REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1995	Final report/Interim Report

4. TITLE AND SUBTITLE

"Magnetic Flux Compressors with Flux Trapping" in English.

5. FUNDING NUMBERS

F6170894W0777

6. AUTHOR(S)

V. Mintsev

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute of Problems of Chemical Physics
Moscow Region
Chernogolovka 142432
Russia

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

EOARD
PSC 802 Box 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 94-4101

11. SUPPLEMENTARY NOTES

Includes one volume "Generation of High Power Microwave Radiation with the Aid of High Explosive" in Russian

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

ABSTRACT (Maximum 200 words)

The present paper looks into the Magnetic Flux Compressors (MFC) from the point of view of their integration with high power microwave sources. First of all the typical constructions and principals of there operations will be considered. After that the possibilities of production of video impulse will be discussed and MFC as a pulsed power system for feeding relativistic microwave generators will be described.

14. SUBJECT TERMS

EOARD, Russian, magnetic, flux, compressors, microwave

15. NUMBER OF PAGES

39 and 93

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INSTITUTE OF CHEMICAL PHYSICS AT CHERNOGOLOVKA
RUSSIA ACADEMY OF SCIENCES
142432, Chernogolovka, Moscow region, Russia.
Tel.: 096-517-1930, Fax: 096-515-3588

MAGNETIC FLUX COMPRESSORS WITH FLUX TRAPPING

Interim REPORT

TO
CONTRACT SPS-94-4101

Principal Investigator: Dr. Victor B.Mintsev,
Tel.: (095) 524-5008, (096) 517-1870
Fax: (096) 515-3588
E-mail: minvb@ficp.ac.ru

CHERNOGOLOVKA - 1995

CONTENTS.

I. LITERATURE OVERVIEW

MAGNETIC FLUX COMPRESSORS FOR HIGH POWER MICROWAVE GENEREATORS.

I.1. INTRODUCTION.

Nowdays high power sources of electrical impulses are widely used to solve problems in modern physics of high energy density. Among the generators of single pulses the explosively driven systems seems to be the most attractive, because they look like rather simple, compact and cheap constructions, which have very high specific characteristics and sufficient reliability. Actually, it is well known that high explosives (HE) stored a large amount of chemical energy up to 10 MJ/kg, this is by 5-6 orders higher then the specific electrical energy stored by capacitors. To convert chemical energy of HE into the energy of electromagnetic pulse special devises, so called Magnetic Flux Compressors (MFC), were designed [1-3].

MFC action is based on the effect of "magnetic cumulation" during compression of magnetic flux by metal conductor pushing by detonation products of HE. One of the typical and simplest construction consists of a helical coil wrapped around a copper cylinder filled with HE. Permanent magnets, piezoceramics or small capacitor supplies an initial current of few hundred amps that creates an initial magnetic field in the gap between the coil and cylinder. The explosion compresses the magnetic field and jets it into the load, where a very short-duration powerful electrical impulse is created.

MFC are unique constructions for obtaining of super high magnetic fields in the laboratory conditions. There were fixed records values of 25 MG [1] and stable achieved values of 10-14 MG [4,5] in the volumes of several cubic centimeters. This technique offers possibility of investigation of the behavior of the matter under super high magnetic fields [6].

MFC have very great possibilities as the pulsed energy sources. Actually there were achieved [2] the level of energies in the load up to 100 MJ, currents up to 300 MA, voltages up to 1 MV, specific energy of 100 KJ/cc, specific power of 10 MW/cc. Top values of energies and powers for special types of MFC are estimated as high as 1 GJ and 100 TW.

In most experiments carried out MFC were switched on the low-inductive loads (1-100 nH), resulting in great efficiency of chemical high explosive energy transformation up to 10% [2]. Last years with the advances in pulsed power technology the great interest is appeared in investigations of possibilities of MFC employment as energy source for unusual high impedance loads such as vacuum diodes [7,8], railguns [9], electron and proton accelerators [10], systems of excitation and feeding of powerful lasers [11] and powerful microwave generators [12-14]. To realize considerable poweres in such loads MFC must have large values of inductance verification of >1 om and has to produce large values of voltages of 0.1-1 MV.

To realize a wide range of parameters for various applications there were worked out a lot of constructions of MFC, which are good for the decision of the concrete scientific problem. The purpose of the present report is to consider the problem of transformation of energy of HE into the energy of electromagnetic wave. The successful decision of this task will lead to the creation of compact pulsed power explosively driven systems with record parameters produced in the laboratory conditions. Also this is of great interest for various practical applications such as action on condensed materials and ionosphere plasma, heating of plasma in thermonuclear reactors, transferring of electrical energy from Space into the Earth, functional influence on alive organism cells, in radiolocation and communication and so on.

To use MFC as a powerful source of electromagnetic waves there are two main ways. On the first one you should organize very quick variation of the current in the load. In this case you can produce in a free space short impulse of ultra wide-band high power microwaves (so called video impulse). To make such variation it is necessary to have a very high values of current or magnetic field inductance derivatives, what can be ensured by short time of the MFC work or by using of fast opening switches for desisting current. Another way is using of MFC as a pulse power feeding system for relativistic generators of coherent microwave radiation. In this case you can obtain high power impulse or bunch of impulses of microwave radiation with definite wave length.

In the present paper we will look on MFC from the point of view of their integration with high power microwave sources. First of all the typical constructions and principals of there operations will be considered. After that the possibilities of production of video impulse will be discussed and MFC as a pulsed power system for feeding relativistic microwave generators will be described.

I.2. TRADITIONAL CONSTRUCTIONS AND PRINCIPALS OF MFC OPERATION.

The first studies on the magnetic cumulation phenomenon are dated from the fifties [1,15]. In the works two principal problems were raised and solved: achieving the maximal intensity magnetic field in a given space and obtaining the maximal energy in the working load. Since then it has been worked out a varies types of magnetic flux compressors which are usually divided by principles of strengthening the magnetic field and heightening the energy into two classes: the field generators and the energy generators.

Let us chose from the former a cylindrical explosion magnetic flux compressor (Fig.1a [1]), the cylindrical liner of which is accelerated by the condensed explosive detonation directed inside of a compressed volume. Introducing the Poiting's vector P= ExH, one can see that for MFC it is normal to the liner surface and directed to the center of the compressed volume. Therefore, in the field generator case the energy is accumulated inside of the generator work-volume.

The main distinction between the two generators (of the energy and of the field) is the division of an electrical circuit into the generated and load parts. The generated energy is accumulated in the working load during the run time of the generator. The Poiting's vector in the energy generators is always directed to the load. The geometry of such generators is extremely various but for all constructions two colliding conductors are the general elements. In spiral MFC (Fig.1b [1]) such elements are a fixed spiral and the cylindric liner concentric to it. The latter is expanded under the action of detonation products of the condensed explosive initiated on the back side and closes turn and turn about the winds of the spiral. Forcing out the magnetic flux into the working load occurs along the spiral winds. In comparison with other constructions the spiral MFC has the highest initial inductancey what permits to raise the initial energy by some orders of value. In strip MFC (Fig.1c [3]) compression and motion of the magnetic field occur between flat current-carrying conductors. Geometrically the flat compressor can be represented as an "unwinded" and stretched in a line spiral compressor. The coaxial MFC consists of two concentric cylinders with one of them being inside and filled up with a condensed explosive. It is known two regimes of operation of such a compressors: a regime of sliding detonation (Fig.1d [1]) when it works like the flat or spiral compressors, and a regime of axial initiation (Fig.1c [16]) when condensed explosive is initiated simultaneously all over the compressor axes. In the last case the flux compression is realized by the whole surface of the liner. The second regime permits to significantly lower the time of compression and get the current pulse with a more short time of growing. One more construction of high-speed MFC is presented in Fig.1f [17]. this is a disks MFC in which the flux is compressed by two coaxial disks while the flux moves from the center to periphery of them. And finally Fig.1g shows a wrap MFC [18] representing one cylindrical wrap with the eccentrically arranged liner.

In the systems operating on the principle of magnetic cumulation the current-currying circuit limiting magnetic flux F is compressed by external forces. As a result of interaction between a moving conductor and magnetic field the mechanical energy transforms into the energy of the magnetic field. Movement of conductors in the magnetic field is characterized by the Reynolds magnetic number Rem= xV/xo which can be considered as a ratio of diffusion time (x**2/xo) to the time of compression (x/V), where x is the characteristic size of the conductor, V is its velocity, xo - is the magnetic diffusion coefficient. At Rem<1 the magnetic field freely threads the conductor. This regime is characteristic of the work of MHD-generators. At Rem>1 the magnetic field does not practically threads the conductor and the flux connected with the current-carrying circuit remains constant. Decreasing the of the circuit area while the conductor motion leads to increasing of the magnetic field induction and of the current in the circuit. This is the main principle of MFC work.

To analyze the process of electric pulse generation in such a systems it is convenient to employ electrotechnical scheme [2,3]. The simplest equivalent electrical circuit of MFC is presented in Fig.2 where the compressor inductance is simulated by time-decreasing function Lg(t) and the load by constant inductance Ln. Resistance R(t) formally includes all losses of magnetic flux. Current I carrying in this circuit is determined by the following differential equation:

$$d(LI)/dt + RI = 0 \qquad 2.1$$

Solving equation (2.1) with respect to the flux F=LI, L = Lg(t) + Ln, for any time we obtain:

$$LI = Lo\ Io\ \exp(-\int_0^t R/L\ dt) = Lo\ Io\ \varphi(t) \qquad 2.2$$

where Io is the current and Lo is the total inductance at the time t= 0, $\varphi(t)$ is the coefficient of conservation of flux. As seen from equations 2.1-2.2 the effective work of MFC (the current increases in the circuit) is reached at condition $|dL/dt| > R$. Therefore, for generator work on a high impedance load it is necessary to develop constructions with possibly higher internal impedance dLg/dt. Voltages induced at these conditions on inductance can be high enough. Really, in the experiments the compressor internal impedance dLg/dt must not be lower than $|dLg/dt| > 10\text{-}100$ Ohm, with the voltages on the load Ln=1 mcH at the initial flux Fo=0,1 Vb being not lower than $Un = (Fo/Ln)|dLg/dt| > 1$ MV.

Thus the undertaken here analysis of the simplest scheme of MFC working onto the high impedance inductance demonstrates the necessity for the generator to operate at high voltages. However, it is obvious that for all the presented schemes the energy transfer to the high impedance load will be the better, the higher voltage can be beared by MFC construction itself.

At present the most high voltages on the load in explosion experiments are obtained by employing step-up pulsed transformers. Thus in work [19] the voltage about 1.2 MV with the rise time ~ 0.3 mcs was realized in the given load at breaking the circuit with the ~2 mcH inductance. Matching of the circuit with the wrap MFC working at the ~35 kV voltage was secured by a transformer. In work [20] the high speed MFC of "bellows" type generated the voltage ~ 40 kV and hooked up by special circuit closers to the transformer with ~ 25 Ohm ohmic load, on which it was obtained the voltages about 1,1 MV. Using this scheme with a vacuum diode the voltage ~ 530 kV was delivered [7].

In these experiments high speed MFC were used with the characteristic time of operation 10 mcs. The inductance of such a generators is minor, Lgo=100 nH, and, therefore, their internal impedance is low 0.01 Ohm. At the same time the well studied helical MFC [21,22] have high initial inductance (>100 mcH) but have long run time 100 mcs. Their run time is limited by the velocity of sliding contact motion. Increasing of the phase velocity of contact points at some fixed velocity of detonation is possible at the expense of diminution of the angle of liner and spiral collision. However, decreasing of the angle is limited by two causes: firstly, a restricted accuracy of spiral and liner fabrication leads to "skipping" the contact point over some sections of the spiral and thus omitting the spaces with their magnetic flux from a generating part of MFC circuit. At diminishing the angle of collision the losses of the flux increase up to such a magnitude that generation of energy is not already possible. Secondly, conditions of plug magnetic flux in a short time from narrow slots appearing at colliding conductors under small angles are connected with a high strength of electrical fields, which leads to break-downs traverse to the circuit and cutting off the magnetic flux. To avoid this effect the spiral wraps are carefully isolated by solid dielectrics of a very high electrical strength, with the isolation having the minimal thickness. In the opposite case, significant flux losses will occur in the isolator itself and the area of current curryING surface of wrap be diminished. Really, the ratio of the contact point velocity to the detonation velocity is failed to be increased more than 20-50 times.

In works [21,22] is shown that high parameters of spiral MFC are realized at voltages no more than 60-70 kV. Original constructions of the compressors are brought forward in works [23-25] where to avoid breakdowns and to deliver the voltage ~ 1 MV a deep vacuuming of the working space are proposed, with the base nodes of the compressors having the magnetic isolation. Analog problems have to be solved at constructing compressors operating on the principle of "trapping" of the magnetic flux [26-28].

I.3. GENERATION OF POWERFUL SHORT IMPULSES OF CURRENTS BY MFC.

It is well known that the radiation power of dipole system is proportional to the second derivative of dipole moment on time in a second power. To have high powers of radiation one should obtain fast variations of current. Magnetic flux compressors can create a very short-duration (up to several microseconds) pulses of current of few hundred million amps. But there is no any publications on direct measurements of the electromagnetic wave power in the experiments with MFC. Estimations show [29] that in the process of magnetic field compression more than 10% of kinetic energy of liner may convert into the electromagnetic wave one. So let us look on the MFC from the point of view of their possibilities of generation of short-duration high power currents.

The most impressive and record parameters of currents up to 300 MA and it's derivative up to 50 TA/s with a characteristic rise-time of 10 mcs have been obtained with the aid of disk-shape MFC [30]. This generator consists (Fig.3) of 1 meter diameter toroidoral load, two conical metal plates with the high explosive in between and another two metal disk plates, which create gap for initial magnetic field. High explosive is initiated along it's axis. Detonation products expand conical plates, magnetic flux is compressed and pushed out into the load. Initial magnetic flux is produced by external discharge current from two helical magnetocumulative generators of MK-2 type. The system is rather huge, the total amount of high explosive exceeds one hundred.

The U.S. Air Force has had to work with similar small-sized (16-in.-wide and 40-in.-long) generators with the 30-million-amp output to fit into modified Air Launched Cruise Missiles [31]. Secrecy-shrouded testing of version of such a generator has been conducted within last years. It is clear from publication [31] that generated electromagnetic wave was strong enough to "unintentionally damage the ignitions and engine controls of privately owned automobiles about 300 meters from the test site". Los Alamos' 2-ft.-wide by 10-ft.-long Procyon-design fast generator also looks very good from the point of view of electromagnetic wave production. It can realize 16-million-amp pulse with the rise time of only 400 nanoseconds.

Another class of small-sized explosively driven generators of electromagnetic wave was considered in the work [32]. In this devices super high frequency radiation of anomalous wide frequency band is forming by fast magnetic field compression. Currents of hundred kiloamperes and voltages of several kilovolts are realized. Their radiation is isontropically space-distributed.

The first generators of this type is the Shock Wave Source and it's more effective spherical variant. Here initial magnetic field is formed in cylindrical or spherical working body - single crystal, insulator - by means of permanent magnets. Converging shock wave transforms the crystal into the state with metallic conductivity and compresses magnetic field. The properties of working body are selected in such a way, that substantial part of magnetic energy is "throwing off" the shock front thanks to the freezing and diffusion. That's why magnetic pressure doesn't exceed hydrodynamics one till the final phase of compression, realizing at thousandth parts of initial radius of the crystal. Thanks to the anomalous low compression radius, very high values of magnetic induction derivatives are realized, creating conditions for electromagnetic energy radiation. The measurements of energy of electromagnetic wave was performed in the band 0.1-20 GHz. Spectral density of irradiated energy changes from 1.E-13 to 1.E-11 J/Hz in this range, the total energy in the space is near 10 J. The super high frequency radiation pulse duration doesn't exceed one nanosecond.

Explosive Magnetic Generator of Frequency represents a parameter amplifier with the load of high quality factor. It includes a helical MFC with low-turn coil as a load, surrounded by HE. Inside the coil a source itself is situated - a helix, connected with capacitor. MFC creates magnetic field inside the coil. After the detonation of HE the coil transforms to a converging liner, which push magnetic field into the helix. Besides oscillations with meander form of current are induced. A multiplicity of harmonics of far higher than that of carrier frequencies is a reason for energy radiation. Spectral density of irradiated energy changes from 1.E-13 to 1.E-11 J/Hz in the 0.1-20 GHz range, the total energy in the space is near 30 J. The duration of pulses is 2-5 mcs.

In the Ferromagnetic Generator of Frequency the current oscillations are formed by shock demagnetization of permanent magnets, surrounded by a coil connected with a capacitor. The radiation is not too powerful in this case 1.E-16 - 1.E-13 J/Hz, but simplicity, small sizes and low cost allow to use it as a jammer.

The main unit of Superconductor Magnetic Field Shock Wave Former is a ring of superconducting thin film placed on an artificial sapphire undercarriage. This field commutator is surrounded by feeding coil. Currents up to 25 KA with short rise time are supplied from small-sized MFC. Magnetic field is localized in interspace between coil and superconductor commutator and does not penetrate inside the commutator because Miessner effect. However, induction of magnetic field is high enough to initiate a phase transition in superconductor and to decrease it's conductivity to a very low value. In this case "dismissed" magnetic field converges to an axis, where its induction increases very fast. This type of generator is less powerful and needs cooling by liquid air but it can be supplied by usual current sources, that is very convenient for laboratory investigations.

I.4. MFC AS PULSED POWER FEEDING SYSTEM.

More promising way to transform energy of high explosive into the energy of microwave seems to be using of MFC as a pulse power feeding system for relativistic generators of coherent microwave radiation. Advances in technology of such devises have made it possible to transform energy of electrical impulse into energy of high power electron beam and intense microwave radiation of multi-gigawatt power level with the characteristic pulse energies of hundred joules. [33-35] In these generators the energy of relativistic electron beam can be converted into the energy of electromagnetic field with an efficiency up to 80%. The mechanism of intensive electron beam formation is the exploding emission which provides significant (up to 1 MA/sq.c.) current density on the "cold" cathode. It is important, that one has succeeded in reaching extremely high powers (up to 20 GW [36]) at this very simple generation set. Moreover, in this systems it is possible to regulate the radiation frequency from 0,5 to 30 GHz, to shape the radiation diagram within a space angle of twenty degrees and to produce SHF-pulses of microsecond duration. The future development in this field depends upon extension of generators powers to higher levels, what is limited now by characteristics of electrofeeding systems - the capacitor banks being very complex, bulky and expensive engineer construction. Magnetic flux compressors are the real alternative source in a megajoule range of energy.

There are only two works in this field published by Russian scientists on *Megagauss-VI conference. Pavlovsky* in works [14,37] have used CMCG-160 helical generator with 9 kilogramm of high explosive to supply relativistic generator of Cherenkov's type. He obtained 100 megawatt power on a wave length 3 centimeter. More promising results, from the point of view of creation of small-sized system, have been published by *Fortov* [12,13,38,39]. In this experiments compact (500 gram of high explosive) two stage generator with flux trapping were used to supply relativistic generator of vircator type. High power relativistic electron beams (10 GW, 600 kV, 16 kA) and microwave radiation (100 MW, 3 GHz, τ=100-200 ns) have been produced by the high explosive .

On Fig.4 block scheme of Pavlovsky experiments [14,37] is shown. Microwave Cherenkov generator was chosen as a source of coherent microwave radiation at ≃10 GHz. In this generator the energy of relativistic electron beam is converted into the electromagnetic radiation energy when it interacts with slowed-down electrodynamic structure. This space extended multiwave structures permit one not only to decrease the strength of the surface electrical field without breakdowns, and therefore, to height the intensity and the length of radiation pulse, but also significantly to increase the efficiency of energy exchange, to form the direction diagram of output radiation. Cherenkov generator, as a modification of surface wave generator, works near the short-wave boundary of opacity band of periodically electrodynamical structure that have a shape of metal-insulator corrugate surface. Accelerator system allows to get ring electron beam with width of 8 mm, diameter of 350 mm, electron energy of 600 keV, currents up to 20 kA and pulse duration of 1 mcs. To focus and to transport electron beam magnetic field of 2 Tl and energy of 1 MJ was created by impulse solenoid with inner diameter of 600 mm and length 1600 mm. The CMCG-160 helical MFC served as an energy source for the high current accelerator and impulse solenoid. This generator can produce energies up to 2 MJ and currents - several megaamps. It has 160 mm diameter and length of 1 m. Step up transformer was used to match the explosive generator and accelerator impedances, also it works as an inductive storage. To sharp the electrical impulses exploding wires and spark gap were used. Exploding wires increase voltage in the circuit. So the whole system have length of 5 m and diameter of 0.6 m.

The relativistic generator - vircator, based on triode with virtual cathode , was chosen by Fortov [13] as a source of coherent microwave radiation at ≃3 GHz. In this generator oscillation of relativistic electron beam between real and virtual cathodes courses high power microwave radiation. It is important, that one has succeeded in production of electron beams exceeding the space charge limiting current without any bulky system for external magnetic field.

At the same time the physical features of microwave generation in triode demand a great deal of the electrofeeding system which must provide high-voltage impulses ($\geqslant$ 300 kV) with the rise time $\leqslant$ 100 ns and the current $\geqslant$ 10 kA [15]. Usually to realize such parameters Marx generators with forming line are used. Electrical exploding opening switches proved to be more effective for the generation of the high power electron beam and X-ray radiation in schemes with an inductive storage. Exploding wires are amplifiers of the electrical impulse power, they may increase voltage in the electrical circuit up to ten times. But for the good exploding wires performance the electrofeeding system should provide energy required for the electrical explosion at the time less then ⩽10 μs.

For this purpose two types of compact (mass of high explosive 200-600 g) high voltage helical magnetic flux compressor with flux trapping were worked up: the cylindrical generators with simultaneous axial initiation of charge and small-sized conical generators with moving contact point. The distinctive feature of these magnetic flux compressor is an ability to produce high voltage (50- 200 kV) pulses directly in generator as a result of rapid (~5-15 μs) change of its high initial inductance. An initial magnetic flux is created by initial energy storage on an outside coil. When the internal coil is crowbared and starts to change its effective inductance as a result of armature movement, a regime with flux trapping is realized.

So an original transformerless electrical scheme of the high power electron beam and microwave generation was worked up on the basis of these high voltage magnetic flux compressor (Fig.5). Some small capacitor C0=100 μF charged to 3 kV were used for current loading of the "booster" cylindrical generator with flux trapping L11 (high explosive mass 200-700 g) and thus intensifying the electric energy of its load - the external coil of high voltage magnetic flux compressor L1 - up to 5-10 kJ. Simple helical generators with the energy in the load up to 60 kJ were used in the experiments with the magnetic flux compressor with axial initiation. The second circuit of high voltage magnetic flux compressor was crowbarred at the moment of reaching the maximal current in L1. At the expansion of liner of high voltage generator the magnetic flux is "trapped" by internal solenoid L2 and thus brings about the appearance of current in the circuit of exploding wires. High voltage magnetic flux compressor work during 6-8 μs, giving the voltage up to 50-200 kV and the current up to 30 kA. The switch consists of some tens of paralleled copper wires with a diameter of 40-50 μm and a length of 0.5-1.0 m, placed in nitrogen under 0.5 MPa pressure. Geometrical sizes of the wires were chosen in such a way that maximal velocity of growing of their electric resistance (the very stadium of electrical explosion) was attained at the end of action of magnetic flux compressor. As the construction of high voltage generator withstood the voltage only up to 200 kV, inductive storage Ln was inserted between magnetic flux compressor and exploding wires. The overvoltage occurring at the current cut off results in a spark in gap, and high voltage impulse supplies anode of vircator producing the exploding emission from cathode, formation of electron beam and generation of microwave radiation. Thus, voltage pulses of the intensity up to 600 kV with a duration of 180-500 ns and rise-time of ~ 60 ns were supplied onto the inlet of vircator. The current amplitude in triode attains 16 kA, that corresponds to a power of relativistic electron beam of ~10 GW. The peak power of microwave radiation brought into the atmosphere has come 100-120 MW at λ = 10 ∓ 0.5 cm with the signal duration 100-200 ns. So the whole system may have length of 1.5 m and diameter of 0.4 m.

This scheme looks like a more advanced and more suitable for the transformation of energy of high explosive into the energy of electromagnetic wave in microwave range. But the problems of efficiency of energy transformation on every step and optimization of the whole system should be solved experimentally and theoretically. In the next paragraph we will consider MFC with flux trapping as one class of explosive generators for feeding pulsed power microwave generators.

II. MAGNETIC FLUX COMPRESSORS WITH FLUX TRAPPING

II.1. Estimations of necessary MFC parameters.

From the electrotechnical point of view the most types of relativistic generators such as vircator could be considered [33] as vacuum diodes, which volt-amperes characteristic is described by Child-Langmure low with anode-cathode distance decreased versus time. There is no any reliable simple model, which associate electrical parameters of vircator and generated microwave power. So we will use the experimental results: to get microwave powers ⩾100 MW it is necessary to have on a diode voltage ⩾500 kV with the rise time $\tau f \leqslant 50$ ns and duration 0.2-1.0 mcs [4].

To focus and to transport electron beam magnetic field of several Tl is necessary in the most types of microwave generators with total energy of several MJ depending upon the working volume. We will not consider the MFC for the magnetic field creation separatly, this task should be solve in every concrete case by using traditional constructions of MFC. For the microwave generators without internal magnetic field such as vircator it is not necessary.

In accordance with the electrotechnical model, MFC performance is described by the consistent RL-circuit with the inductance L decreasing and with the resistance R formally including all the magnetic flux loses [2]. Energy in the circuit increases only in the case $DL=|dL/dt|>2R$. The well known constructions of the fastest MFC works during the time not less than $\tau \geqslant 10$ mcs and the typical values of DL not exceeds ⩽1 om. Moreover, it is difficult to realize voltages higher than 50 kV on explosive generators because of breakdowns. It is seen, that MFC cannot be switched directly on the vircator, it is necessary to use some intermediate elements. They may be a pulsed step-up transformer and a closing switch. As estimations show, to realize desirable values of voltage and time rise on the diode, it is necessary to use a MFC at a megajoule range of energies. But, with the opening switch used in the secondary circuit, the MFC energy about 100 kJ is needed. In this case transformerless scheme with the magnetic flux trapping suggested in [12] seems to be more attractive, resulted in kilojoule level of energies.

As a first step let us consider a circuit on Fig.6 with the opening switch $R=Ro\cdot\exp(Bt)$, inductive store **L** and diode Rd. At the initial moment Id is zero. If Rd=const, the maximum voltage Um on the diode is reached at the moment $tm=\ln(BL/Ro)/B$. The value of Um depends upon the initial energy E in the circuit and the value of L. For fixed E optimal values of L are available, $Lopt\simeq2.5\cdot Rd/B$. From these relations one can find, that to get $tf\leqslant50$ ns, increment of resistance rise B should be greater then 10E+7 1/s, and Lopt should be $\simeq$ 3÷5 mcH. The more correct Child-Langmure low used, these values change slightly. On Fig.7 the results of calculations of the maximum voltages in the diode vs L are presented for various values of the initial energy 1 - E=450 J, 2 - E=1 kJ, 3 - E=4.5 kJ. It is seen, that to obtain U=500 kV it is necessary to have E=1 kJ in the inductive store.

To obtain $B \geqslant 1.E+7$ 1/s it is possible to use exploding wires. Increment B depends upon wire diameter and velocity of energy input. If the current rises linearly, $B\tau=120$ [13], where τ - time of energy input. So, this time should be less than 10 mcs. Estimations show, that to get desired parameters wire diameter should be $d \simeq 50$ mcm, the number of wires $N \simeq 50$ and their length to prevent breakdowns $l \simeq 600 \div 800$ mm. The energy required for wire explosion Ew is about $2 \div 3$ kJ.

On the bases of previous discussion we have suggested [12,13] the principal scheme of feeding relativistic microwave generators by the MFC. MFC works on the inductive store $L \simeq 1$-5 mcH and the exploding wires opening switch during the time $\tau \leqslant 10$ mcs. Stadium of the electrical explosion is attained at the end of the MFC action, when its inductance turns to zero. With the cut off of the current occurring, the overvoltage results in a shorting of the closing switch, high voltage impulse supplied to the microwave generators produces the exploding emission from the cathode, and then an electron beam and a microwave radiation occured.

So, to ensure the required electrical parameters of the feeding system for the microwave generation ($U \geqslant 500$ kV, $\tau f \leqslant 50$ ns), MFC has to produce about 3-4 kJ in time less than 10 mcs to supply the energy for wire explosion (2-3 kJ) and to feed the energy in the inductive store ($L=1 \div 5$ mcH, 1 kJ). As a first step let us consider the MFC performance in the circuit with the inductive store only. In the present paper we will consider MFC with flux trapping as one class of explosive generators possible to produce electrical pulses with the parameters mentioned above.

II.2. Requirements and design of MFC with flux trapping.

The "flux trapping" method was considered for the first time in papers [27,28] to worked out many-cascaded devices. In the present paper three designs are considered: a cylindrical helical generator with simultaneous axial initiation, a cylindrical helical generator and a conical one with sliding contact point. The main features of two cascade generator are described.

MFC with flux trapping consists (Fig.8) of outer solenoid L1, inner solenoid L2 and copper cylindrical armature L3 with HE charge placed in it. The initial magnetic flux in solenoid L2 is produced by discharging a current from the capacitor bank Co or from a "booster" generator Lp. At the moment of the first current maximum (I10) HE charge is initiated. Detonation products expand an armature, which shorted the secondary circuit, magnetic flux trapped is pressed and pushed out into the load. In case of axial simultaneous initiation armature expands as a cylinder axised with MFC helixes. In case of one point initiation armature takes a form of cone, with turns of inner helix L2 switched off successively. Current rise time in the load is determined by the dynamics of armature expansion. The current in the load at the end of MFC operation is defined by the expression [40,41]:

$$I_2 = I_{2k} \circ \varphi$$

Here φ - magnetic flux loses in the secondary circuit, I2k - the final current value in the loss-less circuit

$$I_{2k} = (k_{120} - k_{130}k_{230}) \frac{\sqrt{L_1 L_{20}}}{L_H} I_{10}$$

kij- coupling coefficient of i-th and j-th solenoids. Index 0 is referred to the values of parameters at the moment of flux trapping. Magnetic flux and energy in the secondary circuit are amplified in λ and ψ times correspondently:

$$\lambda = \frac{\Phi_{2k}}{\Phi_{10}} = \frac{(k_{120} - k_{130}k_{230})}{(1 - k_{130}^2)} \sqrt{L_{20} / L_1} \circ \varphi$$

$$\psi = \frac{E_{2k}}{E_{10}} = \frac{(k_{120} - k_{130}k_{230})^2}{(1 - k_{130}^2)} * \frac{L_{20}}{L_H} \circ \varphi^2$$

The large values of inner helix inductance are necessary for MFC effective work in our case. If the time of operation is less than 10 mcs, the great time derivatives of increased magnetic field in MFC volume occur, high electric field appears, resulting in breakdowns and great flux loss. Output voltages for desired parameters (E2k = 4 kJ for time $\tau \leqslant 10$ mcs) in the inductive load of 5mcH will reach the values not less then:

$$U = L_H \cdot \frac{dI_2}{dt} \simeq \sqrt{\frac{2E_{2k}L_H}{\tau}} \simeq 20 \text{ (kV)}$$

Thus, for MFC effective work it is necessary to ensure good turn-to-turn insulation, insulation between armature and inner helix, and interhelix insulation. However, the greater reliable insulation in small-sized MFC, the smaller desirable inductance values. In MFC with simultaneous axial initiation the moving contact point was lacked, so the inner working helix was covered inside with thick layer of insulation. In the generators with sliding contact point the thickness of wire insulation Δ can not be very large because of low MFC effectiveness in this case [27]. For typical values of Ebr=100 kV/mm to prevent breakdowns the thickness of insulation should be greater than $\Delta \geqslant 0.2$ mm.

Another restriction in making a small-sized high inductive MFC is associated with ohmic heating of the helix wires. The smallest possible diameter of the helix wire of the MFC on desired parameters can be estimated from integral of action $J = \int j^2 dt \simeq 2*10E+17\ A^2c/m^4$ for linear increasing of current:

$$d \simeq \sqrt{\frac{\mu_0 \sigma E_H}{L_H J}} \simeq 0,5 \text{ (MM)}$$

These simplest estimations show, that in our case the pitch of the inner helix should be greater than $h \geqslant d+\Delta \simeq 0.9$ mm.

To prevent turn-skipping several mechanical tolerances should be achieved while MFC fabrication. The most important of them are as follows [42,43]. Armature and the stator must be aligned concentrically, so that the accentricity tolerance is $\delta e \leqslant 0.1$ mm. The most difficult tolerance to achieve is an armature wall uniformly thick, so that thickness variations translates into radial difference in the arrival time of the expanding armature wall at the stator must be less than $\delta a \leqslant 0.01$ mm.

To realize required parameters of electrical impulse and to understand mechanical possibilities of MFC fabrication three constructions of explosive helical generators with flux trapping were carried out: MFC with axial simultaneous initiation, cylindrical and conical generators with sliding contact point.

The axial MFC is consist of three axis details: armature, inner solenoid and outer solenoid, with length being 200 mm. HE charge - powdery hexogen with m=600g - was initiated by a copper exploding wire placed in the axis of symmetry. In the cylindrical MFC with moving contact point HE charge (m=200÷400 g) was initiated from butt-end by electric detonator. Solenoids were winded up by copper ties or wires on PTFE tube with rectangular helical grooves, and then were glued by epoxy resin. Insulation between inner and outer solenoids was made by a few turns of wide kapton film. Special insulating ribs were placed and glued over generator to prevent surface breakdowns. Armatures were made from copper tubes with outer diameter of 50-70 mm and with thickness of 2.5 mm. The tubes were stretched out on mandrel and then were externally grind. Conical MFCs are faster then the cylindrical one. The voltages occurred in the conical MFC being greater, fluoroplastic insulated wires were used to wind helixes. The axial length of conical solenoids was 80÷100 mm, the major diameter of the stator cone was 104 mm while the minor diameter was varied within 80÷100 mm. HE mass was 200 ÷ 300 g. Before the experiments insulation strength of every MFC was tested by 50 kV dc voltage.

II.3. Mathematical simulation of the processes in the electrical circuit

To optimize the electrical parameters of the experimental installation system of differential equations for the circuit in Fig.5 has been solved numerically. MFC, exploding wires, spark gap and vircator are nonlinear elements of this circuit. Last cascade of MFC is presented by the inductance L1 of the outer solenoid and L2 of the inner solenoid. Inductance L2 is a time dependent function and it's value depends upon the position of an armature/stator moving contact point. For the estimations of the values of L2 in the case of helix (cylindrical or conical) with constant pitch we use well known relationship [3]:

$$L = \frac{\mu_o N^2 \pi r_m^2}{l} \cdot K(r_m/l)$$

where $r_m^2 = (r_i^2 + r_i r_j + r_j^2)/3$, $K(r/l)$ - correction coefficient [3], r_i, r_j - the biggest and the smallest radius of the cone. In this approximation we replace the conical helix by the cylindrical one with the effective radii r_m. In MFC with simultaneous axial initiation L2 is suggested to be constant. Armature is regarded as single-turned solenoid L3 with increasing radius in the case of its axial-symmetric expansion. In the case of one point initiation of HE, liner takes a form close to the conic one. It has been suggested, that the liner occupies the place of inner helix after the reaching of it. Then the armature may be divided into three parts with corresponding inductances: motionless liner L3, expanding cone L4 and solenoid L5, occupying the inner helix place. All MFC inductances are connected with corresponding coupling coefficients k_{ij}, which change their values while generator work in accordance with solenoids geometry. In accordance with [44] for long helix:

$$k_{ij} = \frac{r_j}{r_i} \frac{(\sqrt{1+y_i^2} - y_i + y_j^2/8y_i)}{[(1-\frac{7y_i}{8}+\frac{y_i^2}{2})(1-\frac{7y_j}{8}+\frac{y_j^2}{2})]^{1/2}} \cdot \sqrt{l_j/l_i}$$

where $y_K = r_K/l_K$, $l_j \leqslant l_i$, $r_j \leqslant r_i$; $K = i, j$.

In the experiments considered time of feeding and MFC's running is small enough, generated currents are small too, so that magnetic field doesn't penetrate into the liner. In this case magnetic fluxes in primary and secondary MFC circuits are coupled with the currents in outer and inner MFC solenoids by the equations:

$$\Phi 1 = [L1 \cdot (1 - \sum_{j=3} k_{1j}^2) + L21k] \cdot I1 + k_s \sqrt{L1 \cdot L2} \cdot I2$$

$$\Phi 2 = [\ L2 \cdot (1 - \sum_{j=3} k_{2j}^2) + Ln] \cdot I2 + k_s \sqrt{L1 \cdot L2} \cdot I1$$

Here $k_s = (k_{12} - \sum_{j=3} k_{1j} k_{2j}) \cdot (1 - \sum_{j=3} k_{1j0}^2 + L21k/Ln)/(1 - \sum_{j=3} k_{1j}^2 + L21k/Ln)$, L21k - residual inductance of the primary circuit, index 0 refers to the initial values of parameters. In accordance with paper [40] magnetic flux loses in MFC with moving contact point are described by introduction of effective resistance $Rf = -\alpha \cdot dL2/dt$.

From the electrical point of view vircator is considered as vacuum diod, which volt-amperes characteristic is described by Child-Langmure low with anode-cathode distance dk decreasing versus time and with the transparency T of latticed anode [33]:

$$I4=\frac{A_oS_kU_d^{3/2}}{(d_k-Vt)^2}\cdot\frac{1-T^2}{1+T^2}$$

where S_k-cathode area, V-plasma front velocity, A_o-constant.

Sharpening spark gap is described as a voltage source with exponential drop: $Ua= Uao\cdot \exp(-t/tk)$, where Uao - breakdown voltage of gap, tk - commutation interval.

To describe the exploding wires behavior semiempirical model is used [13]. In this model three stages of electrical explosion are considered: the stage of heating, the very stadium of the electrical explosion and the stage of breakdown. The electrical resistivity of wires r is represented as a product of two factors: $r=\rho\cdot\eta$, where $\rho=\rho(W)$ is the function of specific energy brought in, $\eta=\eta(W,t)$ - the part of resistance associated with the inertia of the explosion products. The function $\rho(W)$ has piece-leaner form: $\rho=\rho i+Bi\cdot(W-Wi)$, i=1,2,3,4. Here ρi,Wi - the values of quantities in the break points. Bi - angle coefficients. The first point corresponds to the room temperature, the second and the third points - to the beginning and the end of melting, the fourth point - to the bind energy. The dependence of the second factor is described by the equations

$$\eta=I \qquad \text{by } W \leqslant W_5$$

$$\frac{d\eta}{dt} = 2\eta v(W)/d \qquad \text{by } W \geqslant W_5$$

where d – initial wire diameter, W5 - energy, corresponding to the beginning of the explosion stage, v(W) - function with the velocity dimension ("expansion velocity"), which is defined from the experiments on electrical explosion of wires in LC-circuit. Present model is the analog of the "evaporation wave" model of F.Bennett. exploding wires voltage was compared with breakdown voltage of explosion products on every step of integration. If the first one exceeds the second one electrical resistivity sharply decreases up to the values typical to the ionized explosion products.

Equations of the equivalent electrical circuit with the exploding wires equations have the form:

$$\frac{d\phi_1}{dt} = -I_1R_1 \ ; \quad \frac{d\phi_2}{dt} = -U_c + R_fI_2; \quad -L_e\frac{dI_3}{dt} = -U_c + R_eI_3$$

$$-L_d\frac{dI_4}{dt} = -U_c + U_a + U_d \ ; \quad C_{ob}\frac{dU_c}{dt} = I_2 - I_3 - I_4$$

$$\frac{dw}{dt} = rI_3^2/S^2 \ ; \quad \frac{d\eta}{dt} = \frac{2\eta v}{d} \ ; \quad R_e = rl/S \ ; \quad S = N\pi d^2/4$$

The initial conditions for the moment of S3 switch closing are: $I_1=I_{10}$, $I_2=I_3=I_4=0$, $U_c=0$, $\phi_{10}=[L_1(1-\sum_{j=3} k_{1j0}^2)+L_{21k}]\cdot I_{10}$,

$\Phi_{20}= k_{so}\sqrt{L_1L_{20}}\cdot I_{10}$. At the moment of gap breakdown, when

U=Uao, the current I4 is supposed to be zero and continuity conditions of the contour fluxes are made.

To verify the theoretical model as a first step the calculations of MFC performance on the inductive load only were carried out, the necessary semiempirical parameters of MFC was obtained on comparison with the experimental data. After that it was used for planning experiments with the microwave generator of vircator type.

II.4. Experimental results with single-pitch helix generators

Separate series of experimental tests have been carried out with axial, cylindrical, conical and two cascade generators with one-pitch helix [13,40,41]. Results of some typical experiments with three types of MFCs considered are shown in the Table 1. In the course of these experiments the current up to 90kA was realized in high inductive loads L= 1-15 mcH for a time $\tau \leqslant 15$ mcs, with energy impulses being up to 12 kJ. The maximum flux amplifying coefficient has come to λ=6.1, with corresponding energy amplifying coefficient being Ψ=20. The values of flux losses have been calculated with using load currents values in loss-less circuit. For these MFCs typical oscillograph traces are shown in Fig. 9. The shortest run time ≃5÷7 mcs have been realized with conical MFCs. In the whole, the conical MFCs are characterized by energy amplification coefficients up to ψ=2.3, that closed to maximum value of these generators. Flux losses exceed 50% value, that due to thick insulation layer available to

Table 1.

№	L_1 mcH	L_{20} mcH	L_H mcH	E_{10} KJ	I_{2k} KA	E_{2k} KJ	λ	ψ	φ
axial									
a.I	I60,7	35,8	I5,I	I2,6	I6,4	3,I	0,23	0,24	0,34
a.2	204,6	27,5	7,2	I2,5	24,7	4,2	0,I9	0,33	0,35
a.3	I,5	I3,0	7,9	52,2	I9,9	2,I	0,66	0,04	0,I8
cylindrical									
б.I	II,2	I58,6	48,8	9,5	22,2	I2,0	2,63	I,26	0,88
б.2	I,6	I54,0	44,5	0,63	5,5	0,7	6,I0	I,08	0,90
б.3	I5,5	567,2	I,2	0,25	9I,3	5,0	I,37	20,00	0,32
conical									
c.I	3I,9	222,6	4,8	0,9	I7,9	0,8	0,85	0,84	0,I5
c.2	82,5	64,7	4,8	2,5	29,2	2,0	0,52	0,8I	0,34
c.3	I7,5	68,0	4,8	I,I	30,9	2,6	I,33	2,32	0,54
c.4	3I,9	68,0	4,8	2,5	35,0	2,9	I,38	I,I7	0,45

prevent breakdowns. Current and voltage impulses produced by axial MFC are distinguished by sharp steepness at the finish of MFC run. Thus, to produce high output voltage one should use the residual inductance of axial MFC as inductive load. In experiments with exploding wires this devise has stood the voltage impulses up to 200 kV. However, because of small values of inductance reduction ($\simeq$5) the energy transmission coefficient turns out to be small: $\psi \leqslant 33\%$. The cylindrical generators have shown the high flux amplifying λ=6.1 and energy amplifying ψ=20. The cylindrical devices worked out could keep up to 90% flux trapped. However, its run time have been twice as great.

The considered MFCs have small energy amplification. It is necessary to use special booster generators as a feeding system. To supply generator with simultaneous axial initiation we have used [12] helical MFC with the output energy 60 kJ. Magnetic generator with flux trapping works as a high voltage pulse forming system only. To supply fast conical generator we have used [39,40] cylindrical generator with flux trapping and the output energy 5 kJ. On the Fig. 10,11 scheme of two cascade cylindrical generator with the HE mass 550 g and its equivalent electrical circuit are presented. Capacitor C0=100 mcF charged to 3 kV were used as a source of initial magnetic field with the energy 370 J. Booster cylindrical generator with flux trapping intensifies the electric energy on its load ($\simeq$0.5 mcH) - the external coil of fast MFC - up to 4.1 kJ. The last cascade works during 10 mcs giving energy 4.7 kJ on the inductive store $\simeq$5.1 mcH. The recorded currents in the primary and secondary circuits are presented on the Fig. 12. The total amplification of the energy of this generator is $\psi \simeq 13$ and magnetic flux loses $\varphi \simeq 0.13$.

The experimental data were used for developing of theoretical models of MFC with flux trapping performance [40]. Together with semiempirical models of wire explosion and vircator operation, they were used for planning experiments with the microwave generator of vircator type.

To generate electron beam and microwave radiation impulses with the aid of HE energy several sets of experiments have been prepared and carried out. In each experiment current and its derivative in the inductive load, in outer solenoid of high voltage MFC and in the feeding circuit of "booster" generator have been recorded by two Rogovski loops of different sensitivities. The vircator and exploding wires currents and voltages have been measured by inductiveless shunts and resistive dividers. To registrate the electromagnetic radiation impulses horn antenna with lamp SHF-diode detector have been used. The antenna was placed at the 1.5 m distance from the vircator. Radiation power have been estimated from the directional diagram of the radiation with fixed wave length.

The most typical experimental results are shown in the Table, where the subscript "0." corresponds to the experiments with the axial initiated MFC, and "C." - corresponds to the conical MFC. In the course of experiments the values of MFC and load inductances and initial supply currents are varied. Eo is the magnetic field energy at the moment of secondary circuit switching. The output currents have come to 30 kA with the inductive load energy being not more than 2 kJ. The exploding wires parameters are varied too, we investigate the regimes more profitable for getting high voltages on the vircator. The energy required for the wires explosion has come to 2÷3 kJ, thus the total MFC output energy has not exceeded the 2-3 kJ value.

Table 2.

NN	E0 (kJ)	I2Max (kA)	EEOS (1-N)	Ud kV	I4 (kA)
		Ln=8.9 mcH			
0.I	28.8	I6.2	540-28	205	3.8
0.2	32.0	I8.0	470-32	325	7.4
0.3	28.0	I6.4	470-32	270	4.3
0.4	27.3	I5.2	540-32	255	5.4
0.5	27.0	I6.6	470-27	320	6.7
		Ln=7.9 mcH			
0.6	53.I	I9.9	620-42	450	II.6
0.7	63.0	2I.I	870-54	I70	4.2
0.8	60.2	23.6	780-50	250	5.8
C.5	3.0	24.0	680-50	450	10.9
		Ln=4.8 mcH			
0.9	22.0	23.0	720-44	270	7.5
C.I	2.5	25.7	475-42	420	8.0
C.2	2.6	26.6	475-46	430	8.5
C.3	3.0	21.7	720-37	390	9.5
C.4	3.4	30.0	680-50	600	15.5

Thus, voltage pulses of the intensity up to 600 kV with a duration of 180-500 ns and rise-time of ~ 60 ns were supplied onto the inlet of vircator. The current amplitude in triode attains 16 kA, that corresponds to a power of relativistic electron beam of ~10 GW. The peak power of microwave radiation brought into the atmosphere has come 100-120 MW at $\lambda = 10 \mp 0.5$ cm with the signal duration 100-200 ns.

Typical oscillograph records of the voltage and current pulses, obtained in C.3 and C.4 tests (indexes 1 and 2 correspondently), are presented in Fig.13. Also the shapes of SHF-impulse power are shown on Fig.13f - curves N1 and N2. In these experiments the output MFC parameters on the inductive load were similar, but the exploding wires geometrical parameters were different. There wasn't breakdown in the C.3 test, and in the C.4 test the breakdown occurs and you may see incomplete current disconnection. As a result the voltage drop value in C.4 test is one and a half times greater than in C.3 test, although the signal duration being in one and a half times smaller. In both cases one can see some divergence of the moments of approaching the maximal voltage, current and radiation power. Microwave generation begins and proceeds on the voltage and current fall off, that results in nonstability of beam excitation process. This fact testifies that in performed experiments the scheme elements in Fig.10 are matched not enough.

The calculated curves are shown on Fig.13 by dashed lines. On the whole there is a good agreement with the experimental data. Thus this model turns to be very useful for planning of the experiments and forecasting of their results.

In the described experiments to understand the physics of the process of flux trapping in regimes of energy and flux amplification we have studied the simplest single-turn constructions. But several principal questions to be answered appear after these experiments: which are the inductance output law necessary to make a small-sized MFC, the maximal possible physical parameters of these systems and the restrictions in their realization, the optimization of all units and efficiency of the whole system. In the present work we suggest to decide these problems on the example of two cascade MFC with flux trapping which amplifies the initial energy of the magnetic field from several hundreds Joules up to several kilo Joules and supplies high impedance inductive load of several micro Henry in time of 10 mcs. The main idea of this generator is the separation of operation functions of the cascades. The first cascade is an amplifier of the energy of electrical impulse with the aid of high explosive, the second one is responsible for the necessary waveform of electrical impulse in the load.

The starting point of the analyses will be considered as a compactness of the MFC. So one should obtain the required parameters in the system which has as small sizes and HE mass as possible. This system will have the highest efficiency of transformation of HE energy into the energy of desired electrical impulse.

Small sizes of the generator are mainly defined by the physical reasons - possibilities to overstand high voltages and currents - and technological aspects - possibilities of MFC fabrication with the necessary precision.

The MFC efficiency is high when its initial inductance is much greater than the inductance of the load. The requirements of the short run time of MFC will lead to the necessity of work on a high level of voltage. To avoid breakdowns it is needed a good insulation between windings and the liner. But this results in increasing of magnetic flux losses. So good MFC performance is defined by the compromise of these effects.

To increase the initial inductance of the generator one should use the wires with small diameter. But the currents in MFC heat the conductors and the smallest diameter is limited. Dissipation of magnetic flux on the ohmic resistance should be small.

On the basis of the previous discussion and developed models it is possible to make a calculations of the "ideal" construction of the two cascade MFC on the desired parameters. But for this calculations we should explicitly understand the possibilities of our technology of MFC manufacturing and real magnetic flux loses. For example let us consider the calculations of the optimal law of the inductance output for the second cascade of the MFC.

We will start our consideration from the point that the best MFC performance will be achieved when the voltage ε between the end of the helix and the armature is constant. This suggestion is good for short solenoids, when it's length is smaller than that of the expanding armature cone. In this case equations for the second circuit of MFC may be written as:

$$L_{2e}I_2 + k_s\sqrt{L_1L_2}\, I_{10} = -\varepsilon t + \Phi_{20}$$

$$L_H\frac{dI_2}{dt} + I_2R_2 = \varepsilon$$

The second equation defines the law of current increasing if you know the law of changing of resistance R2=R2(t). Then from the first equation we can find the required law of L2(t)/L20. To find out the initial inductance it is necessary to know the time of MFC operation τ and the initial energy in the first circuit $E10=L1*(1-k_{130}^{2})I_{10}^{2}/2$. Maximal magnetic flux - $\phi20m$ - is defined from the relation - $\phi20m=\varepsilon\cdot\tau$, then

$$L_{20}= (\varepsilon\tau/k_{so})^2/2E_{10}\ .$$

On the Figure 14 there are curve of output inductance for the experiment C.2 and calculated optimal curve with the resistance $R2(t)=R20*\exp(\beta t)$, which approximates the heating stage of the exploding wires. It is seen that the initial inductance may be significantly higher.

In this situation the first question to be solved experimentally is: what is the lowest pitch of the MFC helix can be achieved by our technology, and what magnetic flux loses will be in this case. When you know this you may calculate the maximal initial inductance and the optimal law of it output and consequently the maximal energy emplification. This calculations should be done for both cascades separately.

As a first step in this direction we have done three experiments on the low level of initial energies with the simplest single-turn constructions with the pitches of 1.0, 1.5, 2.0 mm and length of 150 mm. The results are presented in the table 3.

h mm	L_1 mcH	L_{20} mcH	L_H mcH	E_{10} J	I_{2k} KA	E_{2k} KJ	ϕ	φ	F
1.0	22.6	1059.1	11.5	58.2	7.0	0.28	4.8	0,29	0.61
1.5	30.2	457.8	5.0	73.1	17.0	0.72	9.8	0,41	0.72
2.0	28.2	260.2	2.3	71.4	24.0	0.65	9.1	0,36	0.71

One of the most important parameter for these experiments is an imperfection factor $F=Le/I*(dI/dL)$. This parameter almost does not depend upon the parameters of the electrical circuit and the MFC length, it defines by the real flux loses and may be a good characteristic of the MFC performance. It is seen that for large pitches values of F are rather high. For h=1 mm imperfection factor falls significantly, that can be explained by the increasing of the flux loses due to the imperfection of the armature expansion.

Experiments with the smaller pitches are on a way now.

II.5. Plan of the future investigations.

1. Continuing of the experiments with small pitches with the aim of defining the real parameters of MFC.
2. Calculation of the "ideal" two cascade generator using real MFC flux loses.
3. Experimental investigations of the optimal first and second cascades separately.
4. Integration of two cascades.

On the basis of these experiments the theoretical model of the two cascade MFC performance will be created. Real laws of inductances and mutual inductances as functions of time will be used in this model. Magnetic flux losses will be taken into account on the basis of the experimental data. This model will allow to forecast the work of MFC on every complex nonlinear load such as exploding wires, microwave generators and so on. When it is necessary to make some principal changes in the scheme, this model will serves as a good basis for its further development.

So as a result of the investigation suggested the optimized two cascade MFC will be worked out. This MFC will supply the energy of several kiloJoules to the inductive store of several micro Henry in time of ten microseconds in the more effective way. The theoretical model of its performance will be created.

R E F E R E N C E S

1. A.D.Sakharov, R.Z.Ludaev, E.N.Smirnov et al. Dokl. Akad. Nauk SSSR, **165**, 65 (1965) (Russian).

2. A.I.Pavlovski, R.Z.Ludaev, The Problems of Experimental and Theoretic Physics, Moscow, Nauka, 1984, p.206(Russian).

3. H.Knoepfel. Pulsed High Magnetic Fields. Amsterdam-London, 1970.

4. F.Bitter. Sci. American **213**(1), 65 (1965).

5. A.I.Pavlovski, N.P.Kolokolchikov et al.In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow.1984, p.19.

6. A.I.Pavlovski, V.V.Druzhinin et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow.1984, p.130.

7. B.L.Freeman, D.J.Ericson, C.M.Fowler et al. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.729.

8. A.I.Pavlovskii , N.F.Popkov, V.I.Kargin et al. In: Megagauss Fields and Pulsed Power Systems. Ed. V.M.Titov, G.A.Shvetsov , Nova Science Publ., N.-Y., 1990, p.449.

9. Fowler C.M., Peterson D.R., Kerrisk J.F., et.al. In: Megagauss fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow.1984, p.282.

10. A.I.Pavlovski, G.D.Kuleschov, R.Z.Ludaev, Atomic Energy. I976, ⊏□, p.I42 (Russian).

11. Jones C.R., Fowler C.M., Ware F.D. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.747.

12. E.I.Azarkevich, A.N.Didenko, P.V.Dolgopolov et al., Dokl. Akad. Nauk SSSR, **319**, 352 (1991).

13. E.I.Azarkevich,A.N.Didenko,A.G.Zherlitsin et al., Generation of Microwave Radiation with the Aid of High Explosive, Preprint, Chernogolovka, 1992 (Russian).

14. A.Y.Brodskiy, V.A.Vdovin, A.V.Korznevskiy et al., Dokl. Akad. Nauk SSSR, **314**, 846 (1990).

15. C.M.Fowler. W.B.Garn, W.B.Caird. J.Appl.Phys., **31**, 588 (1960).

16. E.I.Zharinov, V.A.Demidov, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow.1984, p.282.

17. B.K.Chernishev, N.S.Protasov, V.A.Shvetsov. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.298.

18. A.I.Pavlovski, R.Z.Ludaev, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.292.

19. A.I.Pavlovski, V.A.Basyukov, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.410.

20. D.J.Ericson, R.S.Caird, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.333.

21. V.A.Demidov, E.I.Zharinov, et al. J. of Appl. Mechanics and Techn. Physics, N6, 106 (1981) (Russian).

22. V.A.Demidov, E.I.Zharinov, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.330.

23. R.S.Caird, C.M.Fowler. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.425.

24. C.M.Fowler, R.S.Caird, et al. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.433.

25. B.L.Freeman, C.M.Fowler, et al. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.441.

26. V.K.Chernishev, V.A.Davidov, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.278.

27. A.I.Pavlovski, R.Z.Ludaev, et al. In book: Ultrahigh Magnetic Fields. Physics. Technique. Application. Ed. V.M.Titov, G.A.Shvetsov, Nauka, Moscow. 1984, p.312.

28. E.I.Bichenkov, S.D.Gilev, et al. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.377.

29. A.A.Barmin, O.E.Melnick et al. Mechanics of Fluids and Gases. N6, 166 (1988)(Russian).

30. A.I.Pavlovski, R.Z.Ludaev et al. In book: Ultrahigh Magnetic Fields. Physics. Techniques. Application. Ed. by V.M.Titov, G.A.Shvetsov, Moscow, Nauka, 1984, p.292.

31. D.Fulghum. Aviation Week & Space Technology(May 24,1993).

32. A.B.Prishchepenko, V.V.Kiselev, et al. Int. Symp. on Electromagnetics Envirements and Consequences. Book of abstracts, Bordeaux, 1994, WEP-03-02.

33. A.N.Didenko, A.P.Arsin, A.G.Zherlitsin et al.Relativistic RF Electronics, V.4, Gorky, 1984, pp 104-108 (Russian).

34. S.P.Bugaev, V.N.Kanavets, A.I.Klimov et al. Radiotekhnika Electronika,**32**, 1488 (1987).

35. S.Burkhart, J. Appl. Phys. **62**, 75 (1987).

36. A.Bromborsky, R.A.Kehs, G.A.Hultin et al., IEEE Intern. Conf.in Plasma Science, Abstracts, Arlington, 1987, p.39

37. A.I.Pavlovski, A.S.Kravchenko et al. 6 Int. Conf. on Megagauss Magnetic Fields Generation and Related Topics (Megagauss-V1), Albuquerque, USA, 1992, Book of abstracts, p.123.

38. V.E.Fortov, A.N.Didenko, et al, 6 Int. Conf. on Megagauss Magnetic Fields Generation and Related Topics (Megagauss-V1), Albuquerque, USA, 1992, Book of abstracts, p.126.

39. E.I.Azarkevich, A.N.Didenko, A.G.Zherlitsin et al. High Temperatures, **32**, 127 (1994).

40. V.B.Mintsev, A.E.Ushnurtsev, V.E.Fortov. High Temperatures, **31**, 469 (1993).

41. Yu.V.Karpushin, A.A.Leont'ev, V.B.Mintsev, et al. High Temperatures, **31**, 662 (1993).

42. Chernnyshev V.K., Zharinov E.I.,Kazakov S.A., et al. In: Megagauss Technology and Pulsed Power Applications. Ed. Fowler C.M. Plenum Press. N.-Y., London, 1987, p.455.

43. Pincosy P.A., Abe D.K., Chase I.B. In: Megagauss Fields and Pulsed Power Systems. Ed. V.M.Titov, G.A.Shvetsov, Nova Science Publ., N.-Y., 1990, p.441.

44. Kolontarov P.L., Tseytlin L.A. Calculations of inductances, Energoatomizdat,1986 (Russian).

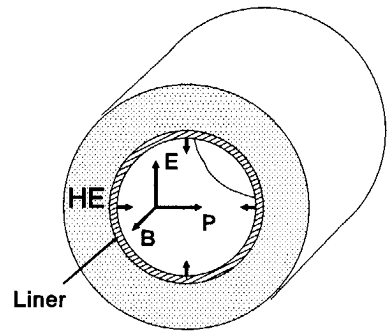

Fig.1a. Cylindrical MFC

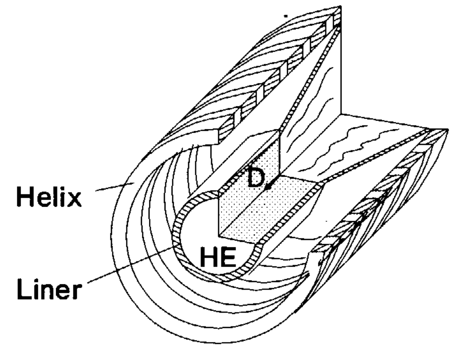

Fig.1b. Helical MFC.

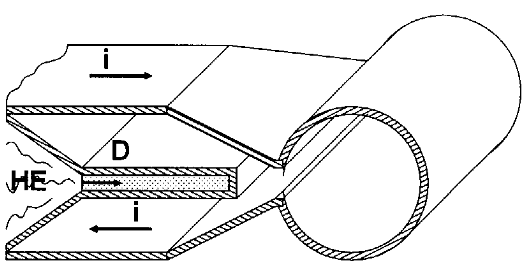

Fig.1c. Strip MFC.

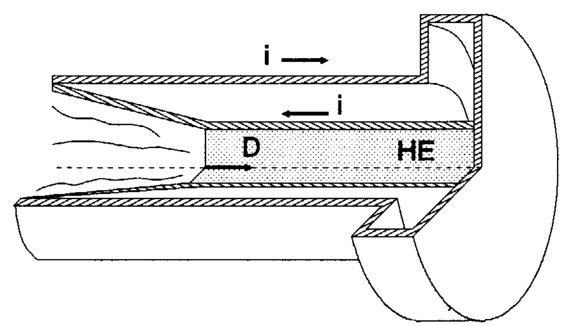

Fig.1d. Coaxial MFC.

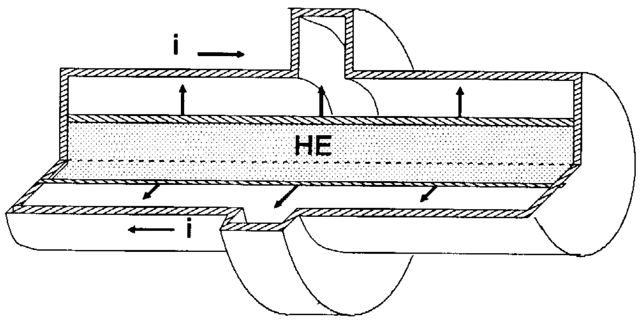

Fig.1e. Coaxial MFC with axial initiation.

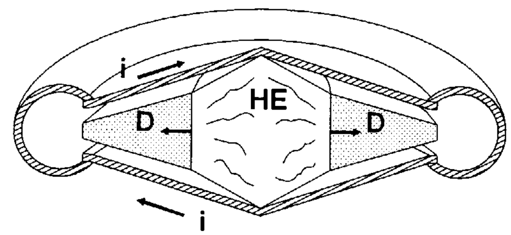

Fig.1f. Disk MFC.

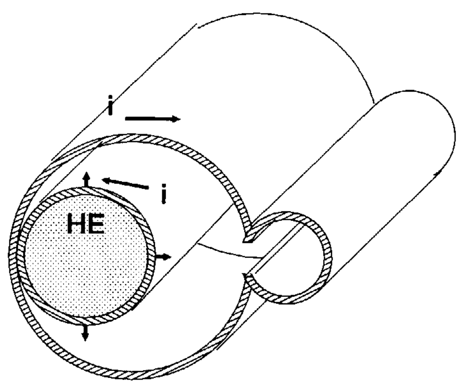

Fig.1g. Wrap MFC.

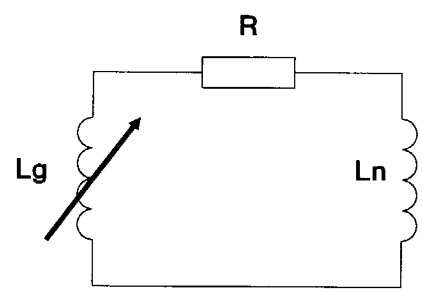

Fig.2. Equivalent electrical curcuit of MFC.

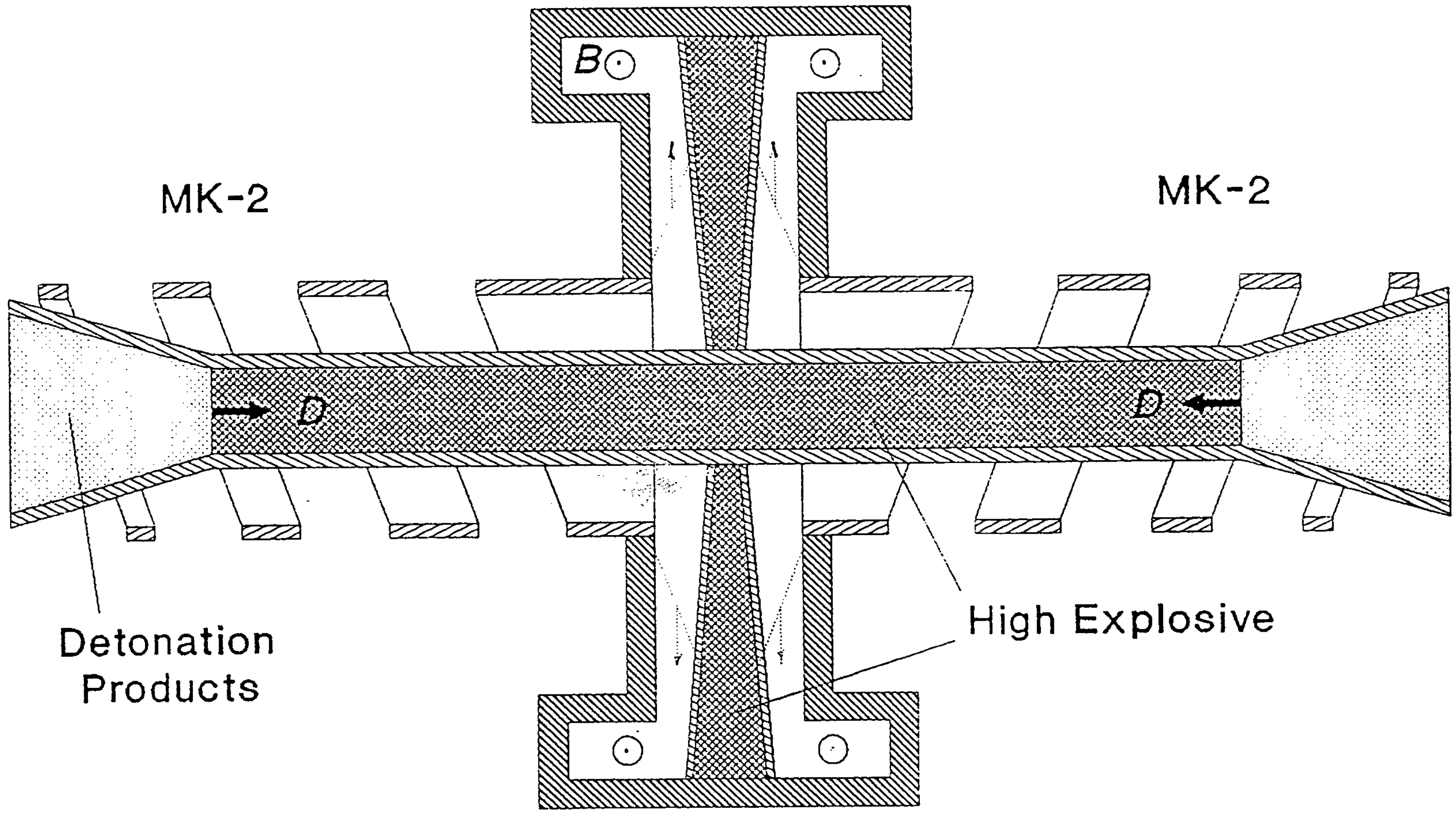

Fig.3. Disk-shape Magnetic Flux Compressor.

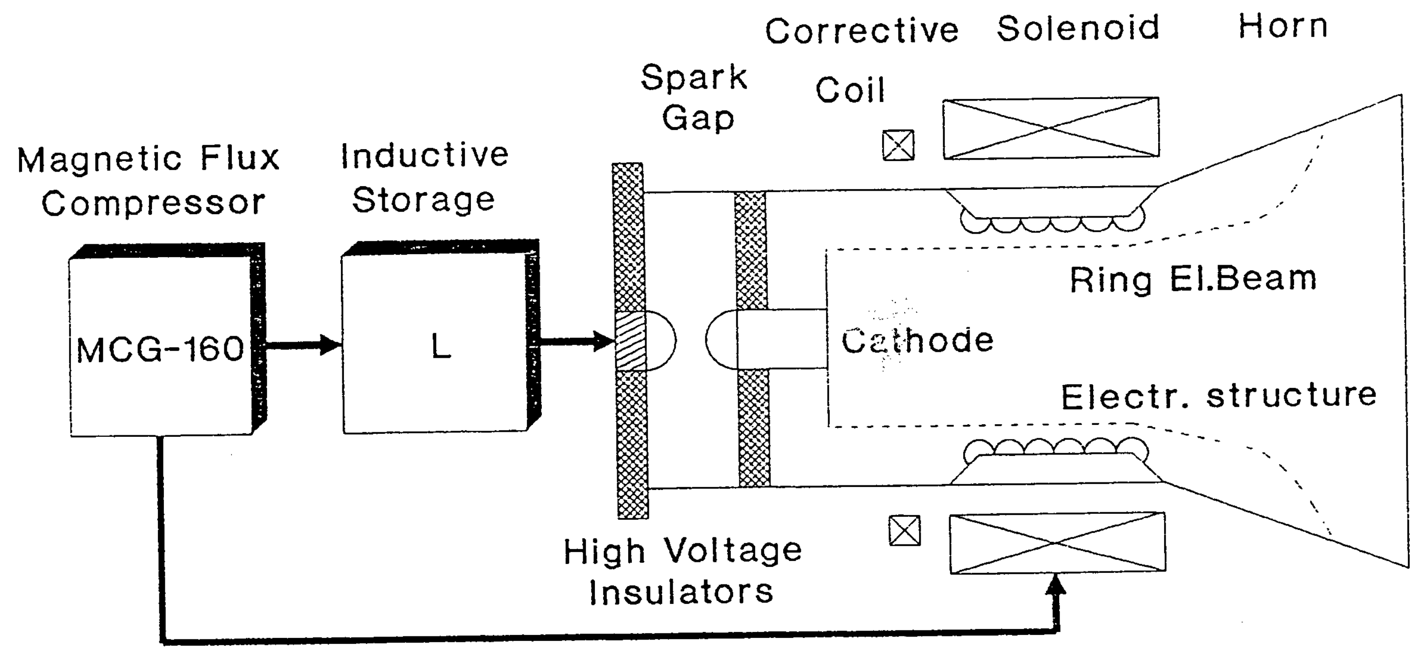

Fig. 4. Block-scheme of experiments with Cerenkov generator.

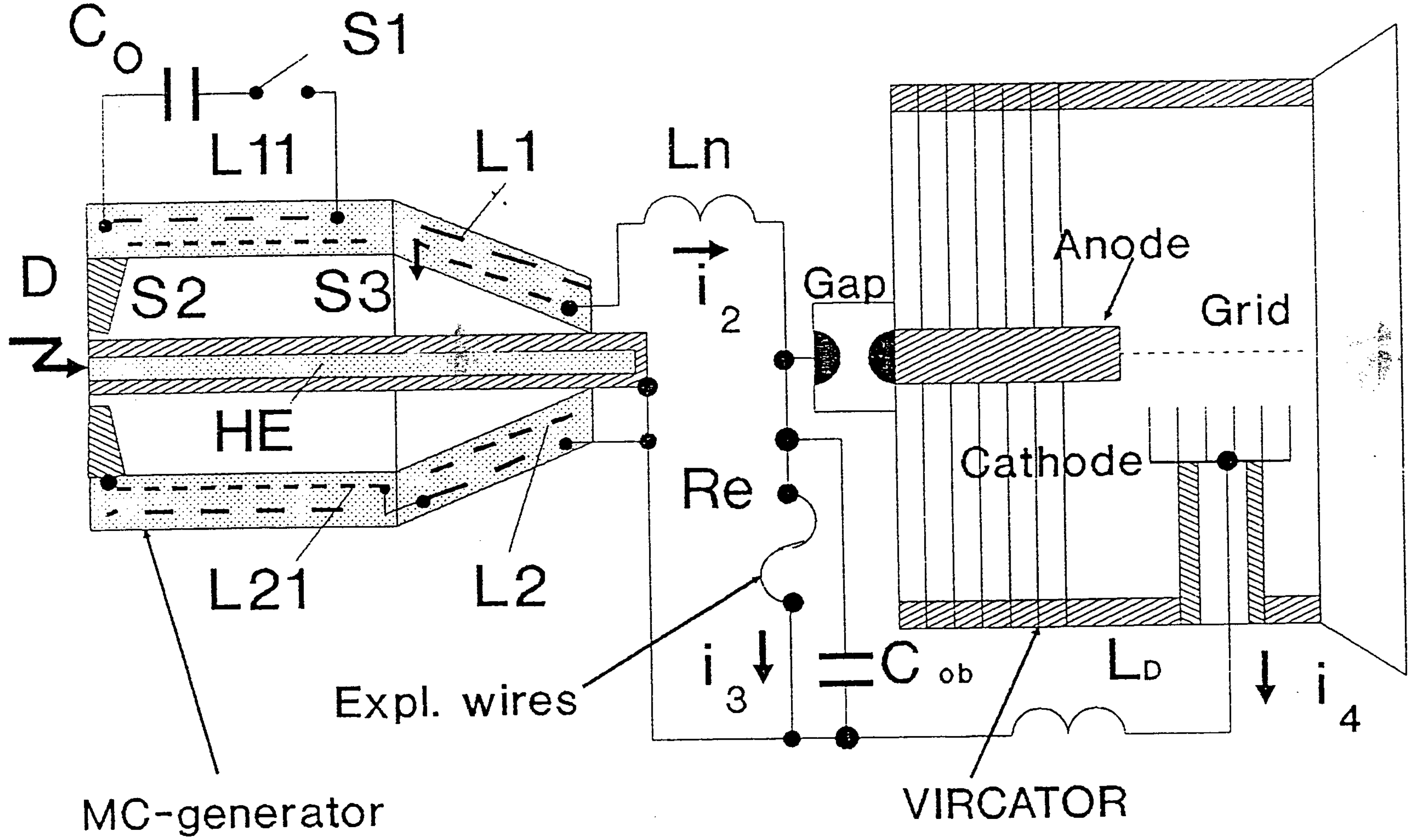

Fig. 5. Scheme of Experiments with Vircator.

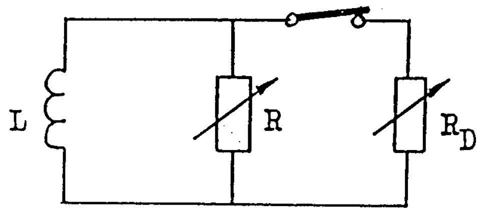

Fig. 6. Scheme of electrical circuit.

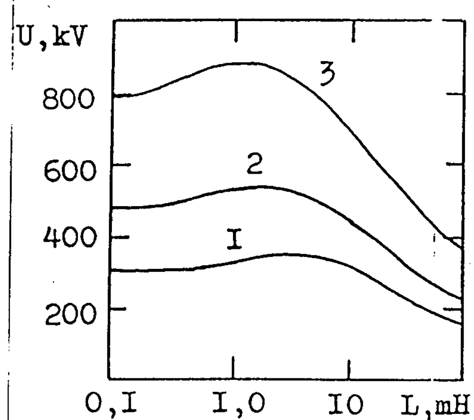

Fig. 7. Maximum voltage vs inductance.

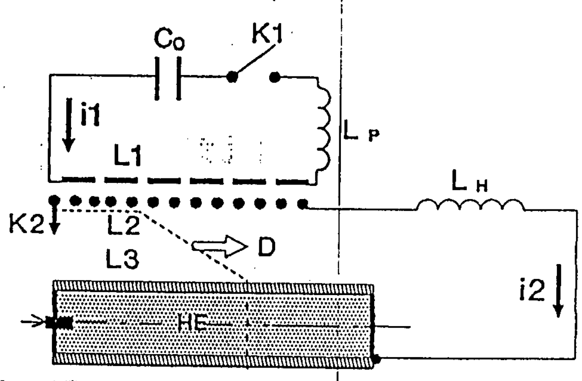

Fig.8. Scheme of MFC with flux trapping.

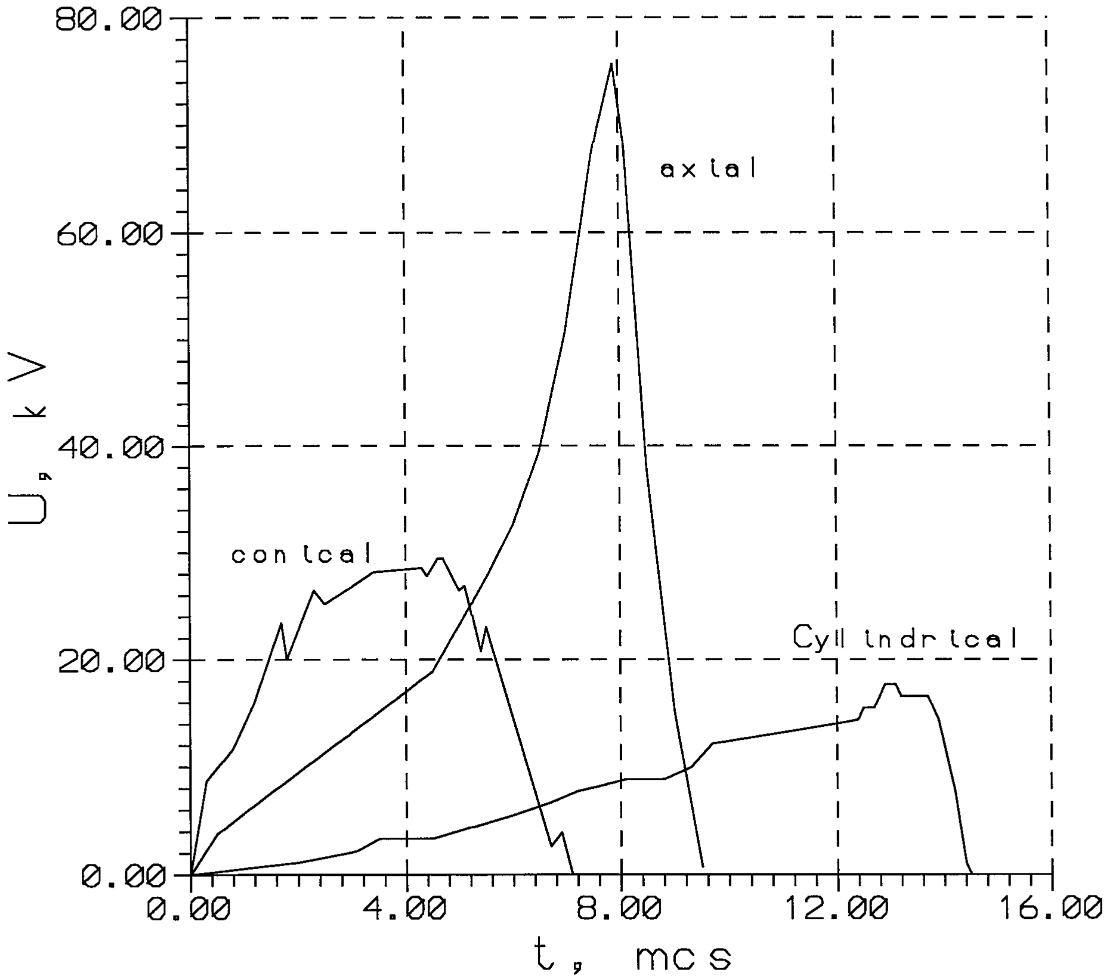

Fig.9a. Typical load voltage impulses.

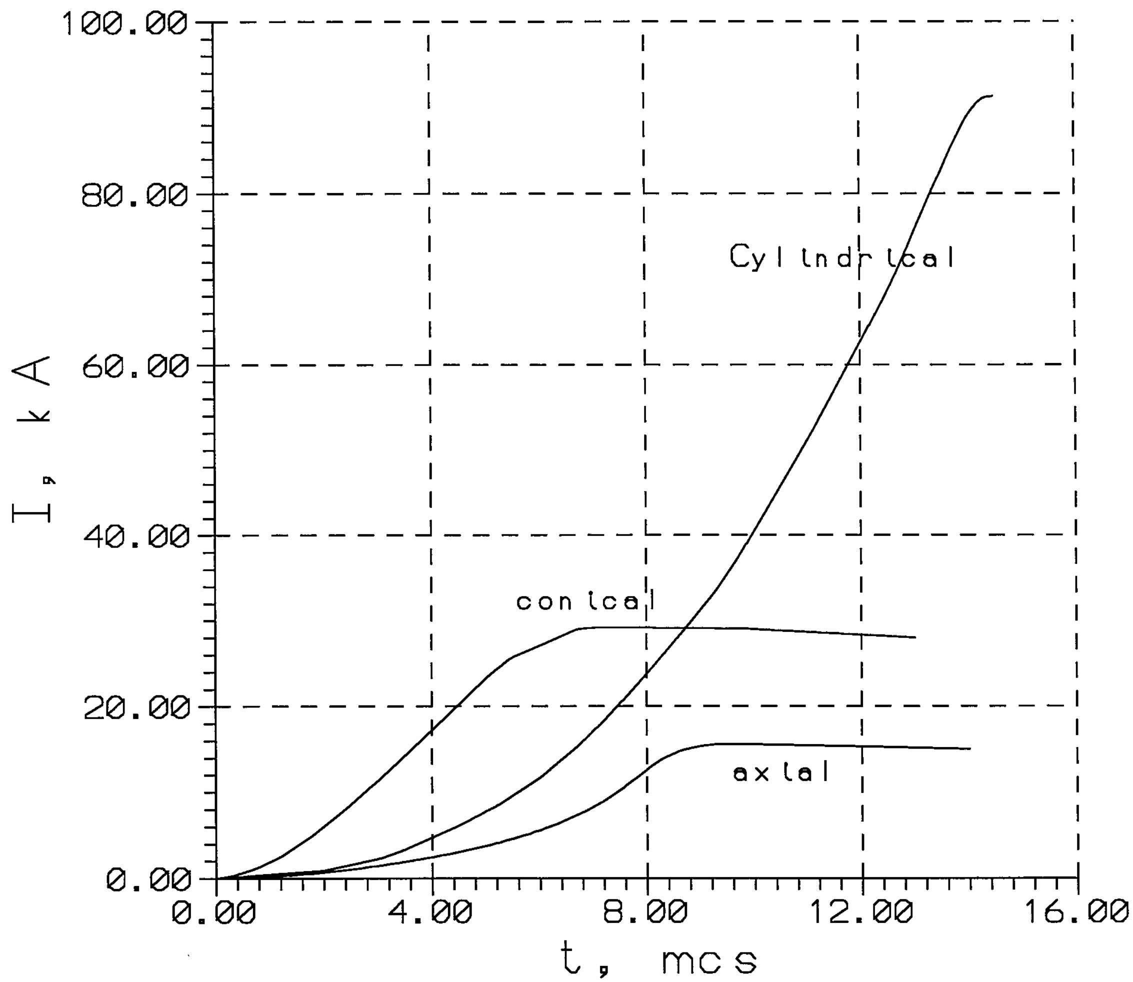

Fig.9b. Typical MFC current impulses.

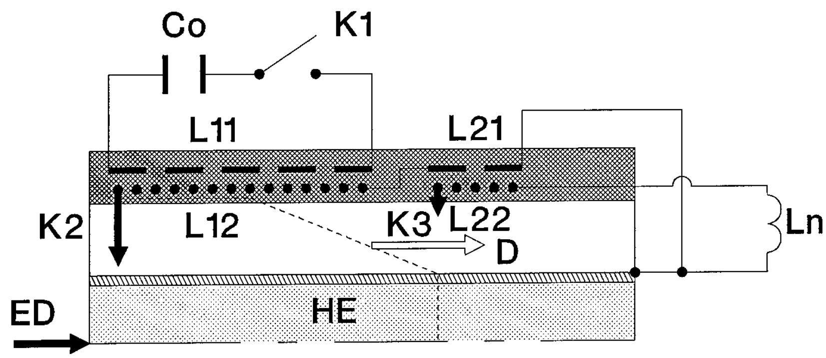

Fig.10. Scheme of two cascade MFC.

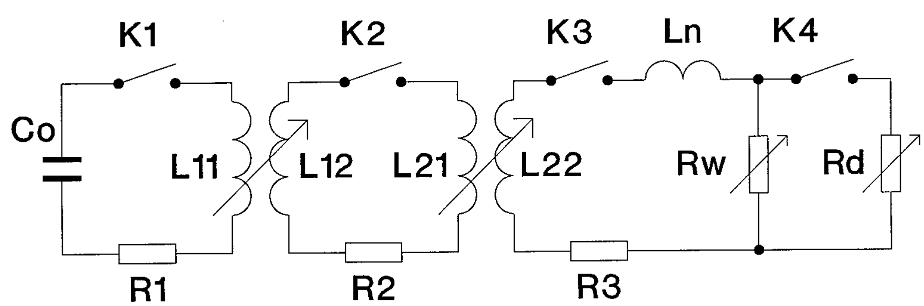

Fig.11. Equivalent electrical circuit.

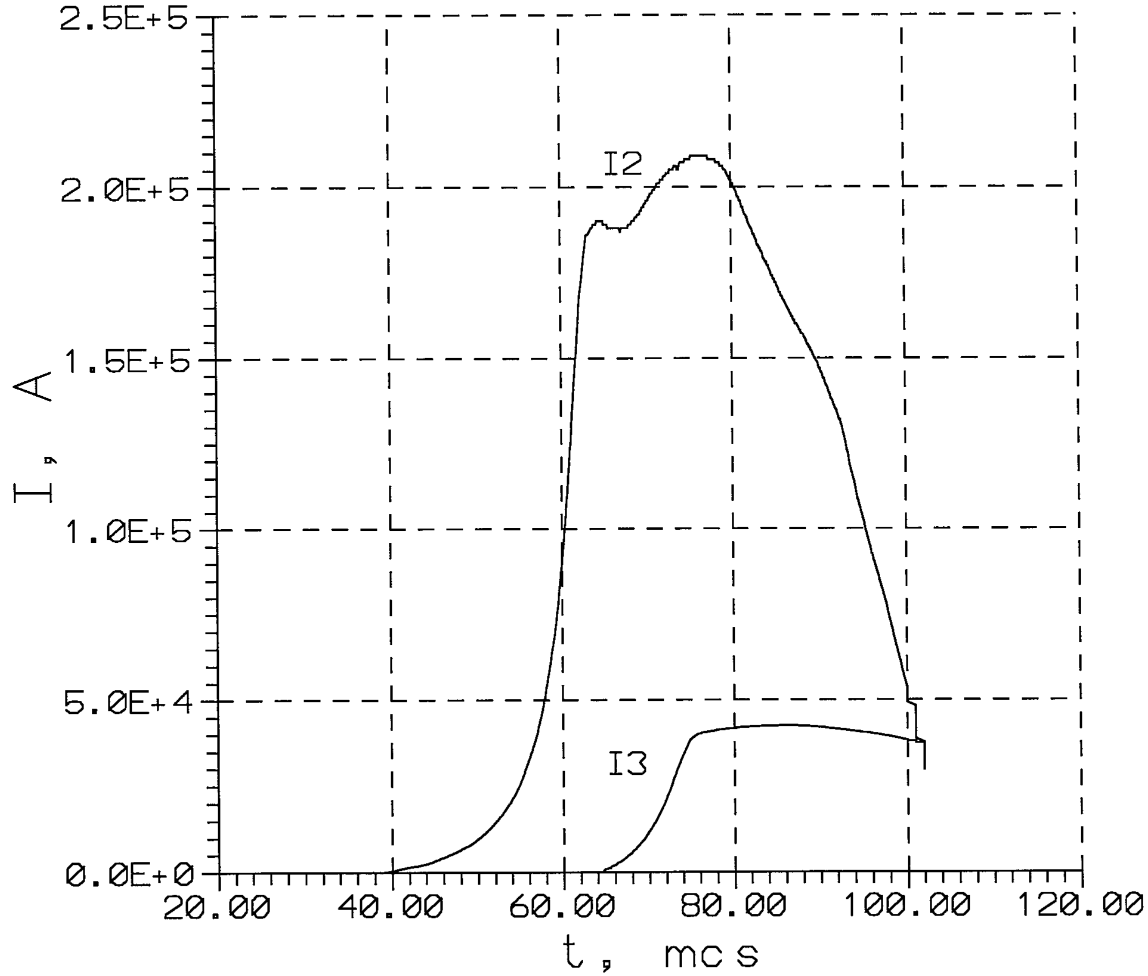

Fig.12. Currents in two cascade MFC.

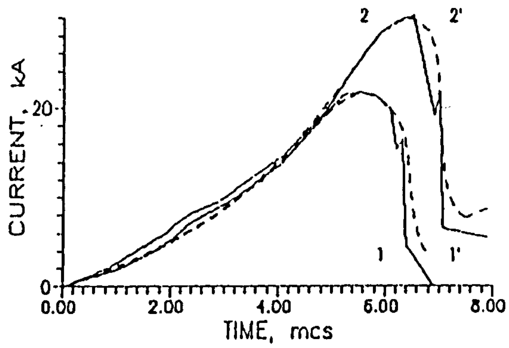

Fig.13a.MCG current waveforms.

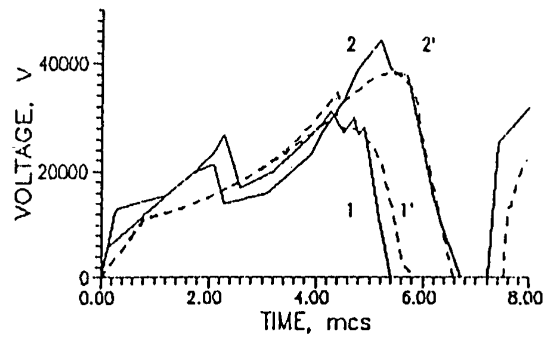

Fig.13b.Inductive load voltage waveforms.

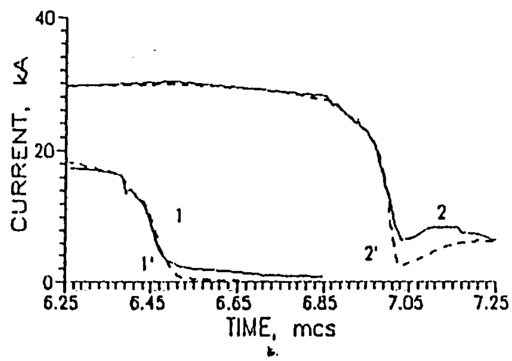

Fig.13c.EEOS current waveforms.

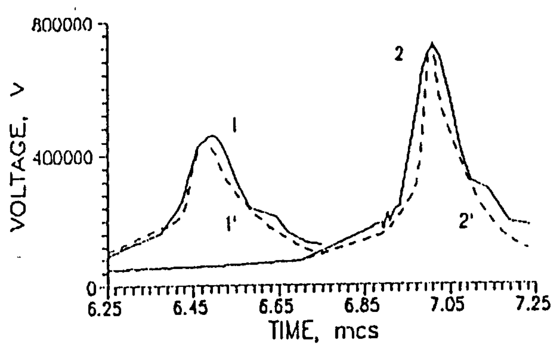

Fig.13d.EEOS voltage waveforms

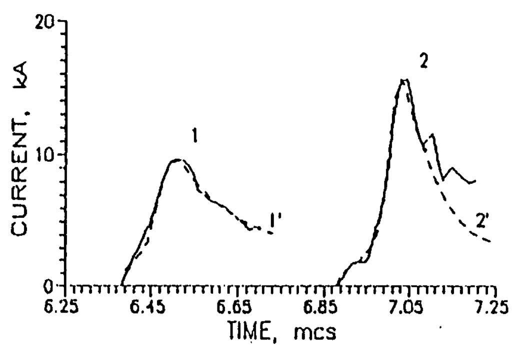

Fig.13e.VIRCATOR current waveforms.

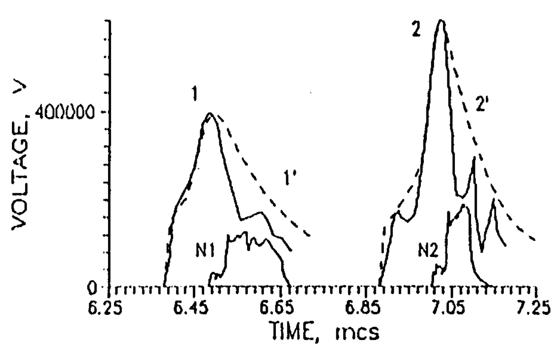

Fig.13f.VIRCATOR voltage and SHF-power waveforms

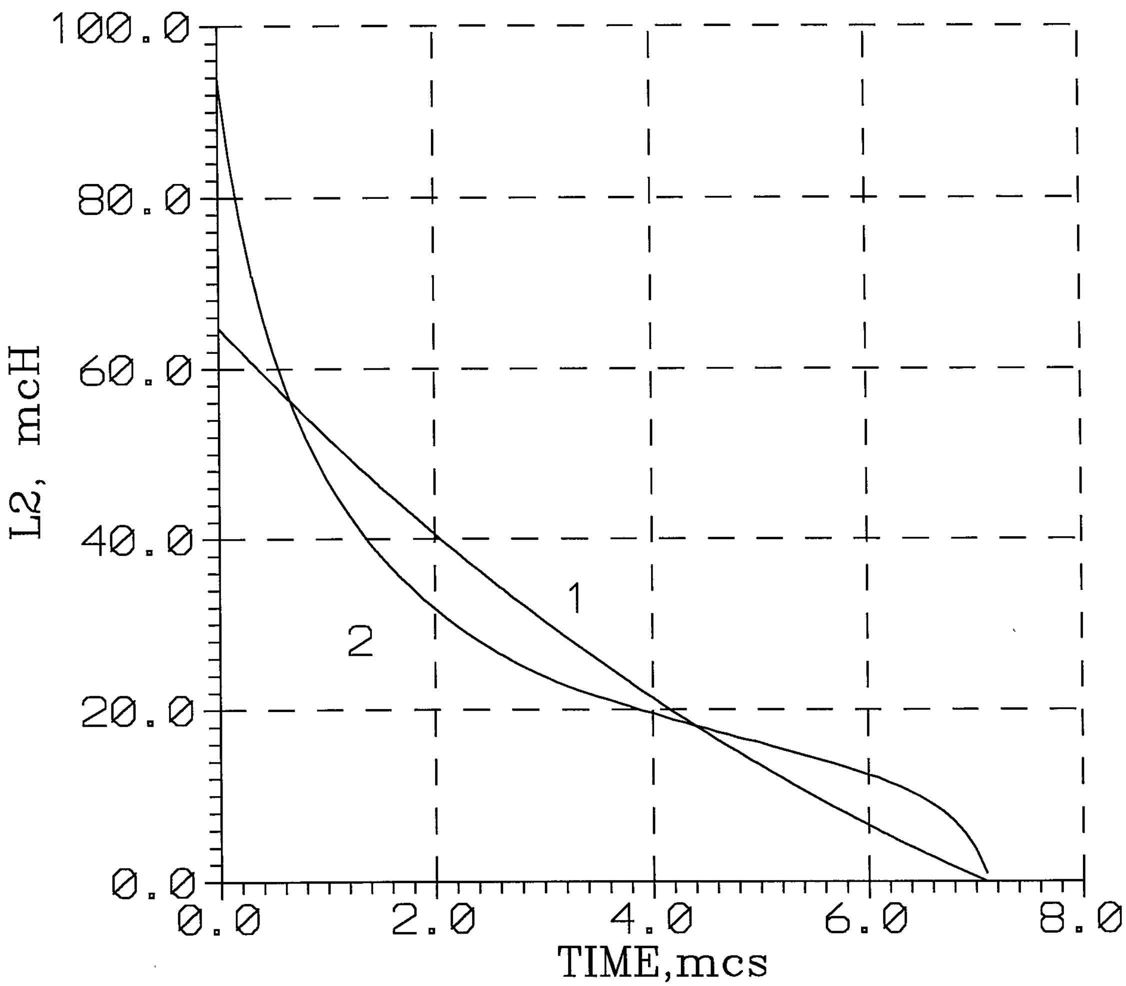

Fig.14. Real (1) and optimal (2) inductance output.