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If a man takes no thought about what is distant,
he will find sorrow near at hand.
/Confucius/

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STABILITY OF MICROPROCESSOR RELAY PROTECTION AND AUTOMATION SYSTEMS AGAINST INTENTIONAL DESTRUCTIVE ELECTROMAGNETIC IMPACTS. PART 1

В статье рассматриваются проблемы воздействия мощных электромагнитных импульсов, генерируемых при ядерном взрыве или с помощью специального оборудования, предназначенных специально для повреждения электронной аппаратуры, в частности микропроцессорных устройств релейной защиты и автоматики, а также меры защиты от этих воздействий.

Problems of impact of the electromagnetic high-power pulses generated at nuclear explosion or by means of the special equipment, intended specially for damage of the electronic equipment, in particular digital protective relays and automatic systems, and also ways of protection from these impacts are considered

1. CHALLENGES OF MODERN POWER INDUSTRY: ELECTROMAGNETIC COMPATIBILITY

For decades, the problems of EMC have been the prerogative of specialists in electronics, radio engineering and communications. Suddenly, over the last 10-15 years, this problem has become critical for the power industry. Of course, high electromagnetic fields have always existed at electric power facilities; however, electromechanical devices, which have been applied for decades in automatics, control and relay protection, were not exposed to electromagnetic fields too much and so no significant EMC problems were encountered. But in the last two decades there has been a sharp change-over from electromechanical relay protection devices to microprocessor-based (MPD) ones and automation. Moreover, the change-over has included both the construction of new substations and power plants and replacing old electromechanical protection relays (EMPR) at the old substations, built in those days when nobody assumed using microprocessor technologies, with the up-to-date MPDs. The latter have proved to be very sensitive to electromagnetic interference coming "out of thin air", penetrating through operating power circuits, voltage circuits and current transformers. Some malfunctions of MPD were caused by mobile phones [1] and similar types of equipment. There have been other cases, such as malfunctions of microprocessor-based devices at the operating capacities of the Mosenergo, Ochakovskaya and Zubovskaya substations. The operating algorithm of protection was affected by lightning, excavators working nearby, electric welding and other types of interference. The Lipetsk substation startup was postponed for six months due to faults of microprocessor-based devices while they spent nearly $1.5 million for the MPDs. As a result, the substation was commissioned using a set of conventional defenses [2]. In practice, a shortcut on the 110 kV side can cause protection failures on the 330 kV side, and interference during switching of the same voltage rating penetrated inputs (through the auxiliary circuits) of the relay protection apparatus operating under the other voltage rating [3]. According to Mosenergo, faults due to improper operation of relay protection amount to 10 % out of total number of malfunctions, and basically refer only to microelectronic-based and microprocessor-based relays [4]. Enabling SIEMENS MP protection at CHP-12 of Mosenergo, OAO, designed by Atomenergoproekt Research Institute, is the most obvious example of such problems, as EMC requirements were not considered in the design at all. Due to interferences there were more than 400 fault data signals detected at discrete and analogue inputs of MPD .during the August-December of 1999 alone [4]. Also, it should be kept in mind that the cost of each MPD fault is 10 times higher than the cost of an electromechanical relay fault because of the high number of functions concentrated in each MPD. Such a high percentage of malfunctions due to insufficient EMC results from the fact that the MPD interference sensitivity is much higher than that of traditional electromechanical protection. For example, according to [4] when an electromechanical relay operation can be affected by the energy of 10^{-3} joule, the energy of only 10^{-7} joule causes the malfunction of the microchips. The difference is about 4 orders of magnitude, or 10000 times.

The level of damage depends on the insensitivity of each circuit component and the energy of the powerful interference as a whole, which can be absorbed into the circuit without the appearance of any defect or failure. For example, although the switching noise caused by the inductive load with an amplitude of 500V is a twofold voltage surge, it is unlikely to lead to the failure of an electromagnetic relay with a 230V AC coil due to its insensitivity to this kind of interference and its short duration (it lasts only several microseconds). The situation is different if the chip is powered from a 5VDC source. The impulse interference with an amplitude of 500V is hundredfold higher than the supply voltage of the electronic component and leads to the inevitable failure and the subsequent destruction of the device. Surge resistance of the chips is several orders of magnitude lower than that of the electromagnetic relays [5]. Long-term statistics confirms that the number of such damages doubles every three to four years [5]. This statistic is in good agreement with the so-called Moore's law [6] who in 1965 showed that the number of semiconductor components in microchips doubles roughly every two years and this trend has remained valid for many years. If some ten years ago, the so-called transistor-transistor logic (TTL) chip contained 10-20 elements per square millimeter, and had a typical supply voltage of 5V, now the popular chip can contain nearly a hundred of CMOS (Complementary Metal-Oxide Semiconductor) transistors on every square millimeter of the surface and has supply voltage of only 1.2 V. The up-to-date solid state technologies, for example, SOS (Silicon-On-Sapphire), raise the number up to 500 elements per square millimeter of the surface [7]. It is obvious that such chips would require even lower supply voltage and it is even more obvious that such improved microelectronics integrity reduces insensitivity of its components to high voltage surge due to the reduced distance between electroconductive elements, lower thickness of insulating layers and reduced operating voltage of semiconductor elements.

Recent trends of technological evolution and ever-growing electromagnetic vulnerability of national infrastructures (power and water supply, communications, etc) have come under military consideration long since. Military research centers of almost all developed nations have carried out intensive research and development on special weapons capable of destroying electronic equipment. Mass media have published dozens of articles discussing methods for increasing efficiency of electromagnetic actions aimed at destroying electronic equipment [8-12].

High-altitude nuclear explosions have an extremely high destructive effect. An explosion at an altitude of 200-300 km wouldn't have any influence on humans and would escape detection while the resultant electromagnetic pulse (rather a range of pulses with different characteristics) would cause a catastrophe for electronics and computers of the whole country (see Table 1). The electric power industry can suffer heavily due to long mileage of overhead electric lines acting as giant antennas absorbing electromagnetic pulse energy over a large territory and delivering it directly to the power stations and substations apparatus. Considering the special hazard of such an explosion to the power energy industry, the International Electrotechnical Commission (IEC) developed a series of specific standards detailing methods for testing electric power lines and other power equipment in order to evaluate their resistance to high-altitude nuclear explosions [13-31].

If the recent tendency (i.e., "Smart Grid" concept) will be widely implemented in power industry, even a single high-altitude nuclear explosion will immediately kill all national power industry, as shown in [32], which makes it especially attractive to warring parties.

2. CLASSIFICATION AND CHARACTERISTICS OF INTENTIONAL DESTRUCTIVE ELECTROMAGNETIC IMPACTS

English-language publications call the intentional destructive electromagnetic impacts as "High Power Electromagnetic Threats (HPEM)" divided into two types: "High-Altitude Electromagnetic Pulse (HEMP)" and "Intentional Electromagnetic Interference (IEMI)".

HEMP is a very powerful electromagnetic pulse resulting from a high-altitude nuclear explosion. It has long been known that powerful electromagnetic pulse following a nuclear explosion is one of the damage effects of such explosion. Theoretical studies on X-ray radiation effects conducted by Arthur Compton, an American scientist specializing in theoretical physics, in 1922 (in 1927 he was awarded with Nobel Prize for this finding) showed that a nuclear explosion is always followed by electromagnetic emission. At that time this effect was neglected and it was noticed only after the first nuclear weapon test explosions. In [33] it is described as follows: At the end of June 1946 a series of nuclear detonation tests was conducted under the codename of Operation Crossroads at Bikini Atoll (Marshall Islands). The purpose was to explore damage effects of nuclear weapons. Test explosions revealed a new physical phenomenon – generation of powerful electromagnetic pulses (EMP) which immediately became of high interest. The highest EMP followed high-altitude explosions. In the summer of 1958 a series of high-altitude nuclear explosions was conducted. The first series of explosions, under the codename of Operation Hardtack, was conducted above the Pacific Ocean near Johnston Island. The series consisted with two megaton-range detonations: Tack – at an altitude of 77 km and Orange - at an altitude of 43 km. In 1962 high-altitude explosions were continued: a 1,4 megaton warhead was detonated at a 450 km altitude under the codename of Starfish Prime. The USSR also conducted a series of test explosions in 1961-1962 aimed to evaluate the impact of high-altitude explosions (180-300 km) to antiballistic missile defense apparatuses. The tests revealed powerful EPM with high damage effects to widely separated electronics, communications and power lines as well as to radio stations and radars.

The relationship of the electronics effective damage area and altitude of a 10 megaton explosion is shown in the following table.

Table 1

Effective damage area in dependence with nuclear explosion altitude

Altitude of explosion, km	Approximate diameter of damage area, km
40	1424
50	1592
100	2.242
200	3.152
300	3.836
400	4.402

According to IEC there are three components of HEMP: E1, E2 and E3.

E1 – is the "fastest" and "shortest" component of HEMP resulting from a powerful stream of high-energy Compton electrons (product of the interaction of γ-quantum of the initial radiation of the nuclear explosion with atoms of the atmosphere) drifting in the geomagnetic field with a velocity close to the speed of light. This interaction between very fast-moving electrons and magnetic field generates a pulse of electromagnetic energy focused by geomagnetic field and oriented to the Earth from the high-altitude. The pulse typically rises to its peak value in about 5 nanoseconds and the magnitude of this pulse typically decays to half of its peak value within 200 nanoseconds. By the IEC definition, this E1 pulse is fully ended at one microsecond (1000 nanoseconds).

E1 results from the most intensive electromagnetic field causing very high voltages in electric circuit and creates impulse voltages up to 50 kV/m with a power density of 6.6 MW per square meter at middle latitudes near to ground-level. E1 causes the most damage to the electronics due to the power surge and electrical breakdown of *p-n*-transitions of semiconductors and isolation. Conventional arresters ensuring protection against atmospheric power surges sometimes are not fast enough to respond in a timely fashion and protect equipment from E1, while the power they dissipate can be inadequate for absorbing energy of the E1 pulse component which results in destruction of such arresters.

E2 – is the intermediate (steepness and time length) component of EMP which according to IEC definition can last from 100 microseconds to 1 millisecond. The E2 component of the pulse has much resemblance to the electromagnetic pulses produced by nearby lightning. Field gradient can reach 100 kV/m. Because of the similarities to lightning-caused pulses and the widespread use of lightning protection technology, the E2 pulse is generally considered to be the easiest to protect against. However, the combined impact of E1 and E2 components makes other problem, as while E1 destroys protection elements E2 penetrates the equipment unchecked.

The **E3** component is very different from the other two major components of nuclear EMP. It is a very slow pulse, lasting tens to hundreds of seconds, that is caused by the nuclear detonation heaving the Earth's magnetic field out of the way, followed by the restoration of the magnetic field to its natural place. The E3 component is similar to a geomagnetic storm caused by a very severe solar flare. Gradient of induced field can reach 1V/km. Like a geomagnetic storm, E3 can produce significant geomagnetic induced currents in long electrical conductors, including long power lines, which can then penetrate power line transformers with following saturation, impedance falling-off and increasing of currents until the coils blow-out.

Since the 80’s of past century, a number of countries have started intensive development of so called "Super EMP" – nuclear charge with amplified electromagnetic emission. The studies have mainly focused on two directions: wrapping the charge in a casing of a substance that emits high-energy **γ**–radiation under a neutron exposure to a nuclear explosion as well as focusing **γ** –radiation. According to experts Super EMP will allow creating a field with a gradient of hundreds and thousands of kilovolts per meter near the Earth’s surface. Moreover, the military makes no secret that the main targets for such EMP weapon in future battles will be the government and military administrations as well as national infrastructures, including power, water supply systems and communications.

However, the nuclear explosion is not the only source of powerful EMP. Today, the non-nuclear source of EMP can be transported with conventional and high-precision means of delivery.

Thus, the problems of defense against EMP impact will be the concern of experts despite the results of nuclear disarmament negotiations.

IEMI – is the second type of non-nuclear deliberate destructive EM impact. First theories on creation of non-nuclear shockwave emitters of superpower EMP (SWE) were formulated in the early 50’s of past century by nuclear physicist Andrei Sakharov during his work on the nuclear weapon.

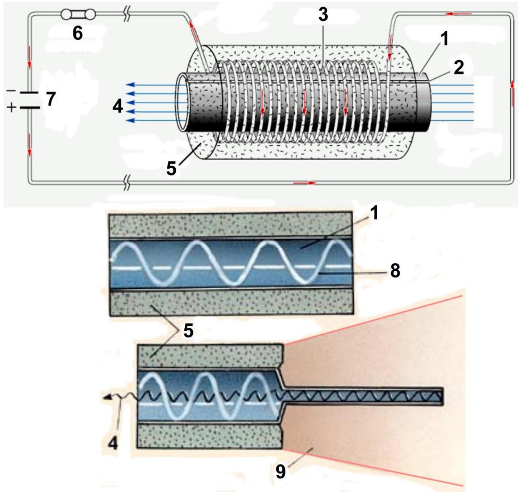
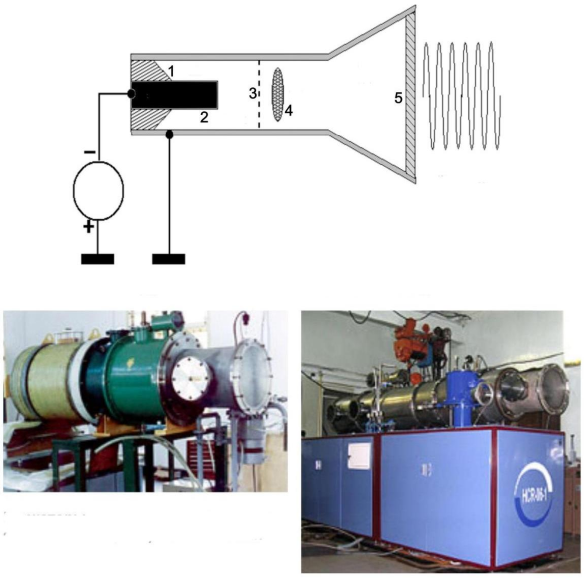


Fig. 1. 1 – electromagnetic cavity; 2 – cut; 3 – coil with non-firing current; 4 – vectored electromagnetic emission; 5 – explosive substance; 6 – switchboard; 7 – energy accumulator (condenser); 8 – standing wave; 9- flying explosion products

Getting primary neutrons initiating the fission process in a nuclear weapon required a superpower source of current pulse. Sakharov’s generator represented a ring of explosive substance surrounding the copper coil. The set simultaneously exploded detonators initiating an axipetal detonation. At the moment of demolition, there was a discharge of power condenser with the current generating magnetic field inside the coil. Enormous pressure of the shock-wave (approximately one million atmospheres) squashed and bridged the windings of the coil which was transformed into a tube enclosing the field inside the coil. The current loop collapsed under a speed of several kilometers per second depending on the type of explosion. As we know from physics, the magnetic field intensity created by the current in this case is in proportion to the speed of inductance change over time. Since the size of the coil changed with considerable speed during the loop collapse, the amplitude of the magnetic field also became huge (tens of millions amperes). At that moment, fusing destroyed one of the resonator cavity ends and converged to the point and deflected a shock-wave back changing the field with the jump. Thus, the standing wave became a high-pulse power traveling wave generating a pulse stream of RF electromagnetic emissions. In fractions of nanoseconds the field changed more suddenly than under the sine law with a period equal to squeezing-dispersing time, which means that the function describing the change included many frequencies. Therefore, the shock-wave source was an ultra-wideband and emitted the pulses at the range of hundreds of MHz to hundreds of GHz lasting for tens-hundreds of microseconds.



Inductive Power Storage VIRCATOR	
Voltage pulse (300 ns), kV	400
Current, kA	12
Power eradiation, MW	350
Duration of eradiated pulse, ns	200
Output frequency, GHz	3.1

Capacitive Power Storage VIRCATOR	
Voltage pulse (100 ns), kV	600
Current, kA	18
Power eradiation, MW	500
Duration of eradiated pulse, ns	80
Output frequency, GHz	3.1

Fig. 2. Powerful vircators developed at Tomsk Polytechnic Institute, 1 – insulator; 2 – metal cathode; 3 – drid anode; 4 – virtual cathode; 5 – dielectric gap

According to American experts, the shock-wave emitters were first demonstrated by Clarence Fowler at Los Alamos National Laboratory at the end of the 50's [34]. In the 60's experts and politicians from USA and USSR realized that such sources of superpower EMP can be the basis of the new kind of weapon. This was declared by N.S. Khrushchev who in the 60's hinted at some fantastic weapon. Surely, it took some time to create the real weapon based on theoretic evidences. The possibility of using SWE as an independent weapon capable of generating superpower EMP was first announced by Prischepenko A.B., Doctor of Science and Head of Laboratory of Special Weapons of Central Research Institute for Chemistry and Mechanics after successful tests were conducted on March 2, 1984 at Krasnoarrneyskiy Research Institute Geodeziya (now FFE RE "Geodeziya") training range. Later Prischepenko A.B., Associate Member of Academy of Military Science and Doctor of Science formulated the general concept for the tactical employment of electromagnetic weapons.

Today, intensive research of IEMI is being conducted in numerous directions and non-explosive shock-wave emitter (SWE) is not the only type of non-nuclear electromagnetic weapon known.

There is a wide range of high-power microwave devices: relativistic klystron tubes and magnetrons, reflex-triodes, backward-wave tubes, gyrotrons, Virtual Cathode Oscillator (Vircator), etc. Construction of a vircator capable of generating high-power single energy pulses is simple and compact allowing using it in a relatively wide range of microwave frequencies. The concept of the vircator lies in accelerating a powerful electron stream with a anode grid. This powerful stream of electrons initially bursts from cathodes (metal cylinder rods with a diameter of a couple of centimeters, see Fig. 2) under the high-voltage pulse (hundreds of kilovolt) and demonstrates electron emission explosive behavior. A significant number of electrons comes through the anode grid forming the charge cloud behind the anode. Under certain circumstances this area of charge cloud oscillates in the anode region. Generated with the frequency of the electronic cloud oscillation, the microwave field is radiated into the environment through dielectric gap. Pre-oscillation generated current in vircators can reach 1-10 kA. Vircators are the most suitable devices for generating nanosecond-range pulses at long-wavelengths within the centimeter range. During the experiments, capacities of 170 kW - 40 GW in the centimeter and decimeter range were obtained on such devices. According to published data the experimental device with a pulse power of approximately 1 GW (265 kW, 3.5 kA) can damage electronics within 800-1000 m.

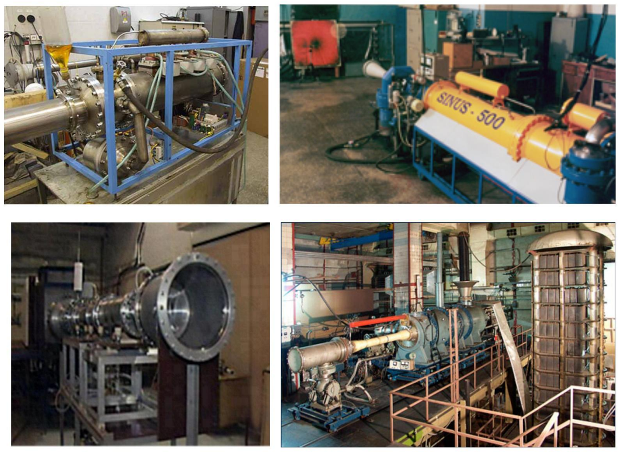


Fig. 3. Relativistic high-power microwave generators based on gyrotrons, vircators and backward-wave tubes developed by different Research Institutes in Russia

Even such well-known devices as high-voltage pulse Marx generators, see Fig. 4, containing the set of high-voltage condensers and tube surge arresters (80 equal sided) can be used as powerful sources of microwave radiation. In such devices all condensers are initially charged in-parallel from the high-voltage power supply and at the moment of cell-type tubes synchronous breakdown all condensers become connected in-series. In the FEBETRON-2020 portable generator, see Fig. 4, current pulses of 6 kA are generated under a voltage of 2.3 MB, resulting in radiation of powerful EMPs.

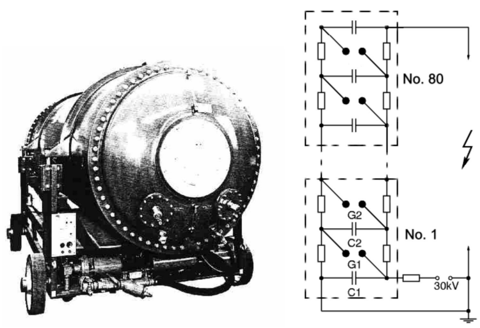


Fig. 4. American unit FEBETRON-2020 constructed on Marx generator principle and its simplified scheme

Another IEMI trend is the so called beam weapon. This weapon is based on the usage of a spot beam of charged or neutral particles generated with different types of accelerators both on the ground and from satellites in space. Development of the beam weapon has been greatly intensified soon after the declaration of Strategic Defense Initiative (SDI) by Ronald Reagan, the President of USA, in 1983. Los Alamos National Laboratory and Livermore National Laboratory have become the central research sites. Some scientists declared that the laboratories were successful in generating streams of high-energy electrons with capacities of a hundred times greater than that generated in research accelerators. At the same laboratory experiments under the Antigone program proved that an ionized channel pre-generated by laser beam in atmosphere allows electron beam to propagate nearly ideal without diffusion.

Powerful compact emitters which can be assembled on a truck or minibus pose a particular risk.

In 1977 a compact generator of high-power (100-1000 MW) plane-polarized mono-directional wave beams of ultra-wideband electromagnetic radiation with pulse of nanosecond and subnanosecond range designed for damaging electronics was developed in Tomsc Institute of High Current Electronics (IHCE), Siberian Branch, Russian Academy of Sciences for researching generation of super-power electric pulses (of giga- and teraWatts range) under the supervision of Gennady Mesyats academician, vice-president of Russian Academy of Sciences see Fig. 5.

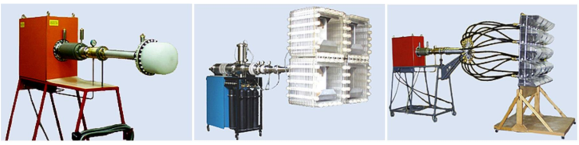


Fig. 5. Compact powerful ultra-wideband sources of radiation with capacity up to 1 GW developed at Tomsc Institute of High Current Electronics

Today, such sources are available from the IHCEfor just $40-60k and can be installed in a minibus or small truck. All contact information for such kind of orders is available at the official web-site of the IHCE. Similar movable and portable sources are also developed in USA, see Fig. 6.

Fig. 6. Compact source of powerful monodirectional ultra-shortwave radiation (95 GHz) developed by Sandia National Laboratories, USA, under Raytheon technology (top), and powerful sources of mono-directional radiation assembled on chassis of Hummer off-roadster and ACP Stryker. More powerful complex is planned to be installed on board of AC-130 airplane

Some countries (USA, Israel, etc.) are developing compact electromagnetic guns with relatively low capacity capable of damaging electronics within 100 m. Such devices are interesting both for military and police. A present-day car, crammed with electronics, has the same demolition objective as any other modern system. An American company, Eureka Aerospace, has developed and launched the production of electromagnetic "stopper" of a moving car (EMP car-stopper).

This weapon damages the microprocessor, igniting system, fuel injection system and other vehicle electronics. What will happen if such weapons fall into the hands of the terrorists (surely, sooner or later this will happen)? Besides, it is not that hard to find such weapons as many popular technical magazines describe numerous self-made systems of such kind, see Fig. 7.

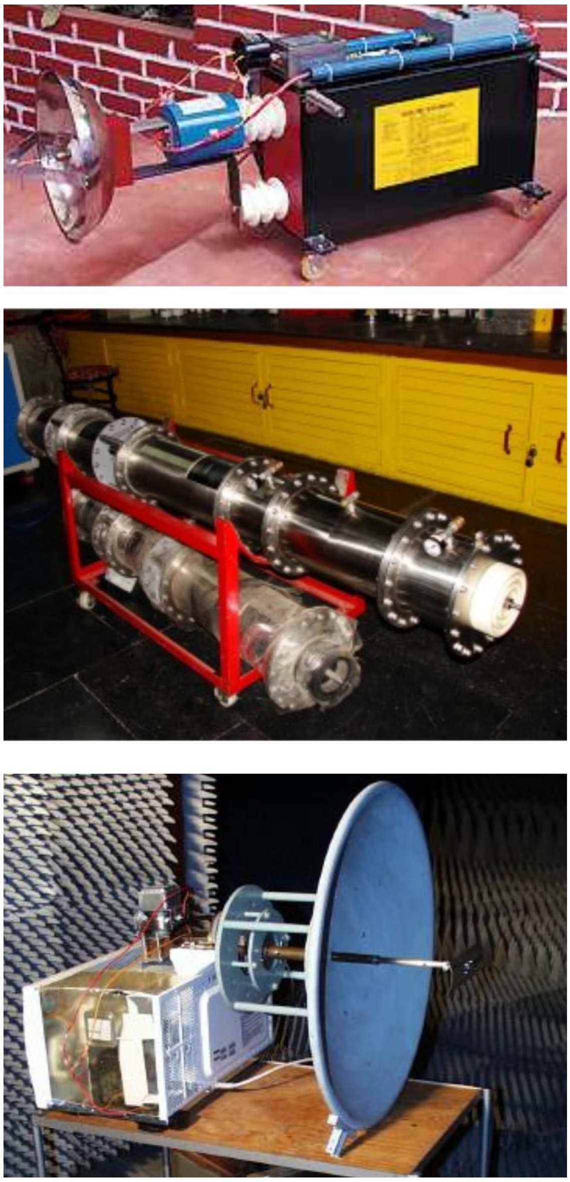


Fig. 7. Directional microwave self-made generators described in popular technical magazines

All this reminds one of the prophetic aphorism of Winston Churchill who many years ago said, that "*The latest refinements of science are linked with the cruelties of the Stone Age*".

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Stability of microprocessor relay protection and automation systems against intentional destructive electromagnetic impacts. Part 1.

Problems of impact of electromagnetic high-power pulses generated at nuclear explosion or by means of special equipment intended specially for damage of electronic equipment, in particular, digital protective relays and automatic systems, along with ways of protection against these impacts are considered.

Key words – **electronic equipment, relay protection, electromagnetic impacts.**