Axial Vircator for Electronic Warfare Applications

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Abstract. *This paper deals with a high power microwave generator with virtual cathode – vircator in axial release for electronic warfare applications. The classification of directed energy weapons microwave (DEWM) is introduced together with basic block diagrams of a particular class of DEWM. In the paper, methods for designing vircator pulsed power supply, axial vircator structure, measurement methods and experimental results are presented. The vircator in electromagnetic ammunition is powered by magneto-cumulative generator and in weapons for defense of objects (WDO), it is powered by Marx generator. The possible applications of a vircator in the DEWM area are discussed.*

Keywords

Electronic warfare, directed energy weapons microwave, high power microwave, magneto-cumulative generator, Marx generator, pulse forming line, vircator.

1. Introduction

Electronic warfare (EW) is defined as the art and science of preserving the use of the electromagnetic spectrum for friendly use while denying its use to the enemy. Electromagnetic spectrum is, of course, reaching from DC to light (and beyond). Thus, electronic warfare covers the full radio frequency spectrum, the infrared spectrum, the optical spectrum, and the ultraviolet spectrum.

Electronic warfare has classically been divided into:

- Electronic warfare support (ES), which includes the receiving part of EW.
- Electronic attack (EA), which includes jamming, chaff, flares used to interfere with the operation of radars, military communication, and head-seeking weapons. Over the last years, EA also includes antiradiation weapons (ARW) and directed energy weapons (DEW).
- Electronic protection (EP), which is directed into design or operation of radars or communication systems to counter the effect EA.

A detailed classification of EW can be found in [1].

Today the directed energy weapons (DEW) are significant in terms of the electronic attack (EA). Considerable financial resources are directed especially to the research of DEW working in microwave band (directed energy weapons microwave − DEWM), which derive their benefits from incidence of electromagnetic pulses (EMP) on electronic devices. The EMP effect was first observed during the early testing of high altitude airburst nuclear weapons [2]. The effect is characterized by production of a very short (hundreds of nanoseconds) but intense electromagnetic pulse, which propagates away from its source with ever diminishing intensity, governed by the theory of electromagnetism. The EMP is in effect an electromagnetic shock wave. This pulse of energy produces a powerful electromagnetic field, particularly within the vicinity of the weapon burst. The field can be sufficiently strong to produce short lived transient voltages of hundreds of volts to kilovolts on exposed electrical conductors, such as wires or conductive tracks on printed circuit boards.

At present, a high intensity EMP can be successfully generate without using nuclear weapons. This fact is very significant especially for applications in the EW area. It is this aspect of the EMP effect which is of military significance, as it can result in irreversible damage to a wide range of electrical and electronic equipment, particularly computers and radio or radar receivers. Depending on the electromagnetic hardness of the electronics (a measure of the equipment's resilience to this effect) and the intensity of the field produced by the weapon, the equipment can be irreversibly damaged or even electrically destroyed. The damage inflicted is not unlike the damage experienced by exposure to close proximity lightning strikes, and may require complete replacement of the equipment, or at least substantial portions of it [3], [4].

2. Directed Energy Weapons Microwave

Directed energy weapons microwave (DEWM) generate very high-powered electromagnetic impulse (EMP) in the microwave band. From the generated signal bandwidth point of view, there are two classes of generators for the design and construction of DEWM in order to produce electromagnetic field with sufficient power:

- Narrowband – very similar to the radar transmitters; usually generate a modulated harmonic signal. This class is called the high power microwave (HPM).
- Ultra-wideband (UWB) – generates high power videosignal illuminated by a broadband antenna.

The application of directed energy weapons microwave (DEWM) determines their design. There are two groups of directed energy weapons microwave:

- Single shot DEWM,
- Repetitive pulsed power systems.

The electromagnetic weapon modes closely relate to the mission of these weapons. Electromagnetic ammunition usually uses single shot DEWM while weapons for defense of objects (WDO) usually use repetitive pulsed power systems. The typical pulse repetition frequency of DEWM is nearly one thousand pulses per seconds. Recently, there has been a trend of increase in the pulse repetition frequency beyond tens of thousands pulses per seconds. The actual DEWM construction depends on the concrete supposed combat use, on the required measure, range and so on. The following text will be dedicated to experimental verification of some technology usable in narrowband DEWM or HPM. Questions regarding classification, construction and possible use of generators for DEWM are answered in more detail in [4], [5] and [6].

2.1 Basic Block Diagram of DEWM

HPM design depends on the specific assumed application of DEWM. There are difference approaches to the design and realization of electromagnetic ammunition and to the design and realization of weapons for defense of objects (WDO). These differences mostly affect the choice of the power sources and the construction of modulators. In electromagnetic ammunition, a highly limiting factor is the demand for low weight and small proportions. This fact also sharply limits the choice of the power microwave tube.

Electromagnetic ammunition usually uses single shot DEWM. The single shot high-energy high-voltage pulsed source has to fulfill hard requirements on the high amount of the delivered energy with respect to the source volume [MJ/m^3]. The best solution of this requirement is a magneto-cumulative generator that reaches up to 8000 MJ/m^3. A block diagram of a HPM generator in electromagnetic ammunition is shown in Fig. 1.

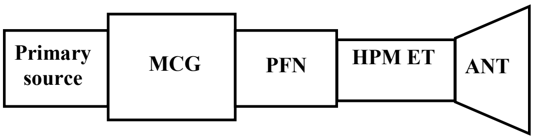


Fig. 1. Block diagram of a HPM generator in electromagnetic ammunition.

In the block diagram, the primary source feeds the stator coil of a magneto-cumulative generator (MCG), which creates a powerful magnetic field in the surrounding fittings filled with an explosive. At the moment of achieving the primary current peak value, the explosive is shooting. The explosion causes expansion of fitting that performs compression of the magnetic field inside the stator coil of MCG. Compression of magnetic field causes dramatic growth of the current flowing through MCG (hundreds of kiloamperes). The MCG output is connected to a pulse forming network that provides transformation of heavy current to an impulse high voltage (hundreds of kilovolts), which feeds a high power microwave electron tube (HPM ET). The generated microwave is emitted through antenna (ANT) to the space.

A block diagram of a HPM generator in weapons for defense of objects (WDO) is shown in Fig. 2.

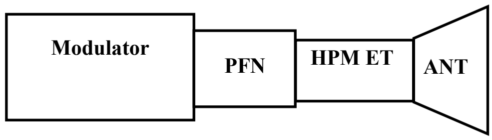


Fig. 2. The block diagram of HPM generator in Weapons for Defense of Objects (WDO).

In weapons for defense of objects (WDO), the HPM generator works similarly as the HPM generator in electromagnetic ammunition. Since WDOs usually generate power microwave pulses repetitively, a modulator with this capability has to be used instead of MCG. Modulators with Marx capacitor banks, Tesla transformers or transductors with fast opening switches are used most often. In this class of DEWM, other types of high power microwave electron tubes (HPM ET) are also used. They may generate microwave pulses with high pulse repetition frequency.

3. Energy Sources for Directed Energy Weapons Microwave

The electromagnetic pulse sources for DEWM are entirely based on energy acquired from the chemical energy of explosion that compresses the magnetic flux made by coil (MCG) or by discharging a capacitor bank. These two possibilities are the best solutions for generation of pulses with sufficient amount of energy in a short time. Other methods were used to generate pulses in the beginning of DEWM research or in laboratory.

3.1 Helical Magneto-Cumulative Generator

MCGs are entirely based on the energy acquired from chemical energy of explosion that compresses magnetic flux made by coil. MCG physical principles, classification and applications are described in more detail in [7]. The main part of research was focused on the possibility of using a magneto-cumulative generator for electromagnetic ammunition power supply. For that reason, 4 versions of low power MCGs were designed, realized and tested in order to verify their characteristics, construction principle, explosive initialization method and verifying a measurement method.

The tested magneto-cumulative generator in Fig. 3 consists of an aluminous cylindrical stator, inside is a 16 screw helical coil from 2 mm copper wire, a copper armature tube with 38 mm outer diameter and 4 mm wall thickness filed by octogen (explosive). The explosive is electrically initiated. The load coil represented by a copper strip in shape of a loop connects the stator with the armature. In the right side of stator, there is a crowbar switch made of a brass plate to perform disconnecting of the primary current source. An insulator circle is responsible for separation of the stator and the armature.

Fig. 3. Low power MCG.

Low power magneto-cumulative generator characteristics:

C_1 = 190 µF − primary capacitor capacity

U_0 = 800 V − voltage of capacitor

L_G = 13.1 µH − stator coil inductance

R = 0.0175 Ω − stator coil resistance

T_0 = 3.13×10^{-4} s − primary current period

I_m = 2750 A − maximum primary current

T_d = 73 µs − explosive initiation delay

Fig. 4 presents the low power magneto-cumulative generator output current time history calculated from the voltage measured by Rogowski coil. The primary current I_m = 2750 A gives the generator peak output current I_{out} = 27 kA. The detailed test description and measured results can be found in [8], [9], [10] and [11]. The purpose of the mentioned tests was:

- Verify the method of generating a high energy pulse by magnetic flux compression using explosive;
- Solve the primary current magneto-cumulative generator power supply;
- Find the peak primary current and an explosive initiation synchronization method;
- Find a high current measurement method.

All the requirements were met.

To use a magneto-cumulative generator for single

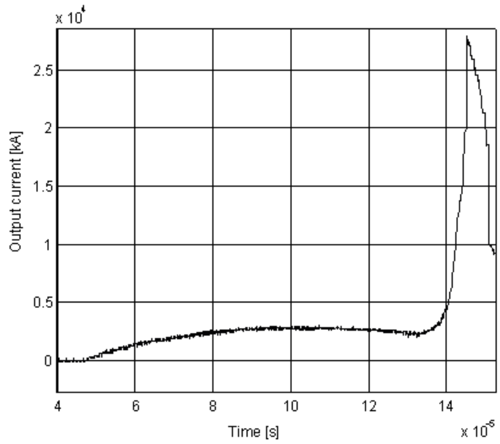
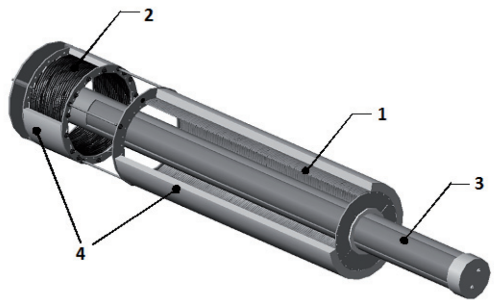


Fig. 4. Low power magneto-cumulative generator output current time history.

shot high power high voltage pulse generator, it is necessary to obtain a high-level output current. Because of that reason, a middle power MCG was designed and realized. It is a two-stage helical magneto-cumulative generator using a dynamic transformer to increase the output voltage. In Fig. 5, there is a schematic plot of the generator's first stage. The magneto-cumulative generator power supply primary current, the initiation of the explosive and the output high current measure was analogical to the low power magneto-cumulative generator described above.



1 – First stage coil, 2 – Load coil, 3 – Armature with explosive, 4 – Insulator

Fig. 5. Schematic drawing of first stage of middle power MCG.

Fig. 6 shows a photo of the middle power magneto-cumulative generator's first stage prepared to the test.

Magneto-cumulative generator characteristics:

C_1 = 125 µF − primary capacitor capacity

U_0 = 5000 V − voltage of capacitor

L_G = 323 µH − stator coil inductance

T_0 = 3×10^{-3} s − primary current period

I_m = 2650 A − maximum primary current value

L_L = 300 nH − load inductance

Fig. 6. The picture of middle power MCG prepared to testing.

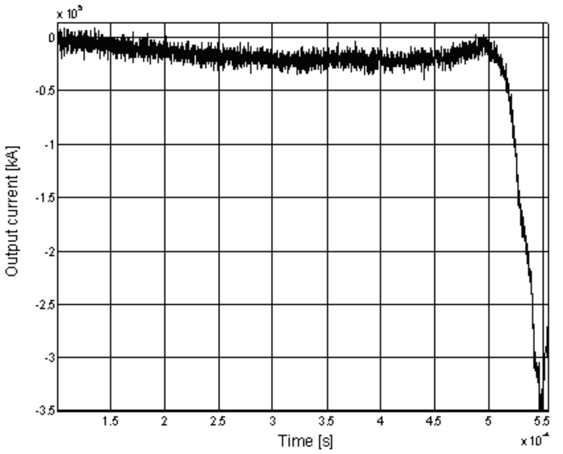


Fig. 7. Middle power magneto-cumulative generator output current time history.

In Fig. 7, the generator output current time history measured during test is shown. The primary current $I_m = 2650$ A gave the generator peak output current $I_{out} = 350$ kA.

The next step in the magneto-cumulative generator research is the implementation and verification of a dynamic transformer. The dynamic transformer's role is an increase of the output voltage to about 70 kV. Magneto-cumulative generator's second stage supplies a load coil through an electric breaker. The beaker interrupts the current in the load circuit in a very short time to enable transfer of the energy from the magnetic field to the high voltage pulse. These activities will be done in the next step of the research and development. The further trends are described in [12].

3.2 Pulsed Power Supply With Capacitive Storage of Energy

For some pulse applications in weapons for defense of objects (WDO), it is desirable to couple the Marx generator directly to the vacuum diode; however, the pulse rise time is then limited by the Marx inductance and capacitance, and the impedance of the generator is greater than typically several tens of ohms. In order to produce short, fast-rising, low-impedance beam outputs, it is customary to use the Marx to charge a pulse-forming line (PFL). Although the PFLs may be constructed in a variety of shapes (strip, coaxial, radial, etc.), they are typically used in only two types of circuits— the simple transmission line, and the double, or Blumlein line. In contrast to the simple transmission line, an alternate circuit invented by A. D. Blumlein is capable of producing an output pulse into a matched load that equals the charge voltage. A cylindrical version of the Blumlein circuit fabricated by our team is represented in Fig. 8. It consists of three coaxial cylinders with the intermediate cylinder being charged by the Marx generator. The Marx generator is shown in Fig. 9. The center cylinder is connected to the outer grounded cylinder by an inductor. Ideally the inductor acts as a short during the charge cycle, and then as an open for the short duration of the output pulse [13]. Pulsed power supply parameters are shown in Tab. 1.

Marx generator		**Pulse forming line**	
Number of stage	n=18	Impedance	9,1 Ω
Capacity of 1stage	100 nF	Length	1 m
Input voltage	U_{in}=25 kV	Pulse duration	60 ns
Output voltage	U_{out}=450 kV	Working medium	water

Tab. 1. Pulsed power supply parameters.

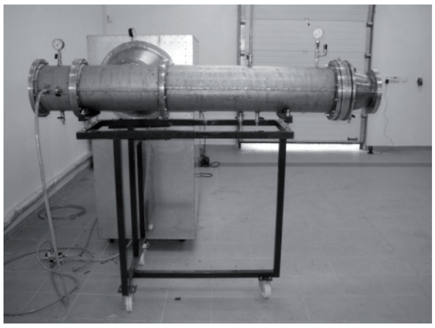


Fig. 8. Cylindrical version of the Blumlein circuit.

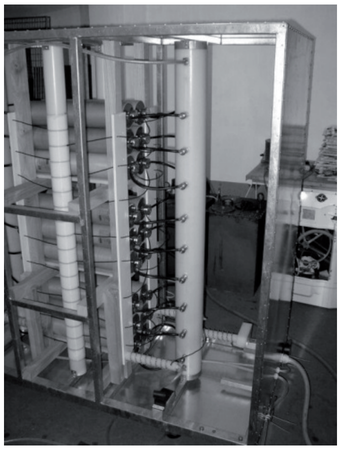


Fig. 9. Marx generator.

4. High Power Microwave Generator

A wide range of HPM devices exists. Relativistic klystrons, magnetrons, slow wave devices, reflex triodes and vircators are all examples of the available technology base [5]. From the perspective of an electromagnetic weapon or warhead designer, the device of choice will be the vircator at this time. The vircator is mainly a one shot device capable of producing a very powerful single pulse of radiation, yet it is mechanically simple, small and robust, and can operate over a relatively broad band of microwave frequencies. The physics of the vircator tube are substantially more complex than those of the preceding devices. The fundamental idea behind the vircator is that of accelerating a high current electron beam against a foil or a grid anode. Many electrons will pass through the anode, forming a bubble of space charge behind the anode. Under the proper conditions, this space charge region will oscillate at microwave frequencies. If the space charge region is placed in a resonant cavity which is appropriately tuned, very high peak powers may be achieved. Conventional microwave engineering techniques may then be used to extract the microwave power from the resonant cavity. Because the frequency of oscillation is dependent upon the electron beam parameters, vircators may be tuned or chirped in frequency, where the microwave cavity will support appropriate modes. Power levels achieved in vircator experiments range from 170 kW to 40 GW over frequencies spanning the decimeter and centimeter bands [5].

4.1 Vircator Operation Fundamentals

The basic idea of the vircator is to accelerate a dense flush of an electron beam against a grid or a foil anode. Plenty of electrons pass through the anode and form a region of a space charge behind the anode called ”virtual cathode“. This region of a space charge at corresponding conditions can oscillate in a region of microwave frequencies. It is possible to tune the vircator in a broad band of frequencies using only a change of a space charge density. There is no necessity to have an external magnetic field for a correct vircator function. In Fig. 10, an axial vircator is shown. Electron beam passes through the foil or the grid anode. Microwave power is brought out axially, too. Frequency changes appear in vircator with standard geometry when the distance between the anode and the cathode gets smaller due to filling the working space by plasma. Efficiency of a standard geometry vircator is ordinarily about ones percent.

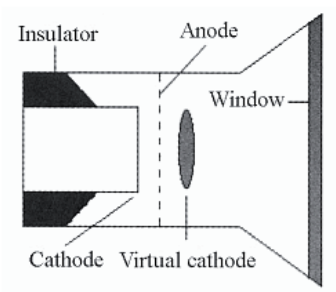


Fig. 10. Schematic drawing of axial vircator.

Despite its low efficiency, vircator is very attractive for army applications because it is very simple to be made, it is a compact device and there it is no need to have an external magnetic field. For more information about construction and properties of various types of vircators you can see e. g. [5], [13] and [14].

4.2 Mathematical Description of Vircator Operation

For microwave frequency generation, it is necessary to meet a number of conditions relevant to the power supply and geometric proportions of a vircator electrode. Determination of these conditions results from [15] and we use simplified geometry displayed in Fig. 11 to derive the mathematical characterization.

The most common case is that a pulse duration τ is much longer than a beam transit time across cavity $\tau >> L/C$.

We assume that an external axial magnetic field obstructs transverse electron motion. The space charge of the beam makes a negative potential energy $e\Phi$ in drift space which breaks the electrons. If the space charge potential reaches the value of accelerating voltage (electrons are stopped in beam), the beam with bigger current cannot expand. There is a value of current which causes stopping of electrons. This value is called the vacuum critical current. There has to be the above mentioned critical current to make the vircator generate microwave oscillations.

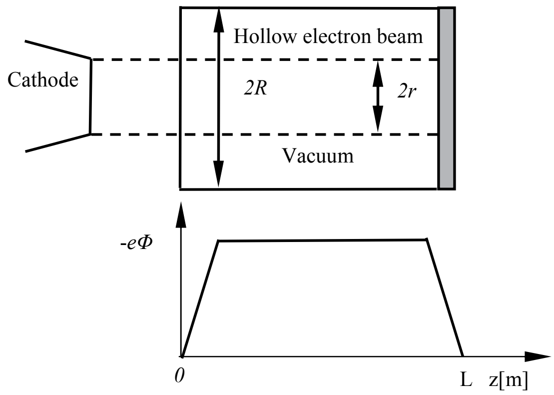


Fig. 11. Simplified geometry of axial vircator.

We suppose a hollow beam; whose charge is concentrated in a thin layer with radius r. Behind the transition space (which is comparable to the radius of chamber – backward conductor), there is nearly homogenous potential. It is possible to determine the potential quantity with consideration that it is a coaxial capacitor and its inner cylinder is saturated by beam charge.

Capacity of the coaxial capacitor is given by

$$C = \frac{2 \cdot \pi \cdot \varepsilon_0}{\lg\left(\frac{R}{r}\right)} \tag{1}$$

where ε_0 is the vacuum electric permittivity, R is the chamber radius, r is the beam radius.

The potential is given by the equation

$$\Phi = \frac{Q}{C} \tag{2}$$

where Q is the charge linear density, C is the capacity per length unit. We can define the charge linear density as

$$Q = \frac{I}{v} \tag{3}$$

where v is an electron module velocity and the current is defined by the equation

$$I = e \cdot n \cdot v \cdot S \tag{4}$$

where e is the charge of an electron, n is the linear electron density, S is the profile of the electron beam.

When (1) and (3) are substituted into (2), we can obtain expression for the potential in the form

$$\Phi = \frac{Q}{C} = \frac{I \cdot \lg\left(\frac{R}{r}\right)}{2 \cdot \pi \cdot \varepsilon_0 \cdot v}. \tag{5}$$

The electron velocity v is associated with its initial energy and potential by the energy preservation law

$$m_e \cdot \gamma_0 \cdot c^2 + e\Phi = m_e \cdot \gamma \cdot c^2 \tag{6}$$

where γ_0 is the initial relativistic factor of the beam, γ is the relativistic factor inside a system reduced due to potential.

The relativistic factor inside a system can be expressed by the equation

$$\gamma = \gamma_0 + \frac{e\Phi}{m_e \cdot c^2} \tag{7}$$

where m_e is the electron mass and c is the speed of light. The relativistic factor can also be expressed by

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \; . \tag{8}$$

The electron velocity in drift space v can be specified from following equations:

$$\gamma^2 = \left(\gamma_0 + \frac{e\Phi}{m_e \cdot c^2}\right)^2 , \tag{9}$$

$$v = c \cdot \sqrt{1 - \frac{1}{\left(\gamma_0 - \frac{e\Phi}{m_e \cdot c^2}\right)^2}} \; . \tag{10}$$

Substituting (10) into (3) and multiplying by $(e \cdot v) / (m \cdot c^3)$, we can get

$$F(\Phi) = \frac{e \cdot \Phi}{m \cdot c^2} \cdot \sqrt{1 - \frac{1}{\left(\gamma_0 - \frac{e\Phi}{m_e \cdot c^2}\right)^2}} = \frac{e \cdot I \cdot \lg\left(\frac{R}{r}\right)}{2 \cdot \pi \cdot \varepsilon_0 \cdot m \cdot c^3} . \tag{11}$$

The function $F(\Phi)$ has its peak value under the conditions describes by

$$\frac{e \cdot \Phi}{m \cdot c^2} = \gamma_0 - \gamma^{\frac{1}{3}} \; . \tag{12}$$

The evaluation is written in the form

$$F(\Phi) = \sqrt{\left(\gamma^{\frac{2}{3}} - 1\right)^3} = \frac{e \cdot I \cdot \lg\left(\frac{R}{r}\right)}{2 \cdot \pi \cdot \varepsilon_0 \cdot m \cdot c^3} \; . \tag{13}$$

There is no possibility to find the solution of (11) for bigger values of function $F(\Phi)$. According to (13), the critical vacuum current is

$$I_{cr} = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot m \cdot c^3}{e \cdot I \cdot \lg\left(\frac{R}{r}\right)} \sqrt{\left(\gamma^{\frac{2}{3}} - 1\right)^3} \; . \tag{14}$$

When we substitute the known constants (like π = 3.1415), we obtain the equation

$$I_{cr} = \frac{8.5}{\lg\left(\frac{R}{r}\right)} \sqrt{\left(\gamma^{\frac{2}{3}} - 1\right)^3} \tag{15}$$

where I_{cr} is the critical vacuum current [kA].

For vircator implementation, energy of electrons of about 500 keV is considered, which corresponds to the relativistic factor of $\gamma_0 = 2$. Thus planar diode current limited by space charge follows the three-half Child-Langmuir law

$$I \approx \frac{U^{\frac{3}{2}} \cdot S_k}{d_{ka}^{\;2}} \tag{16}$$

where U is the voltage between anode and cathode, S_k is the surface of cathode, d_{ka} is the distance between anode and cathode.

An important characteristic of a vacuum planar diode is its impedance, which is given by

$$Z = 1.36 \cdot 10^5 \cdot U^{-\frac{1}{2}} \cdot \frac{d_{ka}^2}{r_k^2} \tag{17}$$

where r_k is the radius of the cathode.

The vacuum critical current is the maximal current that can distribute itself through vacuum. It means it is possible to measure the same current until the distance is bigger than the diameter of beam. It is just the same value when the potential of space charge of electron beam is equal to the accelerating voltage. That is the limit where the virtual cathode is generated and the vircator starts working. The generated frequency depends on the plasma frequency of the electron beam. The plasma frequency is determined by the electron beam current density. The plasma frequency is the frequency of electrons in space charge field oscillations. The electrons can oscillate due to the influence of repulsive force which takes effect between particles with the same charge. The plasma frequency depends on the concentration of electrons in the beam. The current density is given by the number of charges which are able to pass through the surface of 1 m^2 per one second. Thus we can calculate the current density i [Am^{-2}]

$$i = e \cdot n_V \cdot c_e \tag{18}$$

where e is the electron charge, n_V is the electron volume density and c_e is the electron velocity.

Plasma frequency of the electron beam is approximately given by

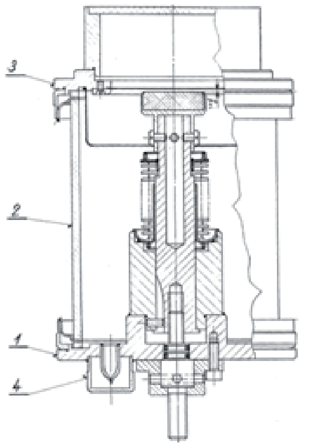
$$f_{pe} = 9 \cdot 10^7 \cdot \sqrt{i} \ . \tag{19}$$

4.3 Axial Vircator Design

Following the theoretical assumptions given above, the axial vircator with grid anode was fabricated. The structure of the grid anode enables repeated operation in contradistinction to vircator with a foil anode. The cathode diameter $r_k = 17.5$ mm and the working chamber radius $R = 40$ mm were chosen in order to decrease the value of the vacuum current. The critical vacuum current is $I_{cr} = 4.63$ kA in this configuration. The vircator impedance matching to the forming line is a very important requirement for vircator's correct operation. Because of that, a cathode with a possibility to change the distance d_{ka} between cathode and anode is fabricated. The cathode is made as a cylindrical carbon block. The anode grid is made from pyrolitic carbon.

In Fig. 12, there is section picture of the built-up axial vircator with the possibility to the change distance between anode and cathode. In Fig. 13, there is a view of the fabricated vircator. The vircator is fed by a pulse generator formed by Marx generator and pulse forming line described in Section 3.2. The connection between the axial vircator and the output of pulse forming line is shown in Fig 14. Vircator voltage is measured by a cylindrical capacitive probe, which is a part of pulse forming line output circuit. Vircator current is measured by Rogowski coil placed in the outer cylinder of the pulse forming line. Vircator voltage time history is displayed in Fig. 15 and vircator current time history is displayed in Fig. 16.

Compared to other types of microwave tubes, the microwaves generated by an axial vircator cover a relatively wide frequency band. In Fig. 17, the frequency spectrum of the signals generated by the realized axial vircator is shown. The dominant frequencies of the generated microwave signals are placed in the band of 0.5 to 1.5 GHz. The frequency spectrum was acquired on the basis of information measured by a digital oscilloscope Tektronix TDS 7704B connected to broadband antenna EMCO 3115. For the measurement the microwave output power of the vircator, a measuring device was designed and made, using calorimetric method for the power measurement. A detailed power sensor description can be found in [18]. A more detailed description the of axial vircator research results is given in [6], [14], [16] and [17].



1 cathode contact ring, *2* ceramic insulator, *3* anode contact ring, *4* pipe for vacuum pumping shelter

Fig. 12. Section picture of built-up axial vircator with possibility to change distance between anode and cathode.

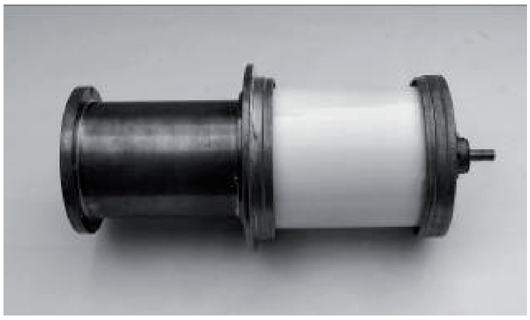


Fig. 13. View of fabricated axial vircator with adjustable distance between anode and cathode.

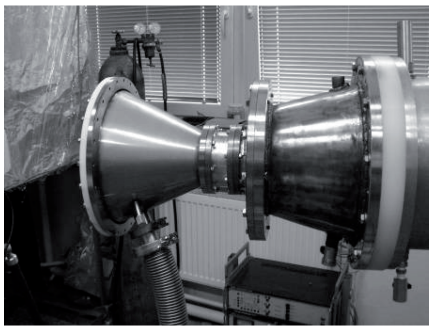


Fig. 14. View of fabricated axial vircator connected to the pulse forming line.

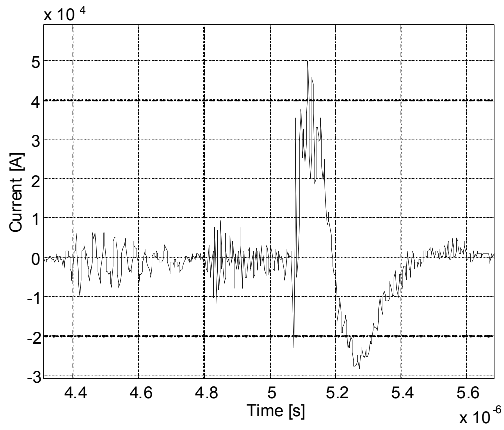


Fig. 15. Vircator current time history.

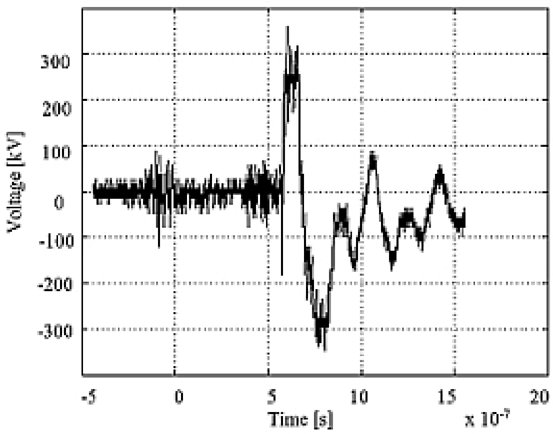


Fig. 16. Vircator voltage time history.

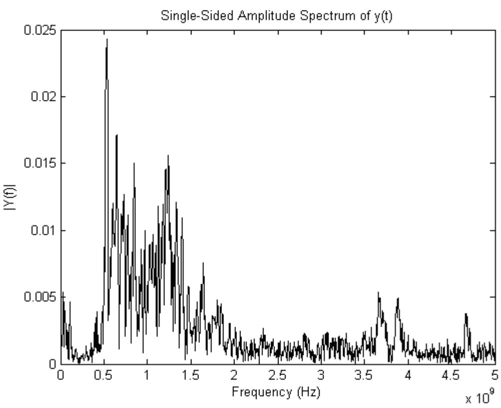


Fig. 17. Frequency spectrum of signals generated by realized axial vircator.

5. Conclusion

The research of directed energy weapons microwave validated substantial technology applicable in electromagnetic ammunition and in weapons for defense of objects (WDO). The axial vircator is the most important component part applicable in both categories of DEWM. Dominant frequencies of the generated microwave signal are placed in band of 0.5 to 1.5 GHz. To fulfill the vircator minimal proportion requirements to be able to use the vircator as a DEWM, it is necessary to shift the vircator dominant frequencies to the 3 GHz band. This requirement can be reached by arranging the cathode size efficiently and consequentially optimizing the distance between anode and cathode. Great attention also has to be paid to increase the specific dielectric strength of the output window of the axial vircator.

Acknowledgements

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