SUPERPOWER EXPLOSIVE MAGNETIC ENERGY SOURCES (XXTH CENTURY RESULTS. TASKS IN THE BEGINNING OF XXIST CENTURY)

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Introduction

The work I would like to talk about is really many-sided and took the whole second half of the XXth century.

In 1951 Academician A.D. Sakharov proposed a very interesting and, as it appeared later, an extremely fruitful idea of **MAGNETIC CUMULATION** (MC) covering the three areas of expertise at once: magnetic gasdynamics, explosion physics and electrodynamics [1, 2].

At the juncture of these three disciplines he decided to charge Division 22 of the Design Bureau-11 (Russ. acronym: KB-11), at that time headed by a known specialist in the field of HE theory and practice of complex explosive systems creation E.A. Feoktistova, with the work on MC.

Already on 08 April 1952 a very talented young specialist R.Z. Lyudayev successfully carried out the FIRST explosive experiment on magnetic cumulation [1] after which the work started developing very rapidly.

The author of this paper, at that time working at adjacent Division 21 under the leadership of a known expert on cumulation M.Ya.Vasiliev, got inspired with the idea of magnetic cumulation but firstly was at that time really obsessed with resolving another problem he believed to be extremely important, and namely with the idea of creating a safe detonator without primary HE. Nobody believed that it was possible because the transition to ED without primary HE, according to the author's estimate results, in an increase of energy needed for their firing by a factor of 10^5.

On the other hand at that time the "electrical" specialists were sure that the problem of generators creation for synchronous firing the safe ED's in big groups was also absolutely unsolvable. That's why the author had to take on himself also a solution of this problem. In 1955 the author was designated as a head of Division 22 and that helped to solve both problems.

Below enumerated are the main goals and the concepts used as the basis for achieving these goals.

Development of Basic Physics of Electric Initiation of High Explosives and Creation of Safe Detonators on this Basis

The author proposed and substantiated the idea of creating the detonators containing no primary explosive. Such substantiation became possible after he performed the analysis of classical works by foreign authors (Kast, Bowden, Gurton, etc.) devoted to explosion excitation theory. The author found some contradictions in their works and on the basis of his own research and results obtained he formulated the thesis that ***a criterion required for explosion excitation is a certain magnitude of density of power flow*** supplied to the initiated HE from the external source (**during a**

given short time interval). Together with the nearest staff members V.N. Lobanov, R.G. Lenskiy he defined this magnitude and demonstrated its independence from the type of the external energy source (explosion of the bridge, flying plate, shock wave, spark discharge, explosion of the primer charge limit).

Later a detailed research into the basic physics of high explosives **electric** initiation was carried out, together with V.N. Lobanov, R.G. Lenskiy, V.V. Vakhrushev, A.Ya. Koshelev and others, a feasibility of creation of a detonator without primary HE was experimentally confirmed, and the working design of the safe detonator D-22, that was successfully applied in the explosive activities, was as well developed.

Development of Electric Systems for Synchronous Initiation of Safe Detonators

Second problem was how to create the generator for safe detonators firing. Having such an excellent energy source as MC-2, it was absolutely necessarily to invent any new way of how to extract very fast this energy to the external load (see next point 3). But first we had to understand deeply how to satisfy the criterion of HE initiation using different L, C, R schemes.

On the basis of very thin and precision research of the energy input mechanism providing a reliable detonation excitation in the high explosive a possibility was demonstrated to develop ***the criterion of efficiency of electric firing systems needed for safe detonators initiation***. The firing generators satisfying the found criterion were developed and tested, and that for the first time made it possible to realize a synchronous (with a root-mean-square deviation from the nominal actuation time of no more than ± 30 ns) firing of the safe detonators in big groups from 100 to 1000 (fig. 1) by means of a small-size generator (then, these quantities were necessary for experimental research conducted by some other VNIIEF scientists). In the foreign literature a feasibility of creation of a safe detonator with an exploded wire and without primary HE was at the stage of discussions [3].

That work resulted in ***the creation and application of safe detonators that in itself was the most important step in fundamental improvement of nuclear weapons safety.***

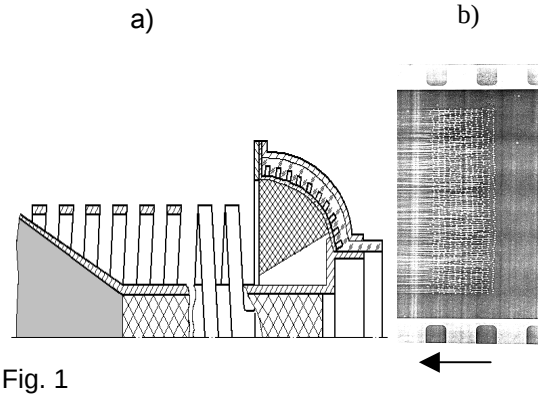

Fig. 1
a) First EMG with explosive energy output from MC-2 contour
b) Simultaneous explosion of 1000 safe detonators (without primary HE)

In addition, from the viewpoint of different experiments carried out with the use of HE, 40 years ago that put an end to all the accidents including those with fatal outcome [4].

Fast Transfer of Electric Energy from EMG to External Load

The author was the first to propose (1958) and together with E.I. Zharinov to realize (1959) the idea of fast energy transfer to the external load from the EMG circuit by means of the circuit break due to a chemical HE charge and also due to conductor electric explosion. Later together with E.I. Zharinov, G.I. Volkov, V.A. Ivanov the main types of super-power current switches both for helical EMG (using explosive technologies) [5] and for disk EMG (using the technology of electric explosion) [6, 7] were developed (see fig. 2, 3, 4, 5).

Having started the research from the level of kilo-ampere currents and the transfer time of tens of a microsecond, we continued the research with considerably higher currents. Thus, a current pulse of 90 MA with the rise time of 1 μs was shaped in the load in the experiments of 1988-1990 (see Proceedings MG-III…MG-IX Conferences).

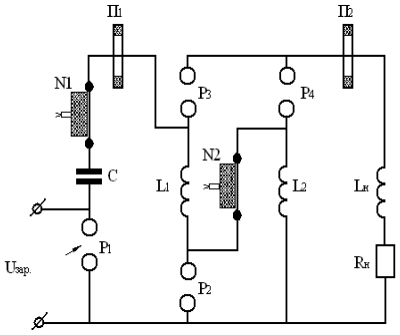

Fig. 2 First shots scheme on contour rupture by using HE charges

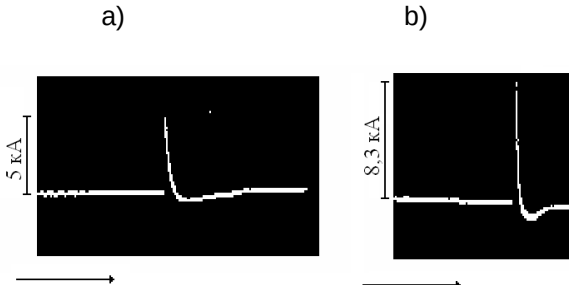

Fig. 3 Opening (rupture) of the circuit:
a) in one contour; b) in two contours. Current rise time < 0,7μs

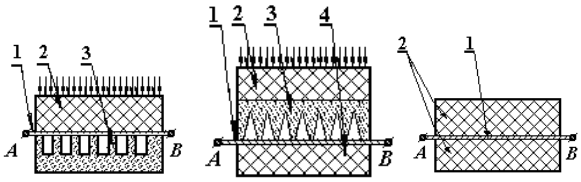

Fig. 4 Different types of fast opening switches

1.Conductor to be destroyed
2.HE charge
3.Dielectric barrier
a)

1. Conductor to be destroyed
2. HE charge
3. Dielectric jetsformer
4. Dielectric suppressor
b)

1. Conductor to be destroyed
2. Dielectric environment
c)

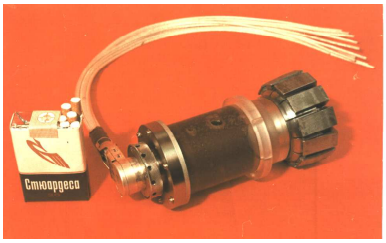

Fig. 5 Small EMG with initial magnetic energy source, fast opening switch and output cable block

Creation of Super-Power Disk Explosive Magnetic Generators (DEMG)

The author advanced the idea (1961) and together with A.I. Korolev experimentally confirmed a feasibility of DEMG creation (1961-1962). Together with a team of talented colleagues including M.S. Protasov, V.A. Shevtsov, A.A. Petrukhin, V.V. Vakhrushev, B.T. Egorytchev and others, they conducted a big number of studies

in this area that resulted in a development of DEMG family called “Potok”(“Flux”). The basic parameters of the three mentioned dimension-types are summarized in Table 1. Disk EMG’s were successfully tested in a big number of experiments: Ø100 cm (16 experiments performed), Ø40 cm (more than 40 experiments), and Ø25 cm (5

DEMG class (of «Potok» family)	Transmission line diameter (mm)	Stored energy (MJ)	DEMG current (MA)	Characteristic current rise time (μs)	Final inductance (nH)
1. Big	1000	100-500 (1000)	130-400	10	2-5
2. Middle	400	20-60 (100)	50-160	4.0	5-10
3. Small	250	10-30 (40)	30-70	1.5-2.0	10-20

Table 1 Three classes of disk EMG

experiments). Switching from helical EMG over to disk generators allowed increasing the current amplitude by one order and to reduce the rise time by two orders [8, 9]. High stability of DEMG operation and record output parameters were achieved in these experiments. Thus, in DEMG Ø 40 cm a current of 150 MA with the rise time of 4 μs was obtained, and in DEMG Ø100 cm the current was 300 MA with the rise time of 12 μs (1988).

Even though the first publication about disk EMGs appeared at the International Conference Megagauss-III held in Novosibirsk in 1983, till the present day none of the world laboratories managed to achieve similar results.

Magnetic Flux Generators

In the known magnetic cumulation systems a bulk of magnetic flux is lost in the compression process due to finite conductivity of conductor material, heating, loops shift under the effect of magnetic pressure, that drastically worsens the output characteristics. Our analysis [10] demonstrated that the method proposed by A.D. Sakharov, consisting in transformer series connection of several EMG even in case hard-to-achieve high (0.9) coefficient of coupling between the transformer windings, allows even theoretically to transfer no more than 30% of stored energy from one DEMG to another. The actual losses were even bigger. That’s why this method is rarely used.

The author together with V.A. Davydov invented a new method [11] of magnetic flux generation, which allowed reducing the losses several times. In addition, this made it possible to obtain a flux amplification factor of 310 at the energy gain of 900,000 already in the first EMG experiments using a new method but conducted yet at low energy.

Creation of Super-Power Explosive Magnetic Sources of Neutrons

A small-size energy source for a new type of powerful transportable neutron sources was developed together with E.I. Zharinov, V.A. Demidov, S.A. Kazakov and was successfully applied for the neutron source powering.

In close cooperation with other VNIIEF scientists (V.A. Tsukerman, N.G. Makeyev) a new system was created, that was successfully tested many times and gave a multi-million (for those times) economic effect.

Fundamental Improvement of MC-2 System

A fundamental improvement of the helical explosive magnetic energy amplifier MC-2, proposed by Academician A.D. Sakharov, was realized under the leadership of the author by a group including E.I. Zharinov, G.I. Volkov, V.A. Demidov, S.V. Pak, V.N. Buzin [12, 13]. This improvement allowed increasing the energy by a factor of 40-100 at the simultaneous rise of the operating speed and specific energy by a factor of 5 (fig. 6, table 2, see Proceedings MG-II…MG-IX Conferences).

	«Potok» 1 MA 25 nH	«Potok» 6 MA 35 nH	«Potok» 0,88 MA 3000 nH	«Potok» 18 MA 60 nH	«Potok» 12 MA 110nH	«Potok» C	«Potok» 35 MA 50nH
Initial inductance, μH	300	22	250	100	115	34÷62	30
Initial energy, kJ	0,02	7	36	20	40	90÷220	50
Inductance of the load, nH	25	35	3000	60	110	50÷750	50
Max. current in the load, MA	1,0	6,0	0,88	18	12	4,6÷21	35
Magnetic energy in the load, MJ	0,012	0,63	1,0	10,0	8,0	8÷11	30
Characteristic current rise time (e-fold), μs	3	9	45	40	35	35÷40	30
Inner diameter, mm	50	100	160	200	160	160	350
Length, mm	250	600	1600	2000	1600	1600	3500
HE mass, kg	0,1	1,6	6,3	25	21	21	120
Total mass, kg	1,8	10	40	90	140	140	550

Table 2

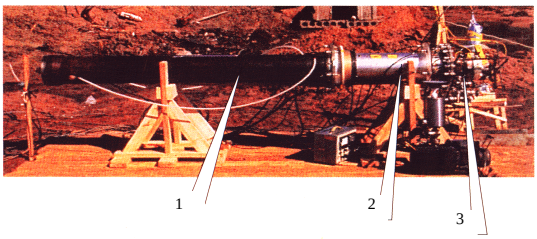

Fig. 6 Helical EMG for MAGO-chamber feeding:
1 – EMG; 2 – FOS; 3 – Plasma chamber

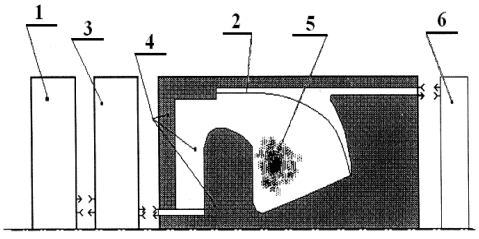

Fig. 7 MAGO scheme with gas ponderomotore unit

1 – Fast helical EMG;
2 – Liner for plasma compression;
3 – Current pulse forming block;
4 – Gas ponderomotore unit;
5 – Preliminary preheated magnetized plasma;
6 - High power disc EMG

Participation in MAGO Concept Development

V.N. Mokhov, V.B. Yakubov and the author proposed and substantiated the original idea of CTF problem solution, based on magnetogasdynamic heating of the target with magnetized plasma up to kiloelectronvolt temperatures and its further fast adiabatic compression by means of magnetogasdynamic driver to a condition of ignition and burning (MAGO concept, brief publication in 1976, 1979, detailed description in1992) [6, 14, 15, 16] .

Plasma magnetization prior to its fast adiabatic compression allows achieving ignition in the intermediate area between Tokamacs and ICF systems using non-traditional approaches and devices (fig. 7). This significantly simplifies the requirements to ignition achievement conditions as compared to the known ICF systems.

Preliminary Heating Experimental Validation

The efficiency of the proposed way was demonstrated experimentally by the works carried out by V.P. Korchagin, A.N. Demin, I.V. Morozov and etc. [16] (table 3, fig. 8, 10):

- basic principles and regimes for generation of pre-heated magnetized D-T plasma up to kiloelectronvolt temperature level were checked;
- stable generation of neutrons (14 MeV) with the yield of 10^{13} fusion reactions was achieved;
- plasma lifetime on the order of 2 μs was obtained.

Initial current feeding	2 MA
Basic (fast (t_f=1.5 μs)) current feeding	7 MA
Neutron DT yield	$5 \cdot 10^{13}$
Neutron pulse duration	2 μs
Electron temperature	500 eV

Table 3

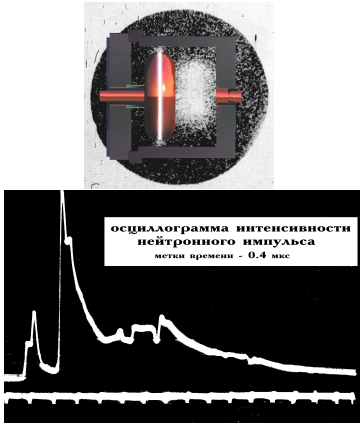

Fig. 8

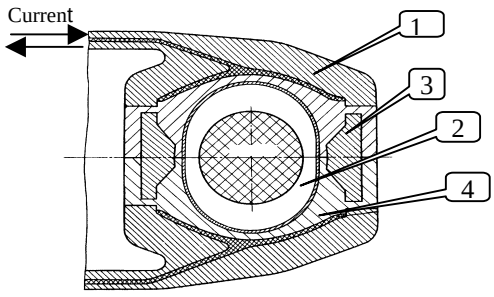

Fig. 9 PU-scheme

1 - conductor; 2 - shell; 3 - insert; 4 - isolator

Liner Physics Unique Results

Feasibility of **quasi-spherical** implosion of liners under the effect of **axially symmetric** magnetic field was proved [15] experimentally (fig. 9,10,11, 12).

- In the area of high energy density a velocity of 50 km/s was achieved during acceleration of the 1g mass liners. The energy density achieved is by a factor of 200 higher than the energy density in chemical explosive.
- Unique liner systems that allow driving the liners of 0.25 kg mass to 15 km/s, and the liner of 1 kg mass to 8 km/s were developed (fig. 13).

All these results were proved experimentally [17, 18].

a) b)

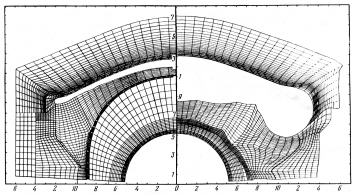

Fig. 10 PU-movement of the shell calculation results
a – initial PU position;
b – PU position just before the impact with the target mock-up

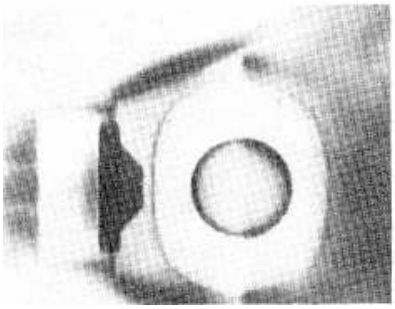

Fig. 11 Experimental result
Initial PU position

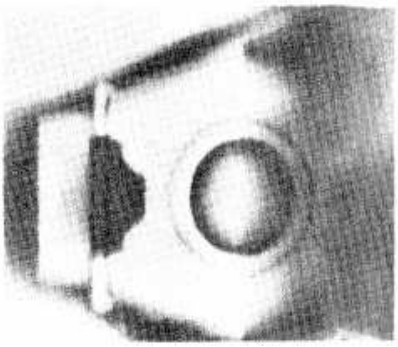

Fig. 12 Experimental result
PU position just before the impact with the target mock-up

The most Powerful Helical EMG

The energy source of a ***helical*** type with ***unique explosive fast opening switch of current based on a principle of conductor cutting by dielectric stream jets and making it possible in addition to enhancement to have additional compression of magnetic flux with energy increase*** (stored energy 30 MJ) was developed. The experiment carried out with this source (fig. 14) provided not only the current of 30 MA but also a fast delivery of current to the external load (15 MA). [19].

Fig. 13 EMG of 100 MJ

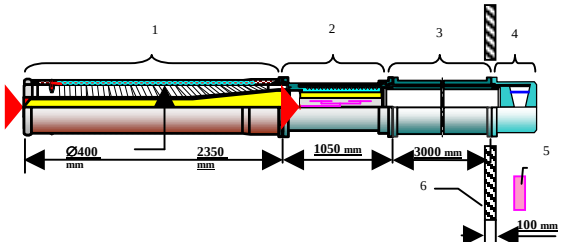

Fig. 14 Experimental set-up for liner implosion system
(stored energy of EMG – 30 MJ)
1 – Helical EMG; 2 – FOS; 3 – transmission line; 4 – Liner chamber; 5 – radiographic equipment; 6 – steel plate

In fig. 14 one can see a schematic of the device, and fig. 15 shows its location at the test site and the participants of the joint experiment.

This allowed obtaining the liner velocity of 10 km/s in the joint Russian-French experiment. Herewith during the implosion of the conical liner along the axis the jet was formed with a velocity of 40-50 km/s (pressure at the impact on the tantalum target was more than 10 Mbar). (The process was reliably recorded by two radiographic images with the interval of 400 ns).

The most Powerful Disk EMG with Fast Opening Switch

There has been developed a middle class ***disk*** explosive magnetic generator

Fig. 15 The most powerful helical EMG with liner load

(ATLAS simulator) of 40 cm in diameter with a ***built-in low-inductive and really small-size electroexploded fast opening switch*** intended for sharpening the current pulse (30 MA with the rise time of no more than 4 ms), that could rather accurately simulate the parameters of the current pulse of a huge (occupies a building) and

expensive ($ 43M) capacitor bank ATLAS built in USA [17, 18]. In the joint Russian-American experiments the use of such generator allowed achieving the current pulse (32 MA, 4 ms) that entirely covers the parameters of the ATLAS facility planned to be recommissioned at the NTS. In the experiment the velocity of the liner was more than 12 km/s prior to the impact of the 50 g cylindrical aluminum liner on the target under good longitudinal and azimuthal symmetry of cylindrical implosion. The general view of the device at the test site is given in fig. 16.

Fig. 16 The most powerful disc EMG of the middle class with liner chamber

RESULTS OF THE XXth CENTURY IN THE AREA OF SUPER-POWERFUL EXPLOSIVE MAGNETIC ENERGY SOURCES FOR FUSION AND PHYSICAL RESEARCH

Scientific breakthrough in the three key areas of modern physics

In the result of the experimental research of systems MC-1 and MC-2 started by the initiative of A.D. Sakharov in Division 22 (now the Electrophysical Department of VNIIEF) of the Design Bureau-11 (KB-11) one of the Russia's leading new scientific schools - and namely the school "Super-Powerful Explosive Magnetic Energy Sources for Fusion and Physical Research" – was founded, grew up and gained world fame and recognition [20].

The works by the scientists and specialists of this school made in close cooperation with such outstanding VNIIEF scientists as Academicians Yu.B. Khariton, A.D. Sakharov, Ya.B. Zeldovich, E.A. Negin, R.I. Ilkaev, Yu.A. Trutnev, talented Doctors of Science D.A. Fishman, V.A. Tsukerman, V.N. Mokhov, L.M. Timonin, V.B. Yakubov and many others realized a scientific breakthrough in three key areas of modern physics:

Super-Powerful Energy Sources Physics

Having no analogues in the world high-speed EMGs of "Potok" family were created.

Conclusion: Already now the energy sources are capable of providing the preliminary heating of magnetized plasma

Magnetized Pasma Physics

Ionized, magnetized, preliminary heated up to the temperature of 0.2…0.5 keV D-T plasma with the life time ~ 2 μs was generated, in which $5 \cdot 10^{13}$ thermonuclear reactions were realized.

Conclusion: Preliminary heated and magnetized plasma is ready for additional compression.

The liner energy density > 1 MJ/g (that exceeded the energy density in HE by a factor of 200) has been achieved experimentally; feasibility of **quasi-spherical** implosion of the shell under the effect of the **axially symmetric** magnetic field was proved experimentally.

Conclusion: The driver and the compression system are ready for the experiments on additional compression of preliminary heated magnetized plasma.

The scope of the performed research and the level of the obtained results suggest taking the following big step, i.e. conducting the first experiments on additional compression of preliminary heated magnetized plasma in order to achieve thermonuclear ignition.

A fundamental physical advantage of MAGNETIC COMPRESSION concept is that the application of magnetized plasma "blocks" the electron conduction and ion conduction and this allows achieving ignition at lower liner velocities and smaller plasma compression as compared with the known ICF projects.

It should be additionally underlined that it is not necessary to construct huge expensive buildings and facilities that cost hundreds millions of dollars (or even more) in order to achieve ignition. The already created super-powerful EMG can be used as the energy sources.

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