

## THE VNIIEF AND LANL INTERACTION IN THE FIELD OF THERMONUCLEAR FUSION USING MAGO SYSTEMS

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In September 1991, at the Kurchatov Institute of Atomic Energy there was a meeting that determined a whole field in the development of the collaboration between the Russian and US nuclear centers. On the Russian side, the participants of this meeting were V.N. Mokhov, S.F. Garanin, V.K. Chernyshev (the head of the electrophysical department), N.P. Bidylo, E.I. Panevkina, and the author of this article. We met with I. Lindemuth from LANL who was coming back from Sochi where the Second International School on Plasma Physics and Controlled Thermonuclear Fusion took place. The VNIIEF delegation gave Lindemuth an official written proposal to work jointly in the field of thermonuclear ignition using the MAGO pulsed thermonuclear system. This proposal had been discussed and approved by the Ministry for Atomic Energy and other governmental agencies in Russia.

In 1992 in Albuquerque (USA) the “Megagauss-VI” conference was held. For the first time a Russian delegation went abroad to take part in this conference. During that visit Chernyshev and his colleagues suggested performing investigations of a condensed liner implosion accelerated by a magnetic field generated by a disk explosive magnetic generator (DEMG) with an electro-explosive foil opening switch (FOS). Parameters of this explosive magnetic device were earlier provided in the paper that I presented at the “Megagauss-V” conference in Novosibirsk in 1989, where LANL scientists expressed their interest in this generator.

On March 15-19, 1993, LANL scientists came to Arzamas-16 to participate in talks. On the American side, they were: S. Younger, C. Ekdahl, D. Ericson, J. Goforth, and I. Lindemuth. On the Russian side participants were Yu. Trutnev, V. Chernyshev, V. Mokhov, A. Petrukhin, A. Voinov, V. Selemir, M. Dolotenko, U. Romanov, V. Rogachev, and E. Gerdova. During discussions of the first joint experiment we made the decision (initiated by V. Mokhov and his colleagues) to replace the condensed liner with a plasma one. The reason for this decision was the fact that VNIIEF had good experience in using a DEMG with FOS for plasma liner implosions, but we had never tested this system to study condensed liner compression. In the future, we would perform successful experiments ALT-1 (1999) and ALT-2 (2001) on implosion of a cylindrical condensed liner driven by a current pulse from a DEMG with FOS. I was assigned to head the experimental work on behalf of VNIIEF. The design and theoretical study were performed by the group of V.N. Mokhov (V.B. Yakubov, E.S. Pavlovskiy, A.M. Bujko, S.F. Garanin, V.M. Mamyshev, and others).

On September 21, 1993, we performed the first joint Russian-American explosive experiment to demonstrate the use of a VNIIEF explosive magnetic system to investigate a plasma liner implosion. All the participants of the first joint experiment were excited. After the operator pushed the button and we heard the sound of the explosion, there was a deep silence in the bunker. Pat Rodriguez opened the steel boxes, which protected the American recording equipment against electrical noise, looked at the computer, and then threw up his hands and said, “Yes!” and immediately it became noisy! The Russian theorists rushed to their oscilloscopes, the Americans crowded near the computer. Then people began to shake hands, hug and congratulate one another.

We arranged some social activities for the Americans. We took them to Diveievo Convent, where our guide was a young nun with a Ph.D. in art history. Our colleagues admired her wide knowledge and wondered why she had preferred God to a career. Even today, the Americans recall our trip to Saransk, to the Erzia museum. This trip was prepared with the

support of the chief architect of Mordovia V.V. Godunov; Saransk mayor U.I. Rybin; and entrepreneur A.G. Salimov. Our guests were impressed by the Erzia sculpture; they did not expect to see such masterpieces. After the museum, there was a reception in the Saransk City Council and then a nice dinner. Tables with food were placed around a big open fire. After the first shots of vodka and good food people began to relax, and their toasts became more and more sophisticated, when all of a sudden as a climax of the day a waiter brought a roasted suckling pig... It was very nice to sit there eating and talking, but we had one more event in Sarov – a concert by a famous singer from Moscow. Steve Younger, a fan of opera singing, reminded us that we had to leave. Our bus was escorted by police cars until we got far beyond the city. The time was dangerous, and we feared we might come under fire. We were in time for the concert. Younger then recalled that he enjoyed that trip very much. Saransk reminded him of the city of his childhood.

In 1995 at VNIIEF we performed the joint test X-Ray-1 to study the formation and initial motion of a liner with a variable mass. The goal was to obtain soft x-rays. The experiment was prepared by VNIIEF and LANL specialists with the participation of a team from the Phillips Lab. The idea was that a plasma bridge would expand by magnetic field under a switching liner as a plasma toroidal “bubble”, imploding at a high speed to the load axis. As a result of this experiment, we obtained valuable information about the liner load operation and evaluated the basic “bubble” experimental parameters. But the experiment showed us significant disagreement between the effects we observed in the liner and the theoretical predictions. Results of the experiment were reported in 1997 at the “Pulsed Power-XI” conference in Baltimore, USA.

The LANL scientists suggested to use the VNIIEF experience in calculation, design, and investigation of condensed liner systems on their “Pegasus-2” pulsed power facility. VNIIEF performed a design study and fabricated liner loads to be tested in the US in a joint test. All in all, we performed five tests on Pegasus-2, Rus-1 through Rus-5. Through these tests we obtained several interesting and important results. These results were published in papers reported at international conferences.

We have very warm memories about the hospitality of the American scientists during our visit to Los Alamos. We remember very well the homes of our colleagues: R. Reinovsky, I. Lindemuth, M. Fowler, C. Ekdahl, B. Atchison, R. Faehl, J. Goforth, and others. Unforgettable for us were the weekends spent at Lindemuth’s dacha. We got to know how Americans live and how they joke. Once we made a stop near a ranch. We saw at the gates a hanged dummy with a sign “We will do the same to anyone who visits us without being invited”. For some reason, we did not want to check whether it was a joke or a serious warning.

An unforgettable memory was a trip to Carlsbad caverns. Decades ago an underground maze was discovered at the border between New Mexico and Texas. Nowadays there are tourist routes in these caves with protective confinements in front of the holes, and sections where speleologists work. The tour of those caves was very impressive. In front of the cave there was an amphitheatre, where tourists could watch thousands of night bats. Unfortunately, we did not see them because they all flew away to Mexico for winter. We were gradually moved down the cave. The path was equipped with motion-sensitive lights that went on for a very short time necessary for observing stalagmites, stalactites, and colored rocks. We heard monotonous sounds of water drops and babbling of water flows, we felt some fresh smell, and then suddenly a smell of sulfur. The caves were of different sizes; some of them were huge, about ten meters height. The path ended with a comfortable elevator. A second later -

and we were on the surface. The first thought to come was, “How nice to be here in the sun”. We feasted our eyes upon valleys of the state of Texas.

Is it possible to forget the wonderful trip to White Sands, where one could ski or snowboard among white dunes? Or the night in Roswell, where even the restaurant signs reminded one about the green men from UFO? Or admiring (with a glass of red wine) a comet tail in the Los Alamos night sky? Or the fantastic views of Grand Canyon, Arizona deserts, petrified forest, continuously changing patterns in the sky because of thousands of birds in their place of wintering on the Rio Grande river, beautiful lakes, or Florida alligators? One can recall these wonderful trips to the USA for a long time.

I can tell many good things about our American colleagues. Here is one interesting episode. The head of Pegasus-2 was Bucky (Jim) Cochrane. A tall, thin man with a military bearing, he looked a little bit phlegmatic, but he was not at all. He came to our experiments in a confederate cap (his charm) with a red top and a black hat band, - an exact copy of a southerner’s cap of the time of the war between Yankees of the North and slaveholders of the South. He knew everything about that war. When we visited his residence in the mountains, he showed us his collection of cars. The pearl of the collection was a Mercedes truck, a vehicle for airborne GI. He offered us a ride in this truck to some interesting place in woods. We filled the open vehicle and went. I don’t remember such an extreme drive in my life. The truck went through wild woods and stones and climbed hills. It was already dark, and no one could see the road, we could only hear tree branches whipped by the truck. We worried about our colleague Chernyshev, but he was smiling and showing a thumb up. Finally, we stopped. It turned out that we were two meters from a cliff. Bucky took his lantern and held the light down. We saw some mushroom-cap rock formations deep down the canyon. It was a great sight! We took several photos and went back home, where lights and good food were waiting for us. Bucky had a dream about getting an Ural triaxial Soviet military truck.

Once Bucky invited us to see his collection of weapons. We went to a canyon. Jim came in his truck which held many steel boxes. He began to open them one by one. What didn’t he have? Everything from old-fashioned flintlock pistols of the Civil War and to an automatic gun of World War II. Every gun was in an ideal state; every gun could shoot! Jim instructed us on safety. Apparently, every man has a taste for weapons. Excited folks snatched rare guns and shot plastic bottles. Jim watched us smiling and reloaded the guns. Our hunters, Yura Gorbachev and Sasha Merzlov, enjoyed shooting so much that they were probably not going to match in Russia. How many bullets did we spend that time? And how much did it cost? Just thinking of it now makes me feel guilty!

In 1998 one of the priority tasks for Los Alamos became the construction of the “ATLAS” facility, which was designed to replace “Pegasus-2”. The program of experiments for the new facility was also under development. However, it turned out that the design study for liner experiments was not sufficient. It was required to have an experimental proof. The LANL management suggested that VNIIEF would make a contract on the preparation and performance of a joint LANL-VNIIEF experiment to simulate parameters for “ATLAS”. VNIIEF developed a special experimental device. The experiments using this device were performed in 1999 (ALT-1) and in 2001 (Alt-2). Every unit worked in a mode close to its design. I should note the great success of the American experimentalists who, outside their country for the first time in an explosive test, which had HE mass over 100 kg, used a VISAR interferometer (LANL measurements) to measure the inner liner velocity as a function of its radius with a maximum velocity 12 km/s. In the ALT-2 experiment we managed to determine some additional data in conditions mostly approximating those that characterize “Atlas” in its limiting mode. These results were published in the proceedings of the “Megagauss-IX”

conference (Moscow-St. Petersburg, Russia) and Pulsed Power-XIII conference (Las Vegas, USA).

Las Vegas left a lasting impression on us. Among the Americans there were some practical joke lovers. Once Brodie Anderson and Bucky Cochrane came to our hotel and invited us to some entertainment. We did not understand exactly what they had in mind, but we trusted them, and we were ready to follow them even to the end of the world. We came to a place where the Americans treated us to some ice cream. While we were enjoying the ice cream, Brodie bought us tickets. Valera Yakubov turned out to be the only smart person among us, as he suspected something and said politely that he would rather skip the entertainment and wait for us. We took seats in open cars (I was in the same car with A. Buyko). There were no seat belts, just a bar that went down automatically to fasten us. All the cars moved up very quickly. O boy! The Earth was moving away from us, while Las Vegas lights were becoming wider and wider. Finally, at the elevation of a 50-story skyscraper our cars stopped and took a horizontal position. All of a sudden, they went down in a free fall as in a dead loop. We were thrown first to the right, then to the left, with no damping and with a terrible sound. We caught hold of handles; everyone was screaming and shrieking, "God help us!" Another dead loop and again swings to the left and right. At the last stage, someone took pictures of each car (we learned about it later).

We finally were on the ground and staggered out. We saw pictures of ourselves with creased eyes and twisted faces. It was possible to buy photos for the cost of the ticket (Welcome to Las Vegas!). I refused; let my family remember me with a decent face. The next day the Americans invited us again to another fun outing, and we managed to understand a key word, "the stratosphere". We politely said, "no", mentioning that we were very busy with work...

The success of the Alt-1 and Alt-2 experiments inspired us and allowed us to think of using a liner for the study of dynamic material strength. For this purpose, we needed to work on designing a system for protecting an x-ray film against the explosion. This work was headed by V.A. Vasyukov. This system worked successfully in experiments RHSR – 0,1,2.

The first experiments (Rus-6, 7) to investigate material strength were supposed to be performed on ATLAS. The experimental set-up was developed by Buyko and Yakubov (from Mokhov's department) using the results from the Russ1 and 2 experiments. VNIIEF specialists designed and fabricated liner cassettes for ATLAS loading. An attempt to perform the Rus-6 test was made at LANL on April 17, 2002. Unfortunately, there was a breakdown of an insulator that reduced the current in the liner and destroyed the symmetry of the current delivery. When we were permitted to go to ATLAS we saw a horrible "datura-flower" that was formed out of torn thick current conductors in the transmission line.

Following the Rus-6 experiment the ATLAS facility was scheduled to be visited by the US and Russian National Lab directors and high authorities from the US DOE and Minatom of Russia. Bob Reinovsky prepared a presentation about new experimental possibilities with the new facility, and here we were with our disaster. However, Bob gave his presentation. He first showed the damage on the transmission line that proved of very high energy accumulated in the facility and said, "Such things also happen". Then everyone examined a similar load under preparation for the next Rus-7 experiments, and after that Reinovsky gave his presentation in his usual quiet and distinct manner. Only his haggard face revealed how he felt at the moment. We thought he deserved a medal "For Courage".

The goal of the Rus-6 experiment was achieved in tests RHSR-0,1,2 performed jointly by VNIIEF and LANL. They were successfully fielded at VNIIEF in 2003-2004. Not only did

the explosive magnetic devices work superbly to provide the planned current amplitude (the current amplitude in the experiments differed by less than 3%), but the radiographic data from all three tests showed the perturbation growth. Such a result became possible due to the unique radiographic two-and -three frame protected diagnostics developed at VNIIEF that provided x-ray pictures under conditions of shock and fragmentation effects from an explosive magnetic device having an HE mass of up to 75 kg.

Of course, when performing experiments, we had various curious situations and surprises. In the RHSR-2 experiment we used a package of three stacked films with amplifying screens. We assumed that the best image would be on the central film. The other films served for quenching mechanical effects, causing film light-striking. The films were developed by Grigory Polienko. Everyone was impatient to know the result. Finally, Grigory came out with a long face and said: "The first film is black, the second one is also black..." Everyone's face became long like his. Grisha savored the effect and continued, "But the third film has something..." And showed us a perfect image of the perturbations. Everyone sighed with relief. That was the quintessence of the test! The American cassette "silver dollar", as the Americans called it, was not damaged, but since it was "free flying" we failed to find it in the February snow (even for the promised remuneration of \$100), in spite of colorful ribbons that we fixed to it.

In 2005, VNIIEF and LANL made plans to perform a set of ten joint experiments, R-Damage, to study spall effects in converging geometry. The liner load and experimental set-up were developed by our American colleagues, Ann Kaul, Walter Atchison and Bob Reinovsky.

VNIIEF specialists prepared a test bed with an explosive magnetic pulse power source. We performed four experiments on that test bed. In all experiments, the targets were recovered. We obtained data about currents in pulsed power sources from VNIIEF induction probes and LANL Faraday probes, x-ray data showing liner movement, liner velocity vs radius (in R-Damage-0 only), inner target velocity (measurements were performed in all tests).

In February 2007, we successfully performed a set of the next three experiments, R-Damage-3,4,5.

The collaboration with our American colleagues goes on. We are planning new sets of experiments.