leave the Editorial Board of the journal.

A great event was the issue (in 2003 and 2005) of extended and considerably revised editions of the book of recollections about the founder of the Russian school of plasma theory, the prominent theoretical physicist M A Leontovich, devoted to his 100th birthday. The first edition of reminiscences about M A Leontovich came out in the very hard year of 1990, and was therefore fairly modest in appearance, but the editorial board (including V I Kogan, V S Lisitsa, V D Novikov, V D Shafranov, and B B Kadomtsev as the Editor-in-Chief) of this first edition managed to receive the reminiscences of those people who were later unable to write them in the 2000s. In the wonderfully edited books of reminiscences about M A Leontovich (published in 2003 and 2005), the head of the editorial board of the jubilee editions, V D Shafranov, a faithful disciple and a worthy successor of Mikhail Aleksandrovich, specially pointed out his kindness, highly spiritual character, and civilian position, uncompromising in respect of administrative ruling, careerism, and injustice. All these human features, rare in our time, were also inherent in Vitaly Dmitrievich. He was exclusively modest, invariably attentive, and humble in relations with people.

A great pleasure for all his colleagues and those close to Vitaly Dmitrievich was the publication of his book, *Unscientific Works* (2009), which is a collection of wonderful poems. These verses, devoted to his friends and close people, adults and children, and certainly nuclear fusion, which was his lifework, reflect one more side of V D Shafranov's talent his poetic gift. As his friend and colleague V I Kogan said,

"A brilliant physicist and a marvelous poet.

What a magnificent combination!"

The departure of the eminent scientist and a splendid person, Academician Vitaly Dmitrievich Shafranov, is an irreplaceable loss for the whole plasma physics community of the world.

E P Velikhov, A G Gibson, V E Zakharov, L M Zelenyi, V S Imshennik, V I Karas', J Clark, B Coppi, A G Litvak, D D Ryutov, V P Silin, V P Smirnov, V E Fortov