**Experimental studies of magnetized thermonuclear plasma. Our experience in the international collaboration.**

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## Introduction

The idea of a joint study of high temperature magnetized plasma aroused wide interest in the scientific community. Among the interested organizations were: The Chinese Academy of Engineering (KAIF), the Institute of Plasma Research (Ahmedabad, India), the National Atomic Energy Commission of Argentina (NKAE, PLADEMA Lab), the Commissariat for Atomic Energy (CEA/DAM, France), the Institute of Plasma and Laser Microfusion (Poland), the Electrotechnical Department of National Research Council of Canada, etc. These are laboratories and institutes whose fundamental scientific interests are in the field of pulsed power physics, high energy density physics, and thermonuclear fusion.

For a variety of reasons, we failed to establish contacts with many of them. But scientists of Los Alamos National Lab (LANL, USA) were very persistent in their interest. They were very enthusiastic about establishing scientific contacts with us and consistently pushed ahead in this direction.

The pioneers of this collaboration were V.K. Chernyshev and A.I. Pavlovskii (VNIIEF) with the active support of G.A. Shvetsov from the Novosibirsk Institute of Hydrodynamics and M. Fowler, S. Younger, and I. Lindemuth (LANL). Of course, nothing could have happened if it were not for the support of the Russian and US Governments and the leadership of VNIIEF and LANL.

## Background of the collaboration

In 1976, the USSR and the USA signed an agreement on limitation of underground nuclear explosions (the maximum permitted explosion yield was 150 kilotons). The agreement was ratified only after 14 years and came into force in December 1990. The reason for such a long period for the treaty to come into force was the fact that neither country had tested and coordinated seismic control methods over explosive yields, and neither of the countries intended to provide access of the other party to their “sanctum sanctorum” – nuclear test sites. However, the agreement made the two countries find a compromise solution, and they performed two joint tests of underground nuclear explosions with controlled yields, first in the USSR (Semipalatinsk test site) and then in the USA (Nevada test site). The USSR team consisted of the best investigators from VNIIEF (Arzamas-16), VNIITF (Chelyabinsk-70), NIIT (Moscow), and representatives of Minsredmash. The US team included professionals from LANL, LLNL and the US Department of Energy.

It should be noted that at that time talks were conducted only between scientists, on the margins of Megagauss conferences, which were the major forum for information exchange in the field of ultra-high magnetic field generation. The US and Soviet authorities not only were against any contacts between scientists but in fact strictly prohibited them.

Thus, the first officially sanctioned contact between research engineers and nuclear weapon developers was a unique and unprecedented event. On both sides, they were the first to develop nuclear weapons for their countries. And if one country strived for world hegemony, the other country wanted to establish parity in nuclear weapons to prevent World War III.

Consequently, the USA and Russia are antipodes. We even live in different hemispheres. However, people are always people and they can establish normal relationships with each other. According to the participants of the joint tests, scientists from weapon labs of both countries were equal in their knowledge, experience, skills, and understanding of specific features of nuclear weapons. Americans were ready to collaborate with us as equals.

The first introduction of foreign scientists to the formerly super secret VNIIEF lab was in 1990. In 1992, there already began intensive activity to establish a scientific collaboration. The beginning of the official collaboration was initiated by the weapon lab director exchange in January- February 1992. These visits resulted in a real collaboration between US National labs - Los Alamos and Livermore, and the Russian Nuclear Weapon labs - VNIIEF and VNIITF. VNIIEF was represented by its director Vladimir Alexandrovich Belugin and scientific leader deputy Alexander Ivanovich Pavlovsky. VNIITF was represented by its director Vladimir Zinovievich Nechay and chief designer Boris Vasilievich Litvinov.

The Cold War was beginning to thaw. The governments of both countries came to the conclusion that since nuclear arsenals were being reduced, and since the unique potential of weapon scientists was not used to its full extent, it was reasonable to use this potential in fundamental scientific programs of interest to both countries. It became clear that joint work on such programs could not only promote the obtaining of new results but increase the mutual trust between the leading scientific centers of the USA and Russia.

When, in September 1991, V.K. Chernyshev, V.N. Mokhov, and their colleagues came to meet I. Lindemuth who was in Moscow at that time, they gave him an official letter with a proposal to begin the scientific collaboration between VNIIEF and LANL in the field of magnetized plasma studies. This proposal was signed by VNIIEF director V.A. Belugin and approved by the Minatom authorities.

At the same time, Chernyshev invited LANL scientists I. Lindemuth, R. Reinovsky, S. Younger and two other scientists to take part in the International Conference "Zababkhin Scientific Readings III" that was to take place in Kyshtym, Chelyabinsk region, in January 1992, and then to visit VNIIEF. Because of the subsequent disintegration of the Soviet Union, LANL did not give an official response. For the same reason, the LANL delegation was reduced to two people: I. Lindemuth and R. Reinovsky.

In November 1992, a large team of specialists from Chernyshev's and Pavlovskii's departments took part in the International Conference "Megagauss-IV" that was held in Albuquerque (New Mexico). After the conference Chernyshev, Pavlovskii, and their teams were invited to visit Los Alamos, where the two leaders and S. Younger signed a historical "Memorandum" and made a "Work Agreement" in which they agreed on the subjects for future joint work and determined the terms and conditions of forthcoming experiments. Scientists of two main weapon labs responded very quickly and specified a spectrum of their mutual interests in the field of not only hot magnetized plasma, but ultra-high explosive magnetic energy sources, high energy density physics, and controlled thermonuclear fusion.

In 1993 two nuclear weapon labs of Russia and the USA began to work jointly, and as a result of their real collaboration really valuable scientific results were achieved.

**The MAGO concept and its development**

The first person to think of a possible thermonuclear reaction using magnetic cumulation without the use of fissile materials was academician A.D. Sakharov. He stated that the use of magnetic cumulation effects would “create a powerful gas discharge in a D-T mix, transforming it into thermonuclear ignition”. Sakharov also put forward a very interesting and fruitful idea of the use of a magnetic field to implode metal shells filled with cool thermonuclear fuel. However, for a long time there was neither a developed concept, nor (which is very important) any ultra-high magnetic energy sources. It took scientists 15 years of intensive work to determine ways to solve the problem of controlled thermonuclear fusion using the implosion of a dense, cold thermonuclear target by a fast-magnetic field. The scientists of the VNIIEF Electrophysical department had created by that time an explosive magnetic generator with unique parameters in power and energy.

In 1976, Yu. B. Khariton reported a general concept of the magneto-hydro-dynamic (MHD) energy cumulation being applied to the solution of the controlled thermonuclear fusion problem to the USSR Academy of Sciences. In 1979, work on investigation of thermonuclear plasma began. The work was performed under the MAGO (Russian abbreviation of magnetic compression) project, which obtained official status based on decrees of the Central Committee of the Communist Party of the USSR and decisions of the State Commission. The concept was aimed at achieving thermonuclear ignition in dense D-T targets using their compression by liners accelerated up to very high velocities by magnetic fields.

Even the first experiments showed that with modest liner and EMG conditions it was very difficult to obtain the necessary linear energy density (> 5-10MJ/cm per length unit) using a single liner, and that it was obviously insufficient for achieving ignition. Actually, insufficient energy was not the only problem. It was difficult to implement the 1-D cylindrical ignition system because of very rigid requirements of compression symmetry. A new course of the MAGO project was connected to a unique idea proposed by E.S. Pavlovsky. The idea was based on MHD heating of preliminarily magnetized plasma target up to 100 eV followed by adiabatic compression up to the ignition and combustion state using an MGD driver. The main idea of this concept was to obtain ultrasonic MHD flow of the preliminarily magnetized plasma through a Laval nozzle and then to convert the kinetic energy to thermal.

The efficiency of the proposed idea was demonstrated by experiments performed by N.N. Moskvichev, V.P. Korchagin and specialists headed by V. Chernyshev.

Even the first experiment showed that the system generated a neutron-producing plasma. The duration of the neutron radiation was several microseconds. We started from a level of $10^6$ neutrons per pulse. With continuous analysis of our results and growing understanding of the processes involved we are now able to obtain a plasma neutron yield up to $6x10^{13}$.

As with any promising idea, the idea of the MHD supersonic flow developed very quickly and gave birth to many new ideas and proposals, requiring much experimental work. Up to the early 90s, work on the MAGO chamber involved basically a variety of experiments (8-12 experiments a year) in which we changed input parameters, chamber geometry, nozzle size, or initial pressure of the working gas.

A great success during that time was the fact that using photography of self-emitted neutrons and soft x-rays we determined that the shape and size of the hot zone (measured in centimeters) takes up more than one third of the deceleration chamber in which the hot plasma forms. The hot zone was volumetric, not a point source as in a plasma focus. This fact was an indirect indication that the plasma generated in the MAGO chamber was of a thermonuclear character and not caused by acceleration processes.

However, the calculational and theoretical analysis of those experiments showed that thermonuclear reaction ignition using this approach was unlikely to be achievable. The main plasma mass (about 95%) remained relatively cool (the experimental temperature was about 100-300 eV), and only a small portion of the plasma was responsible for neutron generation. To obtain ignition of a thermonuclear reaction it is necessary to include in the MAGO concept adiabatic plasma compression (decrease of the plasma volume, aiming to increase its temperature). The requirements of the compression system due to preliminary plasma heating and its initial magnetization are significantly decreased as compared to compression of a solid cold target.

Further investigation showed that the main plasma mass, having a temperature of several hundreds of eV, was that very "warm" plasma that could be considered as a target for compression, and its characteristics determined the possibility of achieving ignition. The main parameters of "warm" plasma, its temperature and life-time, became the subject of our study. We performed investigations based on our measurements of amplitude-time parameters of plasma self-emitted soft x-rays.

The interest of Los Alamos scientists in our chamber with its MHD nozzle was connected with the fact that at approximately the same time Americans developed their approach, Magnetized Target Fusion, in which they gave a theoretical foundation to magnetized fuel compression to achieve ignition. In our MAGO chamber they saw a practical implementation of their theory.
Los Alamos scientists had an effective 2-D calculational method. Using this method and the initial data from VNIIEF/MAGO concept, numerical simulations of the processes in the chamber were performed. The basic conclusions were the following:

Two-dimensional calculations described the plasma behavior in our chamber well.
Additional compression of the plasma which was emitting neutrons would not be effective. The focus must be made on the properties of the main plasma and it must have a reaction temperature of kiloelectron volts.

The properties of this plasma could be determined by measurements of parameters of its self-emitting soft x-ray radiation.

Thus, we formulated a final strategy of achieving thermonuclear ignition in the MAGO/MTF concept.

**Beginning of our work. Brief results**

In 1979, Chernyshev, Mokhov and their colleagues published an article with their idea of possible ways to solve the problem of controlled thermonuclear fusion with the use of an ultra-high magnetic field. Americans analyzed the article and expressed their disbelief in this concept, since such an approach was not studied in the USA. Finally, in 1988, based on results of investigations and calculations, LANL scientists concluded that the Soviet approach was feasible if there were magnetized thermonuclear fuel in a thermonuclear target compressed by high magnetic fields.

In 1991, V. Chernyshev and A. Pavlovsky were in the USA in San Diego, California, where they participated in the VIII International Conference on Pulsed Power (IEEE). For the first time Chernyshev gave a brief presentation and reported VNIIEF successes in the field of controlled thermonuclear fusion. From that talk, American scientists learned for the first time about the Soviet approach called MAGO and about our project on investigation of magnetized thermonuclear plasma properties.

A more detailed paper with results of the MAGO chamber experimental study was submitted to the III Zababakhin Scientific Readings (Kyshtym, Chelyabinsk region, January 1992). By that time the VNIIEF Electrophysical Department had performed about 70 various experiments. The most interesting results were included in the presentations given by Lindemuth and Reinovsky who participated in that conference. They were both then invited to visit VNIIEF. At VNIIEF Lindemuth, Reinovsky, and our scientists determined specific ways for performing joint experiments and made drafts of the first two agreements on conducting a demonstration experiment with a disk explosive magnetic generator (DEMG) with FOS and an experiment with the MAGO system at VNIIEF. The first experiment took place in September 1993, and the second - in April 1994. We obtained all the planned information on the operating conditions of our systems. The Americans used their own diagnostics and in parallel measured the current in every key unit of the experimental systems. A. Petrukhin was responsible for organization of the DEMG experiment, and V. Korchagin was responsible for the work with the MAGO system.

Two MAGO experiments were scheduled to be conducted at LANL in September 1994. The goal of these experiments was to try to measure the electron temperature and the lifetime of the “warm” plasma. We thought these measurements to be feasible due to the combination of the LANL advanced diagnostics and the VNIIEF unique method of pulsed power generation.
According to our contract, we were required to deliver to LANL all the necessary experimental units, auxiliary equipment, spare parts, materials, and so on. We assumed that we needed to involve the Customs to do this, but we did not have the slightest idea of all the difficulties we would have to face with the Customs.

Finally, all the formalities were fulfilled, and our hardware reached Los Alamos a week before our arrival. But we failed to solve the issue of bringing our HE, though the issue was being solved at the highest level. The reason was that at that time our HE had not been properly certified according to the International standards. So our American colleagues had to fabricate HE themselves.

On September 10, 1994 the MAGO team which consisted of V. Korchagin, V. Chernyshev, N. Bidylo, G. Volkov, U. Dolin, A.Demin, V. Ivanov, S. Pak, N. Seleznev, A. Skobelev, I.

Morozov, B. Egorychev, V. Baturin, V. Mokhov, V. Yakubov, S. Garanin, A. Buyko and our interpreter Elena Gerdova went to the USA. Our trip was scheduled to end on October 30.
Americans met us very cordially, accommodated us in the local hotel and left us alone for the rest of the day to adapt a little bit after a long and tiring 12-hour travel across the ocean with several changes of time zones. Next morning, we had a meeting where we determined the basic lines of our work to prepare the first test, specified the date, and formed four working groups responsible for preparing the MAGO main units. The group consisting of Korchagin, Demin, Dolin, and Baturin was responsible for the chamber assembly and for its training with high-current pulse discharges. The second group consisting of Skobelev, Ivanov, Pak, and Seleznev was to assemble and equip EMG. The third group, Morozov and Egorychev, was responsible for coordinating systems for plasma diagnostics. Theorists Garanin, Yakubov, and Buyko were to calculate the plasma chamber powering modes. Every group included our American colleagues.
After the meeting, we went to see the LANL firing point, which was located in a picturesque place in the mountains. We were impressed by the comfortable conditions and well-equipped offices, and we were struck by the abundance of advanced measuring systems and high-current and high-voltage equipment.

The following days were busy with preparations for the experiment. We were instructed on safety, and it turned out that in addition to the standard rules, there were some new ones connected with natural dangers: rattle-snakes, “black widow” spiders, tarantulas, and mice. To our joint credit, we performed the experiment on the exact date: October 7. We obtained the information we had planned; and it was of high quality.

Since our American colleagues were eager to obtain data as soon as possible to evaluate the MAGO plasma efficiency, they used all the diagnostics available at LANL. To estimate plasma state 14 techniques were used. A special LANL technique, employed for the first time, allowed us to see the full pattern of the plasma formation process with time resolution. There were invited diagnostic specialists from other National Labs, Universities, and from the Nevada Nuclear Test Site.

The second experiment was prepared very quickly (in approximately just 10 days) and performed on October 20. All measuring systems, operating in this experiment, provided responding signals on the plasma state. Some signals and their behavior aroused hot discussions, the results of which were later published in joint reports, papers, and articles. We observed in the experiment $5x10^{13}$ thermonuclear reactions, which proved to be a record value in terms of the number of fusion neutrons from D-T mixture that had ever been obtained at LANL.

The detailed comparison between results of 2-D calculations performed by LANL specialists and inductive probe signals, spectrometry, interferometry, and radiography data showed good agreement between experimental and theoretical results. That meant that the plasma obtained in our experiments was good for the following compression in the MAGO/MTF concept.
The results of the joint LANL/VNIIEF experiments of 1994-1995 on magnetized plasma formation appeared to be a big step forward in achieving controlled thermonuclear fusion through MAGO/MTF. It was later confirmed by results of a whole set of experiments performed at the VNIIEF Electrophysical Department in 2003-2006.

Through the experiments with the MAGO system we came to the final stage of the investigations in which we wanted to check experimentally the final phase of the process, the efficiency of the adiabatic compression, and to obtain evidence of the second temperature maximum.

The most valuable part of our collaboration was not just obtaining some new knowledge. We gained mutual trust, understanding, and respect which became the foundation of our collaboration. We worked very efficiently and cooperatively. Neither the Americans nor the Russians tried to worm secrets out of anybody. We did not need them. We knew that working jointly we fulfilled our duties, strengthened our scientific contacts, and helped to relax political tensions.

During the second full-scale experiment, there were about 100 specialists and about 50 reporters from American news-papers and TV companies at the firing point. Right after the experiment I. Lindemuth and R. Reinovsky on the one side, and V. Chernyshev and I on the other side were interviewed for the biggest American TV news network, CNN. We commented on the results and shared our views on the collaboration. The next day the interview was broadcasted on one of the CNN channels.

It was with great regret and perplexity that we learned that the MAGO project did not obtain American financing at VNIIEF. American President Bush Jr. decided that it was not correct to finance the Russian thermonuclear programs. The joint work on the MAGO project was suspended.

**Instead of conclusion**

An experiment such as MAGO is very complicated and time consuming; it requires tremendous manual power and effort. We did our best to do our work accurately, quickly, and honestly. It was not easy to work under a burden of responsibility. We did not have the right to make mistakes.

LANL employees are hardworking folks. They began to work exactly in time and did not have smoke breaks. They all had good equipment, tools, and all the necessary materials required for work. They were equipped with walkie-talkies and used light vans (pickups) to provide quick communication and movement inside the firing point. We did not have such comfortable things on our firing point. Their relations between themselves were friendly and respectful. They always spoke quietly and observed subordination. Once we saw an unusual show in front of the lab office. There was a big vessel filled with water and equipped with an arm. A manager, sometimes of a very high rank, would be seated on one end of the arm, while a target was mounted at the other end. If someone hit the target with a tennis ball, the person sitting there, to everyone's joy, would fall into the water. Anyone who wished to dip their boss in water could buy any number of balls, 5 dollars each, for charity. Very democratic!
Except for the language, we were much the same. Most Russians from the MAGO team were abroad for the first time. Everyone was interested in learning how people live and work in the other country.

Americans are talented and hardworking. They invented many interesting things: automobiles, planes, and space shuttles. They have world-known hotel and medical services. A personal car for an American is as his own feet. An American and his car are the two parts of an integral whole. Maybe because of this Americans take a good care of their roads: they have no bumps or potholes.

The image of an "enemy" was reduced to ashes with the first personal contact. Americans turned out to be open, friendly and always smiling people. They love their country and are not ashamed of this feeling. They never poke into one's political beliefs or private life. Generally, they are religious and attend Church on Sundays. Almost every family has a Bible at home. In many families they say prayers before eating. They enjoy sports and prefer a healthy life style. At the same time, they are a very expansive and driven people. They are sincere, meet other people easily, and speak frankly.

After the hard work, everyone wanted to relax. And our American friends did a good job here. They arranged formal and informal dinners and often invited us to visit their homes. We proposed lots of toasts and were given lots of photos, t-shirts, pins, and baseball caps. Americans received from us Russian souvenirs: vodka and black bread. The Russian black bread was to everyone's liking. They also liked Russian handicraft souvenirs: matreshka-dolls and boxes from Palekh, Khokhloma, Semenov, and Polkh-Maidan. Americans also liked the presents of Russian classical books in the Russian language.

It is difficult to compare life conditions in the USA and in Russia. Perhaps there is no sense in doing this.

We once spent two days at Irv Lindemuth's dacha which is 120 km away from Los Alamos in a most beautiful spot. Wild dear walked around and fearlessly took food from us. Food could be bought right there in a little kiosk. If a guest avoided his duties and displeased a deer, the latter could gently attack him from the back.

A three-day tour over four states left a lasting impression on us. The tour was timed for Columbus Day. We travelled across four states: New Mexico, Colorado, Arizona, and Utah, and made a stop at the Four Corners, an area at the junction of the borders of these four states. The landscape of every state is different, yet unique and peculiar. In Colorado we saw majestic snow-capped mountains covered with thick mixed coniferous and deciduous forest. We saw dark-brown rocks in Arizona sands, and fantastic stone arches in a National Park in the state of Utah. Nature has endowed America lavishly!

Our colleagues arranged a trip to Grand Canyon for us. This place is called the eighth wonder of the world and is really breath taking! Red rocks go down to the depth of a kilometer and a half; the width of the canyon is about 15-18 kilometers, and below the Colorado River rushes to the Bay of California. How many centuries did it take to make such a deep canal! The river was really rapid! We saw waterfalls and heaps of big stones turned by water.

What a show was a Balloon Festival in Albuquerque! Balloonists from all over the world came there to take part in this fest. Hundreds of balloons of various colors and shape soared in the clouds. Yet many balloons were on the ground ready for their start. Those wishing to see a bird's eye view of Albuquerque were invited to have a flight. But the flight cost disagreed with our salaries.

Another great impression was glider flights that made us work out adrenalin. Our pilot made such steep turns that my life flashed through my mind in an instant. The roast beef and good Californian wine helped us to relax that day. The feast was arranged by the LANL authorities on a special occasion. The US DOE released funding for ATLAS.

Our friends arranged other interesting trips for us. We took a train and followed the track which was used to transport gold and silver from Colorado mines. The railway went through a valley

and suddenly went up sharply at the end of the road. Since the train had to decrease its speed here, it was often attacked and robbed by bandits. We saw a staged recreation of this event.
We had a chance to fly over Los Alamos in a small private plane, to see a rodeo, and to attend a University championship in American football. I did not like these two latter spectacles much.
When Americans came to visit us in Sarov we also tried to arrange some interesting social activities for them. We brought them to our place of recreation “Lesnaya Polyana”, and took them to other big and small cities, like Diveievo, Arzamas, Sanaksar, Saransk, and Nizhni Novgorod. In Nizhni Novgorod, in accordance with the preliminary agreement, the American delegation had to hand over a message from the Governor of the state of New Mexico to Nizhni Novgorod Oblast Governor Boris Nemtsov. The meeting was scheduled for 3 p.m., but Nemtsov arrived only after 8 p.m. Americans were not happy with that, but Nemtsov compensated his delay with good food and sincere apologies.

Thus, in the early 90s we became friends with our former potential enemies. Unfortunately, we then began to blow up silos and cut missiles. But that was not about science, and let politicians justify those things. On the whole, the results of our first scientific contacts became a good stimulus for further fruitful collaboration in the field of fundamental physics.
It is unlikely that members of the MAGO team will ever forget the intense work and the following satisfaction from the good results (scientific prestige!). We will keep for ever warm memories about our joint travels, friendly talks and personal contacts with focused and meticulous scientists and project managers S. Younger, I. Lindemuth, C. Ekdahl and R. Reinovsky; a true scientist M. Fowler; talented experimentalists J. Goforth, B. Zerwick, J. Morgan; theorists P. Sheehey, and R. Kirkpatrick; diagnosticians J. Shlachter, G. Idzorek, R. Chrien, and H. Oona; technicians J. King, P. Rodriguez, and B. Anderson; versatile interpreter S. Shakhovskoy (talking with him was always a pleasure for us), and, certainly, J. Neff, who carried the burden of our leisure activities on her delicate shoulders.